Neutrinoless double-beta decay: recent results and future experiments

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THE UNIVERSITY of EDINBURGH

The world's $0\nu\beta\beta$ programme

Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES-III	^{48}Ca	305 kg	^{nat}CaF$_2$ scint. crystals	Operating	Kamioka
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LEGEND-200	^{76}Ge	200 kg	^{enr}Ge semicond. det.	Commissioning	LNGS
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CUPID-0	^{82}Se	10 kg	Zn^{enr}Se scint. bolometers	Prototype	LNGS
SuperNEMO-Dem	^{82}Se	7 kg	^{enr}Se foils/tracking	Operation	Modane
Selena	^{82}Se		^{enr}Se, CMOS	Development	
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SuperNEMO	Any solid	100 kg	Foils/tracking	Proposal	Modane
ZICOS	^{96}Zr	865 kg (@ 50%)	Cherenkov and scint. in liq. scint.	Development	Kamioka
CUPID-Mo	^{100}Mo	4 kg	Li^{enr}MoO$_4$,scint. bolom.	Prototype	LNGS
AMoRE-I	^{100}Mo	6 kg	^{40}Ca^{100}MoO$_4$ bolometers	Operation	YangYang
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CUPID	^{100}Mo	450 kg	Li^{enr}MoO$_4$,scint. bolom.	Proposal	LNGS
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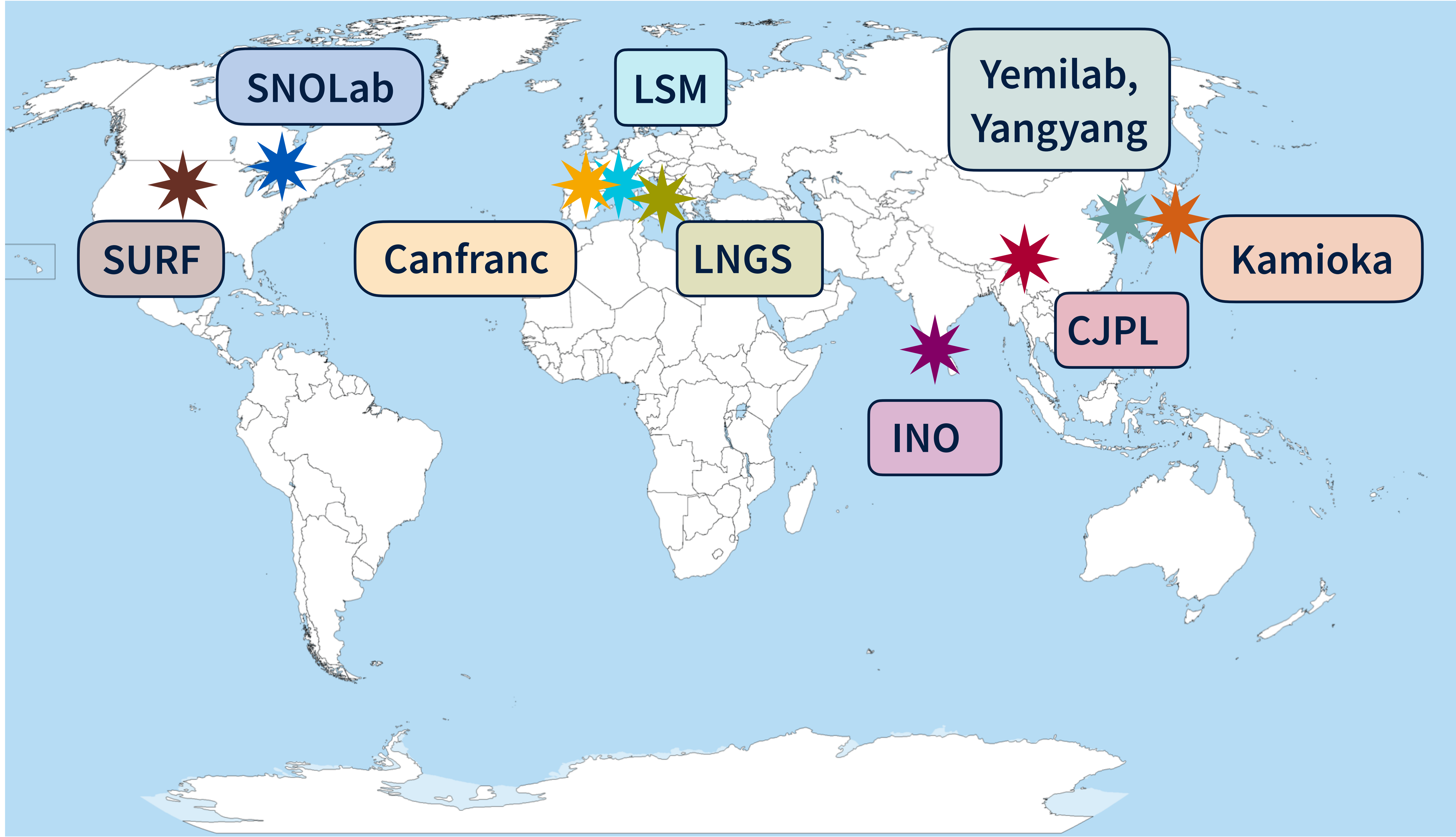
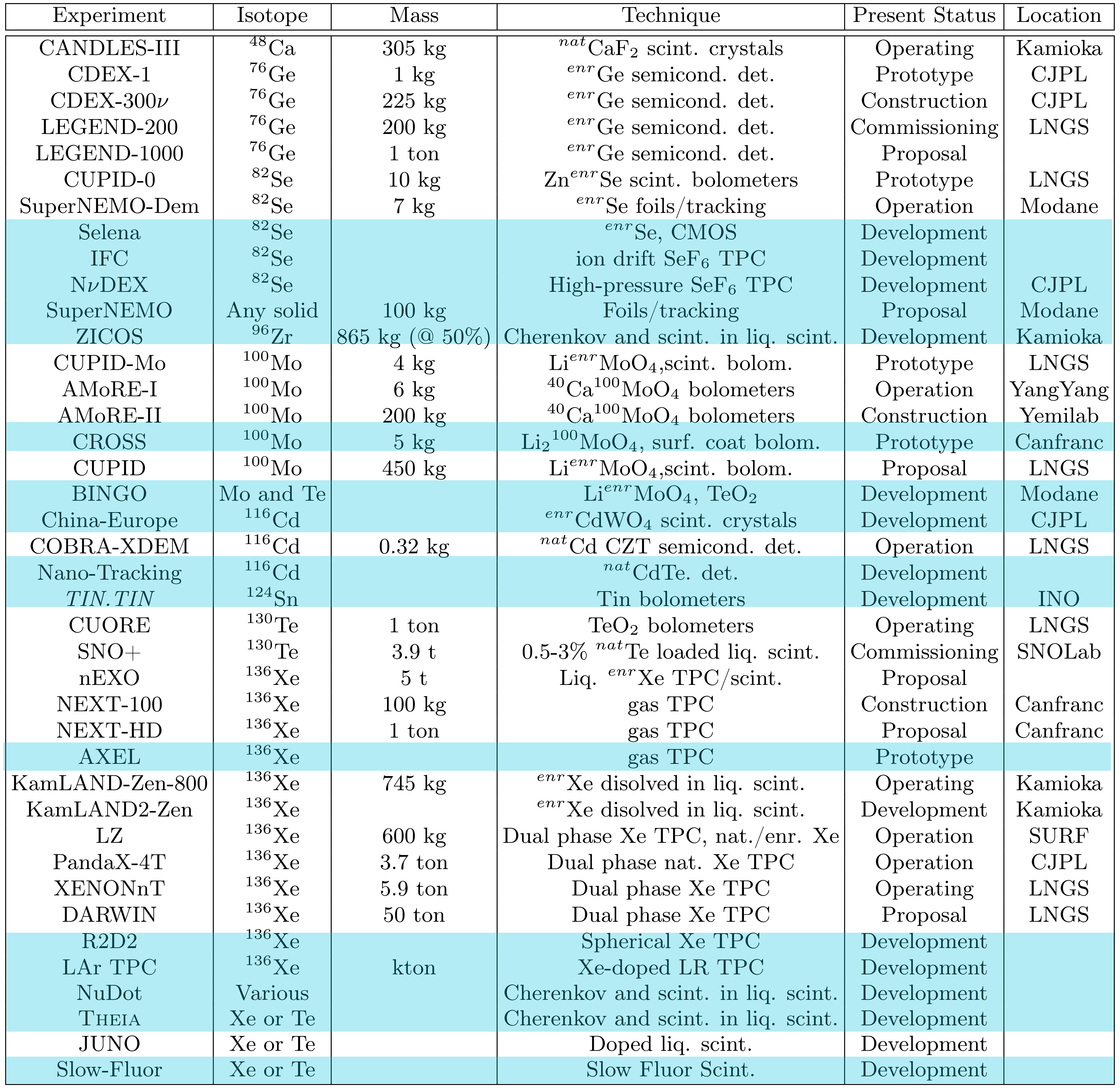
Table adapted from arXiv:2212.11099



The world's $0\nu\beta\beta$ programme



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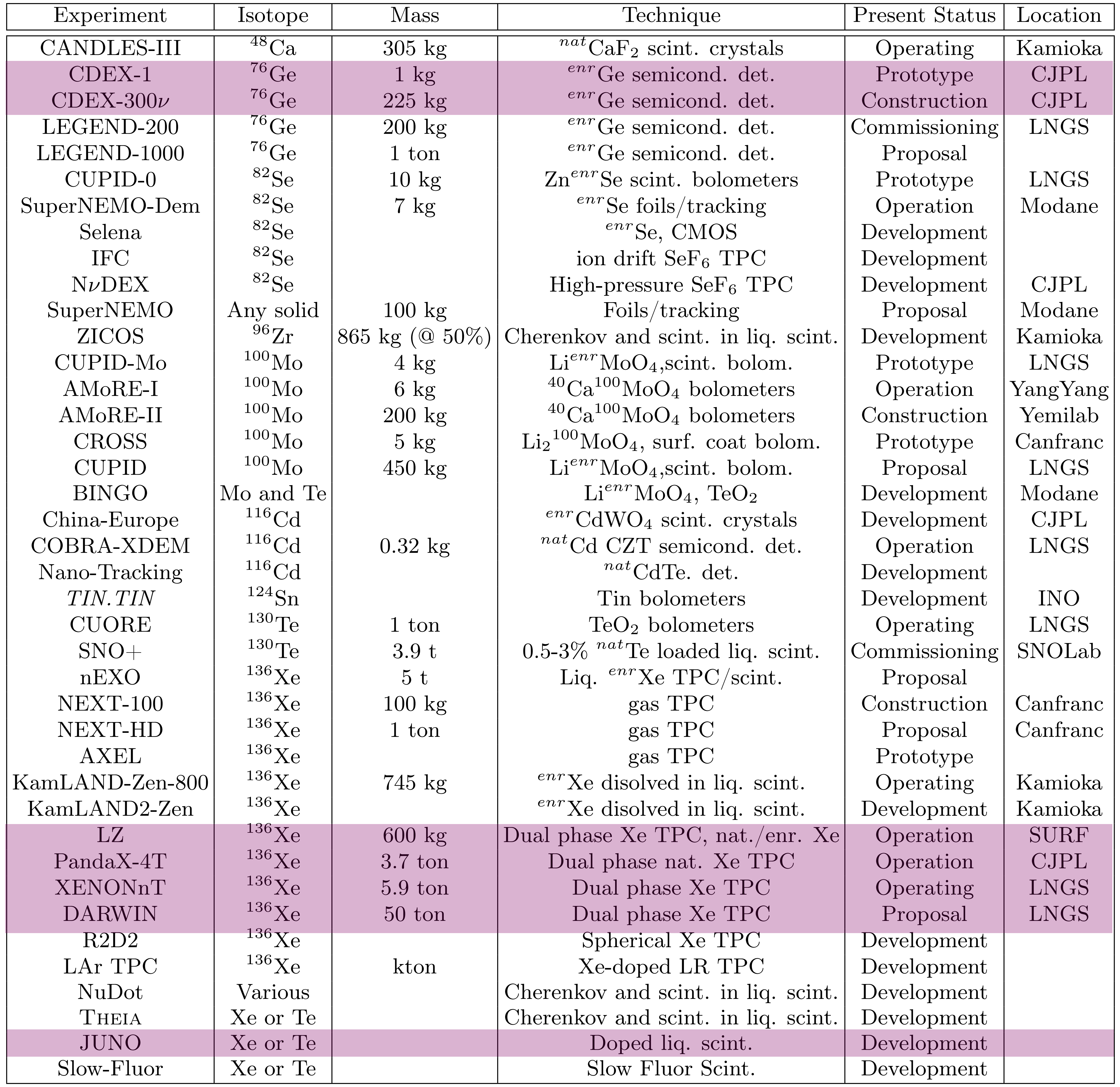
Development / prototyping / conceptual phase

The world's $0\nu\beta\beta$ programme



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Multi-purpose detectors proposing a $0\nu\beta\beta$ aspect

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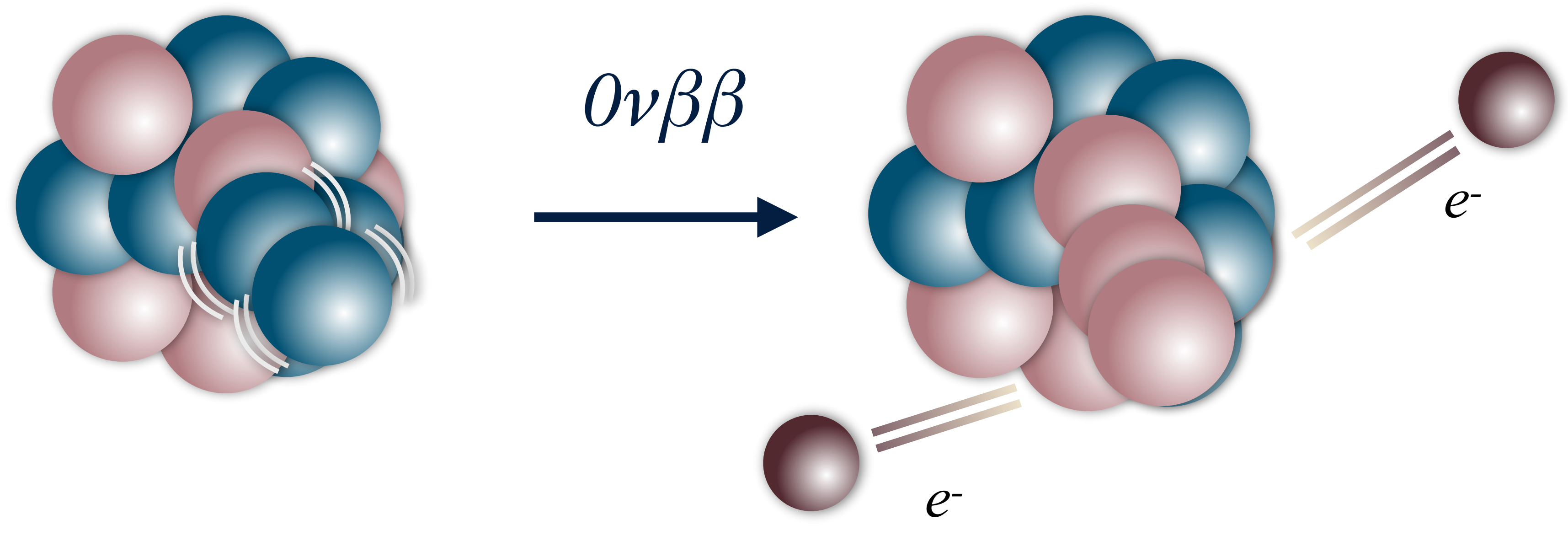
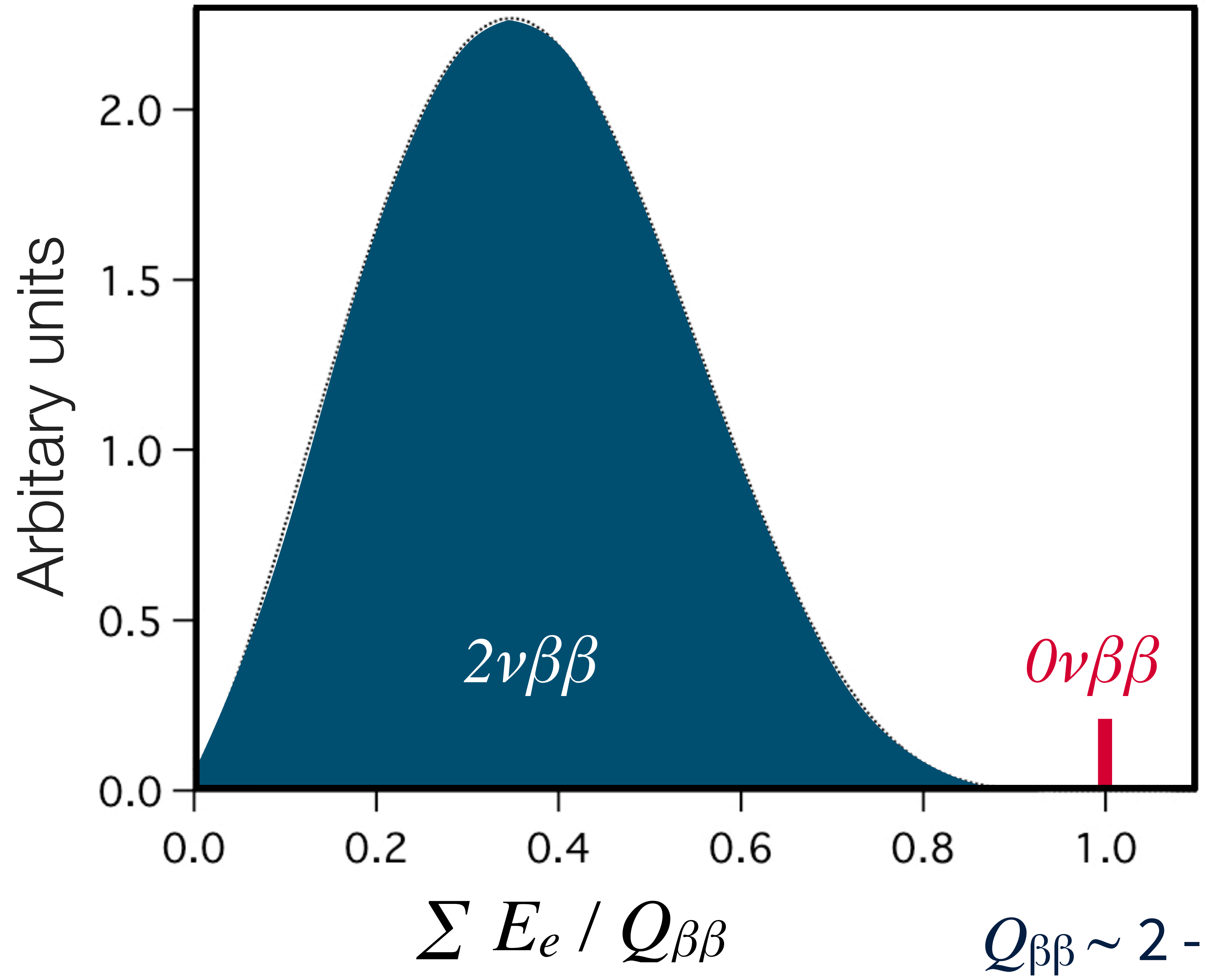
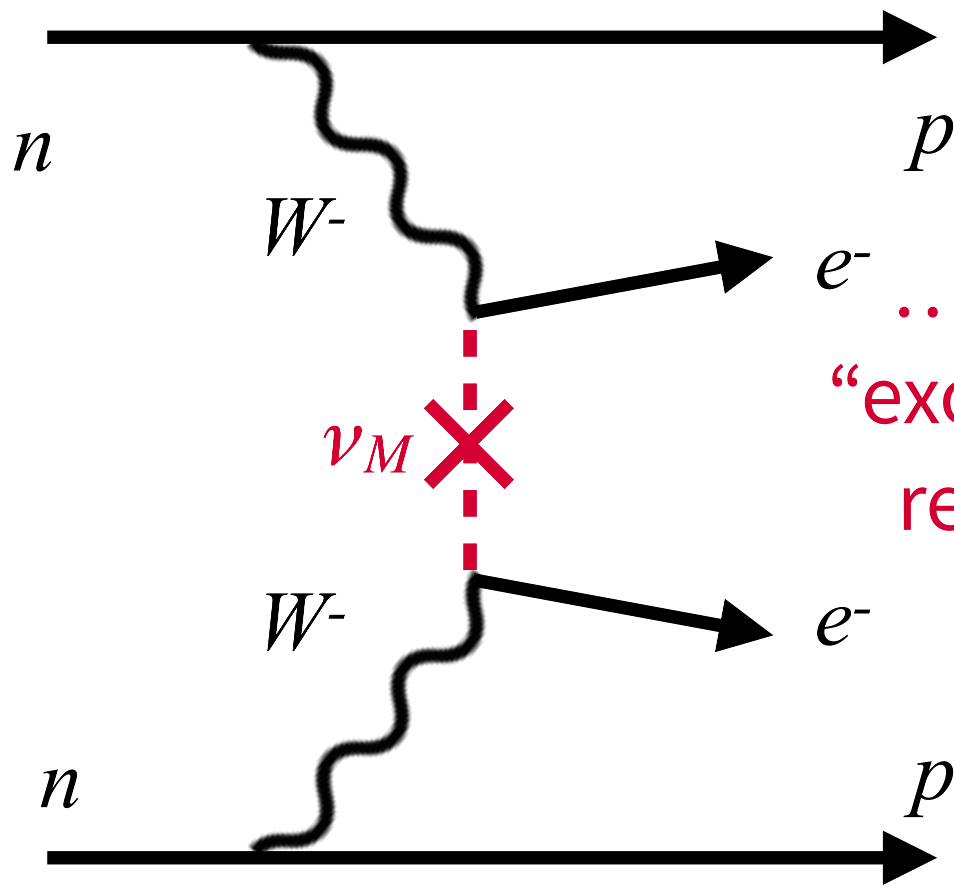
On-going $0\nu\beta\beta$ programmes

Neutrinoless double-beta decay - a reminder

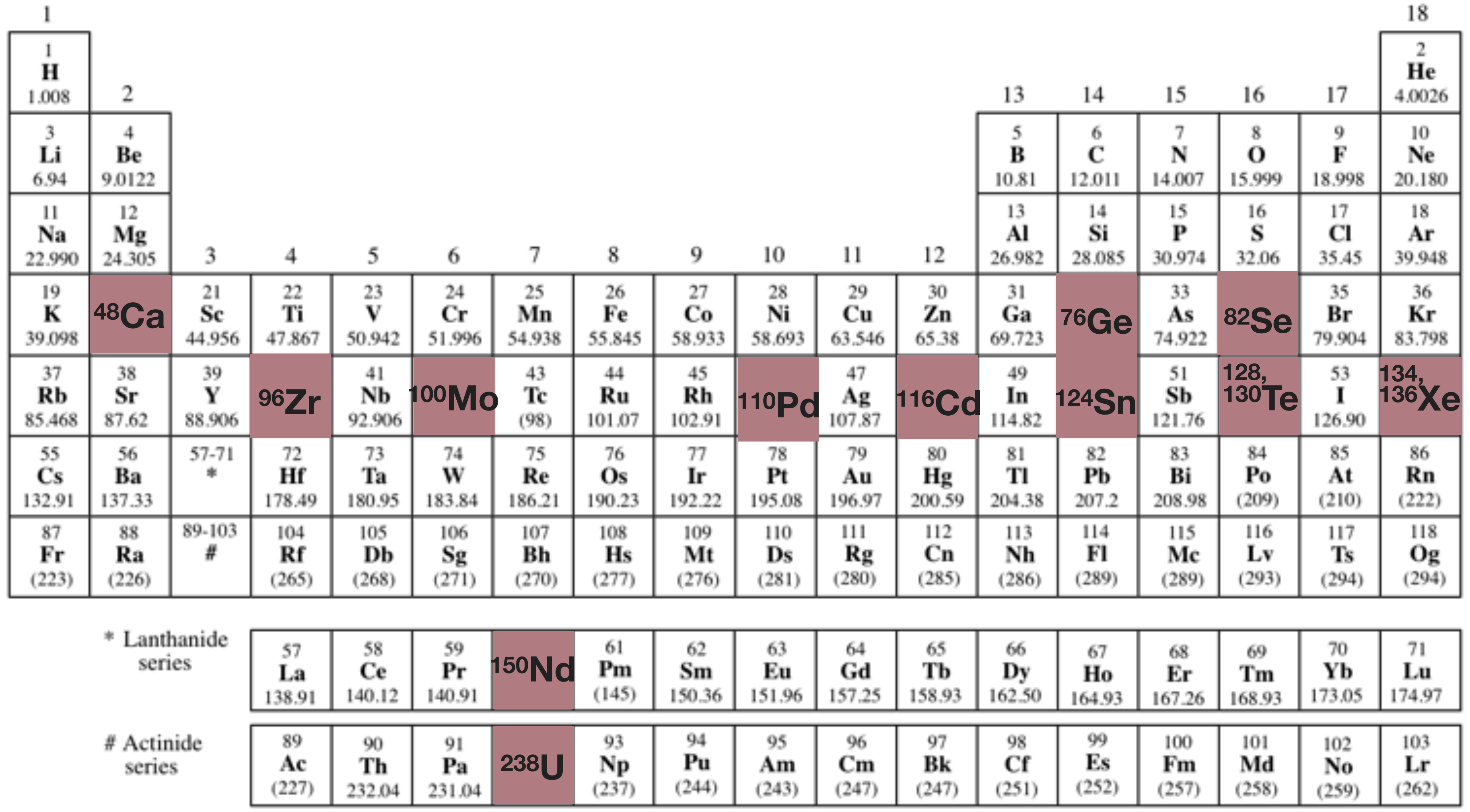




$Q_{\beta\beta}$ ~ 2 - 4 MeV

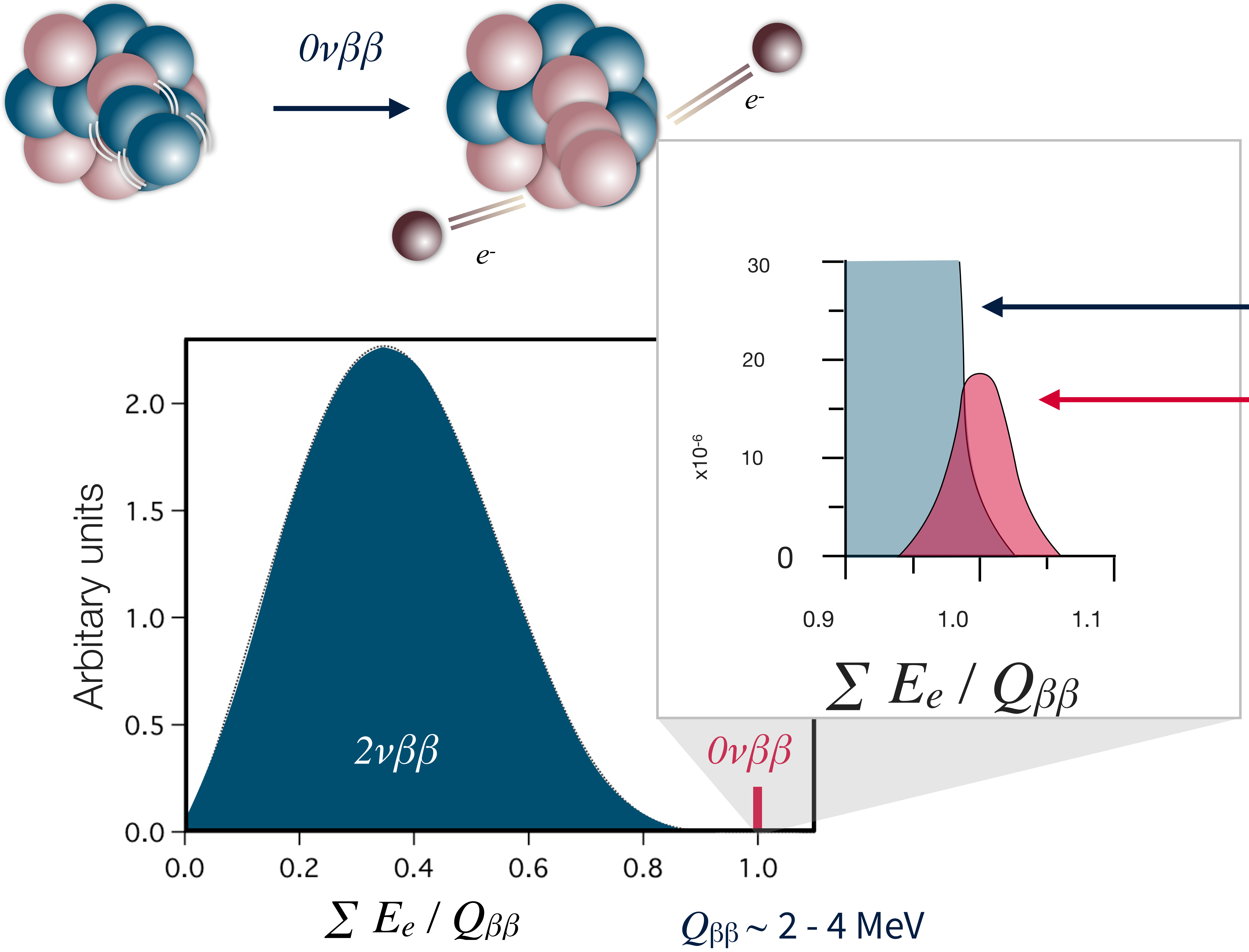


…or various possible “exotic” mechanisms, all requiring a Majorana neutrino (ν=ν̄)



Any $2\nu\beta\beta$ isotope is a candidate (these and more…)

Neutrinoless double-beta decay - a reminder



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Irreducible background ($T_{½}$ ~ 10^{20} years)

Very few events ($T_{½} > 10^{24}$ - 10^{26} years)

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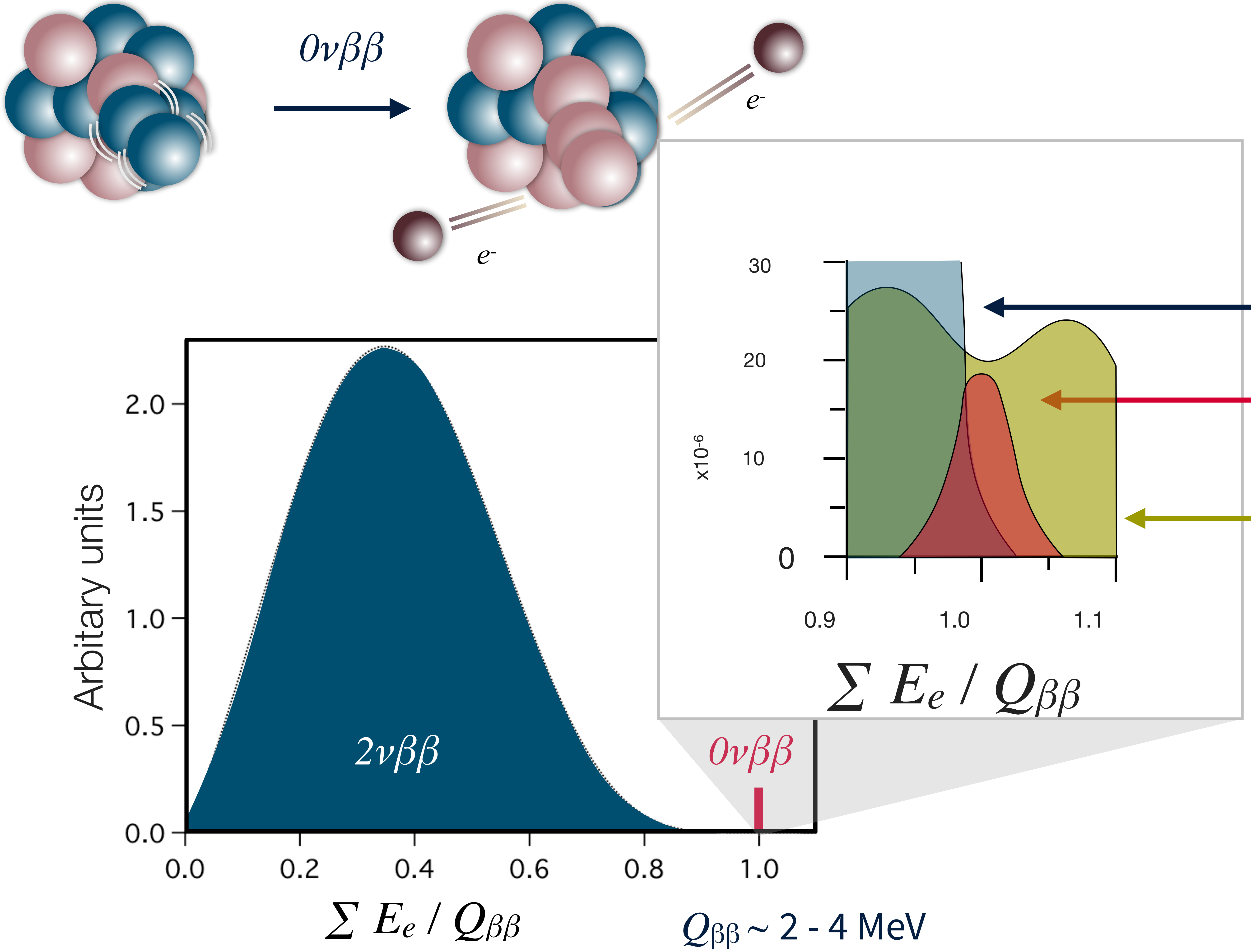

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Other backgrounds

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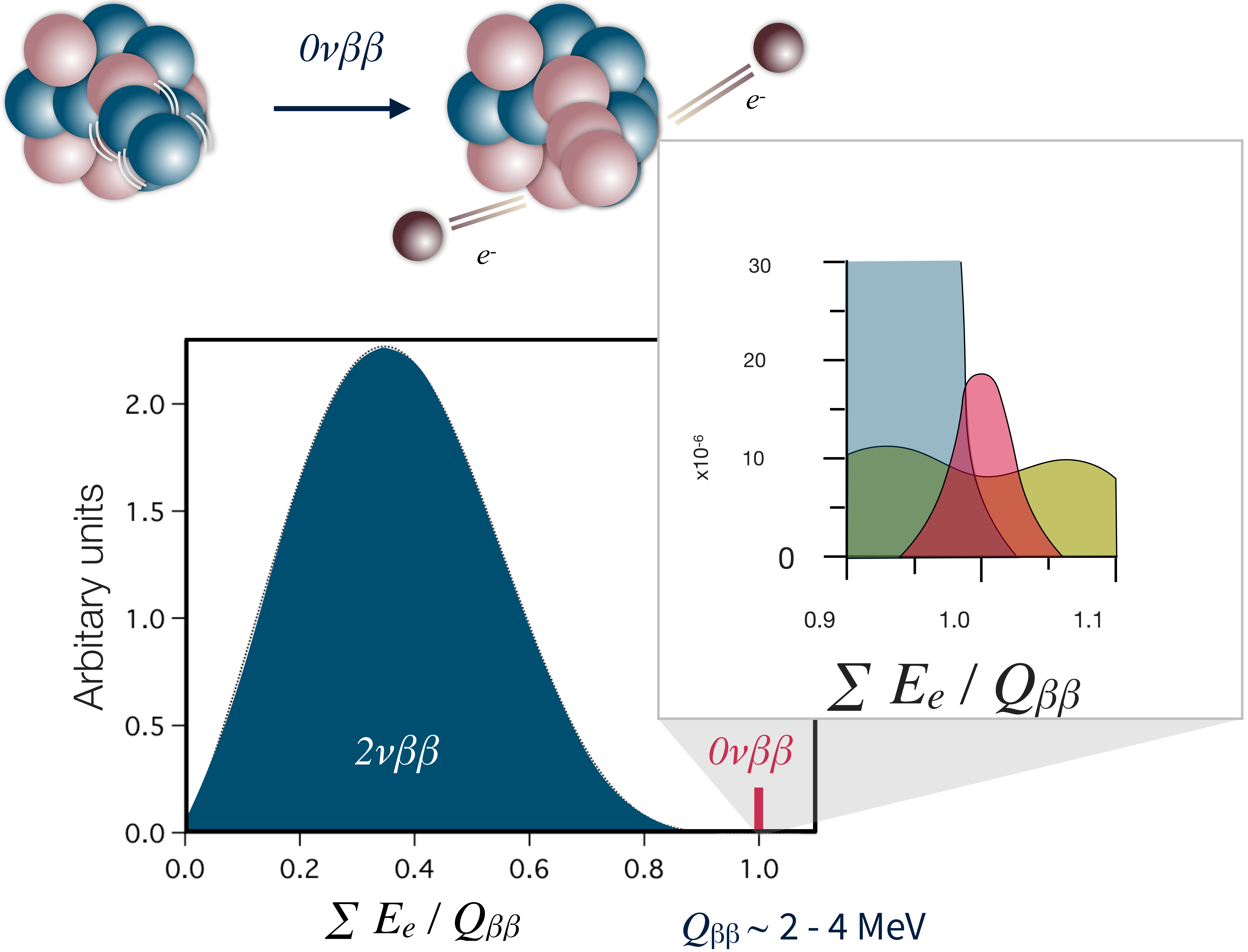

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Reduce backgrounds

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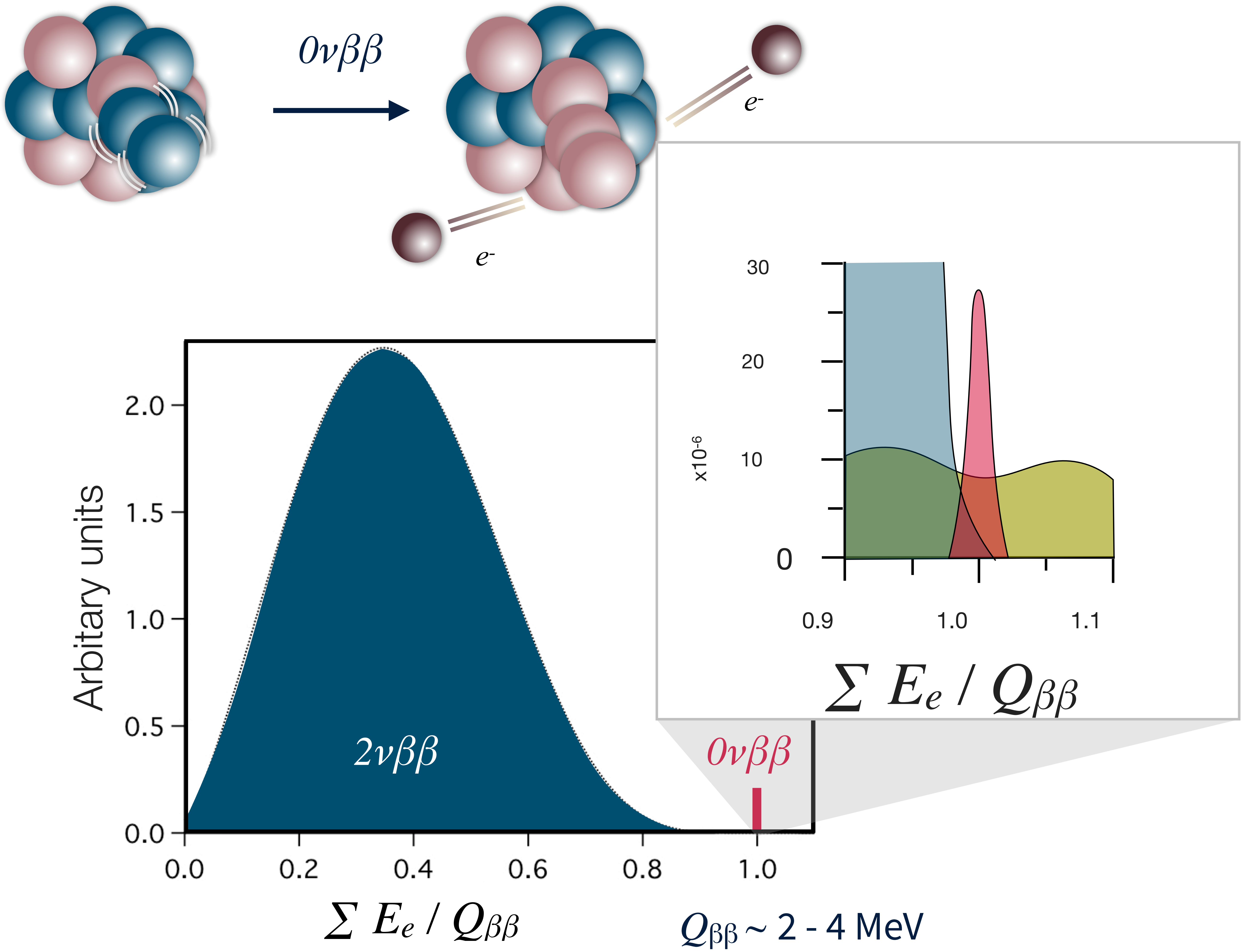


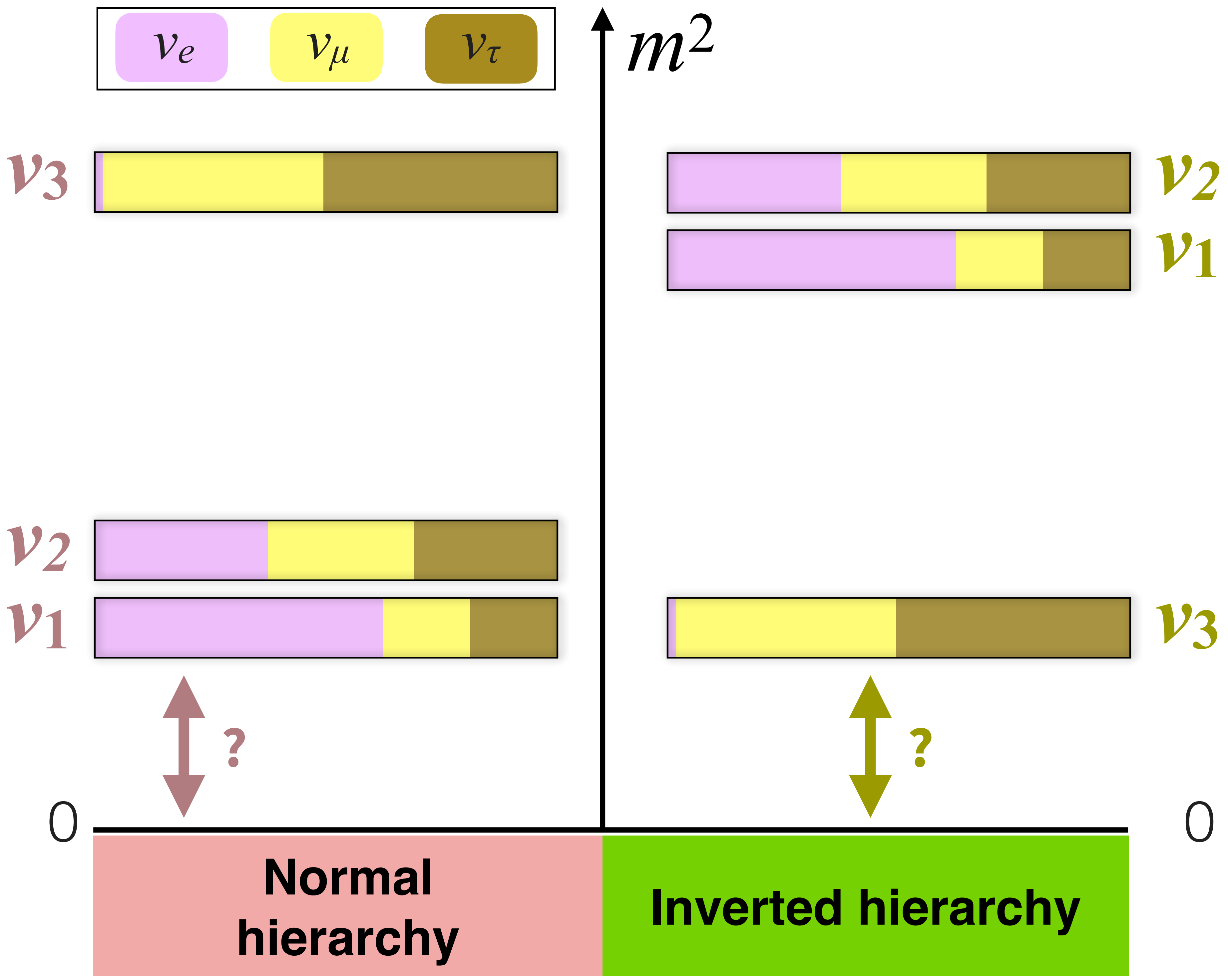
Reduce backgrounds

Improve energy resolution

$0\nu\beta\beta$ and neutrino mass

$0\nu\beta\beta$ rate

$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} = G_{0\nu}(Q_{\beta\beta}, Z) g_A^4 |M_{0\nu}|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$



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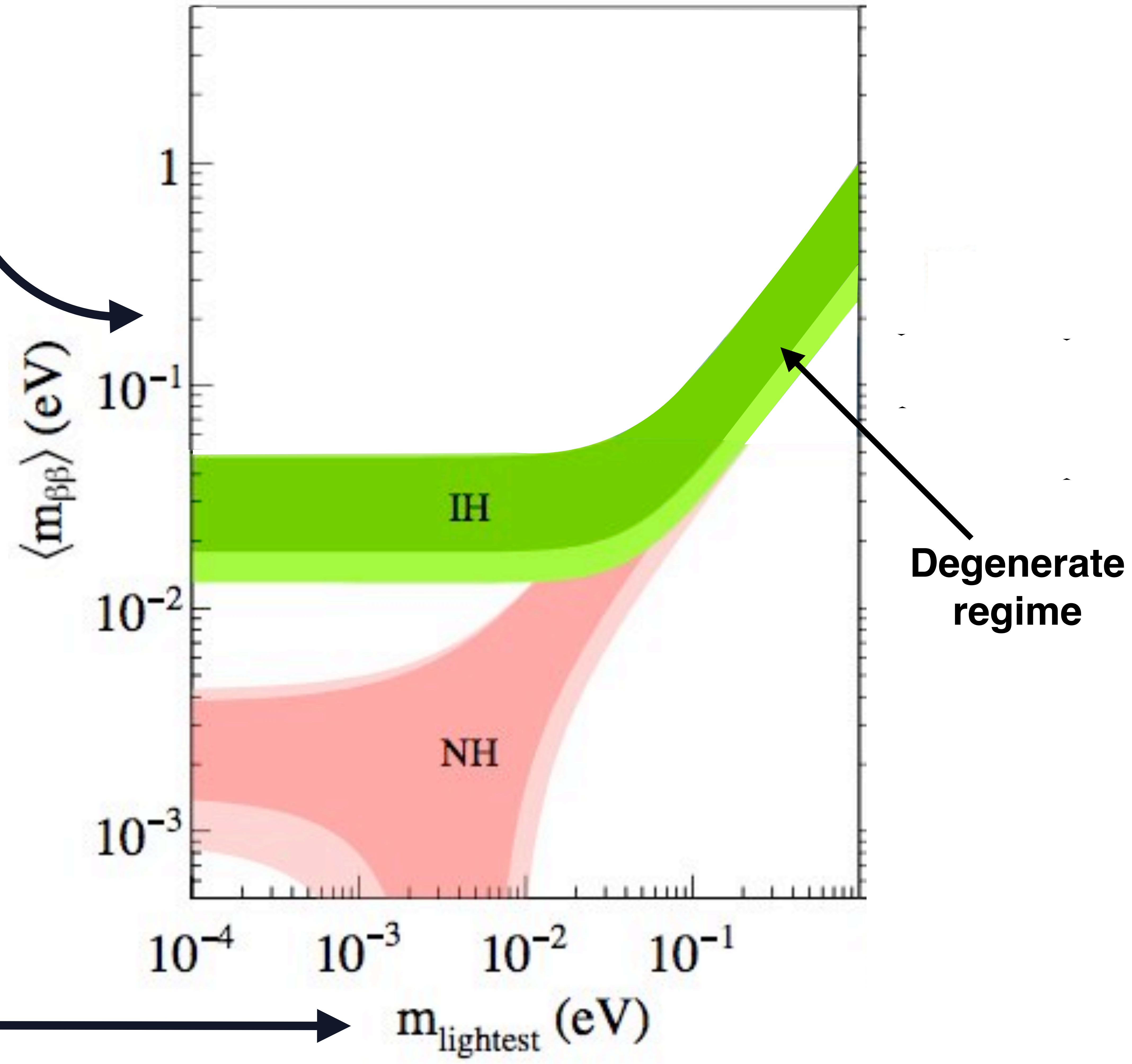

Degenerate regime

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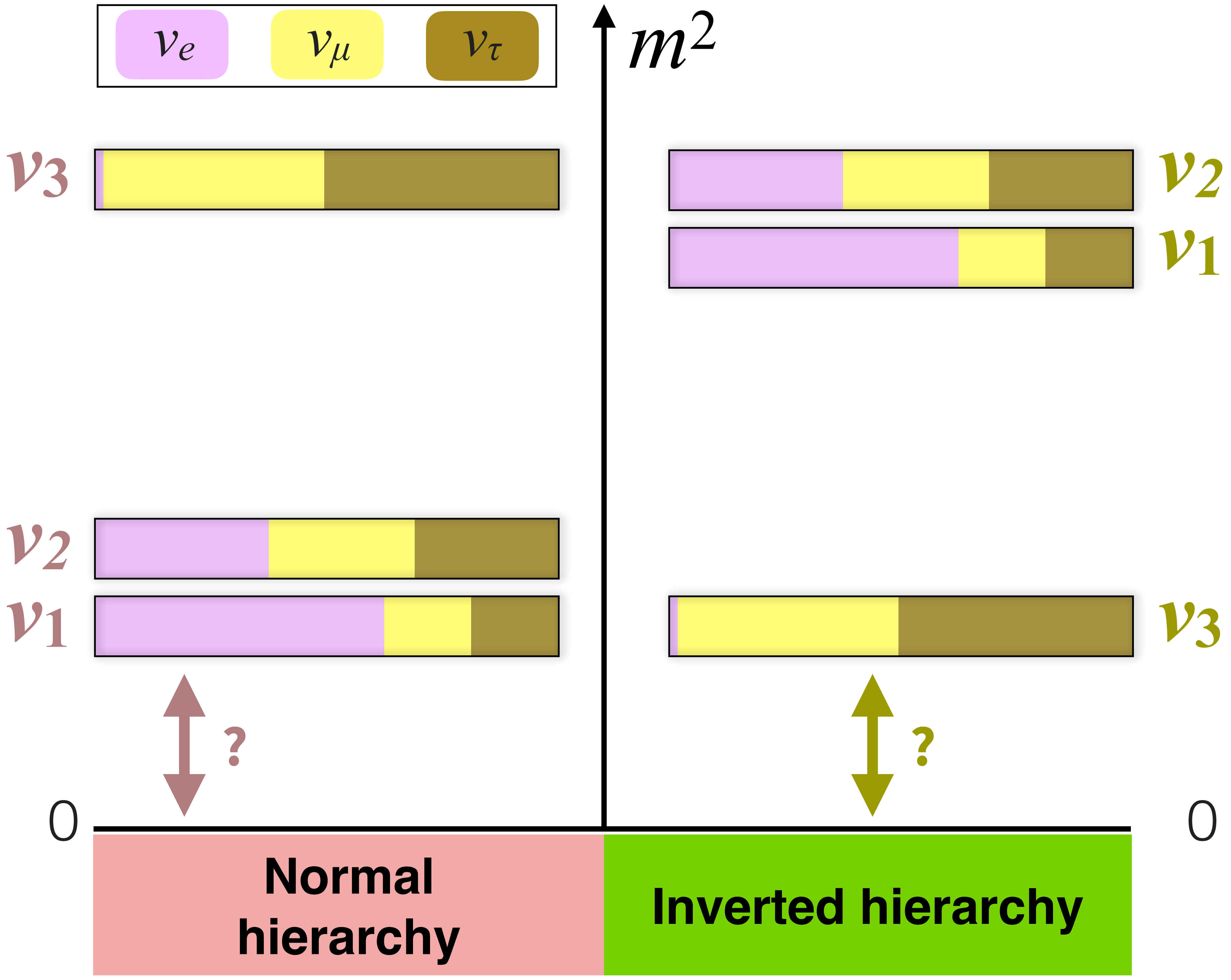

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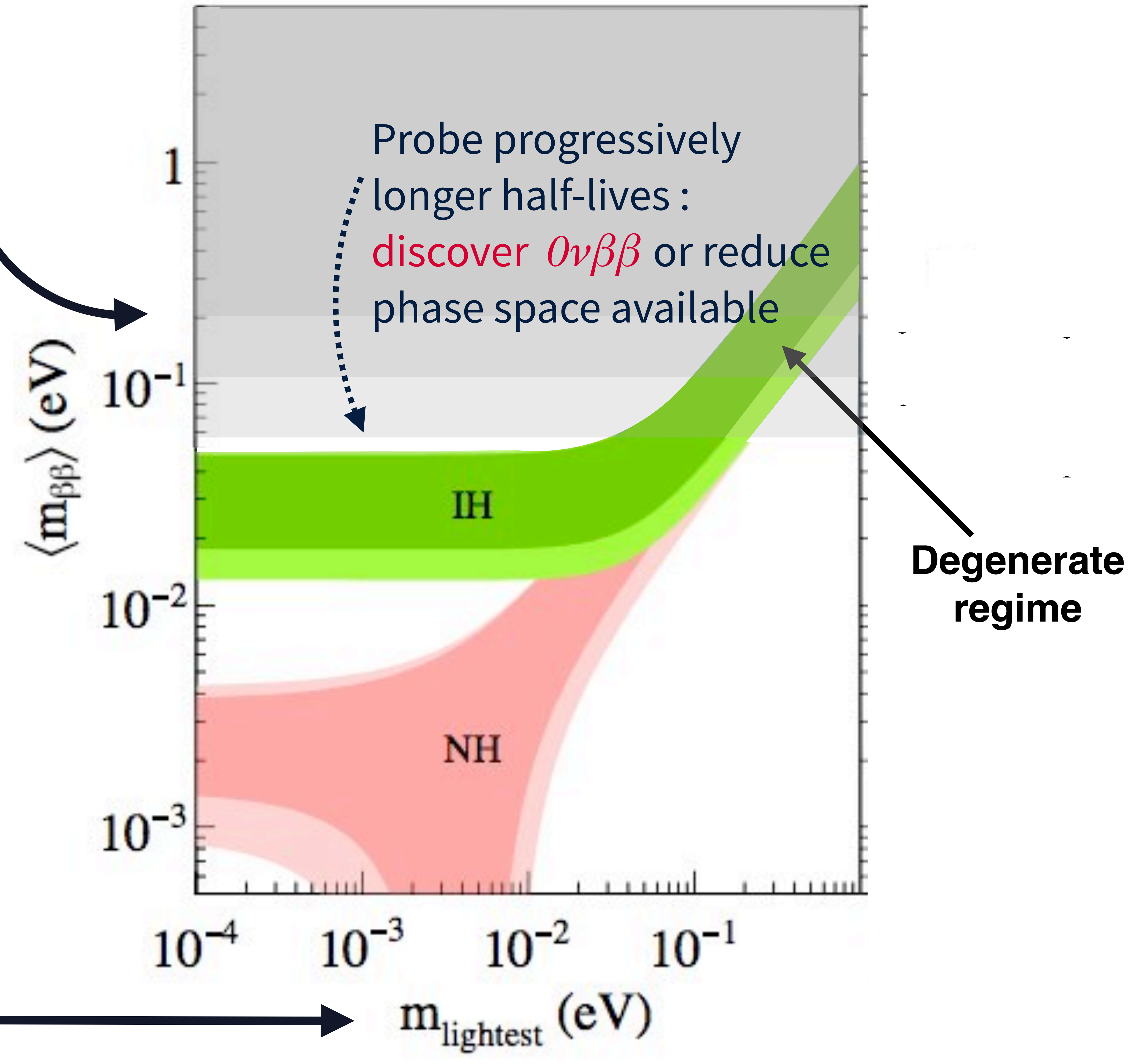

Probe progressively longer half-lives : discover $0\nu\beta\beta$ or reduce phase space available

Degenerate regime

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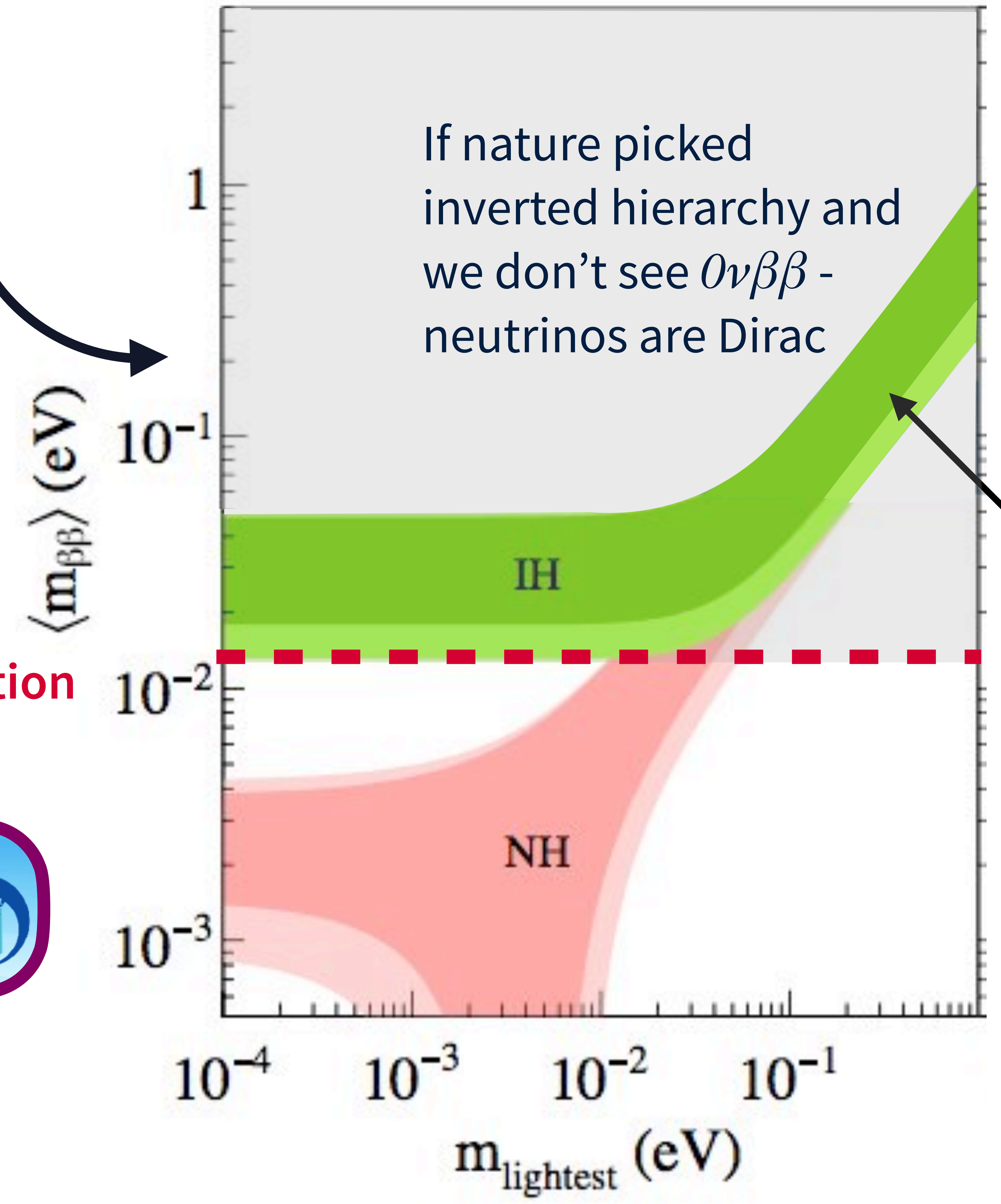

If nature picked inverted hierarchy and we don't see $0\nu\beta\beta$ - neutrinos are Dirac

Degenerate regime

Next-generation experiments

The state of the art

$0\nu\beta\beta$ rate

$$\frac{1}{T^{0\nu\beta\beta}_{1/2}} = G_{0\nu}(Q_{\beta\beta}, Z) g_A^4 |M_{0\nu}|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

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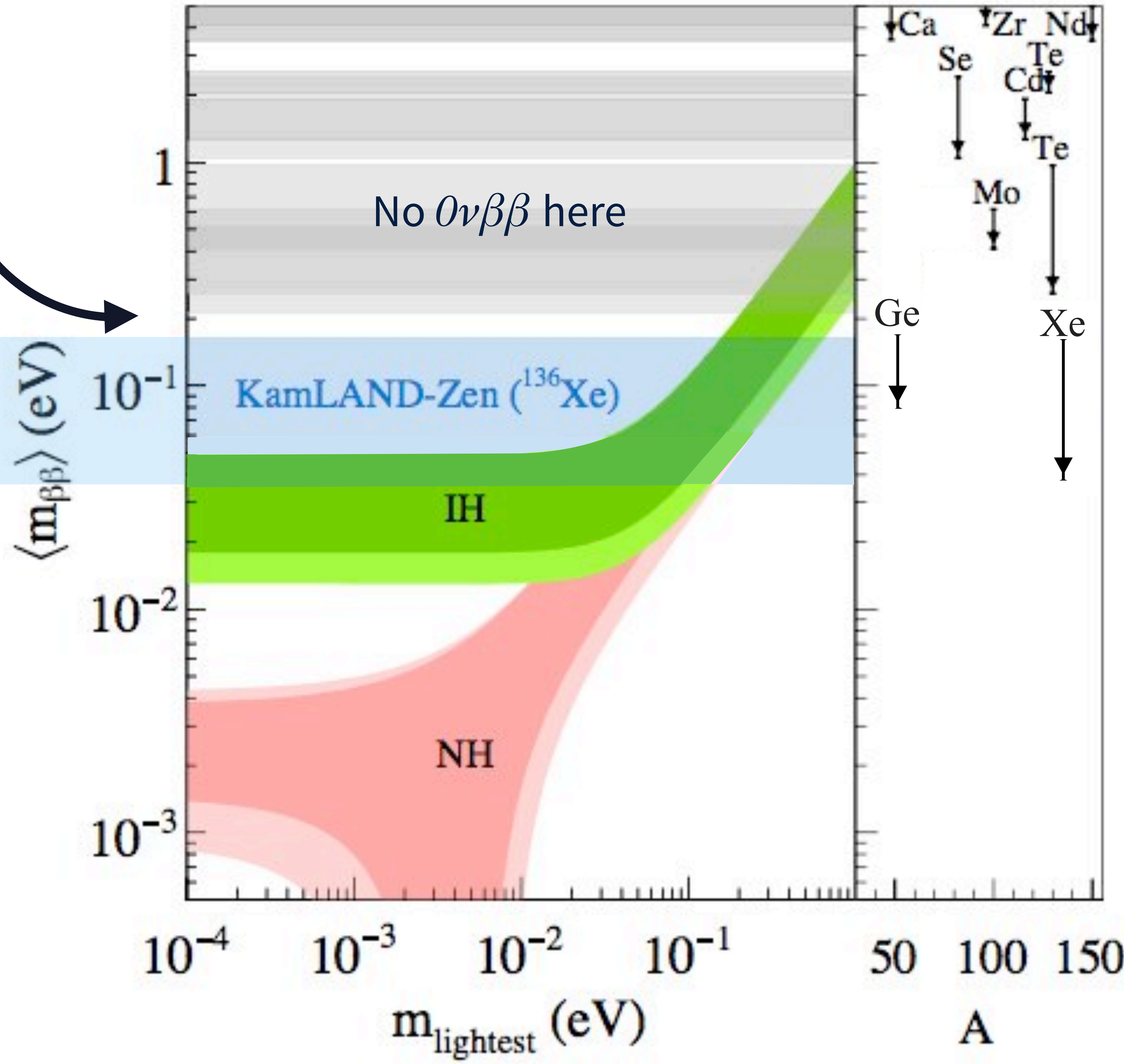
Current best $m_{\beta\beta}$ limit



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Uncertainty on nuclear matrix element leads to broad $m_{\beta\beta}$ band

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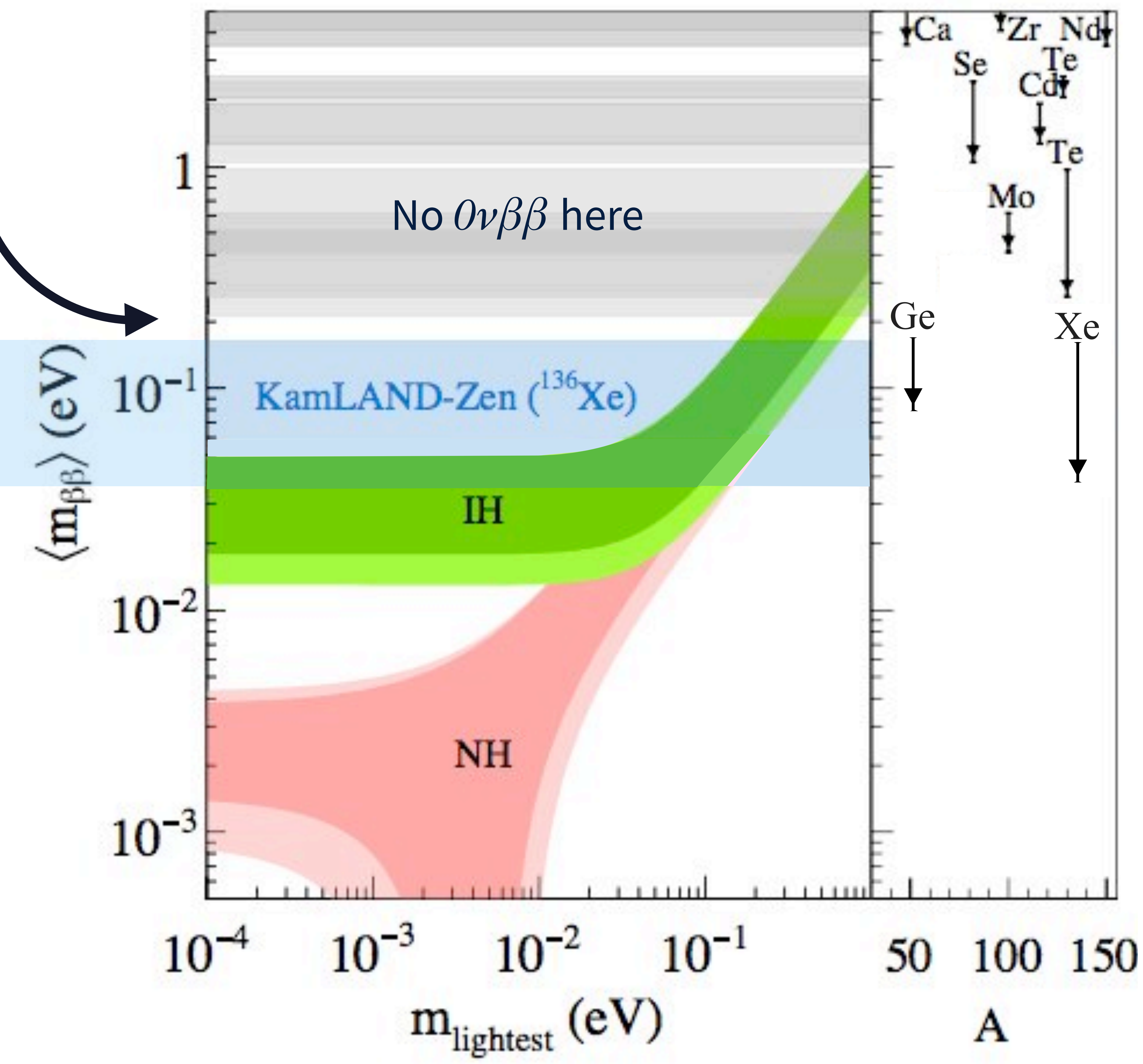

No $0\nu\beta\beta$ here

Designing a *0νββ* detector: the physics

Shorter half life = shorter run time!

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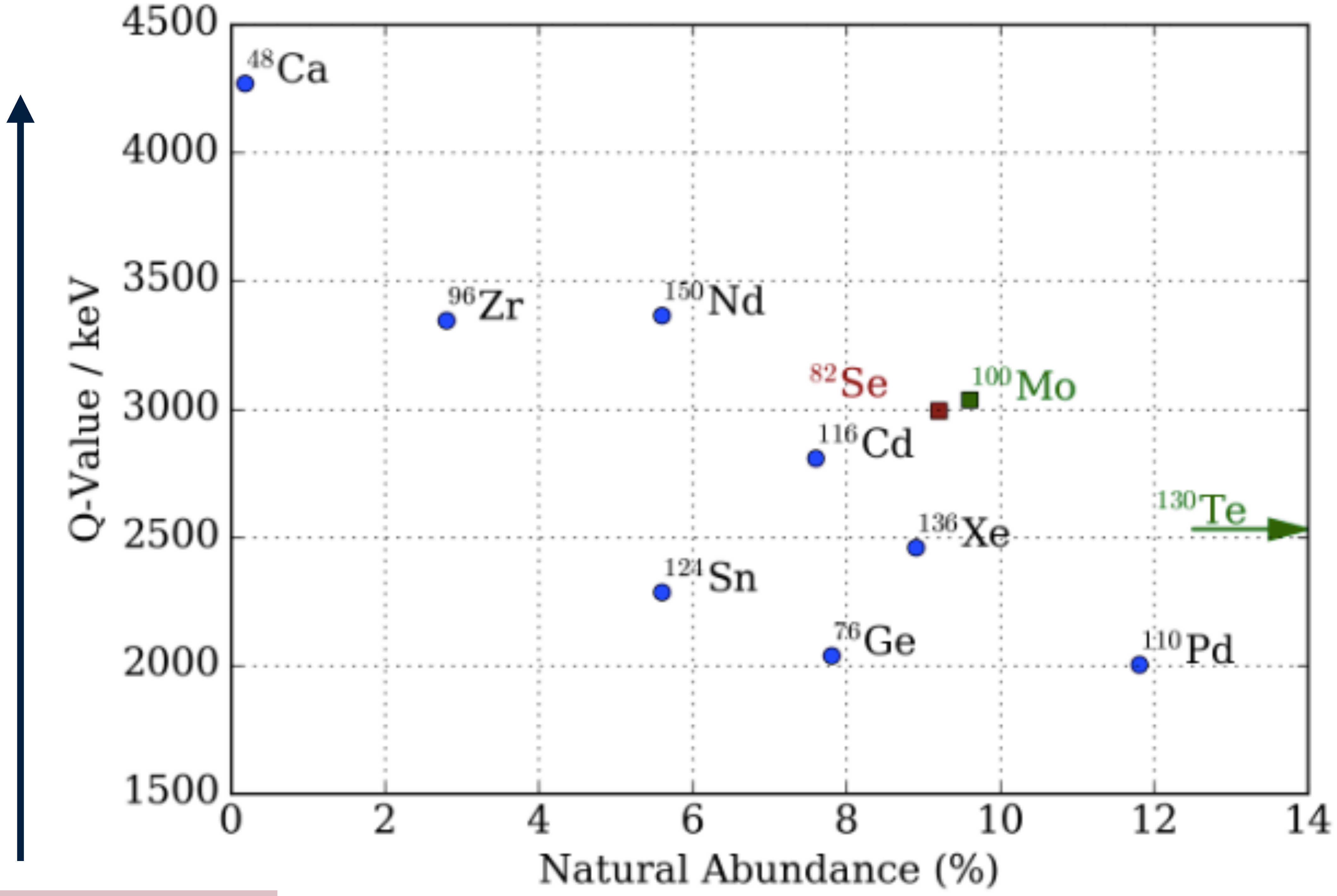

$$T_{1/2}^{0\nu} \propto Q^{-5}$$

- High ***Q*-value**
- Large **atomic number**

Designing a *0νββ* detector: the physics

Shorter half life = shorter run time!

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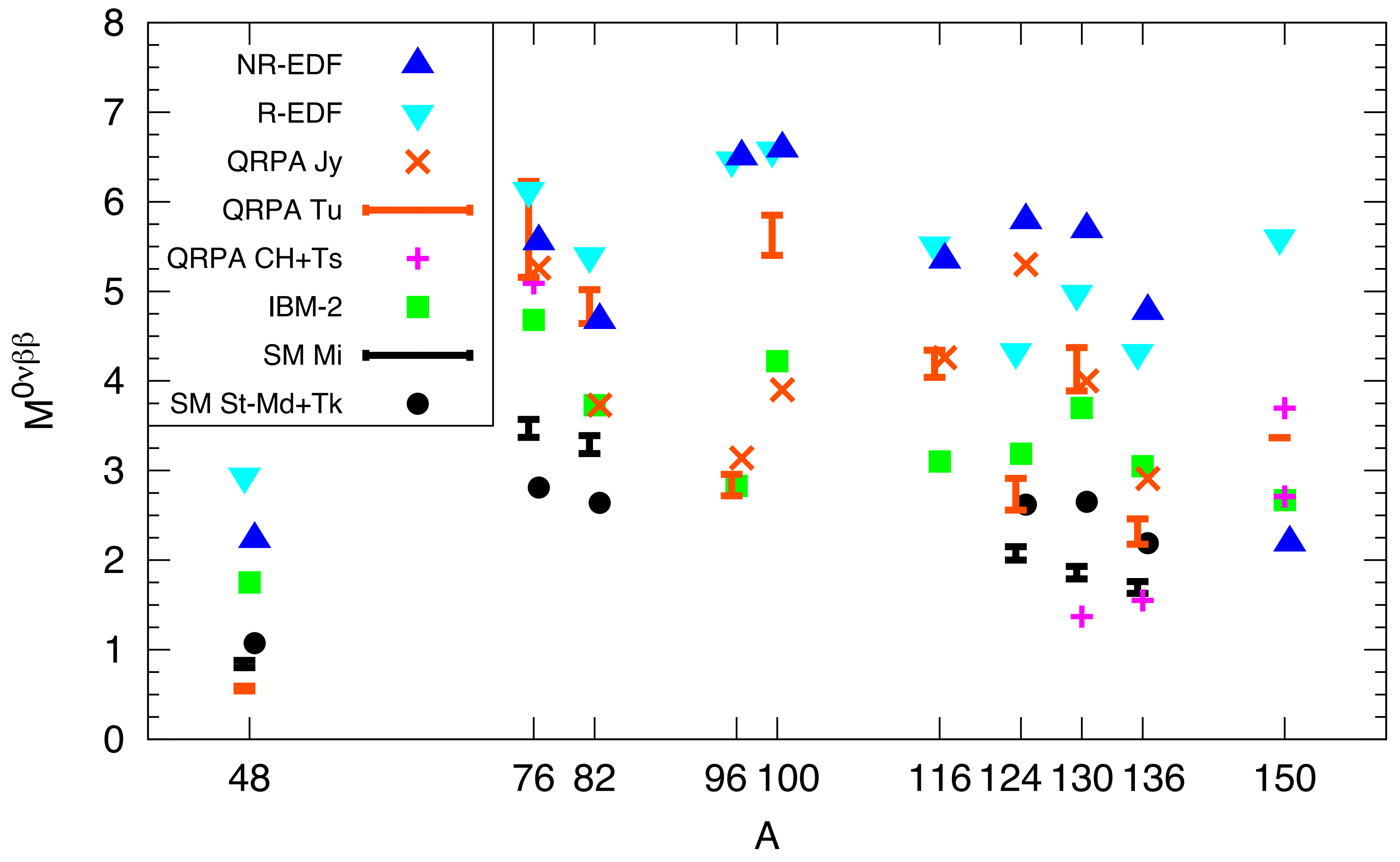
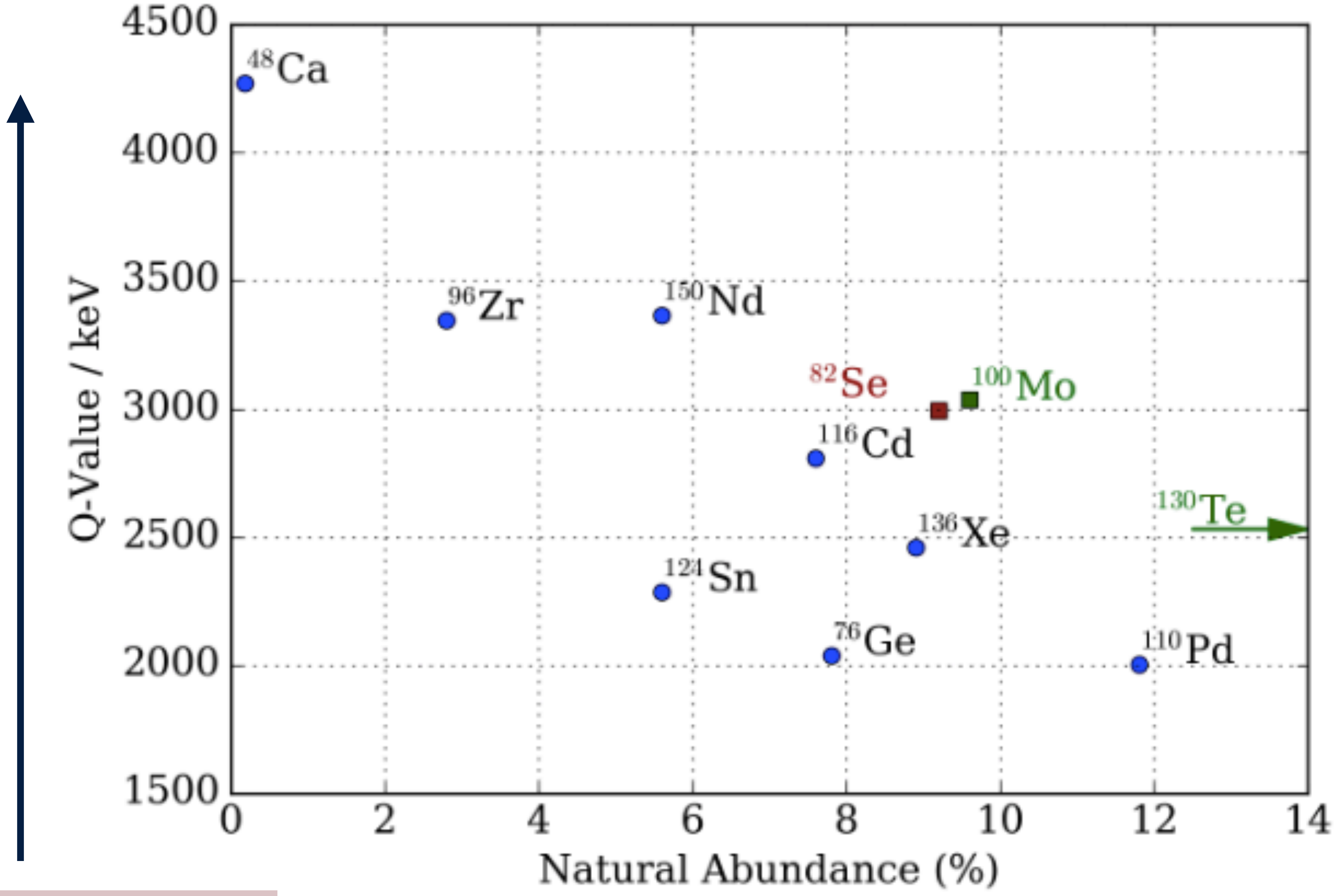




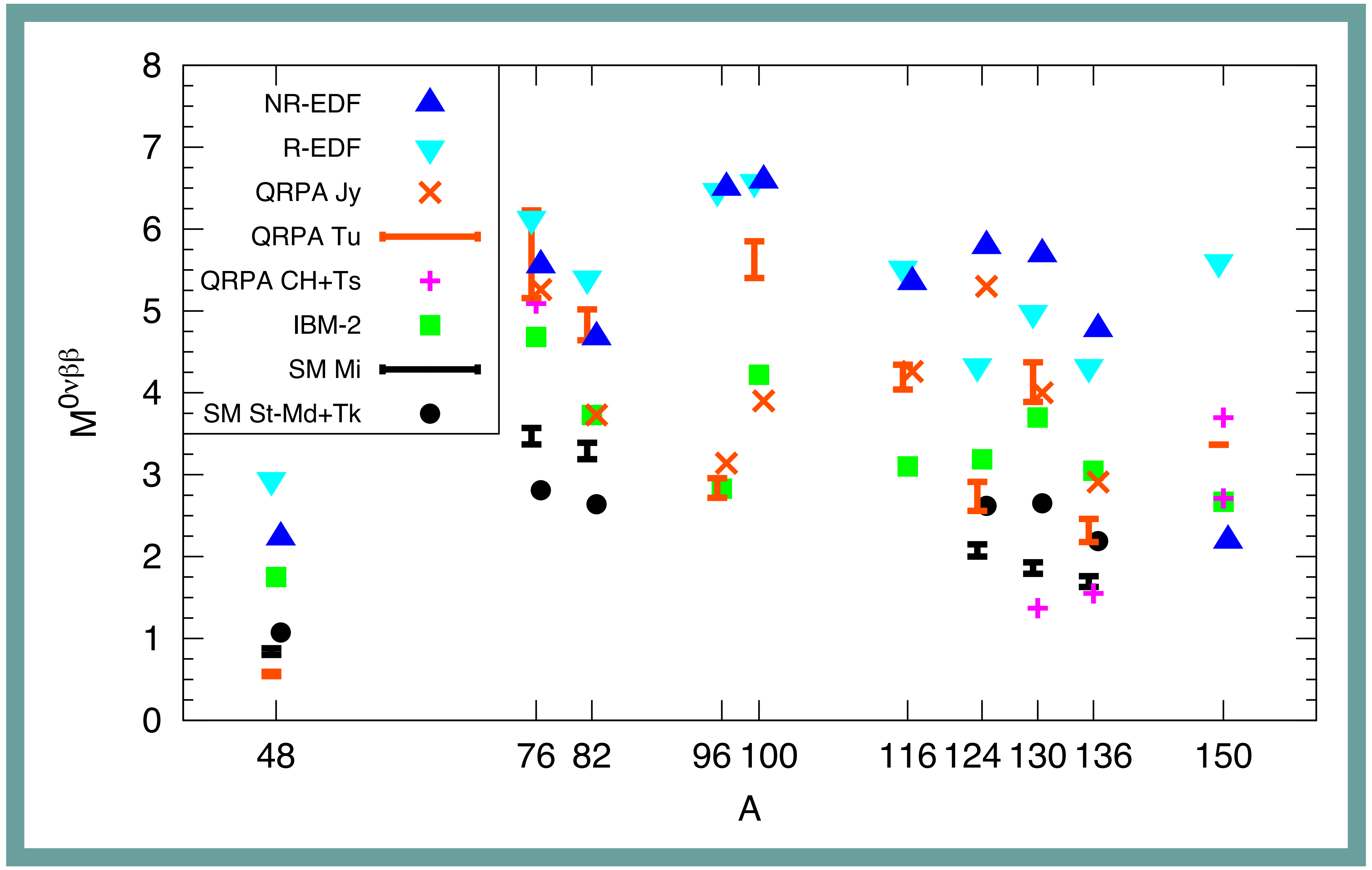
$T_{1/2}^{0\nu} \propto Q^{-5}$

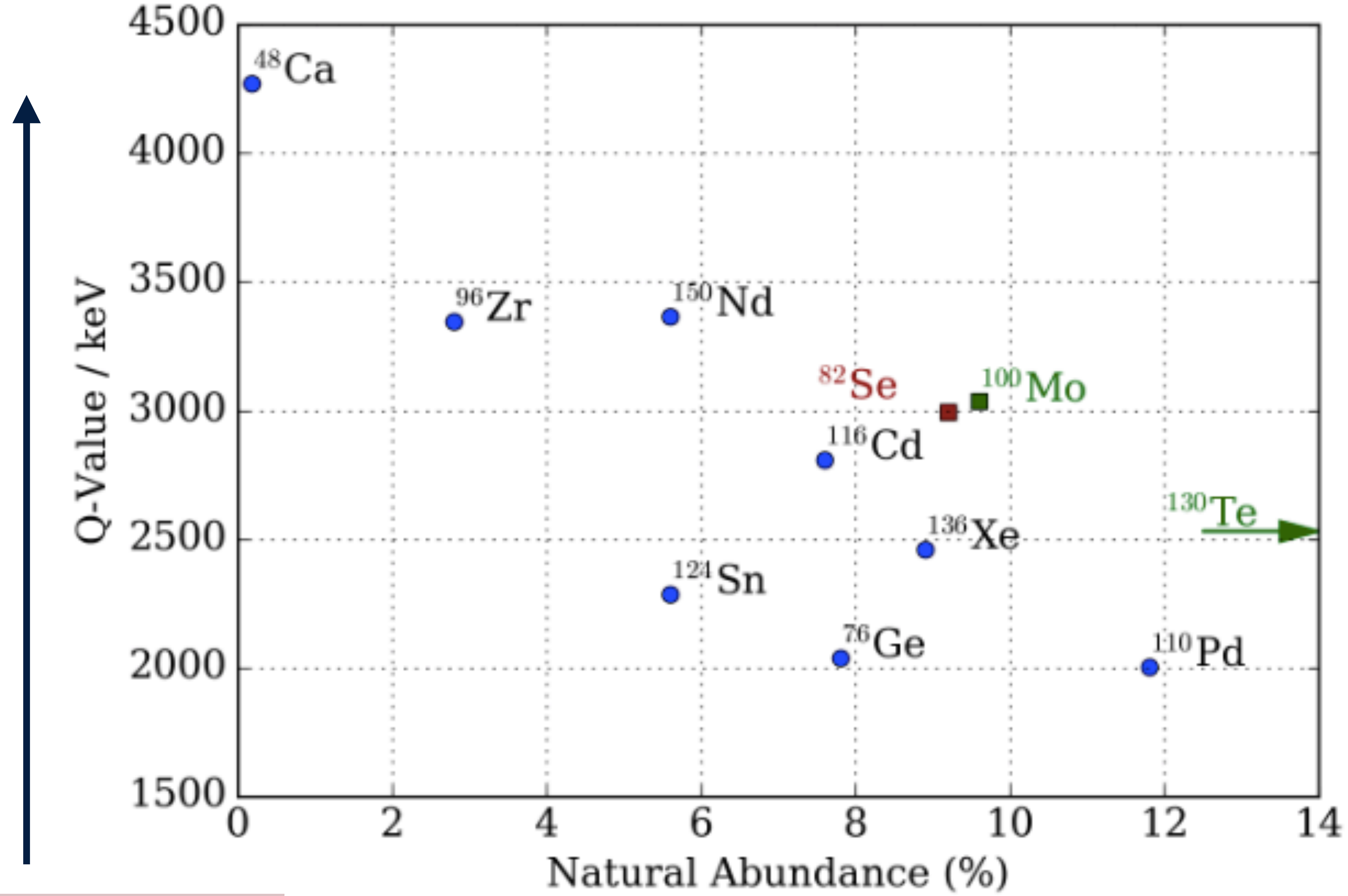
- High **Q-value**
- Large **atomic number**
- Larger **matrix element**

Designing a $0\nu\beta\beta$ detector: the physics

Shorter half life = shorter run time!

$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} = G_{0\nu}(Q_{\beta\beta}, Z) g_A^4 |M_{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$





$T_{1/2}^{0\nu} \propto Q^{-5}$

- High *Q*-value
- Large **atomic number**
- Larger **matrix element**
- **Long $2\nu\beta\beta$ half-life** to reduce background

Designing a $0\nu\beta\beta$ detector: the economics

How expensive is your isotope?

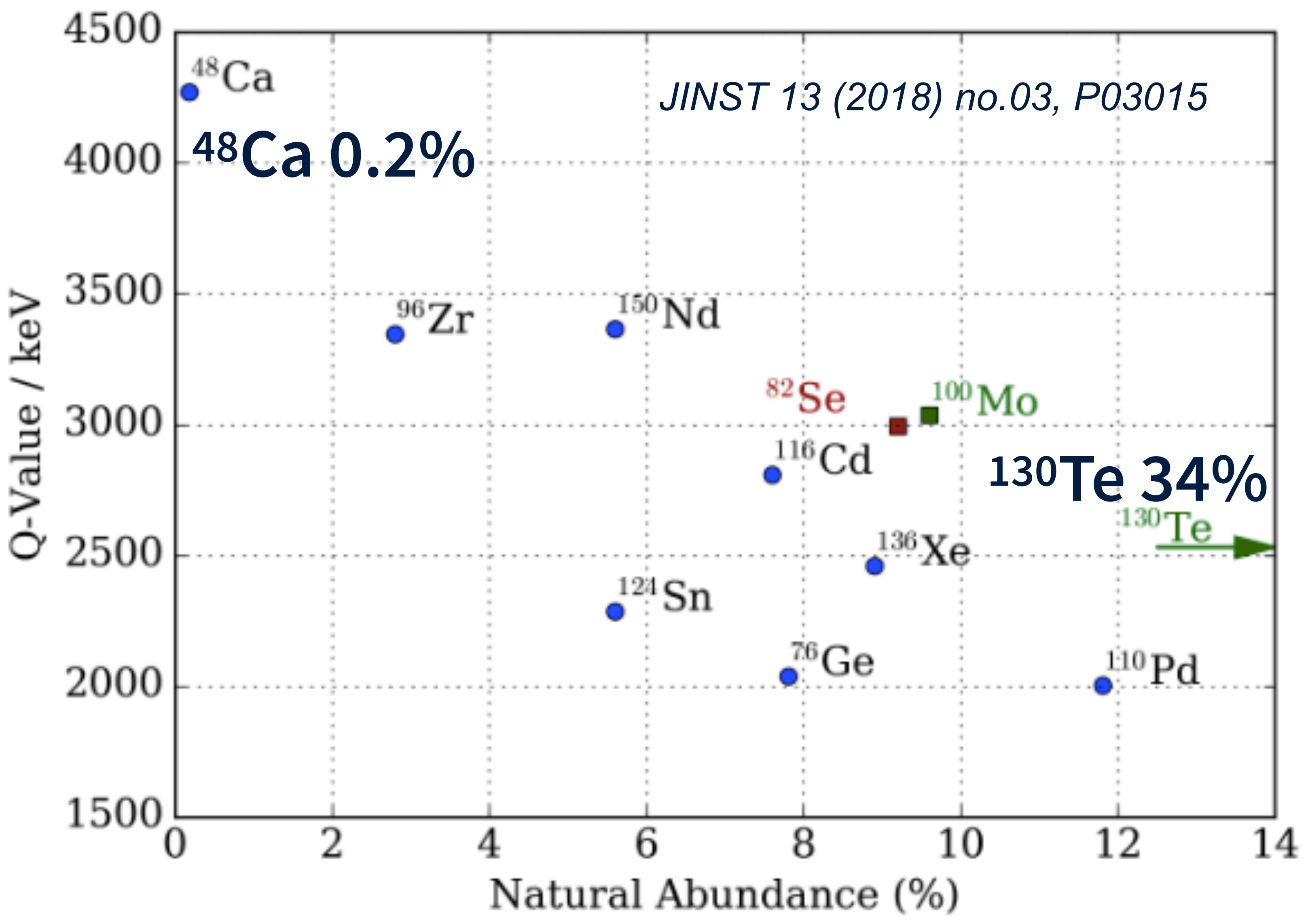
Raw element cost

Xe/ Ge ~ £1000/kg

Se, Te, Ca, Mo ~ few £10 /kg

BUT real cost is from extracting the isotope: can be > £100k / kg

How abundant is your isotope?



→ Better

How hard is it to enrich?

Gas centrifuge

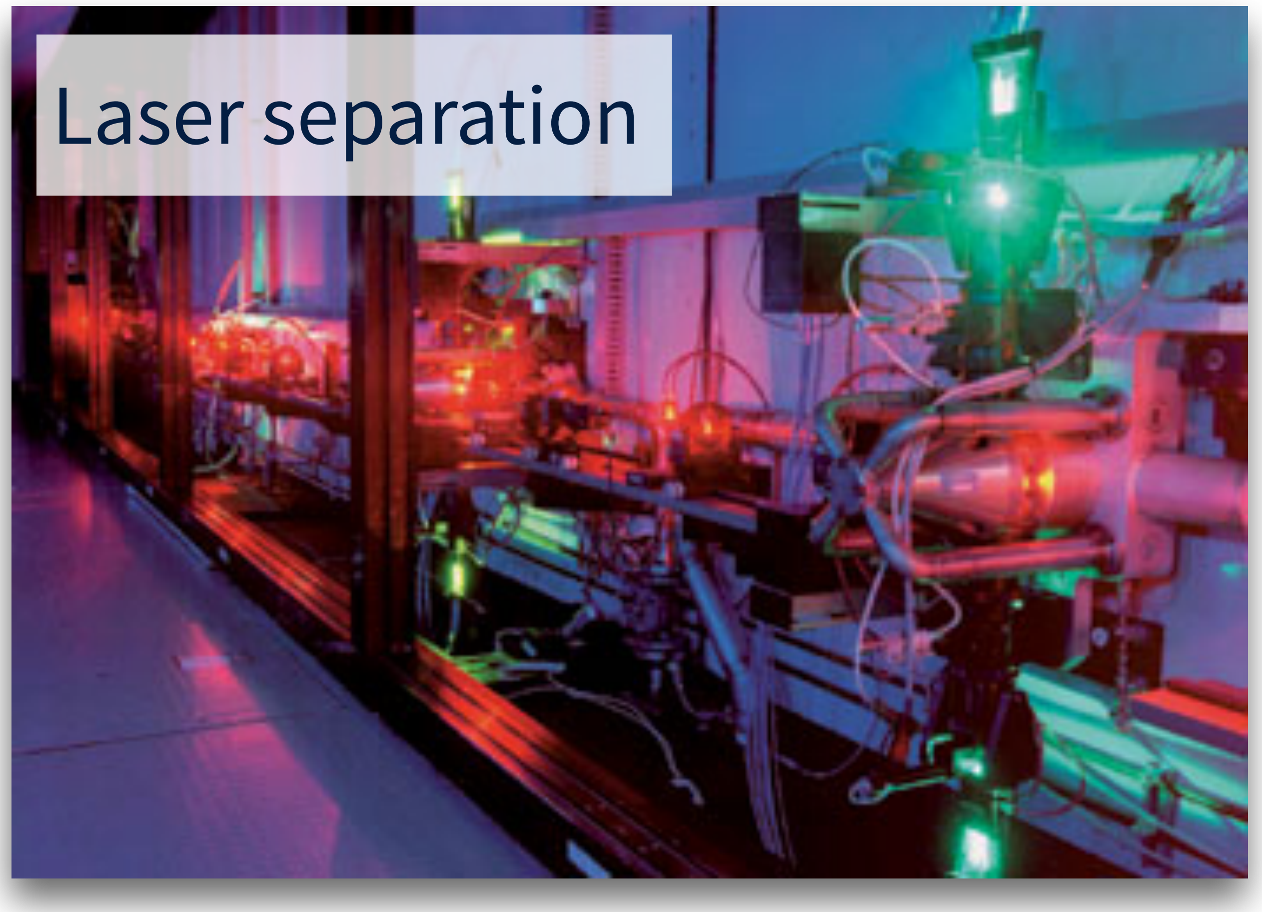
^{48}Ca, ^{150}Nd (hard)

↓

^{136}Xe (easy)

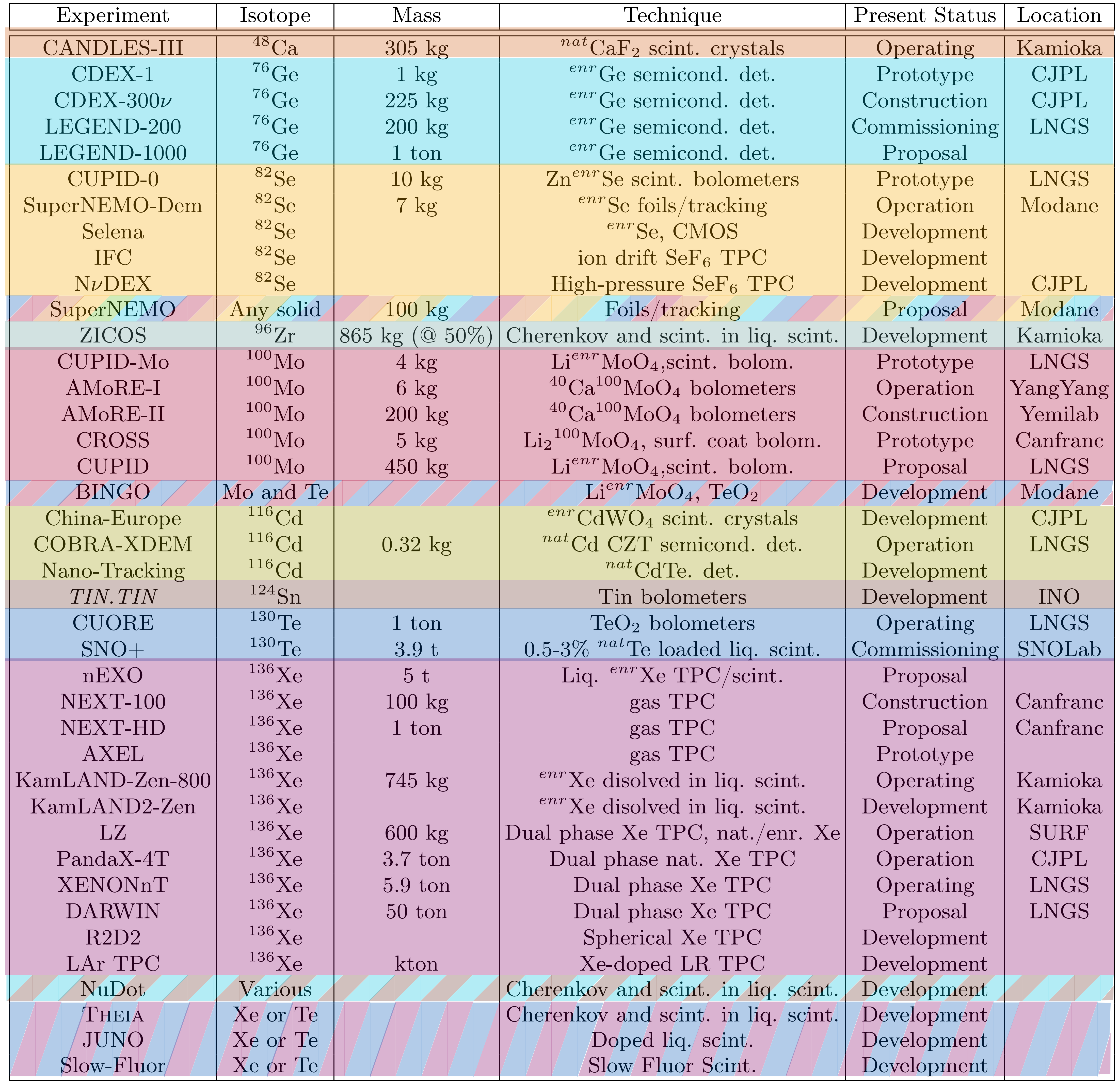
↓

^{130}Te (no need)



Laser separation

The world's $0\nu\beta\beta$ programme: by isotope



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LEGEND-200	^{76}Ge	200 kg	^{enr}Ge semicond. det.	Commissioning	LNGS
LEGEND-1000	^{76}Ge	1 ton	^{enr}Ge semicond. det.	Proposal	
CUPID-0	^{82}Se	10 kg	Zn^{enr}Se scint. bolometers	Prototype	LNGS
SuperNEMO-Dem	^{82}Se	7 kg	^{enr}Se foils/tracking	Operation	Modane
Selena	^{82}Se		^{enr}Se, CMOS	Development	
IFC	^{82}Se		ion drift SeF$_6$ TPC	Development	
NνDEX	^{82}Se		High-pressure SeF$_6$ TPC	Development	CJPL
SuperNEMO	Any solid	100 kg	Foils/tracking	Proposal	Modane
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Table adapted from arXiv:2212.11099

^{48}Ca

^{76}Ge

^{82}Se

^{96}Zr

^{100}Mo

^{116}Cd

^{124}Sn

^{130}Te

^{136}Xe

The world's $0\nu\beta\beta$ programme: by isotope

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^{48}Ca
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^{100}Mo
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^{130}Te
^{136}Xe

DOE strategy

APPEC roadmap

UK core strategy

Can you re-use a detector?

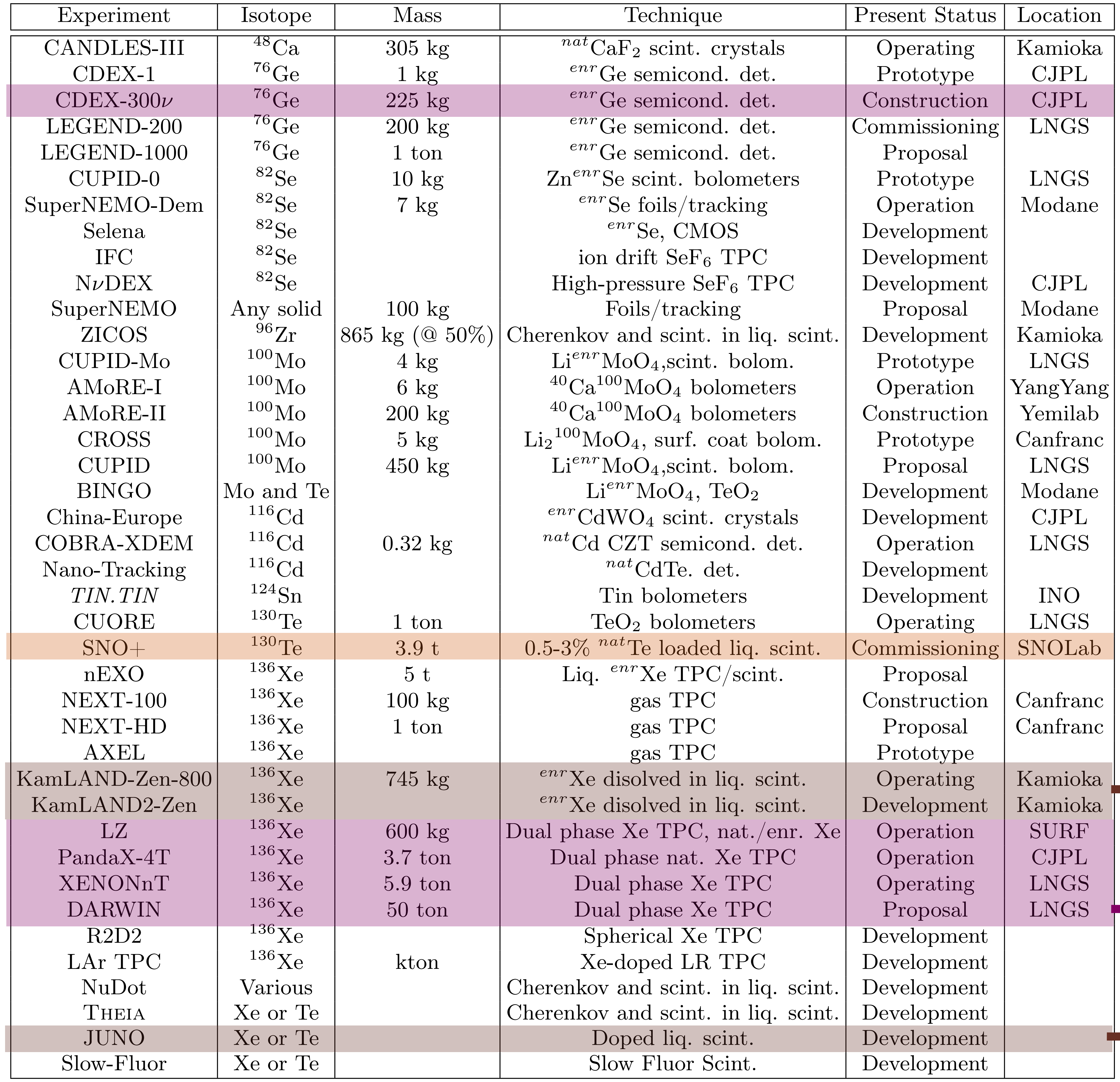

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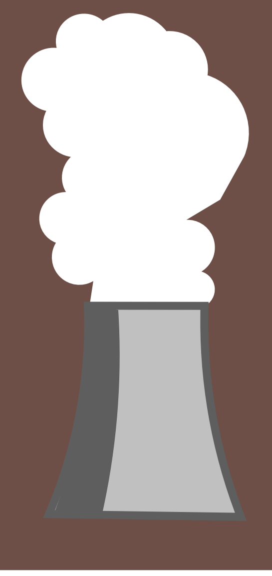
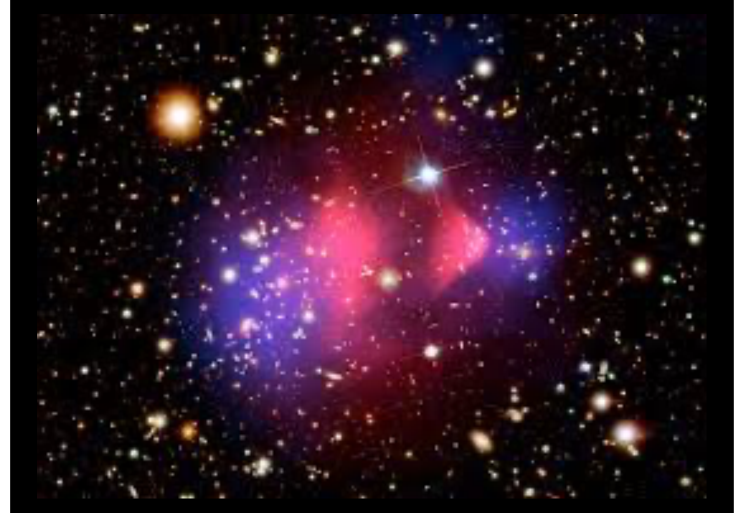
Table adapted from arXiv:2212.11099

SNO (solar neutrinos) → SNO+

KamLAND, JUNO (Reactor neutrinos)



Dark matter



The world's $0\nu\beta\beta$ programme: by technology

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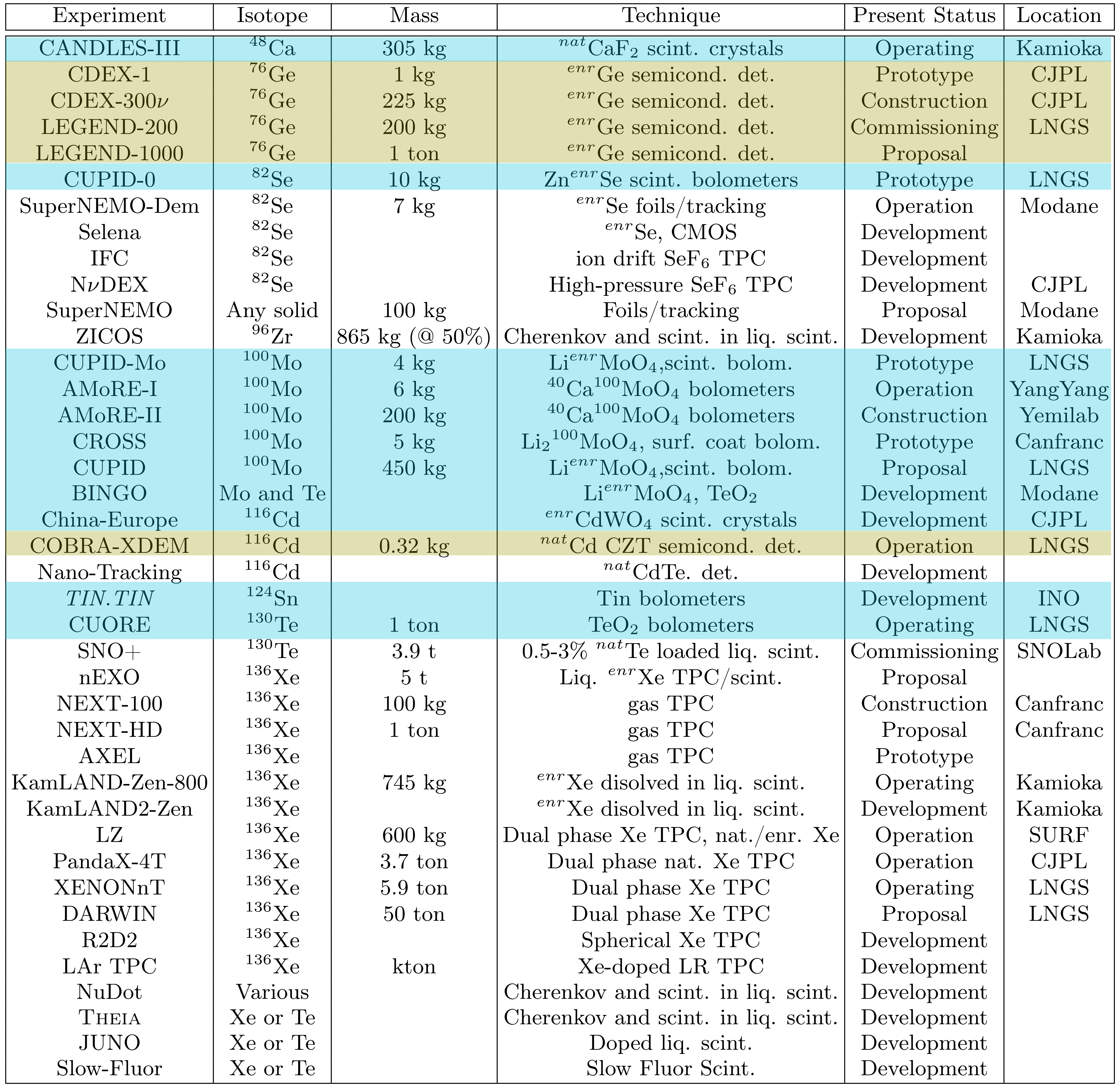

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JUNO	Xe or Te		Doped liq. scint.	Development	
Slow-Fluor	Xe or Te		Slow Fluor Scint.	Development	

Table adapted from arXiv:2212.11099

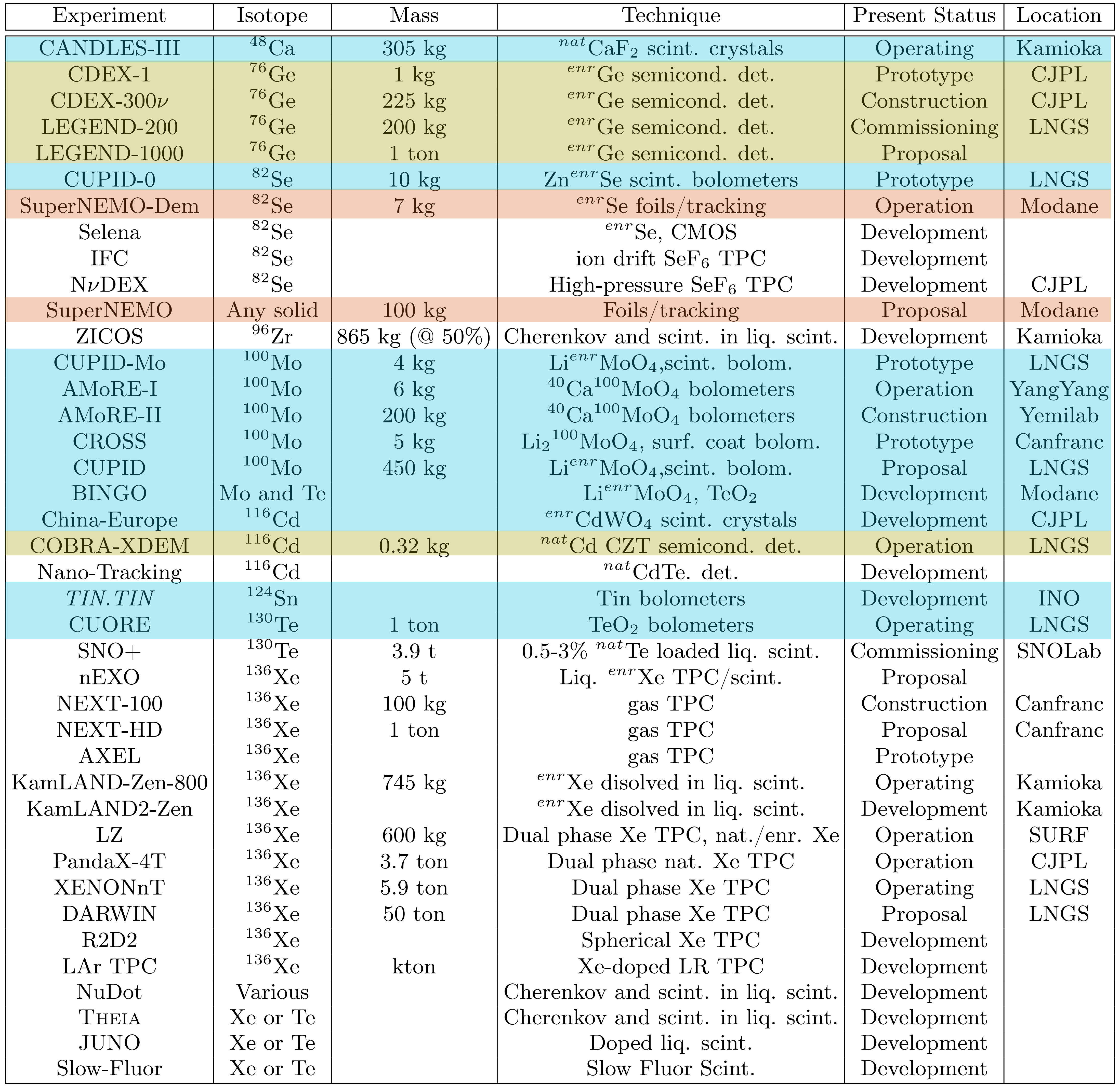
Homogenous detectors:
Source = detector

Crystals

Semiconductors

High efficiency and resolution
Less passive material

The world's $0\nu\beta\beta$ programme: by technology



Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES-III	^{48}Ca	305 kg	^{nat}CaF$_2$ scint. crystals	Operating	Kamioka
CDEX-1	^{76}Ge	1 kg	^{enr}Ge semicond. det.	Prototype	CJPL
CDEX-300ν	^{76}Ge	225 kg	^{enr}Ge semicond. det.	Construction	CJPL
LEGEND-200	^{76}Ge	200 kg	^{enr}Ge semicond. det.	Commissioning	LNGS
LEGEND-1000	^{76}Ge	1 ton	^{enr}Ge semicond. det.	Proposal	
CUPID-0	^{82}Se	10 kg	Zn^{enr}Se scint. bolometers	Prototype	LNGS
SuperNEMO-Dem	^{82}Se	7 kg	^{enr}Se foils/tracking	Operation	Modane
Selena	^{82}Se		^{enr}Se, CMOS	Development	
IFC	^{82}Se		ion drift SeF$_6$ TPC	Development	
NνDEX	^{82}Se		High-pressure SeF$_6$ TPC	Development	CJPL
SuperNEMO	Any solid	100 kg	Foils/tracking	Proposal	Modane
ZICOS	^{96}Zr	865 kg (@ 50%)	Cherenkov and scint. in liq. scint.	Development	Kamioka
CUPID-Mo	^{100}Mo	4 kg	Li^{enr}MoO$_4$,scint. bolom.	Prototype	LNGS
AMoRE-I	^{100}Mo	6 kg	^{40}Ca^{100}MoO$_4$ bolometers	Operation	YangYang
AMoRE-II	^{100}Mo	200 kg	^{40}Ca^{100}MoO$_4$ bolometers	Construction	Yemilab
CROSS	^{100}Mo	5 kg	Li$_2$^{100}MoO$_4$, surf. coat bolom.	Prototype	Canfranc
CUPID	^{100}Mo	450 kg	Li^{enr}MoO$_4$,scint. bolom.	Proposal	LNGS
BINGO	Mo and Te		Li^{enr}MoO$_4$, TeO$_2$	Development	Modane
China-Europe	^{116}Cd		^{enr}CdWO$_4$ scint. crystals	Development	CJPL
COBRA-XDEM	^{116}Cd	0.32 kg	^{nat}Cd CZT semicond. det.	Operation	LNGS
Nano-Tracking	^{116}Cd		^{nat}CdTe. det.	Development	
TIN.TIN	^{124}Sn		Tin bolometers	Development	INO
CUORE	^{130}Te	1 ton	TeO$_2$ bolometers	Operating	LNGS
SNO+	^{130}Te	3.9 t	0.5-3% ^{nat}Te loaded liq. scint.	Commissioning	SNOLab
nEXO	^{136}Xe	5 t	Liq. ^{enr}Xe TPC/scint.	Proposal	
NEXT-100	^{136}Xe	100 kg	gas TPC	Construction	Canfranc
NEXT-HD	^{136}Xe	1 ton	gas TPC	Proposal	Canfranc
AXEL	^{136}Xe		gas TPC	Prototype	
KamLAND-Zen-800	^{136}Xe	745 kg	^{enr}Xe disolved in liq. scint.	Operating	Kamioka
KamLAND2-Zen	^{136}Xe		^{enr}Xe disolved in liq. scint.	Development	Kamioka
LZ	^{136}Xe	600 kg	Dual phase Xe TPC, nat./enr. Xe	Operation	SURF
PandaX-4T	^{136}Xe	3.7 ton	Dual phase nat. Xe TPC	Operation	CJPL
XENONnT	^{136}Xe	5.9 ton	Dual phase Xe TPC	Operating	LNGS
DARWIN	^{136}Xe	50 ton	Dual phase Xe TPC	Proposal	LNGS
R2D2	^{136}Xe		Spherical Xe TPC	Development	
LAr TPC	^{136}Xe	kton	Xe-doped LR TPC	Development	
NuDot	Various		Cherenkov and scint. in liq. scint.	Development	
THEIA	Xe or Te		Cherenkov and scint. in liq. scint.	Development	
JUNO	Xe or Te		Doped liq. scint.	Development	
Slow-Fluor	Xe or Te		Slow Fluor Scint.	Development	

Table adapted from arXiv:2212.11099

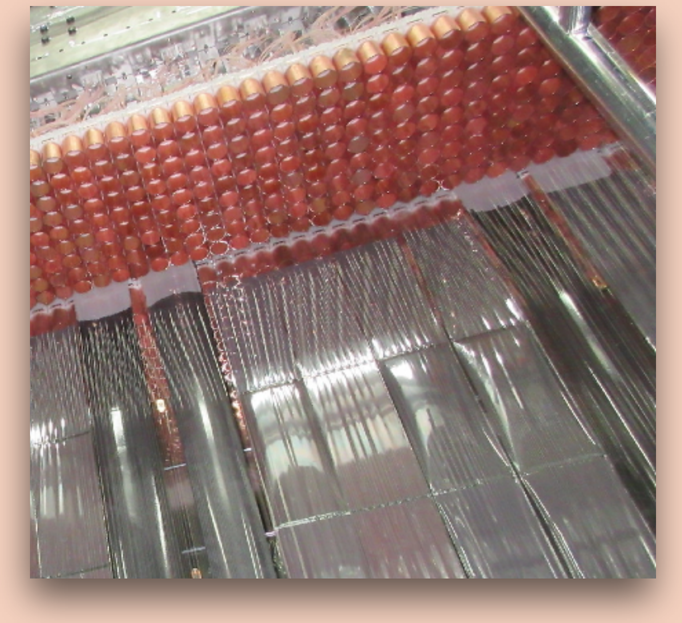
Homogenous detectors:
Source = detector

Crystals

Semiconductors

Tracking detectors:
Source separate from detector

Tracking



Isotope flexibility
Topological reconstruction

The world's $0\nu\beta\beta$ programme: by technology

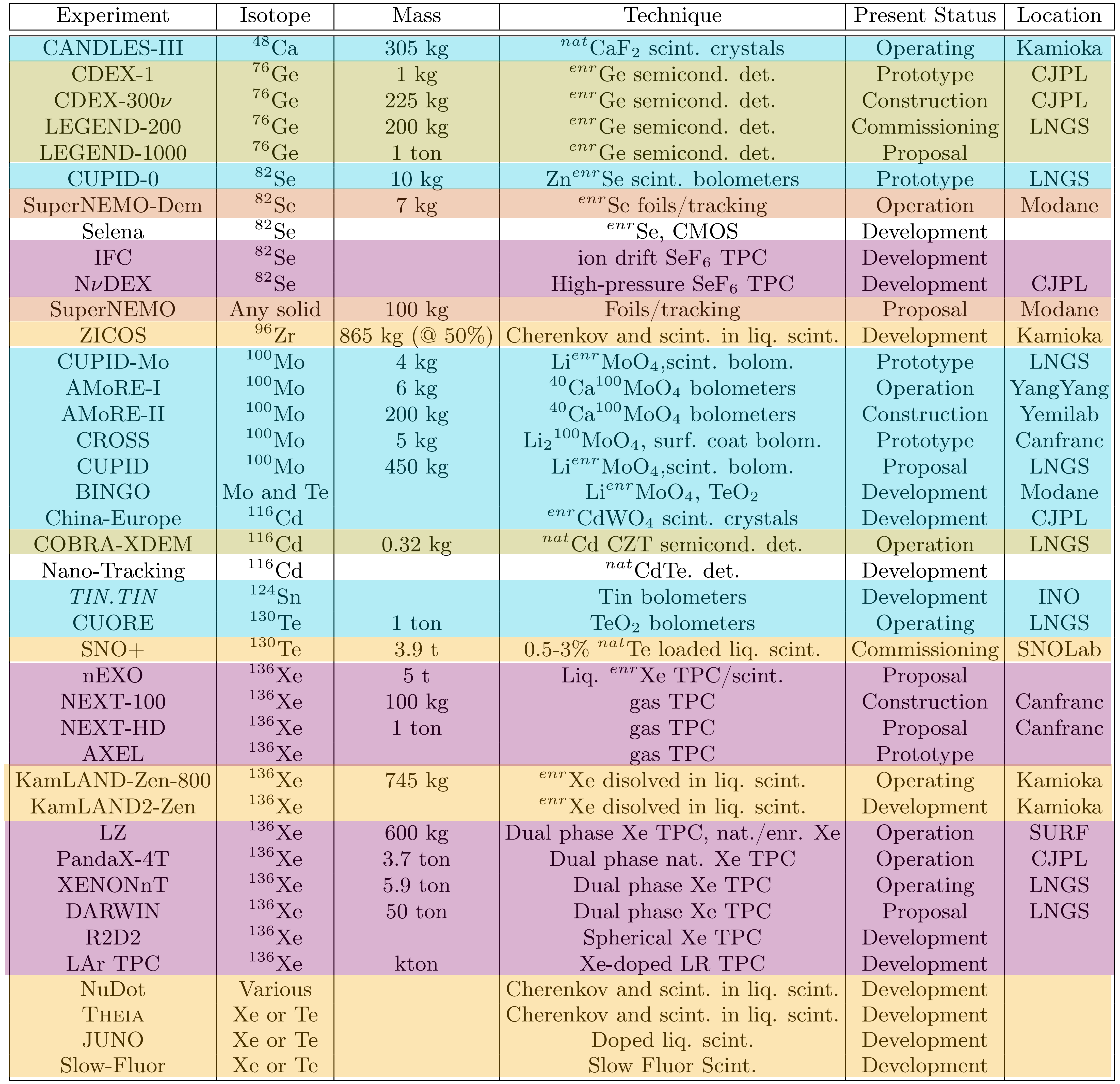


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Table adapted from arXiv:2212.11099

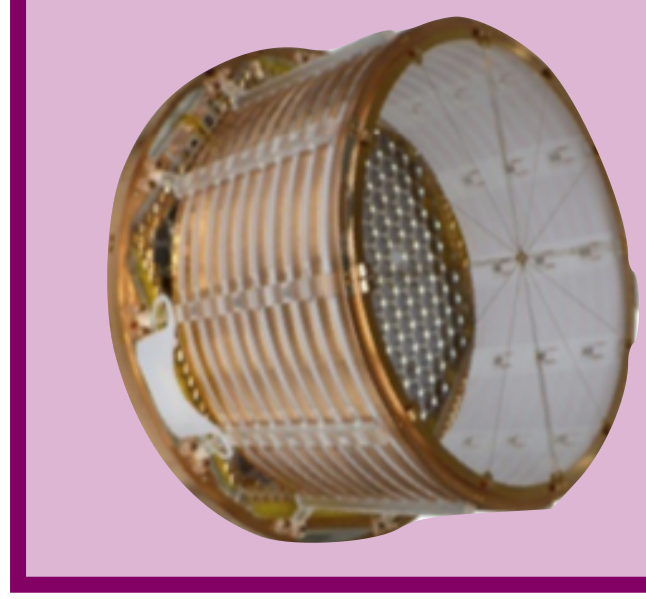
Homogenous detectors:
Source = detector

Combination

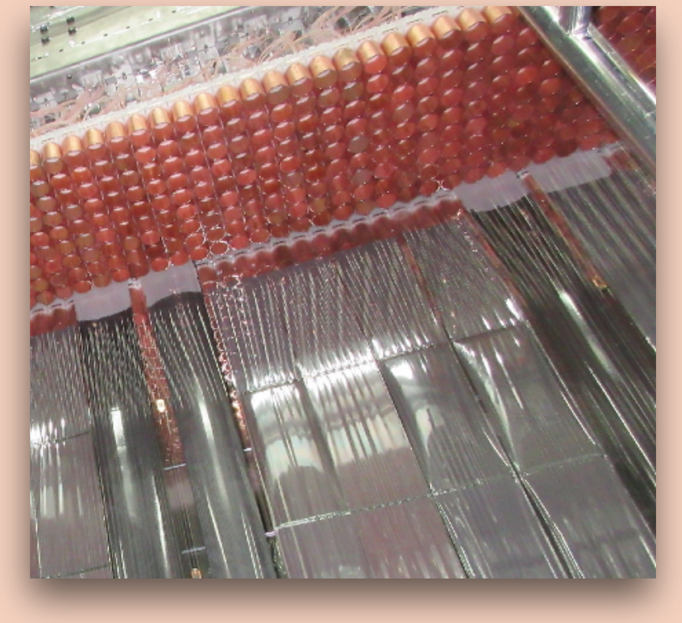
Tracking detectors:
Source separate from
detector

Crystals

TPCs

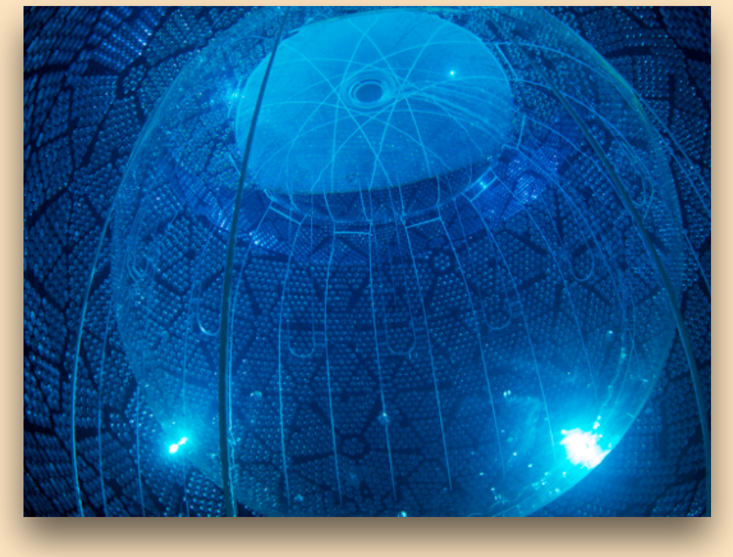


Tracking



Semiconductors

Liquid scintillator



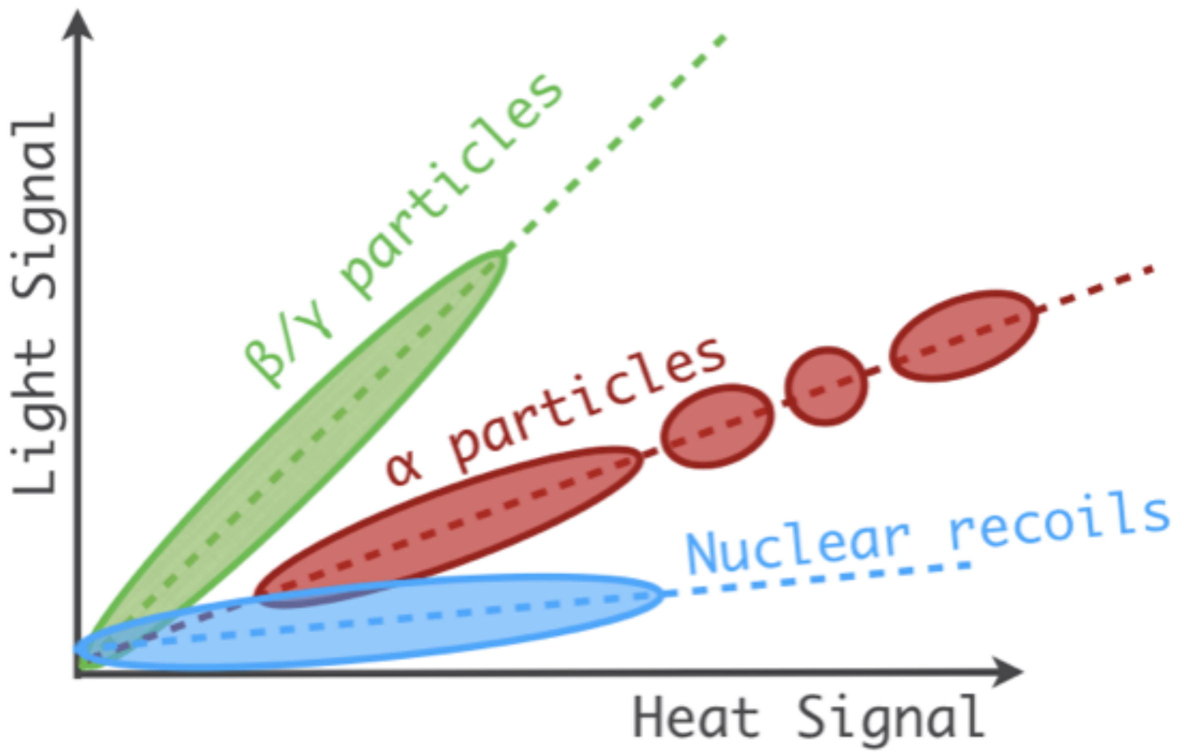
The following contributions come from:

AMoRE	Jeewon Seo & Yoomin Oh (Institute for Basic Science)
Aurora	Fedor Danevich (Institute for Nuclear Research, Kyiv)
BINGO	Claudia Nones (CEA Saclay)
CANDLES	S. Umehara (Osaka University)
CDEX-300v	Hao Ma (Tsinghua University)
CZC crystal R&D	Serge Nagorny (Queen's University)
KamlandZen	Azusa Gando (Tohoku University)
LEGEND	Matteo Agostini (UCL)
nEXO	Samuele Sangiorgio (Lawrence Livermore National Lab)
NEXT	Roxanne Guenette (University of Manchester)
NvDEX	Emilio Ciuffoli (Institute of Modern Physics, Lanzhou)
ORIGIN-X	Samuele Sangiorgio (Lawrence Livermore National Lab)
PandaX	Ke Han (Shanghai Jiao Tong University)
Selena	Alvaro Chavarria (Washington)
SNO+	Jeanne Wilson (King's College, London)
ZICOS	Yoshiyuki Fukuda (Miyagi University of Education)

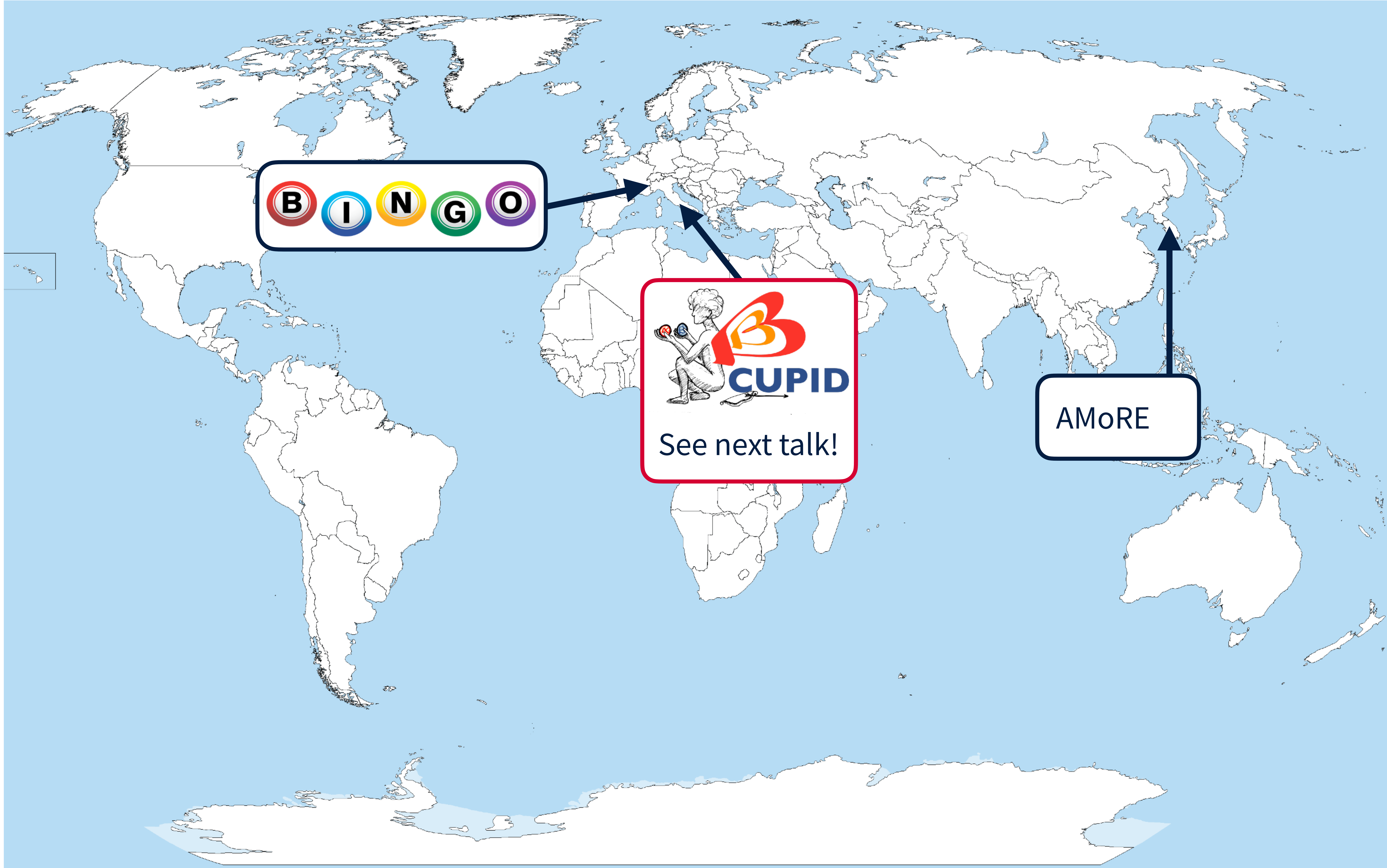
Heat and light signals from decays in ultra-cold crystals

Scintillating/bolometer crystals

^{130}Te,
^{82}Se,
^{100}Mo



L. Pattivina



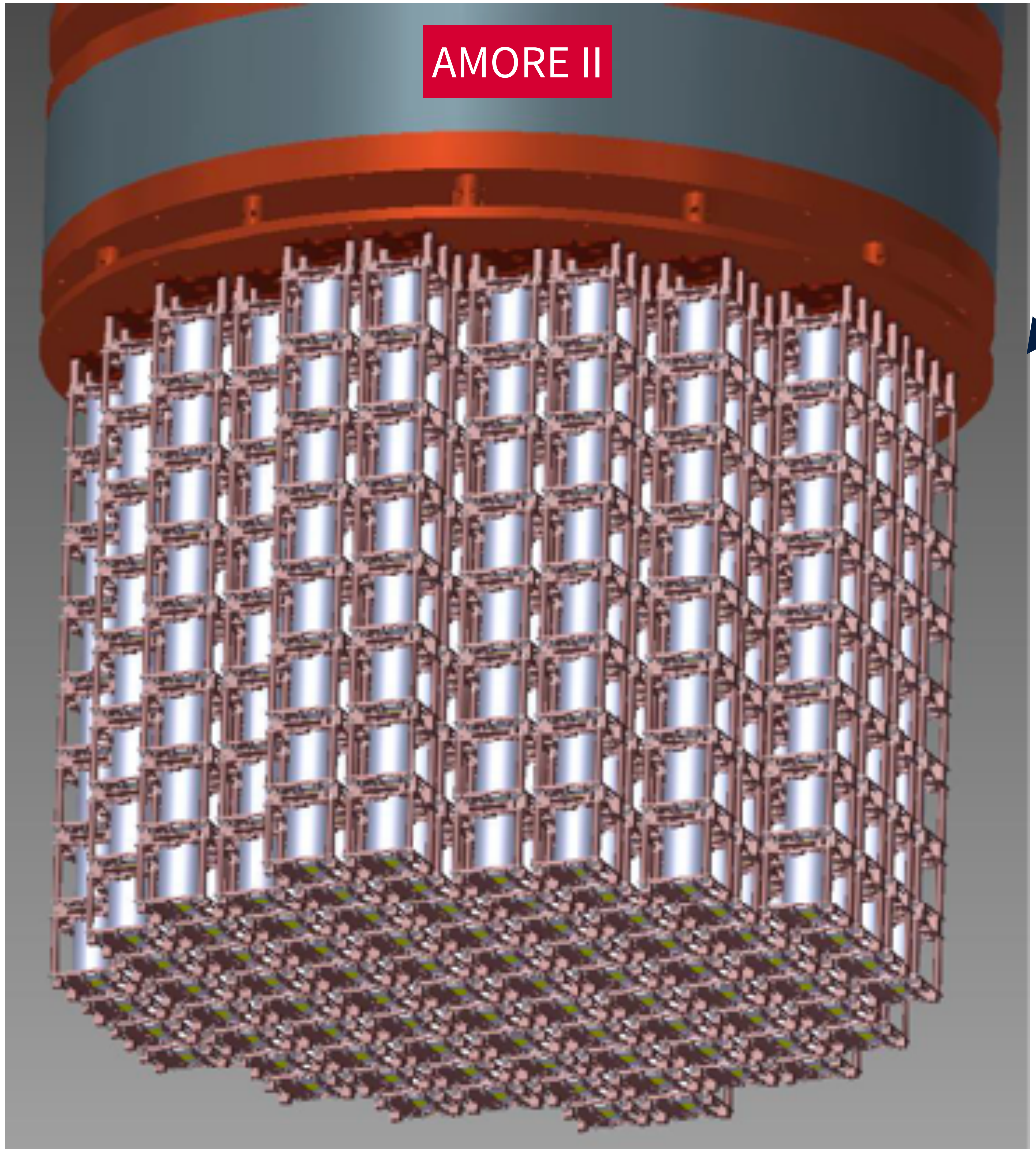
BINGO

CUPID

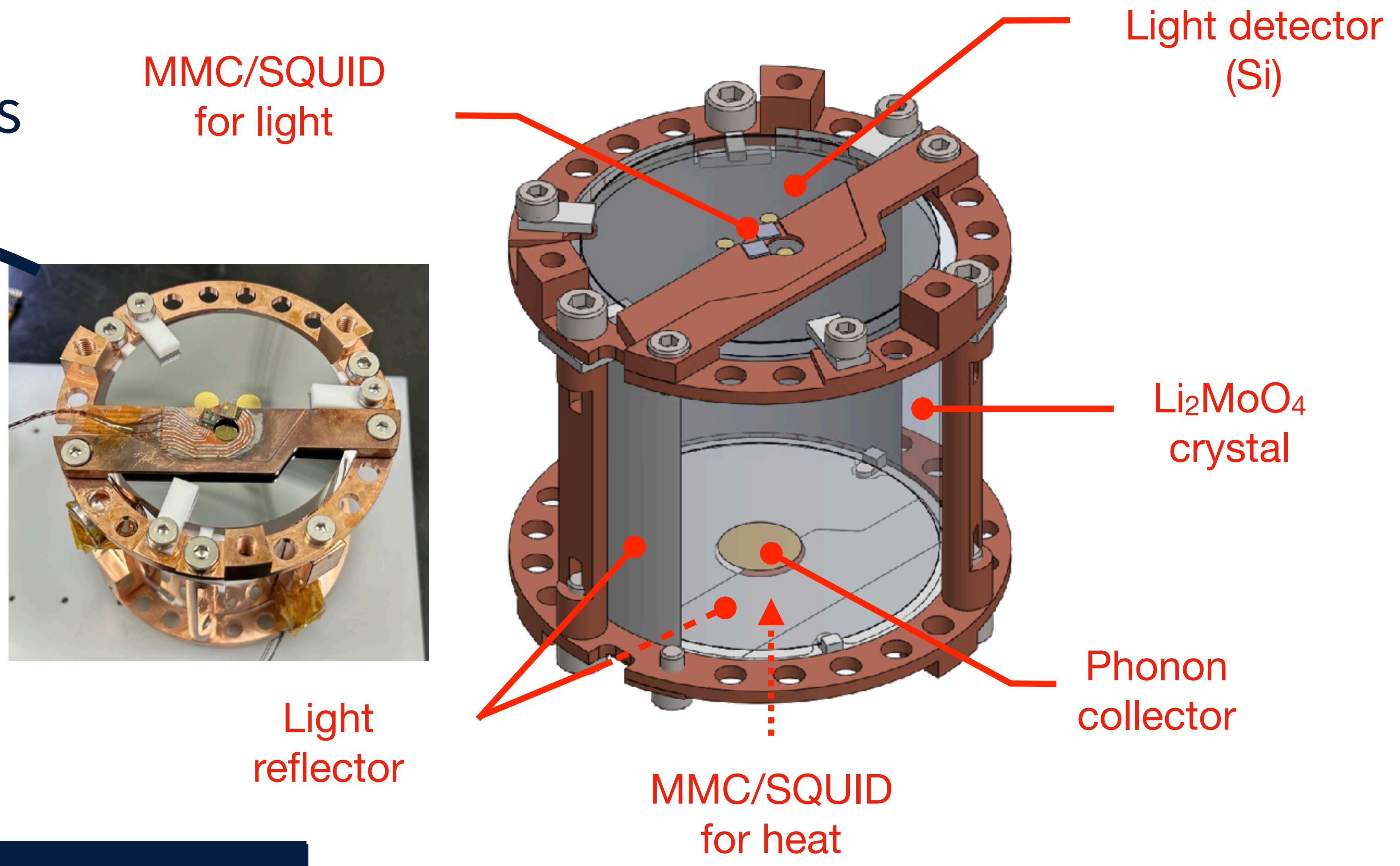
See next talk!

AMoRE

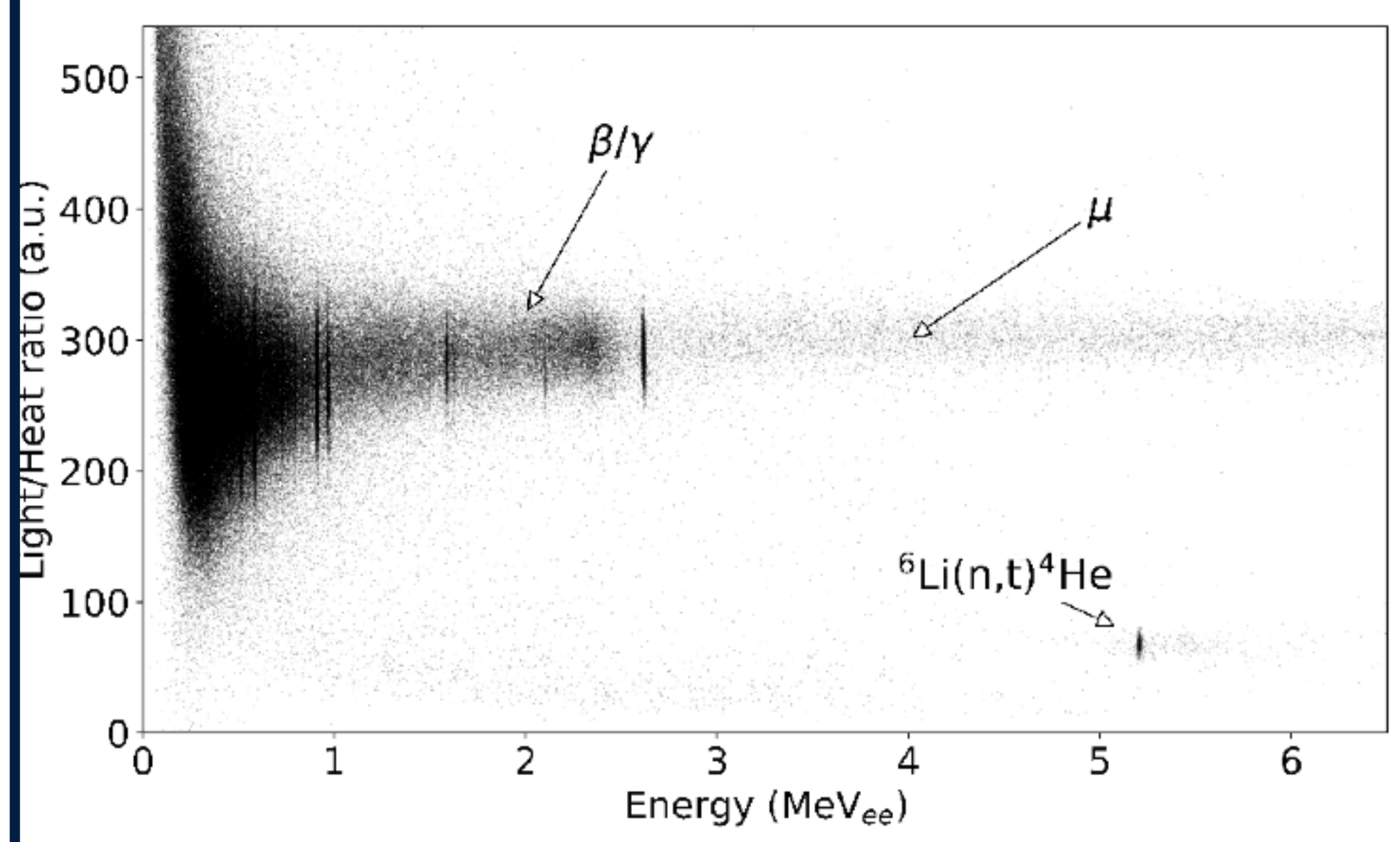
AMoRE: ^{100}Mo with photons and phonons



157 kg of $Li_2{}^{100}MoO_4$ crystals



Background discrimination



< 2×10^{-4} counts/keV/kg/year in $0\nu\beta\beta$ ROI

- AMoRE-I complete: $T_{1/2}^{0\nu} > 3.3\times10^{24}$ years
- AMoRE-II starts 5-year data taking in 2024:
  - 3σ $0\nu\beta\beta$ sensitivity: $T_{1/2}^{0\nu} \sim 4\times10^{26}$ years

BINGO: Bi-Isotope 0νββ Next Generation Observatory

BINGO aims to dramatically reduce the background in the region of interest, through:

Compact assembly:

- Reduce surface radioactivity
- Anti-coincidence cuts

Neganov-Luke light detectors:

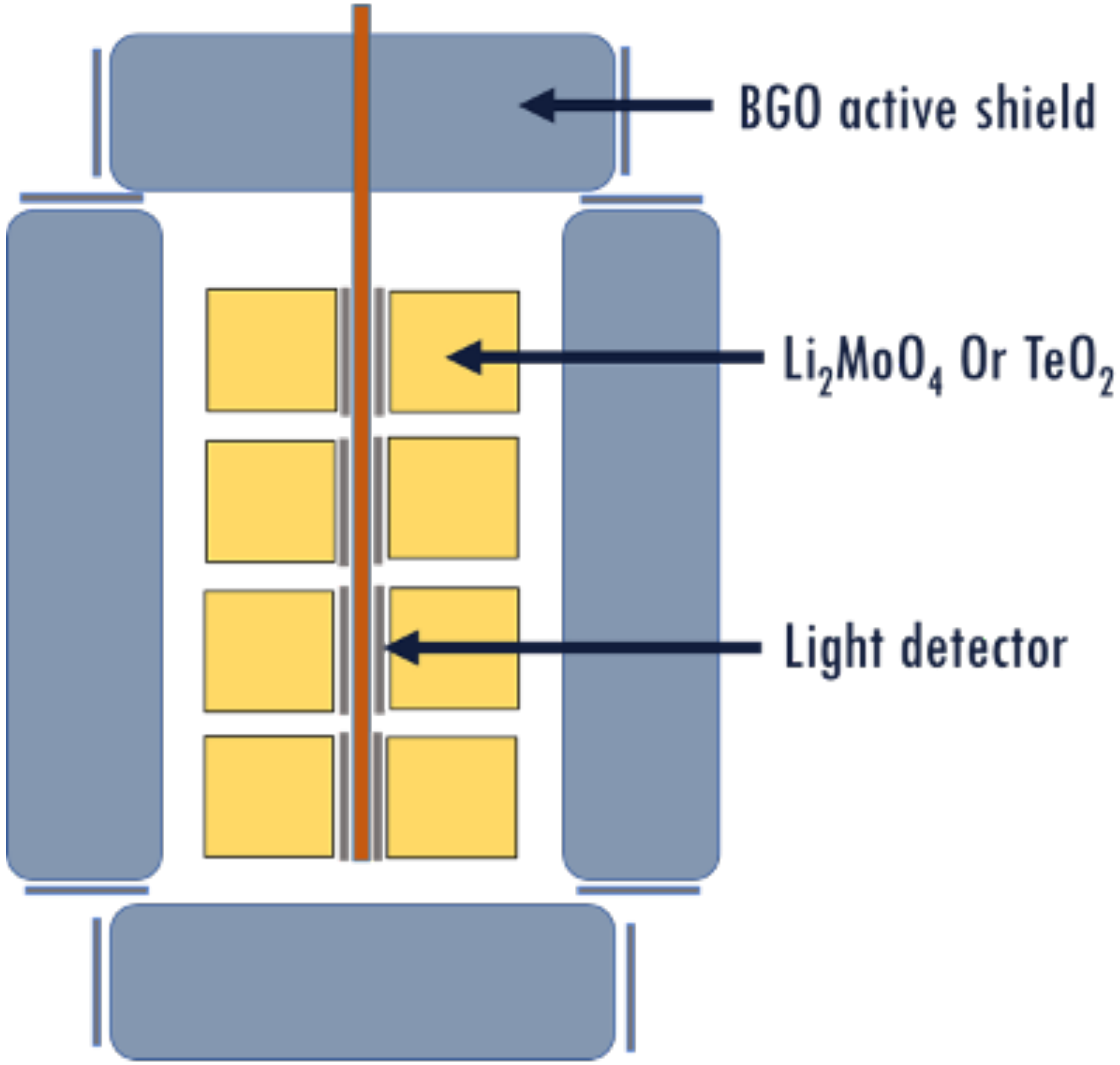
- Amplify the tiny Cherenkov signal (TeO_2) → suppress α's
- Higher sensitivity, lower energy threshold

An active shield based on BGO scintillators::

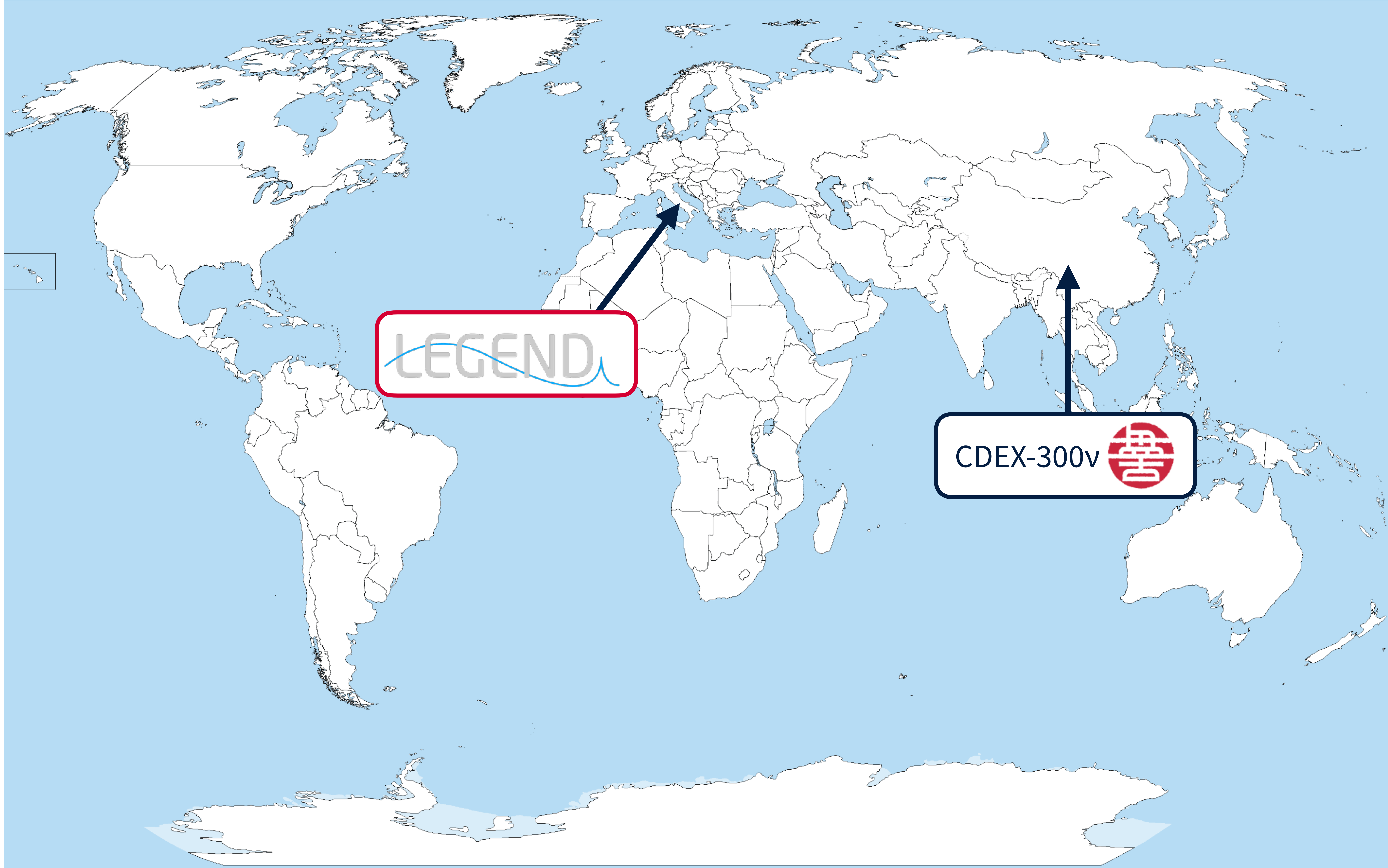
- Suppress the external gamma background

Bi-Isotopic approach: observation in 2 candidates → discovery + confirmation

Mini-BINGO:
12 of each crystal type
Test all detector elements
b $\leq 10^{-4}$ in 1 year of data-taking



Enriched HPGe semiconducting detectors

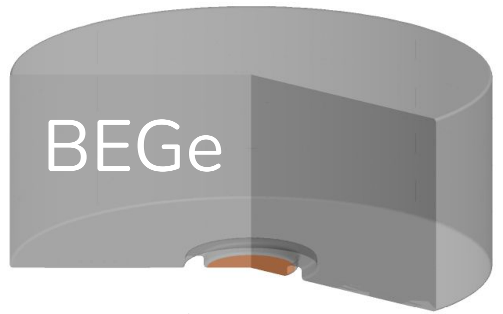


Semiconductor HPGe detectors:

- solid state TPC
- mm-scale event topology
- calorimetric energy measurement

LEGEND-200 - taking data at LNGS

Initial dataset



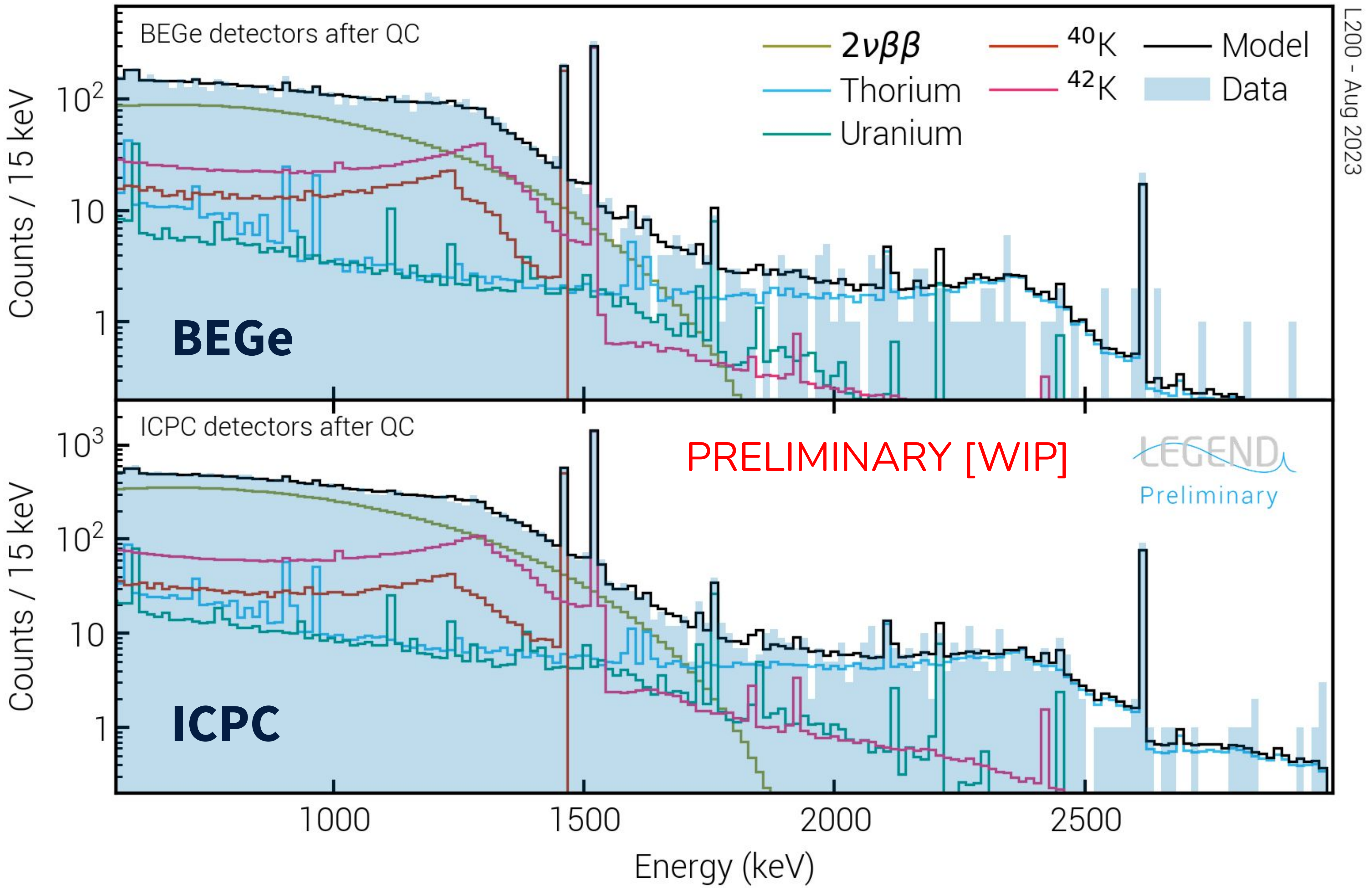
Broad **E**nergy
Germanium

BEGe - 2.1 kg yr

Inverted **C**oaxial
Point **C**ontact

ICPC - 8.0 kg yr

Preliminary background model before analysis cuts

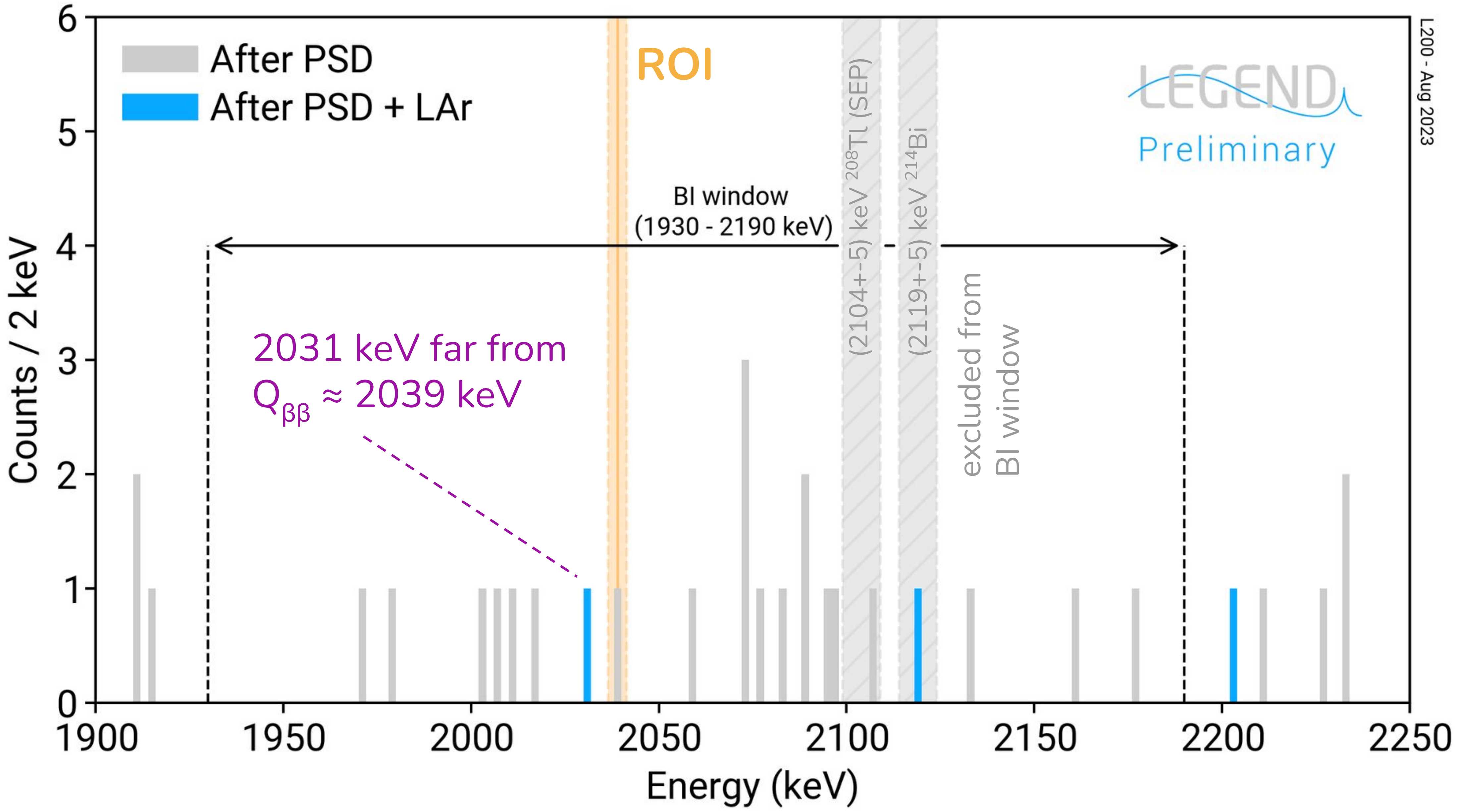


Well described by expected contributions - now accumulating exposure

Backgrounds after cuts

▨ Pulse-shape discrimination (PSD)

🟦 PSD plus liquid-argon veto

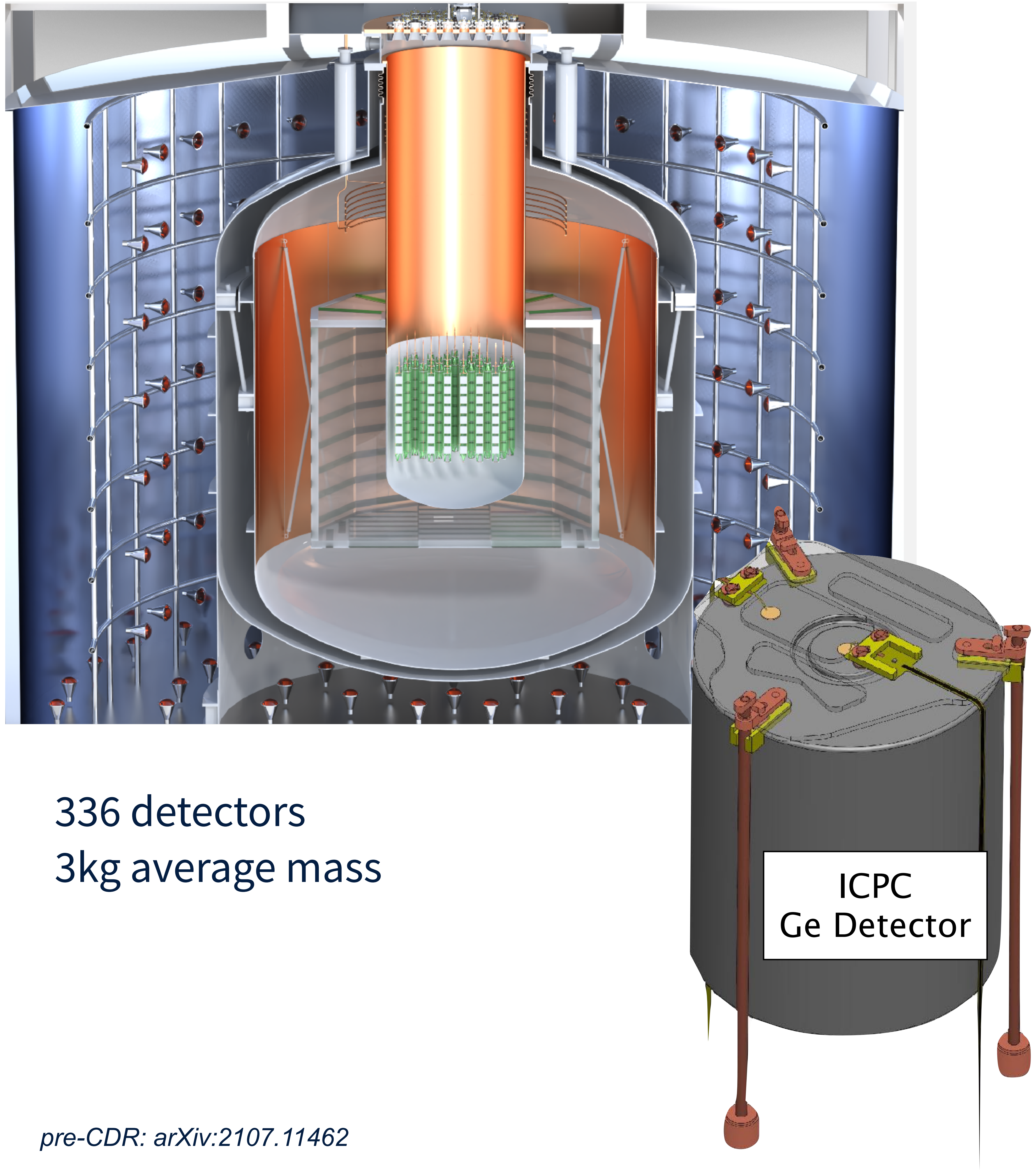


Background index compatible with design goal

2 x 10^{-4} cts/(keV kg yr)

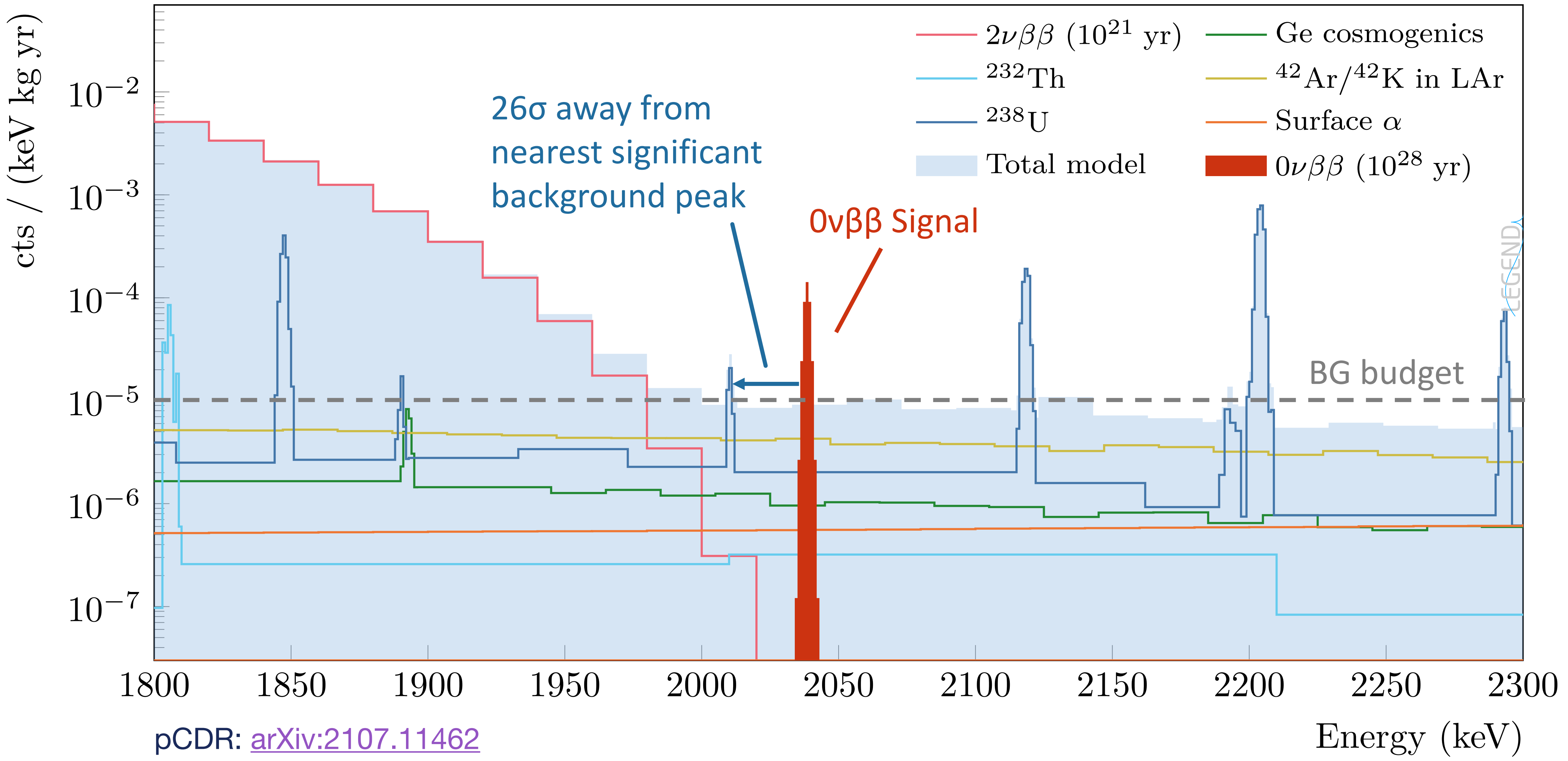
0.48 counts expected; probability to observe #cts > 0 ~38%

LEGEND-1000: planned for LNGS



336 detectors
3kg average mass

pre-CDR: arXiv:2107.11462



26σ away from nearest significant background peak

0νββ Signal

BG budget

pCDR: arXiv:2107.11462

Design & Reviews

First Data

Full Data Taking

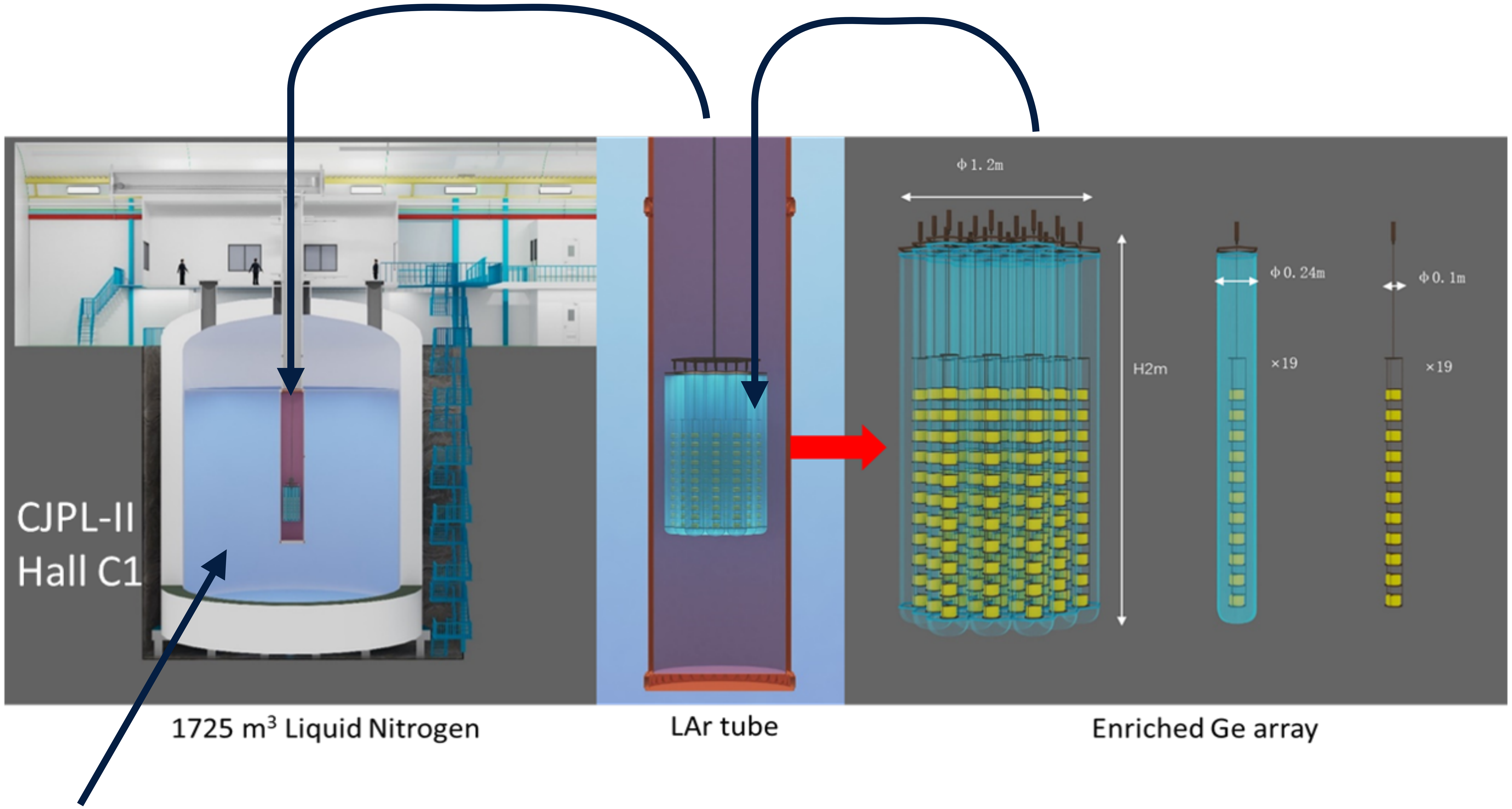
Construction, Detector Production & Installation

*Technically driven schedule

Funding for isotope procurement starts

CD1 review with DOE

CDEX-300ν pre-conceptual design



LAr veto tube

200 Ge detectors in 19 strings

1725 m^3 Liquid Nitrogen

LAr tube

Enriched Ge array

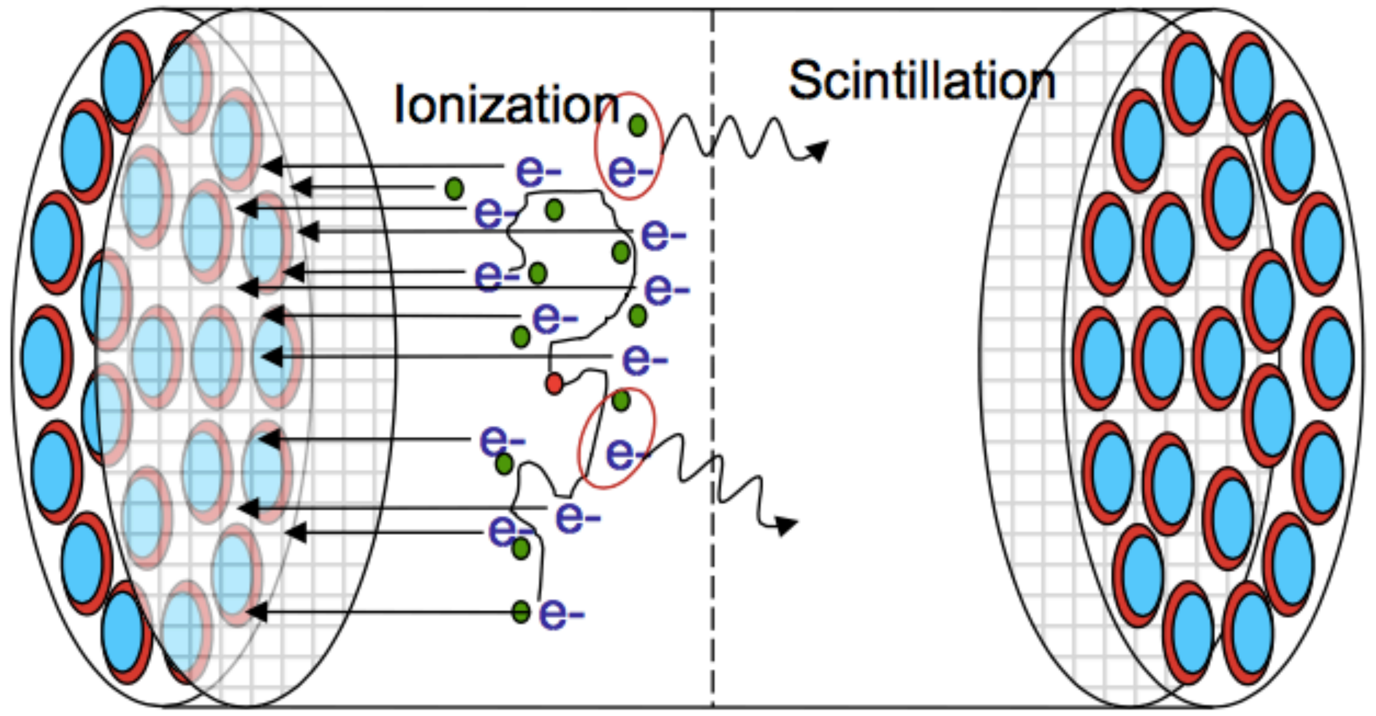
LN$_2$ tank shared with CDEX-50 dark matter experiment

2024:

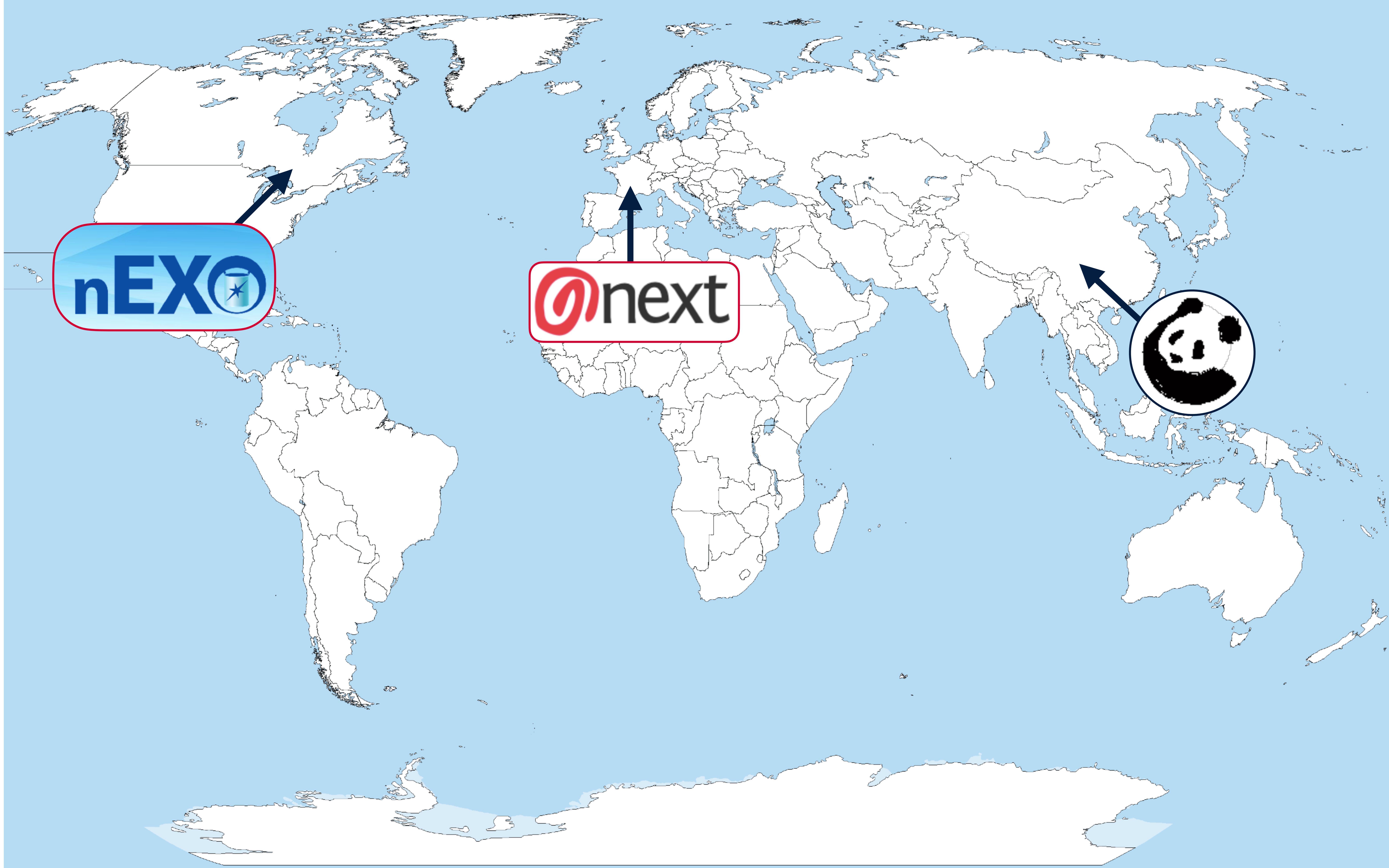
- Operate LAr test facility
- Experimental setup at CJPL
- First batch of Ge detector installation and test

^{136}Xe time-projection chambers

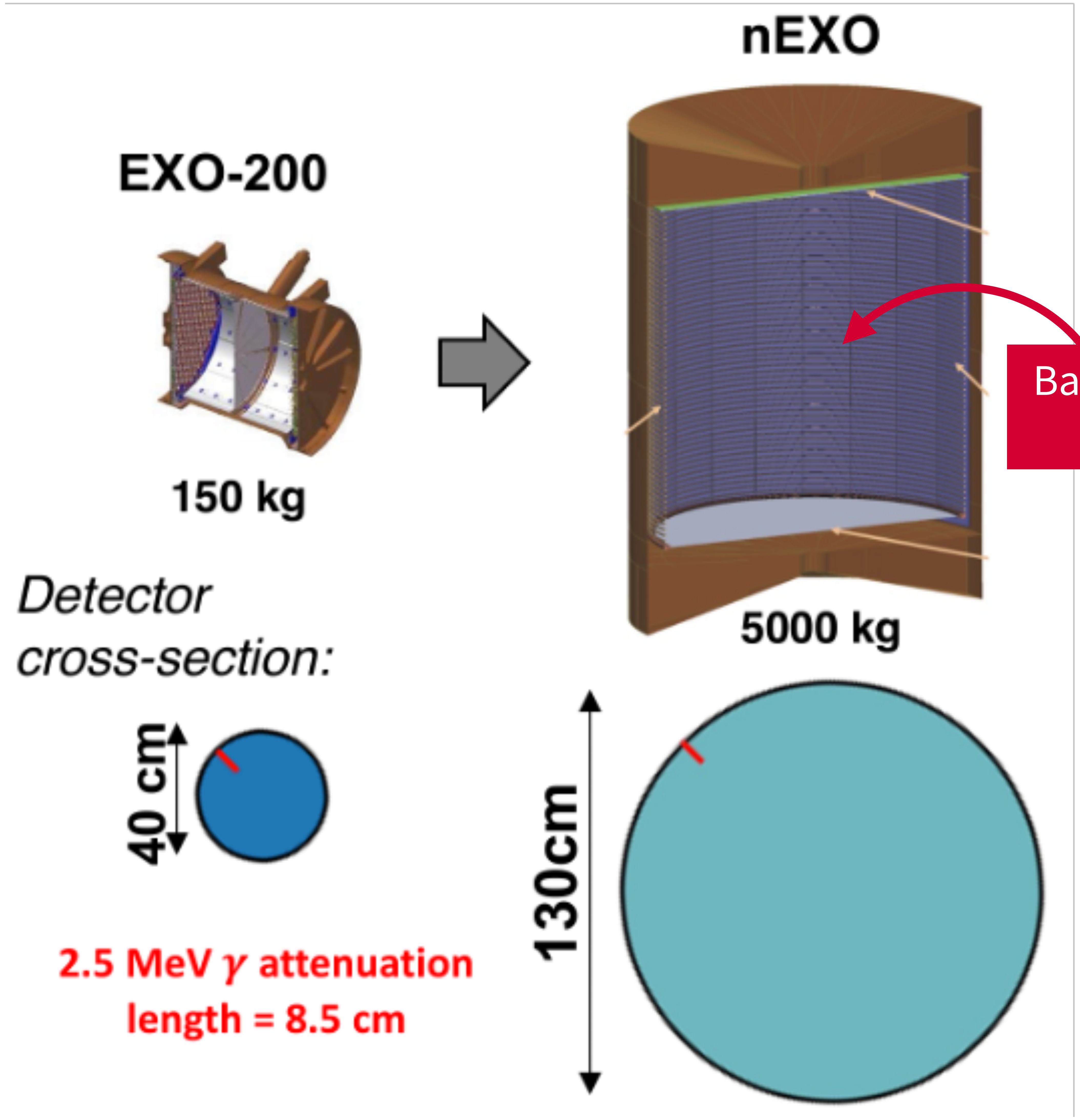
L Yang, Neutrino 2016



Large-volume detectors use ^{136}Xe as
- ββ source
- TPC ionisation medium
- scintillator



nEXO: Tonne-scale $0\nu\beta\beta$ with a LXe TPC

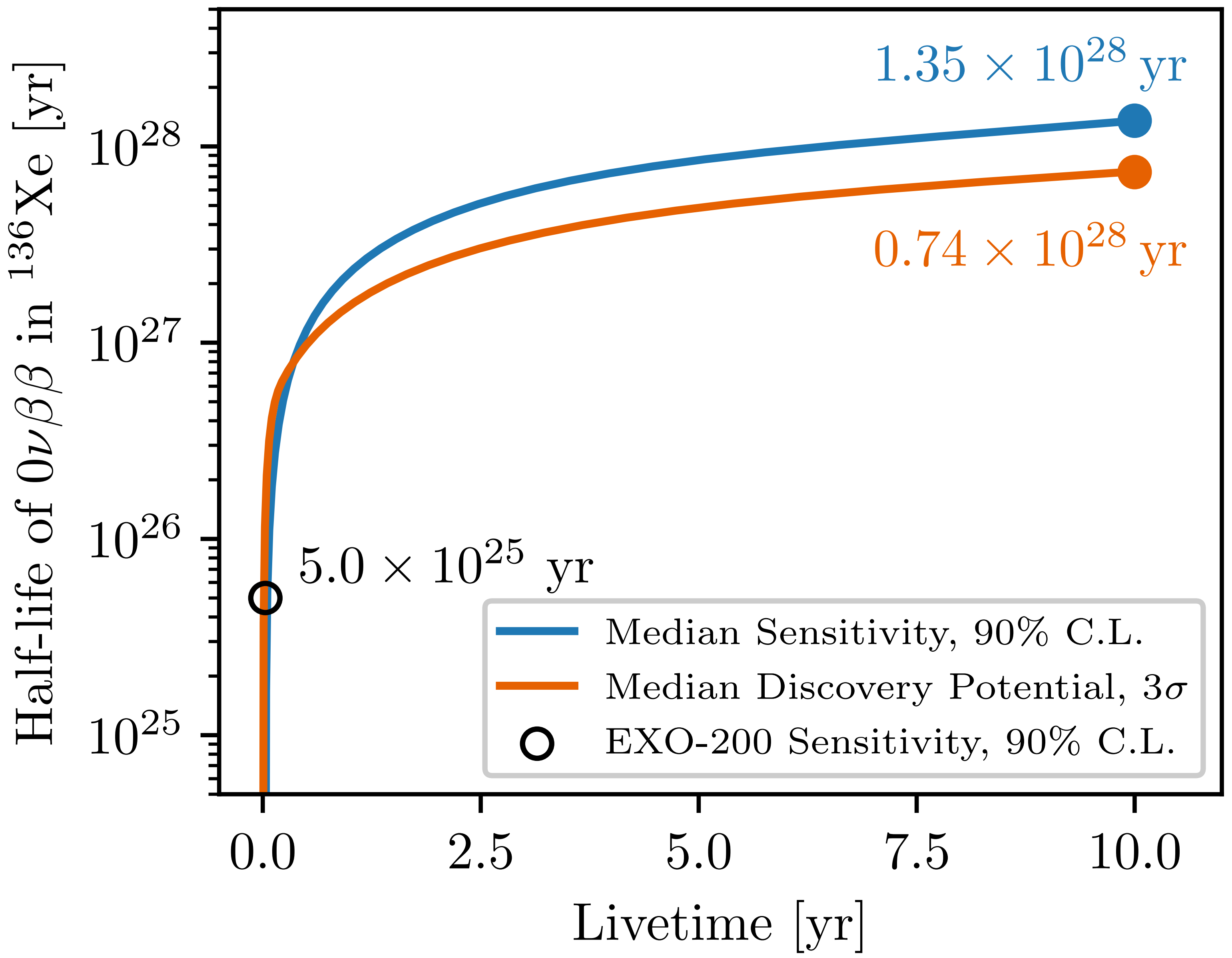


Background-free central region

Conceptual design in progress, projected 3σ discovery sensitivity

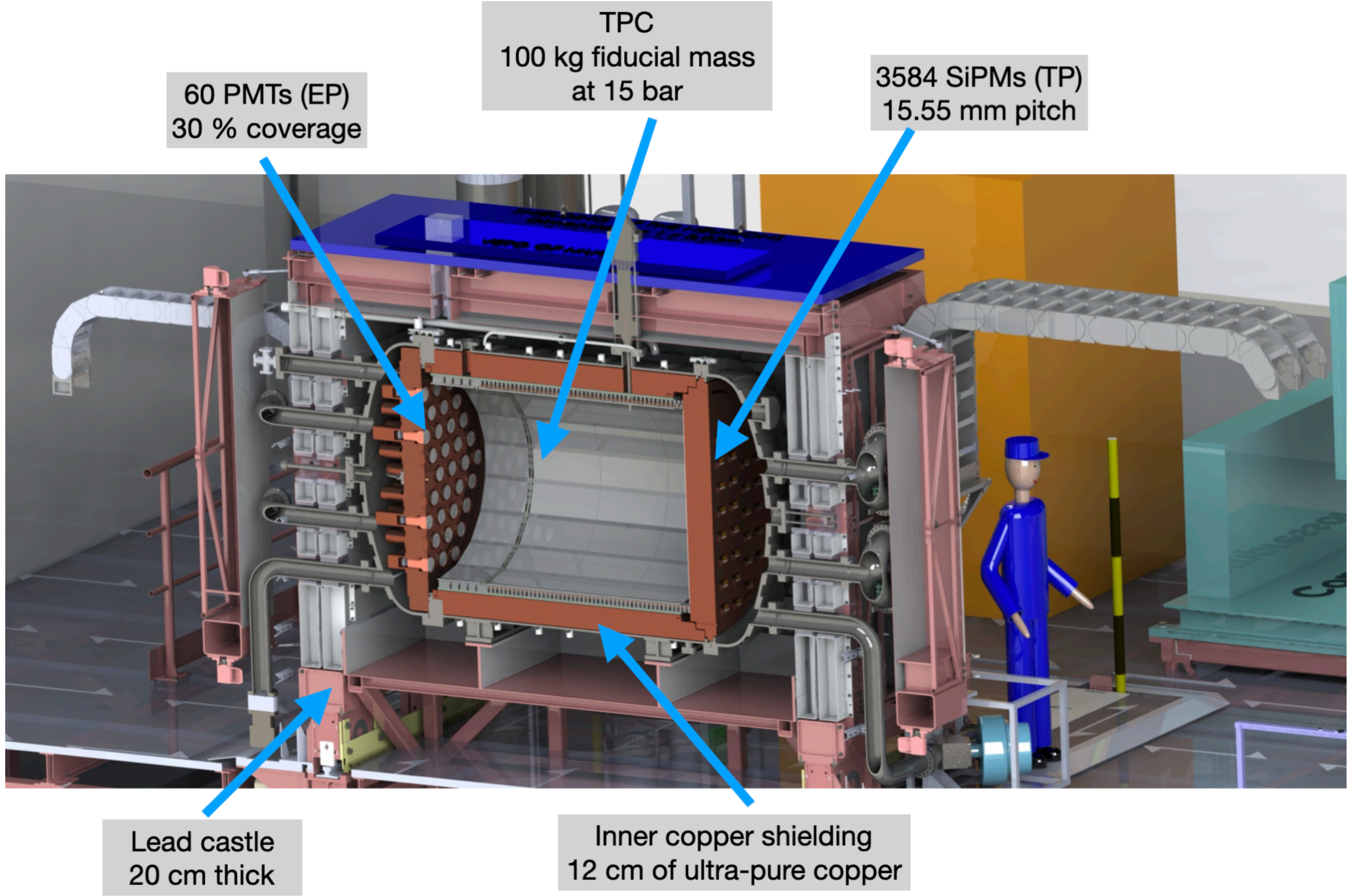
$\langle m_{\beta\beta} \rangle$ = 6-27 meV ($T_{1/2}$ = 0.74 x 10^{28} yr)

Sensitivity vs exposure



nEXO Sensitivity arXiv:2106.16243

NEXT-100 (2023-2026)



TPC
100 kg fiducial mass
at 15 bar

60 PMTs (EP)
30 % coverage

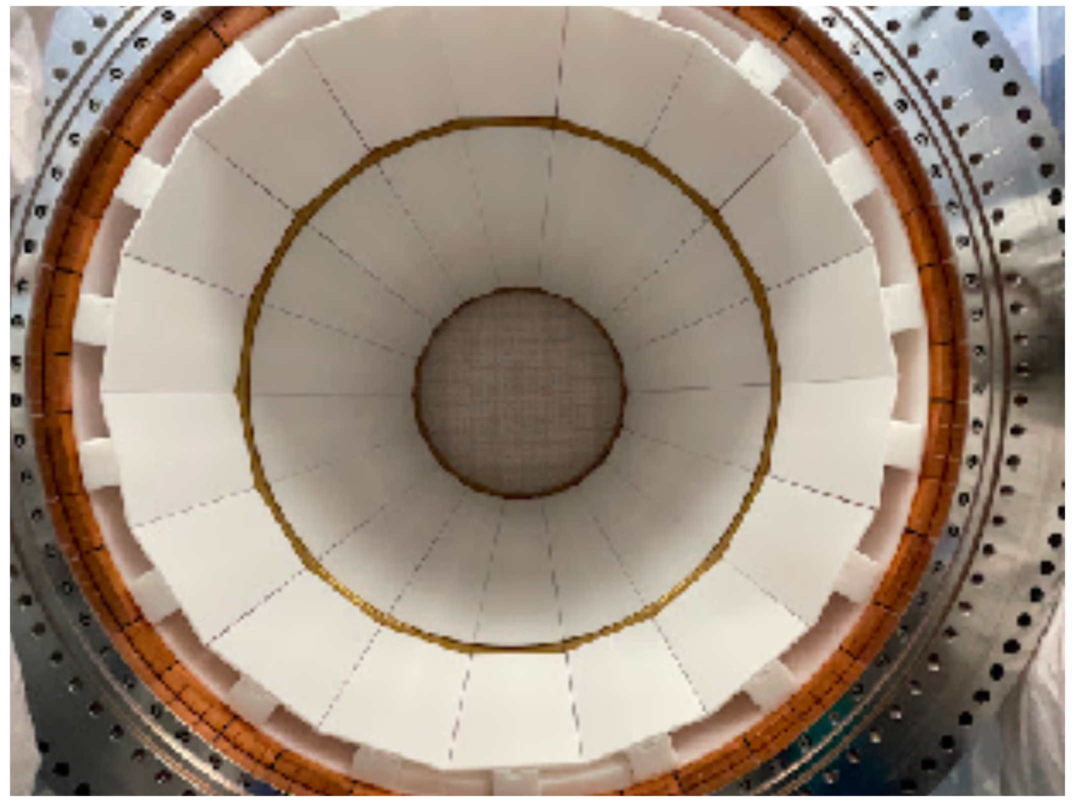
3584 SiPMs (TP)
15.55 mm pitch

Lead castle
20 cm thick

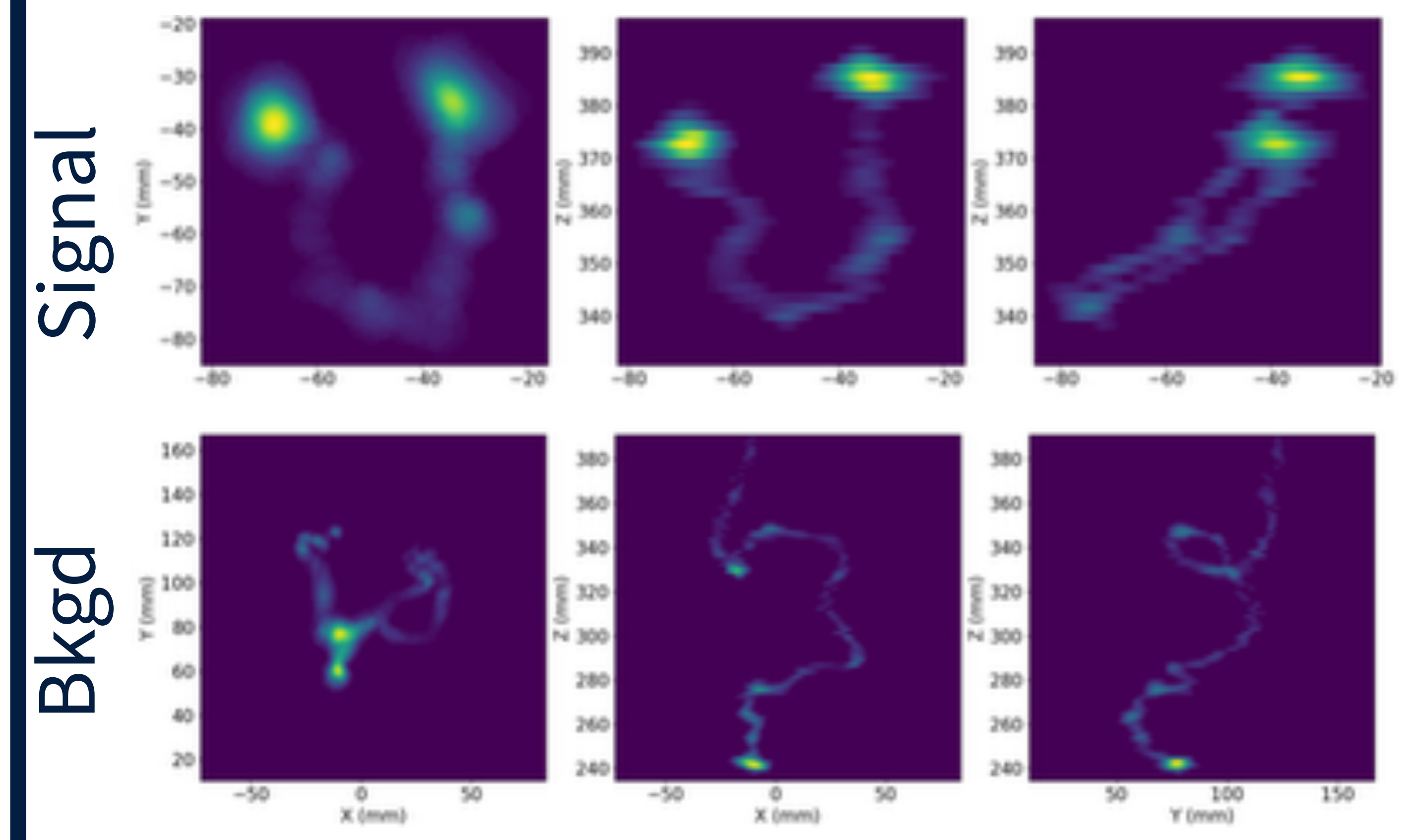
Inner copper shielding
12 cm of ultra-pure copper

NEXT-100 detector fully assembled at LSC

Commissioning starting in January 2024!



Topological identification



Traditional cut-based analysis

~70% efficiency

~20% bkg contamination

NEXT Collaboration, JHEP 10 (2019) 052

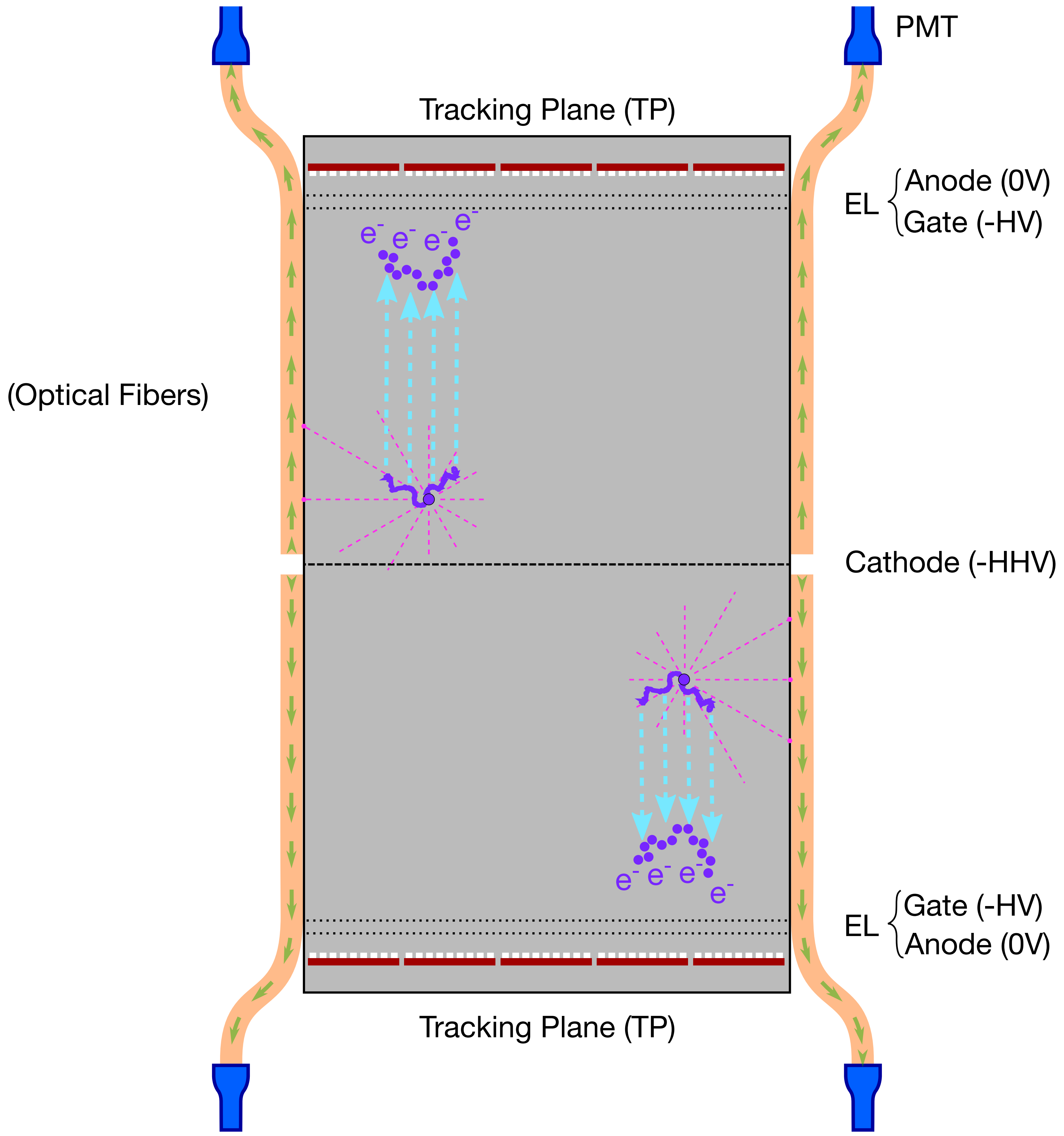
Improvement with DNNs

~5% bkg contamination

NEXT Collaboration, JHEP 01 (2021) 189

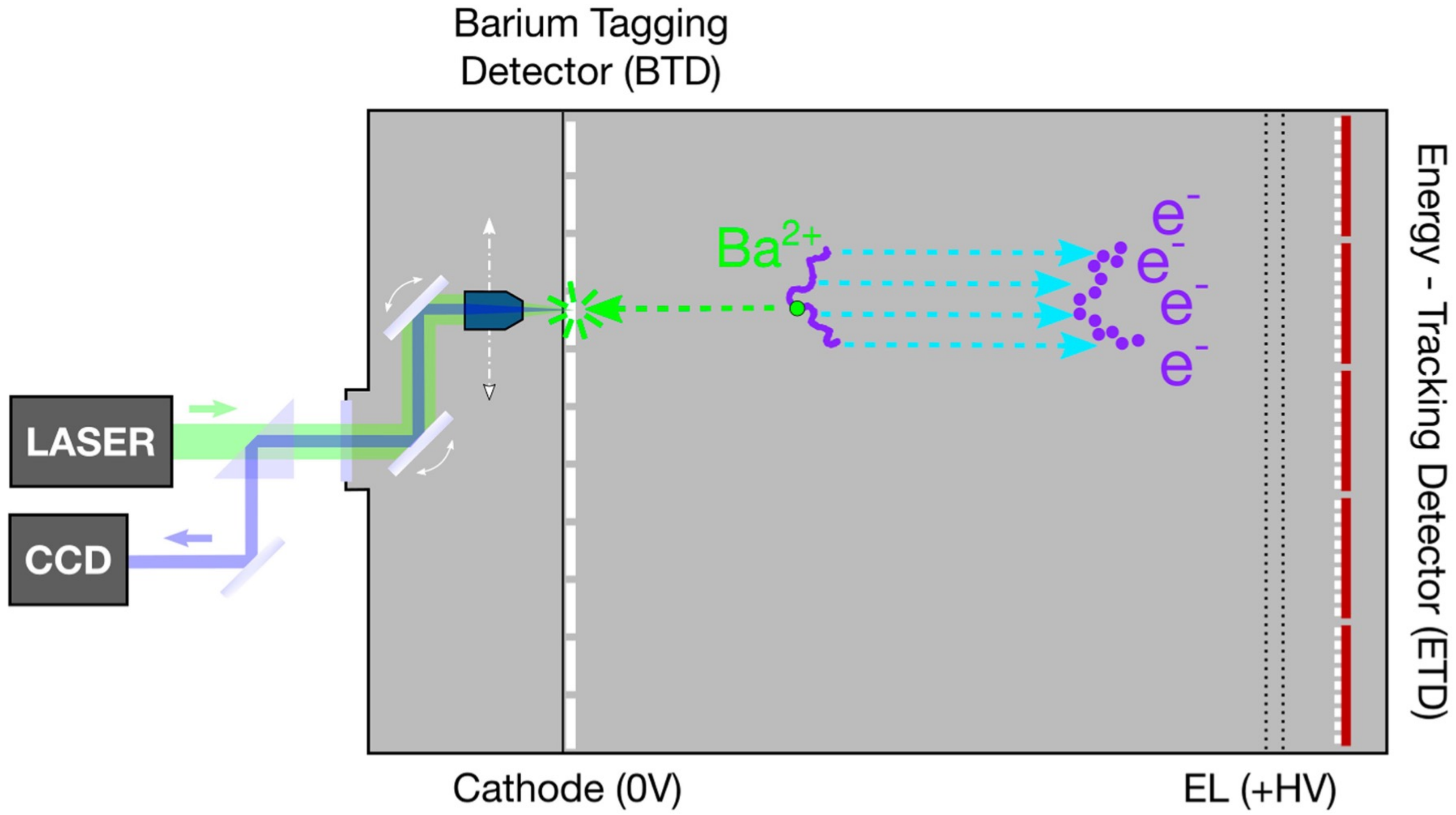
NEXT ton-scale and beyond

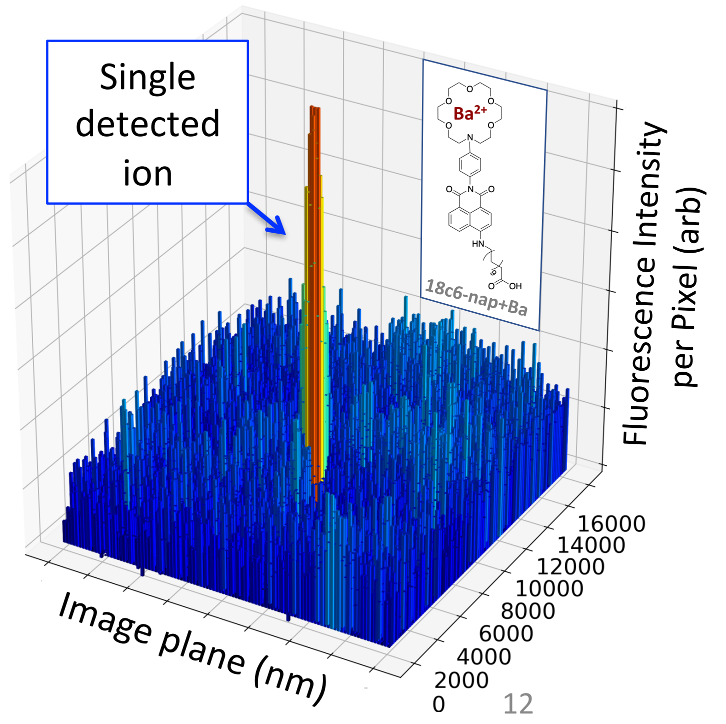
NEXT-HD: $T_{1/2} > \mathbf{10^{27}}$ **yr** $0\nu\beta\beta$ sensitivity with **4 ton.yr** exposure



Next-HD with symmetric TPC design

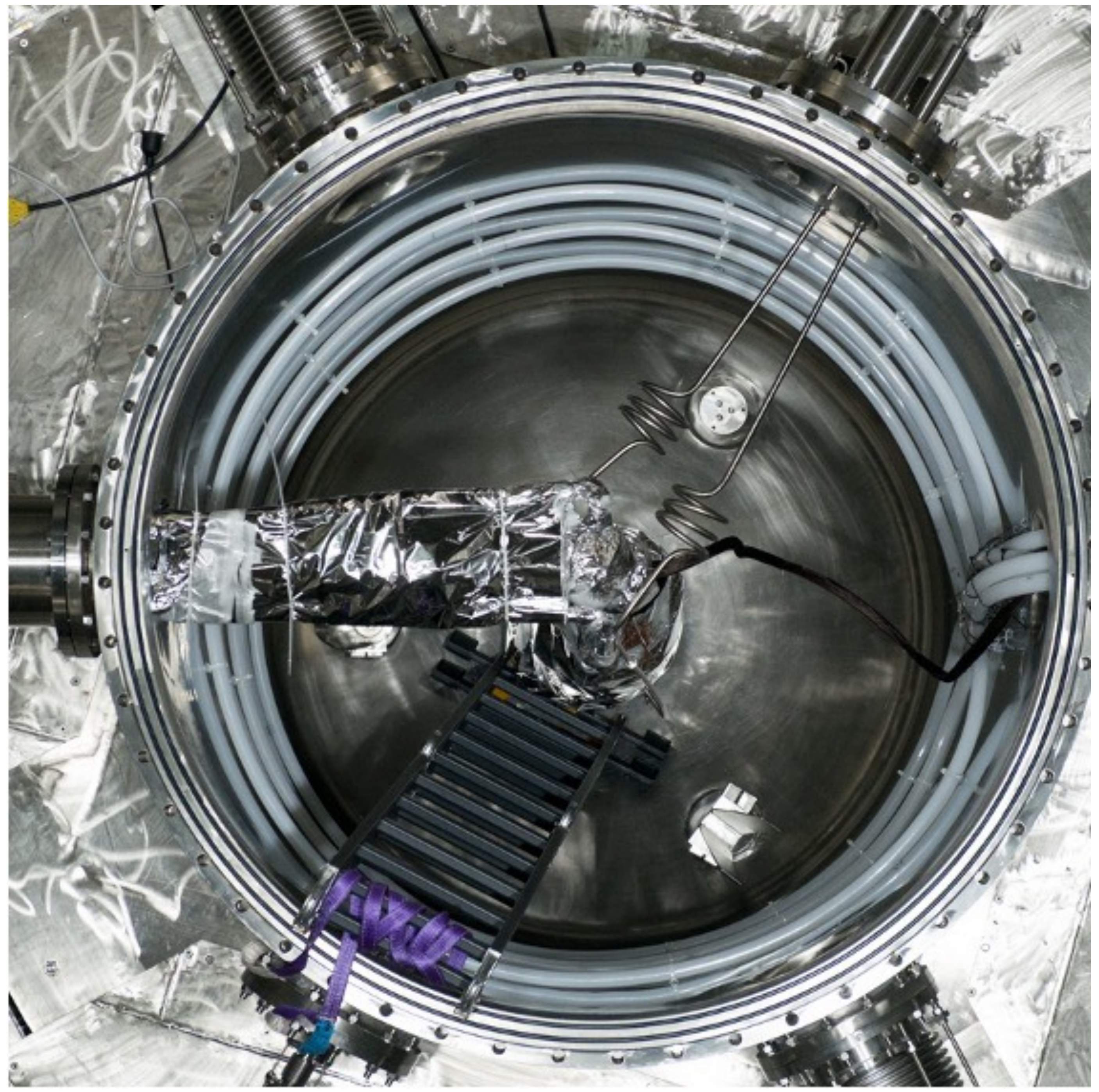
For10^{28}-year sensitivity: **barium tagging (NEXT-BOLD)**

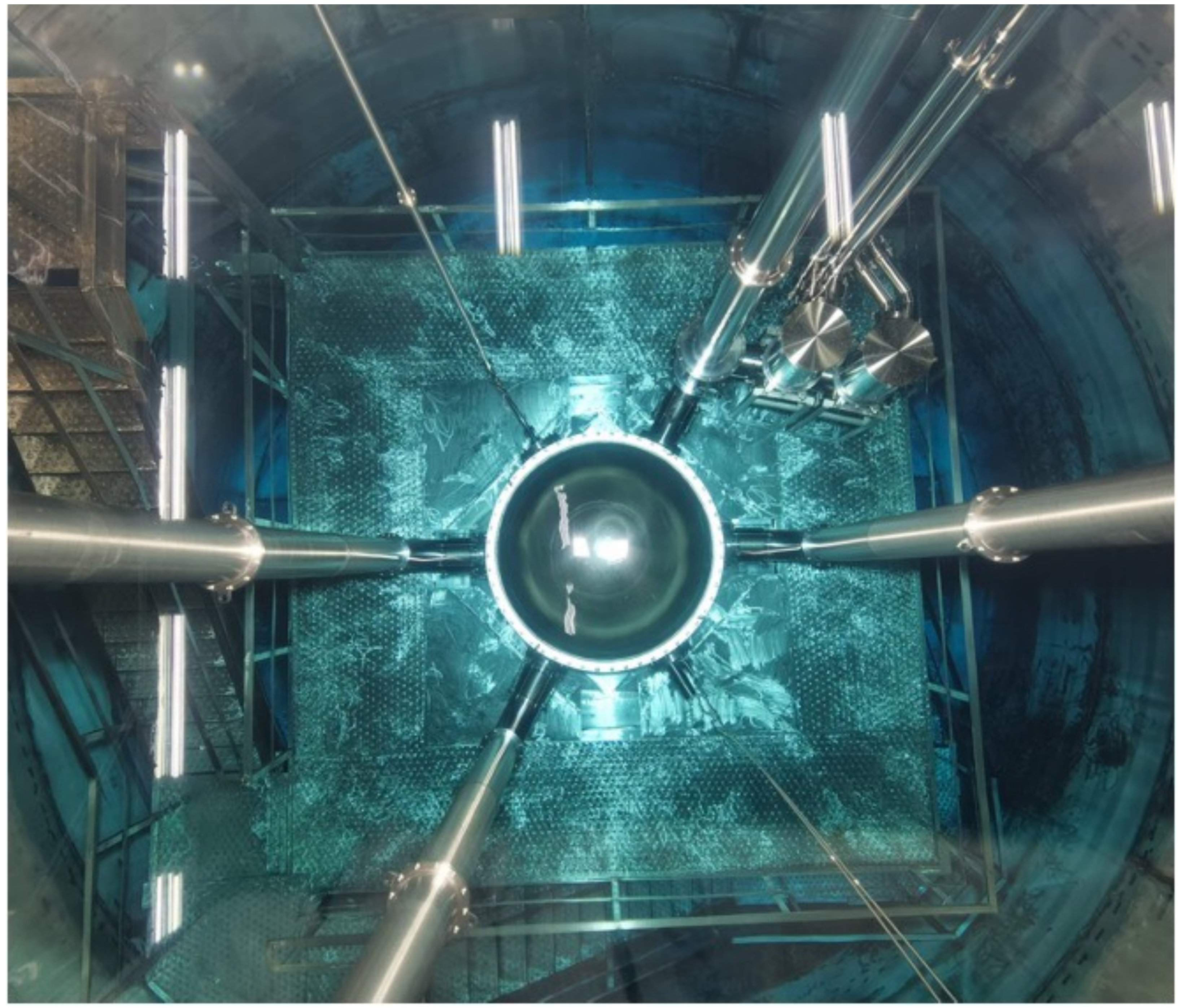




PandaX

- PandaX-4T 3.7 -tons dual-phase natural Xe TPC at CJPL (>300kg ^{136}Xe)
  - Measured $2\nu\beta\beta$ $T_{1/2} = 2.27 \pm 0.03(\text{stat.}) \pm 0.09(\text{syst.}) \times 10^{21}$ year
  - Running since late 2020 (95+154 days)
- Future : PandaX-xT: 4 tons of ^{136}Xe

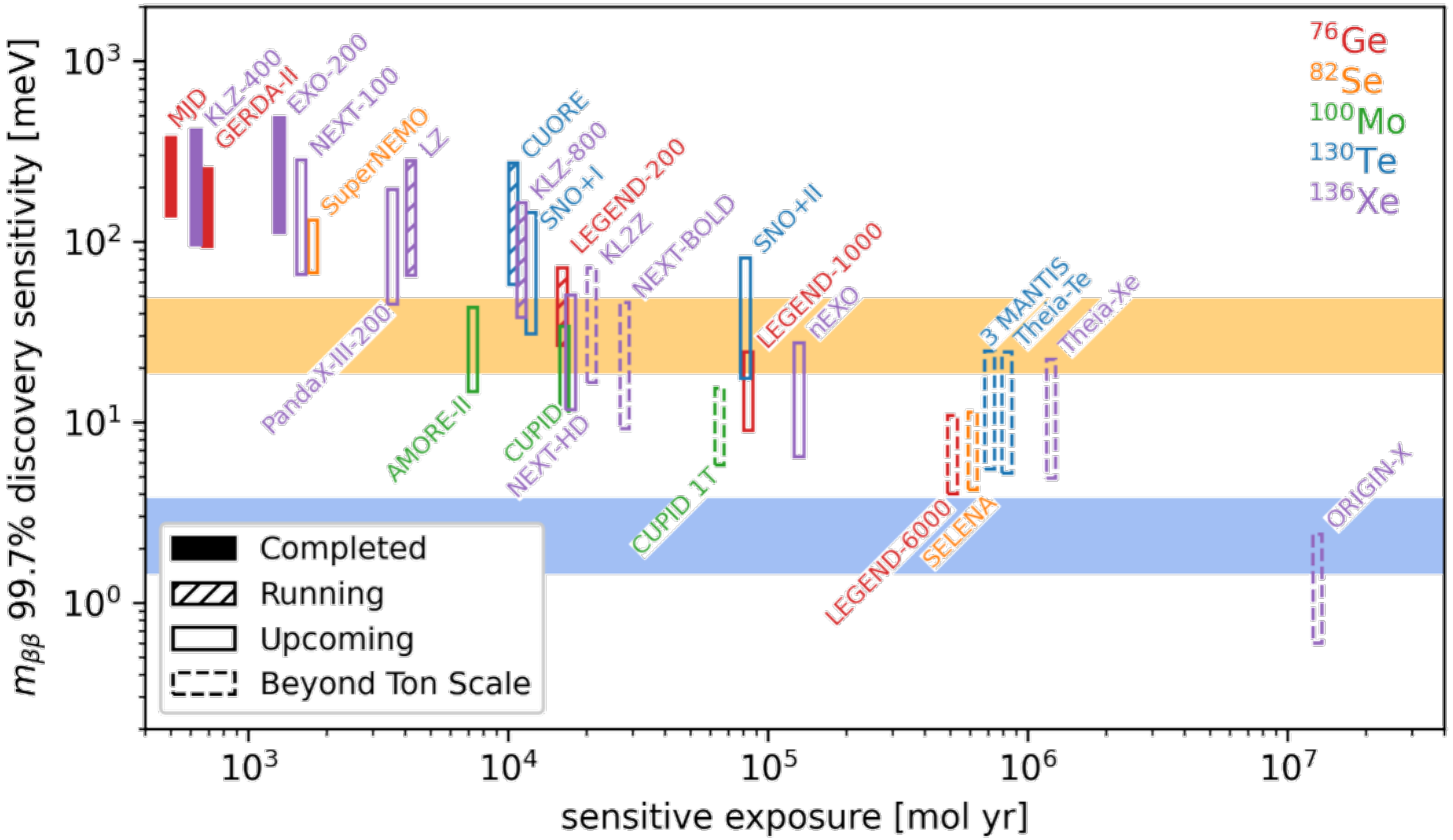




ORIGIN-X - the ultimate $0\nu\beta\beta$ experiment?

- Observing Rare Interactions with a GIaNt Xenon (ORIGIN-X) experiment: a ktonne Xe experiment for $0\nu\beta\beta$.

A. Avasthi, et al, Phys. Rev. D 104, 112007 (2021)



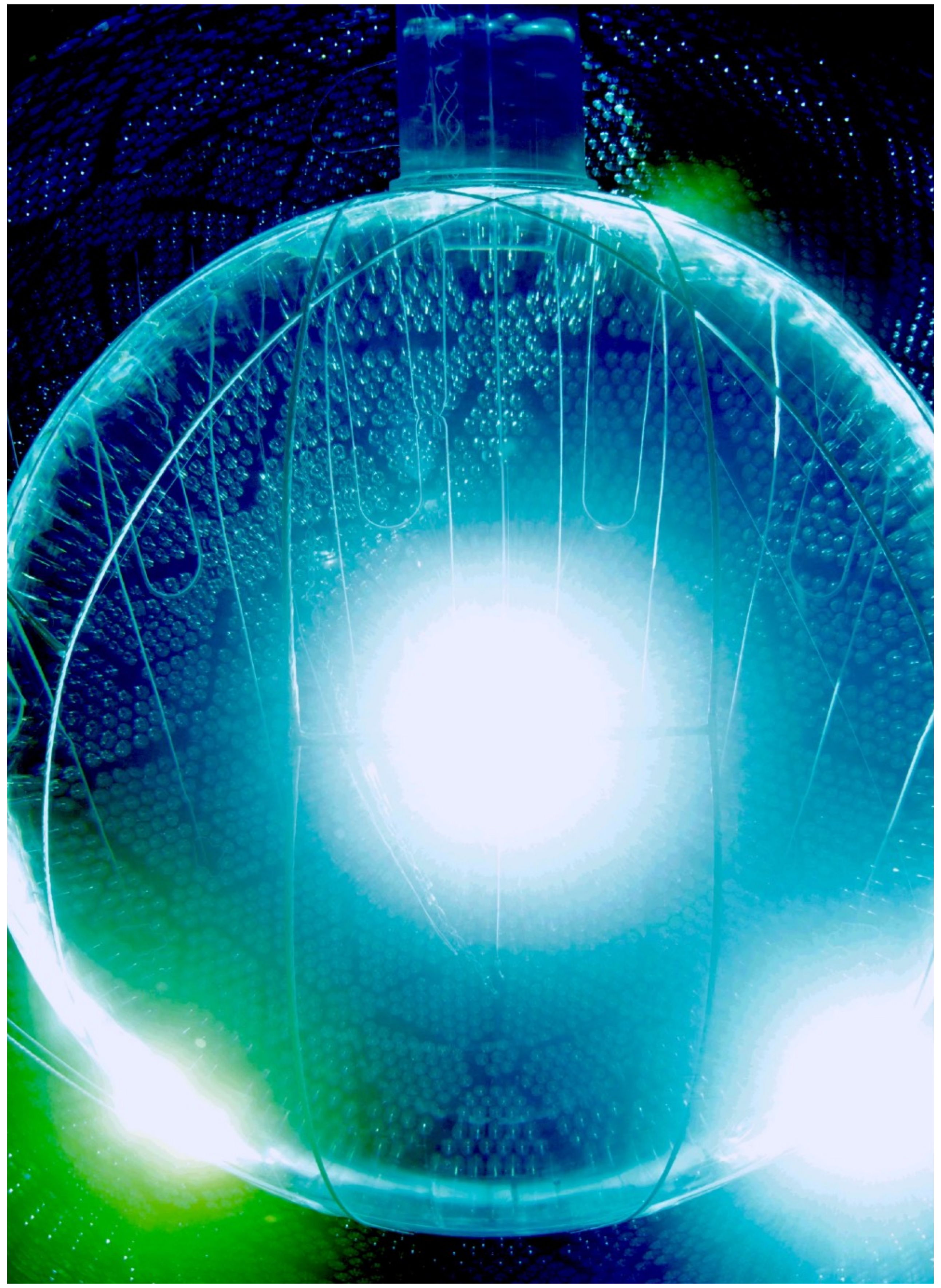
- Xenon is present in the atmosphere at 87 ppb (~0.2 Gt total)
- Current production is a parasitic process in steel industry

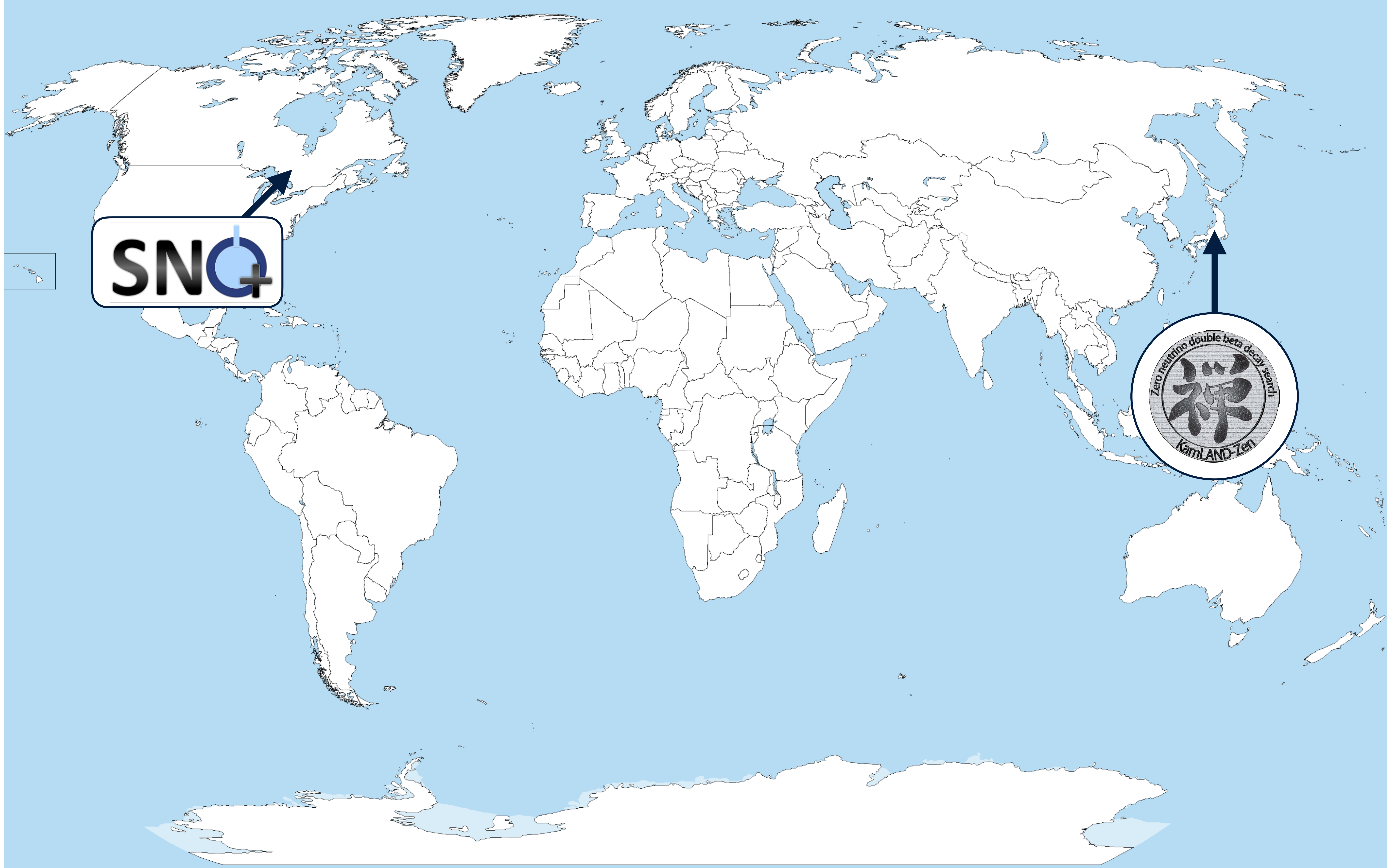
→ 50-100 tons/year globally, subject to high volatility

Can we produce more xenon?

Liquid-scintillator + photomultiplier detectors

Dissolving isotope in scintillator allows for huge ββ masses

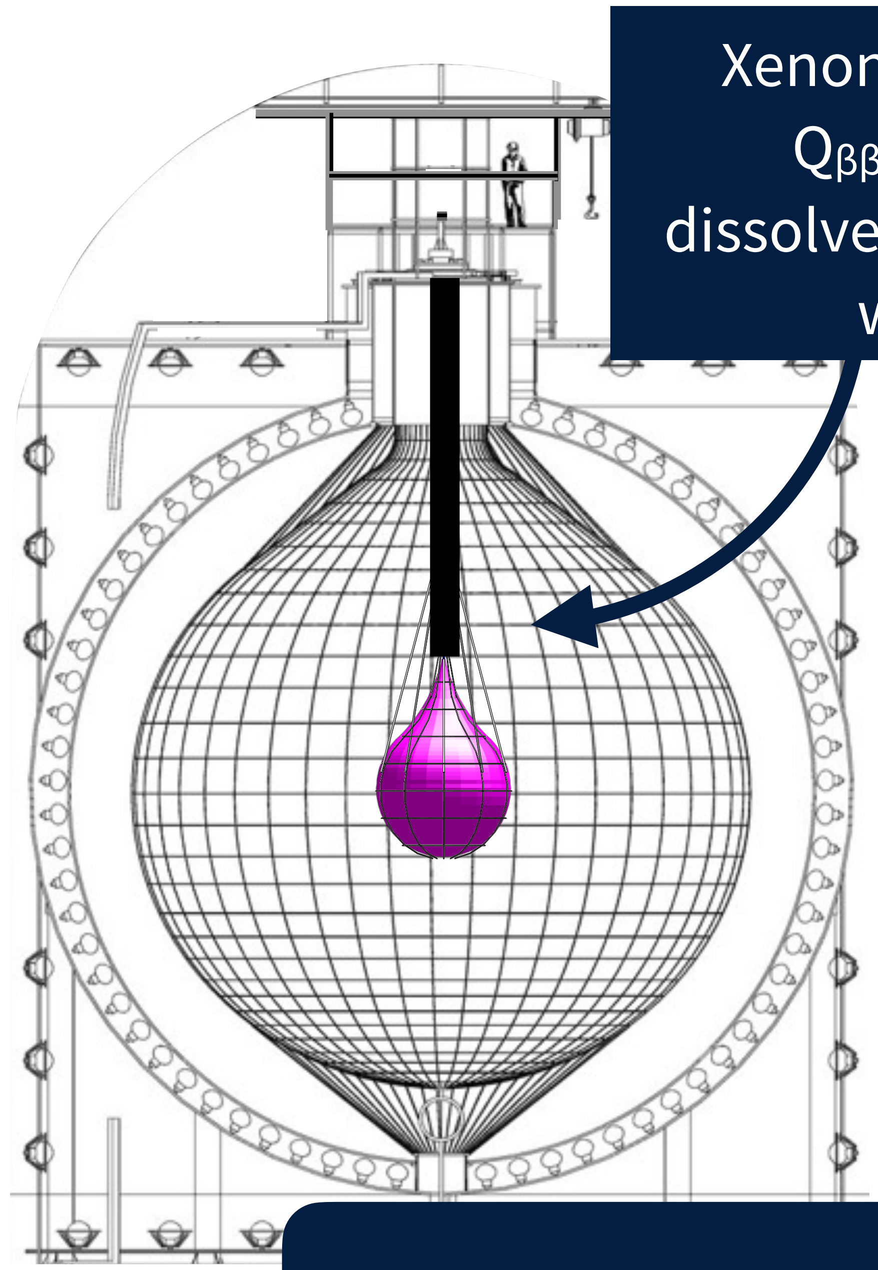




KamLAND-Zen: KamLAND detector modified for ββ decay

KamLAND-Zen 400

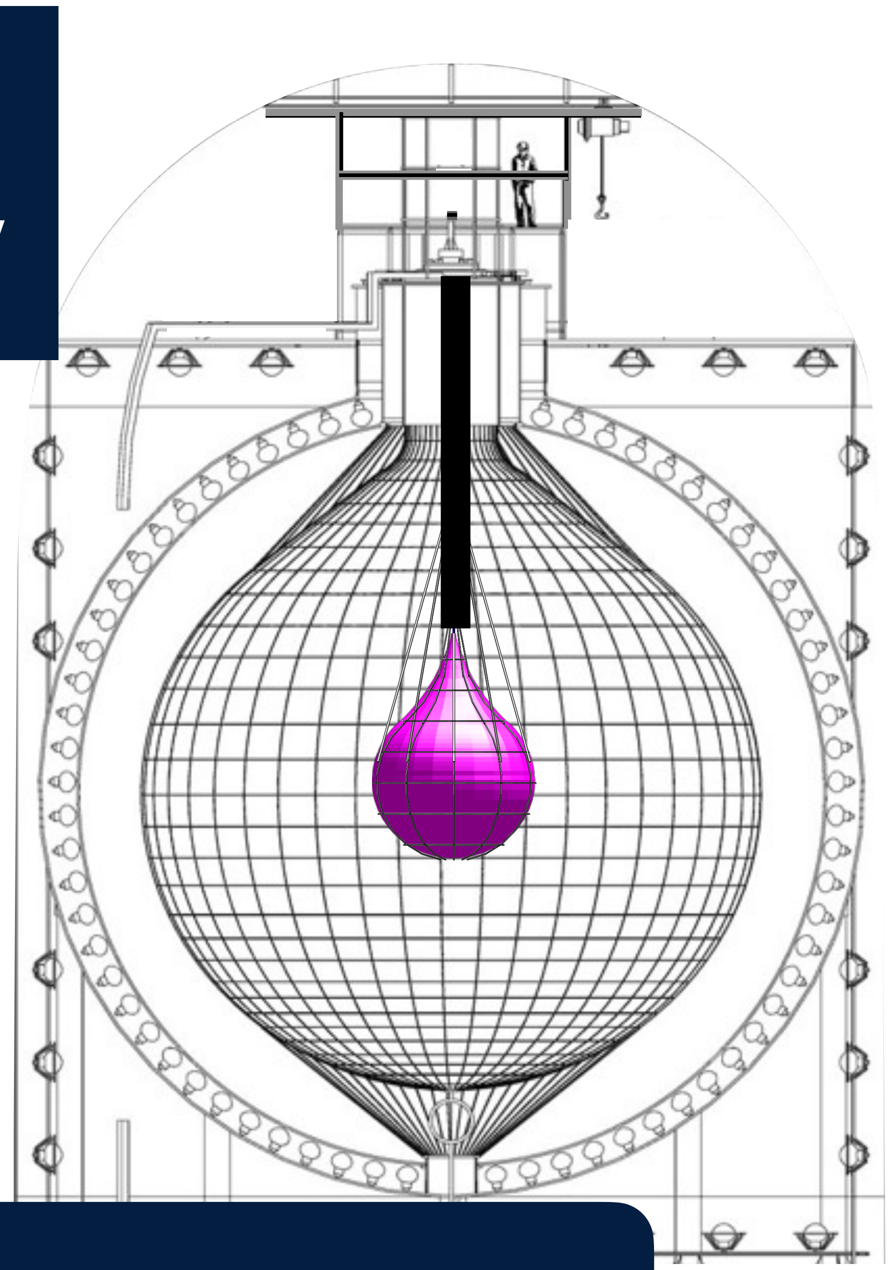
- 2011-2015
- 320-380 kg of Xe
- ~90% enriched



Xenon (90% ^{136}Xe, $Q_{\beta\beta}$~2.4MeV) dissolved in LS (3% by weight)

KamLAND-Zen 800

- ~750 kg of Xe
- DAQ started 2019



KL-Zen 400 & 800 combined limit (90% CL)

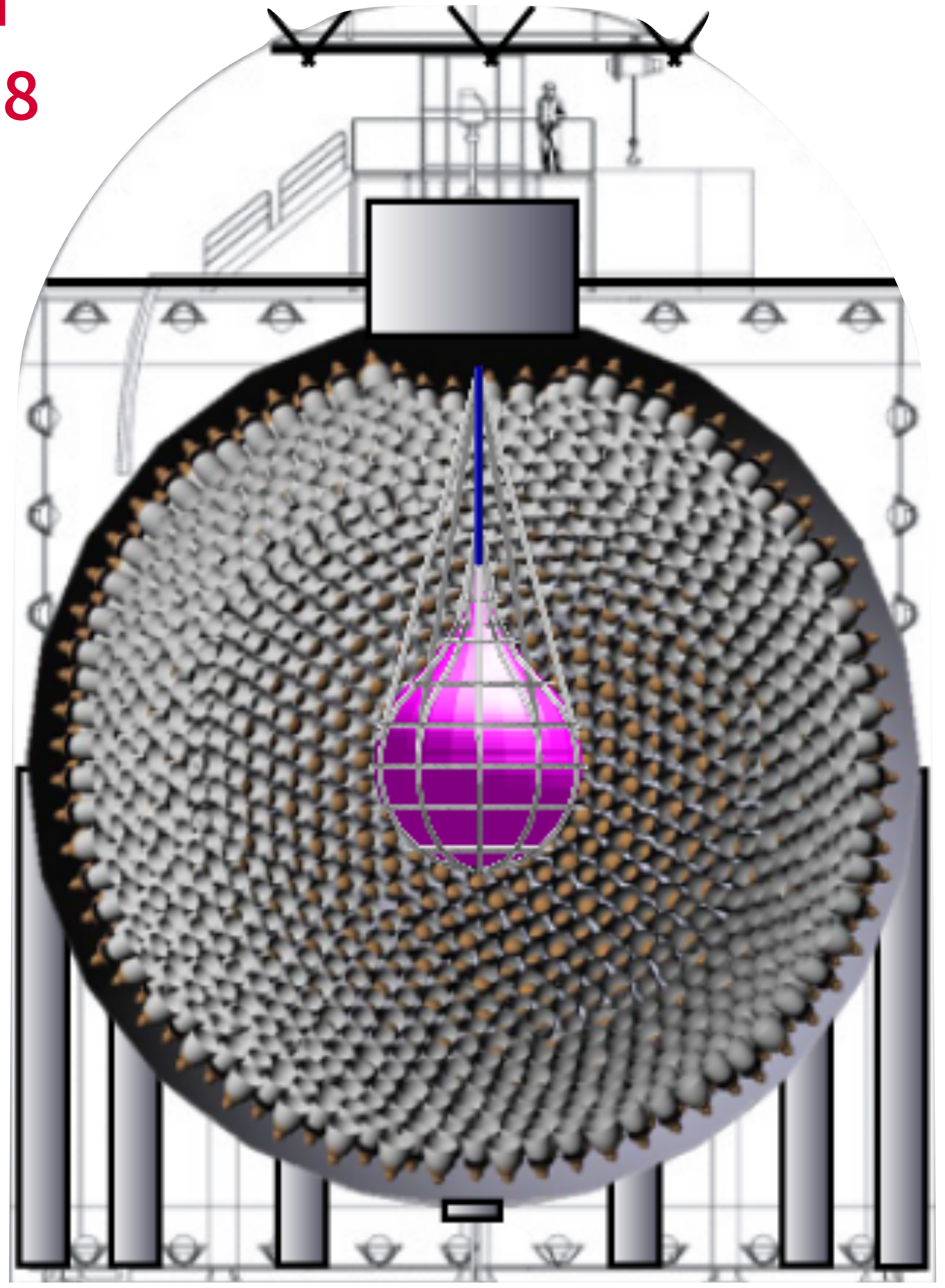
$T_{1/2} > 2.3 \times 10^{26}$ yr

$\langle m_{\beta\beta} \rangle < 36 - 156$ meV

First search for inverted mass ordering!

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

KamLAND2-Zen scheduled 2027-8



High QE PMT & Winstone cone

New electronics

Scintillation inner balloon

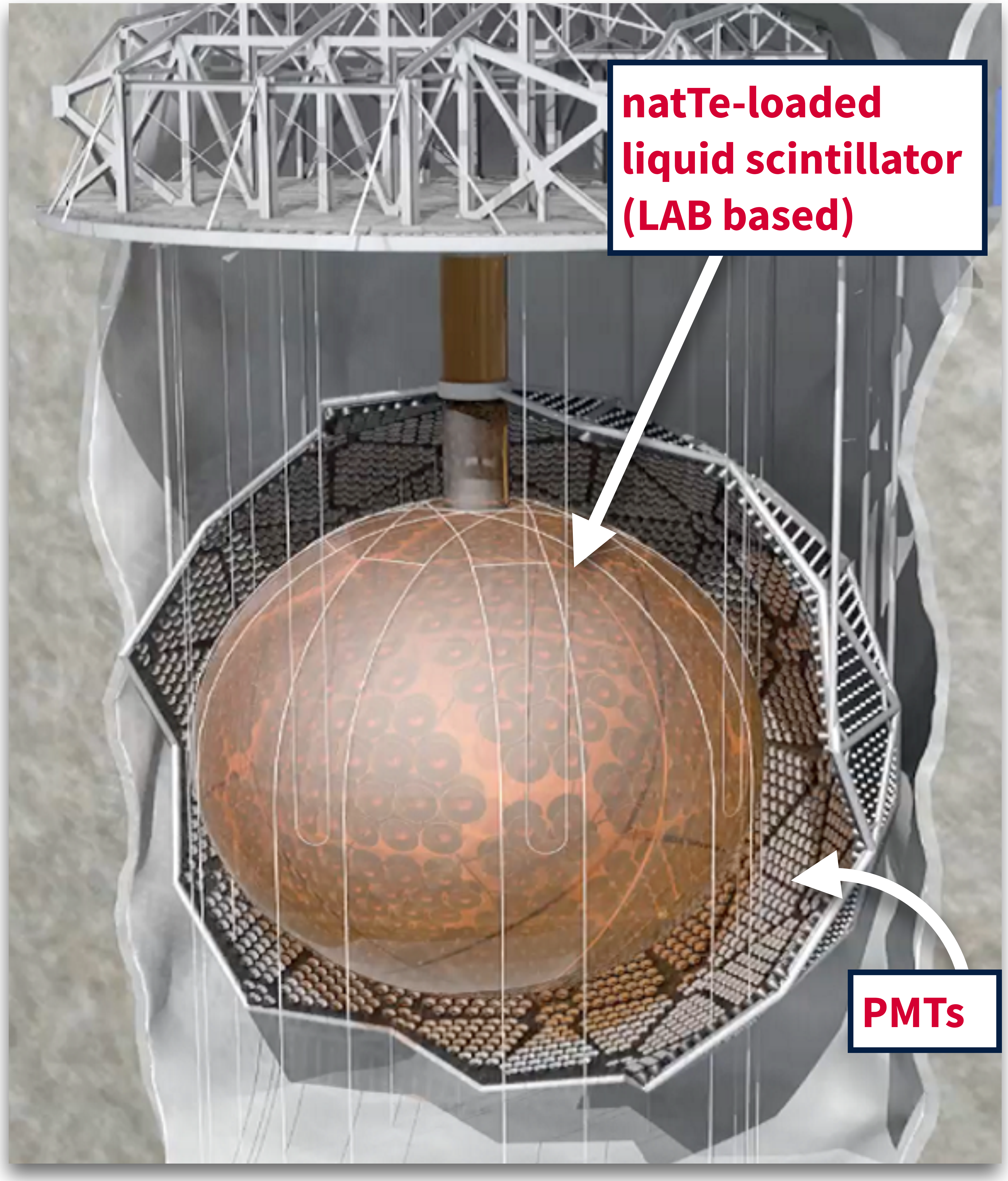
1000kg of Xe

R&D paper: PTEP. Volume 2019, Issue 7, 073H01

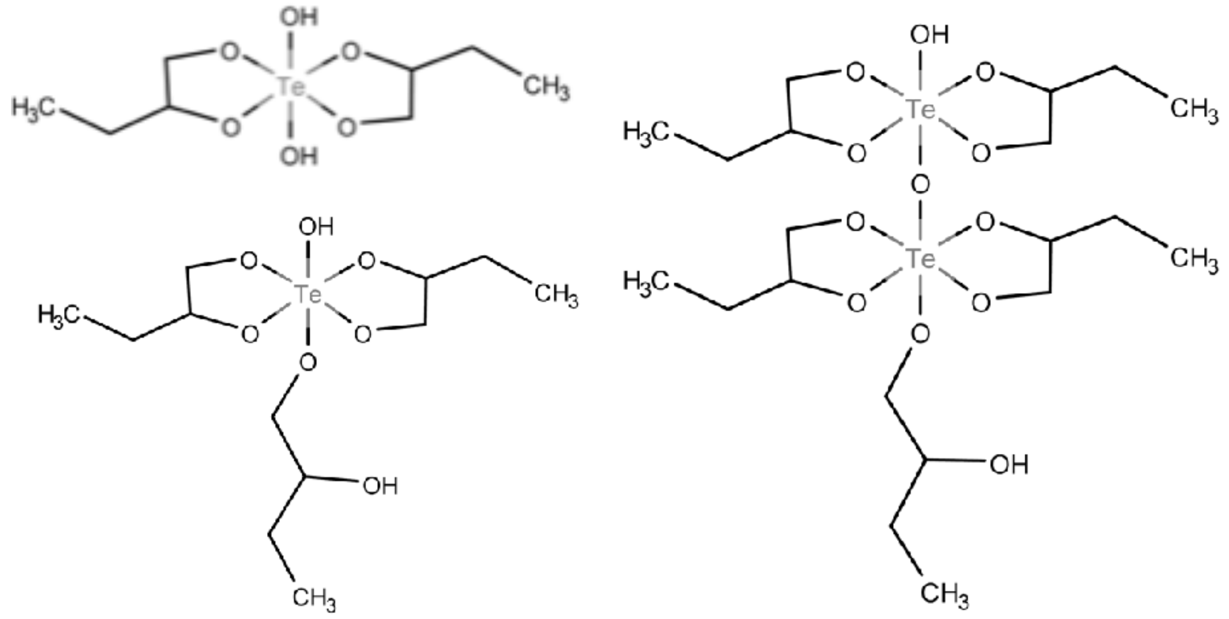
$\sigma(2.6\text{MeV}) = 4\% \rightarrow \sim 2\%$

Target $\langle m_{\beta\beta} \rangle \sim 20$ meV in 5 years

SNO+



Diol Loading of ^{130}Te in Liquid Scintillator



Cost-effective

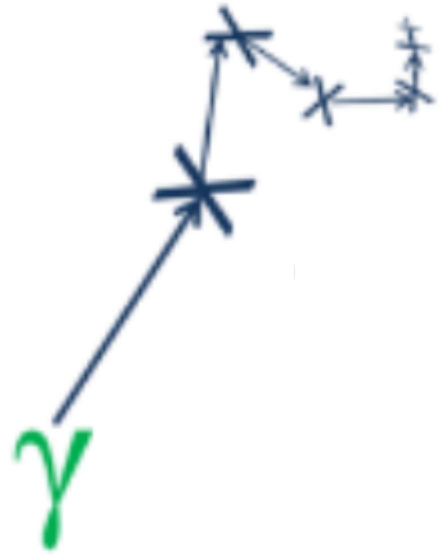
- $\beta\beta$ isotope has high (34%) natural abundance
- Liquid scintillator is also economical

Scalable

- Detector **design** can be scaled up dramatically
- UK-developed techniques can increase **tellurium loading**

Sensitive

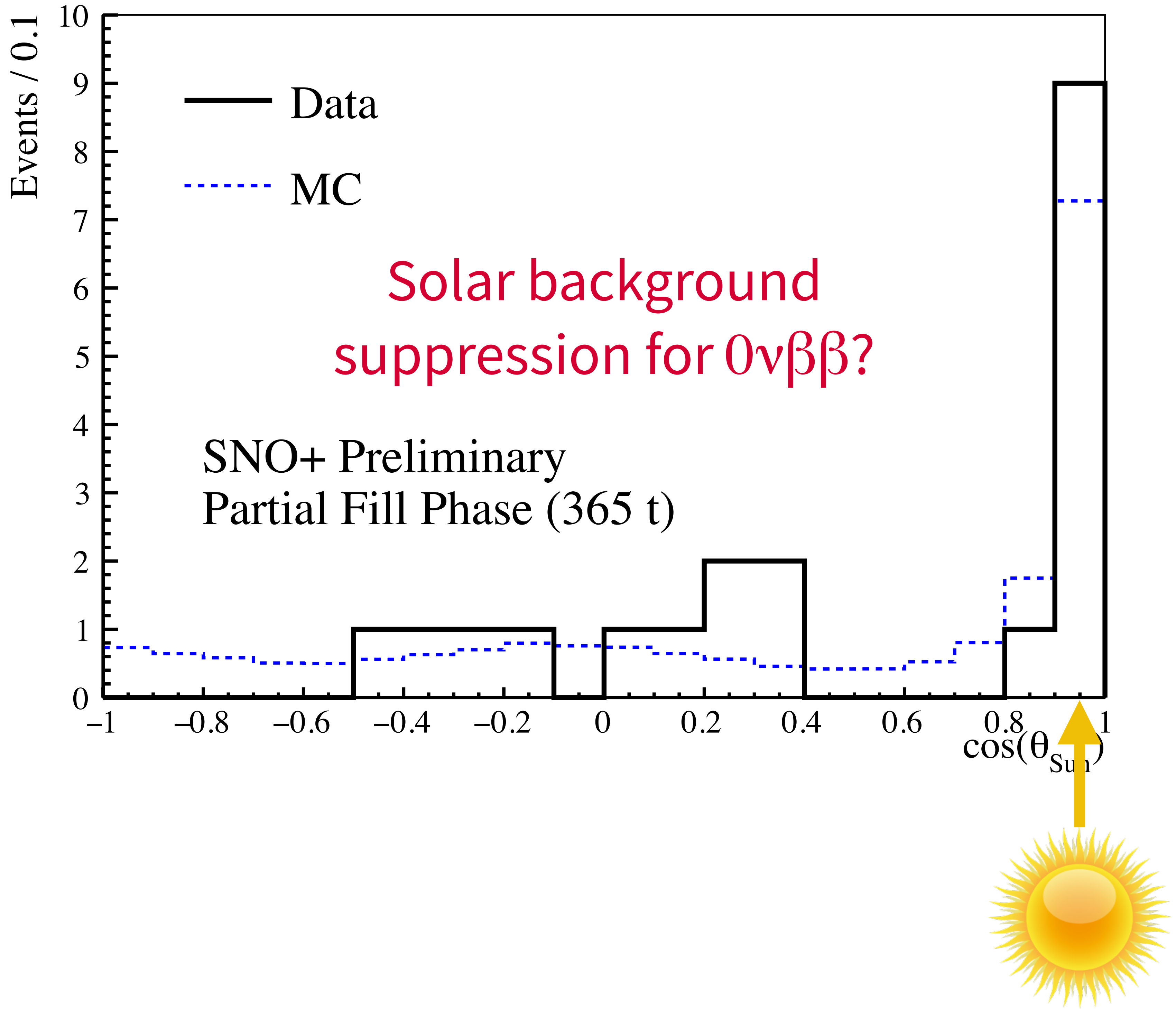
- Single- vs multi-site discrimination keeps backgrounds low



NIM, 943, 162420 (2019)

SNO+ scintillator performance (pre-Te addition)

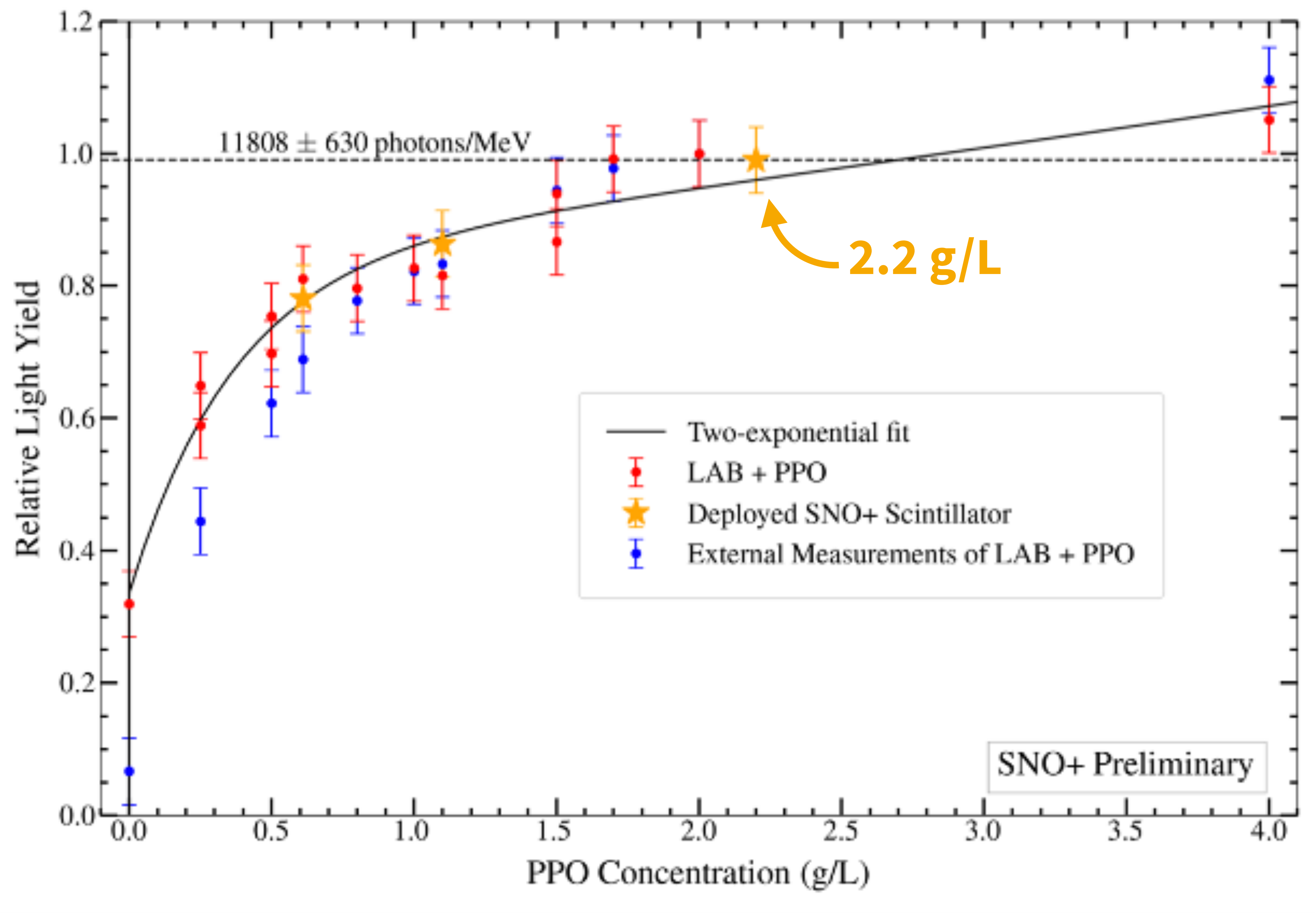
- Detector now loaded with scintillator: 780t LAB+PPO
  - At 0.6 g/L of PPO: first directional solar neutrino measurement



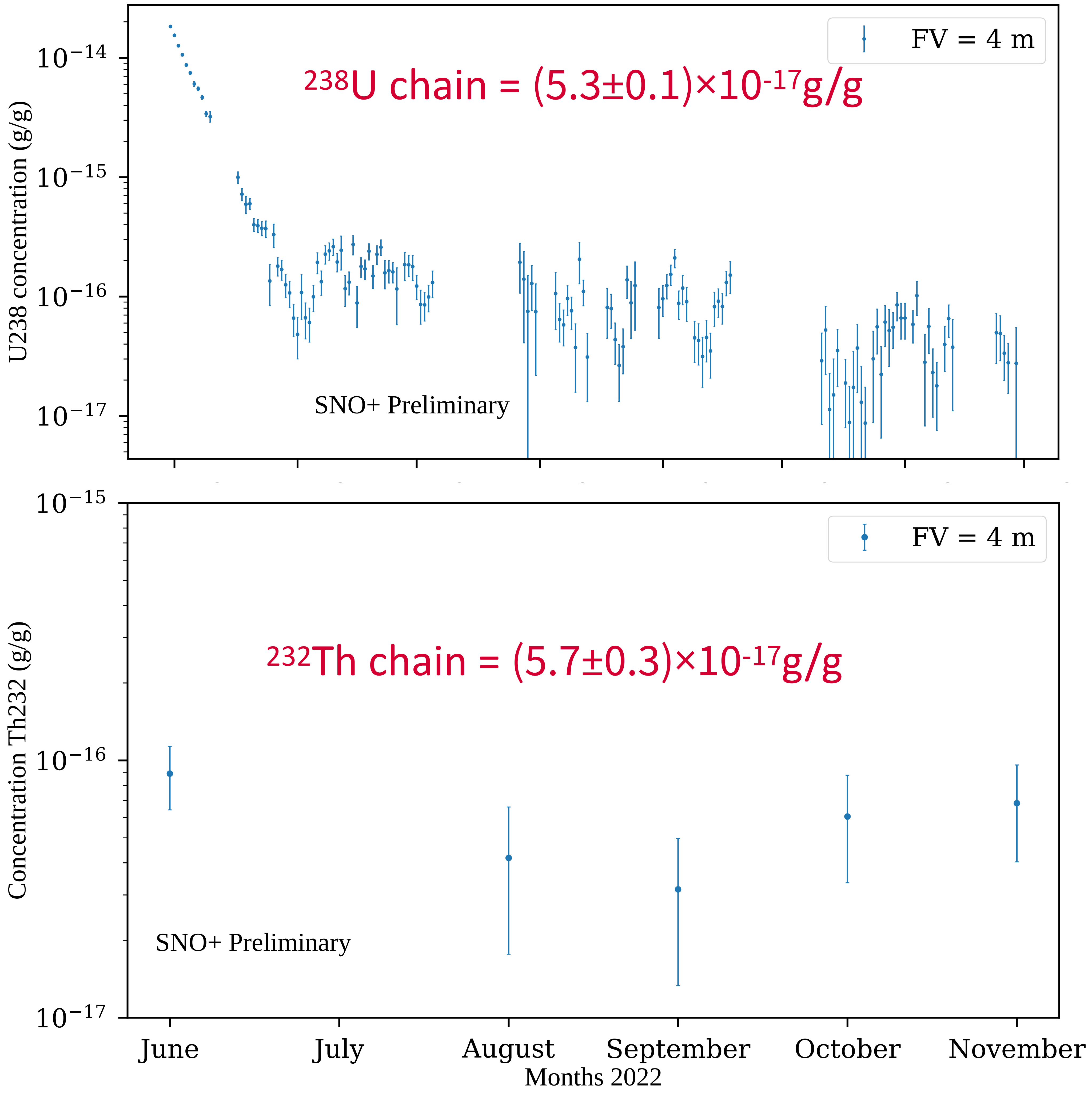
Solar background suppression for 0νββ?

SNO+ scintillator performance (pre-Te addition)

- Detector now loaded with scintillator: 780t LAB+PPO
  - At 0.6 g/L of PPO: first directional solar neutrino measurement
  - At 2.2 g/L - excellent light yield, optical purity
  - Uranium and thorium chain backgrounds low enough for 0νββ measurement



2.2 g/L



^{238}U chain = $(5.3\pm0.1)\times10^{-17}$g/g

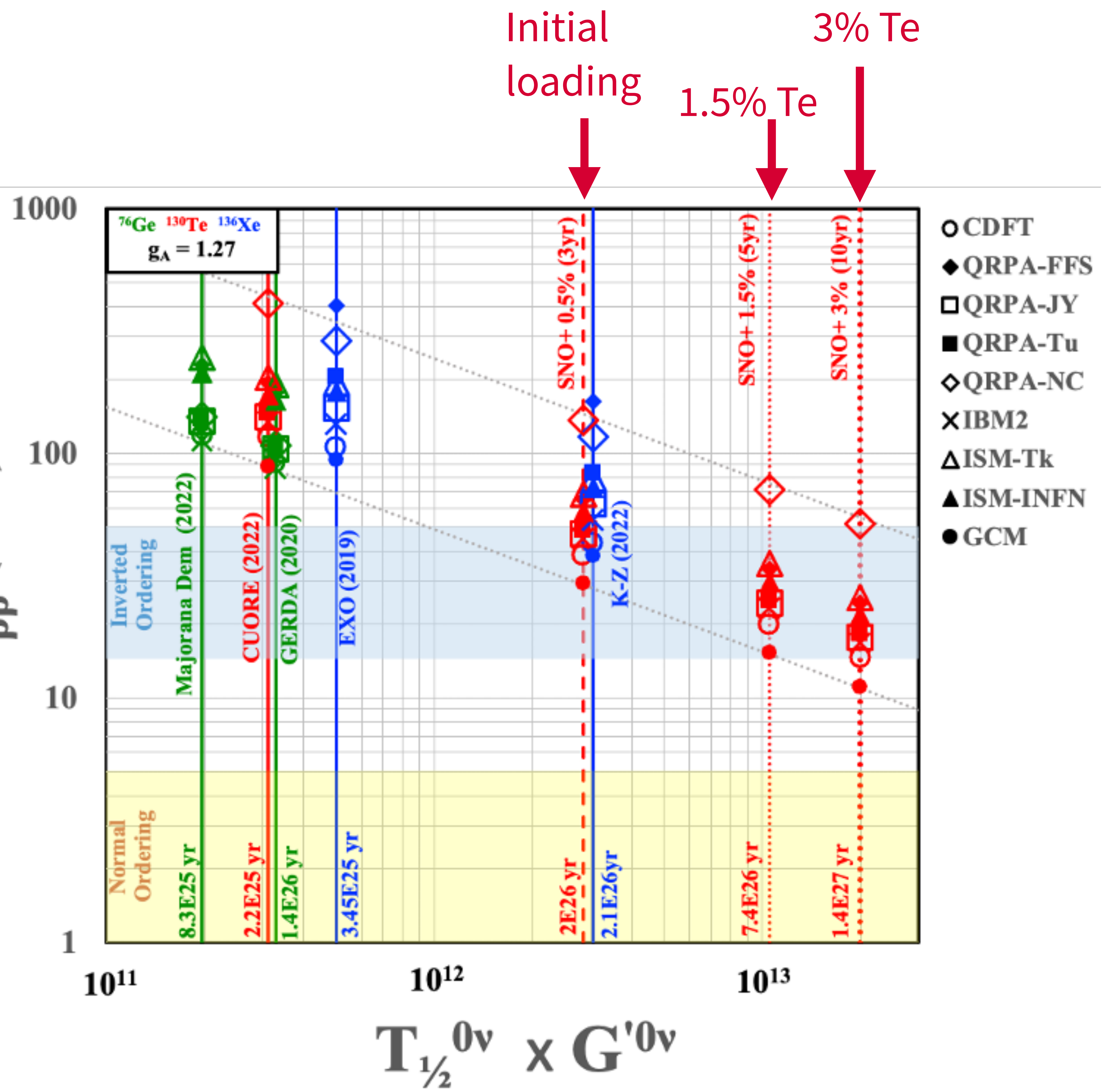
^{232}Th chain = $(5.7\pm0.3)\times10^{-17}$g/g

SNO+ tellurium addition

2024:

- Test batch of telluric acid (TeA) planned for early January
- 200 kg test will prove large-scale TeA production is viable

SNO+ tellurium addition



Initial loading

1.5% Te

3% Te

2024:

- Test batch of telluric acid (TeA) planned for early January
- 200 kg test will prove large-scale TeA production is viable

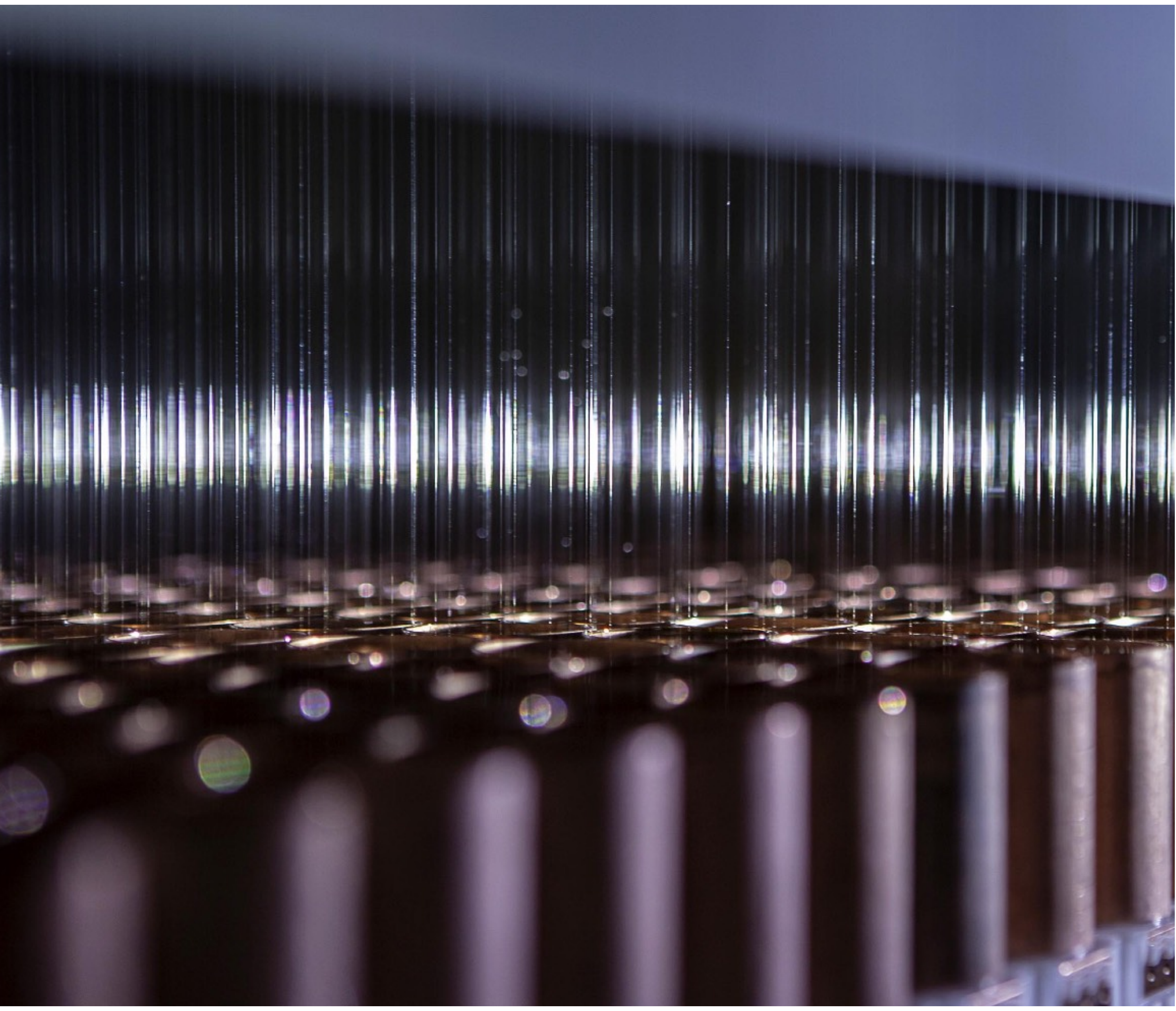
2025:

- Initial loading of 0.5% ^{nat}Te by mass (3.9 tonnes)

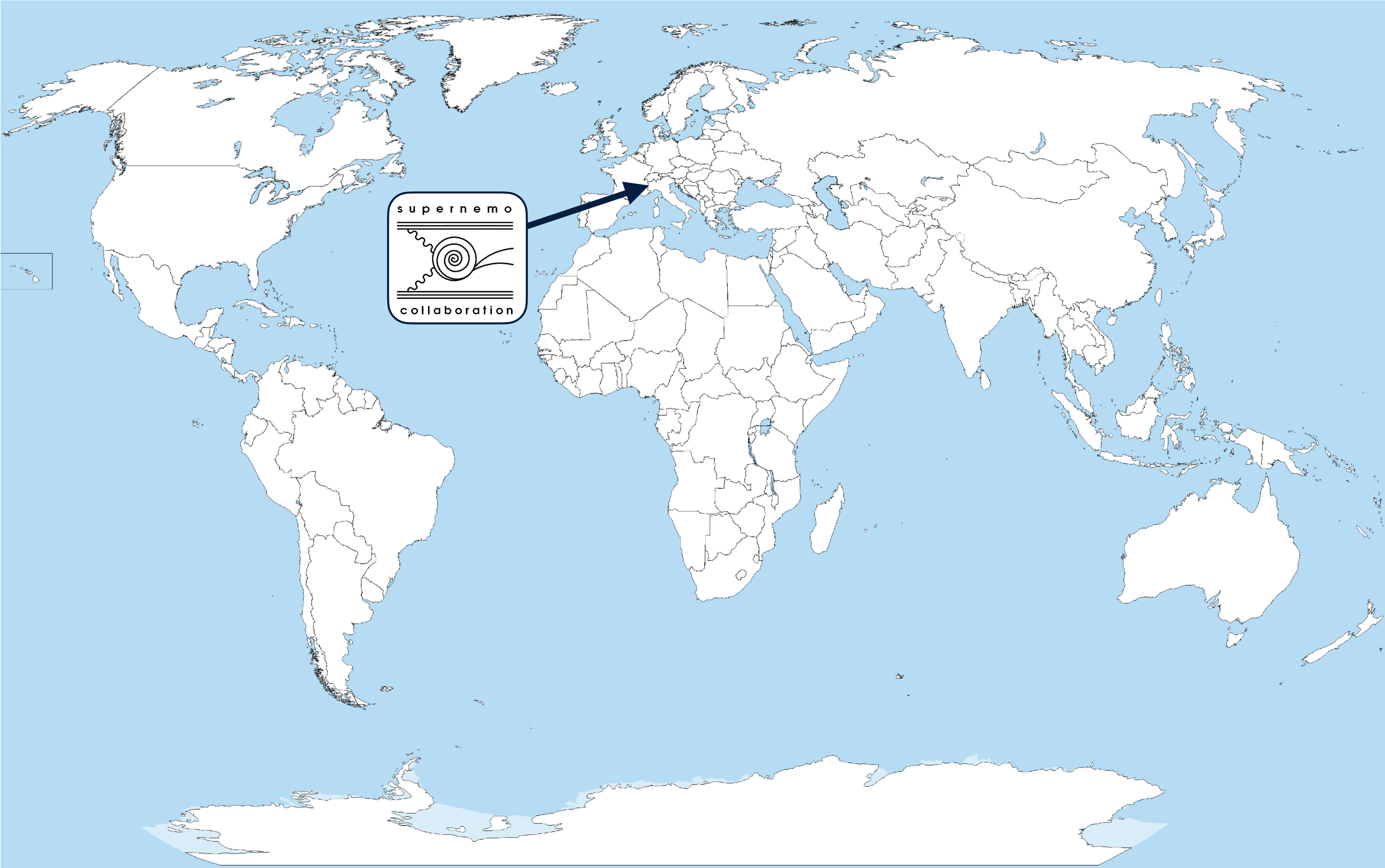
Longer-term:

- Proposal in preparation for higher loading (1.5 – 3% ^{nat}Te)

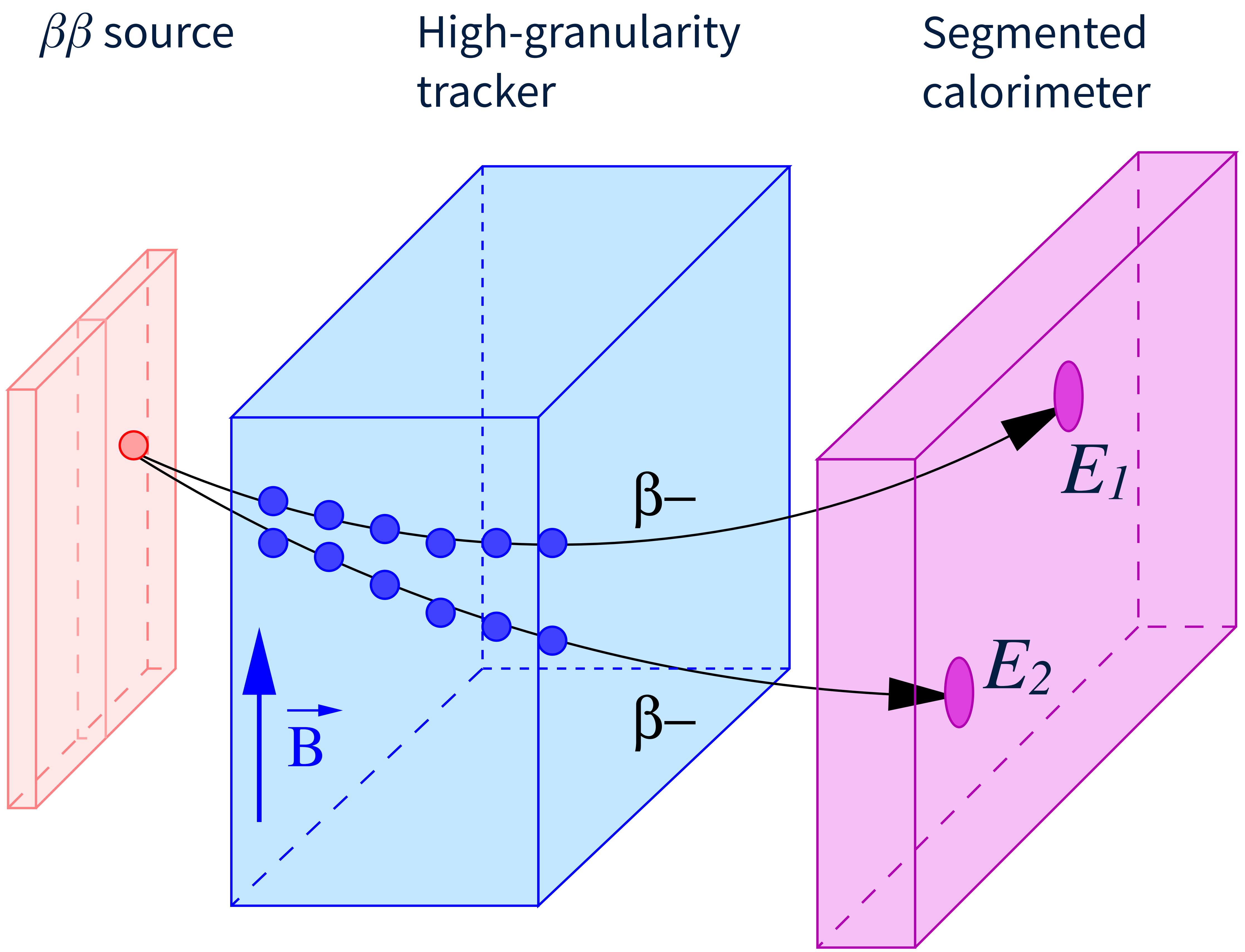
Tracking detectors: SuperNEMO



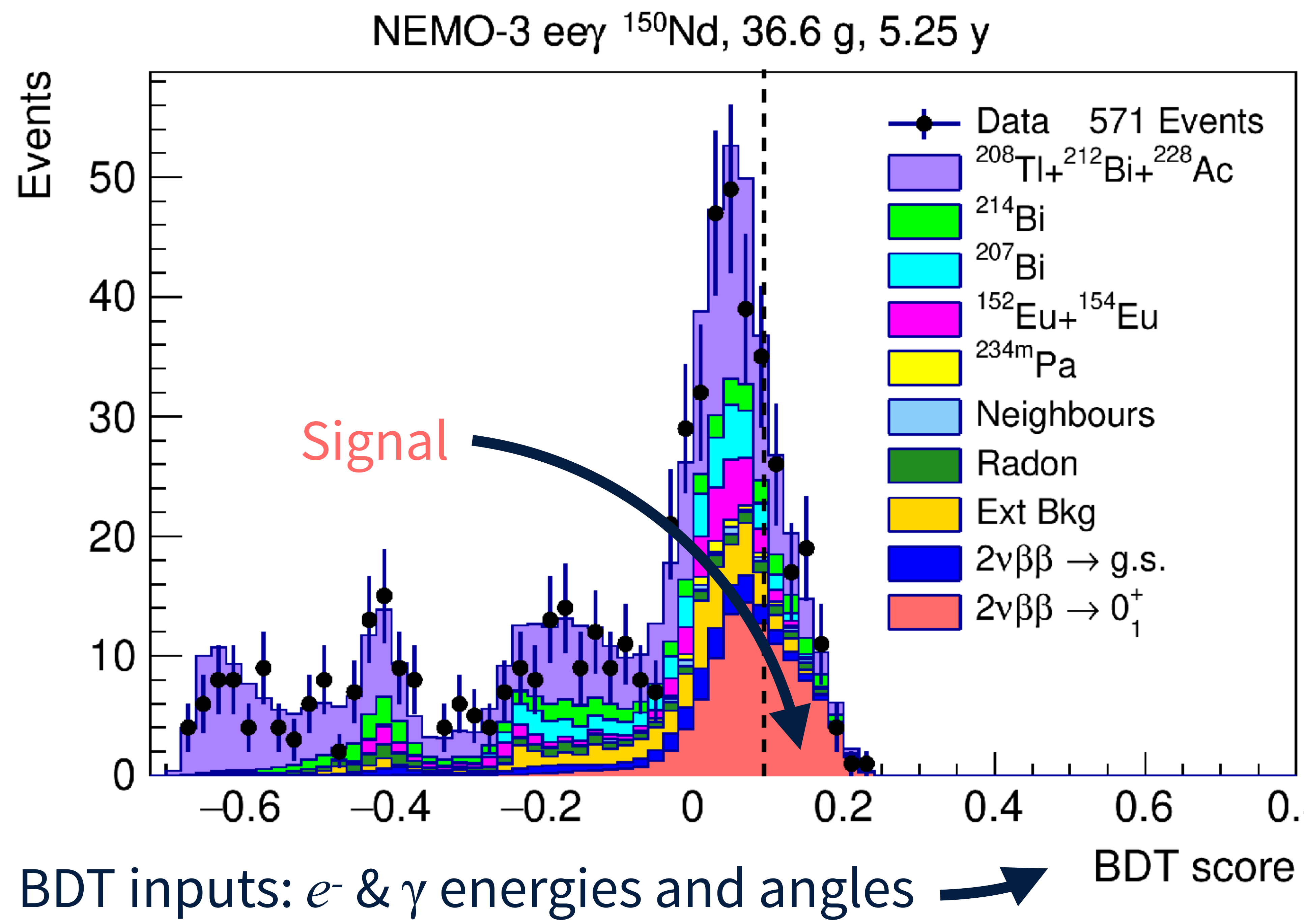
- (Almost) isotope agnostic
- Excellent background rejection
- Nuclear structure effects
- Decays to excited states
- Exotic decay searches



The NEMO principle



The power of NEMO - ^{150}Nd ββ decays to excited states at NEMO-3



BDT inputs: e^- & γ energies and angles →

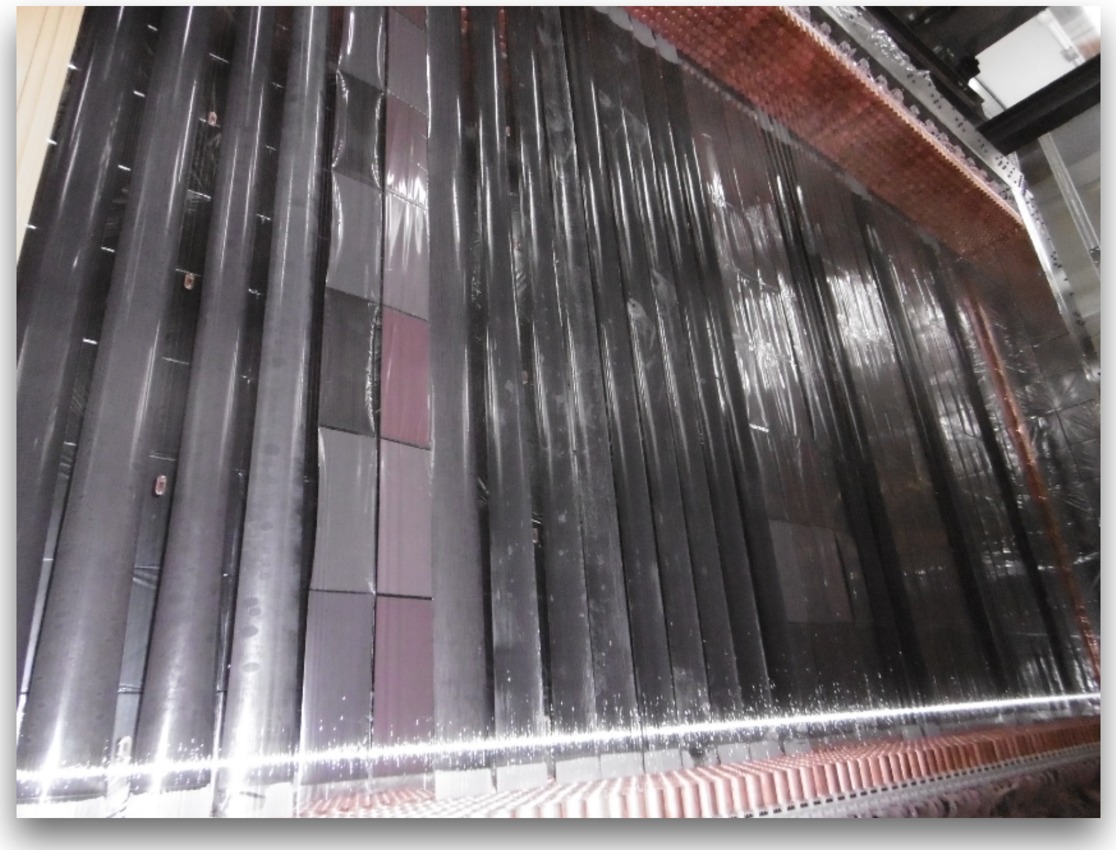
$$T^{2\nu\beta\beta}_{1/2}(0^+_1) = \left[1.11^{+0.19}_{-0.14}\ (\text{stat})^{+0.17}_{-0.15}\ (\text{syst})\right] \times 10^{20}\ \text{yr}$$

*Eur Phys J C **83**, 1117 (2023)*

World's-first observation, using eeγ and eeγγ data

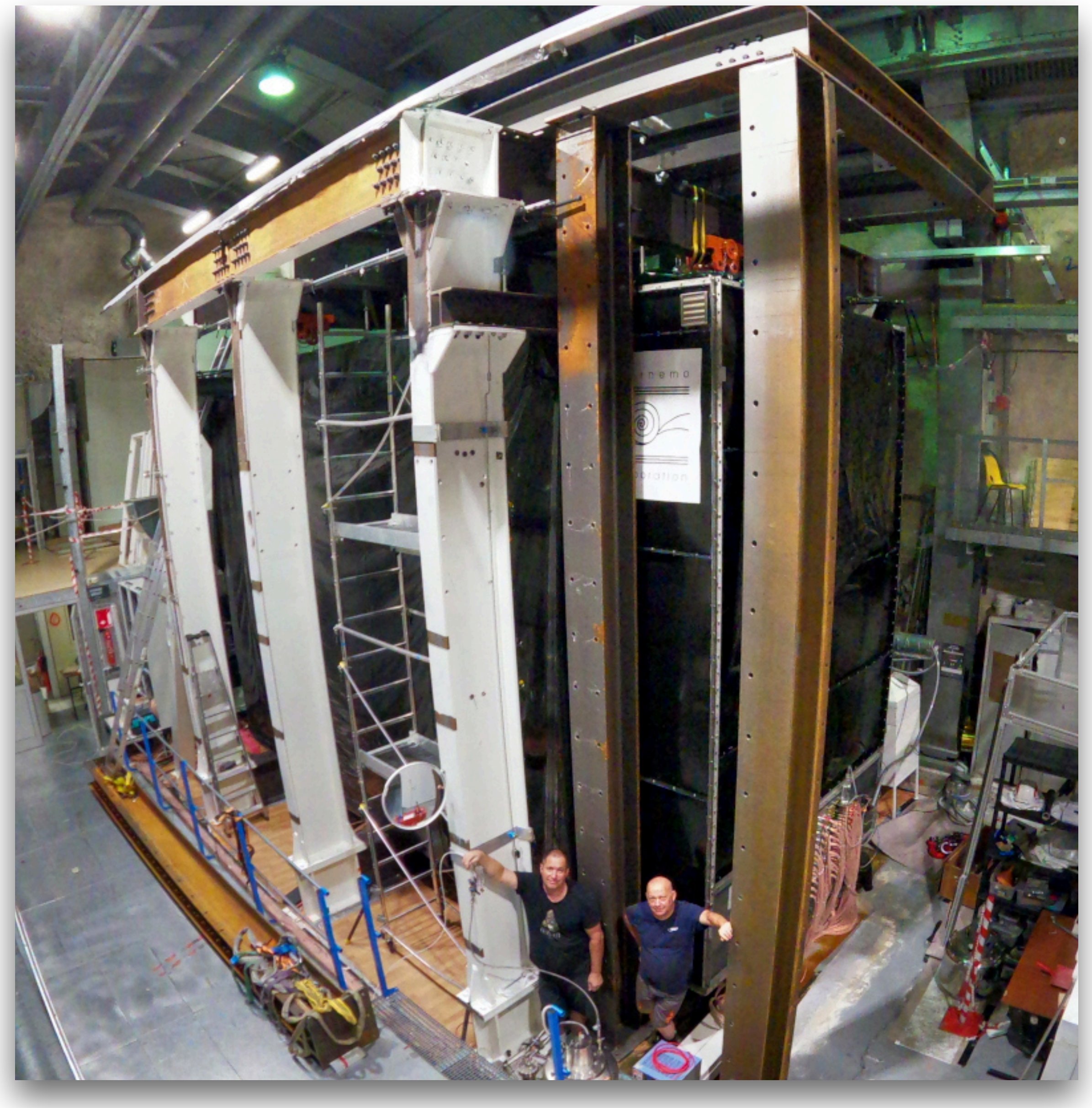
Limits also set on decay to (2^+_1) & $0\nu\beta\beta$ to excited states

SuperNEMO Demonstrator: proof of concept for future tracking detectors

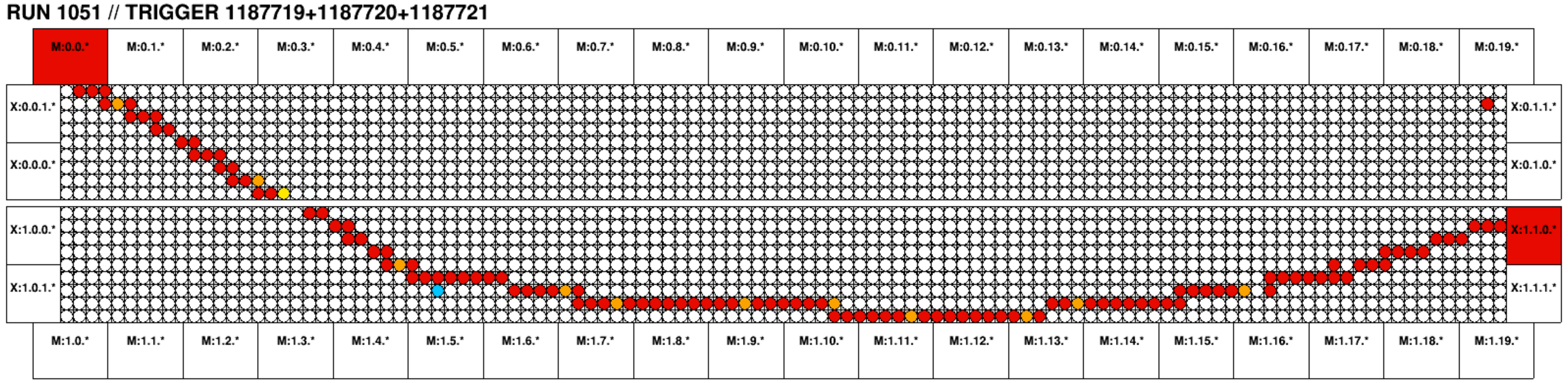


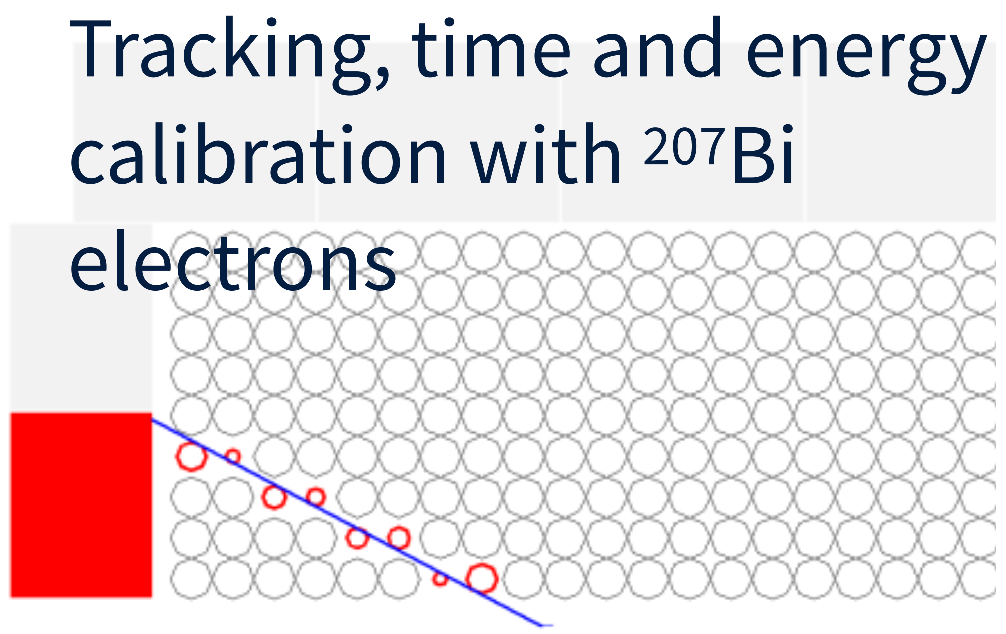
- New source foil designs
- Improved calorimetry
- Better radio-purity
- Improved electronics
- New reconstruction

- Detector fully built
- Shielding installation underway

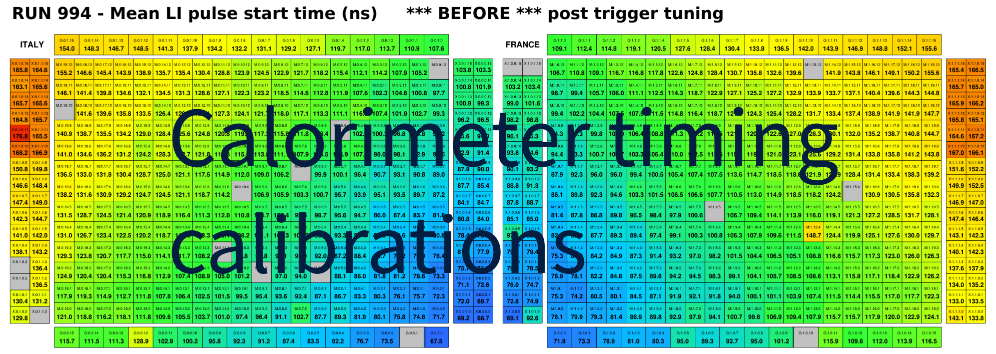


Taking background and calibration data at LSM; 99% of tracker channels live!

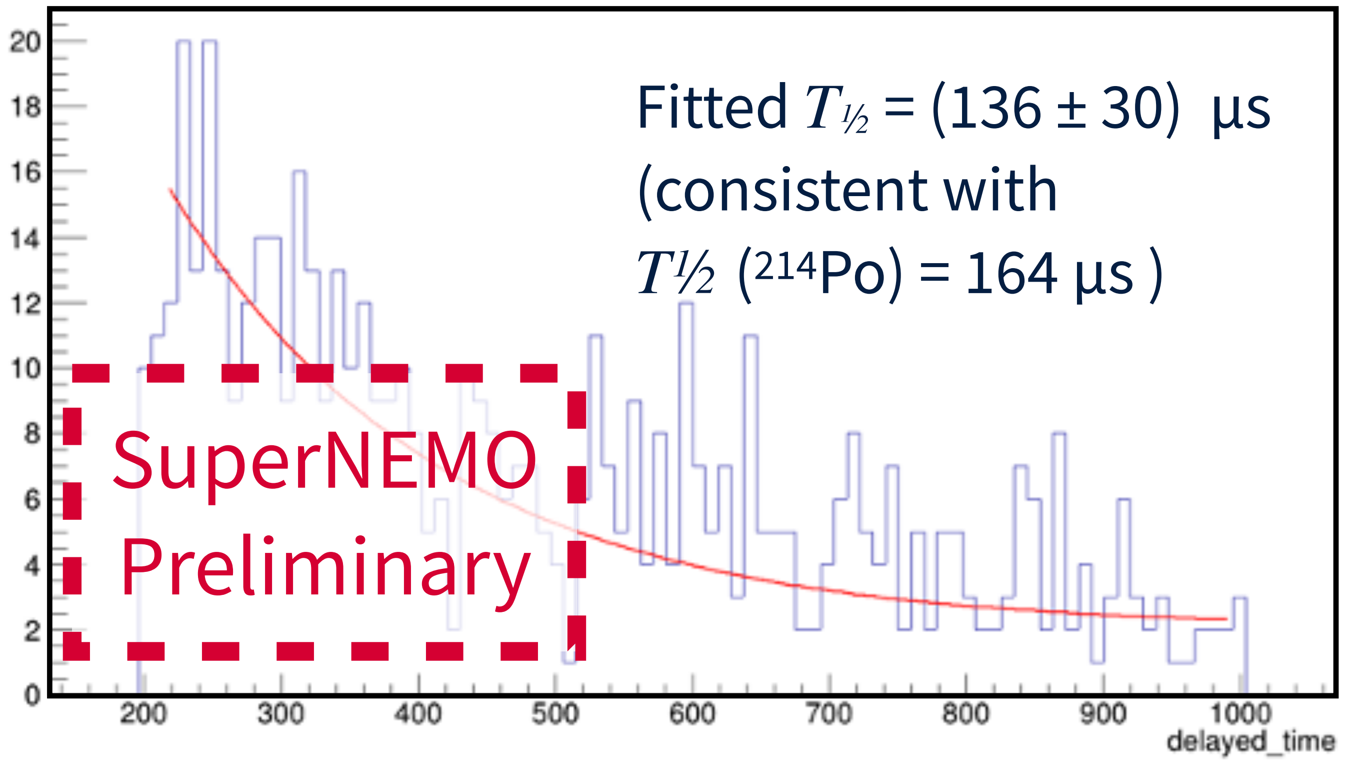




Tracking, time and energy calibration with ^{207}Bi electrons



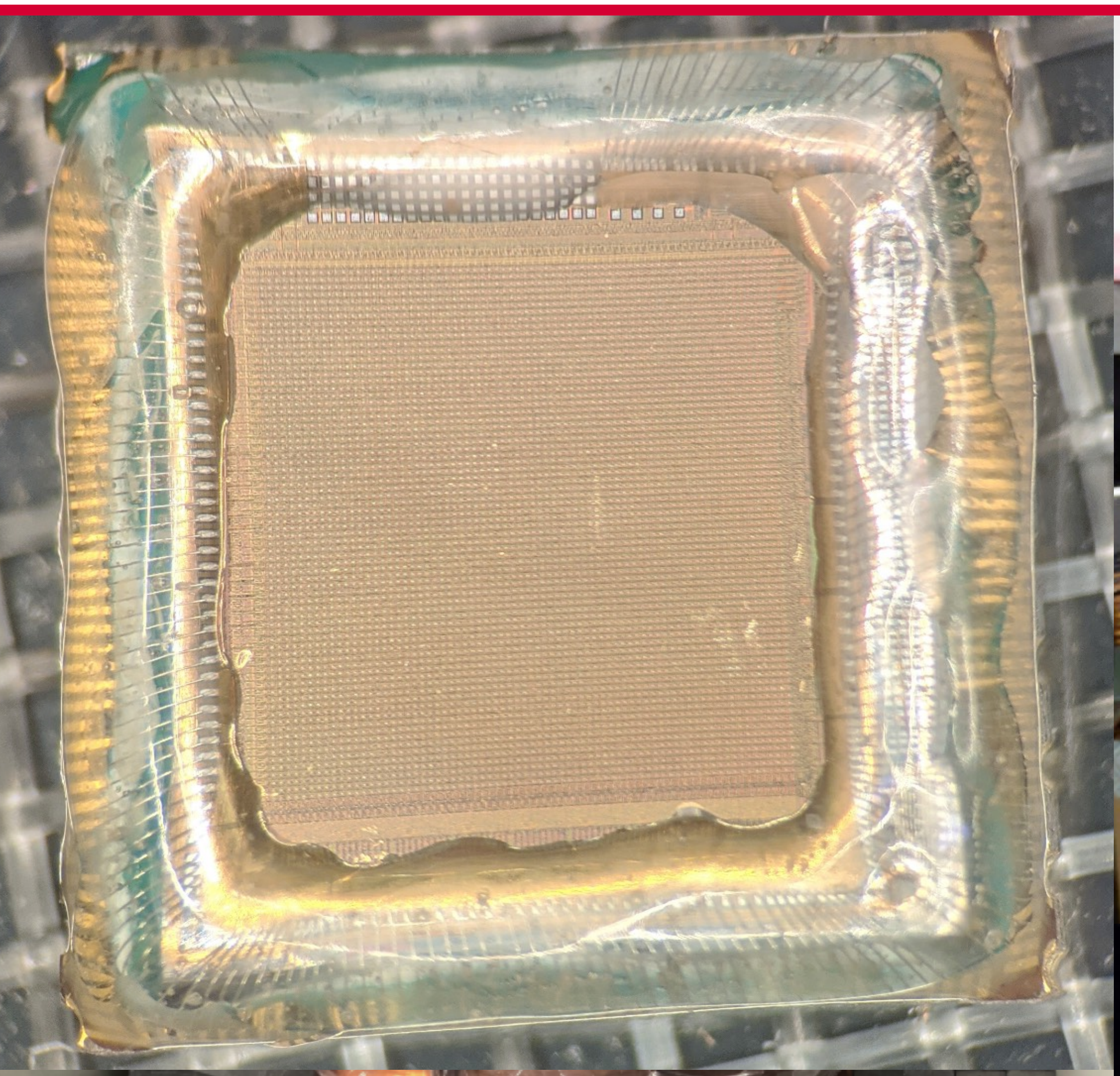
Calorimeter timing calibrations

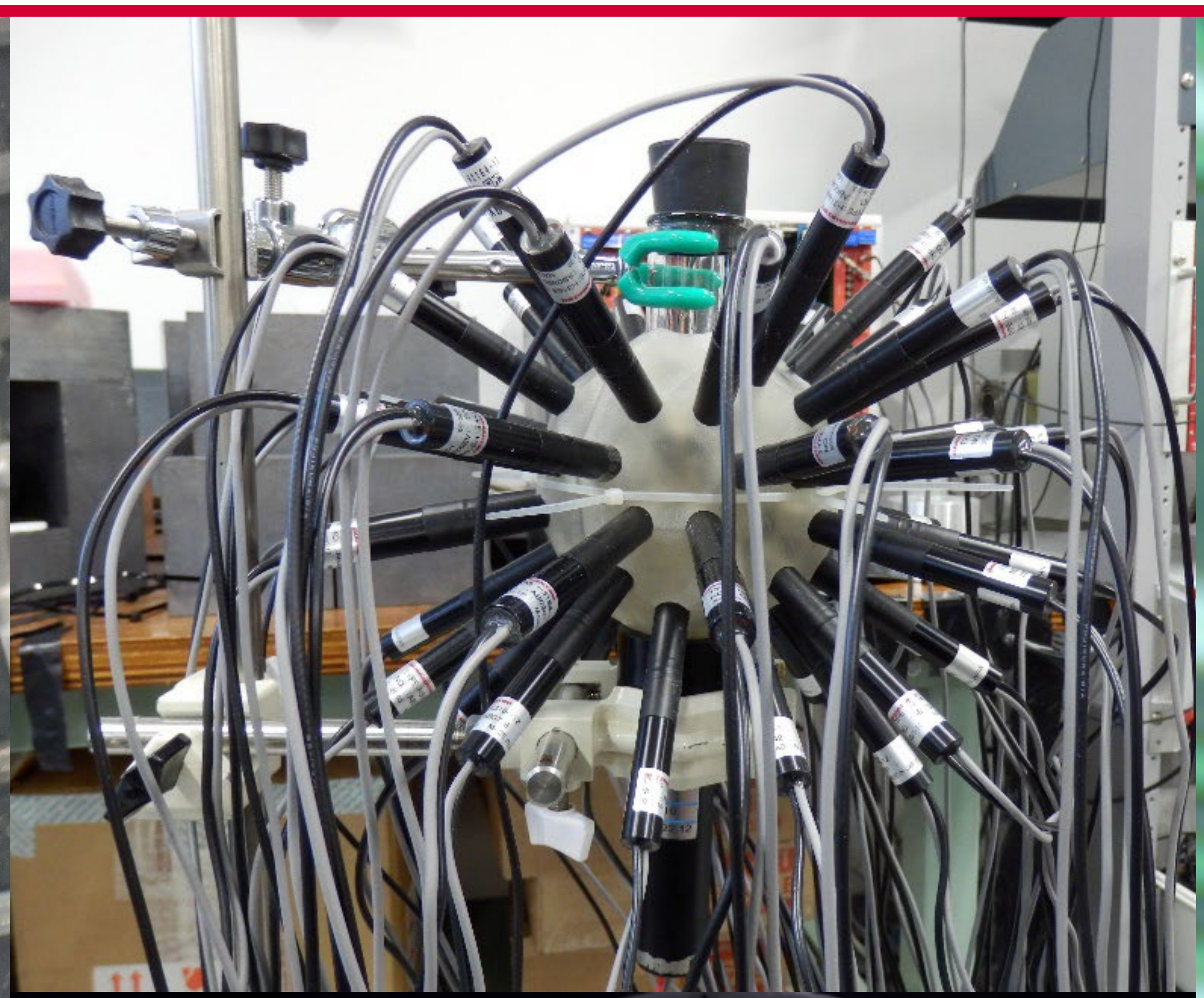


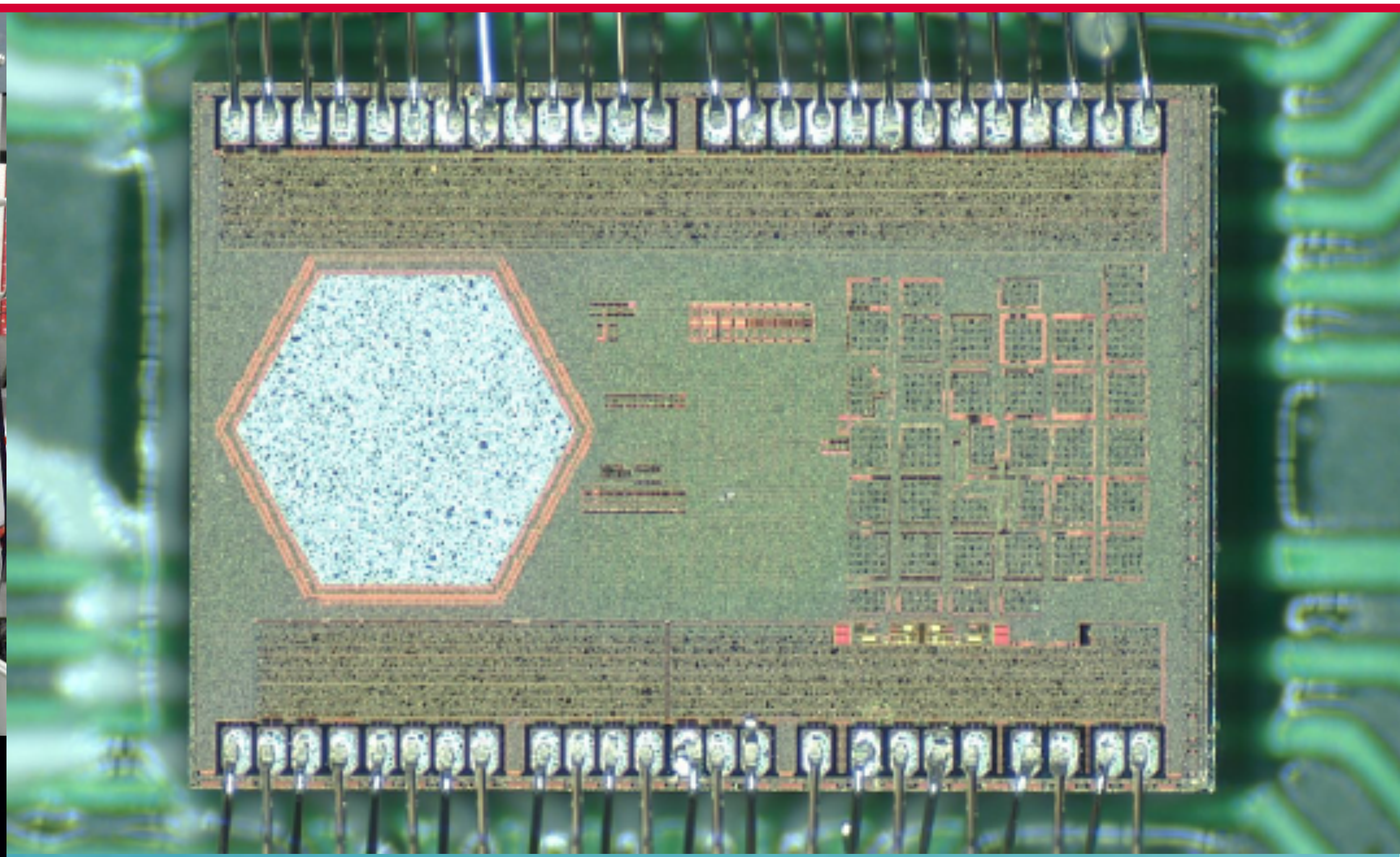
Fitted $T_{½}$ = (136 ± 30) µs (consistent with $T_{½}$ (^{214}Po) = 164 µs)

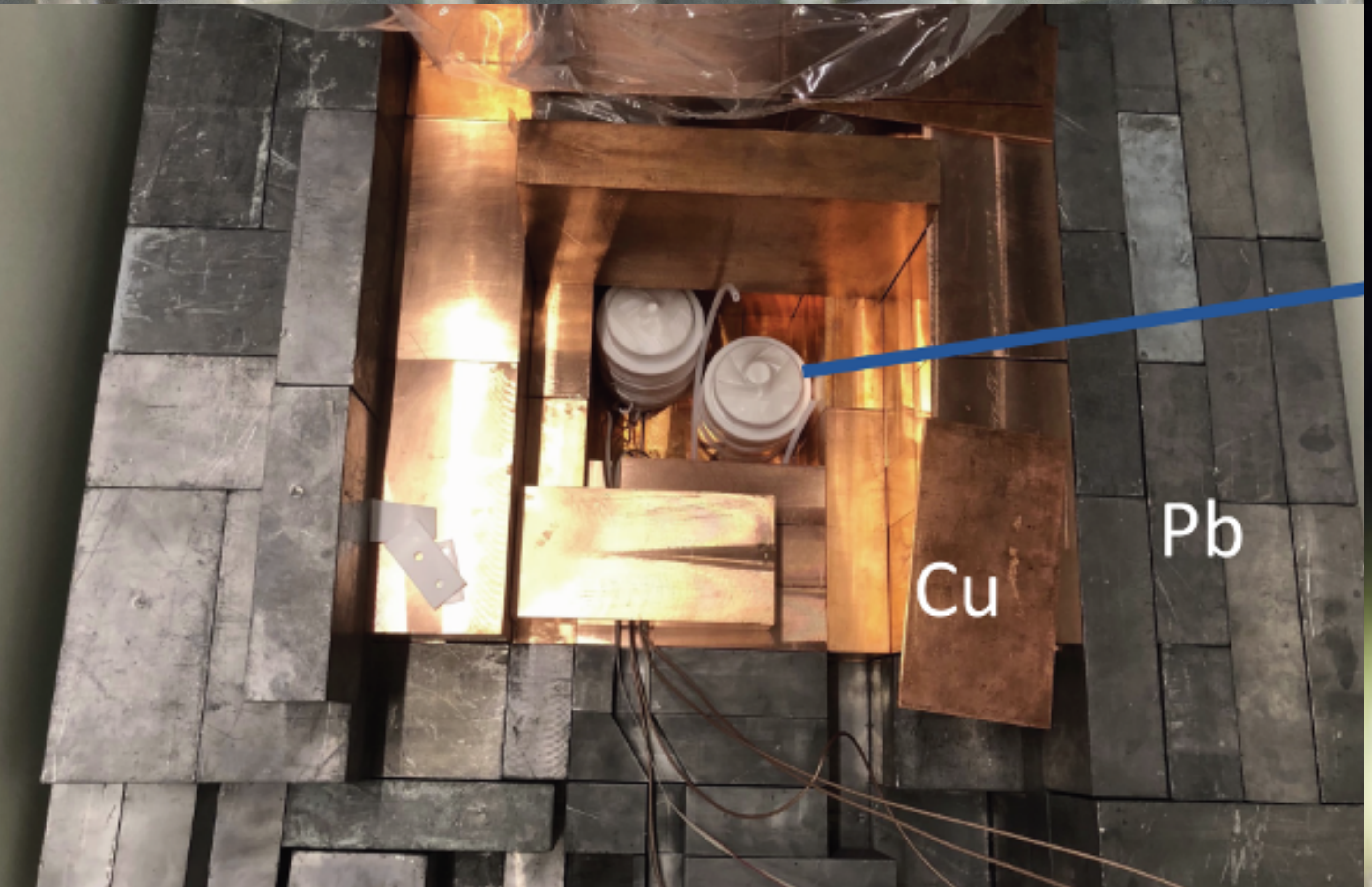
Preliminary activity measurement with BiPo's yields radon level comparable to NEMO-3 (before shielding/radon-free air)

Towards the future - novel R&D





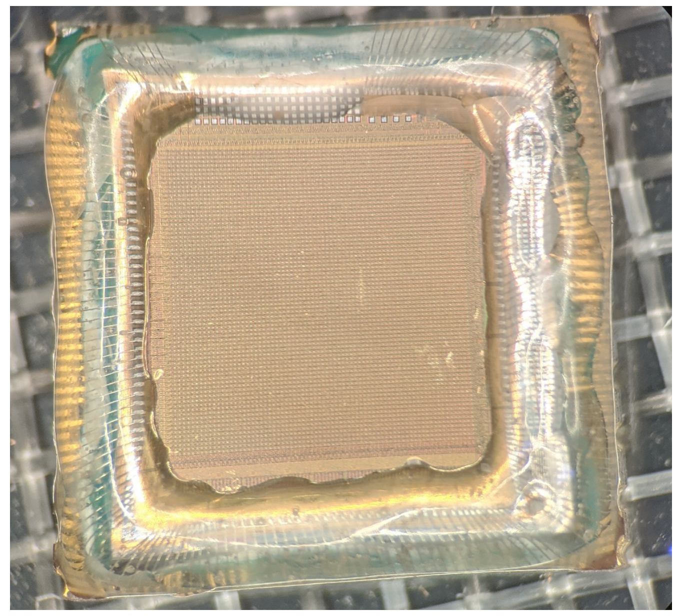


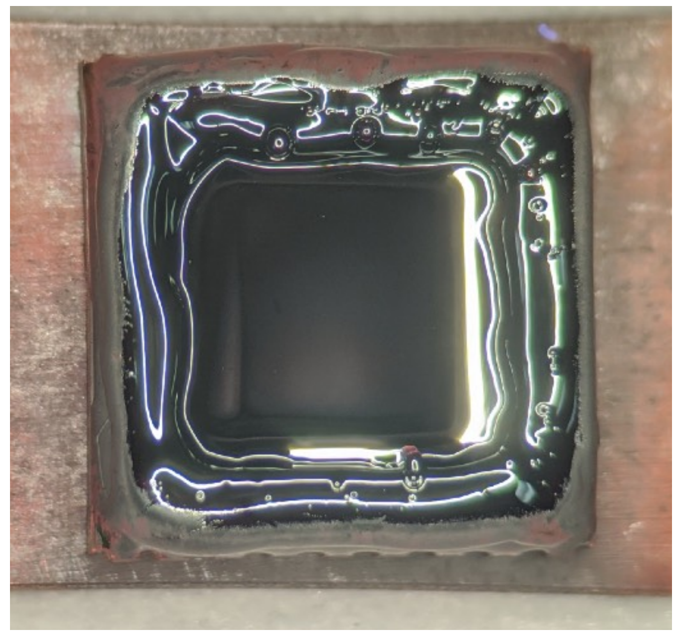


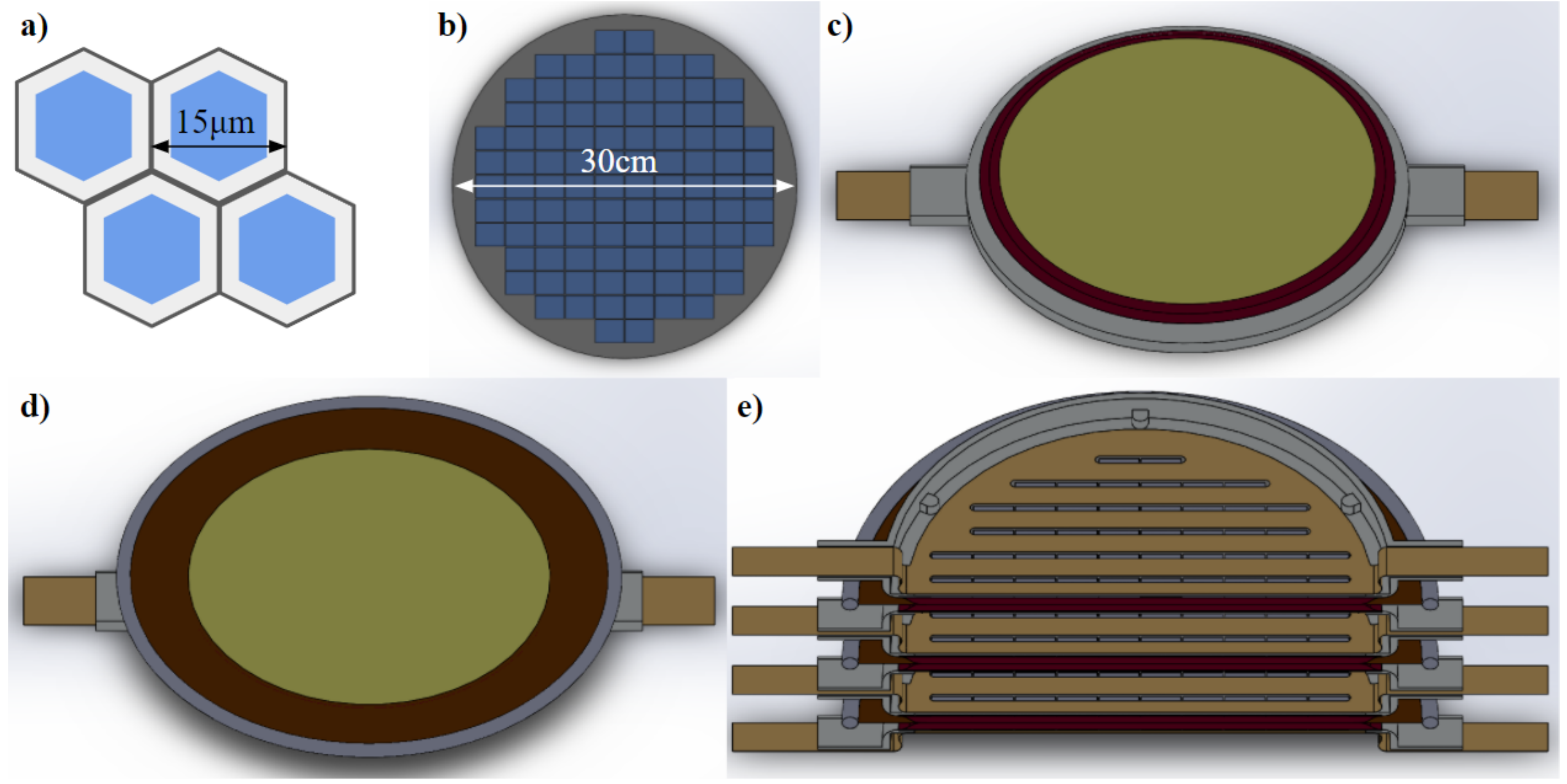
Selena: ^{82}Se deposited on CMOS imagers

Snowmass White Paper: arXiv:2203.08779

Imaging electron tracks for background discrimination





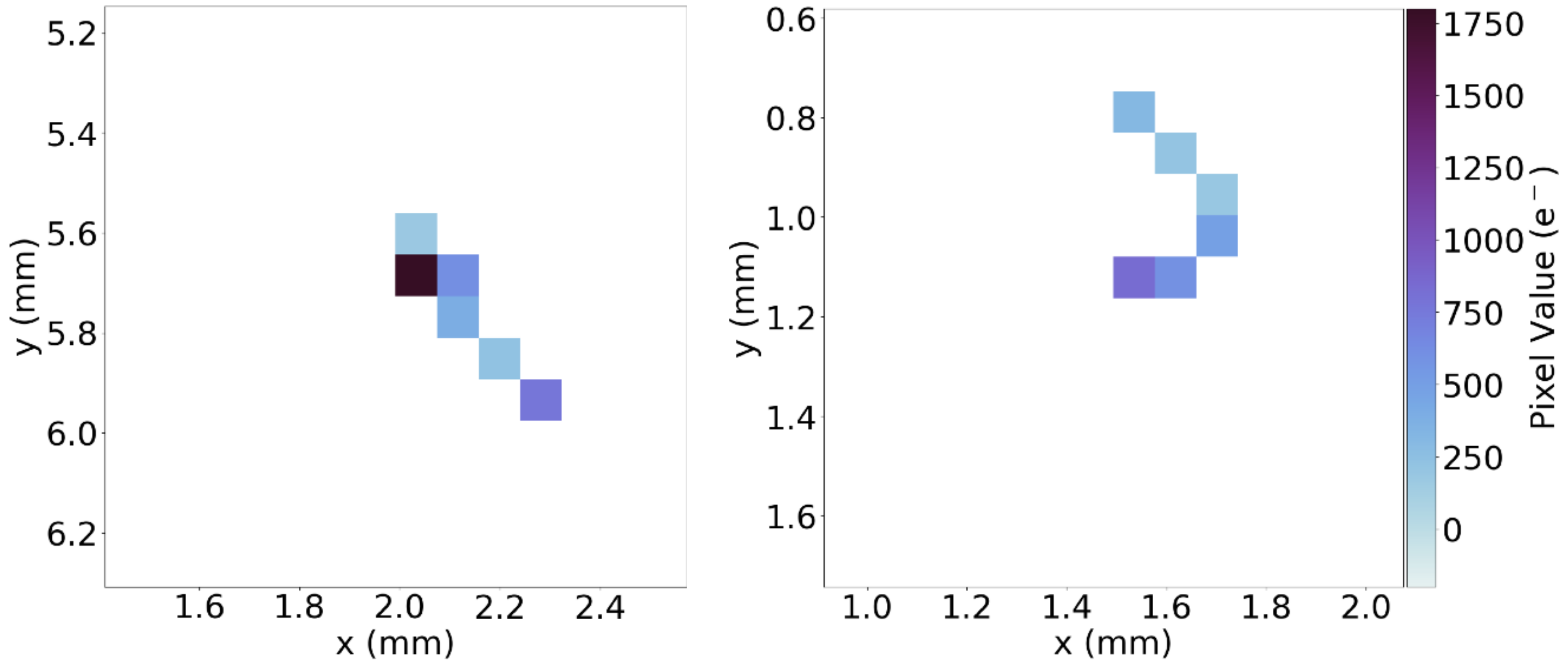


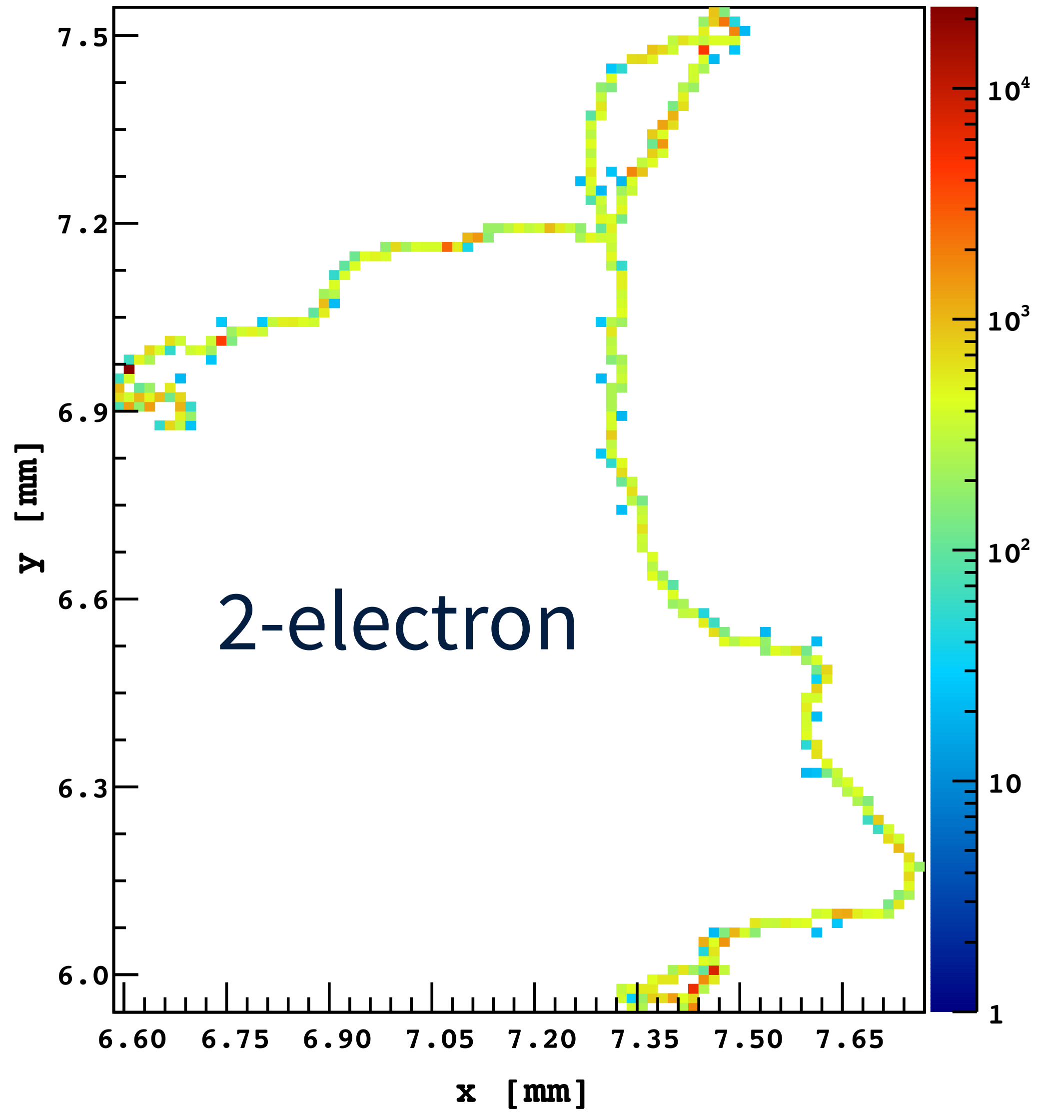
Goal:

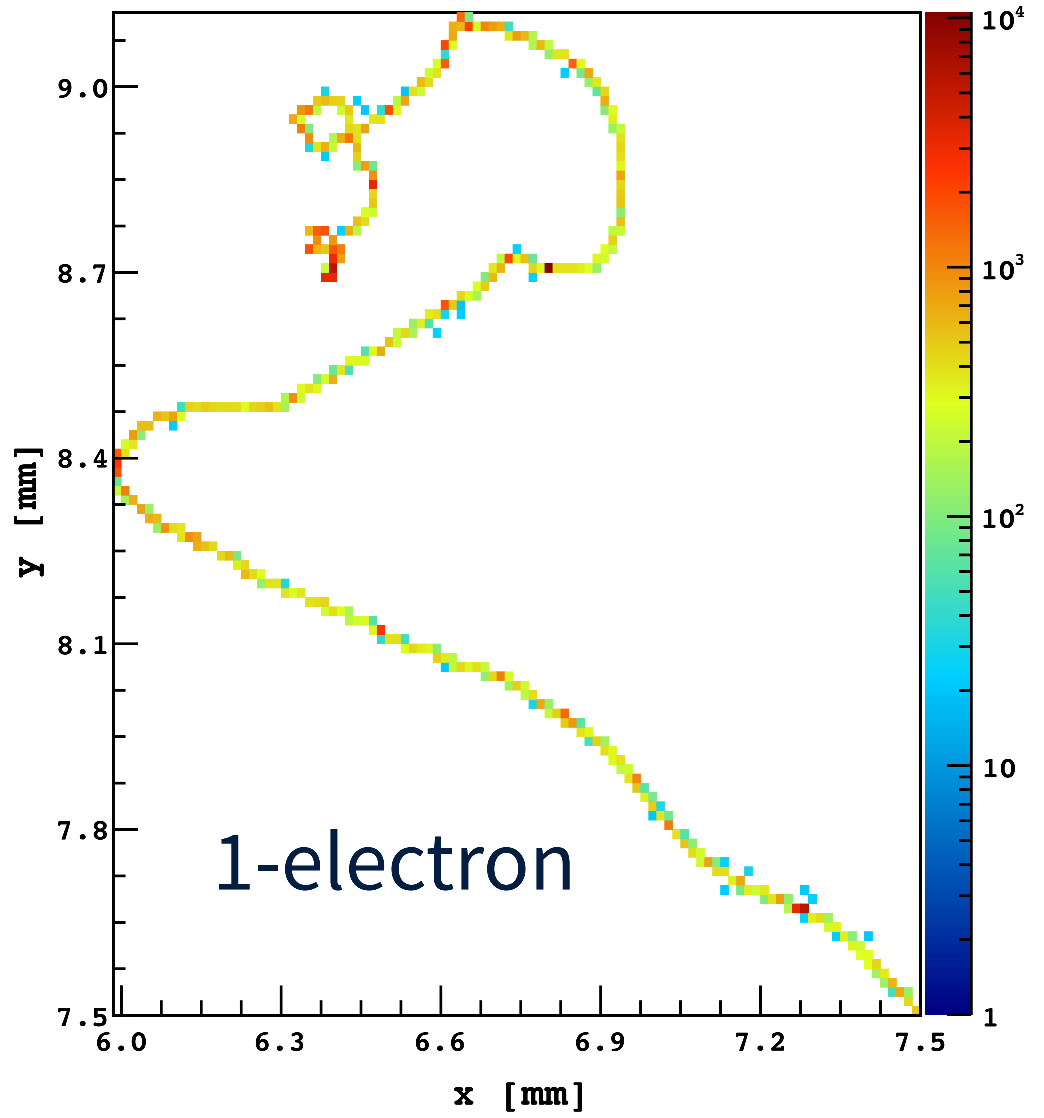
$m_{\beta\beta}$ **= 4 to 8 meV** (3σ)

(10 tons, 10 years)

Or study mechanism!

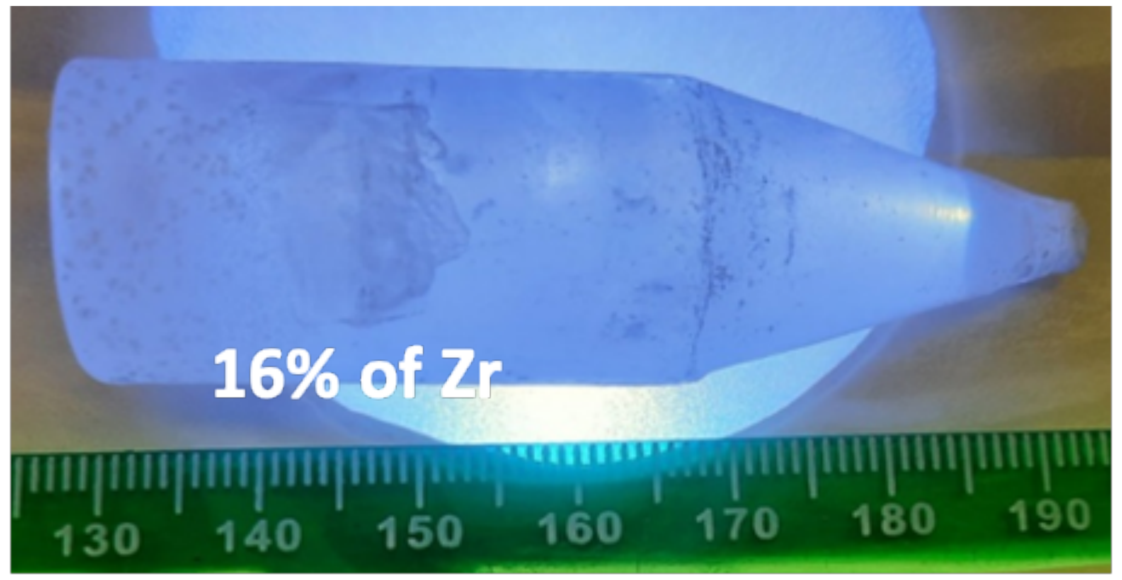






Demonstration of ~MeV electron tracks!

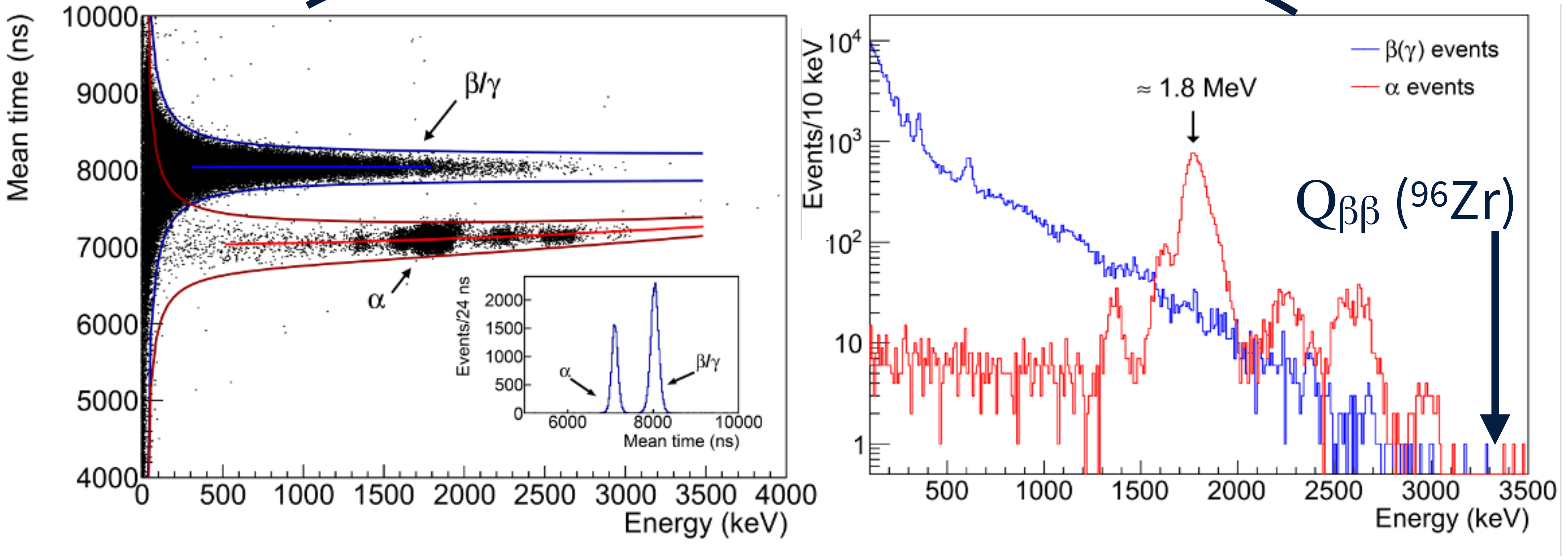
Low-background measurements of Cs_2ZrCl_6 at LNGS (Italy)



∅21.5×60 mm, about 60 g

Cs_2ZrCl_6:
a novel crystal
scintillator

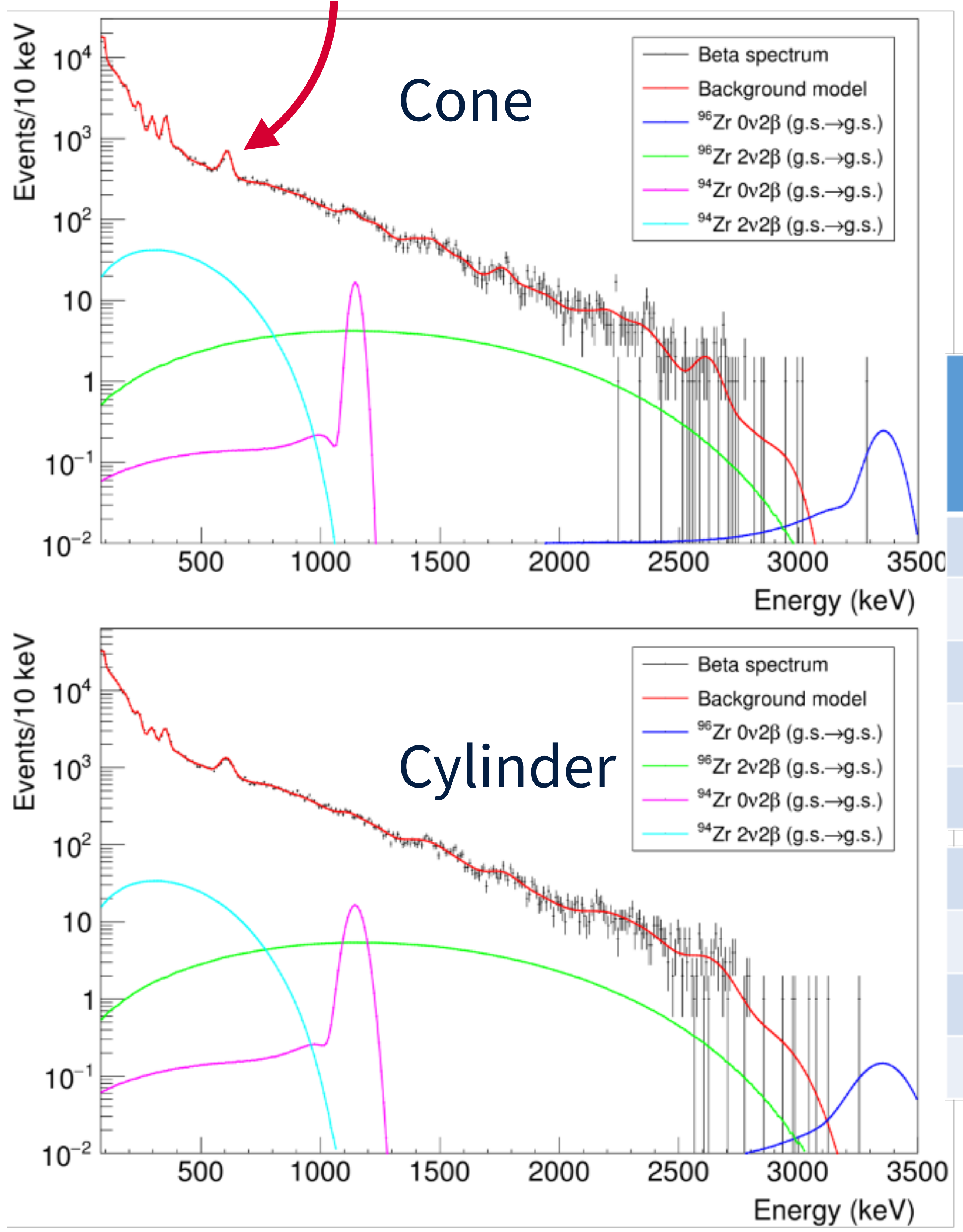
23.95 g ∅21.1×21.2 mm Cylindrical part	&	10.62 g ∅20.5×14 mm Conical part



Pulse-shape discrimination and α event selection

Experimental limits in both ^{94}Zr & ^{96}Zr

Dominant background - external γ from PMTs



↑ ^{94}Zr *0νββ*

↑ ^{96}Zr *0νββ*

Run 1: 456.5 days
+
Run 2: 65 days

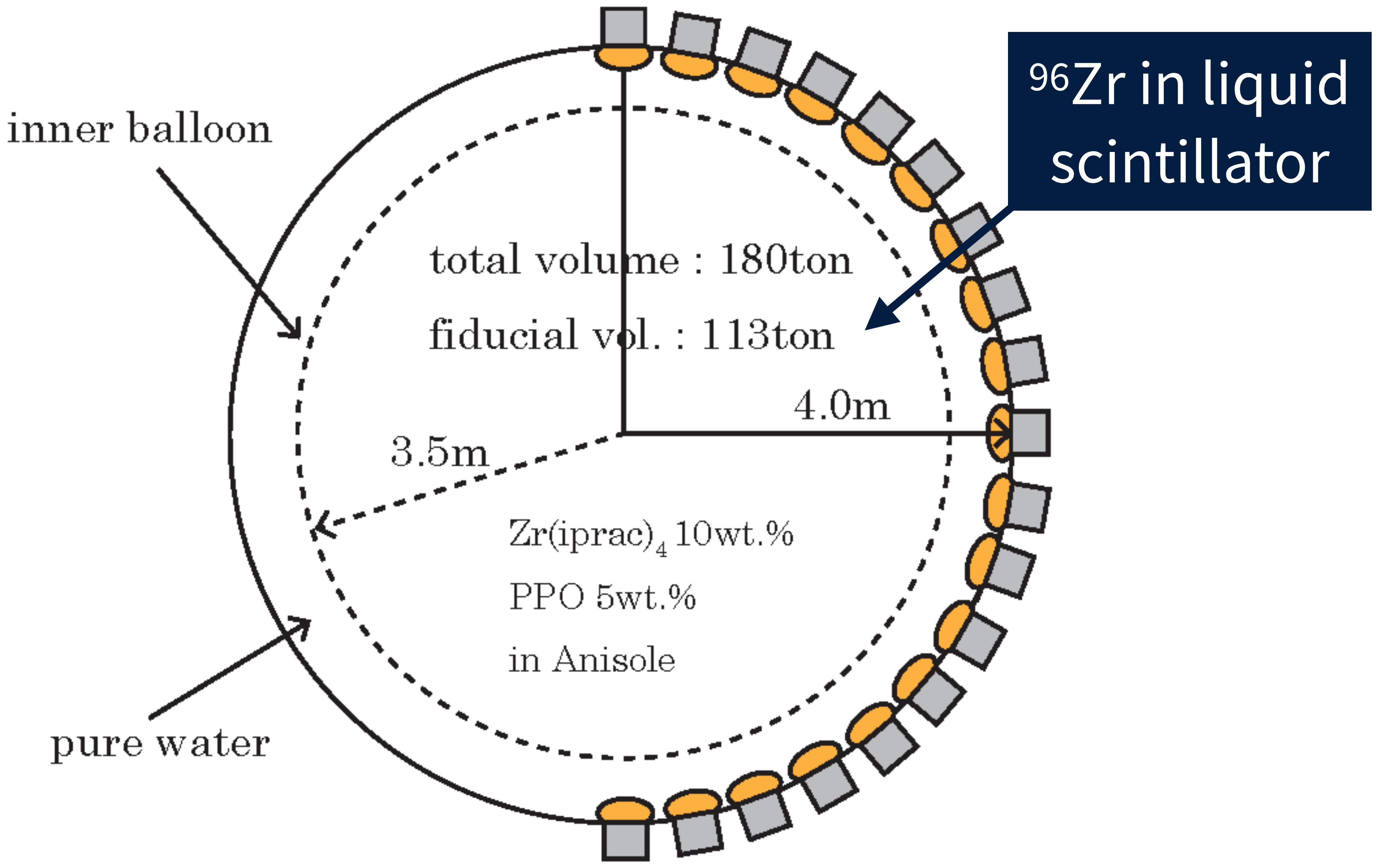
Transition	Decay mode	Final state of daughter nucleus, keV	Experimental limit on $T_{1/2}$ at 90%C.L., yr
$^{96}Zr \rightarrow {}^{96}Mo$	2β0ν	g.s.	**> 1.5×10^{20}**
		2_1^+, 778	> 1.5×10^{19}
	2β2ν	g.s.	> 7.4×10^{17}
		2_1^+, 778	> 3.8×10^{17}
	β	g.s.	> 1.0×10^{17}
$^{94}Zr \rightarrow {}^{94}Mo$	2β0ν	g.s.	> 2.6×10^{19}
		2_1^+, 871	> 3.8×10^{18}
	2β2ν	g.s.	> 2.4×10^{18}
		2_1^+, 871	> 1.9×10^{17}

Eur. Phys. J. A 59 (2023) 176

ZICOS (^{96}Zr at Kamioka)

Phys.Rev.Lett. 117 (2016) 082503

Conceptual design of ZICOS detector

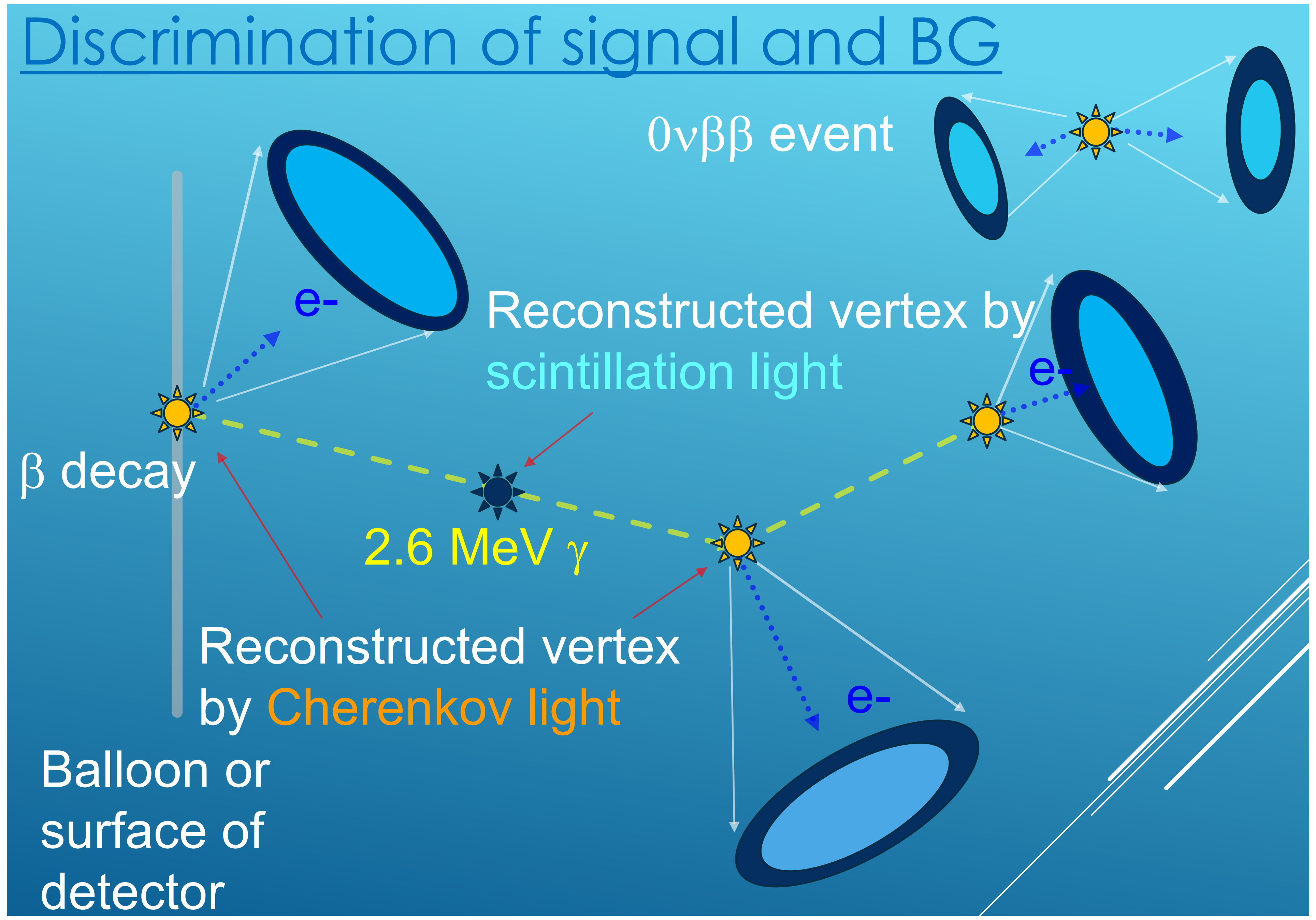


^{96}Zr in liquid scintillator

20" PMD with QE~0.4 and TTS <1ns @ 1pe

Total PMT : 650 Photo coverage : 64%

Scintillation (energy) + Cherenkov (BG reduction)

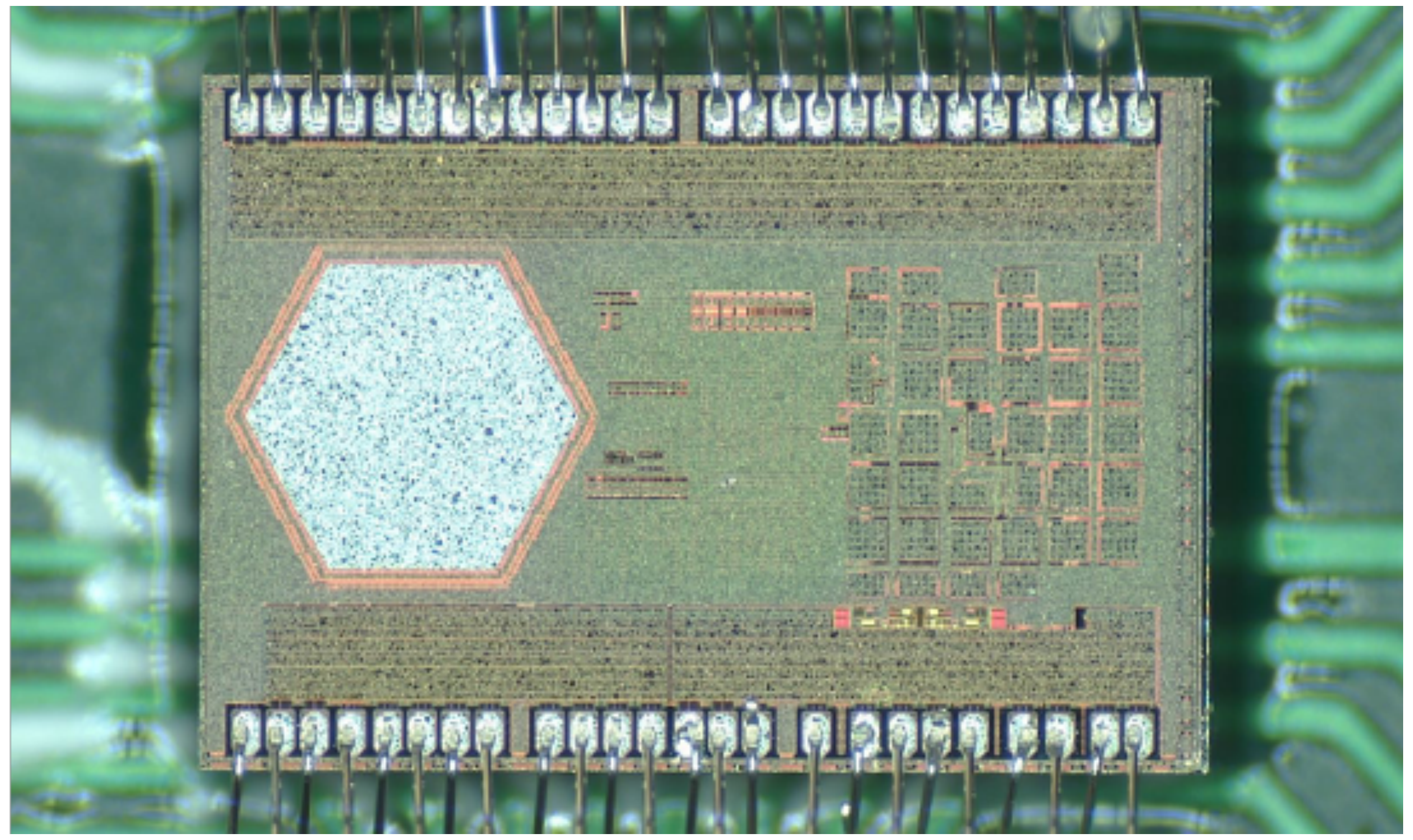


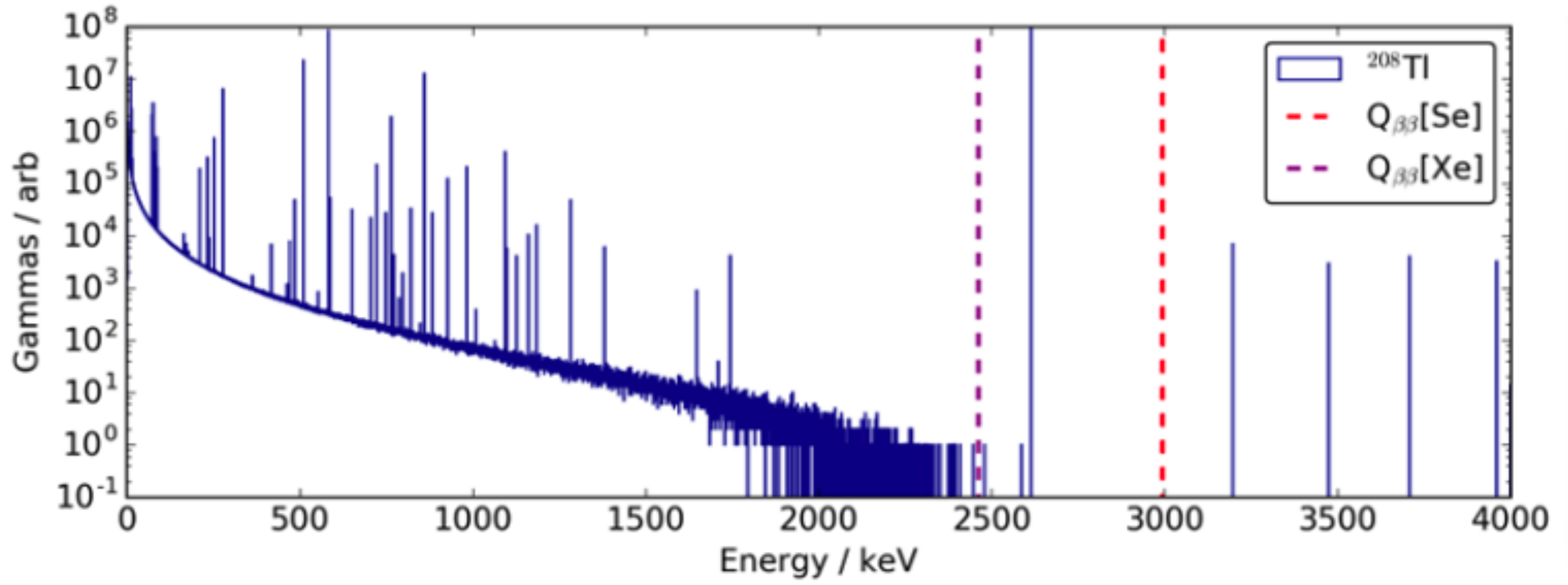
Targets:
45kg nat Zr: $T_{1/2} > 4 \times 10^{25}$ yr
865 kg (50% enriched): $T_{1/2} > 2 \times 10^{26}$ yr
20x background reduction: $T_{1/2} > 2 \times 10^{27}$ yr

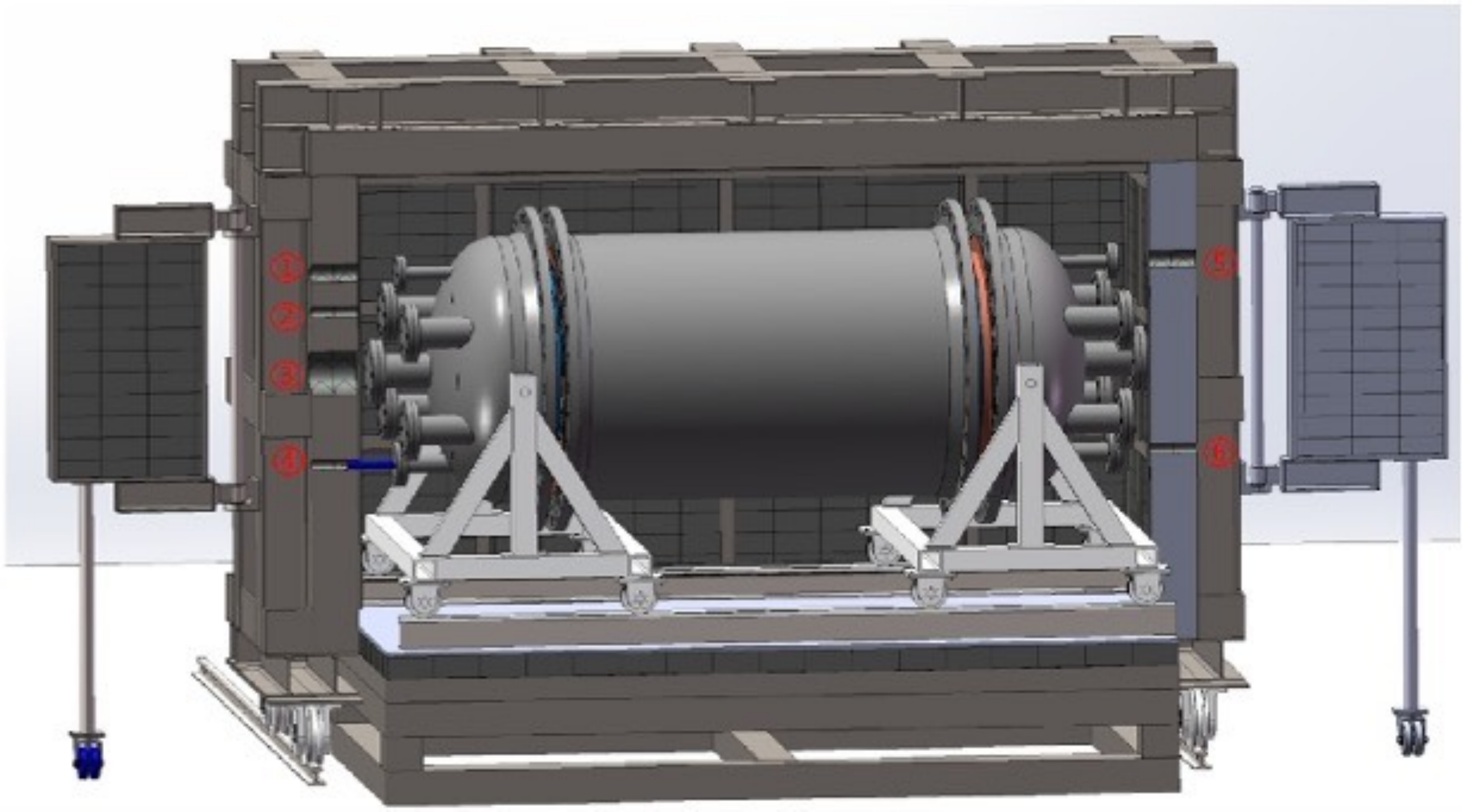
- First $2\nu\beta\beta$ observations next summer: 1l of scintillator and 0.4g of ^{96}Zr
- 100 events expected

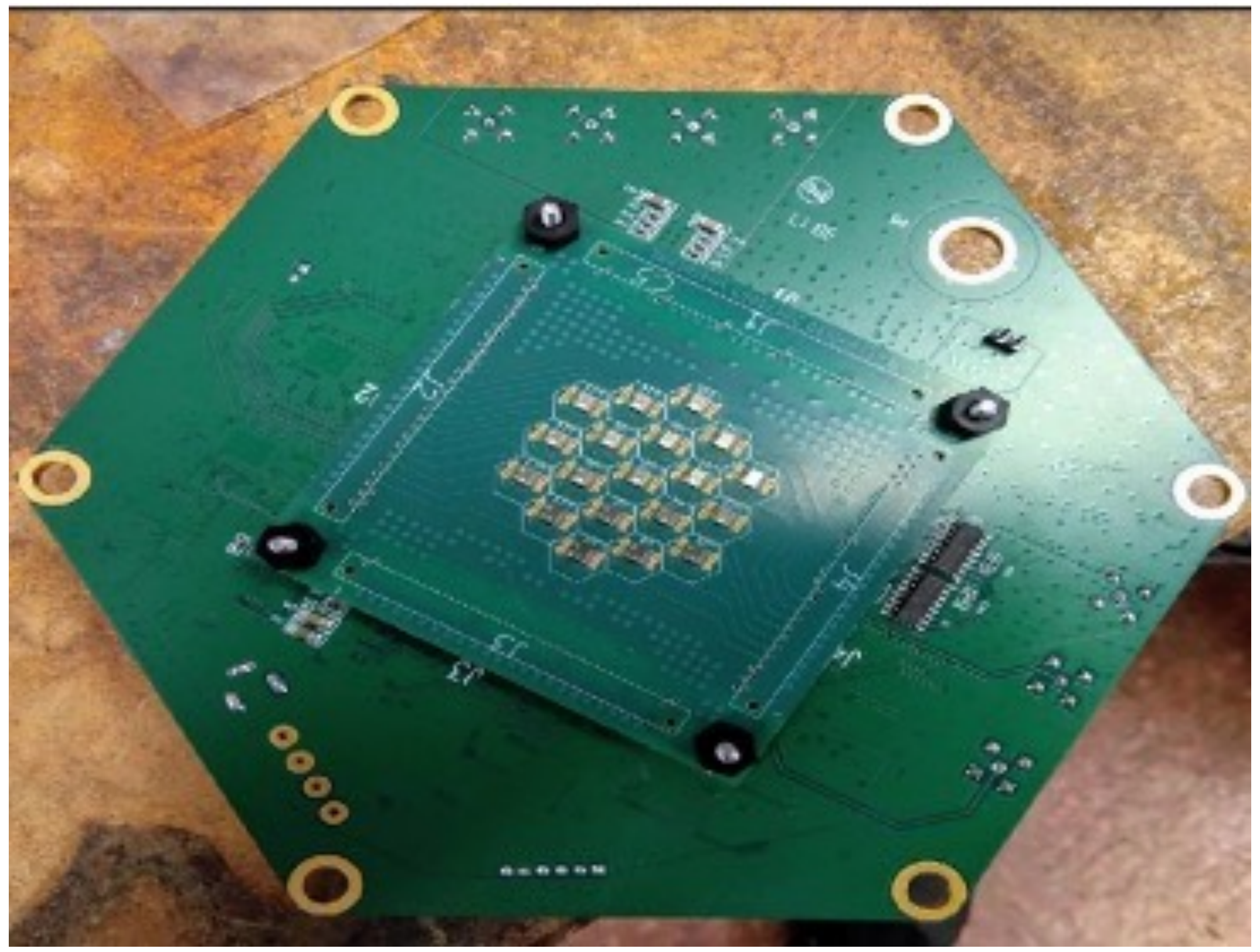
NνDEX at CJPL: $^{82}SeF_6$ high-pressure TPC

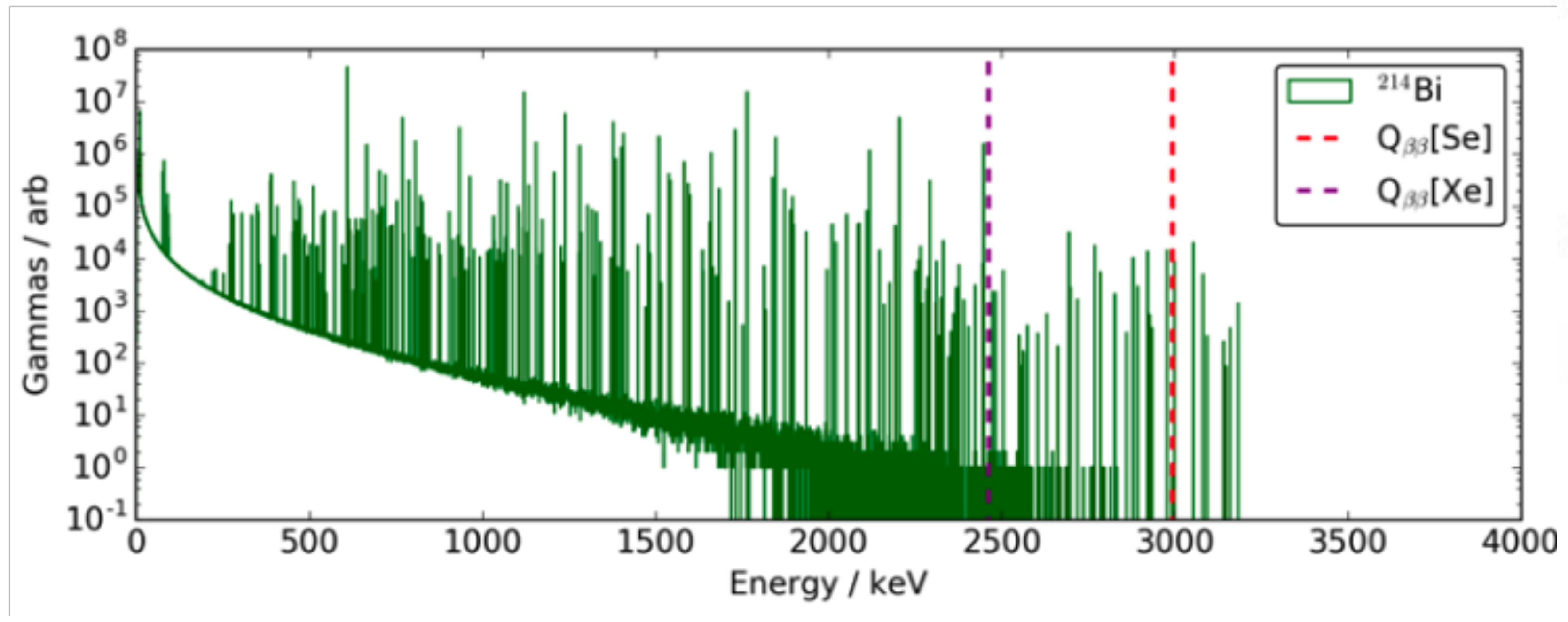
- HP $^{82}SeF_6$ TPC: topology to reject background
- $^{82}SeF_6$ electronegative: Topmetal-S sensor being developed to detect negative ions drifting
- Good energy resolution expected without electron avalanche multiplication: FWHM 1%@3 MeV
- Q-value: 2.996 MeV, higher than most of the background
- To be placed at CJPL: 2400 m rock overburden
- Very low background: 0.05 events/year for 100kg gas, excellent prospects for scalability







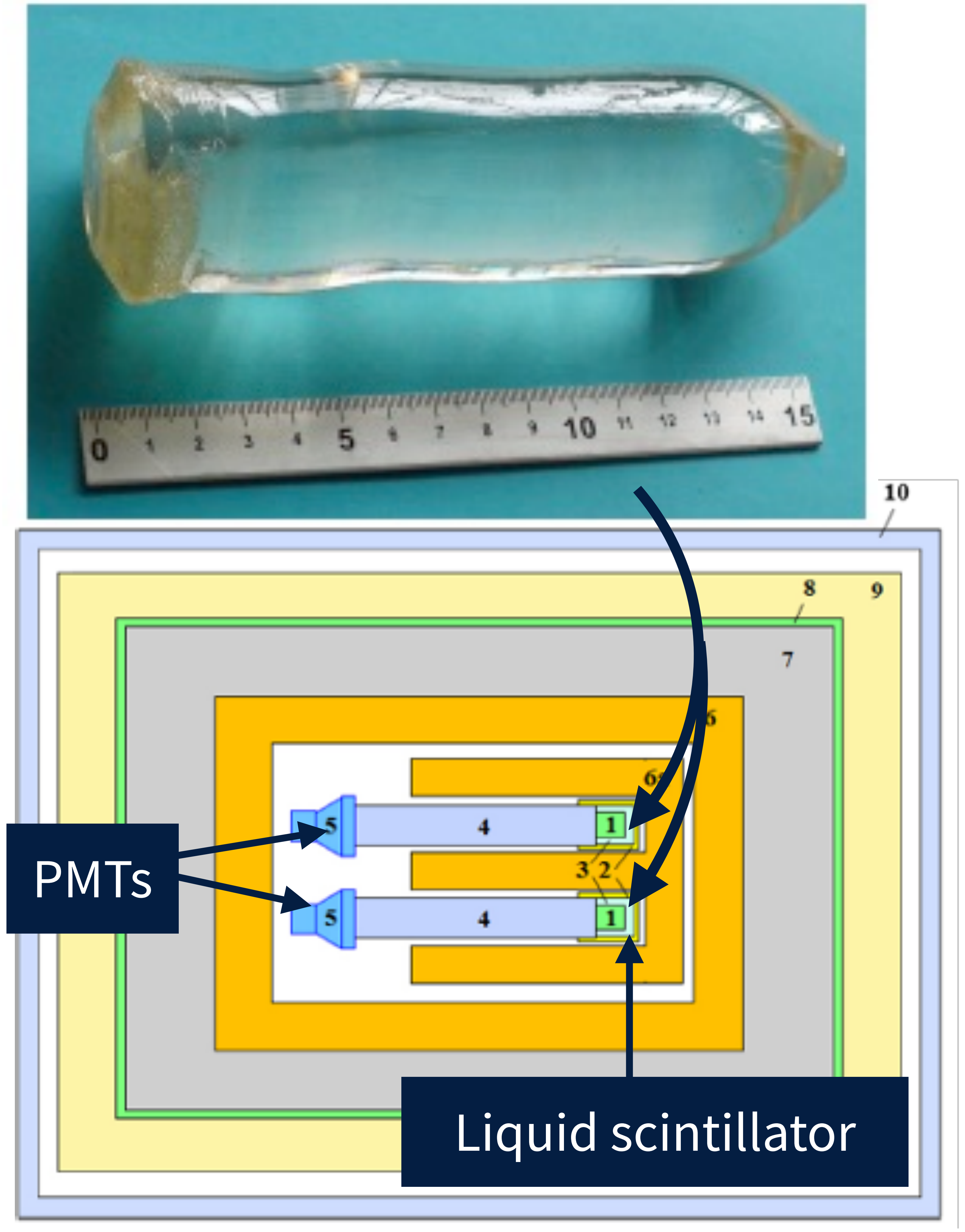




Aurora: ^{116}Cd $\beta\beta$ decay at Gran Sasso

[1] JINST 06 (2011) p08011
[2] PRD 98 (2018) 092007

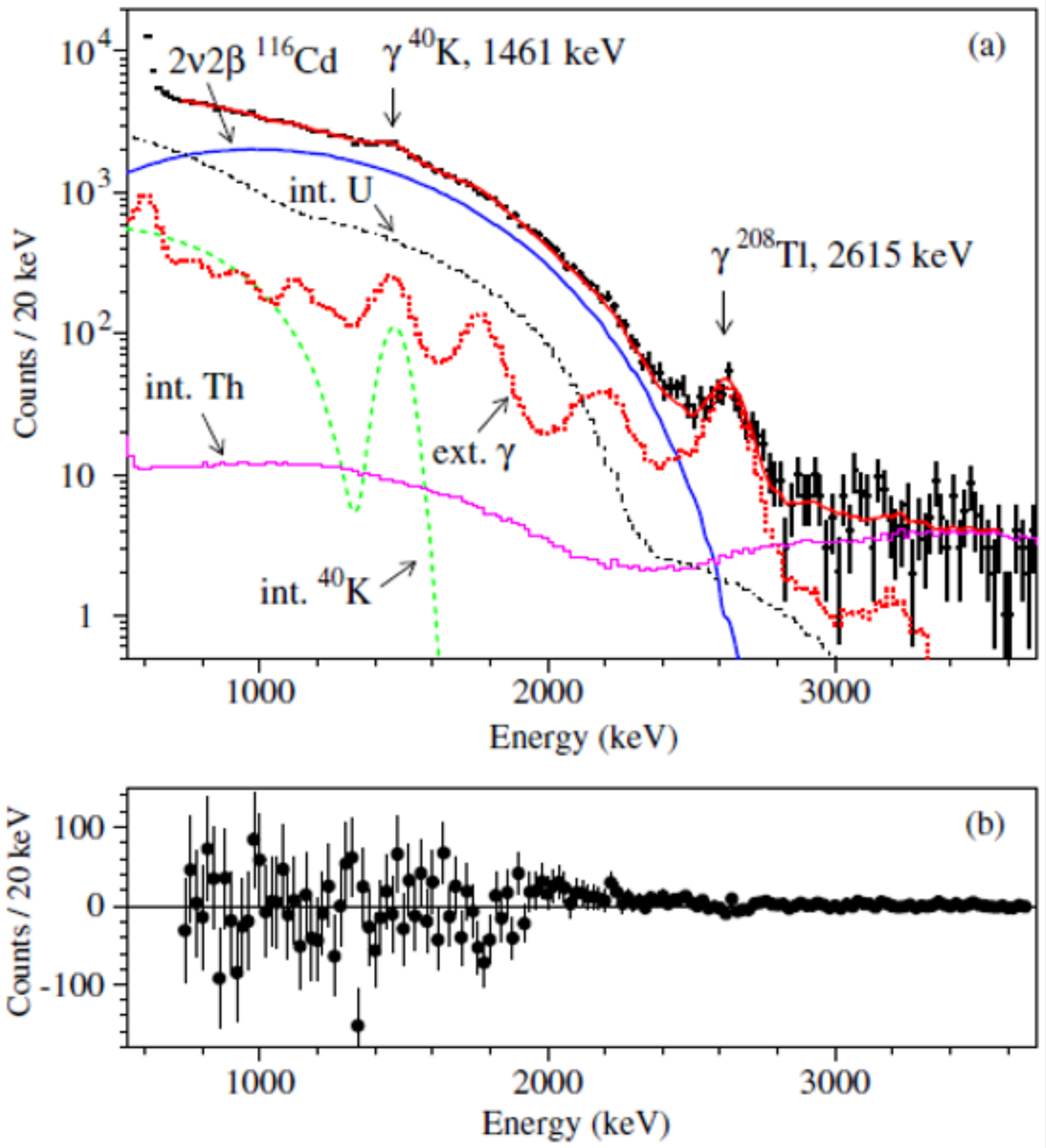
Two ^{116}CdWO$_4$ scintillating crystals (1.16 kg) enriched to 82%

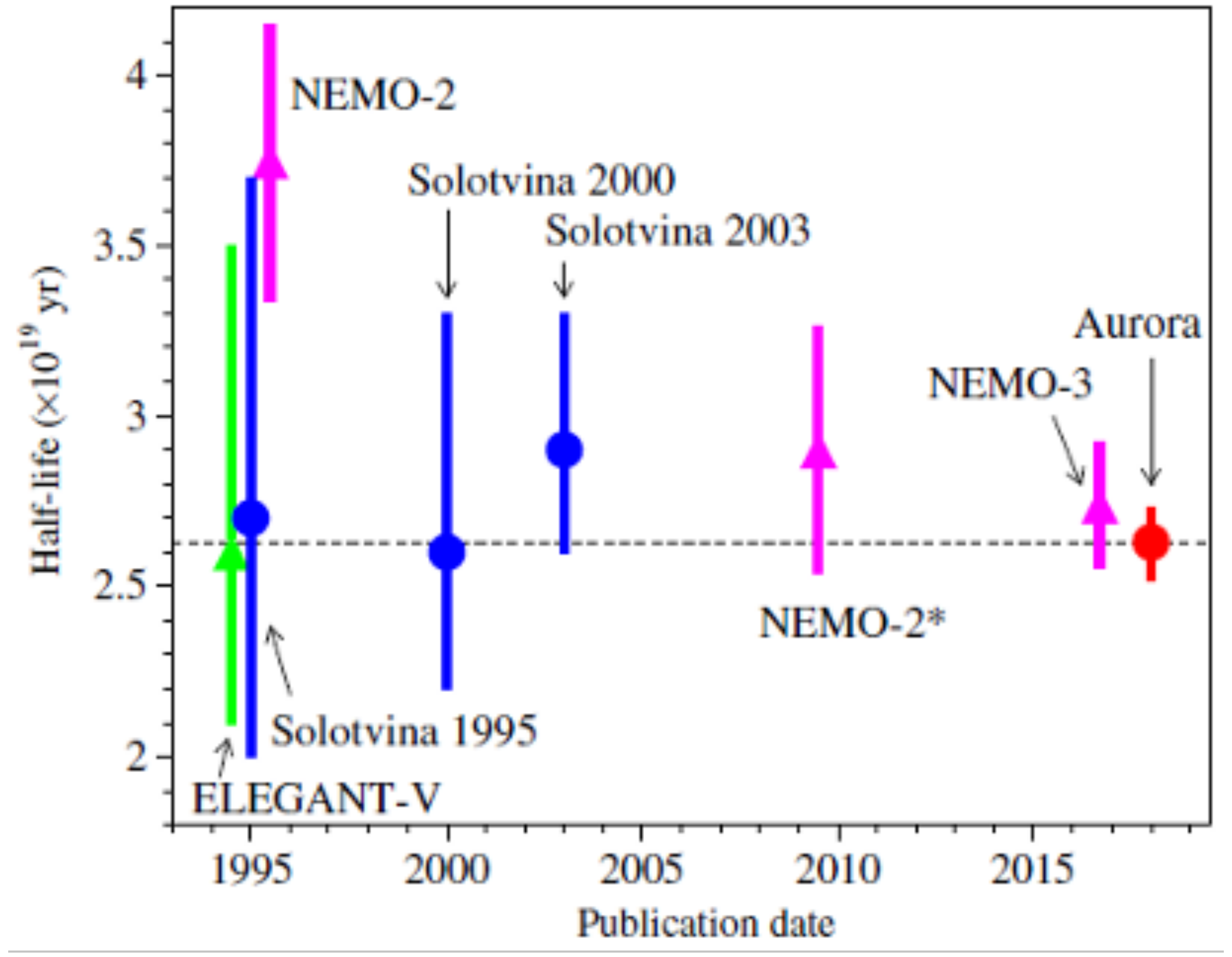


PMTs

Liquid scintillator

Energy resolution FWHM = 6%,
BG ~ 0.15 counts/(keV × yr × kg) at $Q_{\beta\beta}$





$$T_{1/2}^{2\nu2\beta} = [2.63 \pm 0.01(\text{stat})^{+0.11}_{-0.12}(\text{syst})] \times 10^{19} \text{ yr}$$

$$T_{1/2}^{0\nu2\beta} \geq 2.2 \times 10^{23} \text{ yr}, \qquad \langle m_\nu \rangle < (1 - 1.7) \text{ eV}$$

$\langle\lambda\rangle \leq (1.8 - 22) \times 10^{-6}$

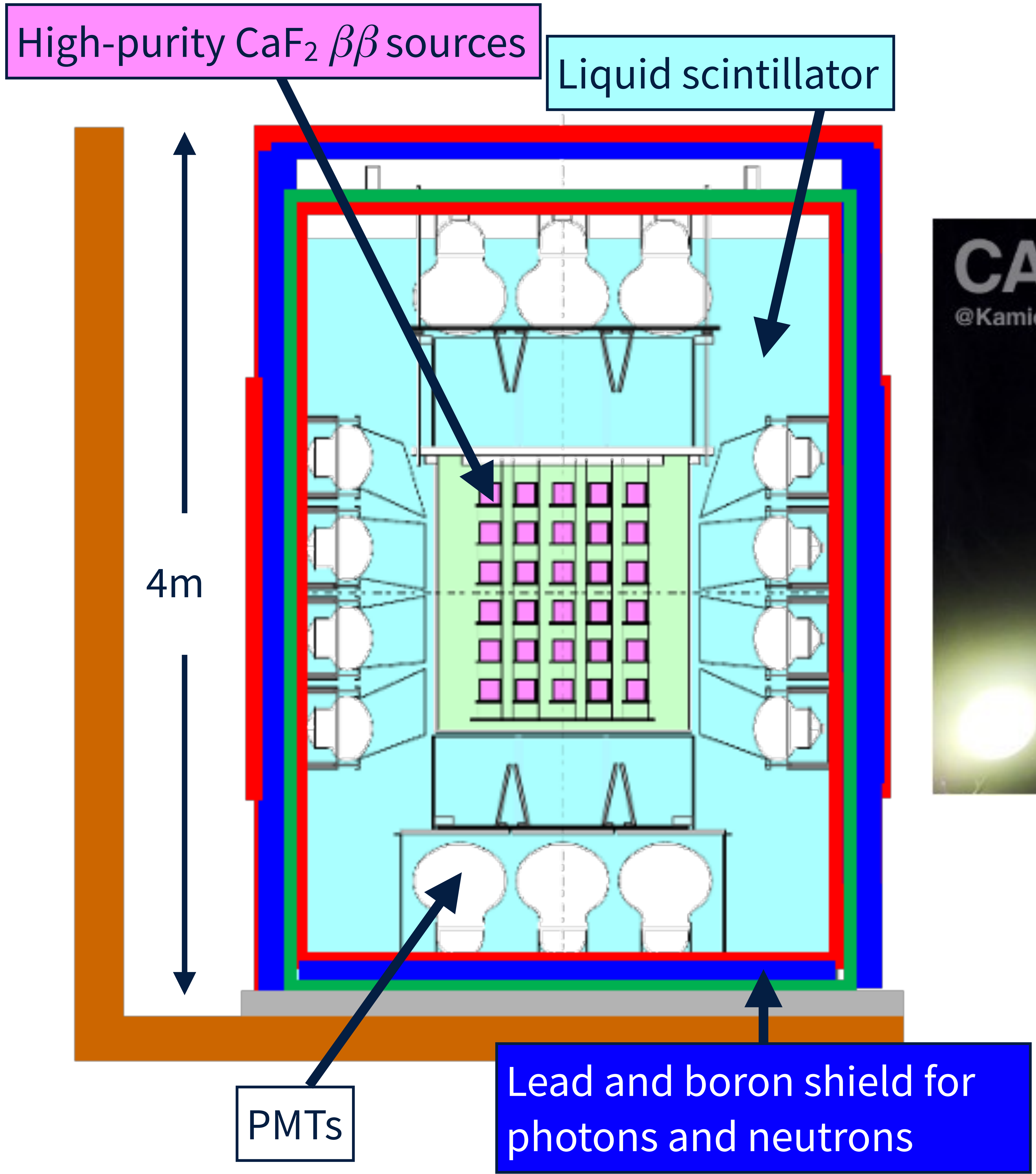
$\langle\eta\rangle \leq (1.6 - 21) \times 10^{-8}$

Lorentz-violating parameter $\mathring{a}^{(3)}_{of} \leq 4 \times 10^{-6}$ GeV

Limits on majorons, heavy ν, R-parity violating parameter, ββ to excited states [2]

^{48}Ca: CANDLES-III at Kamioka Lab

Phys. Rev. D103, (2021), 092008

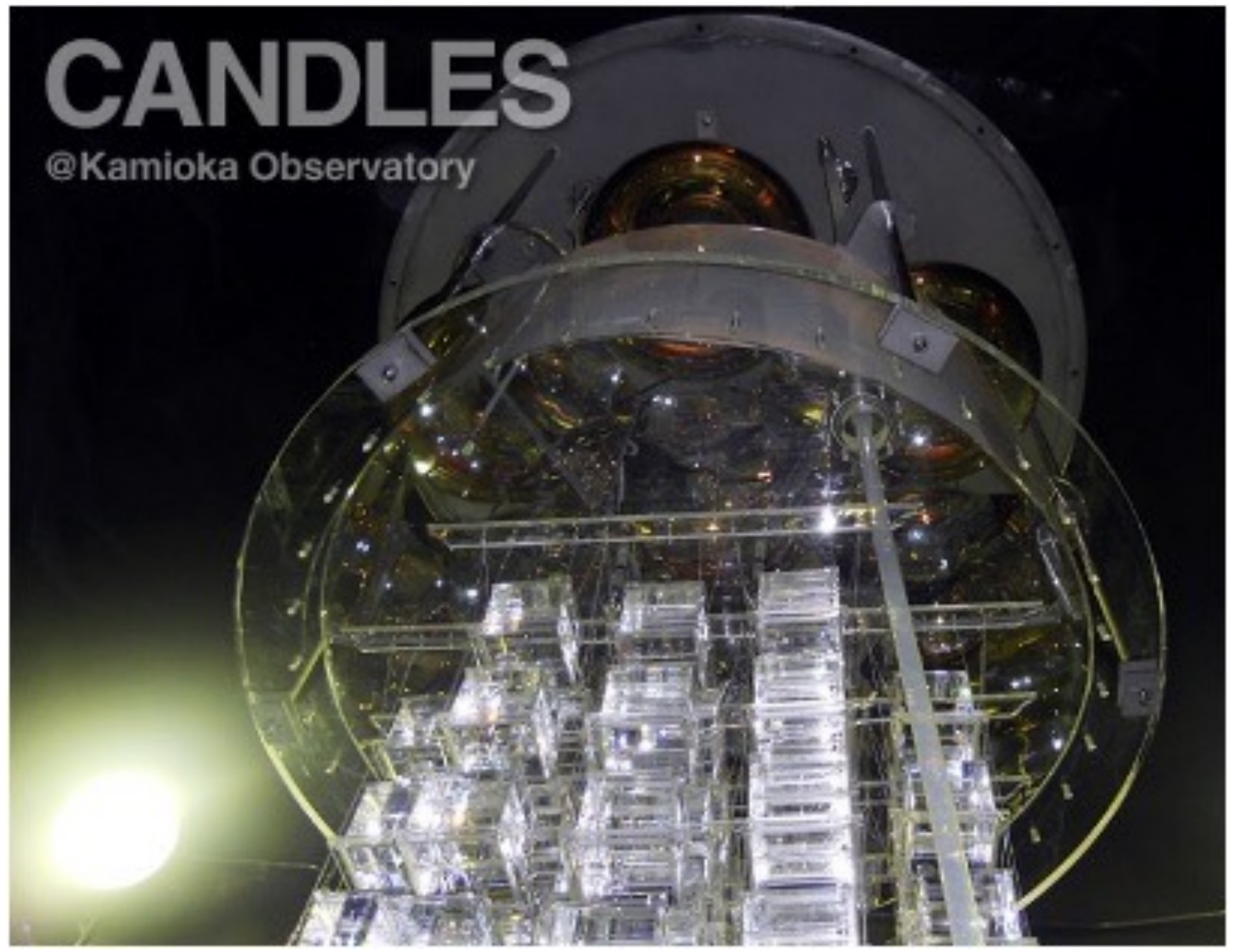


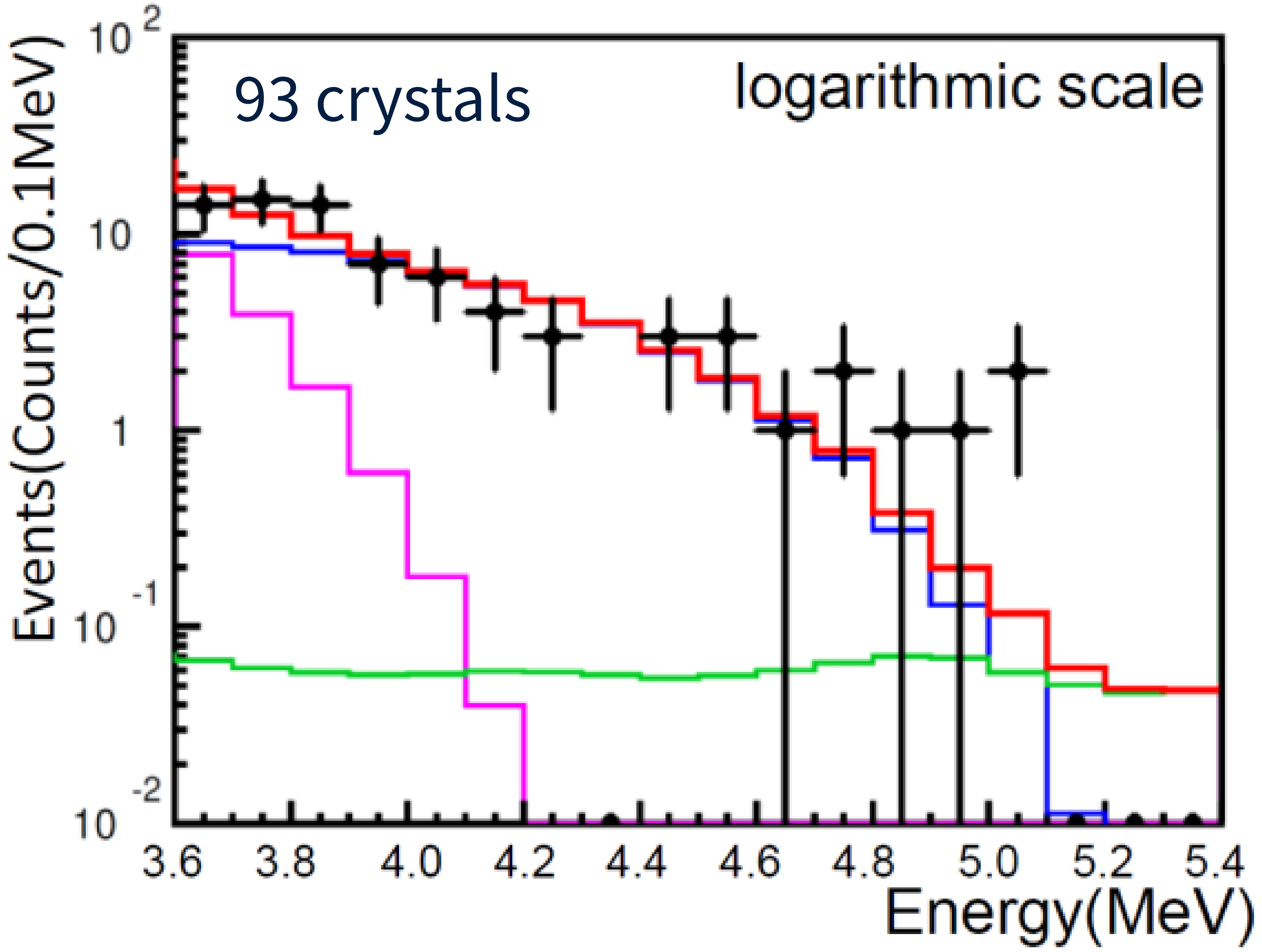
High-purity CaF_2 $\beta\beta$ sources

Liquid scintillator

PMTs

Lead and boron shield for photons and neutrons



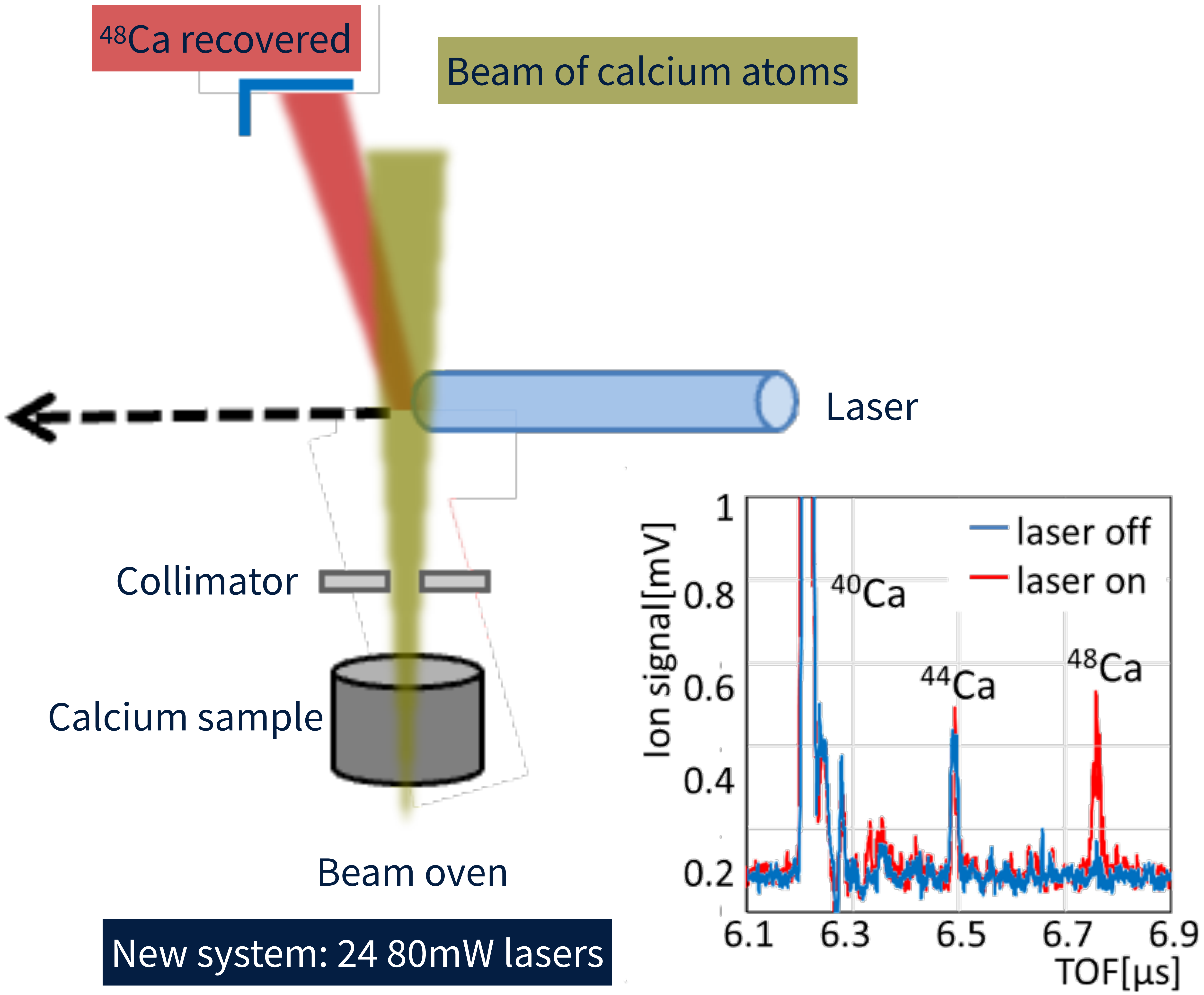


Background rate < 10^{-3} events/keV/year/kg of ^{nat}Ca
- comparable to lowest background level

- 0 events observed (expected background 1.02)
- $0\nu\beta\beta$ $T_{1/2} > 5.6 \times 10^{22}$ years for ^{48}Ca
- Sensitivity: 2.8×10^{22} years

CANDLES: future development for < 10meV sensitivity

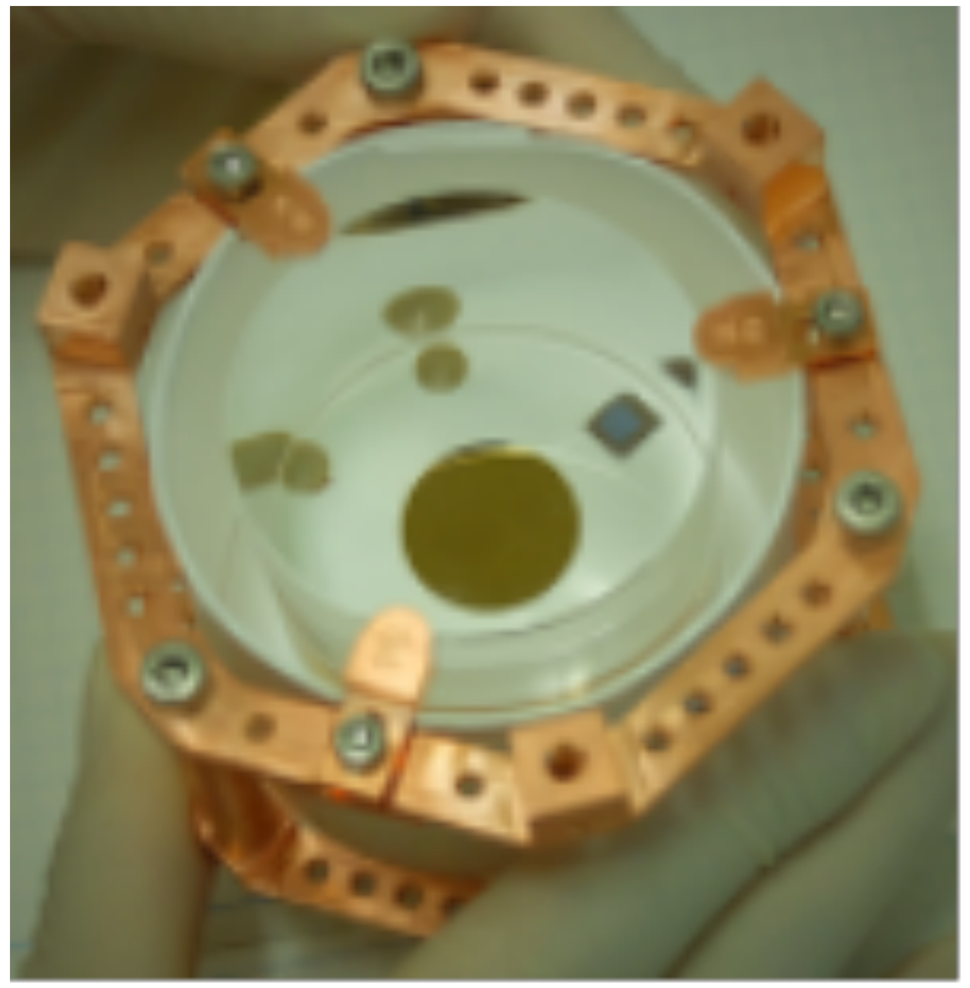
^{48}Ca enrichment using LIS

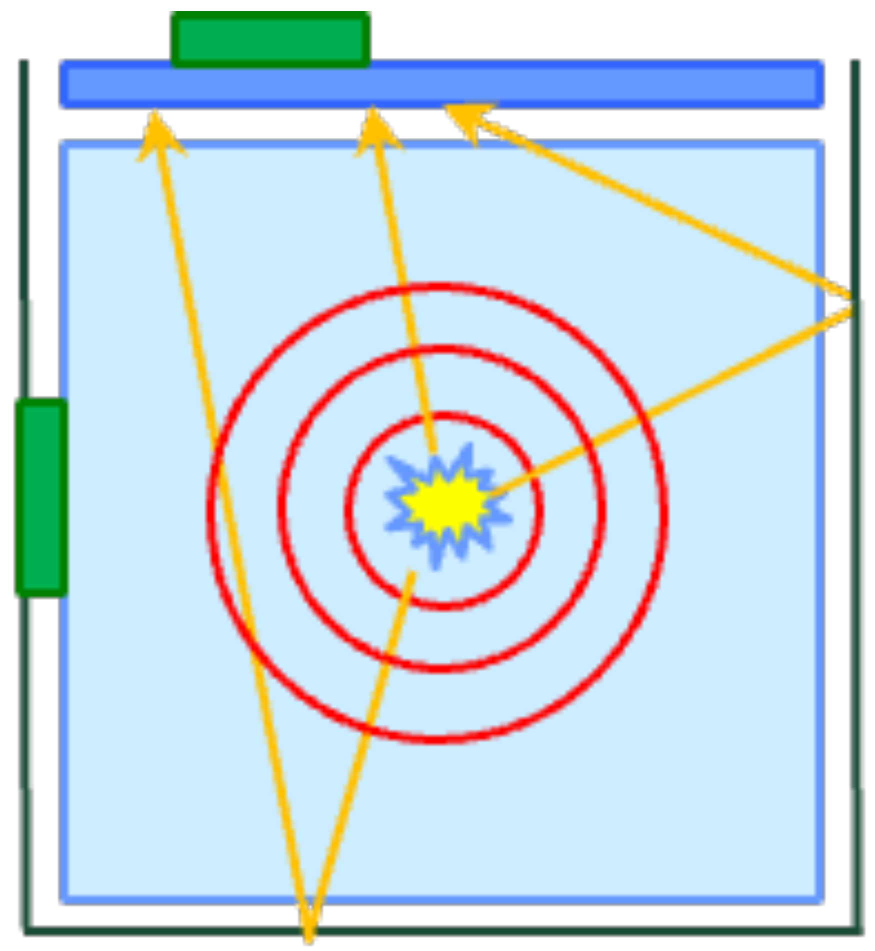


New system: 24 80mW lasers

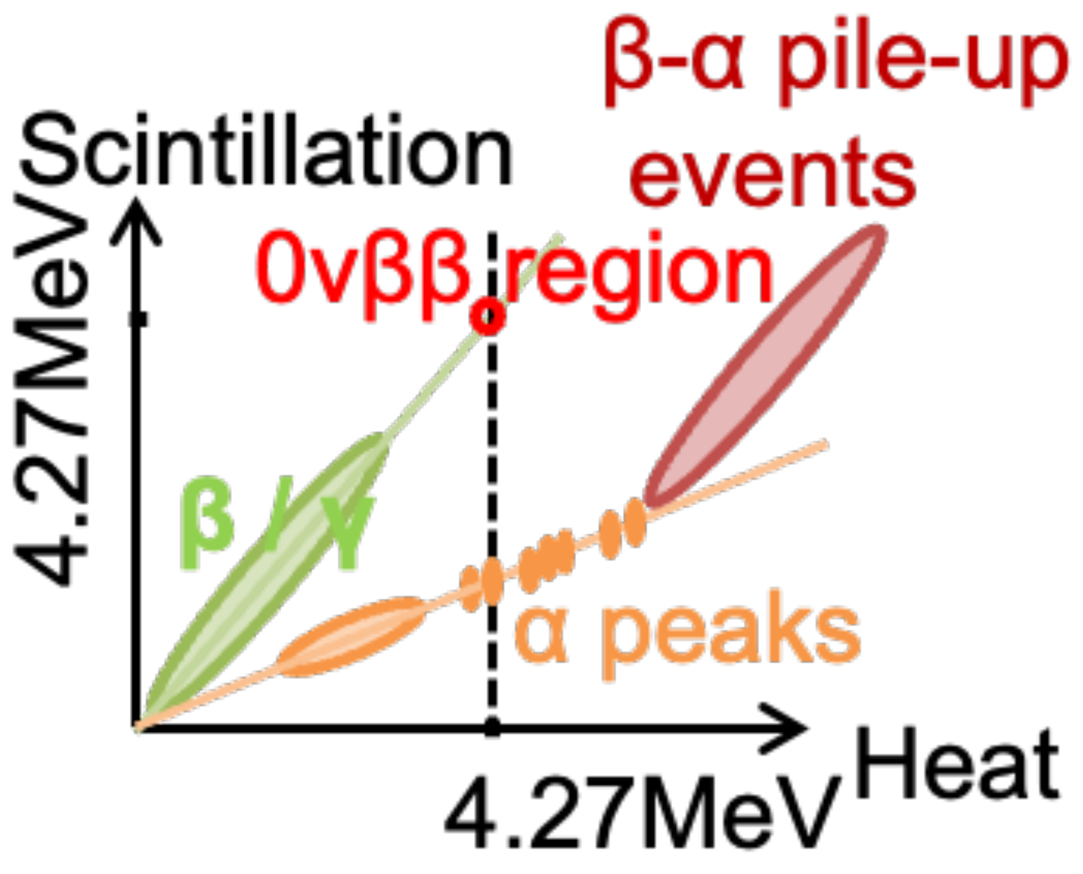
CaF$_2$ scintillating bolometer

Light sensor…



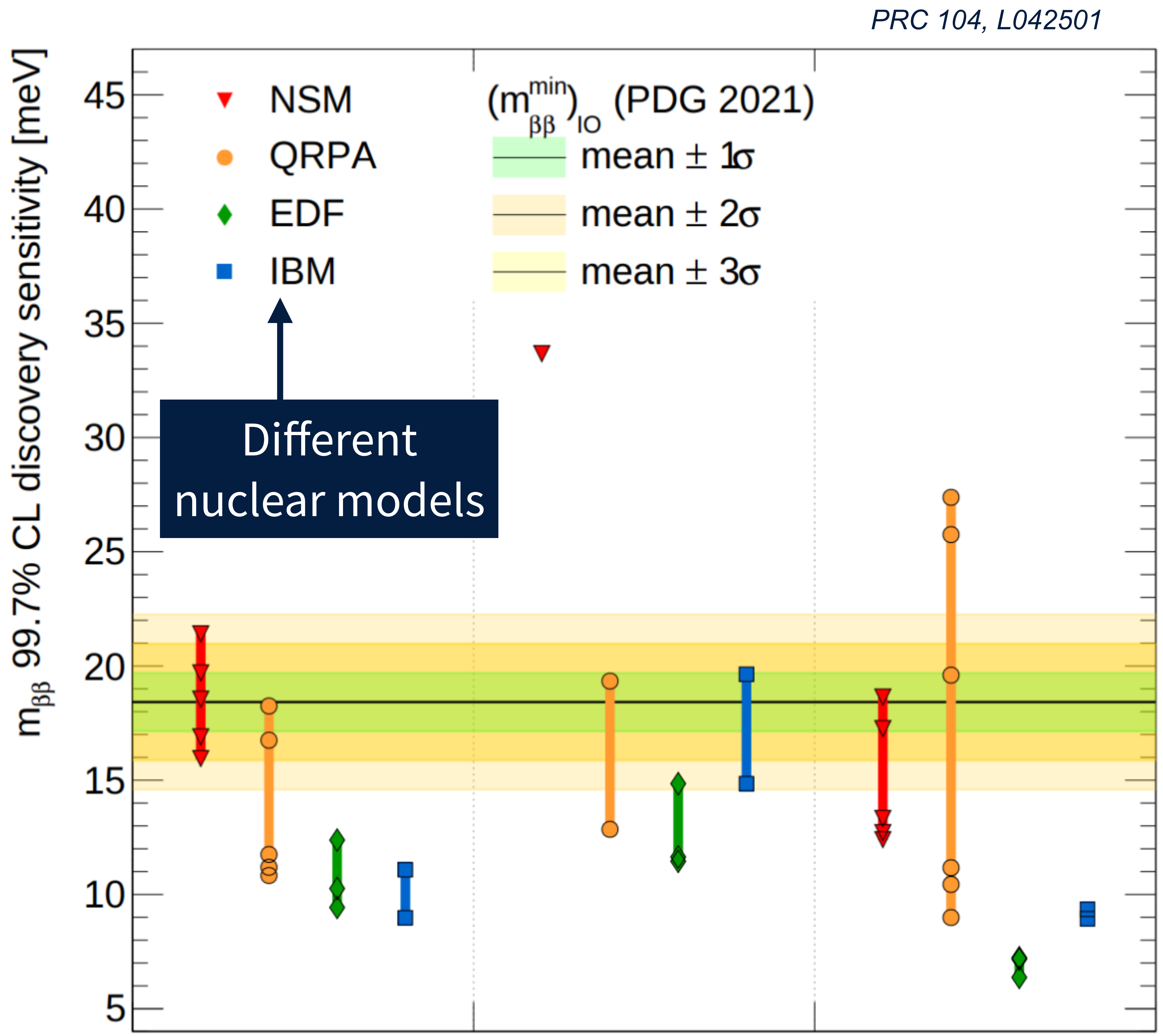


…plus heat sensor



Future prospects

Probing the inverted hierarchy



Different nuclear models

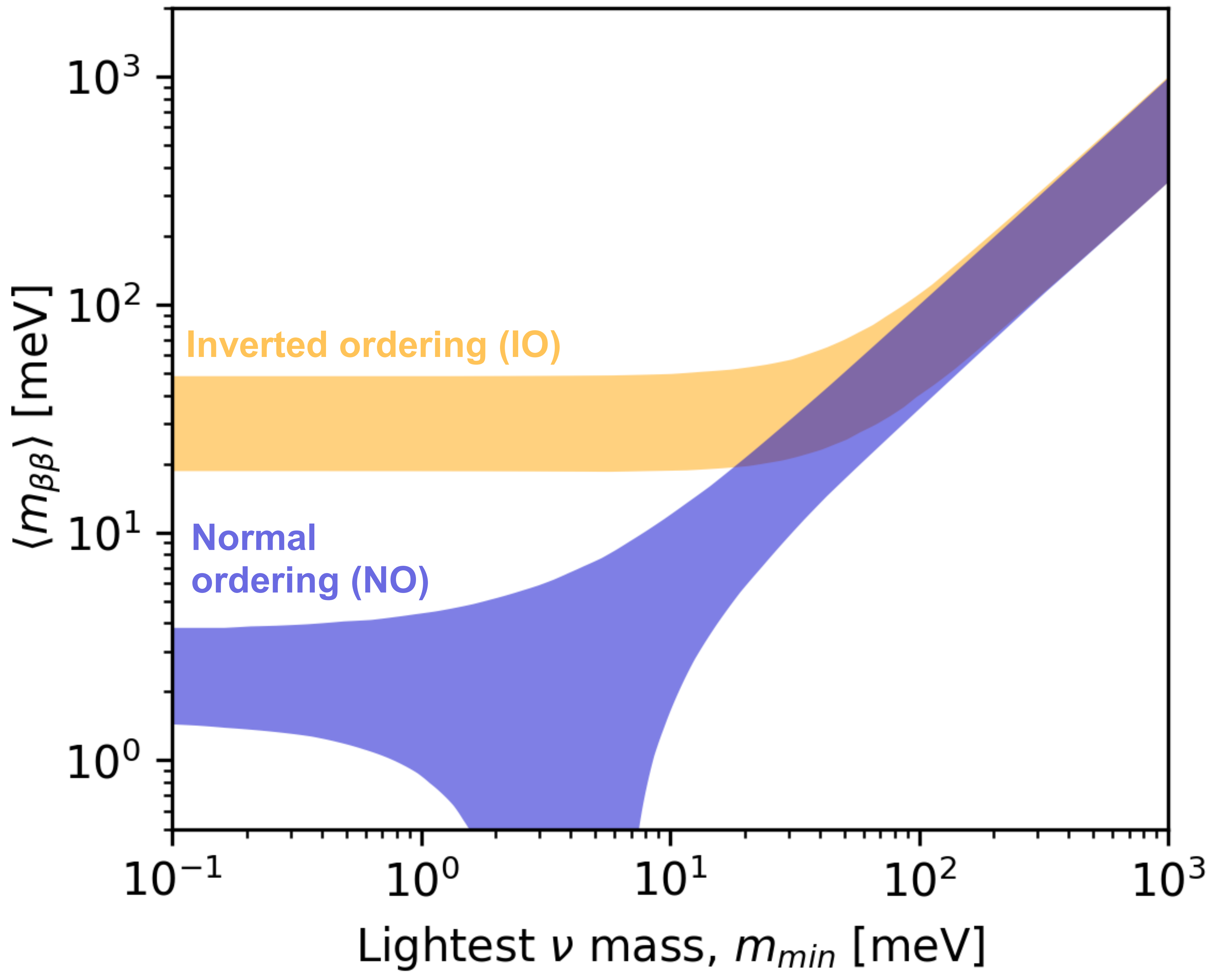
LEGEND CUPID nEXO

^{76}Ge ^{100}Mo ^{136}Xe

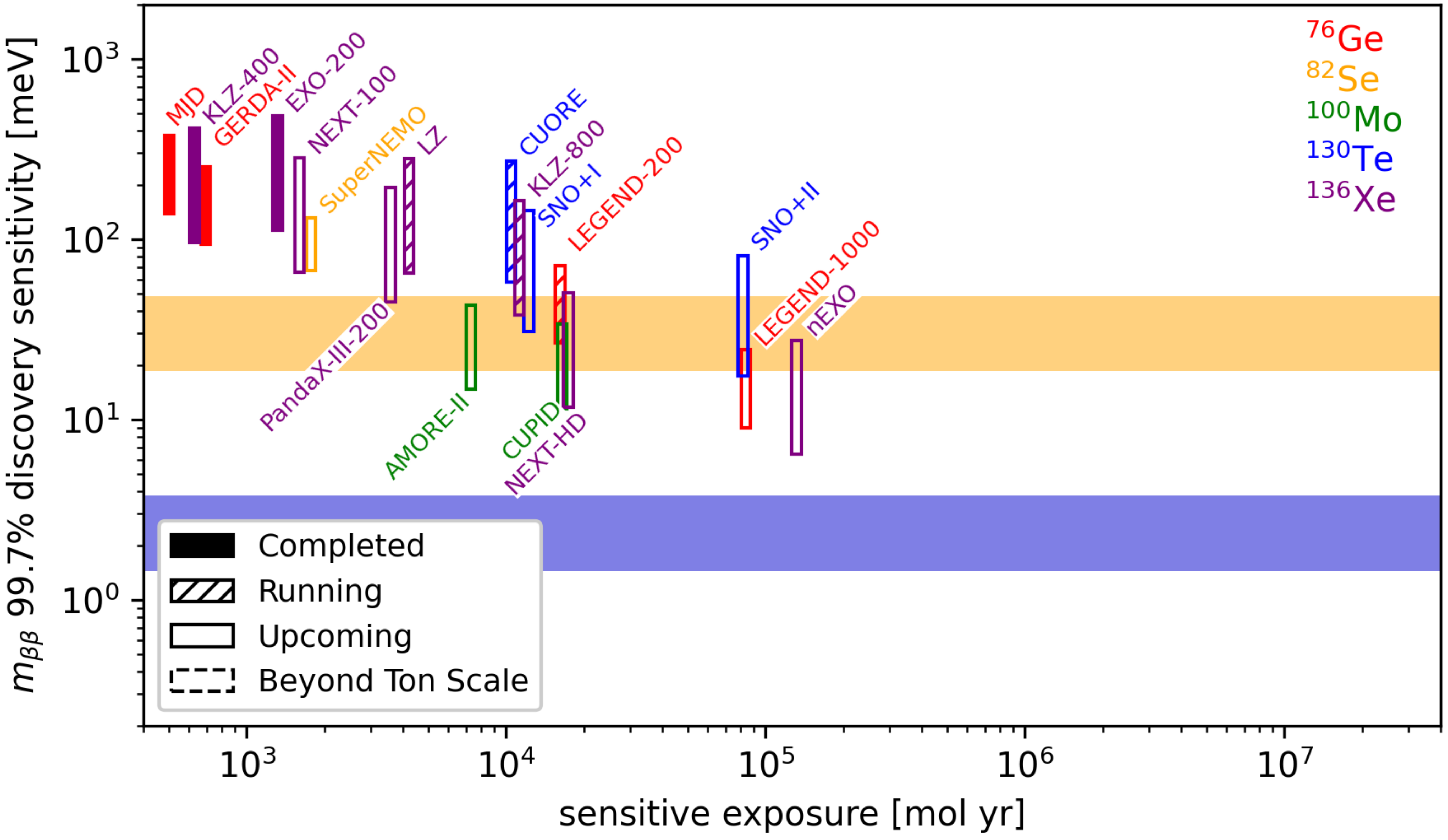
- Tonne-scale experiments have **designs ready to go** to probe inverted hierarchy in 3 different isotopes
- If nature chose inverted hierarchy and neutrinos are Majorana - they'll see $0\nu\beta\beta$!
- If nature chose inverted hierarchy and they don't - neutrinos are Dirac?
- If nature chose normal hierarchy - we may see it anyway
- If not…

Probing the inverted hierarchy

Parameter space vs. mass of lightest ν:



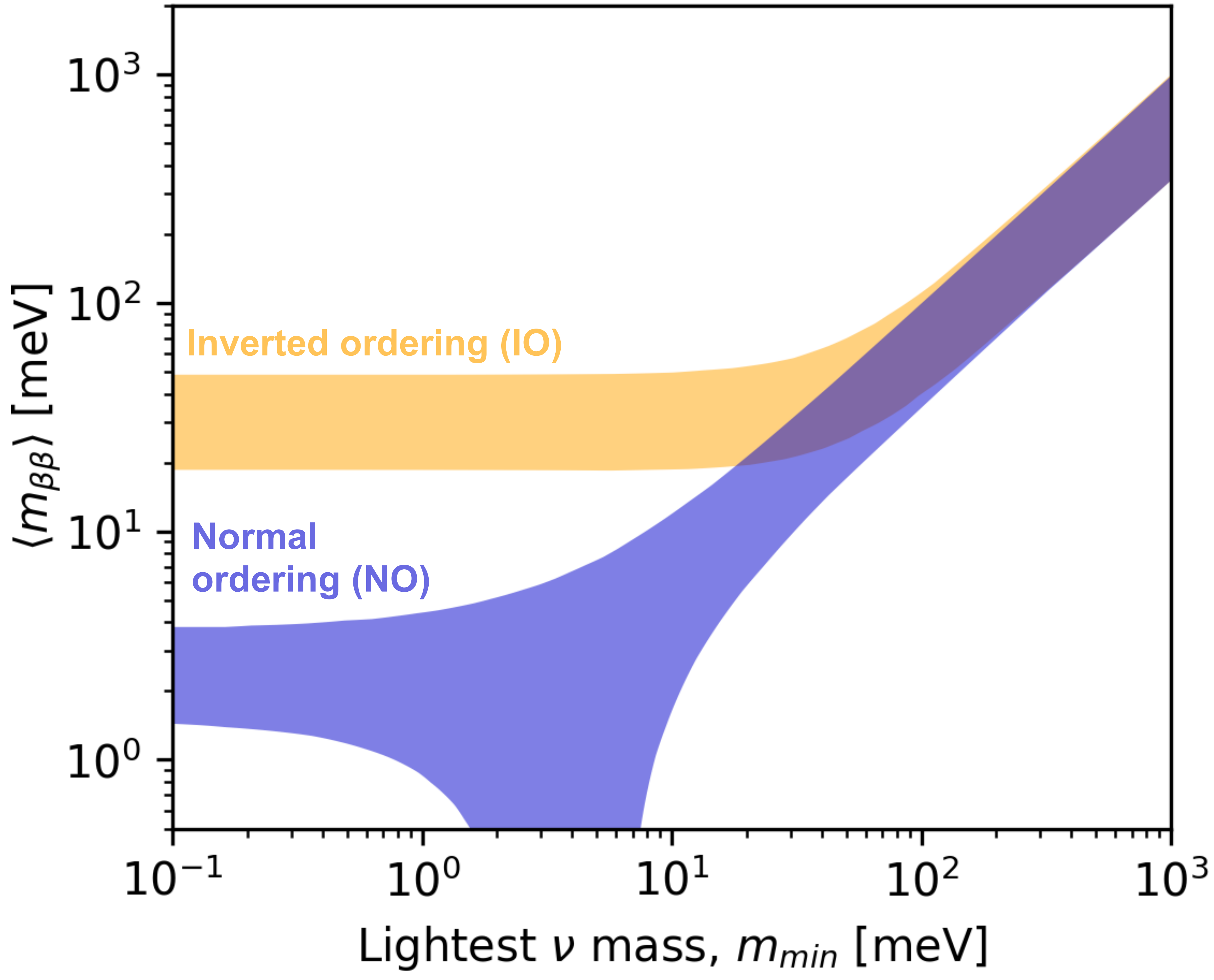
Sensitivity of upcoming experiments:



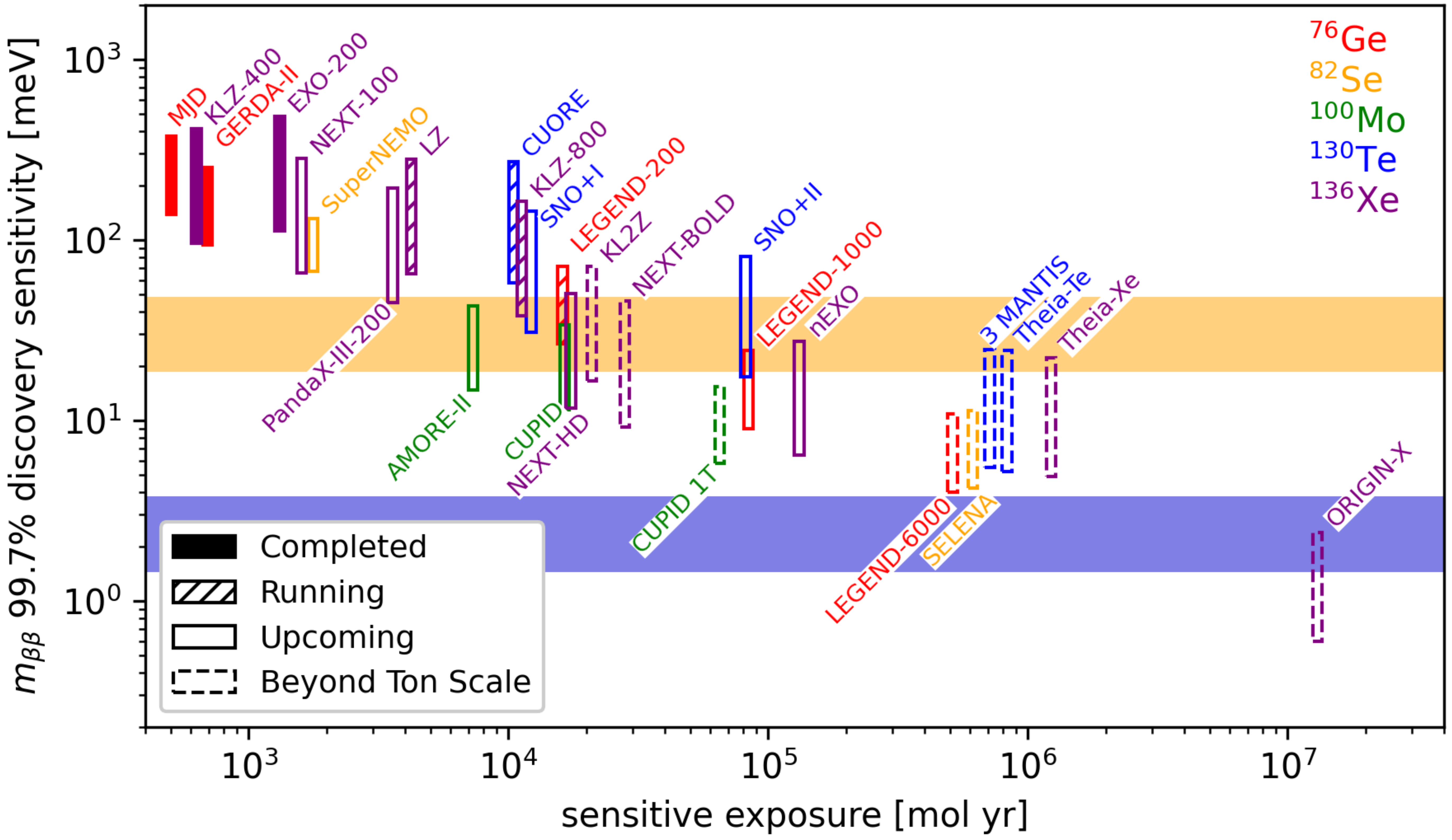
Plot adapted from arXiv:2212.11099 by D Moore for TAUP 2023
https://indico.cern.ch/event/1199289/contributions/5262783

… and beyond?

Parameter space vs. mass of lightest ν:



Sensitivity of proposed beyond ton scale experiments:



Plot adapted from arXiv:2212.11099 by D Moore for TAUP 2023
https://indico.cern.ch/event/1199289/contributions/5262783

Will we get what we want for Christmas this year?

Dear Santa,

For Christmas we want:

Efficient light/charge collection

Cheaper isotope production

Excellent energy resolution

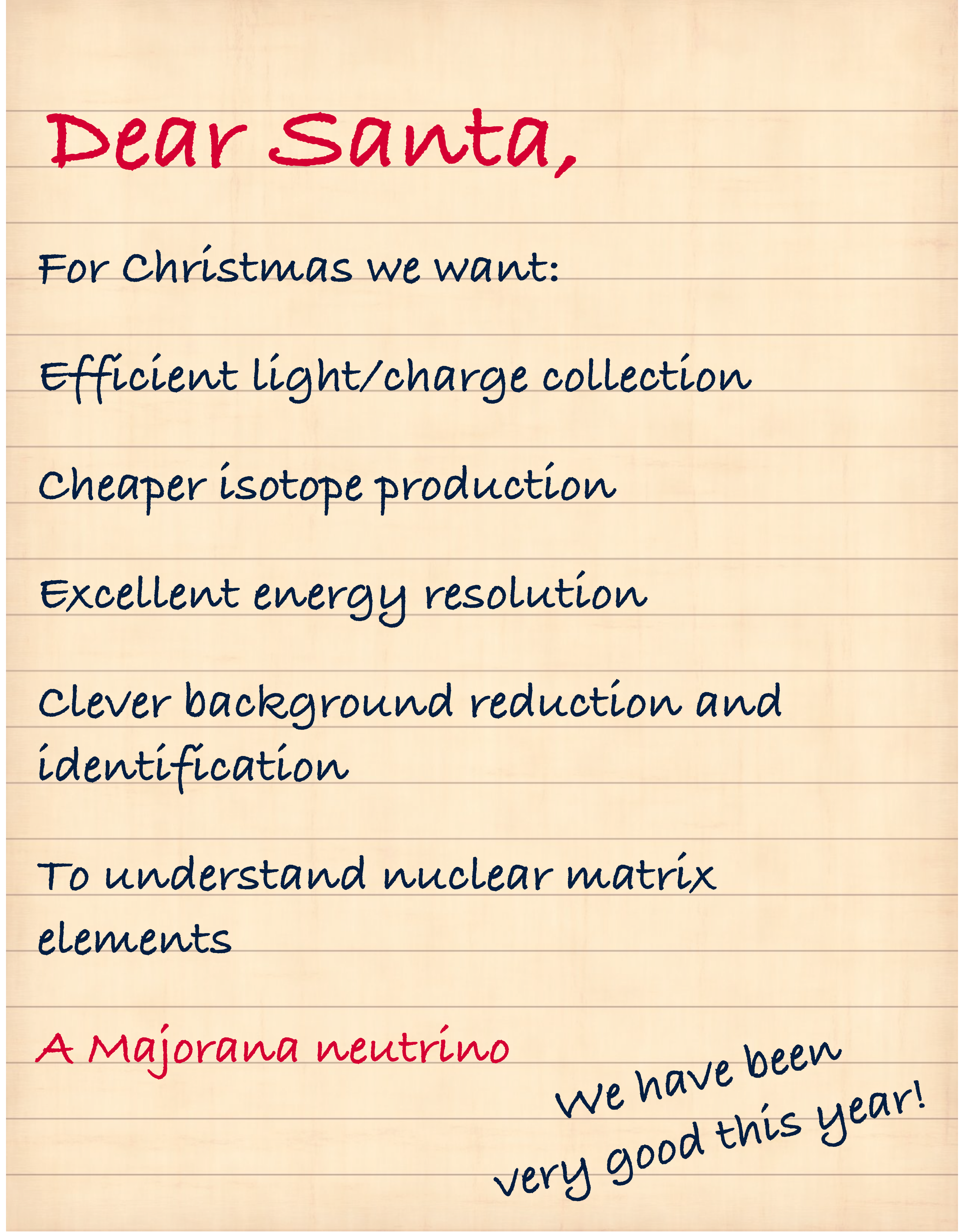
Clever background reduction and identification

To understand nuclear matrix elements

A Majorana neutrino

We have been very good this year!

Will we get what we want for Christmas this year?



Dear Santa,

For Christmas we want:

- Efficient light/charge collection
- Cheaper isotope production
- Excellent energy resolution
- Clever background reduction and identification
- To understand nuclear matrix elements
- A Majorana neutrino

We have been very good this year!

I believe in neutrinoless double-beta decay

Do you?

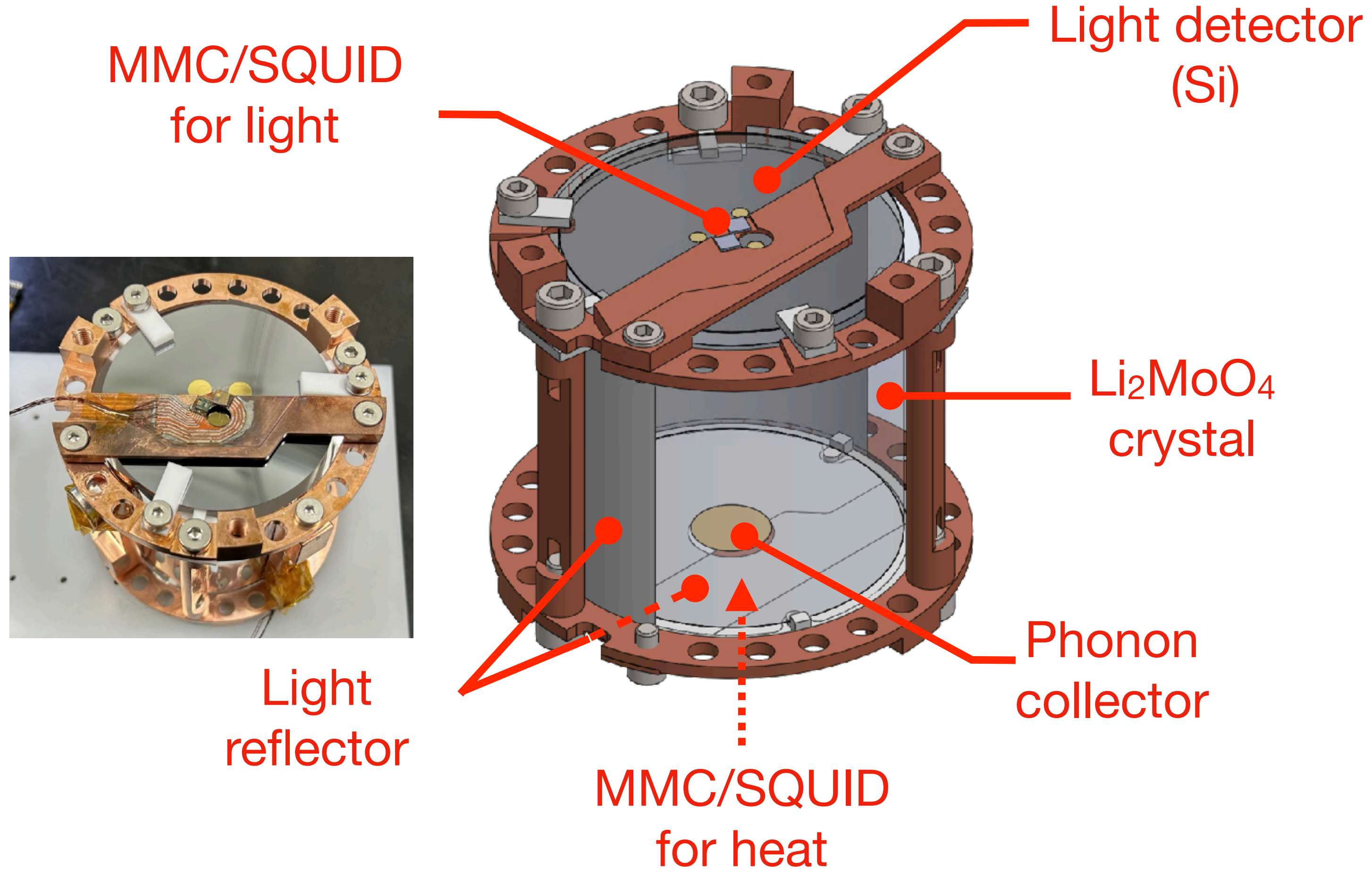
Thank you for your contributions:

AMoRE	Jeewon Seo & Yoomin Oh (Institute for Basic Science)
Aurora	Fedor Danevich (Institute for Nuclear Research, Kyiv)
BINGO	Claudia Nones (CEA Saclay)
CANDLES	S. Umehara (Osaka University)
CDEX-300v	Hao Ma (Tsinghua University)
CZC crystal R&D	Serge Nagorny (Queen's University)
KamlandZen	Azusa Gando (Tohoku University)
LEGEND	Matteo Agostini (UCL)
nEXO	Samuele Sangiorgio (Lawrence Livermore National Lab)
NEXT	Roxanne Guenette (University of Manchester)
NvDEX	Emilio Ciuffoli (Institute of Modern Physics, Lanzhou)
ORIGIN-X	Samuele Sangiorgio (Lawrence Livermore National Lab)
PandaX	Ke Han (Shanghai Jiao Tong University)
Selena	Alvaro Chavarria (Washington)
SNO+	Jeanne Wilson (King’s College, London)
ZICOS	Yoshiyuki Fukuda (Miyagi University of Education)

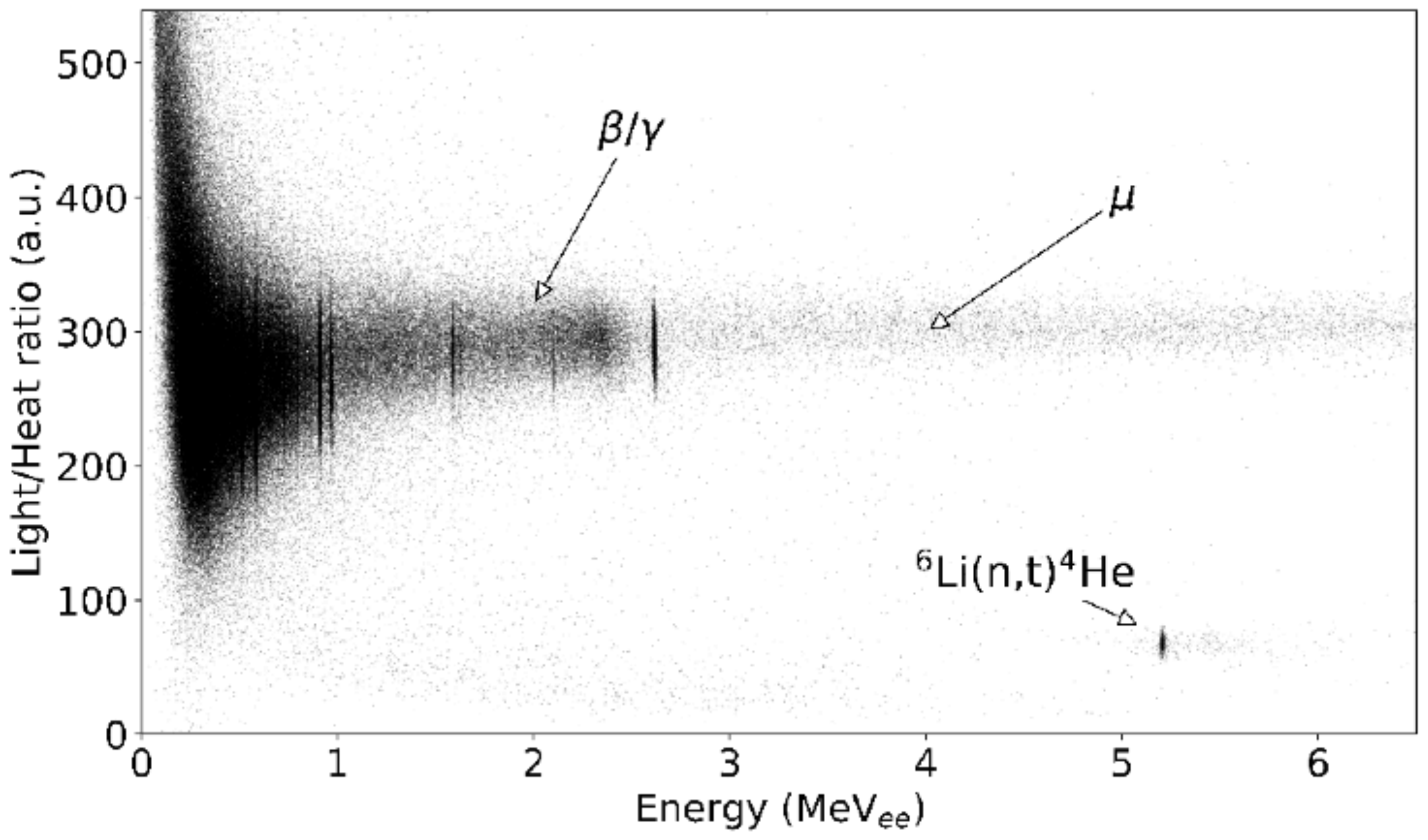
AMoRE: 0vDBD of ^{100}Mo

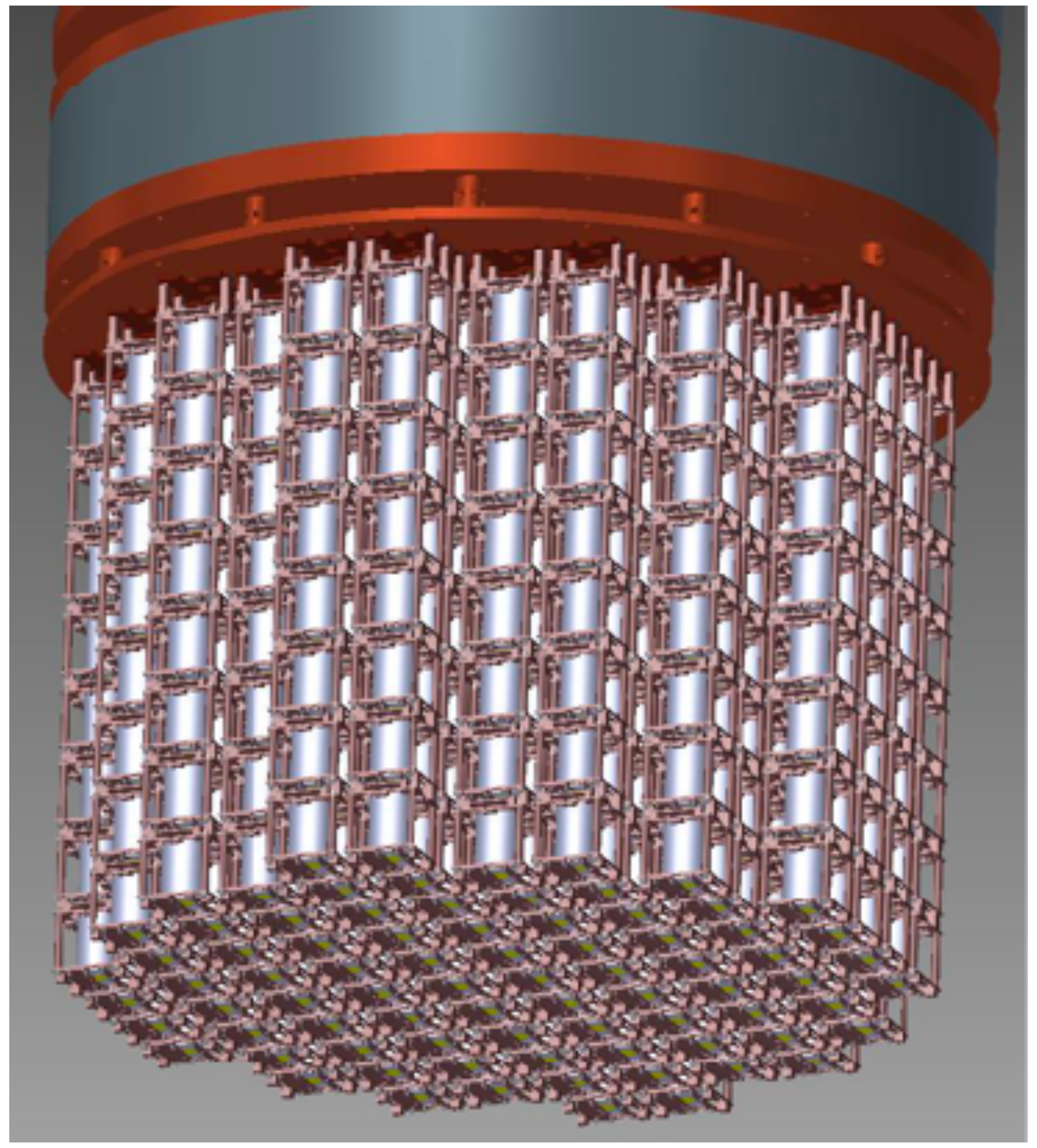
- Phonon and photon signals from $Li_2{}^{100}MoO_4$ ($^{48depl}Ca^{100}MoO_4$) crystal using MMC and SQUID at T~10 mK.
  - Discrimination of β/γ and α events.
- AMoRE-pilot and AMoRE-I completed: $T^{0\nu}_{1/2}$>3.3x10^{24} years (AMoRE-I preliminary, soon to be published).
- Preparing AMoRE-II to start its data taking in 2024.
  - Place: YemiLab, Jeongseon, Korea, 1000 m underground.
  - AMoRE-II: 157 kg of $Li_2{}^{100}MoO_4$ crystals, 5+ year data taking.
  - Background level at ROI ($Q_{\beta\beta}$=3034 keV) goal: less than 2x10^{-4} counts/keV/kg/year.
  - Projected sensitivity for the evident (3σ) 0vDBD signature: $T^{0\nu}_{1/2}$~ 4x10^{26} years.

AMoRE-II detector module



LMO detector for R&D at surface laboratory

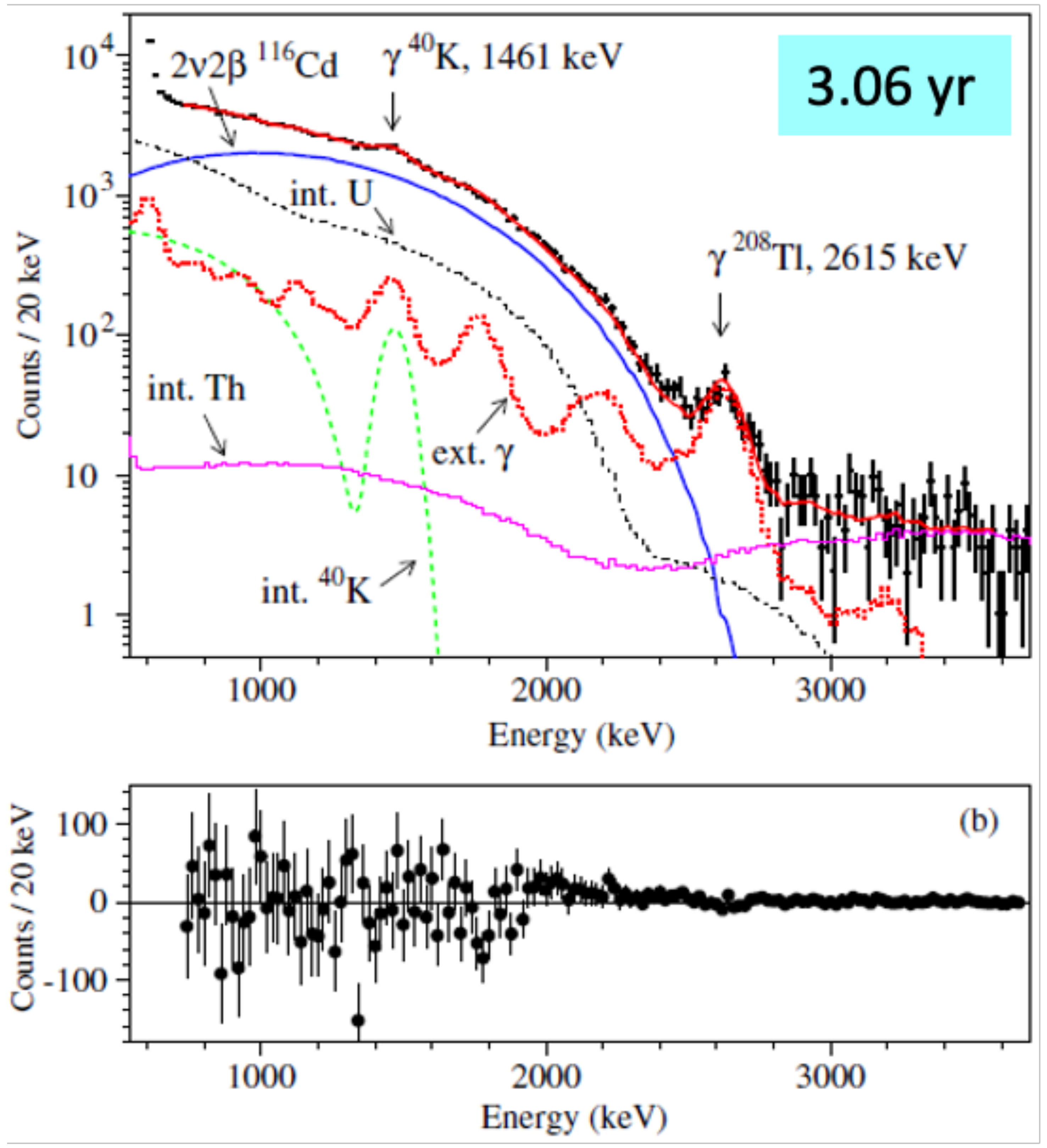


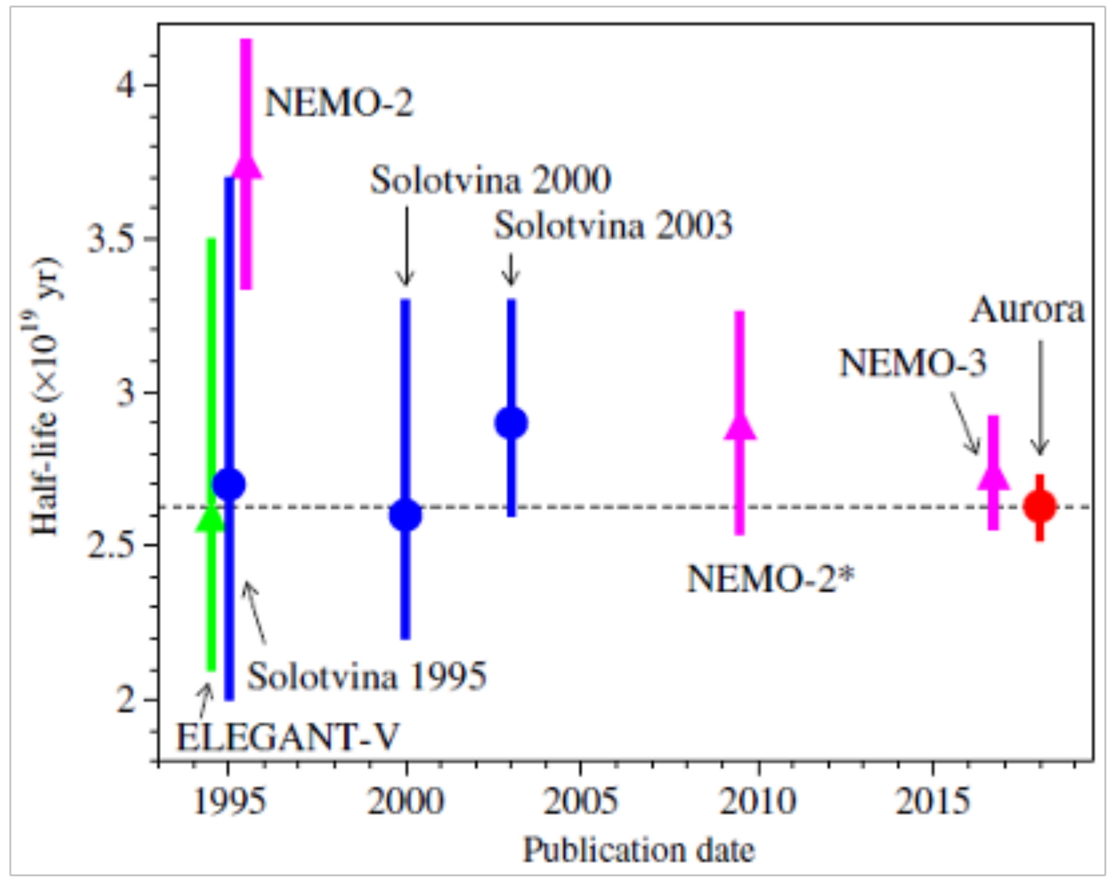


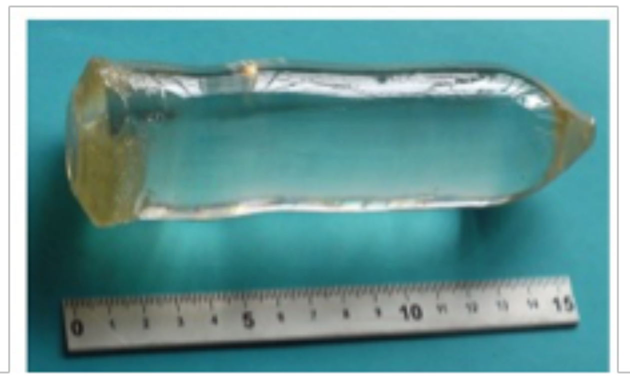
AMoRE-II detector towers

Aurora: 2β decay of ^{116}Cd

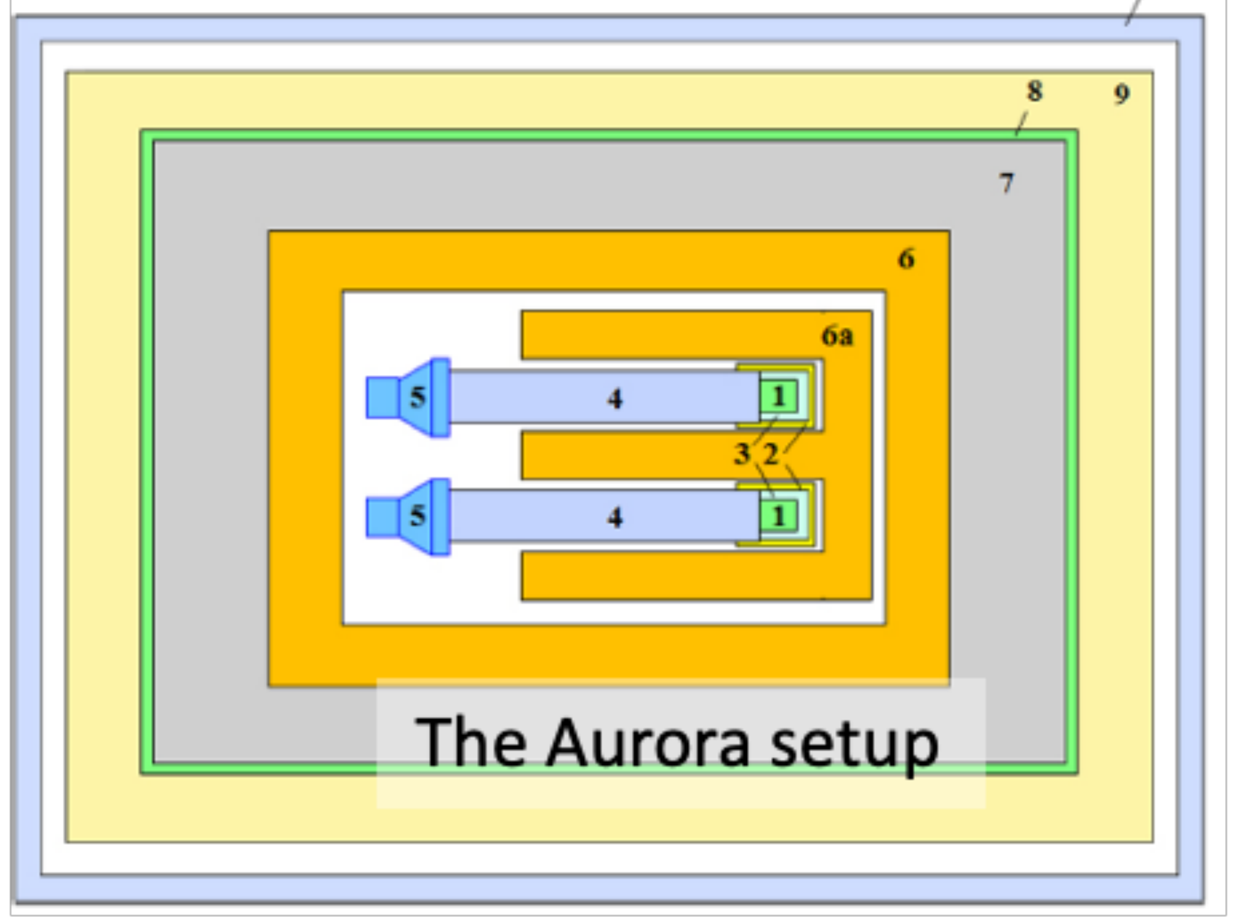
Two ^{116}CdWO$_4$ scintillators (1.16 kg) enriched to 82% [1] at the Gran Sasso UL
Energy resolution FWHM = 6%, BG ≈ 0.15 counts/(keV · yr · kg) at $Q_{2\beta}$







^{116}CdWO$_4$ crystal ≈1.9 kg



The Aurora setup

$$T_{1/2}^{2\nu2\beta} = [2.63 \pm 0.01(\text{stat})^{+0.11}_{-0.12}(\text{syst})] \times 10^{19} \text{ yr}$$

$T_{1/2}^{0\nu2\beta} \geq 2.2 \times 10^{23}$ yr, $\langle m_\nu \rangle < (1 - 1.7)$ eV

$\langle \lambda \rangle \leq (1.8 - 22) \times 10^{-6}$

$\langle \eta \rangle \leq (1.6 - 21) \times 10^{-8}$

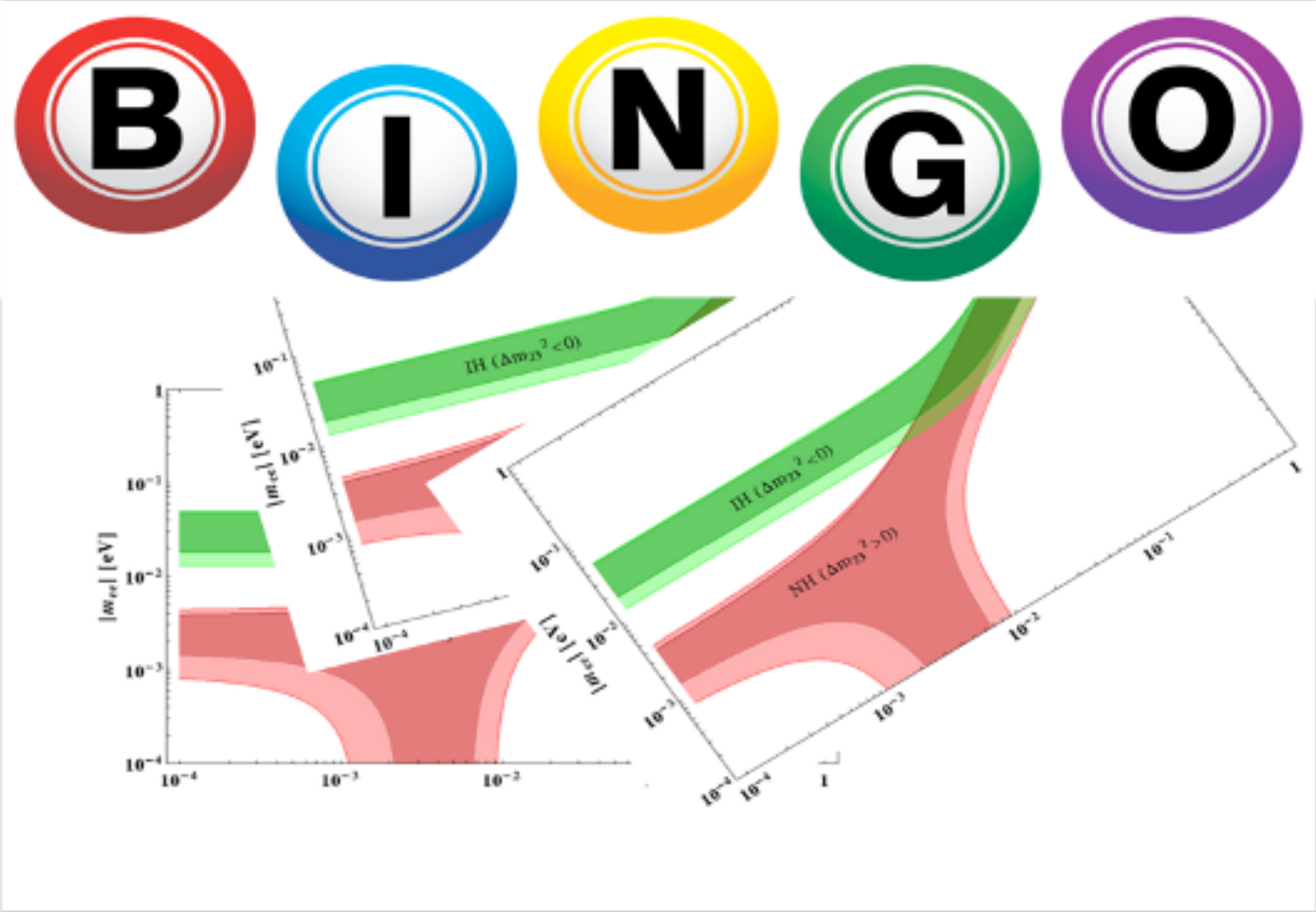
Lorentz-violating parameter $\mathring{a}^{(3)}_{\text{of}} \leq 4 \times 10^{-6}$ GeV

Limits on majorons, heavy ν, R-parity violating parameter, 2β to excited states [2]

[1] JINST 06 (2011) p08011
[2] PRD 98 (2018) 092007

BINGO:

Bi-Isotope $0\nu2\beta$ Next Generation Observatory



Investigation of the Majorana nature of neutrinos at a few meV level of the neutrino mass scale

The goal of BINGO

- BINGO will set the grounds for a large scale bolometric experiment searching for neutrinoless double-beta decay (0v2β) using revolutionary technologies
- It aims to reduce dramatically the background in the region of interest, through:

A revolutionary detector assembly:

- Reduce the Cu material seen by the main absorber → reduction of the total surface radioactivity contribution
- Having a compact assembly → anticoincidence cuts

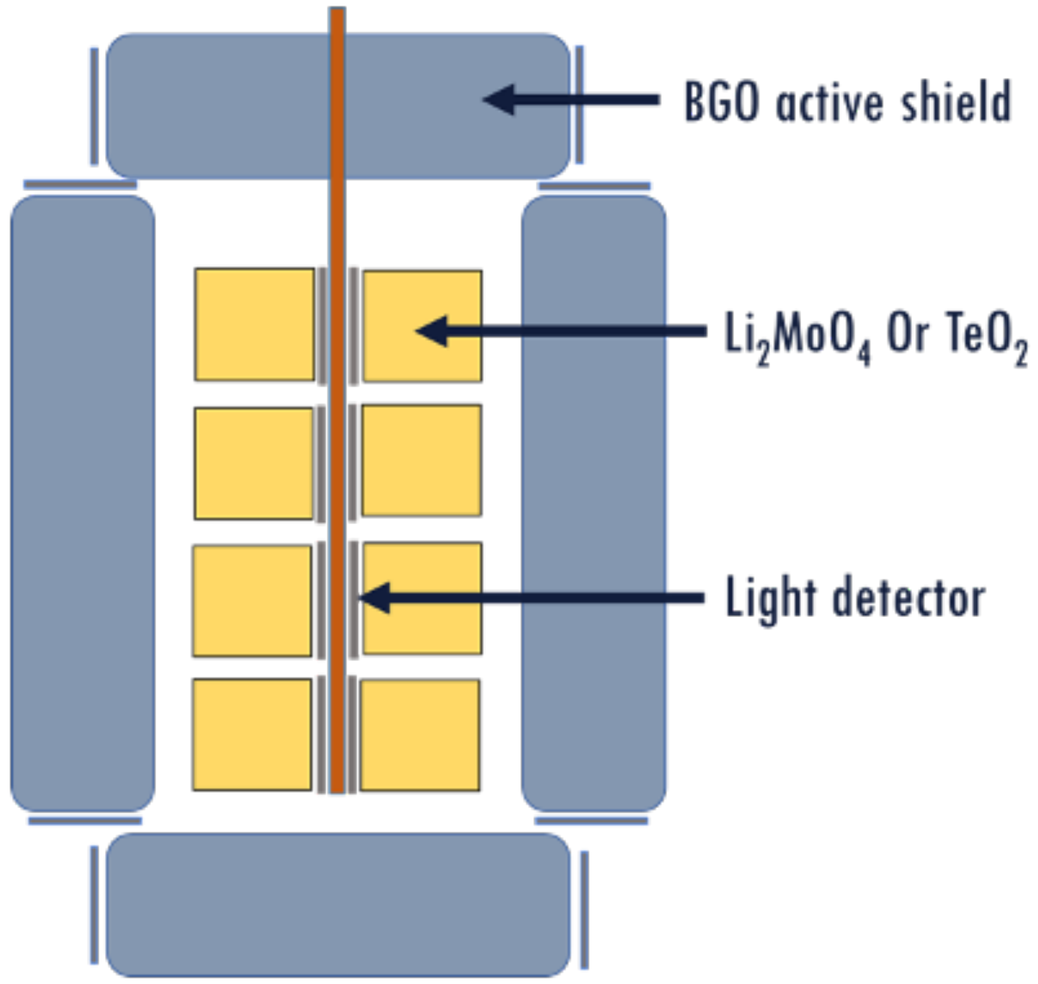
Neganov-Luke light detectors:

- Amplification of the tiny Cherenkov signal (TeO_2) → suppress alphas
- Higher sensitivity, lower energy threshold → suppress external γ background using the active shield

An active shield based on BGO scintillators:

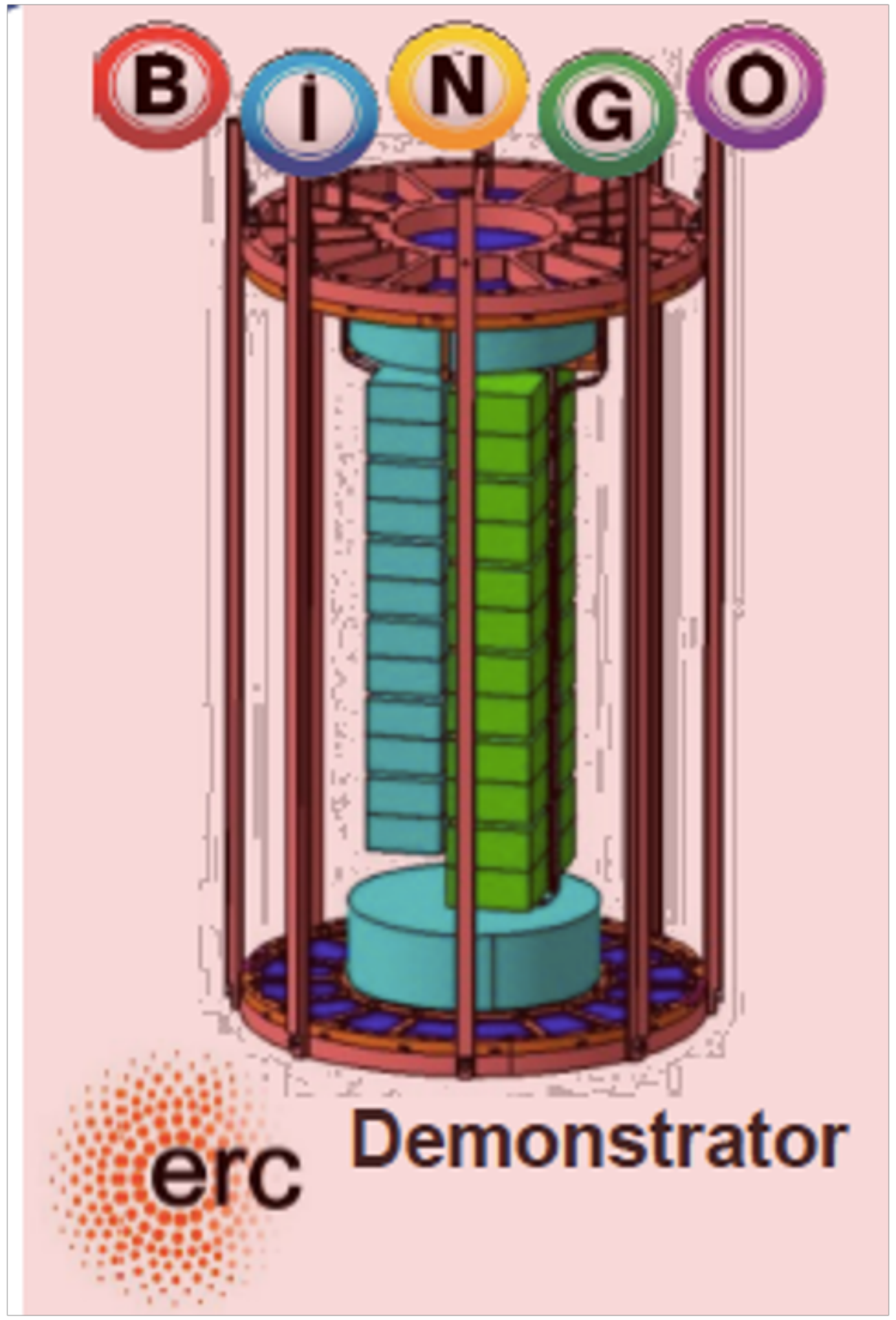
- Suppress the external gamma background (specifically essential for TeO_2)

Bi-Isotopic approach: observation in 2 candidates → discovery + confirmation



The first step: MINI-BINGO underground

MINI-BINGO is the **demonstrator** of the BINGO technology in a dedicated **underground cryostat at LSM**



Small-scale validation of all the BINGO elements

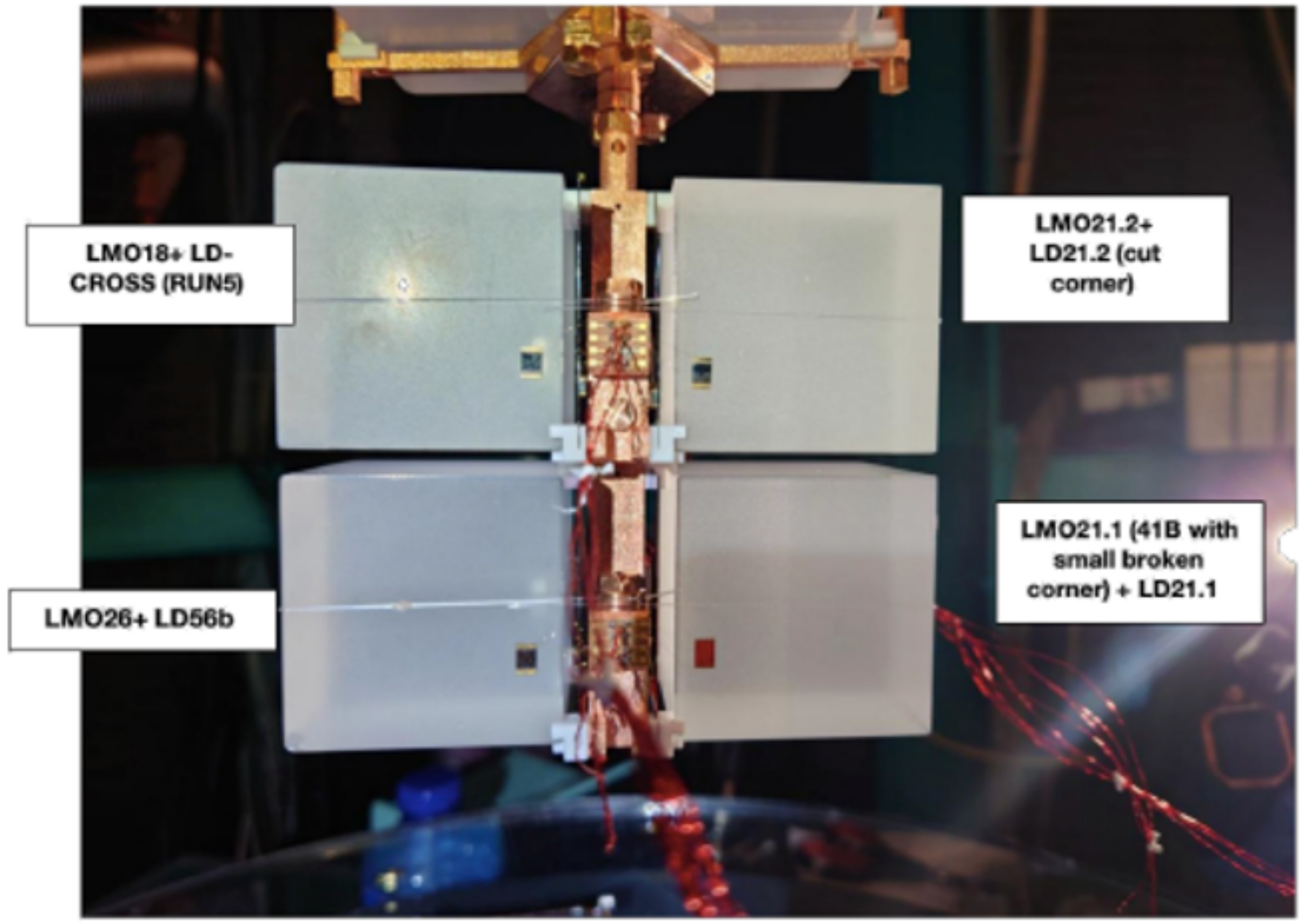
- ☐ 2 isotopes: ^{100}Mo and ^{130}Te
- ☐ 2 towers of 12 crystals each
- ☐ Crystals will see nothing else that is not active
- ☐ BGO crystals for an active cryogenic veto
- ☐ Neganov-Luke light detectors

Scale high enough to demonstrate
$b \leq 10^{-4}$ in **1 y data taking**
Pave the way to **BINGO**

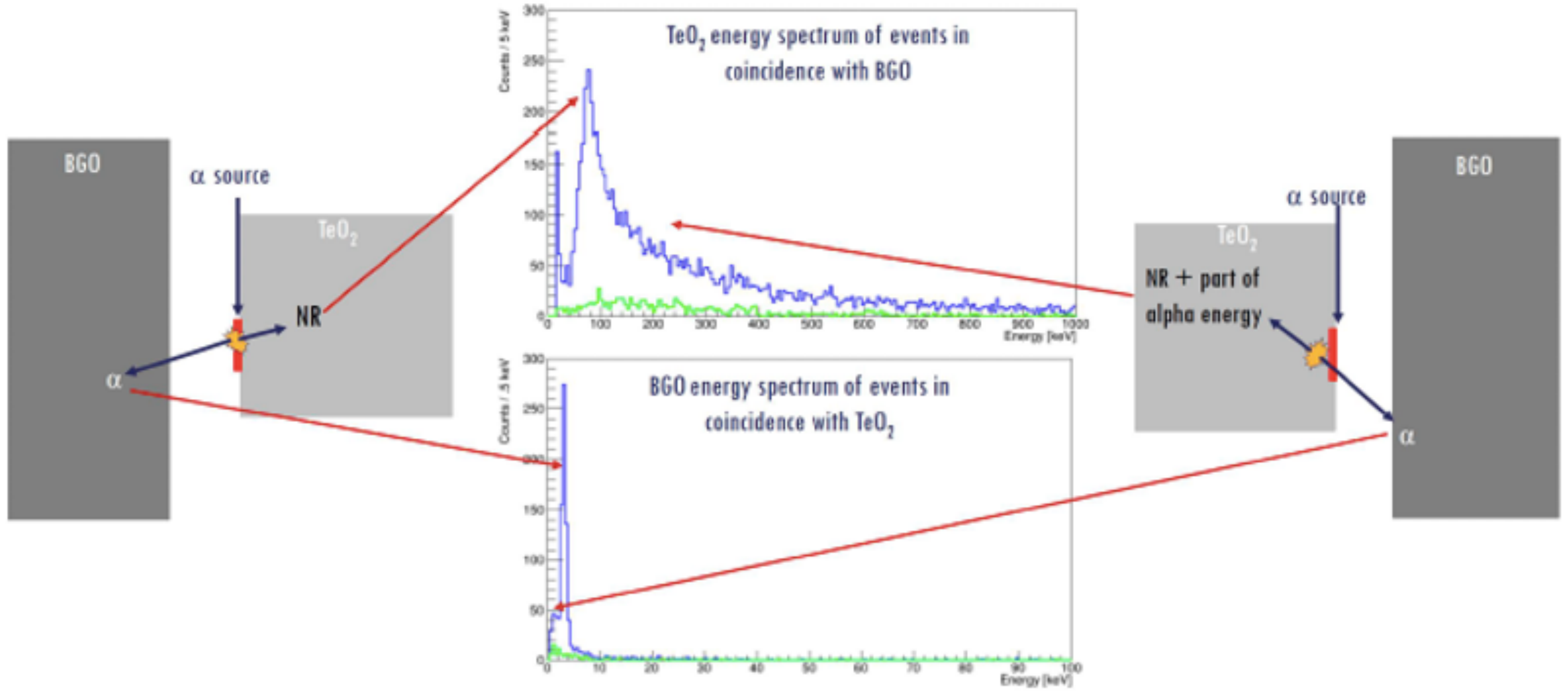
Prototype tests

New nylon-wire assembly

Operated two detector modules (4 Li_2MoO_4 + 4 Ge LDs) at the Canfranc underground laboratory (CROSS)

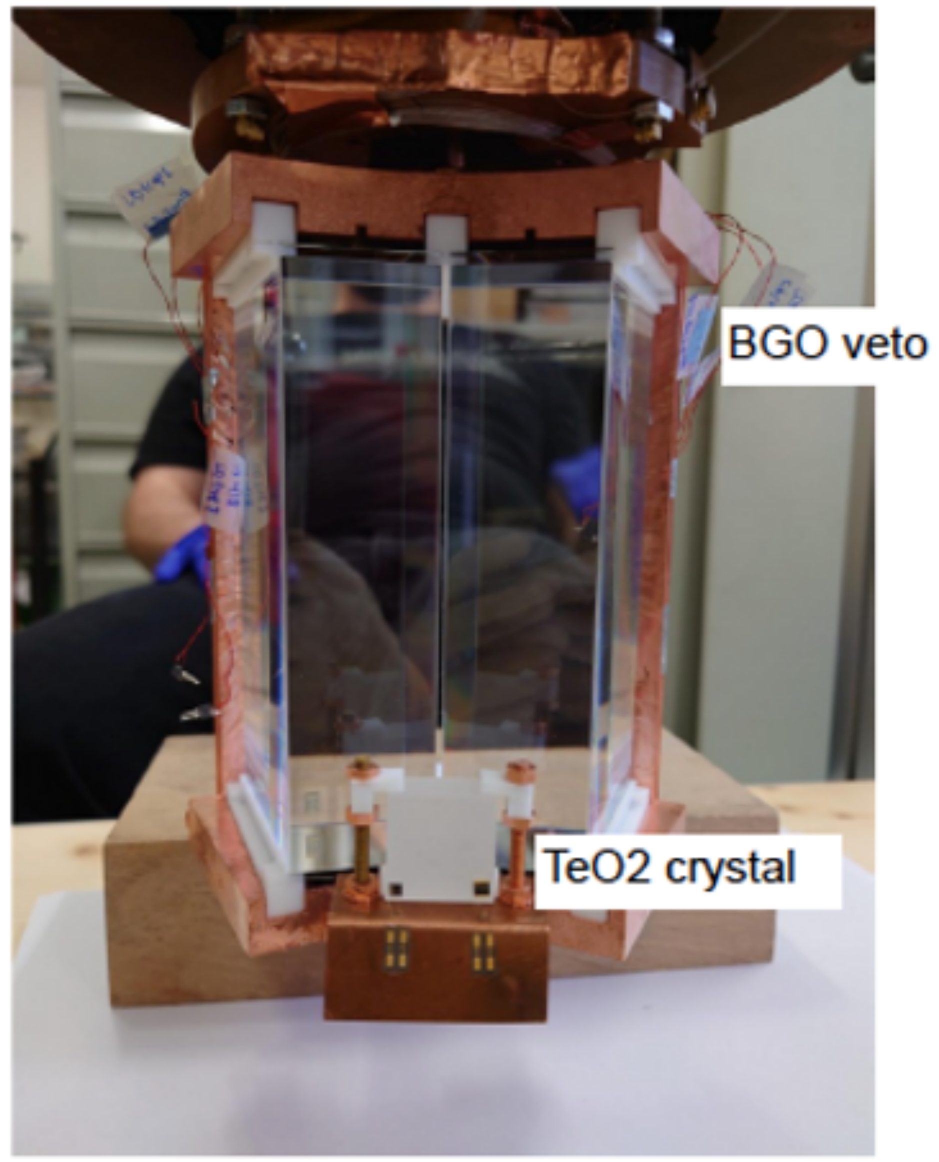


Validated stability against thermal cycling, energy resolution ~2 keV Baseline, O(5) keV at 2615 keV and light yield 0.25 keV/MeV for alpha discrimination



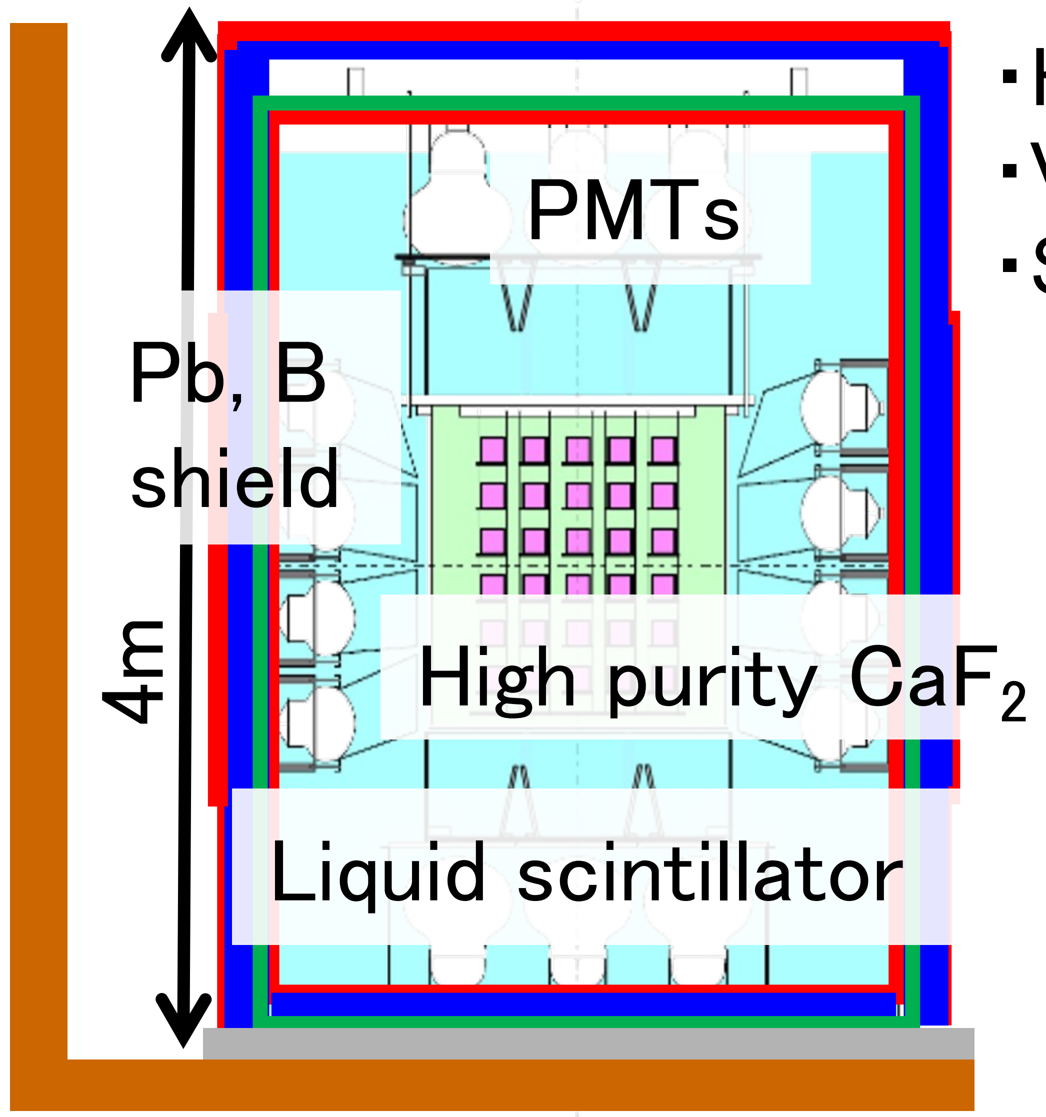
Require: 50 keV threshold in BGO veto
BGO light yield: ~ 7 keV/MeV for beta/gamma
—> Target a 0.3 keV threshold: well in range for NTL light detectors

First cryogenic veto test with BGO

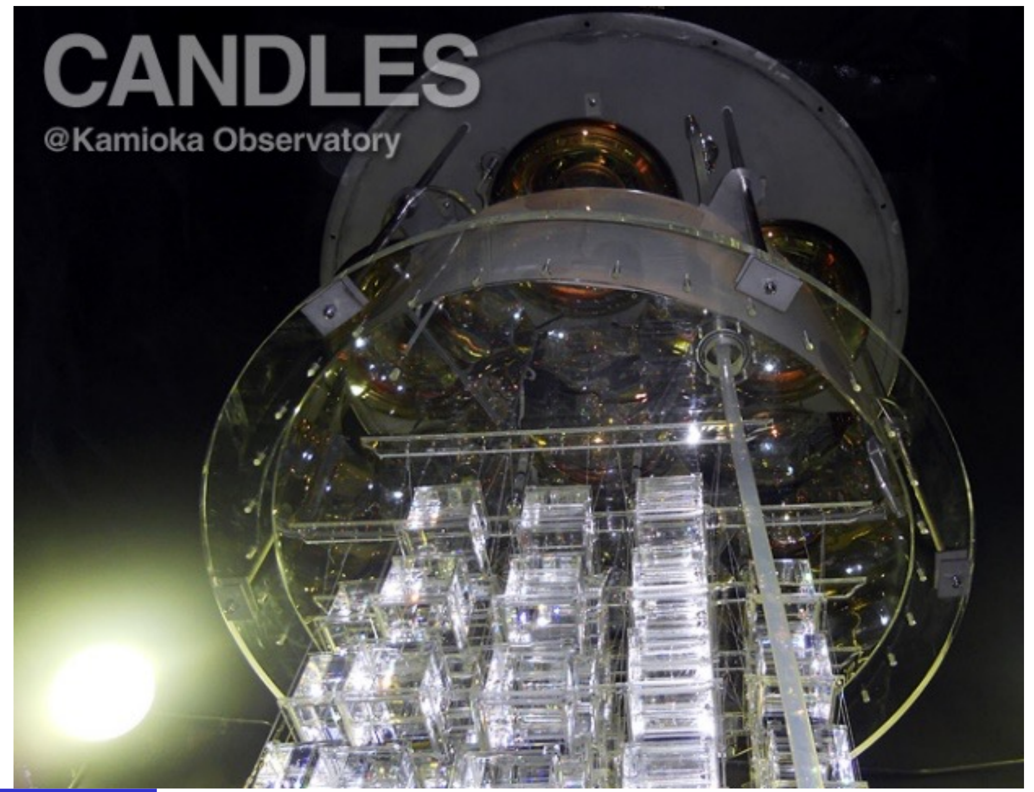


CANDLES III

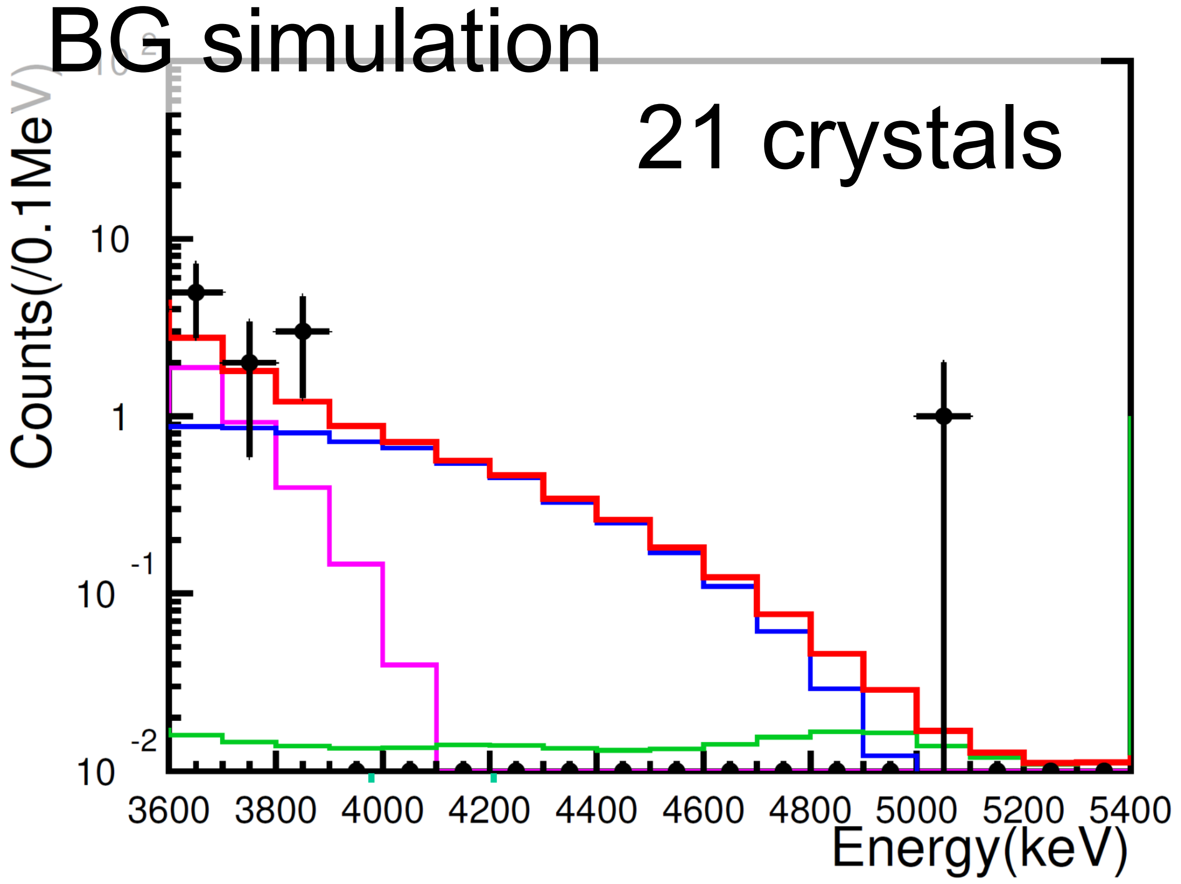
CANDLES III @ Kamioka Lab.

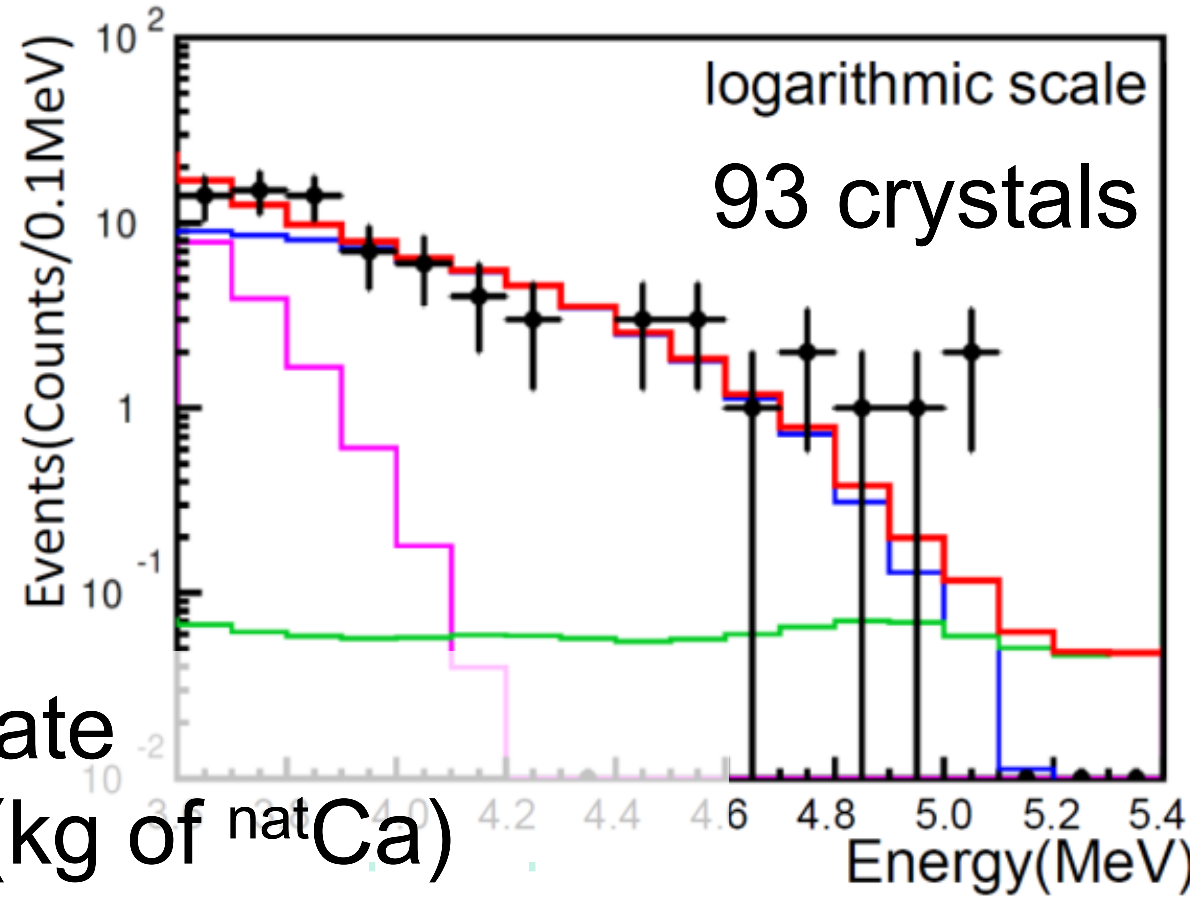


- High purity CaF_2
- Veto system by liquid scintillator
- Shielding system for γ, n



Energy spectrum and BG simulation





	result
Num. of eve.	0
Expected BG	1.02
Half life of ^{48}Ca	$>5.6\times10^{22}$y
Sensitivity	2.8×10^{22}y

*Achieved background rate
< 10^{-3} events/keV/year/(kg of ^{nat}Ca)
comparable to lowest background level

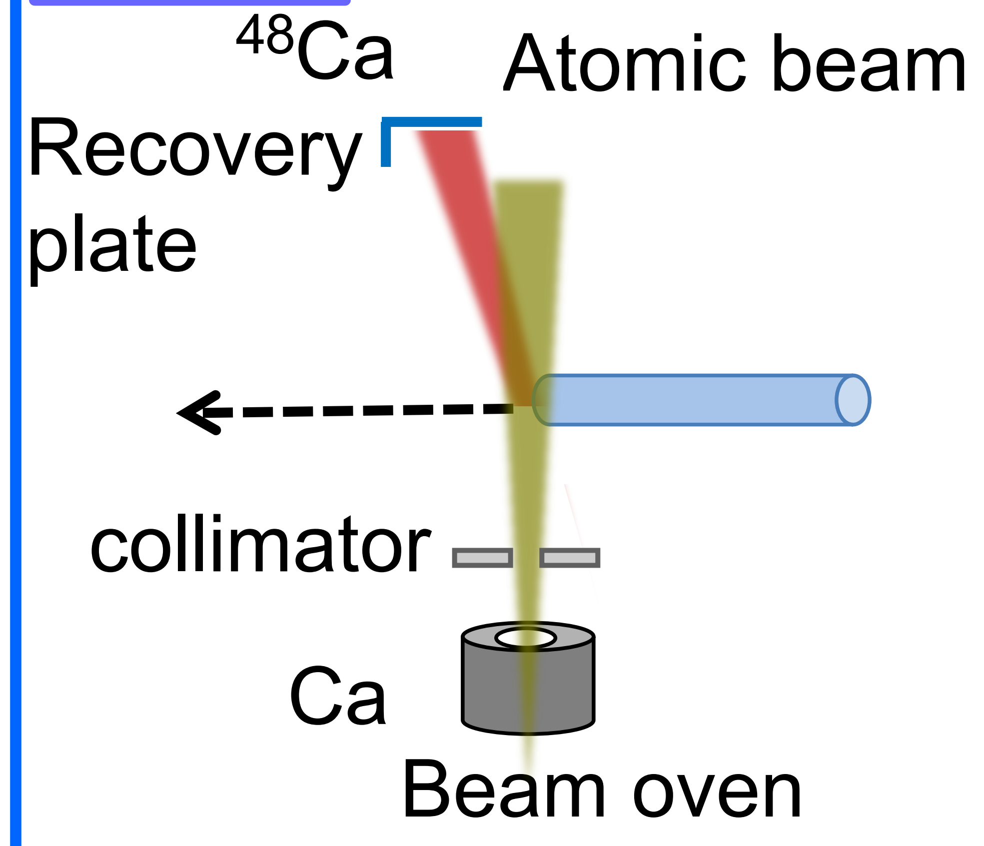
Ref : Phys. Rev. D103, (2021), 092008

Development for next detector system

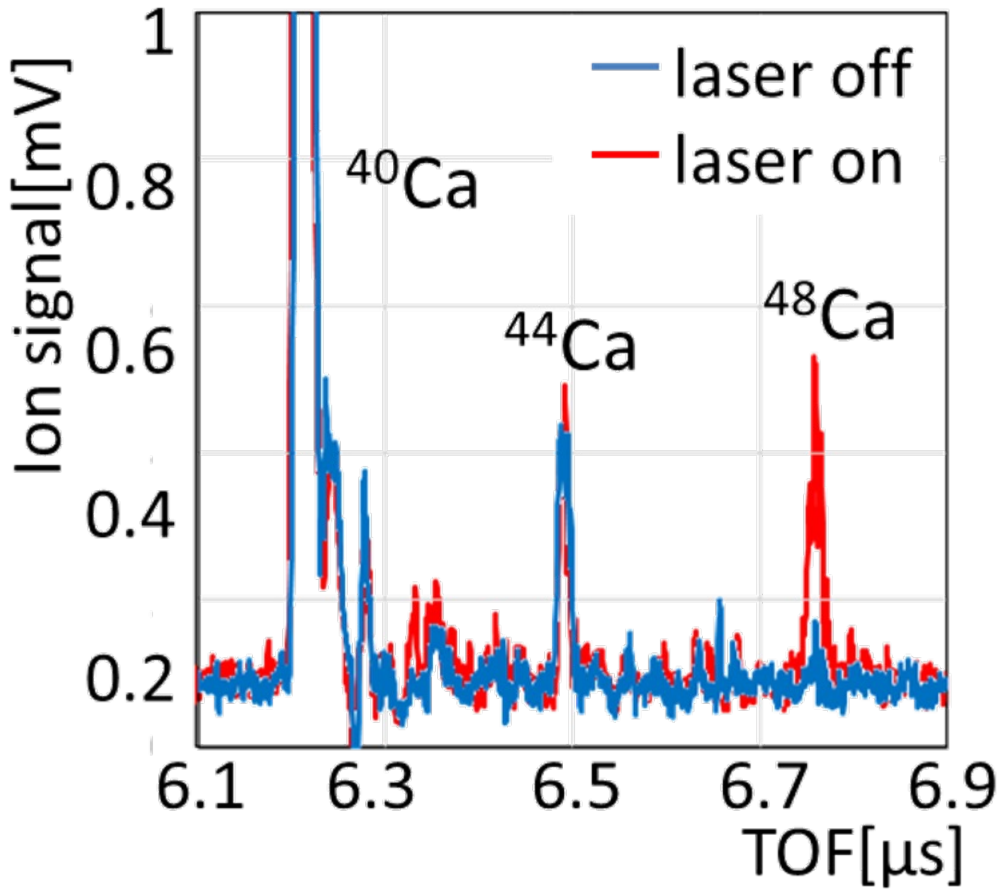
For sensitivity of < 10meV

^{48}Ca enrichment by LIS

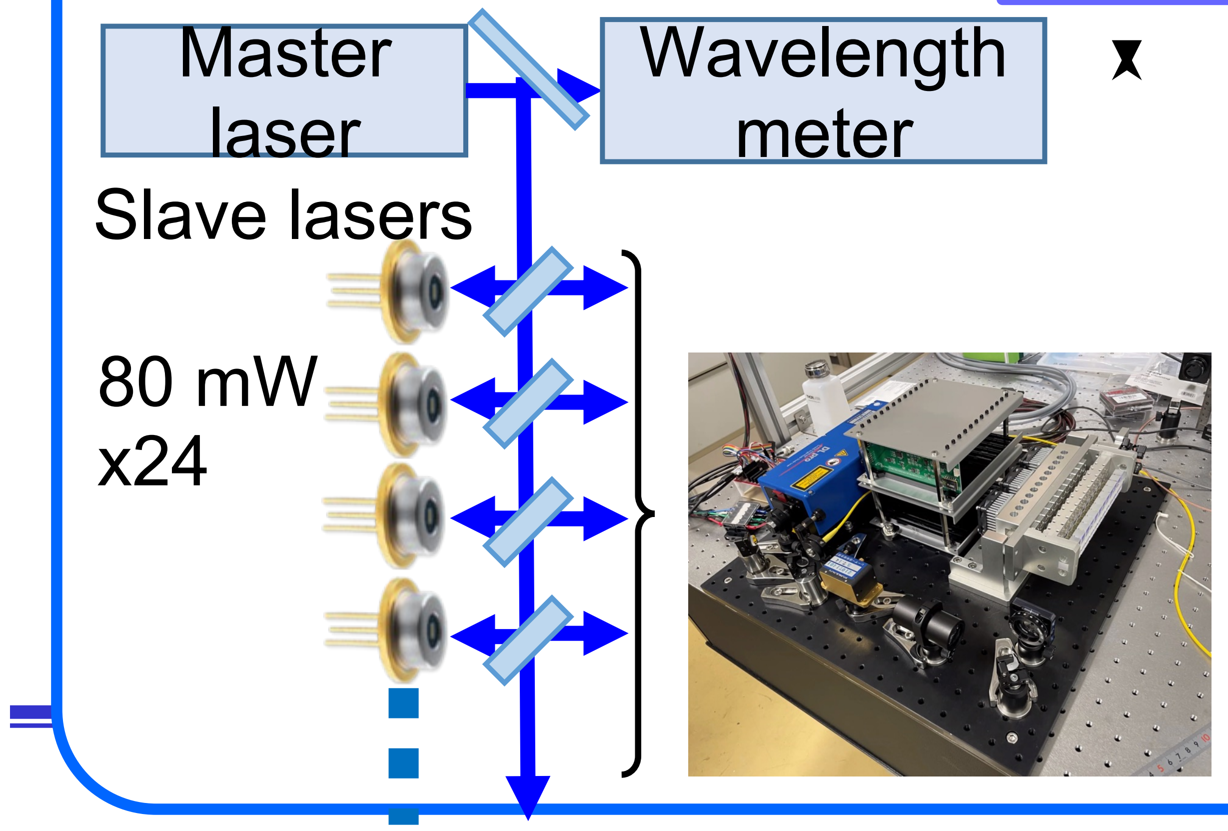
Setup



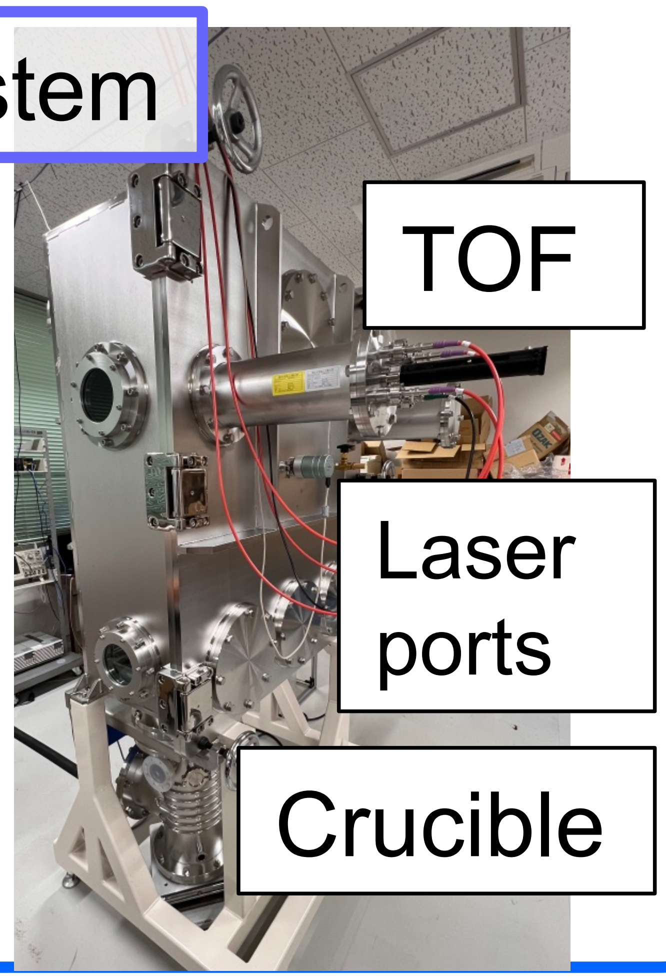
principle experiment



New laser system

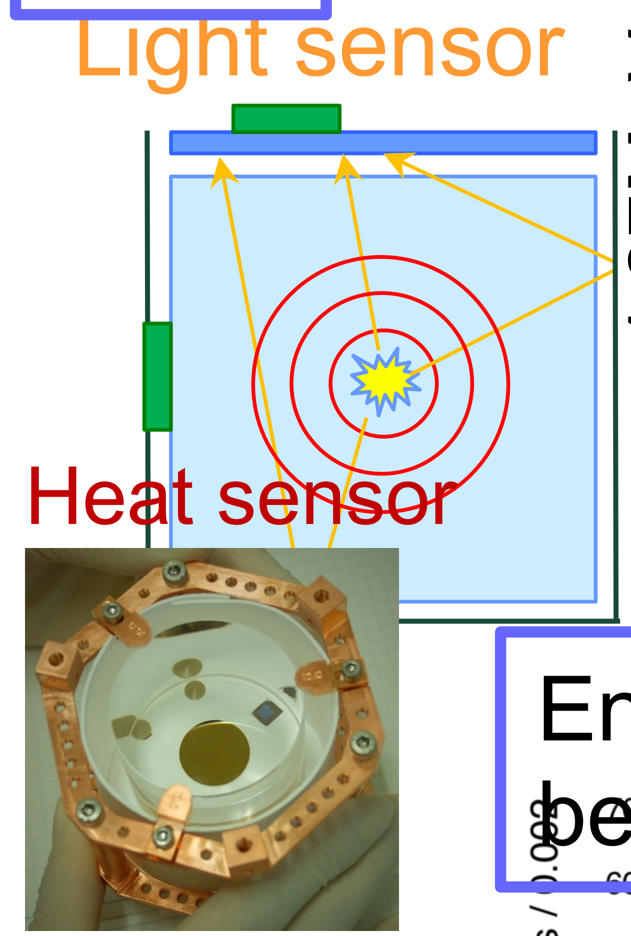


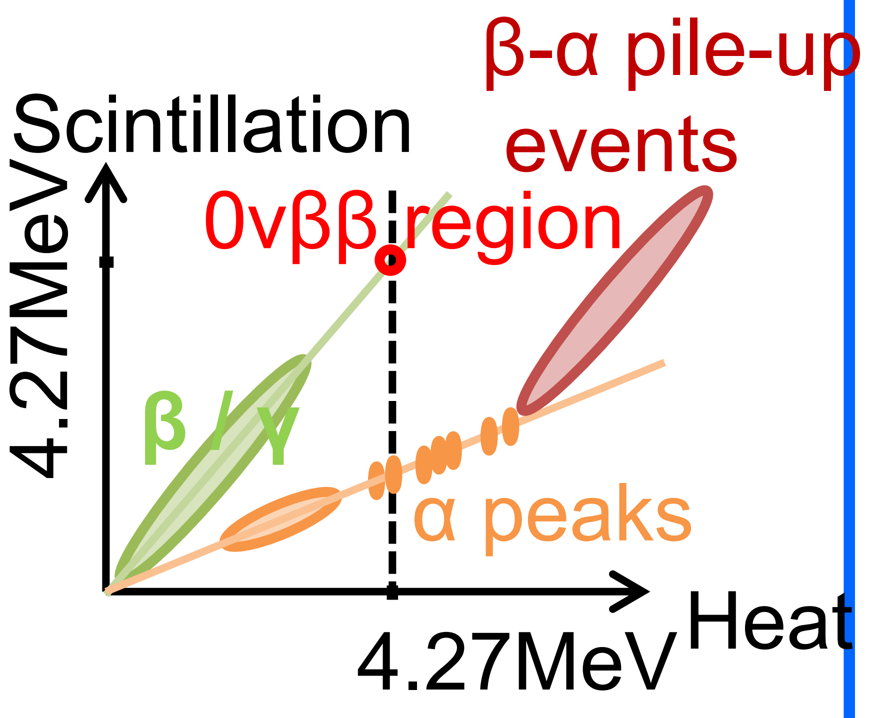
LIS system



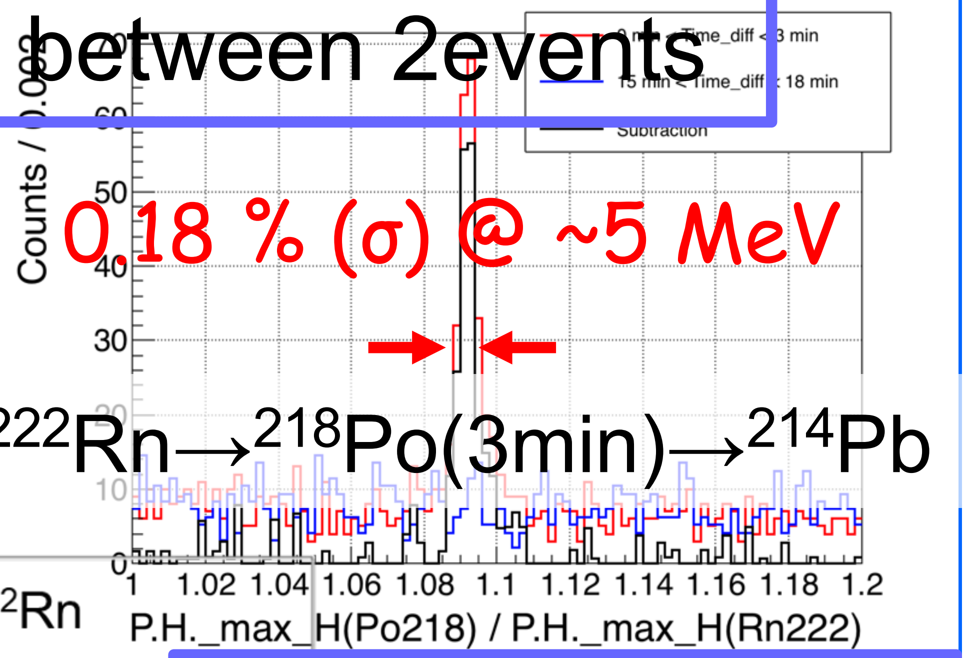
CaF$_2$ scintillating bolometer

Setup



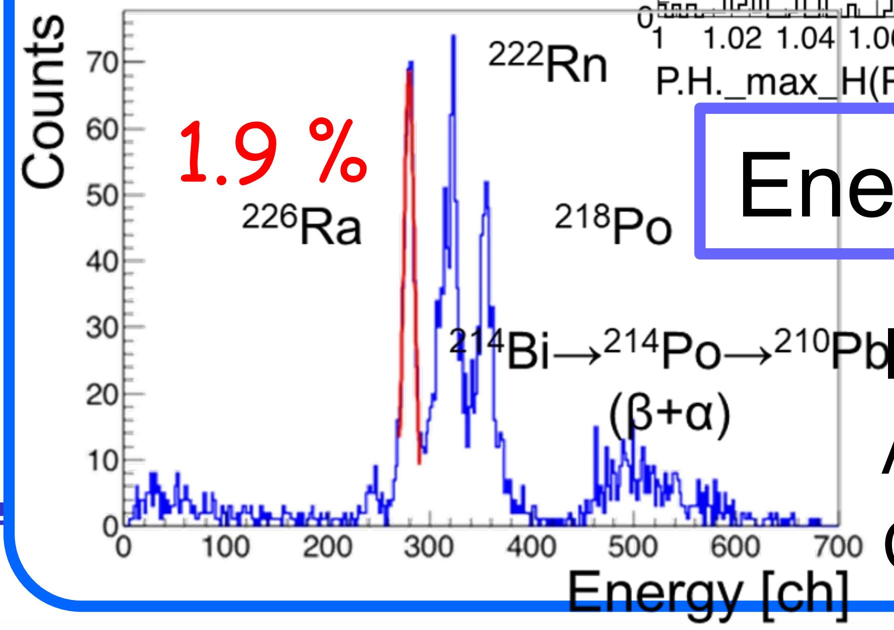


Energy ratio between 2events



^{222}Rn→^{218}Po(3min)→^{214}Pb

Energy resolution

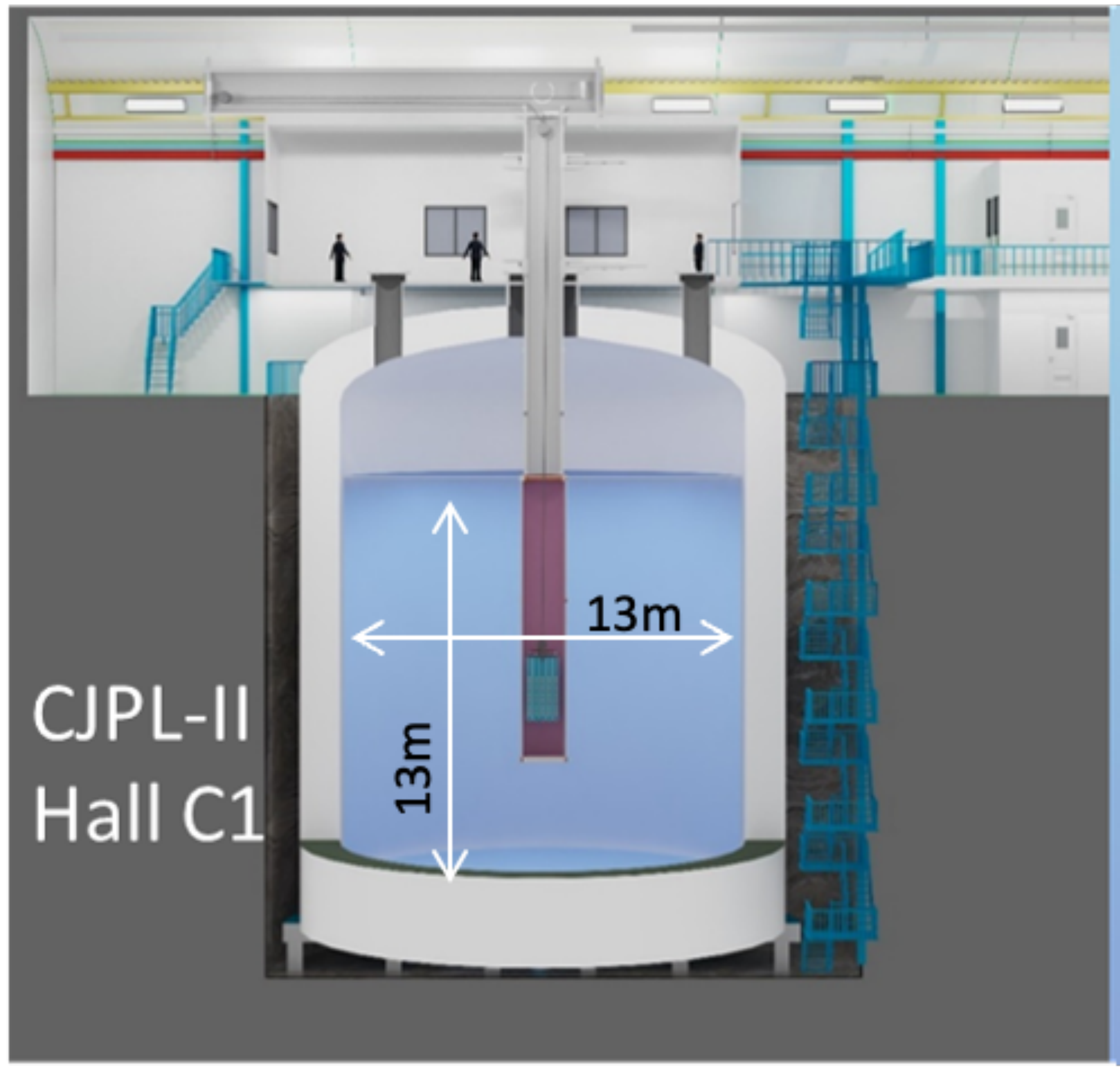


IBS Kim Yong-Hamb
AMoRE sub group
CANDLES sub grou

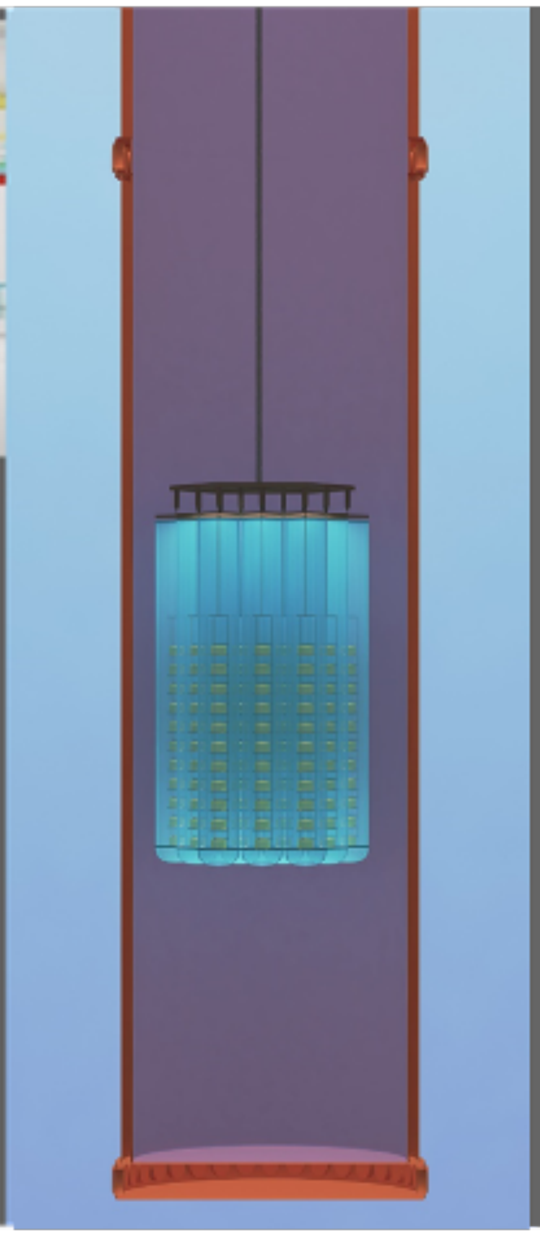
CDEX-300ν pre-Conceptual Design

Overview

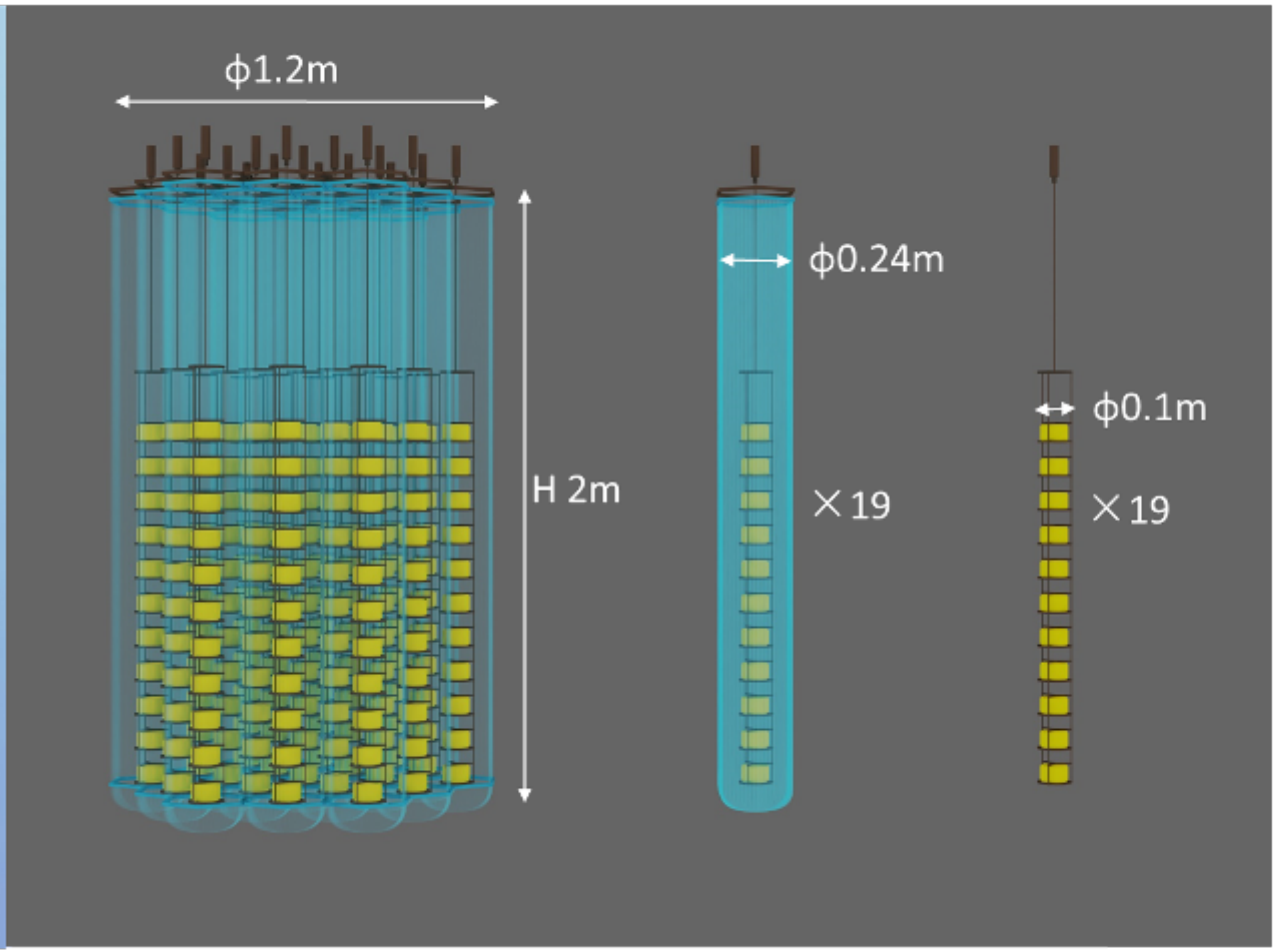
- LN_2 tank shared with CDEX-50 (Dark Matter detection)
- Reentrant tube containing LAr submerged in LN_2
- Ge detector array immersed in LAr (veto) tube
- Ge detectors divided into 19 strings (10-11 det/string, 200 in total)



1725 m³ Liquid Nitrogen



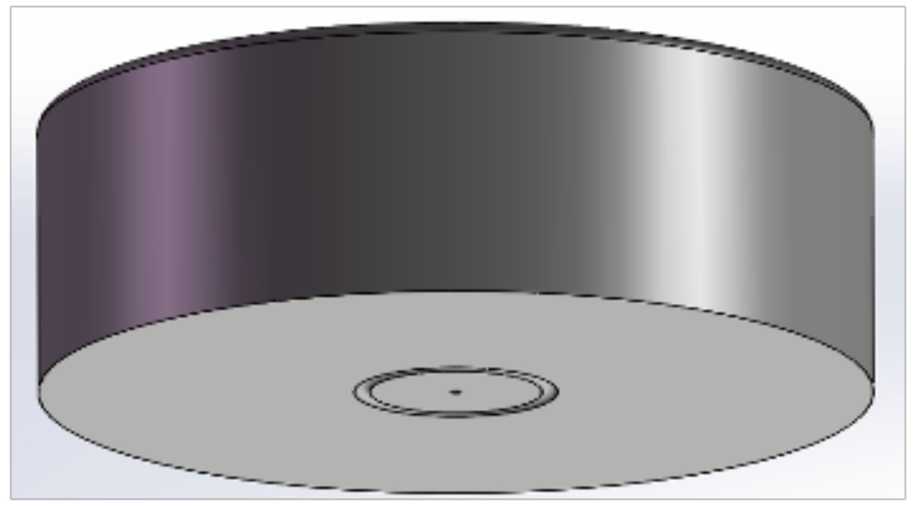
LAr tube



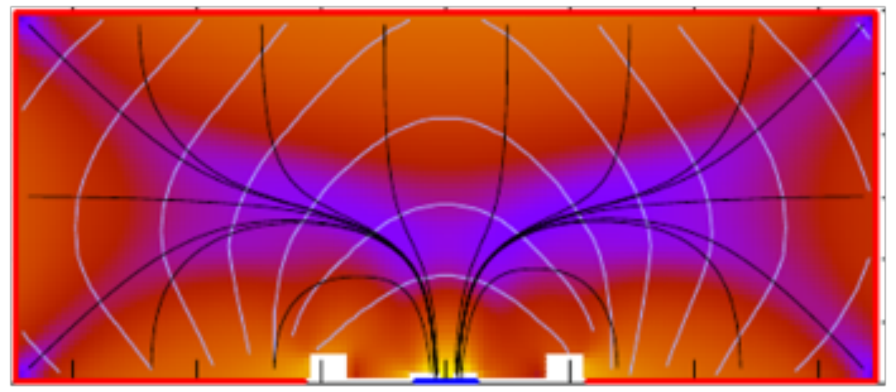
Enriched Ge array

Ge detectors

- **Enriched BEGe (Baseline)**
  - Mass: 1-1.2 kg； Ge-76 > 86%
  - Size: φ80×40 mm
  - Dead layer: 0.6 mm
  - FWHM : <0.15% @2MeV (~2.5keV)
  - Commercial / Home-made

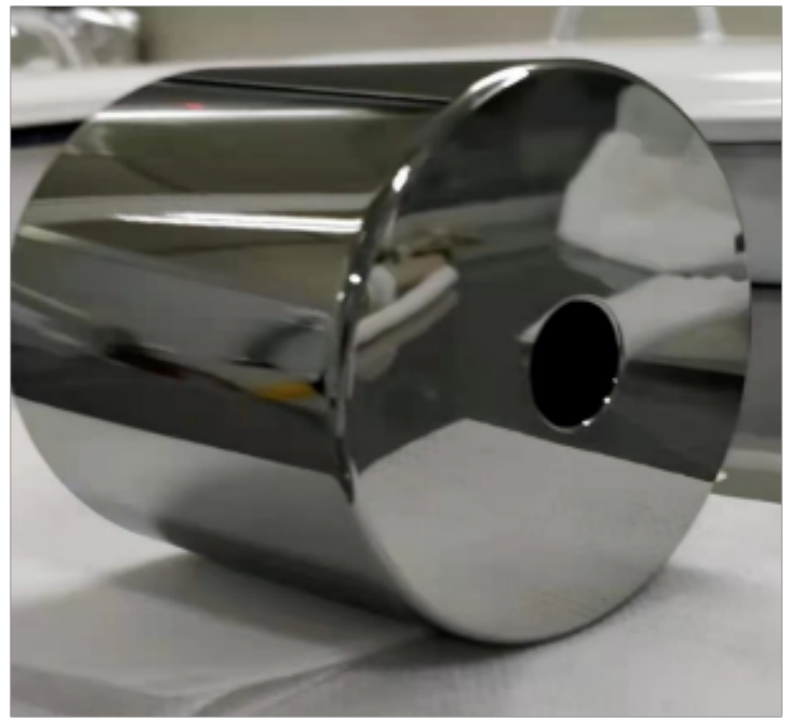


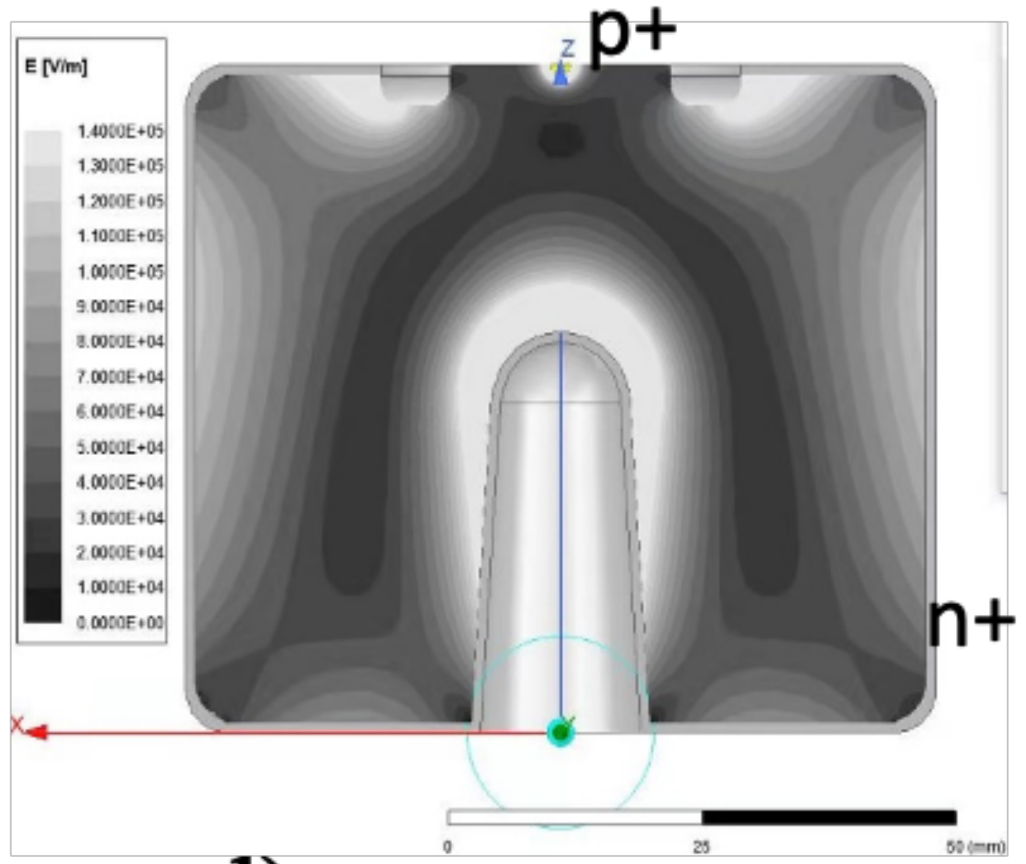
BEGe: Broad Energy Germanium



- **ICPC (optional)**
  - Mass: ~2 kg
  - Size: φ80×80 mm
  - Dead layer: 0.6 mm
  - Home-made
  - Bigger Detector → Less Electronics (background)

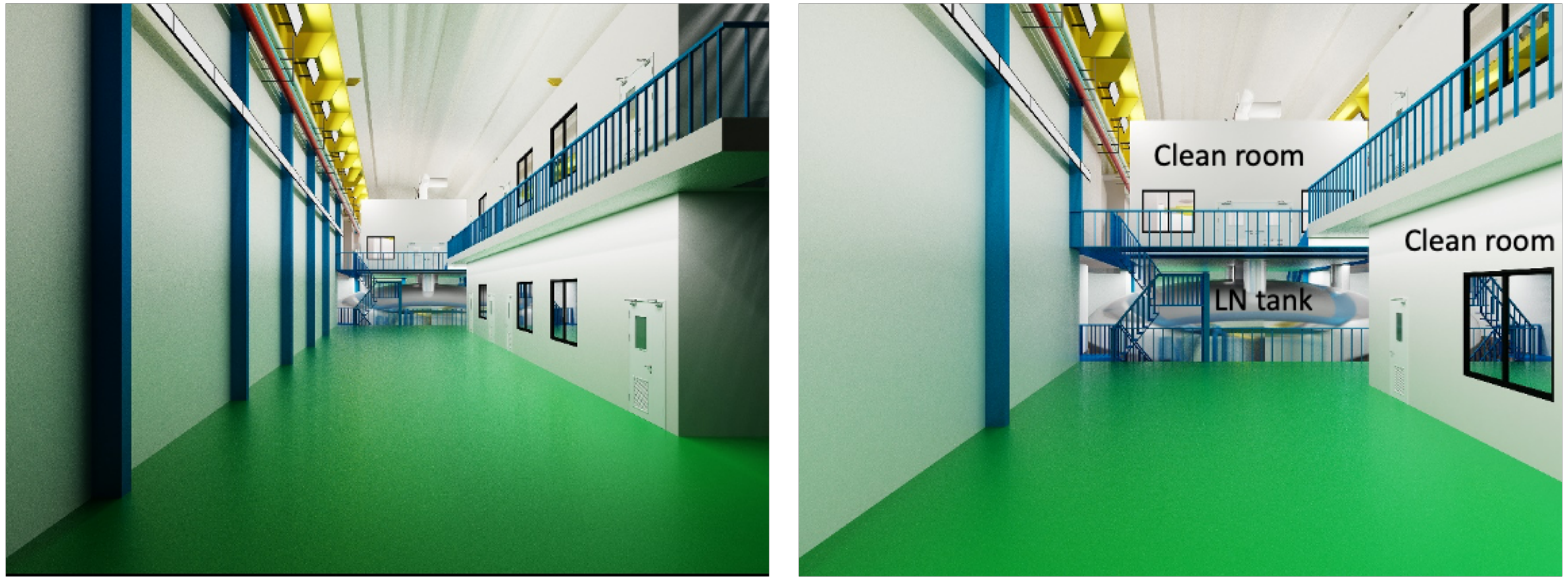
ICPC: Inverted Coaxial Point Contact





CDEX-300ν Plan

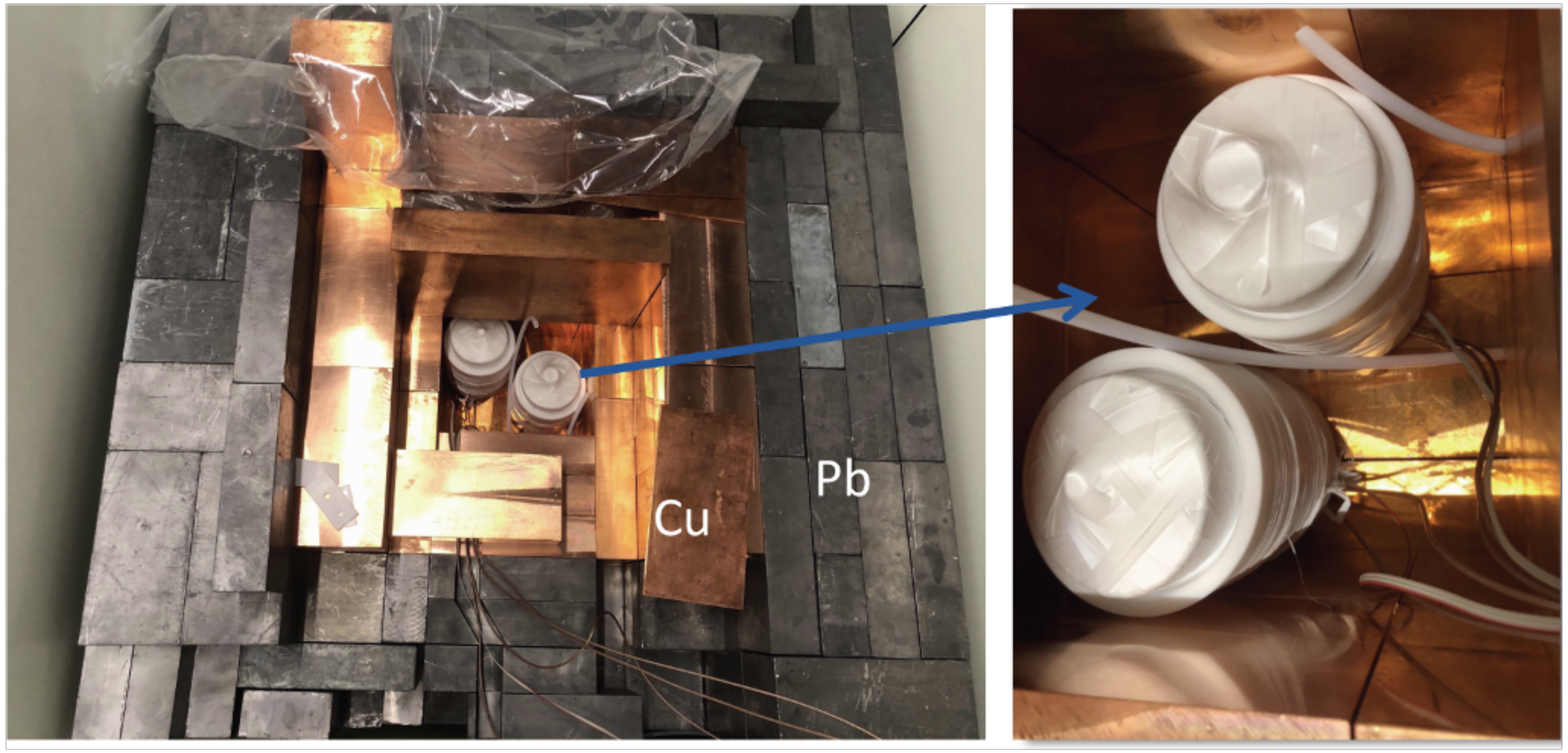
- Enr-Ge detectors test started in 2022 @ CJPL-I
- Test and operate LAr test facility in early 2024
- Hall C1 expected to be ready for experiment this Dec.
- Experimental setup in 2024
- First batch of Ge detector installation and test in 2024



Hall C1 of CJPL-II

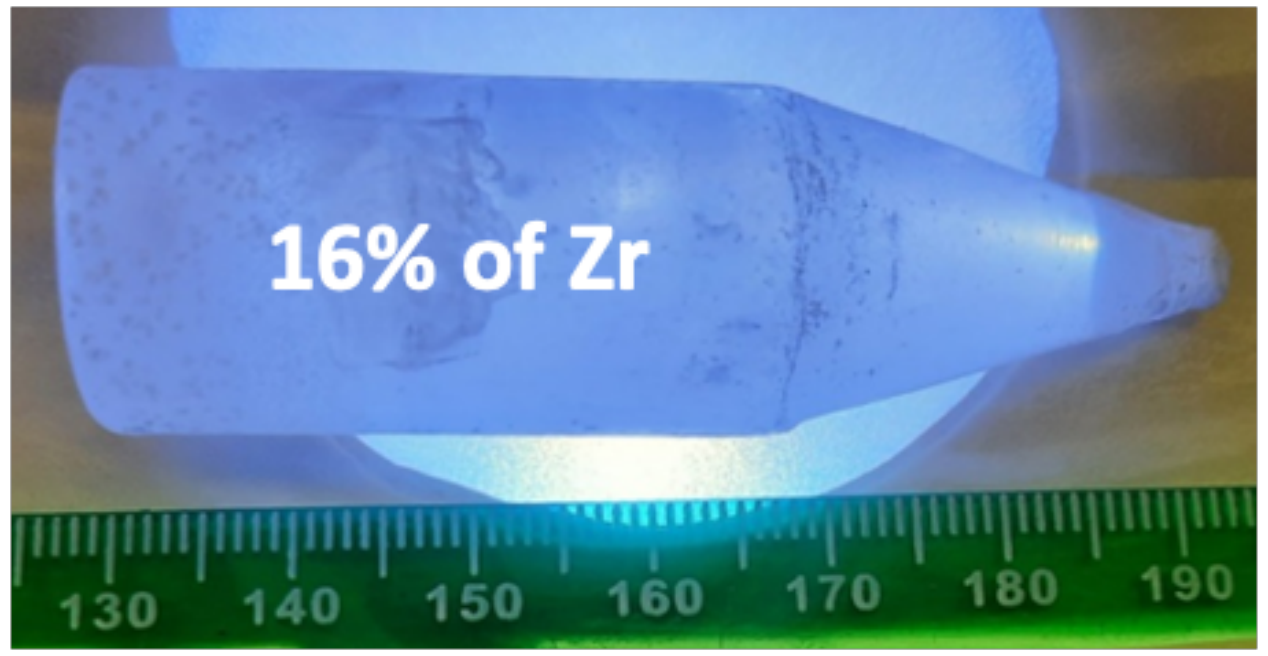
Low-background measurements of Cs_2ZrCl_6 at LNGS (Italy)

DAMA/CRYS low-background setup at LNGS



- OFHC Cu (15 cm)
- Low-activity Pb (20 cm)
- HDPE (5 cm)
- Borated HDPE (5cm)

Cs_2ZrCl_6: a novel crystal scintillator



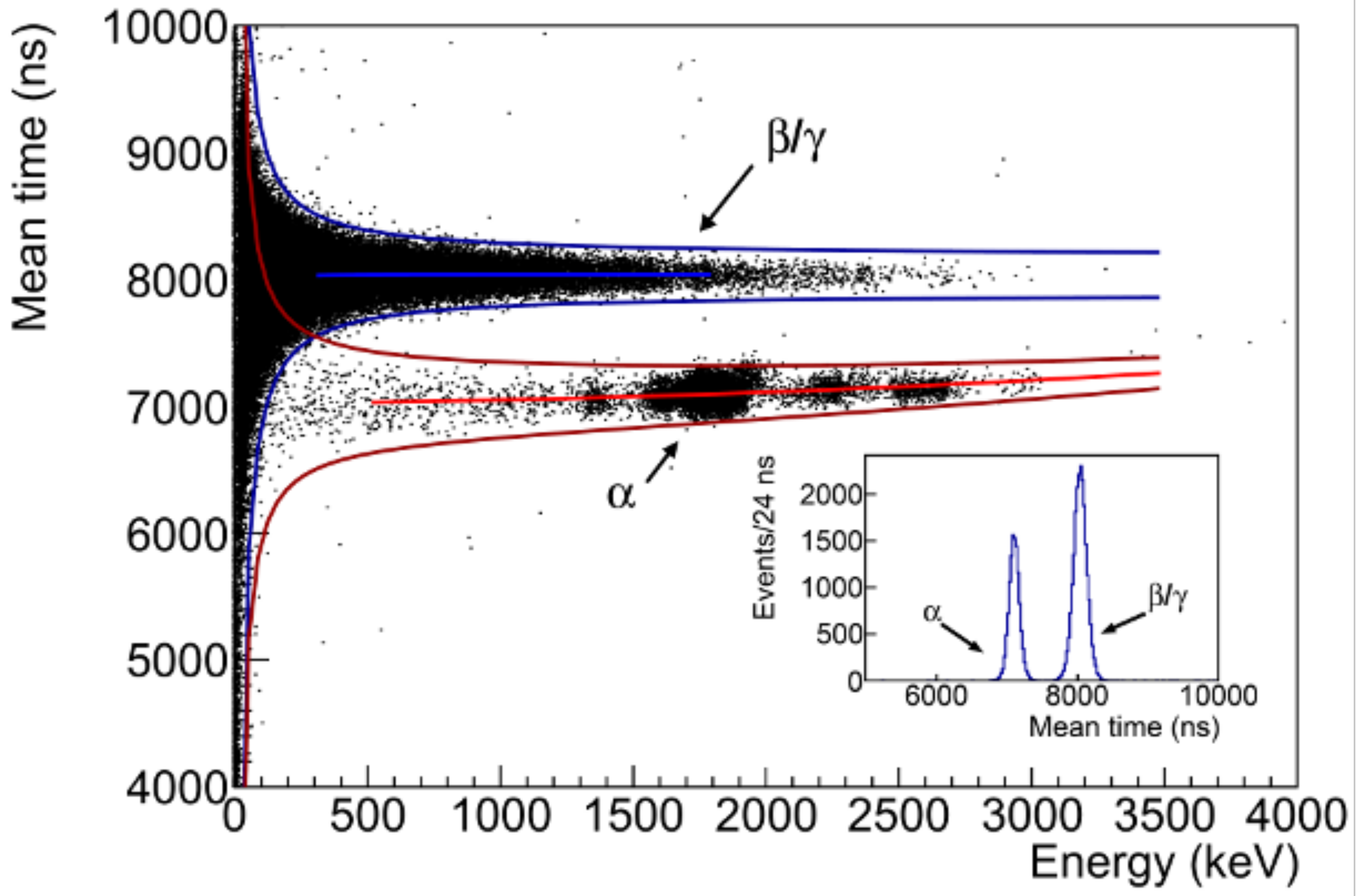
∅21.5×60 mm, about 60 g

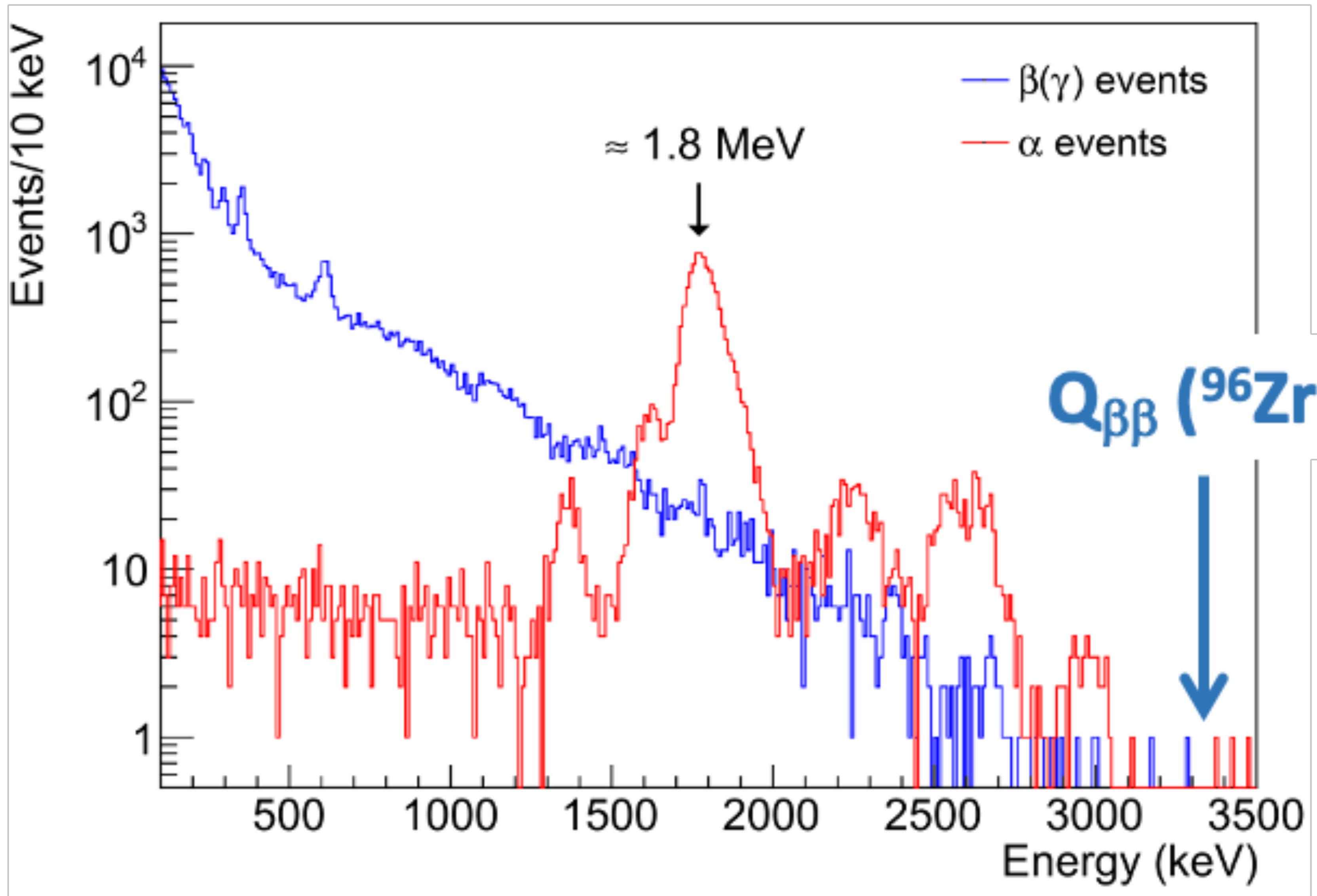
23.95 g **∅21.1×21.2 mm** **Cylindrical part**	**&**	**10.62 g** **∅20.5×14 mm** **Conical part**

<u>Run 1:</u> 456.5 days of data taking (time-window 80 μs), June 2021 - June 2022
<u>Run 2:</u> 65 days of data taking (extended time-window for t-A analysis, 2 ms), Oct-Dec 2022

Cs_2ZrCl_6: Pulse-shape discrimination and α event selection

Cone
FoM = 7.8

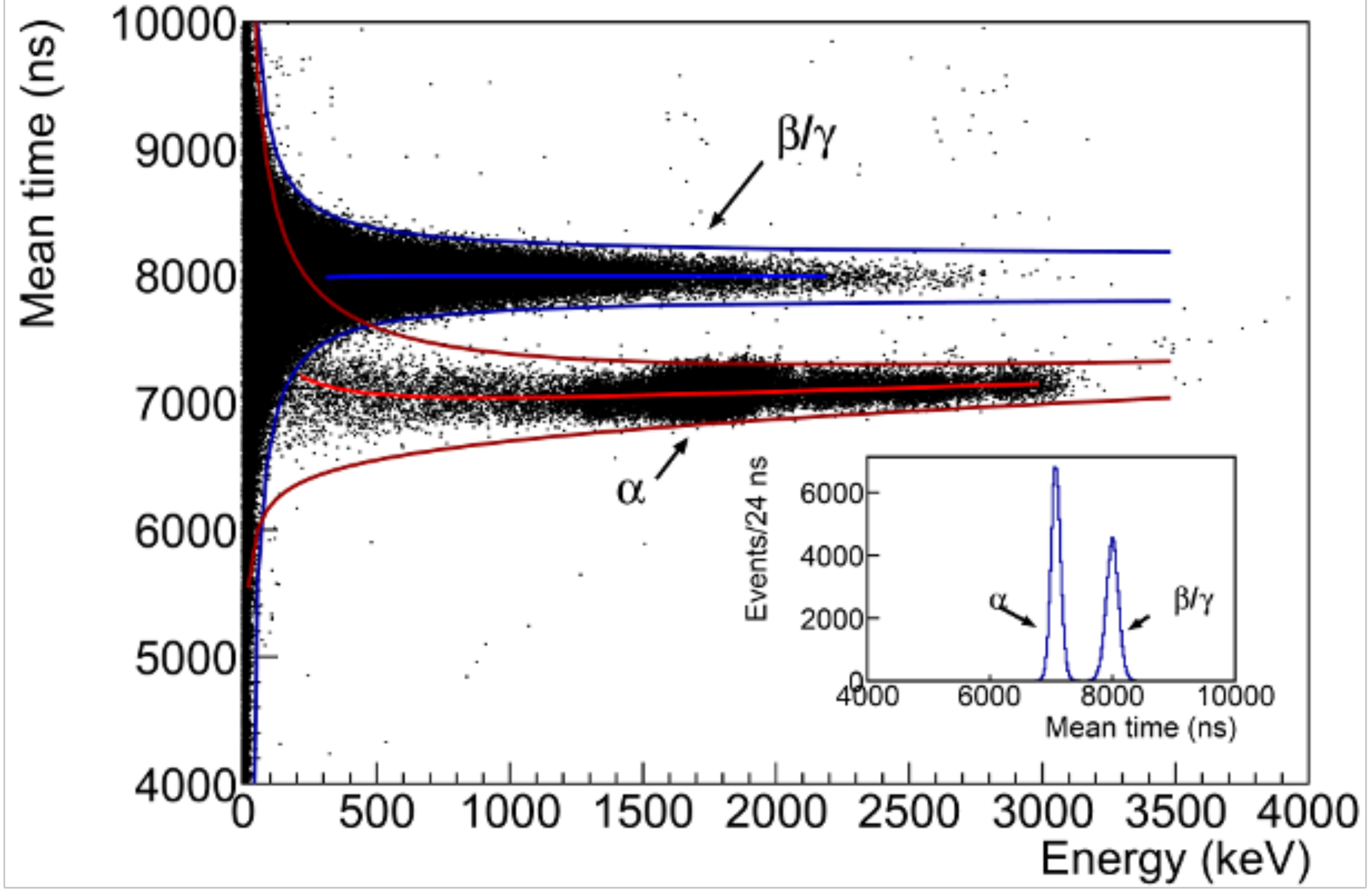


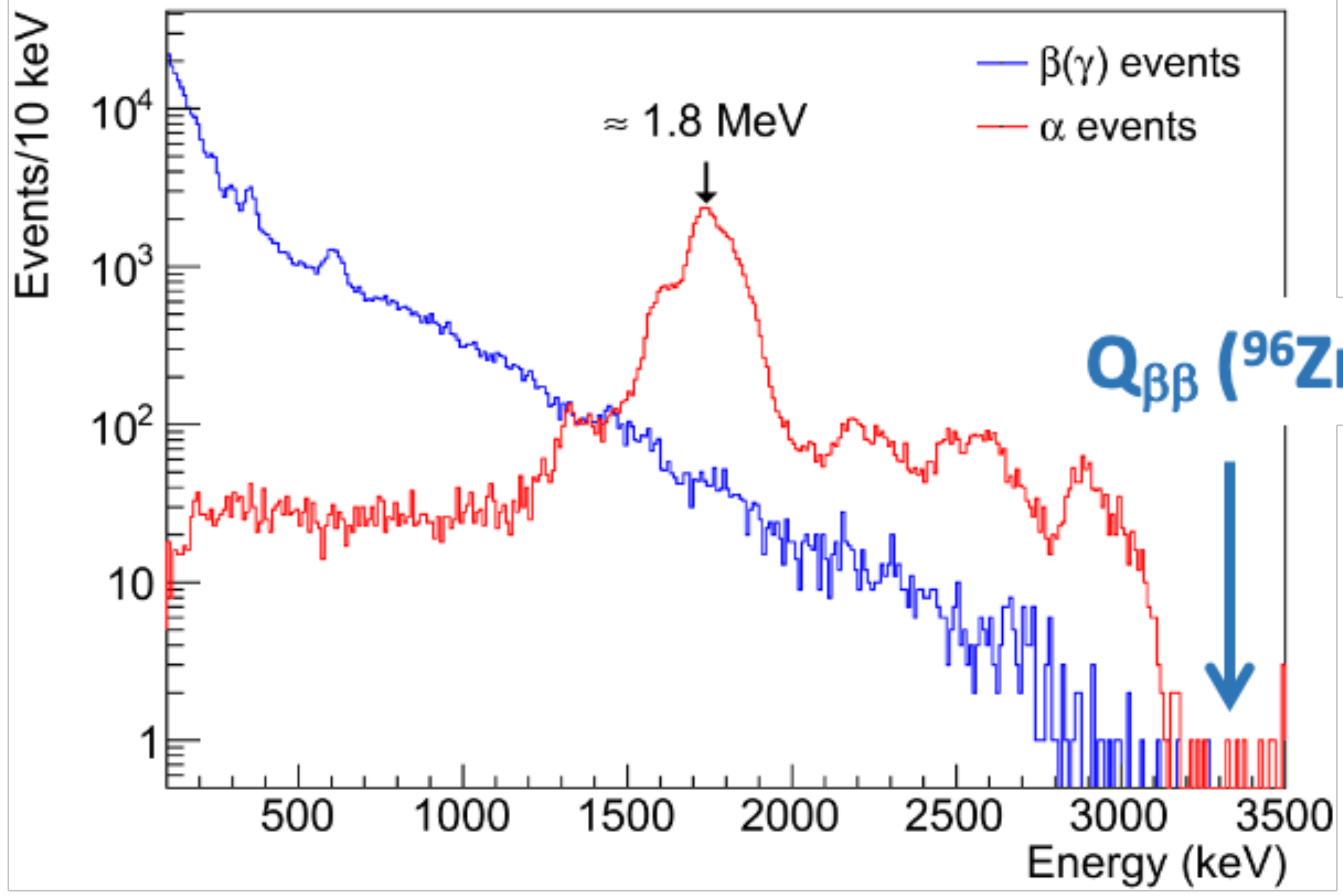


$Q_{\beta\beta}$ (^{96}Zr)

Selection efficiency is 99.7% in [0.1–3.5] MeV

Cylinder
FoM = 7.2



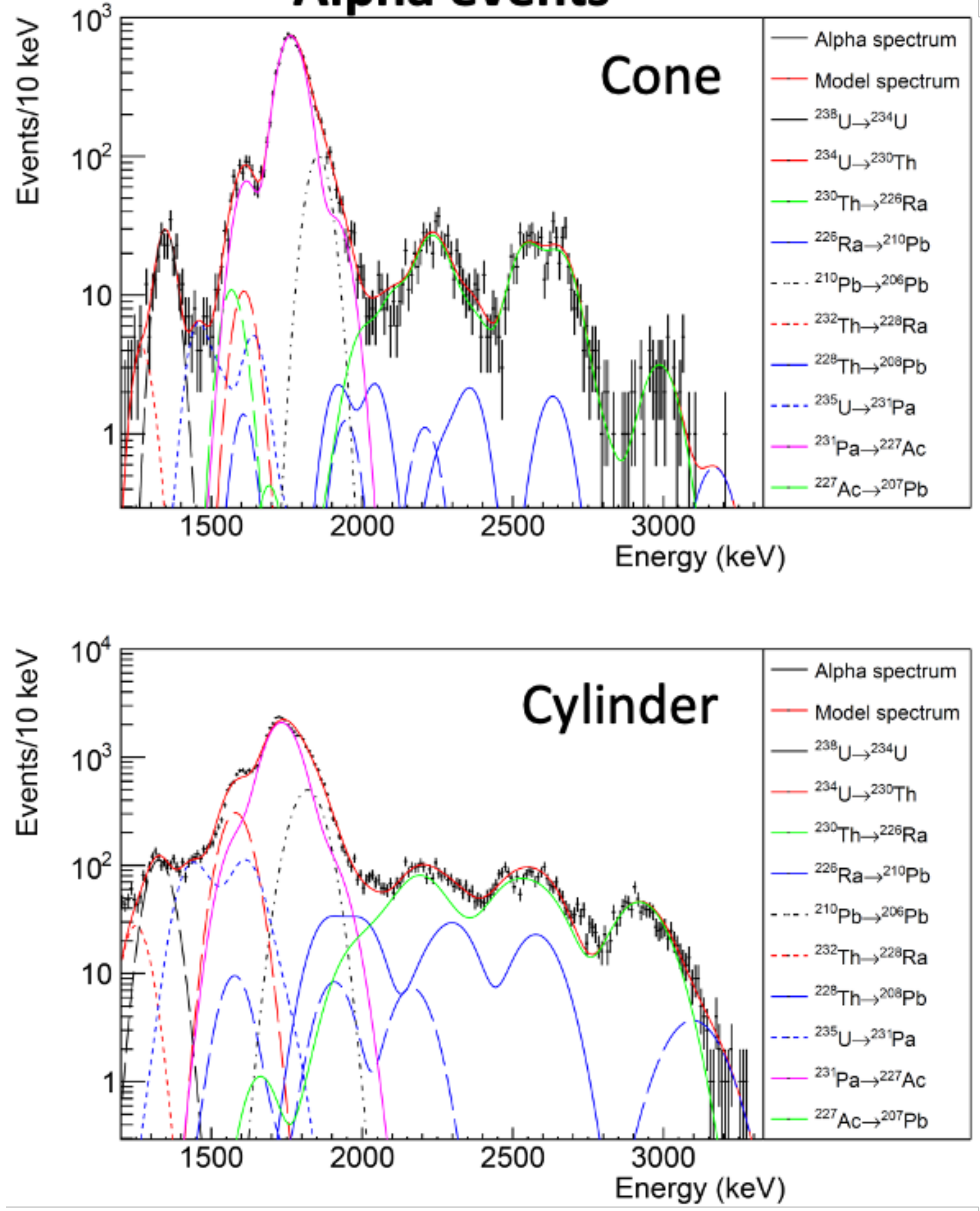


Counting rate at ROI is 0.09 counts/(kg·keV·yr)

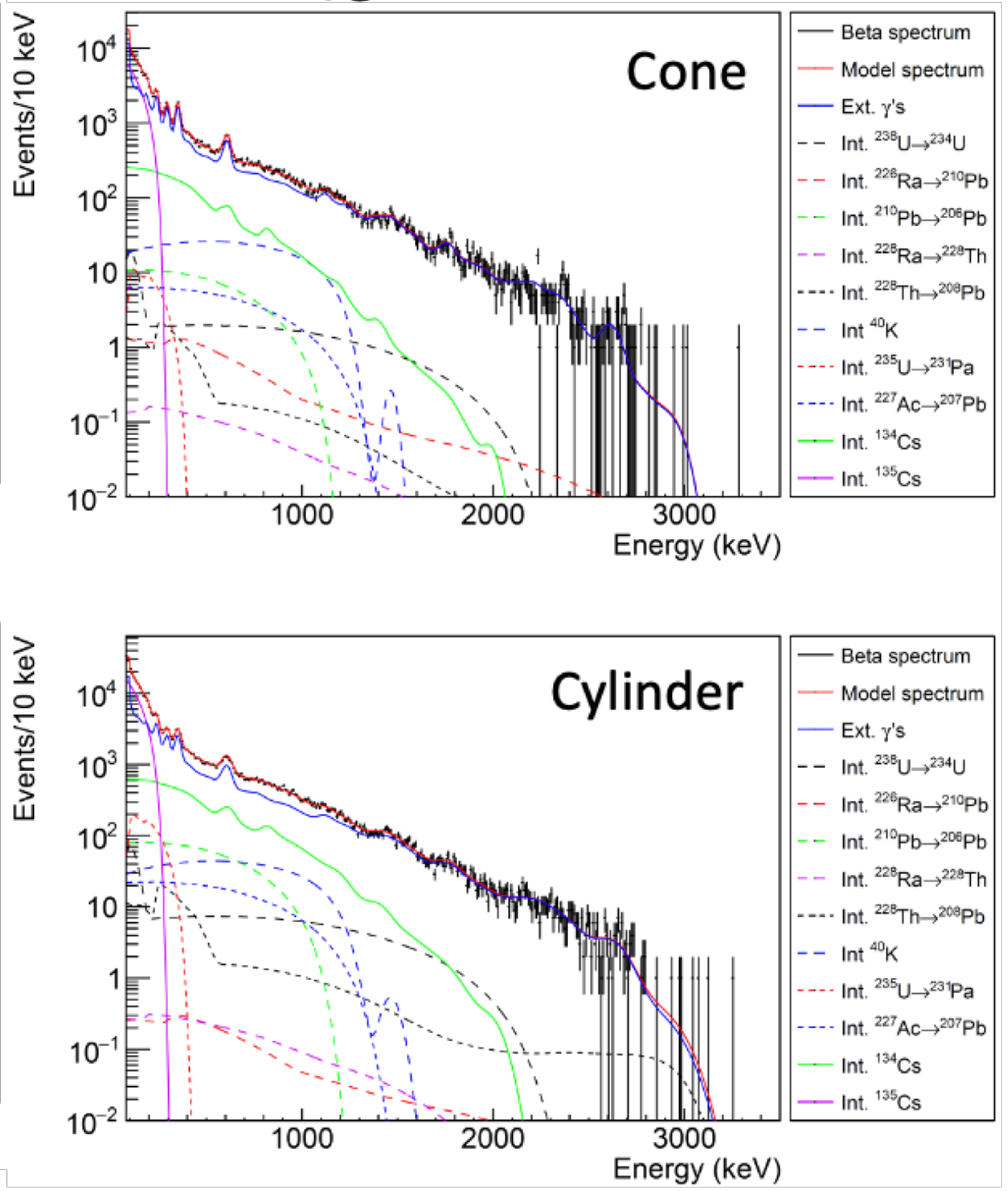
$Q_{\beta\beta}$ (^{96}Zr)

Cs_2ZrCl_6: Background model

Alpha events



Beta/gamma events



Chain	Nuclide	Internal contamination, mBq/kg	
		Cone	Cylinder
^{232}Th	^{232}Th	0.07(2)	0.28(7)
	^{228}Th	0.05(2)	0.44(4)
^{235}U	^{235}U	0.29(4)	3.0(1)
	^{231}Pa	**21.0(3)**	**33.9(3)**
	^{227}Ac	0.70(3)	1.08(3)
^{238}U	^{238}U	0.53(4)	1.17(5)
	^{234}U	0.2(1)	3.8(1)
	^{230}Th	0.23(7)	< 0.02
	^{226}Ra	0.03(3)	0.12(3)
	^{210}Pb	2.2(2)	6.7(3)
	^{40}K	6(1)	5(1)
	^{134}Cs	36(4)	42(2)
	^{135}Cs	**267(4)**	**289(2)**

<u>α/β ratio</u>:

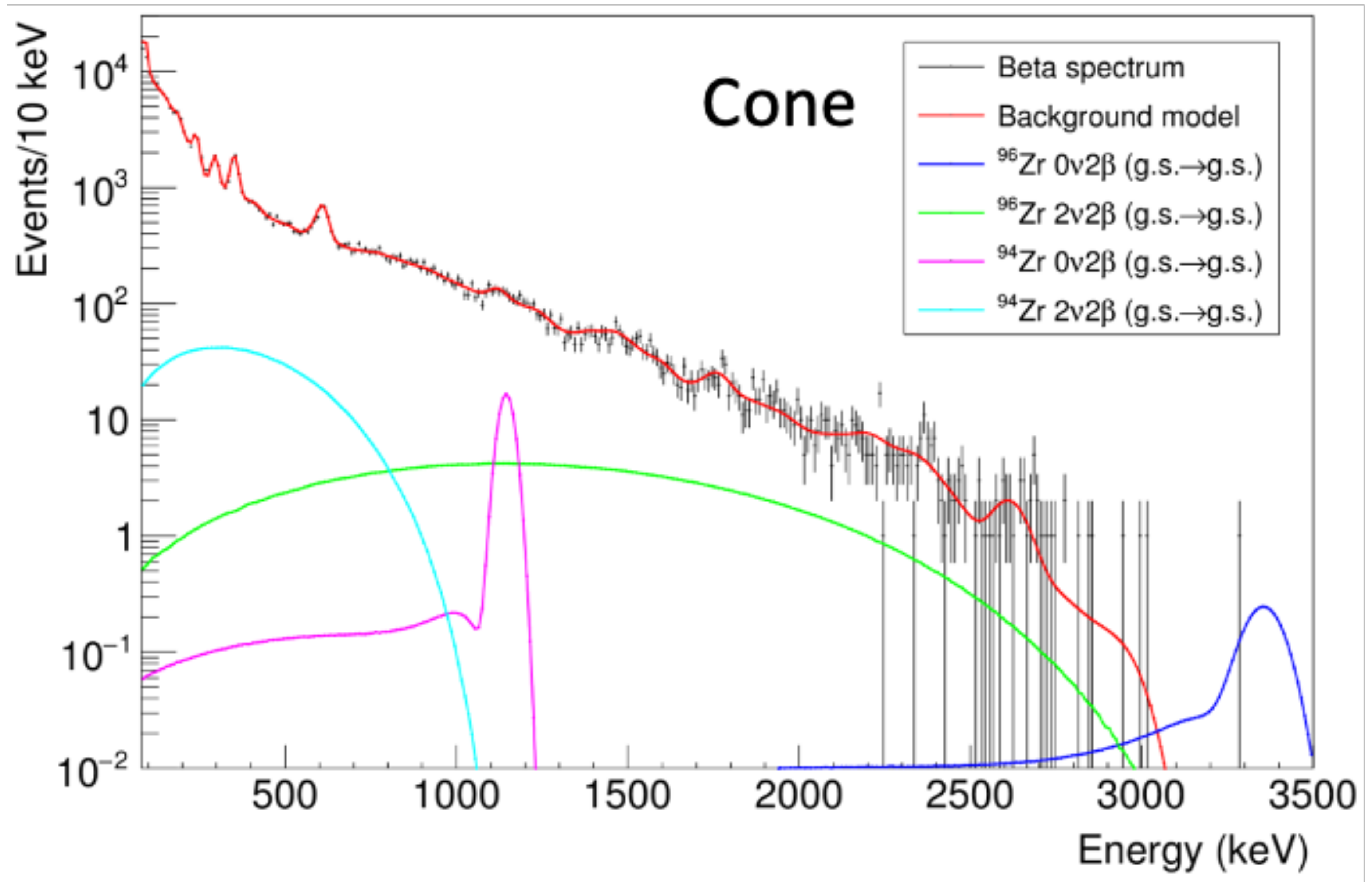
Cone: 0.2113(14) + 0.02607(27) × E_α [MeV]

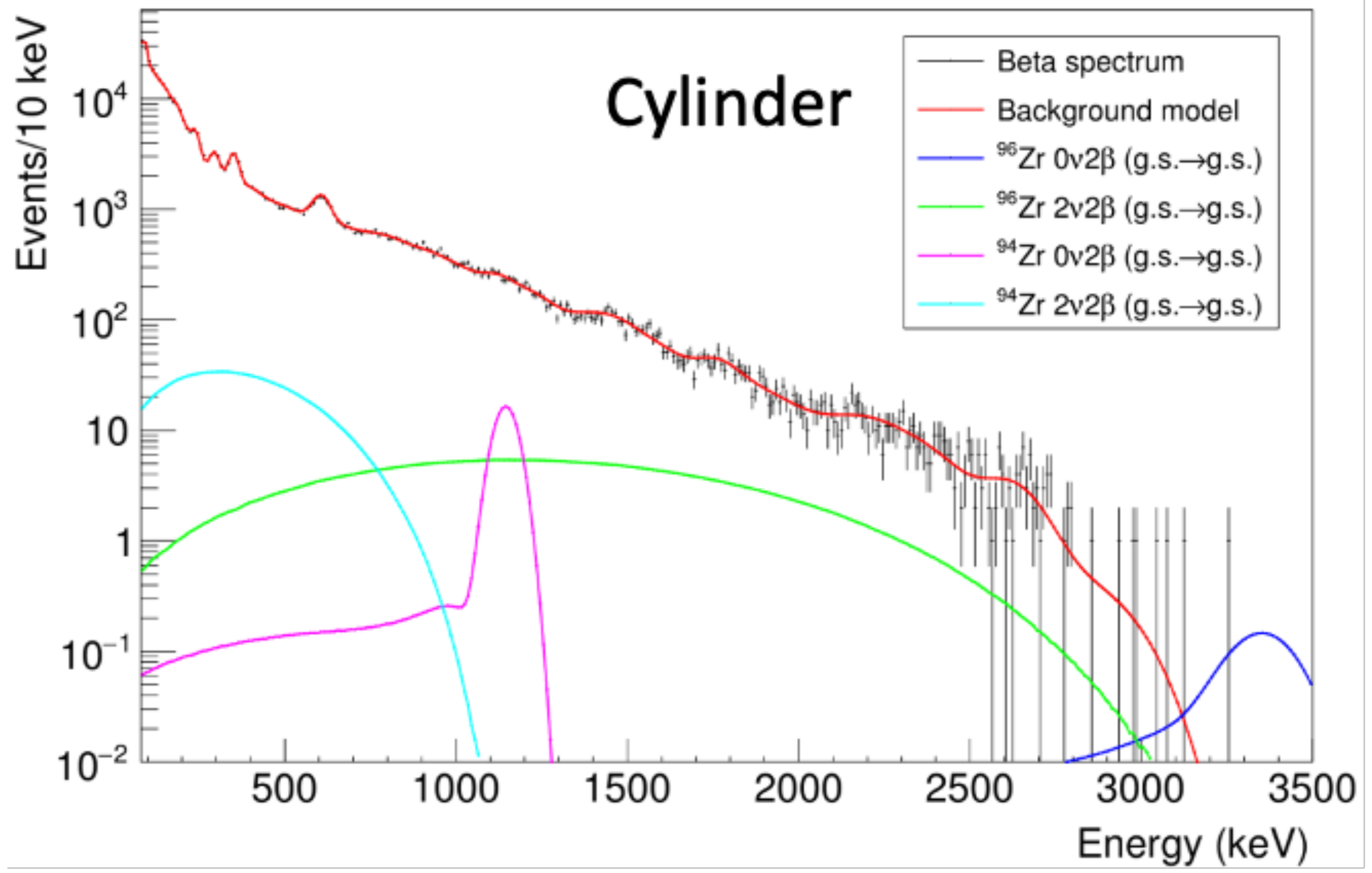
Cylinder: 0.2109(19) + 0.02491(20) × E_α [MeV]

Contribution of external gammas from PMT's is dominant

- Comply with measurements on HPGe
- High contamination by ^{235}U daughters
- Segregation of impurities is observed

Experimental limits on various decay modes in ^{94,96}Zr isotopes





Transition	Decay mode	Final state of daughter nucleus, keV	Experimental limit on $T_{1/2}$ at 90%C.L., yr
$^{96}Zr \rightarrow ^{96}Mo$	$2\beta0\nu$	g.s.	**$> 1.5\times10^{20}$**
		2_1^+, 778	$> 1.5\times10^{19}$
	$2\beta2\nu$	g.s.	$> 7.4\times10^{17}$
		2_1^+, 778	$> 3.8\times10^{17}$
	β	g.s.	$> 1.0\times10^{17}$
$^{94}Zr \rightarrow ^{94}Mo$	$2\beta0\nu$	g.s.	$> 2.6\times10^{19}$
		2_1^+, 871	$> 3.8\times10^{18}$
	$2\beta2\nu$	g.s.	$> 2.4\times10^{18}$
		2_1^+, 871	$> 1.9\times10^{17}$

See more details in ***Eur. Phys. J. A 59 (2023) 176***
https://doi.org/10.1140/epja/s10050-023-01090-9

Big & low BG neutrino detector

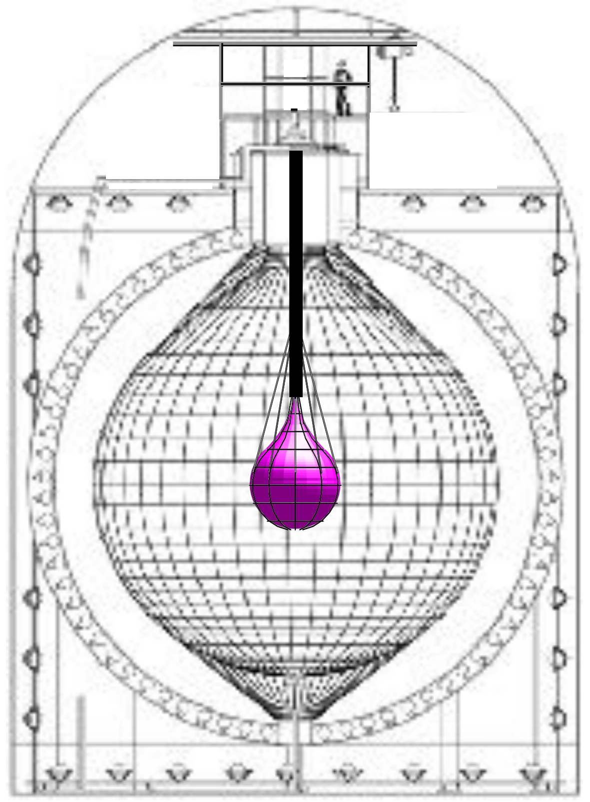
KamLAND-Zen Modification of KamLAND for double beta decay

Double beta decay isotope: ^{136}Xe

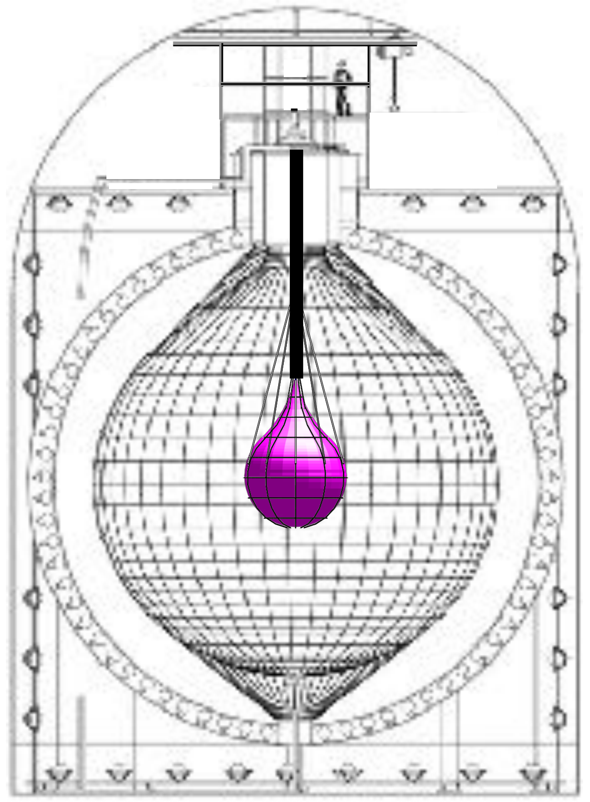
- Q-value 2.458 MeV
- Dissolved into LS ~3% by weight
- Enrichment ~90%
- Half life of 2νββ decay is long (~10^{21} yr)

^{136}Xe loaded liquid scintillator
into the detector center
with inner balloon

Past
KamLAND-Zen 400
320-380 kg of Xenon
Data taking in 2011 - 2015



Present
KamLAND-Zen 800
~750 kg of Xenon
DAQ started in 2019



Reanalysis → combined → **1st result**
$T^{1/2} > 2.0\times10^{26}$ yr
(Feb. 2019 - May 2021)

- Double amount of Xe
- Bigger, cleaner Xe-LS container
- Improved spallation rejection method
- Simultaneous fitting of single event and long-lived products

KL-Zen 400 + 800 limit (90% C.L.)

$T^{1/2} > 2.3\times10^{26}$ yr

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

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

First search for inverted mass ordering!

KamLAND2-Zen

KamLAND → KamLAND2

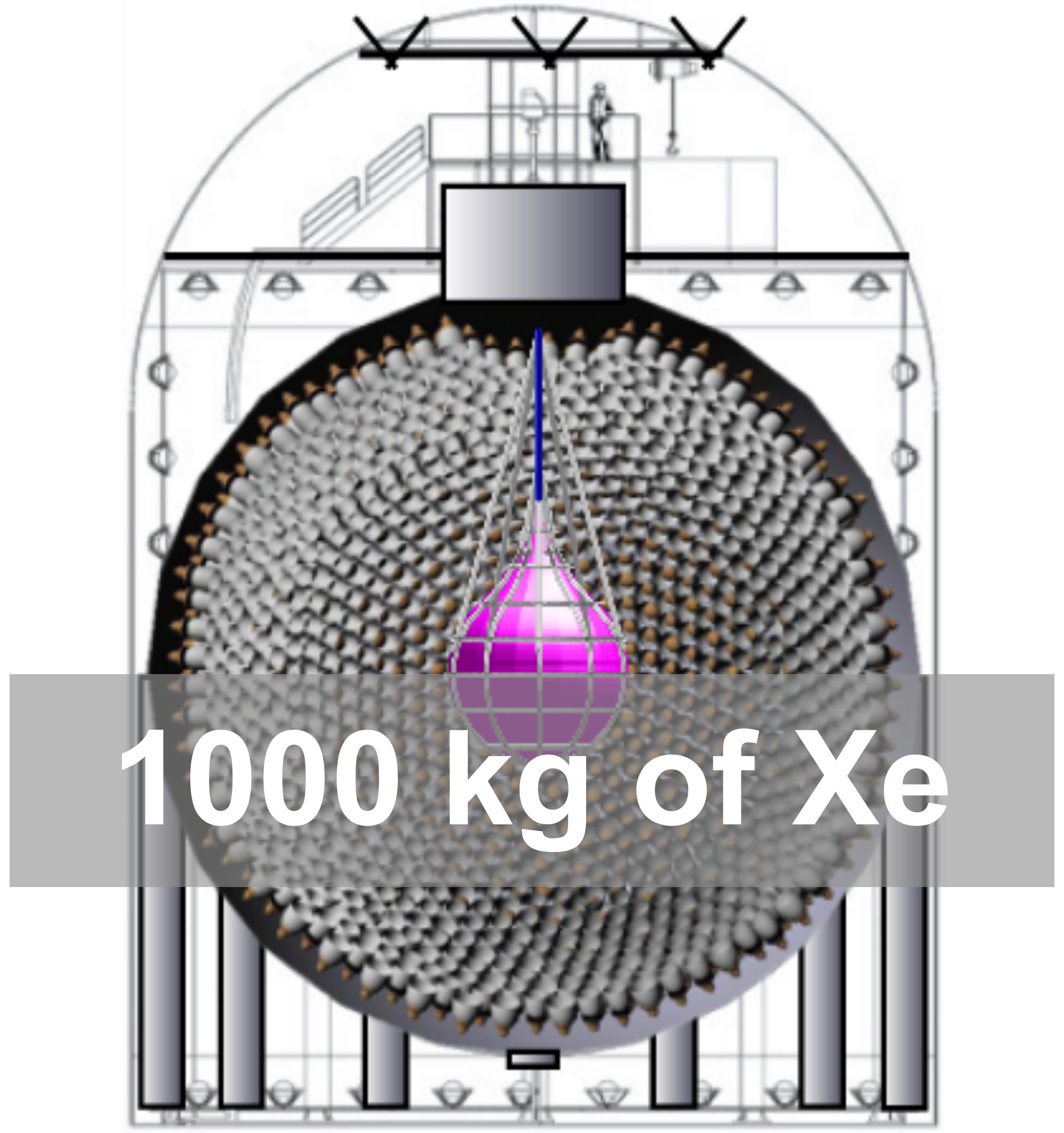
New electronics

To improve long lived isotope background suppression. More neutron tagging.

Scintillation inner balloon

BG reduction from Xe-LS container

R&D paper: PTEP. Volume 2019, Issue 7, 073H01



1000 kg of Xe

High QE PMT & Winstone cone

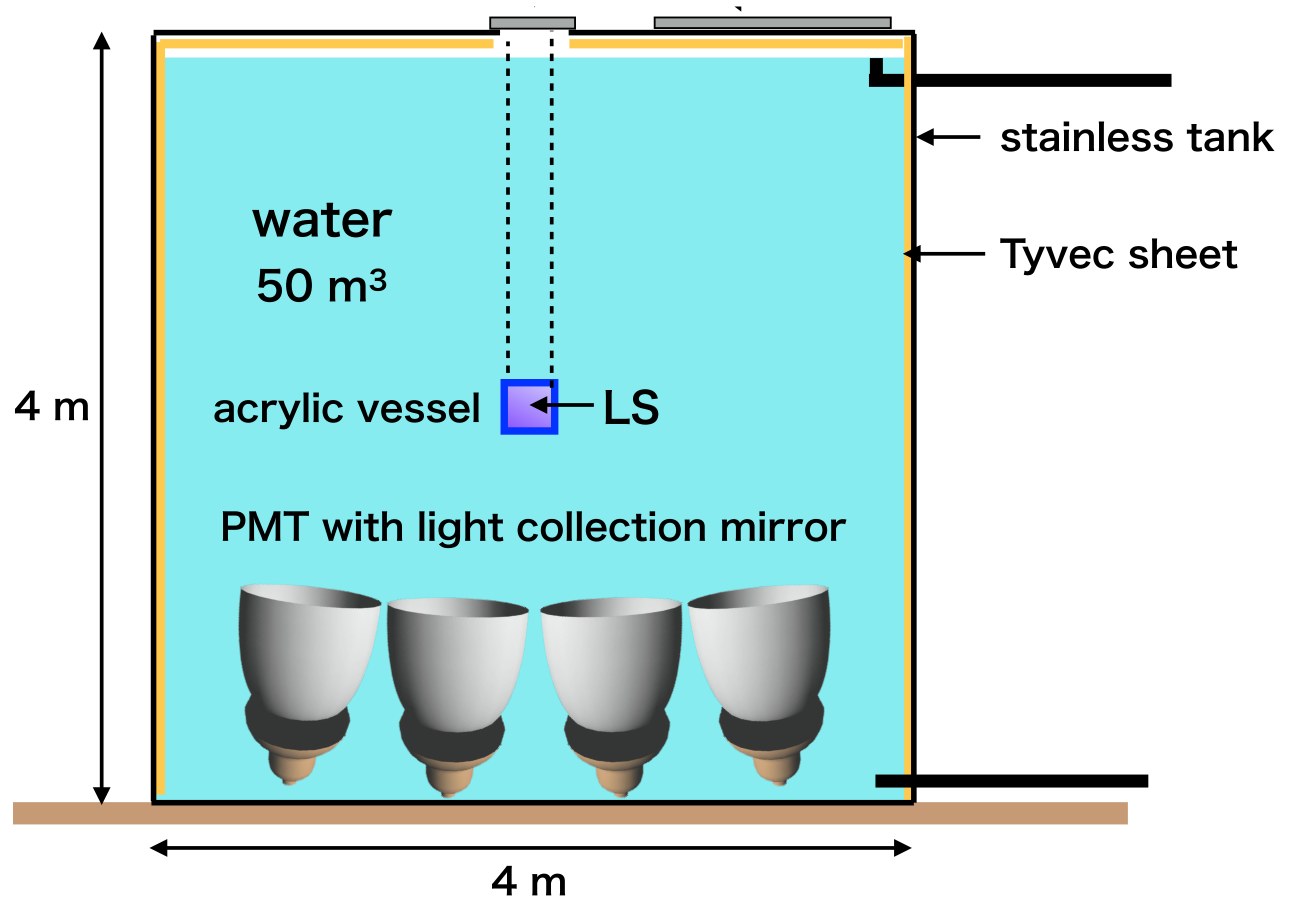
Improve photo coverage and light collection efficiency

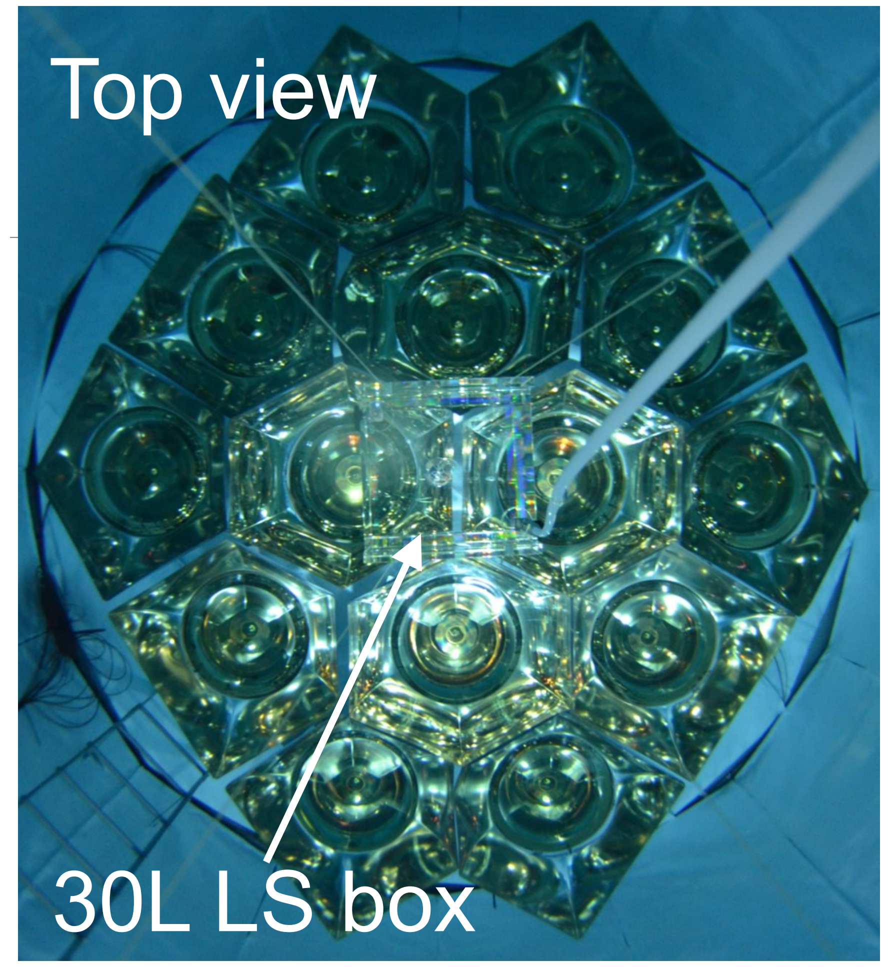
Brighter LS

$\sigma(2.6\text{MeV}) = 4\% \rightarrow \sim 2\%$

Target $\langle m_{\beta\beta} \rangle$ ~20 meV in 5 yrs

Prototype detector

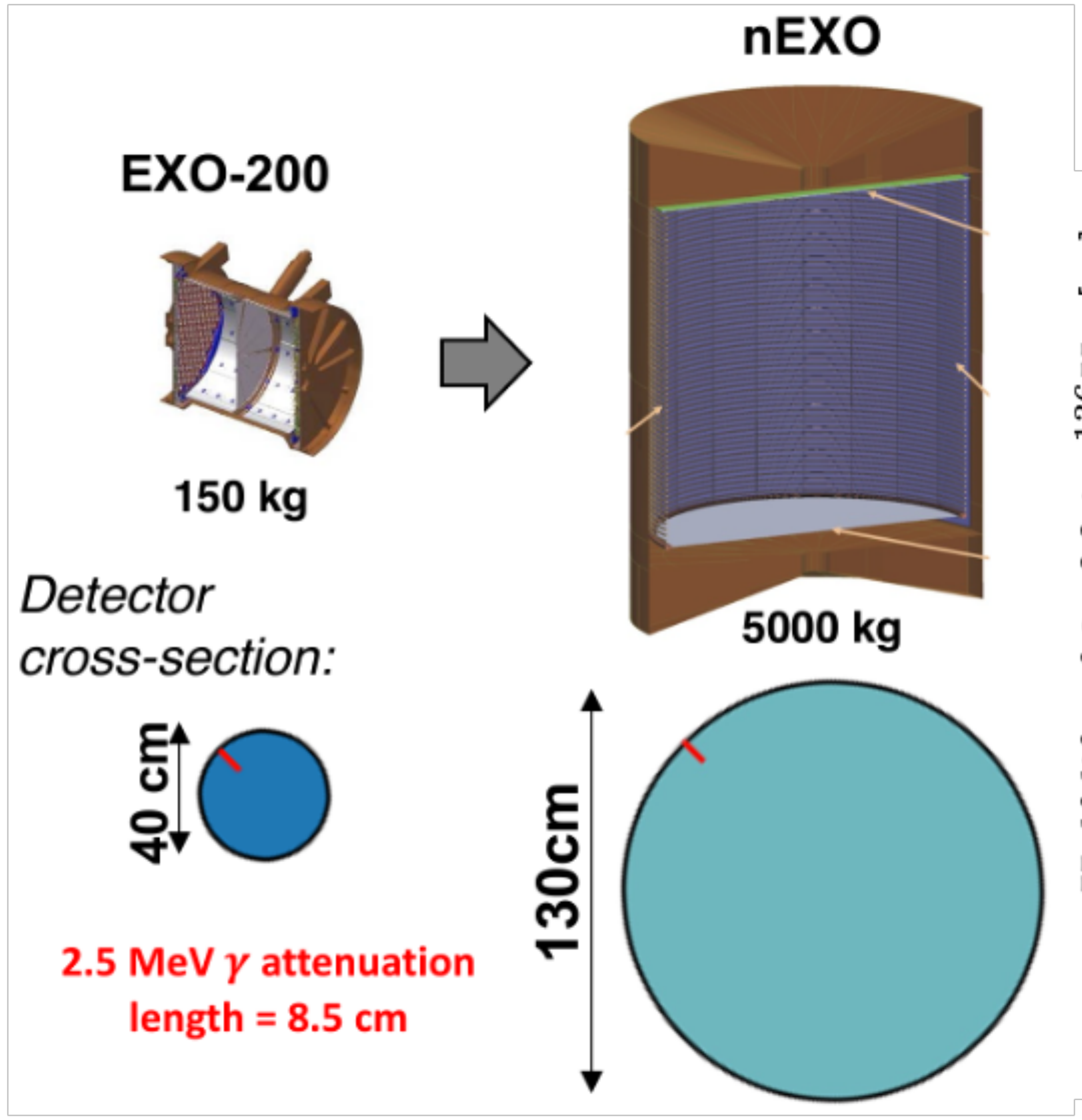


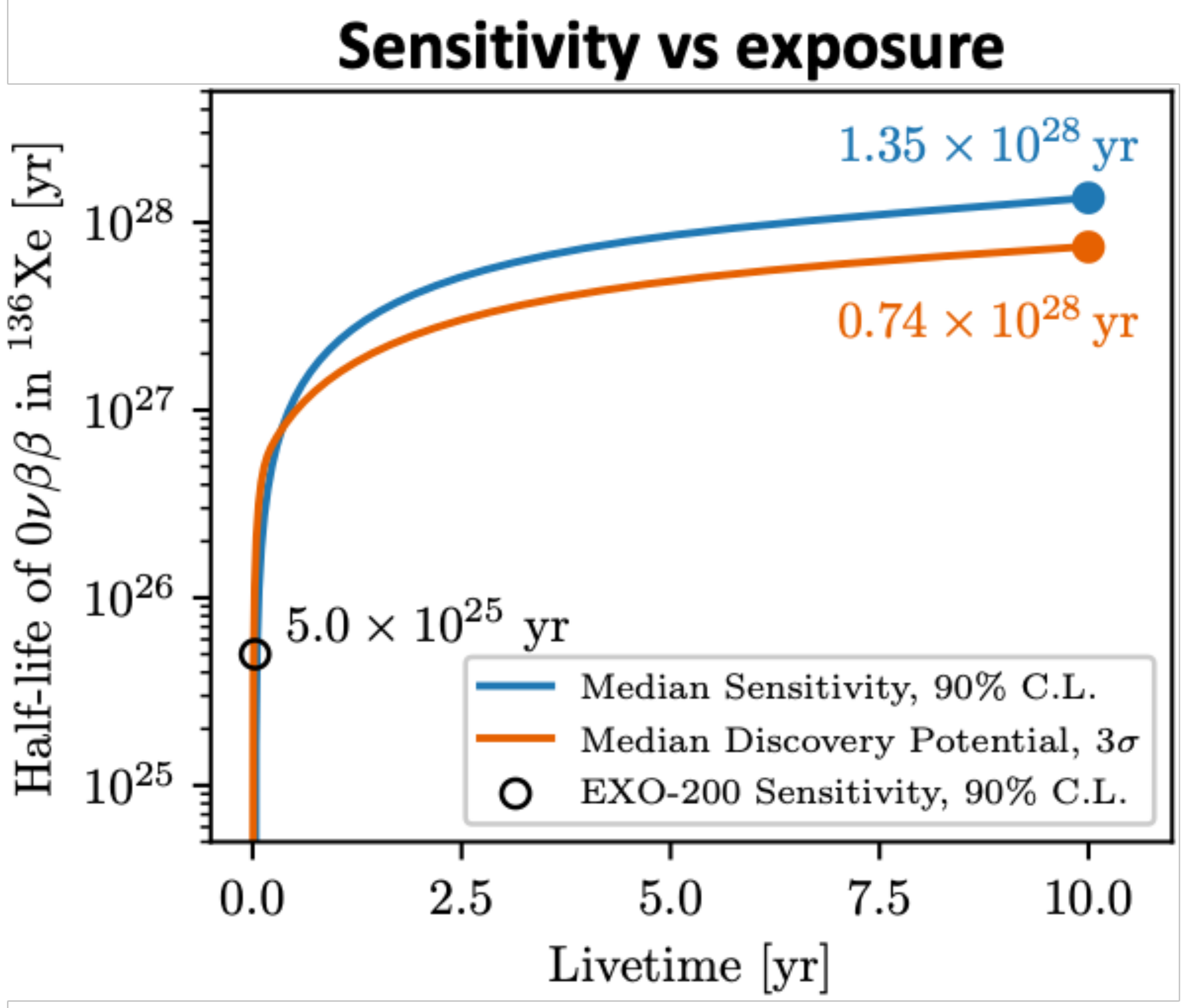


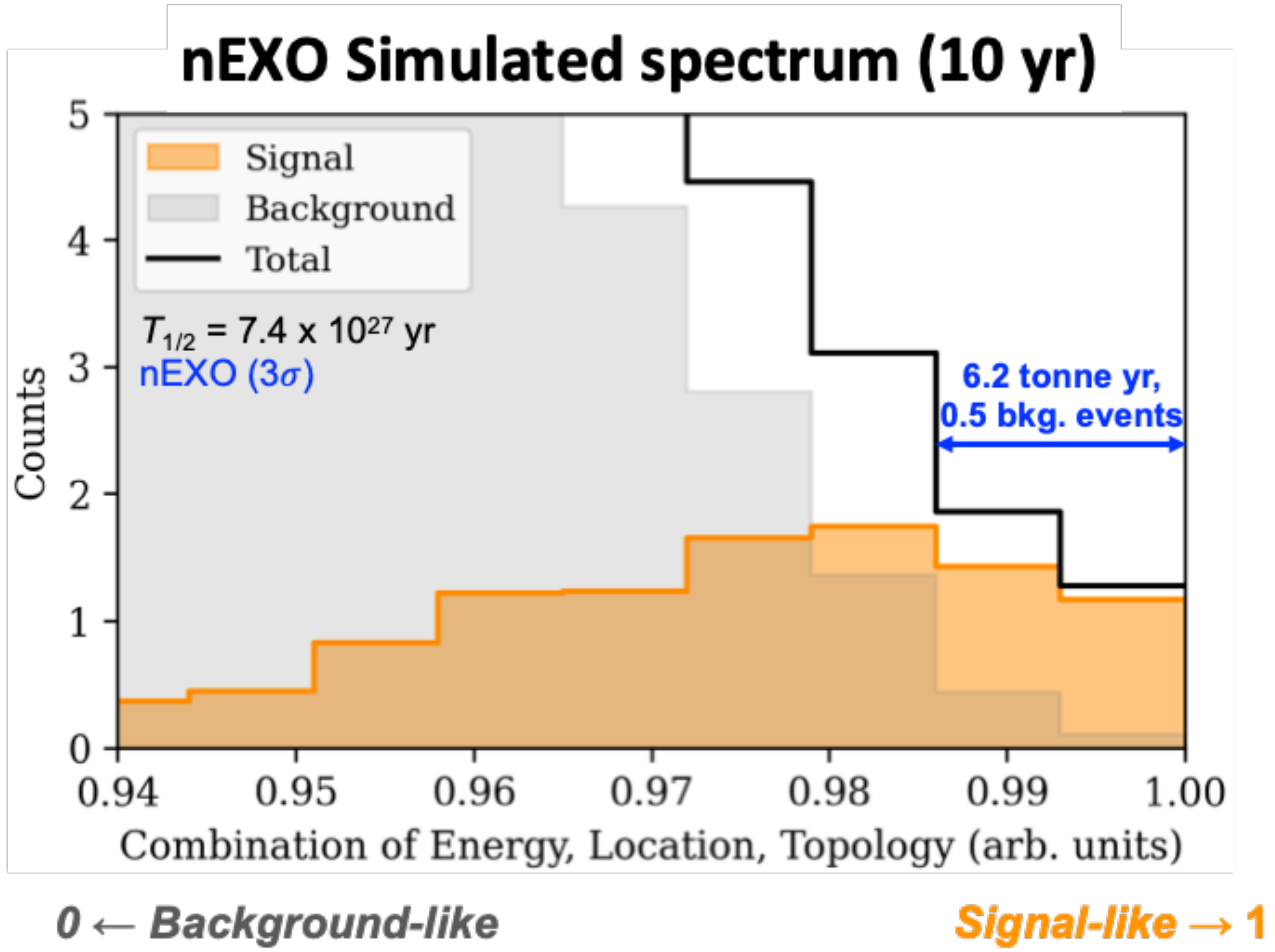
- Solid angle dependence
- Stability (<~5%) for about 1 month
- Energy resolution $\sigma \simeq 5.9\%$ @1MeV
- Data taking ongoing for background analysis

nEXO: Tonne-scale 0νββ with a LXe TPC

- Experiment designed for discovery of 0νββ in ^{136}Xe
- Builds on the completed EXO-200 experiment
- Homogeneous, liquid ^{enr}Xe time projection chamber (TPC) scaled to 5 tonne total mass
  - Dominant external backgrounds exponentially attenuated, leads to background-free central region
- Status: conceptual design in progress, projected 3σ discovery sensitivity $m_{\beta\beta}$ = 6-27 meV ($T_{1/2}$ = 0.74 x 10^{28} yr)



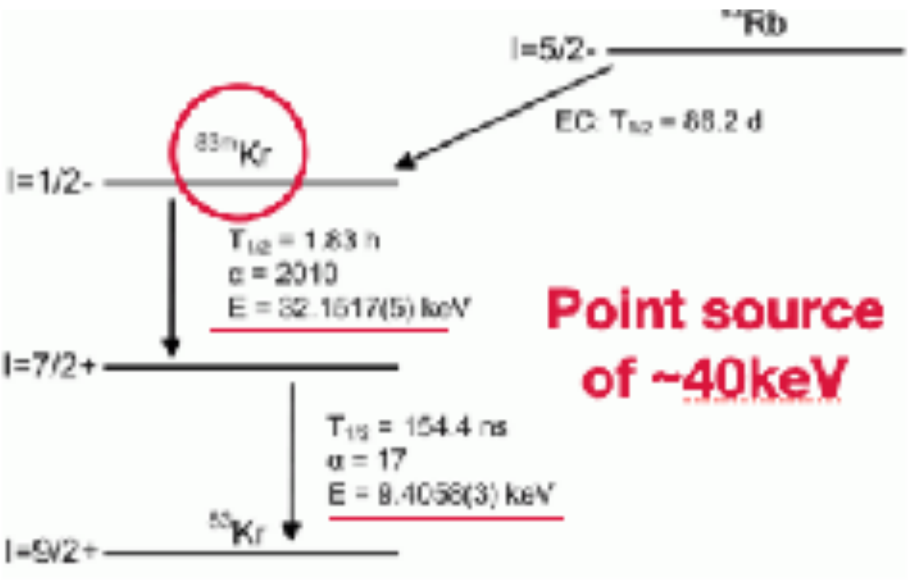

Sensitivity vs exposure


nEXO Simulated spectrum (10 yr)

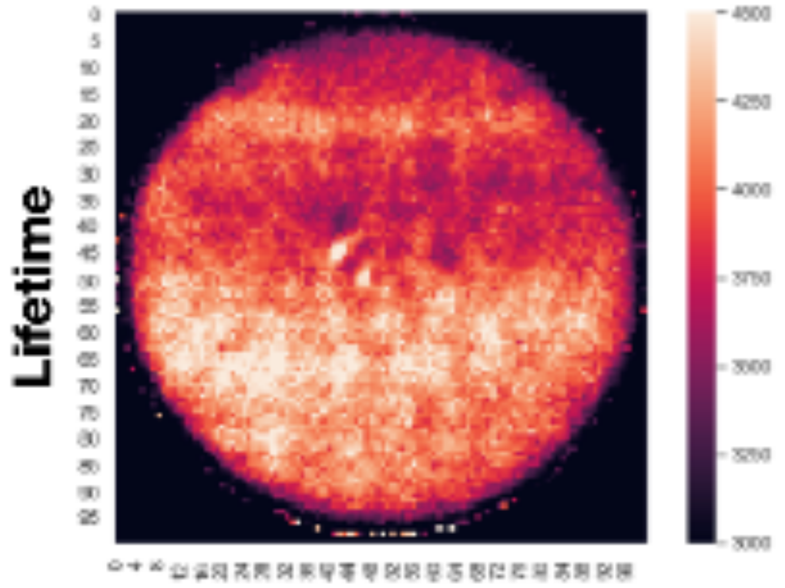
nEXO Sensitivity arXiv:2106.16243

NEXT technology demonstration

Live Kr calibration

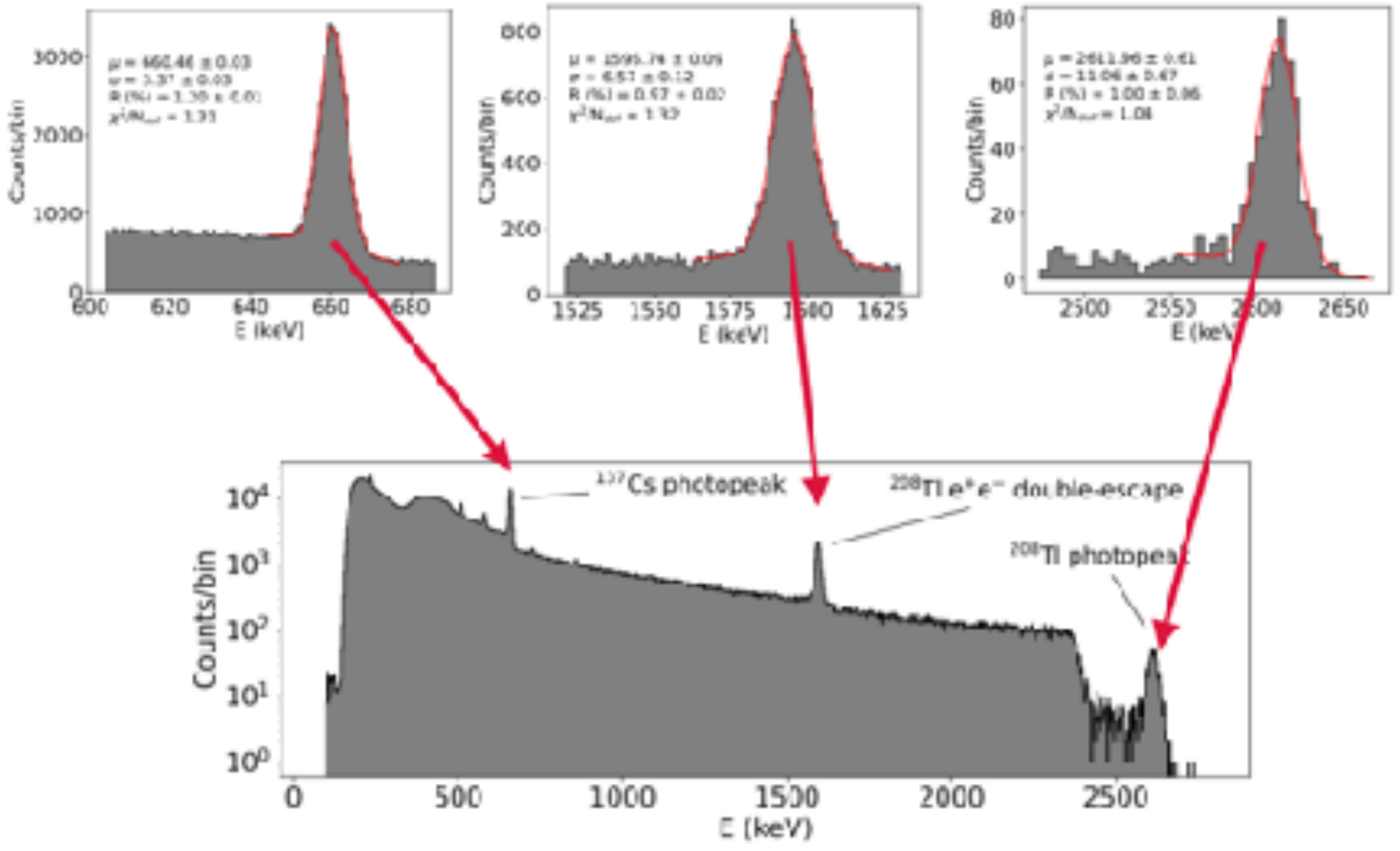


Point source of ~40keV



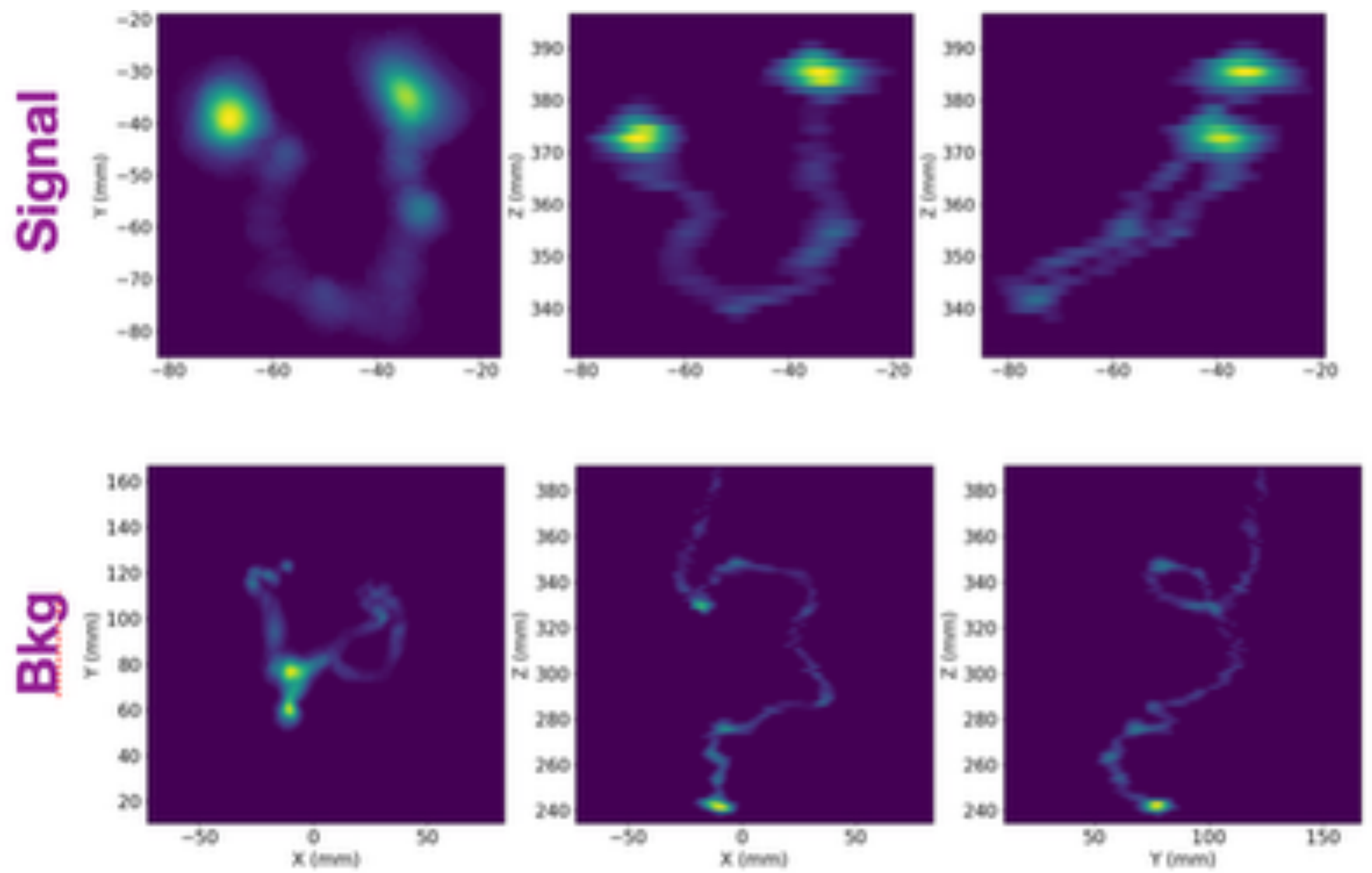
NEXT Collaboration, *JINST* **13** (2018) P10014

Energy resolution better than 1% FWHM



NEXT Collaboration, *JHEP* 10 (2019) 230

Topological Identification



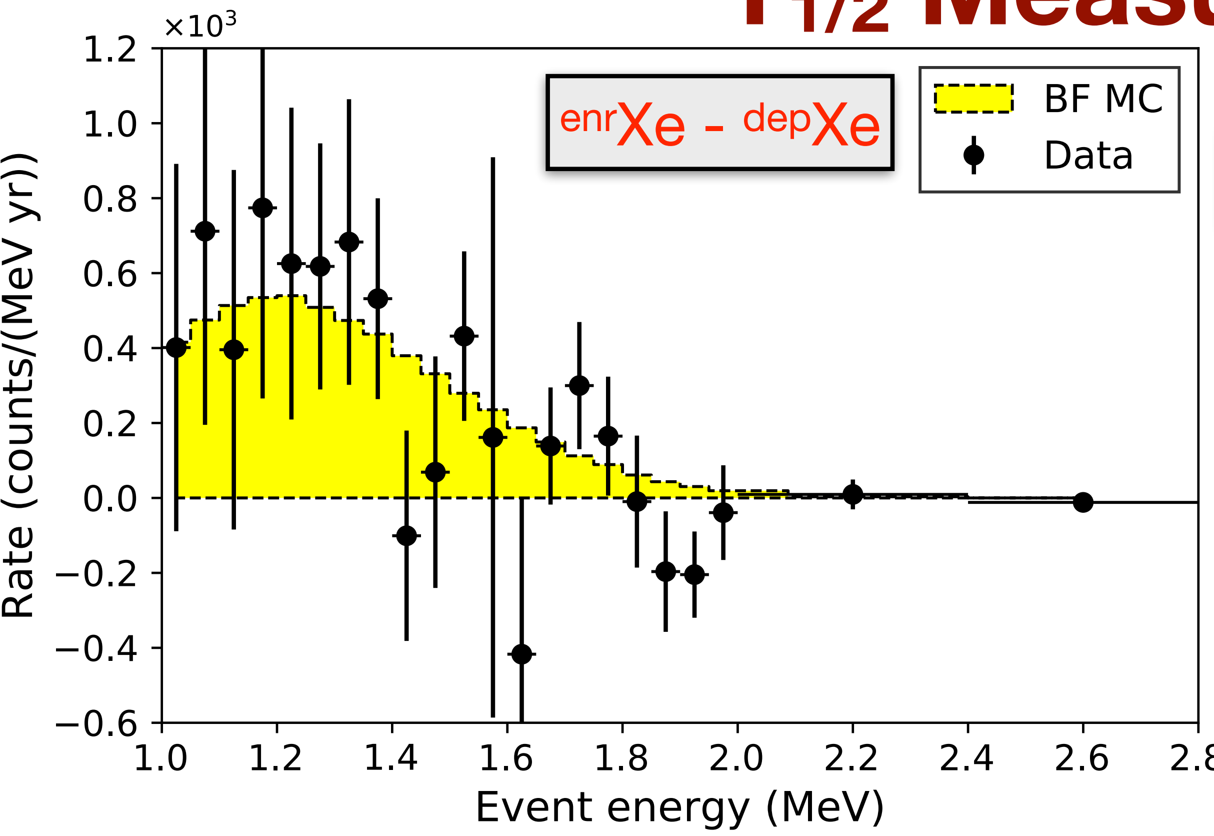
Traditional cut-base analysis
~70% efficiency
~20% bkg contamination

NEXT Collaboration, *JHEP* 10 (2019) 052

Improvement with DNNs
~5% bkg contamination

NEXT Collaboration, *JHEP* 01 (2021) 189

$T_{1/2}$ Measurements



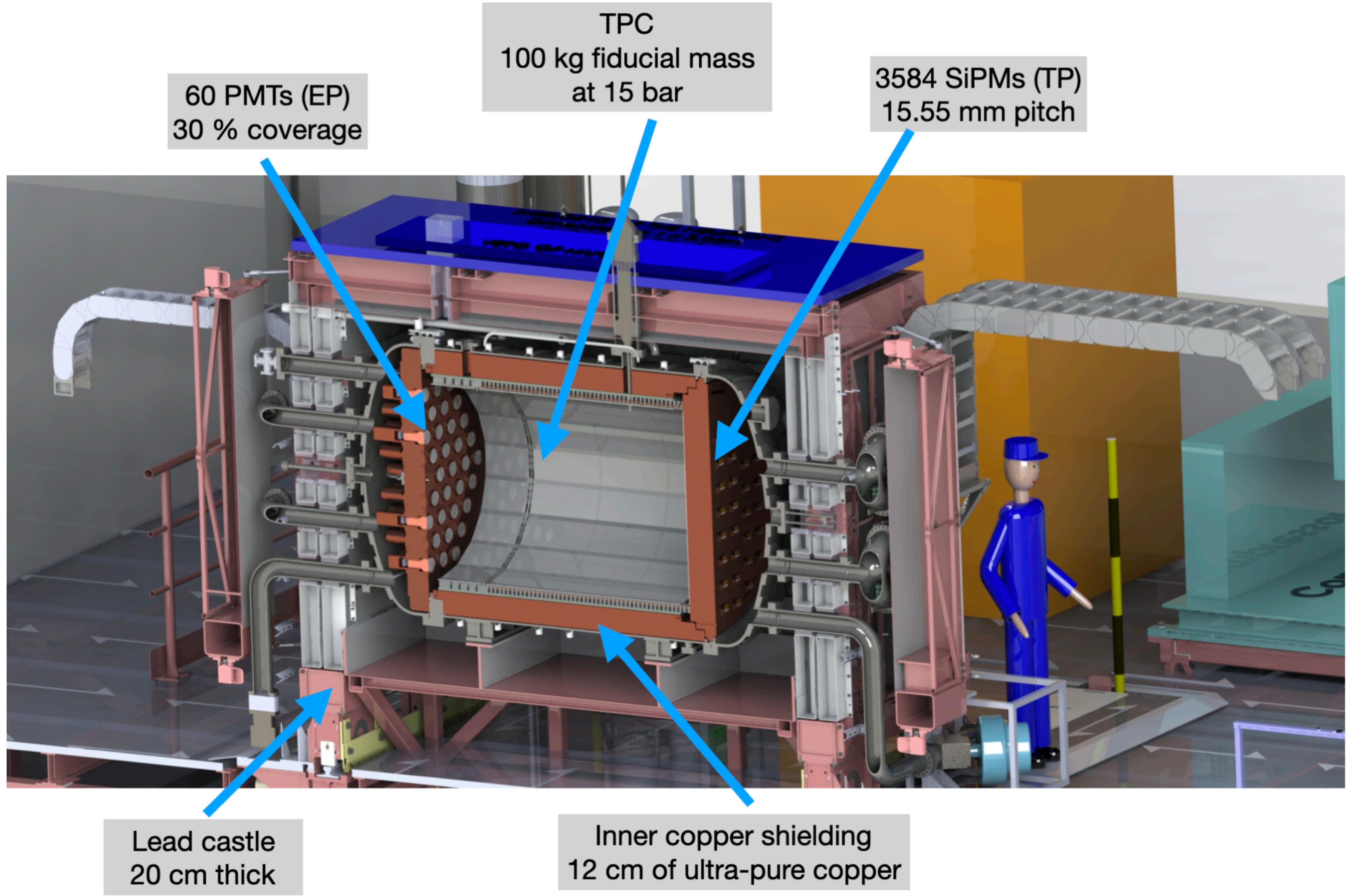
$T_{1/2}^{2\nu} = (2.34\ ^{+0.85}_{-0.49}) \times 10^{21}$ yr

NEXT Collaboration, *PRC* 105 (2022) 5

$T_{1/2}^{0\nu} > 0.6\text{-}1.3 \times 10^{24}$ yr
at 90% CL

NEXT Collaboration, *JHEP* 09 (2023) 190

NEXT-100 (2023-2026)



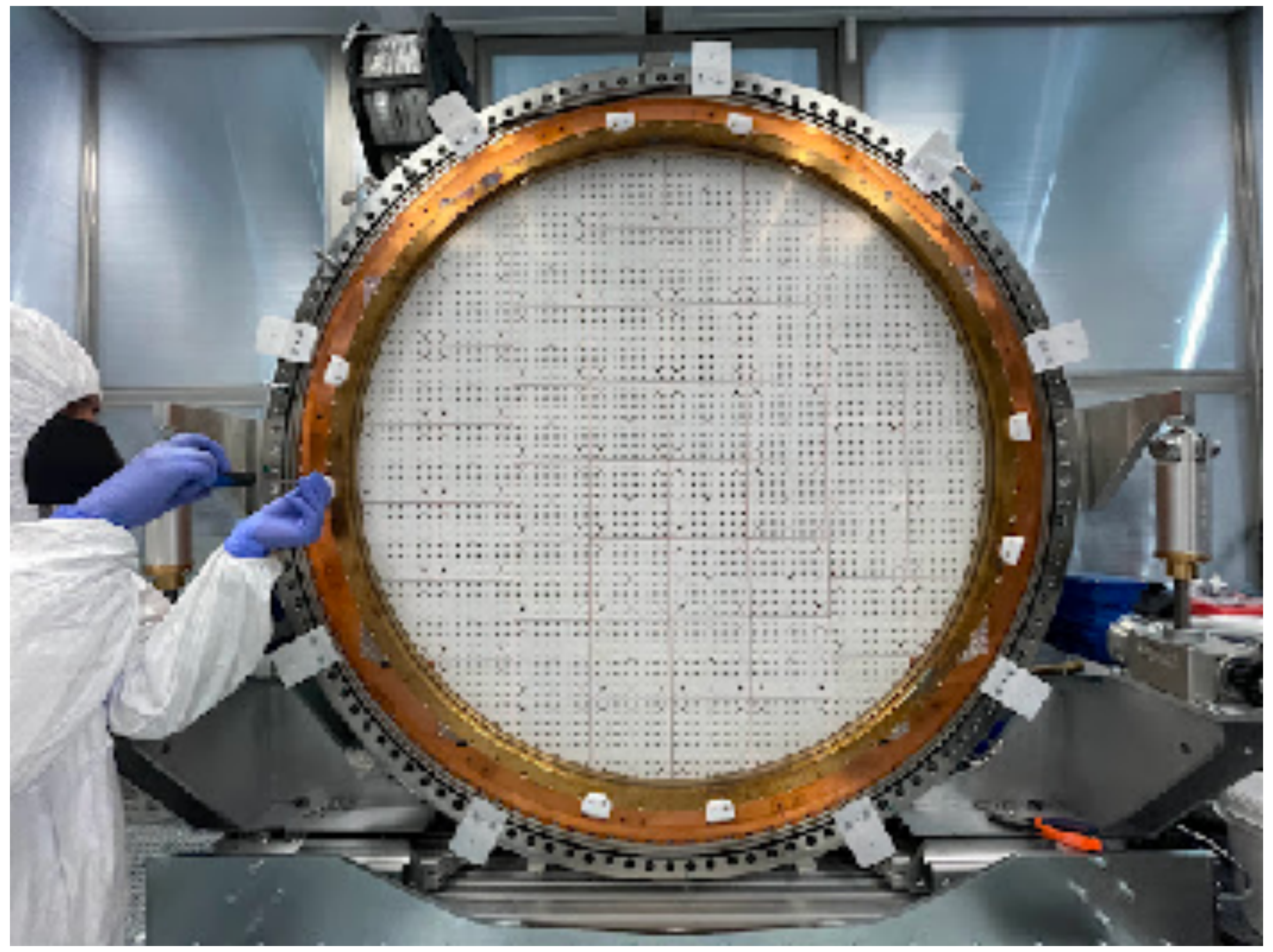
TPC
100 kg fiducial mass
at 15 bar

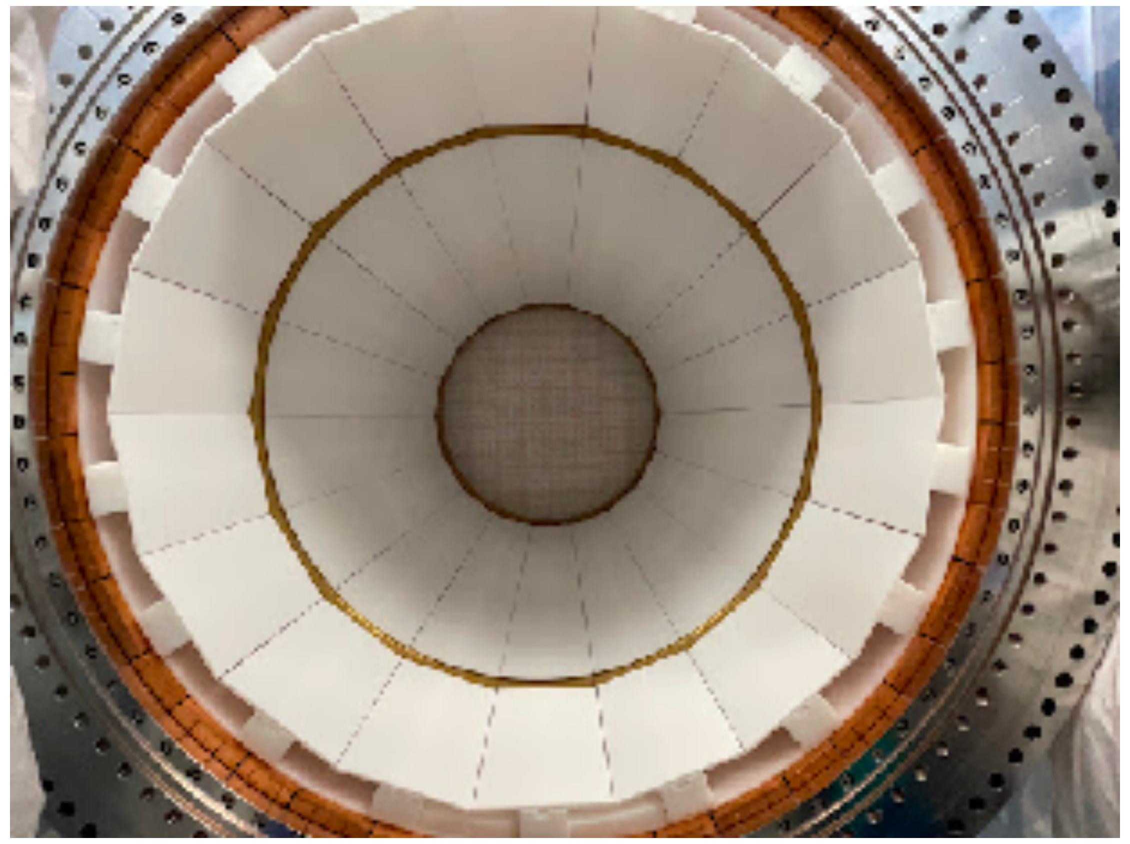
60 PMTs (EP)
30 % coverage

3584 SiPMs (TP)
15.55 mm pitch

Lead castle
20 cm thick

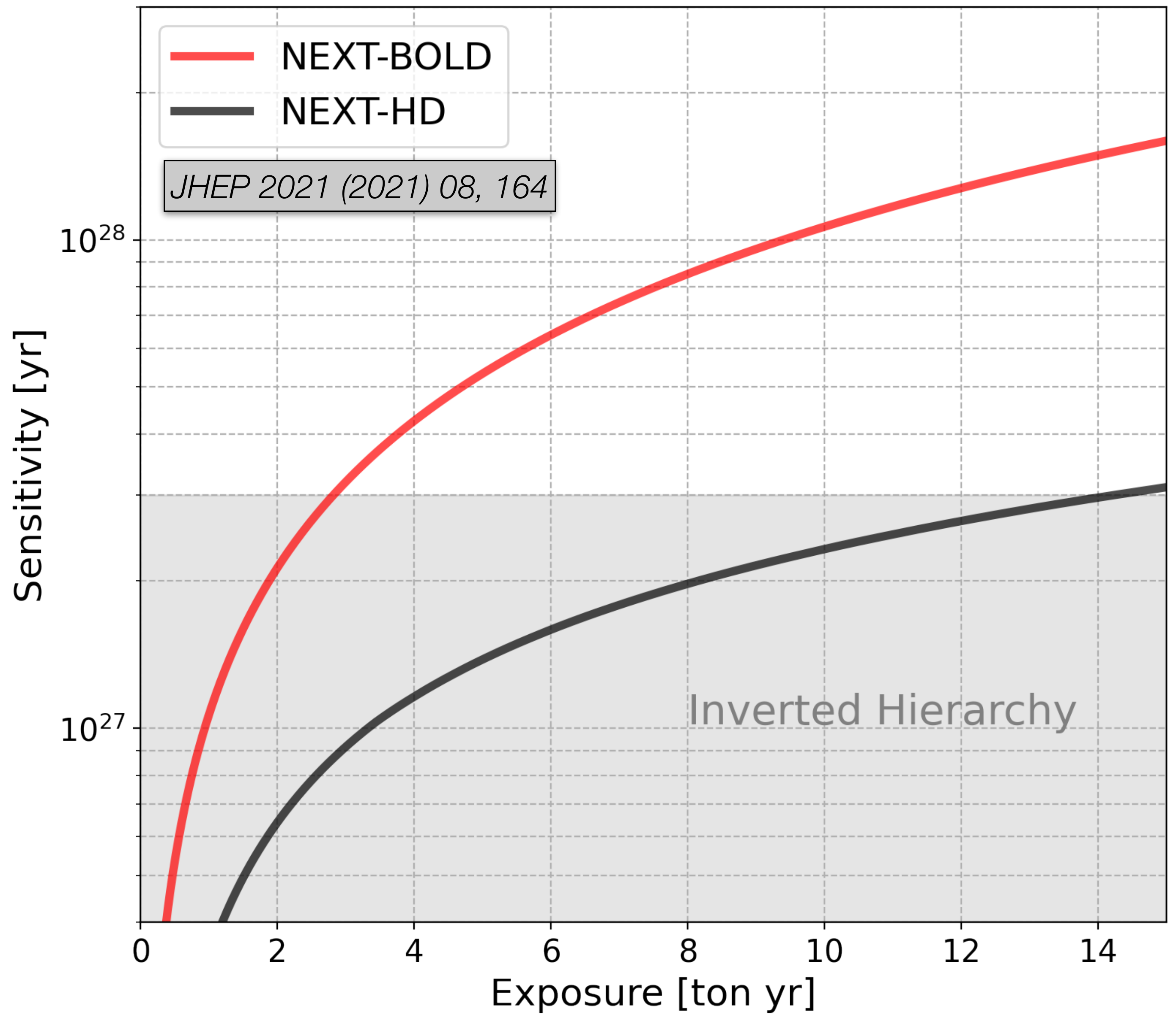
Inner copper shielding
12 cm of ultra-pure copper

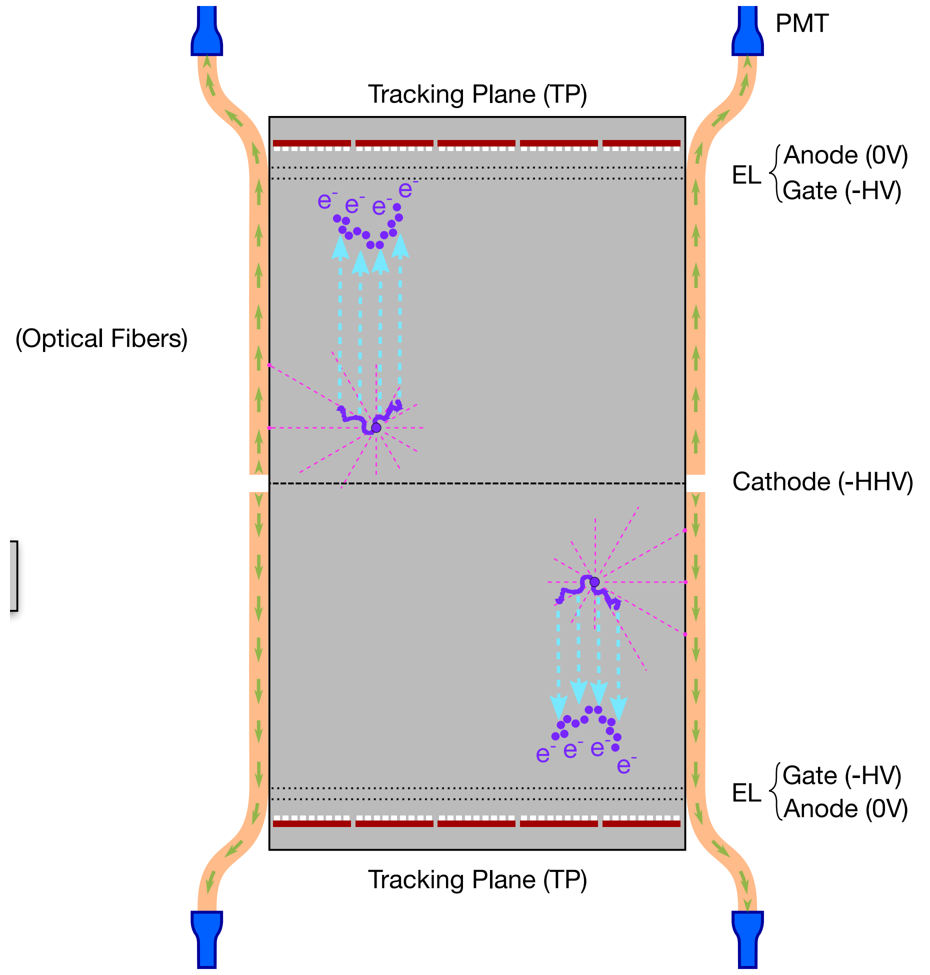




NEXT-100 detector fully assembled at LSC
Commissioning starting in January 2024!

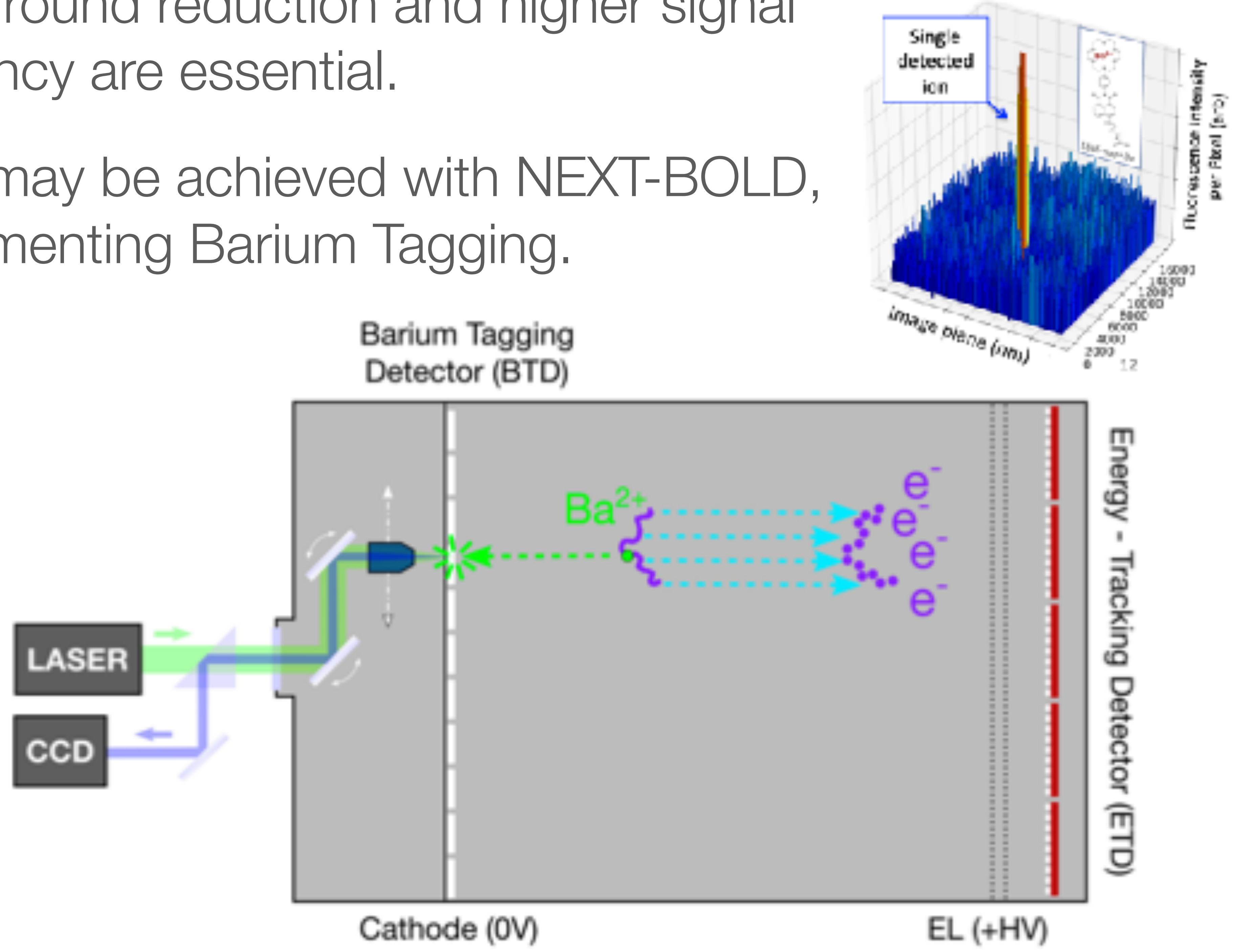
NEXT ton-scale and beyond





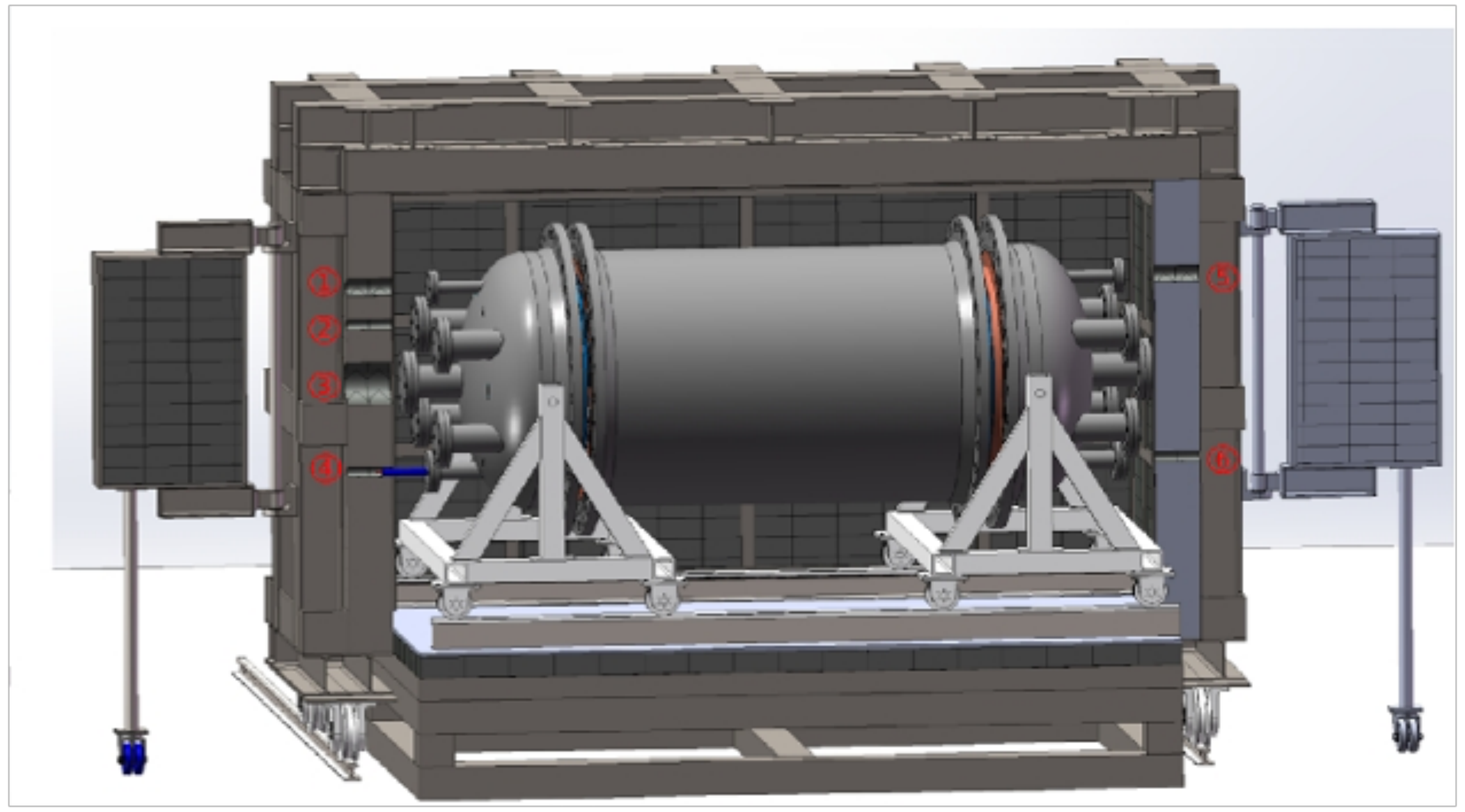
NEXT-HD with symmetric TPC design

- NEXT-HD first module can reach **10^{27} yr** sensitivity with **4 ton·yr** exposure.
- To explore **10^{28} yr** sensitivity, further background reduction and higher signal efficiency are essential.
- Both may be achieved with NEXT-BOLD, implementing Barium Tagging.

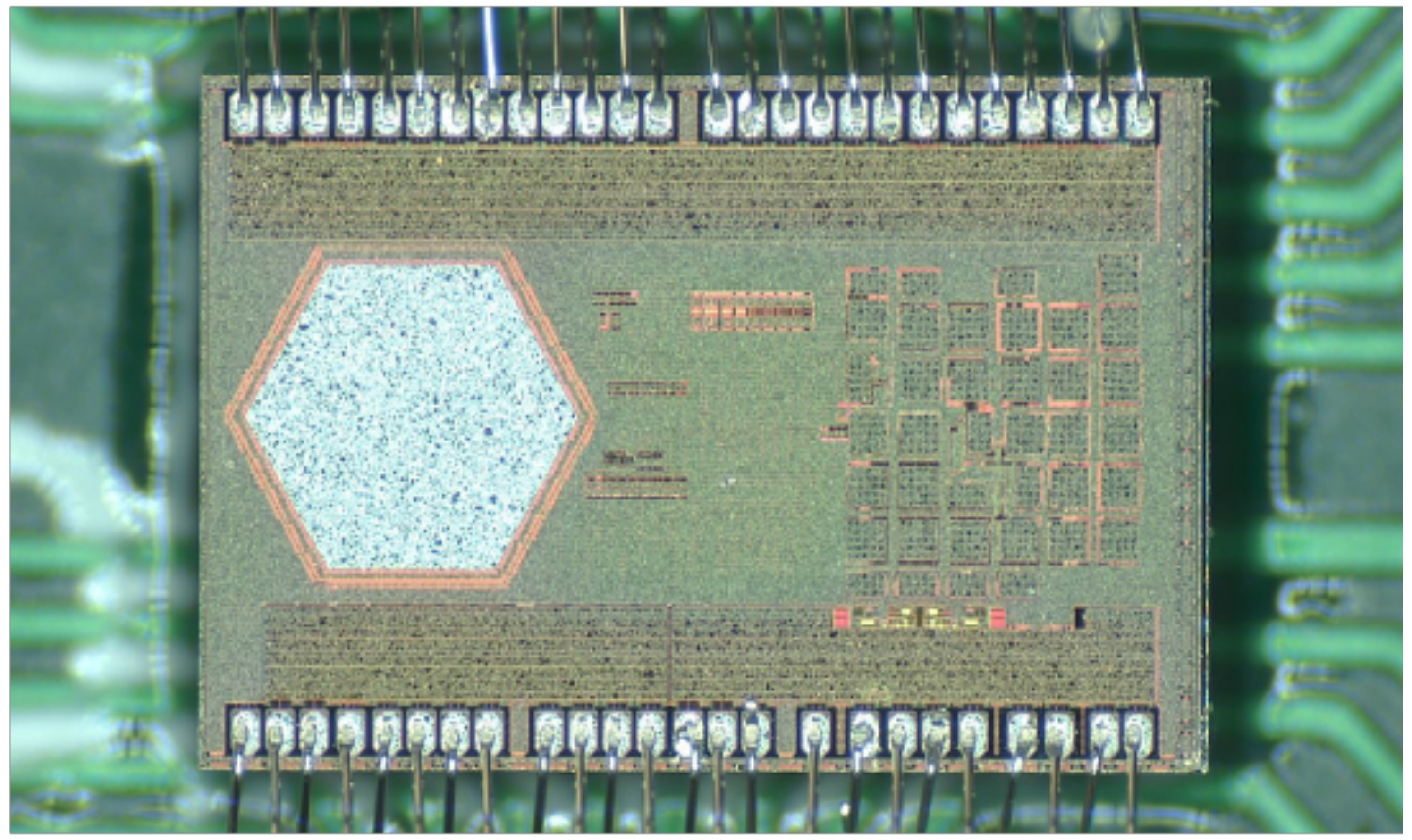


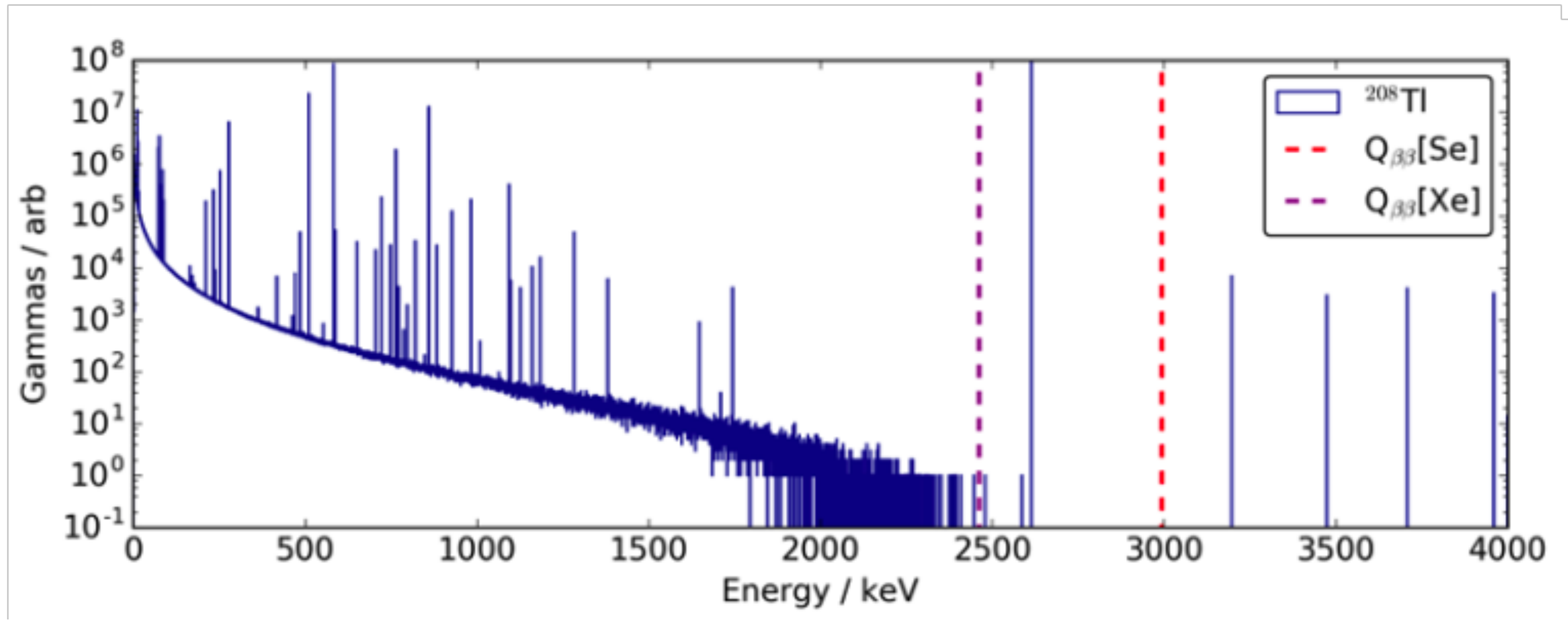
J.Phys.Conf.Ser. 650 (2015) 1, 012002; JINST 11 (2016) 12, P12011; Phys. Rev. Lett. 120 (2018) 13, 132504. Sci.Rep. 9 (2019) 1, 15097; Nature 583 (2020) 7814, 48–54; ACS Sens. (2021) 6, 1, 192–202; arXiv:2201.09099, arXiv:2109.05902

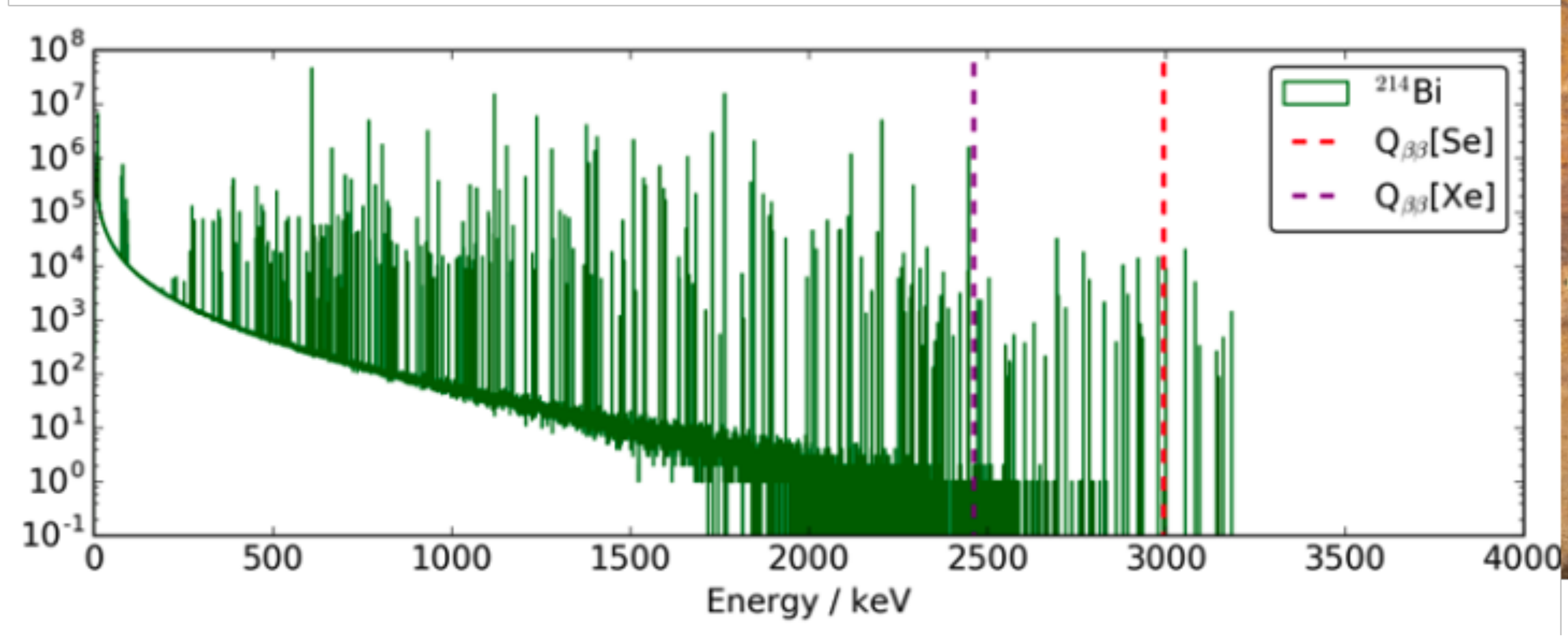
NvDEx: $^{82}SeF_6$ HP TPC

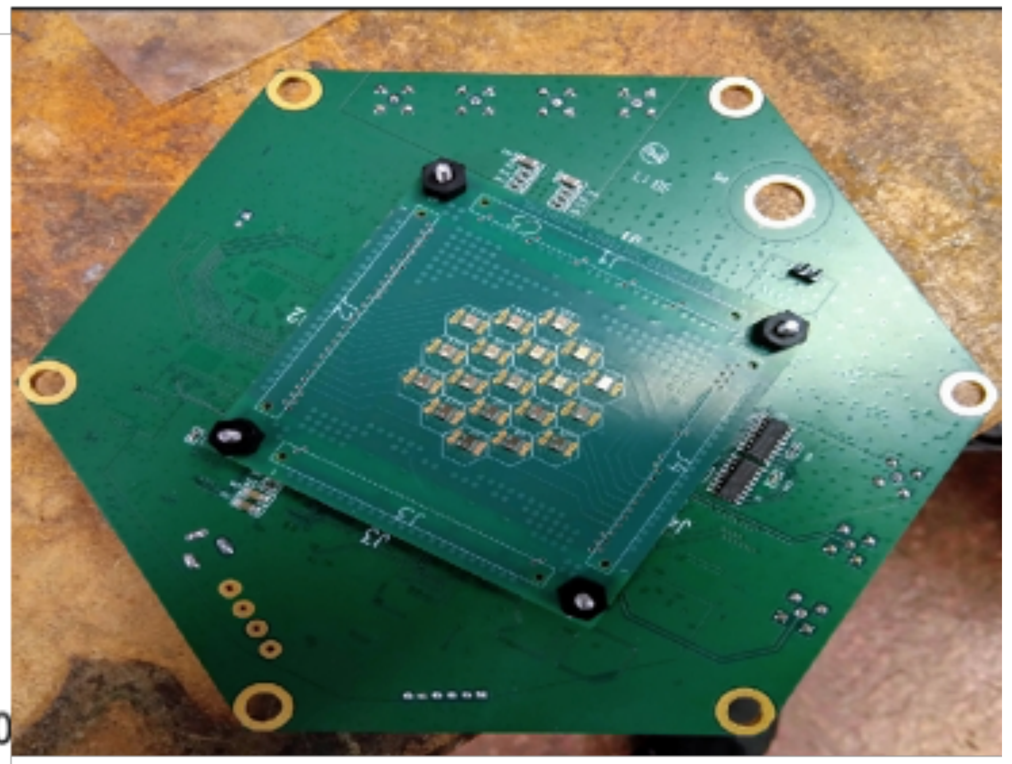


- HP $^{82}SeF_6$ TPC: topology to reject background
- $^{82}SeF_6$ electronegative: Topmetal-S sensor being developed to detect negative ions drifting
- Good energy resolution expected without electron avalanche multiplication: FWHM 1%@3 MeV
- Q-value: 2.996 MeV, higher than most of the background
- To be placed at CJPL: 2400 m rock overburden
- Very low background: 0.05 events/year for 100kg gas, excellent prospects for scalability





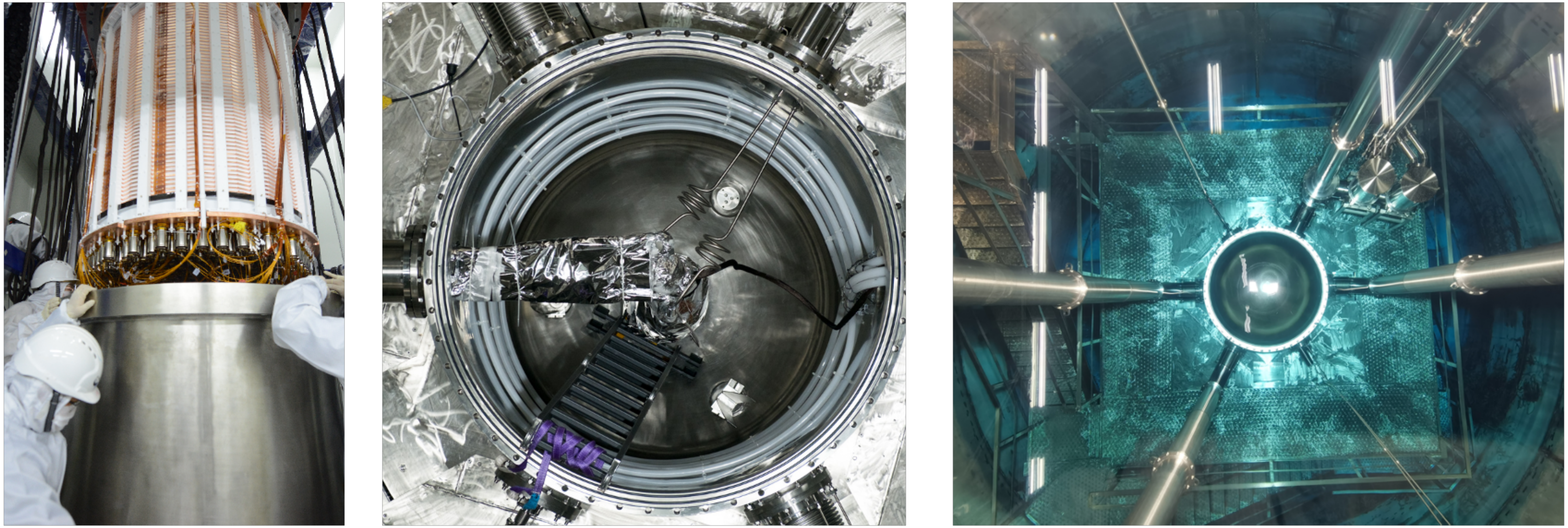




PandaX-4T

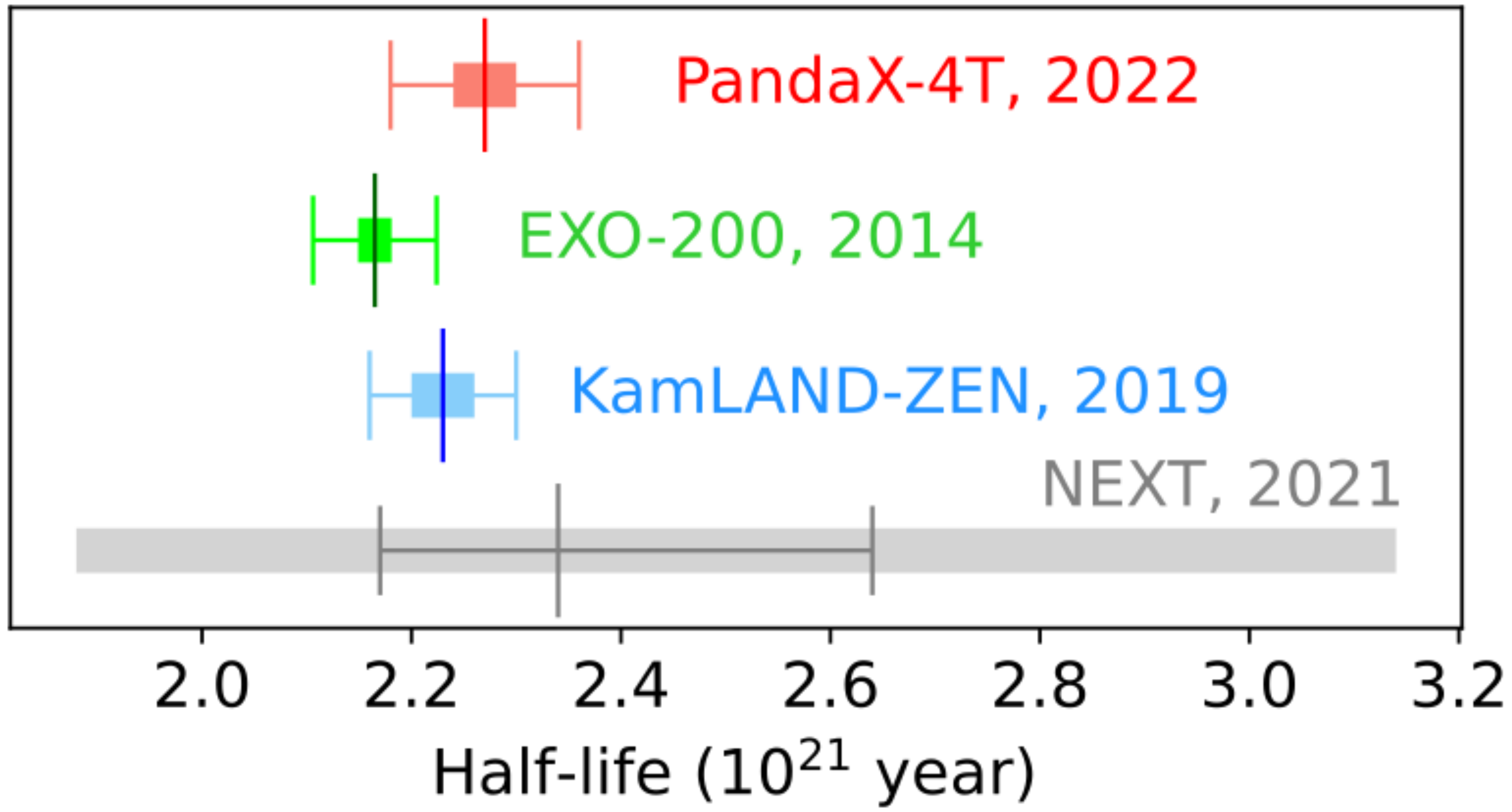
- A dual-phase TPC with 3.7 tons of xenon at China Jinping Underground Laboratory
    - More than 300 kg of ^{136}Xe in the sensitive volume

- Commissioned since late 2020: Run 0 (~ 95 d); Run 1 (~ 154 d live time)

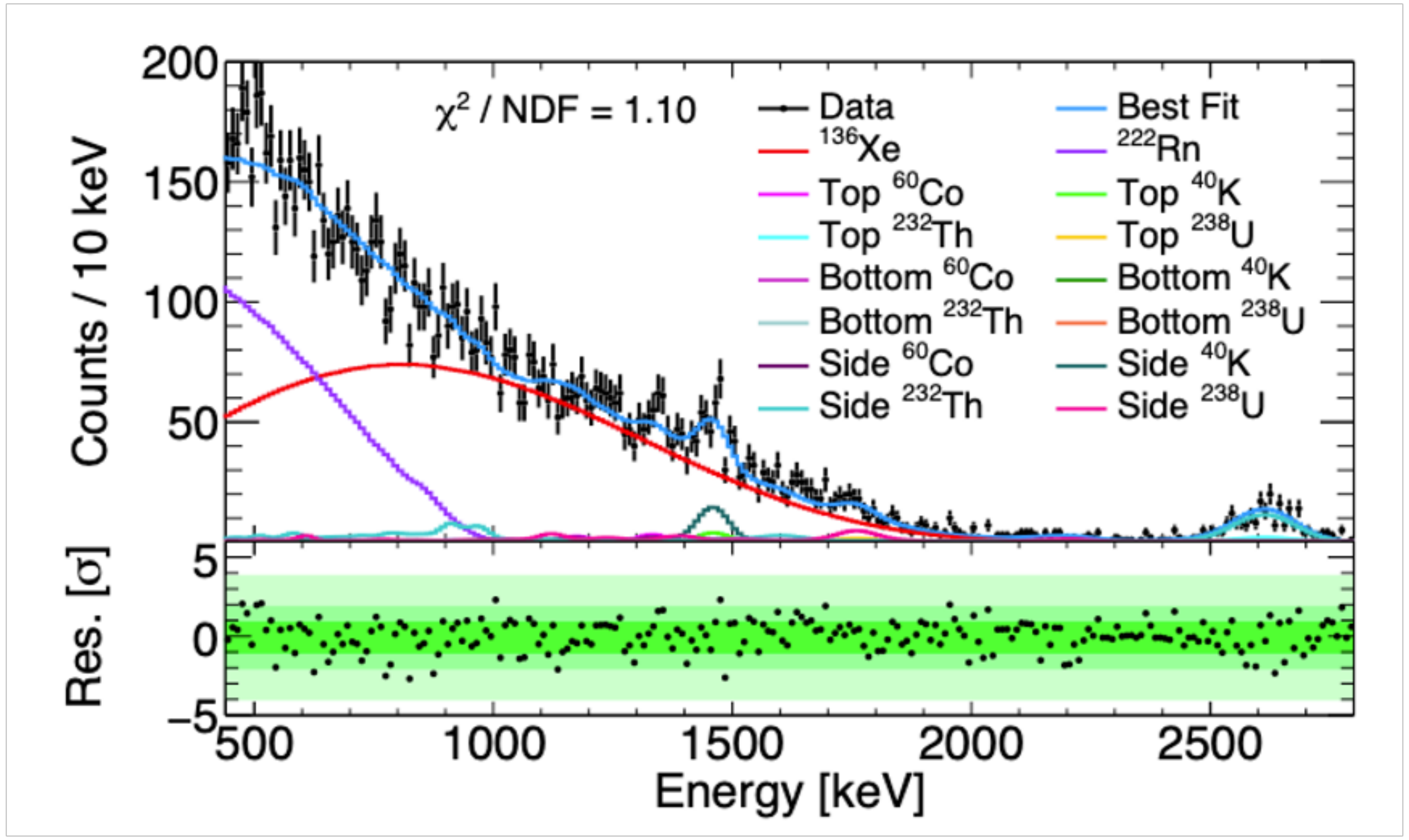


^{136}Xe DBD half-life measurement

- ^{136}Xe DBD half-life measured by PandaX-4T: 2.27 ± 0.03(stat.) ± 0.09(syst.) × 10^{21} year
- 440 keV – 2800 keV range is the widest ROI
- Comparable precision with leading results
- First such measurement from a natural xenon TPC

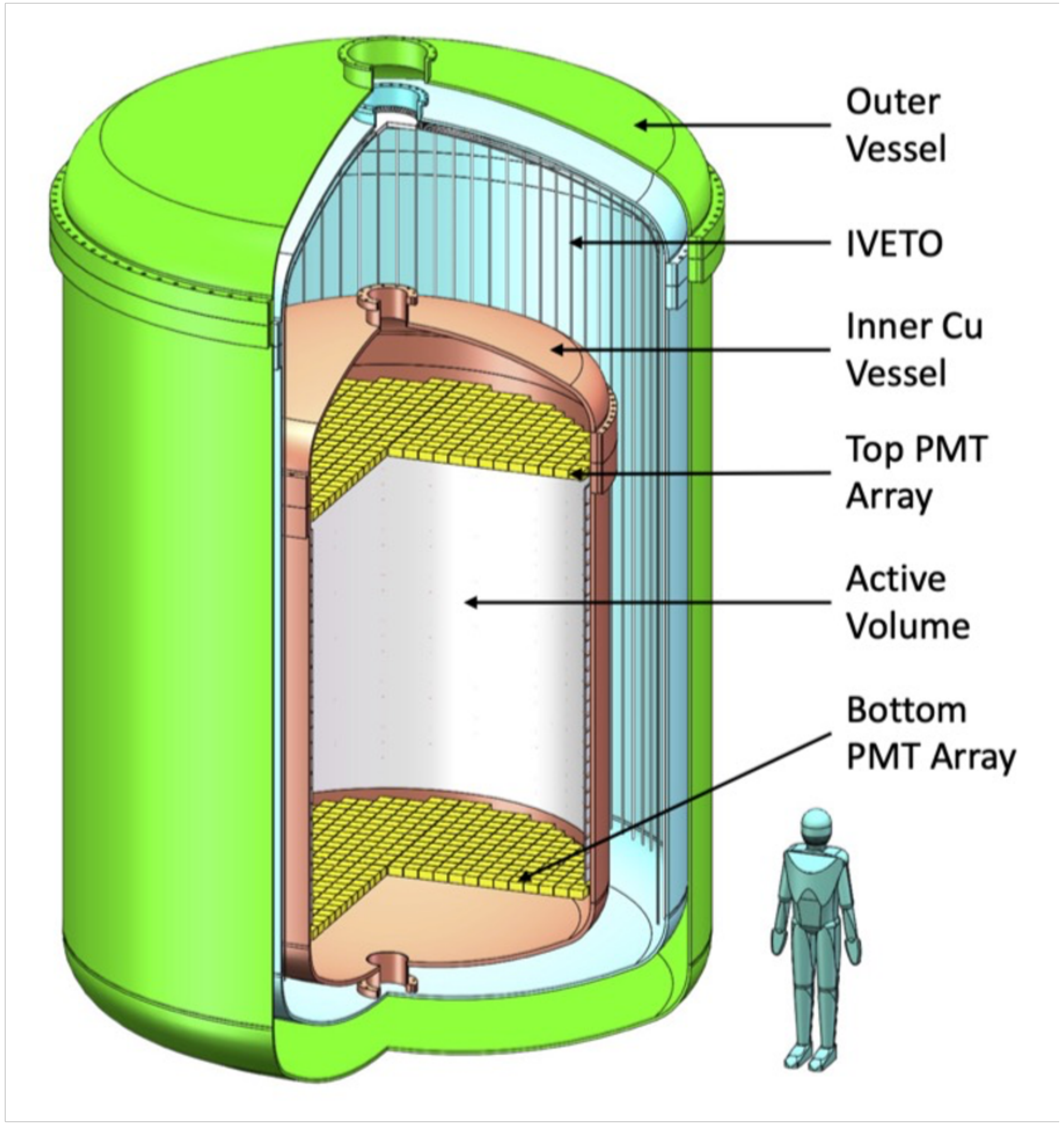


Research, 9798721 (2022)



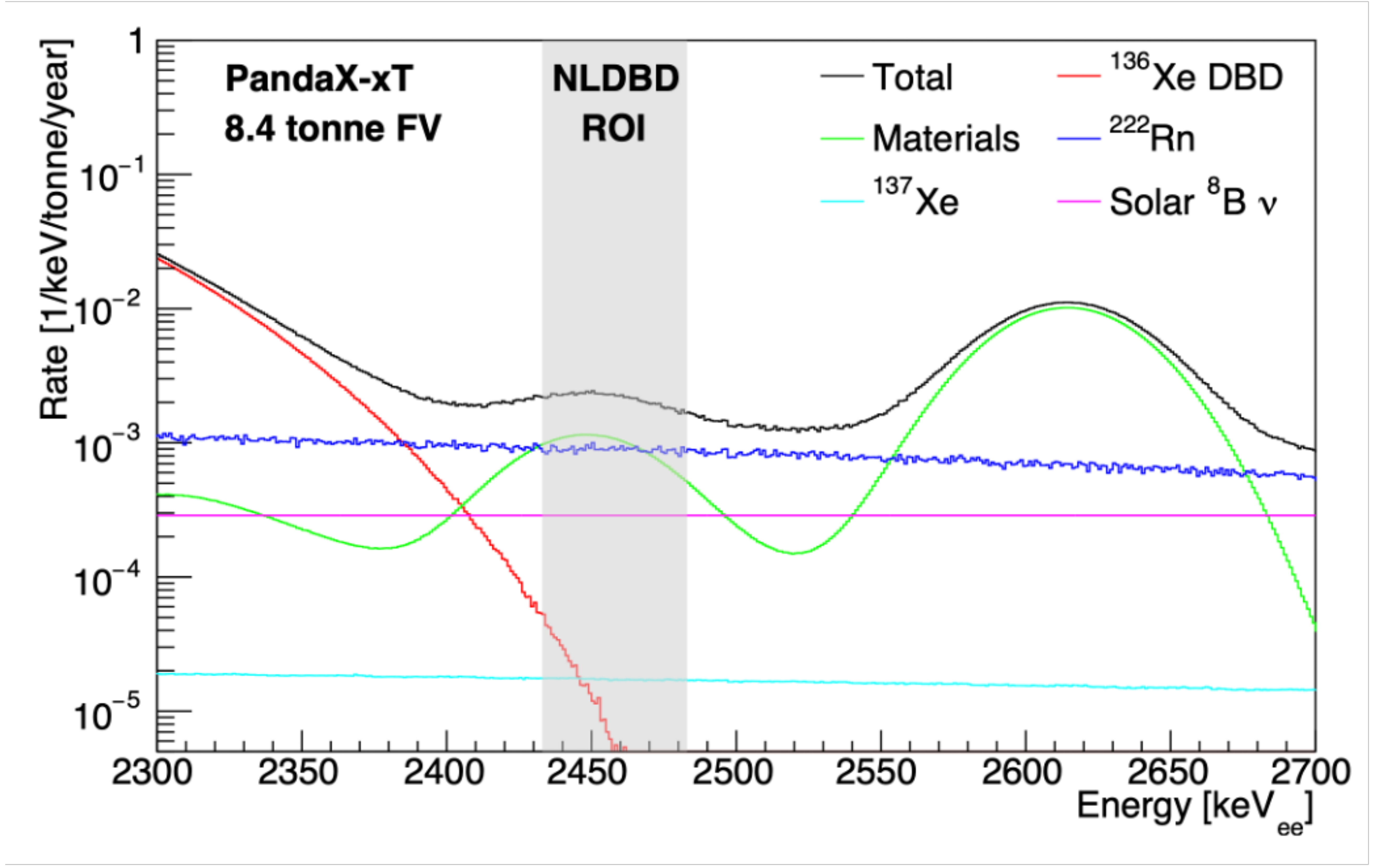
PandaX-xT: Multi-ten-tonne Liquid Xenon Observatory

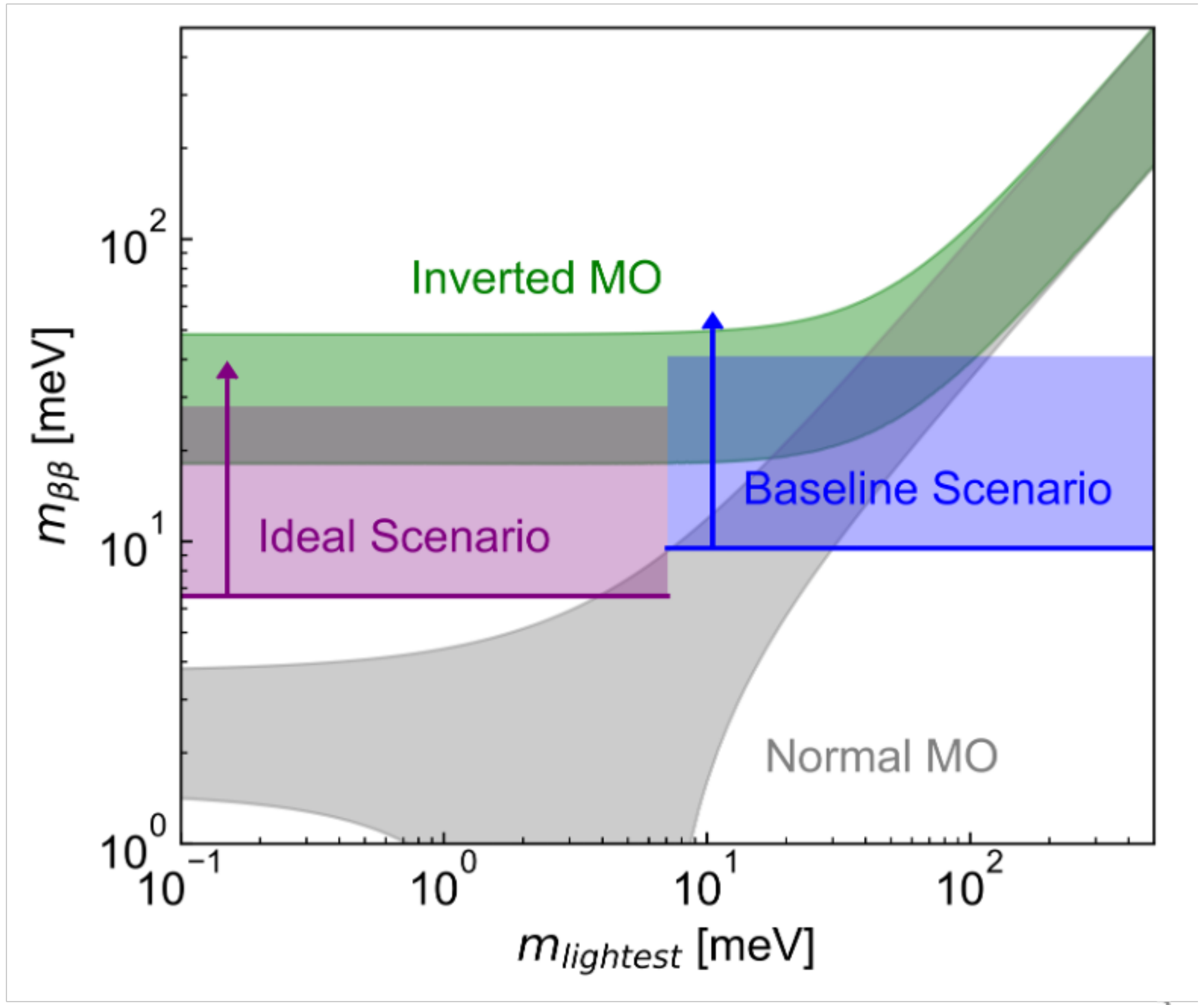
- Active target: 43 ton of Xenon
  - Decisive test to the WIMP paradigm
  - Explore the Dirac/Majorana nature of neutrino
  - Search for astrophysical or terrestrial neutrinos and other ultra-rare interactions
- Improved PMT, veto, vessel radiopurity, etc
- Staged upgrade utilizing isotopic separation on natural xenon.



PandaX-xT for NLDBD

- 4 ton of ^{136}Xe: one of the largest DBD experiments
- Effective self-shielding: Xenon-related background dominates

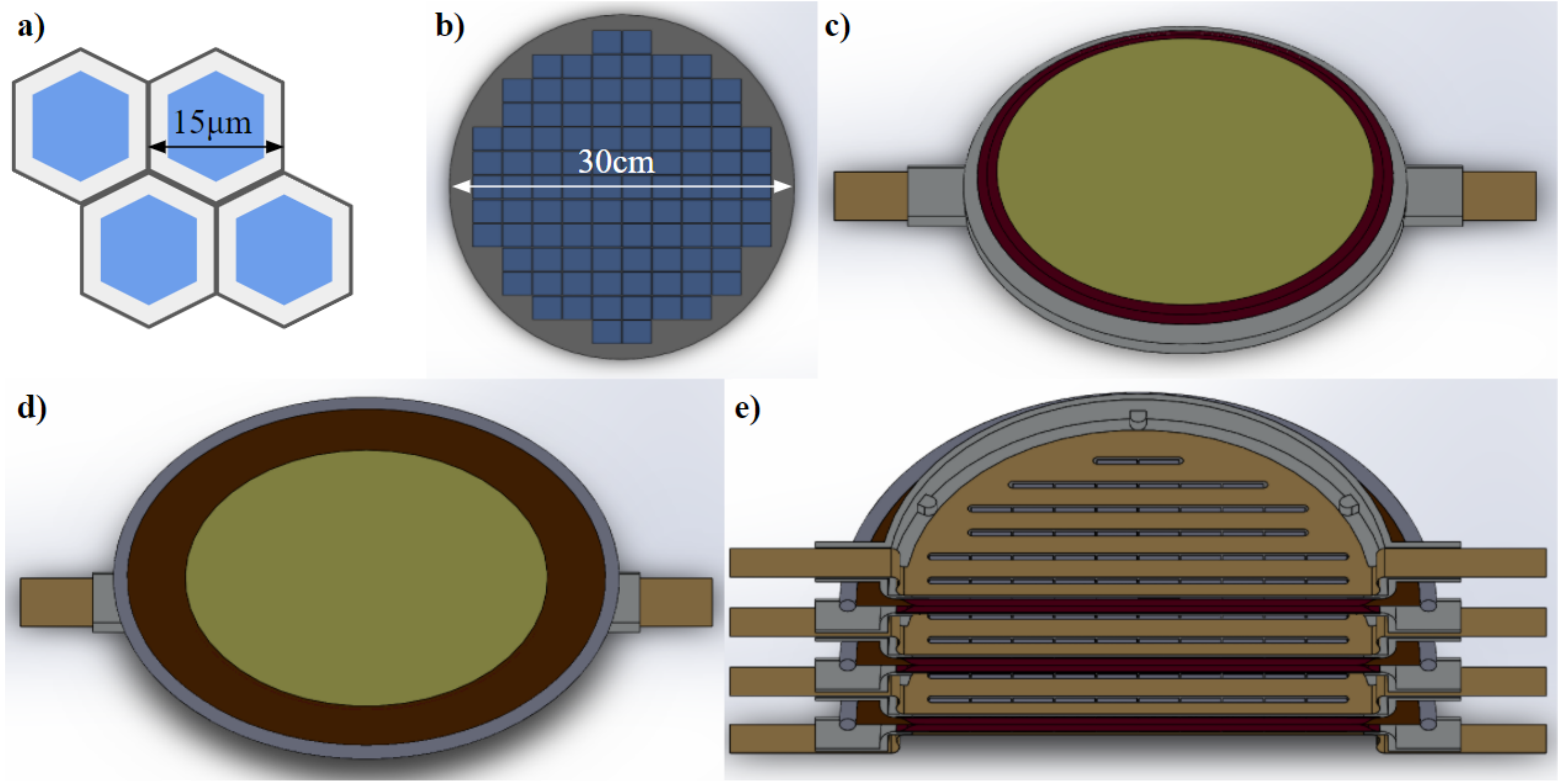


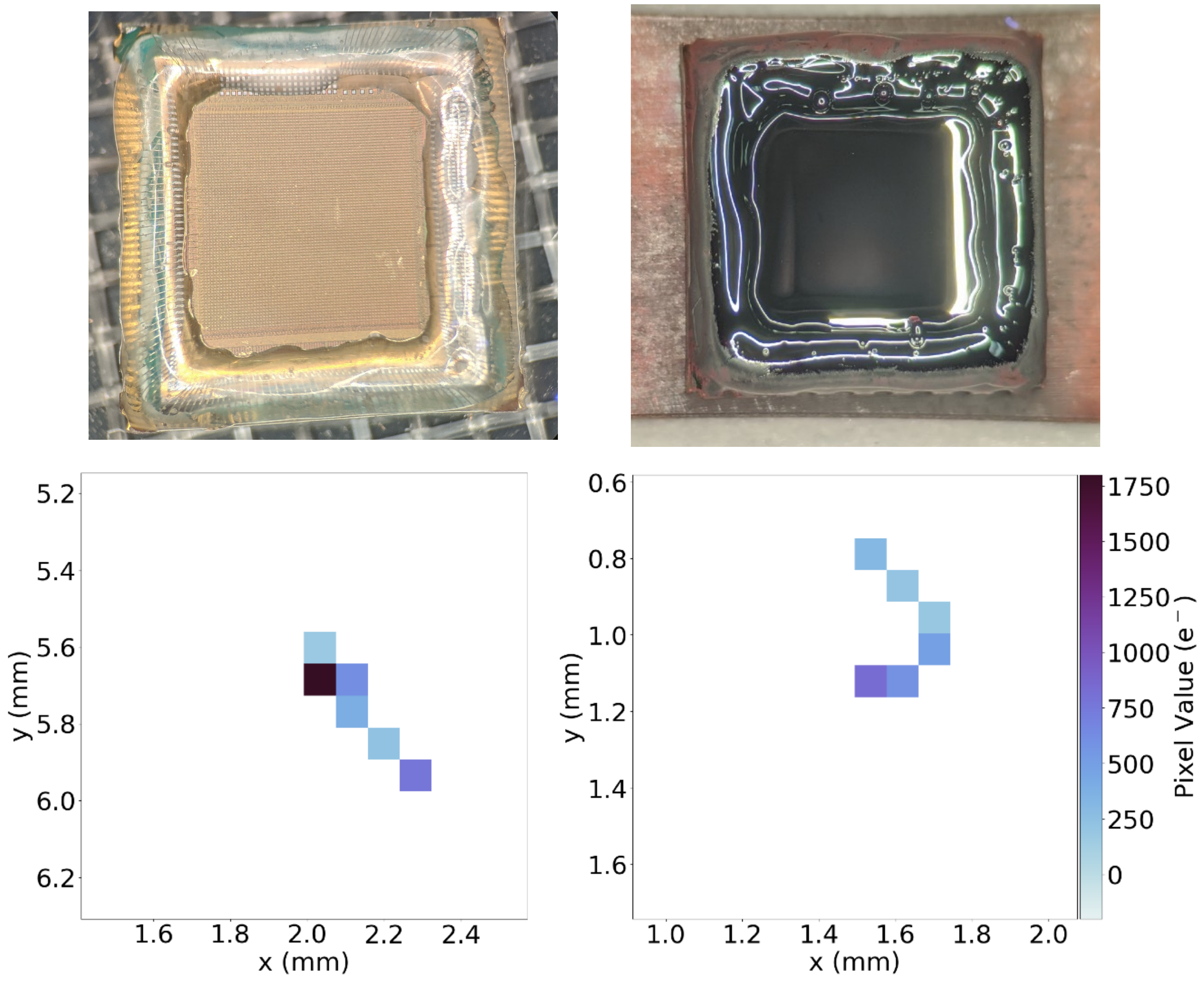


Selena

Snowmass White Paper: arXiv:2203.08779

- 10-ton ^{82}Se active target with exquisite spatial resolution for signal identification.
- Large-area hybrid CMOS imagers with ~5-mm thick layers of amorphous ^{82}Se.
- Leverages existing industrial capabilities for CMOS fabrication and aSe deposition for scalability.
- Neutrinoless $\beta\beta$ decay sensitivity of $\boldsymbol{m_{\beta\beta}}$ **= 4 to 8 meV** (3σ) in 100-ton year.
- Currently in R&D stage with small pixelated devices.





Demonstration of ~MeV electron tracks!

Selena $\beta\beta$

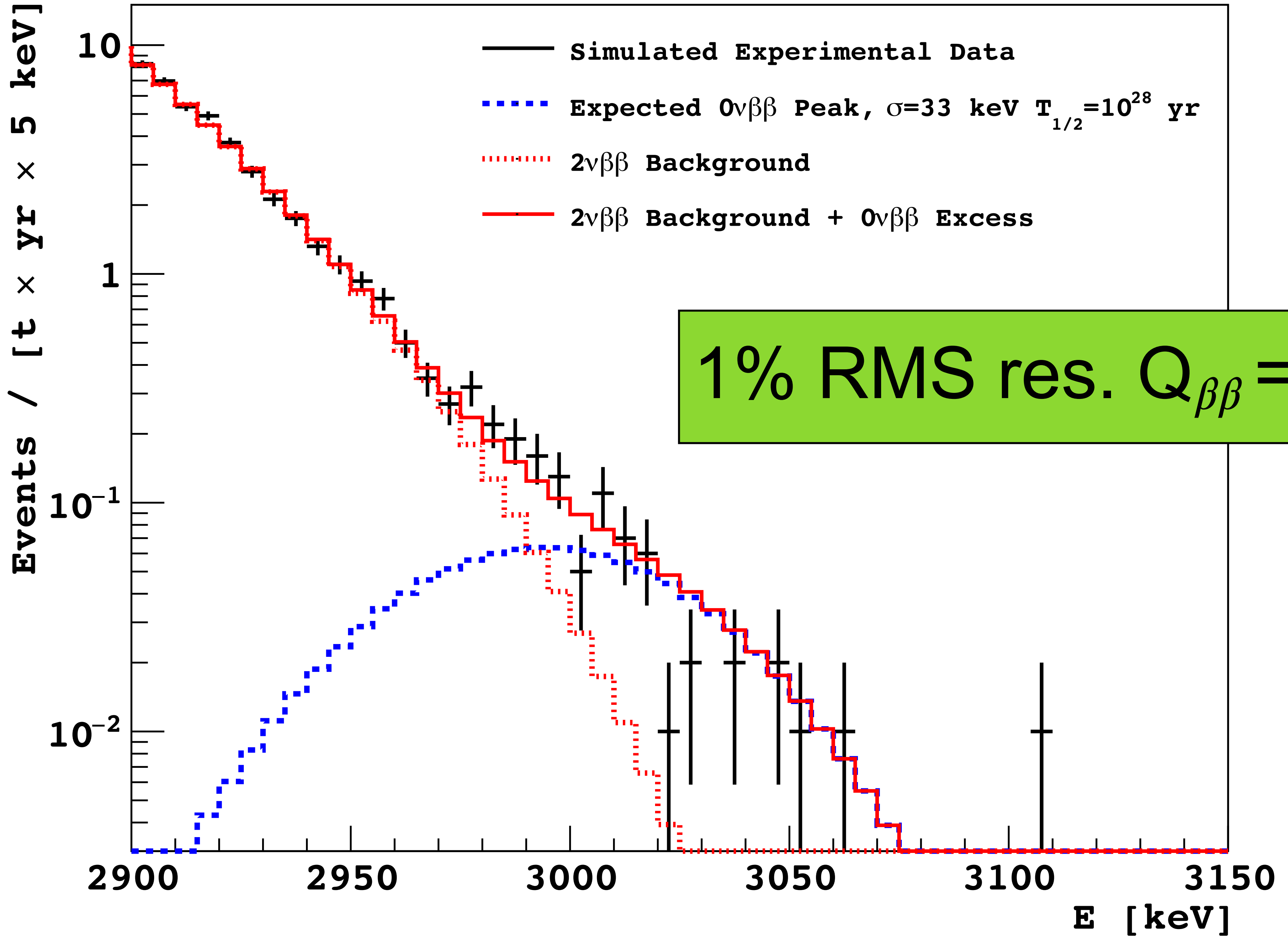
- By identification of Bragg peaks, can achieve 10^{-3} suppression of single electron background, with 50% signal acceptance.
- Bulk backgrounds suppressed by α/β particle ID, spatial correlations.

Background rate <6 x 10^{-5} /keV/ton/year!

3σ discovery for $T_{1/2}$ = **2 x 10^{28} y** in ^{82}Se

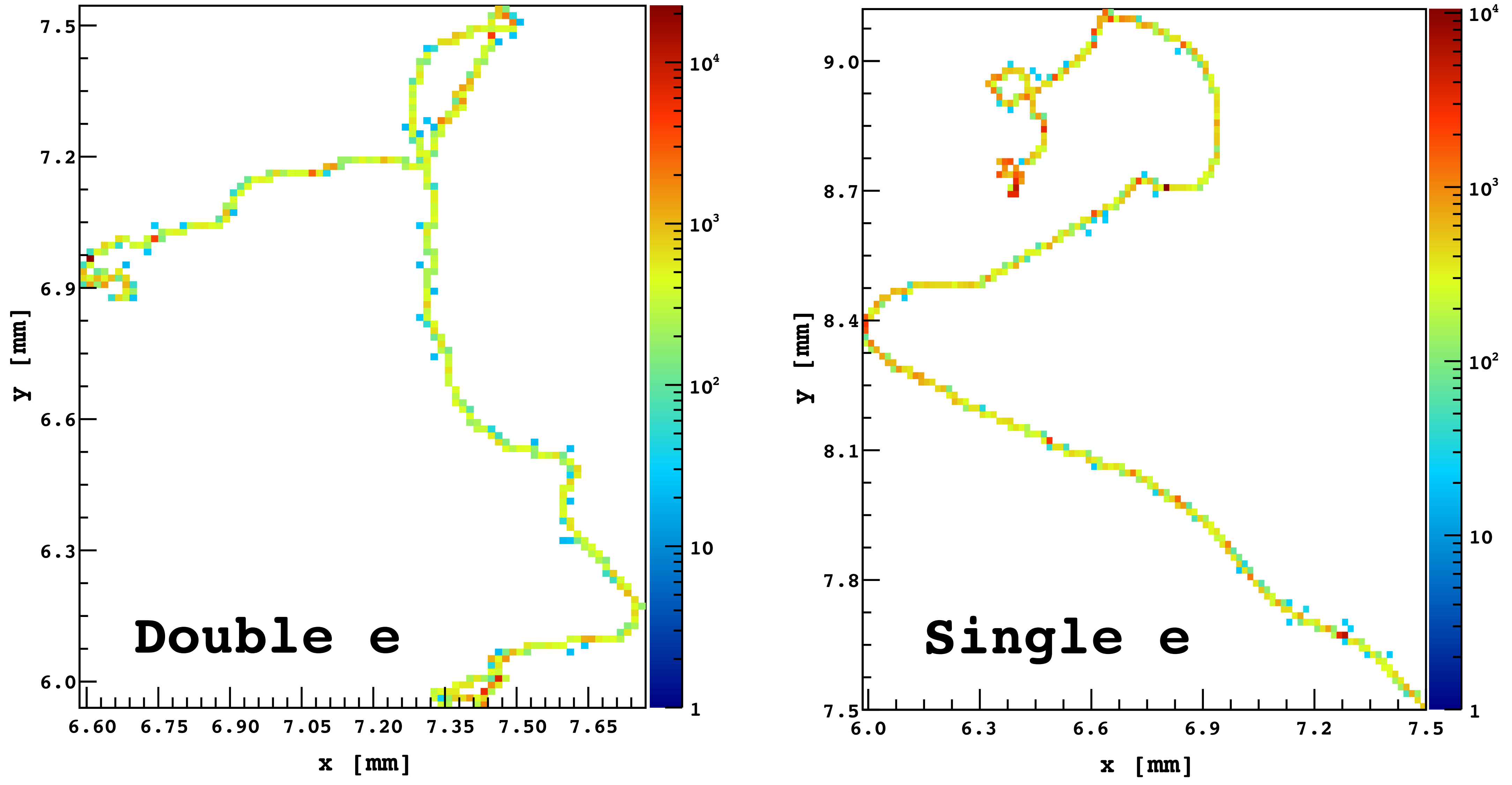
Or study 0$\nu\beta\beta$ mechanism after ton-scale discovery!

100 ton-year simulation



1% RMS res. $Q_{\beta\beta}$ = 3 MeV

Simulation:



SNO+ Detector

Papers

- Detector paper: JINST 16 (2021) 08, P08059 and https://arxiv.org/abs/2104.11687
- Scintillator paper: JINST 16 (2021) P05009 https://doi.org/10.1088/1748-0221/16/05/P05009 and https://arxiv.org/abs/2011.12924
- Te loading paper: NIMA 1051 (2023) 168294 and https://arxiv.org/abs/2011.12924
- Scintillator flow: NIMA 1055 (2023) 168430 https://www.sciencedirect.com/science/article/pii/S0168900223004205 and https://arxiv.org/abs/2212.00251

Posters

Cosmogenic Neutron Multiplicity in Water at SNO+ #46 Katharine Dixon

Measuring Solar Neutrino Oscillations in the SNO+ Detector #58 Daniel Cookman

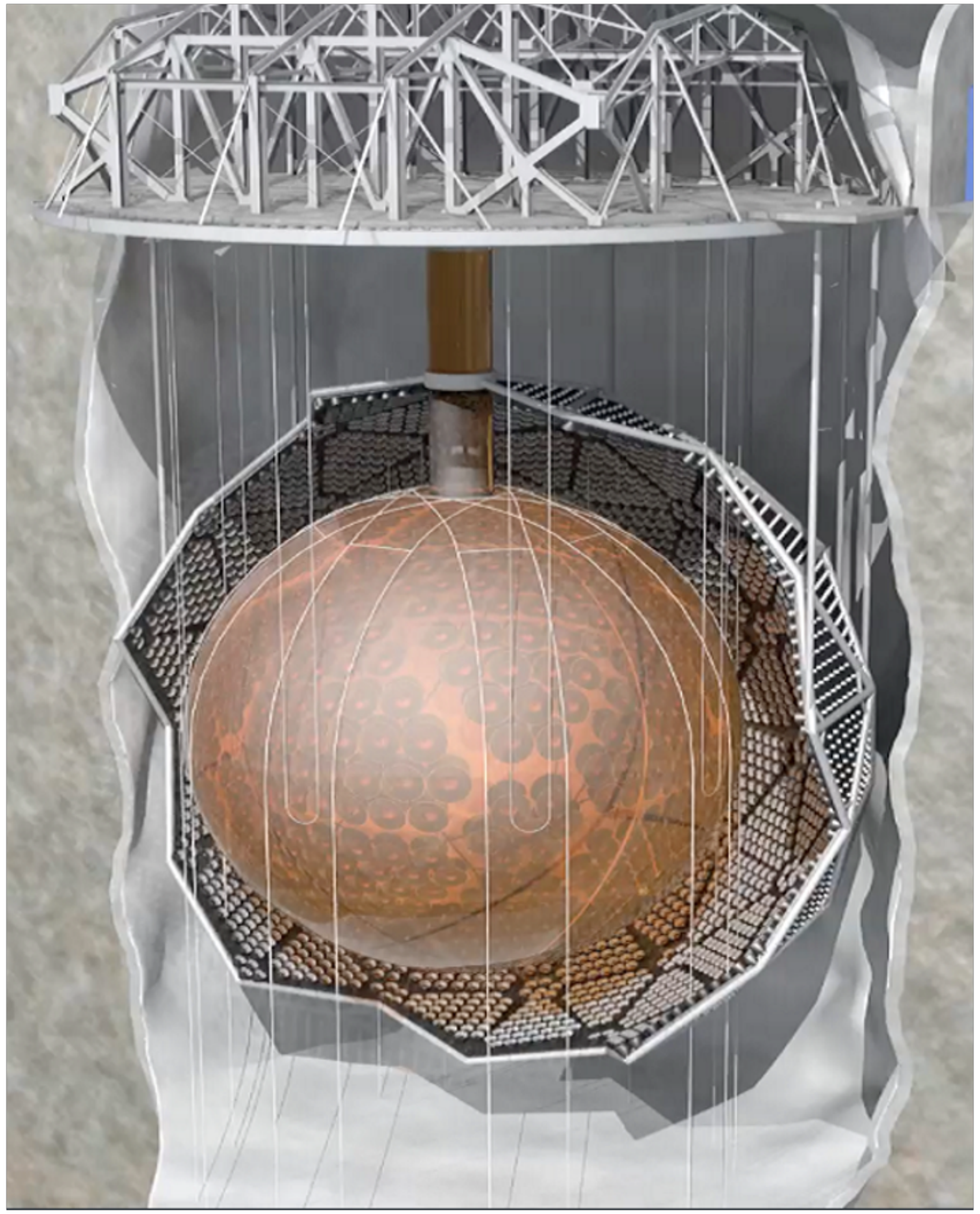
Muon track reconstruction in the scintillator phase of SNO+ #69 Jasmine Simms

Calibration of the Scintillation Timing in SNO+ using In-Situ Backgrounds #76 Rafael Hunt-Stokes

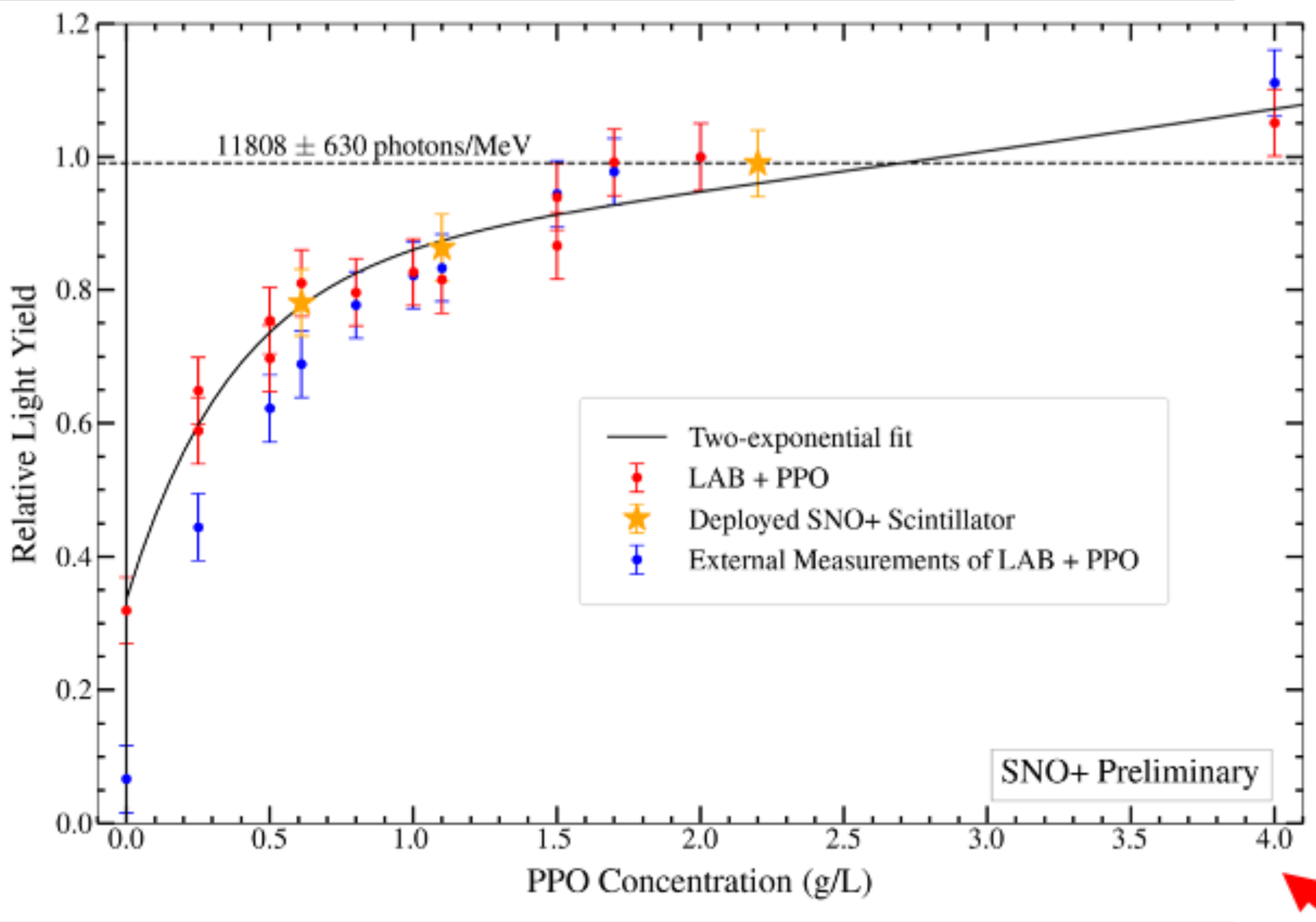
The SNO+ journey towards 0νββ #77 Ana Sofia Carpintiero Inacio

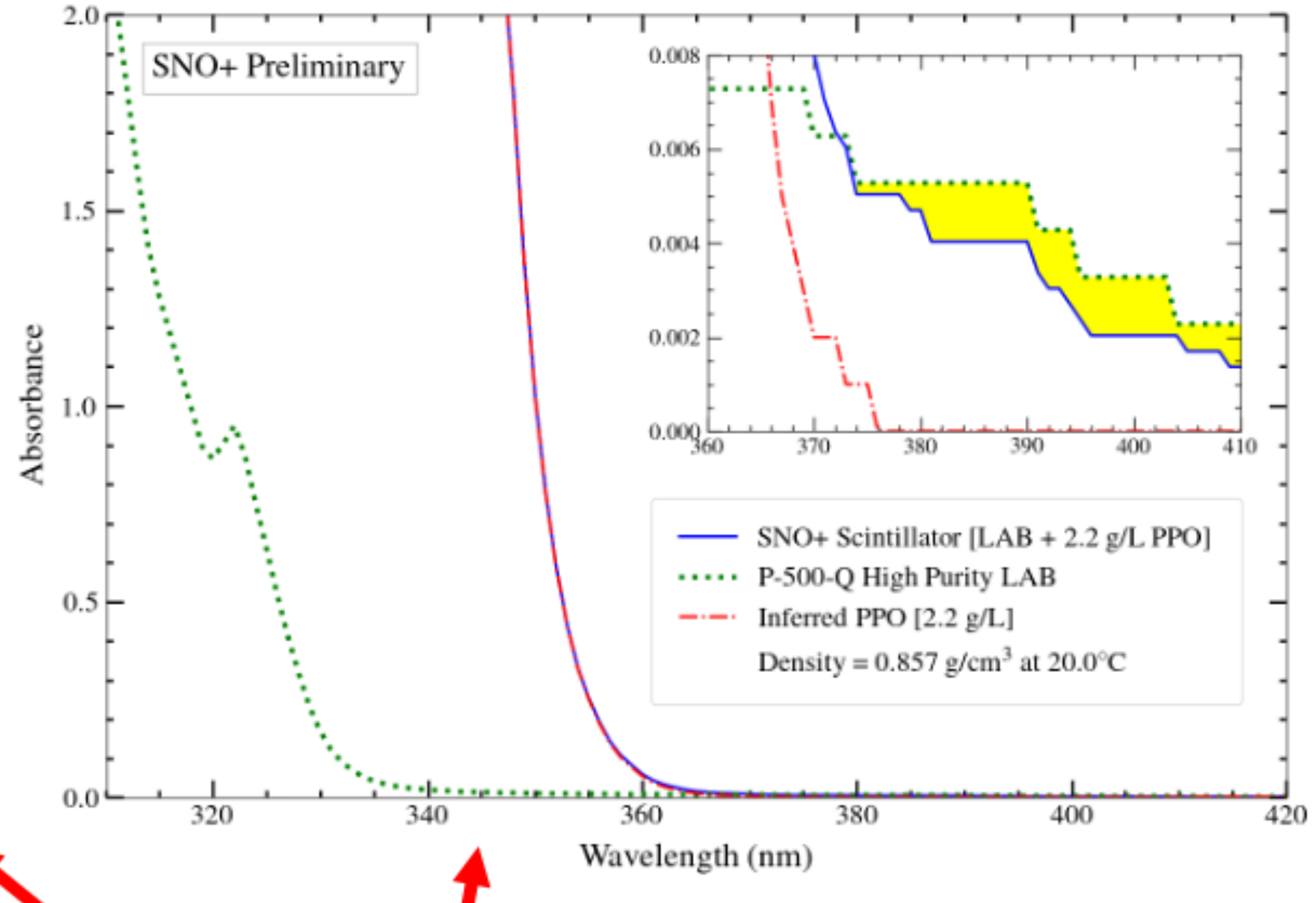
Measuring SNO+ Scintillator Optics with SMELLIE #78 Po-Wei Huang

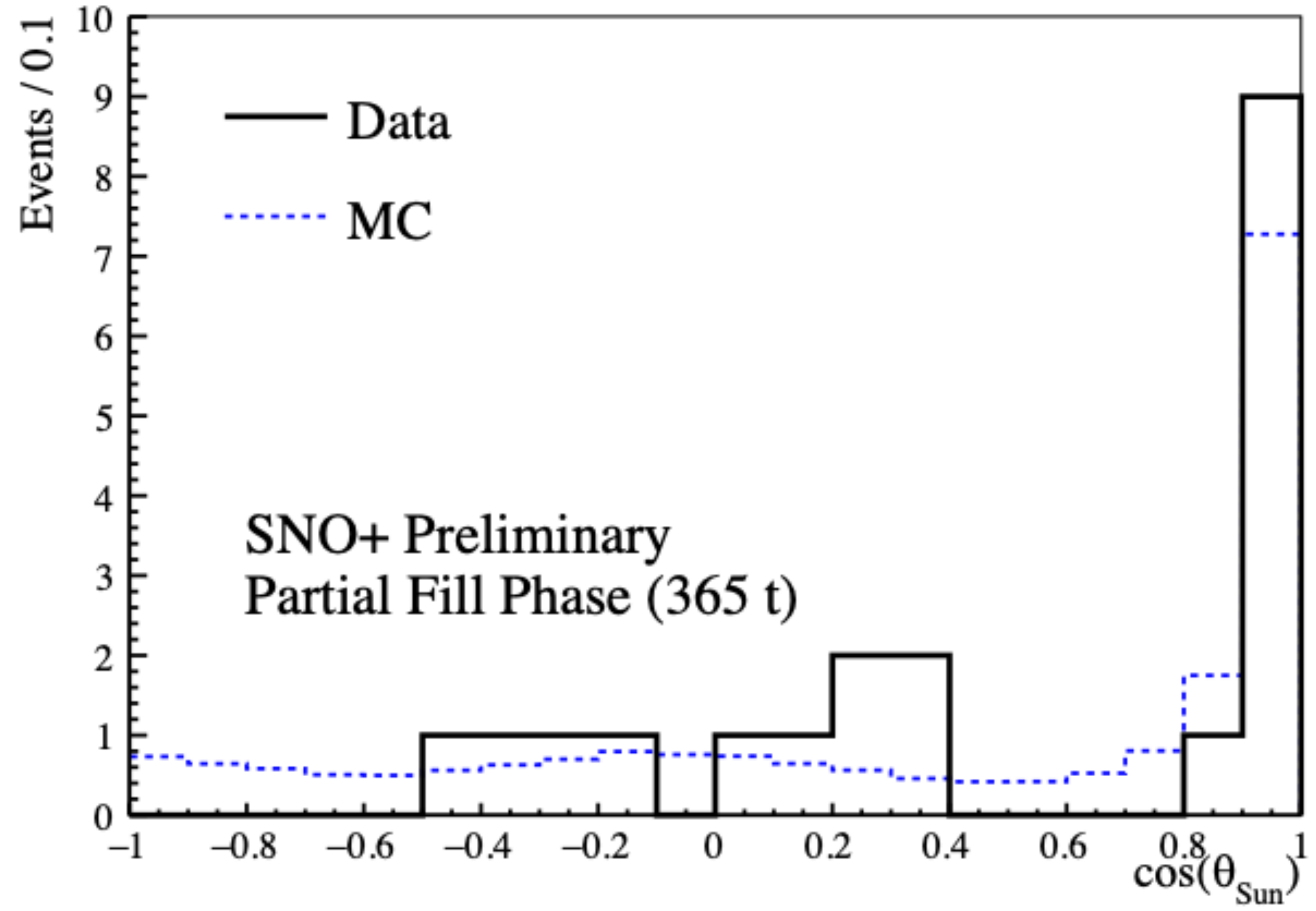
(maybe one more coming by Cal Hewitt)



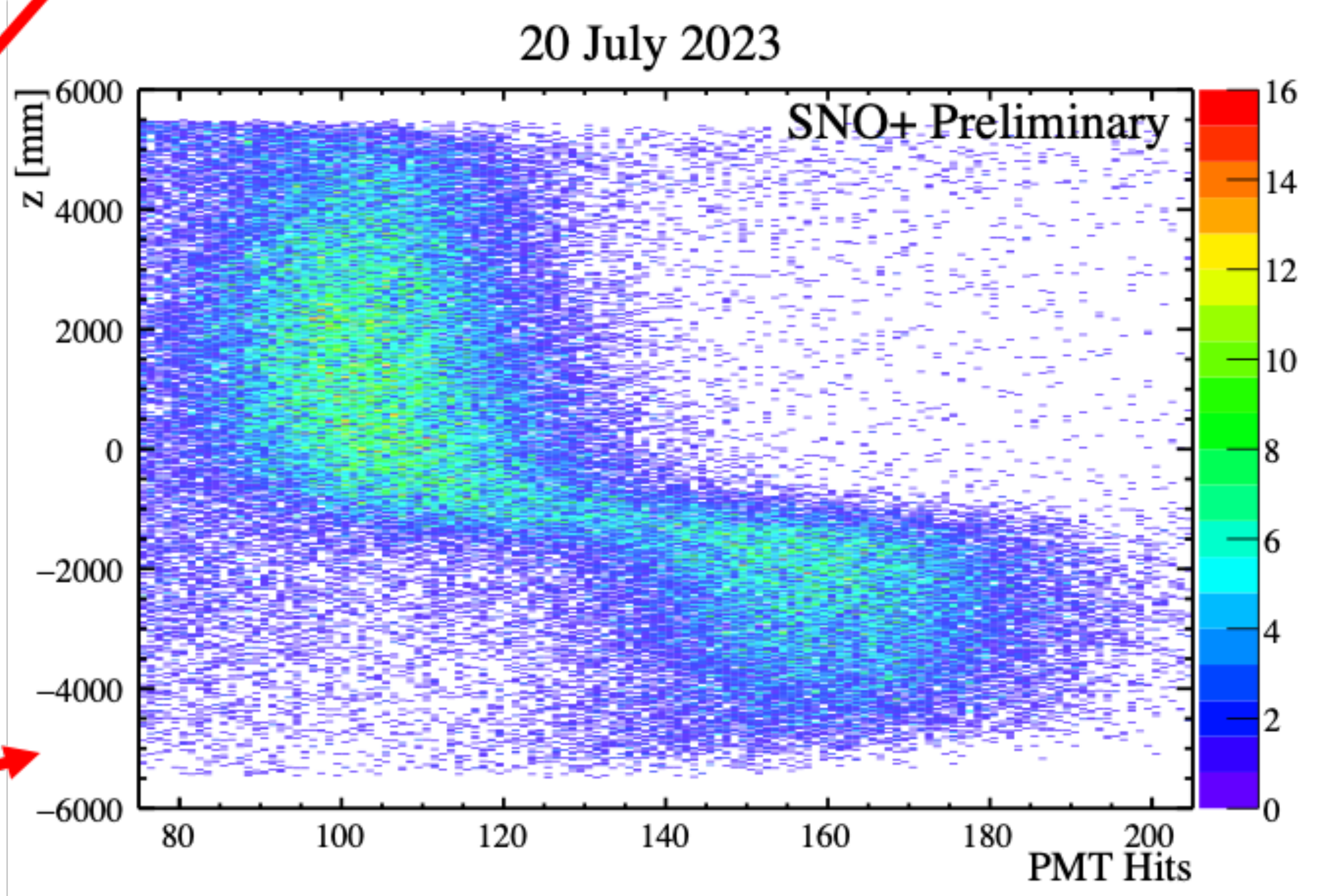
Scintillator Performance







https://arxiv.org/abs/2309.06341



Detector now loaded with 780t LAB+PPO

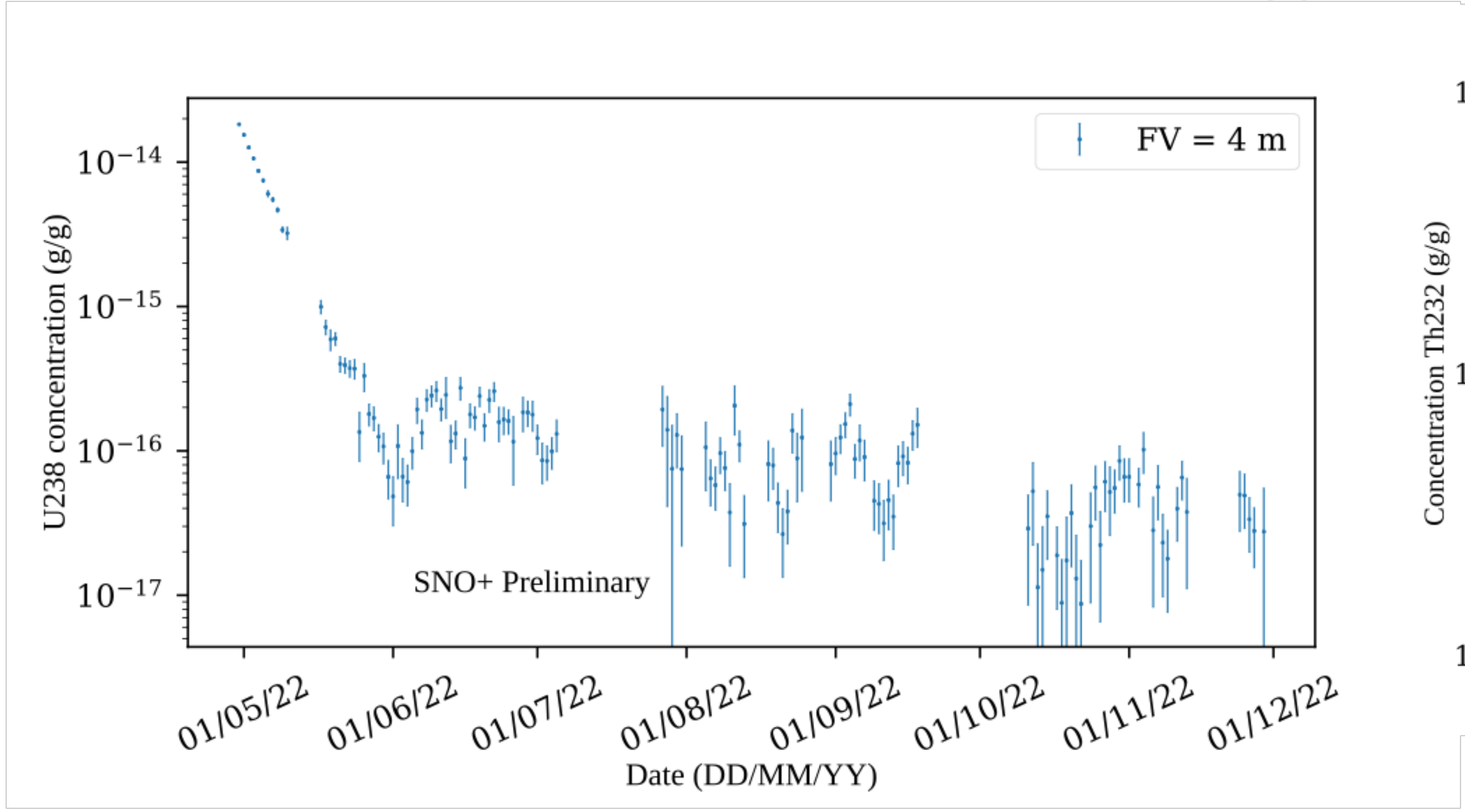
- Data taken at 0.6g/L PPO and 2.2g/L PPO
- High light yield and Excellent optical purity (2.2g/L plots below)
- First event-by-event directional reconstruction of solar neutrinos demonstrated with 0.6g/L PPO
  - Exciting potential for solar background suppression for $0\nu\beta\beta$
- Adding BisMSB to increase light yield further, evaluating light yield as we go
  - Plot shows 0.5kg added from bottom of detector and starting to mix, tracked through ^{210}Po decays

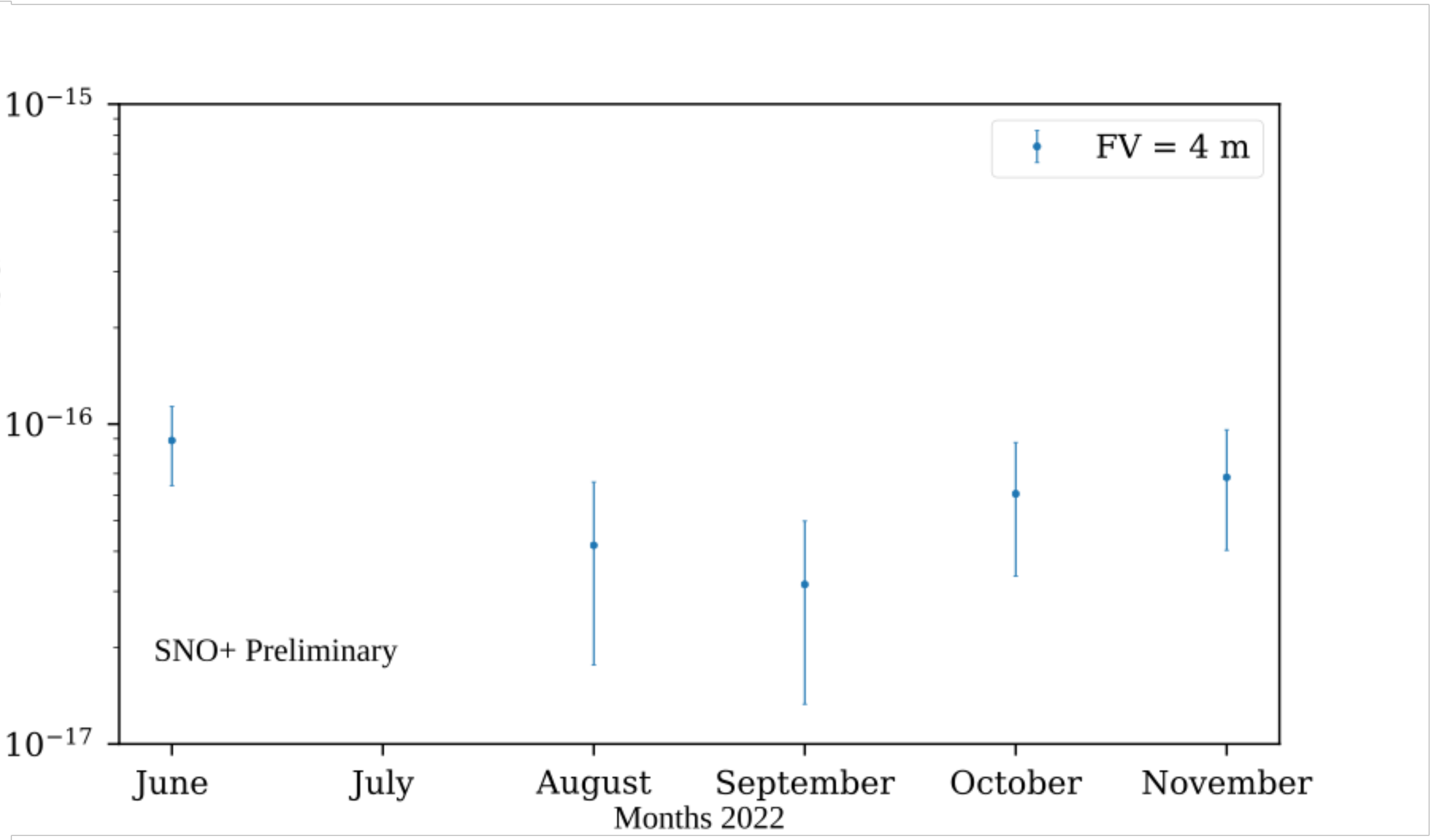
Scintillator Performance

Uranium and Thorium chain backgrounds in 2.2g/L LAB-PPO measured through BiPos:

- ^{238}U chain = $(5.3 \pm 0.1)\times 10^{-17}$g/g
- ^{232}Th chain = $(5.7 \pm 0.3)\times 10^{-17}$g/g

Both below $0\nu\beta\beta$ requirements

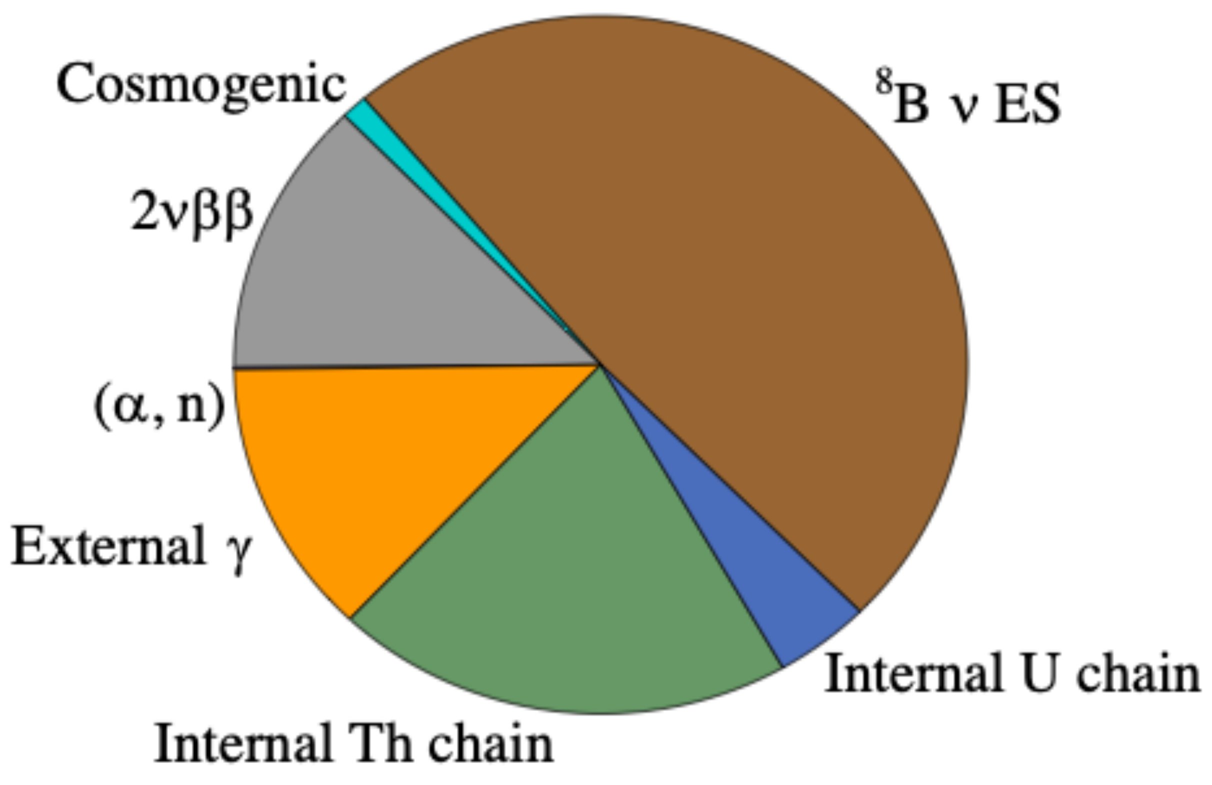


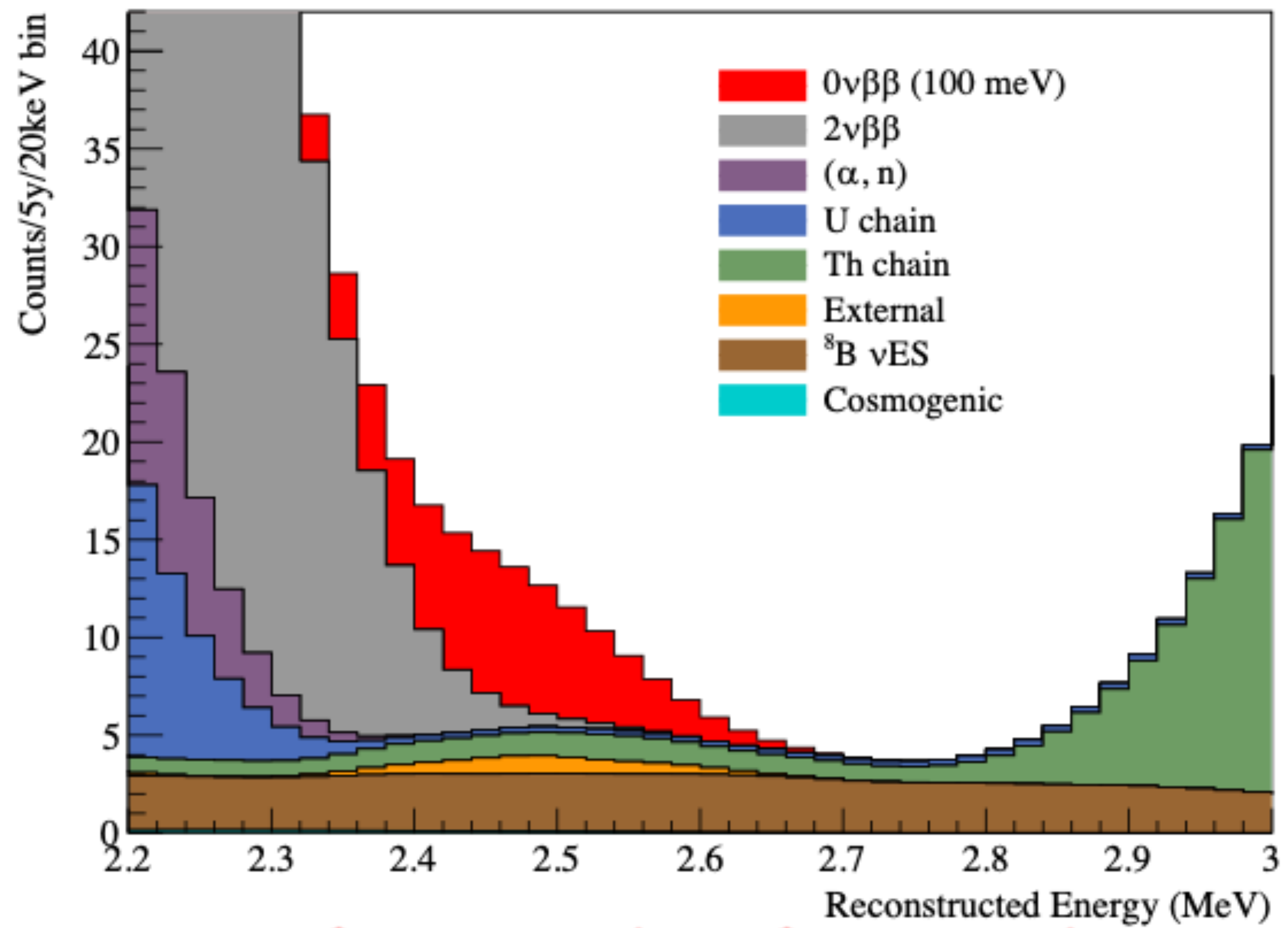


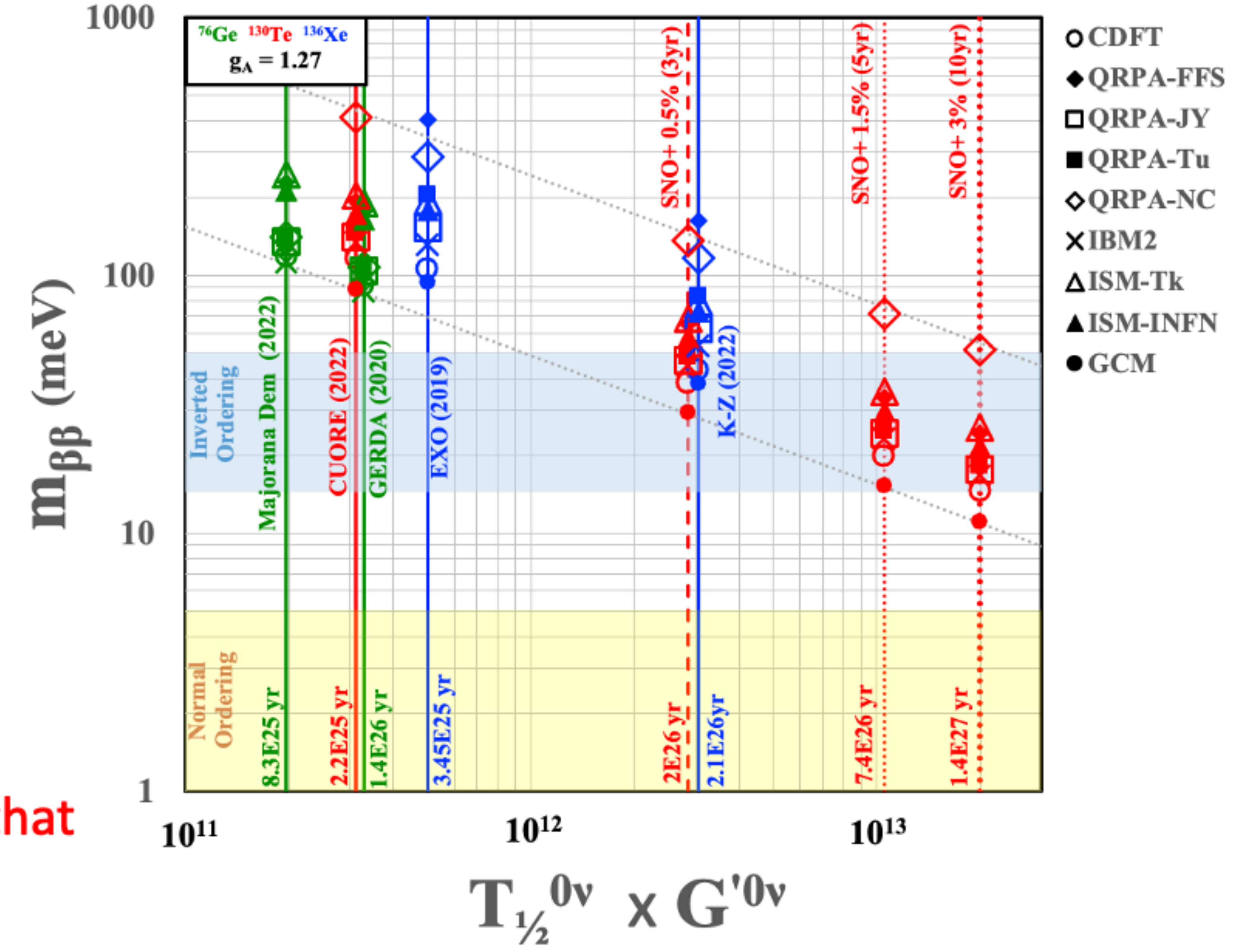
Tellurium Addition

- Initial loading of 0.5% ^{nat}Te by mass (3.9tonnes) in 2025
- Proposal in preparation for higher loading (1.5 – 3% ^{nat}Te) future phases
- Test-batch of purified Telluric-Acid (TeA) in early January

ROI: 2.42 - 2.56 MeV [-0.5σ - 1.5σ]
Counts/Year: 9.47







We are preparing to do a full scale run, purifying 200kg of TeA in the underground plant very soon. If successful (fingers crossed) this will prove that the plant is fully operation and that we can purify the TeA on a large scale.