INSTITUTE for NUCLEAR THEORY

Experimental searches for neutrinoless double beta decay

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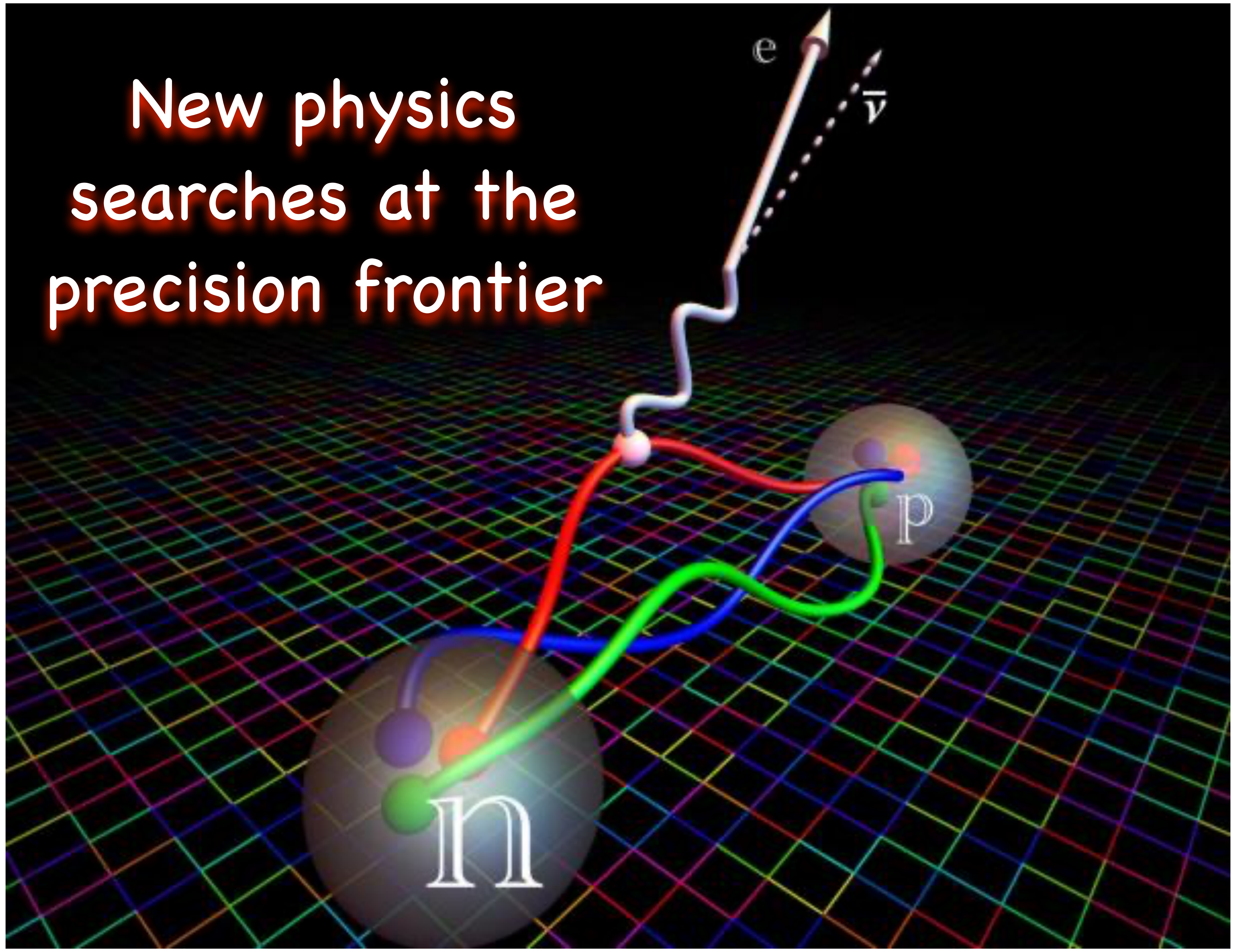
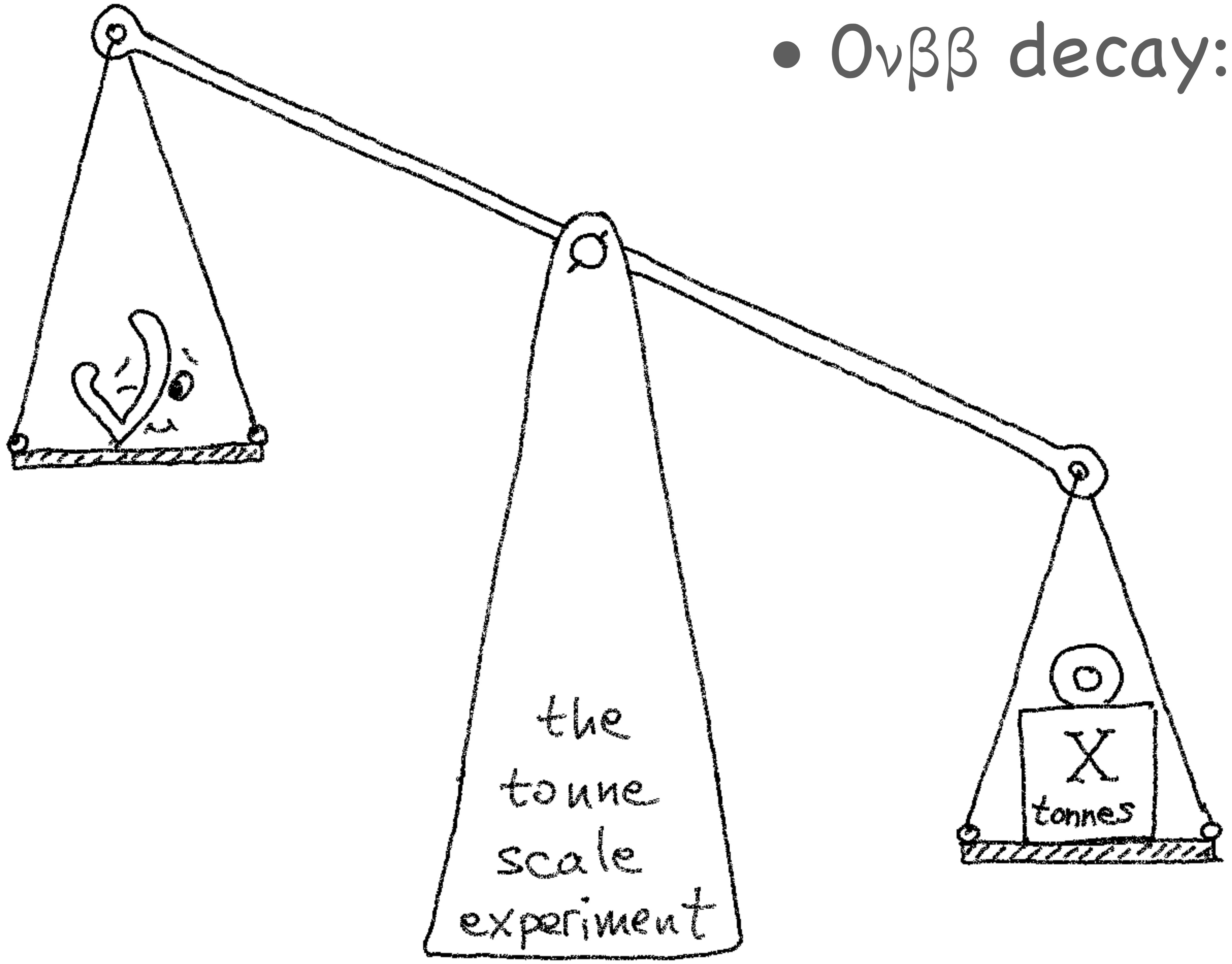
May 12, 2023


New physics searches at the precision frontier

University of Massachusetts Amherst
Amherst Center for Fundamental Interactions
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst
NSF

Synopsis

- Neutrinos, fundamental symmetries
  - 0νββ decay: Massive Dirac or Majorana neutrinos?
  - 0νββ decay: state of the art
  - The experimental landscape:
    - Technologies
    - The tonne-scale program (not just science & technology)
    - Beyond the tonne-scale
  - Auxiliary measurements



Neutrinos — a pillar in the development of the Standard Model

1930 —> the neutrino to the rescue of conservation of energy and angular momentum (Pauli)

1934 —> first theory of weak interactions (Fermi)

1935 —> prediction of $2\nu\beta\beta$ decay and half life calculation (Göppert-Meyer)

1937 —> Majorana neutrinos in $0\nu\beta\beta$ decay (… Majorana, Racah, Furry)

1956 —> first neutrino detection at the Savannah River reactor (Reines, Cowan)

1956/1957 —> prediction/discovery of parity non-conservation, neutrino left-handed helicity (Lee+Yang / C.S. Wu, Goldhaber)

1958 —> neutrino-antineutrino oscillations (Pontecorvo)

1962 —> discovery of muon neutrinos (Lederman, Schwartz, Steinberger)

early 1970's —> detection of solar neutrinos (Davis, Bahcall) (more after the late '80s)

1973 —> discovery of weak neutral currents (Gargamelle)

1978,1986 —> neutrino oscillations in matter (Wolfenstein, Mekeyev+Smirnov)

1987 —> detection of $2\nu\beta\beta$ decay in Se-82 (Moe)

—> detection of Supernova neutrinos (KamiokaNDE, IMB)

1998 —> discovery of atmospheric neutrino oscillations (SuperK, T. Kajita)

2002 —> discovery of solar neutrino oscillations (SNO, A. McDonald)

2003 —> confirmation of solar neutrino oscillation parameters in reactor antineutrinos (KamLAND)

2003-present —> precision neutrino oscillation physics (mixing angles, mass splittings)

2005,2010 —> detection of geo-neutrinos (KamLAND, Borexino)

2012 —> measurement of third neutrino mixing angle (Daya Bay, …)

2013 —> discovery of extra-galactic neutrinos, multi-messenger astrophysics (IceCube)

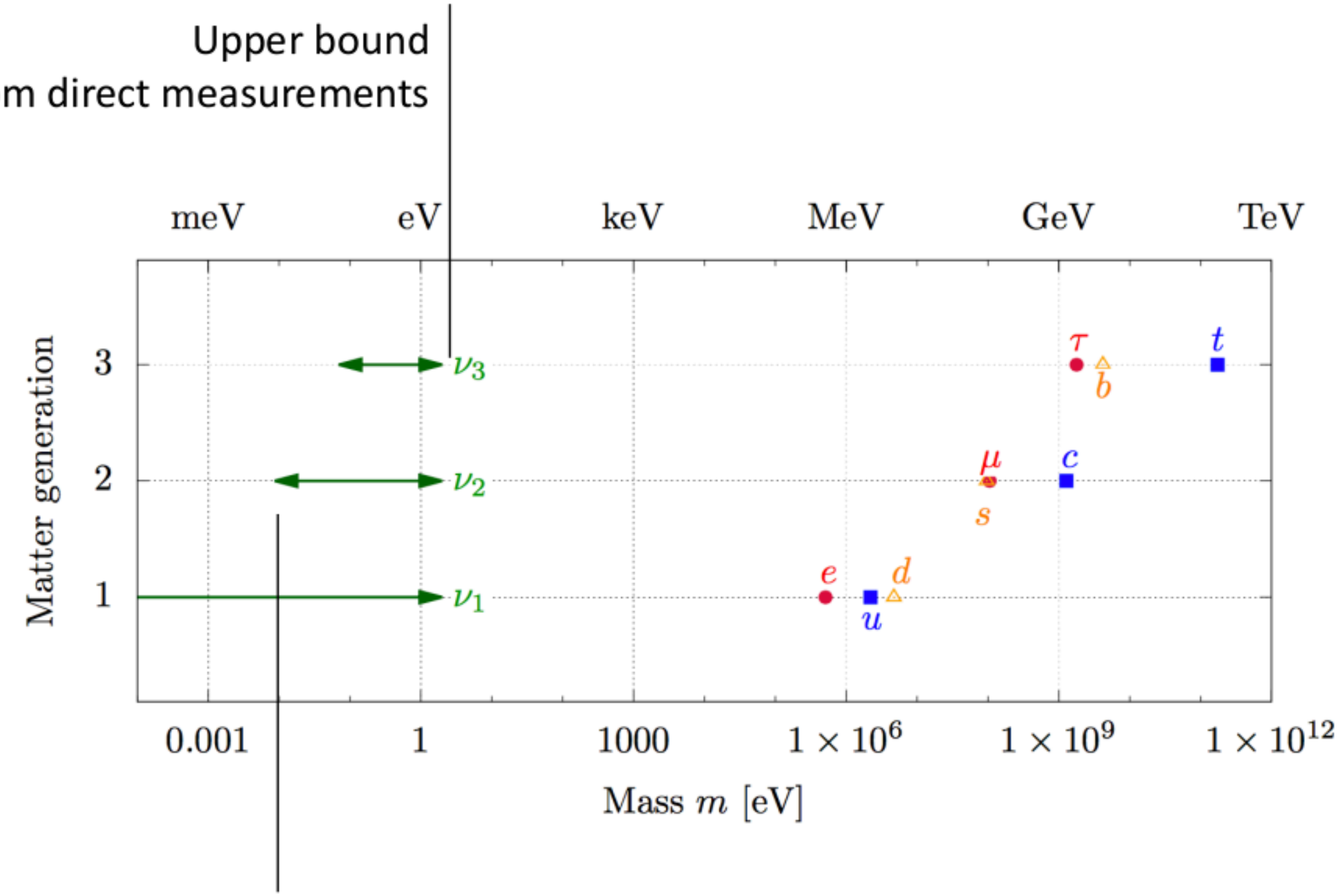
2014, 2020 — detection of solar pp neutrinos, CNO cycle neutrinos (Borexino)

Black: theory breakthrough
Blue: experimental discovery

Fundamental symmetries
Precision measurements
Applied physics

the 'Nobel-est' of particles
4 prizes (3 FPE)
8 scientists

Neutrino masses

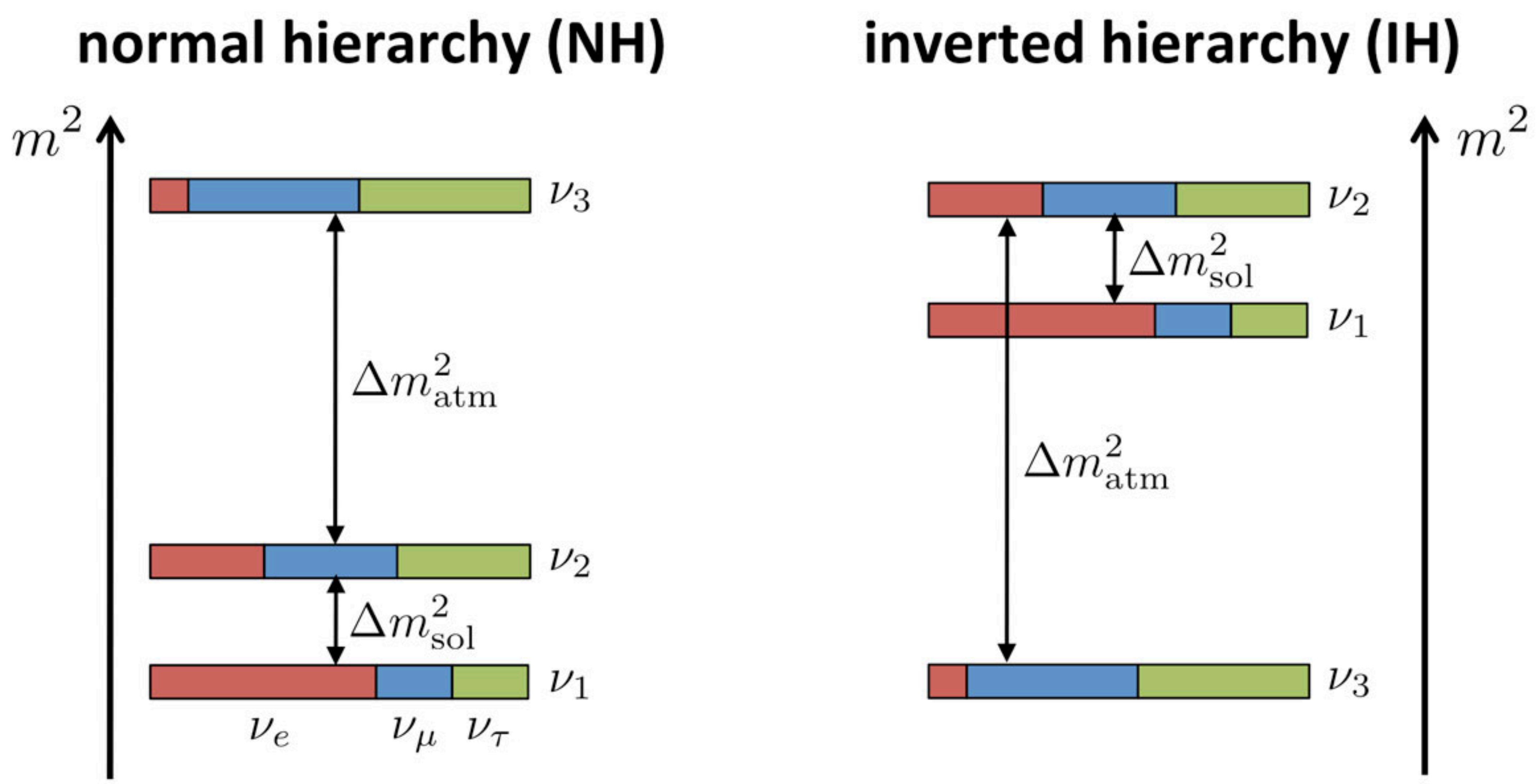


Upper bound
from direct measurements

Lower bound
from oscillation experiments

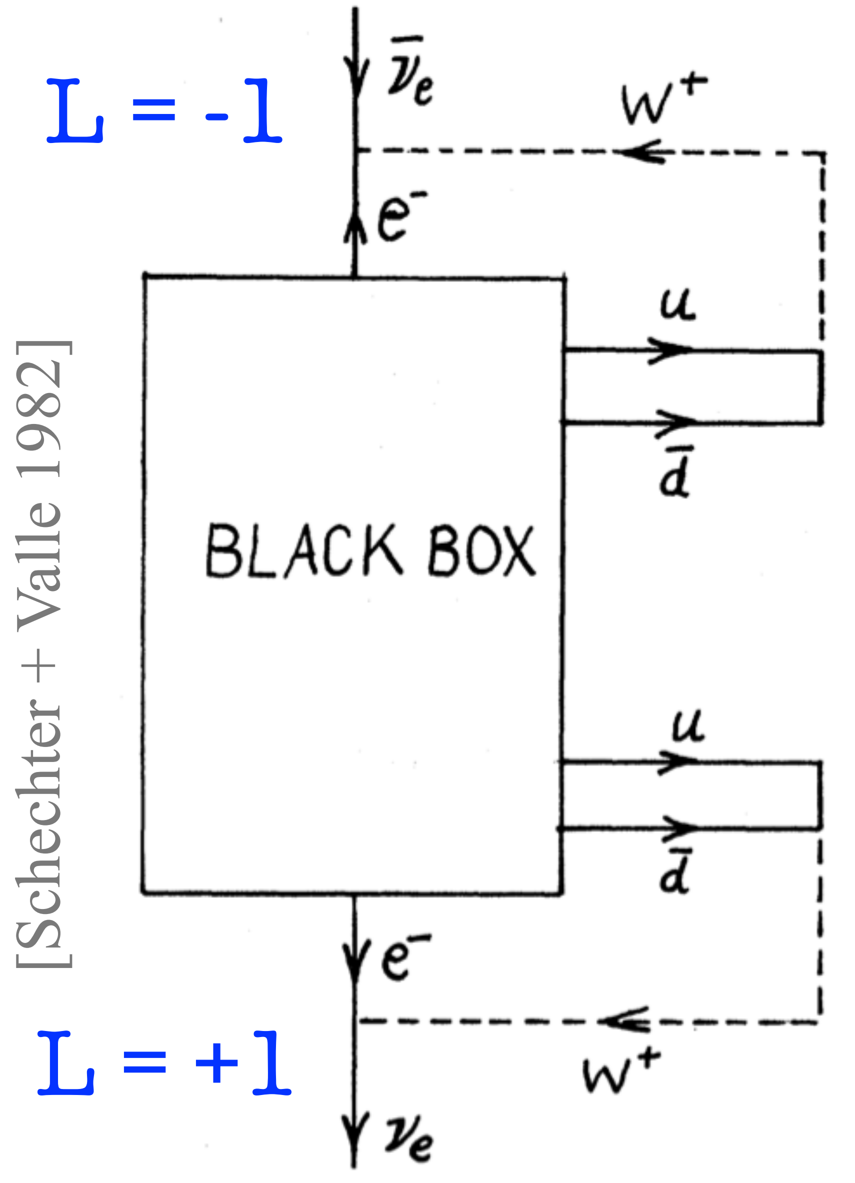
Figure from SNOWMASS neutrino colloquium by S. Mertens

- Why are neutrinos so light?
- What is the scale of neutrino mass?
- How do neutrinos acquire mass?
- How are neutrino masses ordered?


normal hierarchy (NH)

inverted hierarchy (IH)

0νββ decay — implications

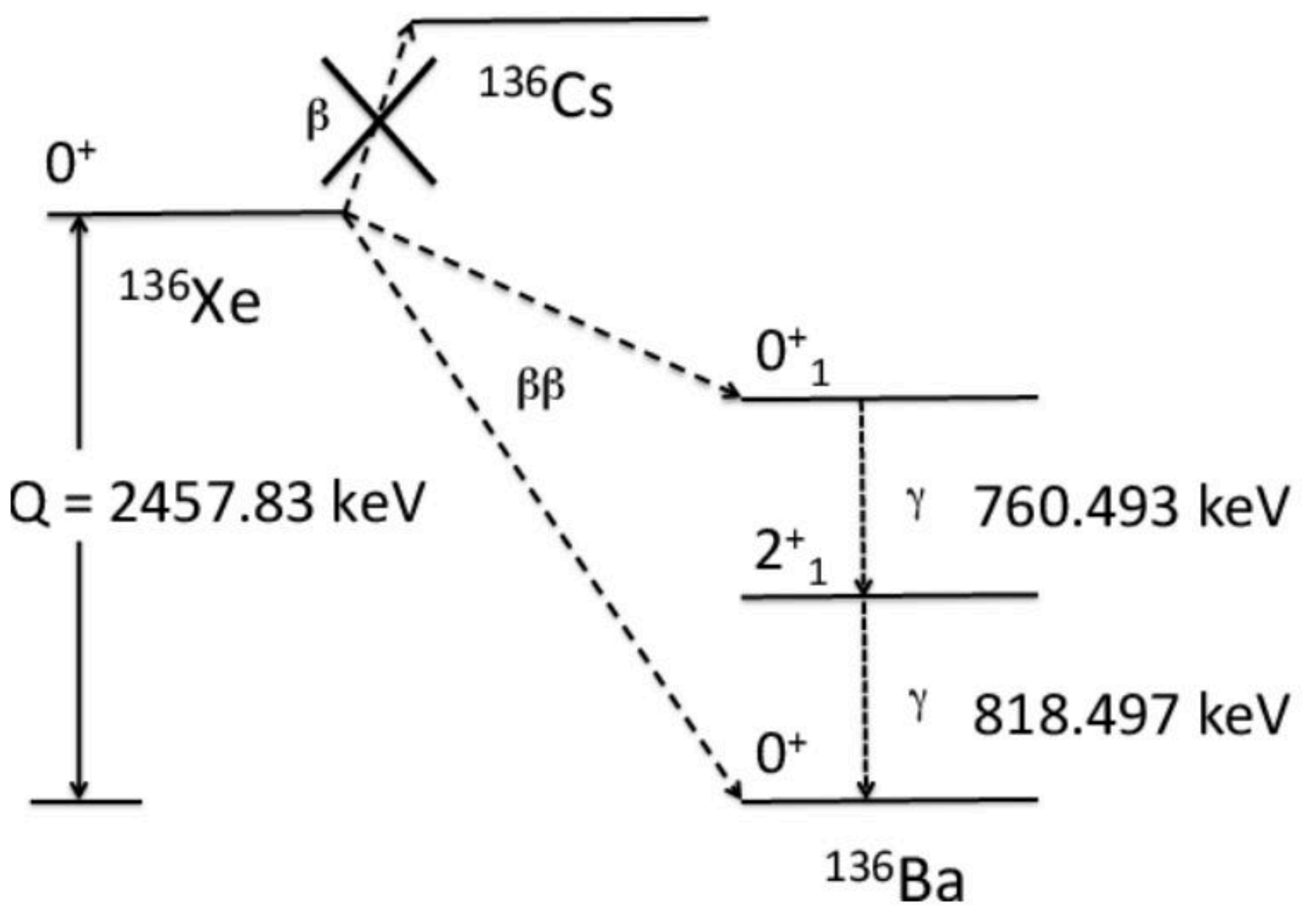


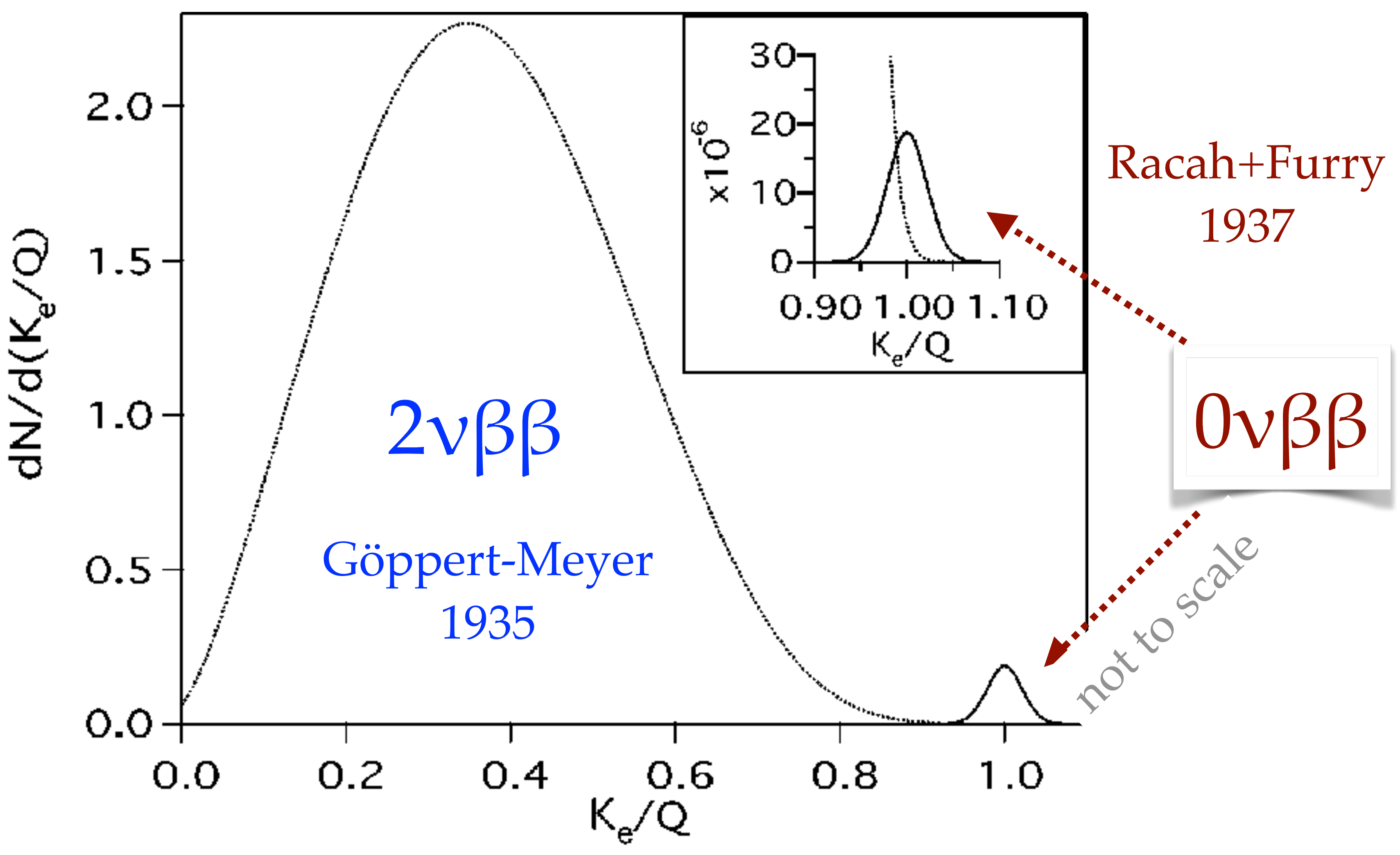
observation of 0νββ decay:

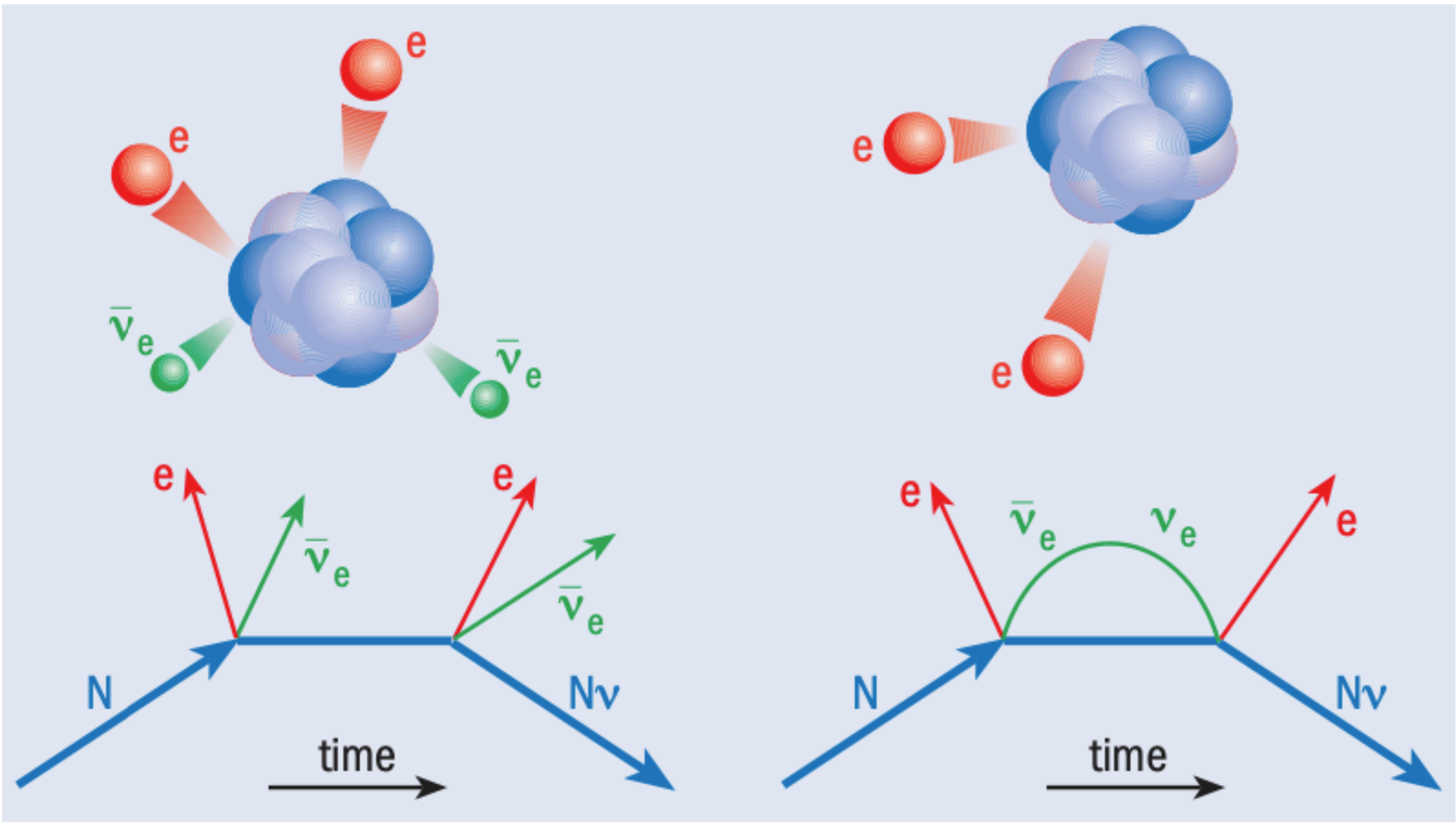
- massive, Majorana neutrinos
- lepton number violation (ΔL=2)
- new mass creation mechanism (non Higgs)
- matter dominance in the universe, Δ(B-L) leptogenesis
- smallness of neutrino mass -> new BSM physics mass scale

0νββ rate

- absolute neutrino mass (model dependent)







Right handed neutrinos: Dirac or Majorana?

Dirac

(4-spinors)

$$m_\nu \bar{\psi}_R \psi_L$$

$$\begin{tikzcd}
\nu_R \arrow[r, "\text{CPT}"] & \overline{\nu}_L \\
\nu_L \arrow[u, "\text{Lorentz}"] \arrow[r, "\text{CPT}"] & \overline{\nu}_R \arrow[u, "\text{Lorentz}"']
\end{tikzcd}$$

CPT transformation:

left-handed particle

↓

right-handed anti-particle

Majorana

(2-spinors)

$$m_L\,\varphi_L^c\varphi_L + m_R\,\varphi_R^c\varphi_R$$

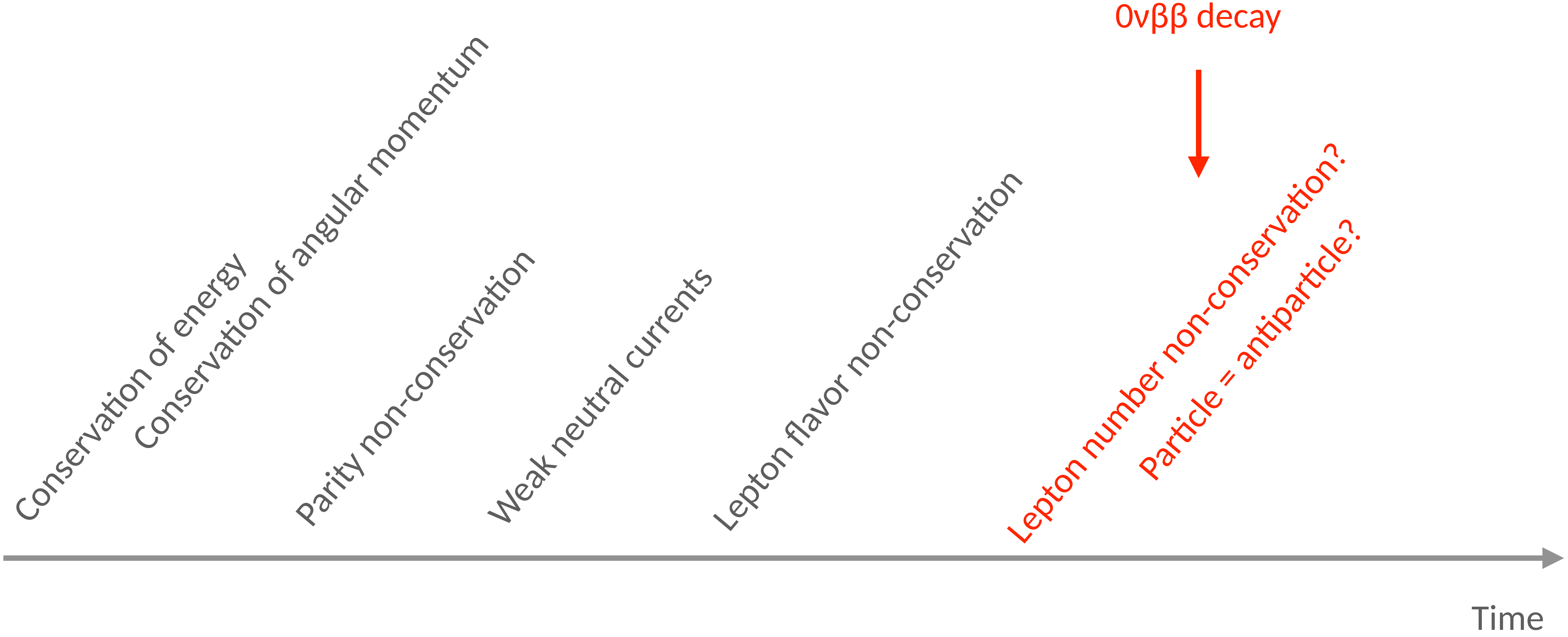
$$\begin{tikzcd}
\nu_L \arrow[r, bend left, "\text{Lorentz}"] \arrow[r, bend right, "\text{CPT}"'] & \nu_R
\end{tikzcd}$$

Difference between
Dirac and Majorana
neutrinos vanishes
for m—>0

Search for Lepton Number Violation (LNV)

(∄ a fundamental reason LN should be conserved)

Neutrinos (and β decay) — a staple for the exploration of fundamental symmetries



Conservation of energy

Conservation of angular momentum

Parity non-conservation

Weak neutral currents

Lepton flavor non-conservation

Lepton number non-conservation?

Particle = antiparticle?

0νββ decay

Time

The experimental observable — 0νββ decay rate

$$\Gamma^{0\nu} = G(Q,Z)\left|M(A,Z)\eta\right|^2$$

transition probability

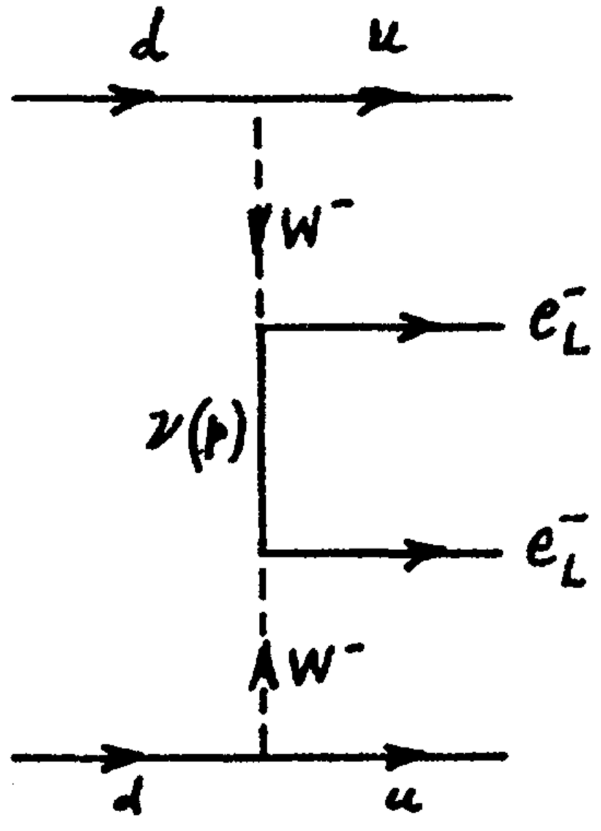
$$\alpha \frac{m}{Q^2} \quad (Q \sim m_e)$$

phase space factor:

$$G \sim G_F^4 g_A^4 m_e^5$$

nuclear matrix element

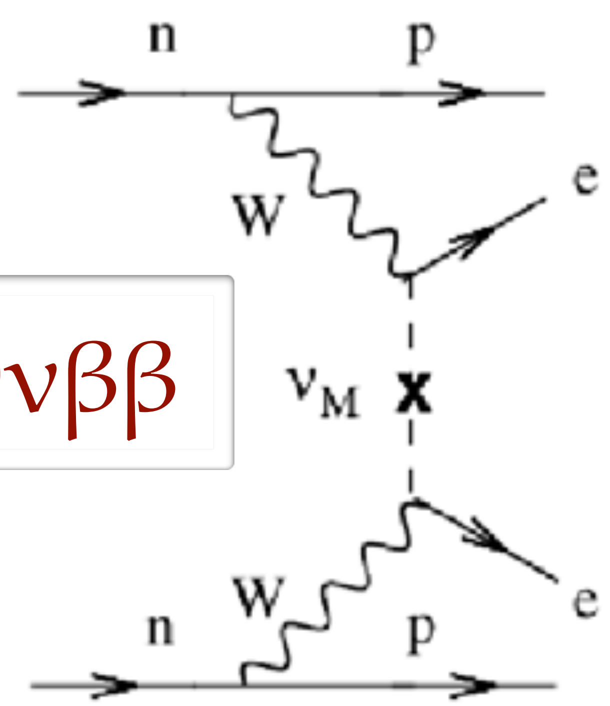
particle physics of the 'black box'



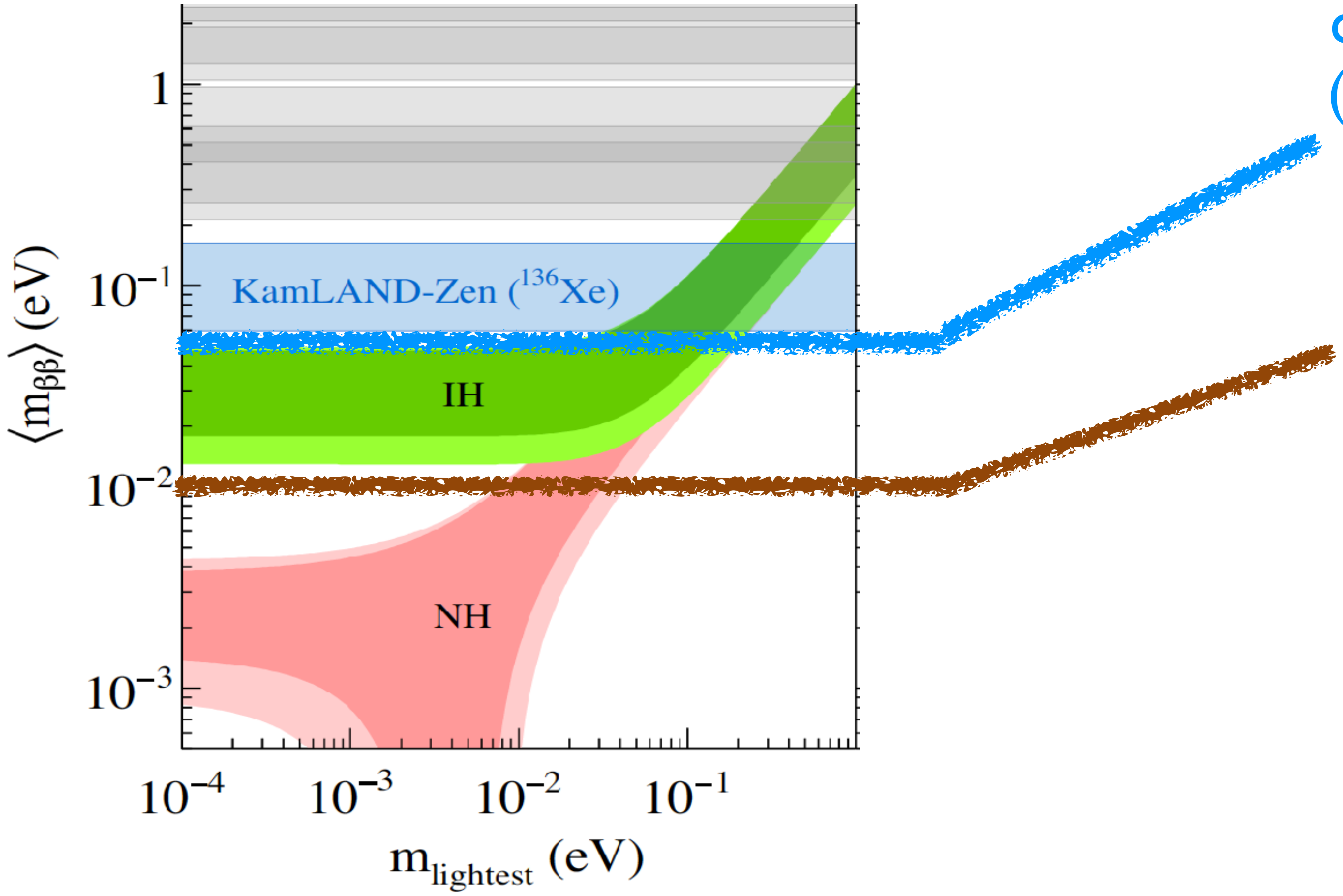
For virtual exchange of light Majorana neutrinos, the decay rate depends on an effective neutrino mass

$$\eta \sim < m_{\beta\beta} >$$

0νββ decay and neutrino mass (See-Saw I mechanism: η ~ <$m_{\beta\beta}$>)



0νββ



current experiments
(~100 kg, $T_{1/2}$~10^{26} y)

“tonne-scale”
($T_{1/2}$~10^{28} y)

coherent superposition

$$\langle m_{\beta\beta}\rangle = \sum_j \underset{\text{PMNS matrix}}{|U_{ej}|^2} \, \underset{\text{Majorana phases (2 independent)}}{e^{i\alpha_j}} m_j$$

PMNS matrix

Majorana phases
(2 independent)

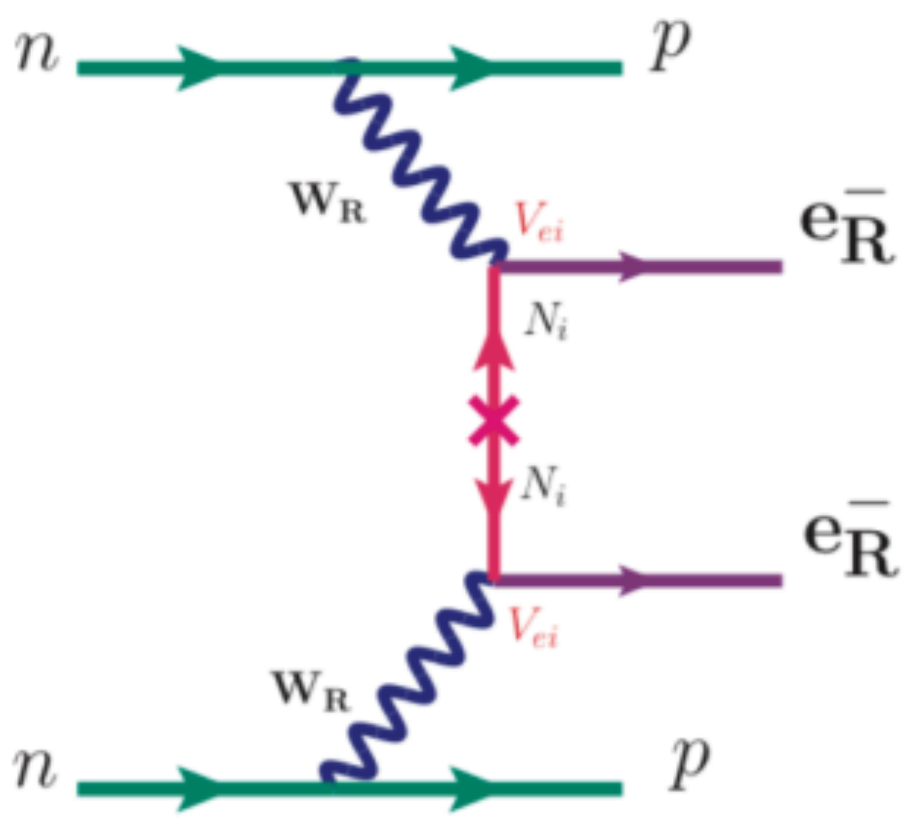
$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}(Q,Z)|M_{0\nu}|^2 < m_{\beta\beta} >^2$$

Nuclear Matrix Element (NME)

$$M_{0\nu} = g_A^2 M_{0\nu}^{GT} - g_V^2 M_{0\nu}^F$$

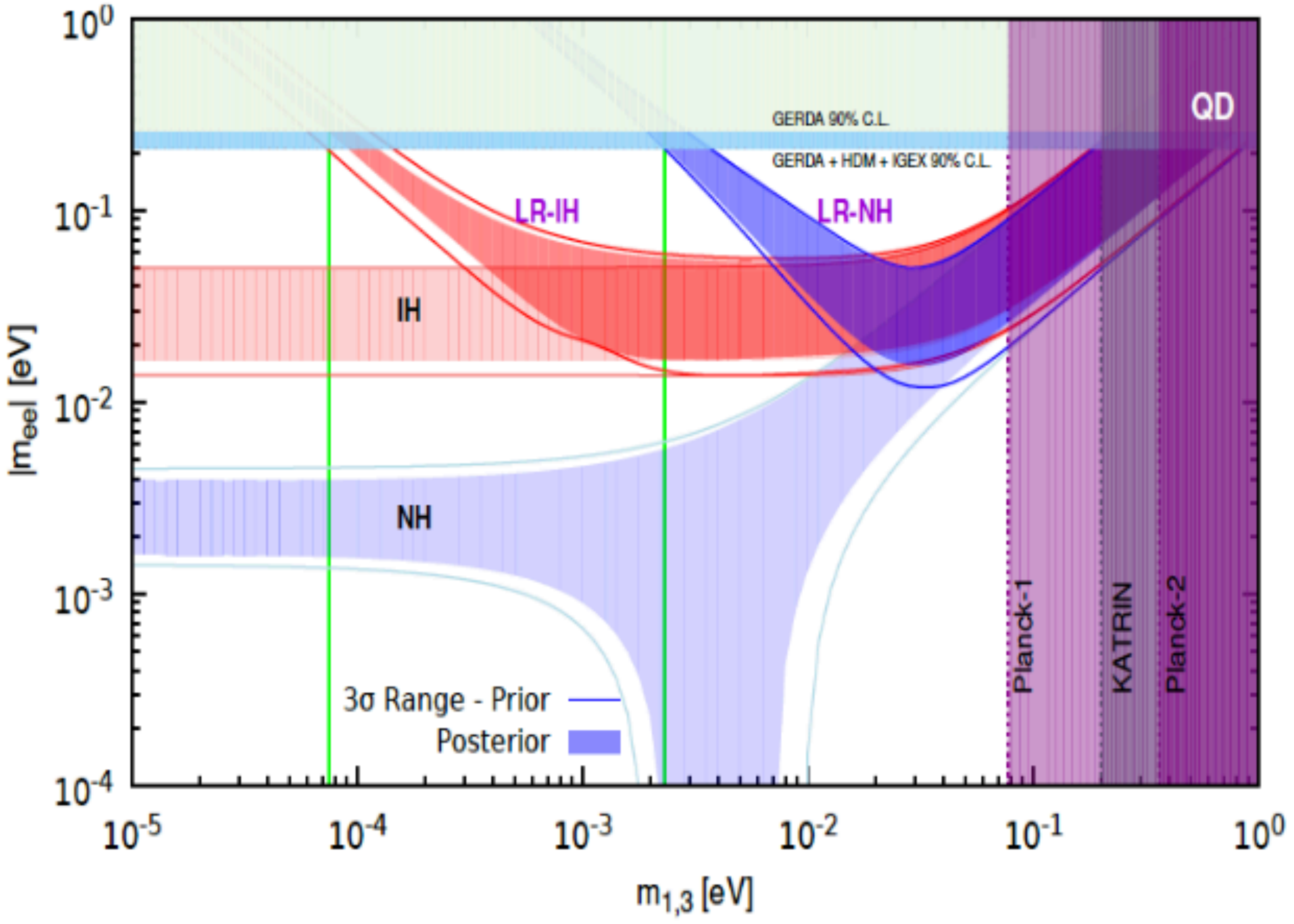
0νββ decay — a rich physics program

- Many ways to generate lepton number violation and essentially all of them can lead to 0νββ decay
- EFT methods allow to understand the phenomenology in more model independent way.
- Measuring angular correlations could help.
- Nuclear matrix elements depend on range of the mediator



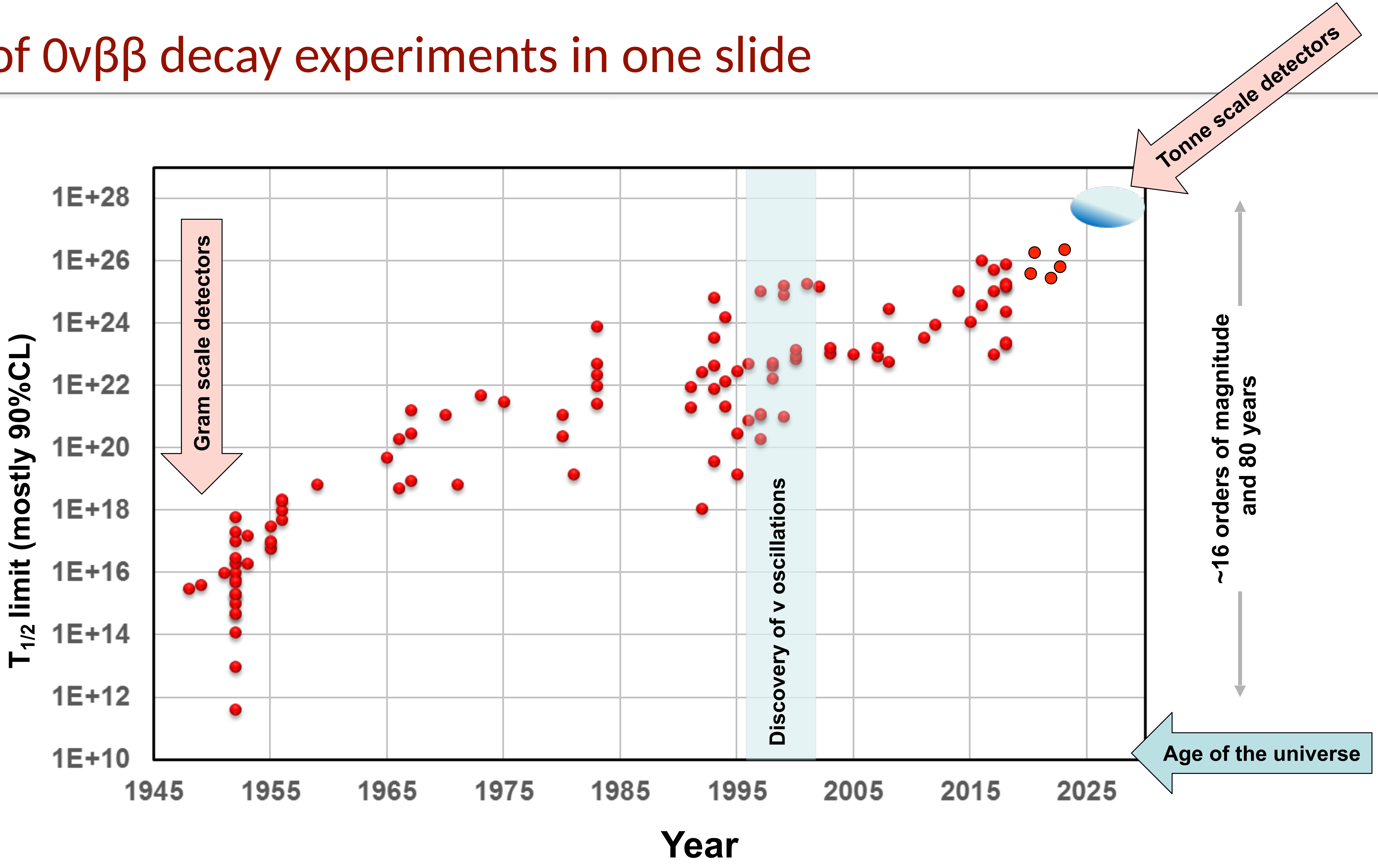
Left-Right Symmetric Model,
M_{W_R} ~ 2 TeV, M_N = 1 TeV,
g_R ~ 2/3 g_L

JHEP 10 (2015) 077



Figures from SNOWMASS neutrino colloquium by J. Gruszko; slide concept from P. Zuber SNOWMASS RPF meeting

The history of 0νββ decay experiments in one slide



Adapted from G. Gratta
Data courtesy of S.Elliott and the PDG.
Not all results are necessarily shown.

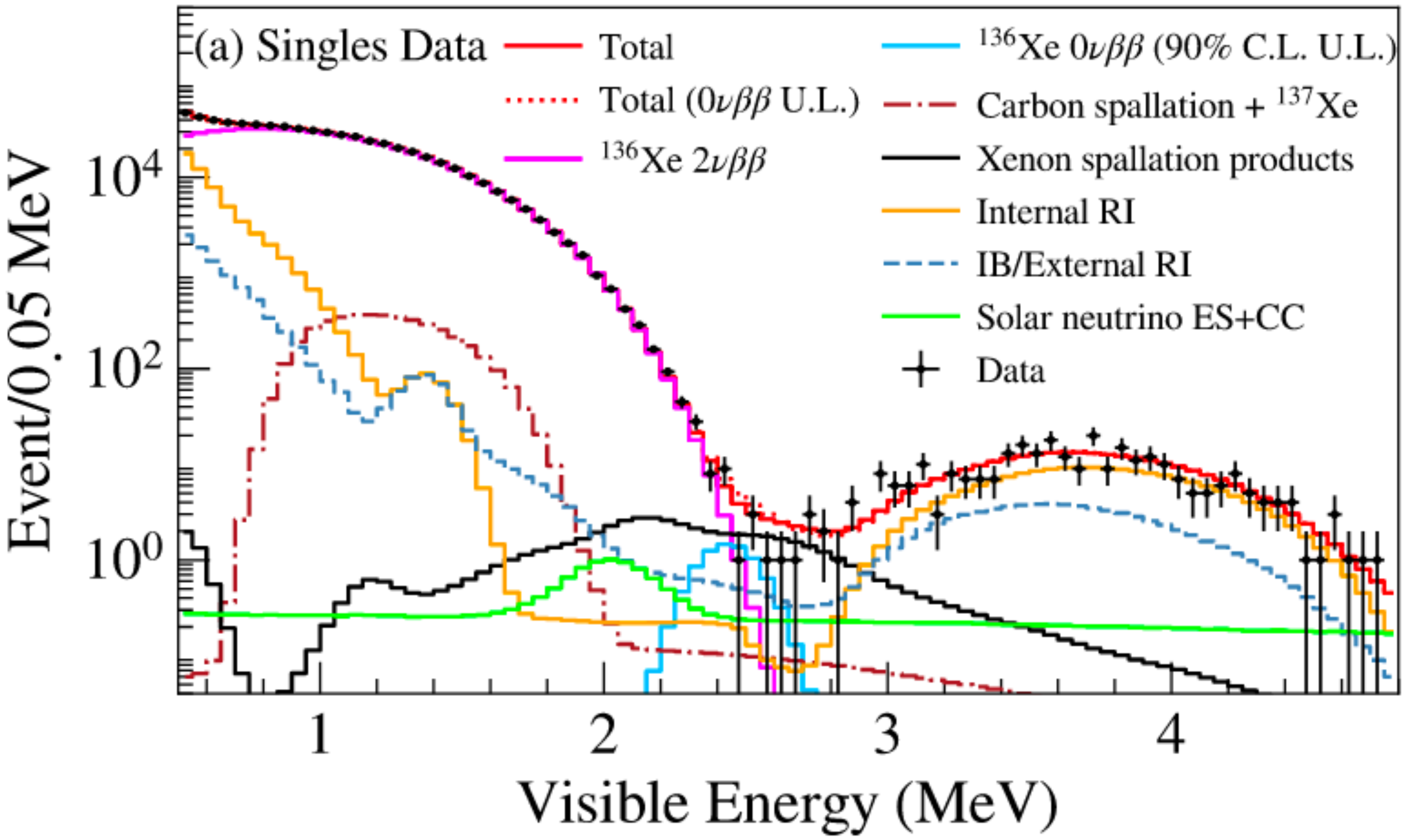
… we are definitely a stubborn bunch!

0νββ decay: current state of the art

$T^{0\nu}_{1/2}\ (10^{25}\ yr)$		isotope	exposure (kg y)	experiment	detector technology	year	status	
(sensitivity)	(lower limit)							
15	>23	Xe-136	970	KamLAND-Zen (phase I+II)	Xe in LS (2%)	2022	running (KLZ-800)	PRL 130, 051801 (2023)
18	>18	Ge-76	127	Gerda (phase I+II)	Ge crystal array with LAr veto	2020	completed	PRL 125, 252502 (2020)
8.1	>8.3	Ge-76	65	Majorana Demonstrator	Ge crystal array	2019	completed	PRL 130, 062501 (2023)
5.0	>3.5	Xe-136	234	EXO-200 (phase I+II)	LXe TPC	2019	completed	PRL 123, 161802 (2019)
2.8	>2.2	Te-130	289	Cuore	Bolometer array	2022	running	Nature 604, 53 (2022)
0.5	>0.35	Se-82	5.3	Cupid-0	Scintillating bolometer array	2019	completed	PRL 123, 032501 (2019)
		Te-130		SNO+	Te in LS (1.5-3%)		planned / commissioning	

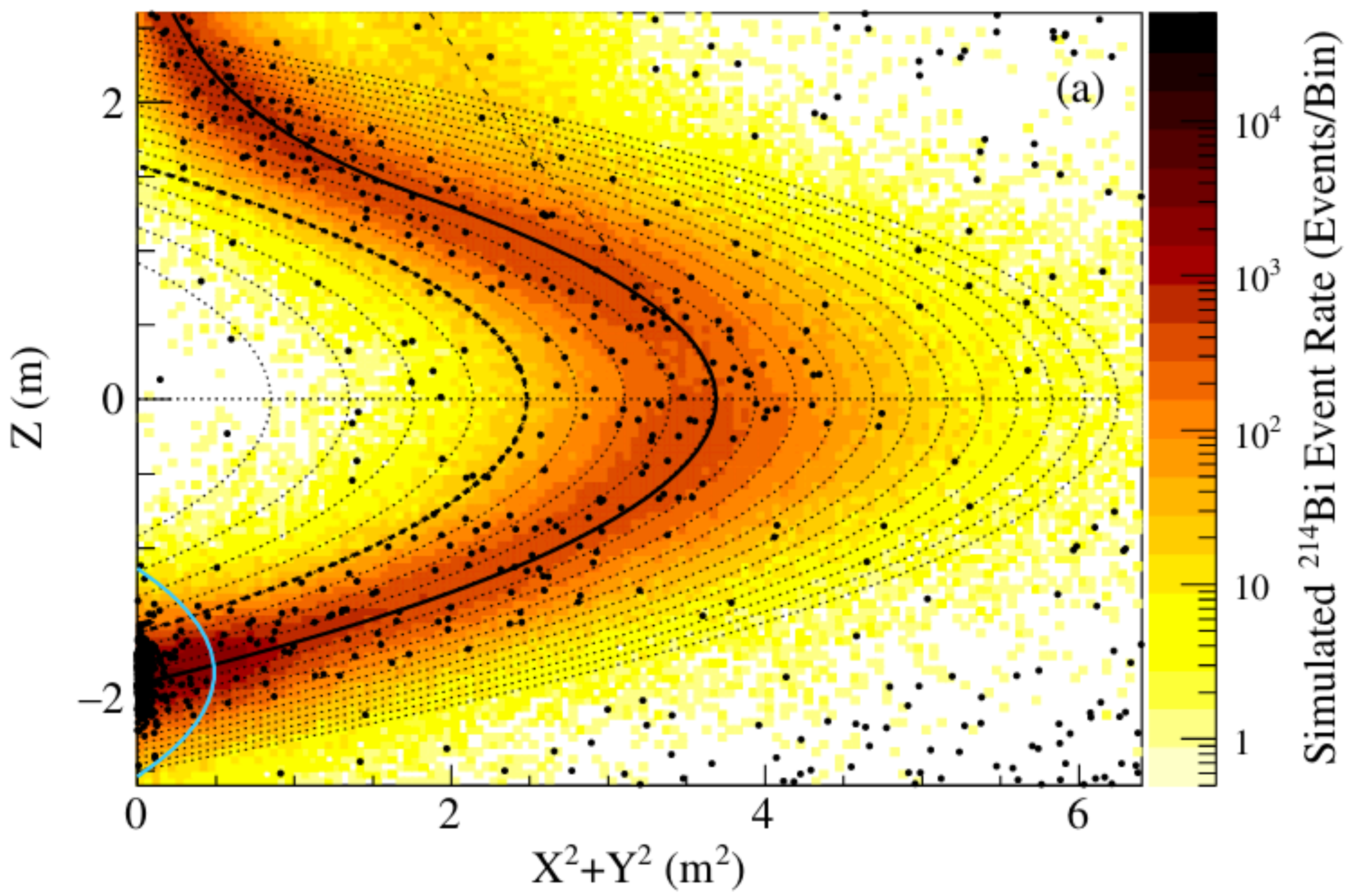
Kamland-Zen world-leading result

PHYSICAL REVIEW LETTERS 130, 051801 (2023)



$T_{1/2}(0\nu) > 2.3 \times 10^{26}$ years (90% C.L.)

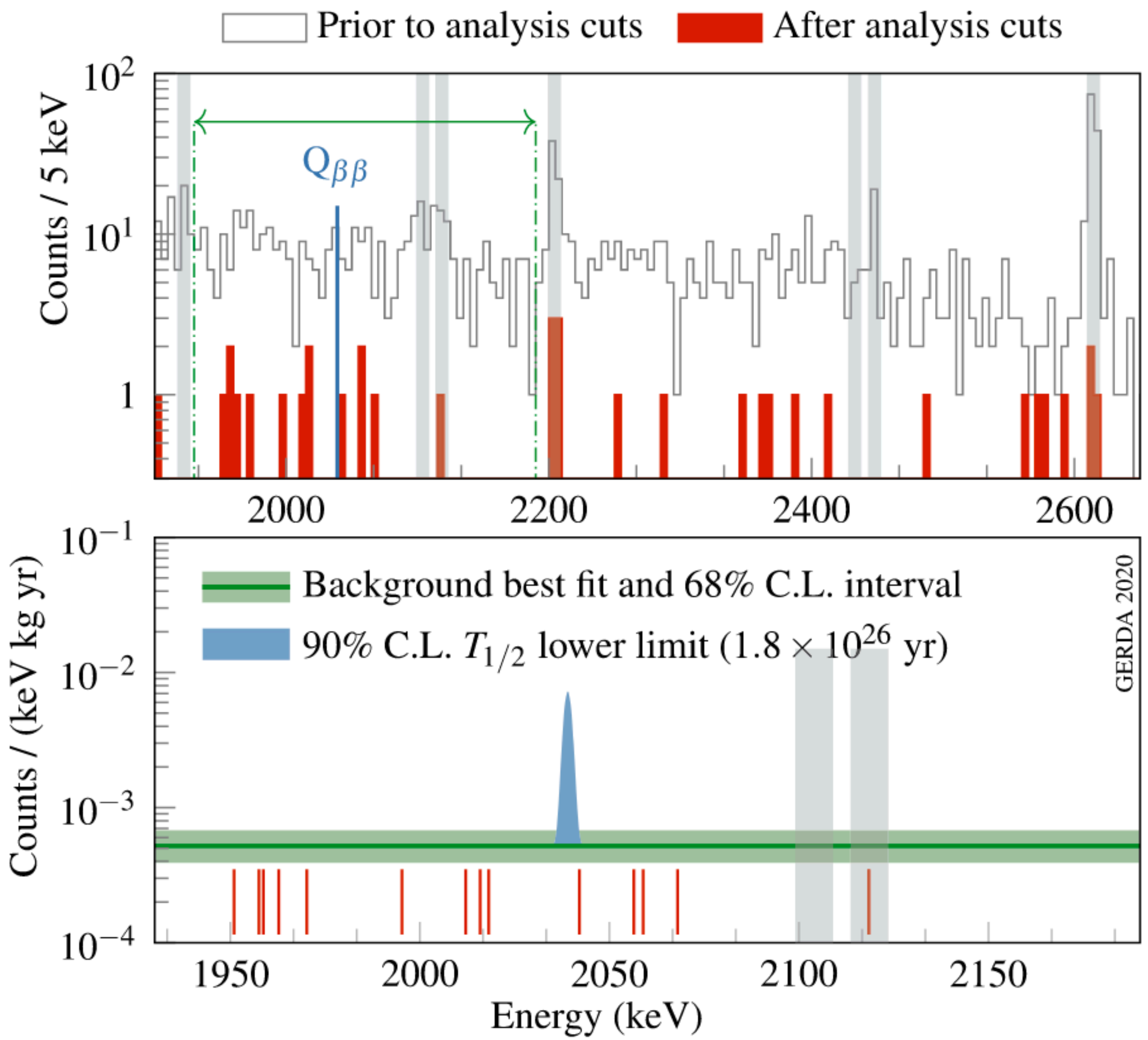
$\langle m_{\beta\beta} \rangle < 36–156$ meV



- Xe dissolved in LS inside a nylon/EVOH mini-balloon
- Volume fiducialization to exploit radiation shielding

Final GERDA result

PHYSICAL REVIEW LETTERS 125, 252502 (2020)



$T_{1/2}(0\nu) > 1.8 \times 10^{26}$ years (90% C.L.)

$\langle m_{\beta\beta} \rangle < 79–180$ meV

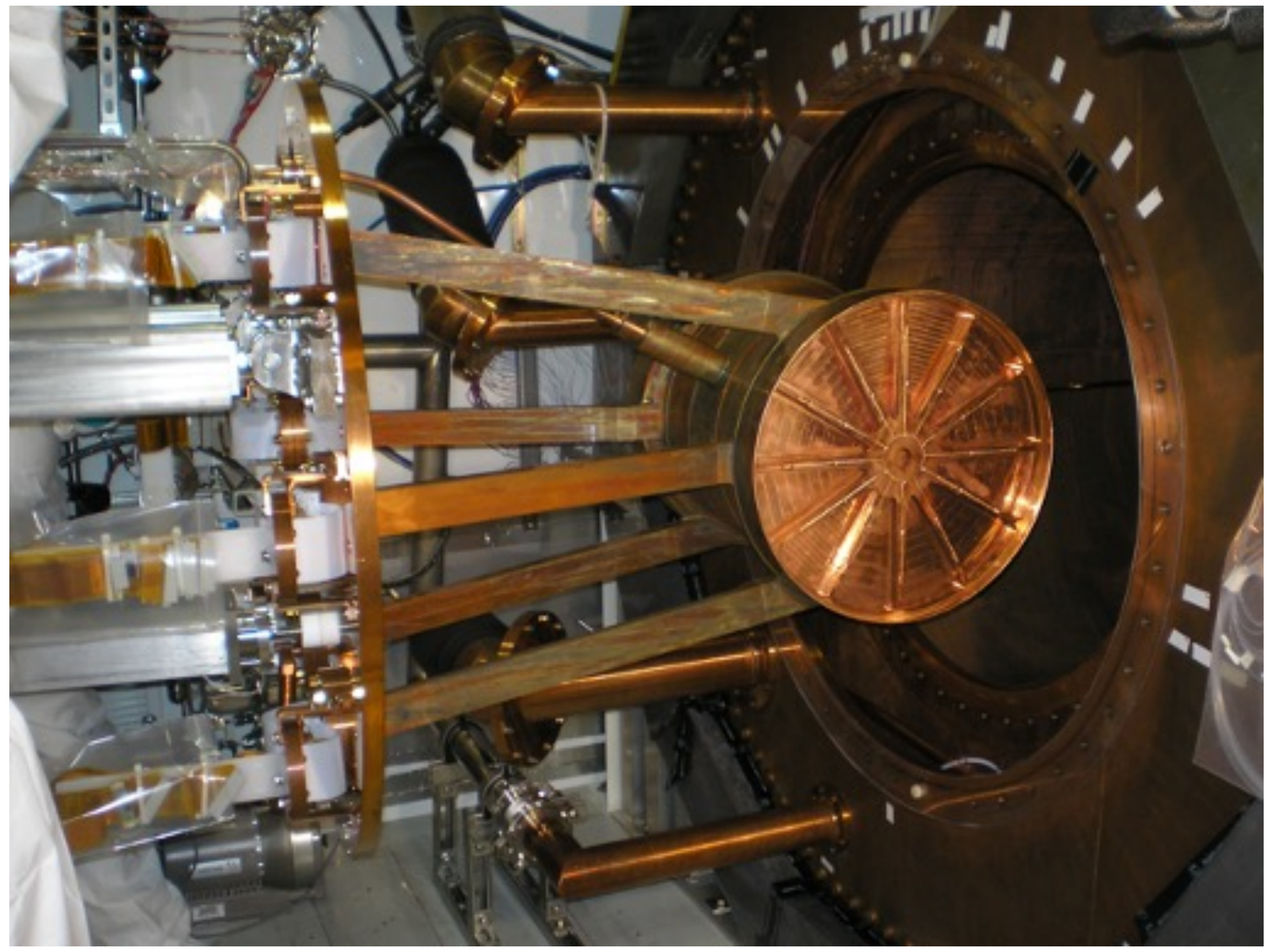
- Excellent energy resolution
- Pulse—shape analysis for β/γ discrimination
- Active LAr veto

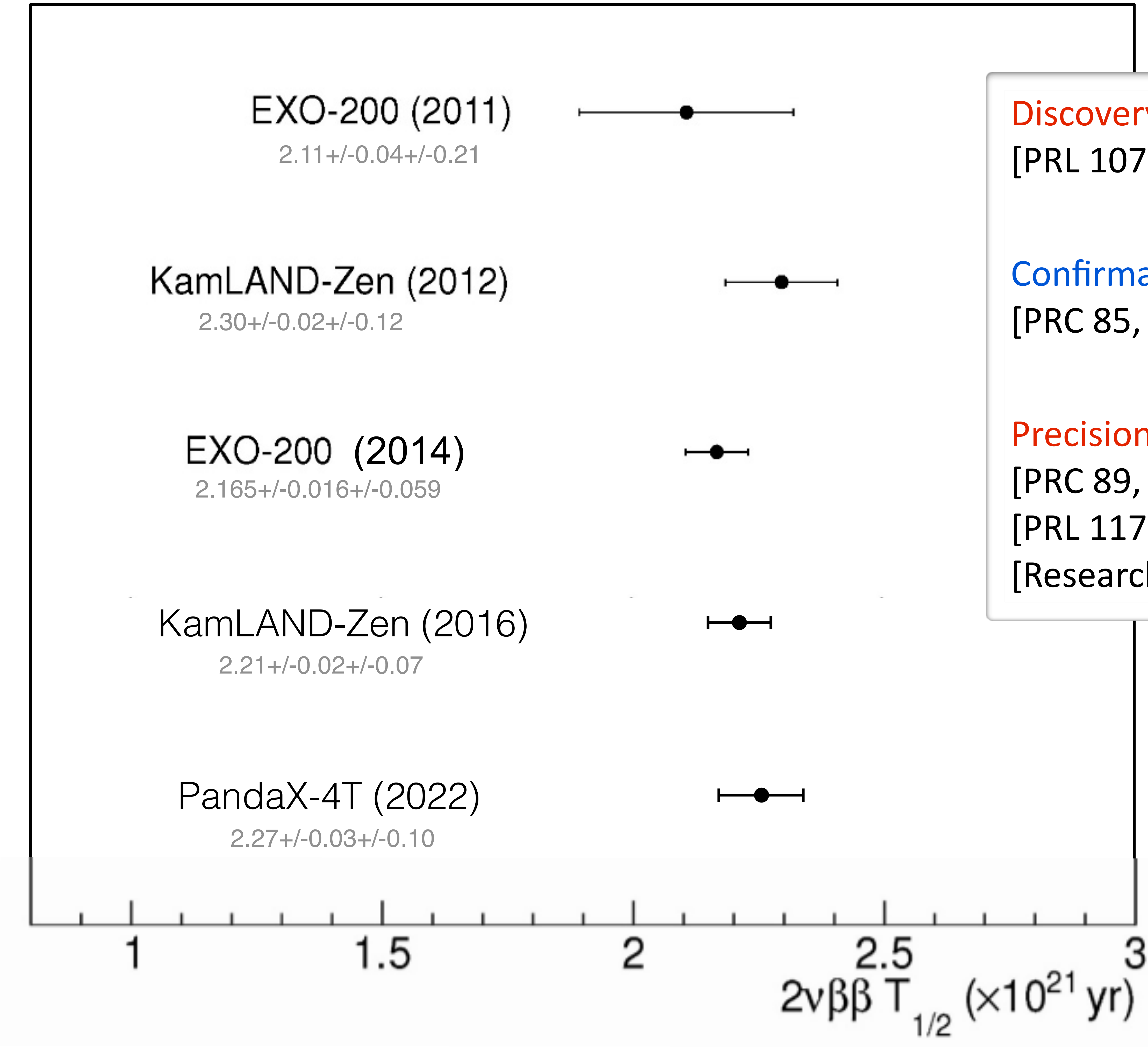
Precision measurement of 2νββ

$$T_{1/2}^{2\nu\beta\beta} = (2.165 \pm 0.016(\mathrm{stat}) \pm 0.059(\mathrm{syst})) \times 10^{21}\,\mathrm{yr}$$

longest, first 2νββ decay half life to be precisely* (directly) measured of all experimentally ‘practical’ isotopes

(* Ge-76 and Te-130 have similarly precise measurements)





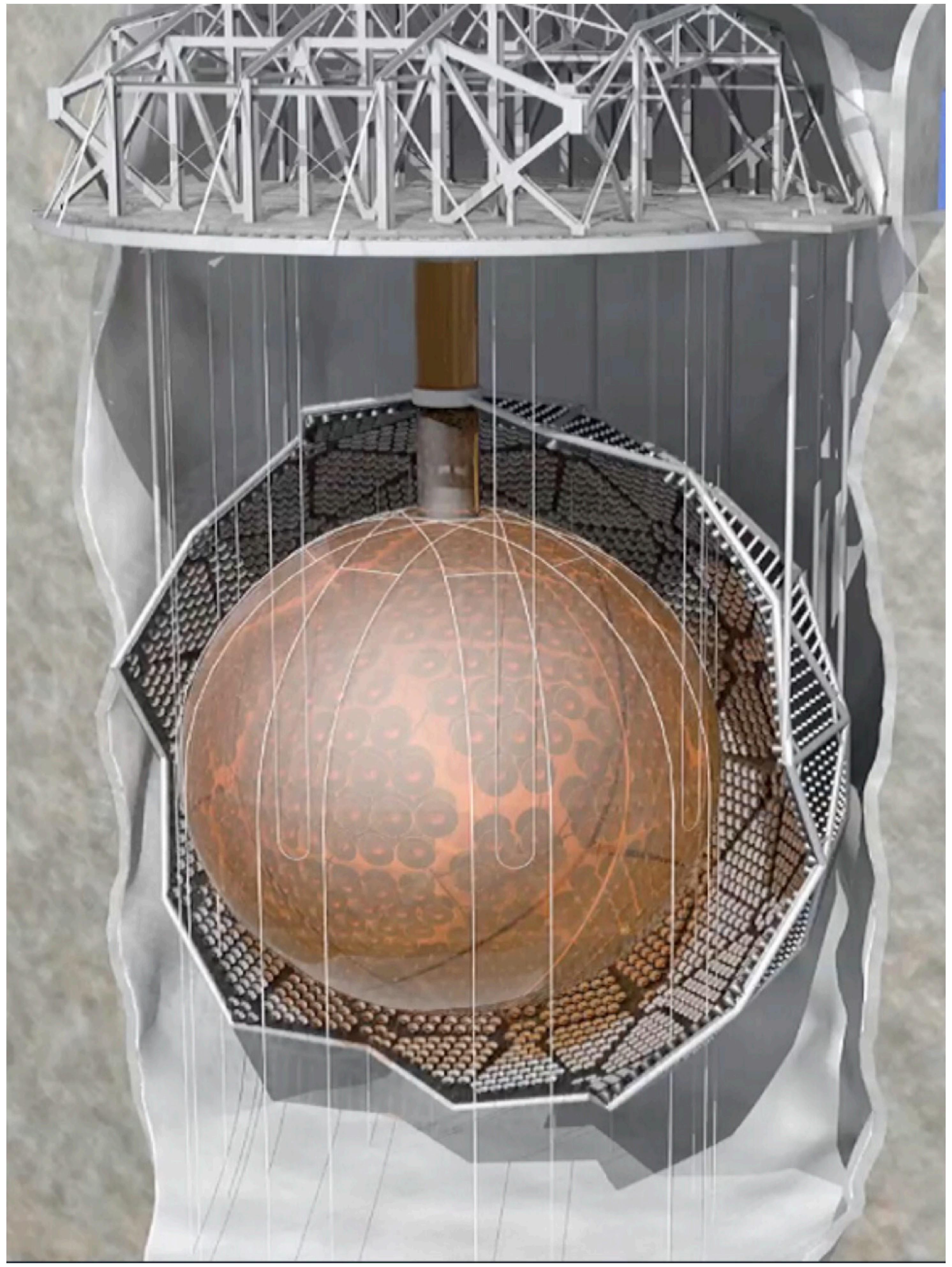
Discovery of 2νββ decay of ^{136}Xe
[PRL 107, 212501 (2011)]

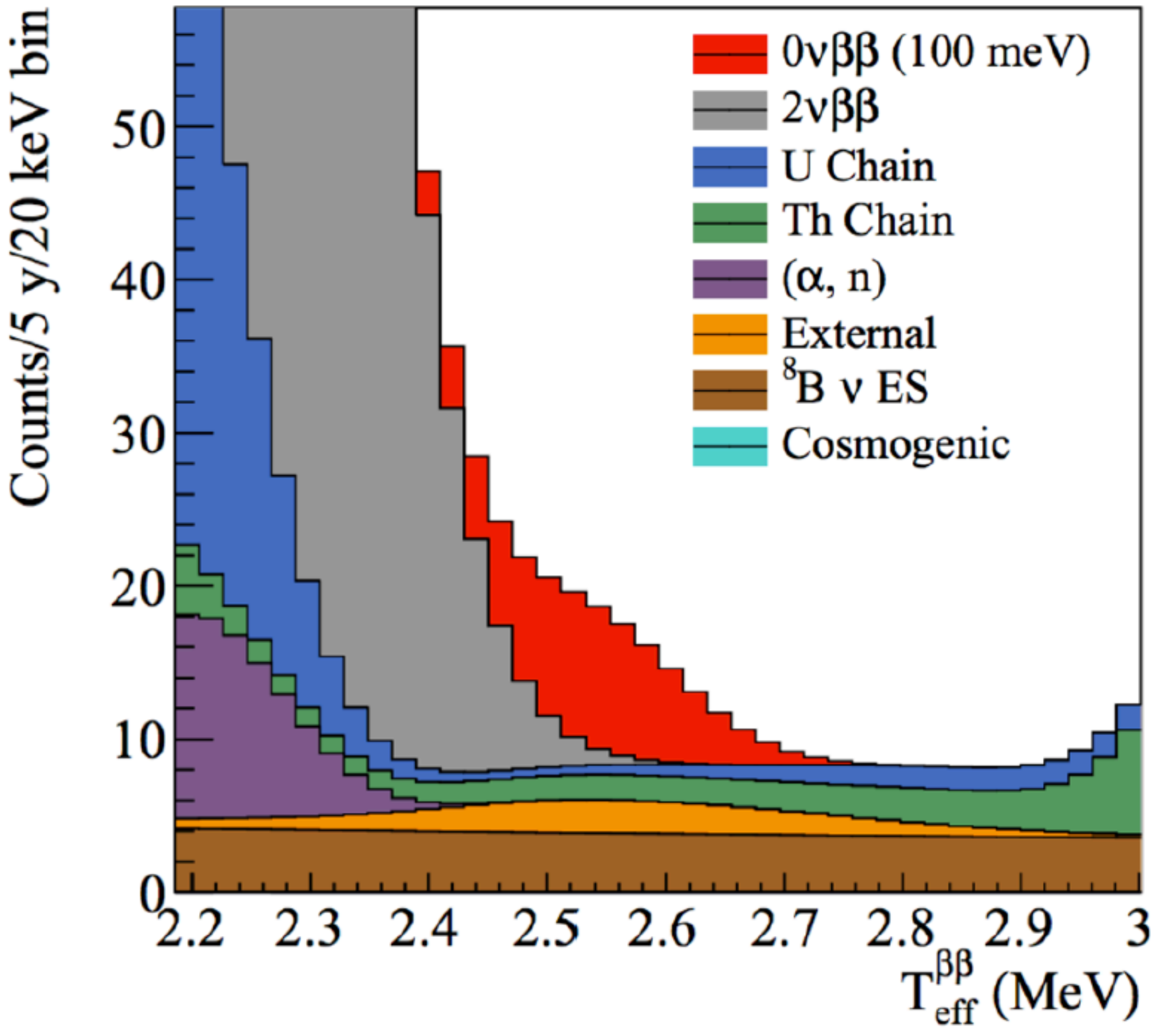
Confirmation by KamLAND-Zen
[PRC 85, 045504 (2012)]

Precision measurements (~3%)
[PRC 89, 015502 (2014)]
[PRL 117, 082503 (2016)]
[Research, 2022, 9798721]

SNO+: an opportunity before tonne-scale experiments come online

- ~kton LS solvent loaded with a few % of natural Tellurium (30% iso. ab.)
- Currently running with our scintillator
- Te plants commissioning should start soon
- Chemistry of Te loading at 1.5-3% to be fully demonstrated



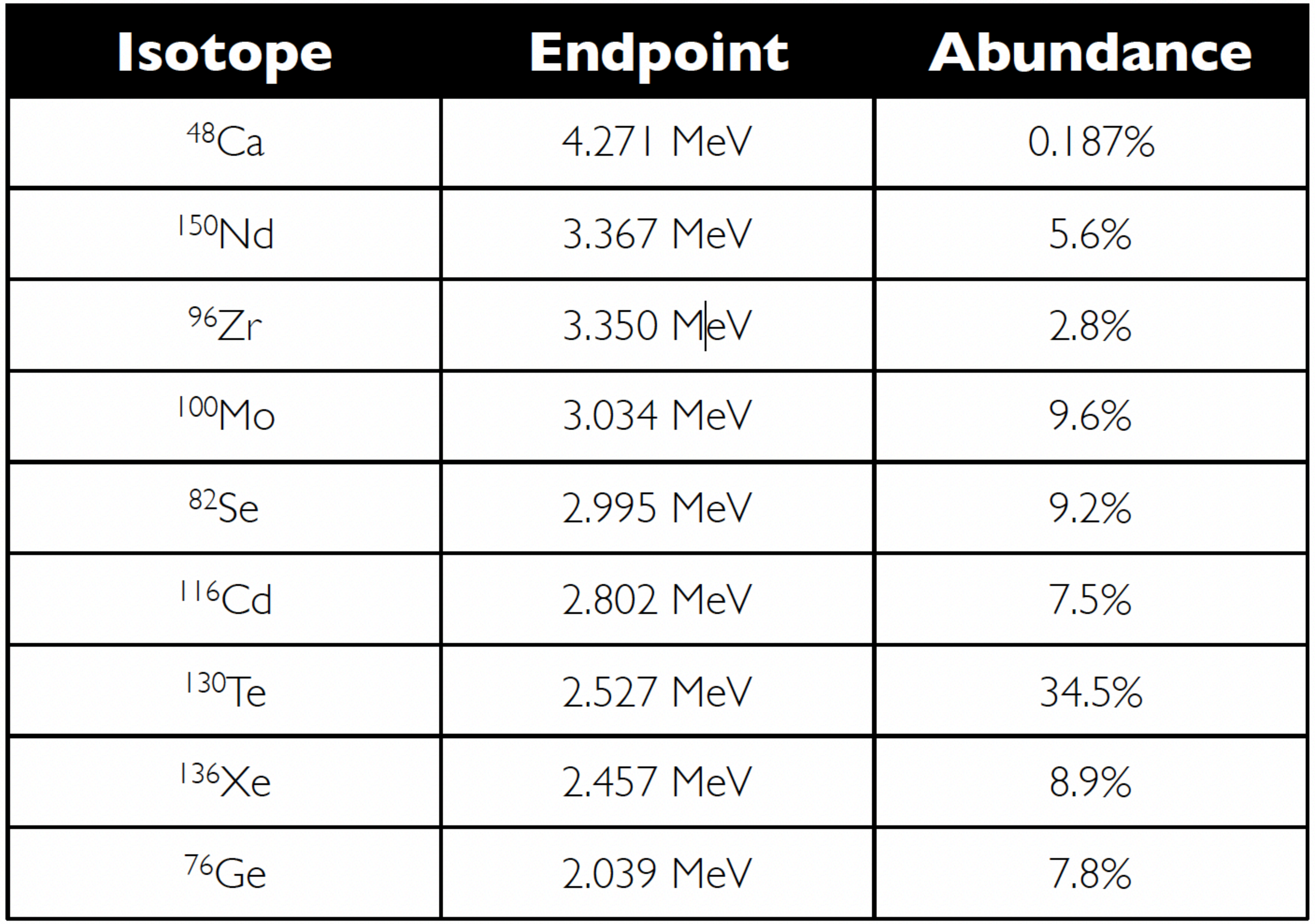


0.5% Te, 5 years

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

(for illustration)

$0\nu\beta\beta$ decay: choosing the isotope



Isotope	Endpoint	Abundance
^{48}Ca	4.271 MeV	0.187%
^{150}Nd	3.367 MeV	5.6%
^{96}Zr	3.350 MeV	2.8%
^{100}Mo	3.034 MeV	9.6%
^{82}Se	2.995 MeV	9.2%
^{116}Cd	2.802 MeV	7.5%
^{130}Te	2.527 MeV	34.5%
^{136}Xe	2.457 MeV	8.9%
^{76}Ge	2.039 MeV	7.8%

A high(er) endpoint energy brings:

- Larger phase space factor —> higher rate
- Better separation from natural radioactivity backgrounds

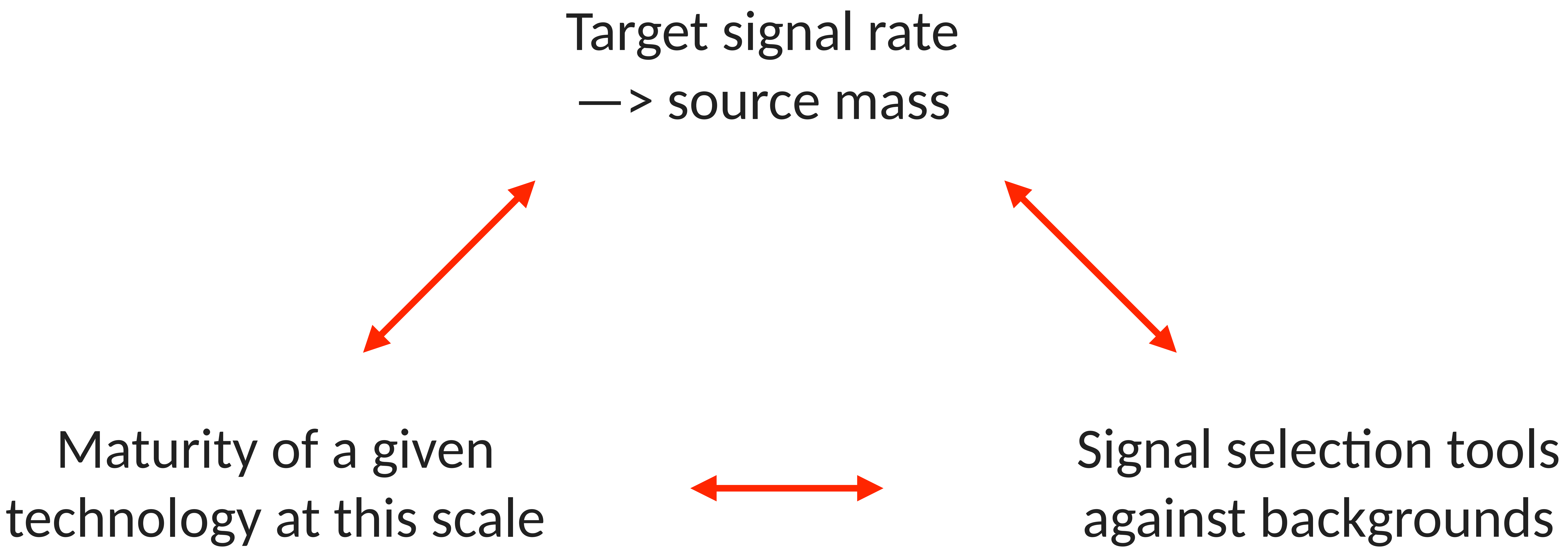
A higher isotopic abundance

- More compact detector

Alert! the choice of the optimal isotope is a multi-dimensional optimization

0νββ decay: isotope and technology

The best experimental choice depends mainly on:



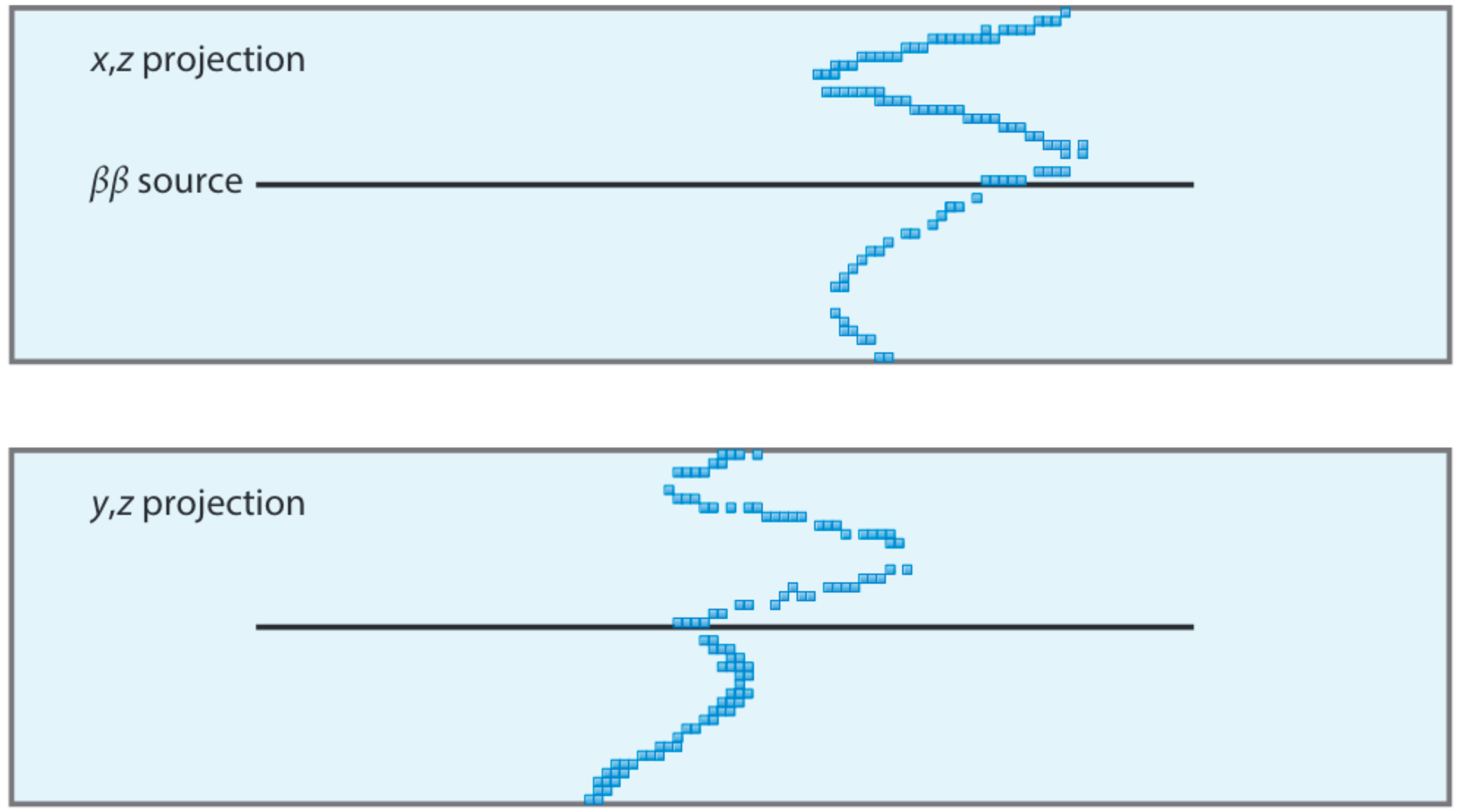
Target signal rate
—> source mass

Maturity of a given
technology at this scale

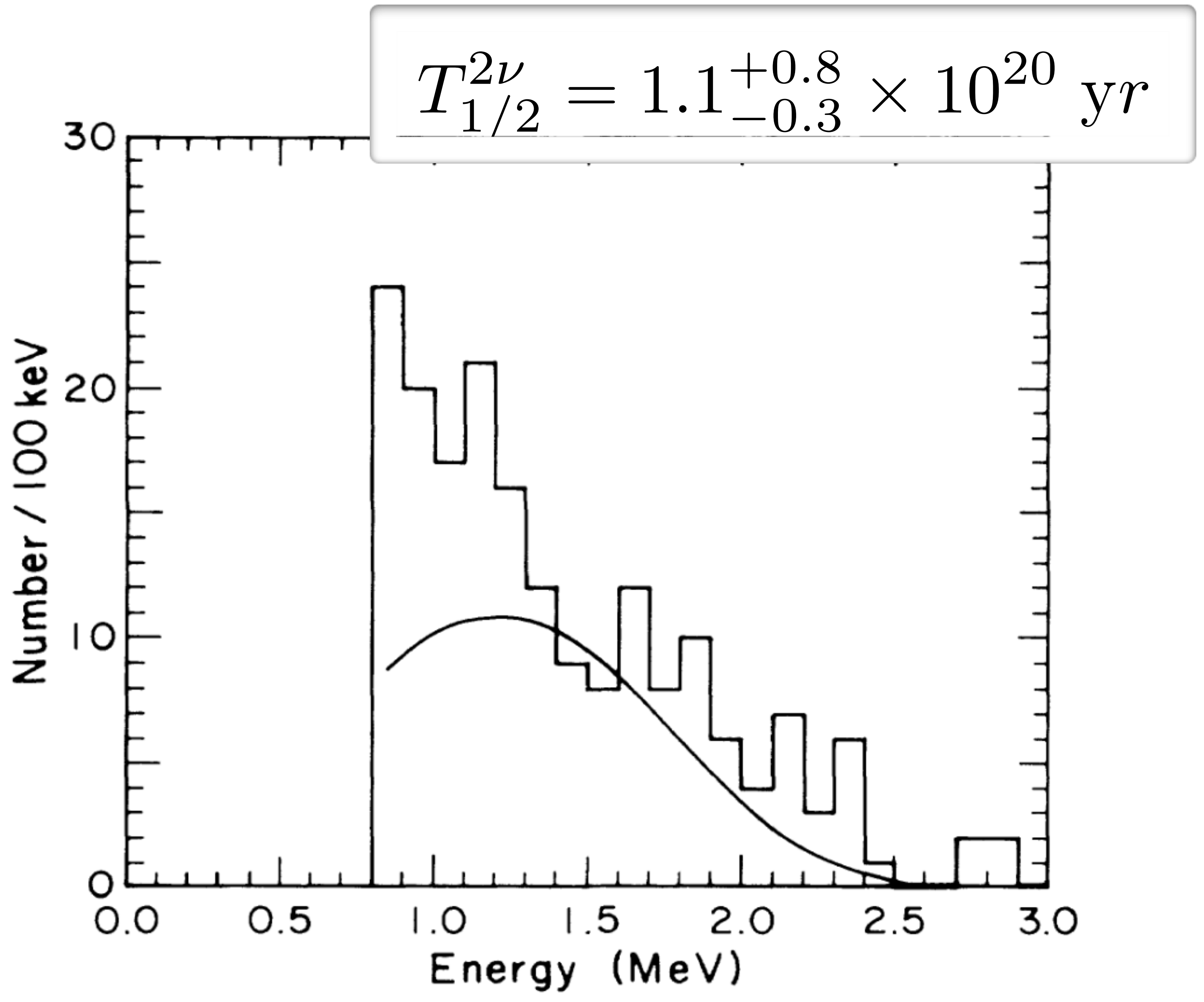
Signal selection tools
against backgrounds

The early days

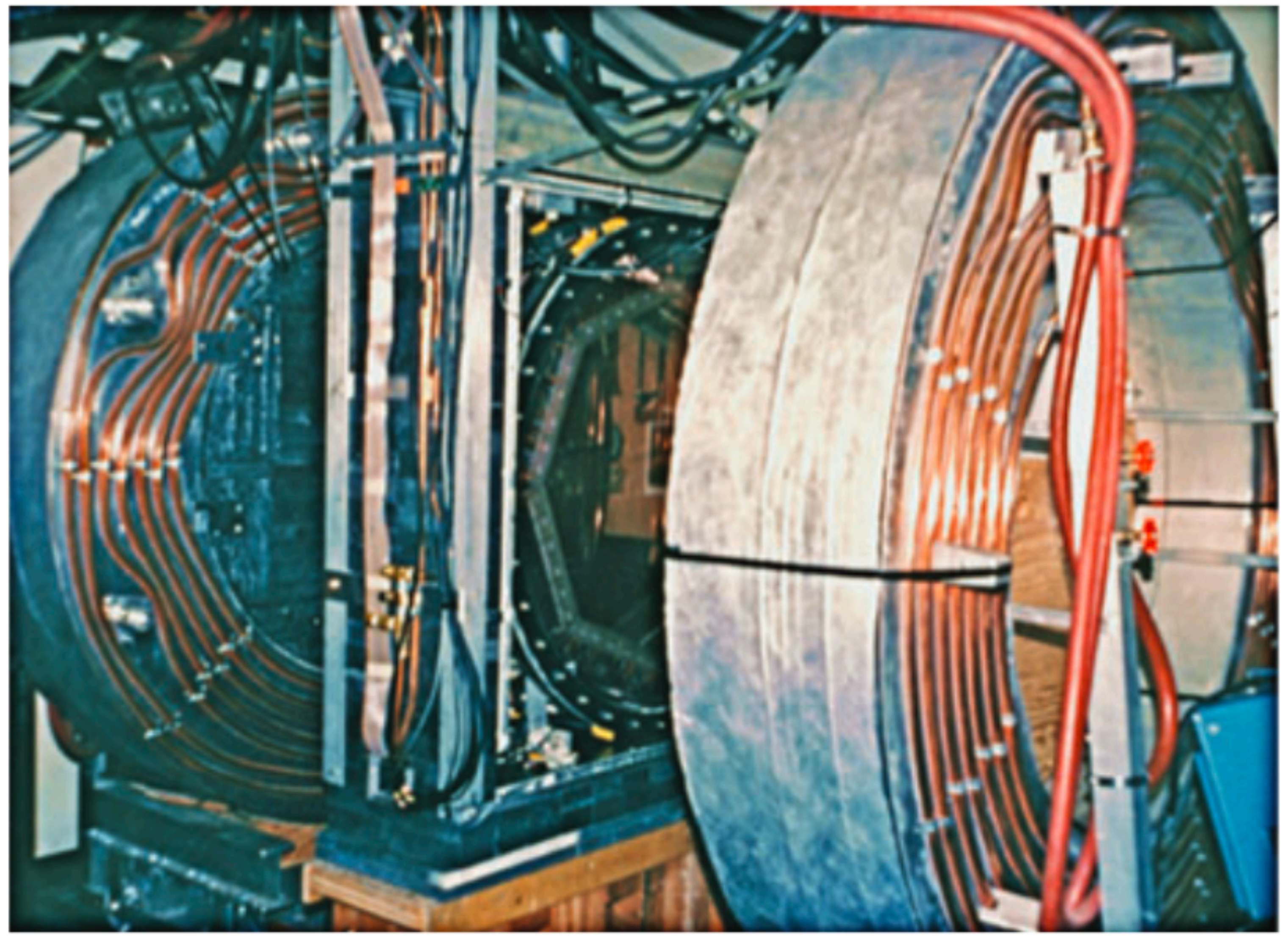
PHYSICAL REVIEW LETTERS 59, 2020 (1987)
Ann. Rev. Nucl. Part. Sci. 64, 247 (2014)



- gas TPC, emitting foil at central cathode
- 14 g of 97%-enriched Se-82 on mylar film
- 700 G magnetic field (0.07 T)
- UCI basement !
- Tl-208 background (and radon …)

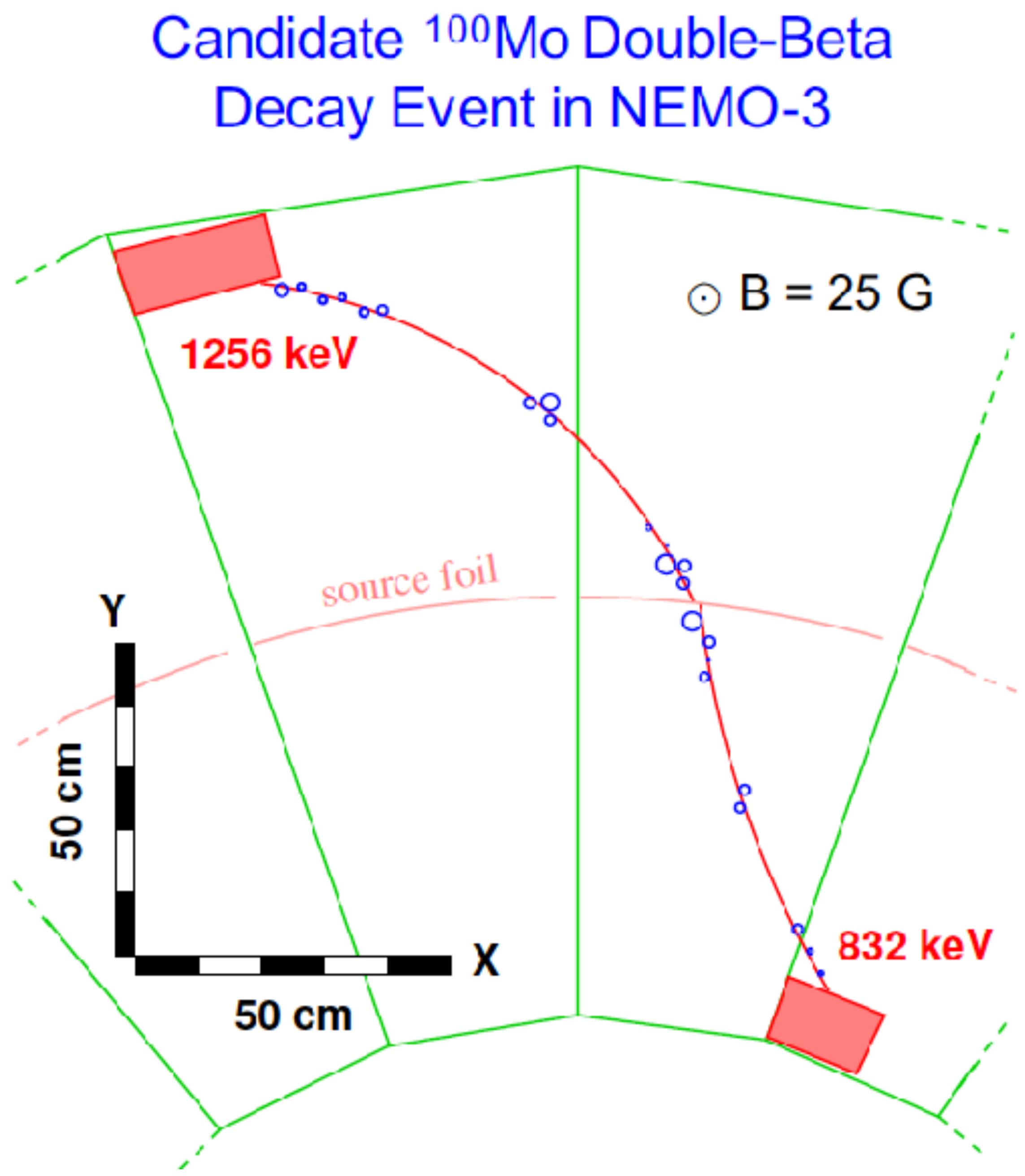


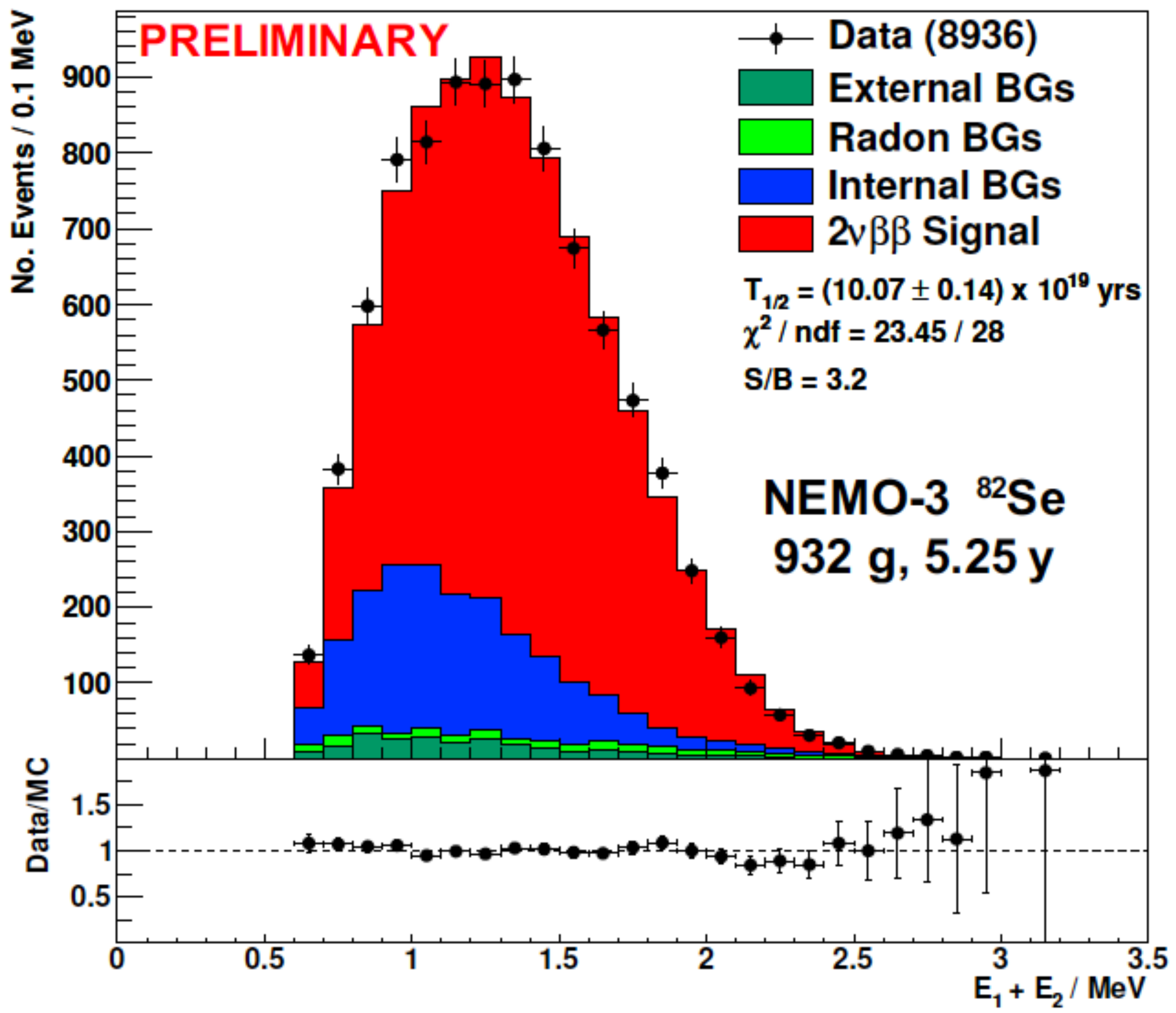
$$T_{1/2}^{2\nu} = 1.1^{+0.8}_{-0.3} \times 10^{20}\ yr$$



NEMO3 - a beautiful electron tracking machine ('03-'11)

- source foils + gas tracker + calorimeter
- most solid isotopes: Ca-48 (7 g), Se-82 (1 kg), Zr-96, Mo-100 (7 kg), Cd-116 (410 g), Te-130, Nd-150 (37 g)
- 25 G magnetic field
- Laboratoire Souterrain de Modane (4,800 m.w.e)
- Particle ID, Rn abatement





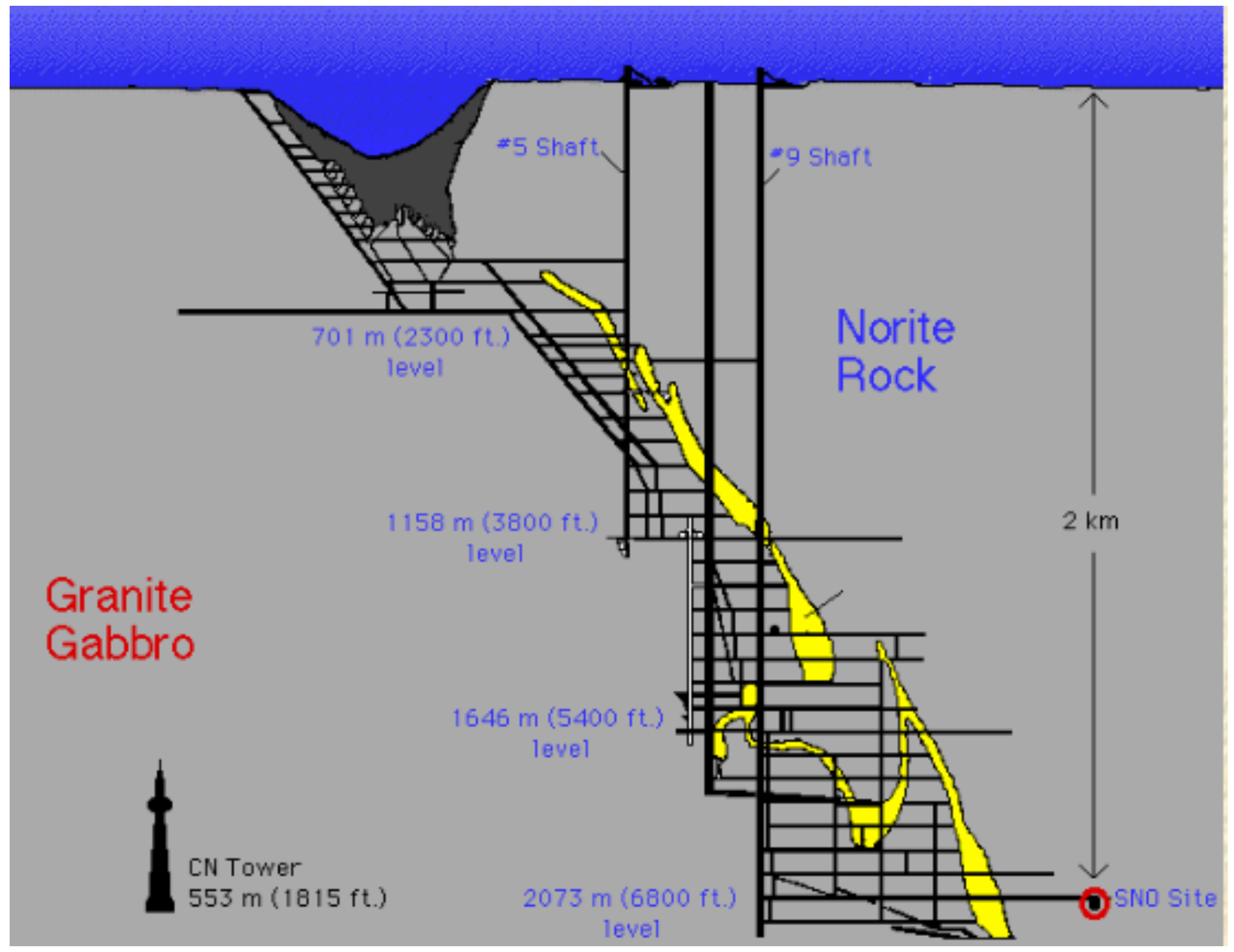
- single-electron reconstruction
- study the DBD mechanism through angular correlations (new operators, Majorons, role of intermediate states in NME)
- excellent measurement of 2νββ
- limited energy resolution
- (first search for 0ν4β decay: Nd-150 –> Gd-150 + 4e-)

Essential ingredients for a successful program today

"And then I thought, What better hedge than a ~~uranium~~ centrifuge?"
xenon

1. Enrichment of the isotope of choice (from ≲10% to 80-90%)
    - For tonne-scale experiments
      -> handling of tens of tonnes of material
    - Current and next generation experiments
      ~all share the source = detector design
    - High signal efficiency

2. Deep underground location
    - Few locations with 1-2 km depth
    - Suppress cosmic rays and activation

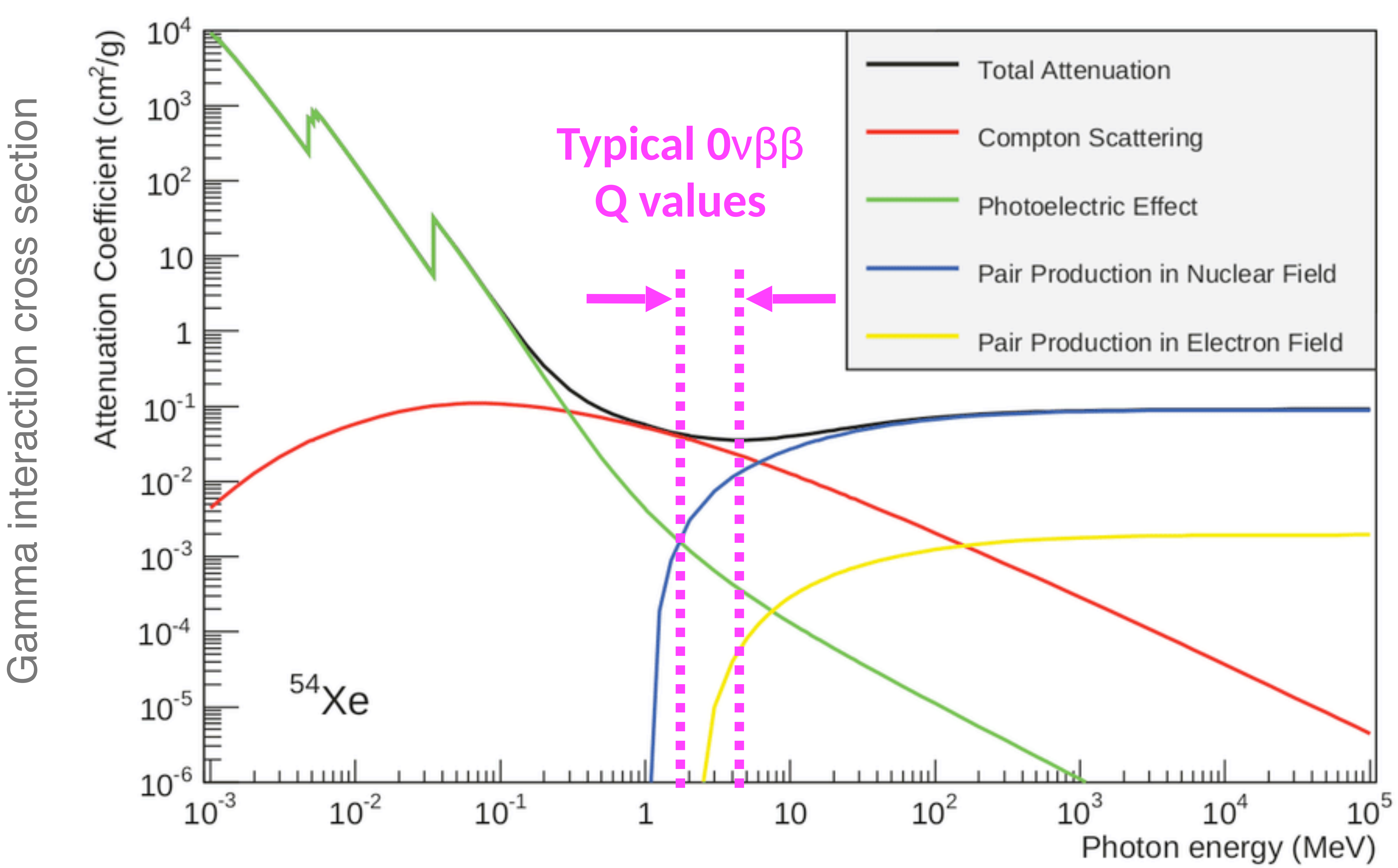


Essential ingredients for a successful program

3. Ultra-low background construction materials
    - ~10-15 g/g for U,Th
    - Radon at ~0.1 μBq/kg

4. Powerful background discrimination techniques
    - Non-trivial for 1 MeV events with limited information
    - Exploit localized nature of 2β event
    - Good energy resolution
    - Actual tracking with low density detector in the way of scaling to very large masses
    - Final state ID may be possible

Key requirement for most experiments: shielding from MeV γ-rays



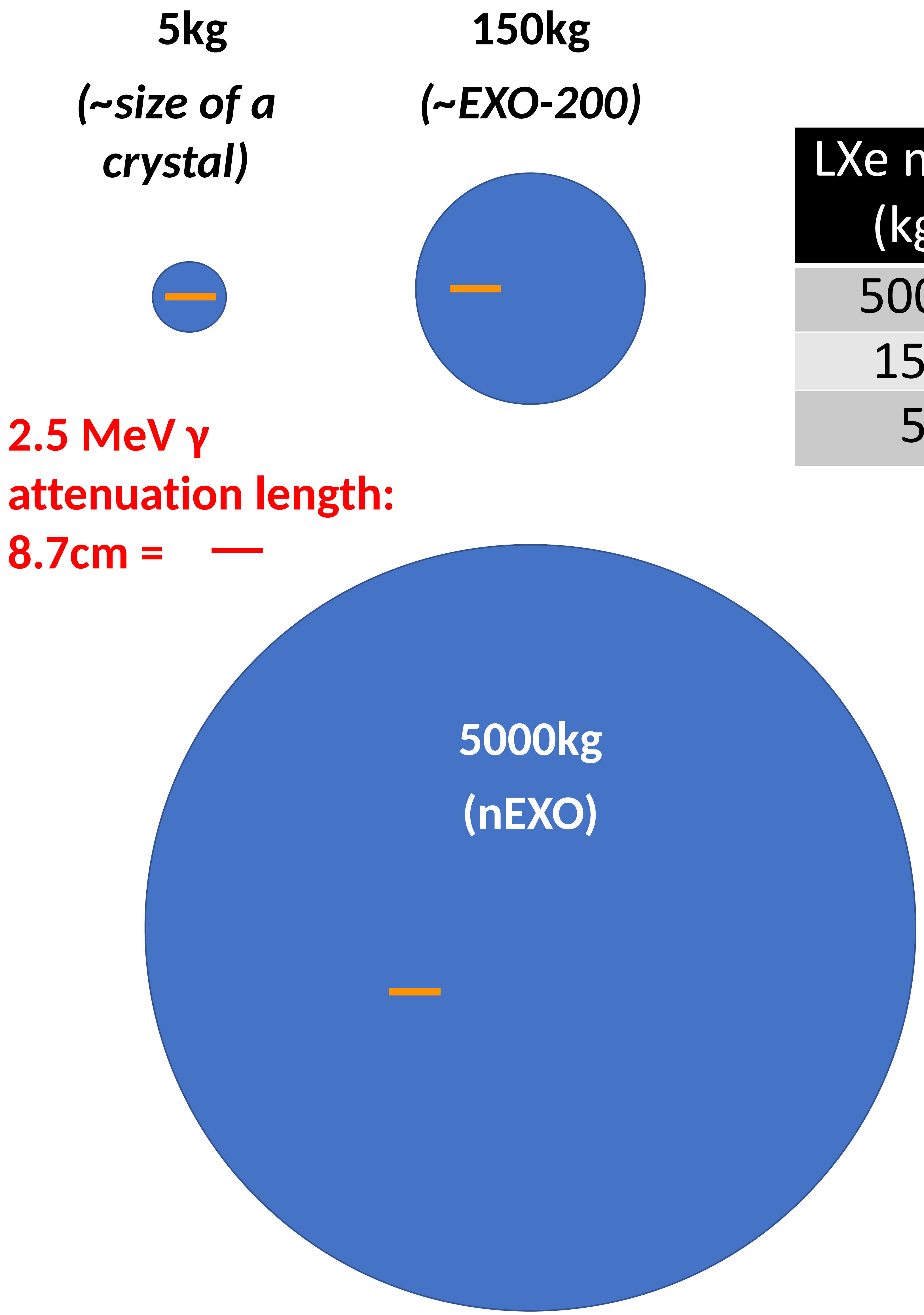
Shielding ββ decay detectors from external electromagnetic background is harder/different than shielding Dark Matter detectors

We are entering the “golden era” of ββ decay experiments as detector sizes exceed gamma-ray interaction lengths

Large, monolithic detectors self-shield

Segmented detectors are developing counter-measures based on tight packing, larger crystals, active vetoes,
(the γ-ray interaction length in Ge is 4.6 cm, comparable to the size of a germanium detector)

Power of self-shielding, monolithic, homogeneous detector



5kg

(~size of a crystal)

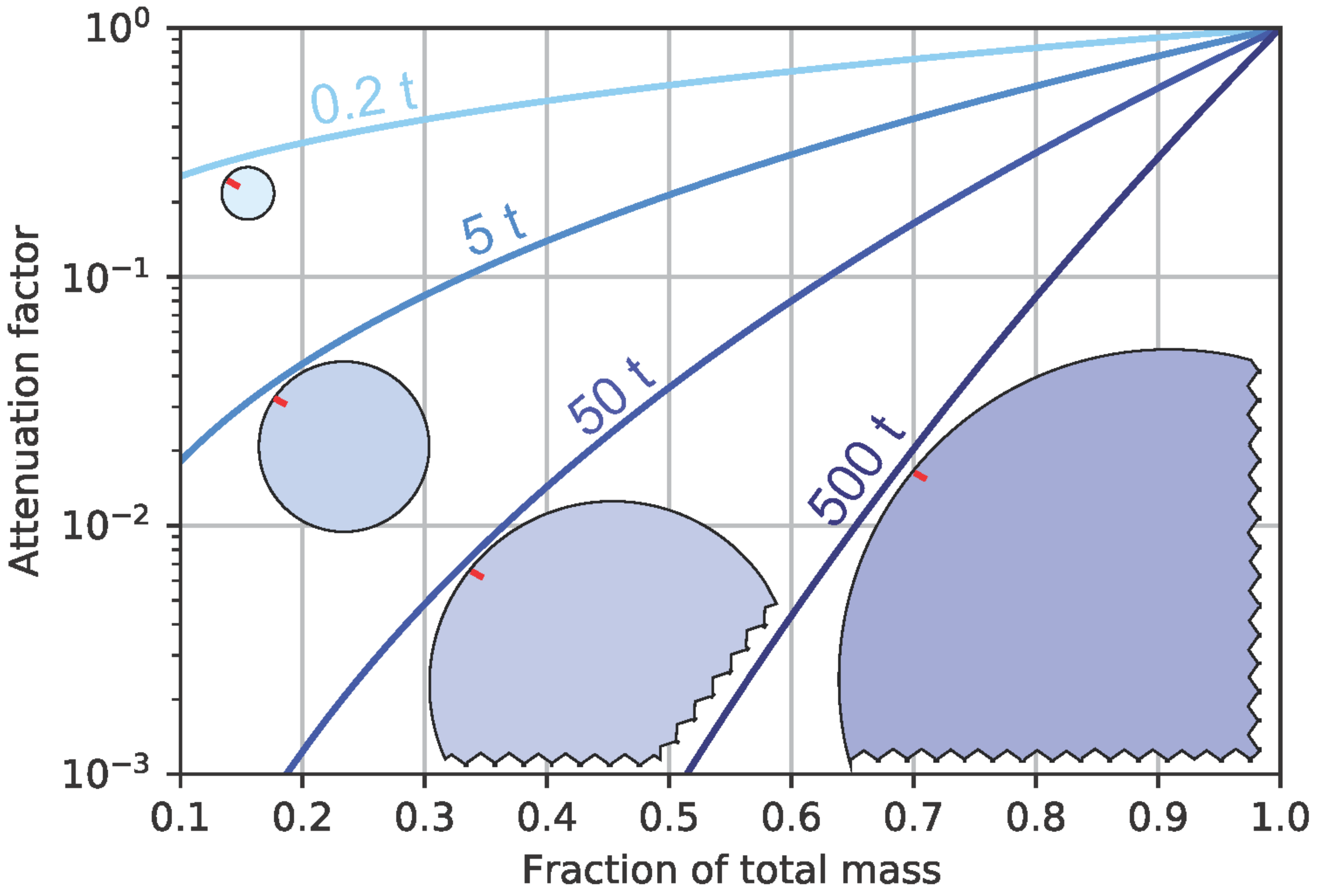
150kg

(~EXO-200)

2.5 MeV γ attenuation length: 8.7cm = —

5000kg (nEXO)

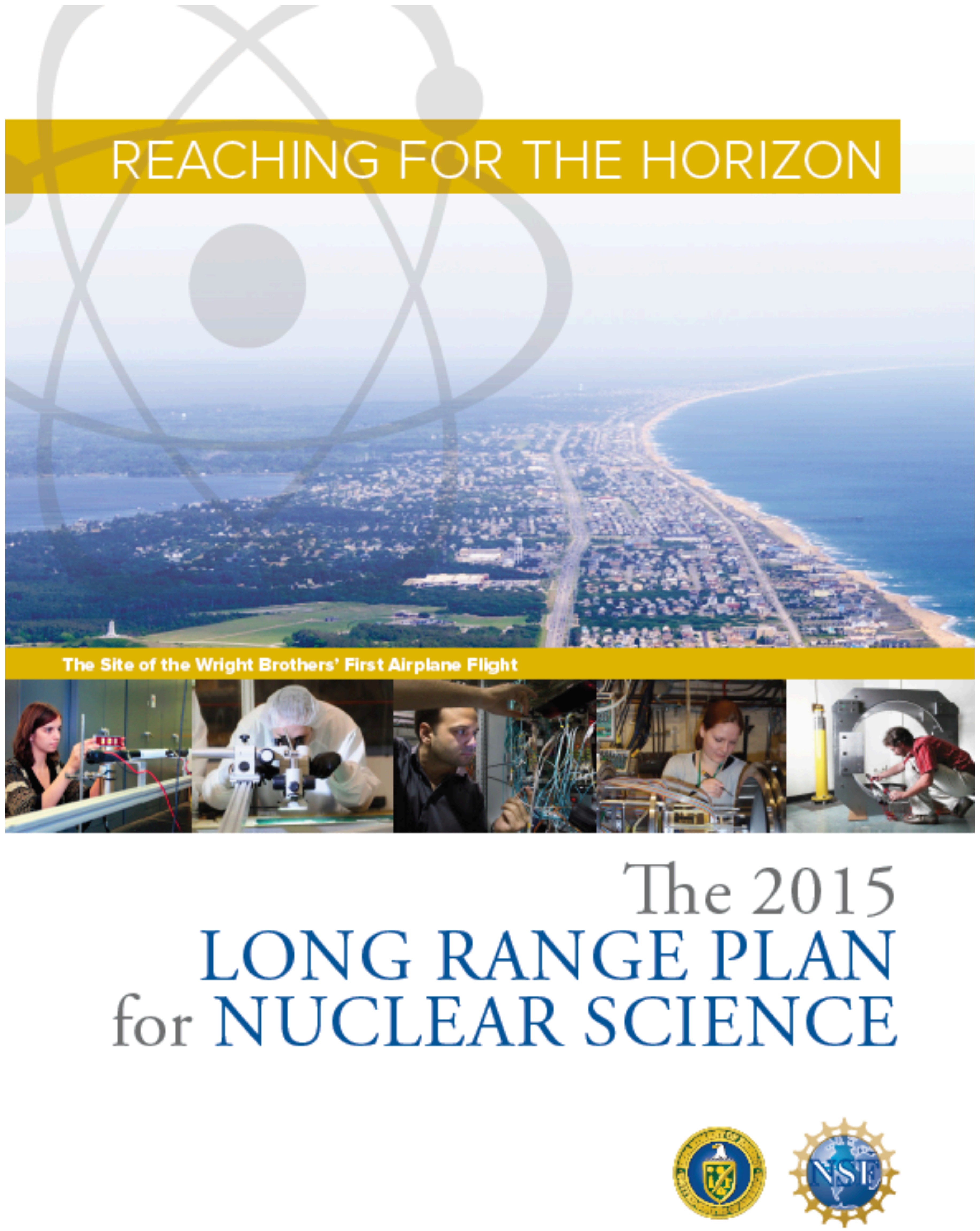
LXe mass (kg)	Linear size (cm)
5000	130
150	40
5	13



Advantages of LXe technology for 0νββ decay:

- *Scalable, re-purifiable, transferable between detectors*
- *Low intrinsic background (fully exploited at the tonne scale)*
- *Particle ID (β/α), event topology (β/γ)*
- *Possibility of no-source control experiment*

The tonne scale program

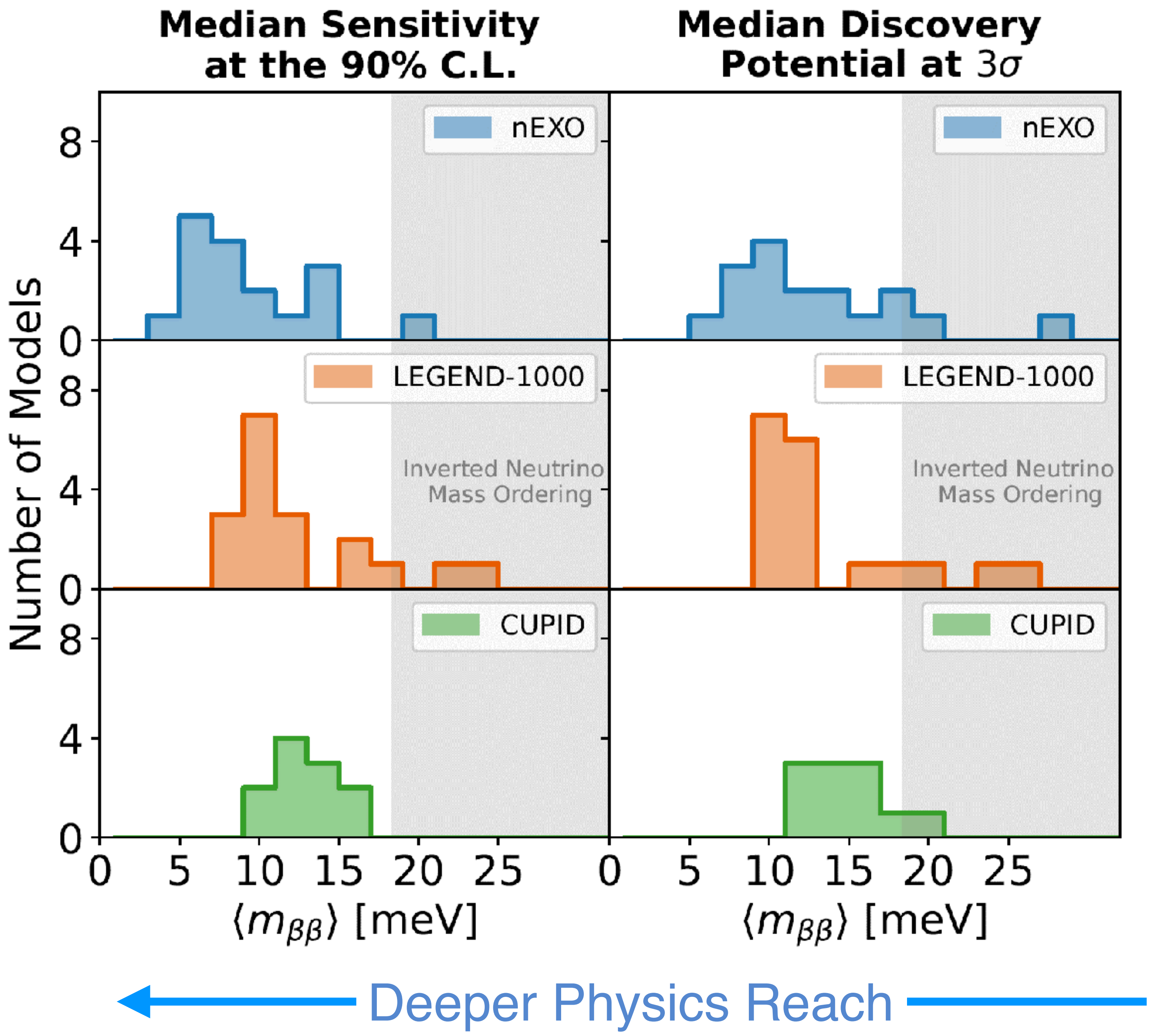

REACHING FOR THE HORIZON

The Site of the Wright Brothers' First Airplane Flight

The 2015
LONG RANGE PLAN
for NUCLEAR SCIENCE

The construction of 1 or more tonne-scale neutrinoless double beta decay experiments is identified as the top new construction priority for US nuclear physics

A DOE Portfolio Review in Summer 2021 identified three US projects to reach $T_{1/2} \sim 10^{28}$ years: CUPID, Legend-1000, nEXO



Heidelberg-Moscow experiment (Ge-76)

- enriched (86%) ^{76}Ge crystals
- superb energy resolution
- LNGS

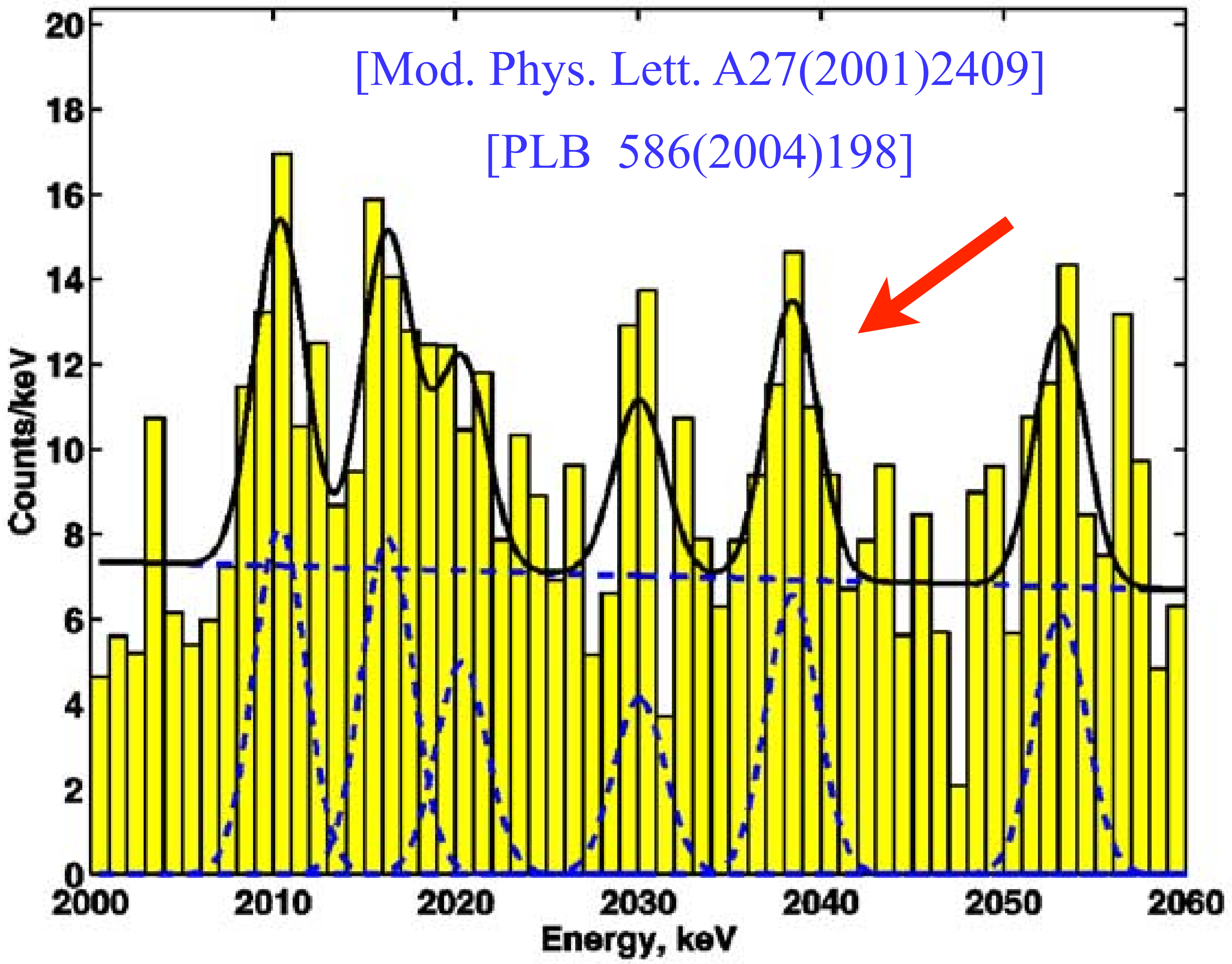
- interpreted as a limit:

$$T^{0\nu}_{1/2} > 1.9 \times 10^{25}\ yr$$

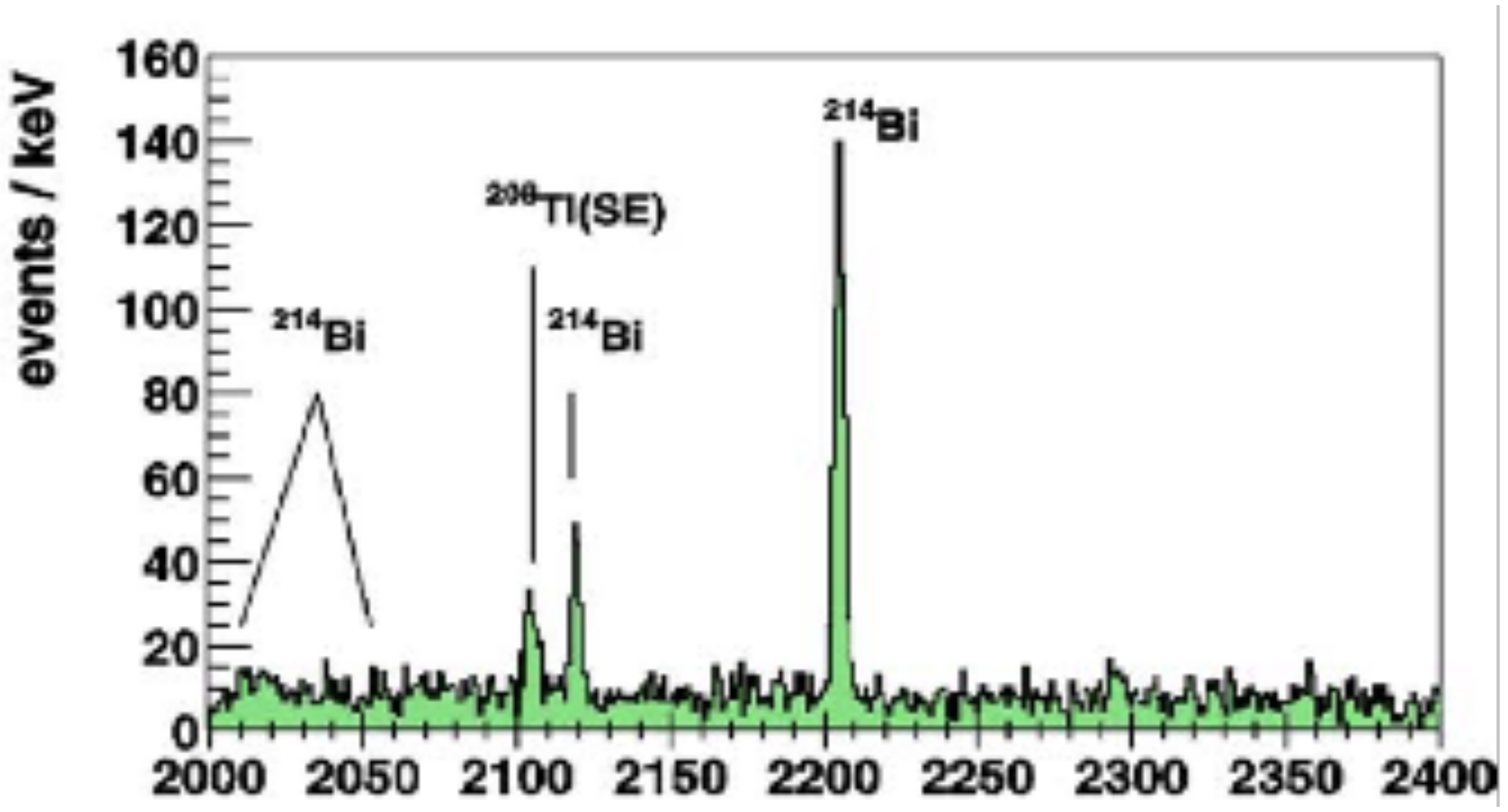
- claimed discovery (now superseded):

$T_{1/2}^{0\nu\beta\beta} = 2.23^{+0.44}_{-0.31} \times 10^{25}$ yr
$m_\nu^{eff} = 0.32 \pm 0.03$ eV

controversial issue:
C.A.Aalseth Mod. Phys. Lett. A17 (2002) 1475
F.Feruglio et al. Nucl.Phys. B637 (2002) 345
Addendum-ibid. B659 (2003) 359
Yu.Zdesenko et al. Phys.Lett. B 546 (2002) 206
H.L.Harney Mod.Phys.Lett. A16 (2001) 2409
A.M.Bakalyarov et al. hep-ex/0309016
H.V.Klapdor-Kleingrouthaus et al. Phys. Lett. B 586 (2004) 198
H.V.Klapdor-Kleingrouthaus et al. Mod. Phys. Lett. 21 (2006) 1547



[Mod. Phys. Lett. A27(2001)2409]
[PLB 586(2004)198]



- Importance of a multi-experiment program
- Ideally, multi-isotope

$T_{1/2}=10^{28}$ y: dura lex, sed lex

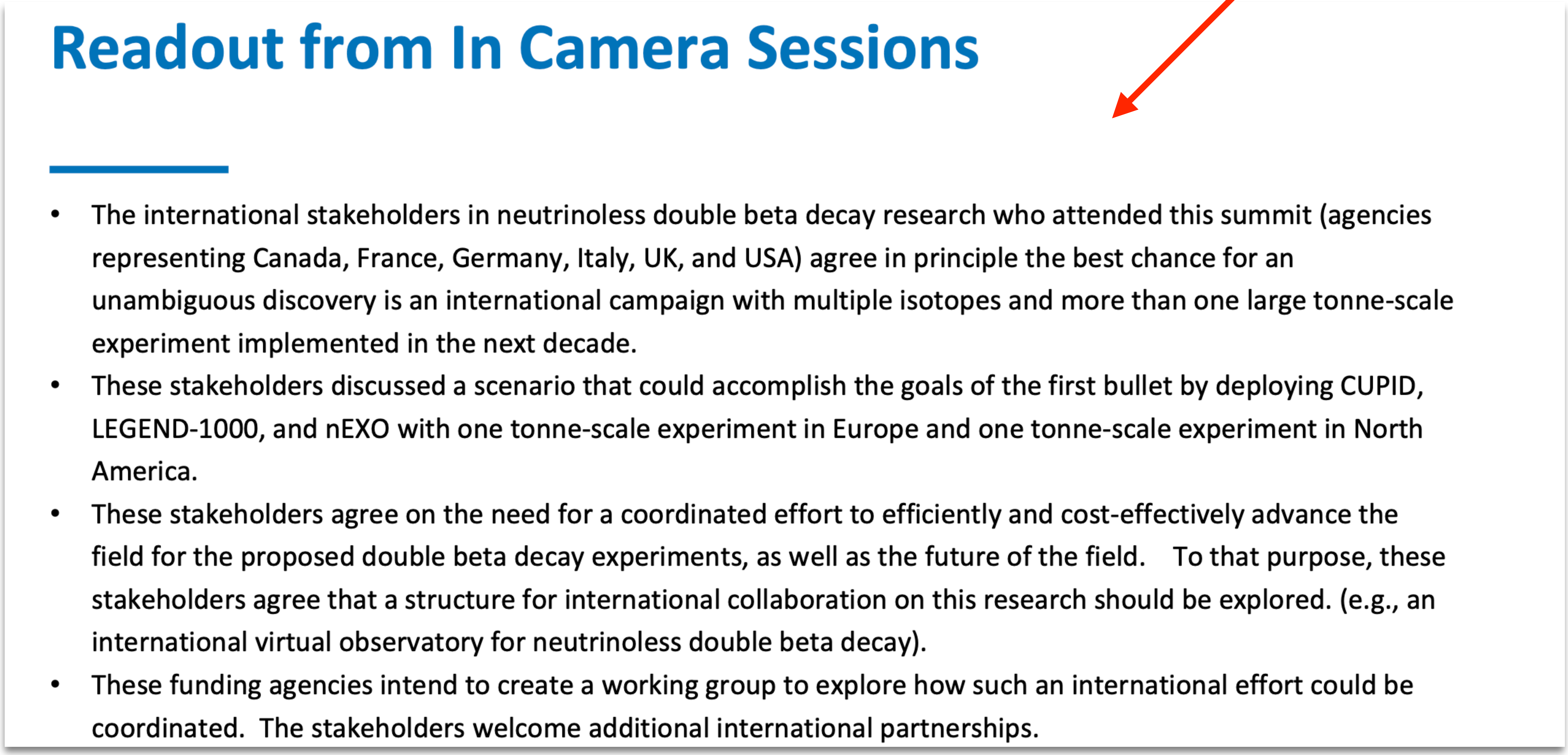
$$\boxed{N_A = 6.022 \times 10^{23}}$$

Amedeo Avogadro

- DBD candidate isotopes: 48→150 grams/mole
- 10^{28} nuclei = 16,600 moles → 800—2,500 kg
- Add-in real-life non-idealities:
  detection efficiency, isotopic fraction, backgrounds, detector live time, ….

International Summits

- First Summit in Fall 2021 at LNGS
- Second Summit in April 2023 at SNOLAB

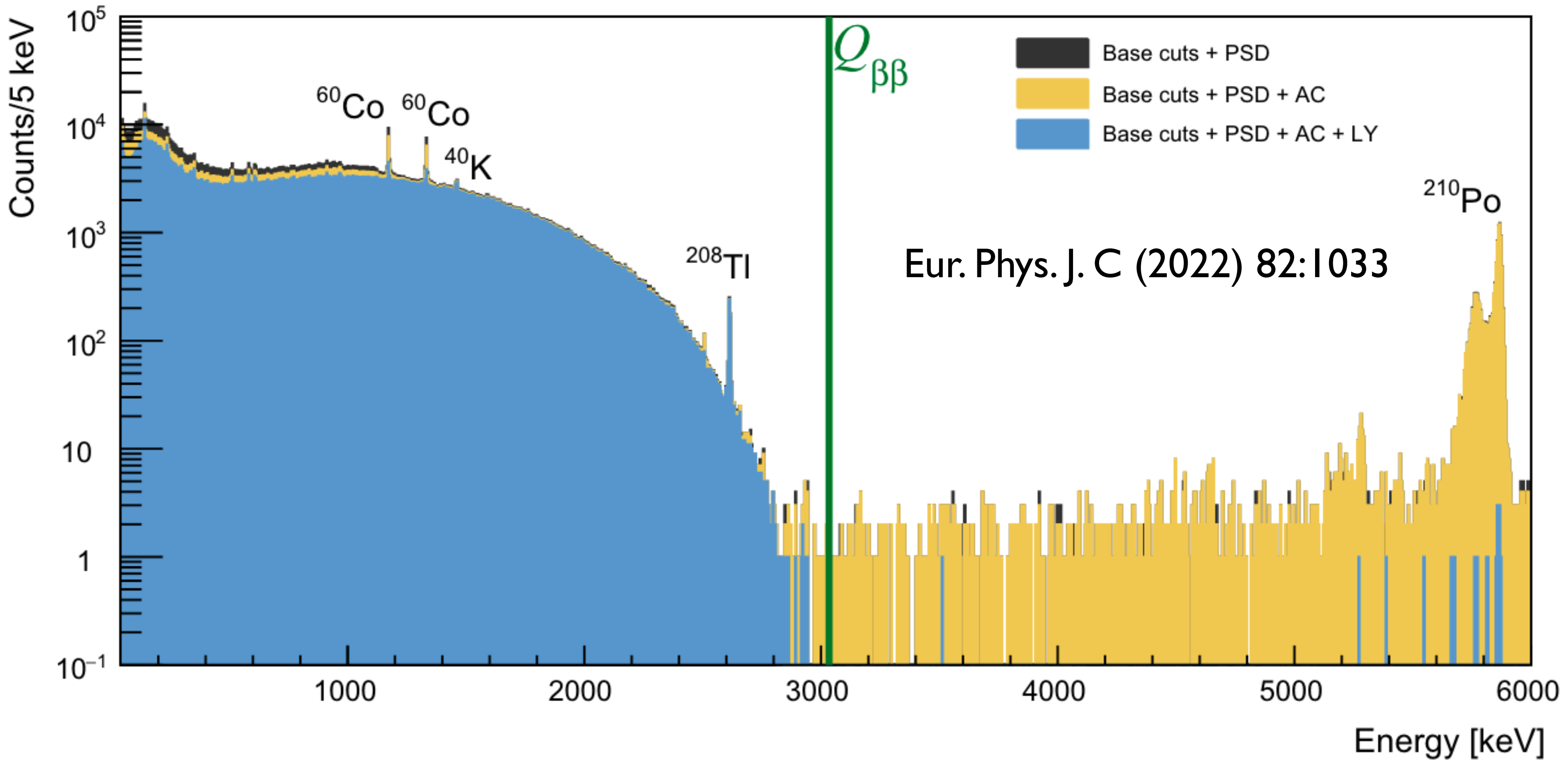


Readout from In Camera Sessions

- The international stakeholders in neutrinoless double beta decay research who attended this summit (agencies representing Canada, France, Germany, Italy, UK, and USA) agree in principle the best chance for an unambiguous discovery is an international campaign with multiple isotopes and more than one large tonne-scale experiment implemented in the next decade.
- These stakeholders discussed a scenario that could accomplish the goals of the first bullet by deploying CUPID, LEGEND-1000, and nEXO with one tonne-scale experiment in Europe and one tonne-scale experiment in North America.
- These stakeholders agree on the need for a coordinated effort to efficiently and cost-effectively advance the field for the proposed double beta decay experiments, as well as the future of the field. To that purpose, these stakeholders agree that a structure for international collaboration on this research should be explored. (e.g., an international virtual observatory for neutrinoless double beta decay).
- These funding agencies intend to create a working group to explore how such an international effort could be coordinated. The stakeholders welcome additional international partnerships.

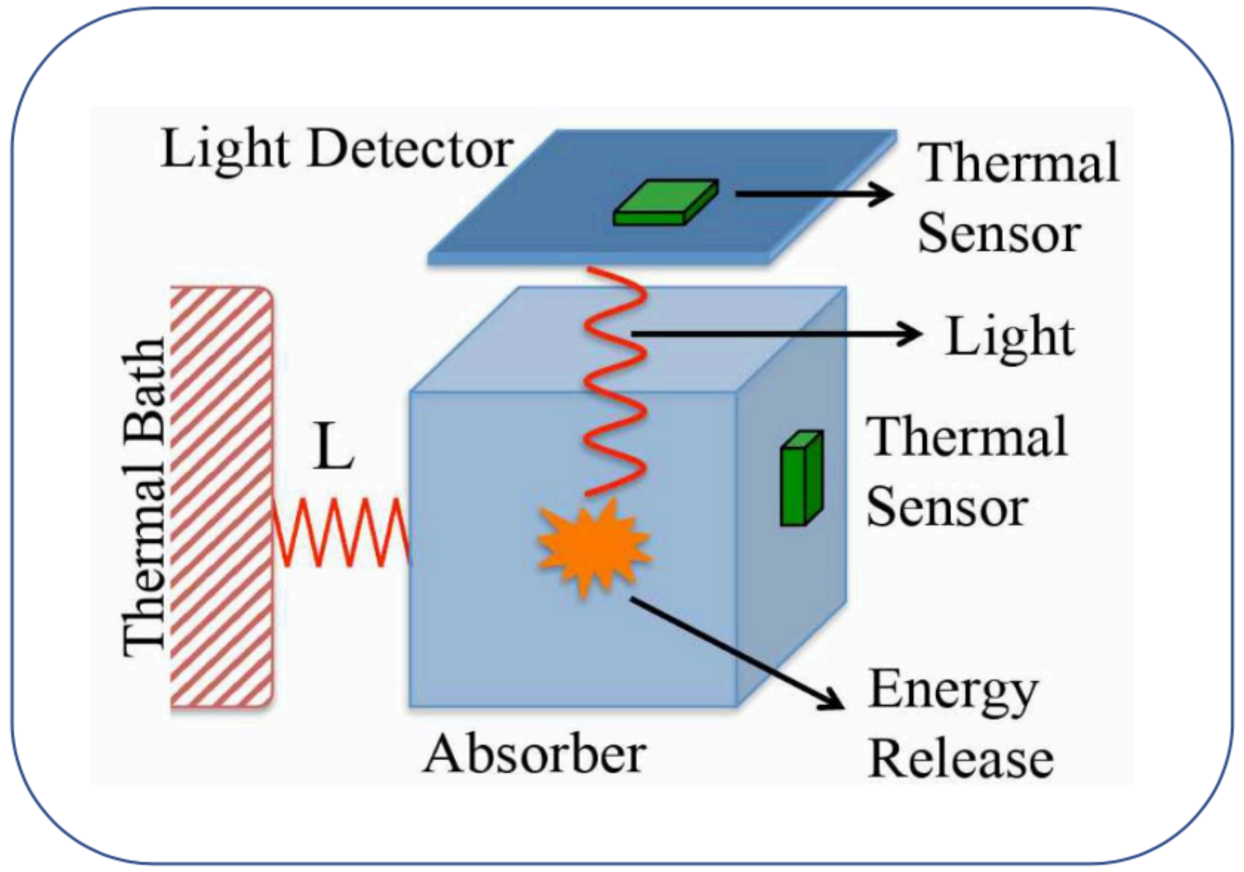
CUPID

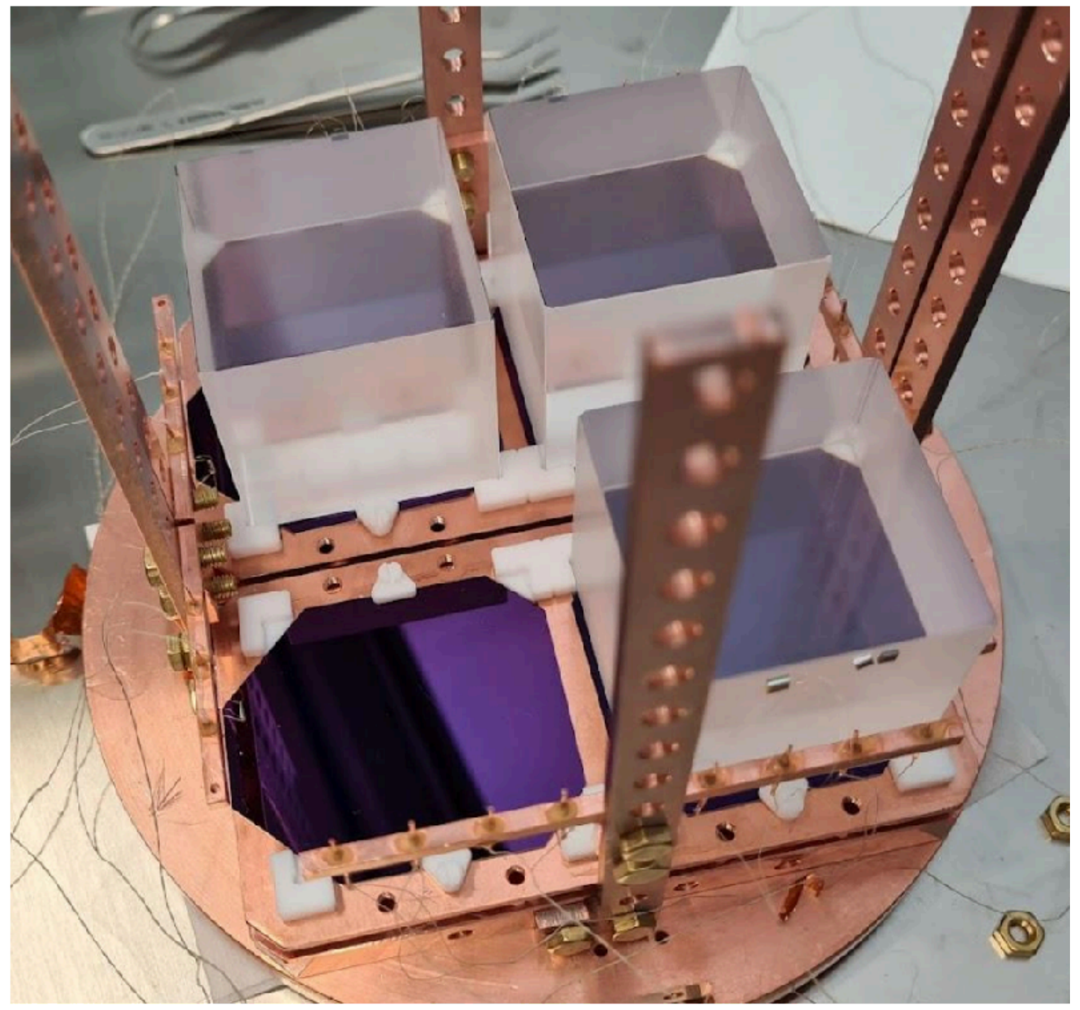
- Array of Li_2MoO_4 scintillating bolometer crystals
- Use CUORE cryostat @ LNGS
- 280 kg of enriched 100Mo, Q=3034 keV
- $T_{1/2} > 10^{27}$ years at 3σ
- $m_{\beta\beta} \sim$ 12-20 meV

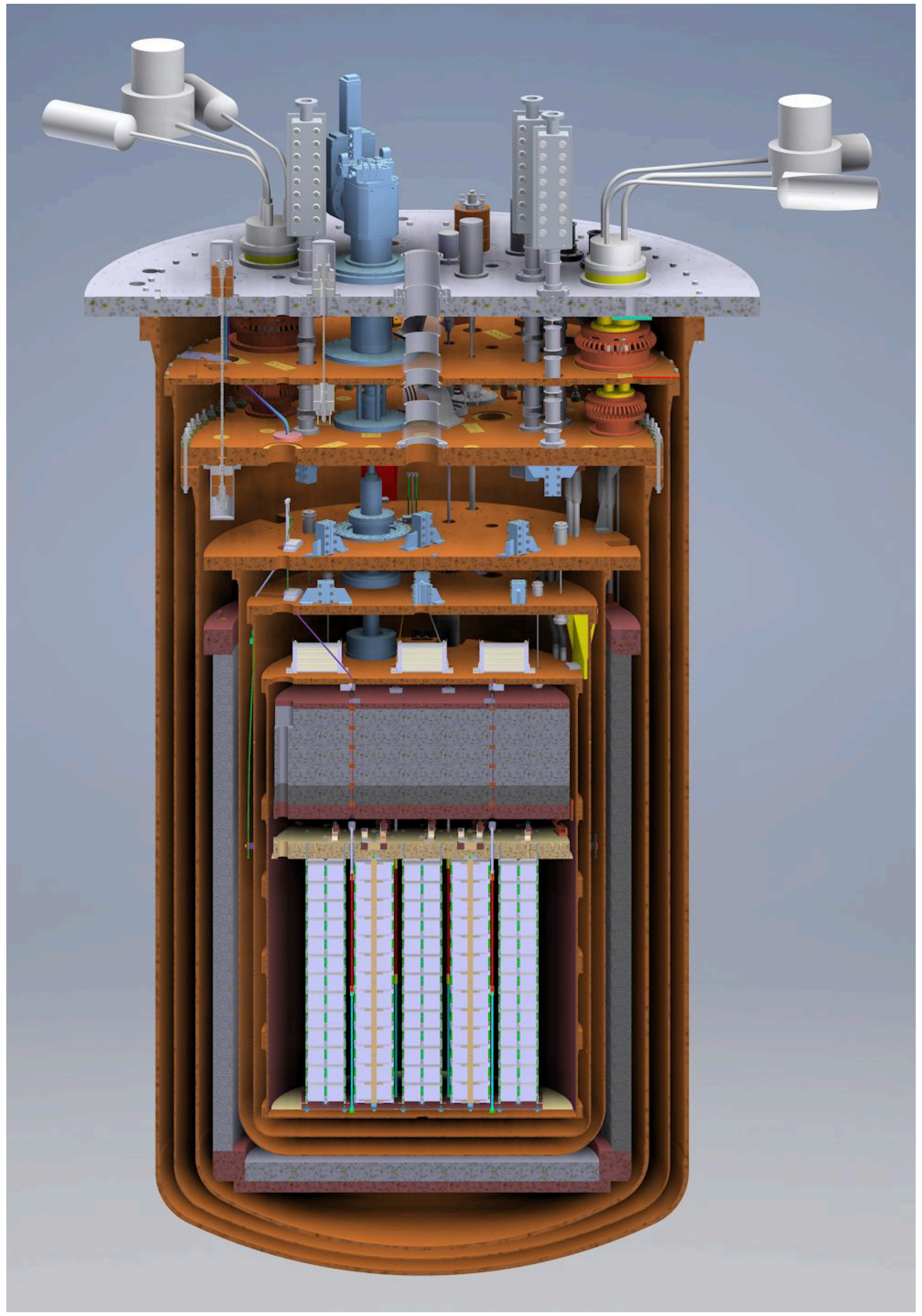


Eur. Phys. J. C (2022) 82:1033

CUPID ^{100}Mo
heat + light
(scintillating bolometer)



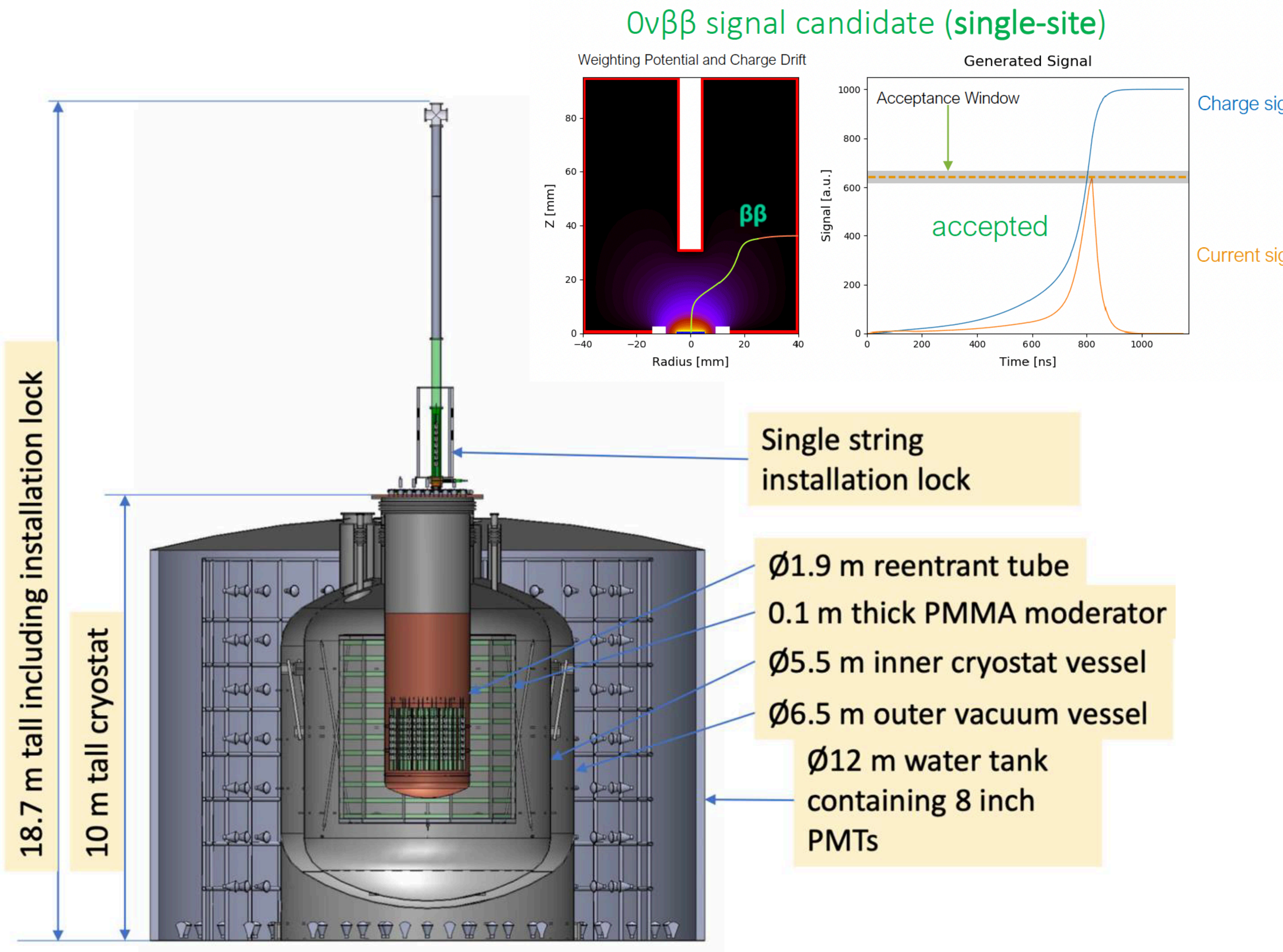




LEGEND-1000

From D. Radford, 2nd International Summit, SNOLAB, April 2023

- Legend combines the GERDA and Majorana Demonstrator collaborations
- Array of enriched ^{76}Ge crystals
- 1000 kg of enriched ^{76}Ge (sensitivity goal $T_{1/2} = 10^{28}$ y)
- Inverted-coaxial point-contact detectors for particle ID via PSD
- Excellent energy resolution
- Liquid argon veto (demonstrated in GERDA)
- Currently commissioning Legend-200 (sensitivity goal $T_{1/2} = 10^{27}$ y)



0νββ signal candidate (**single-site**)

Single string installation lock

Ø1.9 m reentrant tube

0.1 m thick PMMA moderator

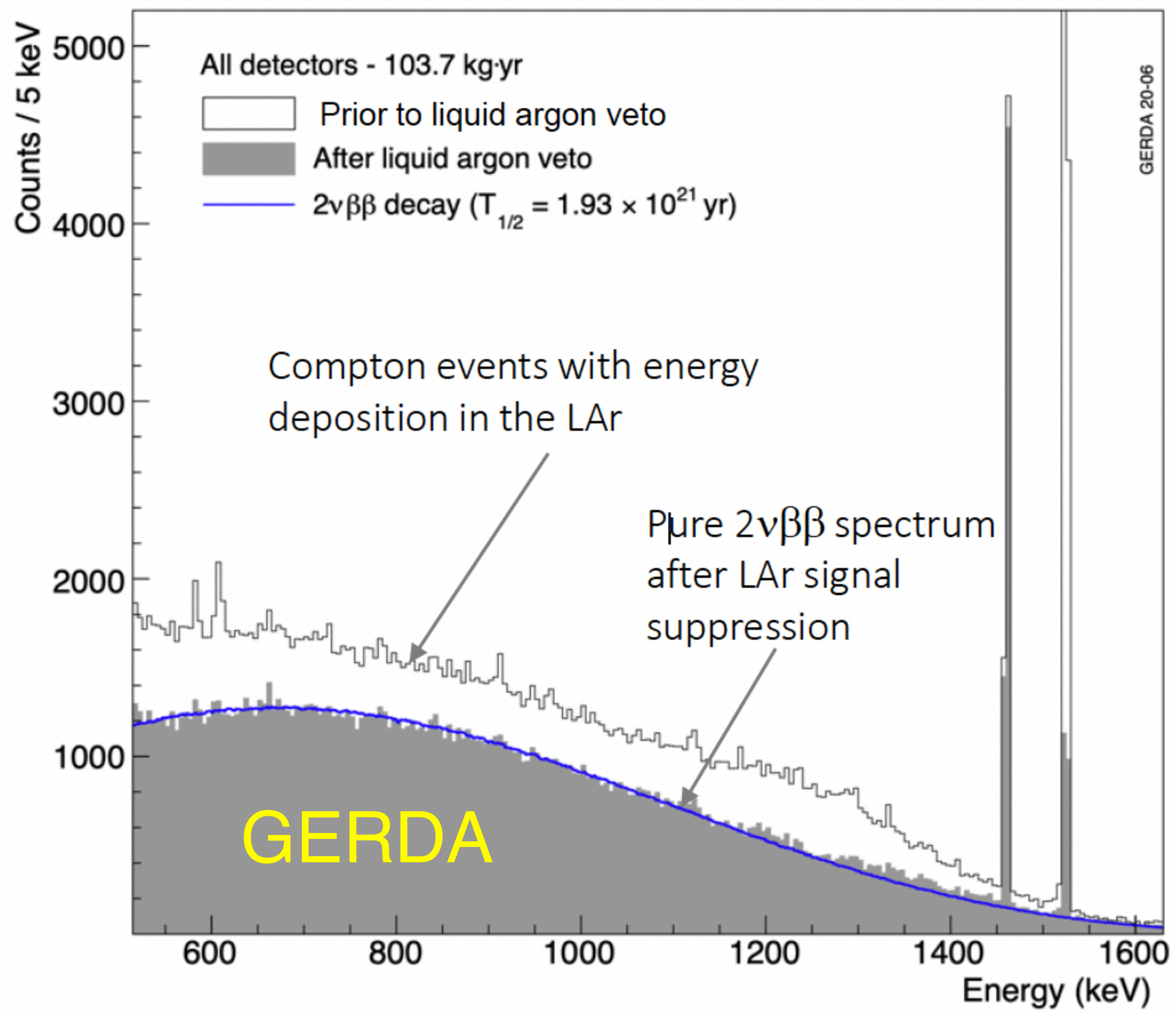
Ø5.5 m inner cryostat vessel

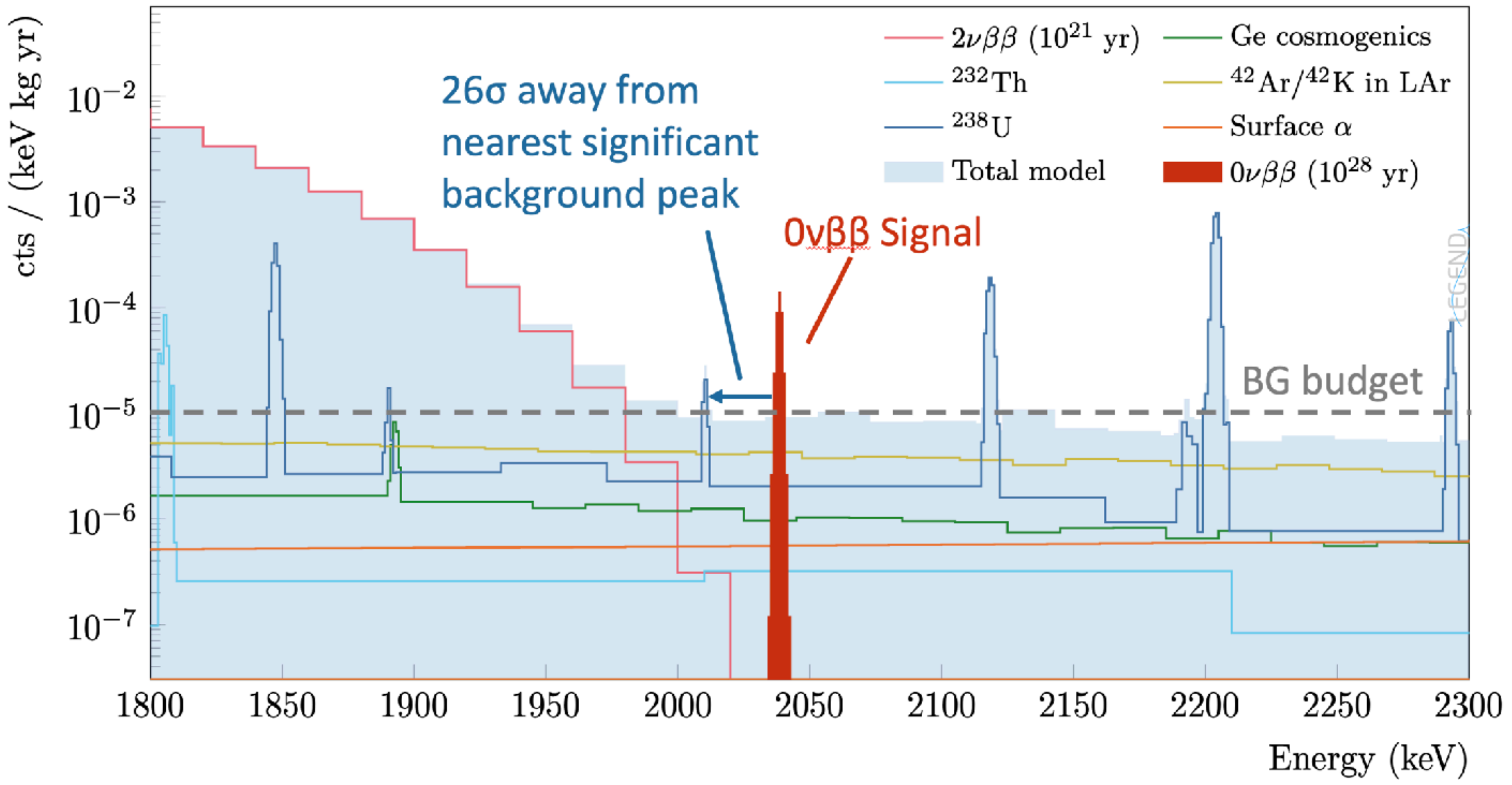
Ø6.5 m outer vacuum vessel

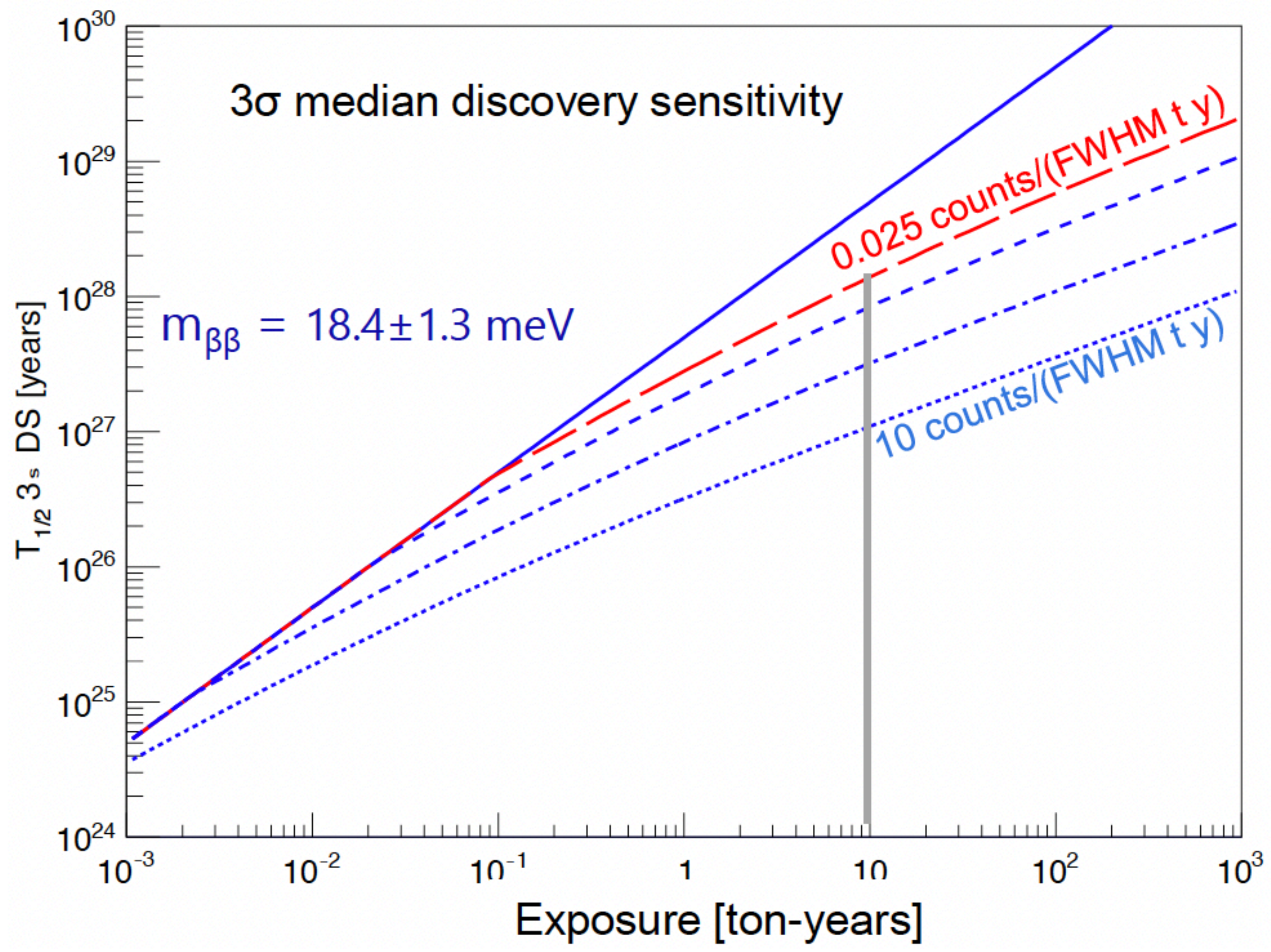
Ø12 m water tank containing 8 inch PMTs

LEGEND-1000

From D. Radford, 2nd International Summit, SNOLAB, April 2023

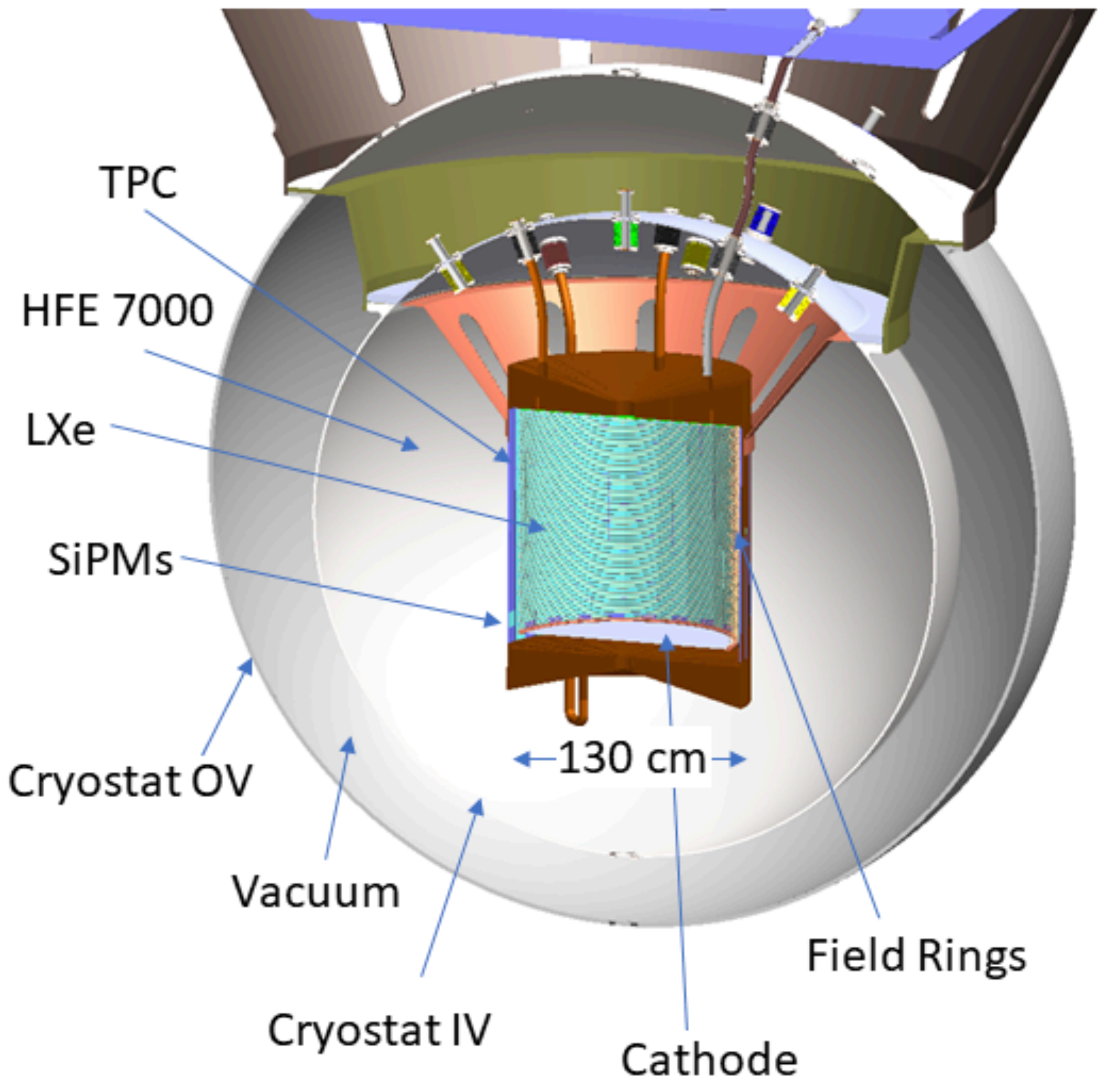


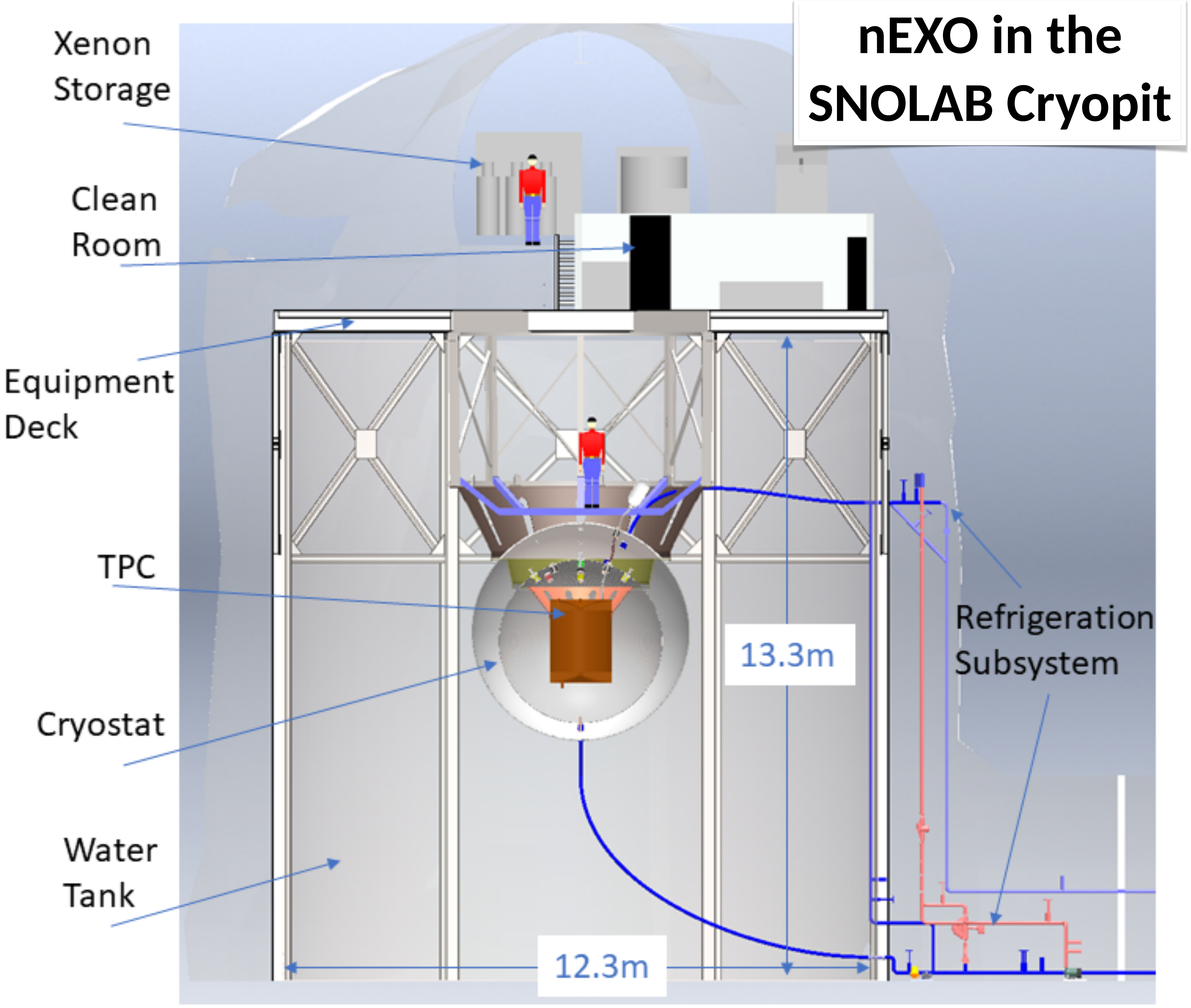




nEXO

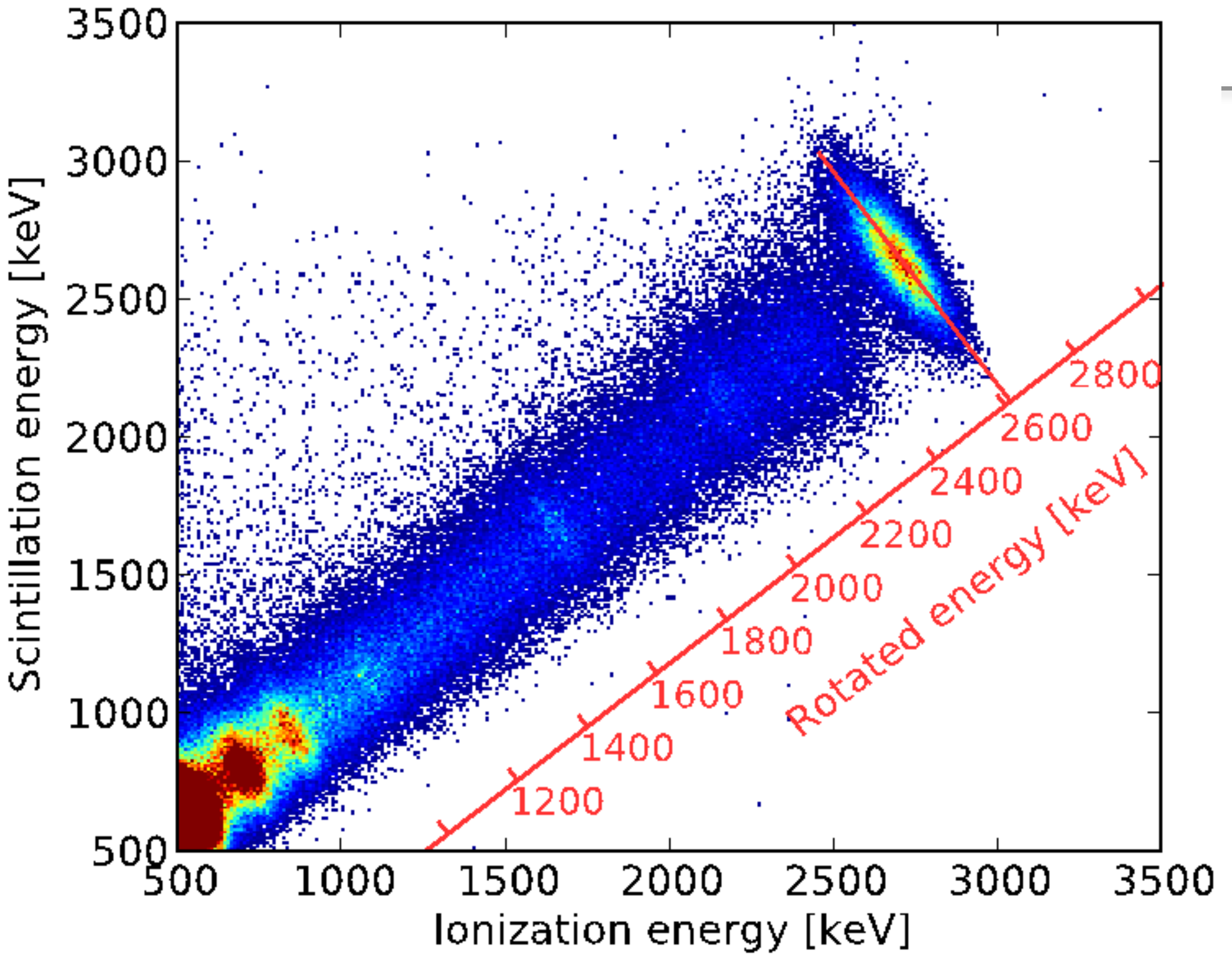
- Single-phase, LXe TPC (monolithic) (rooted in EXO-200)
- 5000 kg of 90%-enriched ^{136}Xe (sensitivity goal $T_{1/2} > 10^{28}$ y)
- Charge readout with strips on tiled anode
- VUV-sensitive SiPM array (>4 m^2)

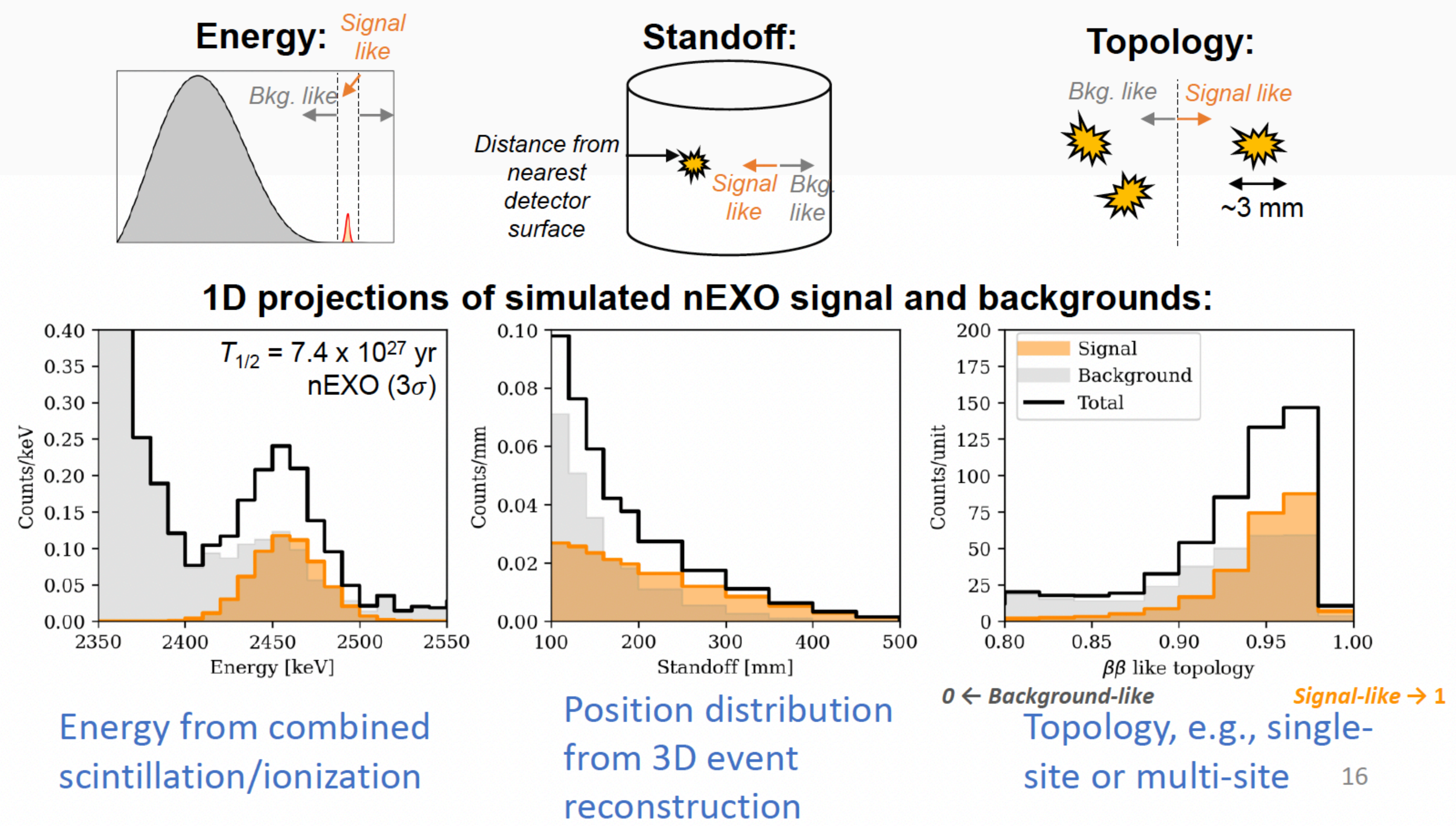



nEXO in the SNOLAB Cryopit

nEXO

- Combined charge-light readout yields good energy resolution and powerful background discrimination (α/β)
- Multi-dimensional parameter space yields “background-free” signal





Energy:

Standoff:

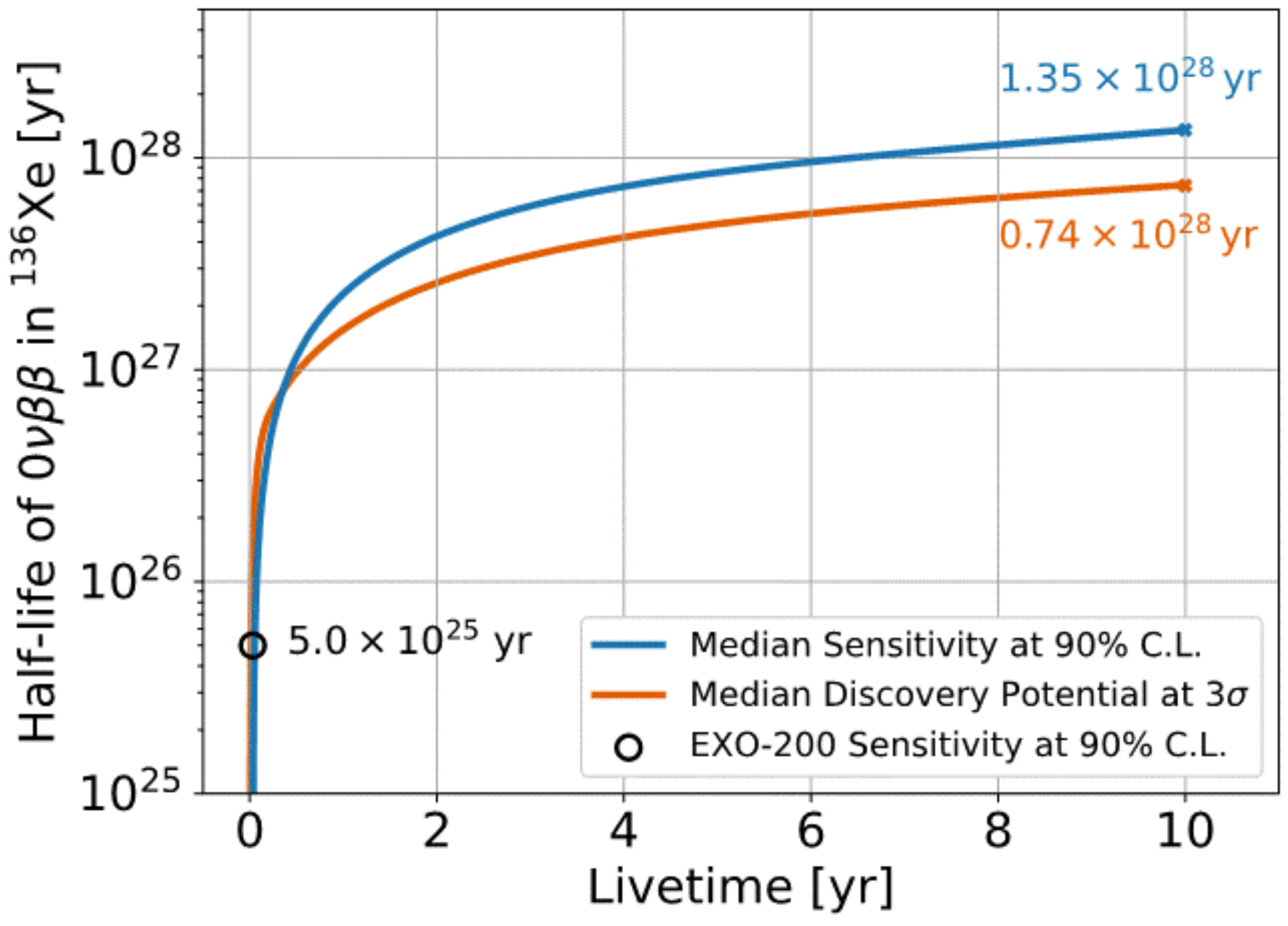
Topology:

1D projections of simulated nEXO signal and backgrounds:

Energy from combined scintillation/ionization

Position distribution from 3D event reconstruction

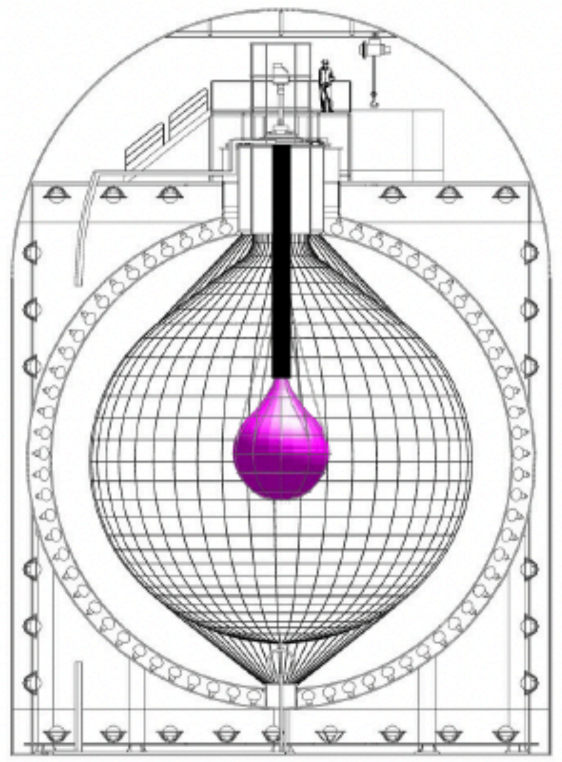
Topology, e.g., single-site or multi-site



Kamland2-Zen and beyond

From A. McDonald, 2nd International Summit, SNOLAB, April 2023

KamLAND-Zen 400

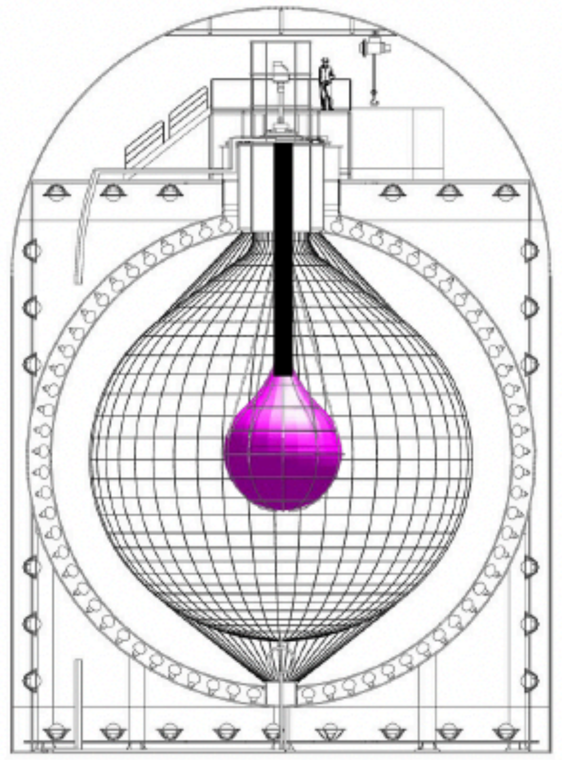


380kg deployed

$T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ yr

PRL117, 082503 (2016)

KamLAND-Zen 800



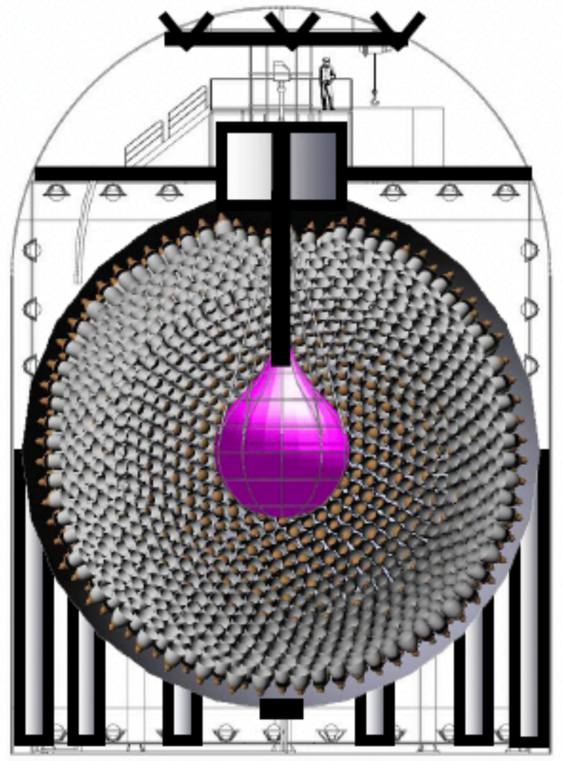
Now, 745kg deployed

$> 2.3 \times 10^{26}$ yr

PRL130, 051801 (2023)

Further improvements going on;
better neutron tagging
machine learning (ML) for long-lived tagging
ML for beta/gamma discrimination
muon-bundle tracking, and so on

KamLAND2-Zen



Mirror
HQE-PMT
new LS
} x5 p.e.
full volume effective
w/ scintillation film

1 ton planned (scalable)

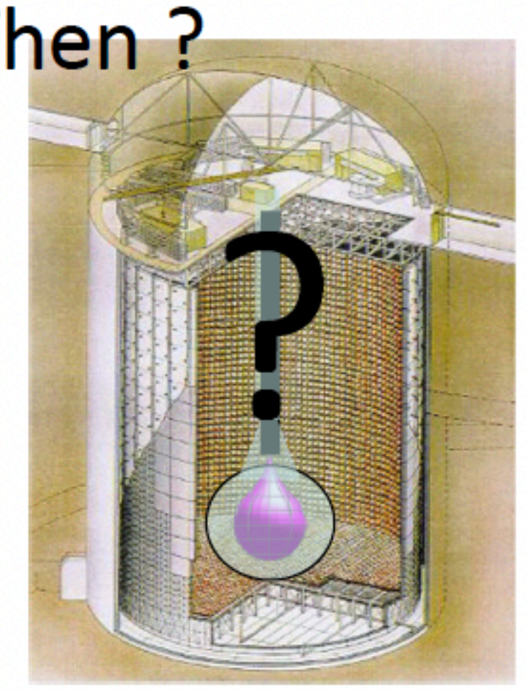
$> 2 \times 10^{27}$ yr (target sensitivity)

$< 12 \sim 53$ meV (corresponding mass limit)

3σ discovery potential is not studied, but ~$1\text{x}10^{27}$ yr

Further technologies being developed
imaging sensor (1/10 reduction of long-lived BG)
high-p xenon deployment (2 times more xenon)

Then ?



It will not be a good choice for the single purpose, but this is multi-purpose detector.

$> 2 \times 10^{28}$ yr
(guesstimated sensitivity)

w/ more than 20 ton xenon
imaging sensor
high-p xenon

For more xenon (possible source)
Extraction from nuclear spent fuel is considered.
More than 100 ton seems to be possible at 44% concentration of Xe-136 without centrifugal enrichment.

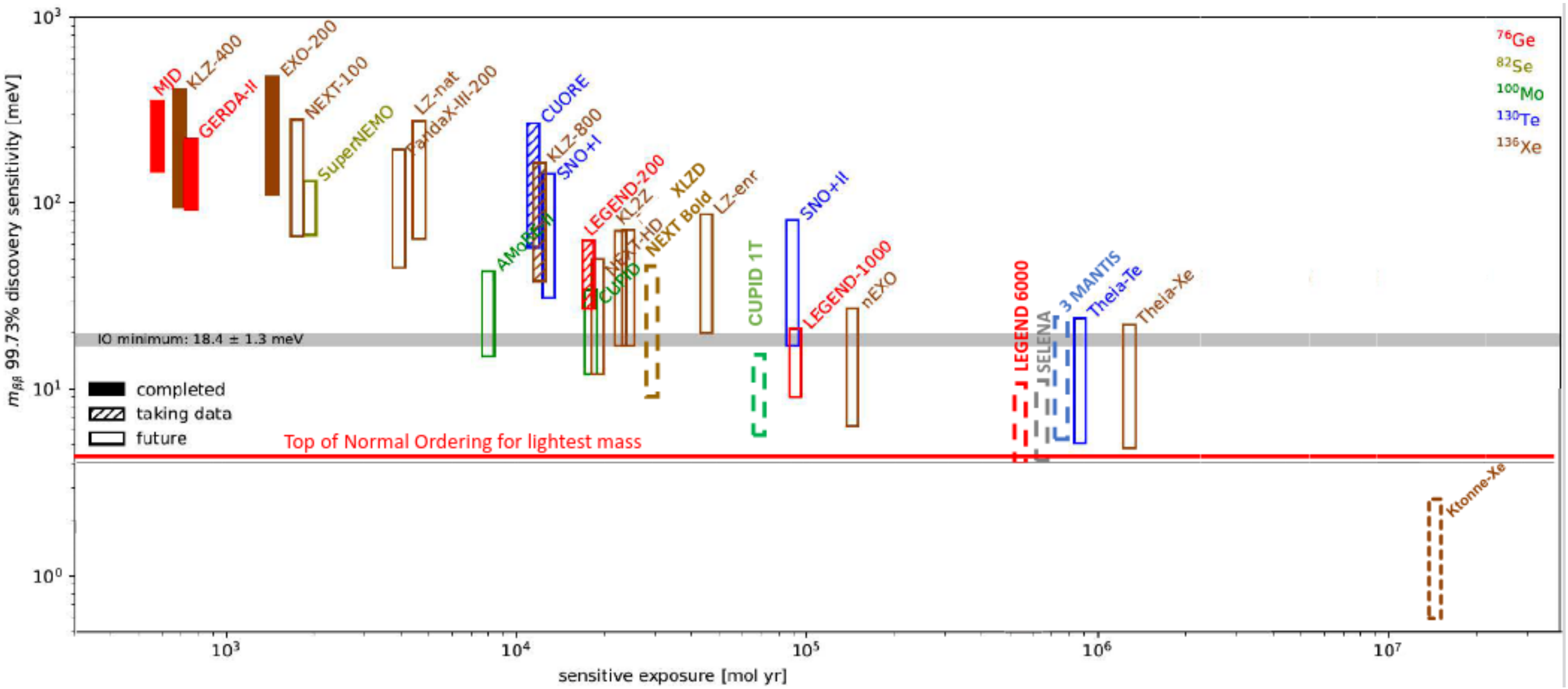
	36 months	atmospheric
^{128}Xe/^{132}Xe	$2.81 \cdot 10^{-3}$	$7.13 \cdot 10^{-2}$
^{129}Xe/^{132}Xe	$4.7 \cdot 10^{-6}$	0.9832
^{130}Xe/^{132}Xe	$3.32 \cdot 10^{-4}$	0.1518
^{131}Xe/^{132}Xe	0.3756	0.7876
^{134}Xe/^{132}Xe	1.3433	0.3883
^{136}Xe/^{132}Xe	2.1176 44%	0.3298 8.9%

Other projects

- The AMoRE collaboration (Korea) is working toward a 100 kg enriched ^{100}Mo experiment with scintillating bolometers (Li_2MoO_4 a la CUPID, also tested $CaMoO_4$)
- The NEXT (Spain) and PandaX (China) collaborations are working toward a 1-tonne HPGXe TPC with enriched ^{136}Xe to exploit topology reconstruction
    - NEXT commissioning NEXT-100 at Canfranc (LSC)
    - NEXT is developing Ba-tagging ID capability
      (both nEXO and NEXT have demonstrated single Ba identification capability)
- Large LXe TPCs for dark matter will have some sensitivity to DBD
  (XENONnT, LZ, PandaX-4T, DARWIN/XLZD)

Timeline for 0νββ decay searches into the future

Summary plot from NSAC LRP White Paper (with additions)

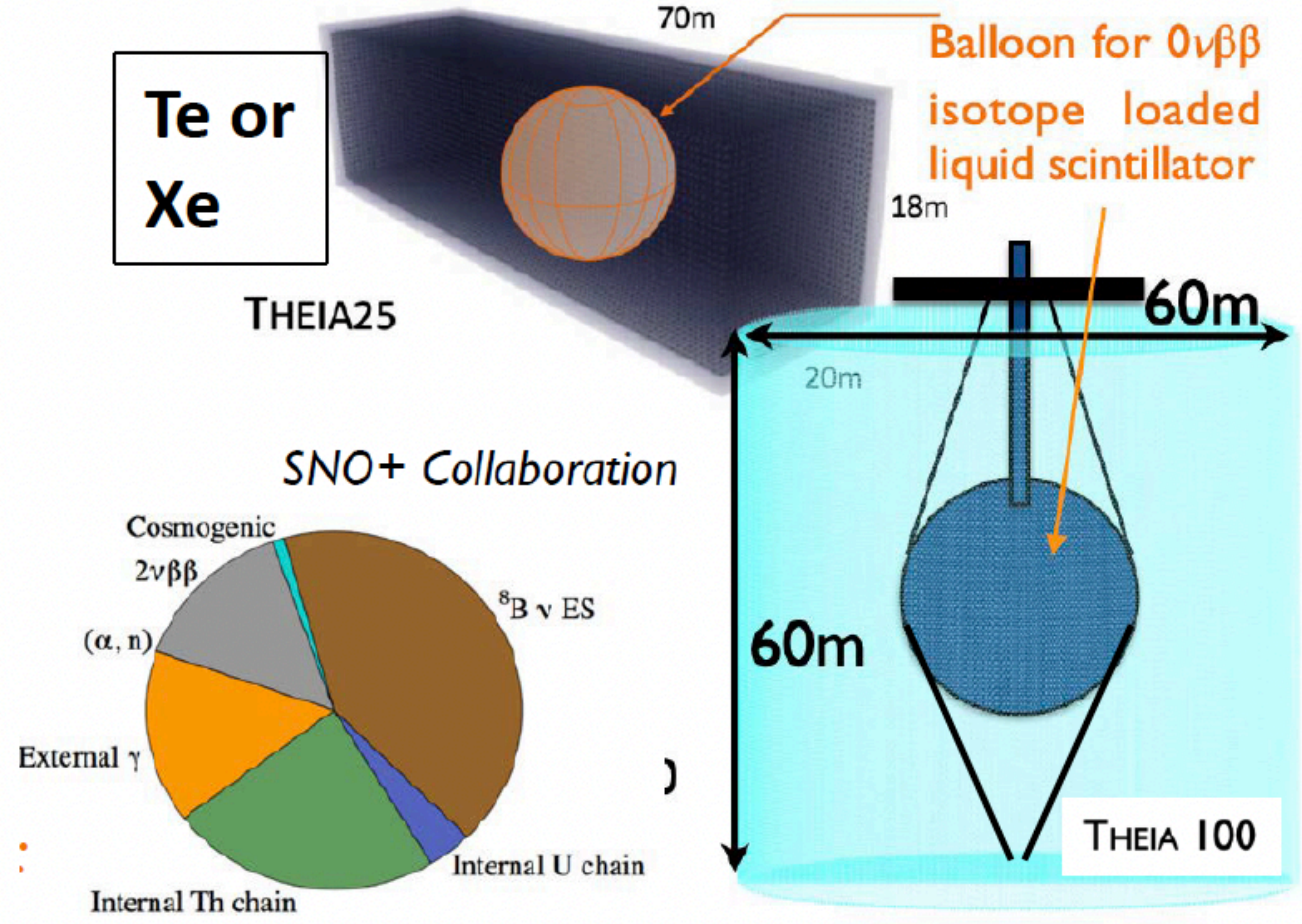


Very large LS detectors — R&D

From A. McDonald, 2nd International Summit, SNOLAB, April 2023

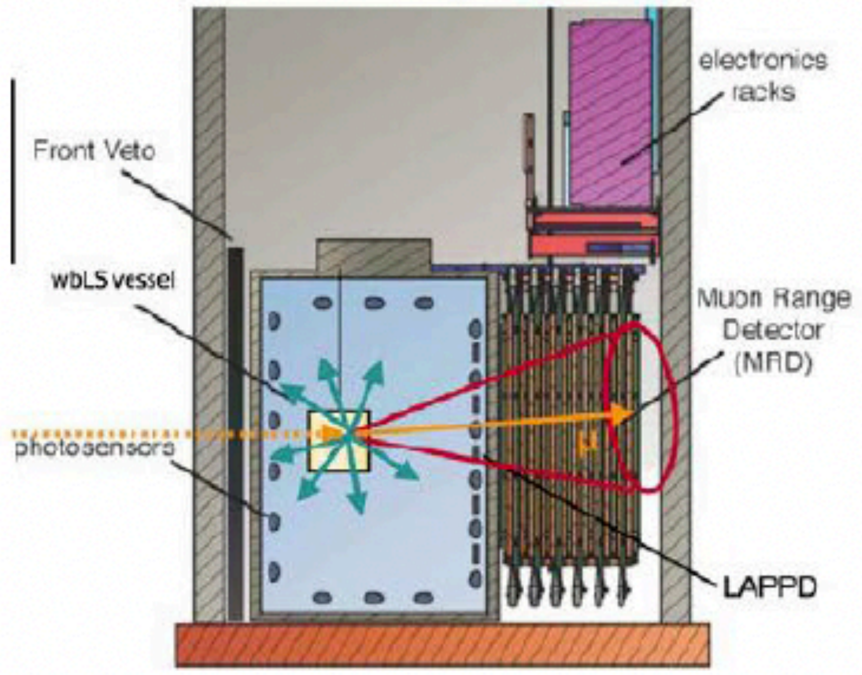
- Hybrid Cherenkov / scintillation detector improves background rejection via PID and event topology
- Scalable, ultra-clean liquid detector
- Potential to deploy a 25-kton THEIA module at LBNF, in a Module of Opportunity
- Mass sensitivity of ~4—22 meV
- Broad program of other physics

Background reduction via event imaging: PID, multi-site, directionality

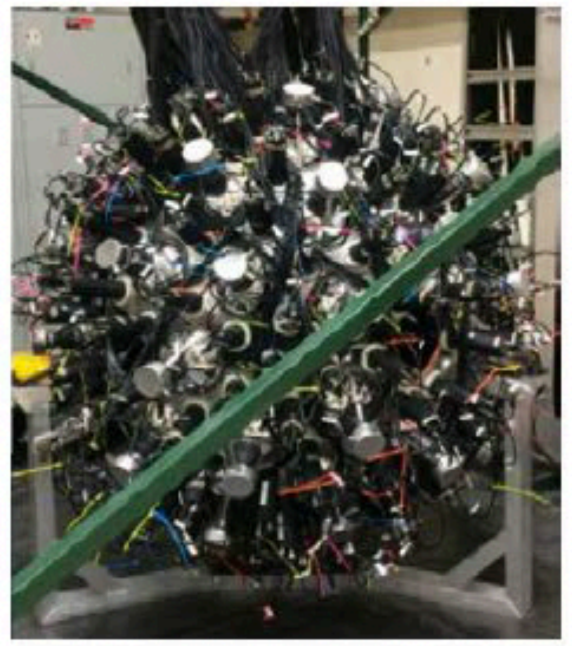


R&D into next-gen LS detectors

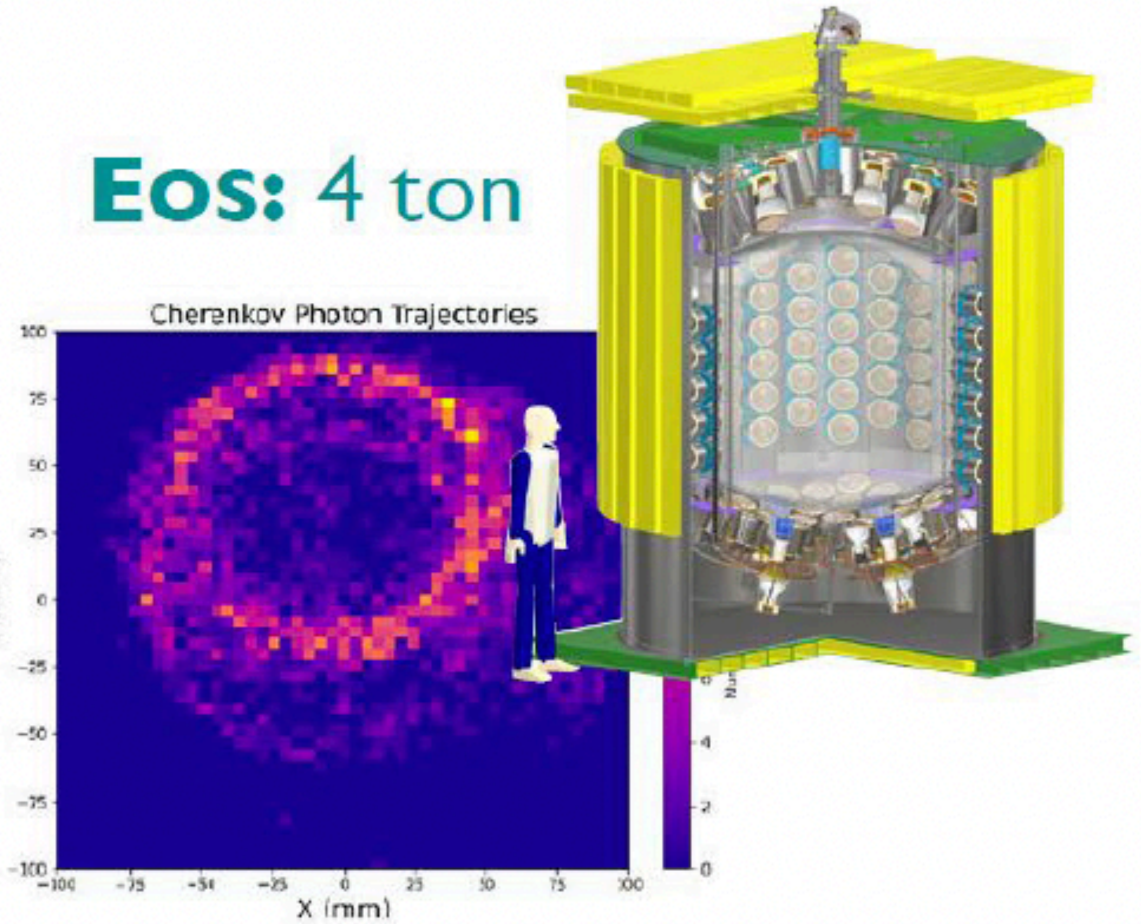
ANNIE: 365 kg



NuDot: 1 ton



Eos: 4 ton

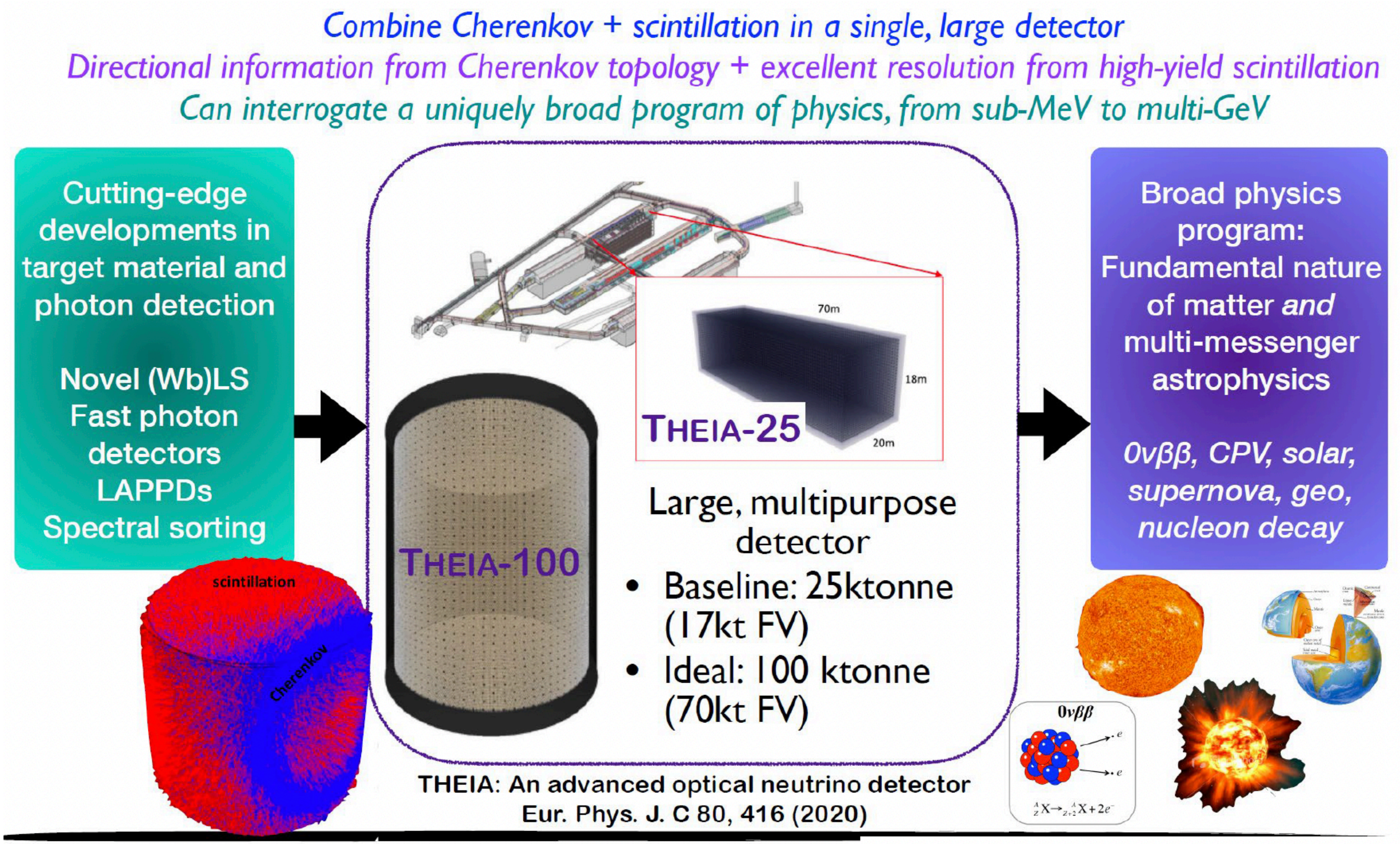


BNL: 1- and 30-ton

Builds on critical developments by KLZ & SNO+ collaborations

THEIA

From A. McDonald, 2nd International Summit, SNOLAB, April 2023



Combine Cherenkov + scintillation in a single, large detector

Directional information from Cherenkov topology + excellent resolution from high-yield scintillation

Can interrogate a uniquely broad program of physics, from sub-MeV to multi-GeV

Cutting-edge developments in target material and photon detection

Novel (Wb)LS
Fast photon detectors
LAPPDs
Spectral sorting

THEIA-25

THEIA-100

Large, multipurpose detector

- Baseline: 25ktonne (17kt FV)
- Ideal: 100 ktonne (70kt FV)

Broad physics program: Fundamental nature of matter *and* multi-messenger astrophysics

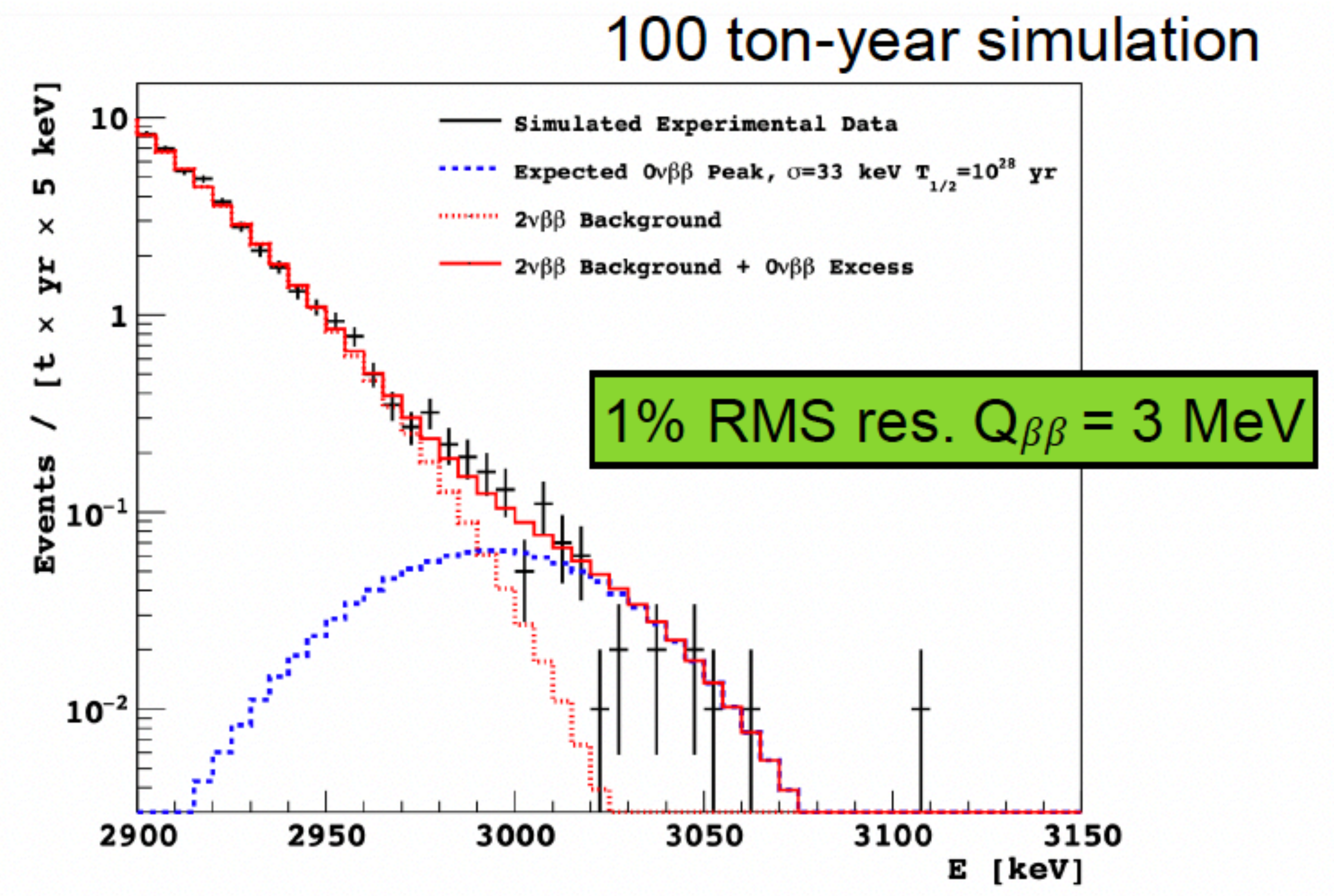
0νββ, CPV, solar, supernova, geo, nucleon decay

THEIA: An advanced optical neutrino detector
Eur. Phys. J. C 80, 416 (2020)

SELENA

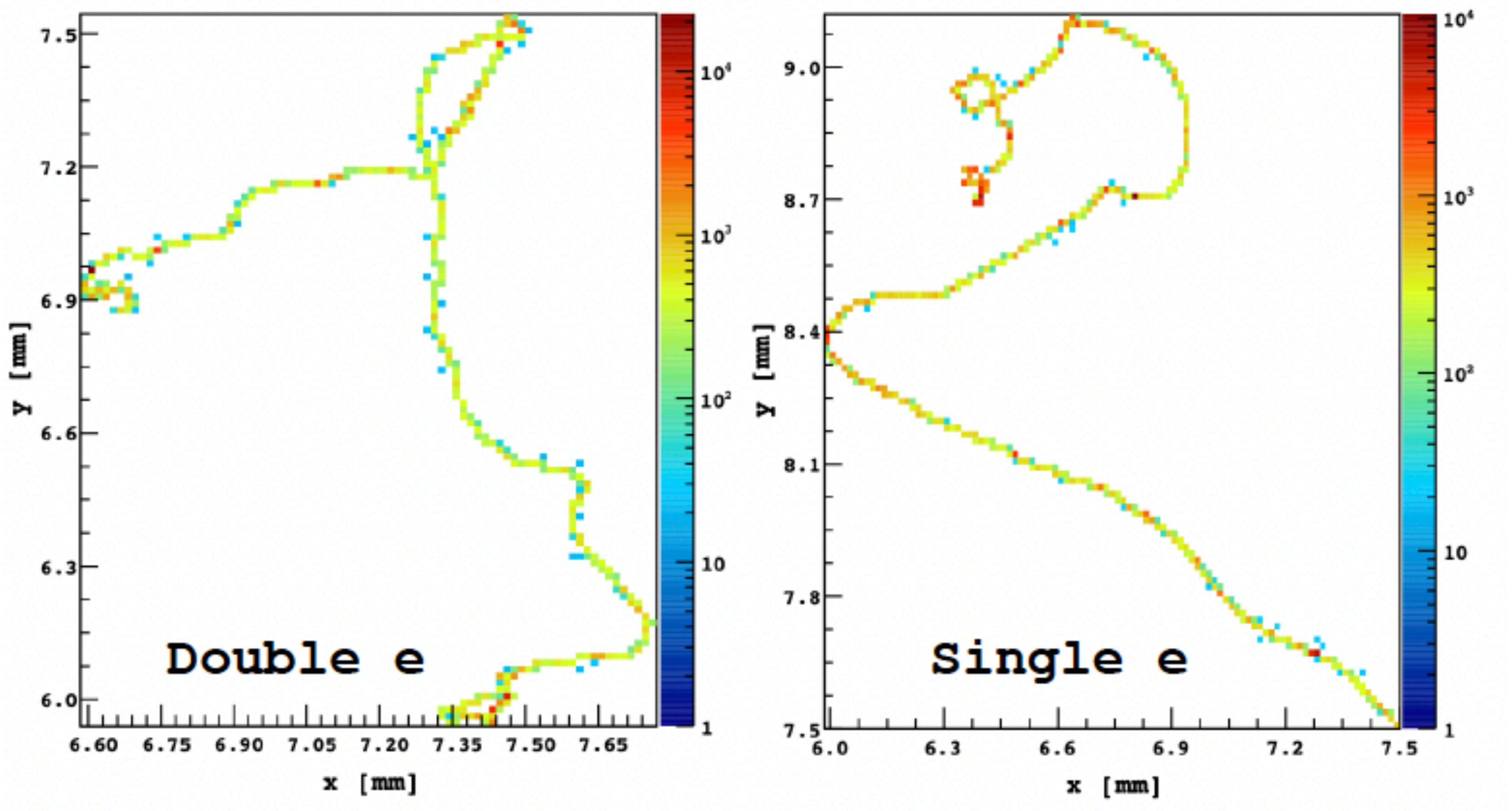
arXiv:2203.08779

- Large-area hybrid CMOS imagers with ~5-mm thick layers of amorphous ^{82}Se
- Neutrinoless *ββ* decay sensitivity of ***$m_{\beta\beta}$*= 4 to 8 meV** (3*σ*) in 100-ton year (T1/2 = 2 × 10^{28} y)
- Identification of Bragg peaks for a 10^{-3} suppression of single-electron background, with 50% signal acceptance
- Spatial α,β correlation in highly pixelated devices



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

Simulation:



Very large (~ kton) Xenon detector

From A. McDonald, 2nd International Summit, SNOLAB, April 2023

1 kton of ^{136}Xe:

$T_{1/2} \sim 10^{30}$ years

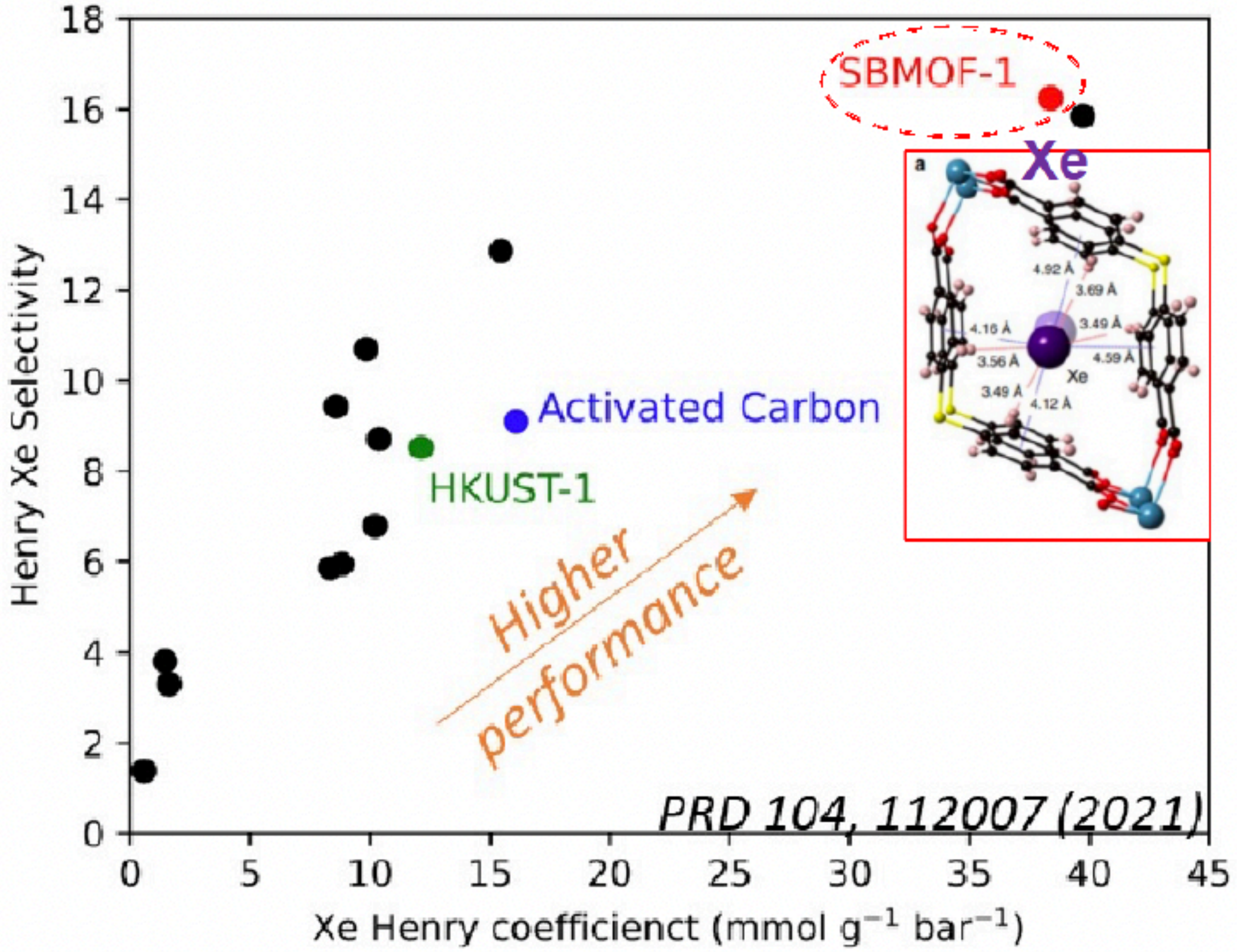
Challenge: Current xenon production worldwide is not sufficient, too expensive and cannot scale to ktonne

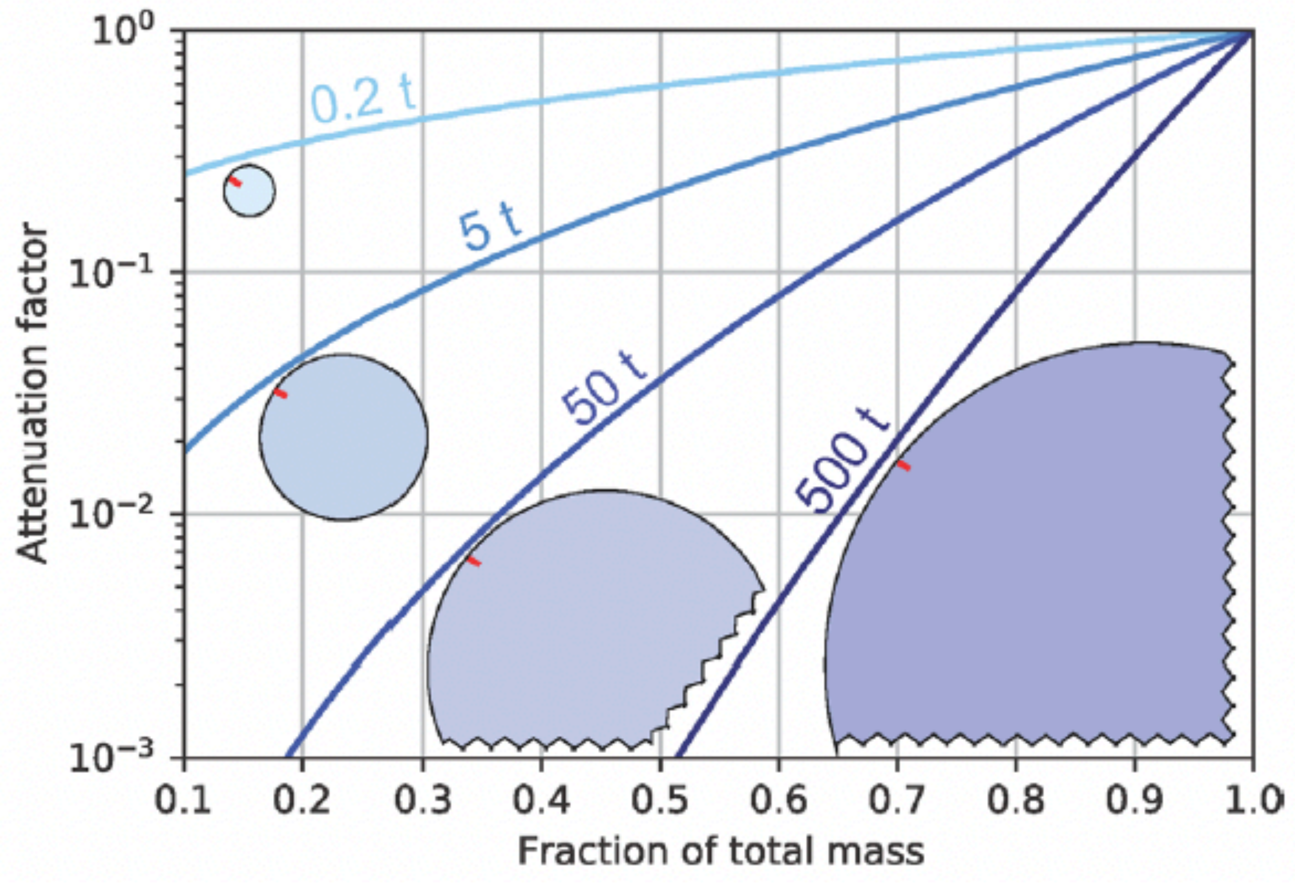
Solution: Develop new technology for Xe separation from air

- **Adsorption-based separation technology (Thermal)**
- **Metal-Organic-Frameworks (MOFs) materials can be engineered with desired characteristics**
- **Among these, a promising candidate SBMOF-1 has been identified**
- **Ongoing R&D focuses on:**
  1. **Scale up synthesis of SBMOF-1**
  2. **Optimized structured adsorbent beds to maximize the mass transfer to SBMOF-1 from the air**
  3. **Energy efficient process cycle**

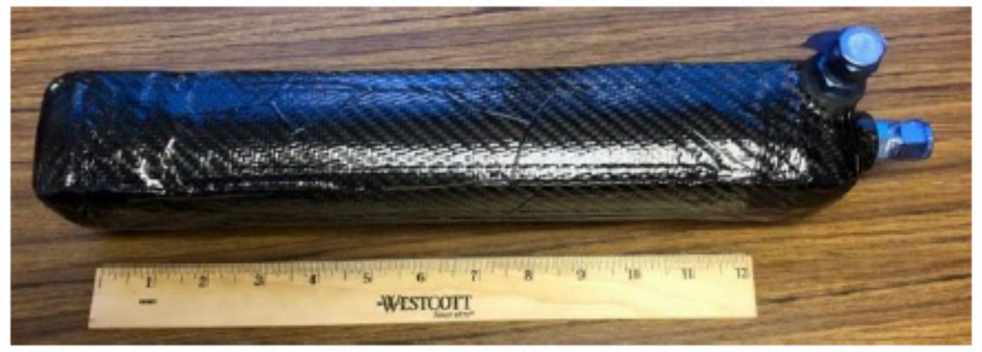
- **Engagement from industry partners**
- **Funding-limited (slow) effort to date, but made significant progress on the 3 objectives**

Xenon selectivity vs adsorption coefficient for different materials





SBMOF-1 structured adsorbent bed prototype (LLNL)



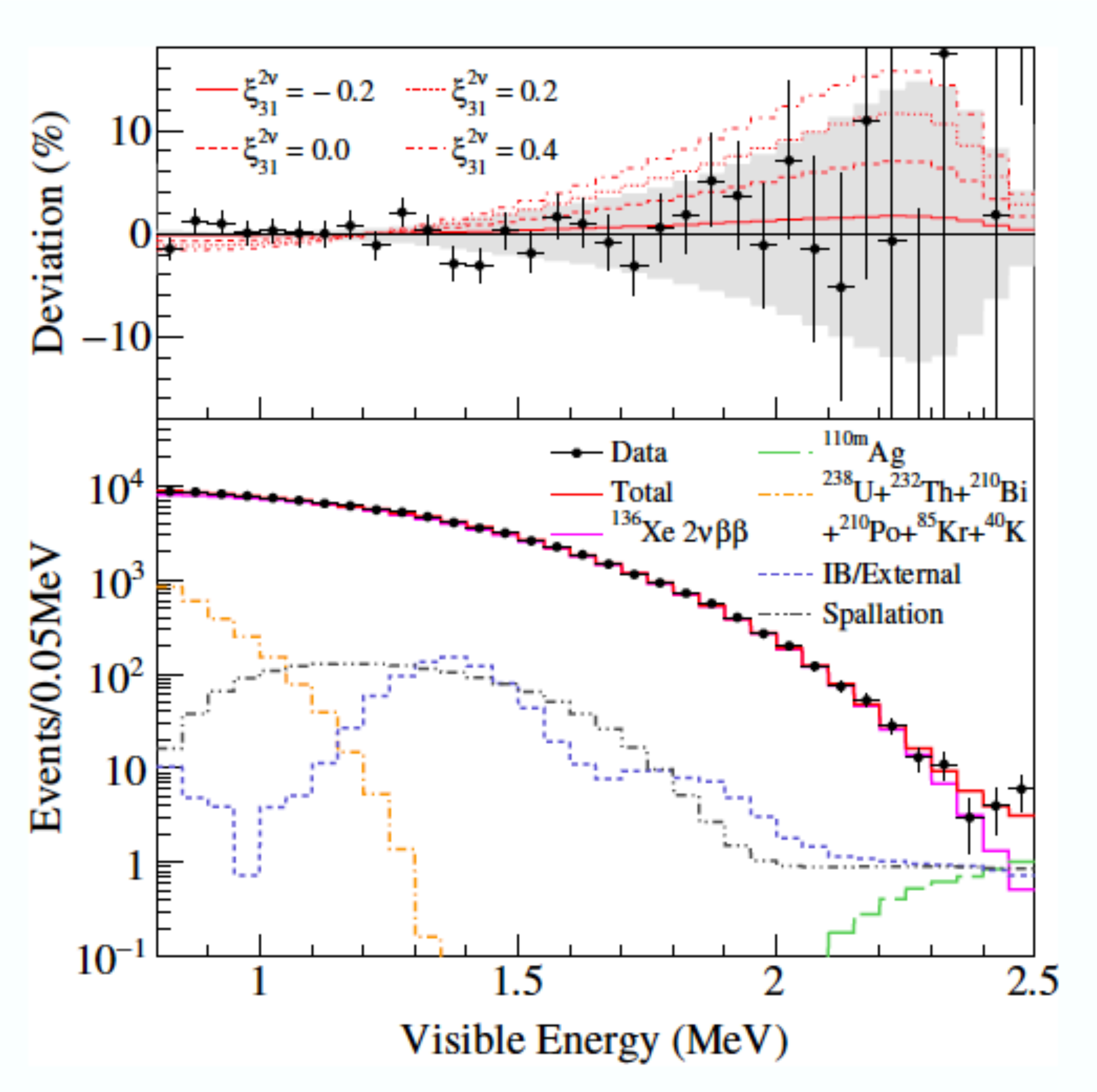
200x scale up of SBMOF-1 synthesis

A. Avasthi et al., "Kiloton-scale xenon detectors for neutrinoless double beta decay and other new physics searches," Phys. Rev. D 104, 112007 (2021), arXiv:2110.01537

Not just $0\nu\beta\beta$ searches ….

Kamland-Zen: Precision 2νββ spectral studies

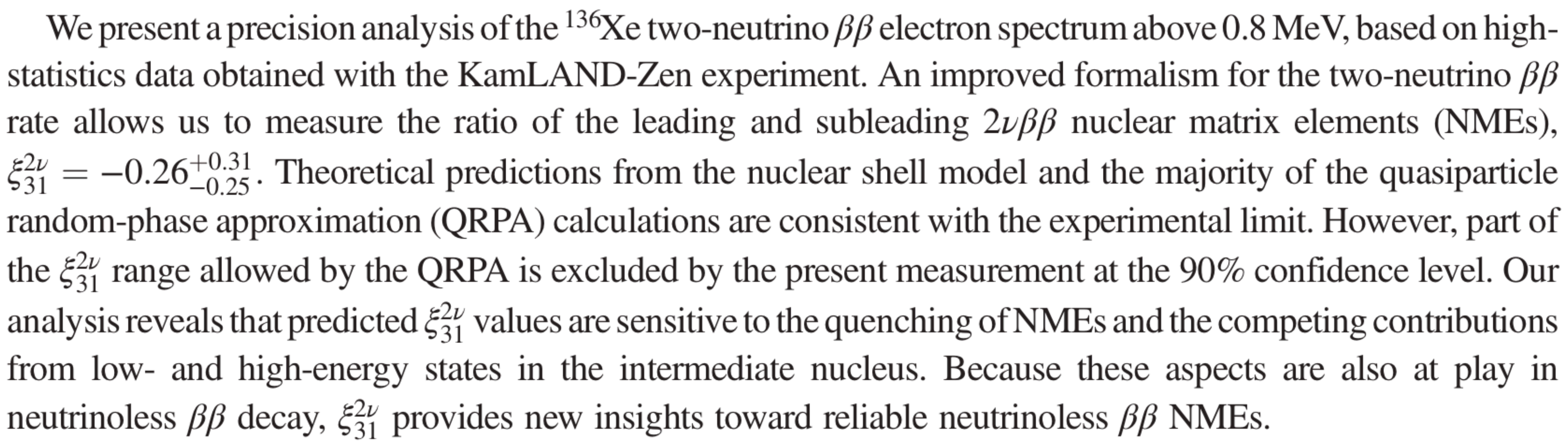
KamLAND-Zen Collab., Menendez, Simkovic,
PHYSICAL REVIEW LETTERS 122, 192501 (2019)



2νββ spectral distortion

(from higher-order NME)

ratio of the leading and sub-leading
2νββ nuclear matrix elements (NMEs)

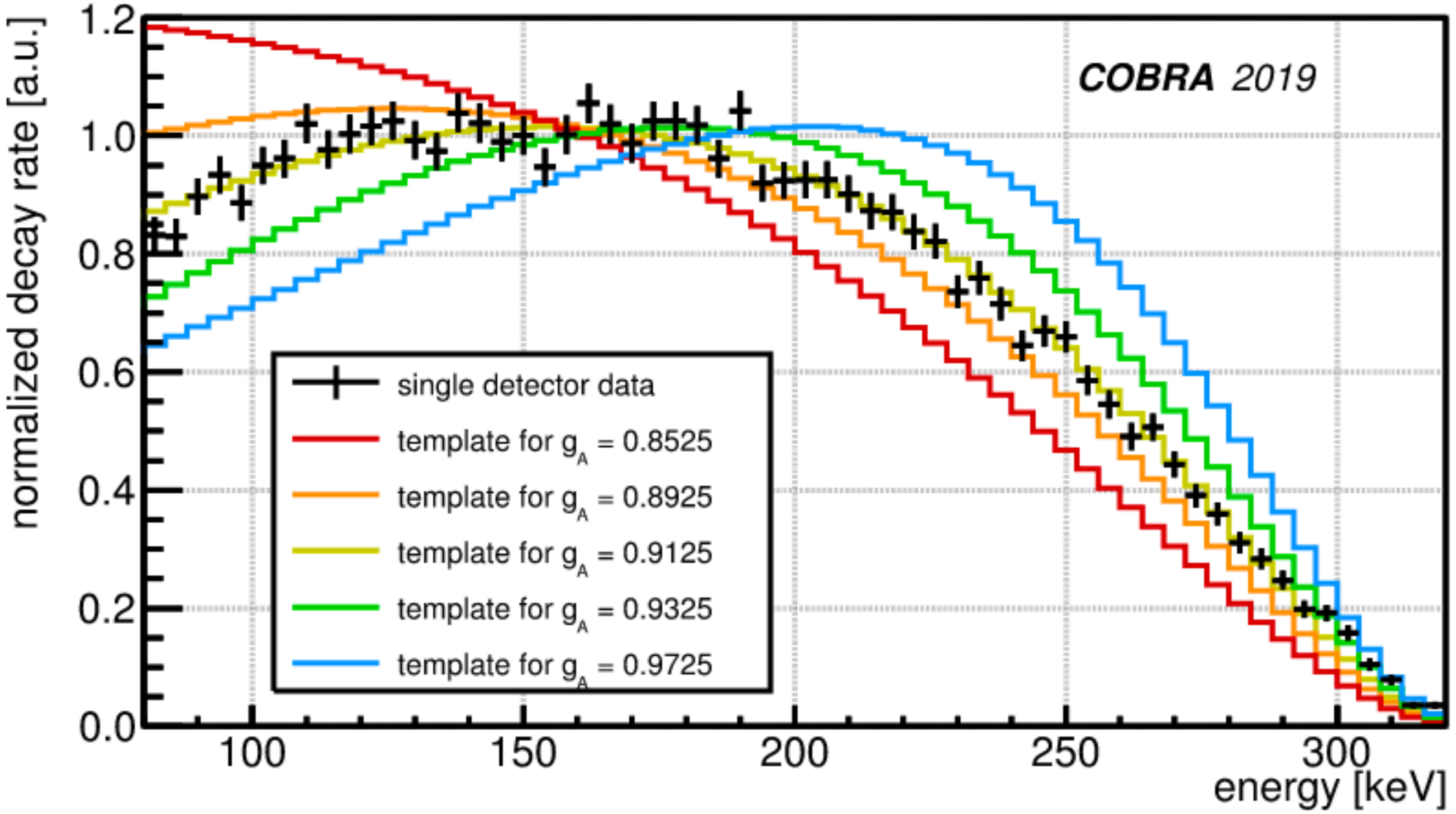


We present a precision analysis of the ^{136}Xe two-neutrino $\beta\beta$ electron spectrum above 0.8 MeV, based on high-statistics data obtained with the KamLAND-Zen experiment. An improved formalism for the two-neutrino $\beta\beta$ rate allows us to measure the ratio of the leading and subleading $2\nu\beta\beta$ nuclear matrix elements (NMEs), $\xi^{2\nu}_{31} = -0.26^{+0.31}_{-0.25}$. Theoretical predictions from the nuclear shell model and the majority of the quasiparticle random-phase approximation (QRPA) calculations are consistent with the experimental limit. However, part of the $\xi^{2\nu}_{31}$ range allowed by the QRPA is excluded by the present measurement at the 90% confidence level. Our analysis reveals that predicted $\xi^{2\nu}_{31}$ values are sensitive to the quenching of NMEs and the competing contributions from low- and high-energy states in the intermediate nucleus. Because these aspects are also at play in neutrinoless $\beta\beta$ decay, $\xi^{2\nu}_{31}$ provides new insights toward reliable neutrinoless $\beta\beta$ NMEs.

g_A — precision β decay spectral measurements

Physics Letters B 800 (2020) 135092

- COBRA collaboration (0νββ decay)
- Array of CdZnTe semiconductor detectors
- ^{113}Cd β-decay spectral shape

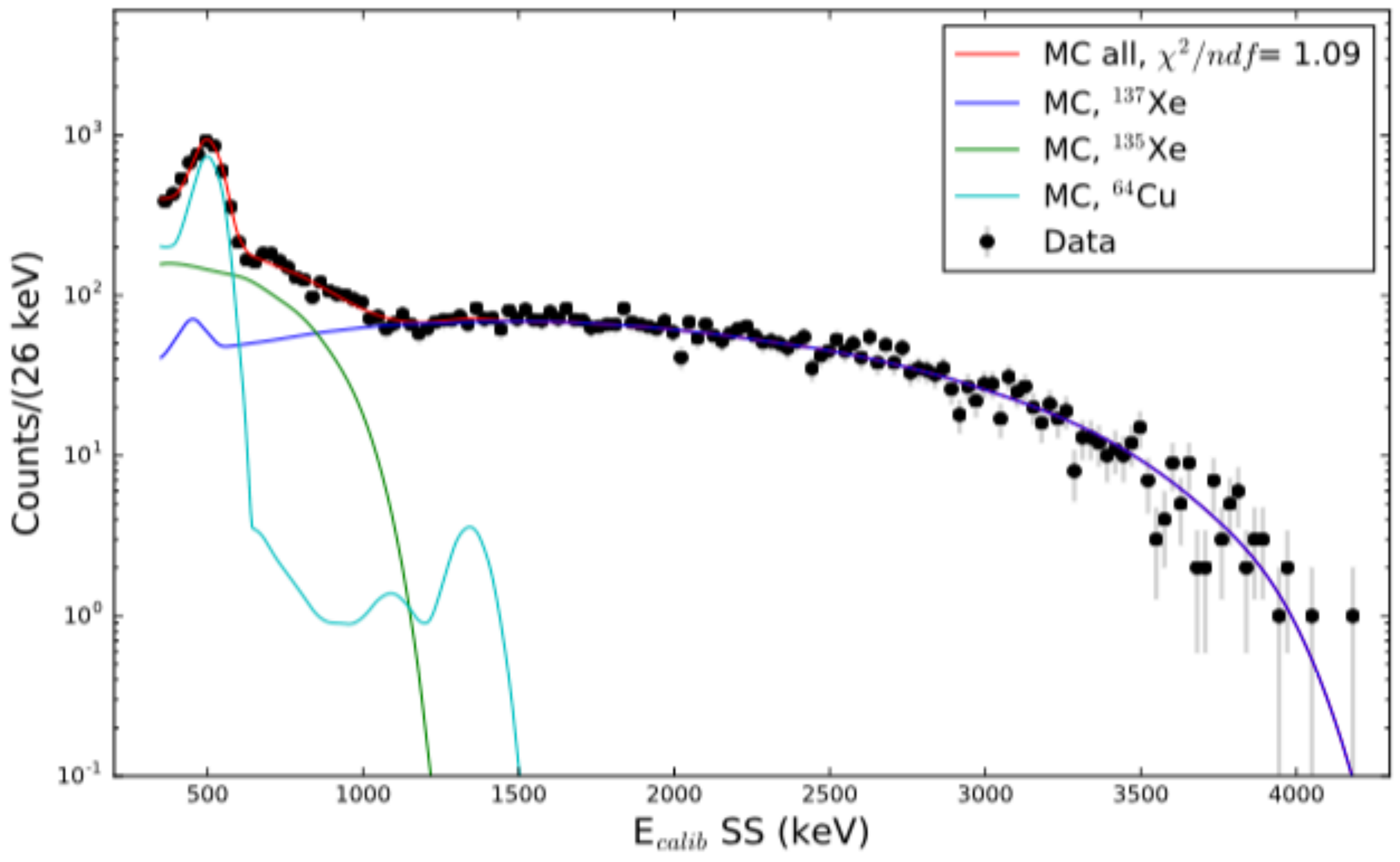


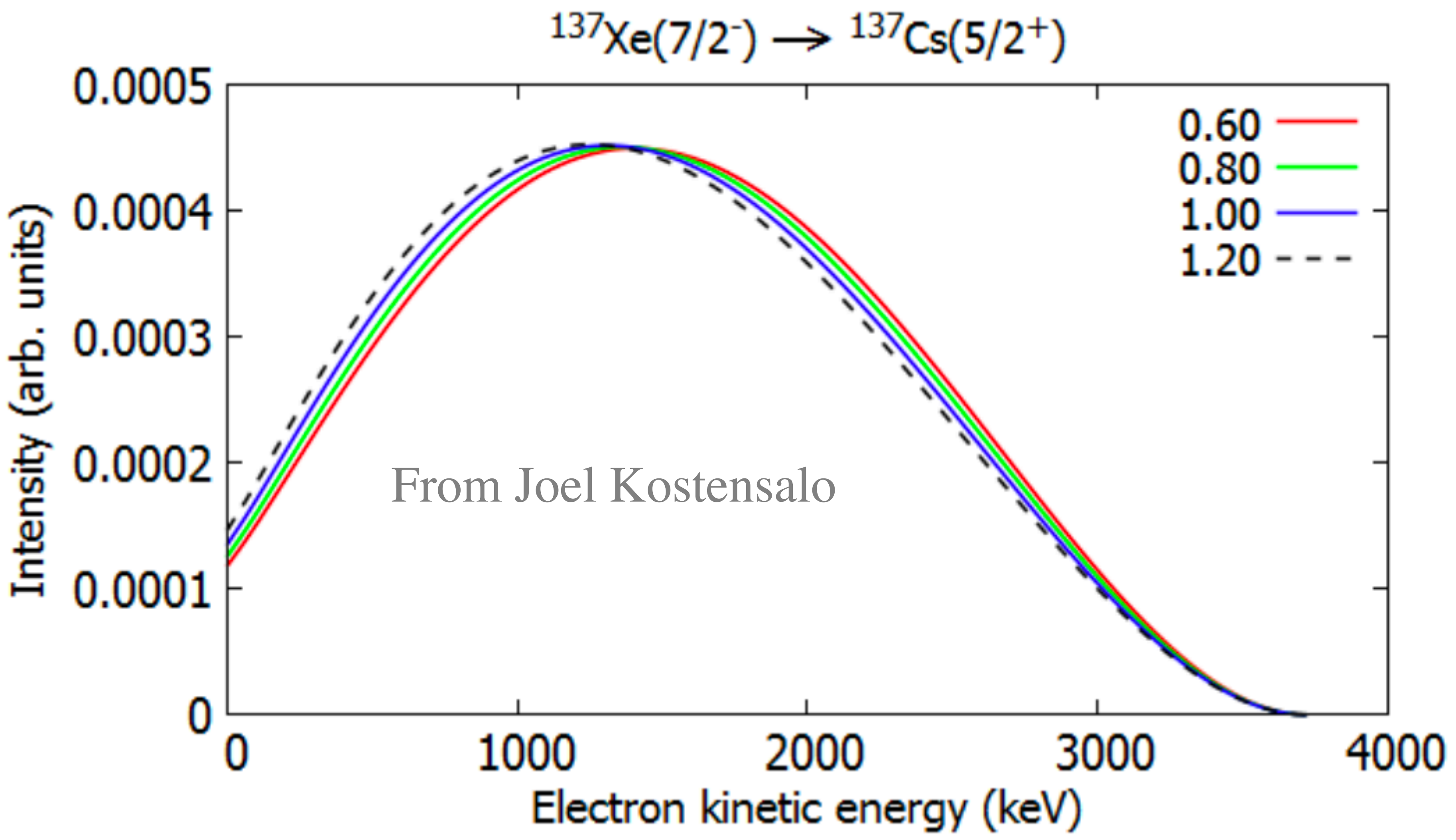
See also: Physics Letters B 822 (2021) 136652

Xe-137 β spectrum

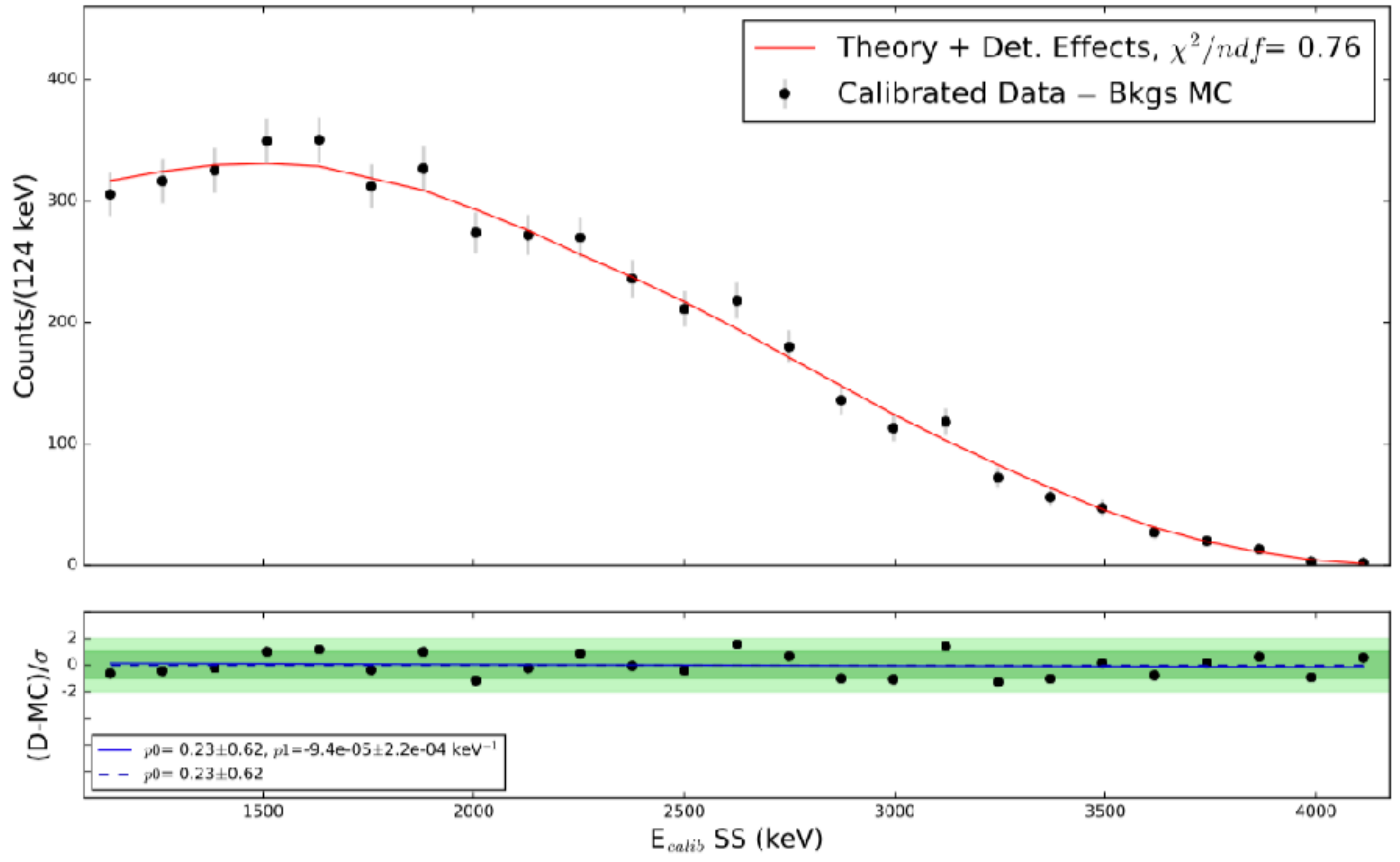
EXO-200 Collaboration, S. Al Kharusi et al, PRL 124, 232502 (2020)
(in collaboration with Suhonen's group)

- Precision measurement of the ^{137}Xe(7/2$^-$) → ^{137}Cs(7/2$^+$) first forbidden, non-unique β-transition
- Reactor neutrino spectrum anomaly
- Supposed to be insensitive to the value of g_A
- Separate ongoing measurement of ^{137}Xe(7/2$^-$) to the first excited state of ^{137}Cs can shed light on effective value of g_A





From Joel Kostensalo



Summary and Outlook

- Searches for $0\nu\beta\beta$ decay have improved >10 orders of magnitude in half-life sensitivity over the past 80 years
- Detectors have grown from gram size and are approaching a (few) ton(s) in the foreseeable future, with half-life sensitivity $\sim 10^{28}$ years
- These searches have evolved alongside detector technology, the establishment of large underground laboratories, and the development of low radioactivity protocols and techniques
- Investigation of Majorana neutrino masses at the inverted neutrino mass ordering (~10 meV) is “around the corner”
- New ideas are emerging for detectors beyond the tonne-scale that could test $0\nu\beta\beta$ decay with $T_{1/2} \sim 10^{30}$ years
- Current $0\nu\beta\beta$ decay detector technology also measuring key nuclear parameters