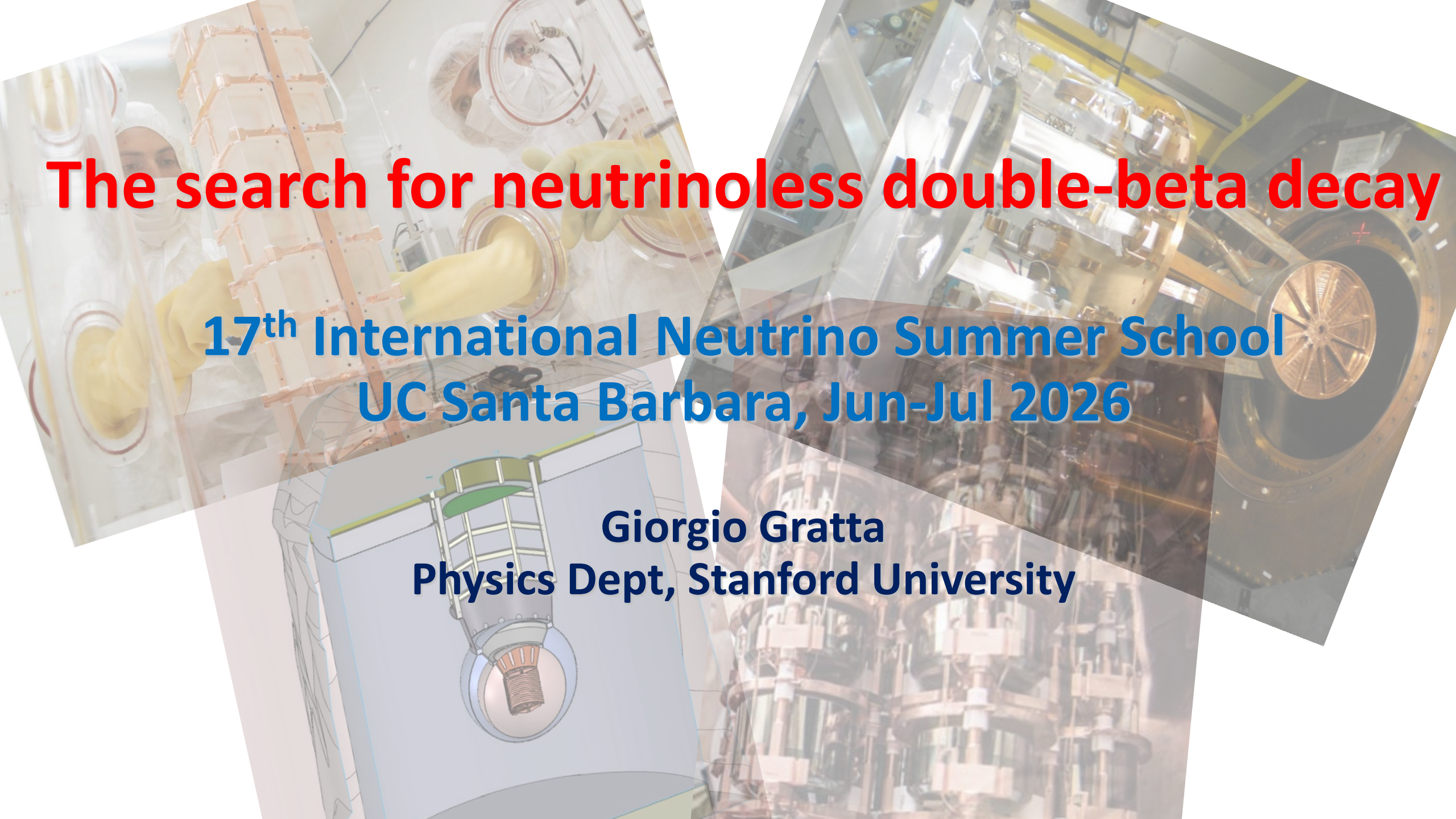






The search for neutrinoless double-beta decay

17th International Neutrino Summer School
UC Santa Barbara, Jun-Jul 2026

Giorgio Gratta
Physics Dept, Stanford University

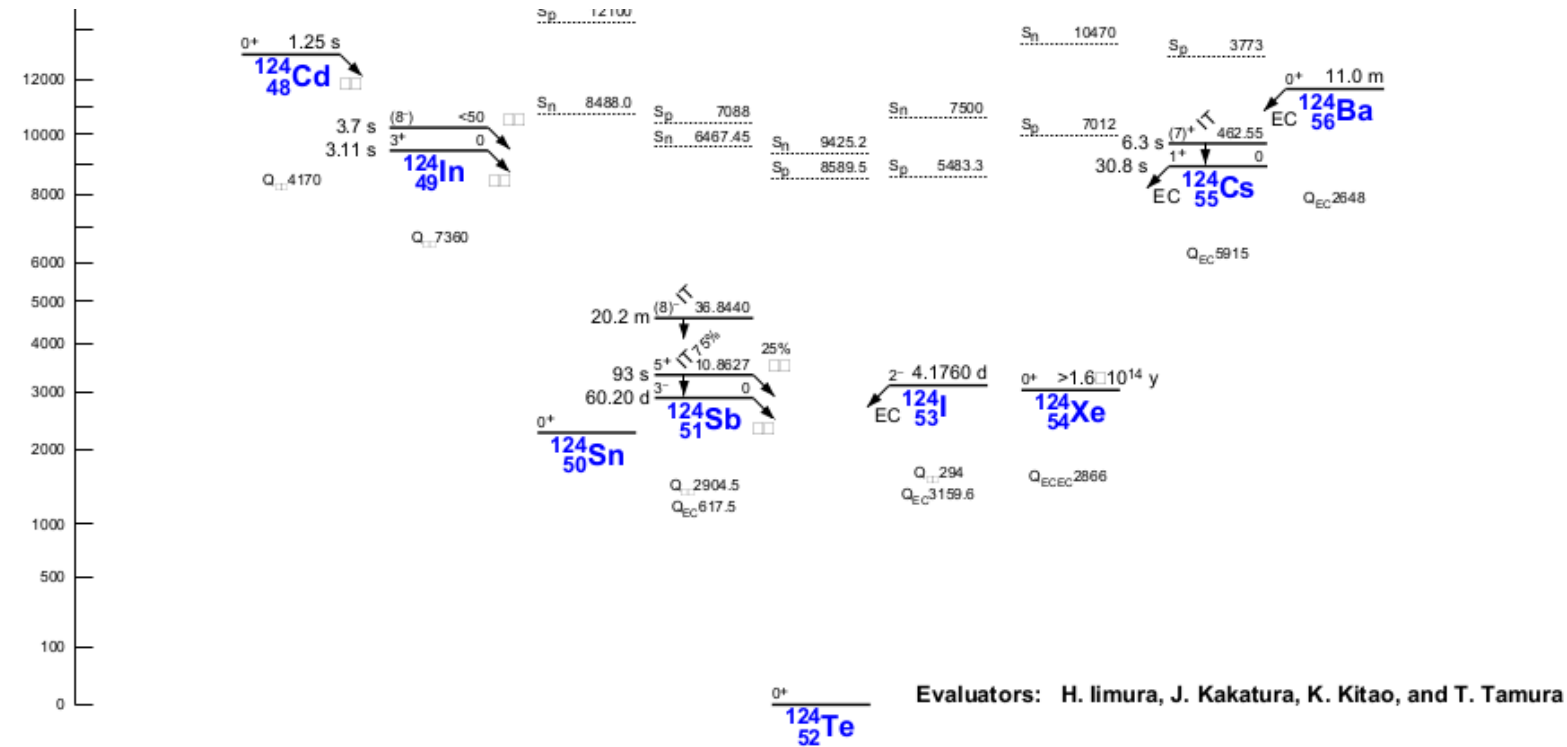
Part 2

Remarkably, the half-life into this mode (up to $\approx 10^{21}$ yr*), in many cases is known to better than 2%! Precision physics!

	Nuclide	$T_{1/2}$ (10^{21} yr)	Rel. Uncertainty (%)	Experiment	Published yr
$2\nu\beta\beta$	^{76}Ge	$2.022 \pm 0.018 \pm 0.038$	2.1	GERDA	2023
	^{82}Se	$(8.69 \pm 0.05^{+0.09}_{-0.06}) \cdot 10^{-2}$	1.2	CUPID-0	2023
	^{100}Mo	$(7.07 \pm 0.02 \pm 0.11) \cdot 10^{-3}$	1.6	CUPID-Mo	2023
	^{130}Te	$(9.32^{+0.06}_{-0.04} \pm 0.07) \cdot 10^{-1}$	1.0	CUORE	2025
	^{136}Xe	$2.165 \pm 0.016 \pm 0.059$	2.8	EXO-200	2014
$2\nu 2\text{EC}$	^{124}Xe	$10.9 \pm 1.4 \pm 0.5$	13.6	LZ	2024

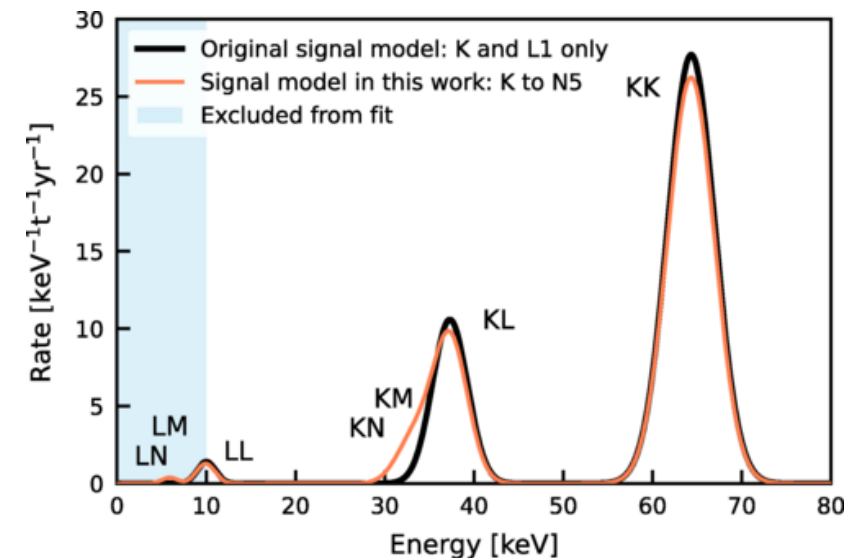
*** In “natural units” this is 10^{11} the age of the Universe!
(I will continue using these natural units on and off).**

In the last few years, also the EC EC $\nu \nu$ has been observed in ^{124}Xe



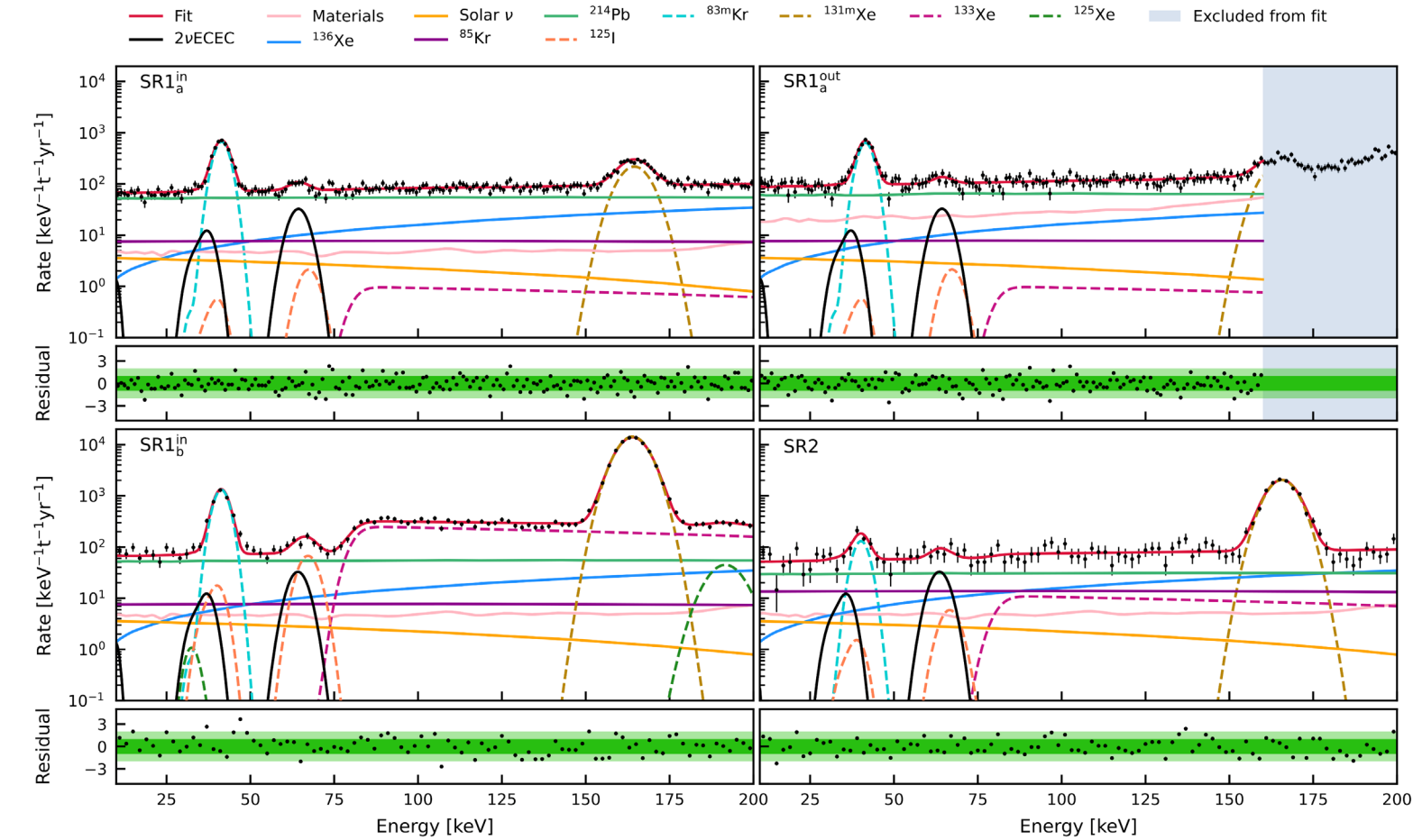
Xenon collaboration, Nature 568 (2019) 532

In this case there are no emitted electrons and the signature is that of the X-rays emitted in the de-excitation of the electron cloud where two electrons from inner shells have disappeared.

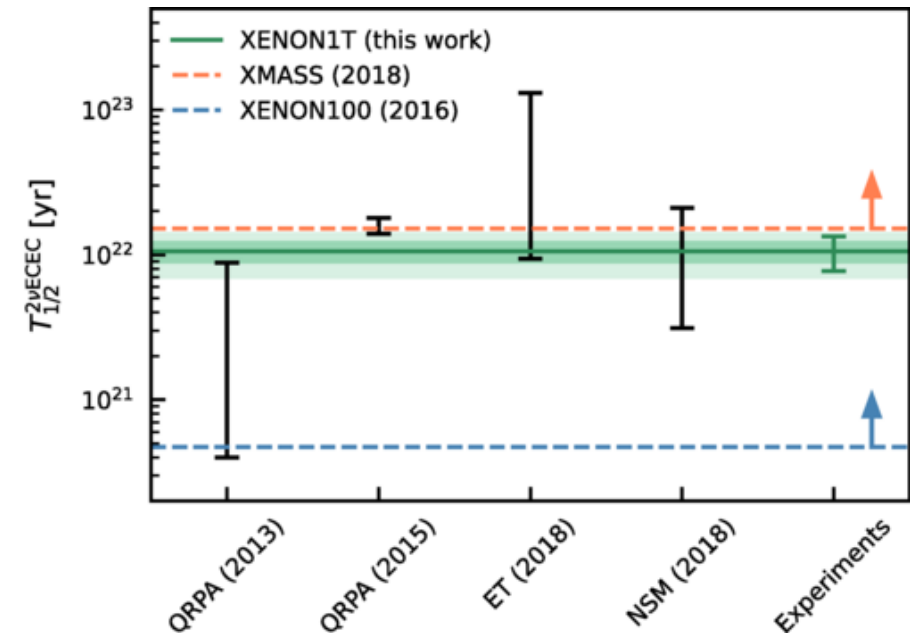


**Q: In this case, the first measurement was done
by XENON1T, PandaX, LZ all Dark Matter detectors. Why?**

Energy spectra from various data periods in XENON1T



Note the low energy required by this analysis and the fact that the signal is actually composed of γ s



Onwards for $0\nu\beta\beta$

A historical note

Early experiments:

- Geochemical or Radiochemical experiments (search for trace amounts of element A in a large amount of B after a long time).
→ Can't discriminate between 0ν and 2ν decays
- Spectroscopic experiments with gram quantities of candidate isotopes.
- Backgrounds largely unknown/unpredicted

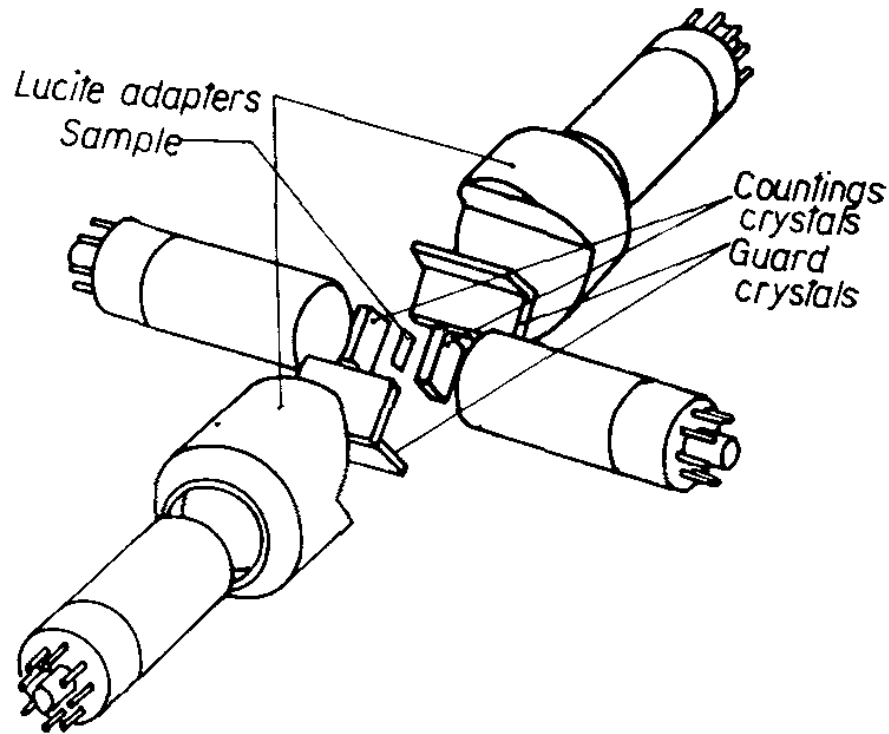
Modern experiments:

- Isotope enrichment (when needed)
- Spectroscopic experiments with ~ 100 kg quantities of enriched material
- Backgrounds well understood

Future experiments:

- Tonne-scale spectroscopic experiments
- Possibly, marry spectroscopy with final state tagging

The obvious choice is to get a sample of the (nominally stable) isotope of interest and try to detect the decay with external counters.



However, this results in limited efficiency because of solid angle and the limited range of MeV electrons in the samples.

Fig. 2. – Schematic view of counting crystals and anticoincidence counters used by Mc-CARTHY [34-36].

e.g. McCarthy Phys Rev 90 (1953) 853

The idea to get around these limitations by building a detector that is also the source is due to Fiorini et al., using $^{nat}\text{Ge}(\text{Li})$ detectors in the sixties.

A new technique is applied to the search for neutrinoless double β decay. A $\text{Ge}(\text{Li})$ crystal is used both as source and as detector of the $^{76}\text{Ge} \rightarrow ^{76}\text{Se}$ transition. Our negative result ($\tau_{1/2} > 3 \times 10^{20} \text{ y}$) is consistent with the lepton conservation law.



Volume 25B, number 10

PHYSICS LETTERS

27 November 1967

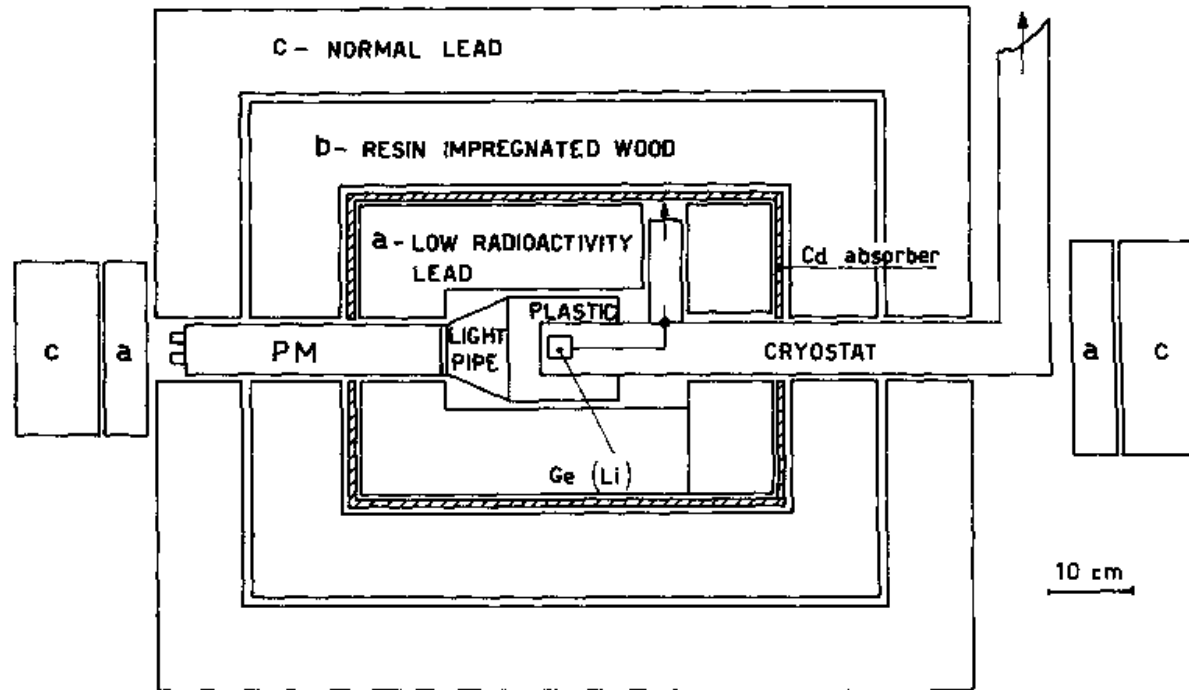


Fig. 1. Experimental setup.

$$T_{1/2} < 3.1 \cdot 10^{20} \text{ yr } 68\% \text{CL}$$

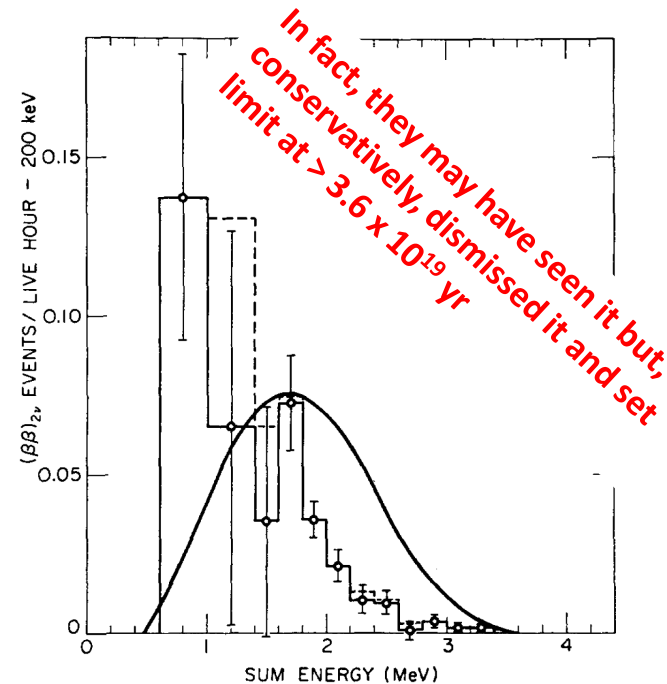
The first result (I think) using enriched material (^{48}Ca) came 3 years later by C-S Wu's group.

The isotope ^{48}Ca was chosen as a source because of its relatively high decay energy (4.24 MeV) and because its calculated lifetime for two-neutrino double beta decay is as short as that of any known nuclides available. Its decay scheme is shown in fig. 1. It is actually unstable against single beta decay to the ground and first two excited states of ^{48}Sc . However, the low energy release and high degree of forbiddenness of these transitions causes their estimated lifetimes[†] to be orders of magnitude longer than the estimated lifetime for double beta decay^{††}.

10.6 g of ^{48}Ca enriched to 97%!!

This is when scientists had clout with DOE/AEC!

Morton Salt Mine, Fairport, Ohio



This is essentially the prototype for NEMO!

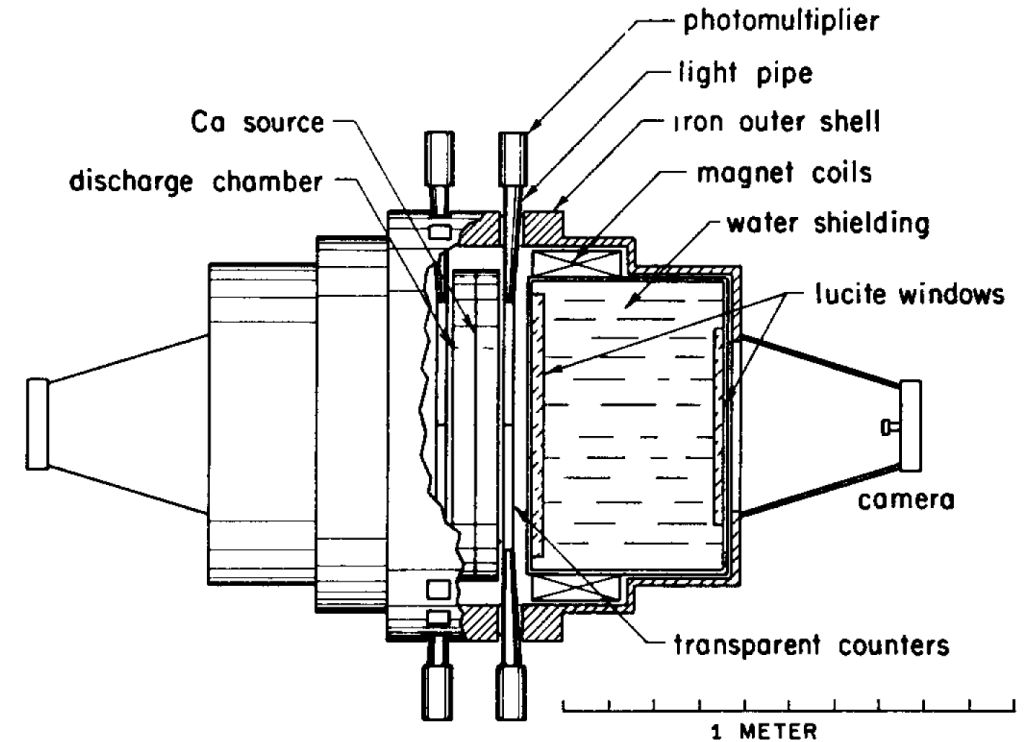


Fig. 3. Cutaway drawing of double beta decay apparatus.

Bardin, Gollon, Ullman, and Wu, Nucl. Phys. A158 (1970) 337

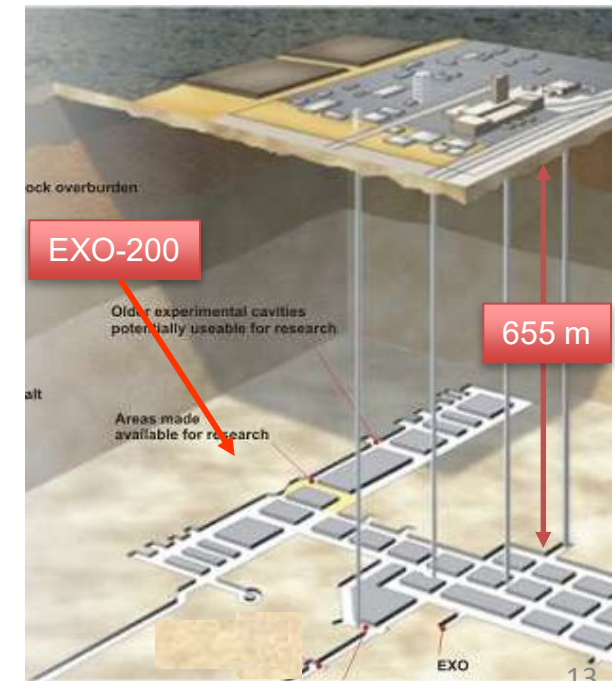
Four fundamental requirements for modern experiments:

1) Isotopic enrichment of the source material (that is generally also the detector)

*At the quantities required today this generally result in
an impressive programs*

2) Underground location to shield cosmic-ray induced background

*Several underground labs around the world, next round of
experiments 1-2 km deep.*



Four fundamental requirements for modern experiments:

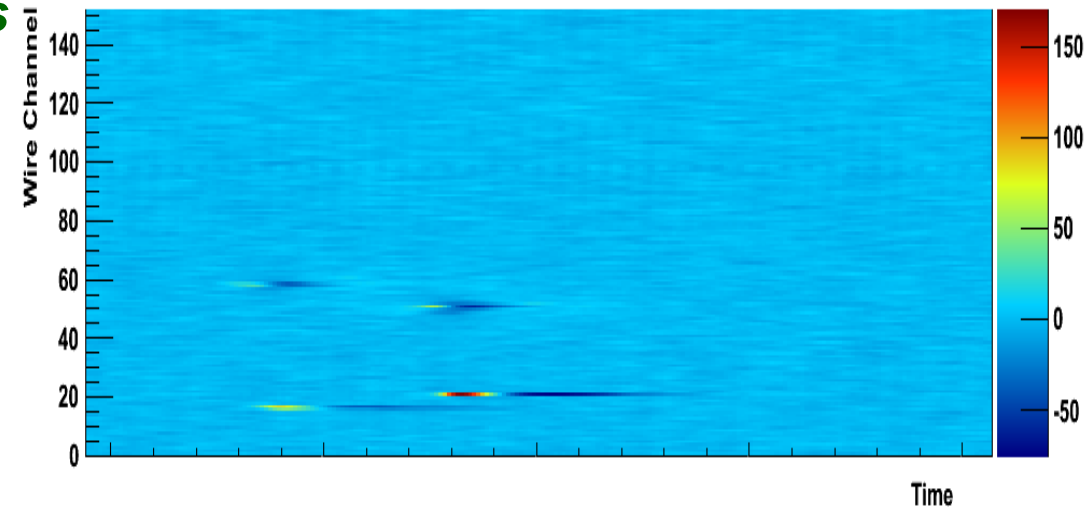
3) Ultra-low radioactive contamination for detector construction components

*Materials used $<10^{-15}$ in U, Th
(U, Th in the earth crust $\sim$ ppm)*

4) New techniques to discriminate signal from background

*Non trivial for $E \sim 1\text{MeV}$ and in many ways conflicts
with the large detector mass/density.*

- *Signal ($2e^-$) more localized than most background.*
- *Good E resolution helps.*
- *Low density shows the two e^- tracks but this is hard for large fiducial masses.*
- *In some cases final state ID may be possible.*



A modern classification of techniques (with examples)

Low density trackers

- NEXT
- Initial EXO idea
- NEMO/SuperNEMO (foils and tracking, any isotope)

Pros: Superb topological information

Cons: Very large size

Liquid (organic) scintillators

- KamLAND-ZEN (^{136}Xe)
- SNO+ (^{130}Te)

Pros: “simple”, large detectors exist, self-shielding, scalable

Cons: Not very specific, 2v background

Crystals

- GERDA, Majorana, LEGEND (^{76}Ge)
- CUORE, AMORE, CUPID (^{130}Te , ^{100}Mo)

Pros: Superb energy resolution, possibly 2-parameter measurement

Cons: Intrinsically fragmented with some extraneous material in the middle

Liquid TPC

- EXO-200, nEXO (^{136}Xe)

Pros: Homogeneous with good E resolution and topology, scalable. Can run w/ depleted Xe.

Cons: Does not excel in any single parameter

A modern classification of techniques (with examples)

Low density trackers

- NEXT
- Initial EXO idea
- NEMO/SuperNEMO (foils and tracking, any isotope)

Pros: Superb topological information

Cons: Very large size

Liquid (organic) scintillators

- KamLAND-2
- SNO

Detectors exist, self-shielding, scalable
specific, 2v background

Crystals

- GERDA, Majorana, LEGEND (^{76}Ge)
- CUORE, AMORE, CUPID (^{130}Te)

Pros: Superb energy resolution, calorimeter measurement

Cons: Intrinsically self-shielding, no extraneous material in the middle

Liquid TPC

- EXO-200, nEXO (^{136}Xe)

Pros: Homogeneous with good E resolution and topology, scalable. Can run w/ depleted Xe.

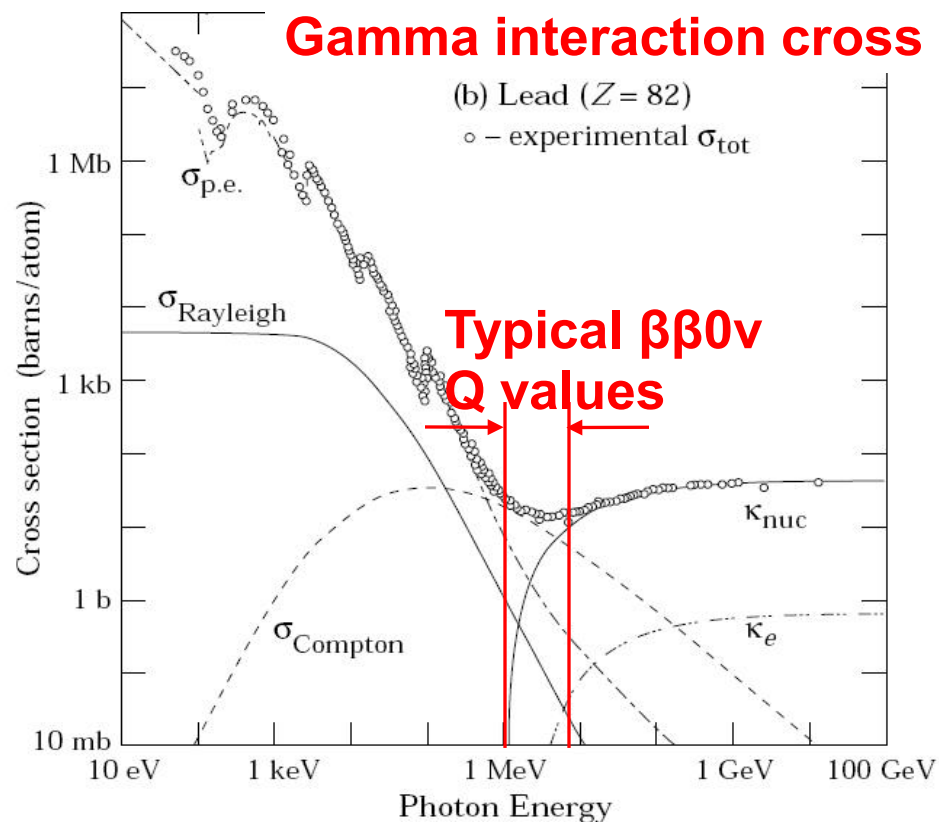
Cons: Does not excel in any single parameter

Which technique “works better” depends on time (technology development) and time (how large the detector needs to be)

Dark matter detectors use self shielding against external (gamma) radiation.

Q: Is this the same for $0\nu\beta\beta$ decay detectors?

Shielding a detector from MeV γ s is difficult!



Example:
 γ interaction length
in Ge is 4.6 cm,
comparable to the size
of a germanium detector.

Shielding $\beta\beta$ decay detectors is much harder than shielding Dark Matter ones

We are entering the “golden era” of $\beta\beta$ decay experiments as detector sizes exceed interaction length

Note that for detector mass $\rightarrow \infty$, $0\nu\beta\beta$ detector $\approx$ DM detector

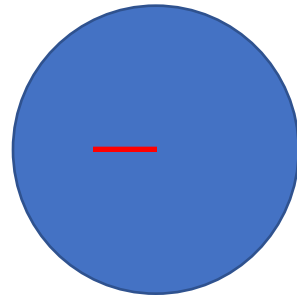
(assuming that both can measure well MeV energies)

LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

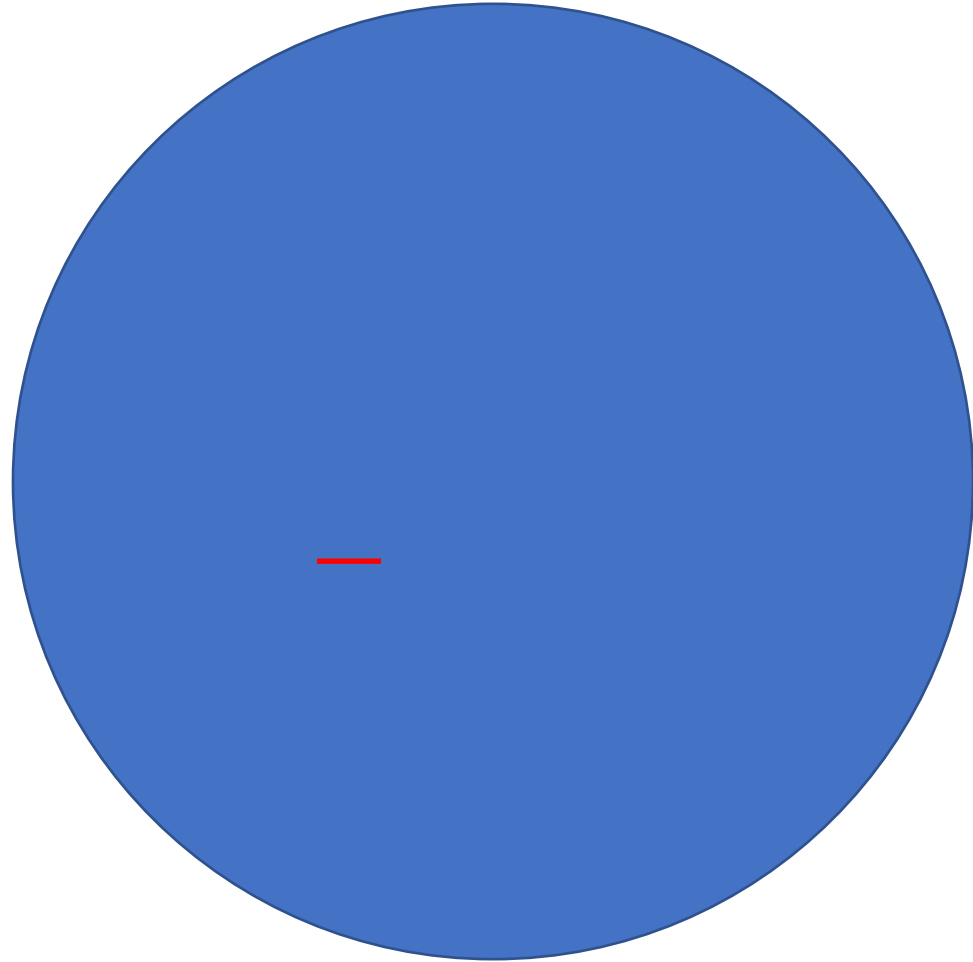
2.5MeV γ
attenuation length
8.5cm = —



5kg



150kg
(EXO-200)



5000kg
(nEXO)

Monolithic detectors take full advantage of this, and tonne scale is where those effect become really dominant.

As we start describing specific experiments, we should realize that this is an area with plenty of invention and clever ideas.

So, the list is long, with some experiments being demonstration of ideas and others building very large detectors, after demonstrations at a smaller scale.

This is not because the community is indecisive or feckless, the optimization is tricky, nuclides and detector technology need to be matched one another and people are creative!

At the risk of making enemies, I will refrain from providing endless lists but apply some judgment and select experiments that are representative of a technique, or that achieved notable results, or that are building some particularly sensitive device.

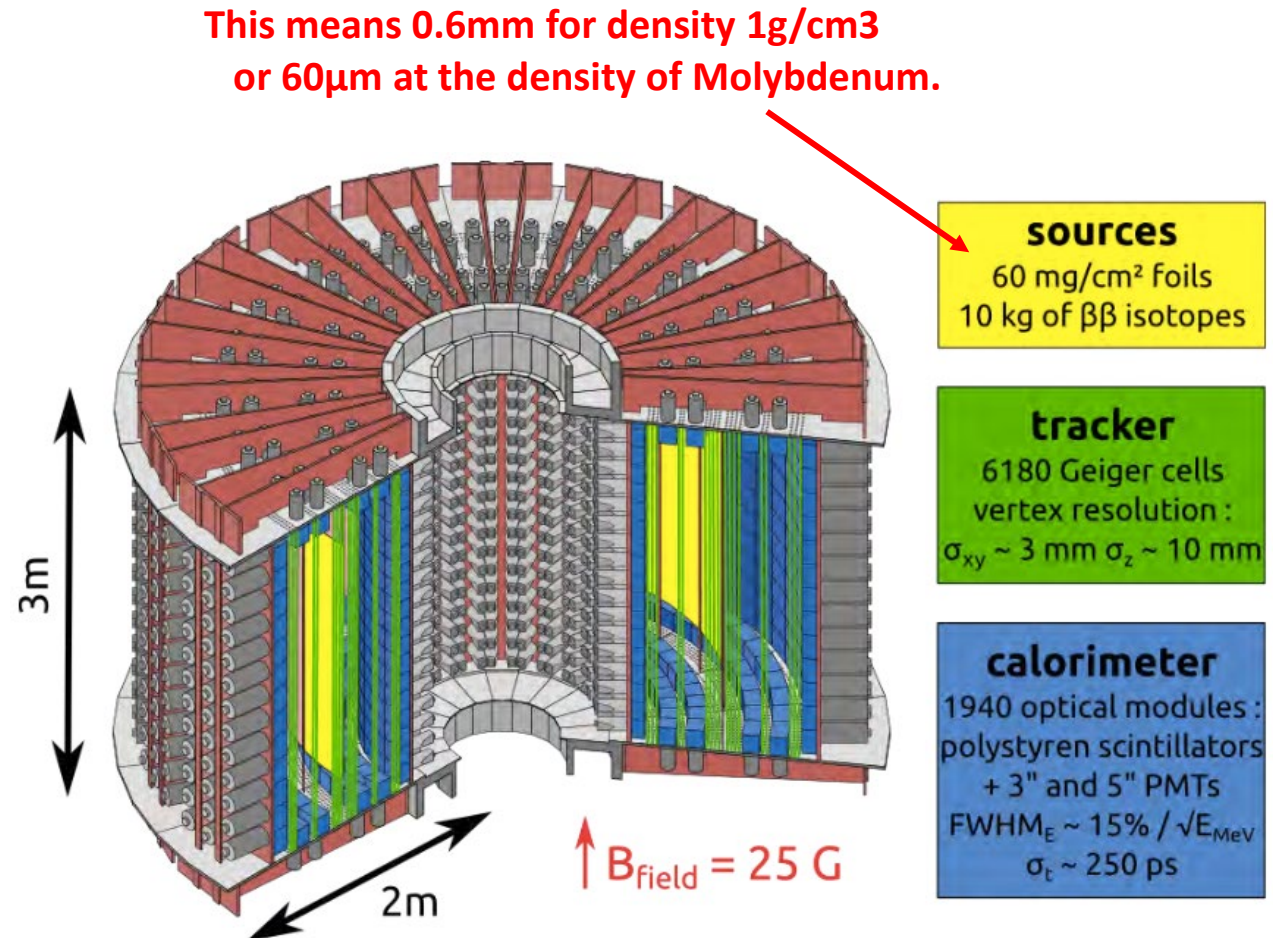
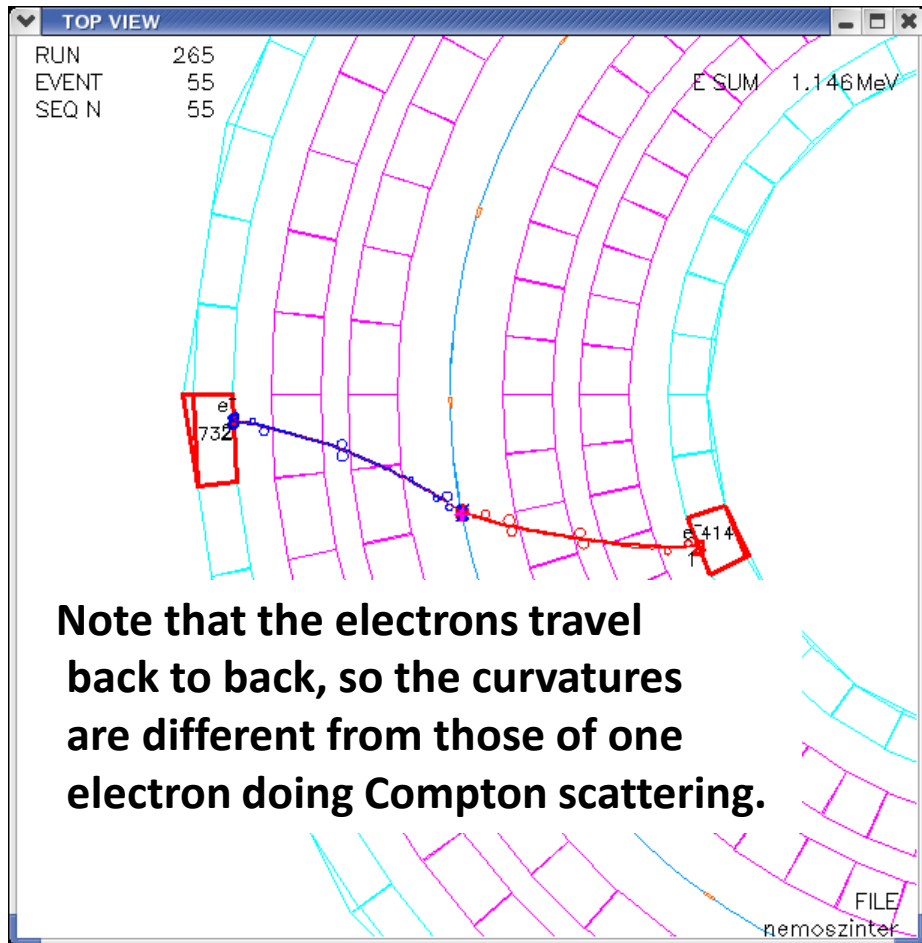
A selection of modern experiments

Technology	Nuclide	Last Experiment taking data			Nuclide	Next planned experiment	
		Name	Nuclide mass			Name	Nuclide mass
Foils & tracking	Many/ ¹⁰⁰ Mo	NEMO-3	¹⁰⁰ Mo: ≈7 kg	➔	⁸² Se	SuperNEMO	6.23 kg
Germanium counters	⁷⁶ Ge	LEGEND-200	200 kg	➔	⁷⁶ Ge	LEGEND-1000	1000 kg
Bolometers	¹³⁰ Te	CUORE	206 kg	➔	¹⁰⁰ Mo	CUPID	240 kg
	¹⁰⁰ Mo	AMORE-I	≈4 kg	➔		AMORE-2	85 kg
Liquid Xe TPC	¹³⁶ Xe	EXO-200	150 kg	➔	¹³⁶ Xe	nEXO	5000 kg
Gas Xe TPC		NExT-100	100 kg	➔		NExT-XX?	≈1000 kg?
Liquid scintillator	¹³⁶ Xe	KamLAND-ZEN	380➔745 kg	➔	¹³⁶ Xe	KamLAND2-ZEN	1000 kg
	¹³⁰ Te	SNO+	1330 kg	➔	¹³⁰ Te	SNO+ II	4000-6600 kg

*In general, omitted are speculative ideas for very large future detector
and small efforts that are exploratory in nature*

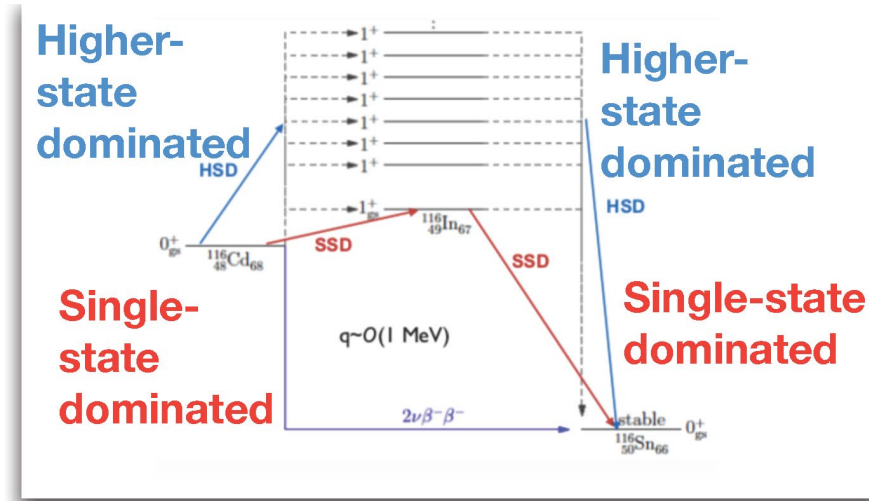
NEMO-3

The ideal detector can detect and measure the direction and energy/momentum of each electron. This is obtained with a thin foil source “seen” by light trackers in a magnetic field and calorimeters. If you worked on a collider, this would sound totally familiar! Unfortunately, the source has to be really thin, so that it is not very practical for a large source mass.



NEMO-3 results

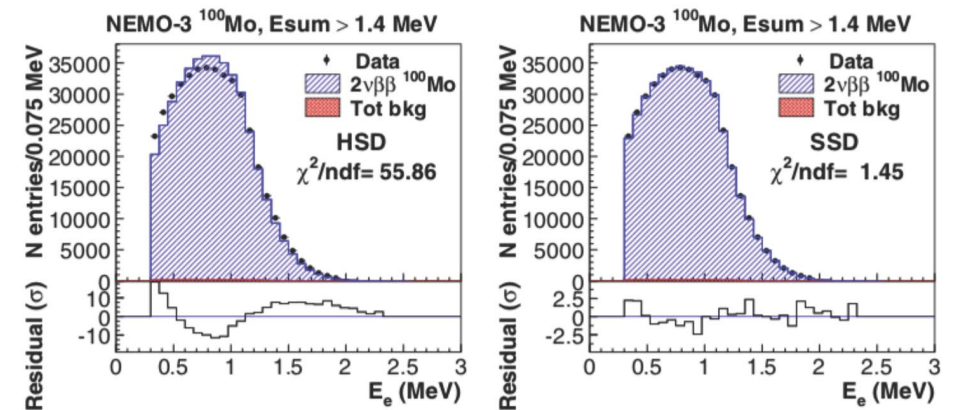
- ^{100}Mo (Eur. Phys. J. C 79 (2019) 440)
- ^{82}Se (Eur. Phys. J. C 78 (2018) 821)
- ^{48}Ca (Phys. Rev. D 93 (2016) 112008)
- ^{150}Nd (Phys. Rev. D 94 (2016) 072003)
- ^{116}Cd (Phys. Rev. D 95 (2017) 012007)
- ^{130}Te (Phys. Rev. Lett. 107 (2011) 062504)
- ^{96}Zr (Nucl. Phys. A 847 (2010) 168)



5×10^5 events
Signal / bkgd ~ 80

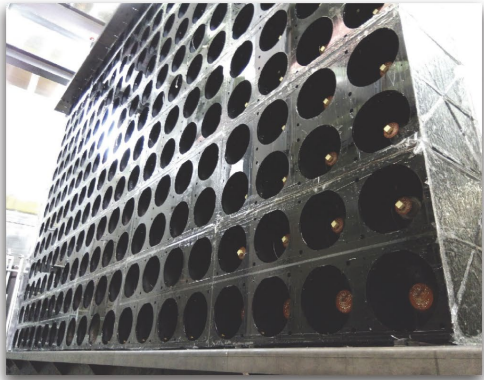
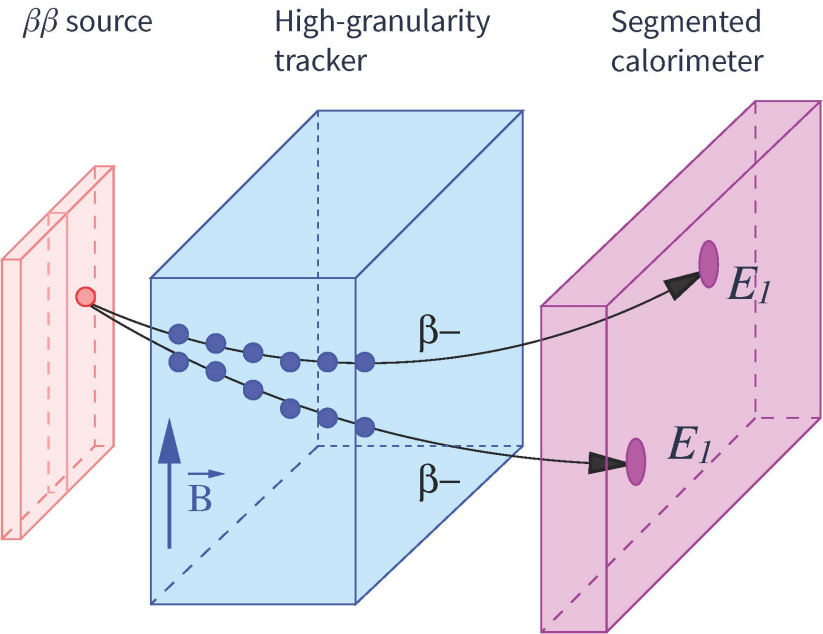


Note that this detector can measure the energy of each of the electrons separately. This is of interest for the 2ν and will be required to start understanding the 0ν mechanism, once this will have been discovered.



Similar principle used in Super-NEMO

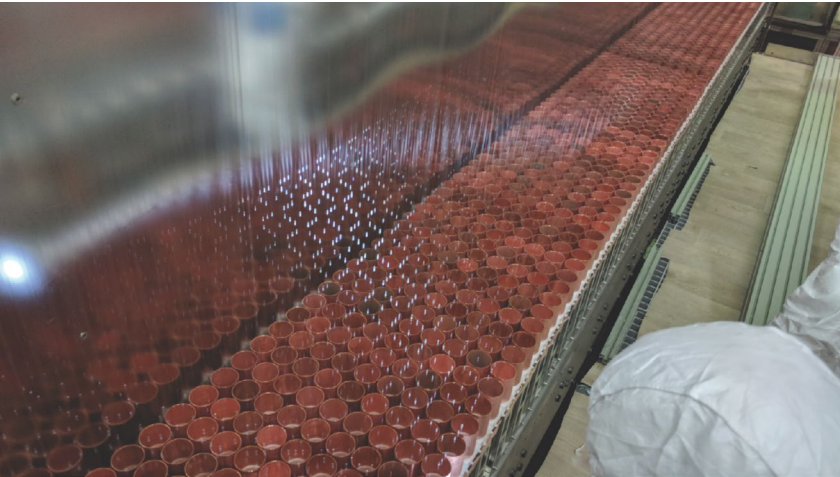
Quite some R&D to improve the calorimeter's resolution.



712 optical modules
 σ/E 1.8% at 3 MeV



Angle between tracks
+ particle / charge ID + Individual energies
& times





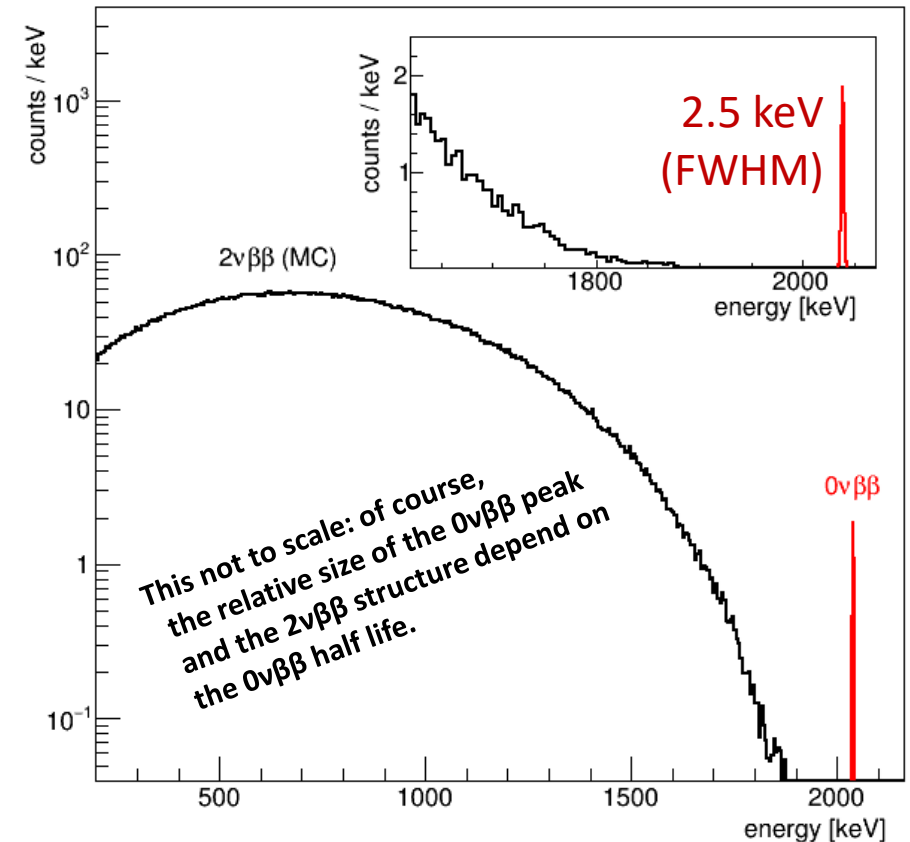
^{76}Ge $0\nu\beta\beta$ detectors

First example of detectors scalable to the tonne regime

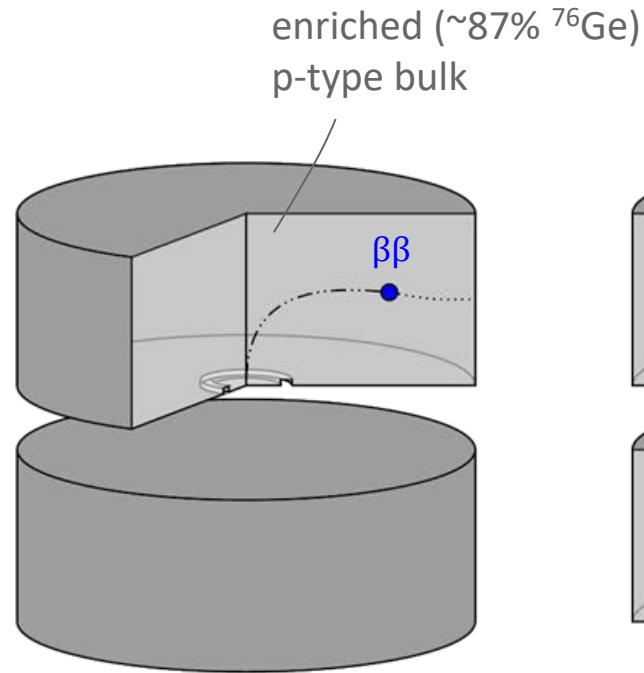
- Basic principle very old! Germanium is both the source and a superb radiation detector.
- $^{76}\text{Ge} \rightarrow ^{76}\text{Se} + 2e^-$
- Q-value of ^{76}Ge : $Q_{\beta\beta} = 2039 \text{ keV}$
- Isotope enrichment on a grand scale ($\sim 90\%$ ^{76}Ge)
- source = detector $\rightarrow$ high detection efficiency
- high semiconductor purity $\rightarrow$ no intrinsic background
- high density $\rightarrow$ $0\nu\beta\beta$ are point like events
- Energy resolution $\sim 0.1\%$ (FWHM) at $Q_{\beta\beta}$
 - $\rightarrow$ $0\nu\beta\beta$ signature:
 - Point-like energy deposition in detector bulk volume
 - Sharp energy peak at 2039 keV (FWHM $\sim 2.5 \text{ keV}$)

Two slightly different approaches:

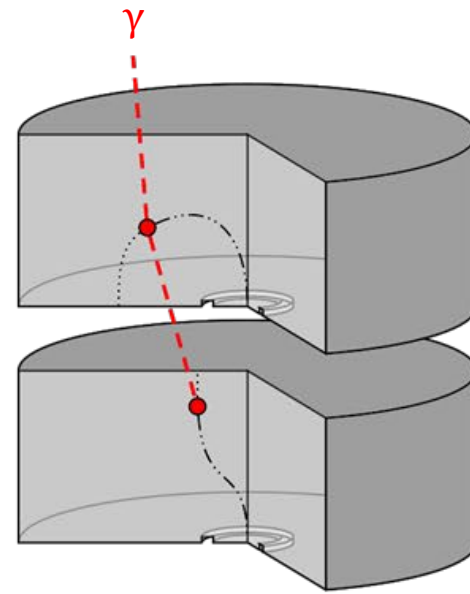
- Majorana (demonstrator) $\rightarrow$ classic detectors in vacuum with “ultra fancy” copper cryostats
- GERDA $\rightarrow$ LEGEND: detectors suspended in liquid argon



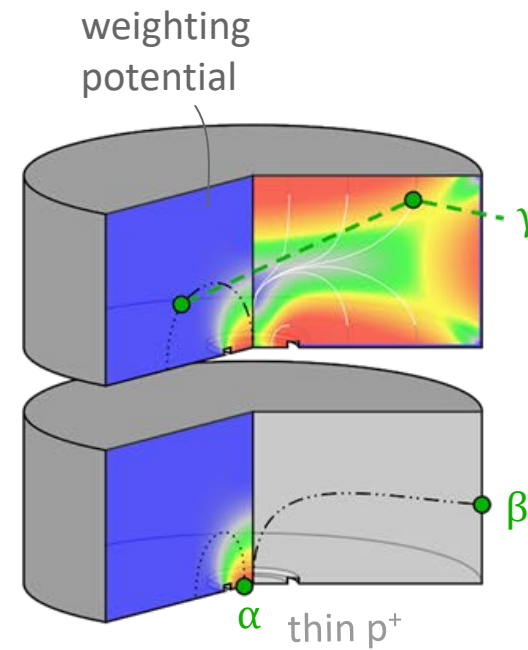
Topology discrimination (similarly used in any of the modern Ge experiments)



differentiate **point-like**
 $\beta\beta$ topology from:

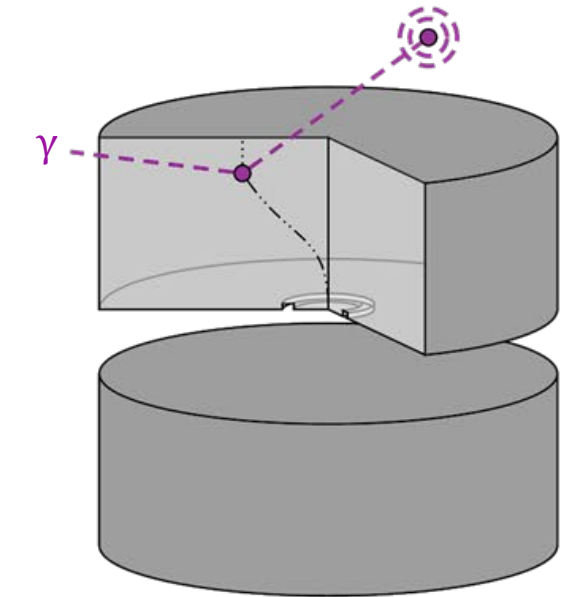


multi-detector
interactions



multi-site/surface
interactions

VUV detection in Ar provides a
veto function for interactions
happening, in part, on the outside



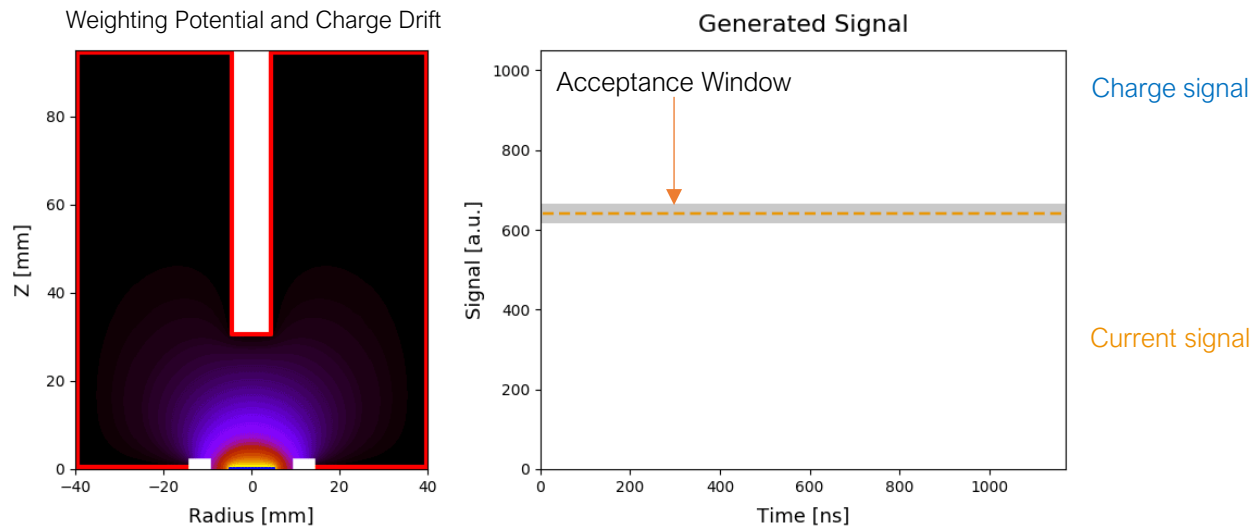
interactions with **partial**
energy depositions

This only applies to GERDA/LEGEND

Instrumentation innovation: Ge Detectors

Event Topologies

$0\nu\beta\beta$ signal candidate (single-site)



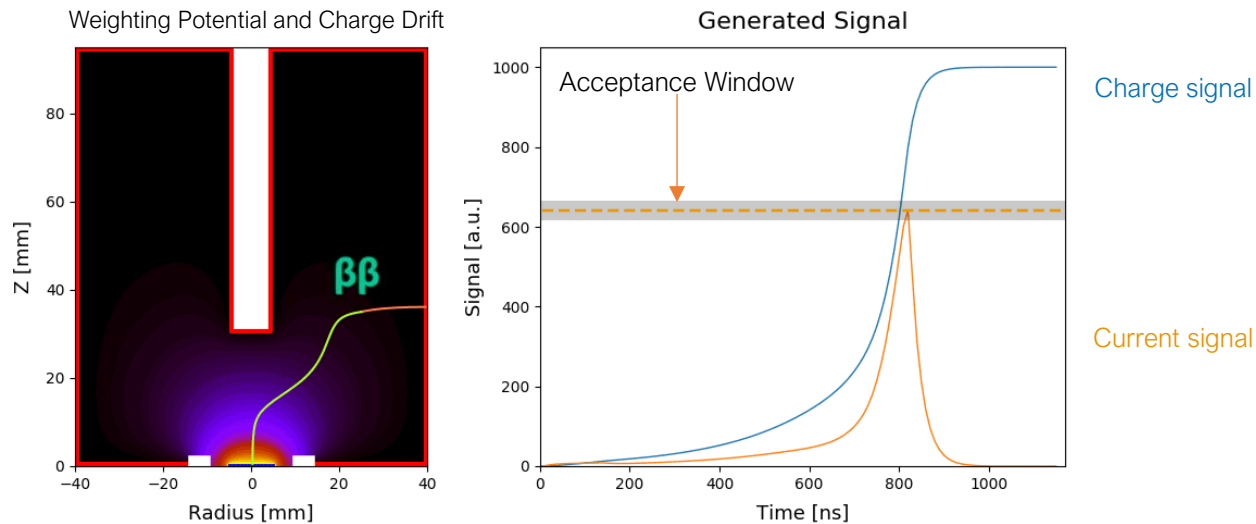
Shockley-Ramo Theorem: $Q(t) = -q\phi_w(\mathbf{x}_q(t))$
Weighting Potential: ϕ_w

N.B. animation only visible in pptx

Instrumentation innovation: Ge Detectors

Event Topologies

$0\nu\beta\beta$ signal candidate (single-site)

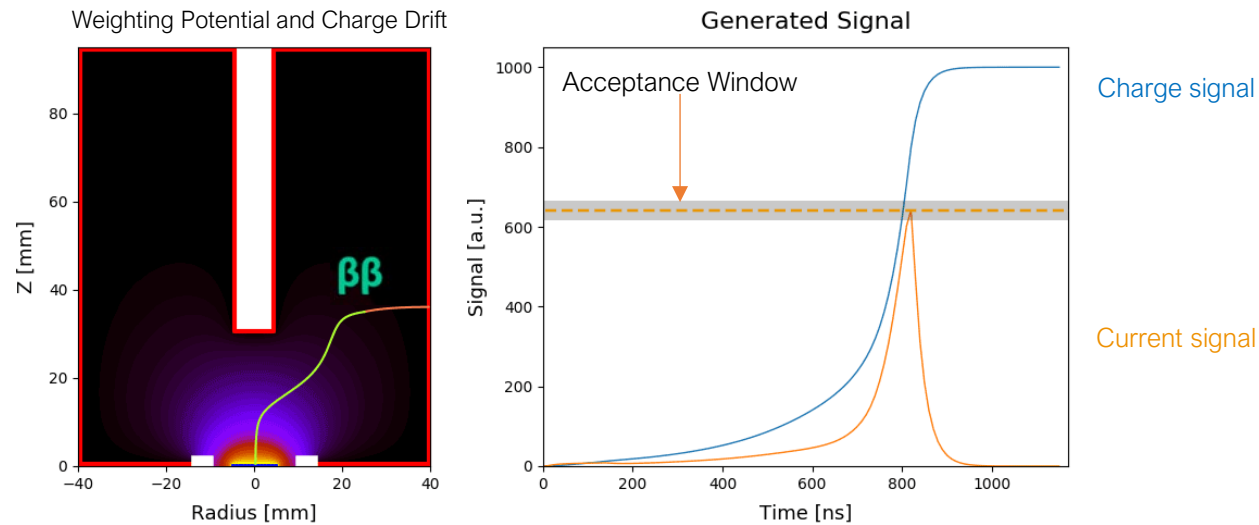


Shockley-Ramo Theorem: $Q(t) = -q\phi_w(\mathbf{x}_q(t))$
Weighting Potential: ϕ_w

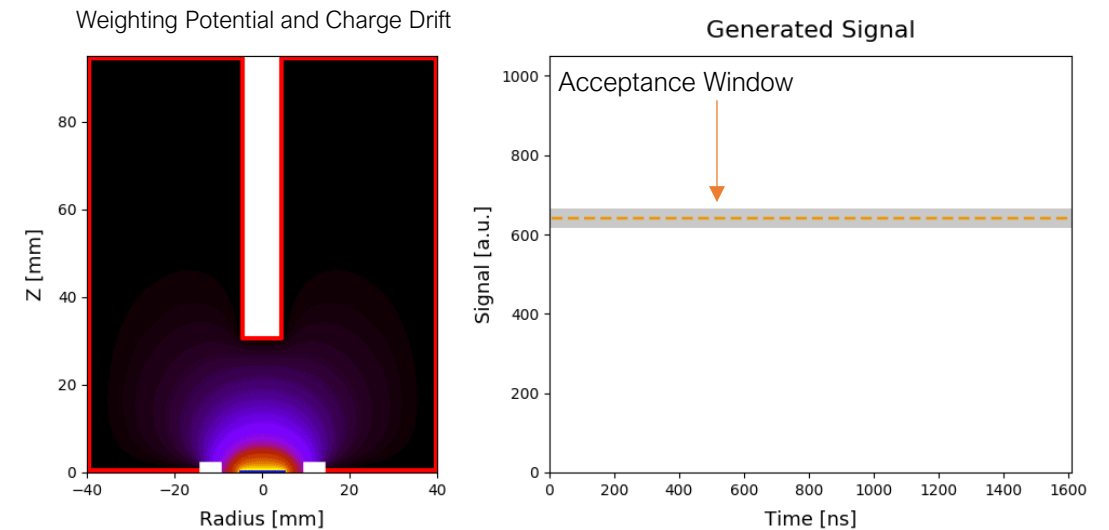
Instrumentation innovation: Ge Detectors

Event Topologies

$0\nu\beta\beta$ signal candidate (single-site)



γ -background (multi-site)

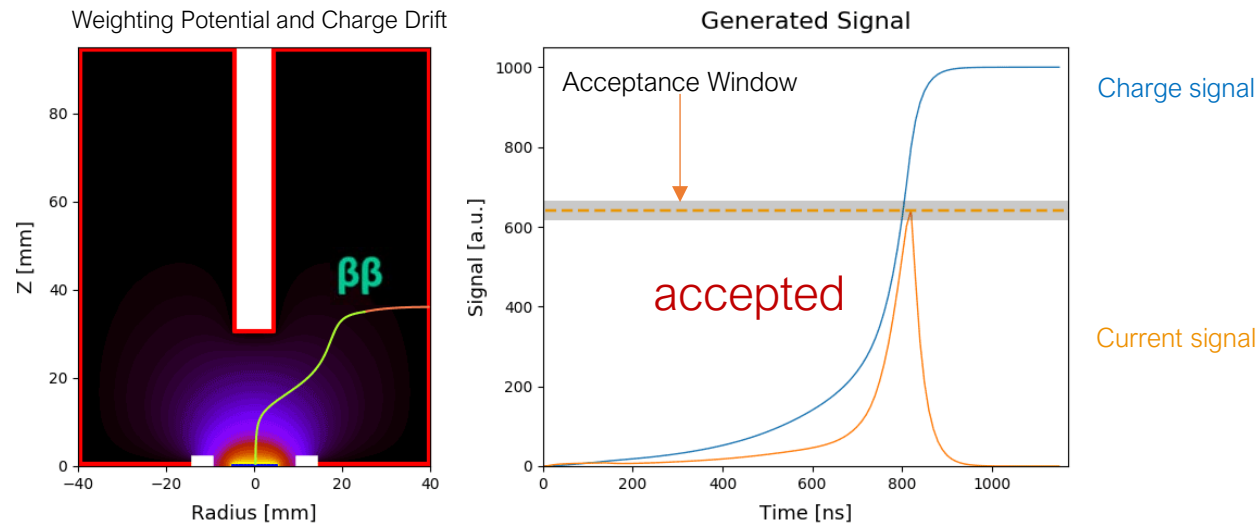


Shockley-Ramo Theorem: $Q(t) = -q\phi_w(\mathbf{x}_q(t))$
Weighting Potential: ϕ_w

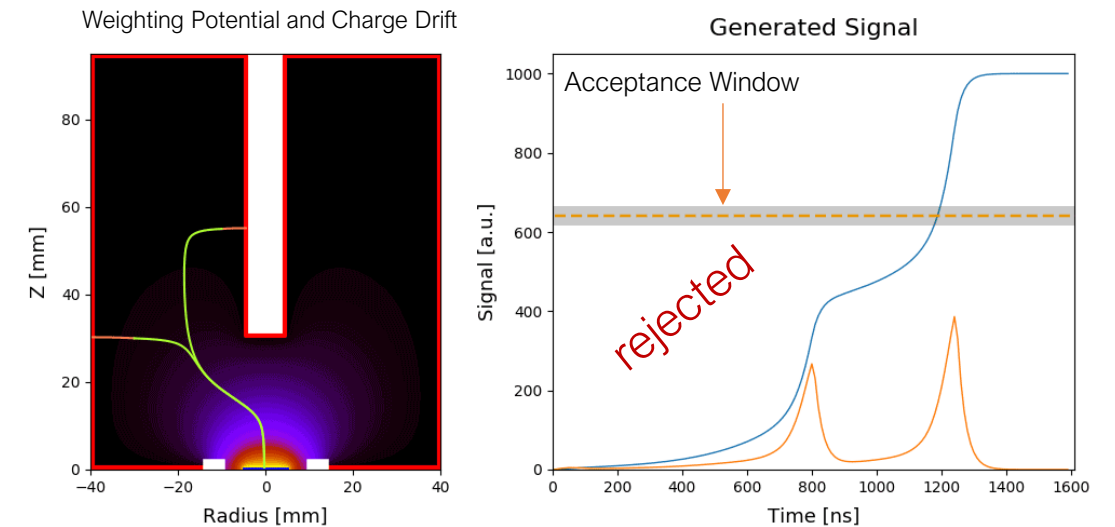
Instrumentation innovation: Ge Detectors

Event Topologies

$0\nu\beta\beta$ signal candidate (single-site)



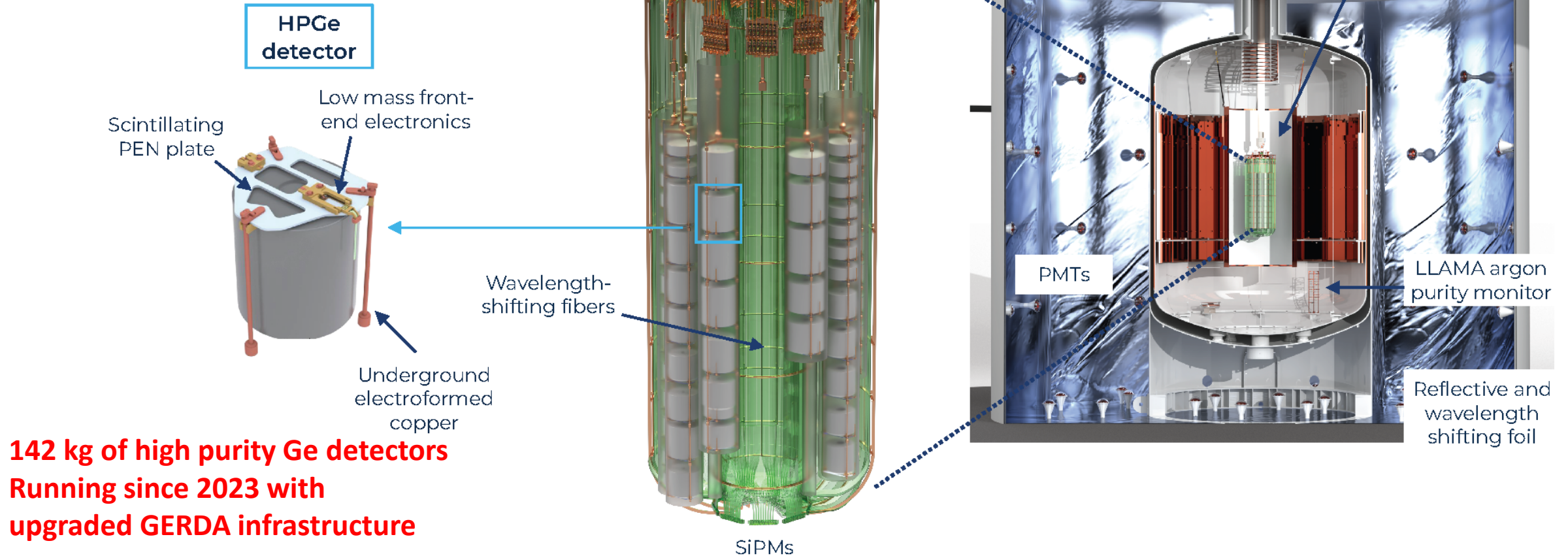
γ -background (multi-site)



Shockley-Ramo Theorem: $Q(t) = -q\phi_w(\mathbf{x}_q(t))$
Weighting Potential: ϕ_w

LEGEND-200 Experimental Overview

LEGEND is designed to minimize backgrounds and efficiently suppress them employing a layered active shield system.



142 kg of high purity Ge detectors
Running since 2023 with
upgraded GERDA infrastructure

- Data taking from March 2023 to February 2024: **61 kg yr exposure**.
- **11 events** surviving in the BI region after cuts, including 1 event near $Q_{\beta\beta}$.
- **Background index:** $5.4^{+2.7}_{-2.0} \times 10^{-4}$ cts / (keV kg yr) in the “**golden** dataset” (48 kg yr).
- **GERDA + MJD + LEGEND-200 combined:** Exclusion sensitivity: 2.8×10^{26} yr.
 $T_{1/2}(0\nu\beta\beta) > 1.9 \times 10^{26}$ yr (90% CL).
- Full beginning to end **secondary analysis stack** in full agreement with the primary analysis.

PRL **136**, 022701 (2026)

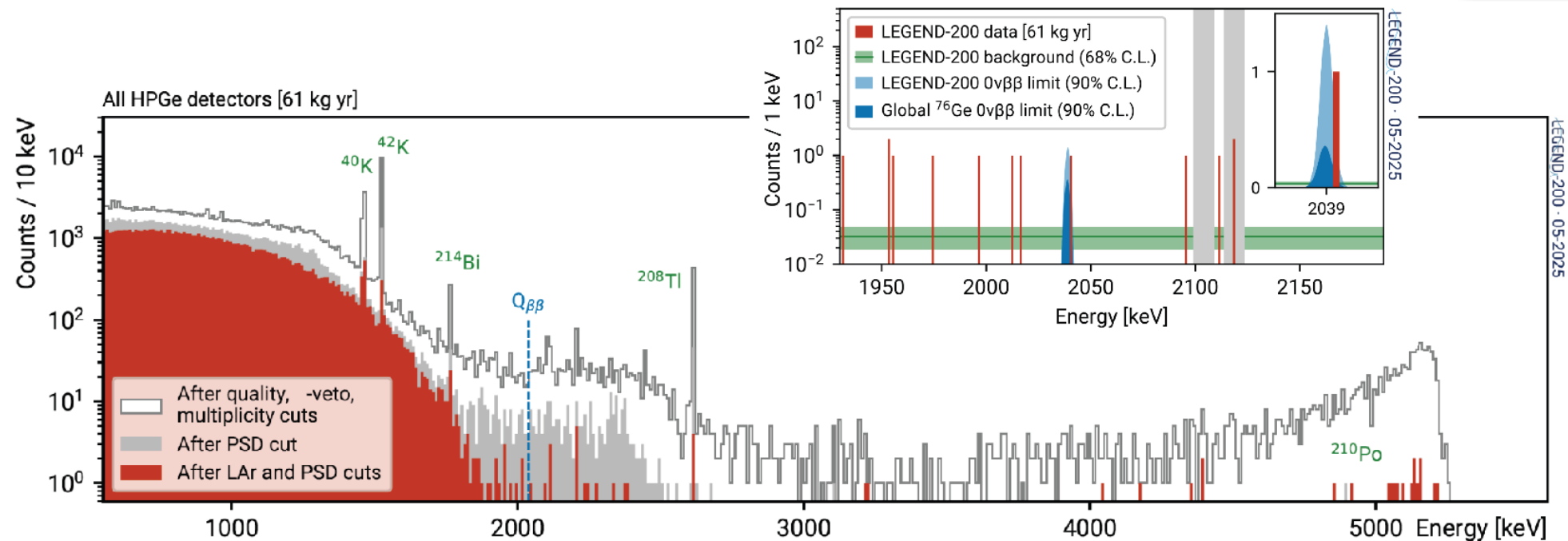
[arXiv:2605.22479](https://arxiv.org/abs/2605.22479) (submitted to EPJC)

Poster - G. Duran

Poster - I. Guinn

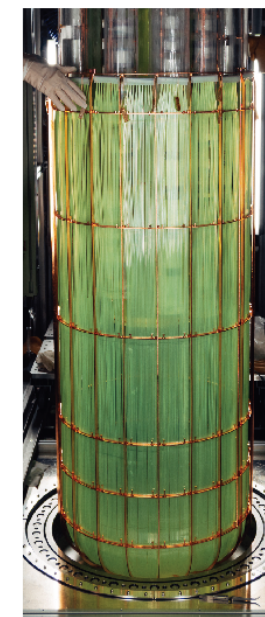
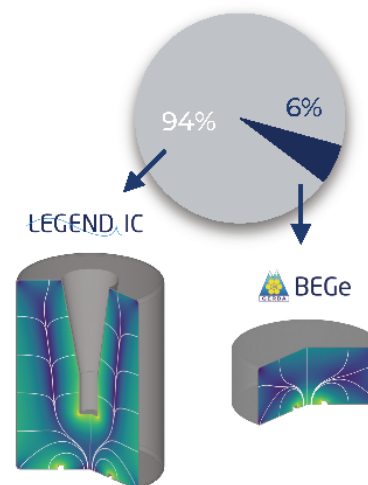
Poster - G. Marshall

Poster - A. Gieb

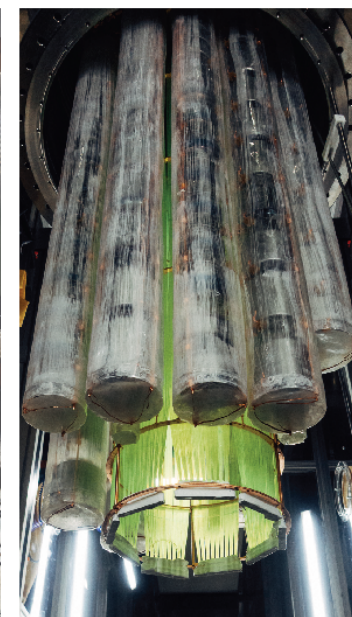




- Final BI **~2.5 higher** than predicted $\rightarrow$ **elevated U (^{214}Bi)/Th (^{208}Tl)** levels before cuts.
- **Forensic campaign:**
 - ✦ Special runs: **outer fiber barrel** and **nylon mini-shrouds** removed.
 - ✦ Array dismantled and all components sent for **assay**.
 - ✦ Results from assays: elevated U (^{214}Bi)/Th (^{208}Tl) in some components: hypothesized **surface contamination**, BI dominated by U (^{214}Bi).
- **2025 redeployment:**
 - ✦ Change of paradigm: **most** of L200 HPGe detectors **large-mass IC-detectors** (L1000-type).
 - ✦ Conversion of Coax, PPC, BEGe and underperforming detectors **to IC** meeting L1000 mass requirements.
 - ✦ All components re-etched/leached.
 - ✦ Total of **138 kg Ge** detectors deployed in July 2025. ICs and BEGs arranged in 9 strings.

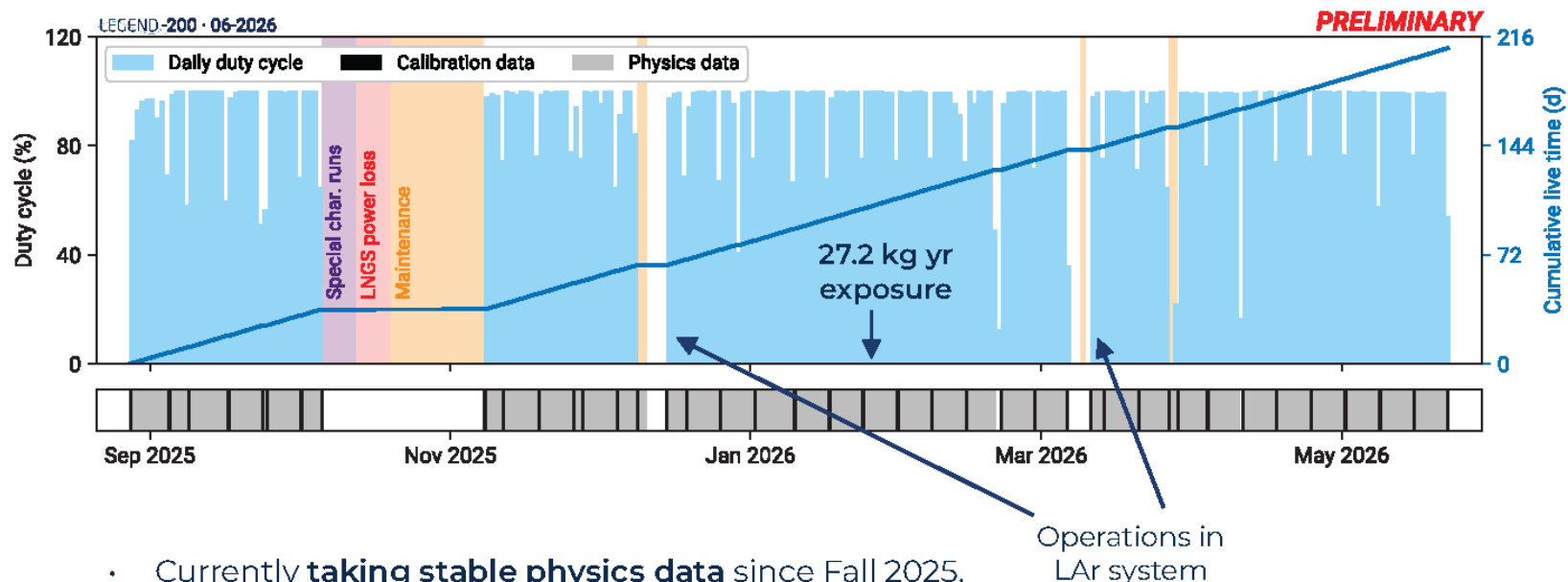


Outer barrel



Nylon mini-shrouds

Redeployment Operations and Performance



- Currently **taking stable physics data** since Fall 2025.
- Downtimes for special calibrations and maintenance.
- **Duty cycle:** 95% (70%) without/with downtimes.
- Data validated and shown here up to end of Jan 2026: **27.2 kg yr exposure** (no PSD consideration).

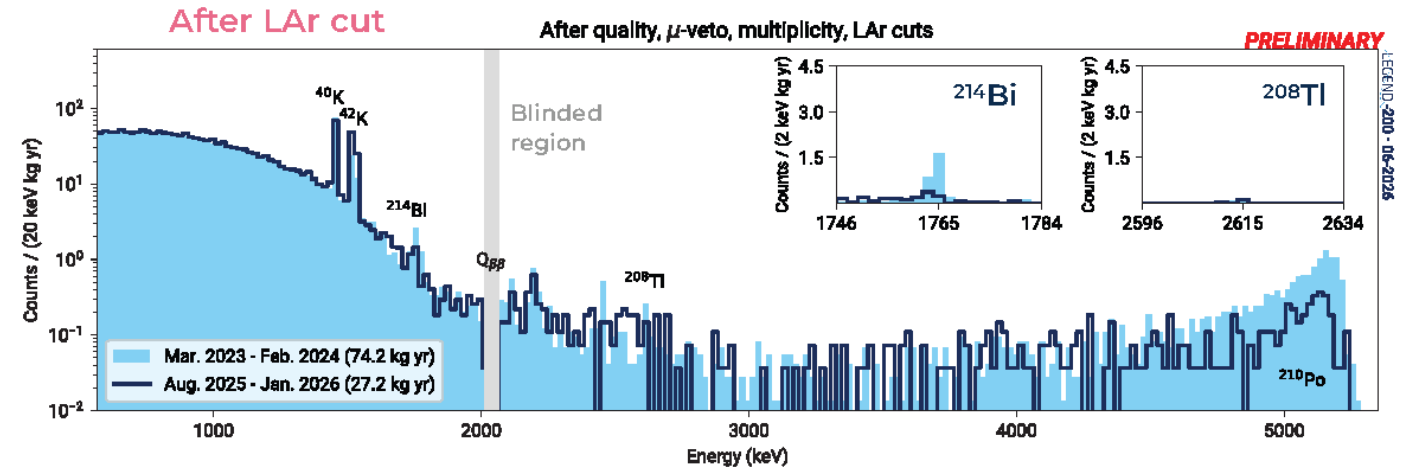
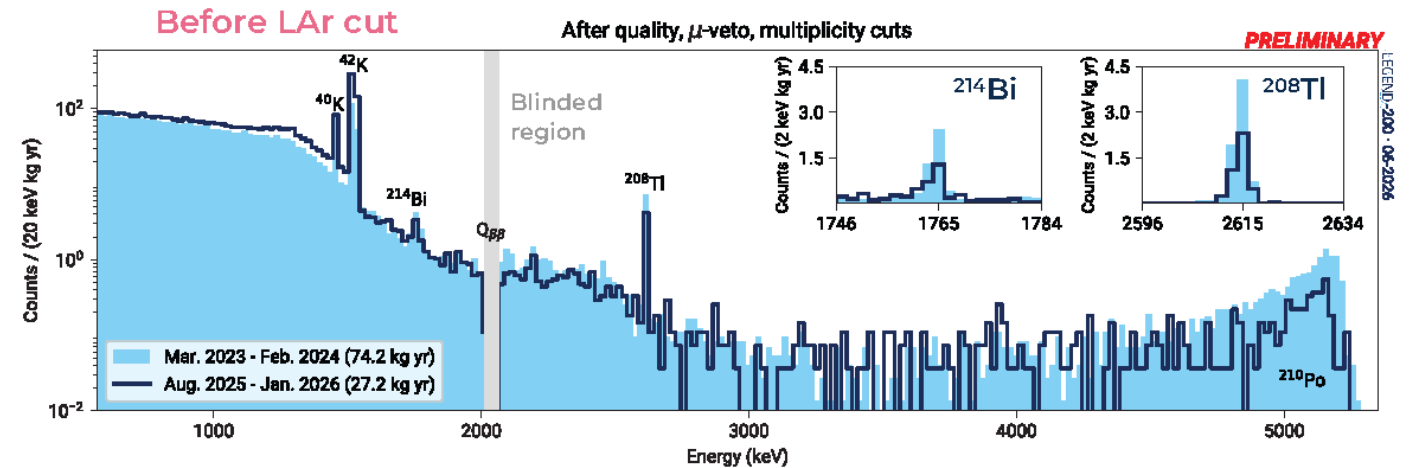
- ^{214}Bi (U)/ ^{208}Tl (Th) reduced by $\sim x2$ before cuts relative to the first-year results.
- After LAr cut:
 - ✦ x5 overall reduction of ^{214}Bi 1764 keV gamma-line!
 - ✦ ^{208}Tl ~ **eliminated** at current statistics.

➔ Effectiveness of etching and leaching.

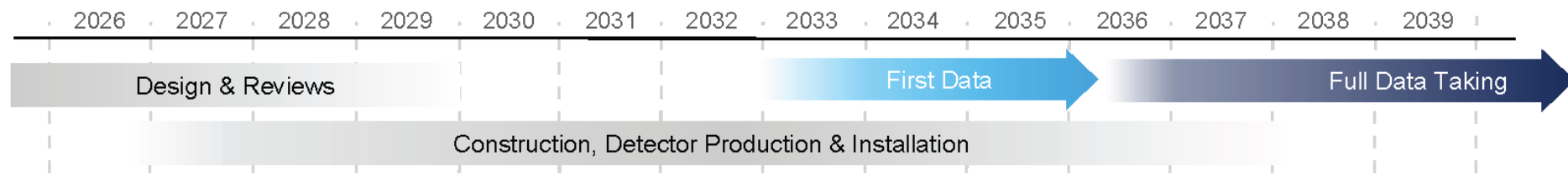
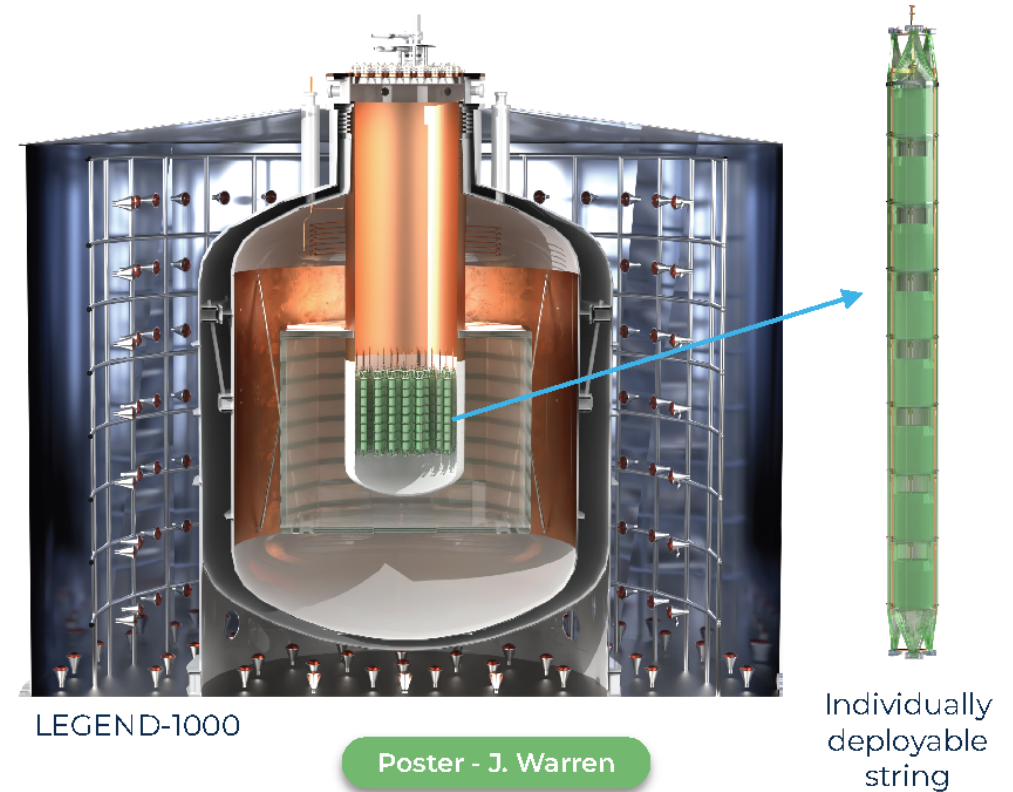
➔ Key input to L1000 background model.

➔ Expected to improve on L200 physics searches.

- After LAr + PSD cuts: remaining backgrounds seem to be dominated by ^{42}K surface events.
 - ✦ Work in progress: optimize analysis methods to reject ^{42}K surface events.
 - ✦ ^{42}K expected to be mitigated in L1000 with **underground-sourced argon** (UAR).



- Tonne scale experiment with large **background reduction compared to L200** to reach $0\nu\beta\beta$ discovery sensitivity $> 10^{28}$ yr, BI goal of 10^{-5} cts/(keV kg yr) and 10 t yr exposure.
- Key **improvements**:
 - ✦ All larger-mass **IC detectors** (~3 kg).
 - ✦ Inner volume of **UAr**: removes $^{42}\text{Ar}/^{42}\text{K}$ backgrounds.
 - ✦ **Single-string modules**, individually deployable.
 - ✦ **ASIC-based** readout electronics.
 - ✦ New **atmospheric argon instrumentation** (neutron moderator + light detection modules).
- LEGEND-1000 **funding**:
 - ✦ **US**: NSF (final design phase MREFC) & DOE (CD-1 review).
 - ✦ **Europe**: MPG and DFG support; German FIS National Research Infrastructure process (decision July 2026); INFN flagship project; contributions from Switzerland and Poland; UK roadmap pending.
- LEGEND-1000 **schedule**:



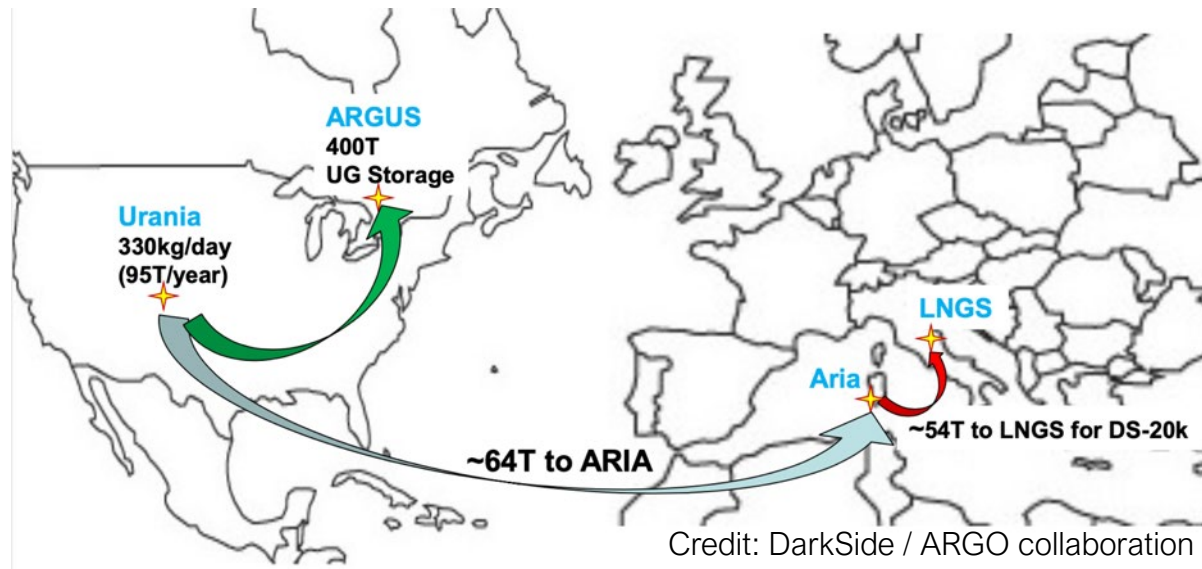
Q: where does Helium come from?

and how about Xenon?

...and Argon?

The Baseline Design: Underground Liquid Argon

- L1000 needs 20-25 t of UGLAr
- Builds on pioneering work of DarkSide collaboration
- UGAr will be mined at Urania facility (U.S.) 95 t/y
- Logistics and storage technology under development by DarkSide/ARGO collaboration for LNGS and SNOLAB
- Expression of interest from INFN president¹ and DarkSide leadership
- UGAr production for LEGEND-1000 in 2023 (after DS-20k)



UGAr is depleted in ^{42}Ar (^{39}Ar)

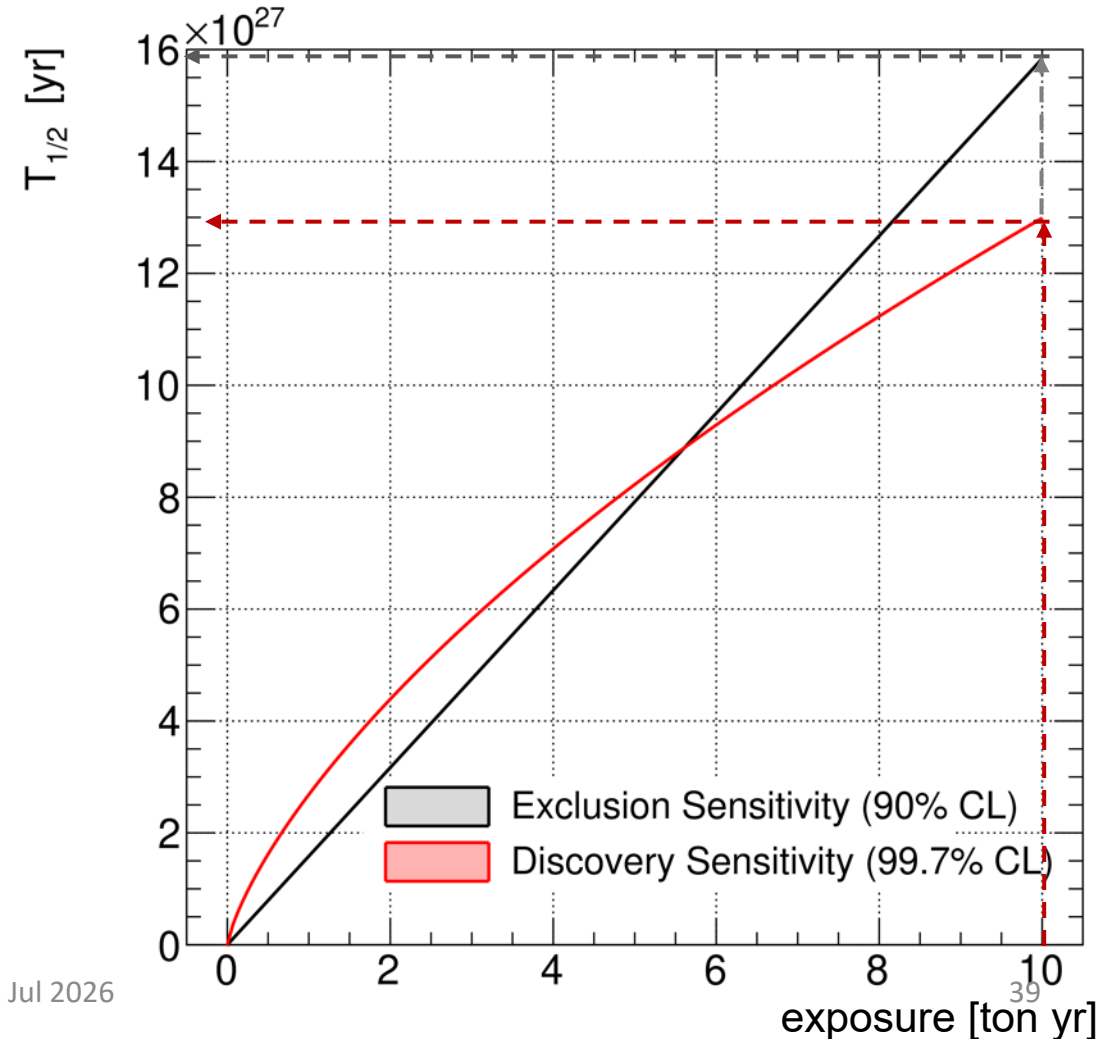
Iso- tope	Abun- dance	Half-life ($t_{1/2}$)	Decay mode	Pro- duct
^{36}Ar	0.334%	stable		
^{37}Ar	syn	35 d	ϵ	^{37}Cl
^{38}Ar	0.063%	stable		
^{39}Ar	trace	269 y	β^-	^{39}K
^{40}Ar	99.604%	stable		
^{41}Ar	syn	109.34 min	β^-	^{41}K
^{42}Ar	syn	32.9 y	β^-	^{42}K

Sensitivity $T_{1/2}$

- $T_{1/2} \propto \mathcal{E}/N_{0\nu\beta\beta}$
- Background free $\rightarrow$ linear sensitivity growth
- 10^{28} yr in discovery mode (x100 better than GERDA & MAJORANA)

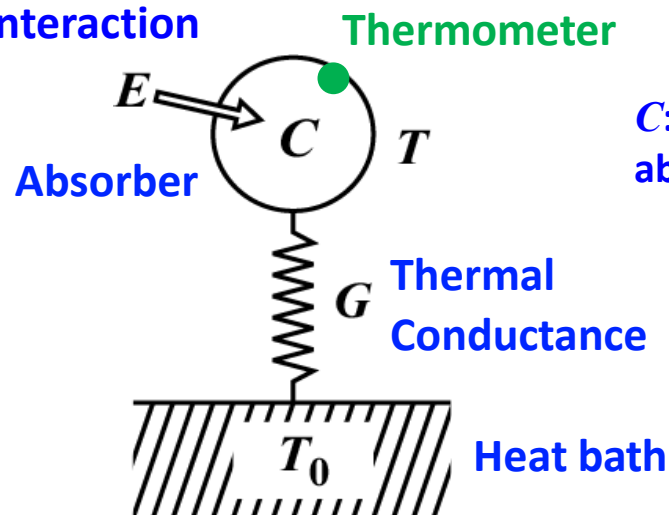
LEGEND will explore uncharted territory
and open new energy frontiers
New physics can manifest at any $T_{1/2}$ value!

90% CL exclusion sensitivity @ 10 ton-yr	$1.6 \cdot 10^{28}$ yr
3σ discovery sensitivity @ 10 ton-yr	$1.3 \cdot 10^{28}$ yr



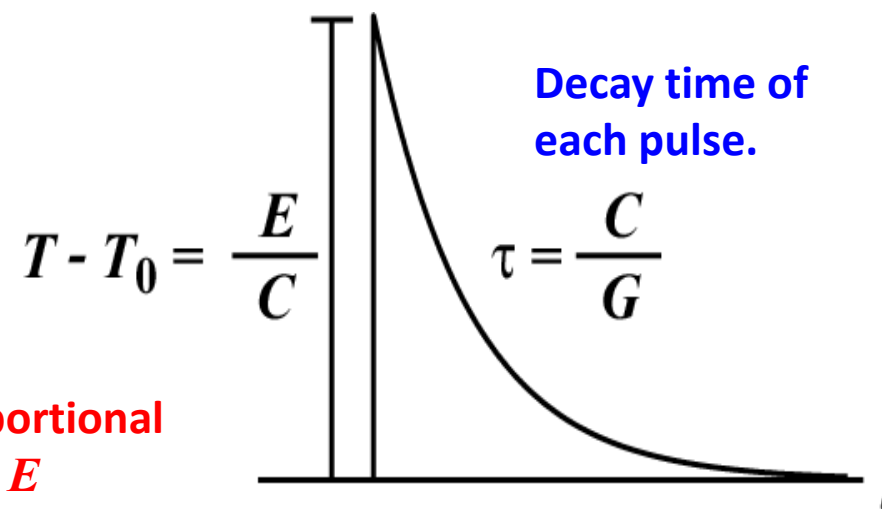
Cryogenic Bolometers

Particle interaction
or decay



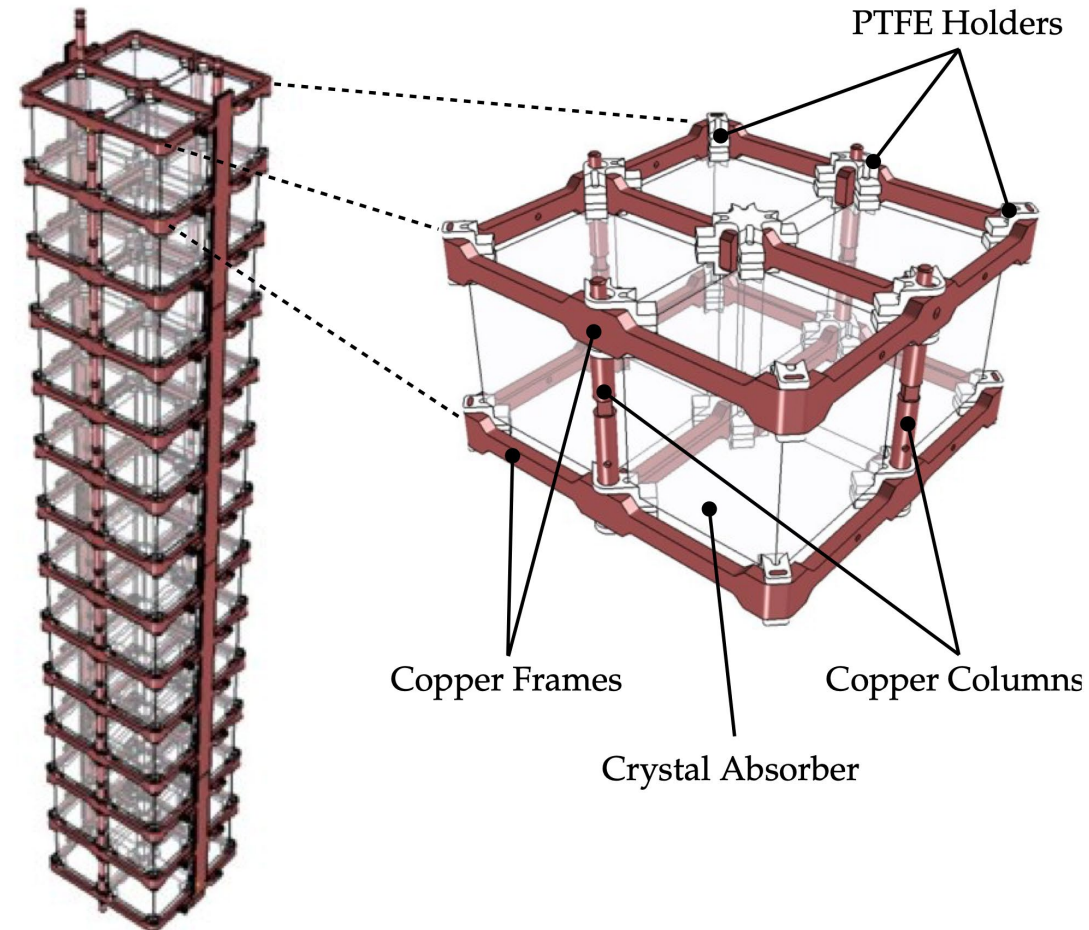
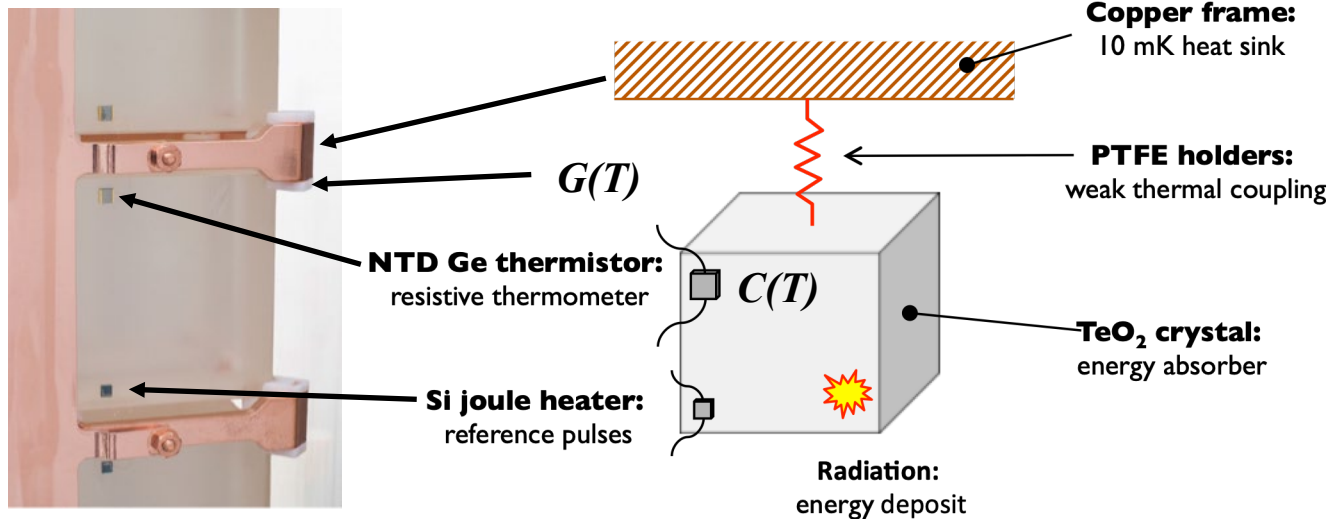
C : heat capacity of
absorber and thermometer

True calorimeters:
 $\Delta T = T - T_0$ will be proportional
to the energy deposition, E



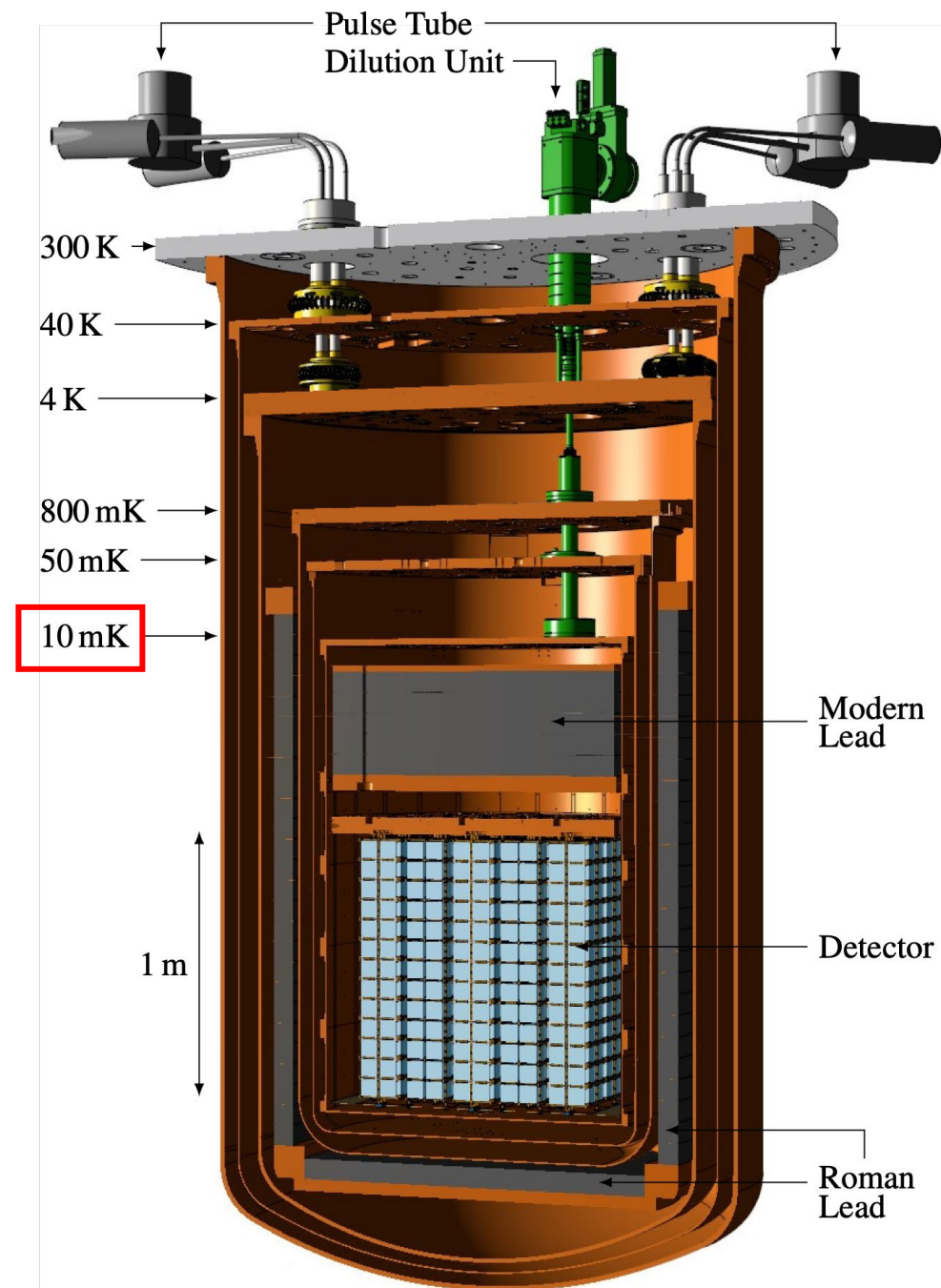
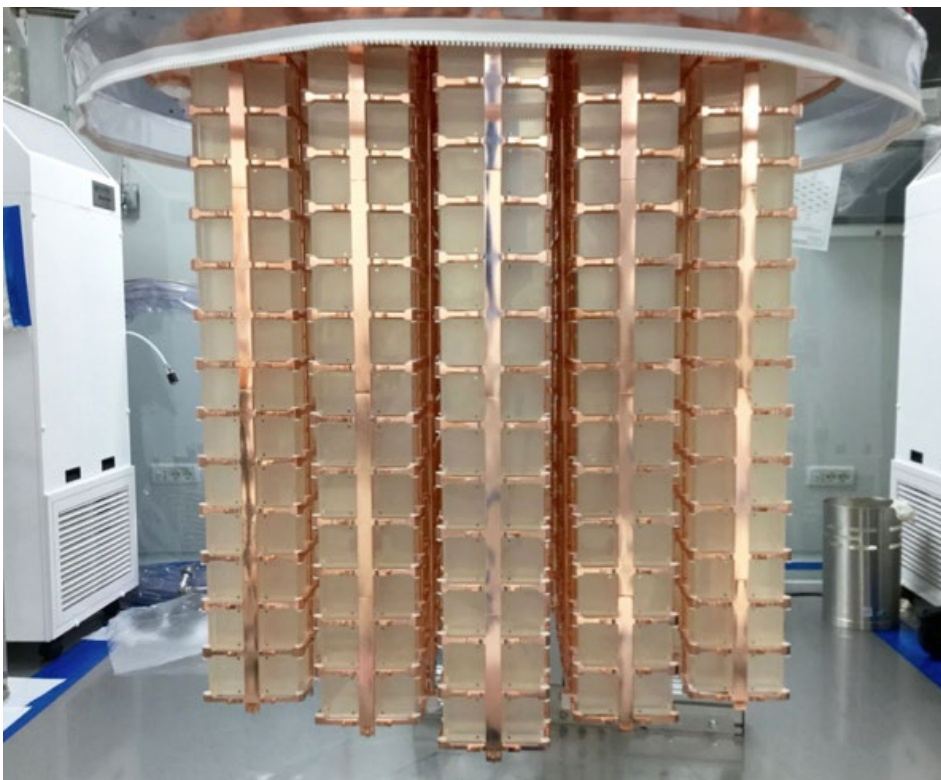
- To some extent, this is nuclide-agnostic.
- A few inorganic crystals for cryogenic double beta decay have Debye temperature(T_D), ~ 300 K. The heat capacity ($C \propto (\frac{T}{T_D})^3$) of such crystals of a few hundred grams are order of 10^{-10} - 10^{-9} J/K at 10 mK temperature.
- ~ 3 MeV signal of neutrinoless double beta decay will increase the temperature of the crystal (absorber) by $\sim$ mK.

Use ^{130}Te in the form of TeO_2 crystals
 Natural Te is sufficient: ^{130}Te 34.1% abundance
 Energy resolution $\approx 0.2\%$ @ $T \approx 10\text{mK}$
 Slow response $\approx$ a few Hz



“The coldest m³ in the Universe!”

- 19 towers suspended in a cylindrical structure
- 13 levels, 4 crystals each
- 5x5x5 cm³ (750g each)
- ¹³⁰Te: 34.1% natural isotope abundance
- 742 kg TeO₂ → 206 kg ¹³⁰Te



Roman Lead Shield



Times Roman

- Lead is an excellent material for shielding but normally it contains ^{210}Pb with 10-1000 Bq/kg (from the ^{238}U decay chain, half life ~ 22 y)
- Romans extracted the Ag from the Pb (and ^{238}U with it)
- Ingots from a shipwreck near Sardinia (I century B.C.)
- After ≈ 50 half-lives, ^{210}Pb in roman Pb < 4 mBq/kg
- Measures required both to safeguard historical artefacts and the low background features:
 - Remove the “skin” with Roman markings
→ museum
 - Cast “core material” N_2 atmosphere with clean SS molds
 - Machining with selected tools and liquids

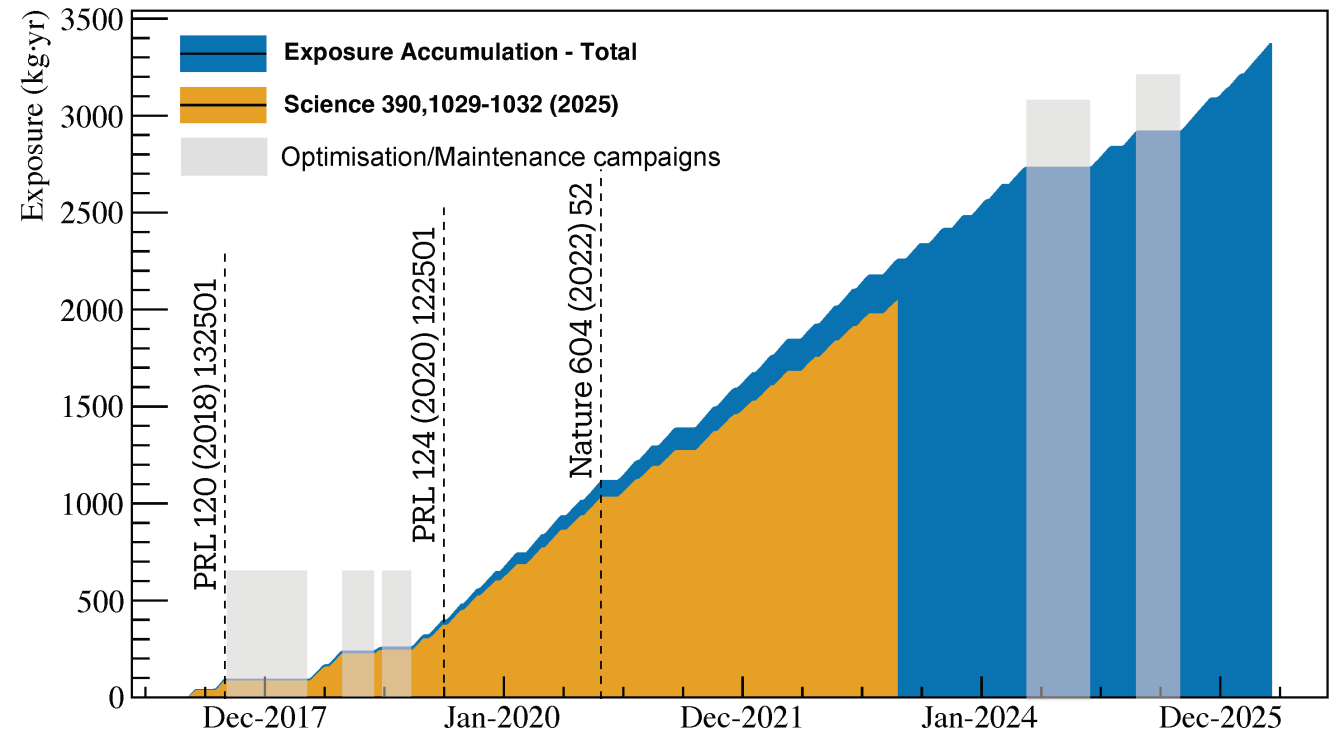
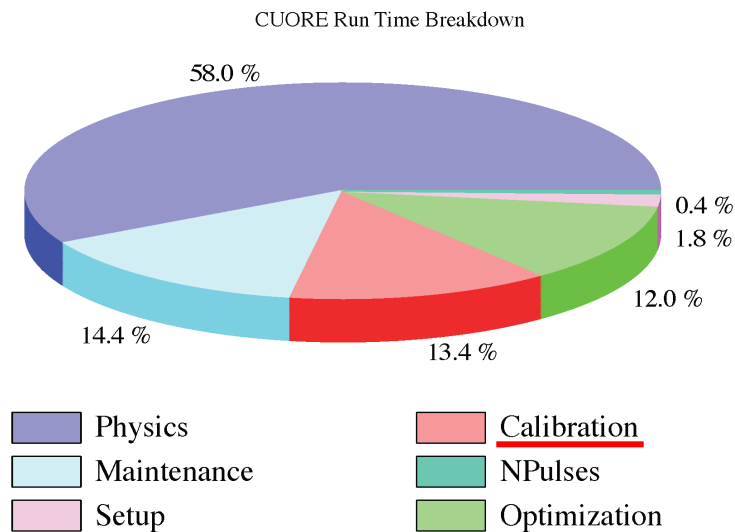


CUORE DATA ACCUMULATION

~ 10 YEARS OF CUORE DATA TAKING (2017-2026)

- ▶ **CUORE completed its $0\nu\beta\beta$ data-taking campaign on June 9, 2026** 🎉
- ▶ **Nearly a decade of stable cryogenic operation with > 99% active detectors**
- ▶ A benchmark for future large-scale cryogenic experiments
- ▶ Total accumulated data: **3.37 tonne-year of TeO_2** (before analysis cuts)

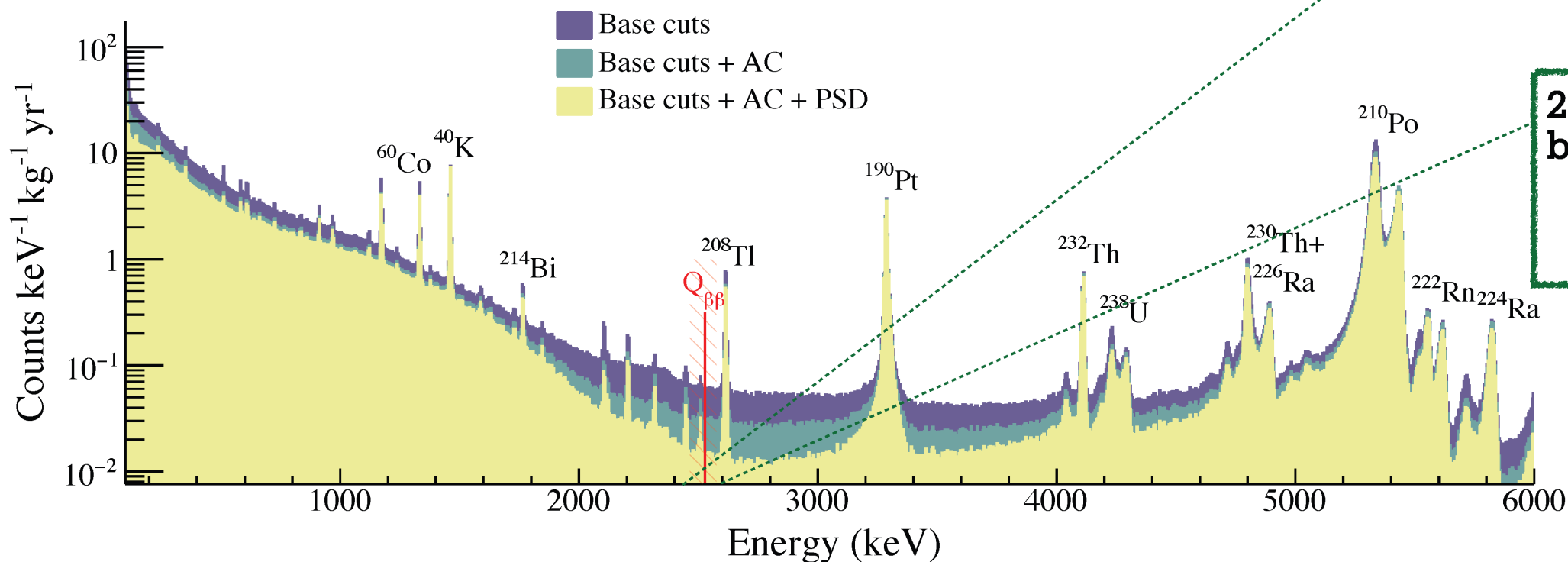
2019 – 2026 operation efficiency:



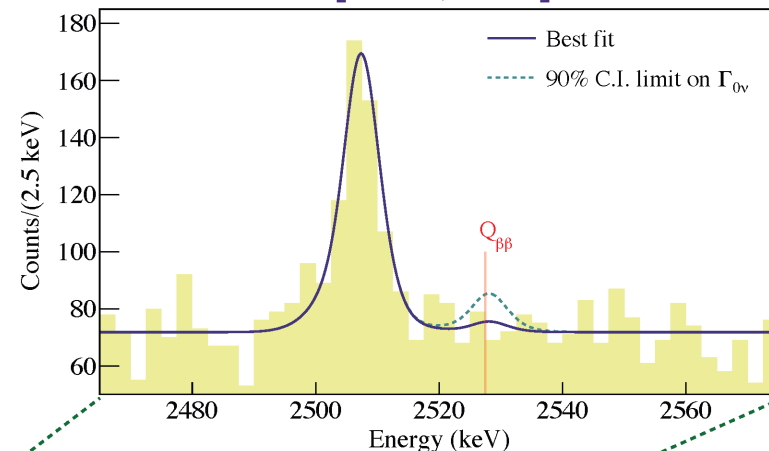
CUORE 2 TONNE-YEAR SPECTRUM

AFTER ANALYSIS CUTS

- Several sequential analysis cuts (analysis threshold = 40 keV):
 - ♦ **Base cuts:** trigger, energy reconstruction, pile-up
 - ♦ **Anti-coincidence (AC):** only single-crystal events
 - ♦ **Pulse shape discrimination (PSD):** only signal-like events
- **Total analysis cut efficiency:** 93.4(18)%



ROI [2465,2575] keV



**2 tonne-year average
bkg index in the ROI:**
 $(1.42^{+0.03}_{-0.02}) \times 10^{-2}$
counts/keV/kg/y

[Science.390\(2025\)](https://doi.org/10.1126/science.1258111)

CUORE ^{130}Te $0\nu\beta\beta$ SEARCH RESULTS

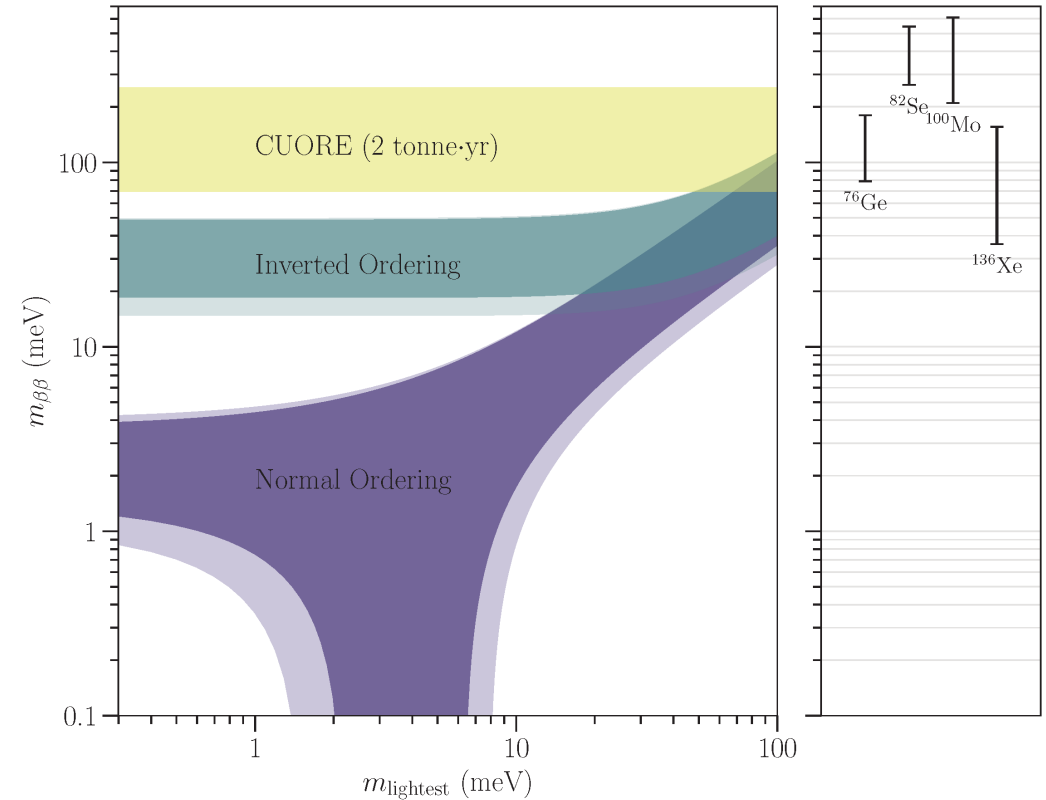
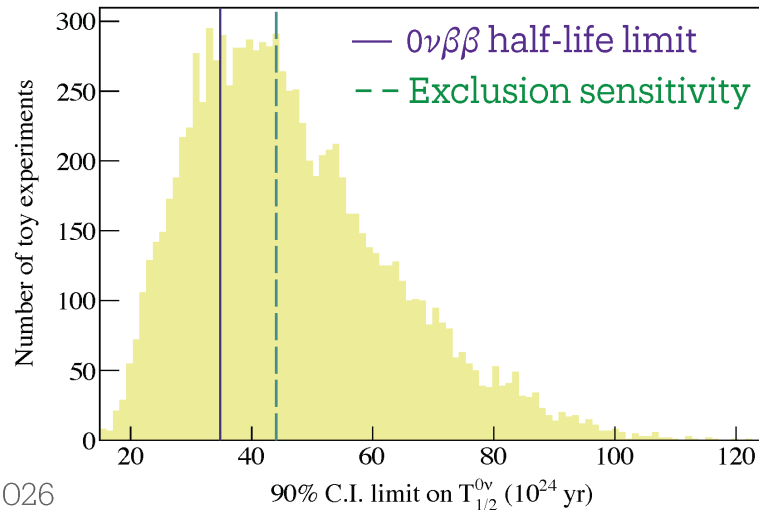
2 TONNE-YEAR EXPOSURE

[Science.390\(2025\)](#)

- Unbinned Bayesian fit with $\Gamma_{0\nu} > 0$
- Decay rate limit $\Gamma_{0\nu} < 2.0 \times 10^{-26}/\text{yr}$ (90% C.I.)
- **We find no evidence of ^{130}Te $0\nu\beta\beta$ decay:**

^{130}Te $0\nu\beta\beta$ half-life $T_{1/2} > 3.5 \times 10^{25}$ yr (90% C.I.)

- Median exclusion sensitivity from 10^4 toy MC experiments in background-only hypothesis: $T_{1/2} = 4.4 \times 10^{25}$ yr (90% C.I.)

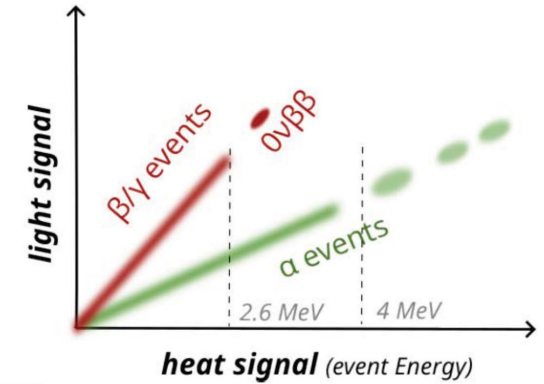
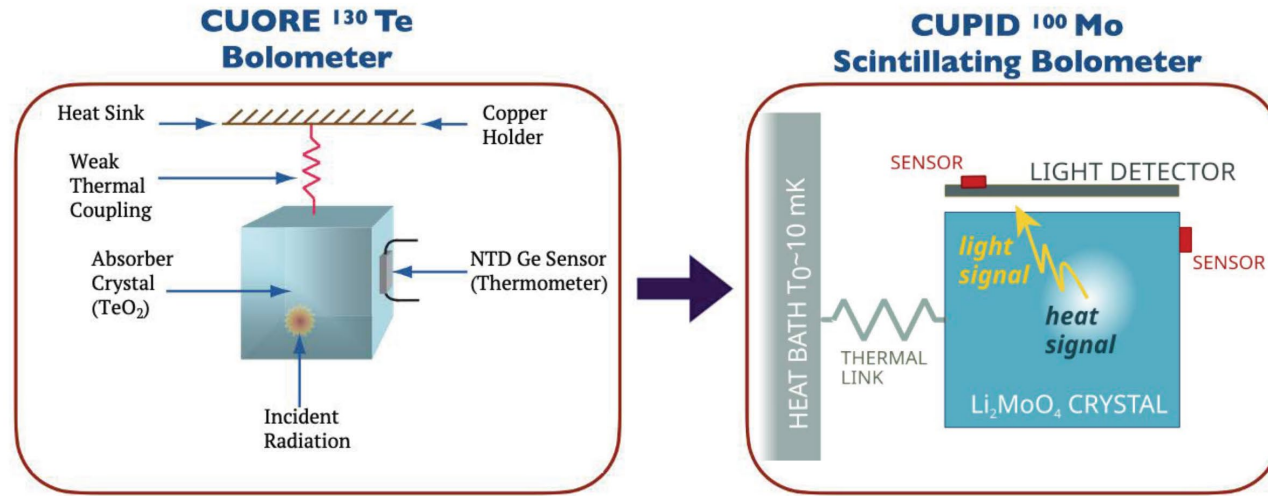


Assuming the exchange of a light Majorana ν , the limit on the effective Majorana mass with 2 tonne-year of data of CUORE is:
 $m_{\beta\beta} < 70\text{--}250$ meV at 90% C.I.

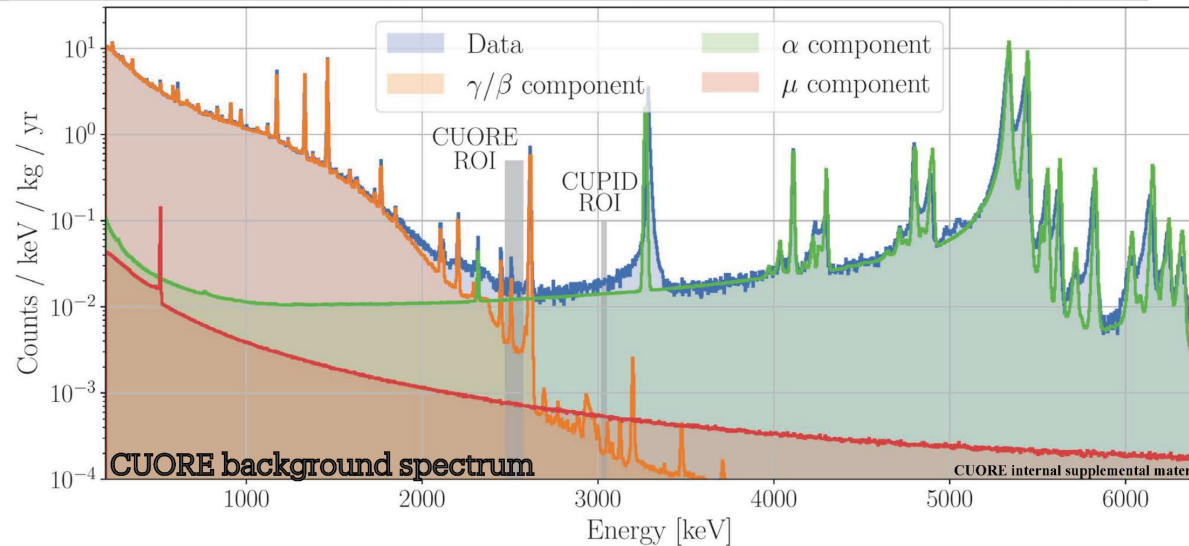
CUORE UPGRADE WITH PARTICLE IDENTIFICATION

SCINTILLATING CRYOGENIC CALORIMETERS FOR SIMULTANEOUS HEAT+LIGHT MEASUREMENT

Cryogenic detectors with PID:



^{100}Mo as $0\nu\beta\beta$ candidate isotope ($Q_{\beta\beta} = 3034.4$ keV) natural i.a. 9.7%



Li_2MoO_4 scintillating absorbers

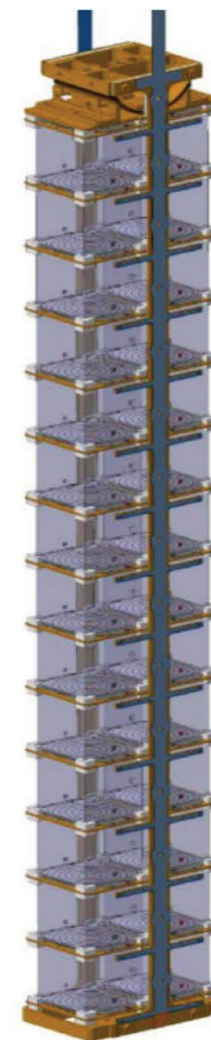
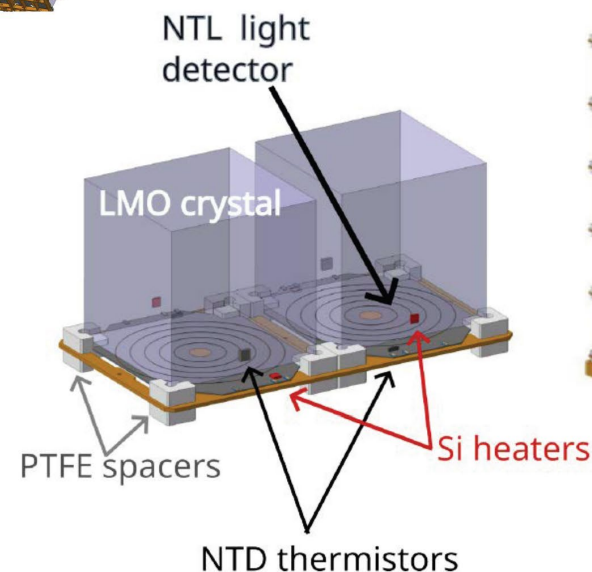
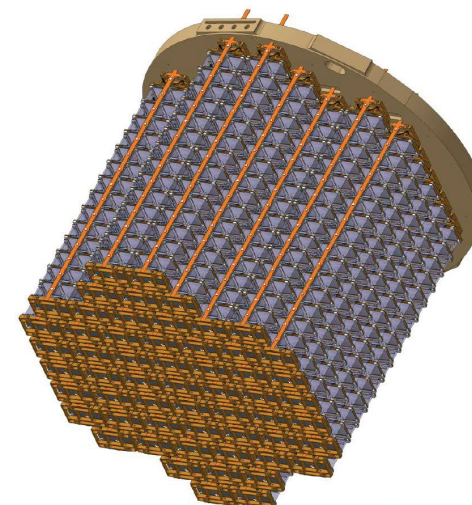
CUORE data driven background model: PRD.110(2024)

CUPID BASELINE DESIGN

IN THE CUORE INFRASTRUCTURE

- ▶ **45×45×45 mm³ Li₂¹⁰⁰MoO₄ crystals**
 - Single crystal mass: 280 g
- ▶ **1596 crystals in the array**
 - 450 kg of Li₂¹⁰⁰MoO₄ (LMO)
 - 95% enrichment in ¹⁰⁰Mo: 240 kg of ¹⁰⁰Mo
 - 57 towers of 14-floors, 28 crystals each
- ▶ **Ge light detectors (LD) with SiO anti-reflective coating**
 - Top and bottom LD for each crystal: 1710 LDs
 - Open geometry to maximise coincidence tagging
 - Signal amplification via the Neganov-Trofimov-Luke (NTL) effect

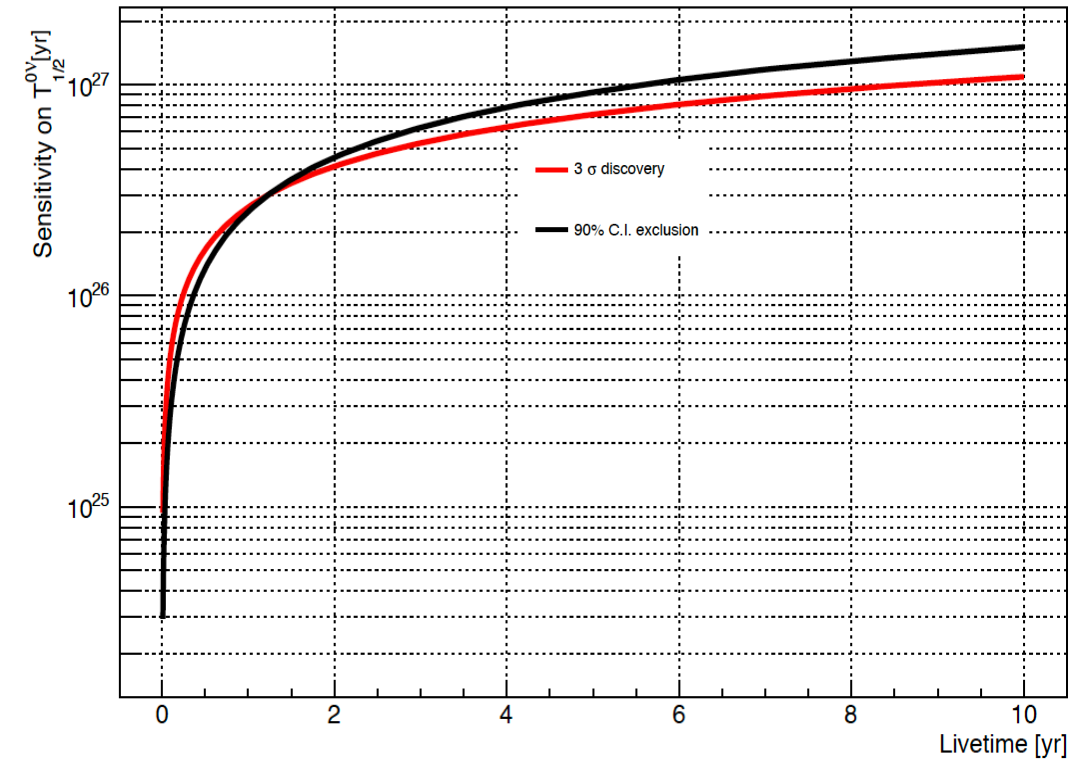
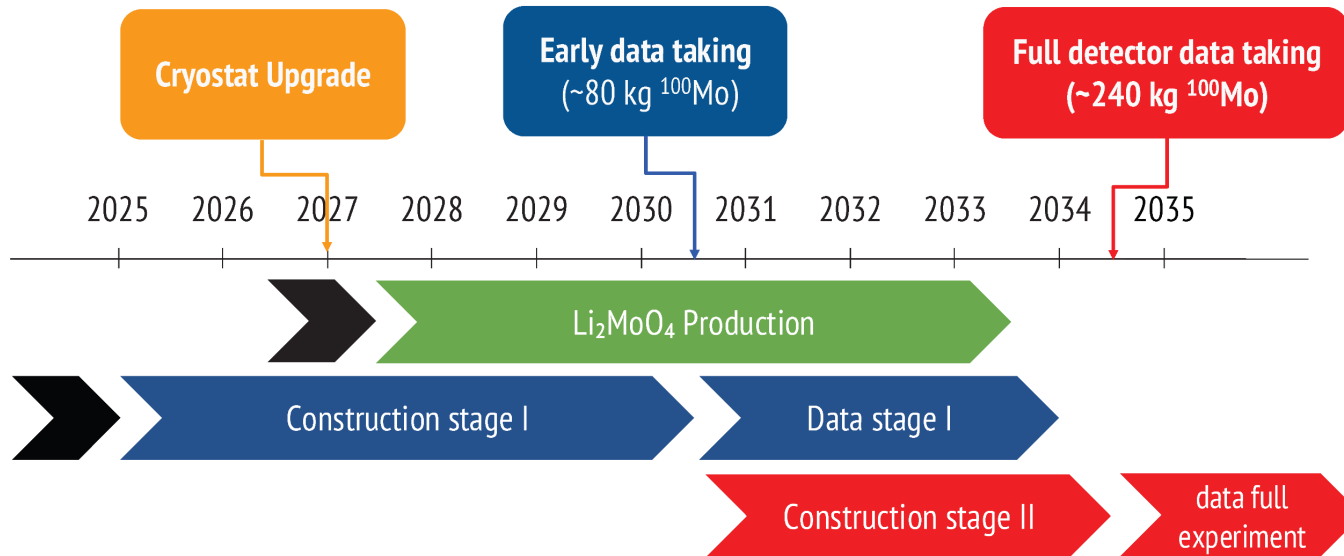
[EPJC.85\(2025\)737](#)



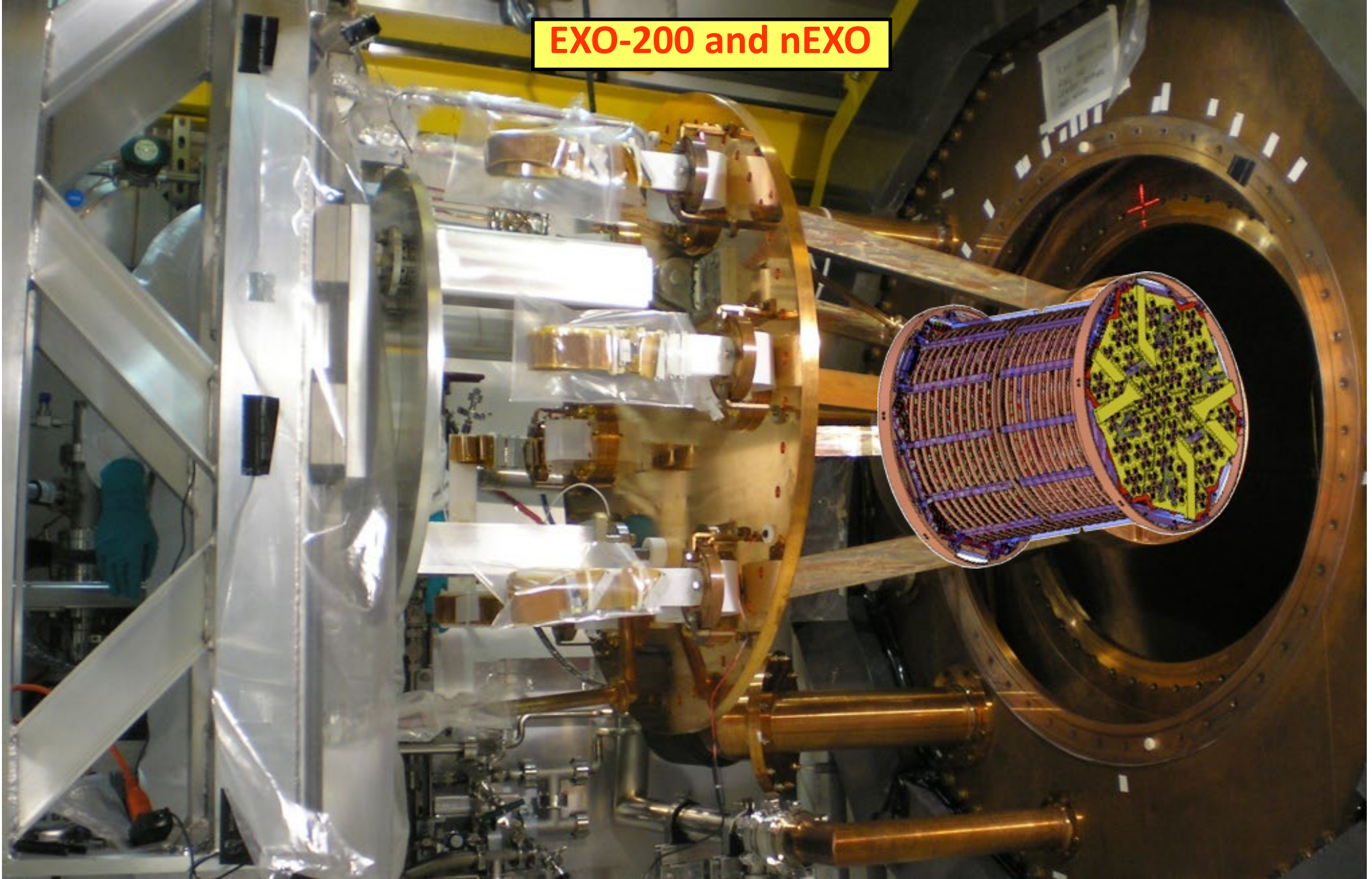
CUPID TIMELINE

STAGED DEPLOYMENT AND EARLY PHYSICS DATA

- ▶ **CUPID-Stage I:** installation of 1/3 of the final CUPID array (~532 enriched LMO crystals) in the refurbished CUORE cryostat, enabling an in-situ assessment of the overall performance.
- ▶ **CUPID-Stage II:** full CUPID detector deployment

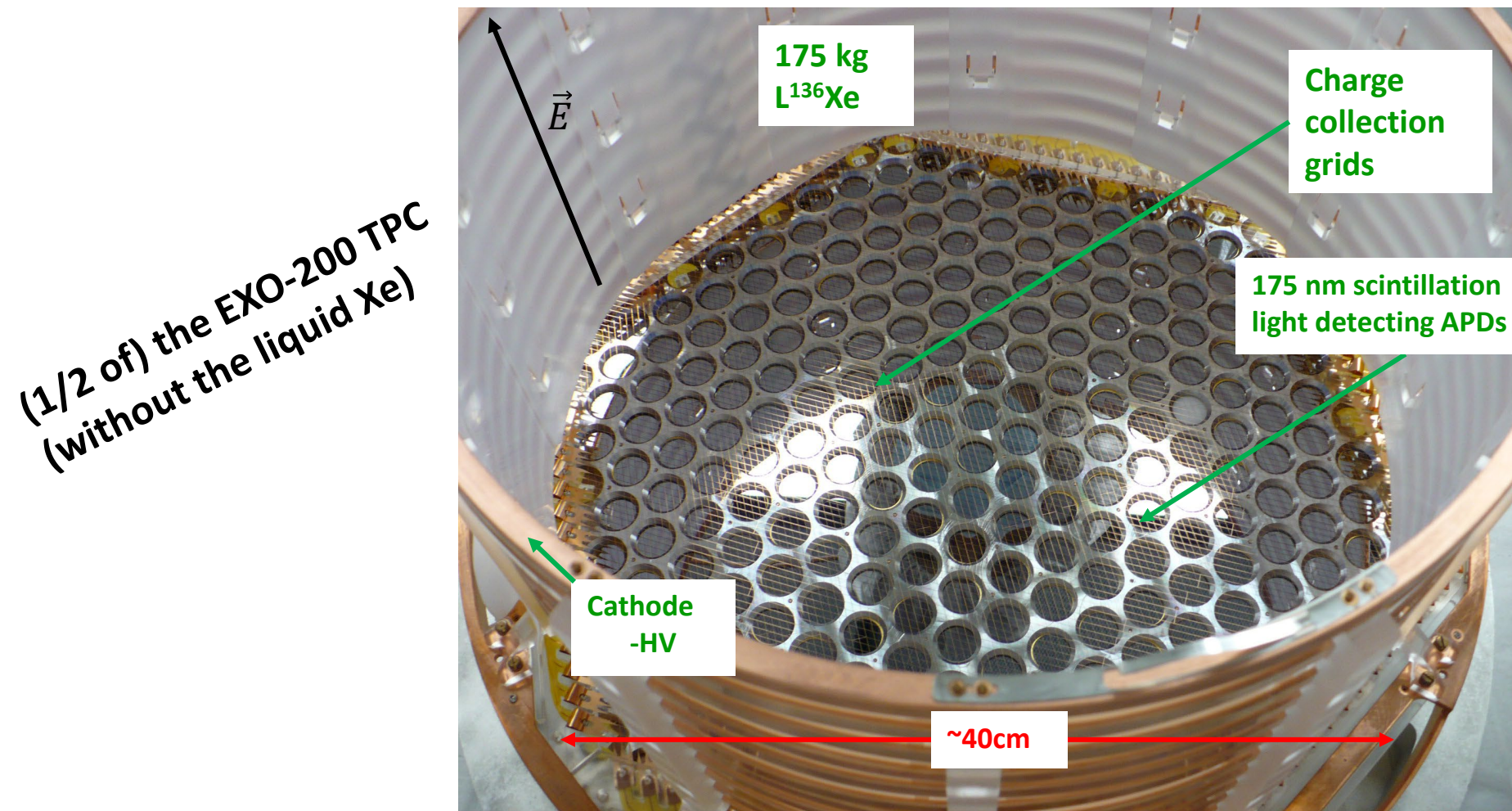


EXO-200 and nEXO



Time Projection Chambers can measure charge depositions in 3-D, with nothing but the active material in the volume and all the instrumentation at the outer surface.

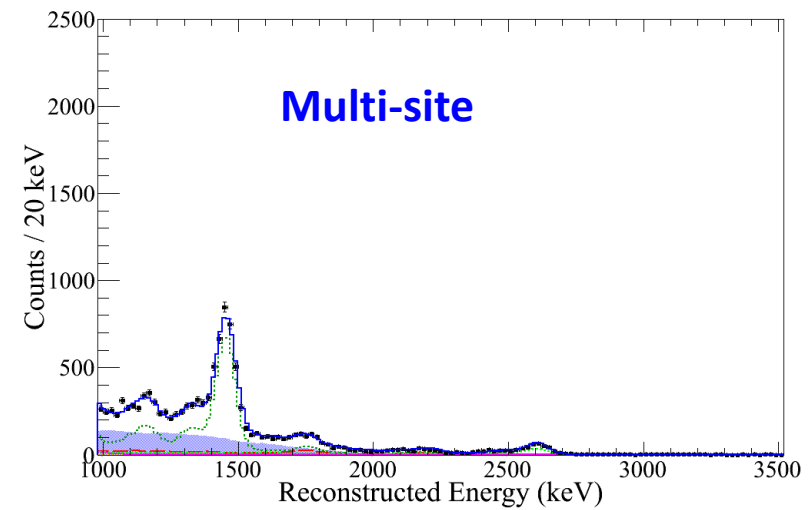
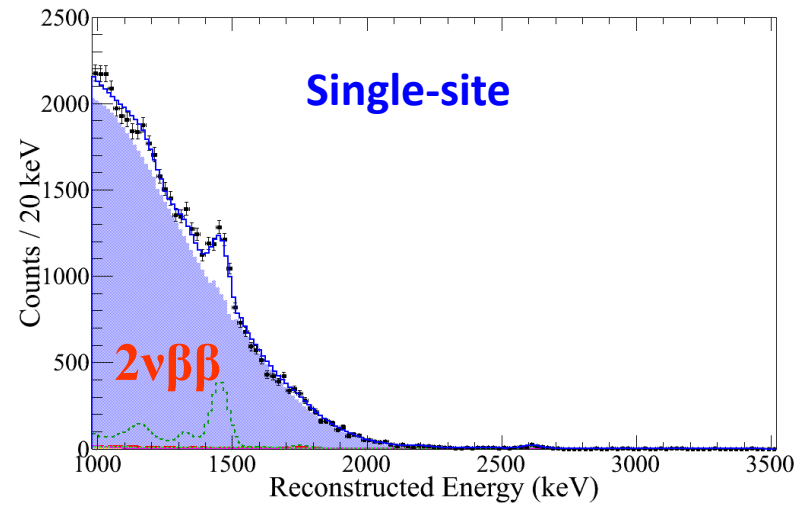
When events are not correlated with an external trigger, scintillation light can be used to signal the start of the drift and allow for the measurement of the z coordinate.



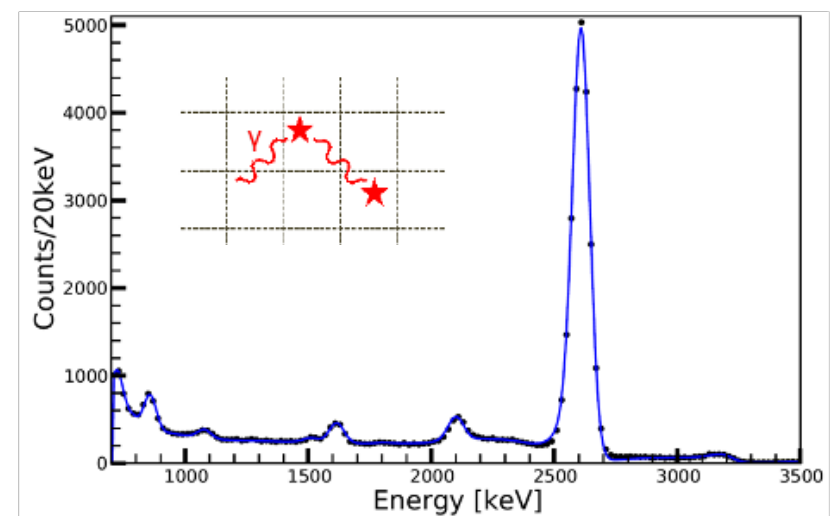
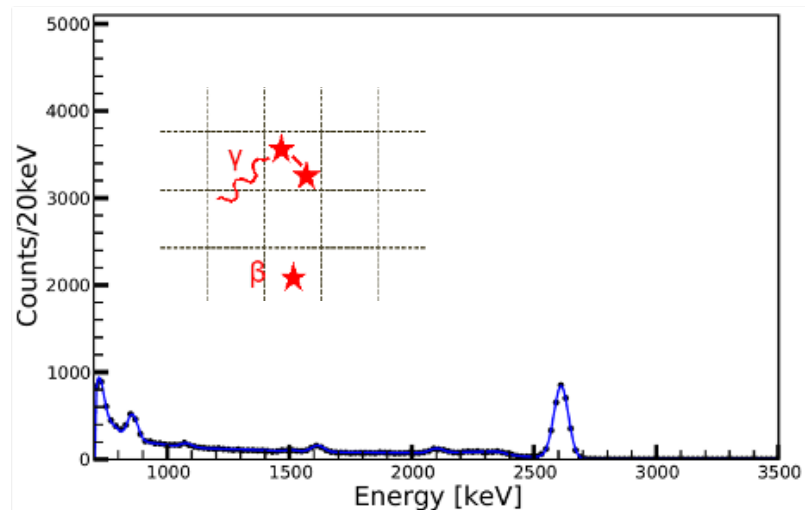
Using event multiplicity to recognize backgrounds

EXO-200 data

Low background
data



^{228}Th calibration
source

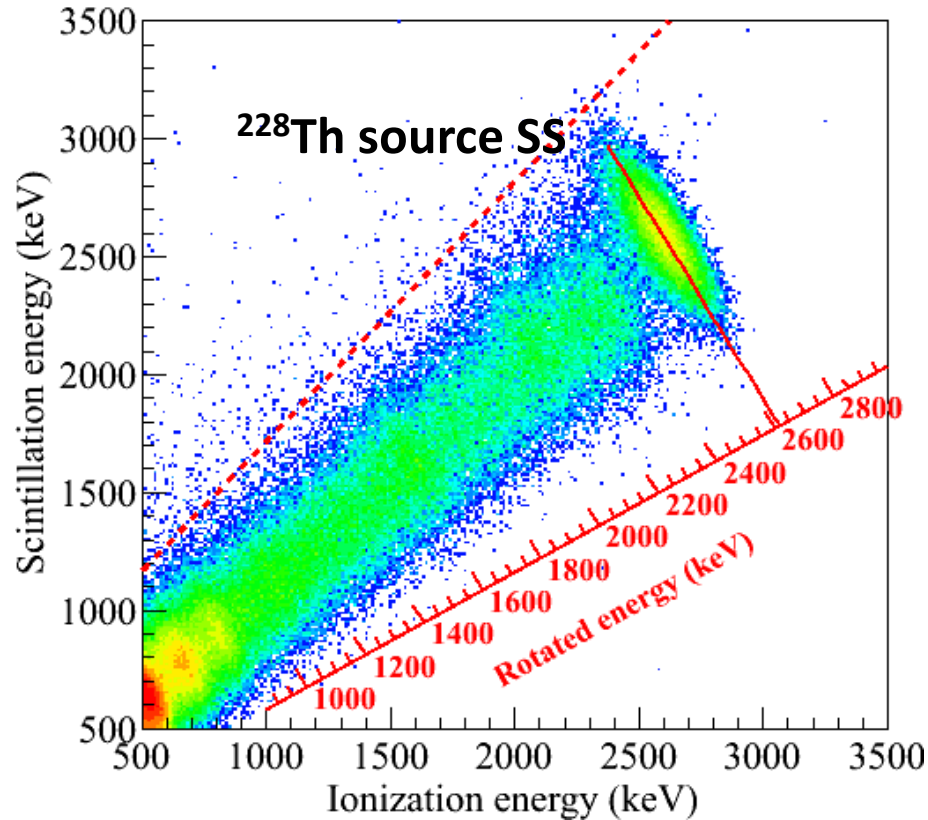


In addition, the scintillation light was found to be anticorrelated with the free ionization, so that combining the two yields the best energy resolution.

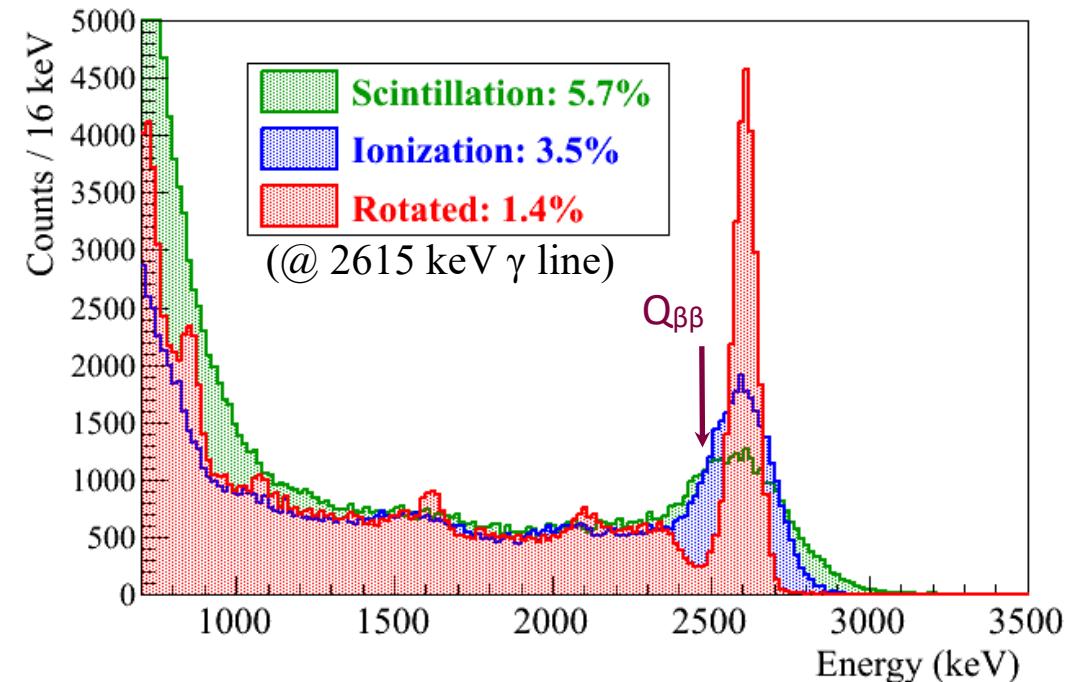
Anticorrelation between scintillation and ionization in LXe known since early EXO R&D

E.Conti et al. Phys Rev B 68 (2003) 054201

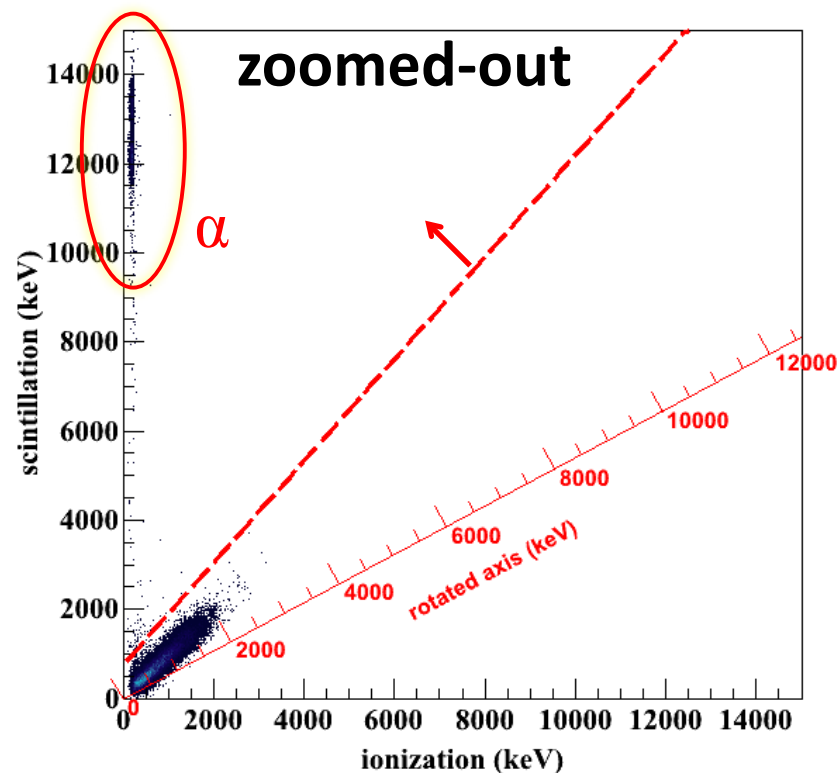
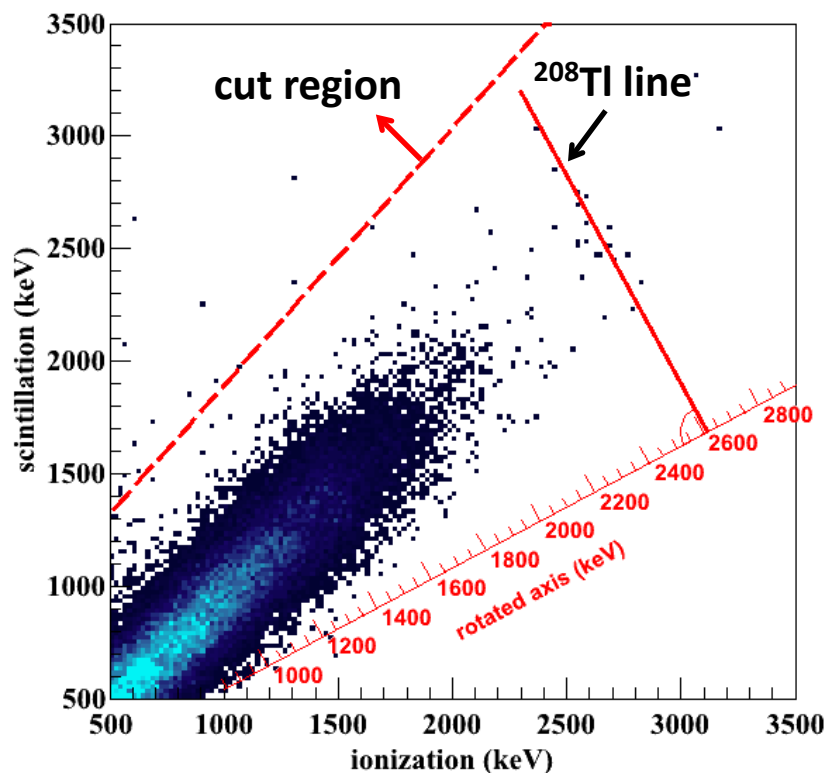
By now this is a common technique in LXe



Rotation angle chosen to optimize energy resolution near $Q_{\beta\beta} = 2457.83$ keV



The relative strength of free ionization vs scintillation is also very powerful in discriminating against α or events at the edge of the TPC.



Events removed by diagonal cut:

- α (larger ionization density $\rightarrow$ more recombination $\rightarrow$ more scintillation light)
- events near detector edge $\rightarrow$ not all charge is collected

Radioactivity in EXO-200 was successfully predicted before turning on the detector

➔ Massive effort on material radioactive qualification, using:

- NAA
- Low background γ -spectroscopy
- α -counting
- Radon counting
- High performance GD-MS and ICP-MS

The materials database includes >300 entries

D.S. Leonard et al., Nucl. Ins. Meth. A 591 (2008) 490

D.S. Leonard et al., Nucl. Inst. Meth. A 871 (2017) 169

M. Auger et al., J. Inst. 7 (2012) P05010.

The background can then be directly measured in the data:

J.B. Albert et al. Phys. Rev. C 92 (2015) 015503.

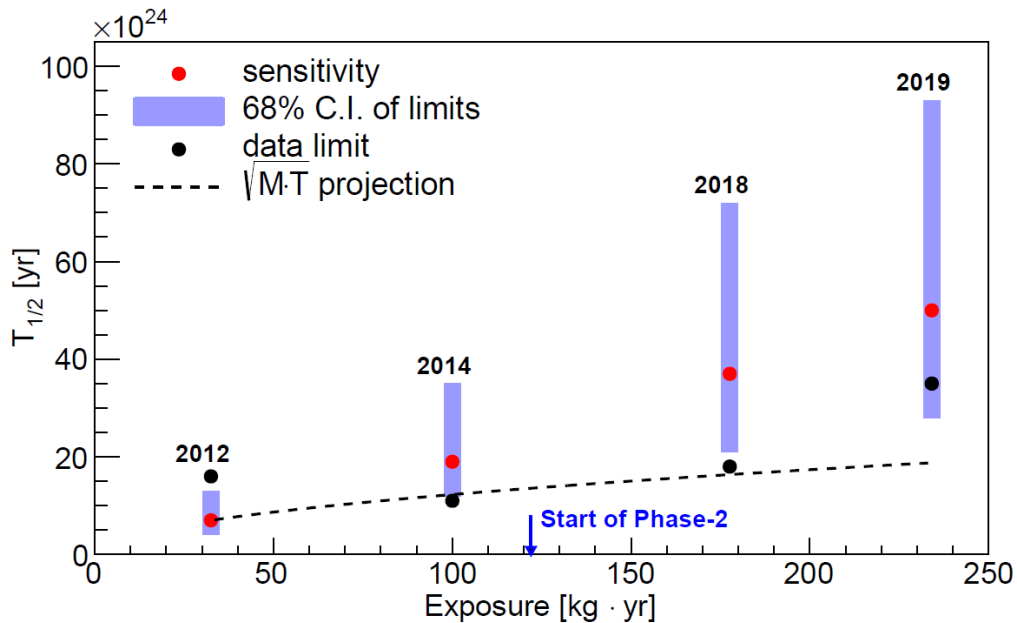
Cosmogenic backgrounds:

J.B. Albert et al., JCAP 04 (2016) 029.

Events in $\pm 2\sigma$ around Q	Radioactive bkgd prediction using certification data and G4 Monte Carlo	^{137}Xe bkgd	Background from 0v analysis fit
90%CL Upper	56	18	63.2 ± 4.7 (65 events observed)
90%CL Lower	8.2		

Also in EXO-200 the sensitivity grew linearly with exposure

- First 100 kg-class experiment to take data.
- Excellent background, very well predicted by the massive material characterization program (and the simulation). *This is essential for nEXO design.*
- Sensitivity increased linearly with exposure.
- More papers on non- $\beta\beta$ decay physics.



2012: *Phys.Rev.Lett.* 109 (2012) 032505

2014: *Nature* 510 (2014) 229-234

2018: *Phys. Rev. Lett.* 120, 072701 (2018)

2019: *Phys. Rev. Lett.* 123 (2019) 161802

Final result

Phase I+II: 234.1 kg yr of ^{136}Xe exposure

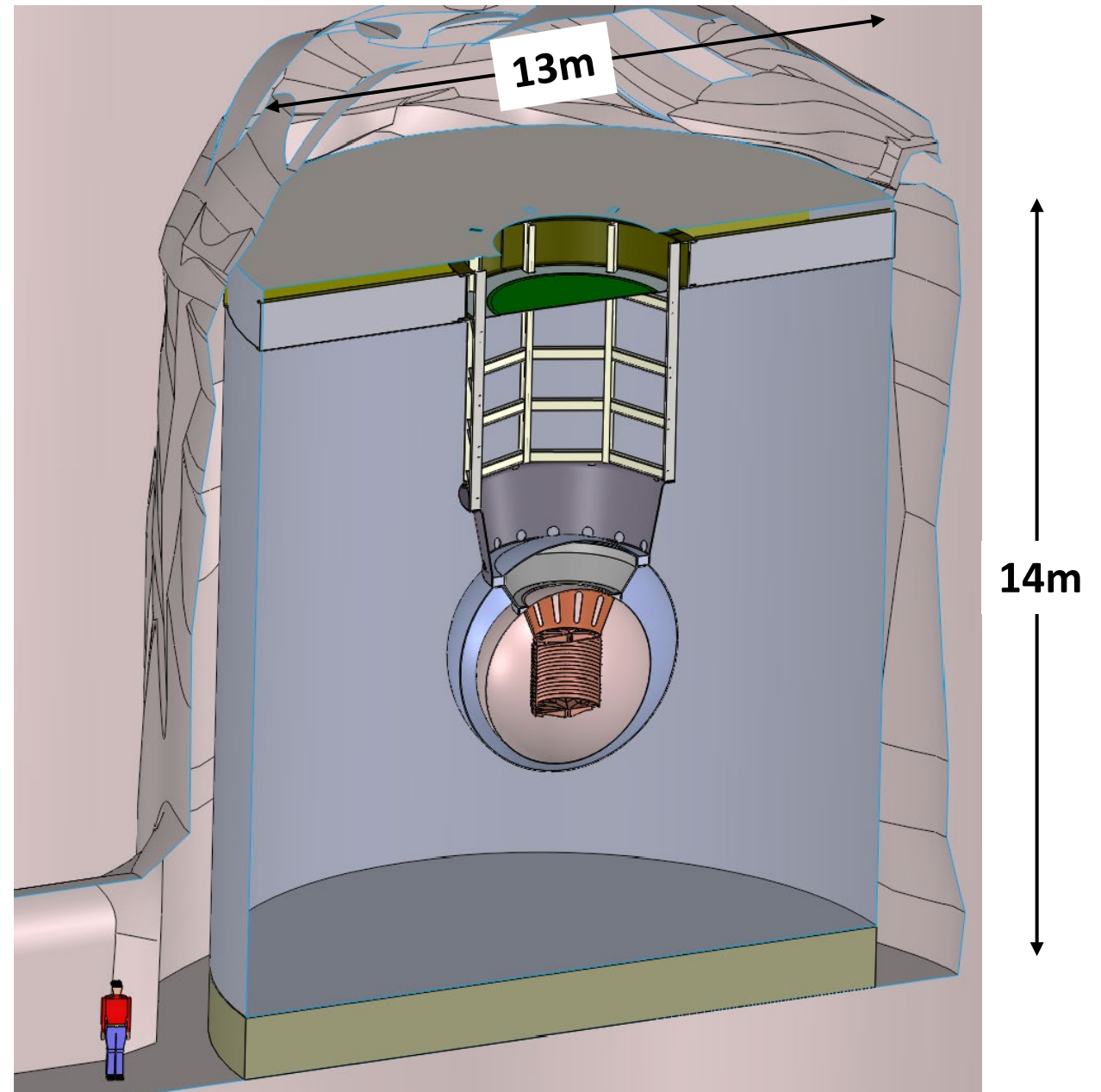
Limit: $T_{1/2}^{0\nu\beta\beta} > 3.5 \times 10^{25}$ yr (90% CL)

$\langle m_{\beta\beta} \rangle < (93 - 286)$ meV

Sensitivity: 5.0×10^{25} yr

nEXO

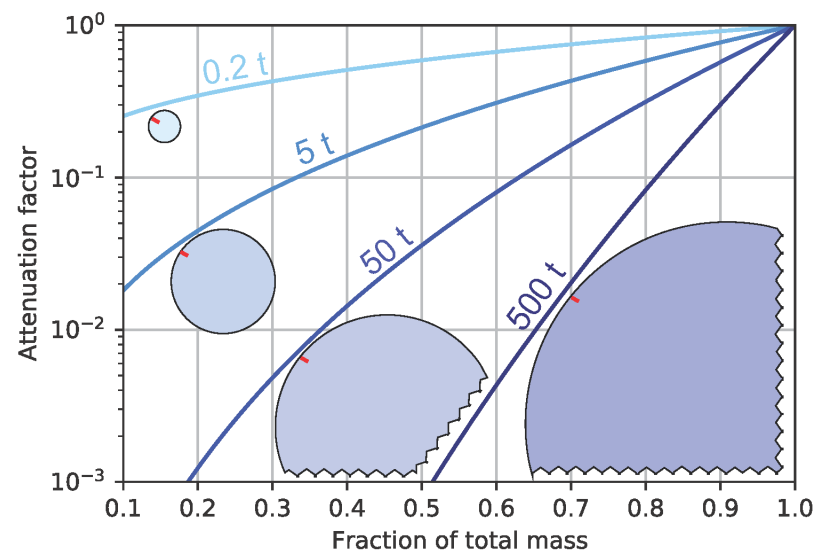
*A 5000 kg enriched LXe TPC,
directly extrapolated from EXO-200*



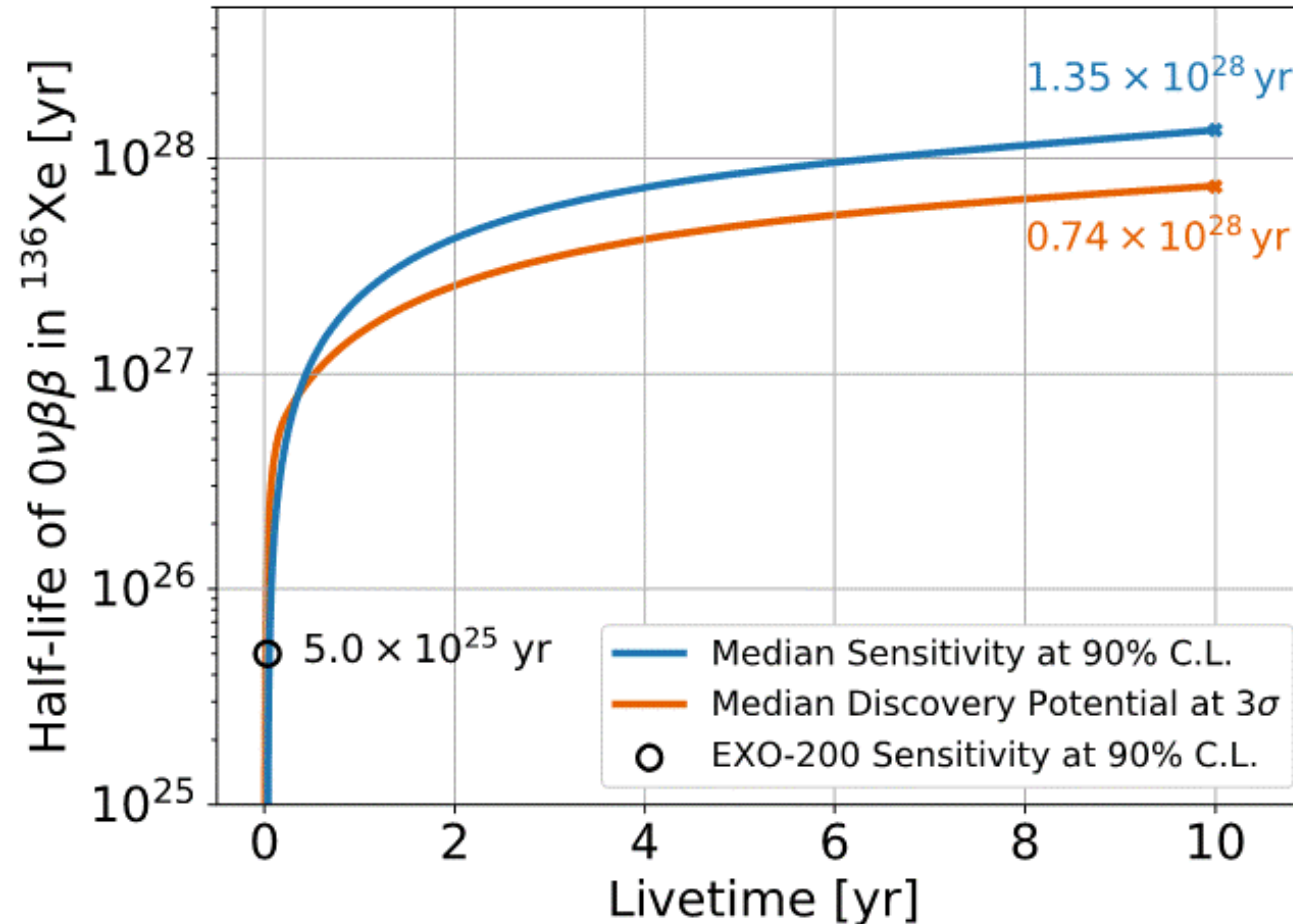
Other Unique Features of nEXO:

- LXe reduces risk, as the purification system can be upgraded if unexpected backgrounds are discovered and/or if new technology becomes available.
- nEXO can make a discovery by itself, by repeating the experiment with non-enriched Xenon to confirm that a signal goes away
- If nEXO discovers $0\nu\beta\beta$ decay: The enriched xenon is NOT “frozen” in a particular detector. Should $0\nu\beta\beta$ decay be discovered by nEXO, the xenon could be re-used in a different experimental configuration to investigate the underlying physics.
This is particularly important at the tonne scale, given the cost of the material.

- If nEXO does not discover $0\nu\beta\beta$ decay: The advantages of the homogeneous detector keep improving with size. Should $0\nu\beta\beta$ decay not be discovered by nEXO, larger detectors using the same technology are possible (A.Avasthi et al, Phys. Rev. D 104, 112007 (2021))
The technology needs to be developed with an eye to the future.



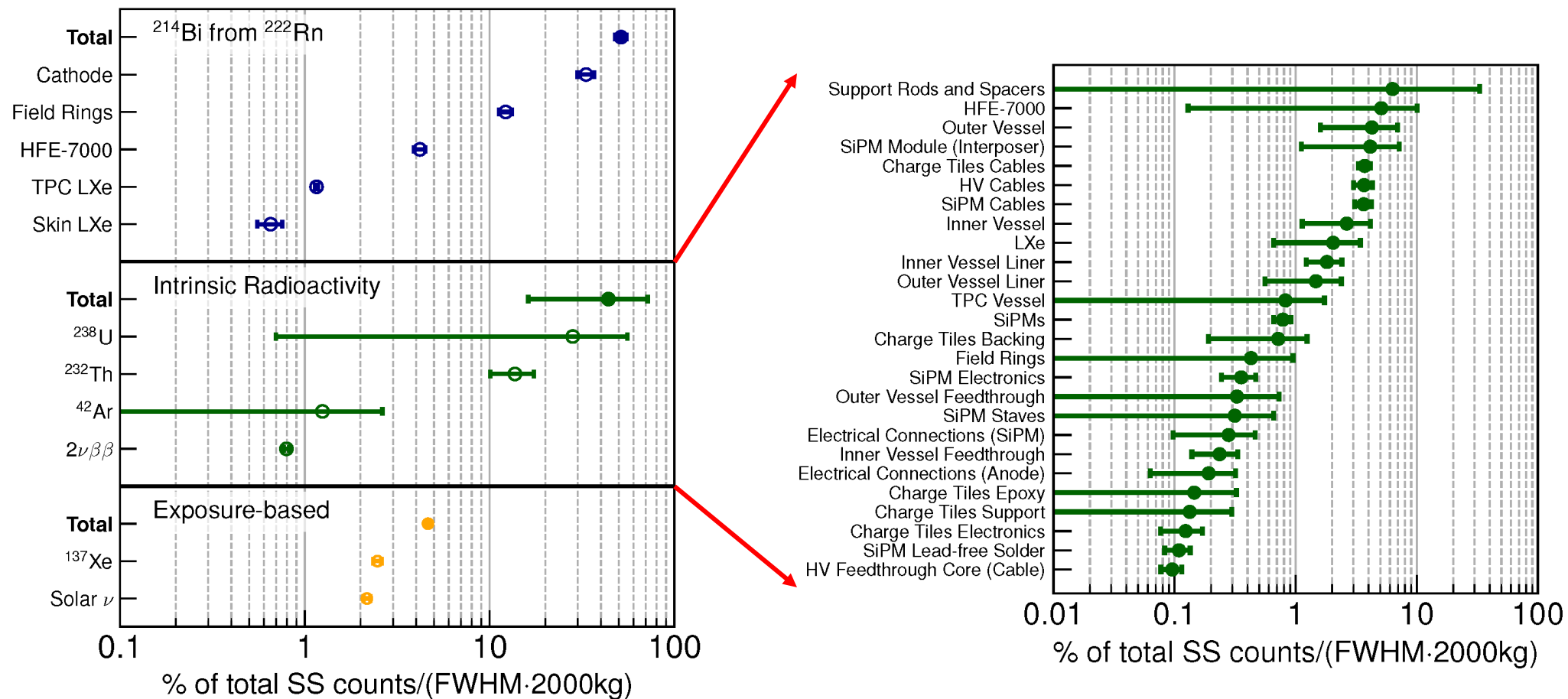
nEXO: In the land of large, scalable double-beta decay experiments



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

nEXO optimization

No detector component dominates the background.



What about ^{136}Xe in gas phase?

This was pioneered by the Gotthard experiment, using 5 kg of enriched Xe in a 5-bar gas TPC

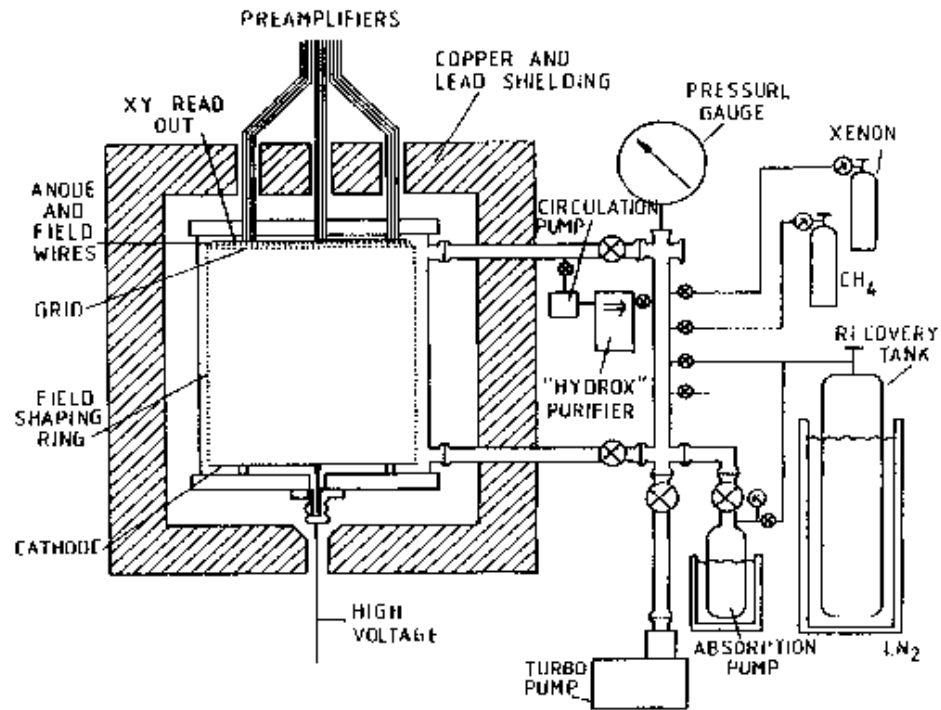
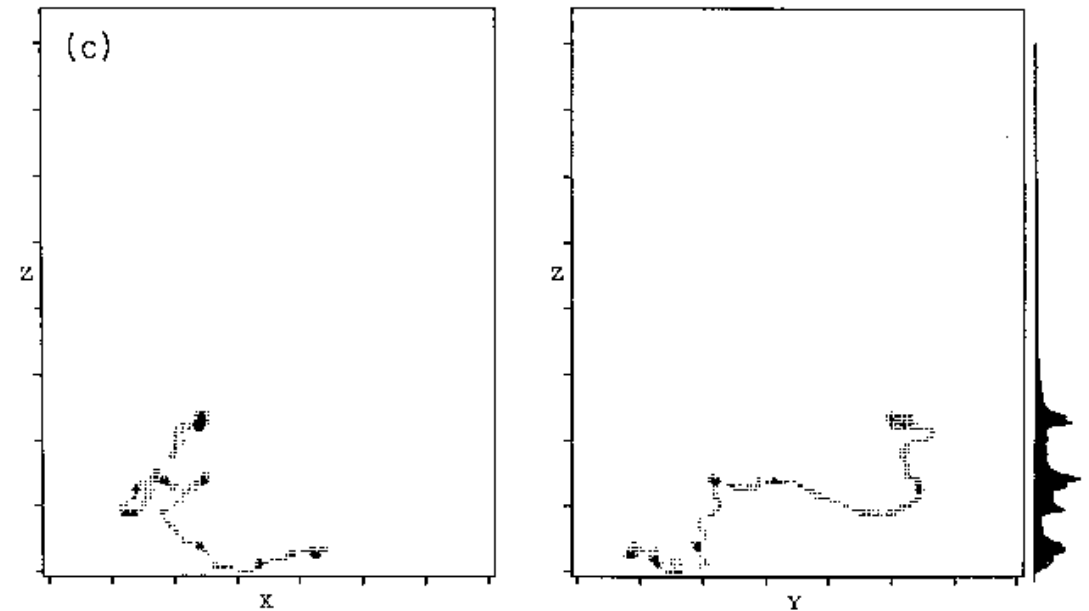
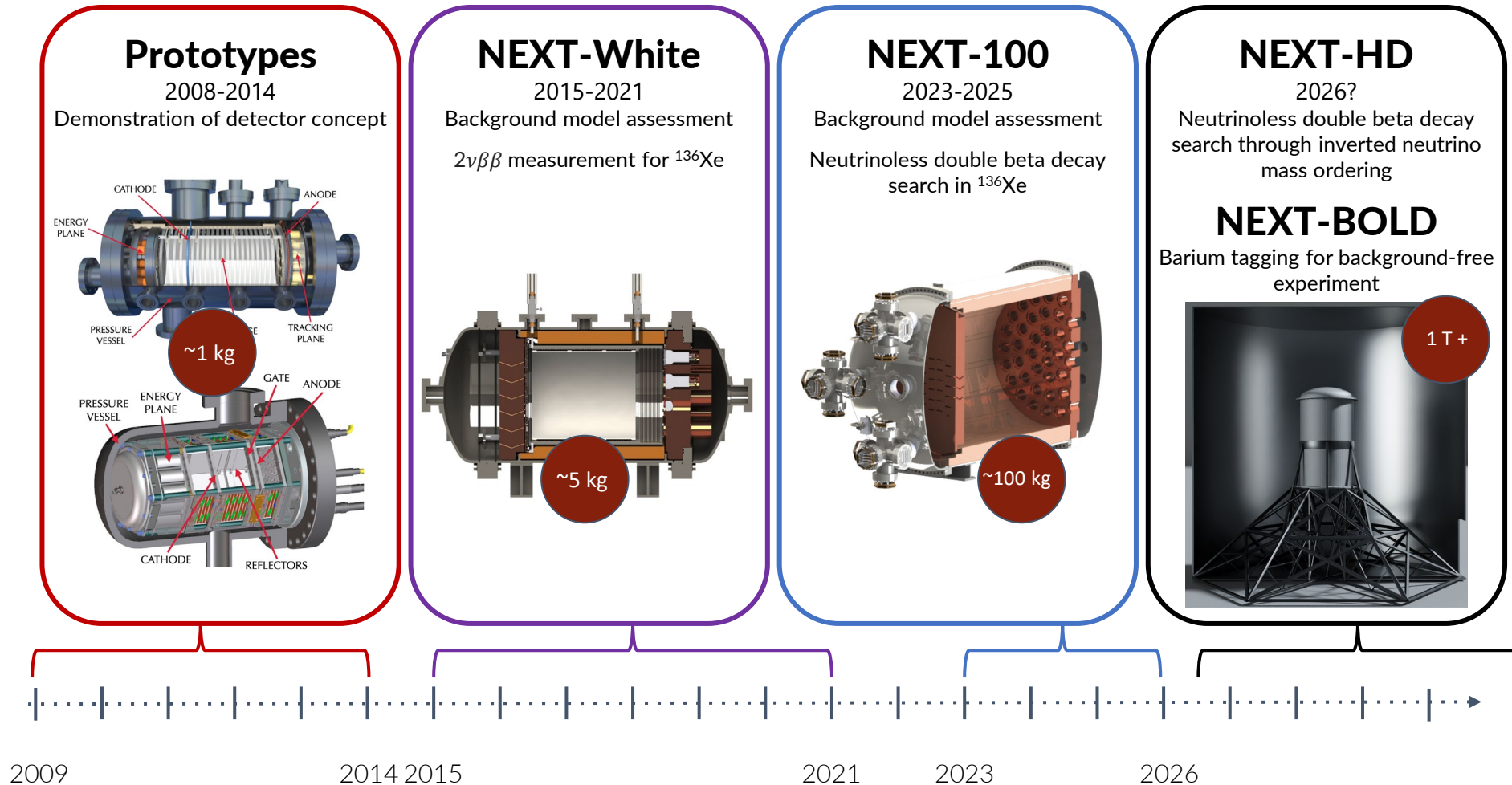


FIG. 2. Schematic diagram of the time projection chamber with the associated setup.



J-L. Vuilleumier et al., Phys Rev D 48 (1993) 1009

In recent times, this was continued, with modern techniques by 



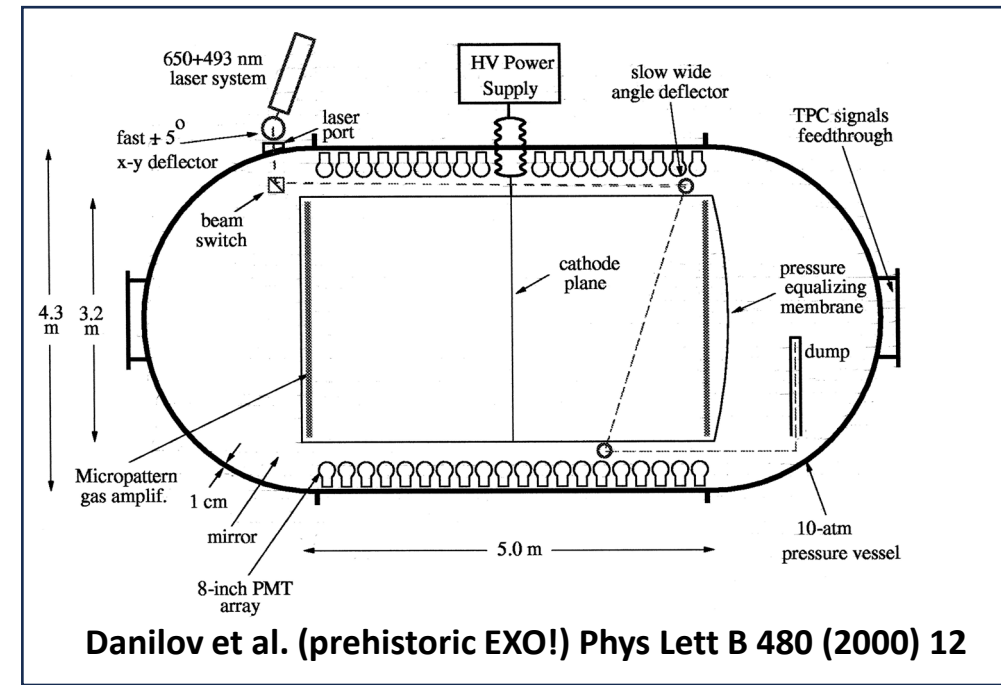
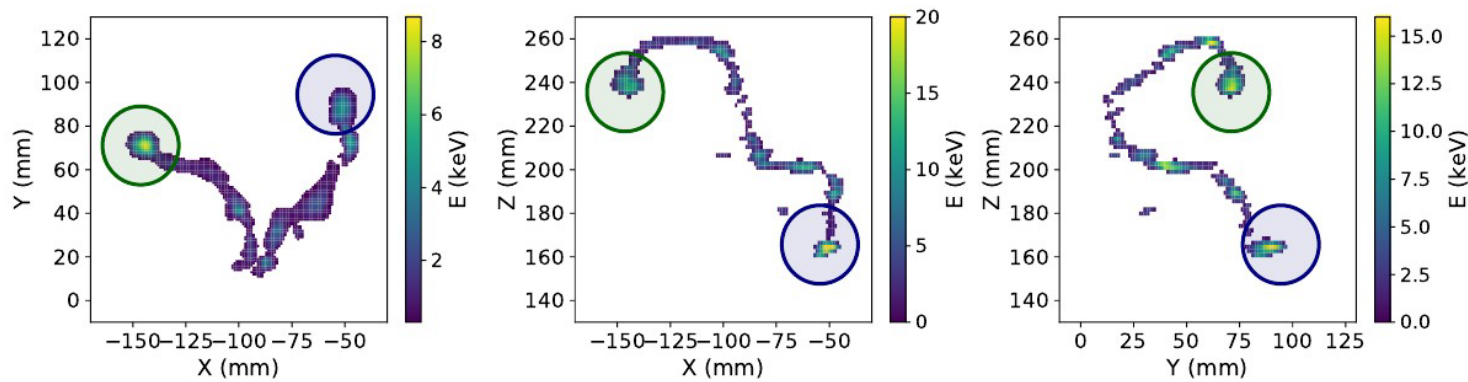
Typical tradeoffs between liquid and gas phase

GXe - Better energy resolution

- Track reconstruction (depends on pressure)

LXe - Substantially smaller detector

- No high pressure



← Typical $0\nu\beta\beta$ decay candidate at 2.45 MeV in NeXT
arXiv:2305.09435, submitted to JHEP

To a large extent, these are the same issues making NEMO-type detectors not competitive at the current discovery frontier.

*However, the very detailed reconstruction will become handy once the decay is discovered.
And at that point we will know how large is large enough and for what pressure to design for.*

And now... a very different detector optimization:

- **Not very specific**
- **Very large, cheap and self shielding**

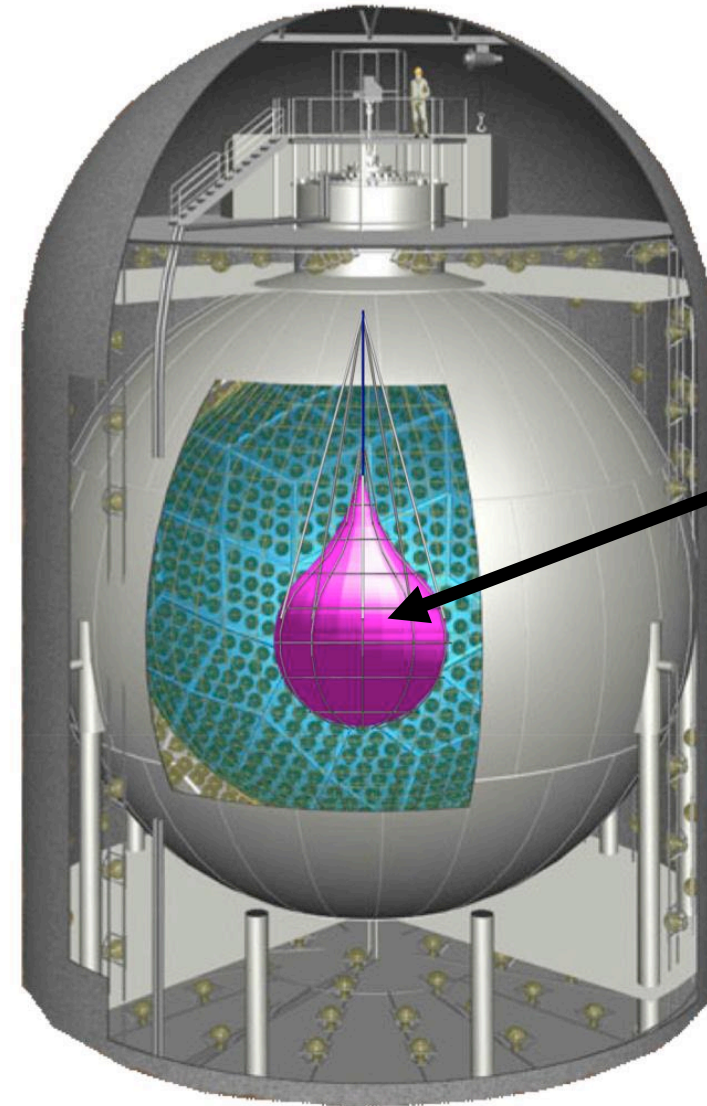
Enter scintillation detectors.

***Of course, those have a glorious history of discovery:
e.g. Borexino, KamLAND***

KamLAND-Zen

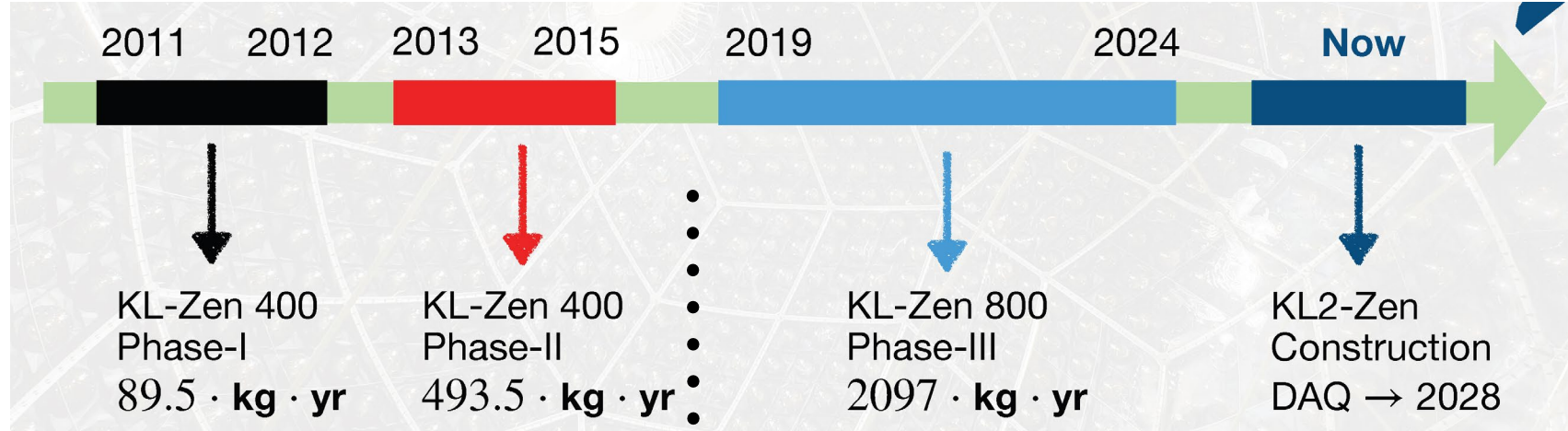
- + Well-understood detector
- + Highly pure, self-shielding environment
- + Large $\beta\beta$ source mass, scalable
- Relatively poor energy resolution
- No particle identification

- 1 kton Scintillation Detector
- 6.5m radius balloon filled with:
 - 20% Pseudocumene
 - 80% Dodecane (oil)
 - PPO
- 34% PMT coverage
- ~1300 17" fast PMTs
- ~ 550 20" large PMTs
- $\sigma/E \sim 4\%$ at $\sim 2.4\text{MeV}$
- Water Cherenkov veto
- Operational since 2002
- "Mini-balloon" containing doped scintillator



745 kg of ^{136}Xe
dissolved in Liquid
Scintillator

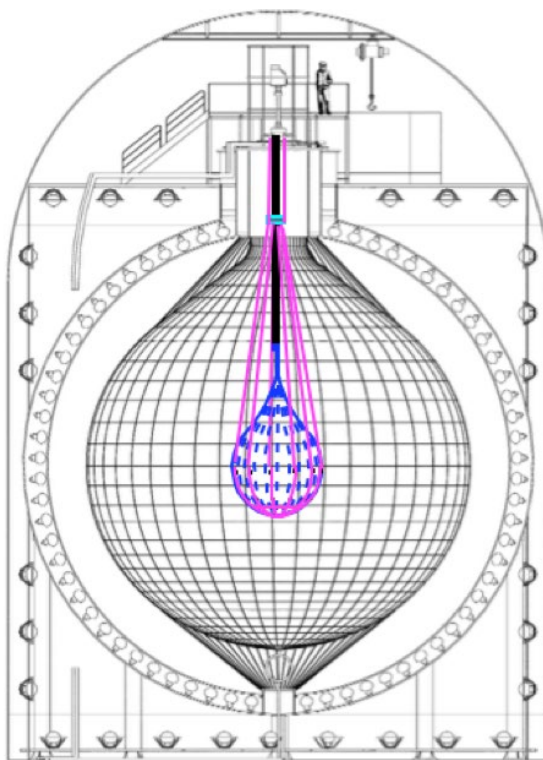
KamLAND-Zen



KamLAND-Zen 400

- Mini-balloon radius 1.54m
- 320 - 380kg ^{136}Xe
- 2011 - 2015

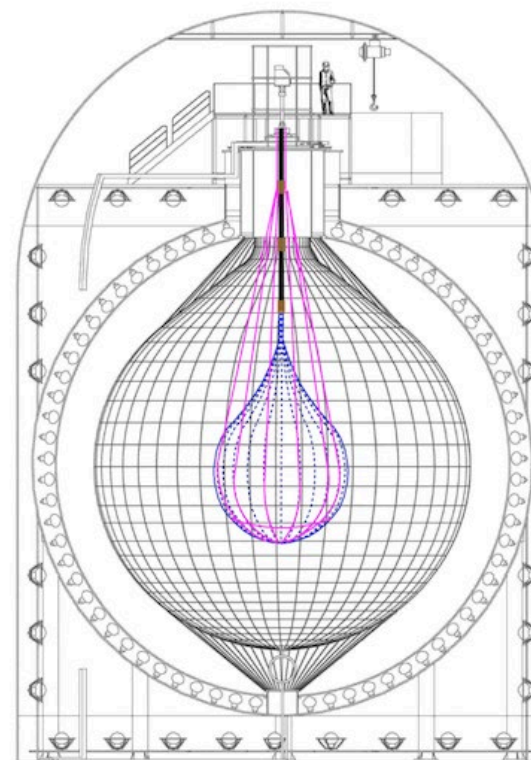
$$T_{1/2}^{0\nu} > 1.07 \times 10^{26} \text{ yr}$$



KamLAND-Zen Coll, Phys. Rev. Lett. 117, 082503 (2016); arXiv:1605.02889

KamLAND-Zen 800

- Mini-balloon radius 1.90m
- 745kg Xe (90% ^{136}Xe)
- Start Jan 2, 2019
- Dataset:
Feb, 2019 - May 8, 2021



KamLAND-Zen Coll, Phys. Rev. Lett. 130, 051801 (2023), arXiv:2203.02139

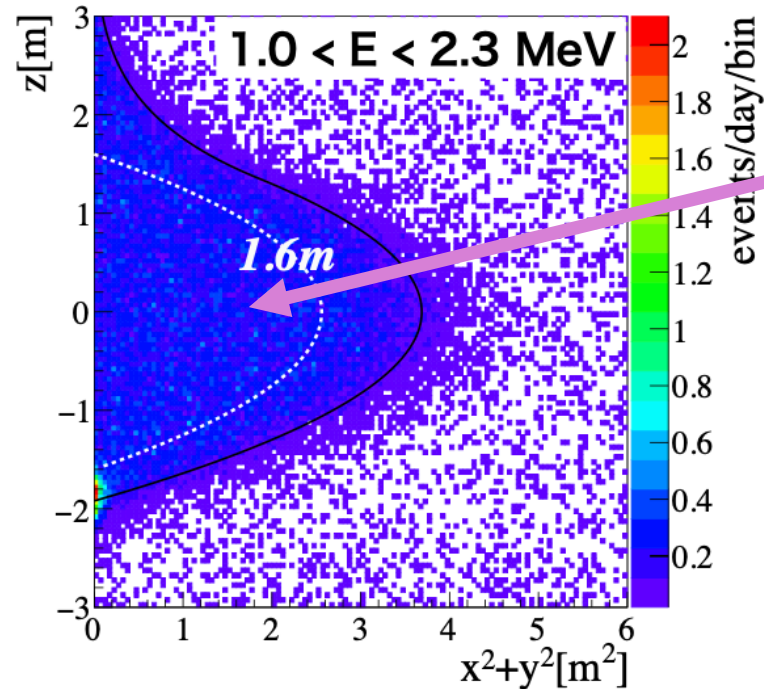
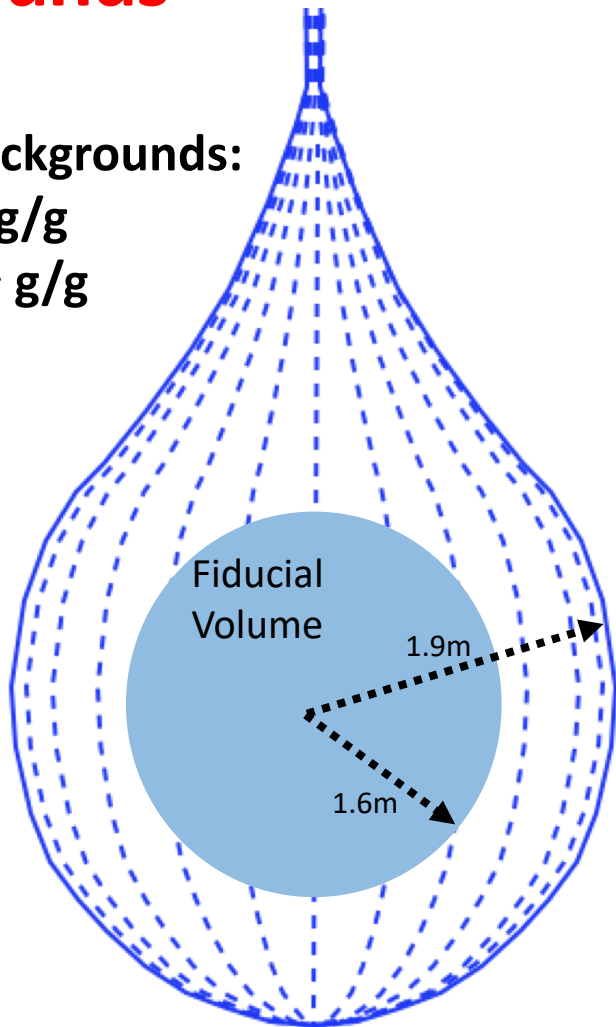
KLZ 800 Mini-Ballon Backgrounds

Balloon film backgrounds:

$$^{238}\text{U} \sim 3 \times 10^{-12} \text{ g/g}$$

$$^{232}\text{Th} \sim 4 \times 10^{-11} \text{ g/g}$$

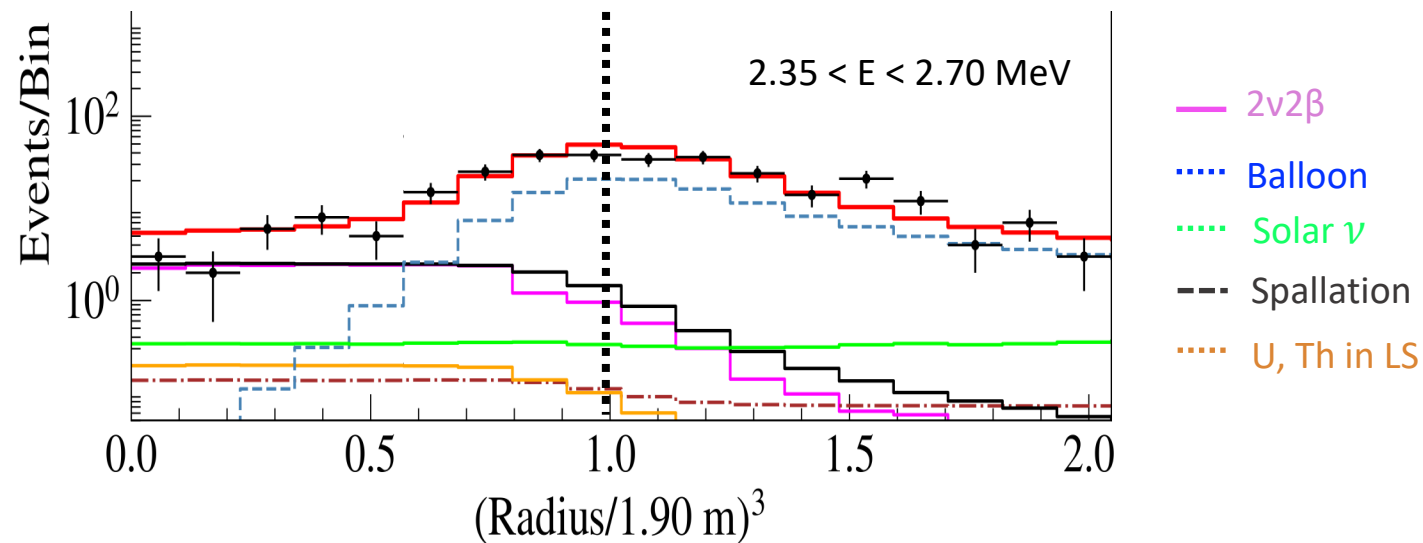
10x reduction
compared to
KLZ 400



Xe-LS backgrounds:

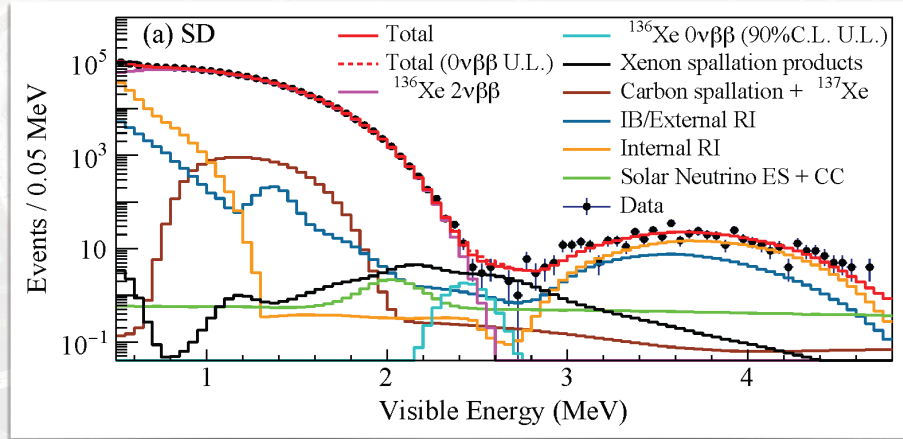
$$^{238}\text{U} \sim 1.5 \pm 0.4 \times 10^{-17} \text{ g/g}$$

$$^{232}\text{Th} \sim 3.0 \pm 0.4 \times 10^{-16} \text{ g/g}$$

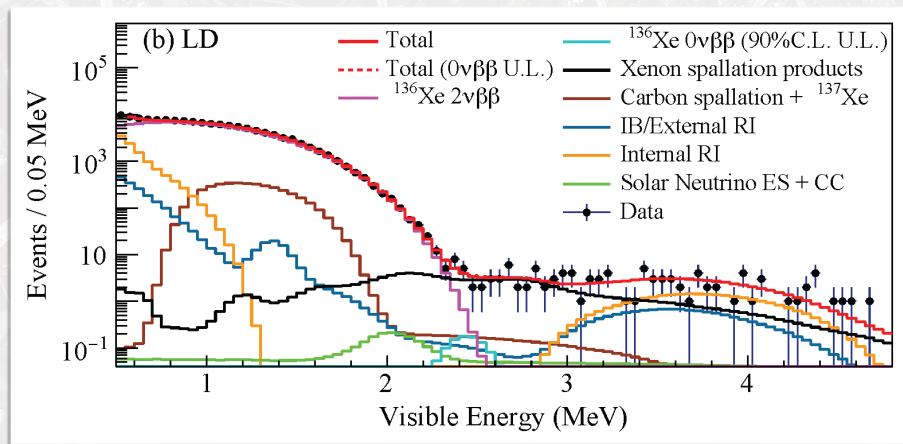


Spectral Analysis

Singles Data (SD) $E \sim 90\% \sim 1131$ days



Long-Lived Data (LD) $E \sim 10\% \sim 111$ days



SD = Untagged/ Singles Data $\rightarrow 90\%$ Exposure
LD = Long-Lived TaggedData with isotope $\tau \geq 100$ sec

Analysis Range

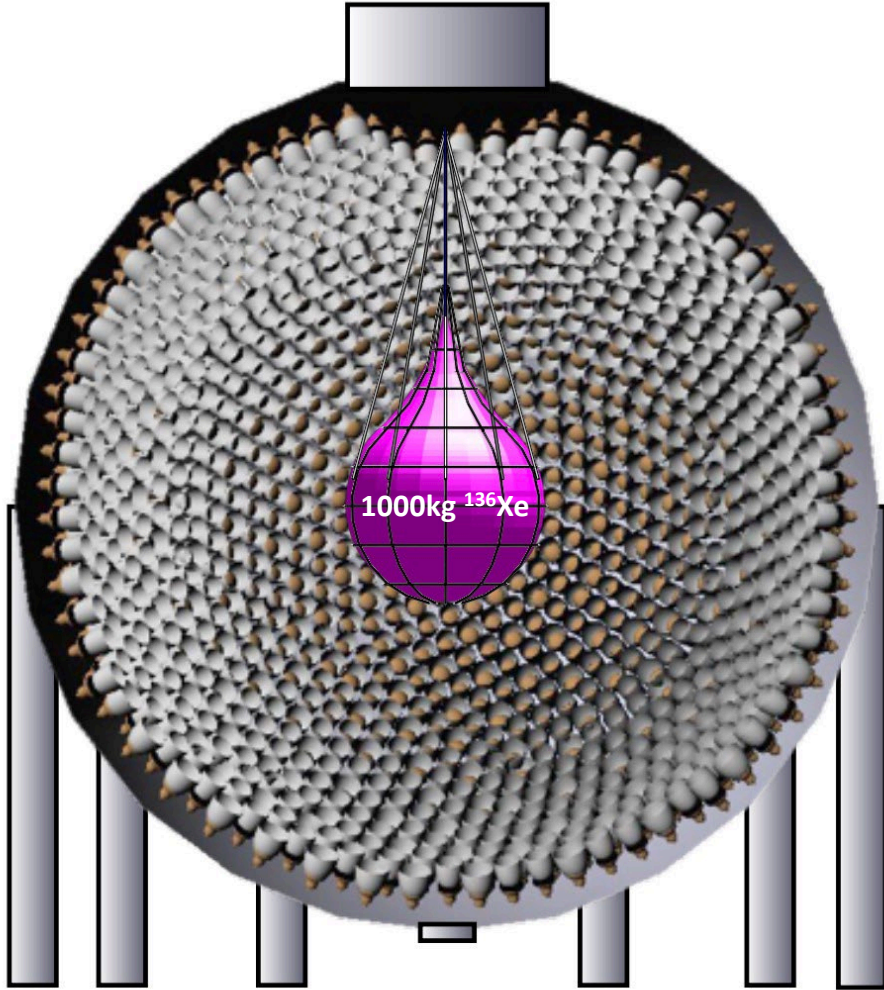
$[0.5, 4.8]$ MeV for $R < 250$ cm
Exposure = $2.1 \cdot \text{ton} \cdot \text{year}$ of ^{136}Xe
Plots show $R < 157$ cm

$T_{1/2}^{0\nu\beta\beta} > 3.8 \times 10^{26}$ years
(Combined KLZ-400 + 800 based on **Wilks**)

We also performed **Feldman-Cousins** and
Bayesian Calculations $\rightarrow$ consistent

Phys. Rev. Lett. **135** (2025) 262501

KamLAND2-Zen



- Improved photon yield & energy resolution:
 - Winston Cones (x1.8)
 - New LS (x1.4)
 - High-QE PMTs (x1.9) $\sigma/E: 4\% \rightarrow 2\%$ (x100 reduction in $2\nu\beta\beta$ background rate)
- State-of-the-art electronics:
 - Improve BG suppression, better tag long-lived spallation
- Improved inner balloon: scintillating balloon:
 - Reduce BG originating from balloon

Design sensitivity of $T_{1/2} > 2 \times 10^{27}$ yrs

Liquid scintillation detectors are “photon starved” and generally optimized to detect as many of the emitted photons as possible. Conventional wisdom has it that this makes imaging impossible.

Q: Is conventional wisdom correct?

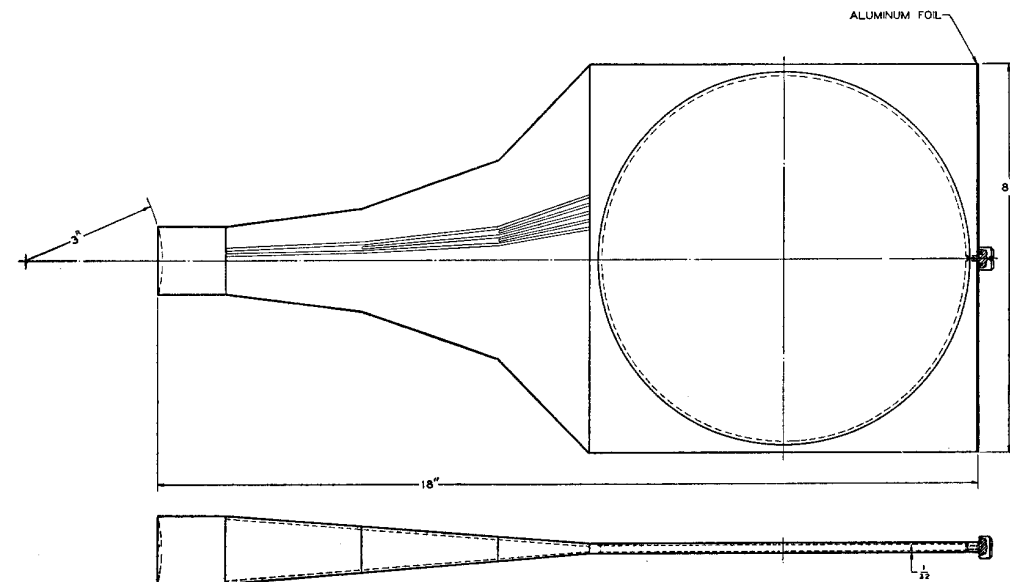
It is a frustration of mine that we are still using ~the same organic scintillators developed in the 1920's, readout by vacuum tubes also developed in the 1920's. Somehow our field has not been reached by modern advances in material science.

So, it is fitting to cite a couple of old papers:



R. L. Garwin "The Design of Liquid Scintillation Cells"
Rev Sci Inst 23, 755 (1952)

R. L. Garwin "The Collection of Light from Scintillation
Counters" Rev Sci Inst 31, 1010 (1960)



These papers, basically, mark the beginning of "adiabatic lightguides" and can be summarized by saying that "evil M. Liouville" is at the origin of lots of trouble.



Applied to large scintillation detectors, this principle puts serious constraints on the possibility of imaging tracks. This is because there are very few photons produced by a scintillator* and these photons are produced with an emittance

$$\eta = V \times 4\pi$$

where V is the entire volume of the detector and 4π is the full solid angle.

** This is not to say scintillators are “stupid”. Typical energetic efficiencies are in the neighborhood of 10%, which is only one order of magnitude different from 100% and this explains why it is so hard to make better scintillators!*

Waiiit a minute,

Q: Isn't the scintillation source ~point-like?

Waiiit another minute,

Q: what about Δt in the emittance?

Applied to large scintillation detectors, this principle puts serious constraints on the possibility of imaging tracks. This is because there are very few photons produced by a scintillator* and these photons are produced with an emittance

$$\eta = V \times 4\pi$$

where V is the entire volume of the detector and 4π is the full solid angle.

Quibbles and notes:

- 1) Strictly speaking this is not true, for a point-like source $\eta = 4\pi$, because V is small, but, unfortunately, we do not know where the event is in the detector, so, in practice the emittance contains the entire volume of the detector.
- 2) The emittance also contains Δt and ΔE , or equivalent. For photons one has really only access to Δt . Indeed Δt can be traded for other variables. An infinitely reflective sphere can extract all photons out of a tiny hole by waiting an arbitrarily long time. In practice infinitely reflective things do not exist and I am not sure it is wise to give up timing, so I will ignore this possibility.

** This is not to say scintillators are “stupid”. Typical energetic efficiencies are in the neighborhood of 10%, which is only one order of magnitude different from 100% and this explains why it is so hard to make better scintillators!*

Hence imaging in a scintillator with a (a few) camera(s) with finite size lenses is a non-starter:

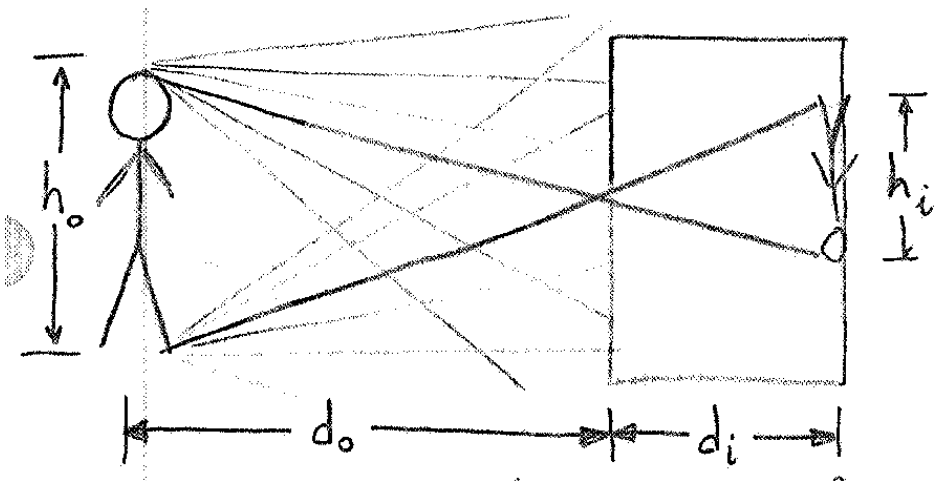
- A conventional lens arrangement selects few photons to produce images
- The smaller the aperture the more depth of field and, because of the huge emittance, we need a pinhole!

Not enough photons!

This is irrespective of the sensitivity/gain/whatever of the camera.

Can one be more clever?

Two extreme cases of “imaging”



Pinhole camera:

Pro: image infinitely sharp

Con: infinitely inefficient

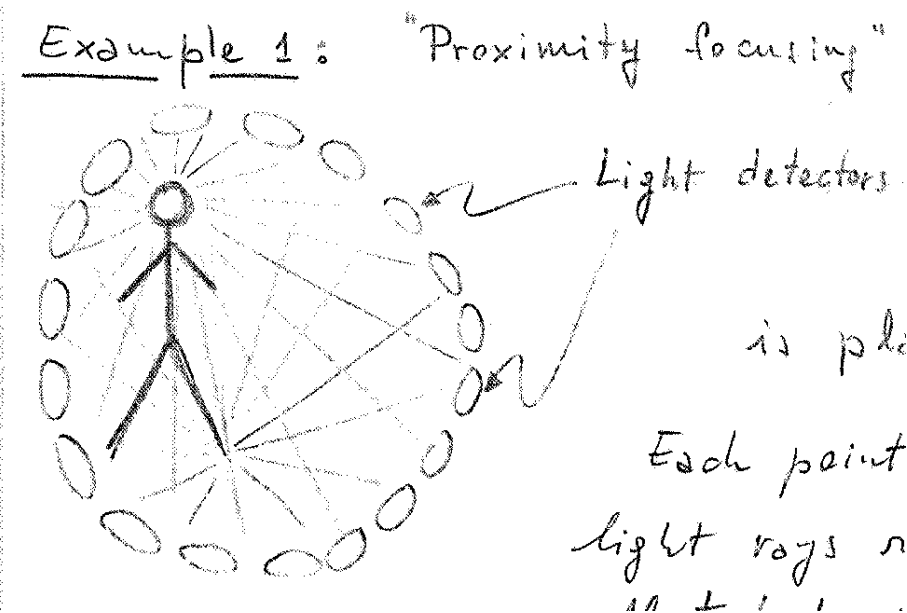
Large liquid scintillation detector:

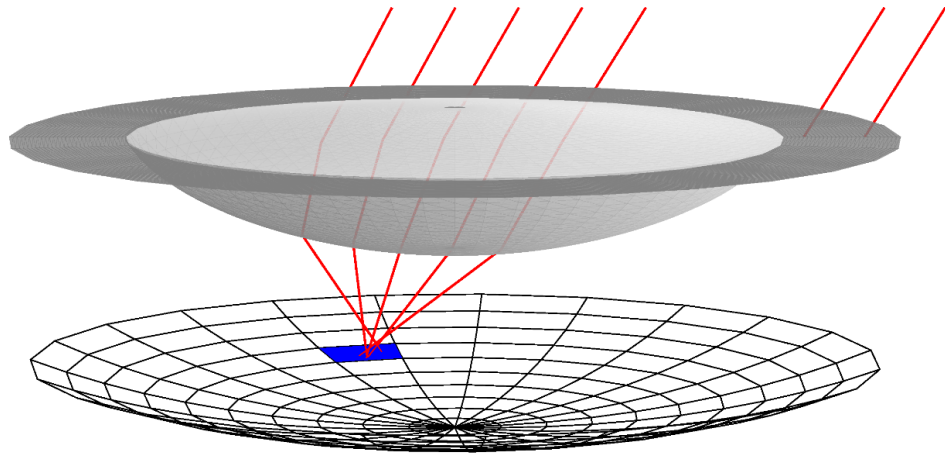
Pro: collect every single photon

Con: no imaging

However, note that the rays hitting a particular PMT here do contain angular information.

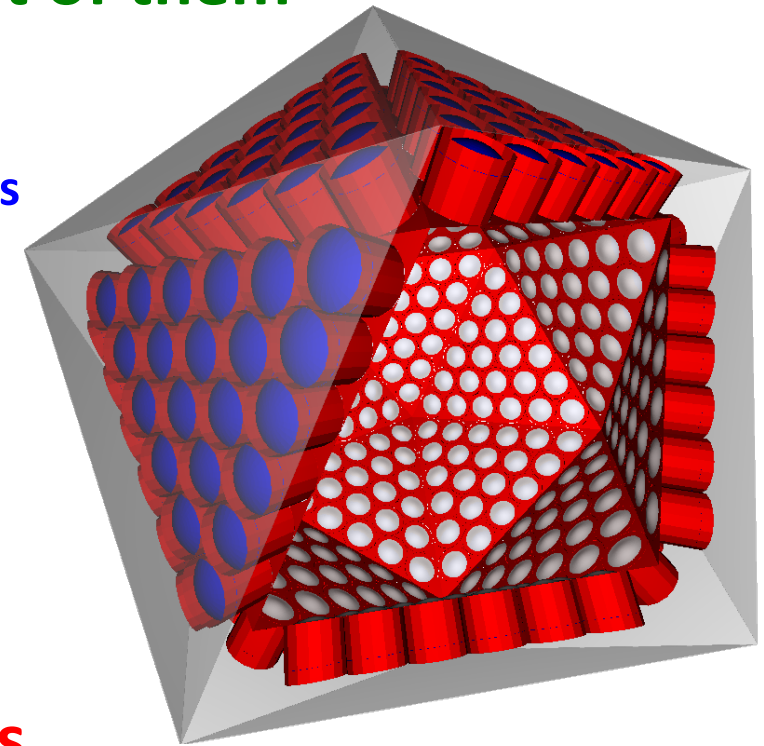
...if we only knew how to record it!





Use a similar principle:

- further pixelate large photodetectors (think of the KamLAND PMTs pixelated)
- use lenses in front of them



Topological reconstruction then proceeds as tracking in a TPC: Each photon has

- a position of impact -- on the “optical module”, with uncertainty related to its diameter
- a direction of origin -- related to the quality of the lens and the size of the pixels

*Warning: don't get confused, in this “mode” depth of focus means nothing.
All lenses are focused to infinity!*

Note that no lens “owns” an image, not enough photons.

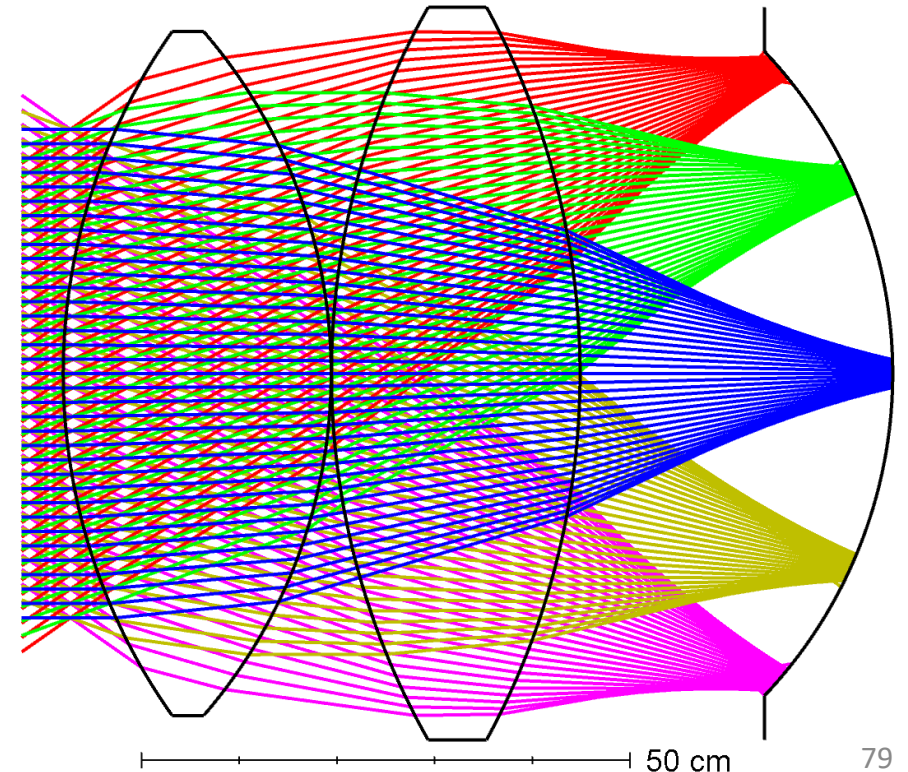
This is an important difference with respect to plenoptic cameras.

Here only putting together many lenses results in imaging.

Lens design is non-trivial

- Want a realistic system, in particular has to work in scintillator with $n_{\text{scint}} = 1.5$
- Require a very large NA (this is a very non-paraxial system, so forget most of what they taught you in school!)
- The focal surface is a spherical segment (simplifies the lens system)
- At least chromatic aberrations are not an issue (since scintillation light is ~monochromatic)
- Turns out that a single asphere is not necessarily the best solution, because “good practice” is to limit large changes of refractive at single surfaces
- From a first look air lenses appear less good, but I do not think we have investigated this enough

Parameter	Value
Number of elements	2 (spherical)
$\text{NA}_{\text{MAX}} (=n_{\text{scint}} \sin[\text{atan}(R_{\text{pupil}}/f_{\text{eff}})])$	0.64
Field of view	$\pm 40^\circ$
$R_{\text{lens}}/R_{\text{focal_surface}}$	1
Angular resolution	4°
n_{lens} (glass: S-NPH2, Ohara)	1.98



How to optimize a detector

Set the total number of pixels

→ our choice is 10^5

This sets the ~cost of the detector

*(for 2000 KamLAND-style PMTs would mean
~8x8 pixels in the place of one 20-inch PMT)*

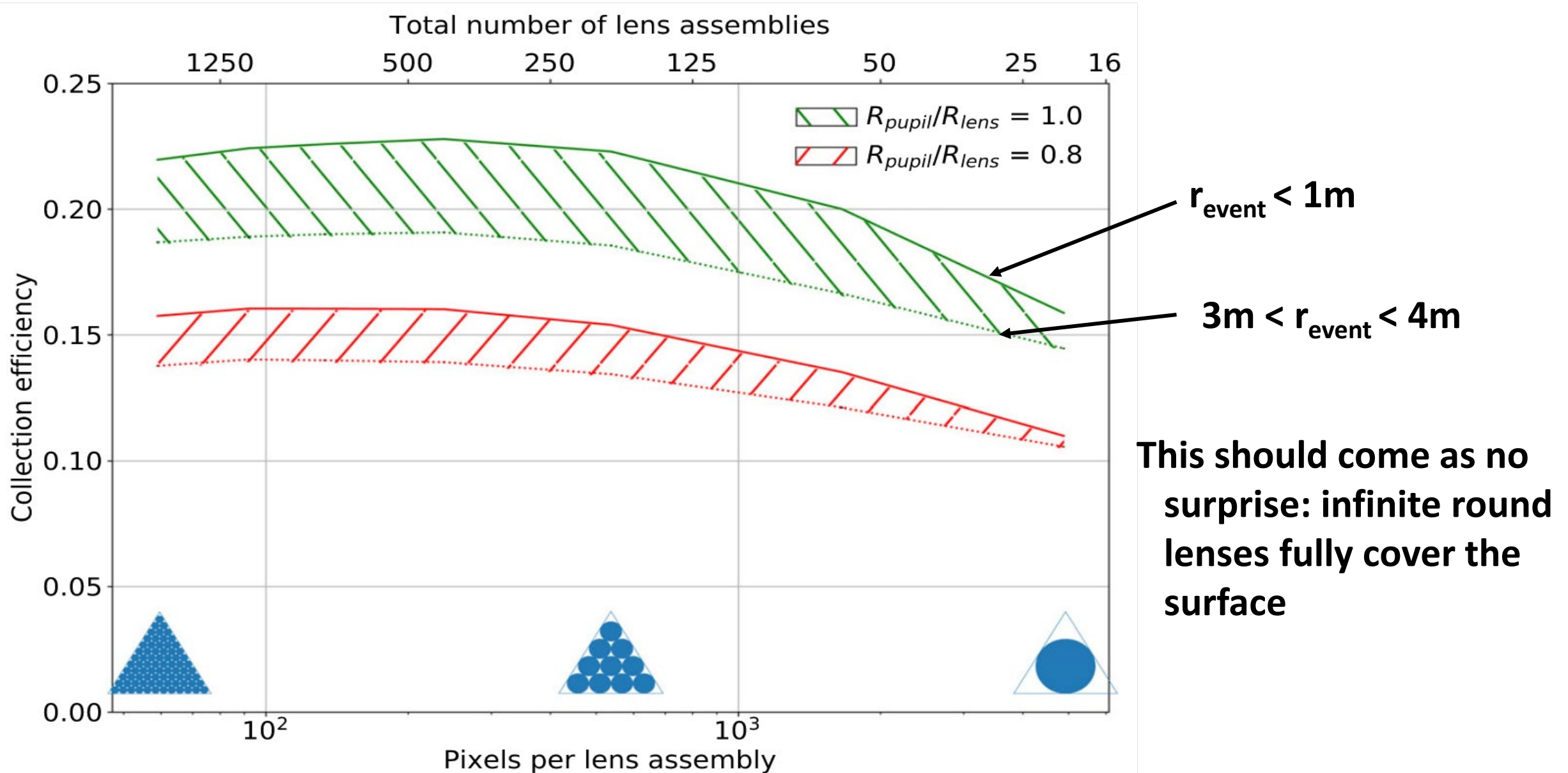
Change the size of the lenses, hence changing the number of pixels/lens and find the best performance, given some desired property.

Larger lenses → more pixels/lens → better angular resolution for the direction of the photons → worse position resolution for the origin of the photon track

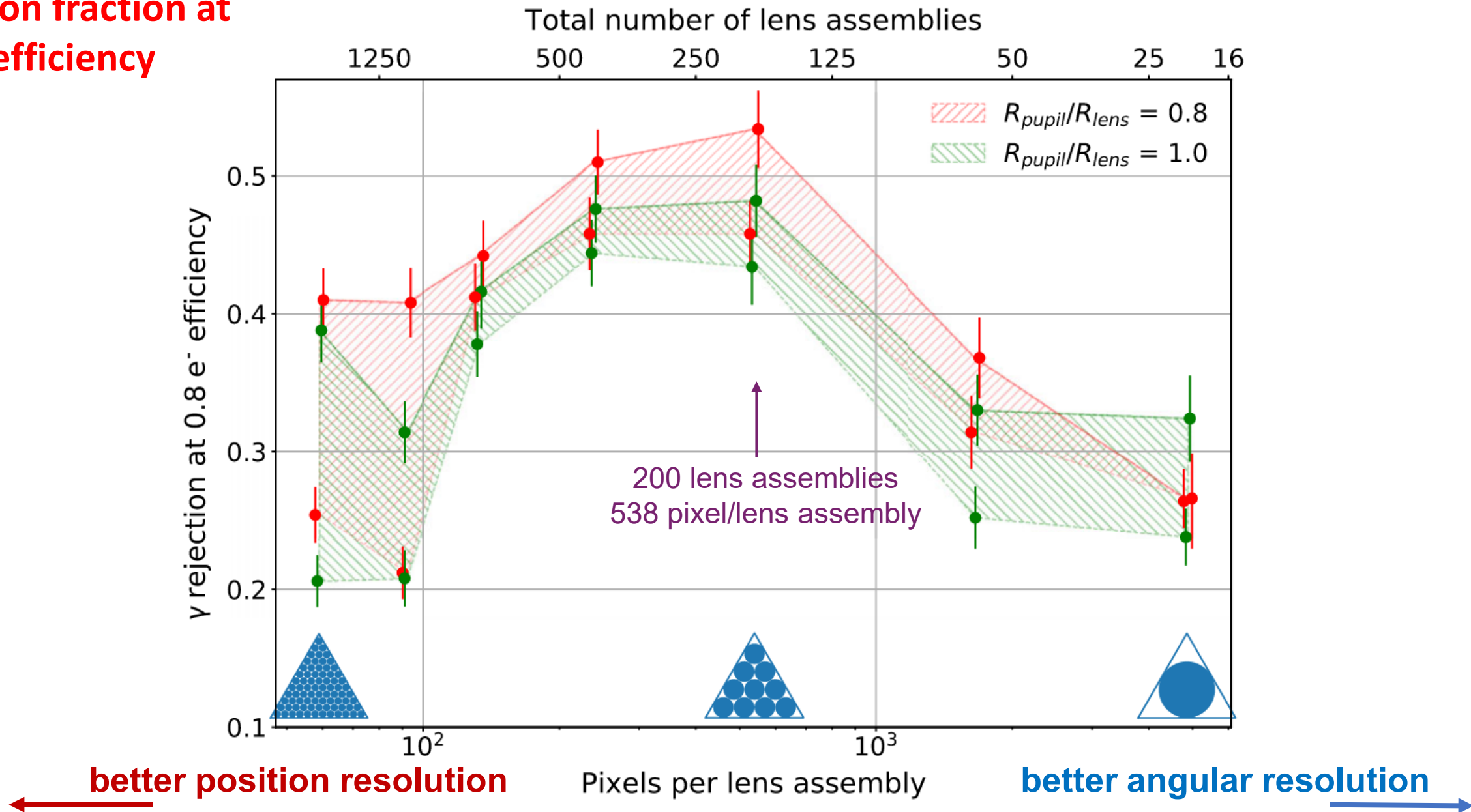
Smaller lenses → fewer pixels/lens → worse angular resolution → better position resolution

Note that lenses scale by similar transformations, so no need to re-design the lens in the optimization process.

Results (2MeV deposited in the scintillator)



**γ rejection fraction at
80% e^- efficiency**



Conclusions

- Neutrinoless double-beta decay is likely to be the only feasible measurement bringing new physics from the neutrino sector in the next decade!
- Such a momentous discovery is by no means assured but certainly would be exciting!
- In the search for neutrinoless double-beta decay, detectors are very integrated with the physics, the choice of isotope, the backgrounds.
“They barely work” –and this is a compliment!
- For these reasons, the “right mix” for a competitive detector changes with time (better, with the number of moles to use and the sensitivity sought).
- At the same time, these things are complex and expensive, so a progression in size is usually a good idea and anyway required by funding agencies.

Acknowledgements: **(it takes a ~~village~~ planet**

- All EXO-200 and nEXO colleagues!
- Gabriel Orebi-Gan who allowed me to use the input she got for Neutrino 2026
by many colleagues from around the world
- Said colleagues from around the world
- Omer Penek, Carmen Romo-Luque, Monica Sisti, from whose Neutrino 2026
talks I shamelessly stole slides.

While the responsibility for omissions and mistakes is only mine.