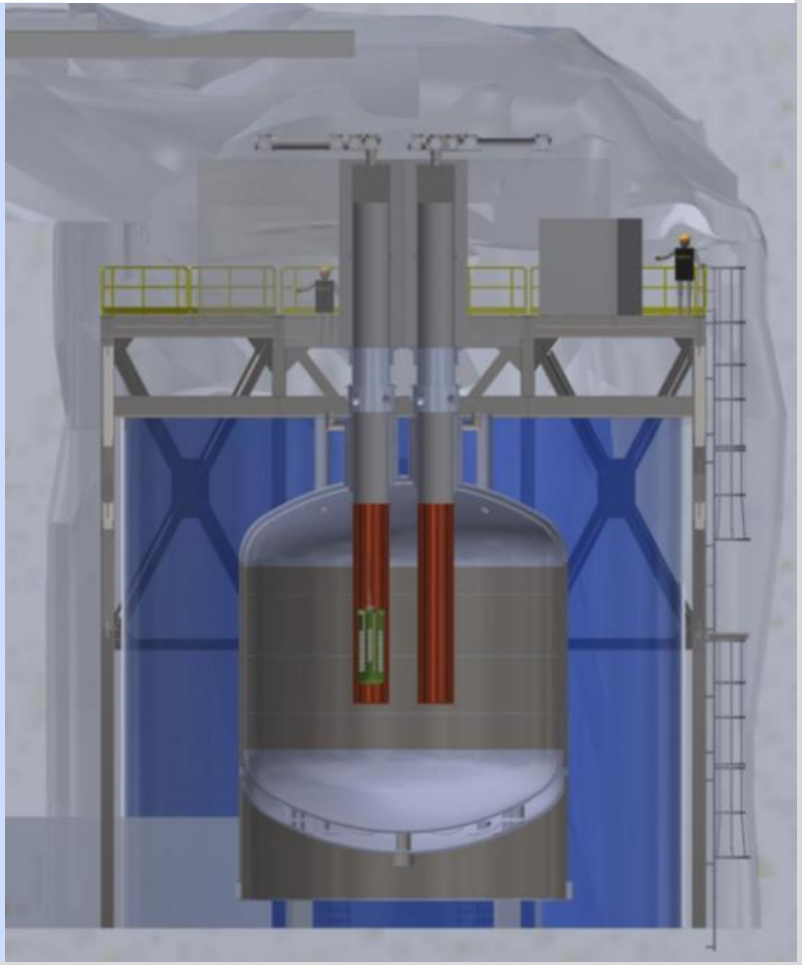
The LEGEND Neutrinoless Double Beta Decay Experiments

LEGEND

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay



Christopher Jillings

2025-02-04

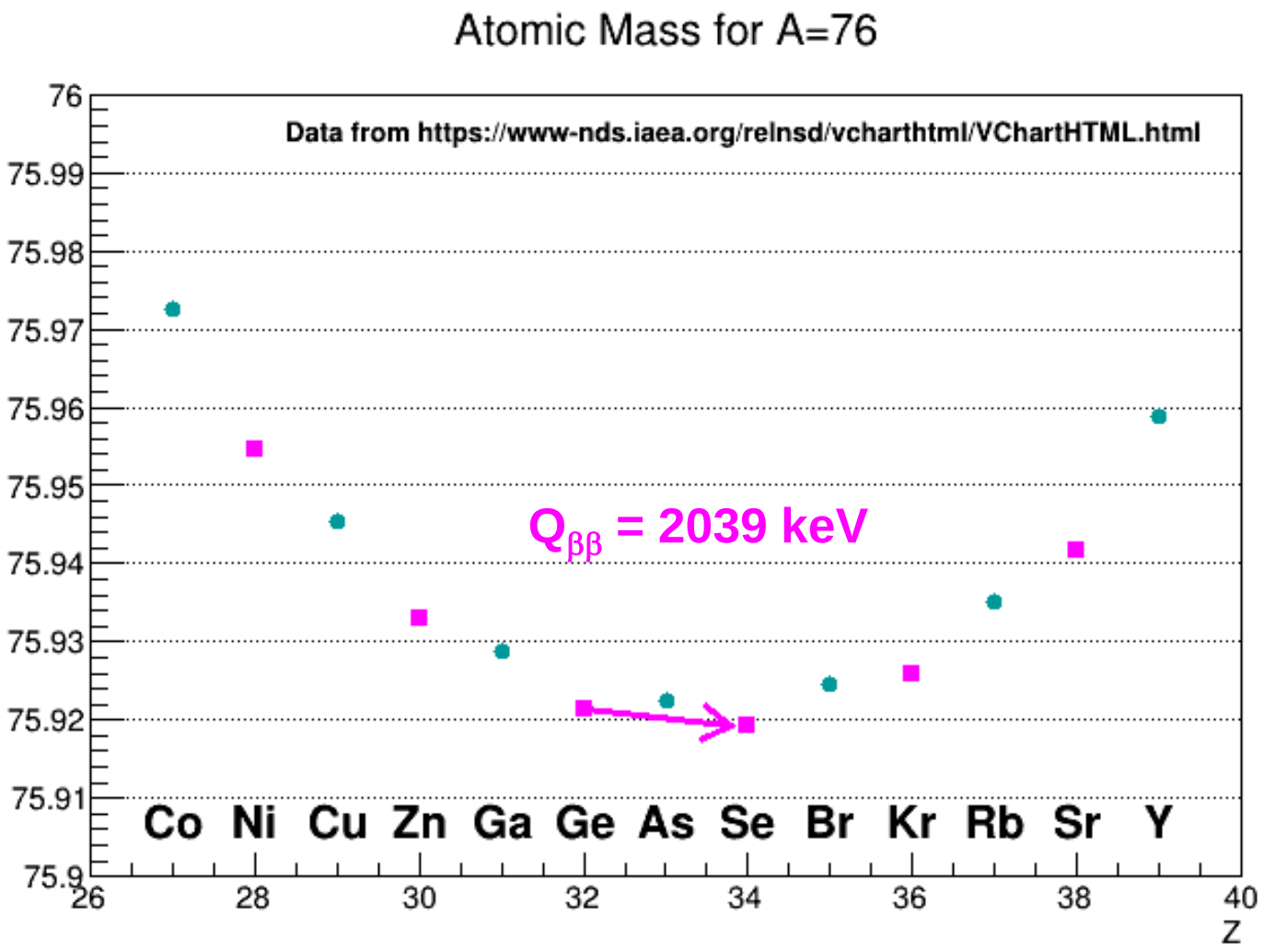
SNOLAB SEF meeting

CIEMAT
Comenius Univ.
Czech Tech. Univ. Prague and IEAP
Daresbury Lab.
Duke Univ. and TUNL
Gran Sasso Science Inst.
Indiana Univ. Bloomington
Inst. Nucl. Res. Rus. Acad. Sci.
Jagiellonian Univ.
Joint Inst. for Nucl. Res.
Joint Res. Centre Geel
Lab. Naz. Gran Sasso
Lancaster Univ.
Leibniz Inst. for Crystal Growth
Leibniz Inst. for Polymer Research
Los Alamos Natl. Lab.
Max Planck Inst. for Nucl. Phy.
Max Planck Inst. for Physics
Natl. Res. Center Kurchatov Inst.
Natl. Res. Nucl. Univ. MEPhI
North Carolina State Univ.
Oak Ridge Natl. Lab.
Polytech. Univ. of Milan
Princeton Univ.
Queen's Univ.
Roma Tre Univ. and INFN
Simon Fraser Univ.
SNOLAB
South Dakota Mines
Tech. Univ. Dresden
Tech. Univ. Munich
Tennessee Tech. Univ.
Univ. of California and LBNL
Univ. College London
Univ. of L'Aquila and INFN
Univ. of Cagliari and INFN
Univ. of California San Diego
Univ. of Houston
Univ. of Liverpool
Univ. of Milan and INFN
Univ. of Milano Bicocca and INFN
Univ. of New Mexico
Univ. of North Carolina at Chapel Hill
Univ. of Padova and INFN
Univ. of Regina
Univ. of South Carolina
Univ. of South Dakota
Univ. of Tennessee
Univ. of Texas at Austin
Univ. of Tuebingen
Univ. of Warwick
Univ. of Washington and CENPA
Univ. of Zurich
Williams College

Outline

- Double Beta Decay with Germanium Detectors
- LEGEND Concept and Background Control
- LEGEND-200 Results and Plans
- LEGEND-1000 Development

0νββ candidates are even-even nuclei as the mass parabola for odd-odd nuclei is shifted

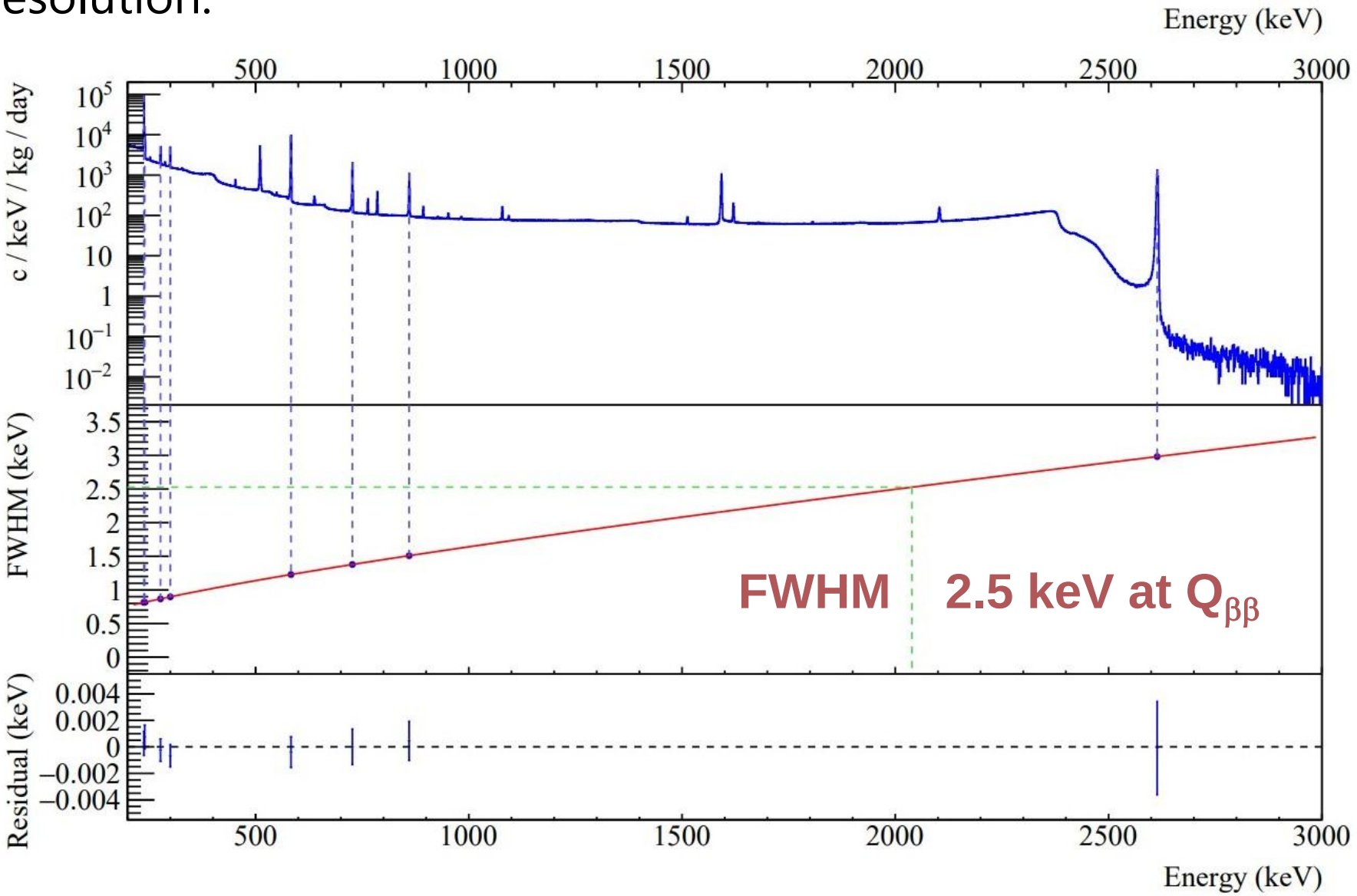


Odd odd nuclei

Even even nuclei

Single beta decay to As is energetically forbidden

Ge crystals with point-contact and electronics near crystal allows for exceptional pulse shape discrimination while maintaining energy resolution.

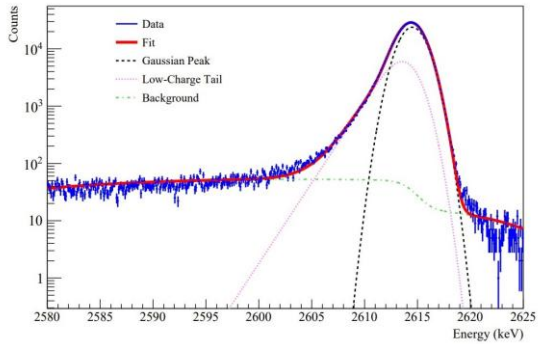


Combined energy calibration for DS0-6

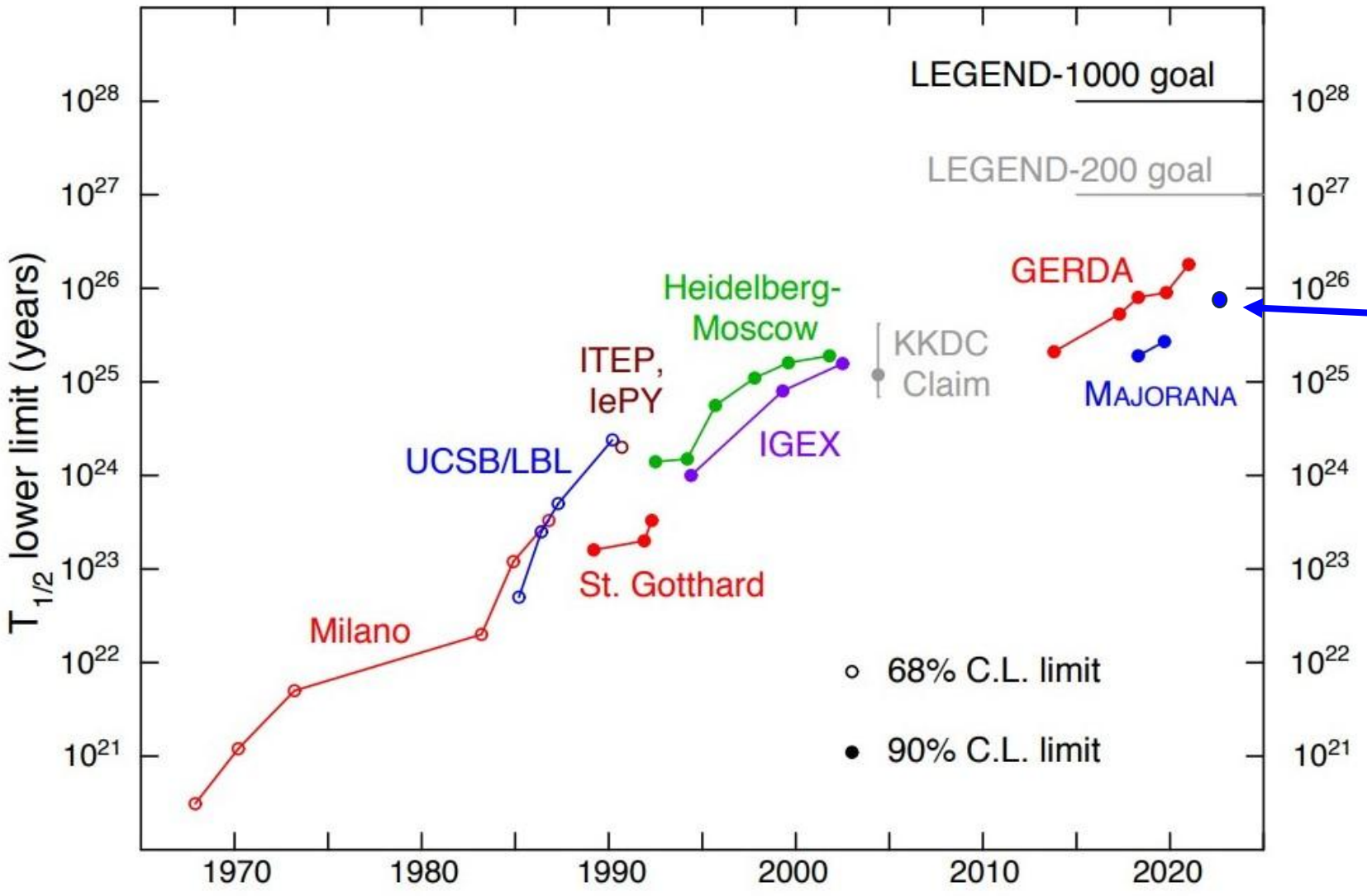
Majorana Demonstrator

https://arxiv.org/abs/1902.02299

Zoom into Tl-208 peak



Ge-76 has a long history in 0vbb searches



PRL 130, 062501 (2023)
$T_{1/2} > 8.3 \times 10^{25}$ yr (90%CL)

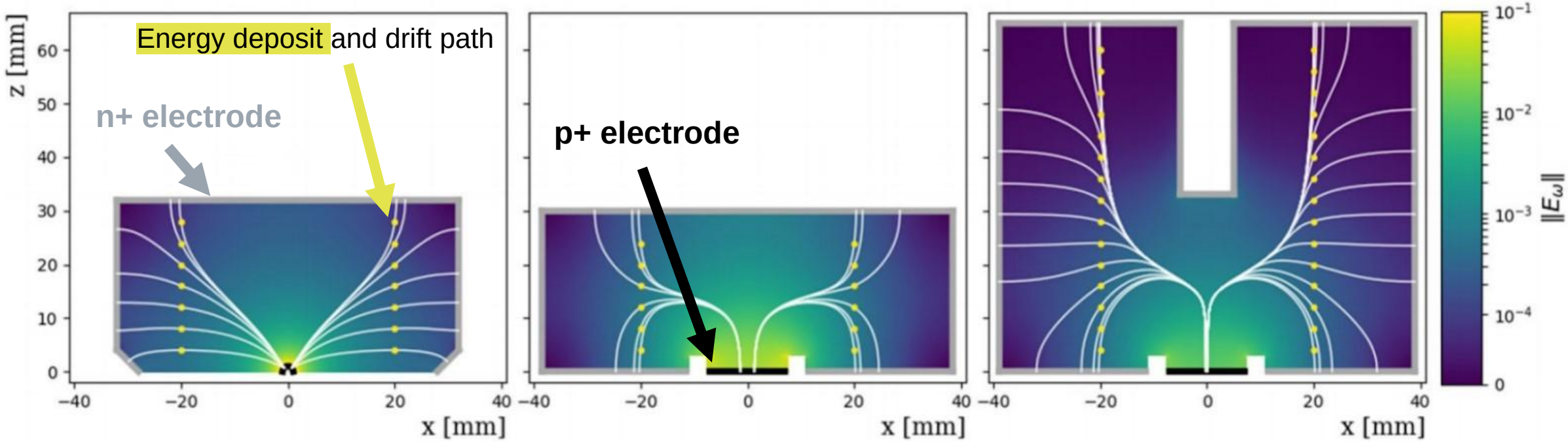
Data tabulated in review by Avignone and Elliott.
https://doi.org/10.3389/fphy.2019.00006
https://arXiv.org/abs/1901.02805

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

80 mm

60 mm

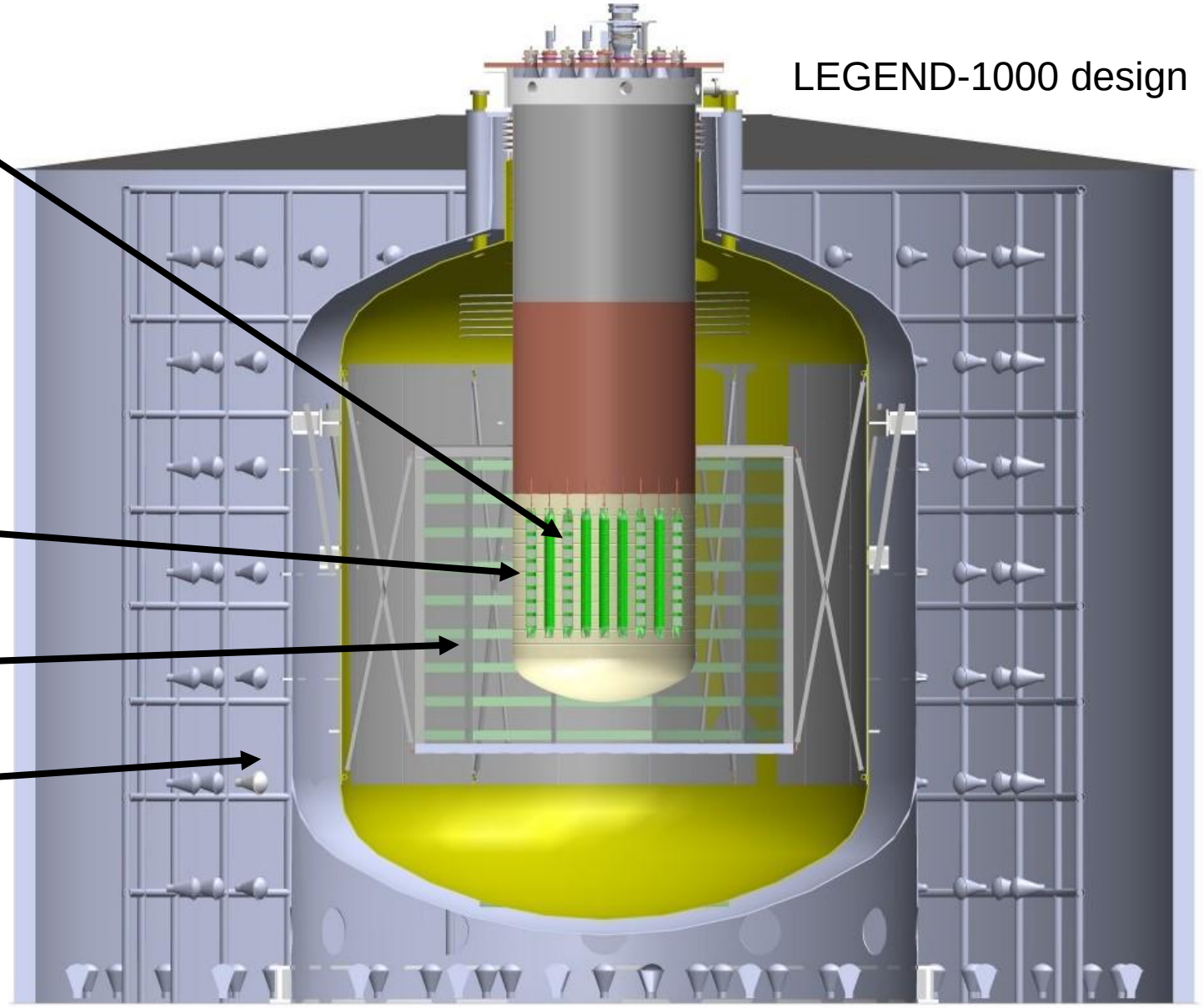
Inverted
Coaxial
Point
Contact



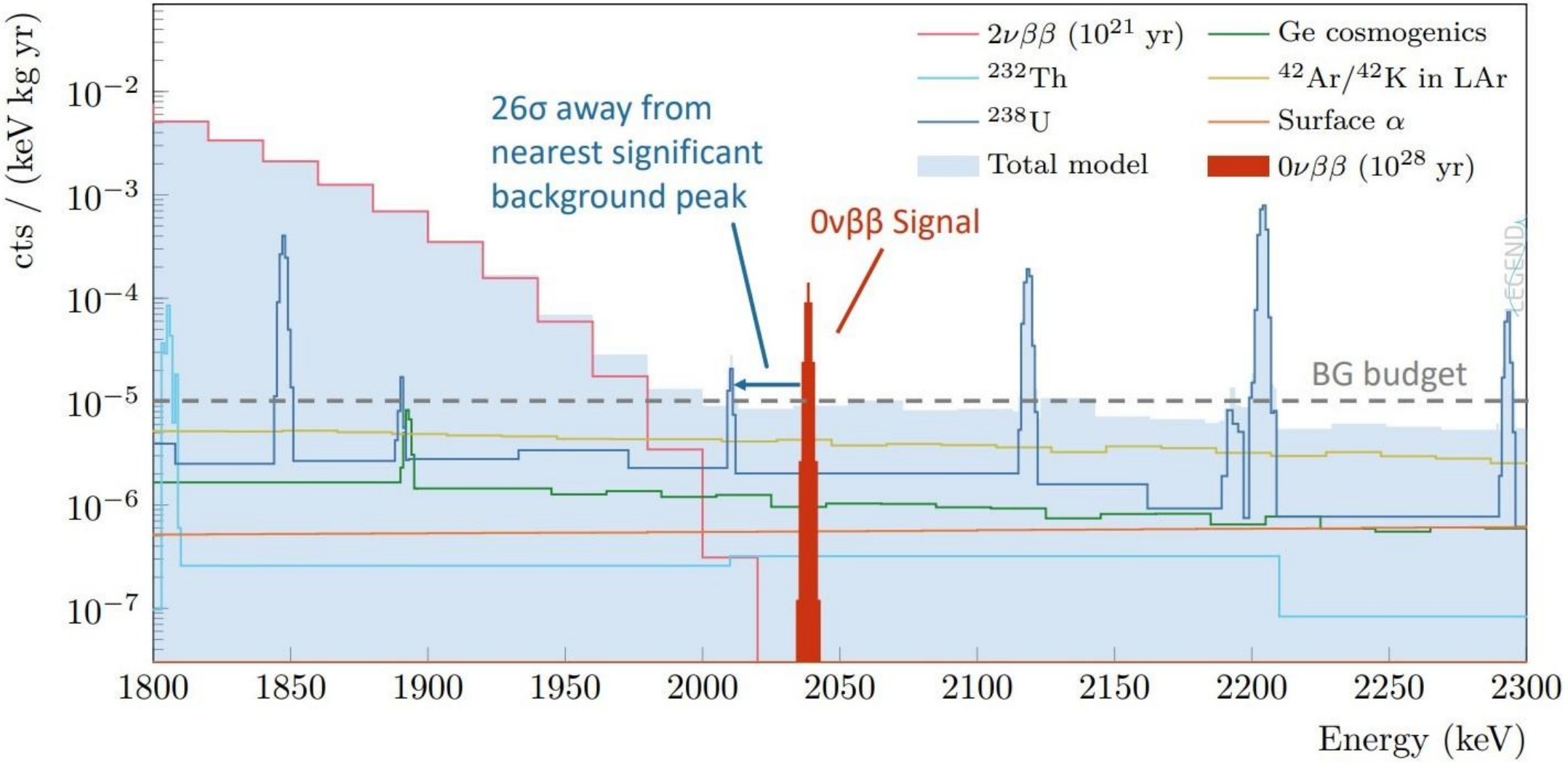
Majorana GERDA LEGEND

Many techniques are used to control background:

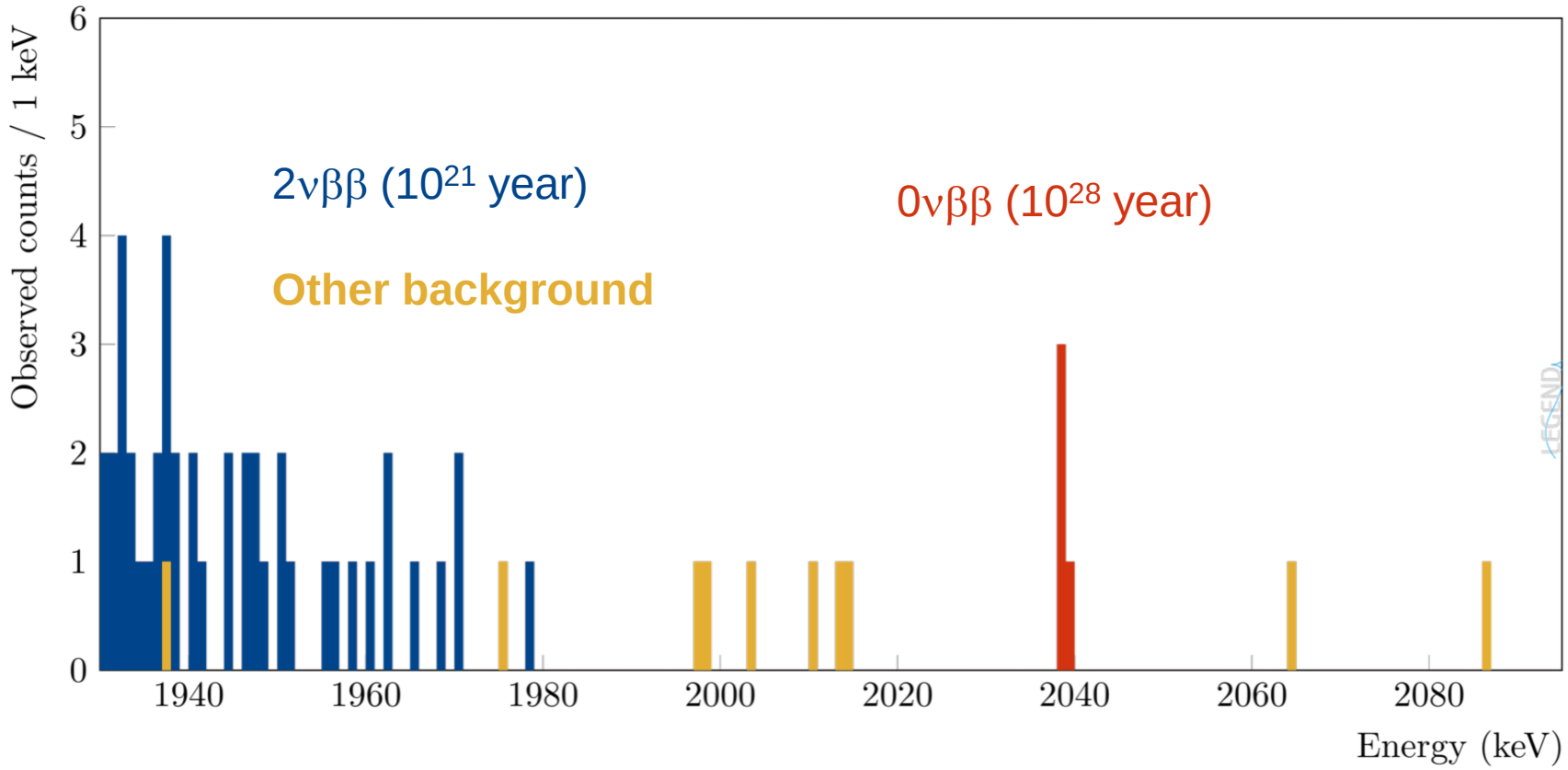
- Bare crystals with small-mass electronics (ASIC) near crystal:
  Exquisite energy resolution
- PSD in analysis to reject multi-site events
- Crystals in instrumented liquid-argon bath for cooling and Compton rejection.
  (Atmospheric Argon for LEGEND-200 and Underground Argon for LEGEND-1000)
- Instrumented atmospheric argon shield
- Instrumented water shielding tank



LEGEND-1000 Background Model

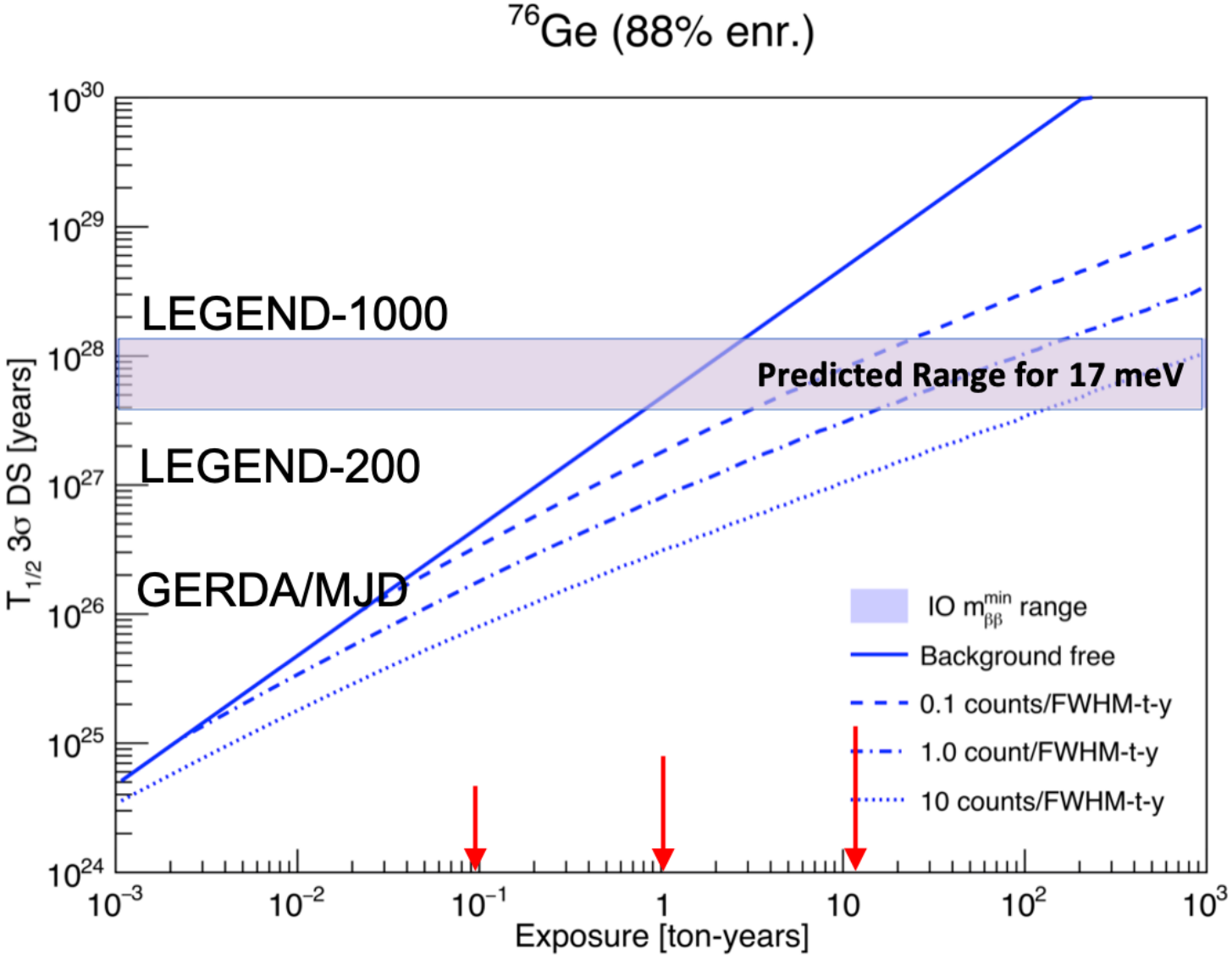


A sample 10 t-yr synthetic data set illustrates discovery potential



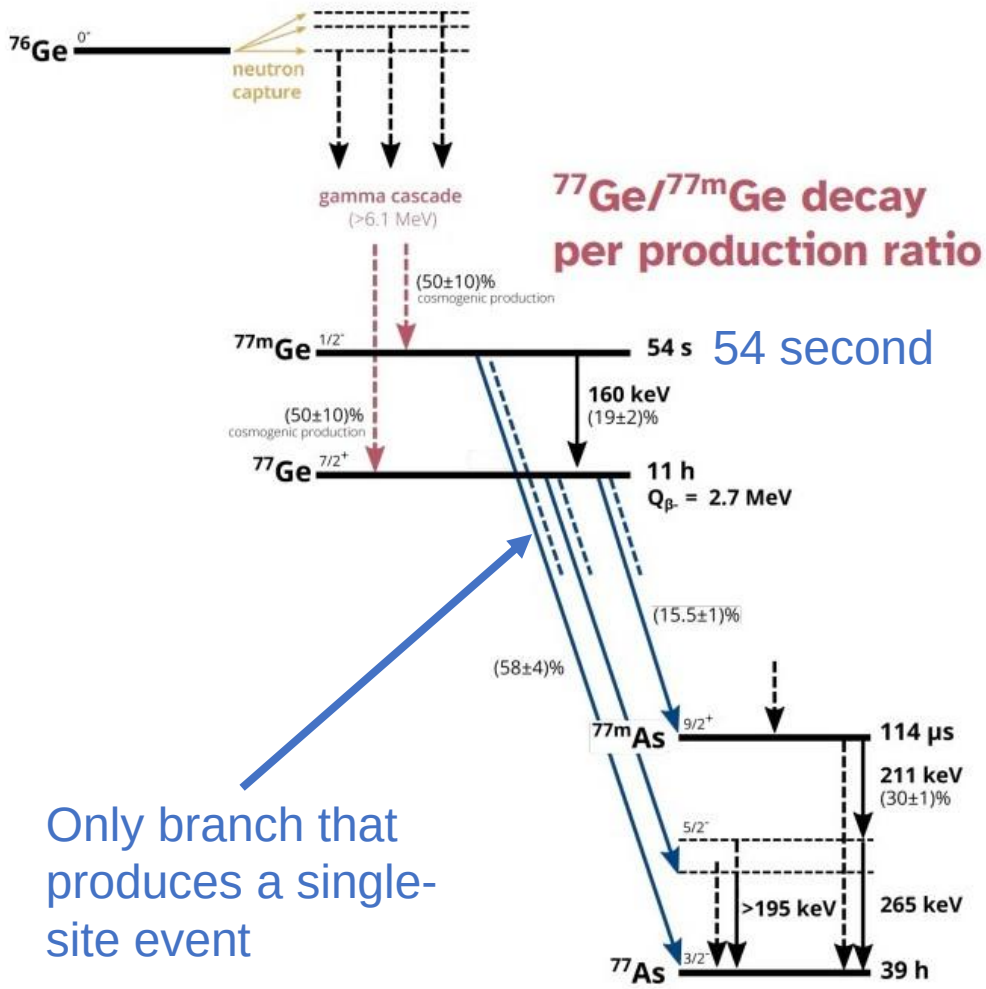
Discovery: a 50% chance or greater that a 10 tonne-year results in a signal 3σ above null hypothesis

LEGEND-1000 is designed to have 0νββ discovery potential at a 10^{28} year half life



Strategy for Suppressing Ge-77m Background (from cosmogenic activation of Ge-76)

- Acrylic panels are added to design in outer argon detector to thermalize neutrons
- A method for tagging cosmogenic fast neutrons has been developed in the instrumented outer (atmospheric) argon.
- Only one branch of Ge-77m produces a single-site event in LEGEND. Use a veto after a neutron signal.
- With a loss of ~3% detection efficiency, the total background rate at LNGS similar to that at SNOLAB.
- With this improvement in place, the physics reach at LNGS and SNOLAB are very similar.
- The detailed study will be published shortly
- A search for Ge-77m in LEGEND-200 is underway – will be upcoming publication.



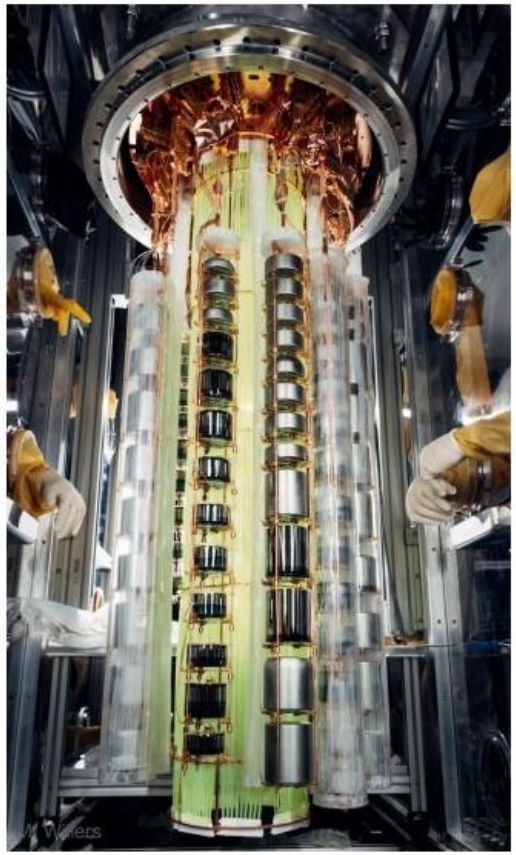
LEGEND-200 commissioning showing crystals and liquid argon readout

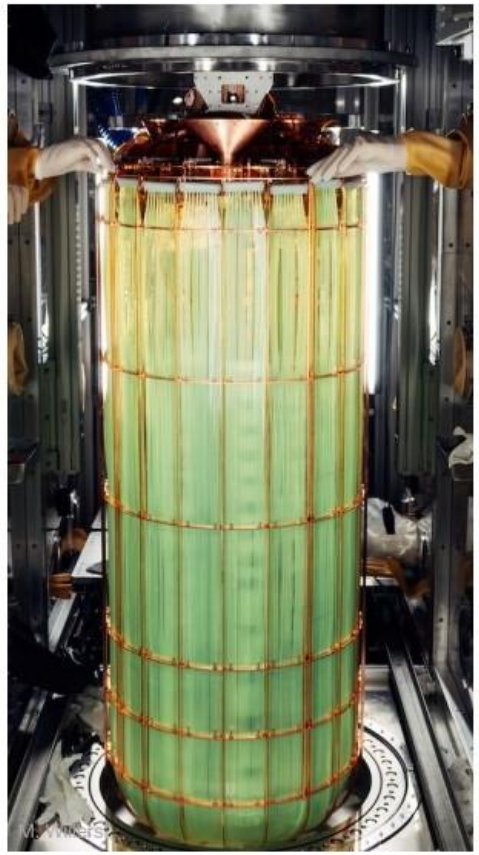

E. Sacchetti


Photo: E. Sacchetti

LAr instrumentation:
Construction & commissioning of LAr instr. hardware & readout electronics.

60 kg campaign:
First operation of 60 kg of HPGe detectors and full LAr instr.
Final hardware optimisations
Special calibration runs





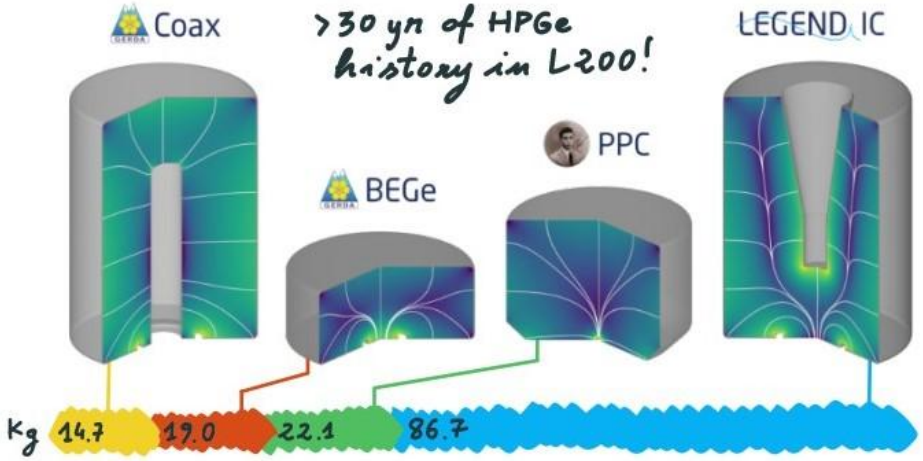
142 kg installation:
Installation of all available HPGe detectors as well as full LAr installation, DAQ, readout electronics

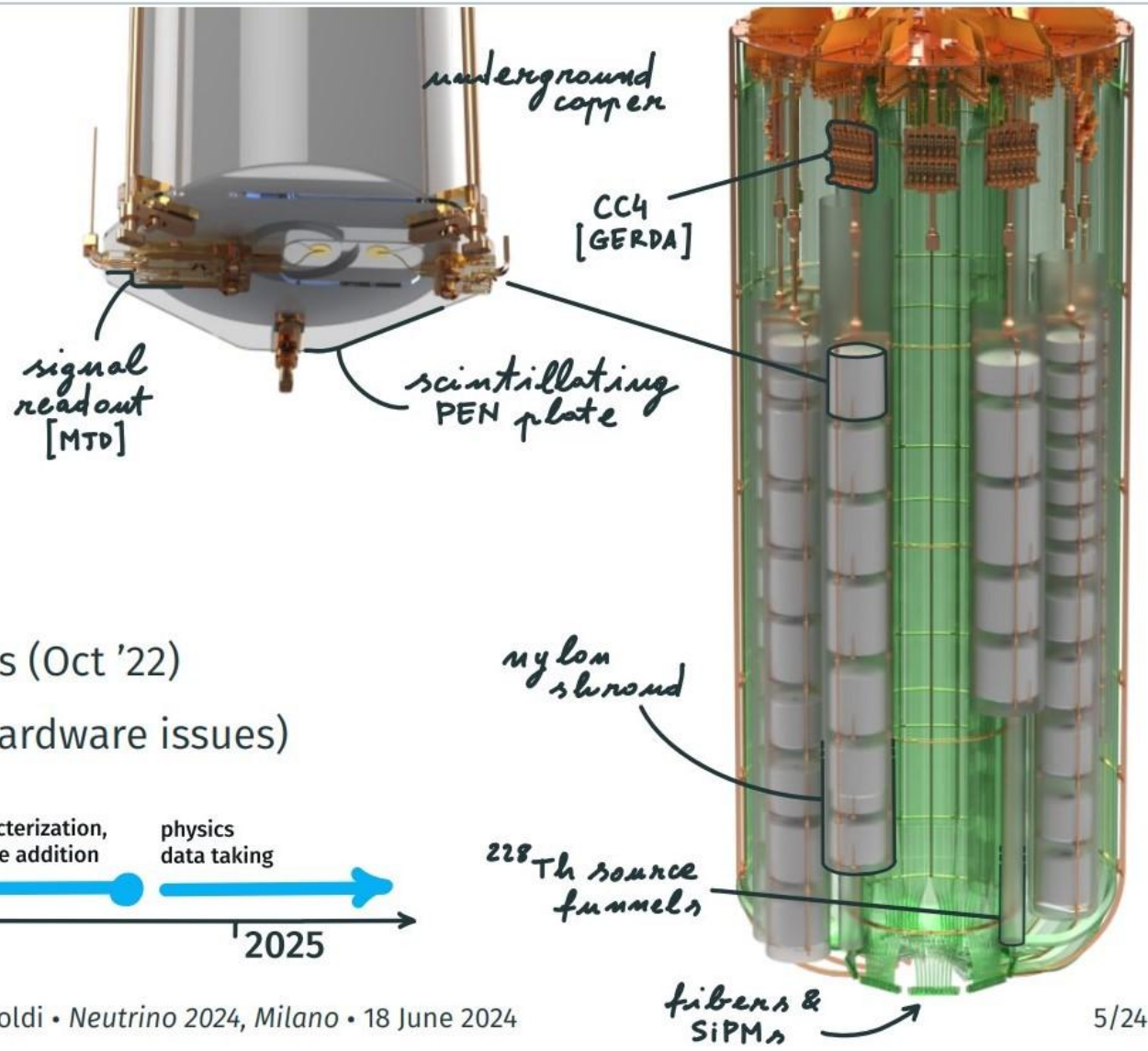
Electronics & LAr instrumentation commissioning | 60 kg campaign + special calibration | 142 kg installation & commissioning | **Physics data taking**

2022 — 2023

Data Release at Neutrino 2024

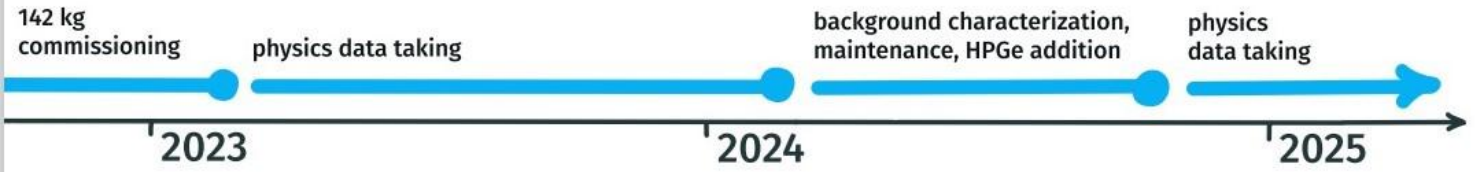
THE LEGEND -200 EXPERIMENT AT LNGS





Hardware status — see talk at [TAUP23]

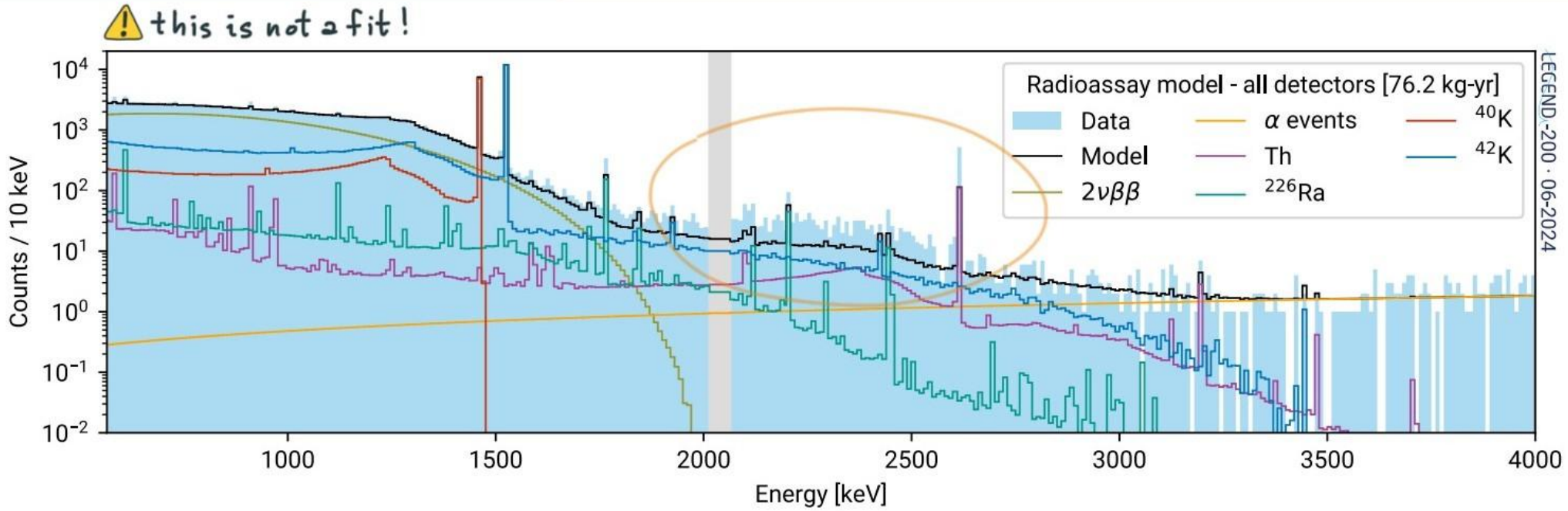
- Installed first **142 kg** of HPGe detectors (Oct '22)
- 130 kg operational (12 kg OFF due to hardware issues)



Results Presented at Neutrino 2024

MODELING DATA BEFORE ANALYSIS CUTS [SILVER]

POSTER *THE LEGEND-200 BACKGROUND MODEL* • T. Dixon, S. Calgaro

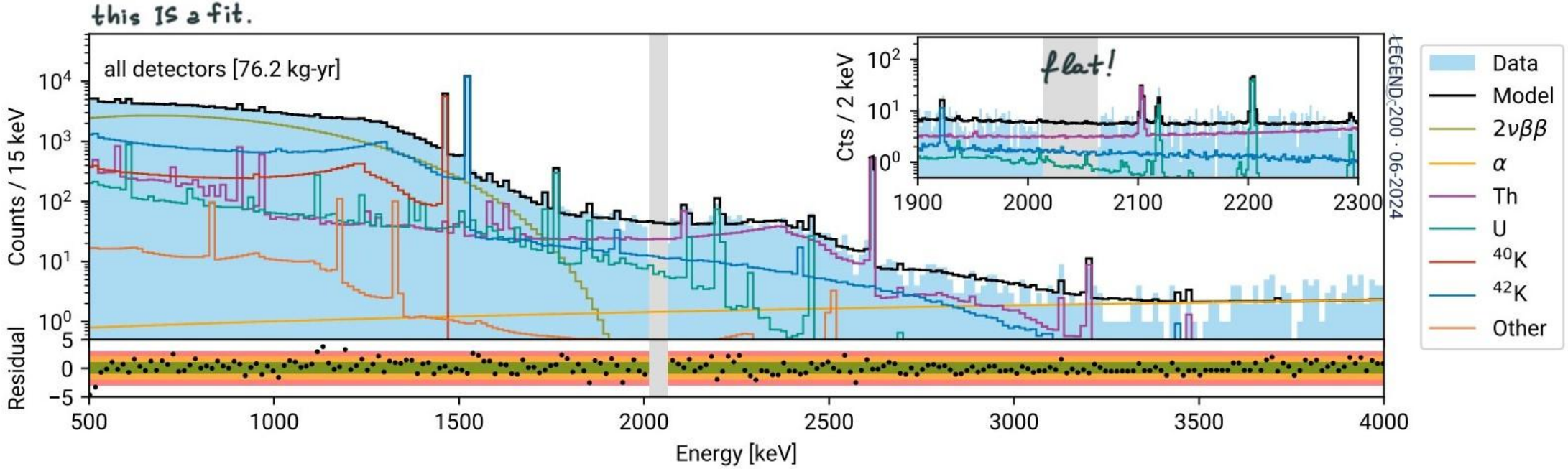


- Simulations and material radioassay underpredict ^{228}Th in physics data
  - *Hard to estimate systematic uncertainty on the assay results*
  - *ICP-MS not predictive if secular equilibrium is broken*
- This background is efficiently suppressed by analysis cuts

Results Presented at Neutrino 2024

MODELING DATA BEFORE ANALYSIS CUTS [SILVER]

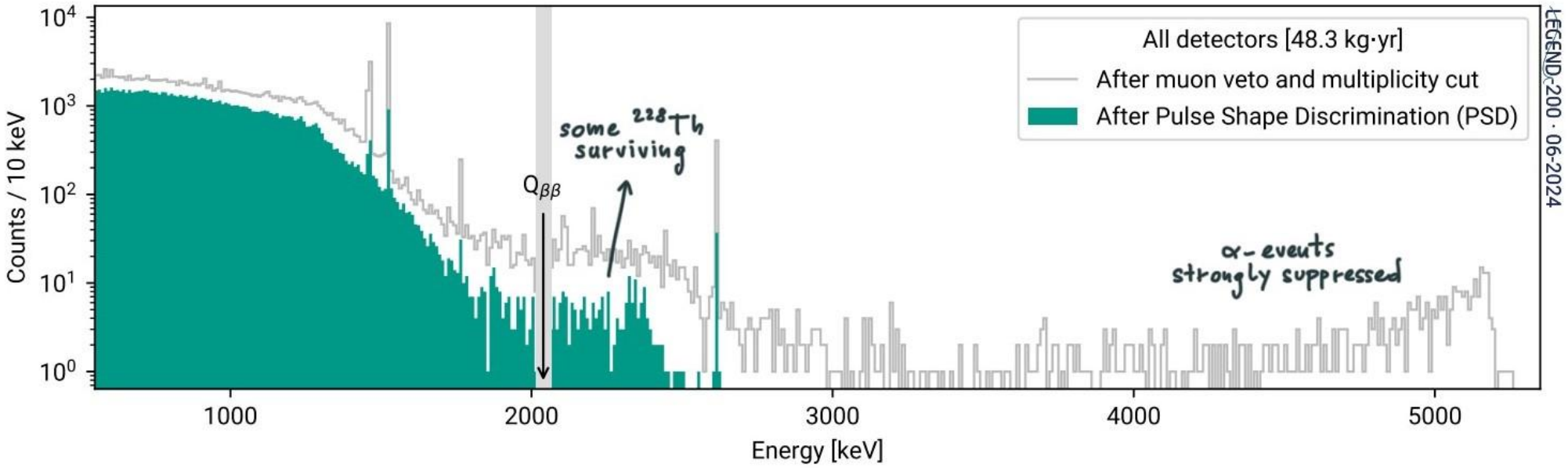
POSTER THE LEGEND-200 BACKGROUND MODEL • T. Dixon, S. Calgaro



- Bayesian background model using data before analysis cuts [SILVER]
  - *Includes 10.2 kg yr from special "background characterization" runs*
- Data well reproduced, model is flat at $Q_{\beta\beta}$
  - *No "hotspot" or significant asymmetry observed in data*
  - *Model can test hypotheses on the origin of ^{228}Th*

Results Presented at Neutrino 2024

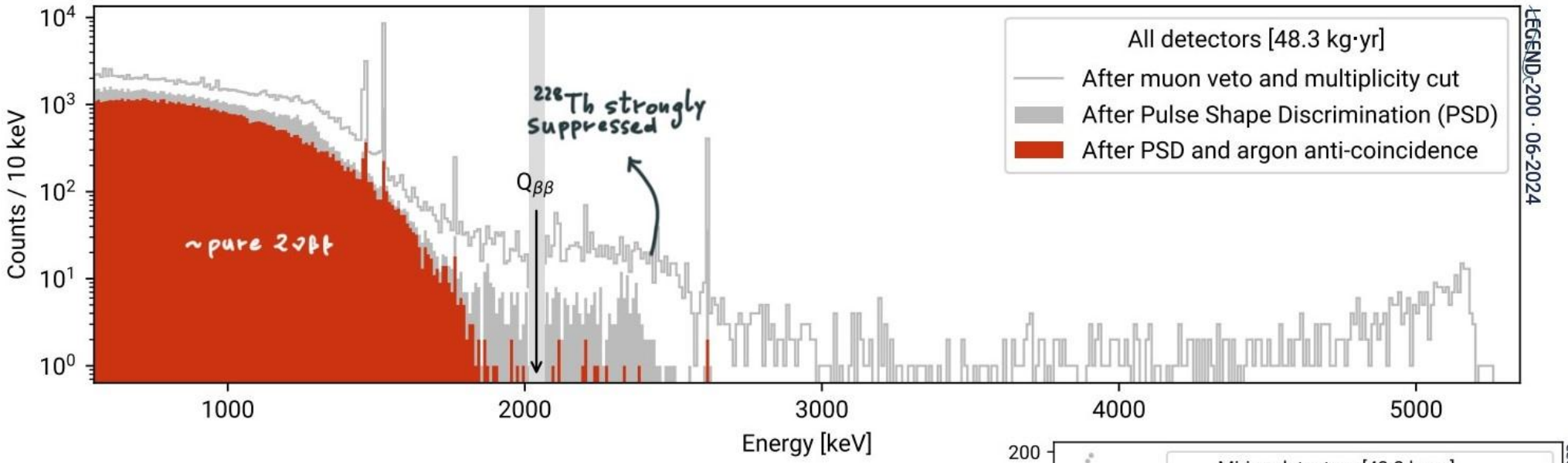
DATA AFTER PULSE SHAPE DISCRIMINATION [GOLDEN]



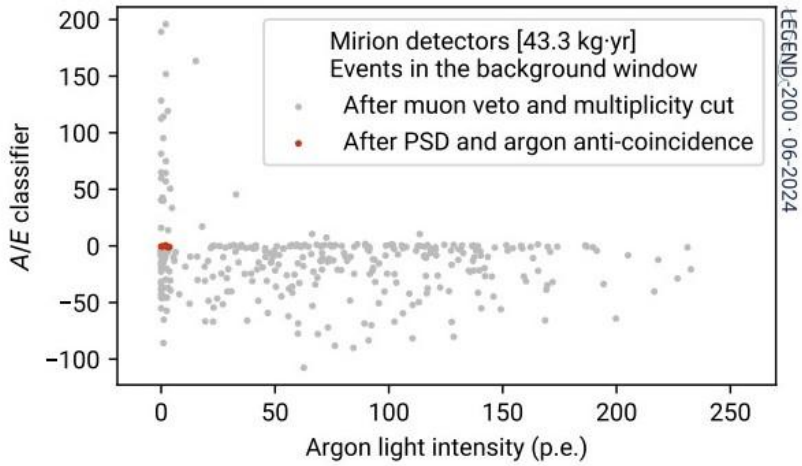
- Strong suppression of surface α and β (^{42}K) events
- ~60% suppression of Compton multi-site events at $Q_{\beta\beta}$
- 0νββ survival fraction of ~85%

Results Presented at Neutrino 2024

DATA AFTER PULSE SHAPE DISCRIMINATION AND ARGON ANTI-COINCIDENCE CUT [GOLDEN]



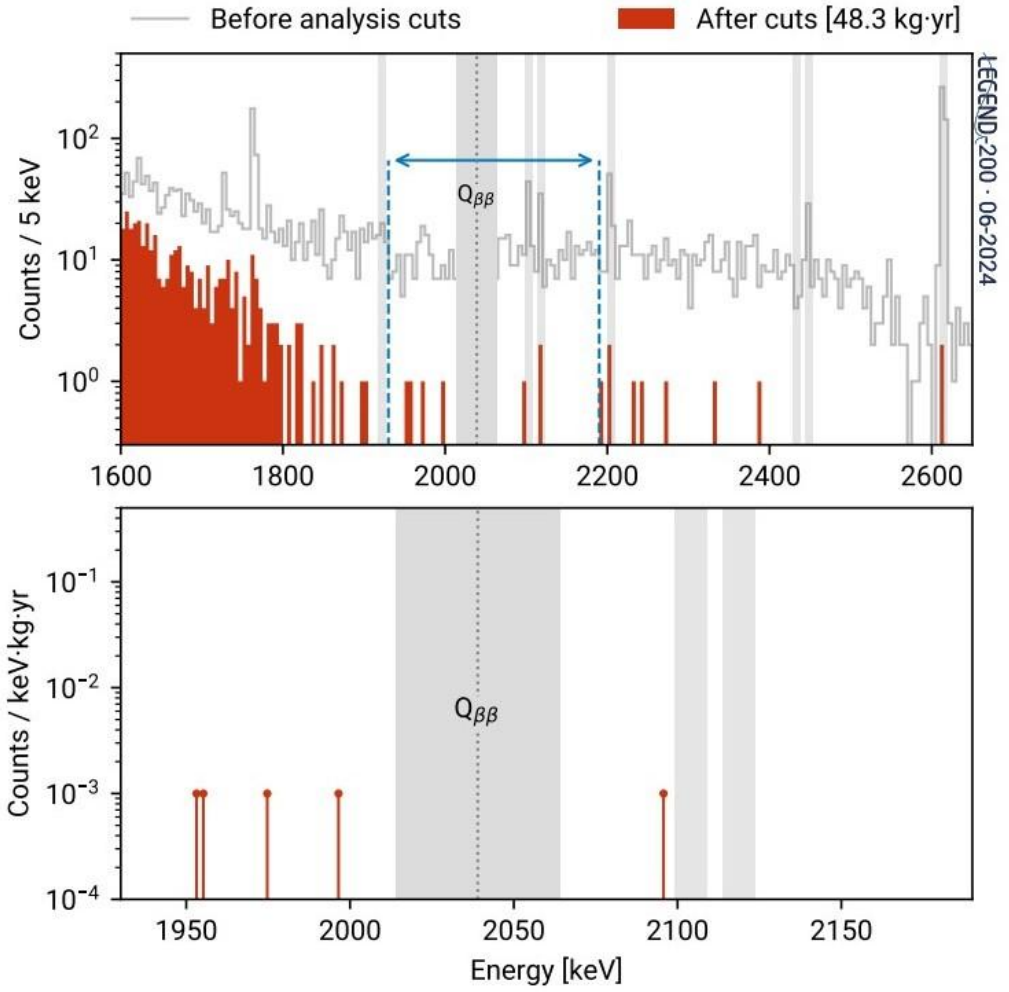
- Strong anti-correlation of argon and PSD cuts
- Overall 0νββ survival fraction of ~60%
- "Pure" 2νββ distribution, few events surviving at $Q_{\beta\beta}$



Results Presented at Neutrino 2024

DATA IN THE REGION OF INTEREST!

5 events surviving in the
“background estimation window”



Results Presented at Neutrino 2024

DATA IN THE REGION OF INTEREST — AFTER UNBLINDING LAST WEEK!

- 7 events surviving. Background index
  BI = $5.3 \pm 2.2 \cdot 10^{-4}$ cts / (keV kg yr)

PRELIMINARY!

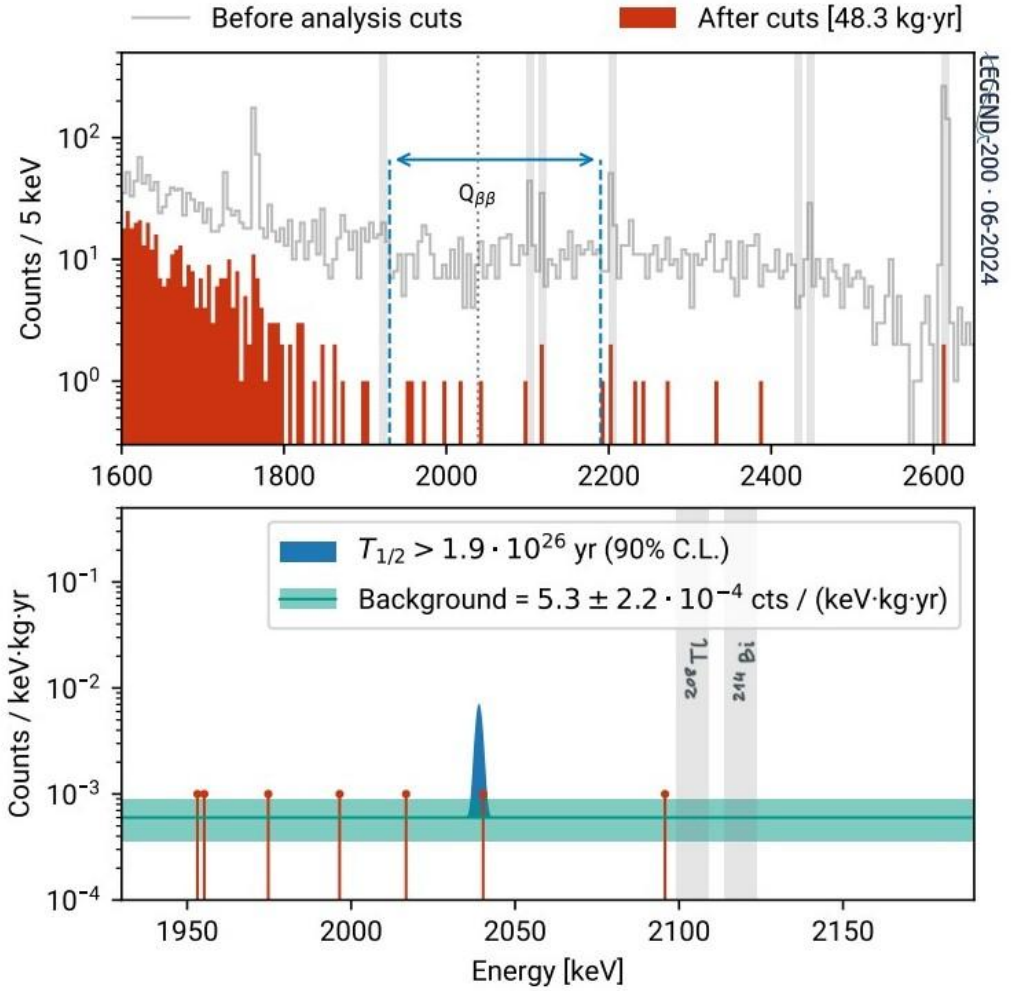
GERDA, MAJORANA and LEGEND combined fit

- *p*-value of background-only = 26%
- $T^{0\nu}_{1/2}$ lower limits (90% frequentist C.L.)

Observed	Sensitivity
$> 1.9 \cdot 10^{26}$ yr	$2.8 \cdot 10^{26}$ yr

LEGEND-200 contribution

- +30% of limit median expectation
- event at 1.4 σ from $Q_{\beta\beta}$ weakens combined limit



Next LEGEND-200 Results

- The collaboration is working on a LEGEND-200 paper that will including data beyond the Neutrino 2024 results.
- The data are blind and unblinding will follow usual LEGEND procedures.

LEGEND-1000 Project Notes

- The DOE launched an ongoing process to examine alternatives for LEGEND-1000.
- Draft recommendations include
  - LEGEND-1000 is needed to meet the 10^{28} year half life sensitivity and therefore cover the inverted hierarchy space. (LEGEND-200 will reach 10^{27} years.)
  - LNGS is the baseline location. The LNGS site has reduced cost to the DOE while maintaining the physics goal.

LEGEND-1000 Project Notes

DOE-NP publicly announced just before Christmas 2024 its support for LEGEND-1000. The announcement restated the importance of double beta decay and its prominent recommendation in the NSAC 2023 Long Range Plan. This announcement included a decision to move forward with LEGEND-1000 in the near term while supporting R&D for other major double beta decay efforts. The intention is to hold a Critical Decision 1 review during calendar year 2025. The ORNL project office has made great strides in preparing budget and schedule analyses for a CD-1 review

LEGEND-1000 Project Notes

- European partners are proceeding:

A proposal to Germany's BMBF has been submitted. The design of the cryostat is also advancing through German funding. LNGS and INFN are proceeding with the removal of Borexino and preparing for installaNon of the LEGEND water tank. Collaborators from Switzerland, Poland, and the UK have submitted, or are in the process of submitting, requests for support.

LEGEND-1000 Project Notes

The mid-scale proposal to the NSF was submitted and declared “Acceptable as Proposed” by both the Site Visit and Reverse Site Visit panels. Further response is expected early in calendar year 2025.

The work on LEGEND at SNOLAB has been scaled back, given the emphasis on deployment at LNGS. Therefore, the efforts will be focused on low-background work: assays and some studies that are consistent with the broader SNOLAB program. The fraction of effort to be spent on LEGEND by Jillings will shrink.

LEGEND-1000 Project Notes

The work on LEGEND at SNOLAB has been scaled back, given the emphasis on deployment at LNGS. Therefore, the efforts will be focused on low-background work: assays and some studies that are consistent with the broader SNOLAB program. The fraction of effort to be spent on LEGEND by Jillings is shrinking.

Summary

- LEGEND-200 is running at LNGS with recent results presented at Neutrino 2024 and further results forthcoming.
- LEGEND-1000 is in advanced design for deployment at LNGS with SNOLAB as the alternate site.
- 1000 kg of enriched Ge crystals with exquisite energy resolution in an ultra-low background environment have discovery potential with a half life of 10^{28} years for $0\nu\beta\beta$ in ^{76}Ge.