The Search of Neutrinoless Double-Beta Decay and the LEGEND Experiment

Large Enriched
Germanium Experiment
for Neutrinoless ββ Decay

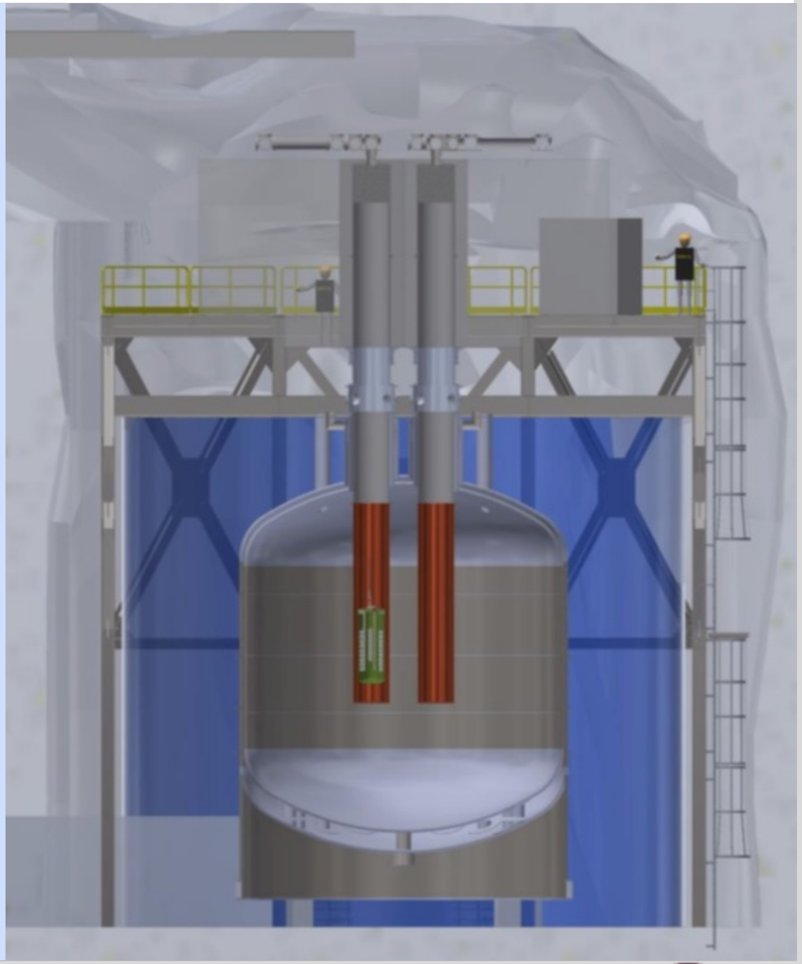
Wenqin Xu

University of South Dakota

On behalf of the LEGEND Collaboration

September 3rd 2022

14th Conference on the Intersections of Particle and Nuclear Physics



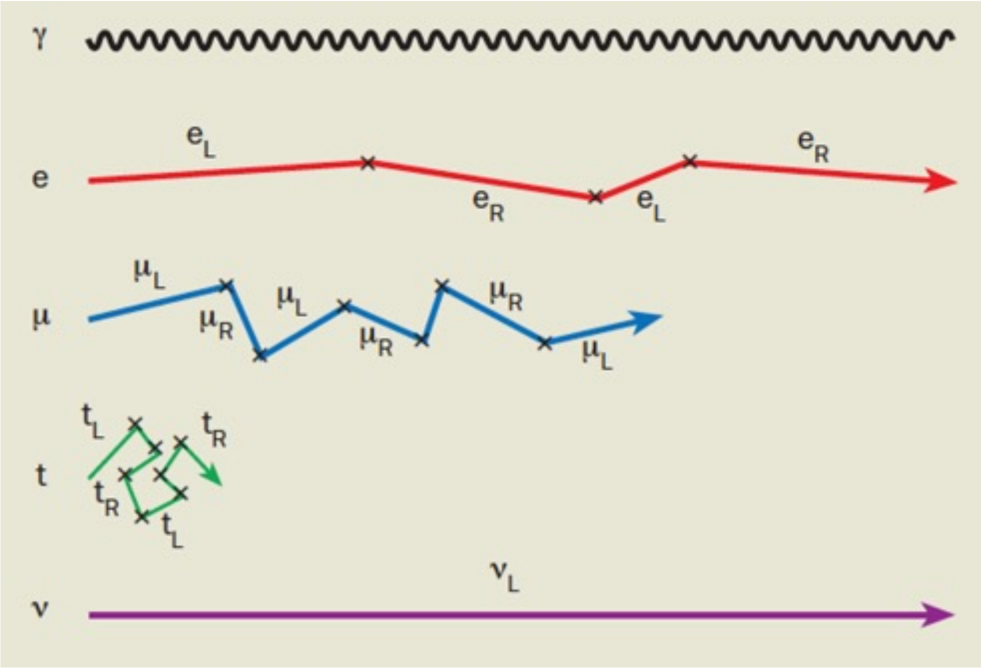
UNIVERSITY OF SOUTH DAKOTA

INTERSECTIONS

Part I
Motivation for the Discovery of Neutrinoless Double-Beta Decay

Neutrino Mass is Beyond the Standard Model

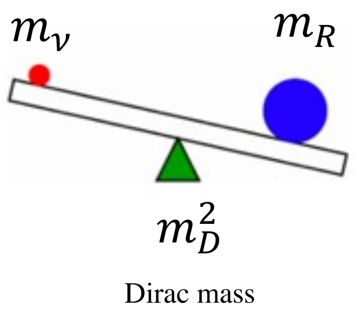
H. Murayama, Physics World, May 2002



Right-handed neutrinos never discovered

- ➢ Neutrinos have zero mass in the Standard Model
- ➢ Non-zero neutrino mass is **physics beyond-the-Standard Model (BSM)**

Heavy right-handed neutrino mass

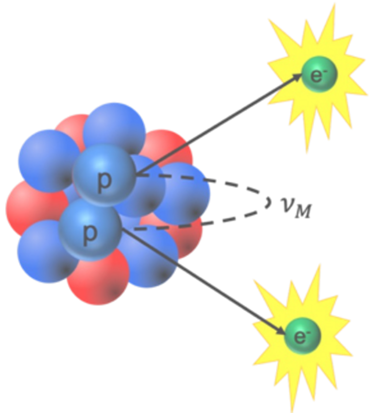


The seesaw model

$$m_\nu = \frac{m_D^2}{m_R}$$

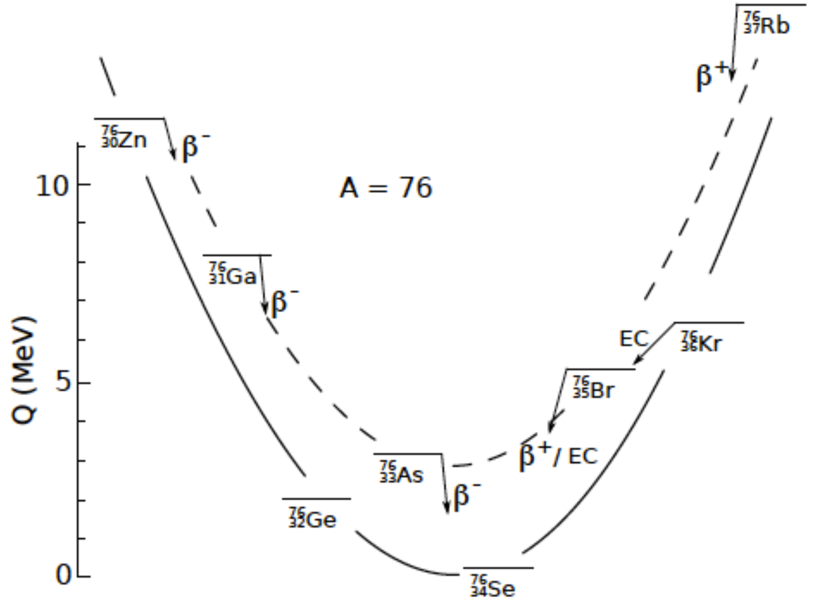
Dirac masses would allow for Majorana masses neutrinos

- ➢ Seesaw mechanism explains the tininess of m_ν
- ➢ Majorana neutrinos are their own anti-particles
- ➢ Neutrinoless double beta decay ($0\nu\beta\beta$) is the only experimentally feasible way to establish neutrinos are Majorana.



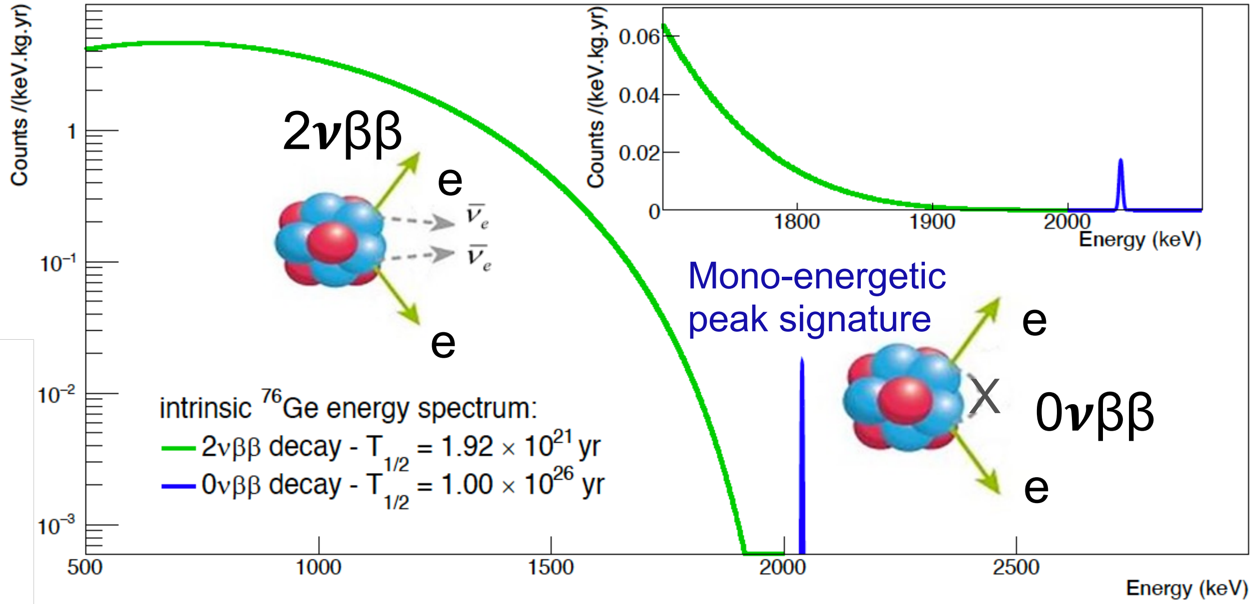
Wenqin Xu| LEGEND | CIPANP2022 09/03

Neutrinoless Double-beta Decay ($0\nu\beta\beta$)



Double-beta decay is possible when energetically favored

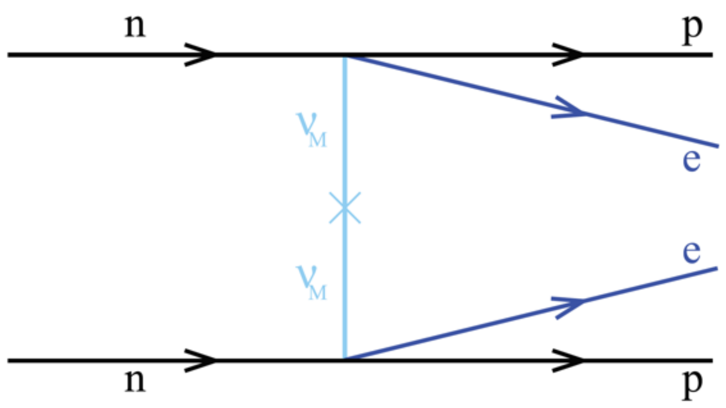
Two neutrino double-beta decay ($2\nu\beta\beta$) is an observed Standard Model process



Observation of Neutrinoless double-beta decay (0νββ) would

- **prove the total lepton number is violated by 2 units ($\Delta L = 2$)**
- imply massive neutrinos are Majorana particles

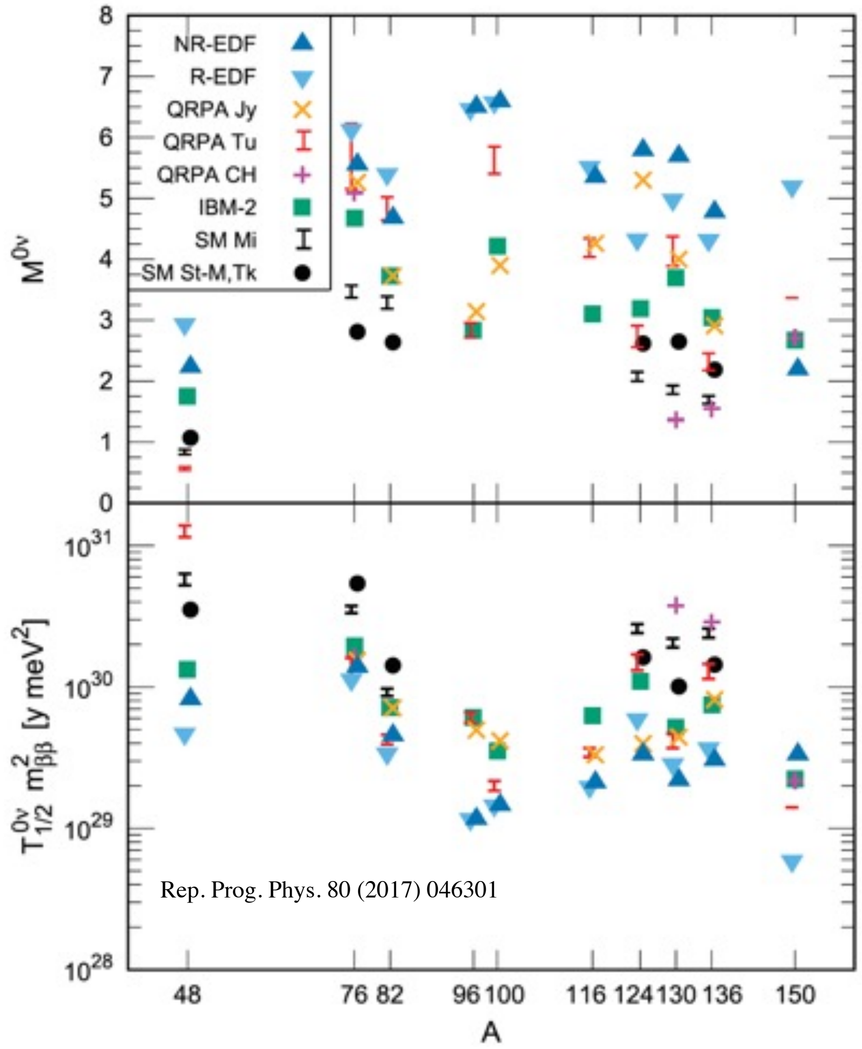
$0\boldsymbol{\nu}\beta\beta$ Half Life and Effective Neutrino Mass



For light neutrino exchange model only:

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}\,|M_{0\nu}|^2\left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

Nuclear Matrix Element



Also see Emanuele Mereghetti's talk in the Nu session

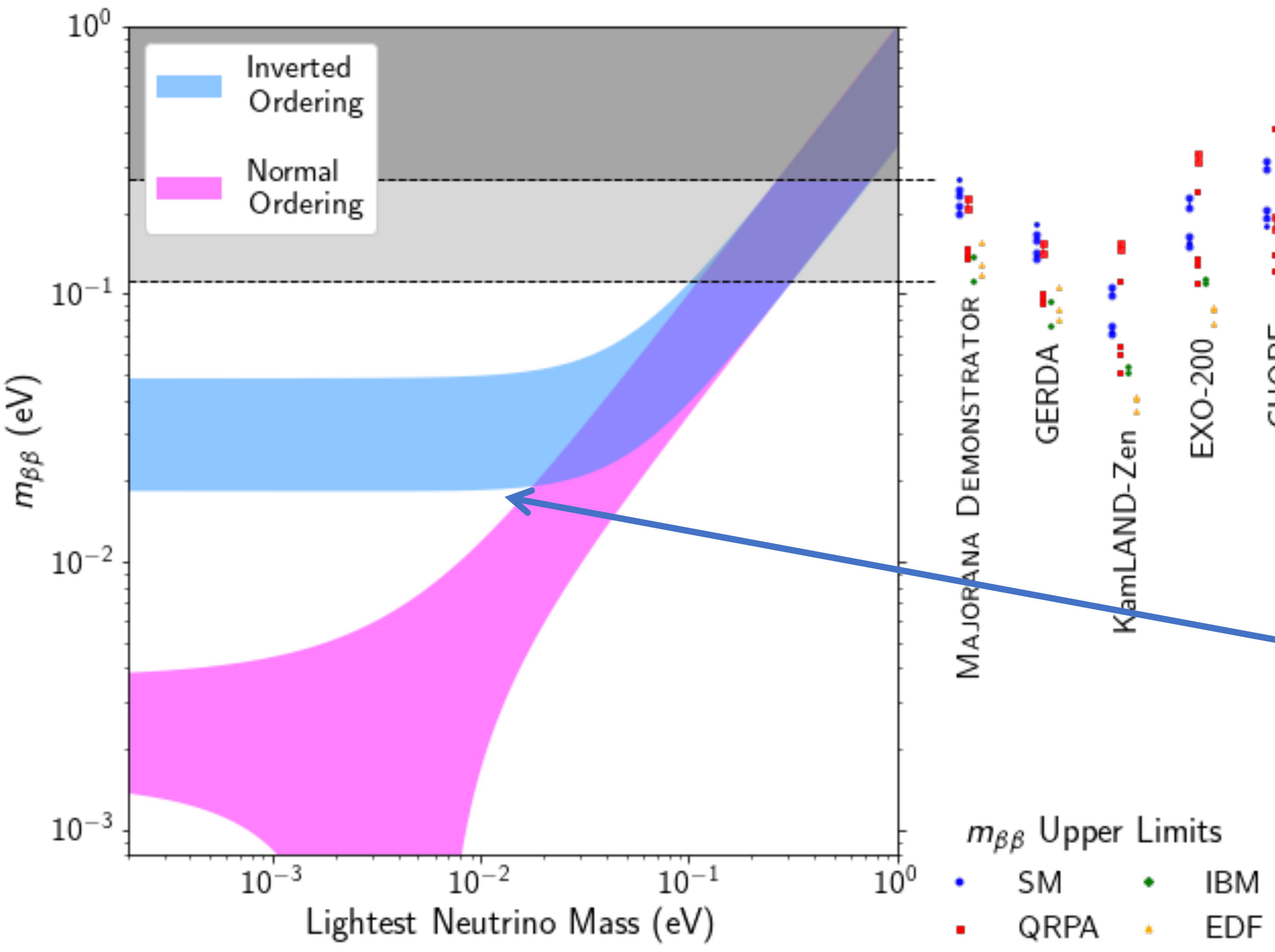
$0\boldsymbol{\nu}\beta\beta$

- Half life relates to the effective neutrino mass

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

- Theoretical calculations of the nuclear matrix element have uncertainties

Phase Space for Discovery



A variety of isotopes and techniques in use for $0\nu\beta\beta$ searches

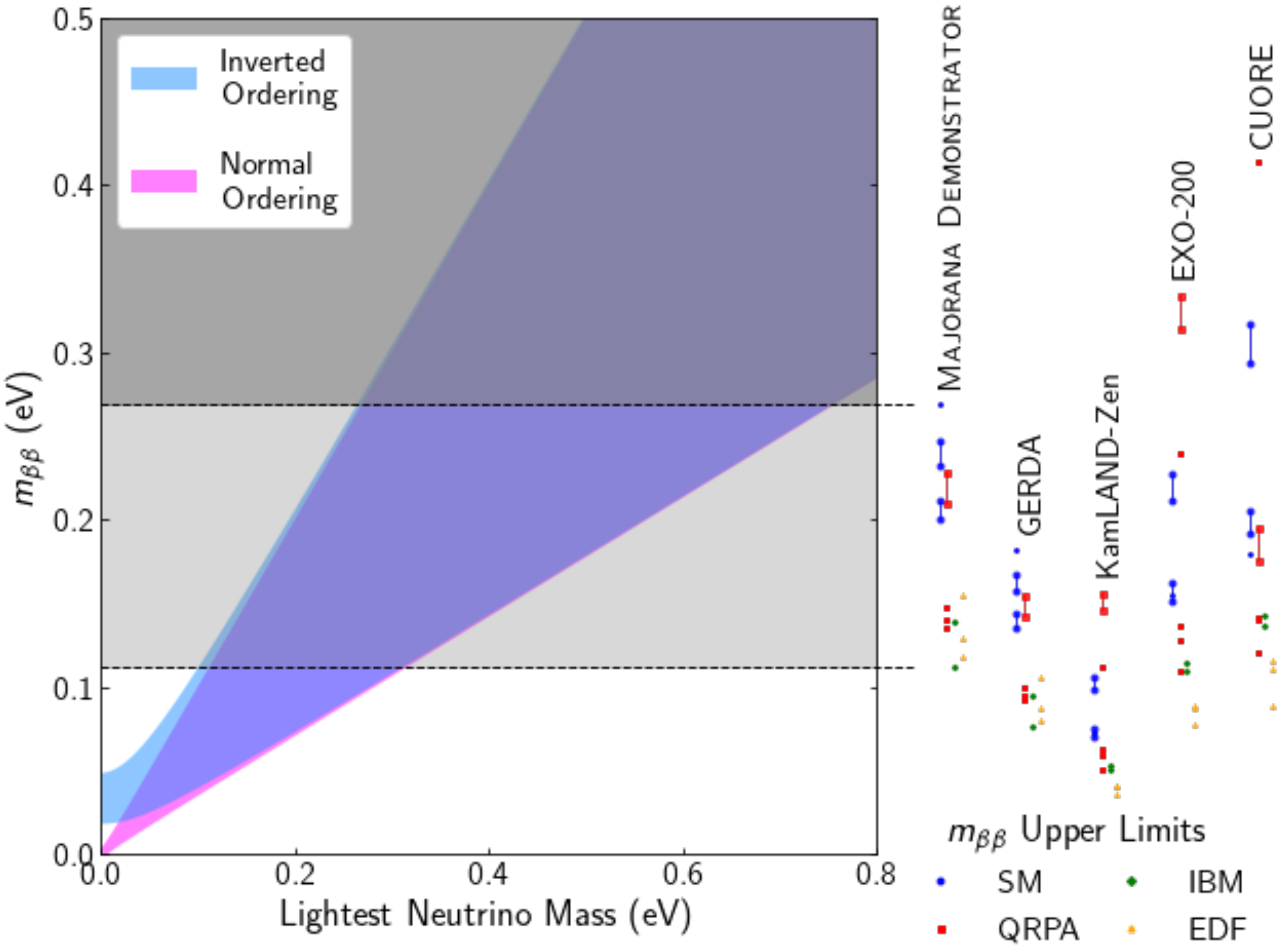
Current generation experiments make steady progresses in probing the phase space possible for $0\nu\beta\beta$ with constant technology developments

Significant discovery potential to be realized by next generation ton-scale experiments

- probing the entire inverted neutrino mass ordering assuming the light neutrino exchange model
- large discovery potential also in the normal mass ordering

Phase Space for Discovery

Linear Y-axis



A variety of isotopes and techniques in use for $0\nu\beta\beta$ searches

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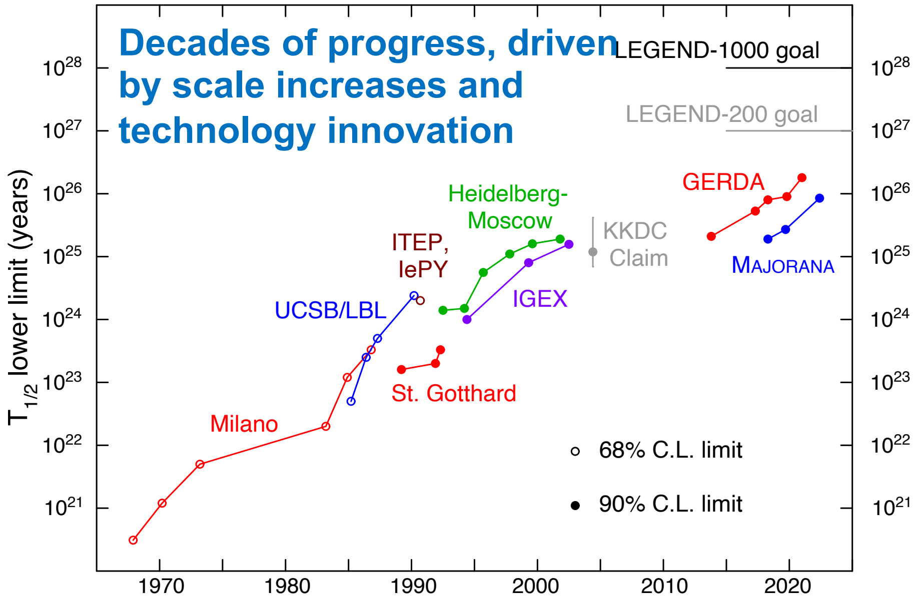
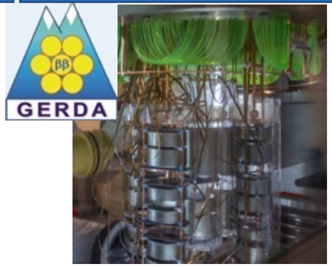
Part II
Proven Ge Technologies for the Discovery of Neutrinoless Double-Beta Decay

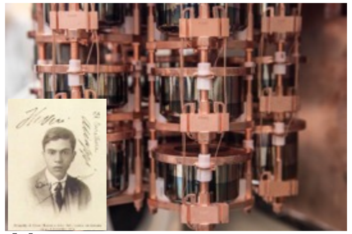
Generations of Ge searches of 0νββ

LEGEND



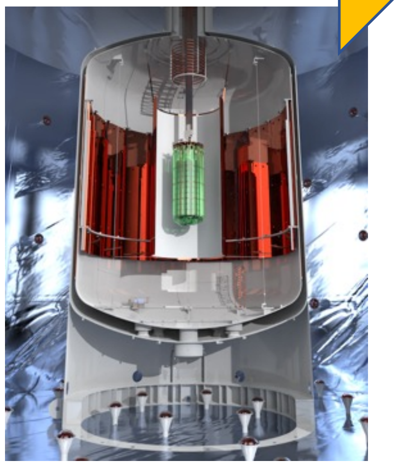
Most recent (~30-40 kg)





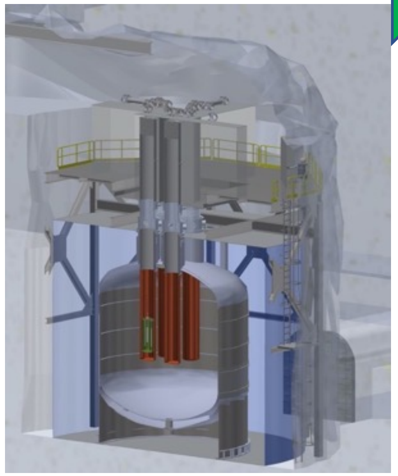
MAJORANA

Ongoing (~200 kg)



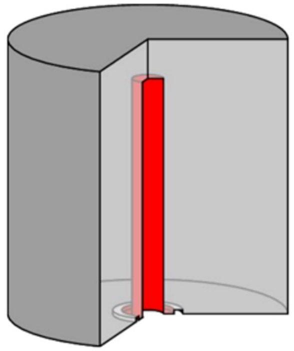
LEGEND-200

proceeding to CD-1 **(~1000kg)**



LEGEND-1000

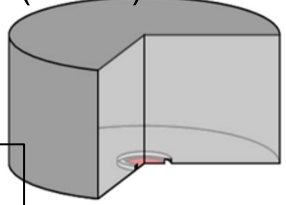
(Semi)-Coaxial



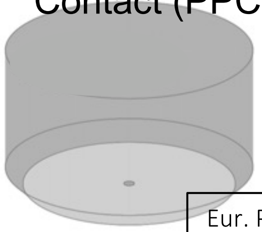
- Large mass (2-3 kg)
- Imperfect background rejection

IEEE Trans. on Nuc. Sci., 36, 1, 926-930 (1989)

GERDA Broad Energy Ge (BEGe)



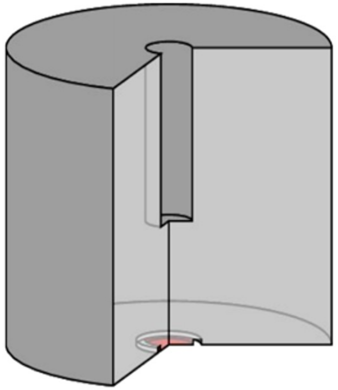
MAJORANA P-type Point Contact (PPC)



Eur. Phys. J. C 79, 978 (2019)

- Small mass (< 1 kg)
- Excellent background rejection

Inverted-Coaxial Point Contact (ICPC)



NIMA ,891, 106-110, (2018)

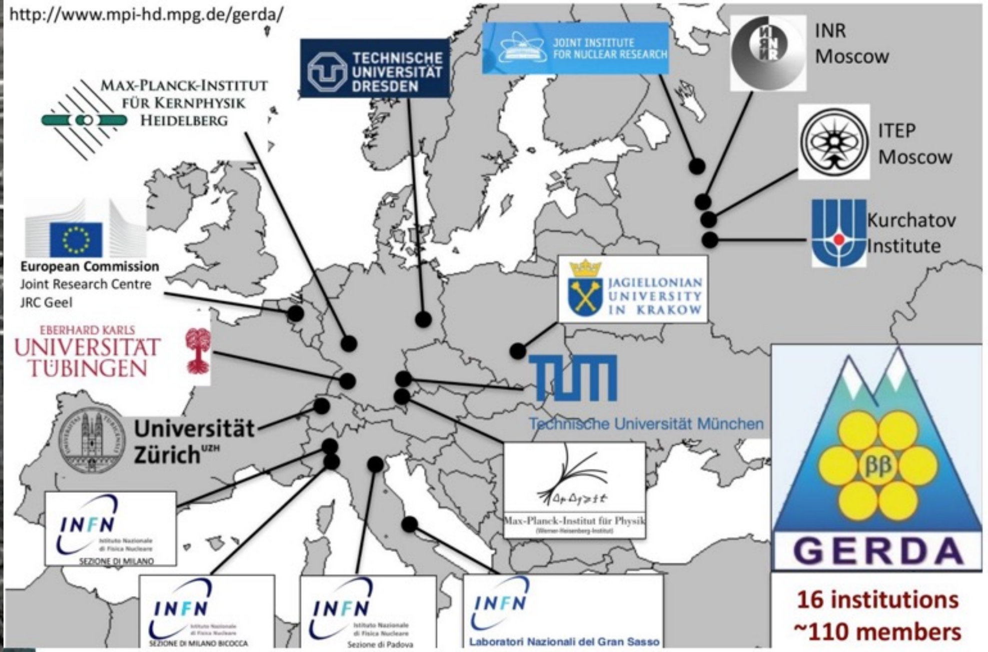
- Newly developed for LEGEND
- Large mass (up to 4 kg)
- Excellent background rejection

GERmanium Detector Array - GERDA Collaboration

https://www.aip.org/fyi/2022/doe-nuclear-physics-program-approaches-pivot-point

the GERDA *Collaboration*

(Image credit – © Kai Freund / LNGS-INFN)

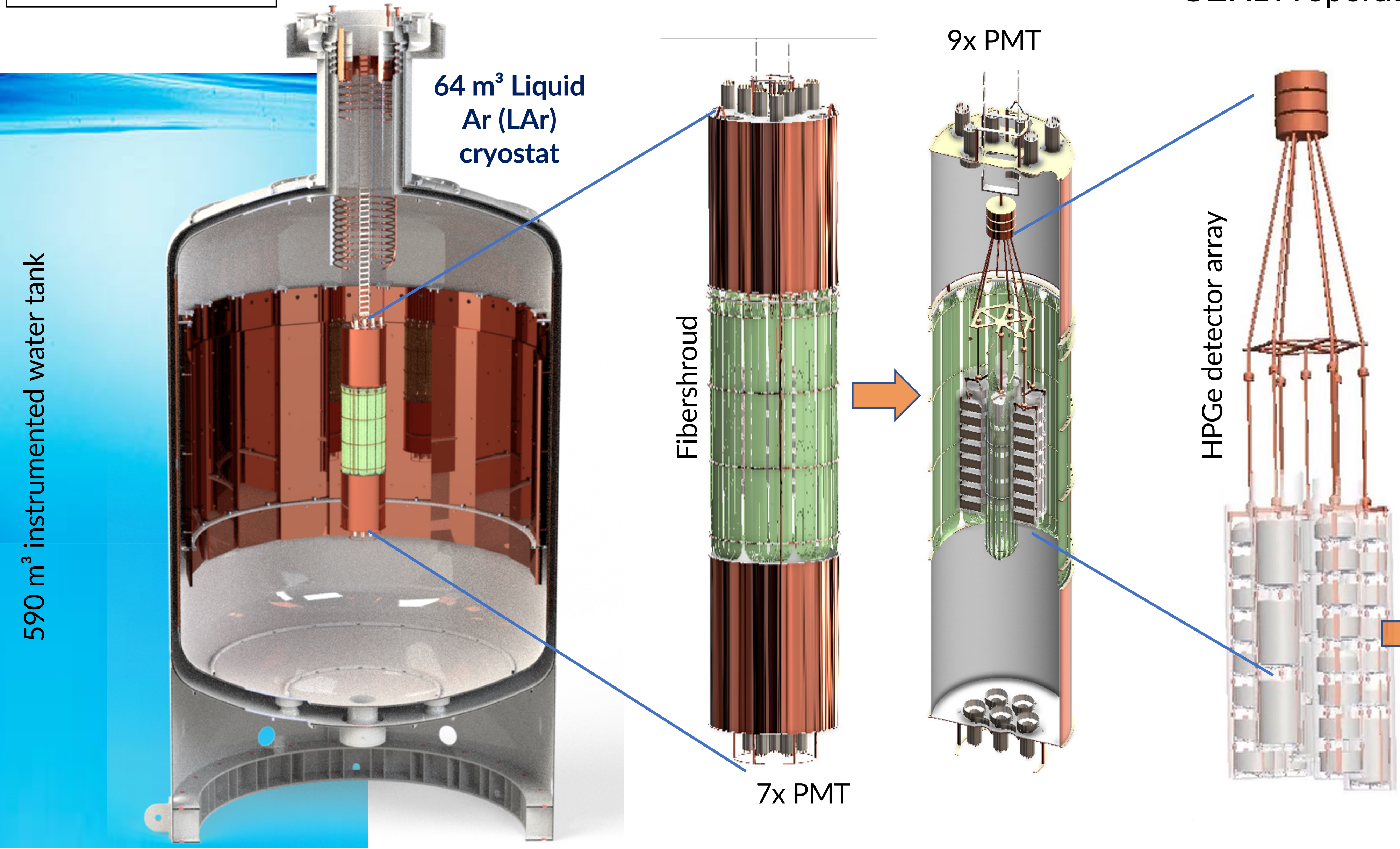


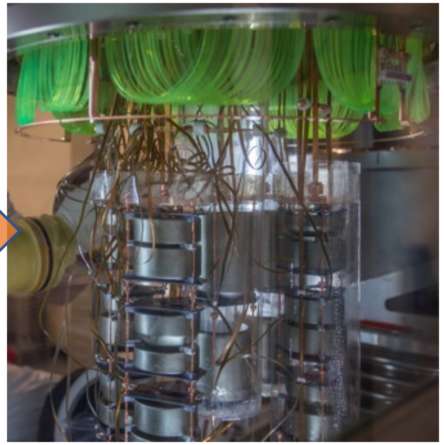
L Shtembari, ICHEP 2022

GERDA at Gran Sasso National Laboratory (LNGS)

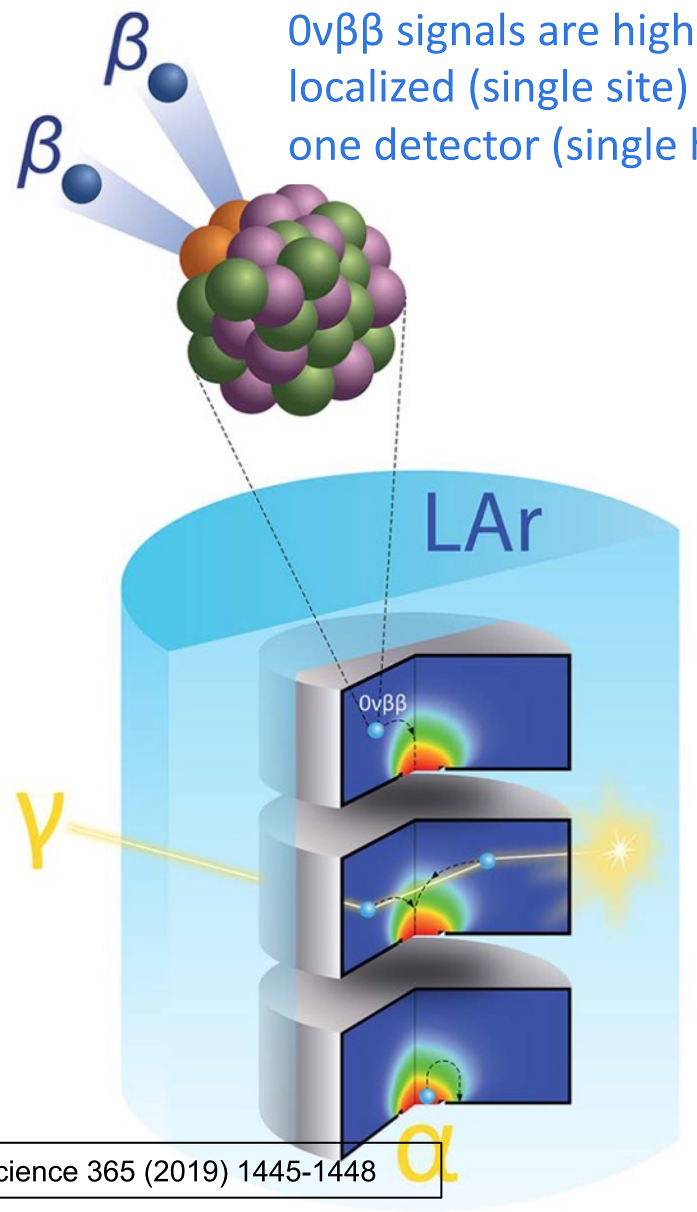
EPJC 78, 388 (2018)

- GERDA operated an active LAr veto
- Low-Z shielding





GERDA Background Rejection Strategy



0νββ signals are highly localized (single site) in one detector (single hit)

0νββ signals

Multi-site backgrounds

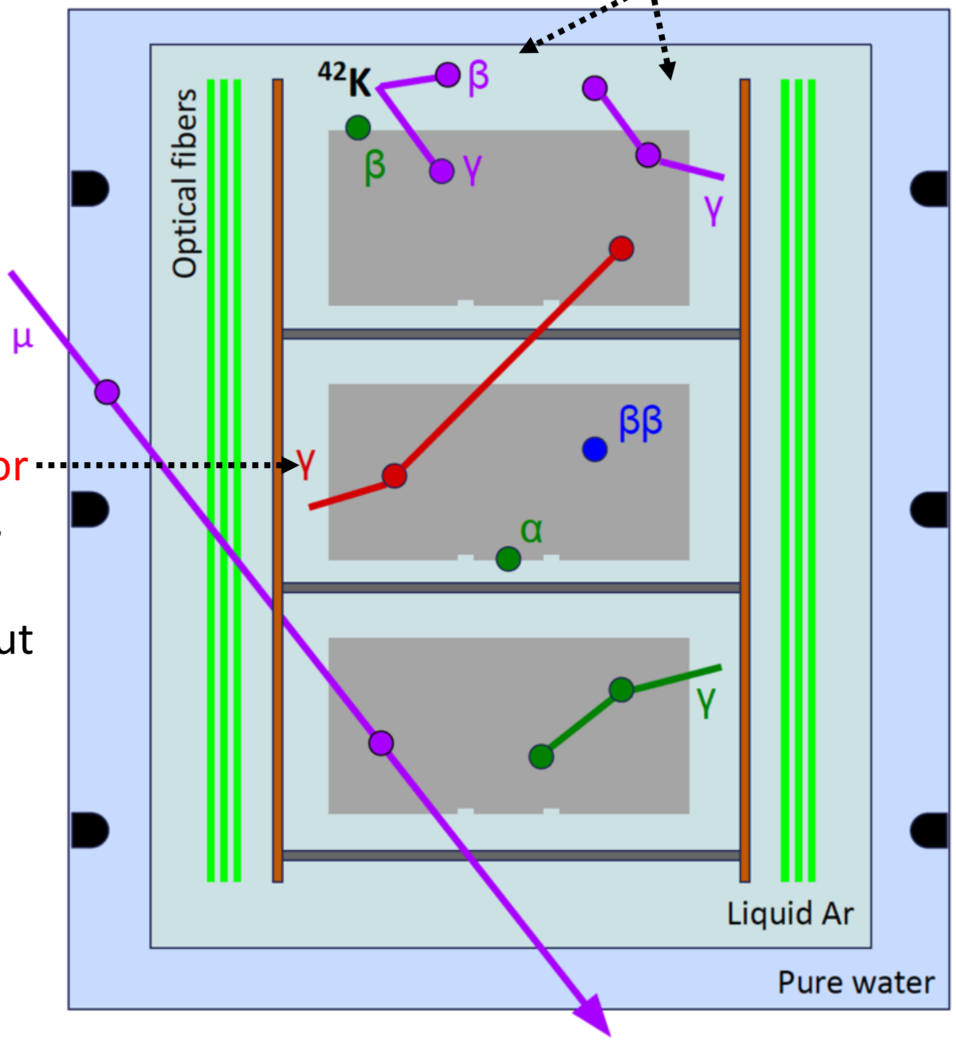
Surface backgrounds

Rejected by Pulse Shape Analysis

Science 365 (2019) 1445-1448

Backgrounds with energy depositions in LAr, rejected by LAr veto

Multi-detector backgrounds, rejected by multiplicity cut



muon backgrounds, rejected by muon veto

Pulse Shape Analysis (PSA) for HPGe detectors

Amplitude of current pulse is suppressed for a multi-site event compared to a single-site event of the same event **E**nergy

Comparing **A** against **E** effectively rejects multi-site backgrounds

Various powerful PSA event topology tools can be used to reject different backgrounds

Alternative machine learning algorithms are available

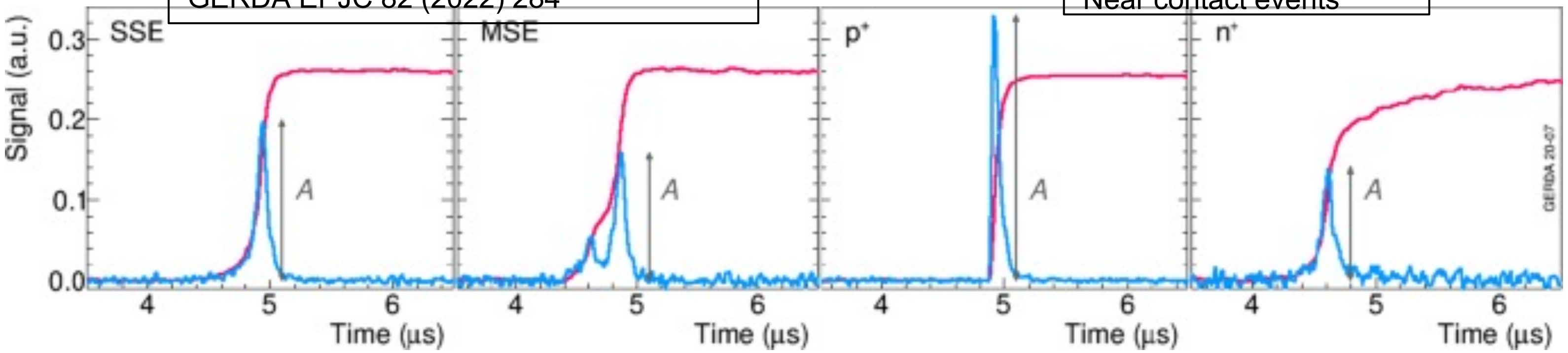
GERDA EPJC 82 (2022) 284

MAJORANA arXiv: 2207.10710

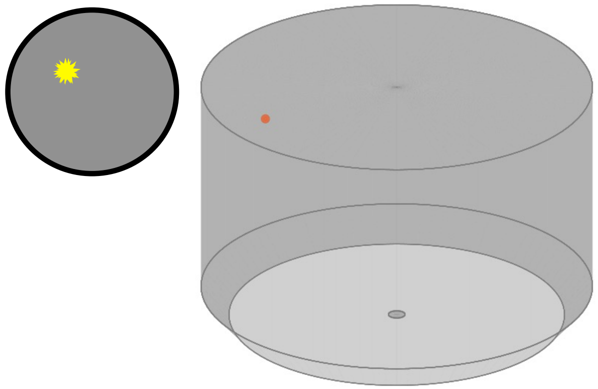
Also see L. Paudel
***Pulse-Shape-Based Analysis using Machine learning in the MAJORANA DEMONSTRATOR*,**
Nu session Aug. 30th

GERDA EPJC 82 (2022) 284

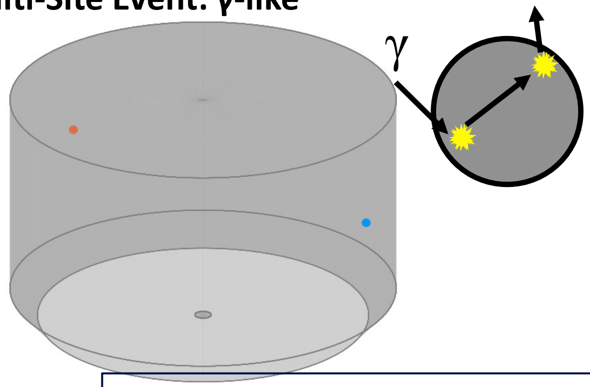
Near contact events



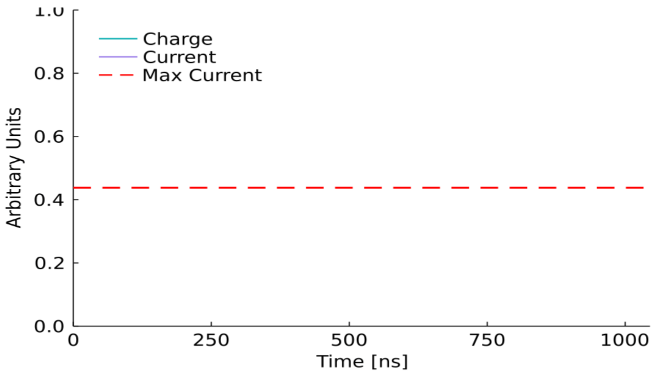
Single-Site Event (SSE):0νββ-like

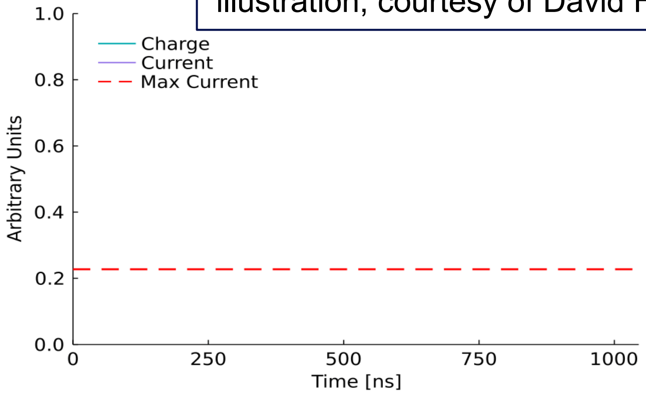


Multi-Site Event: γ-like

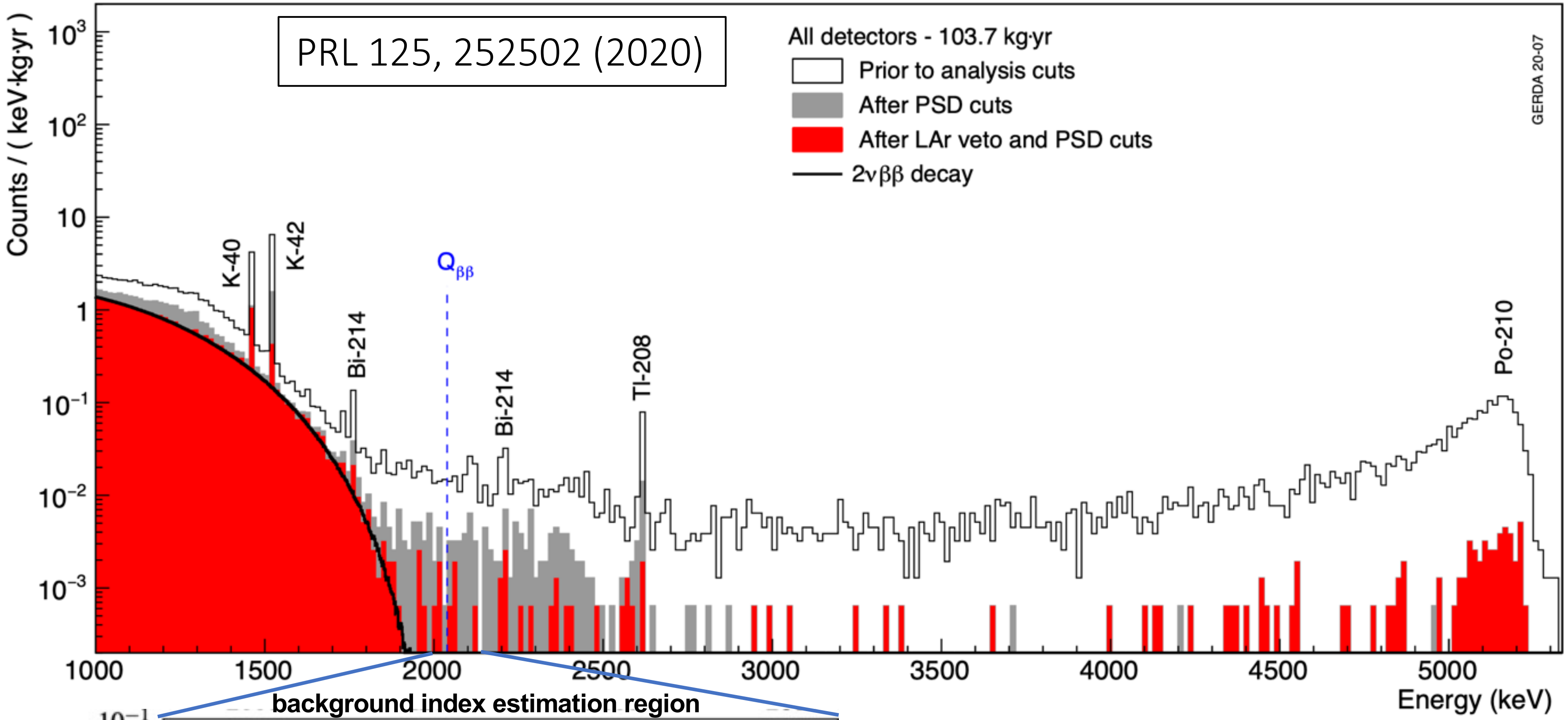


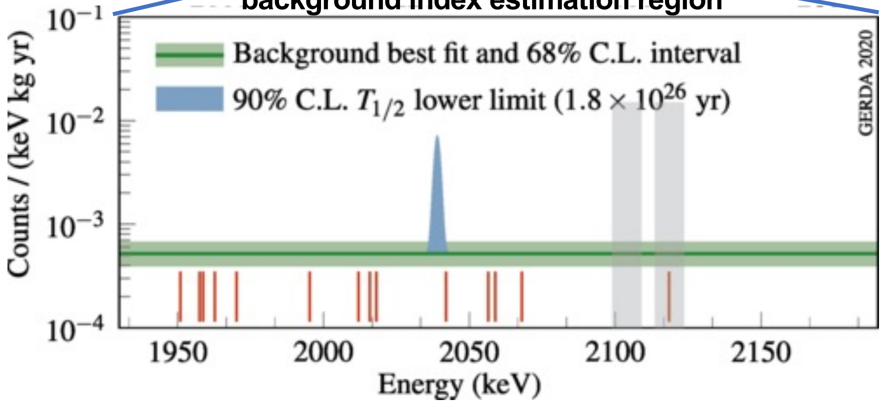
Simulations for MAJORANA PPC for illustration, courtesy of David Hervas.





Final Results of GERDA





Background index:
$5.2^{+1.6}_{-1.3} \cdot 10^{-4}$
cts/(keV kg yr)

Energy resolution:

~2.6 keV (FWHM)

Frequentist limit:

$T_{1/2} > 1.8 \cdot 10^{26}$ yr at 90% C.L.

Bayesian: flat prior on rate:

$T_{1/2} > 1.4 \cdot 10^{26}$ yr at 90% C.I.

$m_{\beta\beta}$ < 79 - 180 meV

GERDA finished by surpassing all design goals:
100 kg yr exposure , < 10^{-3} cts/(keV kg yr) background, >10^{26} yr sensitivity

Lowest background for 0νββ searches if normalized by the energy resolution

The MAJORANA DEMONSTRATOR

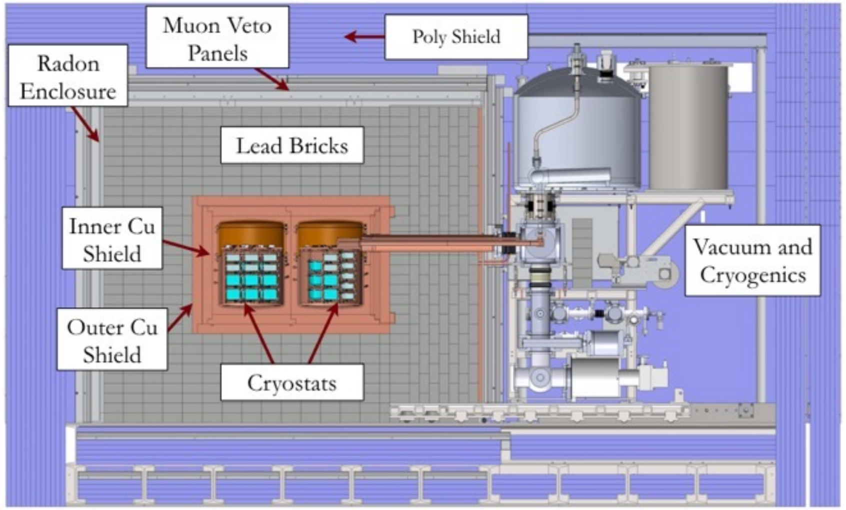
Searching for neutrinoless double-beta decay of ^{76}Ge in HPGe detectors, probing additional physics beyond the standard model, and informing the design of the next-generation LEGEND experiment

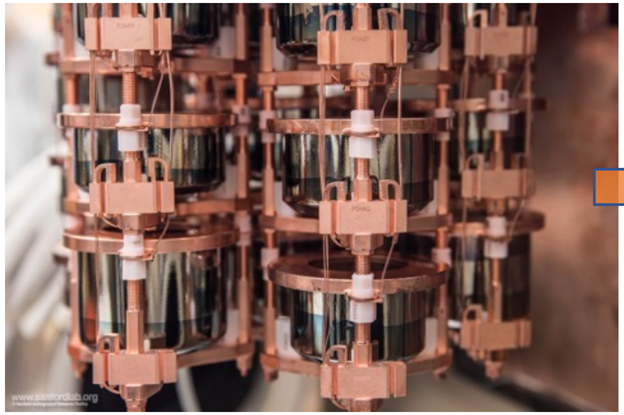
Source & Detector: Array of p-type, point contact detectors
30 kg of 88% enriched ^{76}Ge crystals - 14 kg of natural Ge crystals
Included 6.7 kg of ^{76}Ge inverted coaxial, point contact detectors in final run

Excellent Energy Resolution: 2.5 keV FWHM @ 2039 keV
and **Analysis Threshold:** 1 keV

Low Background: 2 modules within a compact graded shield and active muon veto using ultra-clean materials

Reached an exposure of ~65 kg-yr before removal of the enriched detectors for the LEGEND-200 experiment at LNGS





Continuing to operate at the Sanford Underground Research Facility with natural detectors for background studies and other physics

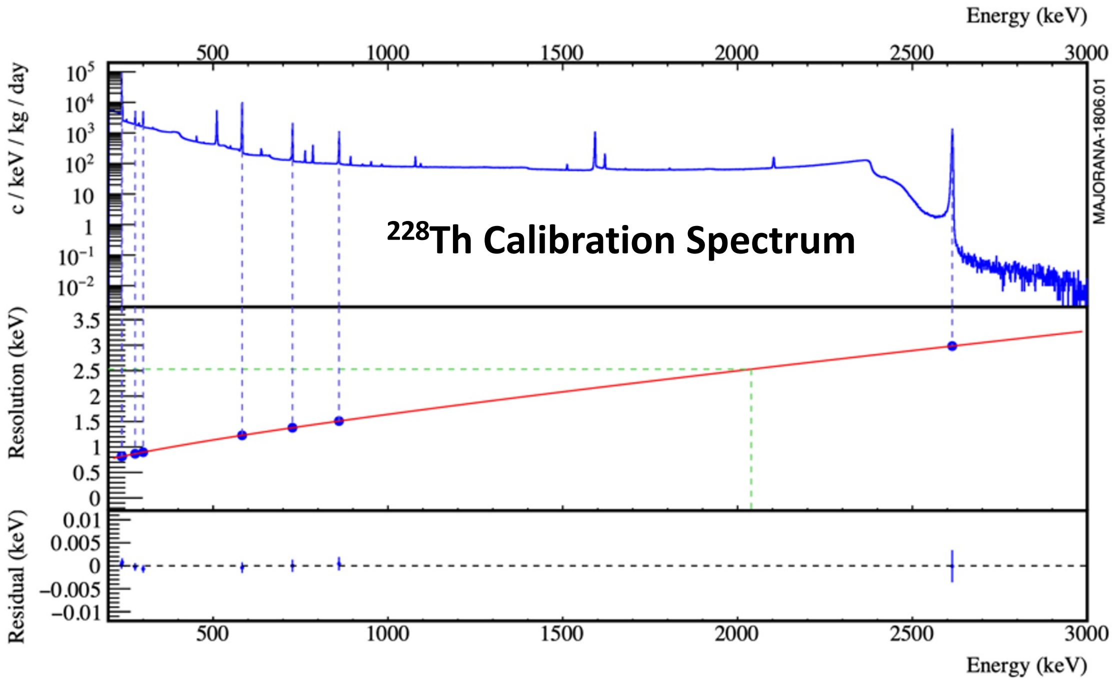
See W. Pettus,
***Final Results from the MAJORANA DEMONSTRATOR*,**
Plenary session, Sept. 03

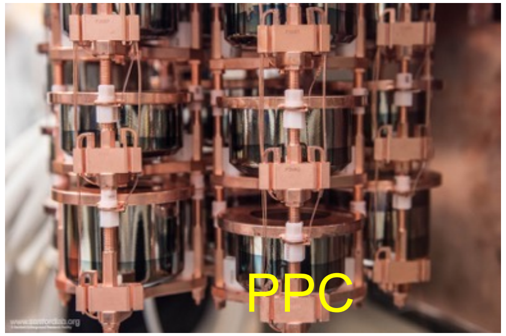
the MAJORANA *Collaboration*

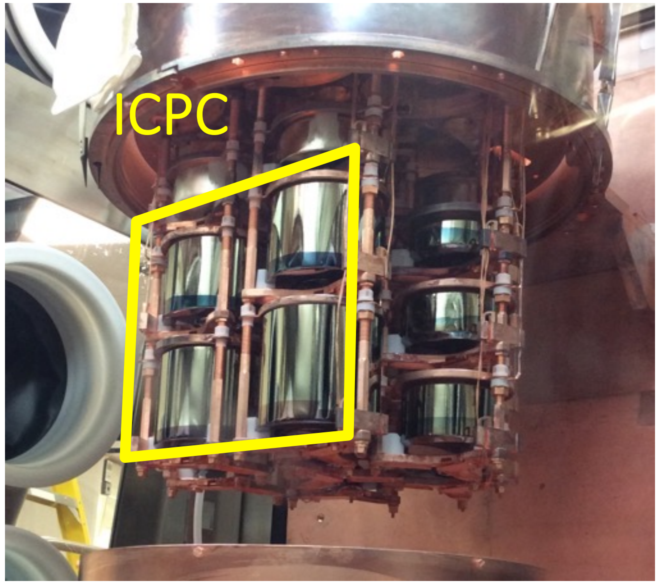
Superb Energy Resolution for Unambiguous Discovery

FWHM of 2.5 keV at $Q_{\beta\beta}$ of 2039 keV (0.12%)

Best energy resolution for 0νββ searches







MAJORANA also operated 4 LEGEND ICPC detectors

- Larger range of drift times requires new analysis techniques
- Combined energy resolution of ICPCs is 2.55 keV FWHM at 2039 keV

Less than 0.1 keV energy scale offset at low energy 1 keV~10keV
Important for BSM physics

NIMA 872 (2017) 16

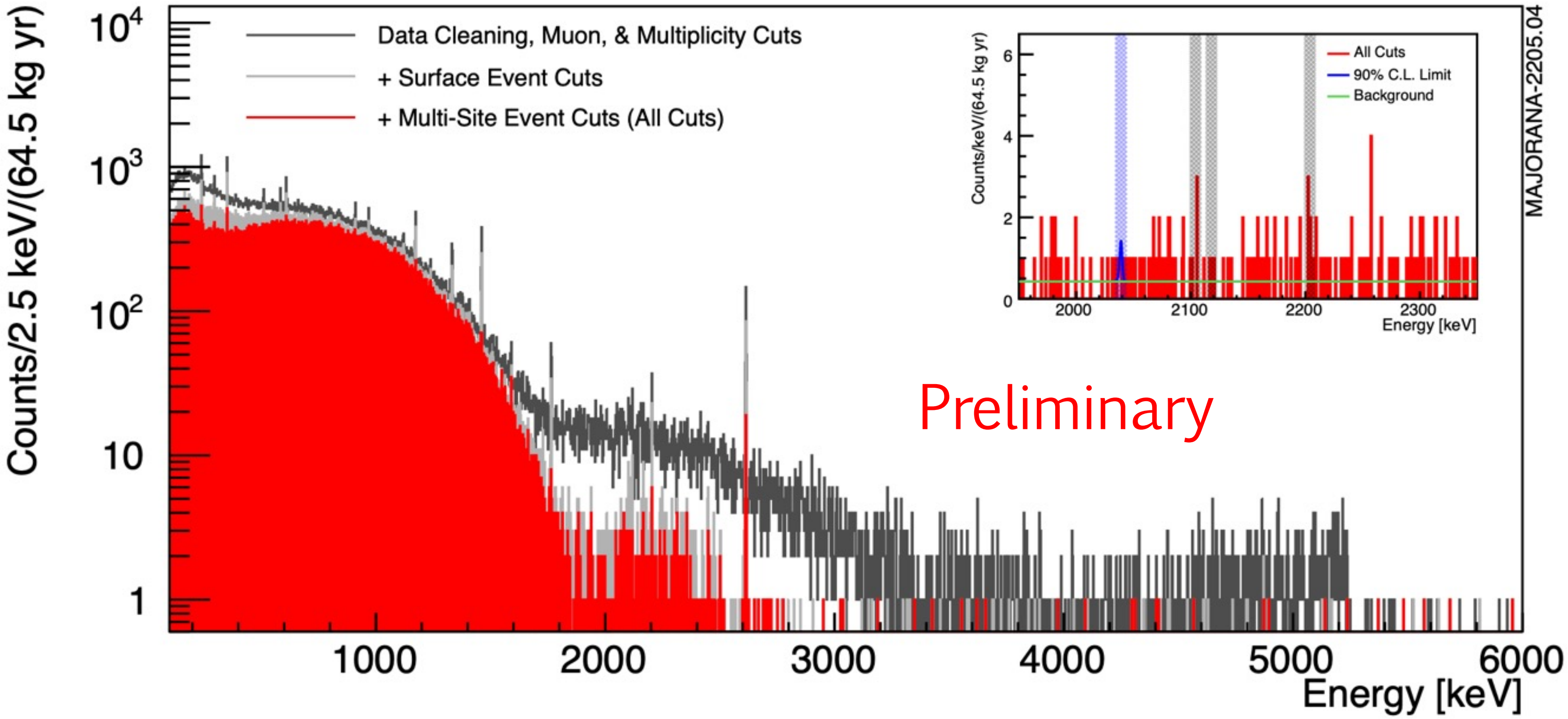
JINST 17 T05003 (2022)

IEEE Trans. Nucl. Sci. 68 (2021) 359

Final Results of MAJORANA DEMONSTRATOR

Operated in a low background regime, particularly with extreme radiopurity of near-detector parts, benefiting from excellent energy resolution

arXiv: 2207.07638



Full spectrum with a total of 65 kg-yr.

Final enriched detector active exposure:

64.5 ± 0.9 kg yrs

Background Index:

$(6.2 \pm 0.6) \times 10^{-3}$ cts/(keV kg yr)

Energy resolution:

2.5 keV FWHM @ $Q_{\beta\beta}$

Frequentist Limit:

Limit: $T_{1/2} > 8.3 \times 10^{25}$ yr (90% C.L.)

Bayesian Limit: (flat prior on rate)

Limit: $T_{1/2} > 7.0 \times 10^{25}$ yr (90% C.I.)

$m_{\beta\beta} < 113 - 269$ meV

Using $M_{0\nu} = 2.66 - 6.34$

Continuing to operate at the Sanford Underground Research Facility with natural detectors for background studies and other physics

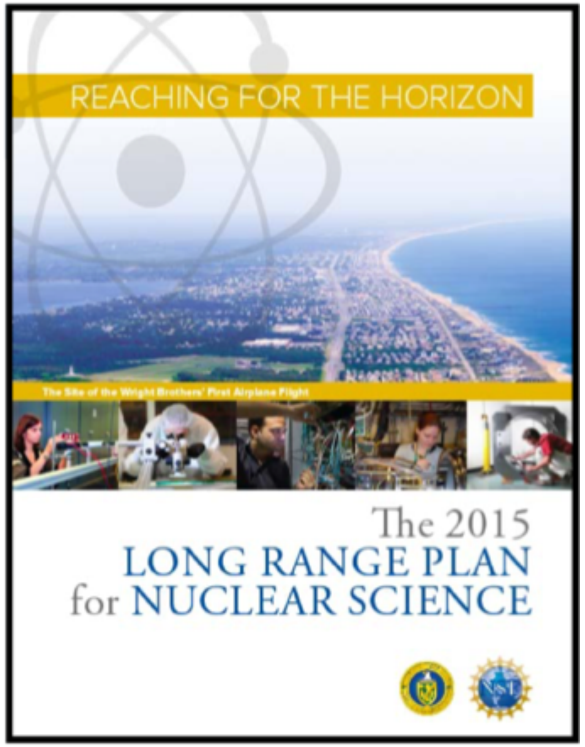
Part III
LEGEND for the Discovery of Neutrinoless Double-Beta Decay

Large Enriched Germanium Experiment for Neutrinoless ββ Decay
(LEGEND)

The European and North-American Process

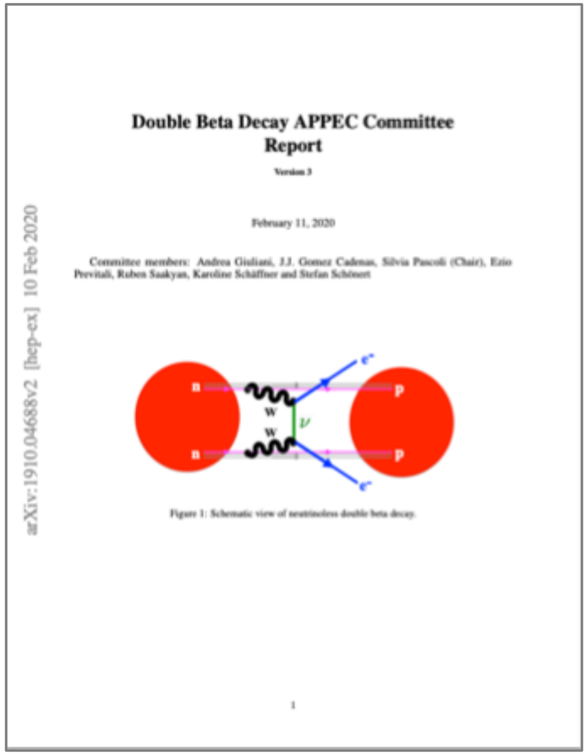
Compiled by S. Schönert @ Neutrino 2022

https://science.osti.gov/np/nsac



"We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment."

https://arxiv.org/abs/1910.04688



arXiv:1910.04688v2 [hep-ex] 10 Feb 2020

Double Beta Decay APPEC Committee Report

Version 3

February 11, 2020

Committee members: Andrea Giuliani, J.J. Gomez Cadenas, Silvia Pascoli (Chair), Ezio Previtali, Ruben Saakyan, Karoline Schäffner and Stefan Schönert

Figure 1: Schematic view of neutrinoless double beta decay.

1

- Oct 2019: Roadmap document for the APPEC SAC on the future $0\nu\beta\beta$ decay experimental programme in Europe
- $0\nu\beta\beta$ town meeting London
- Roadmap update 2022, town meeting in Berlin, June 2022

DOE NP Portfolio Review
July 2021
CUPID
LEGEND-1000
nEXO

- Outcome: Realize international portfolio LEGEND-1000, nEXO and CUPID with European partners
- LEGEND-1000 was evaluated extremely positively at the Portfolio review. Now being funded by DOE to move to the next step, CD-1

https://agenda.infn.it/event/27143/

"The international stakeholders in neutrino-less double beta decay research do agree in principle that the best chance for success is an international campaign with more than one large ton-scale experiment implemented in the next decade, with one ton scale experiment in Europe and the other in North America. "

LEGEND

Mission: “The collaboration aims to develop a phased, **Ge-76 based** double-beta decay experimental program with discovery potential at a **half-life beyond 10^{28} years, using existing resources as appropriate to expedite physics results**.”

Build upon best and proven technologies from GERDA and the MAJORANA DEMONSTRATOR

MAJORANA
- Radiopurity of nearby parts (FETs, cables, Cu mounts, etc.)
- Low noise electronics improves PSD
- Low energy threshold (helps reject cosmogenic background)

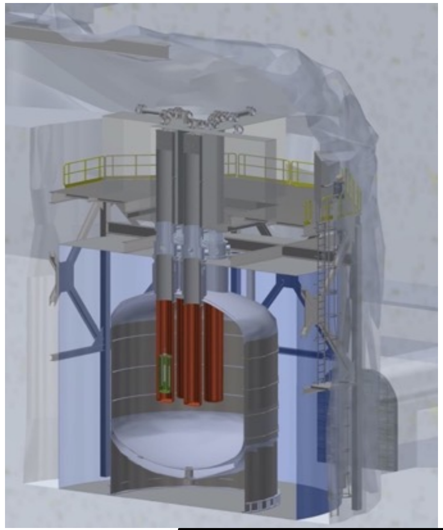
GERDA
- LAr veto
- Low-A shield, no Pb

Both
- Clean fabrication techniques
- Control of surface exposure
- Development of large point-contact detectors
- **Lowest background and best resolution $0\nu\beta\beta$ experiments**

LEGEND-200
- 200 kg in upgrade of existing infrastructure at LNGS
- Background goal:

  < 0.6 cts/(FWHM t yr)

  i.e. < 2×10^{-4} cts/(keV kg yr)
- Discovery sensitivity 10^{27} years
- Currently commissioning
- Physics data starting in 2022



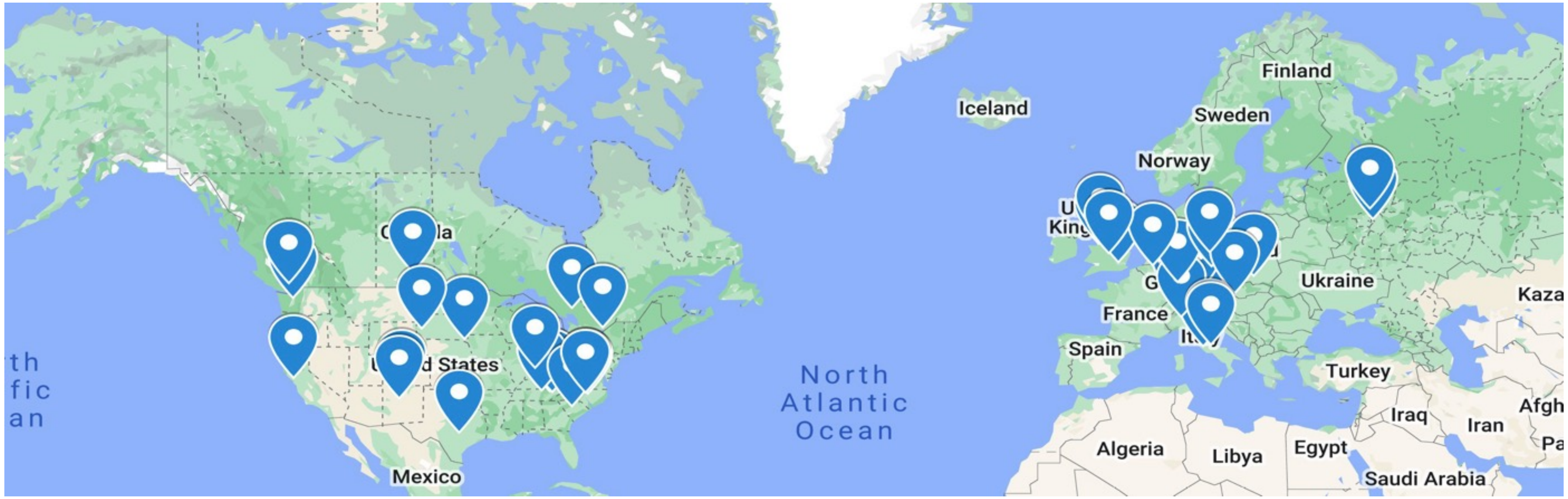
LEGEND-1000
- 1000 kg, staged via individual payloads
- Timeline connected to review process
- Background goal:

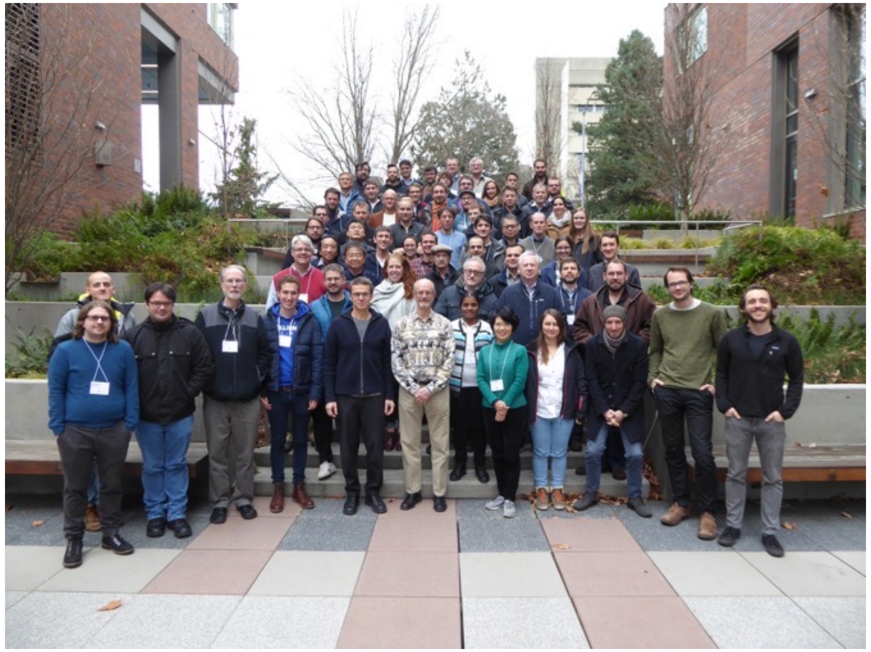
  <0.025 cts/(FWHM t yr)

  i.e. <1×10^{-5} cts/(keV kg yr)
- Discovery sensitivity beyond 10^{28} years
- Location to be selected

Preconceptual Design Report arXiv: 2107.11462

The LEGEND Collaboration





Approximately 250 members,

49 institutions,

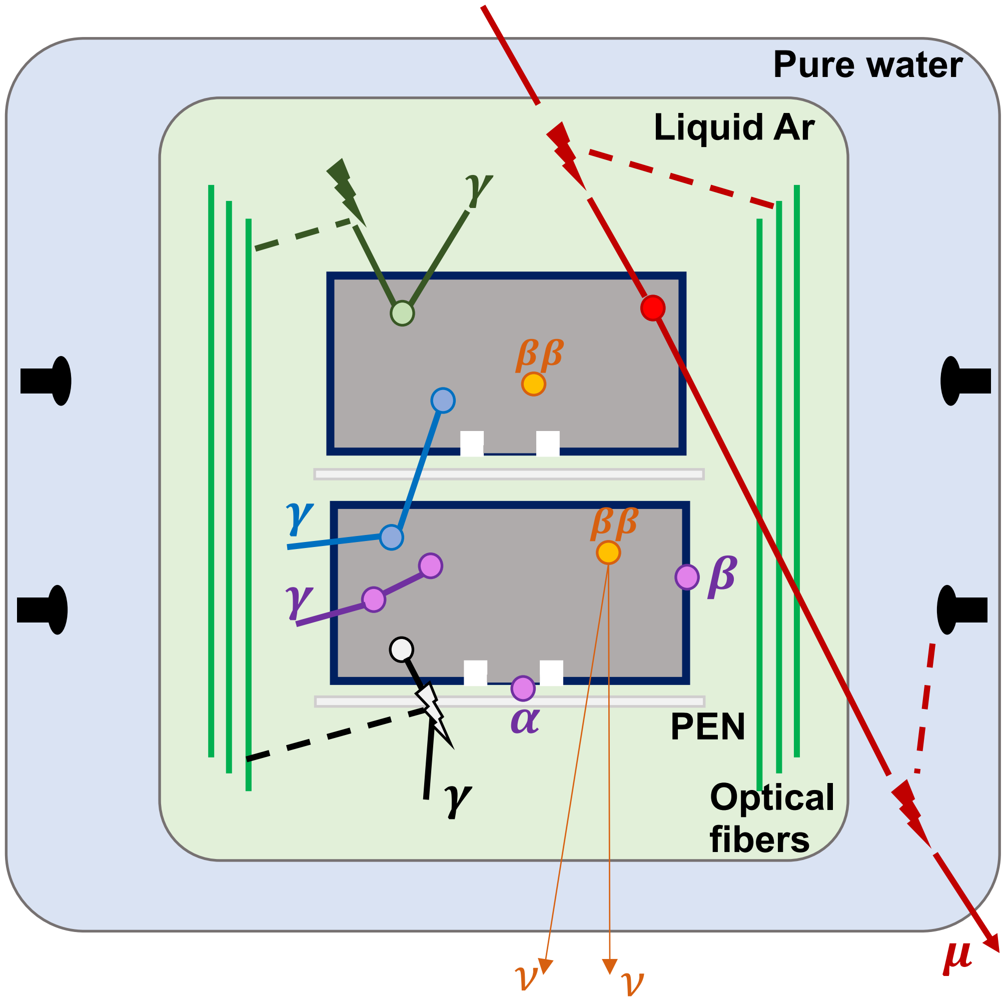
11 countries

https://legend-exp.org/

LEGEND Background Rejection

$\beta\beta$ decay signal: single energy deposition in a 1 mm^3 volume

Ge detector with PEN plate holders



Pulse shape discrimination (PSD) for multi-site and surface α events

Ge detector anti-coincidence

Scintillating PEN plate holder under test

LAr veto based on Ar scintillation light read by fibers and SiPM

Muon veto

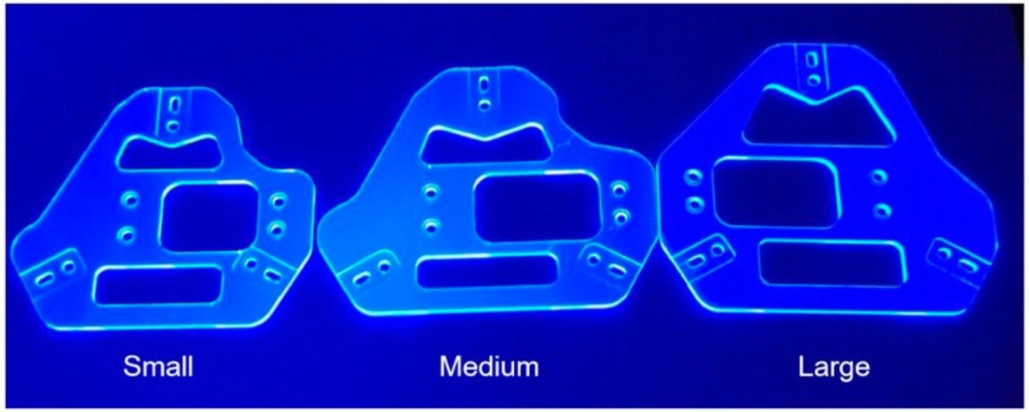
LEGEND-200 background goal is x2.5 reduction from GERDA

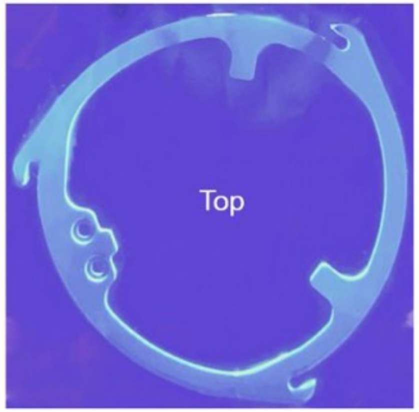
LEGEND-1000 background goal is x20 reduction from LEGEND-200

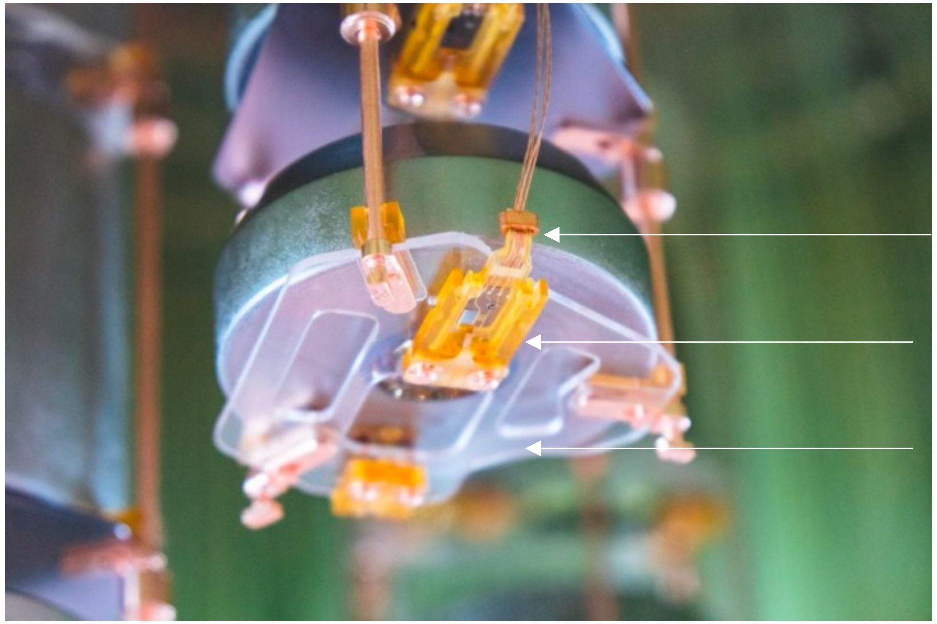
Background Reduction: PEN Holding Structures

Polyethylene naphthalate (PEN). Scintillating plastic/active material

JINST 17, P01010 (2022)







Testing Ge detector

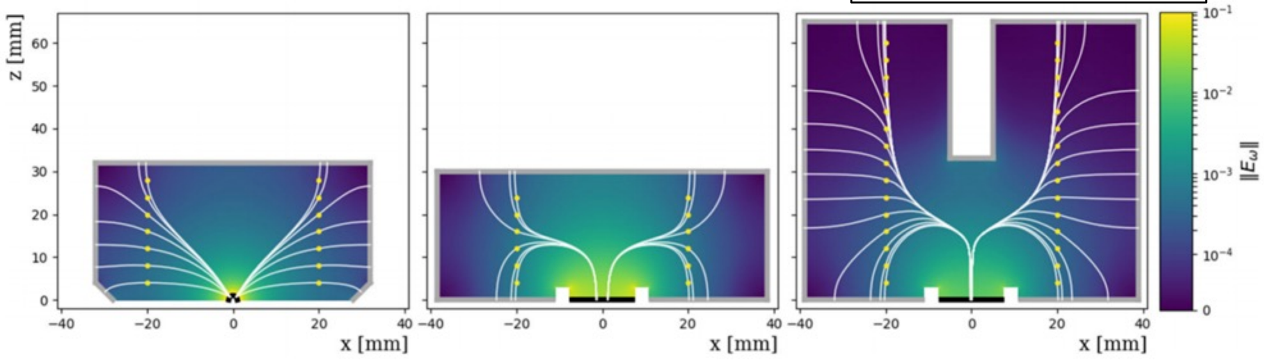
Low-mass front-end electronics

PEN plate

Adapted from F. Hagemann, 18th Rencontres du Vietnam on Neutrino Physics 2022

Background Reduction: LEGEND-1000

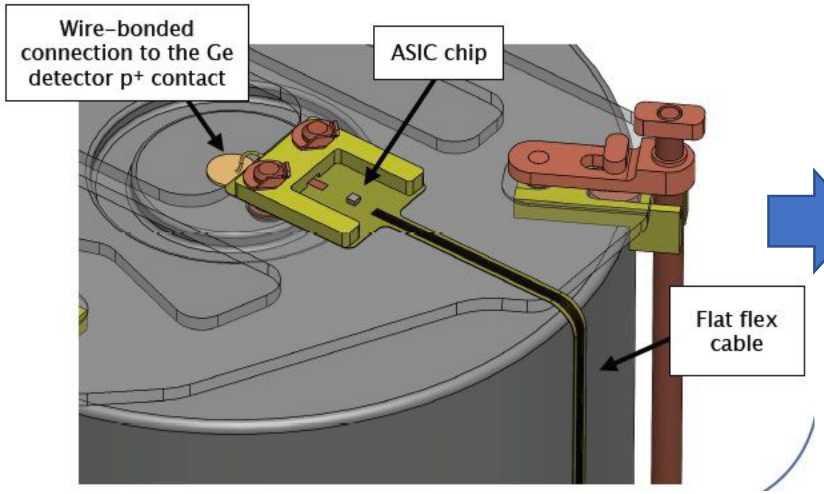
Eur. Phys. J. C 81, 76 (2021)



MAJORANA PPC GERDA BEGe
Used by LEGEND-200 as well

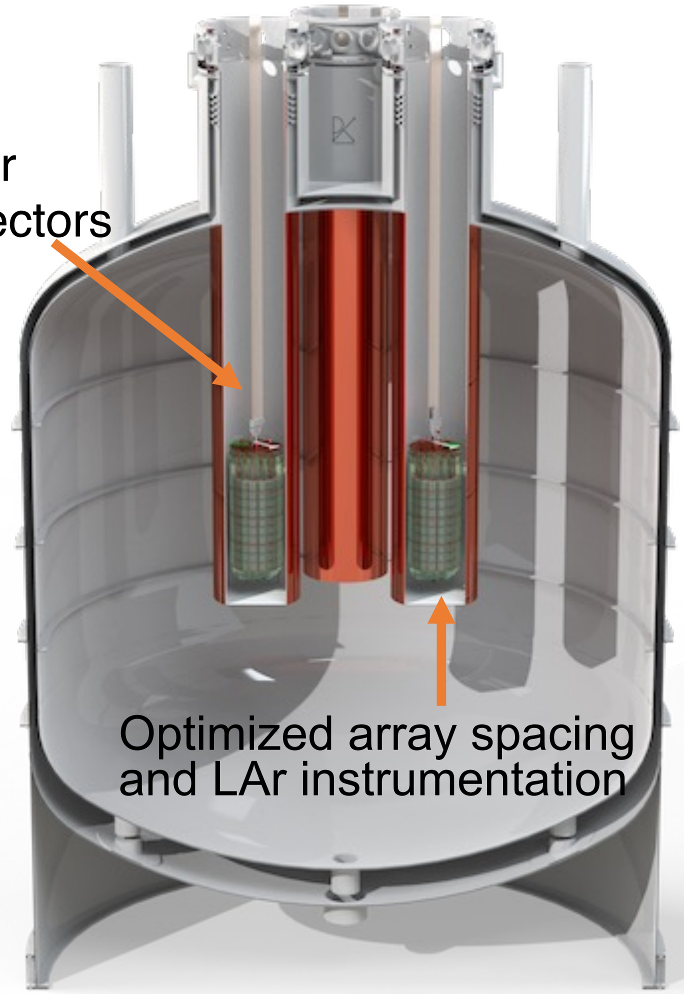
LEGEND-1000 uses only larger ICPC detectors, average 2.6 kg

Significant reduction of number of channels and hence total radioactivity to near-detector materials



New and less-radioactive cables and new application-specific integrated circuit (ASIC) read-out for LEGEND-1000

Underground LAr surrounding detectors

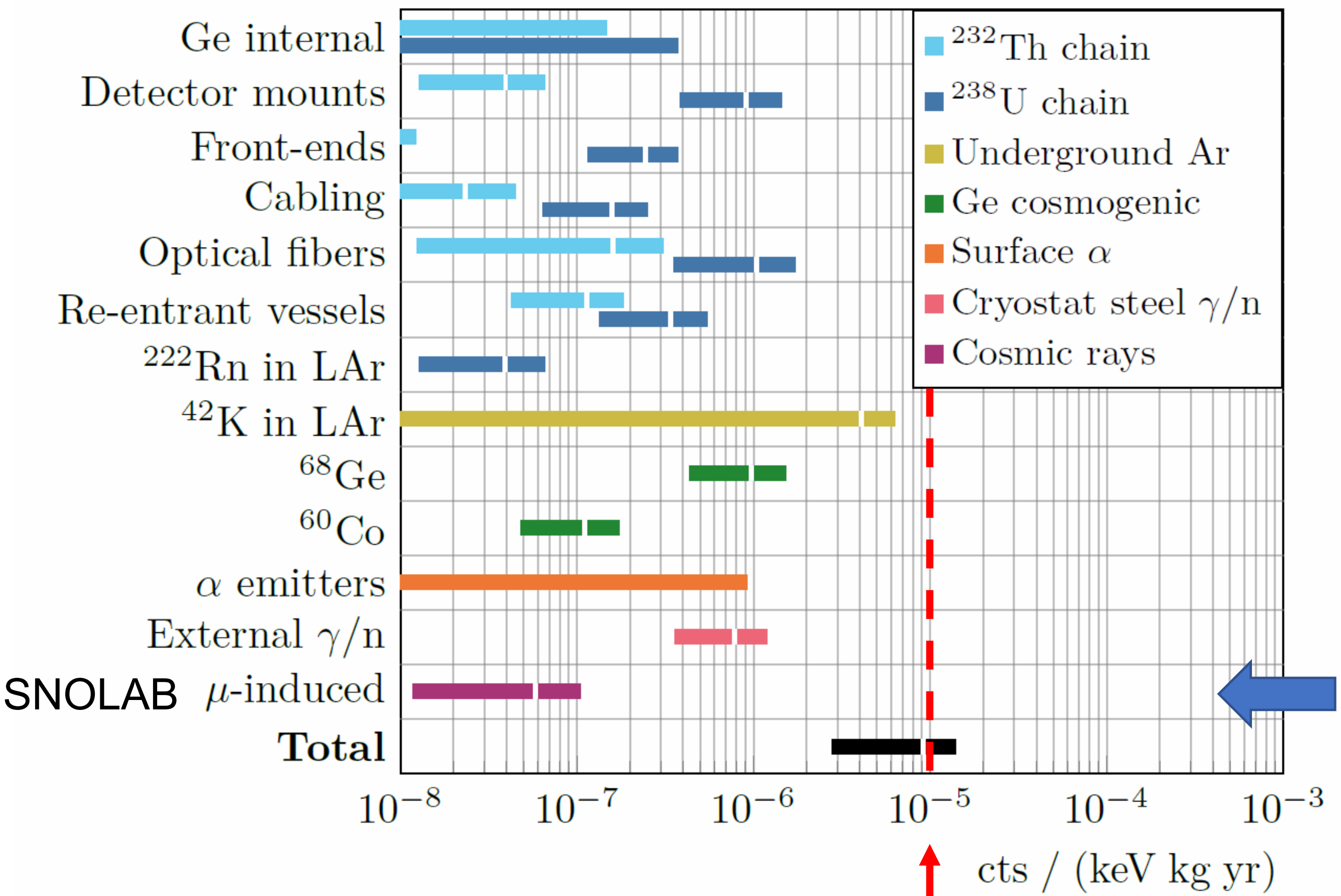


Optimized array spacing and LAr instrumentation

Deeper underground site or additional neutron shielding & tagging: SNOLAB and LNGS options

LEGEND-1000 Background Projections

Background index at $Q_{\beta\beta}$ after all cuts



LEGEND-1000 background goal

arXiv: 2107.11462

Projected background index after all cuts:

$$9.1^{+4.9}_{-6.3} \times 10^{-6} \text{ counts/(keV kg yr)}$$

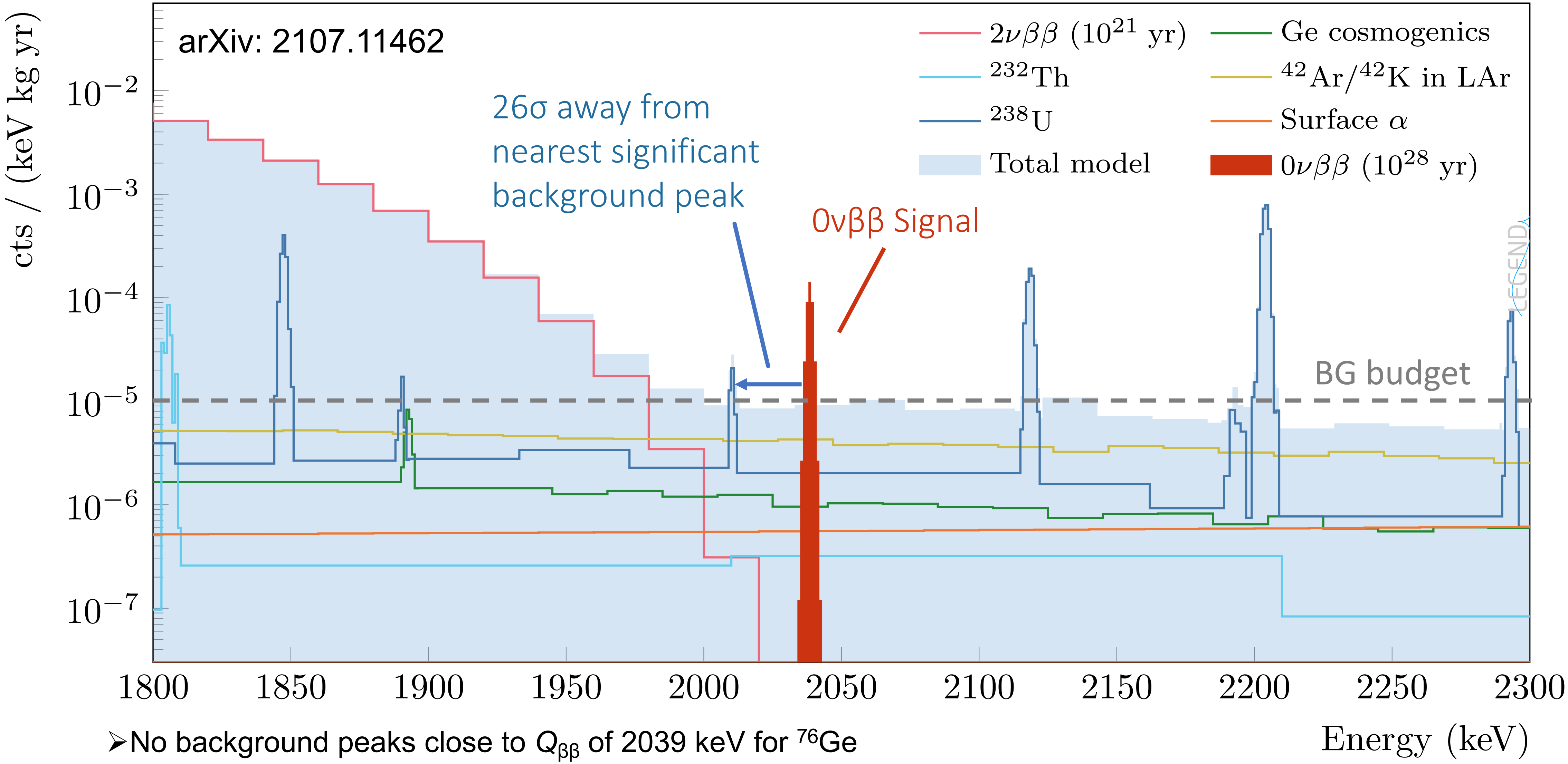
See C. Barton

An update on muon-induced backgrounds in LEGEND-1000

Nu session Aug. 30th

for details on muon-induced backgrounds and additional neutron shielding for LNGS option.

The LEGEND-1000 Background Model

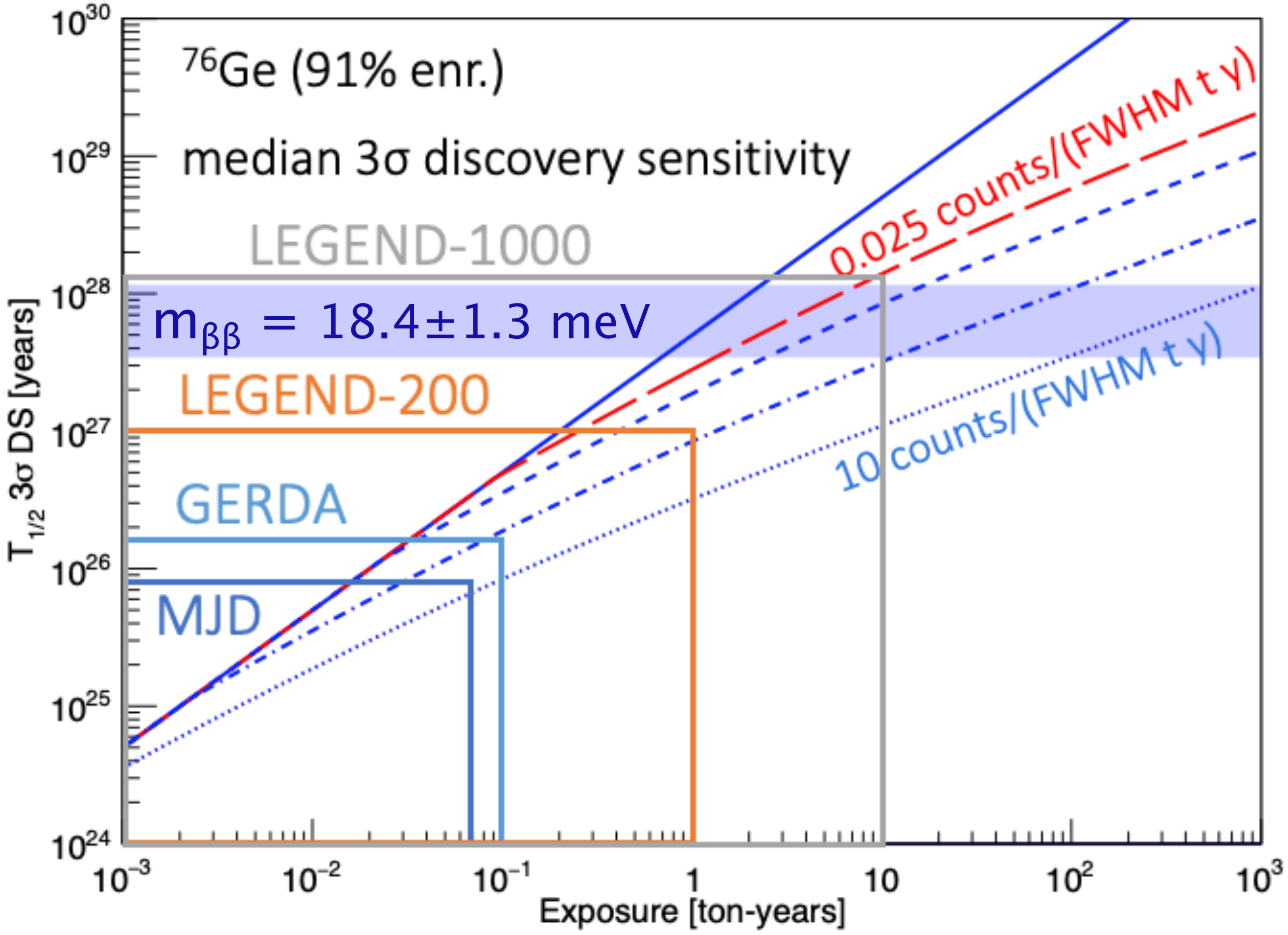


- No background peaks close to $Q_{\beta\beta}$ of 2039 keV for ^{76}Ge
- Background is flat and well understood. No reliance on background modeling
- No 2νββ background

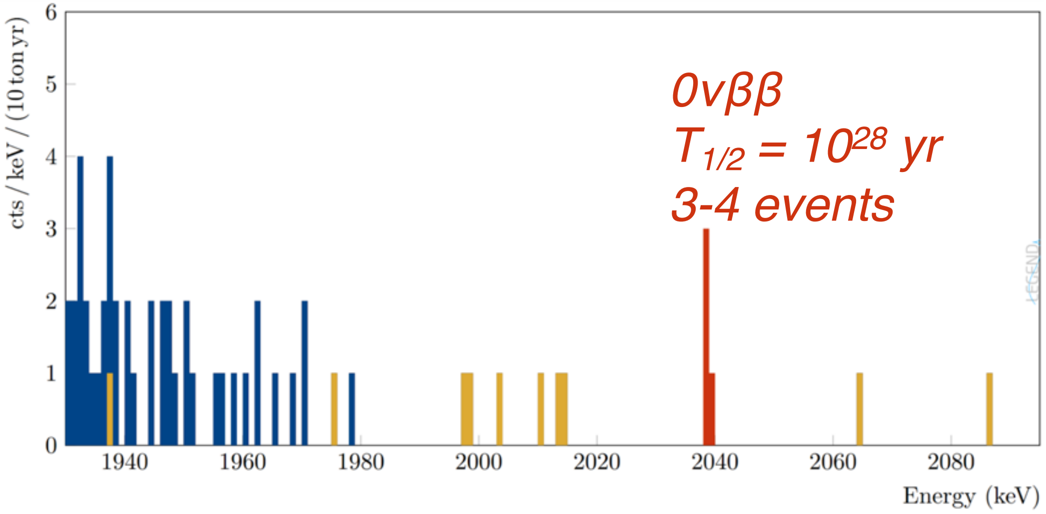
Discovering Sensitivity Enabled

The LEGEND program builds on successes of current generation experiments to probe half-lives beyond 10^{28} yrs

- Unambiguous discovery enabled by best energy resolution and lowest background



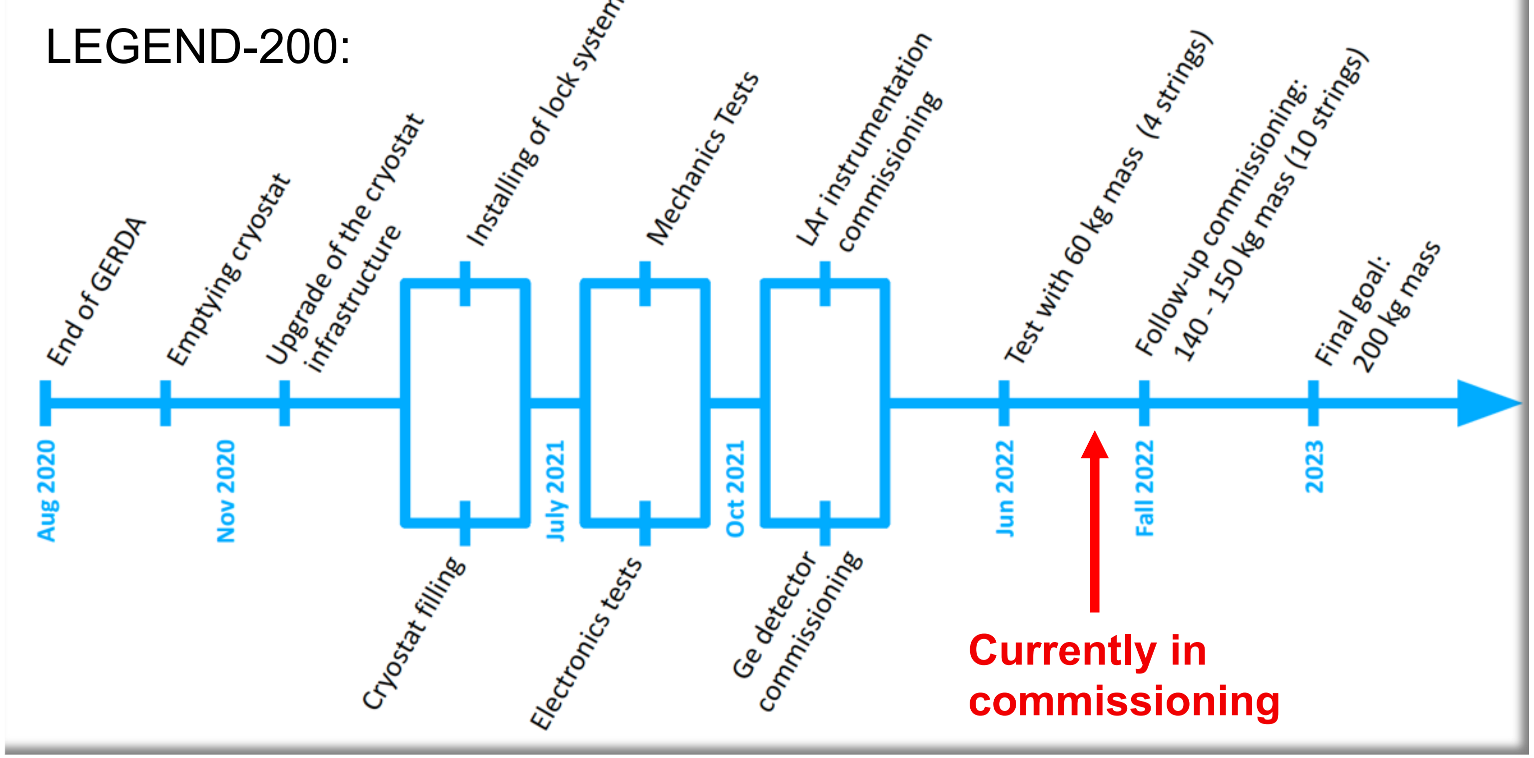
Simulated LEGEND-1000 example spectrum for $T_{1/2} = 10^{28}$ yrs, BI < 10^{-5} cts/keV kg yr, after cuts, from 10 years of data



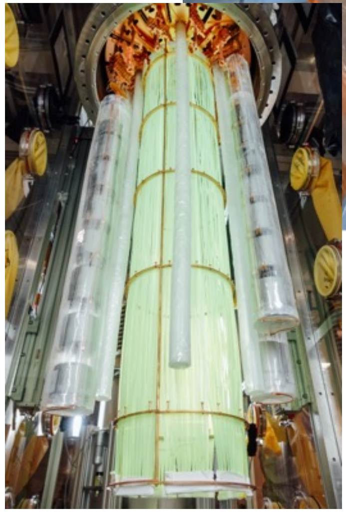
Quasi-background free operation up to 10 ton-year exposure, for unambiguous convincing discovery beyond 10^{28} years

LEGEND Timelines

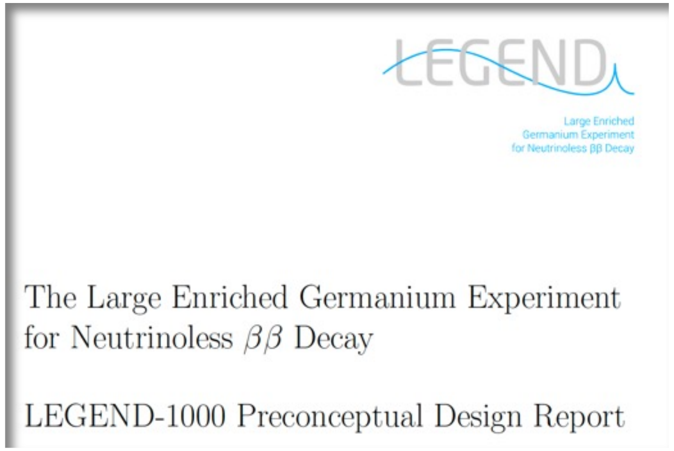
Adapted from F. Hagemann, 18th Rencontres du Vietnam on Neutrino Physics 2022



WaveLength-Shifting Reflector (WSLR) installed



4 string installed with optical fibers



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

LEGEND-1000 Preconceptual Design Report

LEGEND-1000:

- Pre-Conceptual Design Report released:
  arXiv: 2107.11462
- Developing a conceptual design with a refined technical design and background model, proceeding to CD-1
- R&D activities are ongoing

Part IV
LEGEND Physics Beyond Neutrinoless Double-Beta Decay

Rich and Broad Physics Programs at LEGEND-1000

Fundamental Symmetries

- **L violation in 0νββ decays**
- **B violation in Baryon decays**
- **Pauli Exclusion Principle violation**
- **Lorentz violation and Majorons in 2νββ**
- **BSM Physics in Ar**
- **Charge violation**

^{39}Ar reduction due to the use of underground-sourced argon enables a suite of BSM physics searches

Standard Model Nuclear Physics

- **2νββ decays**
- **In-situ cosmogenics**
- **neutron physics**

Superb Energy Resolution
High Granularity
Low Backgrounds

Dark Matter Signatures

- **Pseudoscalar dark matter**
- **Vector dark matter**
- **Fermionic dark matter**
- **Sterile neutrino**
- **Solar Axions**

Exotic Physics

- **Lightly ionizing particles**
- **Quantum Wavefunction collapse**

+ Prompt Supernova Neutrinos, SuperWIMPS, Solar Neutrinos, …

BSM Physics

Superb Energy Resolution, High Granularity, and Low Backgrounds make HPGe detectors excellent in a range of BSM physics searches using analyses looking at peaks, spectral distortion, time correlation, and more

Non-inclusive list of examples

Mechanism	Signature	Energy range
Bosonic Dark Matter	Peak at m_b	5 — 100keV
Baryon Decay	Time Correlation, High Energy	0-10 MeV
Fractionally Charged Cosmic rays	High Multiplicity-coincidence events	Few keV
WIMP searches	Exponential Excess + Annual Modulation. Migdal Effect	< 10 keV
Solar axions	Peaked Spectra + daily modulation	< 10 keV
Majoron Emission	2νββ spectral distortion	$Q_{\beta\beta}$
Lorentz Violation	2νββ spectral distortion	$Q_{\beta\beta}$
Electron Decay	Peak at 11.8 keV	~10 keV
Pauli Exclusion Principle Violation	Peak at 10.6 keV	~ 10 keV

These BSM Physics are parts of the rich and broad physics programs of LEGEND-1000

Rich and Broad Physics with HPGe detectors: Examples

BSM Physics

Temporal-Energy solar axion analysis at low energy region ~ keV

On the Cover

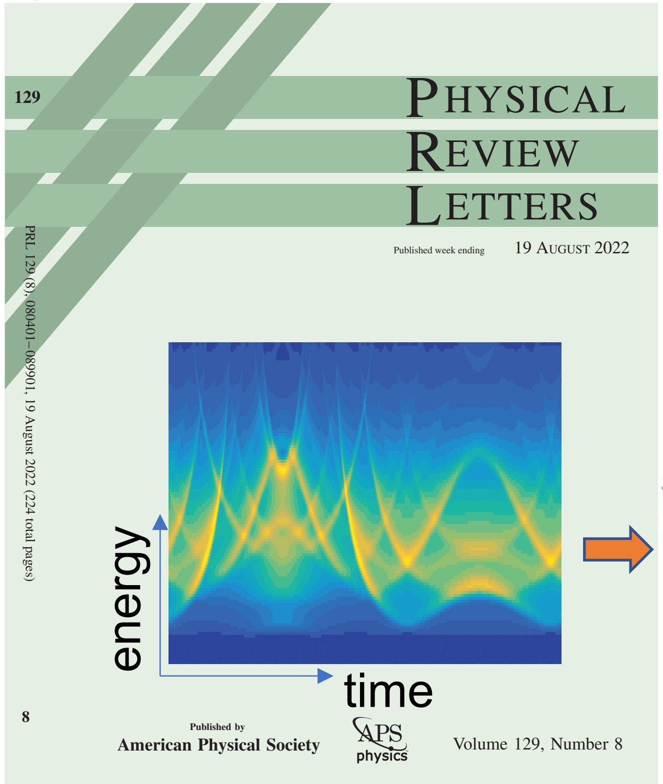
Axion signatures from coherent Primakoff-Bragg scattering over a 24-hour period.

From the article:

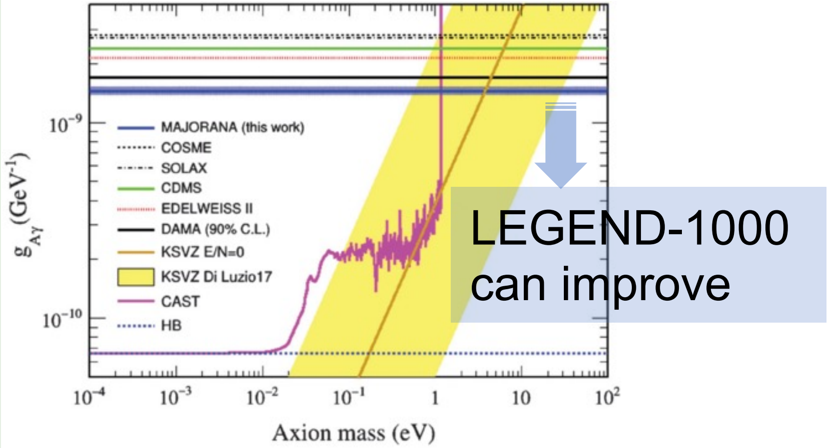
Search for Solar Axions via Axion-Photon Coupling with the MAJORANA DEMONSTRATOR

I.J. Arnquist *et al.* (MAJORANA Collaboration)

Phys. Rev. Lett. **129**, 081803 (2022)



https://journals.aps.org/prl/issues/129/8



Superb Energy Resolution
Low Backgrounds

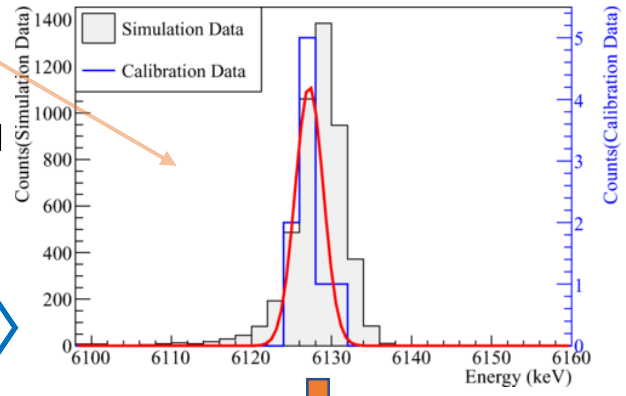
Standard Model Nuclear Physics

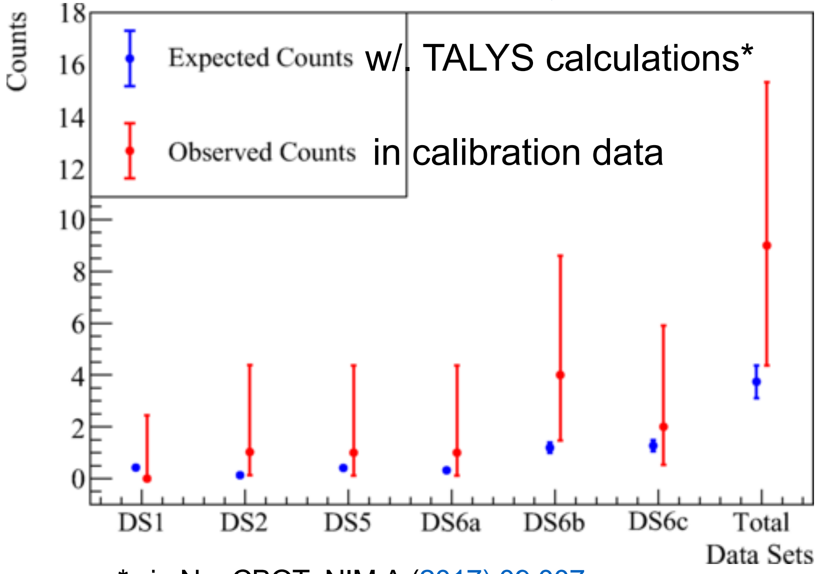
Peak analysis at high energy region ~ MeV. Calibration data

Experimental study of $^{13}C(\alpha, n)^{16}O$ reactions in the MAJORANA DEMONSTRATOR calibration data

I. J. Arnquist *et al.* (MAJORANA Collaboration)
Phys. Rev. C **105**, 064610 – Published 21 June 2022

6.13MeV isomeric photons observed





* via NeuCBOT, NIM A (2017) 09 007

Rich and Broad Physics with HPGe detectors: Delivered

References from MAJORANA DEMONSTRATOR and GERDA

Fundamental Symmetries
- **L violation in 0νββ decays**
- **B violation in Baryon decays**
- **Pauli Exclusion Principle violation**
- **Lorentz violation and Majorons in 2νββ**
- **BSM Physics in Ar**
- **Charge violation**

PRC **100** 025501 (2019)
Several 0νββ papers

PRD **99** 072004 (2019)

arXiv:2203.02033

Eur. Phys.J. C75 (2015) 416

Superb Energy Resolution
High Granularity
Low Backgrounds

Standard Model Nuclear Physics
- **2νββ decays**
- **In-situ cosmogenics**
- **neutron physics**

PRC **105** 014617 (2022)

PRC **105** 064610 (2022)

Astroparticle Physics 84 (2016) 29

Dark Matter Signatures
- **Pseudoscalar dark matter**
- **Vector dark matter**
- **Fermionic dark matter**
- **Sterile neutrino**
- **Solar Axions**

PRL **118** 161801 (2017)

PRL **125** 011801 (2020)

PRL **129** 081803 (2022)

arXiv:2206.10638

Exotic Physics
- **Lightly ionizing particles**
- **Quantum Wavefunction collapse**

PRL **120** 211804 (2018)

PRL **129** 080411 (2022)

See C. Wisemen
Exotic dark matter searches with the Majorana Demonstrator
DM session Aug. 30th

Summary

Non-zero neutrino mass is physics beyond the Standard Model and a compelling mystery

$0\nu\beta\beta$ searches determine the status of total lepton number conservation and probe the Majorana or Dirac nature of massive neutrinos

Ge-based technology captures significant $0\nu\beta\beta$ discovery potential

Current-generation ^{76}Ge experiments have achieved great successes

- MAJORANA DEMONSTRATOR achieved $T_{1/2} > 8.3 \times 10^{25}$ yr and the best energy resolution
- GERDA achieved $T_{1/2} > 1.8 \times 10^{26}$ yr and the lowest background if normalized to energy resolution

Combing the best technologies, the phased LEGEND project is designed for an unambiguous discovery of $0\nu\beta\beta$

- LEGEND-200 is in commissioning at LNGS with data-taking beginning later this year
- ➢ Goal : Discovery sensitivity of 10^{27} years with modest background reduction relative to GERDA
- LEGEND-1000 is proceeding to CD-1 with, R&D and conceptual design development ongoing
- ➢ Goal : Discovery potential at a half-life beyond 10^{28} years

Ge-based experiments including LEGEND have rich and broad physics other than $0\nu\beta\beta$

- Physics results can be extracted in wide energy range with various analysis techniques

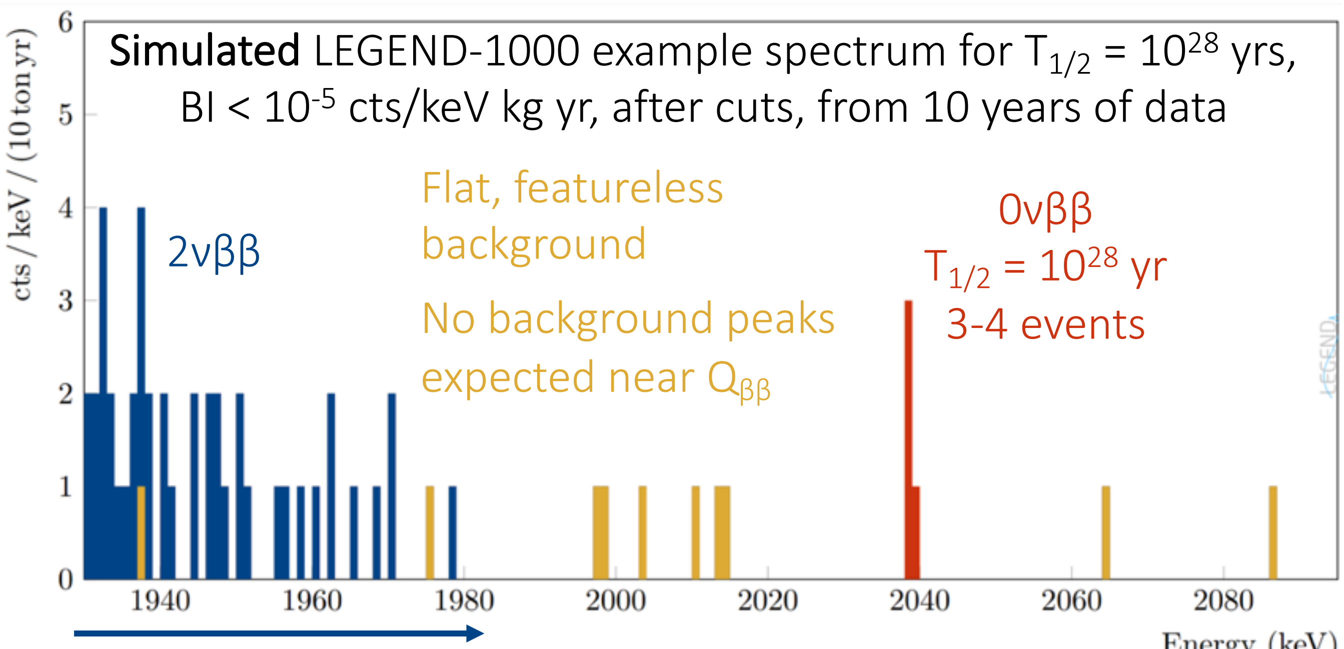
Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No. 1812356 and No. 2111140. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s)and do not necessarily reflect the views of the National Science Foundation.

Backup Slides

Ge is Ideal for Unambiguous Discovery of $0\nu\beta\beta$

- High Purity Ge (HPGe) detectors have superb energy resolution: $\sigma/Q_{\beta\beta}$ = 0.05%
  - No background peaks close to $Q_{\beta\beta}$ of 2039 keV for ^{76}Ge
  - Background is flat and well understood. No reliance on background modeling
  - No $2\nu\beta\beta$ background



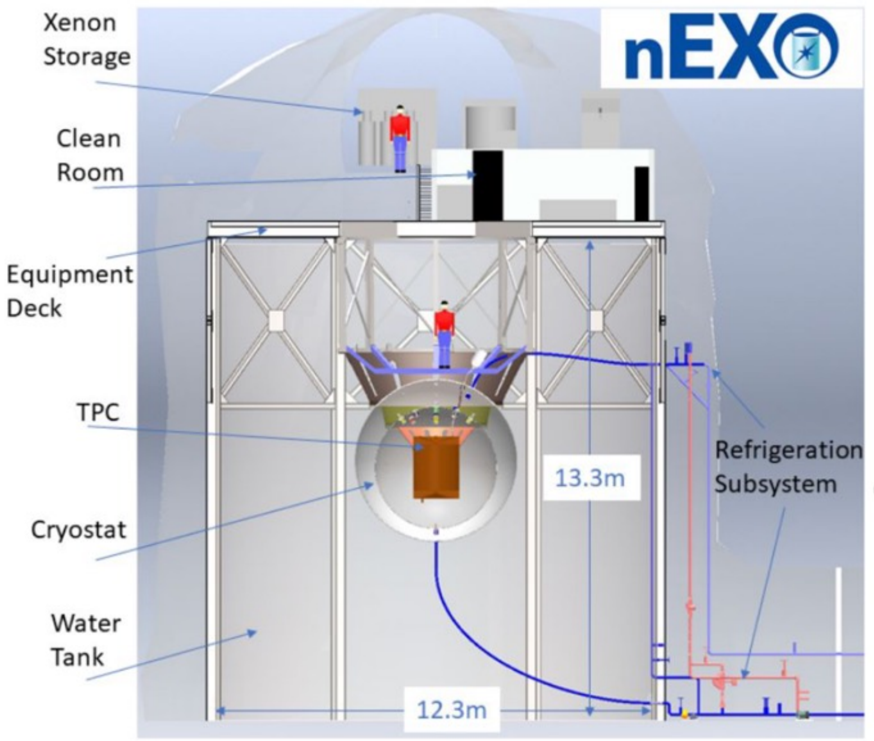
Tail of $2\nu\beta\beta$ events leak into in $Q_{\beta\beta}\pm2\sigma$

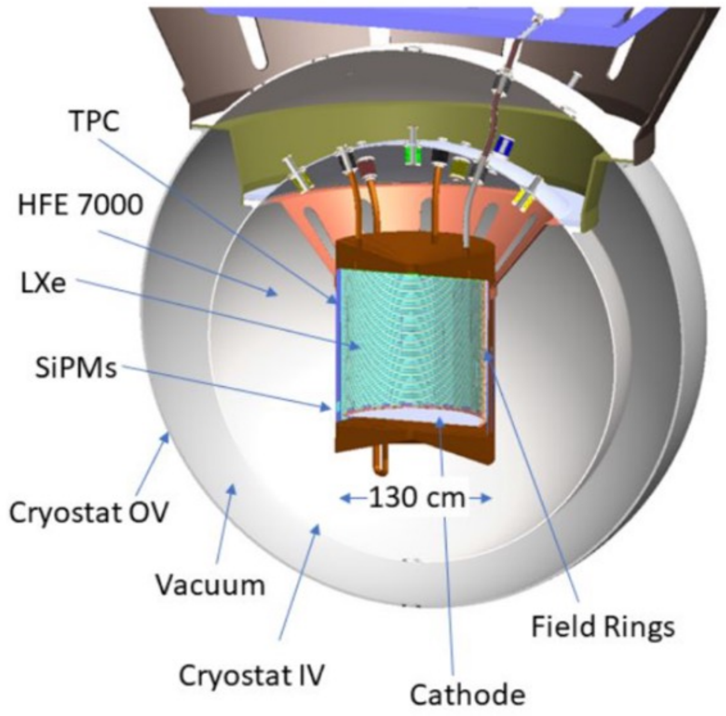
An observed signal in Ge will be convincing as an unambiguous discovery

nEXO by P.A. Breur NDM2022

P.A. Breur NDM2022

nEXO Design





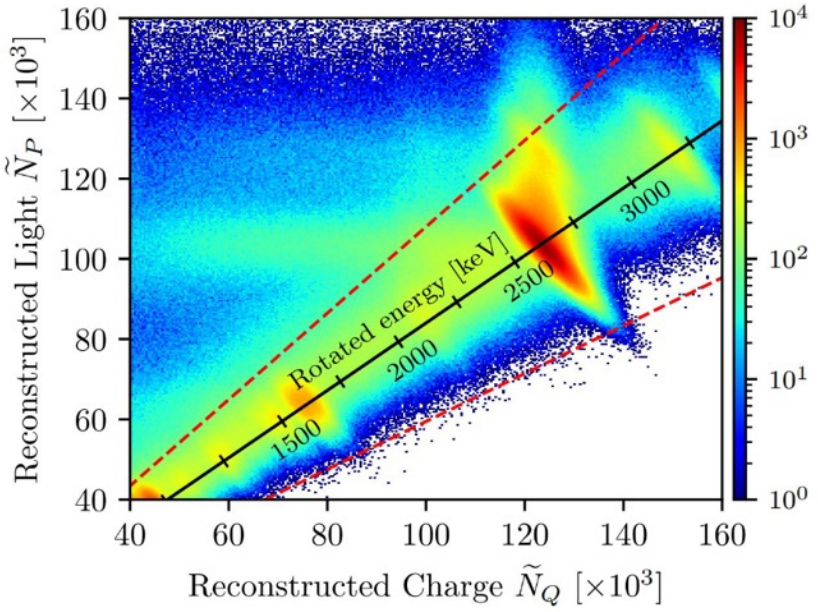
Credit: Ako Jamil

P.A. (Sander) Breur NDM 2022 May 18, 2022 6

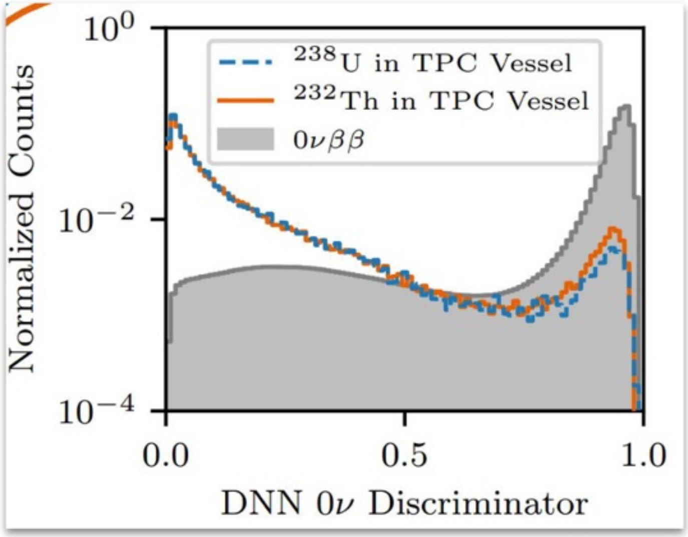
https://indico.phy.ornl.gov/event/142/contributions/712/

nEXO by P.A. Breur NDM2022

Energy reconstruction & single vs multisite discrimination



Simulated ^{232}Th in fiducial volume in TPC

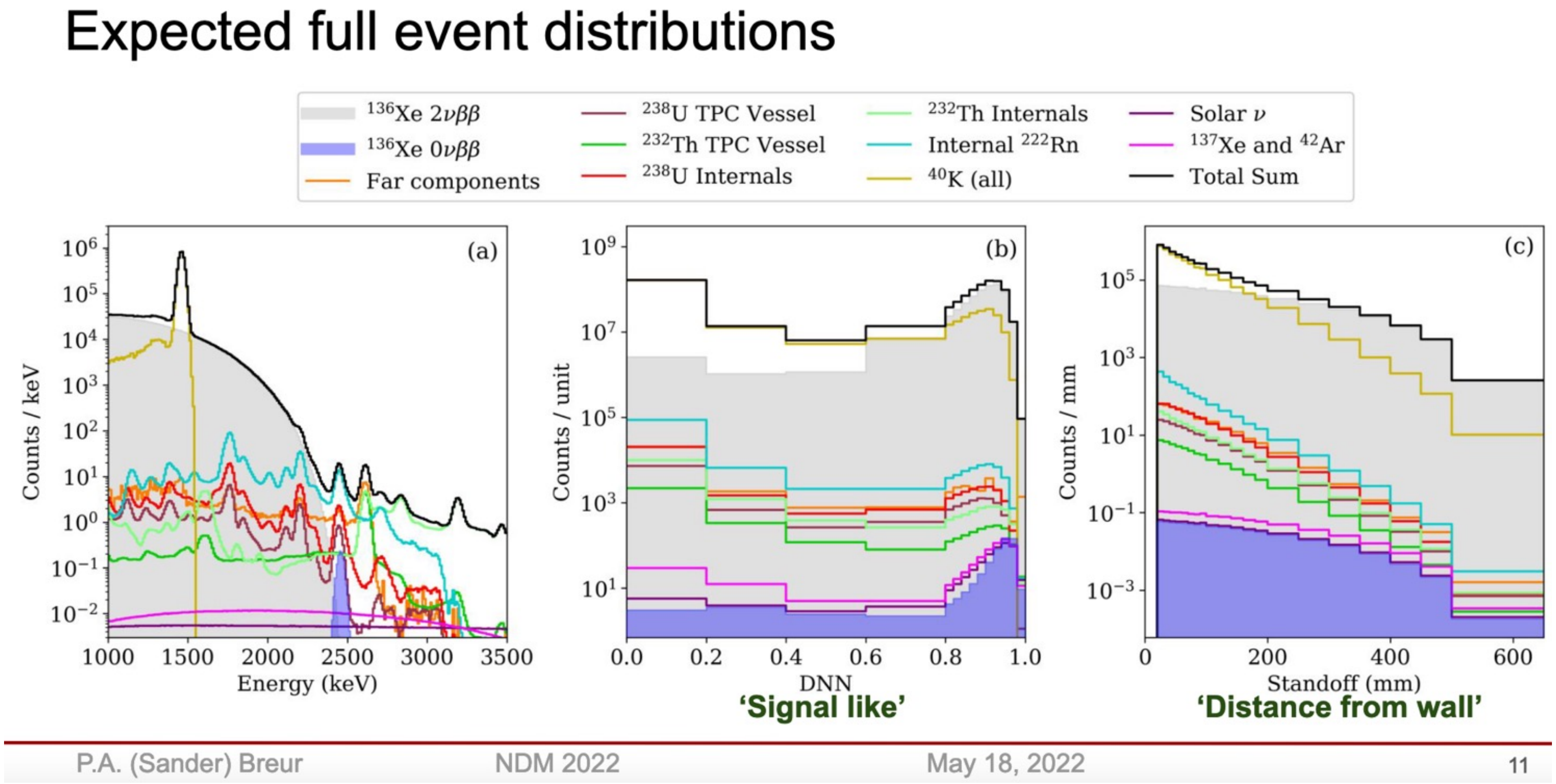


'Single scatter' or 'Signal' like

P.A. Breur NDM2022

nEXO by P.A. Breur NDM2022

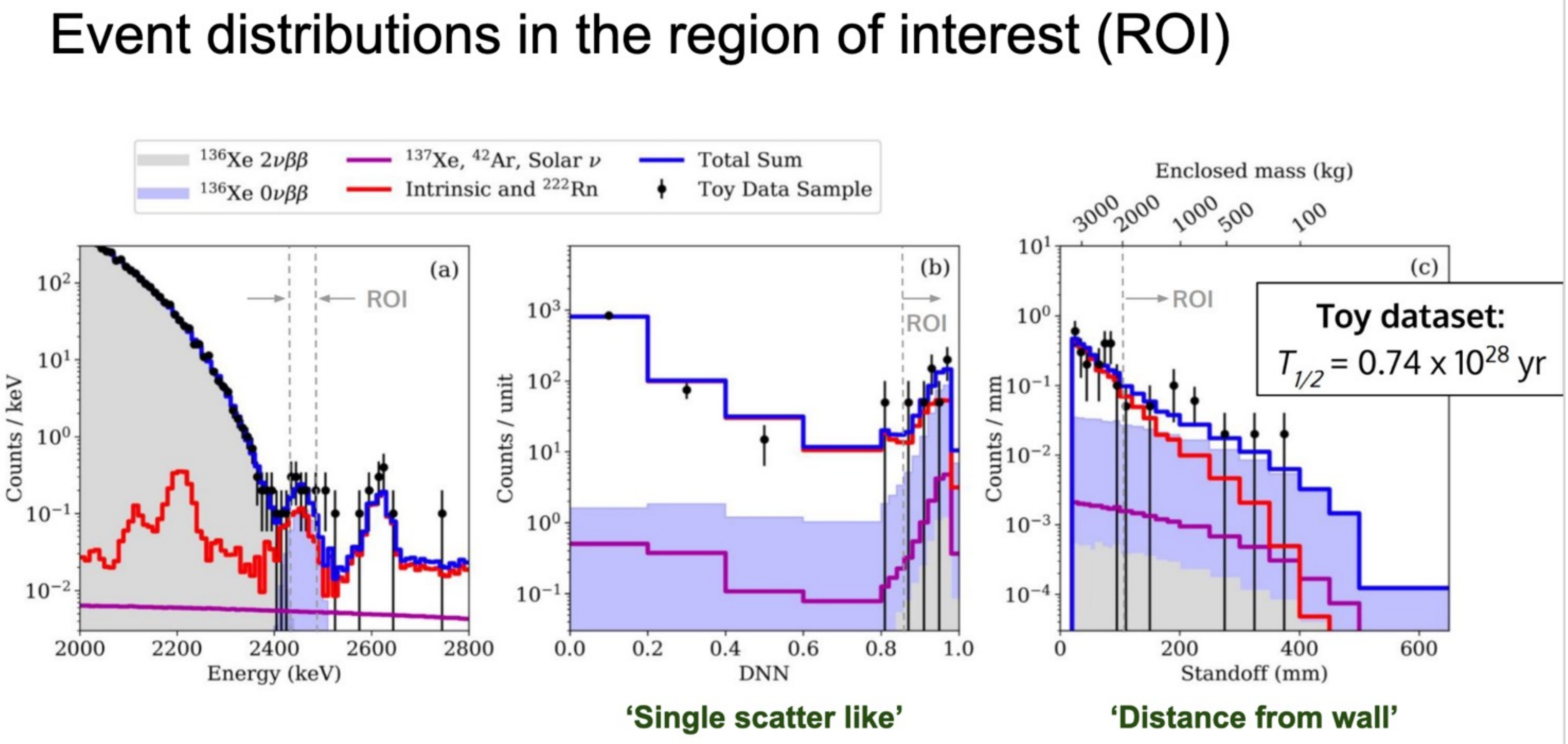
Signal: 0.7x 10^{28} y



P.A. Breur NDM2022

nEXO by P.A. Breur NDM2022

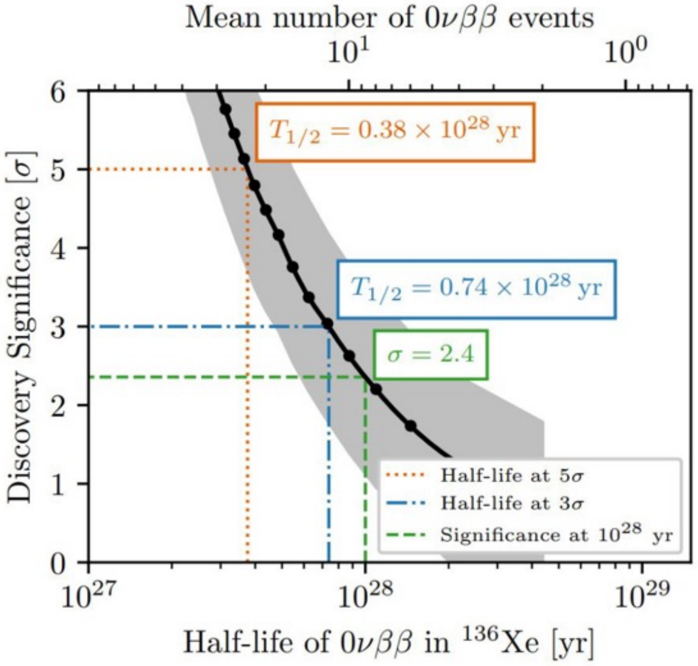
Signal: 0.7x 10^{28} y



P.A. Breur NDM2022

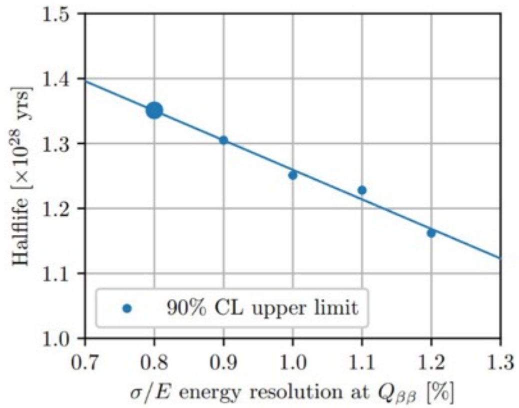
nEXO by P.A. Breur NDM2022

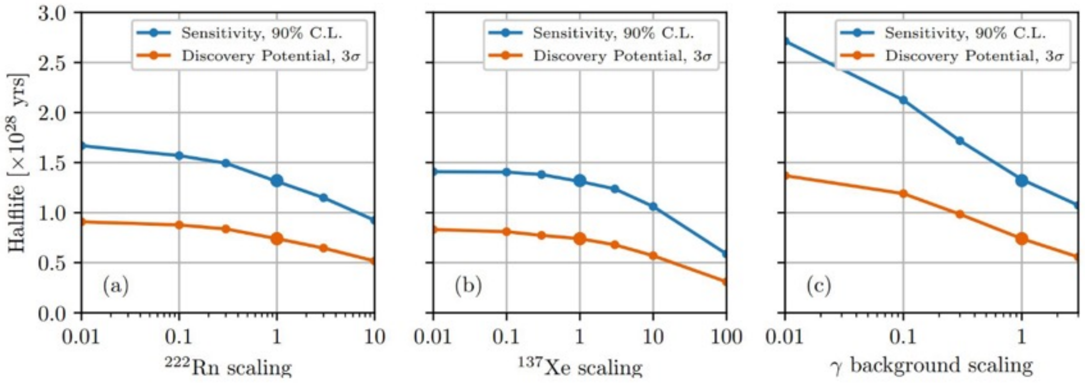
Discovery potential and scaling



Baseline Numbers:

- 10 years science data
- energy resolution: 0.8%
- Radon concentration: 600 atoms in steady-state
- 137Xe: 0.85x 10-3 atoms/kg* year





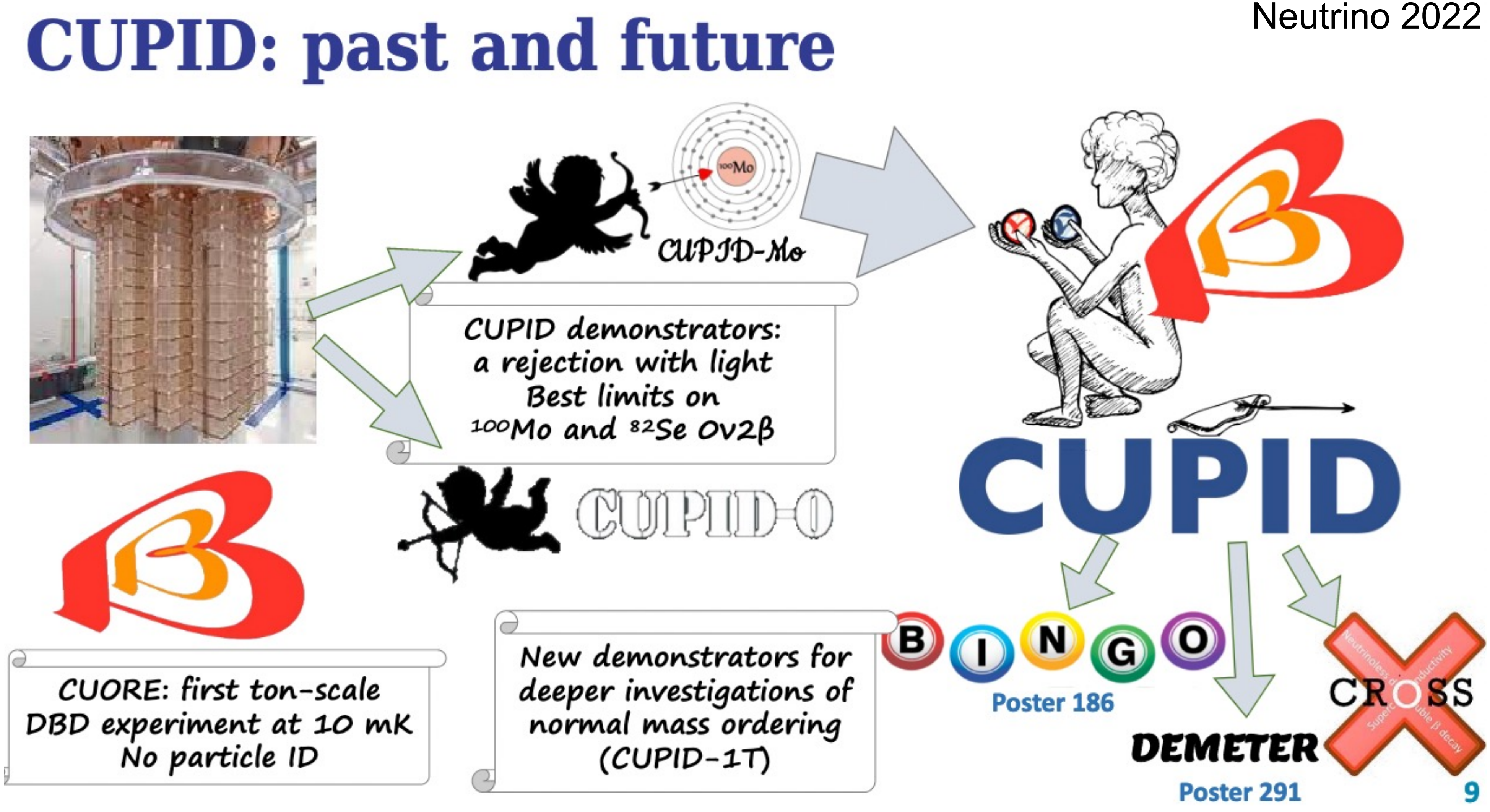
P.A. (Sander) Breur NDM 2022 May 18, 2022 13

P.A. Breur NDM2022

CUPID by Anastasiia ZOLOTAROVA Neutrino 2022

https://indico.kps.or.kr/event/30/contributions/863/

Anastasiia ZOLOTAROVA
Neutrino 2022



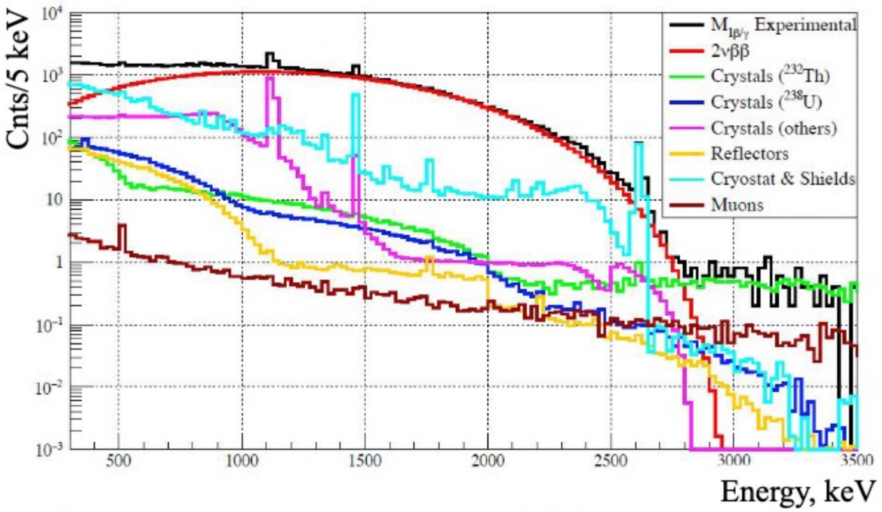
CUPID by Anastasiia ZOLOTAROVA Neutrino 2022

Anastasiia ZOLOTAROVA
Neutrino 2022

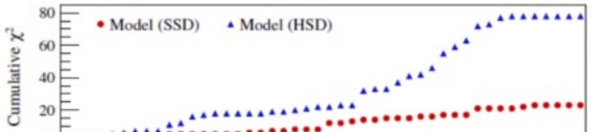
CUPID-0 results

FWHM @ $Q_{\beta\beta}$=(20.05 ± 0.34) keV

- Successfull demonstration of advantages of **dual-readout technique**
- High scientific potential: best limit on 0ν2β, most precise measurement of ^{82}Se 2ν2β, CPT violation search, SSD vs HSD, excited states



$$T_{1/2}^{2\nu} = [8.60 \pm 0.03(\text{stat})^{+0.19}_{-0.13}(\text{syst})] \times 10^{19} \text{ yr}$$



CUPID-0 results

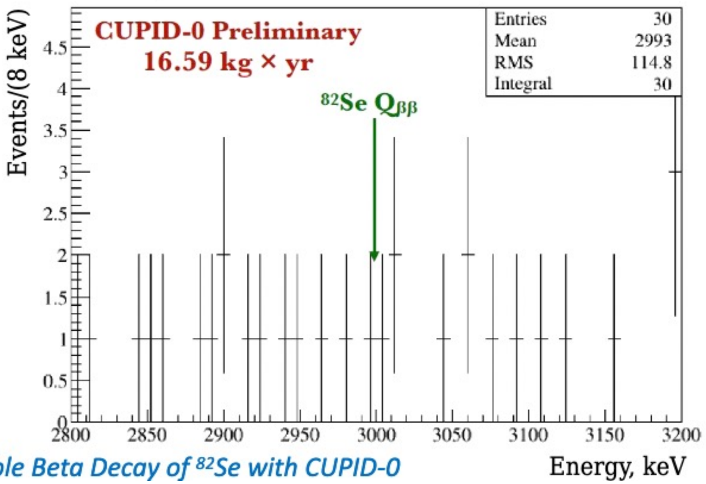
FWHM @ $Q_{\beta\beta}$=20.05 ± 0.34 keV

- Successfull demonstration of advantages of **dual-readout technique**
- High scientific potential: best limit on 0ν2β, most precise measurement of ^{82}Se 2ν2β, CPT violation search, SSD vs HSD, excited states

$$T_{1/2}^{0v} > 4.7 \times 10^{24} yr \text{ (90\% C. I. limit)}$$

$m_{\beta\beta}$<276-570 meV

PRD 100, 092002 (2019)
PRL 123, 262501 (2019)
EPJC 79, 583 (2019)
EPJC 81, 722 (2021)



See also posters:

- **492, Pagnanini, Lorenzo:** *Final Result on the Neutrinoless Double Beta Decay of ^{82}Se with CUPID-0*

CUPID by Anastasiia ZOLOTAROVA Neutrino 2022

Anastasiia ZOLOTAROVA
Neutrino 2022

CUPID: baseline

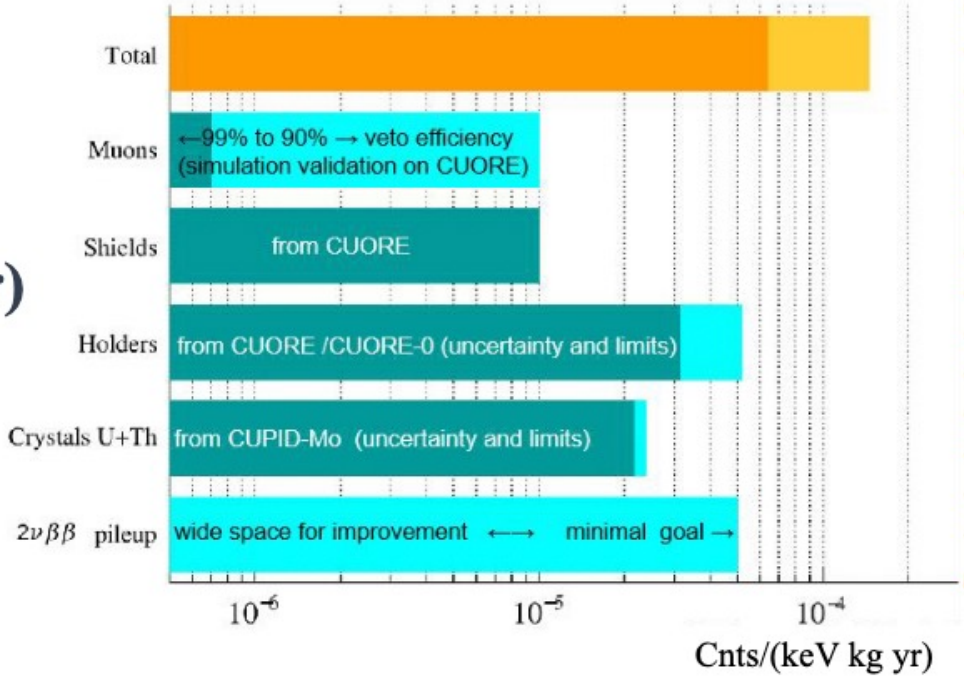
- **$Li_2{}^{100}MoO_4$ scintillating bolometers**
- α rejection using light signal
- Enrichment > 95%
- 1596 crystals and 240 kg of ^{100}Mo
- FWHM <10 keV at $Q_{\beta\beta}$ (3034 keV)

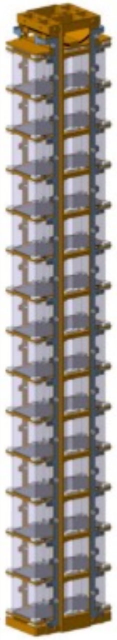
Background goal: 10^{-4} cnts/(keV kg yr)

Discovery sensitivity at 3σ:

$T_{1/2}(^{100}Mo) = 10^{27}$ yr

$m_{\beta\beta}$ ~12-20 meV





21

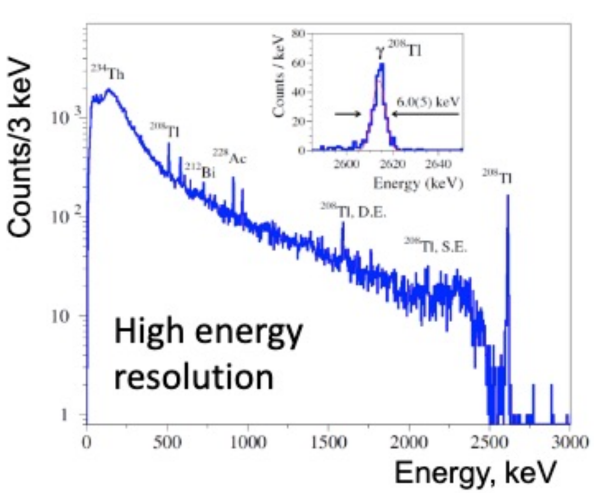
CUPID by Anastasiia ZOLOTAROVA Neutrino 2022

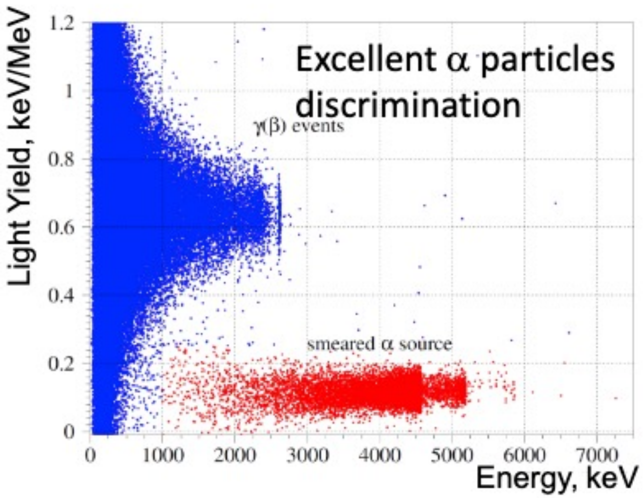
Anastasiia ZOLOTAROVA
Neutrino 2022

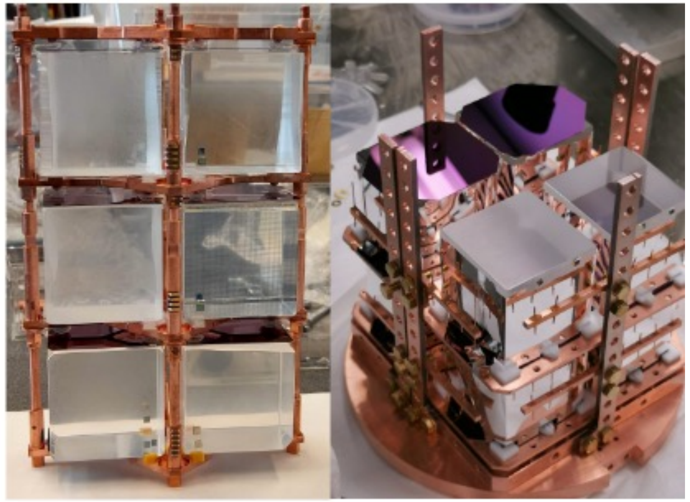
CUPID: R&D

- Series of cryogenic tests at LNGS and LSC performed to define the final **structure of CUPID**
- Maximally effective use of experimental space
- Studies of pile-up rejection: both synthetic and induced pulses used for analysis

Eur. Phys. J. C (2021) 81: 104
JINST 16 (2021) P02037
arXiv:2011.11726
arXiv:2202.06279







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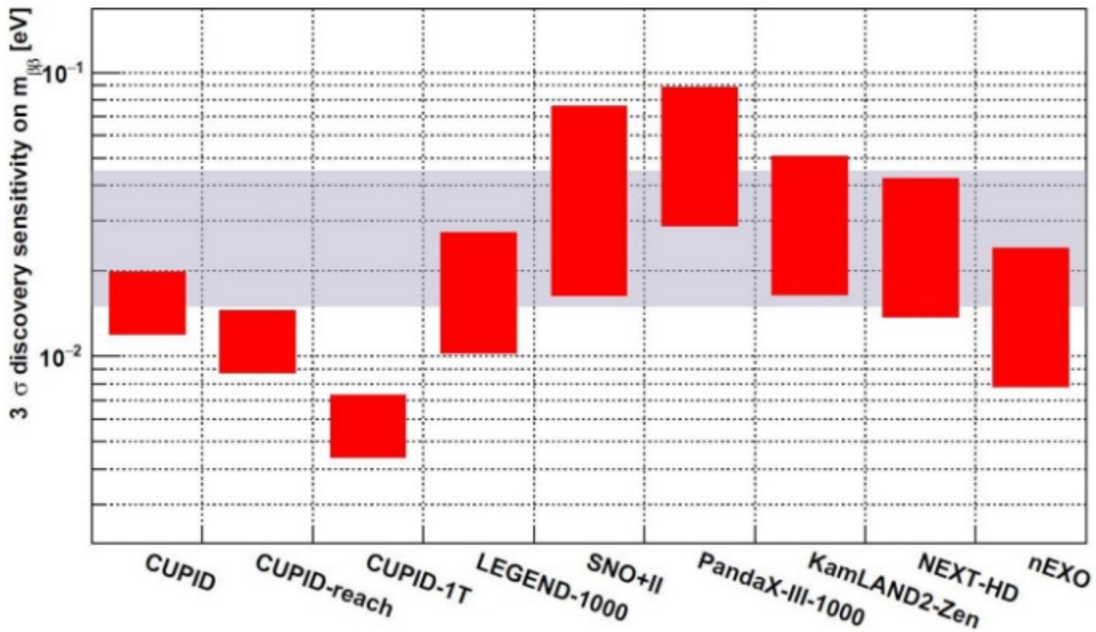
CUPID by Anastasiia ZOLOTAROVA Neutrino 2022

Anastasiia ZOLOTAROVA
Neutrino 2022

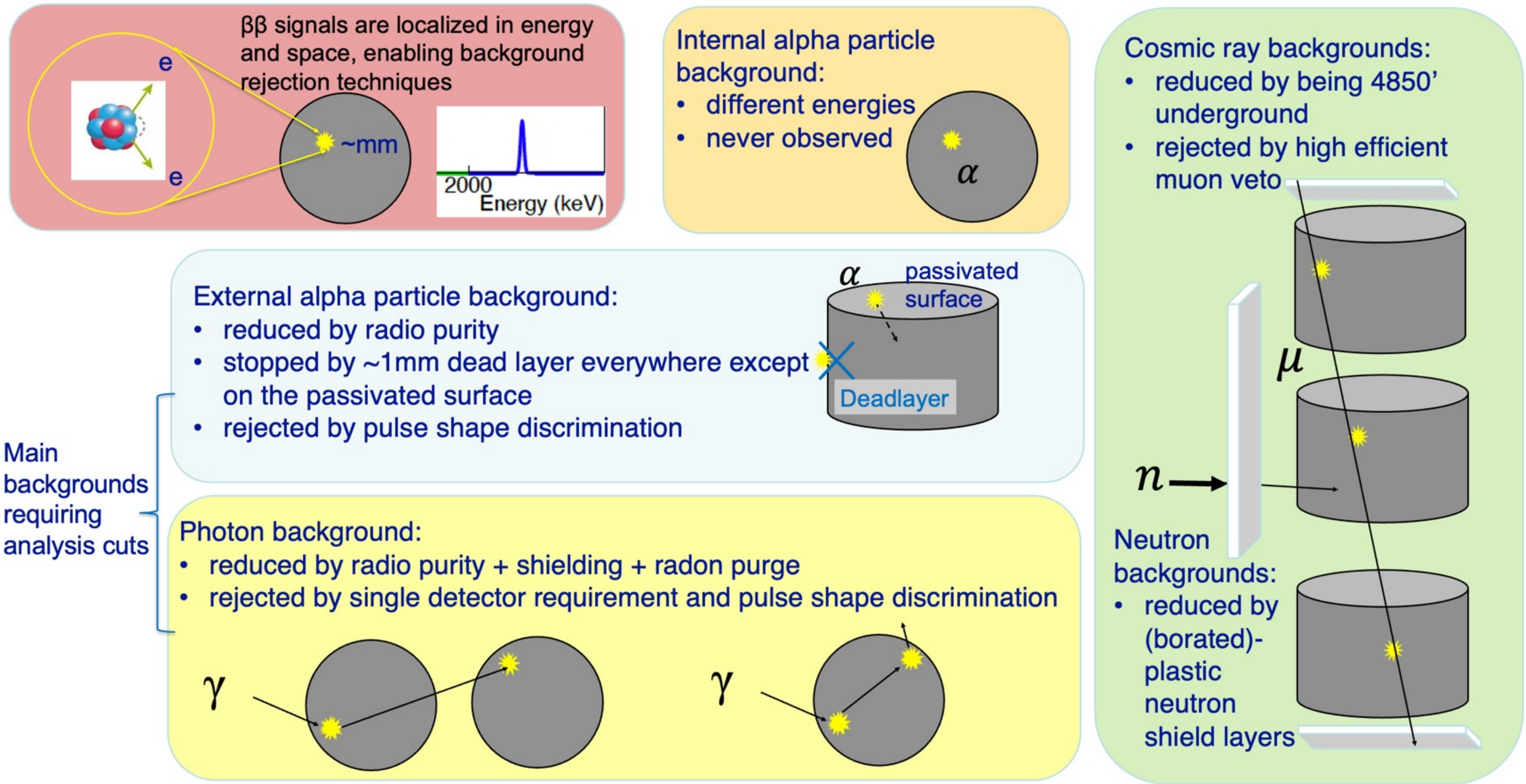
CUPID sensitivity



- CUPID: Exactly what we start building: **10^{-4}** cnts/keV/kg/yr
- CUPID-reach: improvements before construction: **2×10^{-5}** cnts/keV/kg/yr
- CUPID-1T: 1 ton ^{100}Mo in new cryostat: **5×10^{-6}** cnts/keV/kg/yr

28

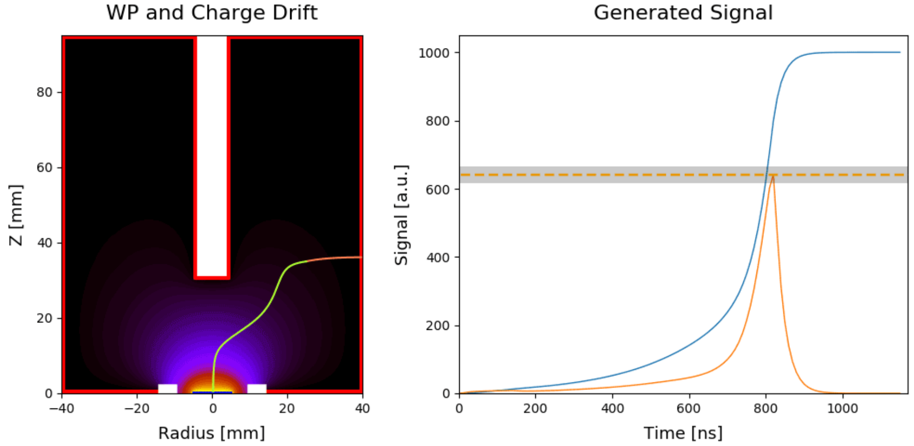
MAJORANA Background Reduction



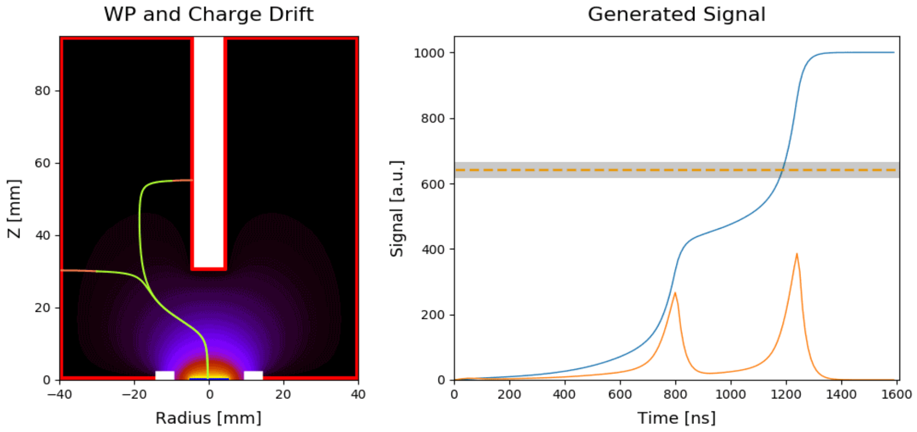
Adapted from W. Xu, APS April meeting 2022

From the Current Generation to the Ton Scale

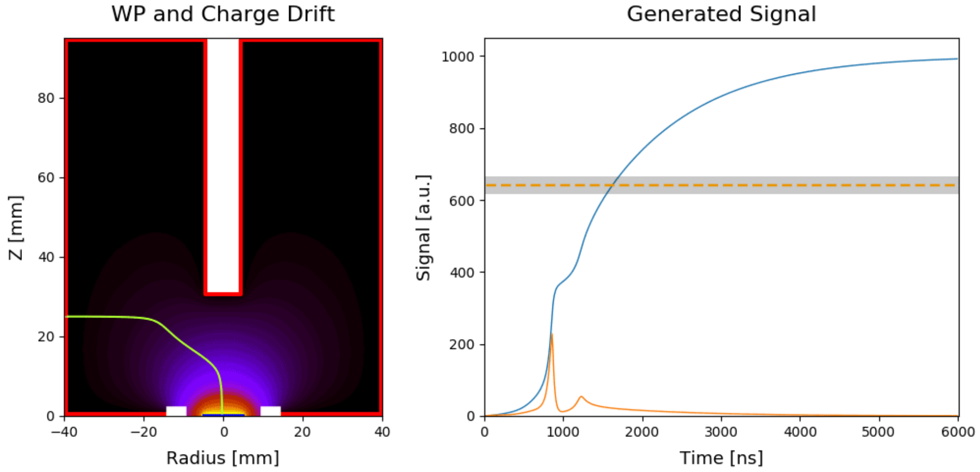
0νββ signal candidate (single-site)



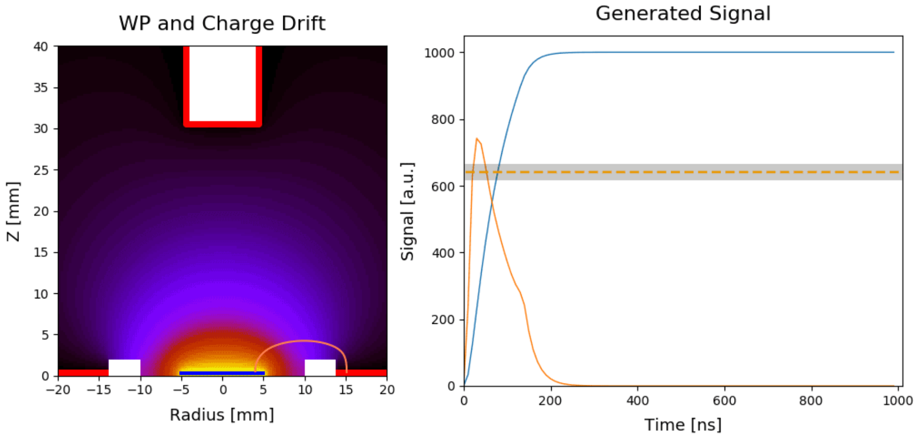
γ-background (multi-site)



Surface background on n+ contact



Surface background on p+ contact

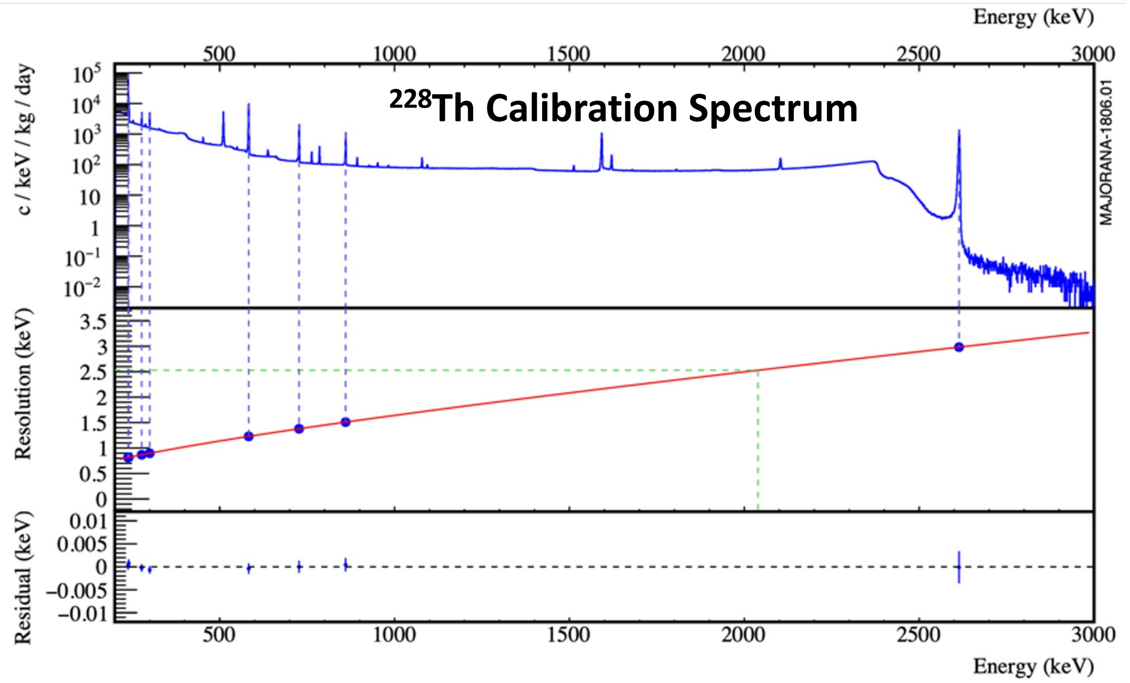


External α, β, and γ backgrounds all create distinctive pulse shapes, allowing for highly efficient ββ decay event selection

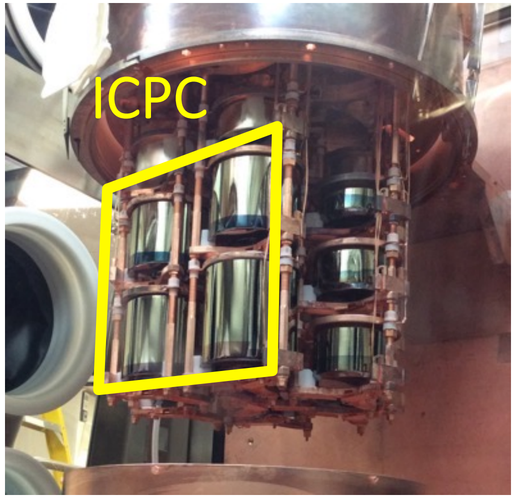
Energy Reconstruction and ICPC Detectors

Energy estimated via optimized trapezoidal filter of ADC-nonlinearity-corrected* traces with charge-trapping correction

FWHM of 2.5 keV at $Q_{\beta\beta}$ of 2039 keV (0.12%) is a record for 0νββ searches

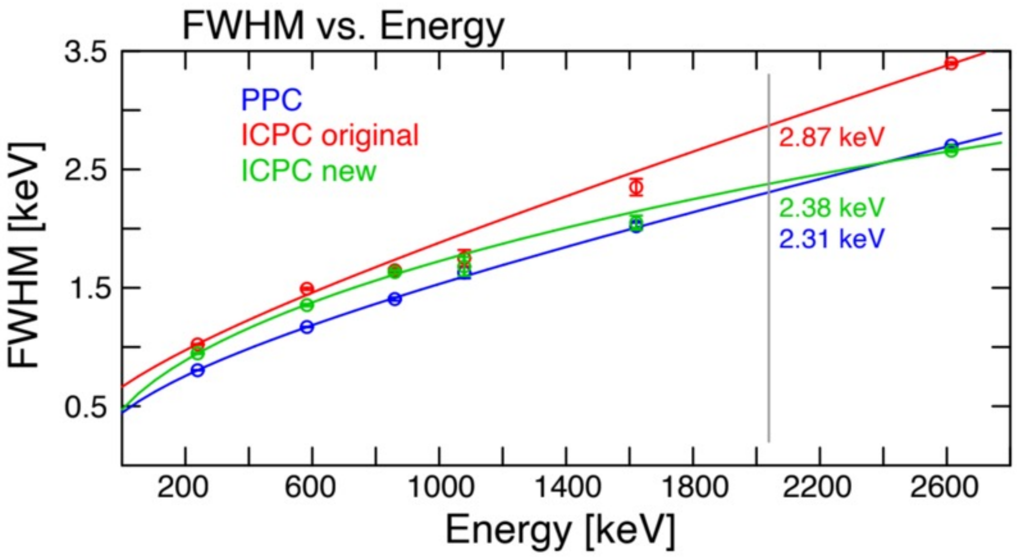


FWHM of combined enriched detectors in the MAJORANA DEMONSTRATOR, measured using ^{228}Th calibration data



MAJORANA operated 4 Inverted-Coaxial Point Contact Detectors from Aug. 2020 to Mar. 2021

- Larger range of drift times requires new analysis techniques
- Best energy resolution for ICPCs to date!



Combined energy resolution of ICPCs improved from 2.9 keV to 2.4 keV FWHM at 2039 keV with new technique

NIMA 872 (2017) 16

* IEEE Trans. on Nuc Sci 10.1109/TNS.2020.3043671

LEGEND-200 Design and Commissioning

Improvements from GERDA/MJD:

- Larger detectors
- Improved LAr light collection: higher purity Ar and improved readout
- Cleaner, lower mass cables
- Lower noise electronics
- UGEFCu and self-vetoing PEN plated for detector mounts

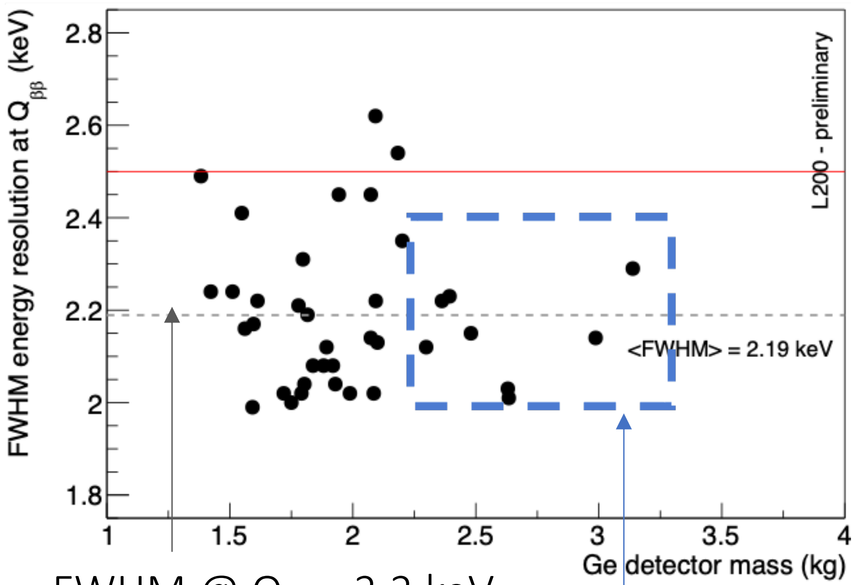
→ Factor of 3 reduction in backgrounds relative to GERDA

Quasi-background free operation up to 1 ton-year exposure, for unambiguous discovery up to 10^{27} yrs

Photo: Enrico Sacchetti

Detector Characterization:

ICPC Energy Resolution



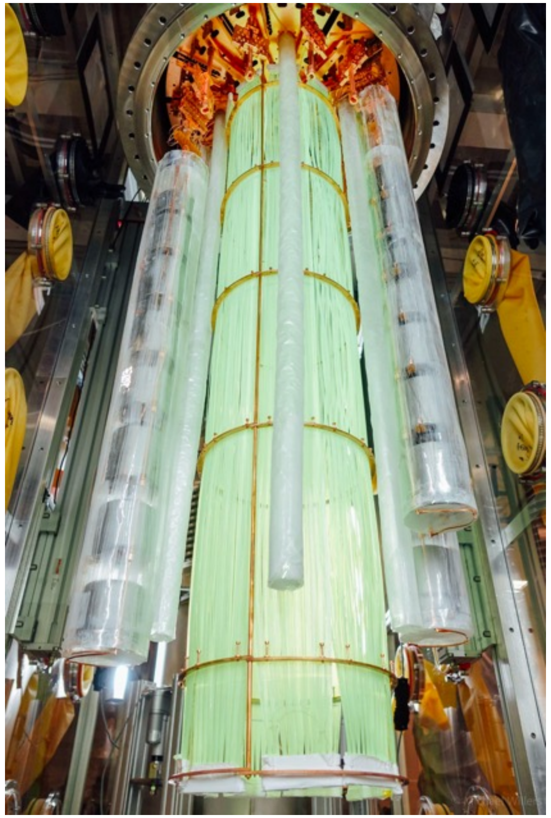
FWHM @ $Q_{\beta\beta}$: 2.2 keV

Large-mass detectors show excellent energy resolution

First integrated commissioning run now underway:
4 strings of HPGe detectors, operating with full LAr system

LEGEND Enriched Detectors

LEGEND-200



- 15% MAJORANA PPC detectors
- 23% GERDA BEGe detectors
- 62% LEGEND larger ICPCs

LEGEND-1000

90 x 76 mm
2.68 kg

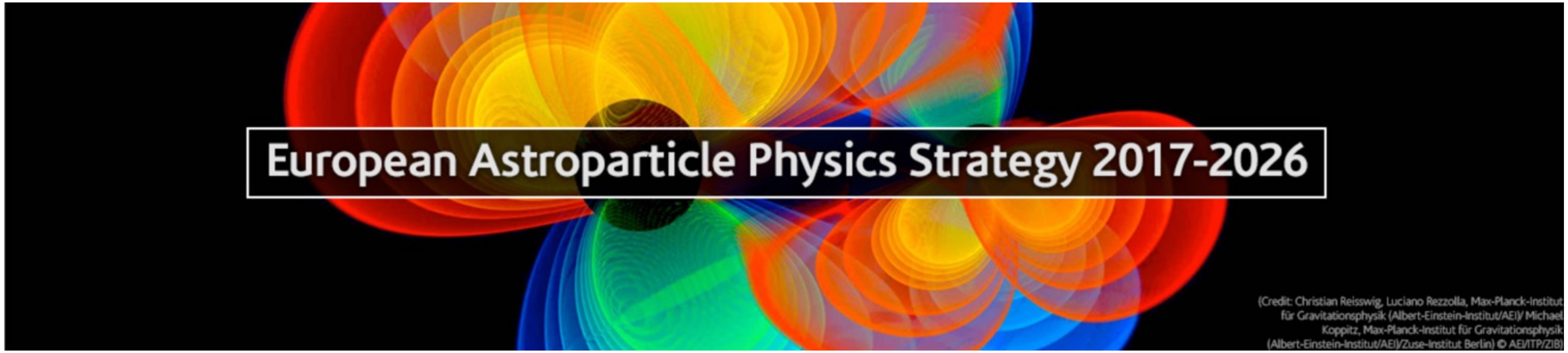
92 x 112 mm
4.11 kg

90 x 76 mm
2.68 kg

LEGEND-1000 uses only larger ICPC detectors, average 2.6 kg

- ➢ **LEGEND-200 background goal is x2.5 reduction from GERDA**
- ➢ **LEGEND-1000 background goal is x20 reduction from LEGEND-200**

Next Generation Experiments



Report on the North America-Europe workshop on Double Beta Decay (Sep. 29th - Oct. 1st 2022)

"After three days of fruitful and deep discussion, the representatives of ***several European and North American funding agencies****,* ***Ministerial representatives and Laboratory Directors*** *have met in a closed session. They unanimously agreed that the strong scientific motivation and the need to cross-check any potential signal with different isotopes justifies the effort to support three experiments,* ***CUPID at Gran Sasso, and LEGEND and nEXO, where one should be located in North America and one in Europe. "***

https://www.appec.org/news/report-on-the-north-america-europe-workshop-on-double-beta-decay

If I introduce new fields, I have to write down all possible interactions allowed by the gauge symmetries given the (new) field content Adapted from Walter Winter, WIN 2017

Because neutrinos are electrically neutral, ν_R would allow a Majorana mass term $\sim m_R(\overline{\nu_L}\nu_R^c + \bar{\nu}_R^c\nu_L)$

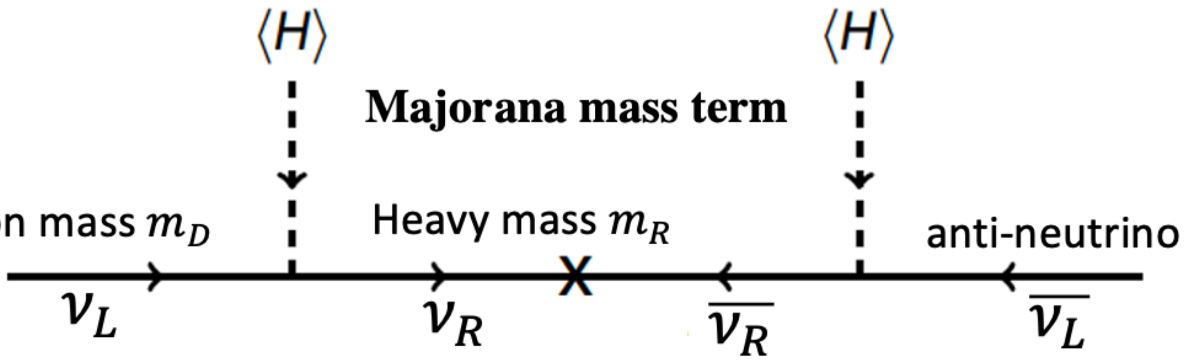


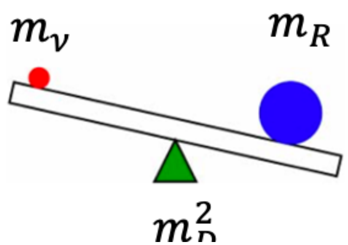
Figure adapted from Jon Engel

ν_R is assumed to be very heavy in the seesaw model. It can only participate as a virtual particle in the process above. It cannot be easily produced and detected.

The physical neutrino is a mixture

$$\nu = c_1\nu_R^c + c_2\nu_L$$

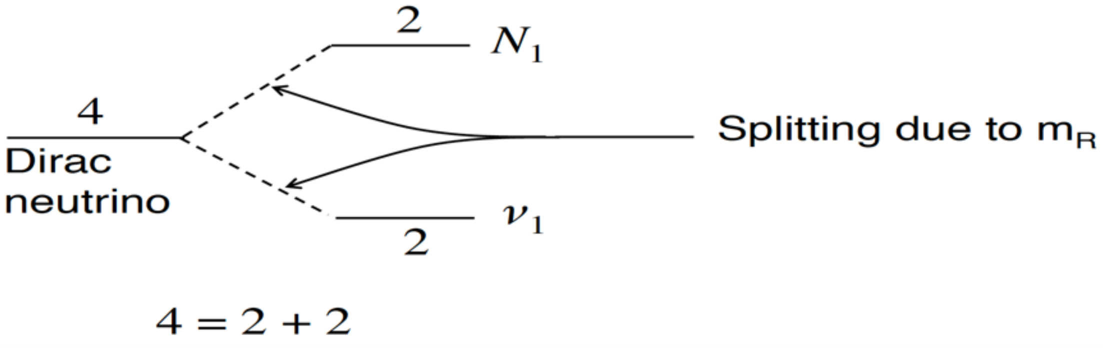
with a mass highly suppressed by m_R ➡ $m_\nu = \frac{m_D^2}{m_R}$



The seesaw model

The Majorana mass term split a Dirac neutrino into two Majorana neutrinos.

Boris Kayser 2018 INSS lecture



Say MeV - TeV

Say 10^16 GeV

$$\mathcal{L}_{m_\nu} = -m_D \overline{\nu^0_R} \nu^0_L - \frac{m_R}{2} \overline{(\nu^0_R)^c} \nu^0_R + \text{h. c.}$$

$$= -\frac{1}{2} [\overline{(\nu^0_L)^c}, \overline{\nu^0_R}] \begin{bmatrix} 0 & m_D \\ m_D & m_R \end{bmatrix} \begin{bmatrix} \nu^0_L \\ (\nu^0_R)^c \end{bmatrix} + \text{h. c.}$$

m_D (Dirac mass) and
m_R (Right-handed Majorana mass term).
V^0_L and V^0_R are bases of theory, not yet physical (underlying fields out of which a model is constructed).
V^0_R and m_R not constrained by SM. *i.e.* if Dirac term exists,
-> V^0_R exists,
-> no reason for Majorana term does not exist

Entirely following Boris arXiv:hep-ph/0211134

Emmy Noether

Noether's Theorem: continuous symmetry leads to conservation laws

Baryon- and Lepton-Nonconserving Processes

Also F. Wilczek and A. Zee Phys. Rev. Lett. 43. 1571(1979)

Steven Weinberg
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138, and Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138

Phys. Rev. Lett.43.1566 (1979)
(Received 13 August 1979)

A number of properties of possible baryon- and lepton-nonconserving processes are shown to follow under very general assumptions. Attention is drawn to the importance of measuring μ^+ polarizations and $\bar{\nu}_e/e^+$ ratios in nucleon decay as a means of discriminating among specific models.

Not fundamental

but accidental

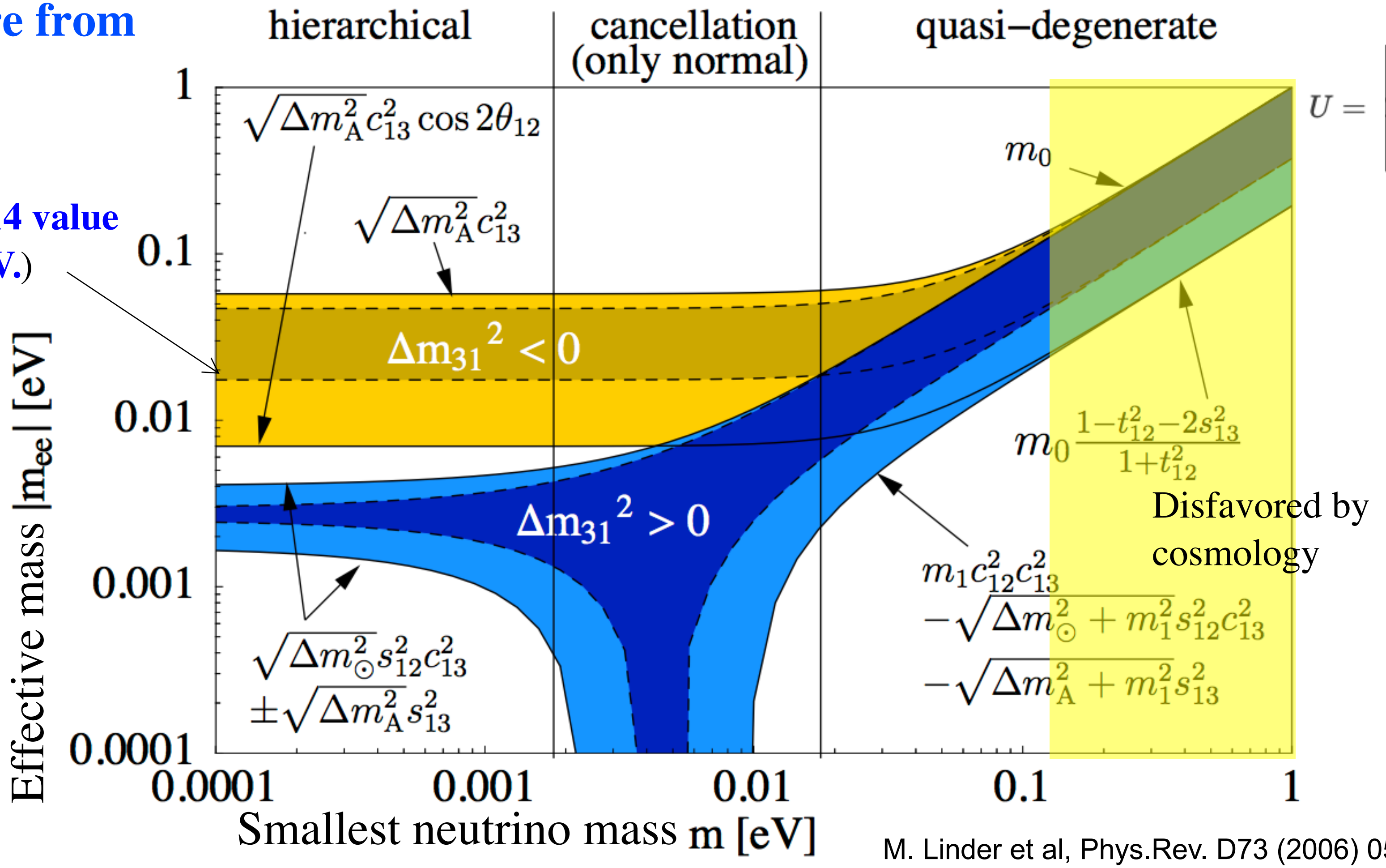
Of the supposedly exact conservation laws of physics, two are especially questionable: the conservation of baryon number and lepton number. As far as we know, there is no necessity for an *a priori* principle of baryon and lepton conservation. As we shall see, even without such a principle, the fact that the weak, electromagnetic, and strong interactions of ordinary quarks and leptons conserve baryon and lepton number can be understood as simply a consequence of the SU(2) ⊗ U(1) and SU(3) gauge symmetries. Also, in contrast with the conservation of charge, collision are likely to occur in grand unified theories that combine the gauge theory of weak and electromagnetic interactions with that of strong interactions and have leptons and quarks in the same gauge multiplets, and such violations have been found in various of these models.[3]

The purpose of this paper is to point out those features of baryon- or lepton-nonconserving processes that are to be expected on very general grounds. Other features will be indicated that may be used to discriminate among specific models.

Such as the Majorana mass term

Figure from 2006

(**PDG 14 value ~15meV.**)

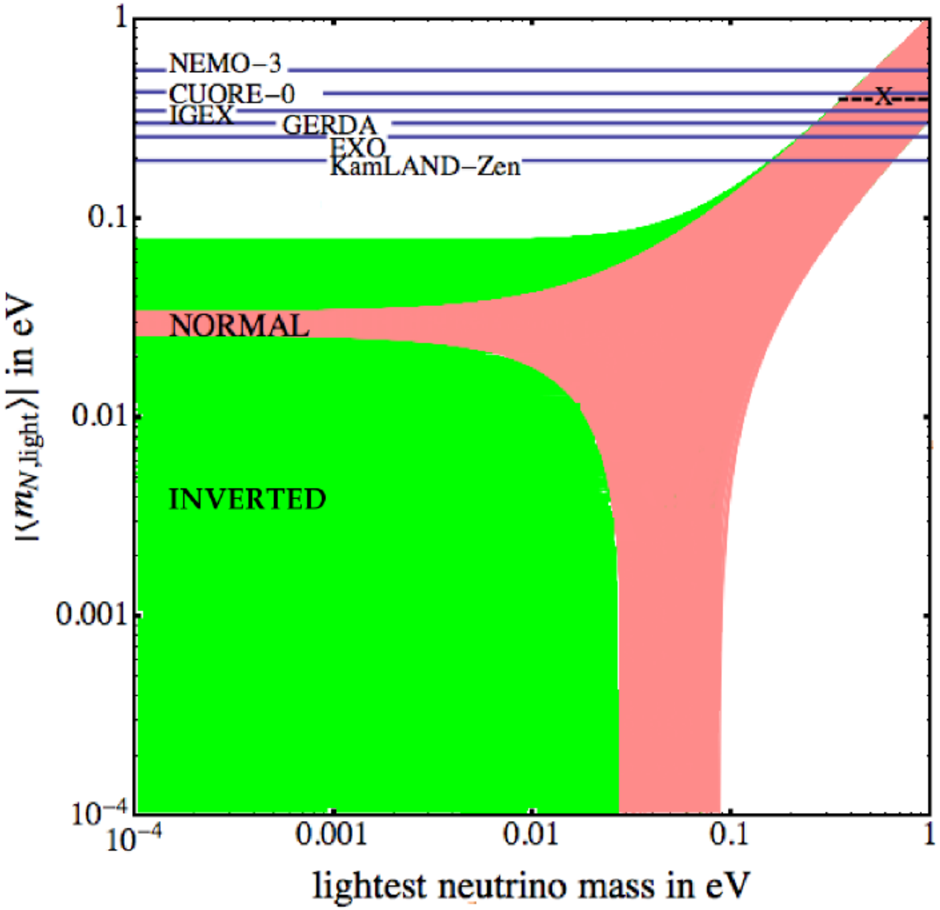


M. Linder et al, Phys.Rev. D73 (2006) 053005

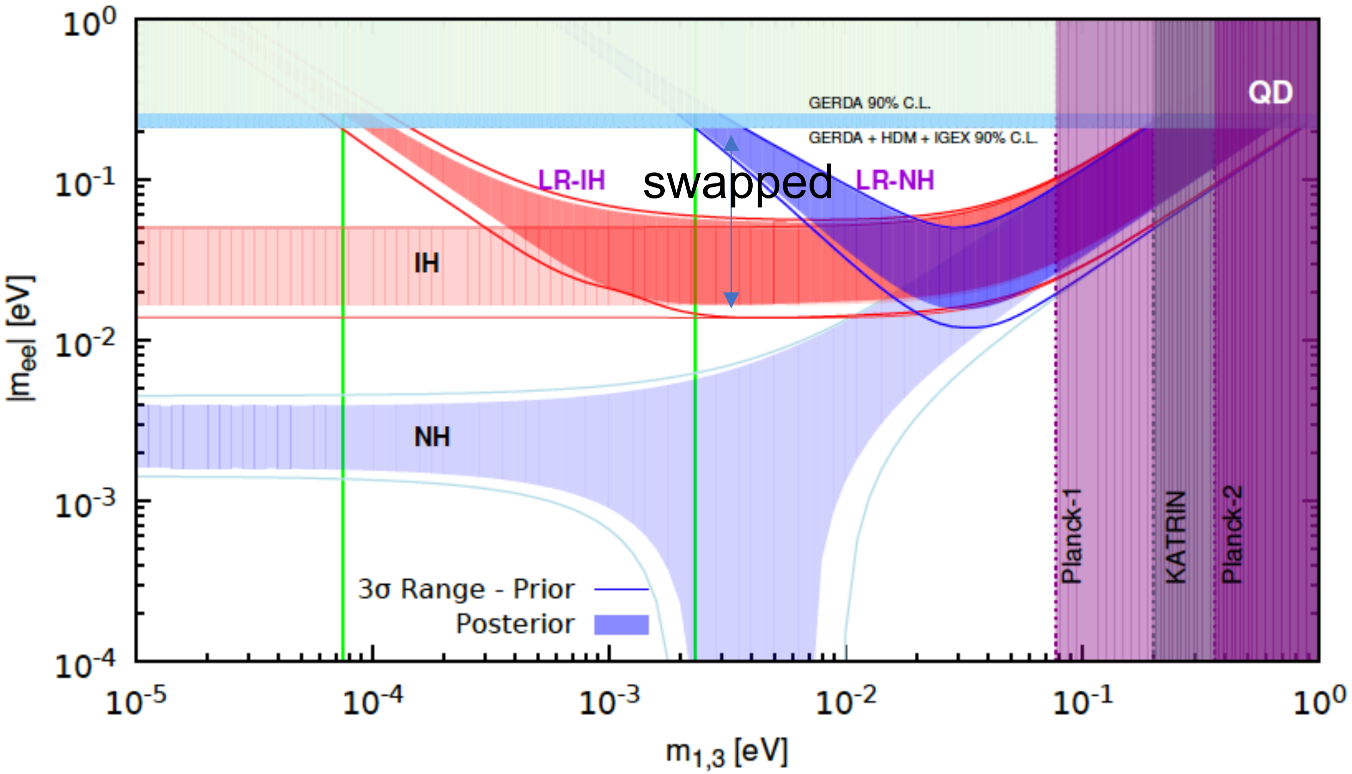
$$U = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}$$

CP-violating Dirac phase as δ. Majorana phases, which do not appear in the probabilities measured by the oscillation experiments, are not shown.

$$|m_{ee}| = f(\theta_{12}, \theta_{13}, \alpha, \beta, m_1, m_2, m_3).$$



Light sterile neutrino contribution
An example: PRD92, 093001 (2015)



Left-Right symm., Type II contributions
From J. 3 neutrino paradigm HEP 10, 077 (2015)

arxiv:2203.12169

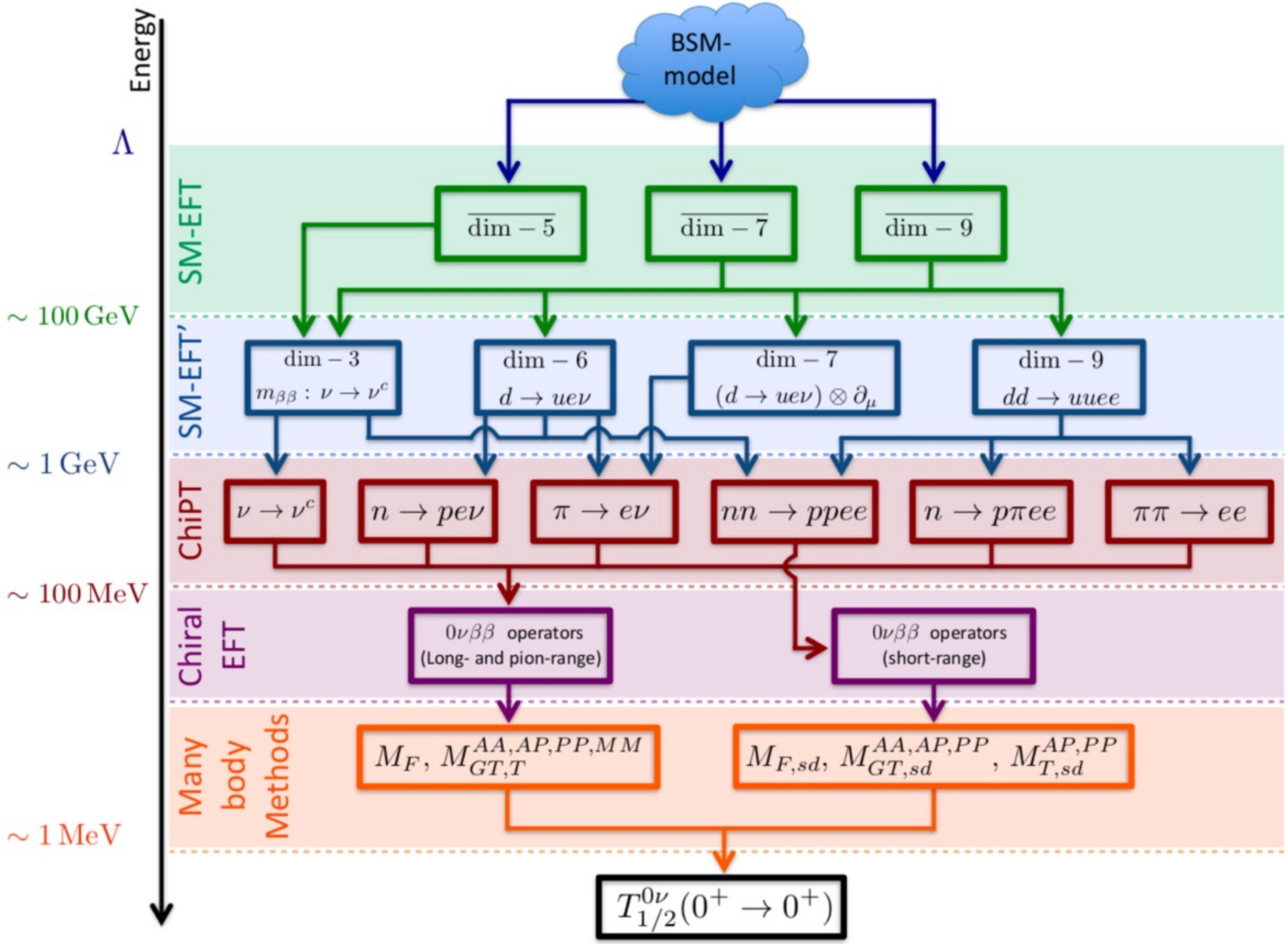


FIG. 10. The tower of EFTs for $0\nu\beta\beta$ decay. At the electroweak scale, LNV operators are described by operators of odd dimension in the SMEFT. Heavy SM degrees of freedom can be integrated out by matching SMEFT onto LEFT (denoted as SMEFT′ in the figure). Quark-level operators are then matched onto hadronic operators. The construction of hadronic operators is performed in χPT and chiral EFT, while the determination of the low-energy couplings requires non-perturbative techniques, such as lattice QCD. The $0\nu\beta\beta$ transition operators constructed in chiral EFT are then evaluated with nuclear many-body

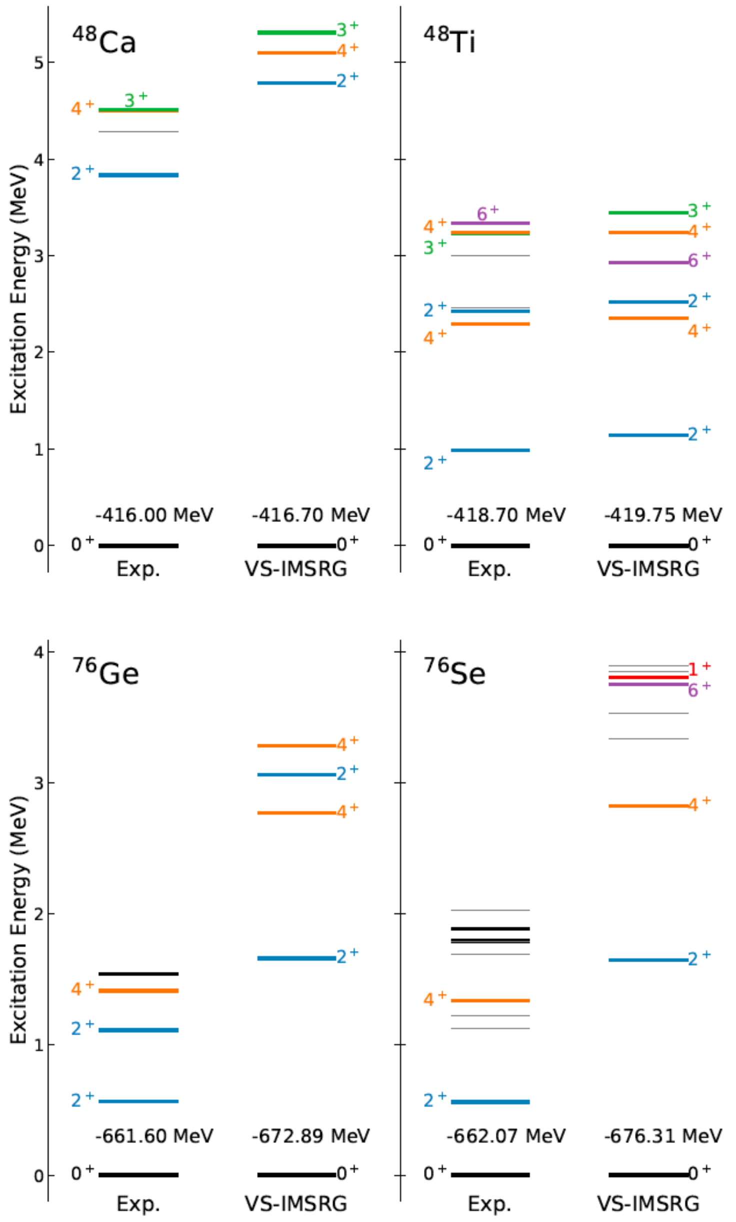


FIG. 2. Excitation spectra of ^{48}Ca/Ti and ^{76}Ge/Se from the VS-IMSRG compared to experimental values [53, 54]. Certain states have been highlighted to help guide the comparison.

Phys. Rev. Lett. 126, 042502