Neutrinoless Double-Beta Decay

[On a path of discovery with the neutrino]

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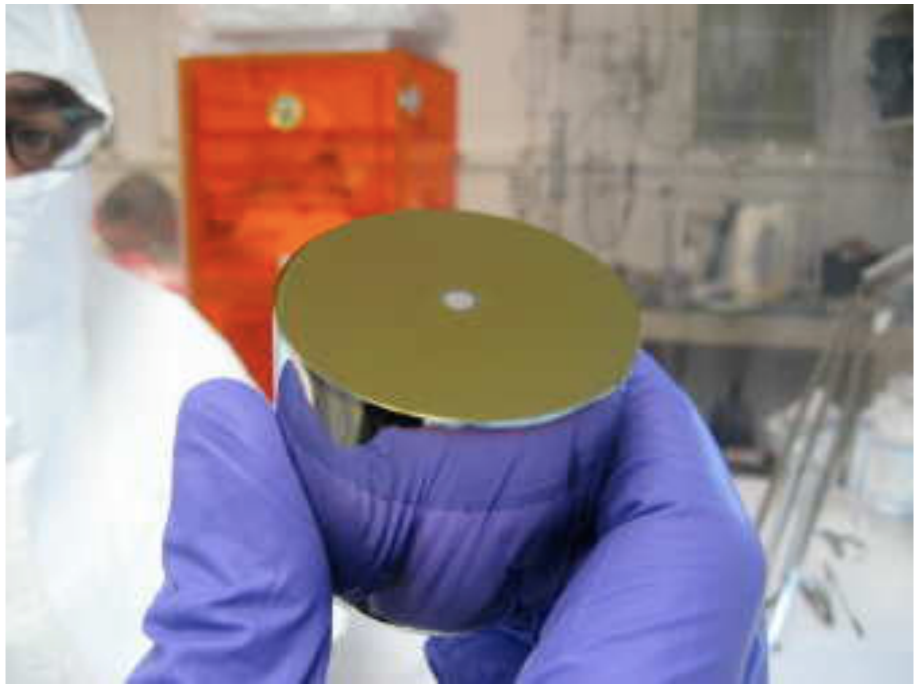
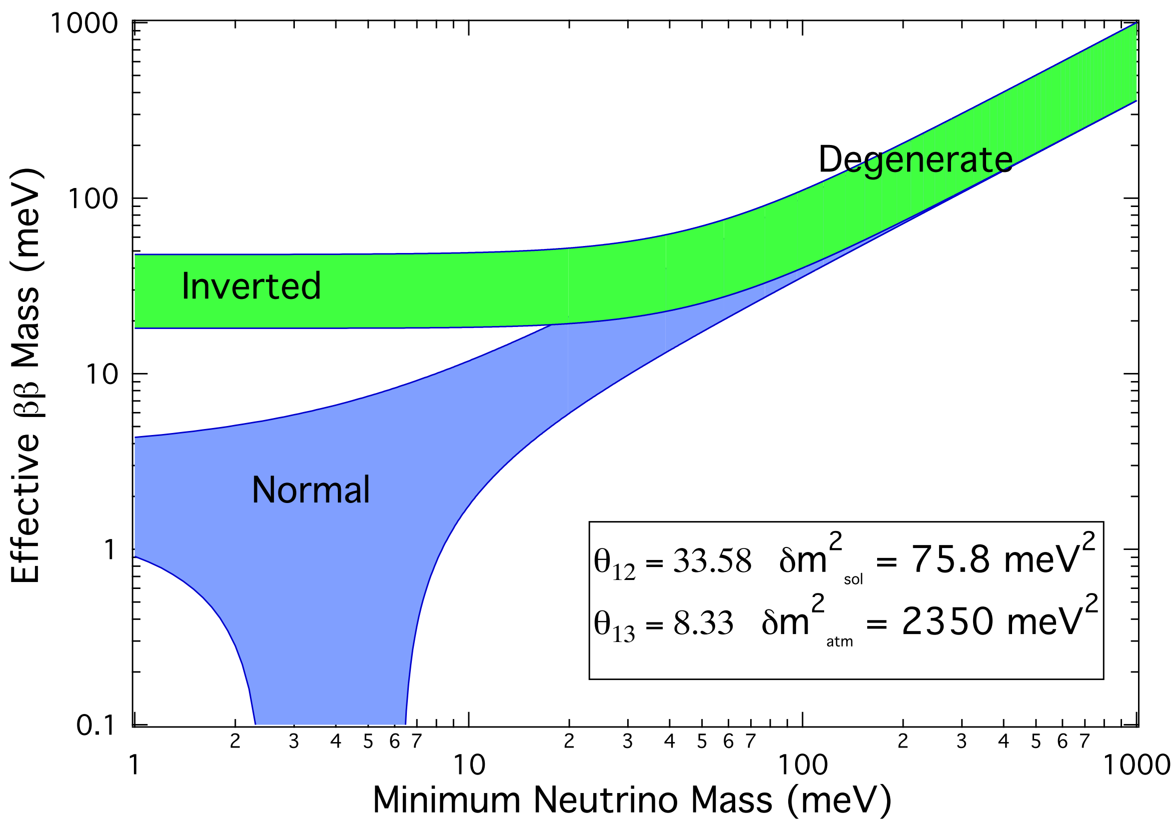
Outline

- Neutrino discoveries
- State of neutrino physics
- Open questions - New discoveries
- Neutrinoless double-beta decay
- The MAJORANA Program

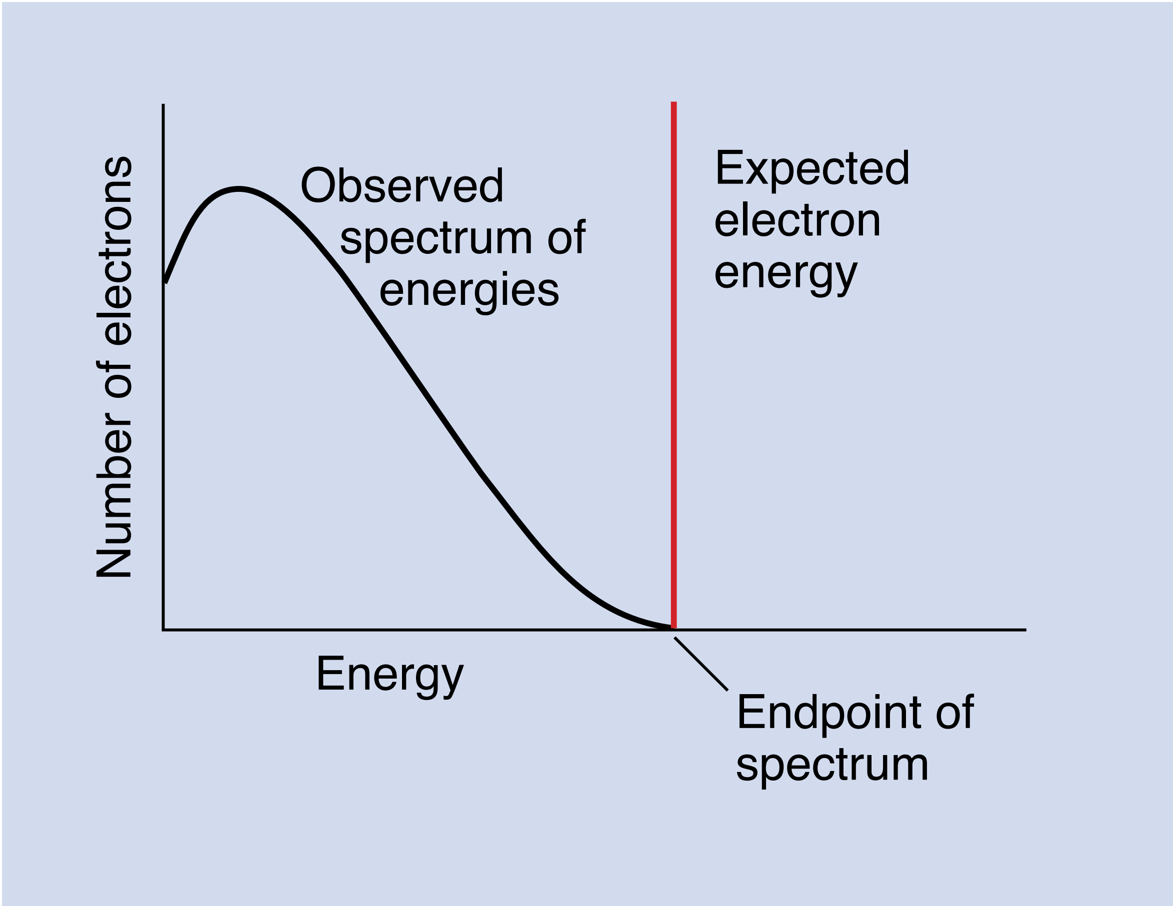




The Neutrino is Born

- Pauli postulates the need for a neutrino
  - Missing energy in continuous β spectrum

$$(N, Z) \rightarrow (N-1, Z+1) + e^{-} + ??$$



"Dear radioactive ladies and gentlemen,
... I have hit upon a desperate remedy to save the `exchange theorem' of statistics and the energy theorem. Namely [there is] the possibility that there could exist in the nuclei electrically neutral particles that I wish to call neutrons, ..."

Pauli, 1930

The Neutrino is Born

- Fermi's theory of beta decay
  - Explained the existence of the neutrino
  - A weak interaction

$$\text{Beta Decay: } n \rightarrow p + e^- + \bar{\nu}_e$$

$$\text{Electron Capture: } e^- + p \rightarrow n + \nu_e$$

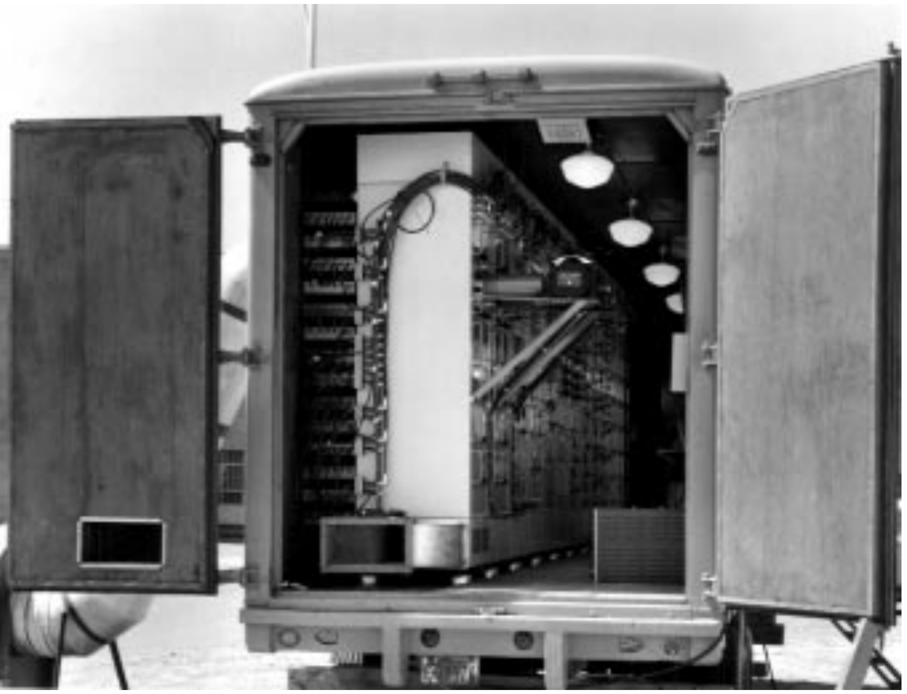
$$\text{Inverse Beta Decay: } \bar{\nu}_e + p \rightarrow n + e^+$$

  - Correctly explained all aspects of beta decay
- Now, must detect a neutrino to confirm their existence

$$\text{typical } \sigma = 1.2 \times 10^{-43}\,\text{cm}^2$$

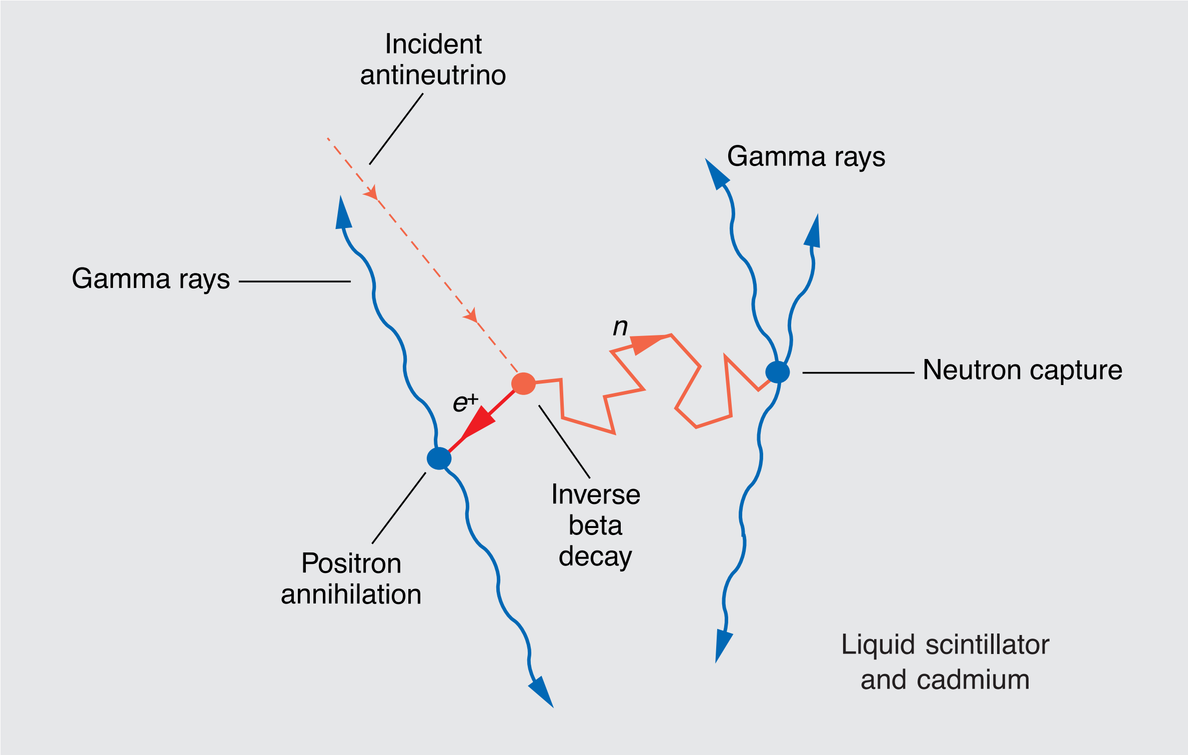
- Path length of 10 light-years!

The Neutrino is Detected



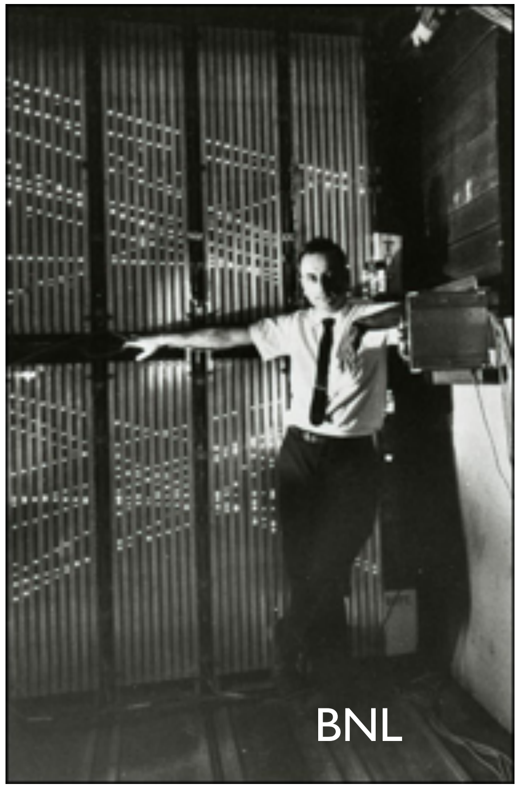
- Reines & Cowan (1956)
  - Exploit the unique signature of inverse beta decay

Inverse Beta Decay: $\bar{\nu}_e + p \rightarrow n + e^+$

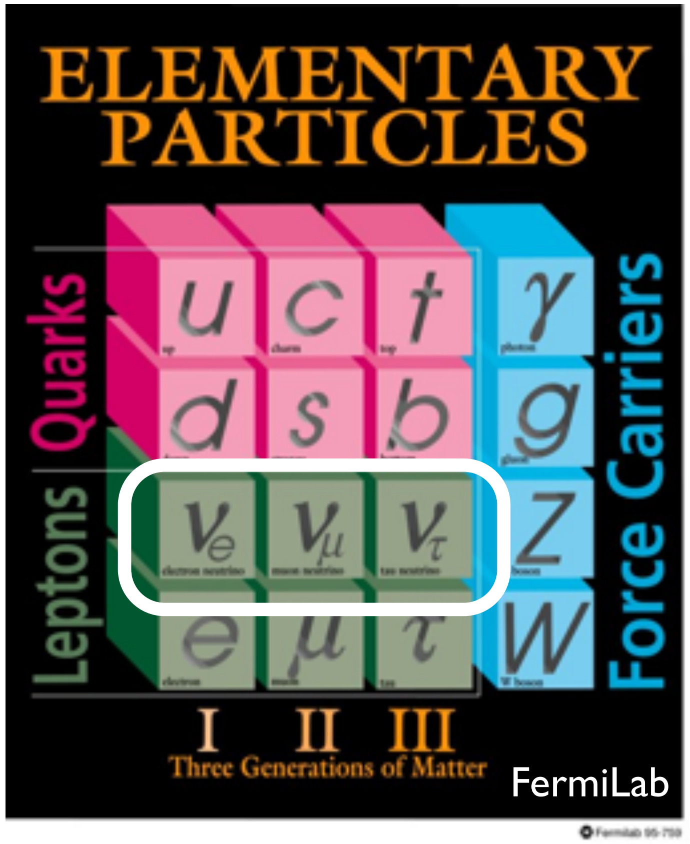


  - Liquid scintillator detectors at Hanford Site and Savannah River
  - Detected reactor antineutrinos with a proton target

Flavors of Neutrinos



- More than just electron-type neutrinos
- Lederman, Schwartz, Steinberger (1962)
  - muon-type neutrino detected in a muon beam at BNL
  - 10 ton Al spark chamber
- Fermilab experiment (2000)
  - tau-type neutrino detected in a mixed neutrino beam at Fermilab

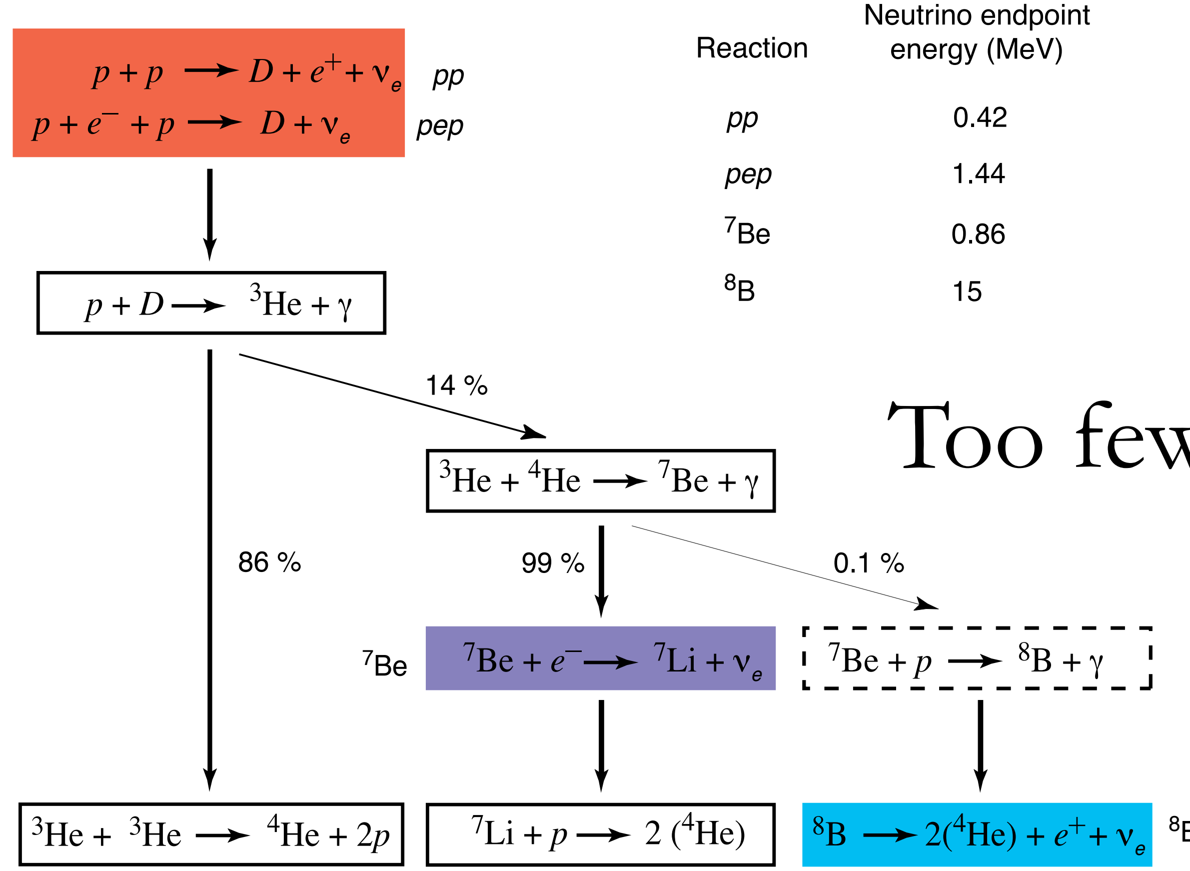


Neutrino Problem

- Ray Davis
  - Solar Neutrinos fusion produce neutrinos
  - CCl_4 target 1500-m underground in Homestake, SD
  - Inverse beta decay:

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}$$

$$\nu_e + n \rightarrow e^- + p$$



Reaction	Neutrino endpoint energy (MeV)
pp	0.42
pep	1.44
^{7}Be	0.86
^{8}B	15

Too few detected!

Los Alamos Science, no. 25 (1997)

Neutrino Problem Confirmation

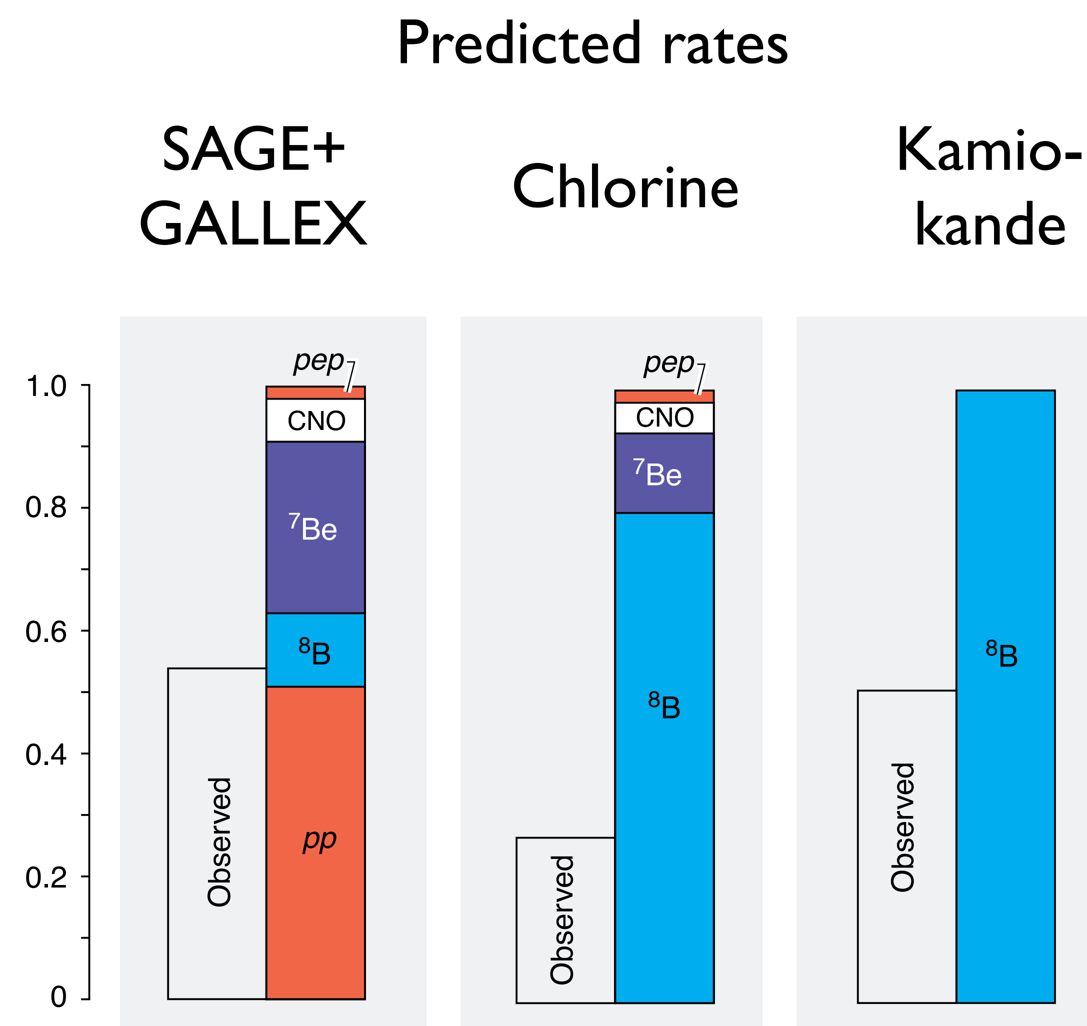
- Kamioka detector
  - Water Cerenkov Detector, 3,000 tons
  - Elastic scattering

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

- Gallium Experiments: SAGE and GALLEX
  - radiochemical experiment using Ga
  - inverse beta decay

$$\nu_e + {}^{71}\text{Ga} \rightarrow e^- + {}^{71}\text{Ge}$$

- All three sensitive to separate and overlapping regions of the ν spectrum



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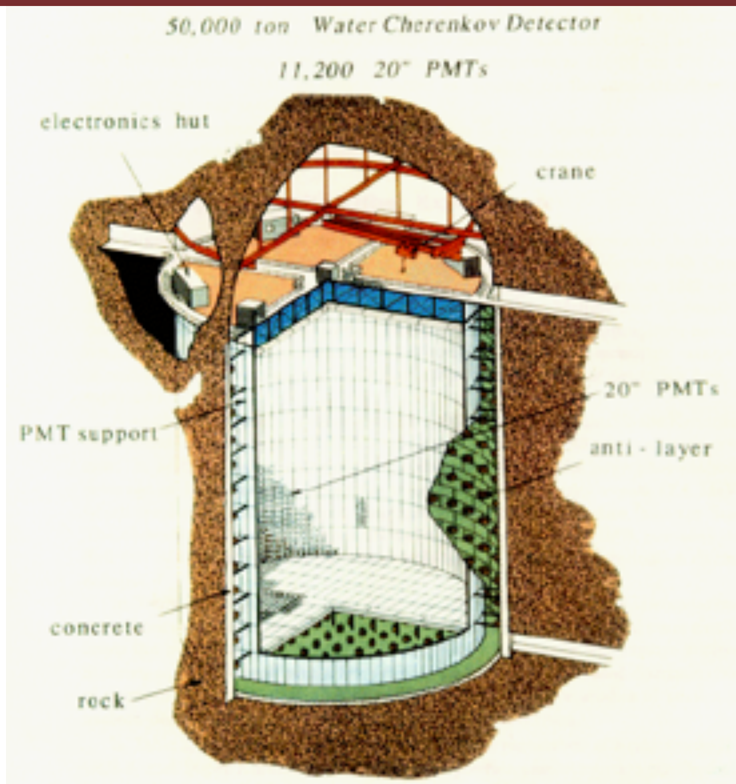
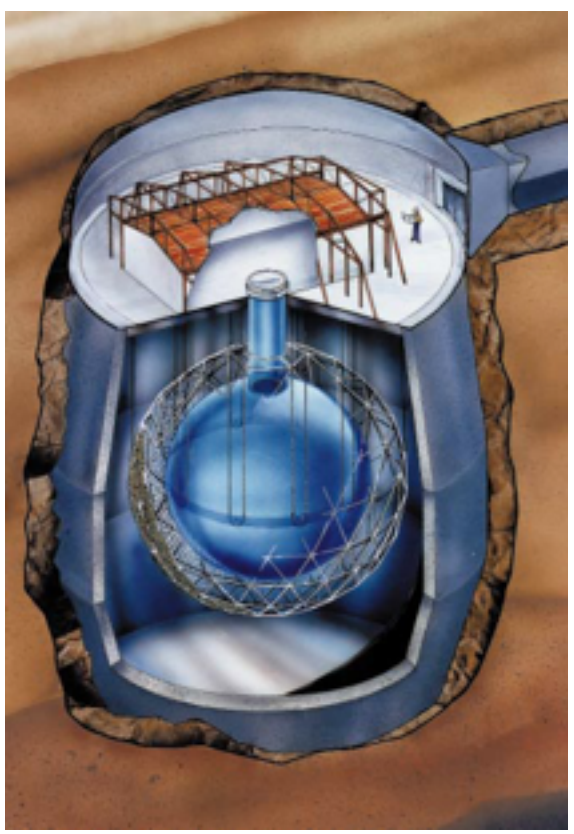
Neutrinos Found





- ✦ SuperKamiokande (1998)
  - Water Cerenkov detector, 50,000 tons
  - atmospheric neutrinos

$$\text{Charged Current: } \nu_l + N \rightarrow l + X$$

- ✦ SNO Detector
  - Water Cerenkov and neutron detection
  - Sensitive to all flavors of neutrinos

$$\text{Elastic Scattering: } \nu_i + e^- \rightarrow \nu_i + e^-$$

$$\text{Charged Current: } \nu_e + d \rightarrow e^- + p + p$$

$$\text{Neutral Current: } \nu_i + d \rightarrow \nu_i + n + p$$

- ✦ No longer missing neutrinos (if all flavors counted)

2015 Nobel Prize in Physics

Photo: A. Mahmoud

Takaaki Kajita

Prize share: 1/2

Photo: A. Mahmoud

Arthur B. McDonald

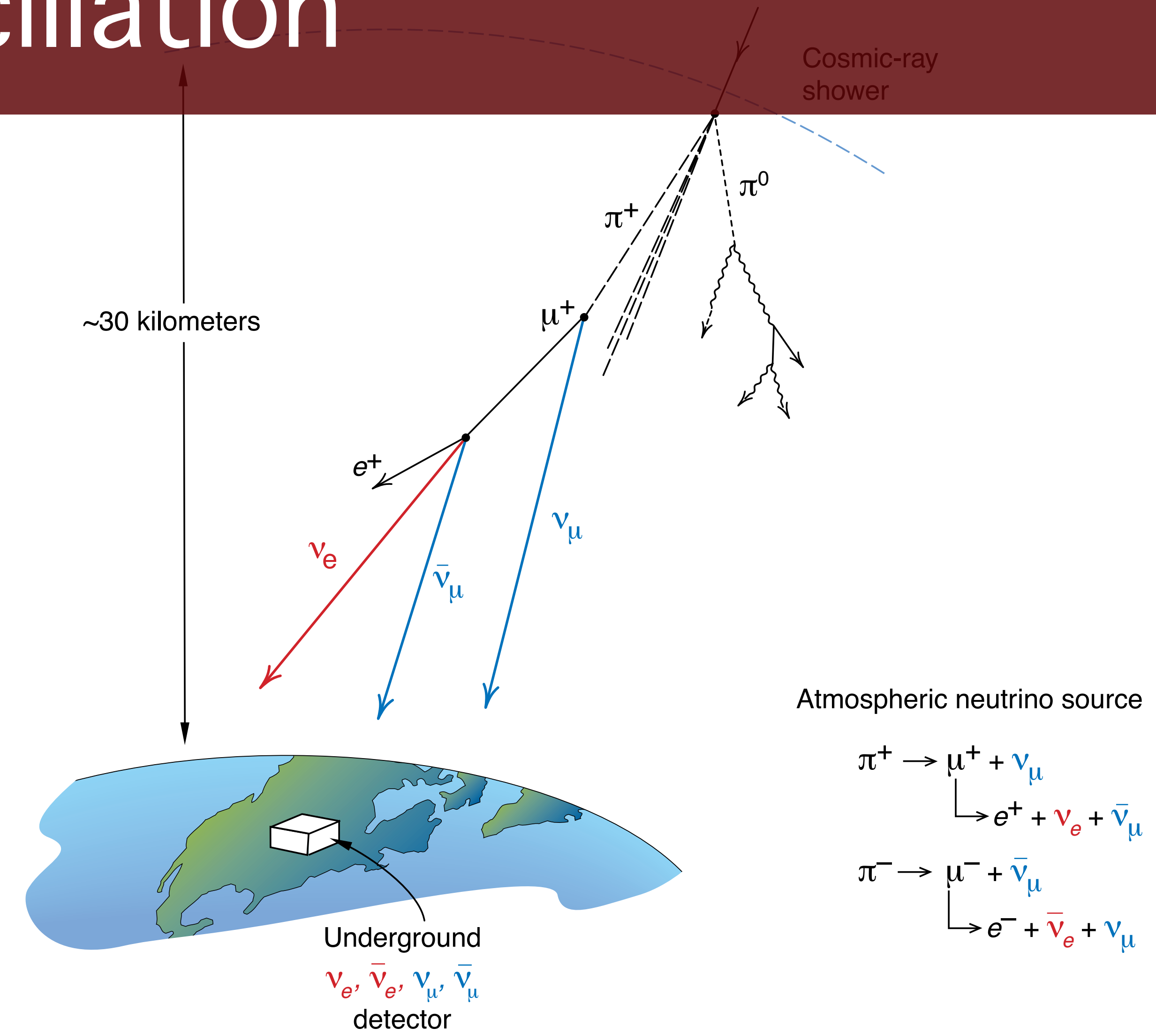
Prize share: 1/2

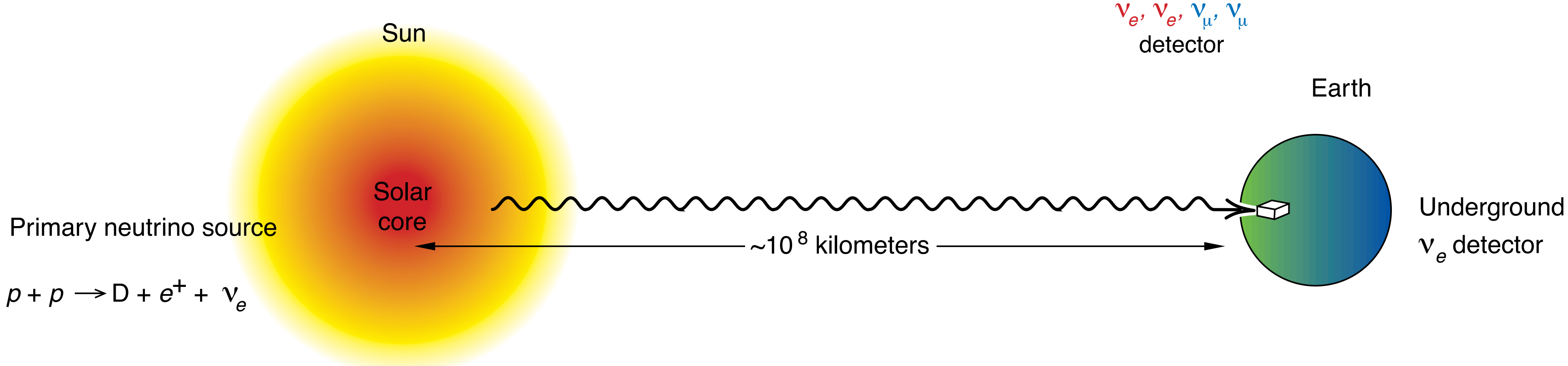
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

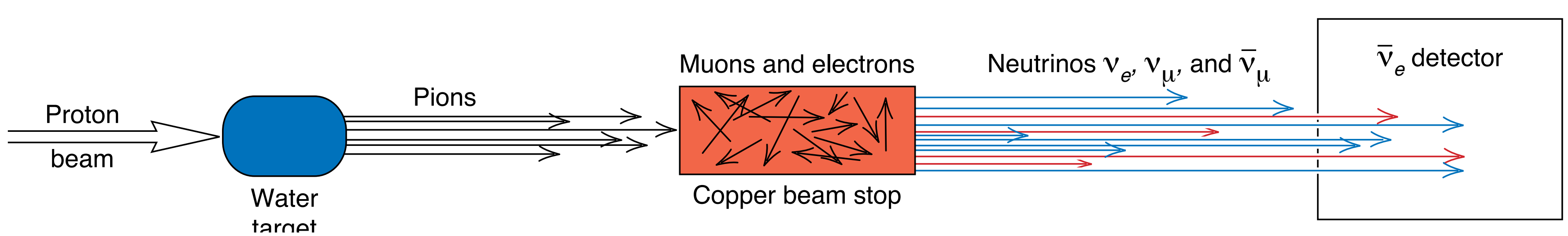
"The Nobel Prize in Physics 2015". Nobelprize.org. Nobel Media AB 2014. Web. 25 Jul 2017. <http://www.nobelprize.org/nobel_prizes/physics/laureates/2015/>

Flavor Oscillation

- Flavor oscillation:
  - a neutrino is born as one flavor and detected as another
  - Requires that they have mass
- Verified and constrained by solar, atmospheric, reactor, and accelerator experiments
  - appearance and disappearance







Los Alamos Science, no. 25 (1997)

Neutrino Mixing

Flavor states are linear combinations of the mass states

Neutrino Flavors →

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

← Neutrino Masses

- ✦ Mixing via the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix
- ✦ Under the 3 neutrino model,
  - the mixing matrix described by 3 angles θ_{ij}
  - Oscillation probability determined by mass squared differences Δm^2_{ij}
  - CP violating phase and Majorana phase

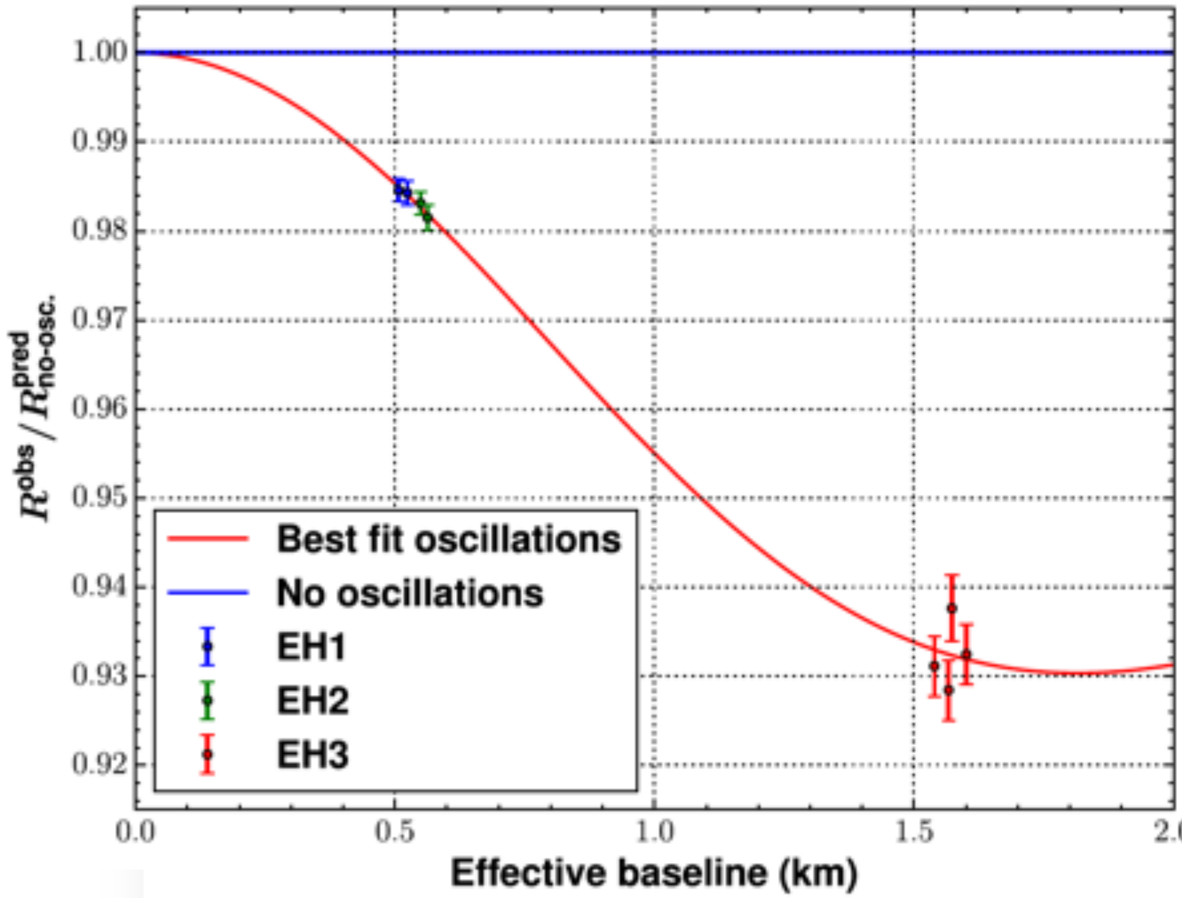
By convention:

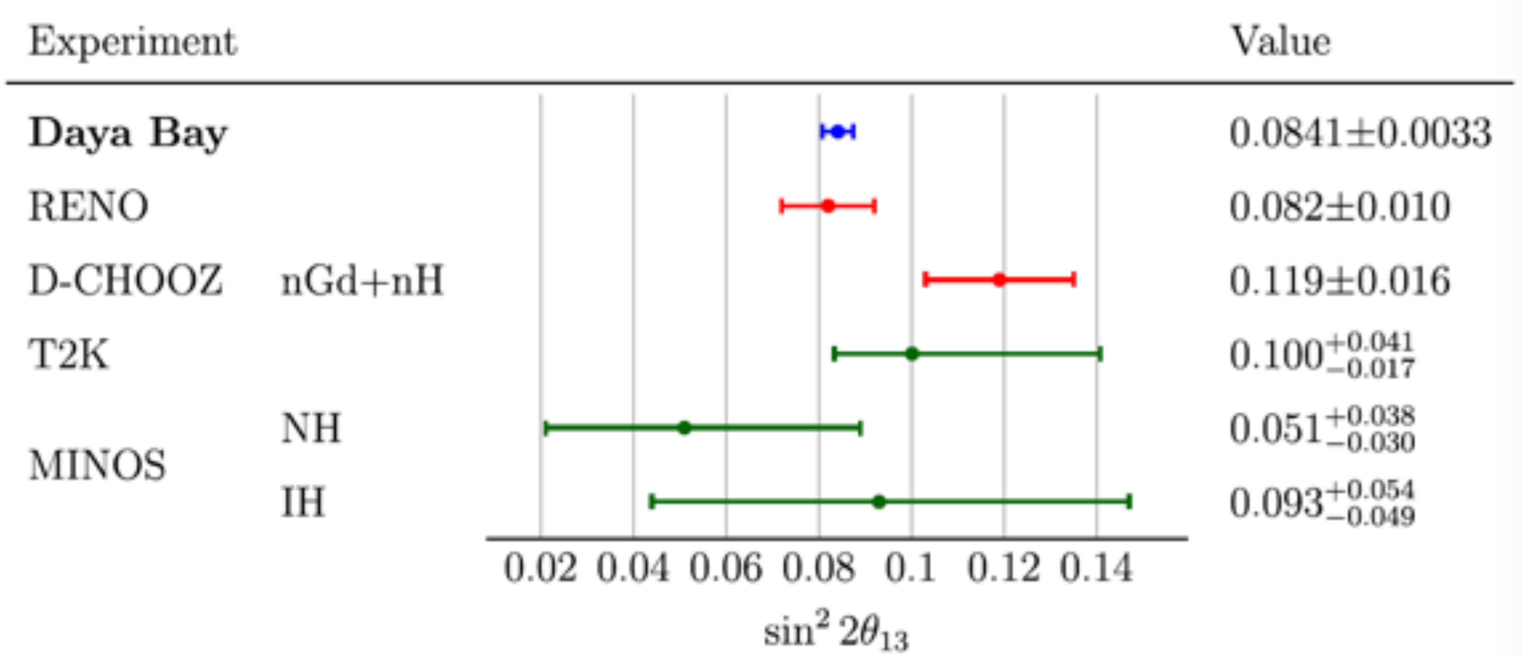
$$\Delta m^2_{21} = m^2_2 - m^2_1 > 0$$ Small and positive (solar scale)

$$\Delta m^2_{31} = m^2_3 - m^2_1$$ Larger and sign unknown (atmospheric scale)

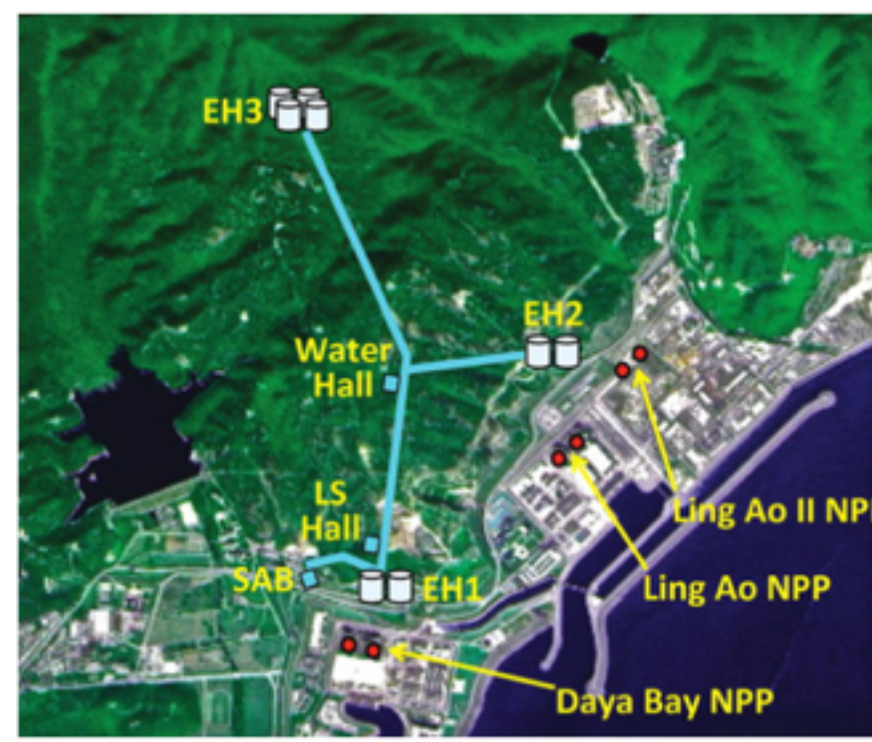
Neutrino Mixing

- Rich program of measuring the oscillation parameters
- Example: the search for θ_{13}
  - Data Bay Reactor Experiment
    - $\bar{\nu}_e$ disappearance through inverse beta decay in scintillating target





PHYSICAL REVIEW D 95, 072006 (2017)



Neutrino Mixing

Flavor states are linear combinations of the mass states

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & -c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \end{pmatrix} \begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0\\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}}\end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

(where $c_{12} = \cos\theta_{12}$, etc)

Global Fit to oscillation parameters

$$\delta m^2 = m_2^2 - m_1^2 = 7.37 \times 10^{-5} eV^2$$

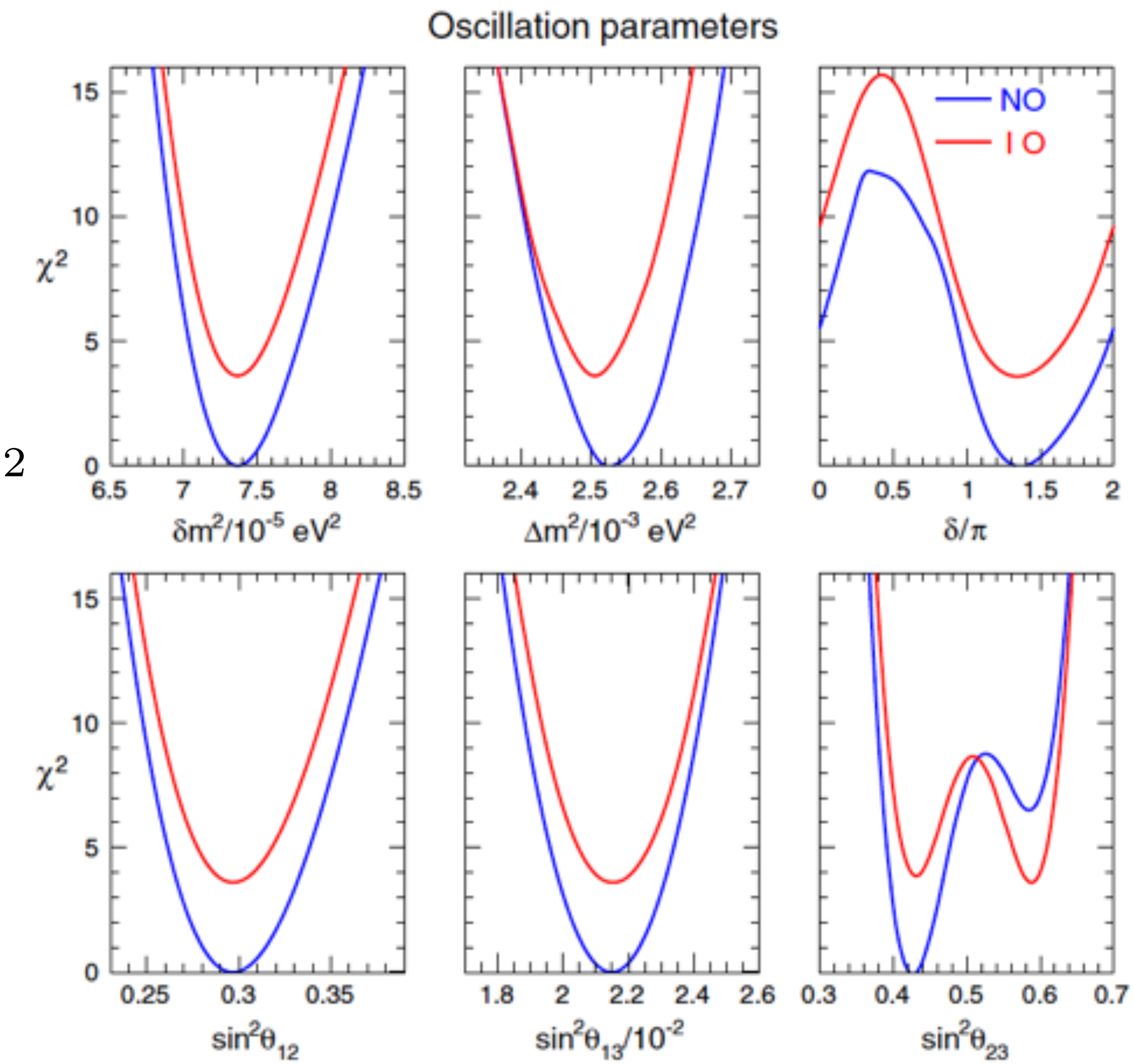
$$|\Delta m^2| = \left| m_3^2 - \frac{m_2^2 + m_1^2}{2} \right| = 2.525 \times 10^{-3} eV^2$$

$$\sin^2\theta_{12} = 0.297$$

$$\sin^2\theta_{23} = 0.425$$

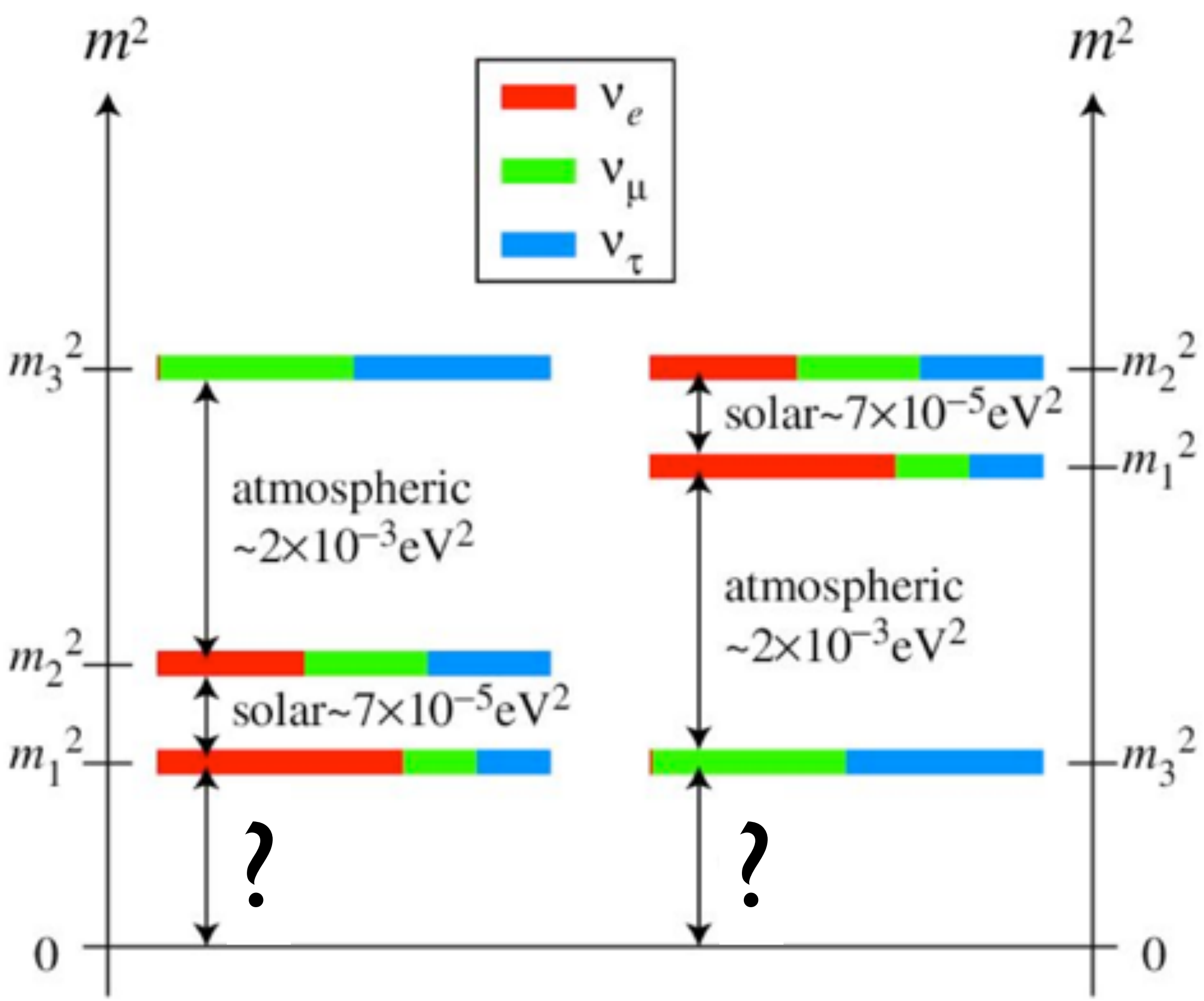
$$\sin^2\theta_{13} = 0.0215$$

Capozzi et al. PhysRevD **95**, 096014 (2017)



Normal Inverted

We Have More to Learn About Neutrinos



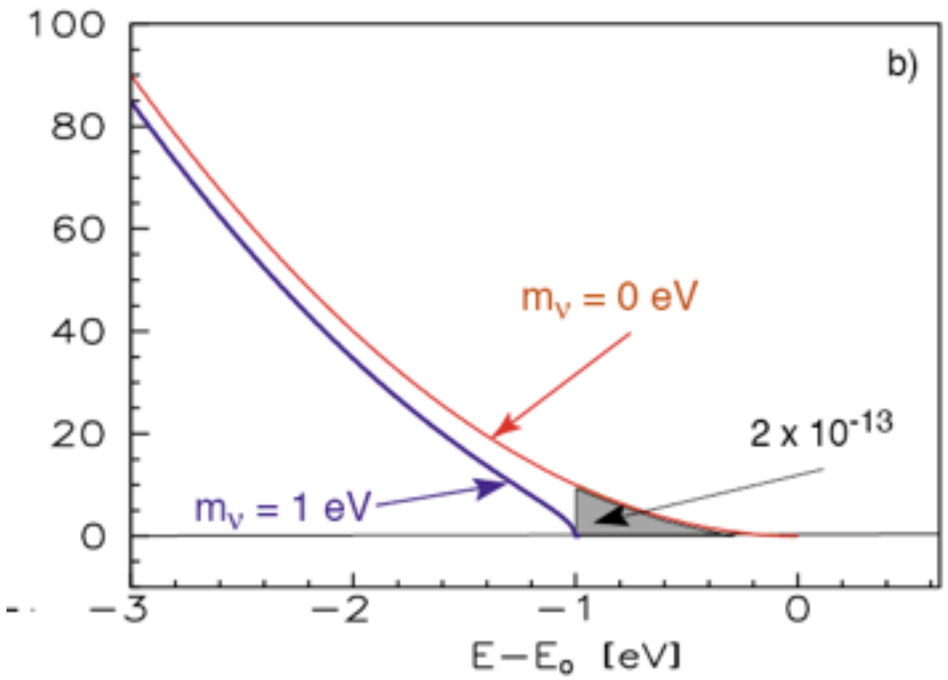
$$\Delta L \neq 0$$

$$\nu_\mu \rightarrow \nu_e \neq \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

- What we DON'T know about neutrinos
  - How massive are they?
    - What is the absolute scale?
  - Which one is the heaviest?
    - Which hierarchy is correct?
  - Are they their own anti-particle?
    - Can $\nu_e = \bar{\nu}_e$
  - Is Lepton # violated
  - Is there Leptonic CP-invariance violation

We Have More to Learn About Neutrinos

Beta decay endpoint



KATRIN

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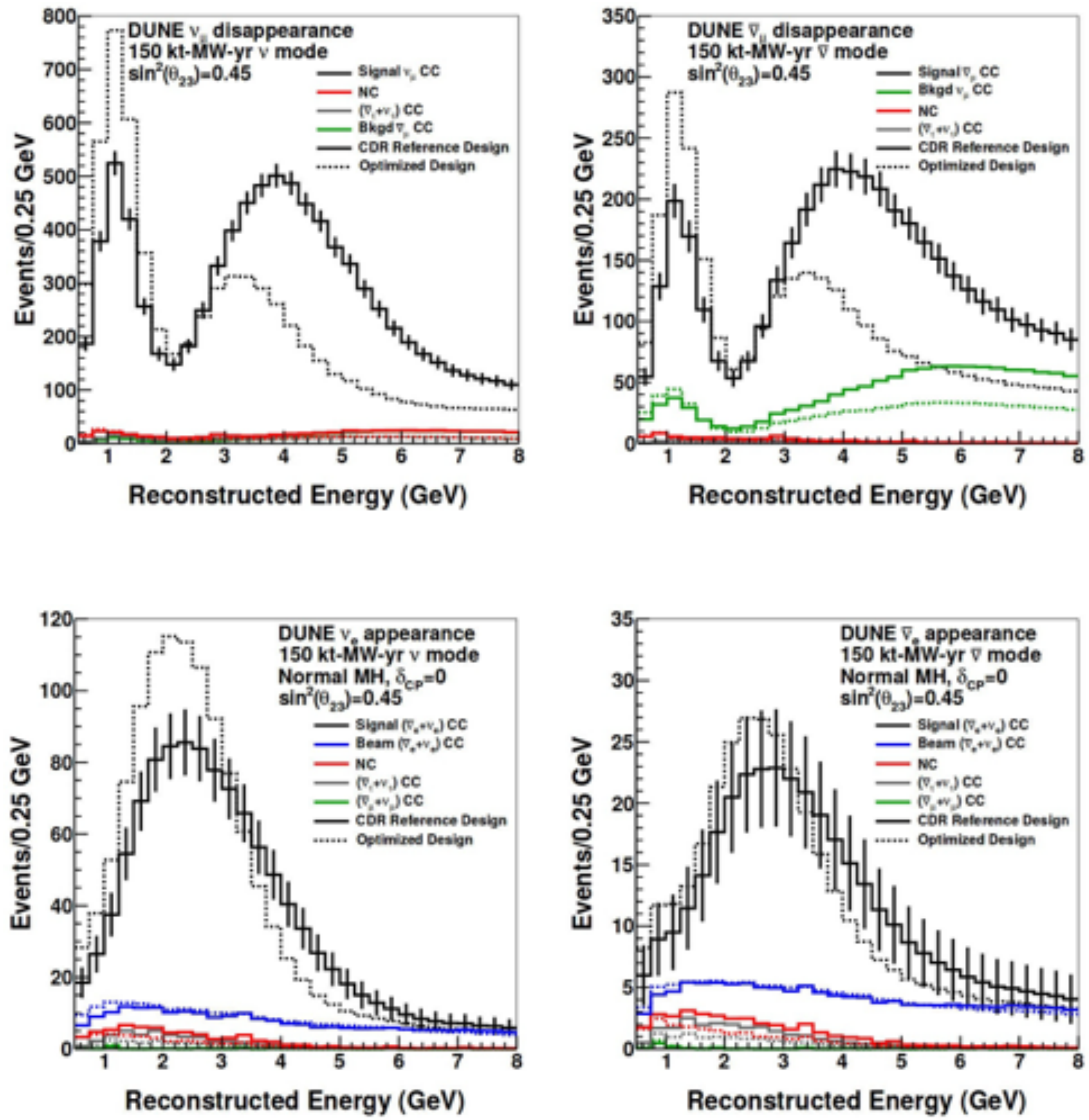
We Have More to Learn About Neutrinos

Long Baseline Neutrino Oscillation



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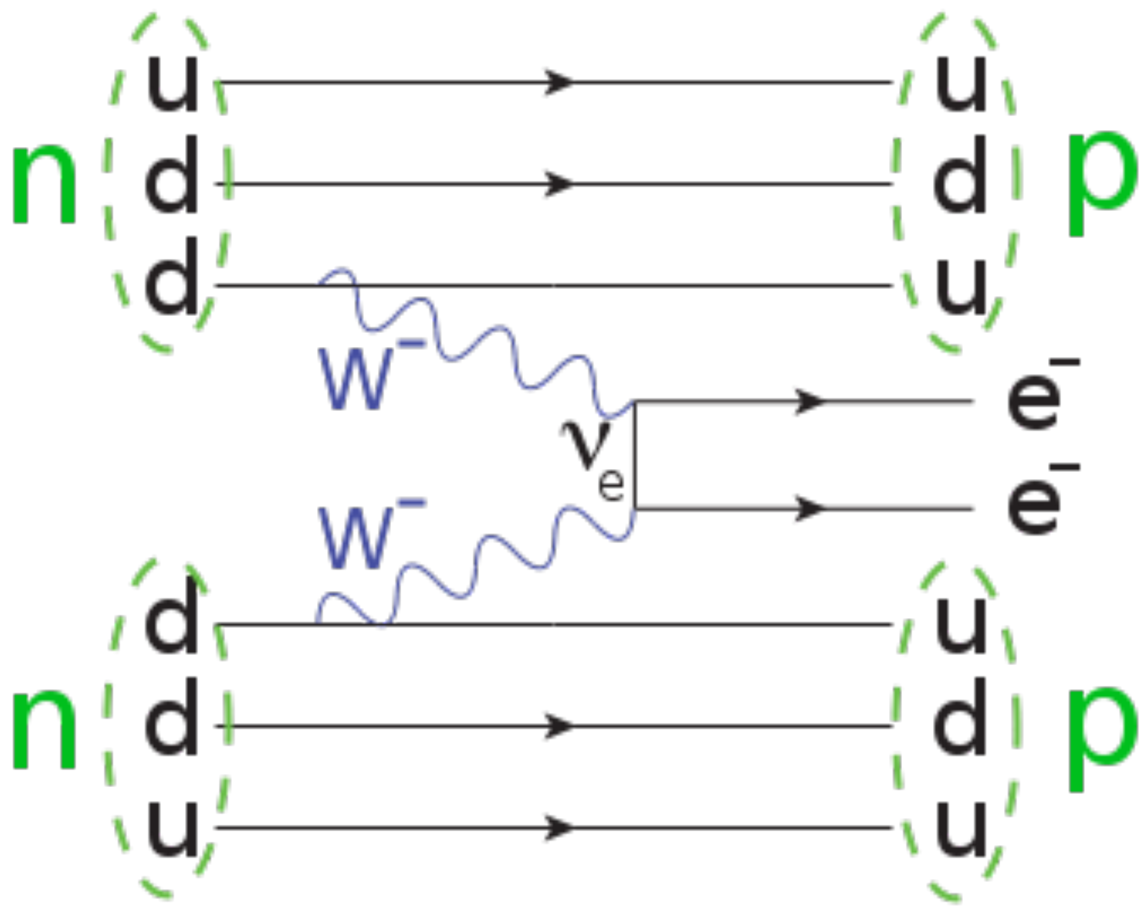
We Have More to Learn About Neutrinos

Neutrinoless double-beta decay



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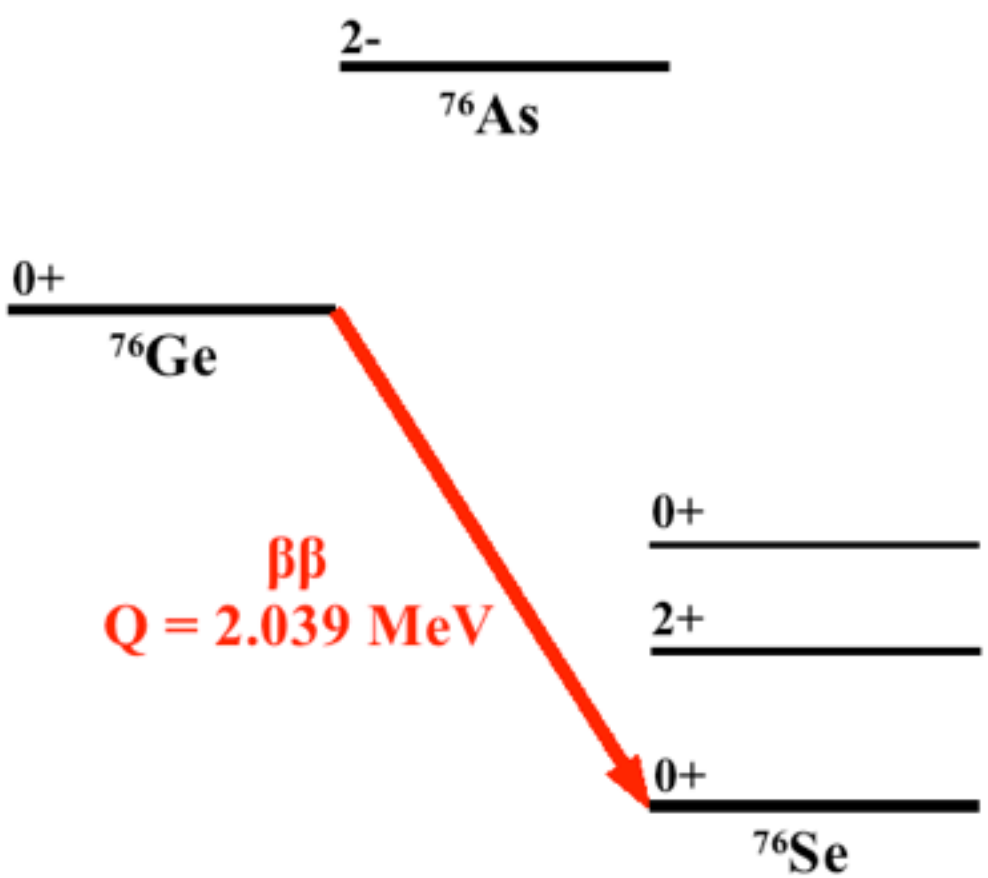
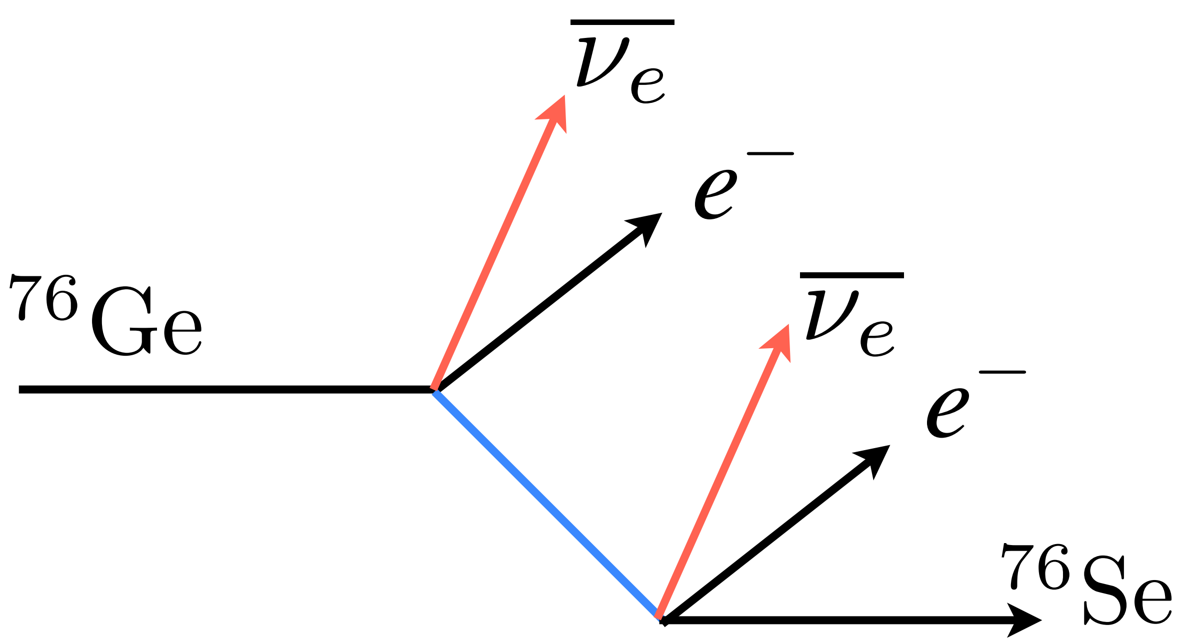
Two Neutrino Double-Beta Decay

- An allowed nuclear physics process
  - Can occur when single β decay not allowed
  - Lepton number is conserved
  - Observed in a number of isotopes

$$^{76}Ge \Rightarrow ^{76}Se + 2e^- + 2\overline{\nu_e}$$





Observed in ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{150}Nd, ^{238}U

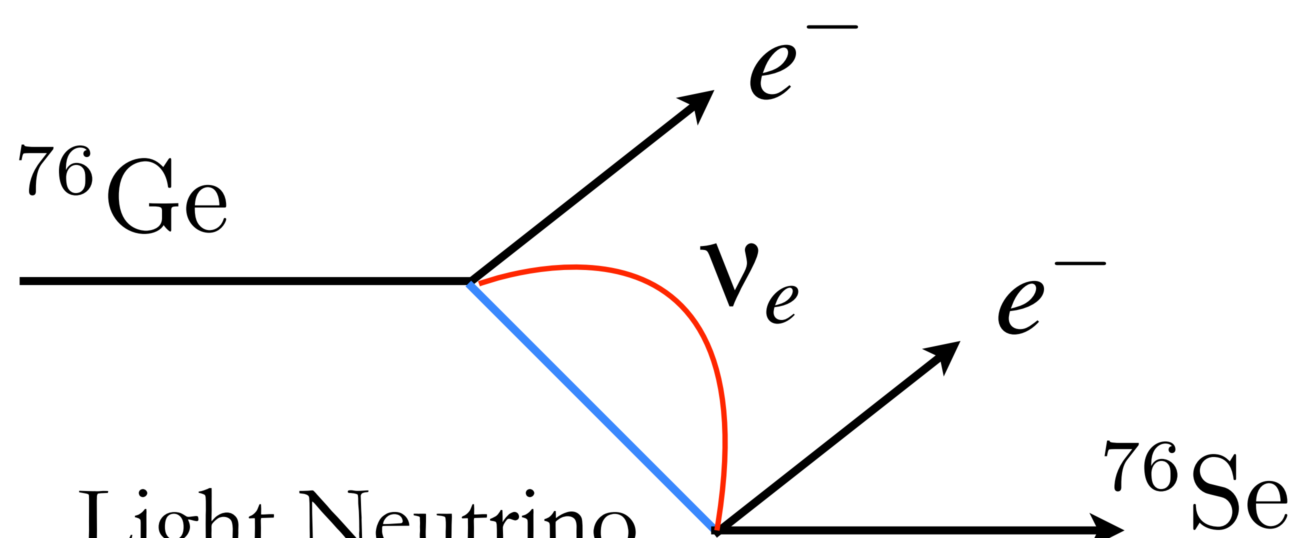
Neutrinoless Double-Beta Decay

- No neutrinos emitted
- Discovery provides:
  - Neutrino is own antiparticle (Majorana)
  - Lepton number violation
  - Neutrino mass

$$^{76}\mathrm{Ge} \Rightarrow {}^{76}\mathrm{Se} + 2e^-$$

$$n \Rightarrow p + e^- + \overline{\nu}_e \quad (RH\ \overline{\nu}_e)$$

$$(LH\ \nu_e) \quad \nu_e + n \Rightarrow p + e^-$$

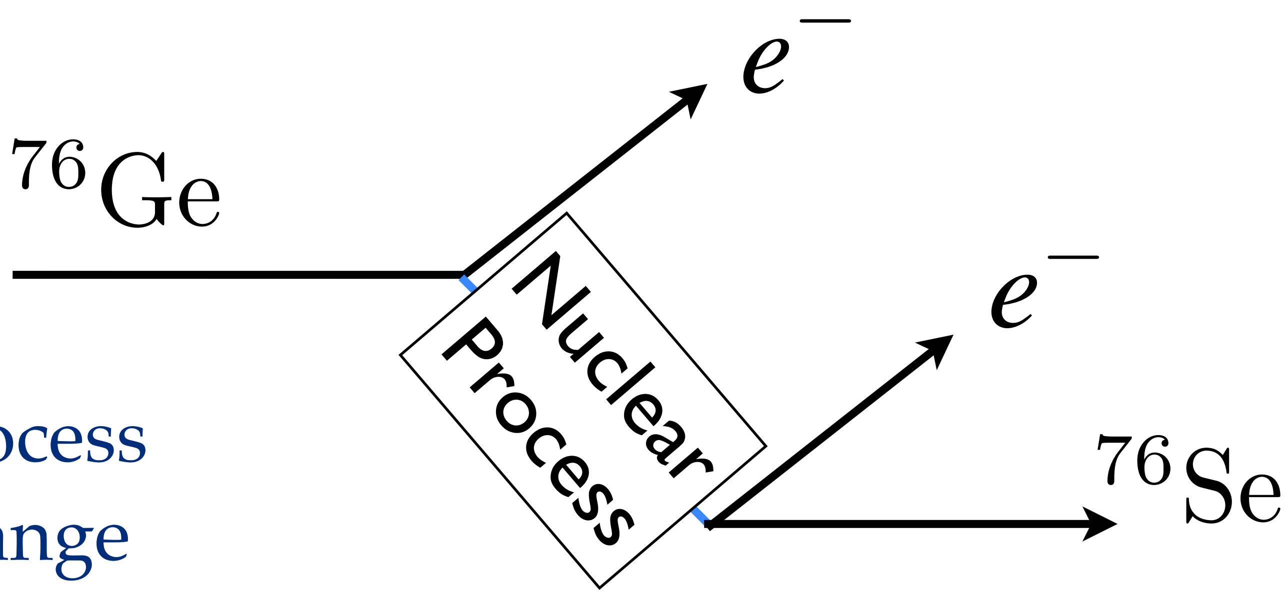


Light Neutrino Exchange

Neutrinoless Double-Beta Decay

- ✦ No neutrinos emitted
- ✦ Discovery provides:
  - Neutrino is own antiparticle (Majorana)
  - Lepton number violation
  - Neutrino mass

$$^{76}\mathrm{Ge} \Rightarrow {}^{76}\mathrm{Se} + 2e^{-}$$

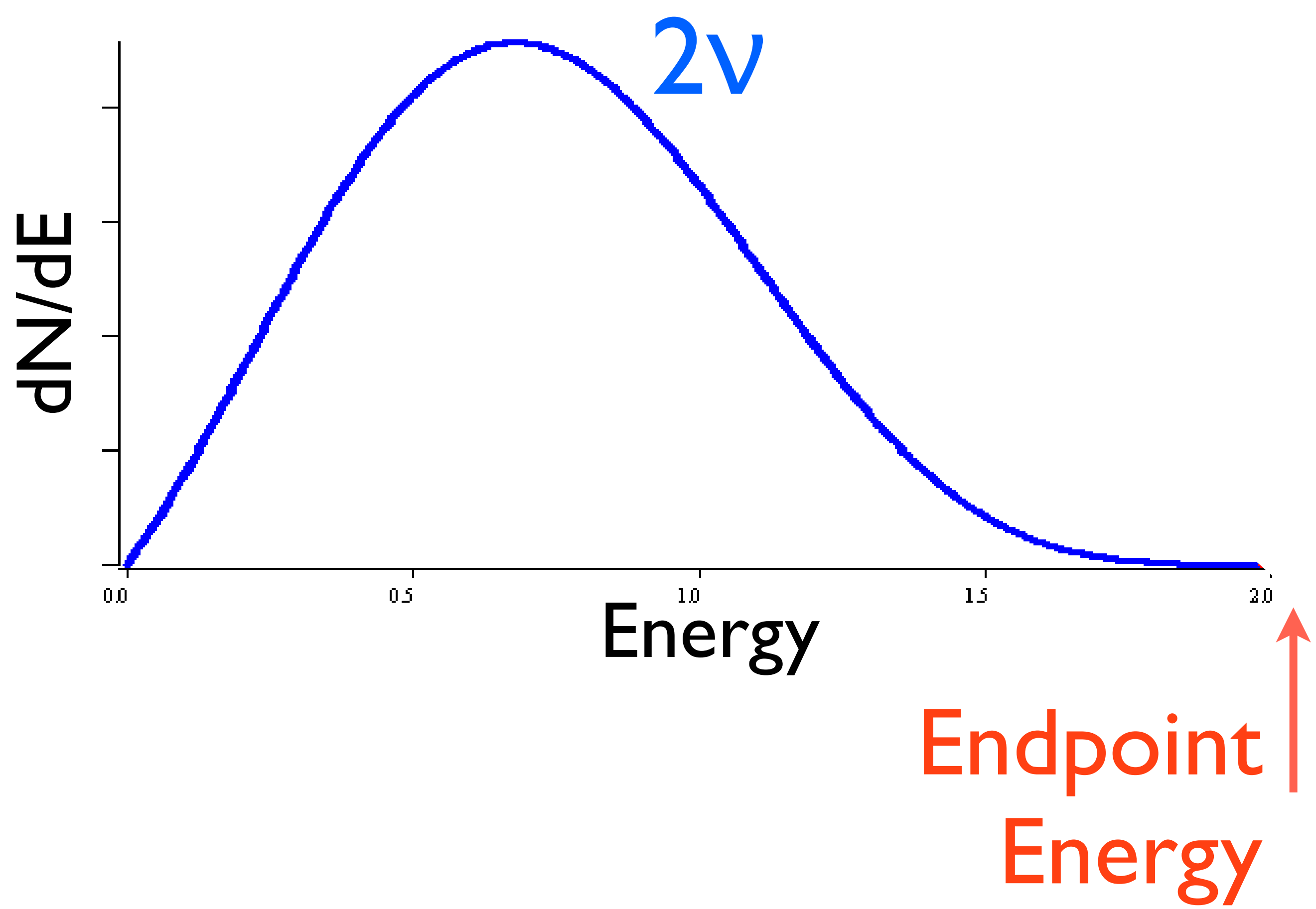


- ✦ Could be some other nuclear process other than a light neutrino exchange

How to Measure ββ

Observe double-beta decay by collecting the energy of the 2 e^- in a detector

- With 2 neutrino double-beta decay, the electrons share the decay energy with the neutrinos
- With neutrinoless double-beta decay, the electrons carry the full decay energy

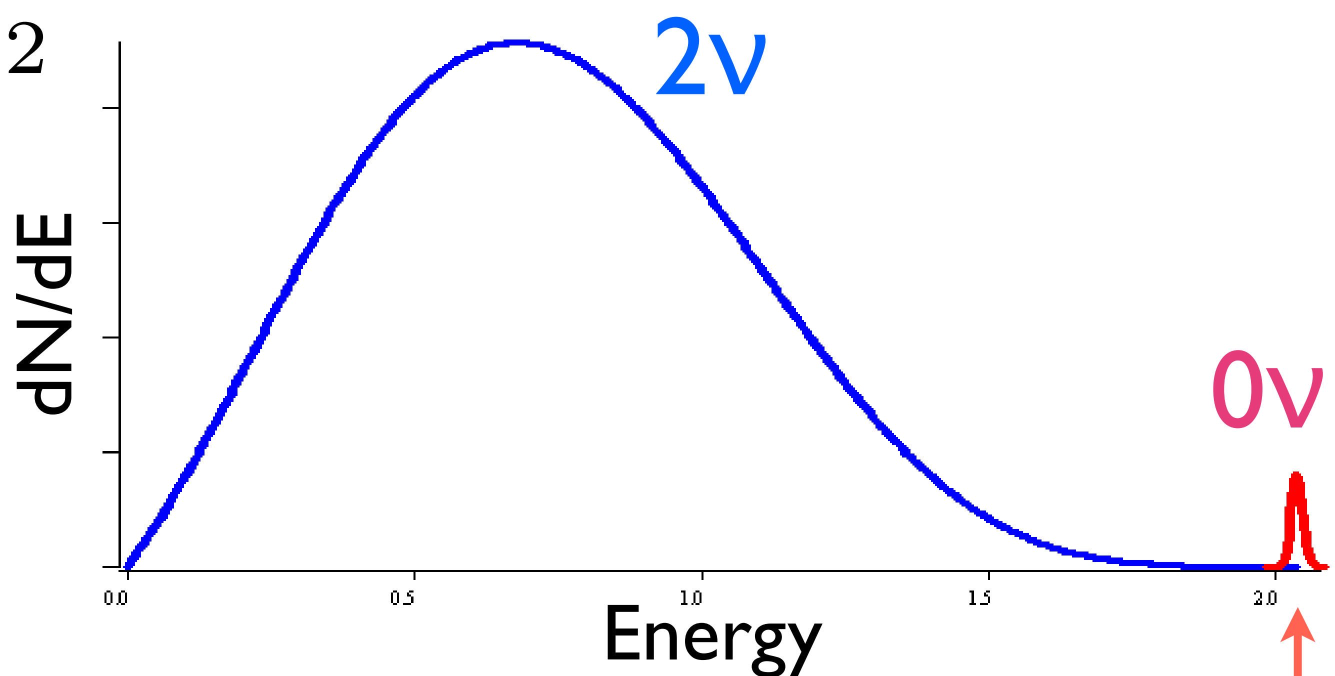


Q=2.039 MeV

How ββ Relates to the Neutrino

Measure decay rate of to get neutrino absolute mass scale

$$\Gamma_{0\nu} = G_{0\nu} |M_{0\nu}|^2 \langle m_{\beta\beta} \rangle^2$$



Endpoint Energy

Q=2.039 MeV

- G are calculable phase space factors
- M are nuclear physics matrix elements
  - Uncertainties among models
- $m_{\beta\beta}$ is the effective Majorana mass

Neutrino Mixing Matrix and Mass

Neutrino Flavors →

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

← Neutrino Masses

Effective Majorana Mass:

No Mixing: $\langle m_{\beta\beta} \rangle = m_{\nu_e} = m_1$

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

- There is an ambiguity in the sign of one of the larger mass-squared differences
  - Leads to two alternative mass orderings (or hierarchies)

Neutrino Mixing Matrix and Mass

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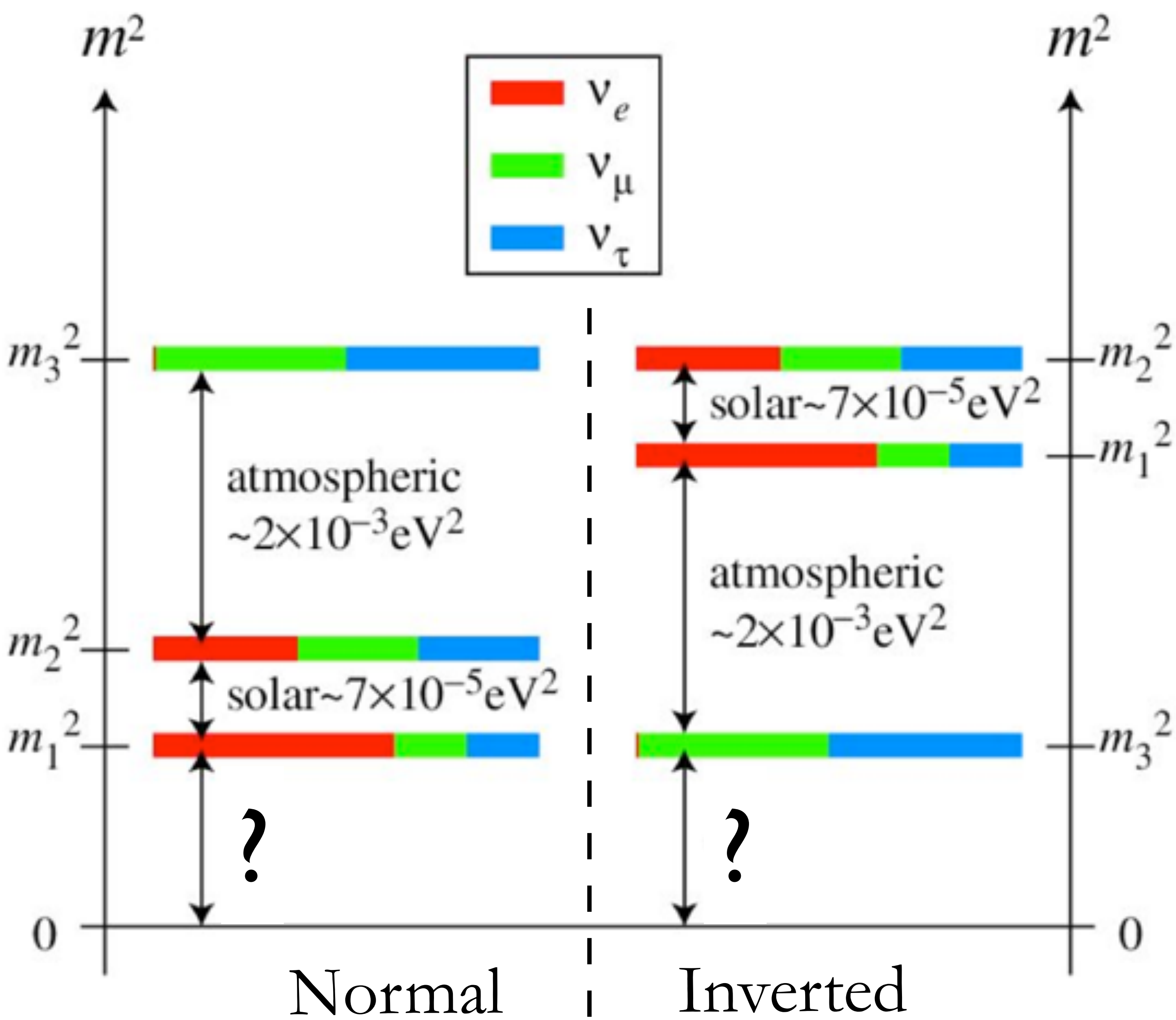
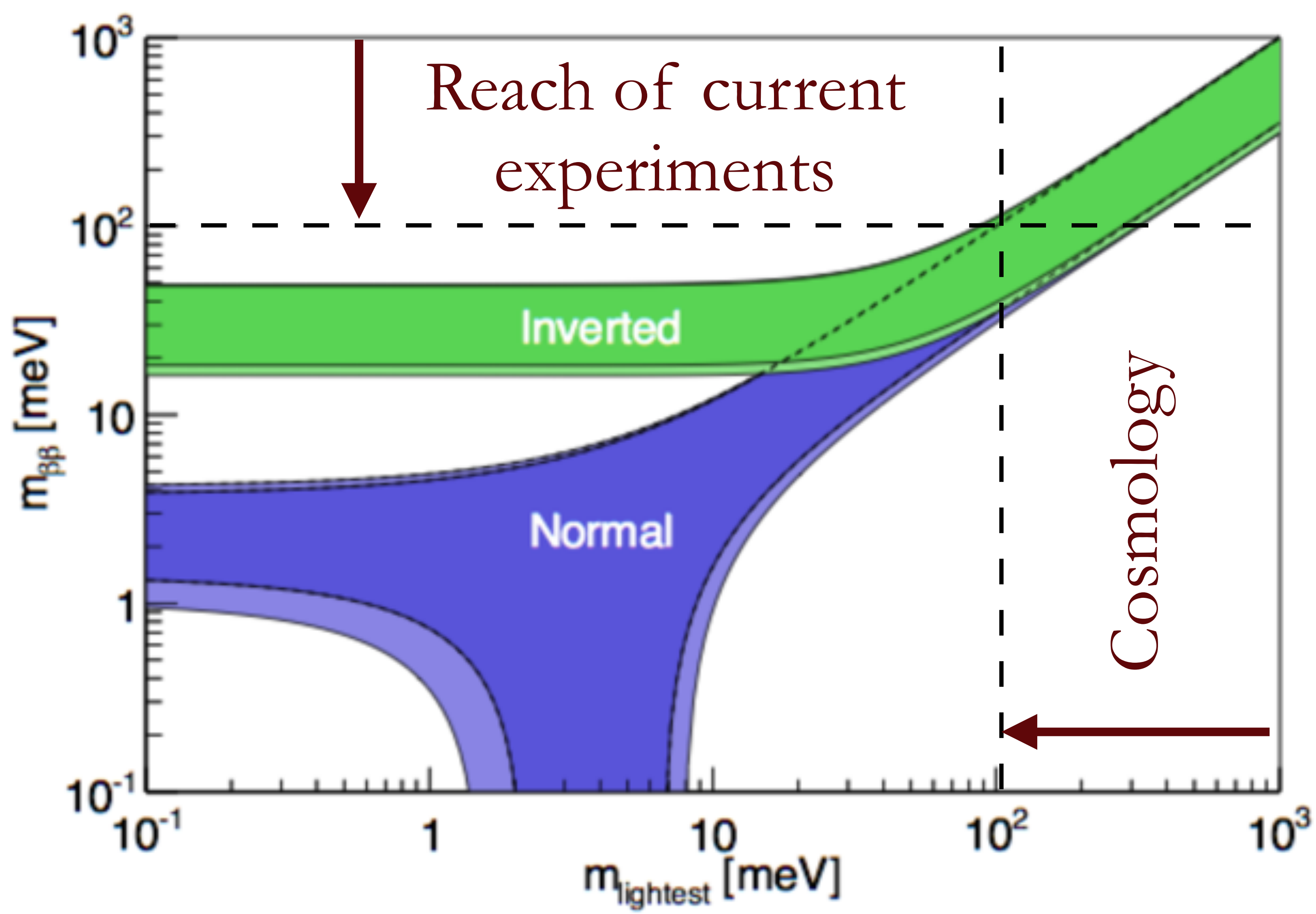


Allowed Mass Ranges

The standard way the two mass hierarchies are plotted for effective Majorana mass vs lightest ν mass

- Inverted and normal refer to unknown mass hierarchy
  - Current understanding of ν oscillation parameters
- Experiments only sensitive to effective ββ mass



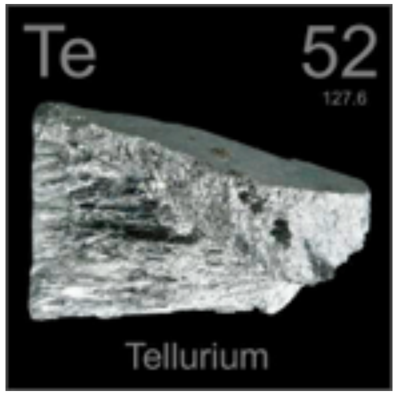
$$\langle m_{\beta\beta} \rangle = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|$$

Experimental Approach

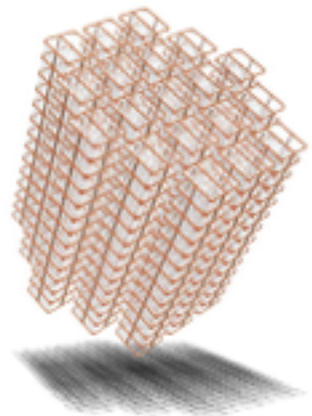
How to best detect neutrinoless double-beta decay?

- ✦ Source of decay = detector
  - minimizes extra mass and unneeded backgrounds
- ✦ Good energy resolution
  - maximize signal to background. Always facing background from 2νββ
- ✦ Extremely low backgrounds in the region of interest
  - requires ultra-pure materials
  - analysis techniques to discriminate backgrounds from signal
  - large Q value to exceed many natural backgrounds
  - backgrounds of <0.1 event per year for next generation sensitivities

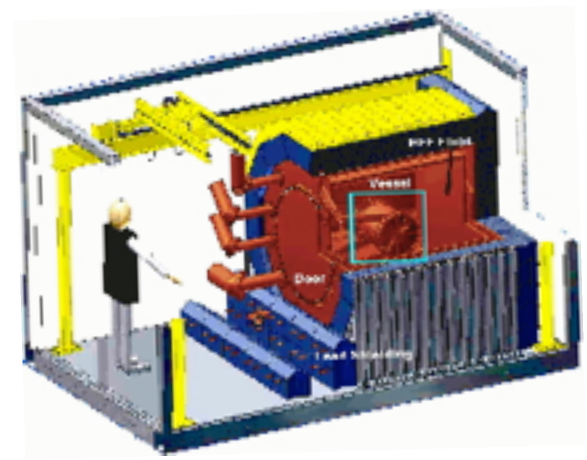
- ✦ Tag decay daughter
  - smoking gun of decay, but also 2νββ
- ✦ Slow 2νββ rate
  - to minimize its background contribution
- ✦ Some isotopes have better nuclear theory

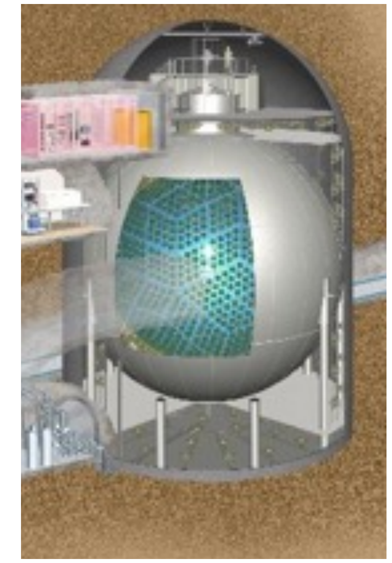


Current Experiments

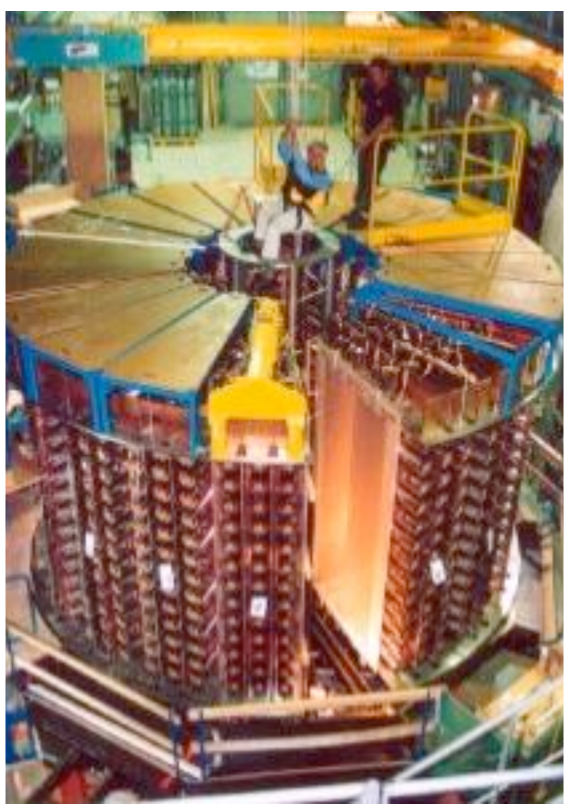


CUORE: TeO_2 bolometers

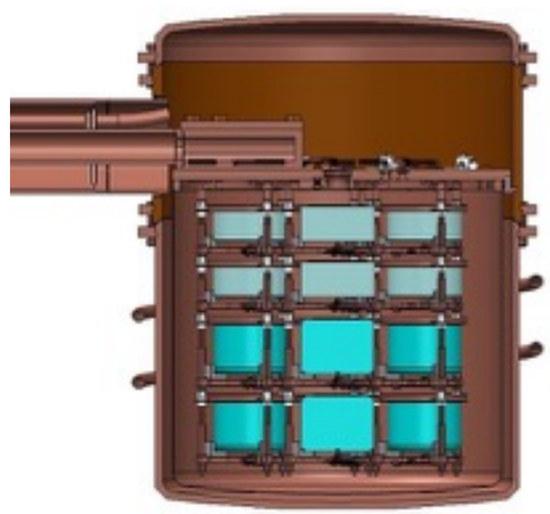


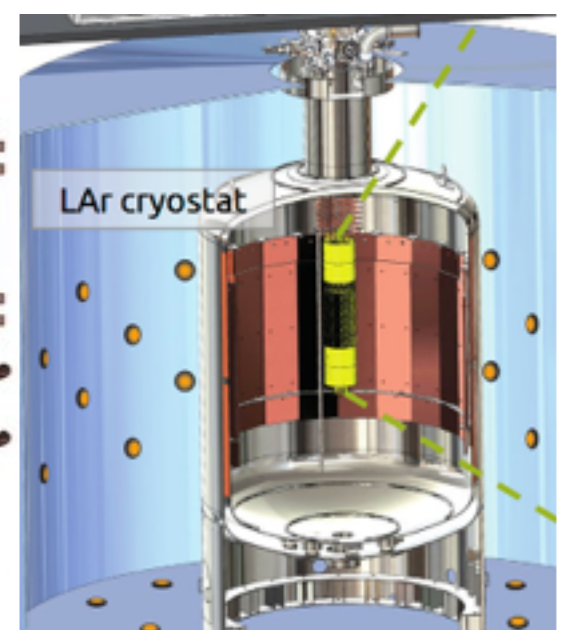


EXO-200, KamLAND-Zen
LXe

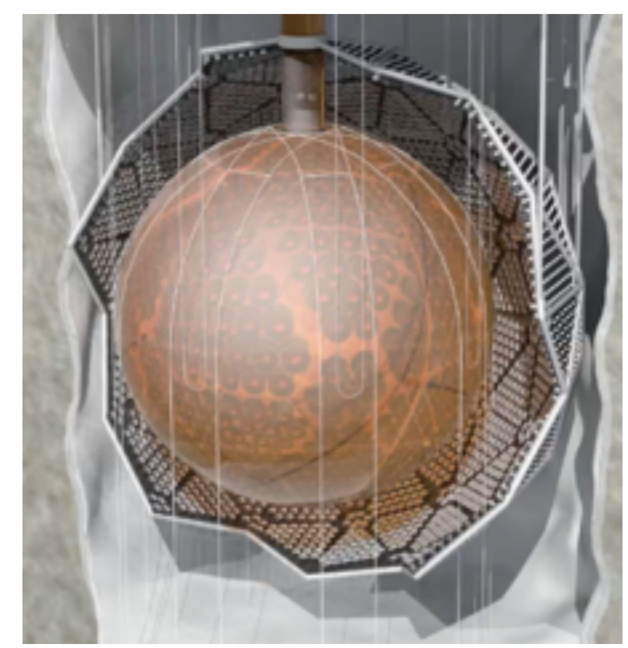


NEMO 3
Tracking





MAJORANA/ GERDA :
^{76}Ge diodes



SNO+: ^{130}Te liquid scintillation

Highlights from Current Experiments

- CUORE:
  - $T_{1/2} > 4.0 \times 10^{24}$ yr [Physical Review Letters 115, 102502 (2015)]
- EXO-200
  - $T_{1/2} > 1.1 \times 10^{25}$ yr [J.B.Albertet al., Nature 510 (2014) 299
- GERDA Phase II
  - $T_{1/2} > 5.3 \times 10^{25}$ yr [M. Agostini *et al.*, Nature 554, 47–52 (2017)]
- KamLAND
  - $T_{1/2} > 1.07 \times 10^{26}$ yr [PRL 117, 082503 (2016)]
- NEMO 3
  - $T_{1/2} > 1.1 \times 10^{24}$ [R. Arnold et al., Phys. Rev. D 89, 111101(R) (2014)]

Age of the universe: 1.38×10^{10} yr

Experimental Progress

Current best limits on $0\nu\beta\beta$

Isotope	$T_{1/2}$ [yr]	$\langle m_\nu \rangle$ [eV]	Experiment
^{48}Ca	$> 5.8 \times 10^{22}$	< 3.1 - 15.4	CANDLES
^{76}Ge	$> 5.3 \times 10^{25}$	< 0.15 - 0.33	GERDA
^{82}Se	$> 3.6 \times 10^{23}$	< 1 - 2.4	NEMO-3
^{96}Zr	$> 9.2 \times 10^{21}$	< 3.6 - 10.4	NEMO-3
^{100}Mo	$> 1.1 \times 10^{24}$	< 0.33 - 0.62	NEMO-3
^{116}Cd	$> 1.9 \times 10^{23}$	< 1 - 1.8	AURORA
^{128}Te	$> 1.5 \times 10^{24}$	< 2.3 - 4.6	geochemical
^{130}Te	$> 4 \times 10^{24}$	< 0.26 - 0.97	CUORE
^{136}Xe	$> 1.07 \times 10^{28}$	< 0.06 - 0.16	KanLAND-Zen
^{140}Nd	$> 2 \times 10^{22}$	< 1.6 - 5.3	NEMO-3

adapted from Barabash, arXiv:1702.06340 (2017)

Current and Planned Experiments

Current and near-term sensitivities

Experiment	Isotope	M, kg	Sensitivity $T_{1/2}$, yr	Sensitivity $\langle m_\nu \rangle$, meV	Status
CUORE [34]	^{130}Te	200	9.5×10^{25}	53–200	in progress
GERDA [35]	^{76}Ge	35	1×10^{26}	110–280	current
		1000	6×10^{27}	14–37	R&D
MAJORANA [36]	^{76}Ge	30	1×10^{26}	110–280	current
		1000	6×10^{27}	14-37	R&D
EXO [37]	^{136}Xe	200	4×10^{25}	100–270	current
		5000	$10^{27} - 10^{28}$	6–53	R&D
SuperNEMO [38]	^{82}Se	7	6.5×10^{24}	240–570	in progress
		100–200	$(1–2) \times 10^{26}$	40–140	R&D
KamLAND-Zen [39]	^{136}Xe	750	2×10^{26}	45–120	in progress
		1000	6×10^{26}	26-69	R&D
SNO+ [40]	^{130}Te	800	9×10^{25}	55–205	in progress
		8000	7×10^{26}	20-73	R&D

Barabash, arXiv:1702.06340 (2017)

Plus several others:

AMORE, CAMEO, CANDLES, CARVEL, COBRA, DCBA, GEM, GSO, HPXETPC, KamLAND, MOON, NEXT, LUCIFER, LUCINEU, XMASS, ...

Current and Planned Experiments

Future Experiments:

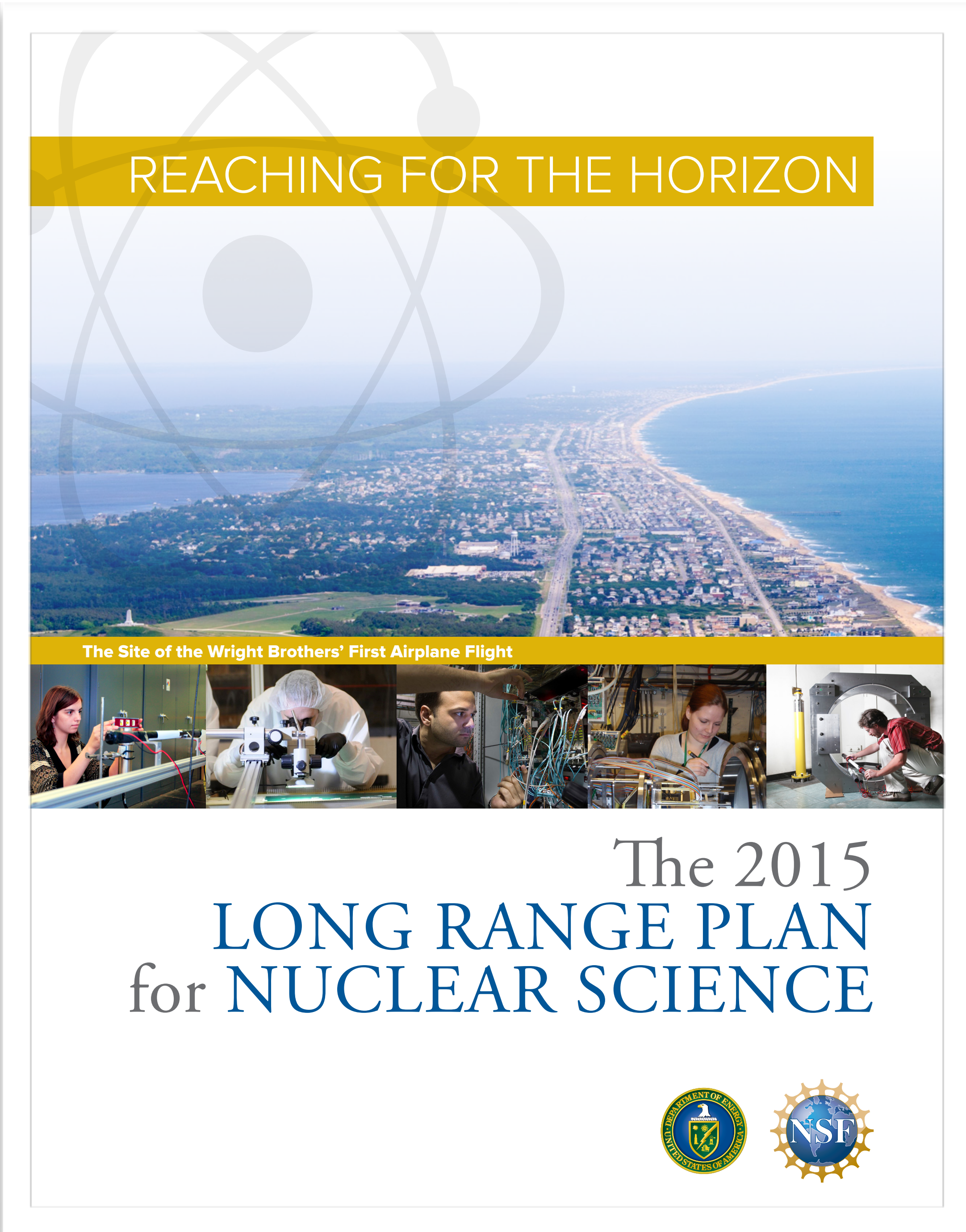
- These are large and expensive projects
  - Will require international cooperation
  - Should only move forward with the best designs worldwide

Experiment	Start of data taking, yr
KamLAND2-Zen (1000 kg of ^{136}Xe)	$\sim 2020-2022$
SNO+ (8000 kg of ^{nat}Te)	$\sim 2020-2022$
CUPID (^{100}Mo, ^{82}Se, ^{116}Cd,...)	~ 2022
LEGEND-I (200 kg of ^{76}Ge)	$\sim 2022-2025$
LEGEND (1000 kg of ^{76}Ge)	$\sim 2025-2030$
nEXO (5000 kg of ^{136}Xe)	$\sim 2025-2030$

Barabash, arXiv:1702.06340 (2017)

Nuclear Science Long Range Plan

The 2015 Nuclear Science Advisory Committee recommended the development of neutrinoless double-beta decay searches



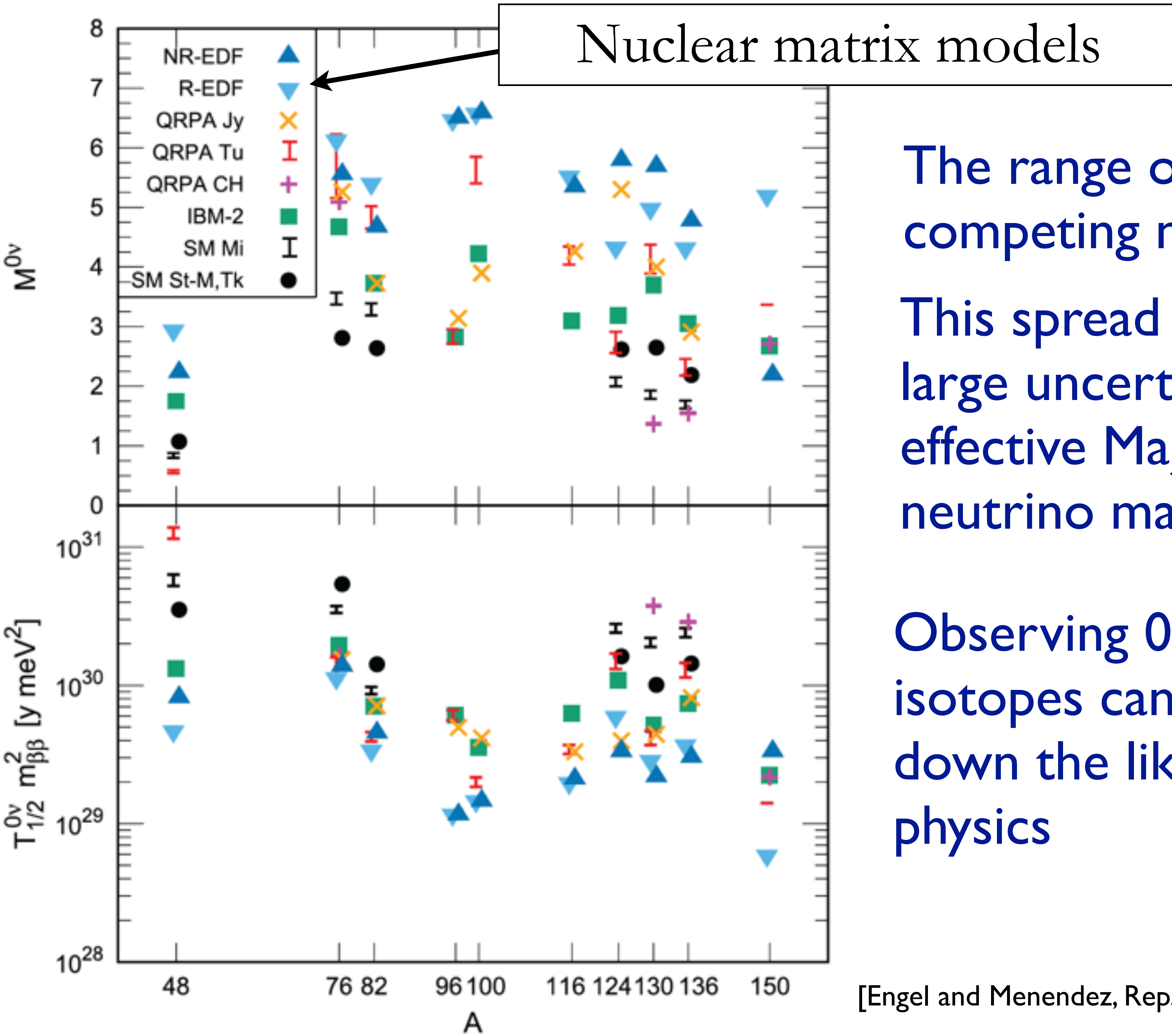
RECOMMENDATION II

The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.

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

A ton-scale instrument designed to search for this as-yet unseen nuclear decay will provide the most powerful test of the particle-antiparticle nature of neutrinos ever performed. With recent experimental breakthroughs pioneered by U.S. physicists and the availability of deep underground laboratories, we are poised to make a major discovery.

Do we need this many experiments?



The range of decay rates due to competing nuclear models

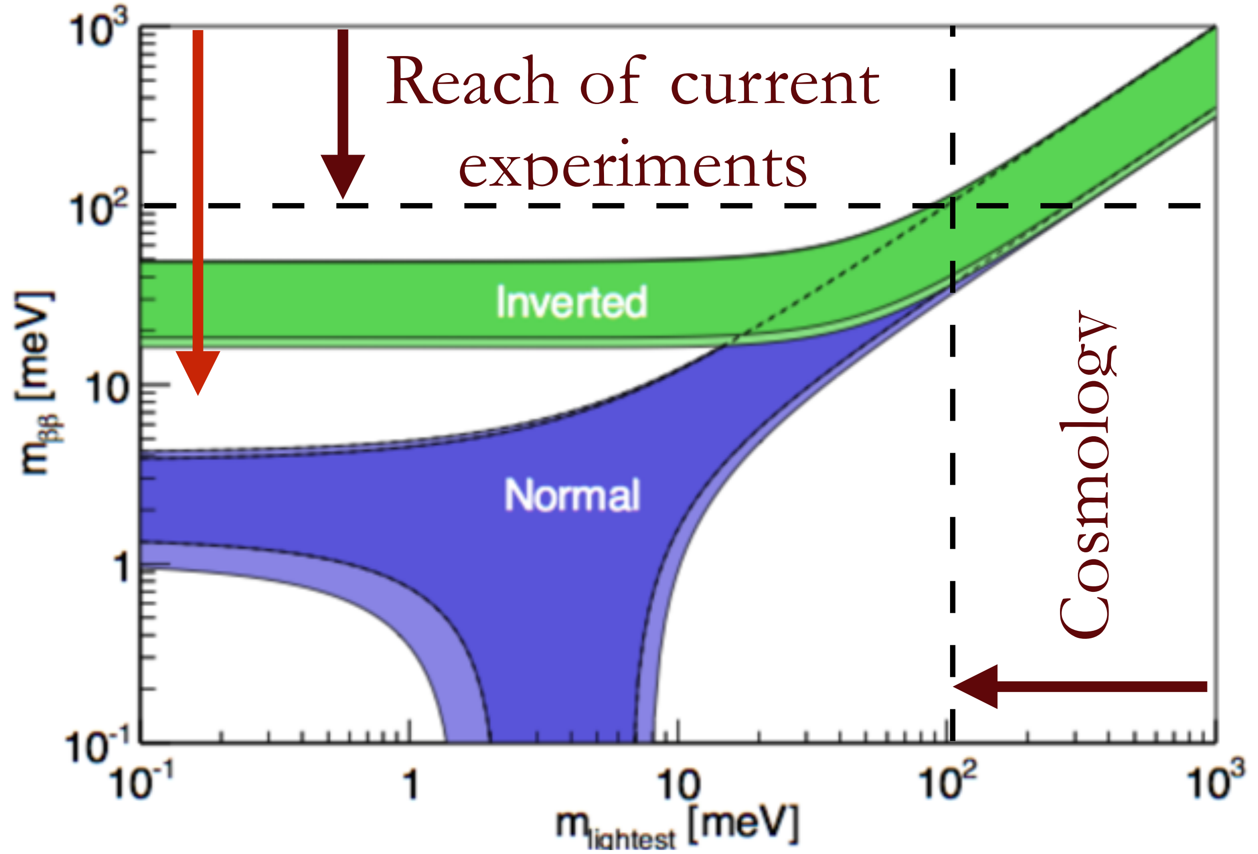
This spread introduces a large uncertainty in the effective Majorana neutrino mass

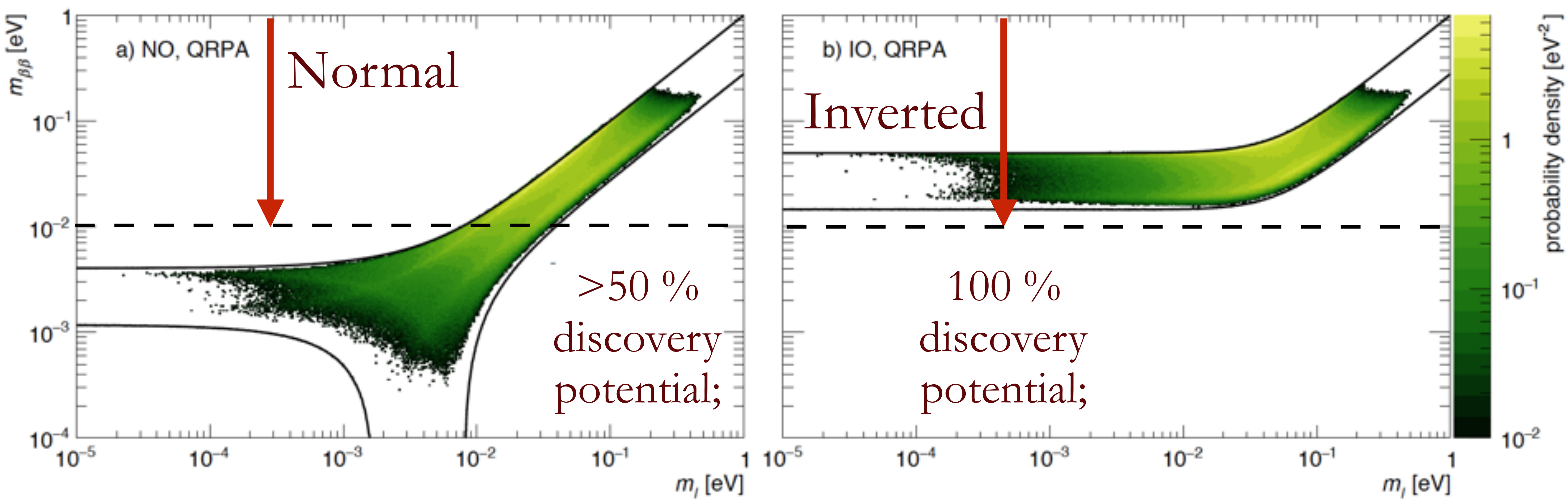
Observing $0\nu\beta\beta$ in several isotopes can help pin down the likely underlying physics

[Engel and Menendez, Rep. Prog. Phys. 80 (2017) 046301]

Reach of Next Generation Experiments

- ✦ Next generation experiments aim to push through through the inverted mass ordering.
- ✦ But then what? Can the normal mass region ever be fully explored?
  - Better to ask, what are the Bayesian posterior distributions?

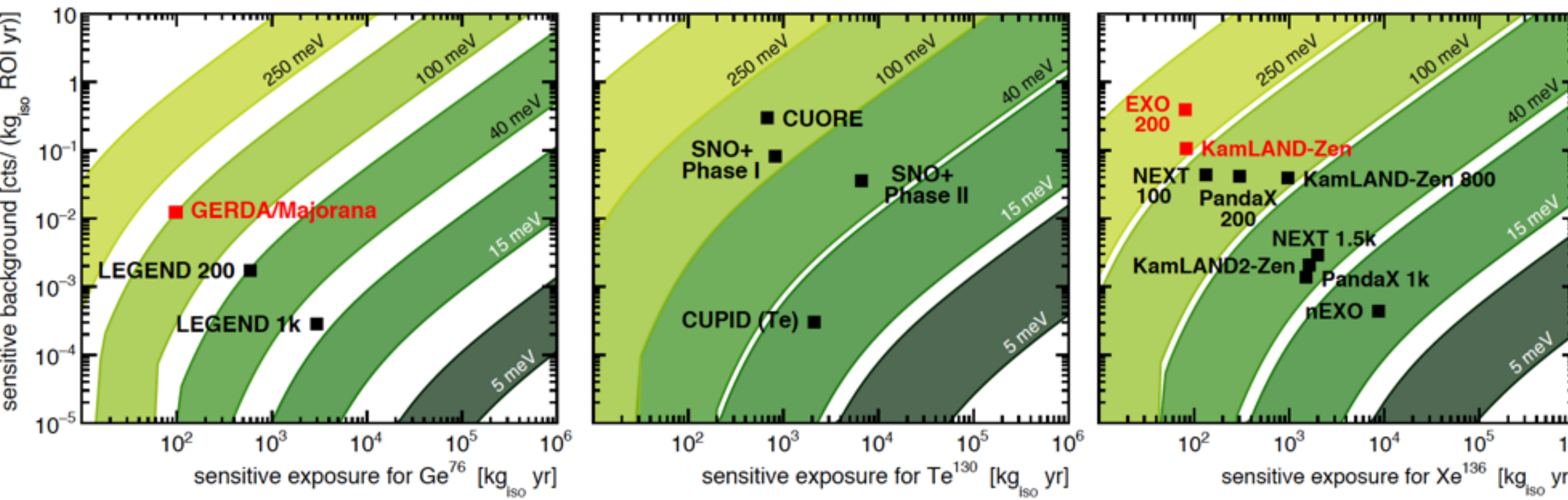




[Agostini, Benato, Detweiler (2017) arXiv:1705.02996v3]

Reach of Next Generation Experiments

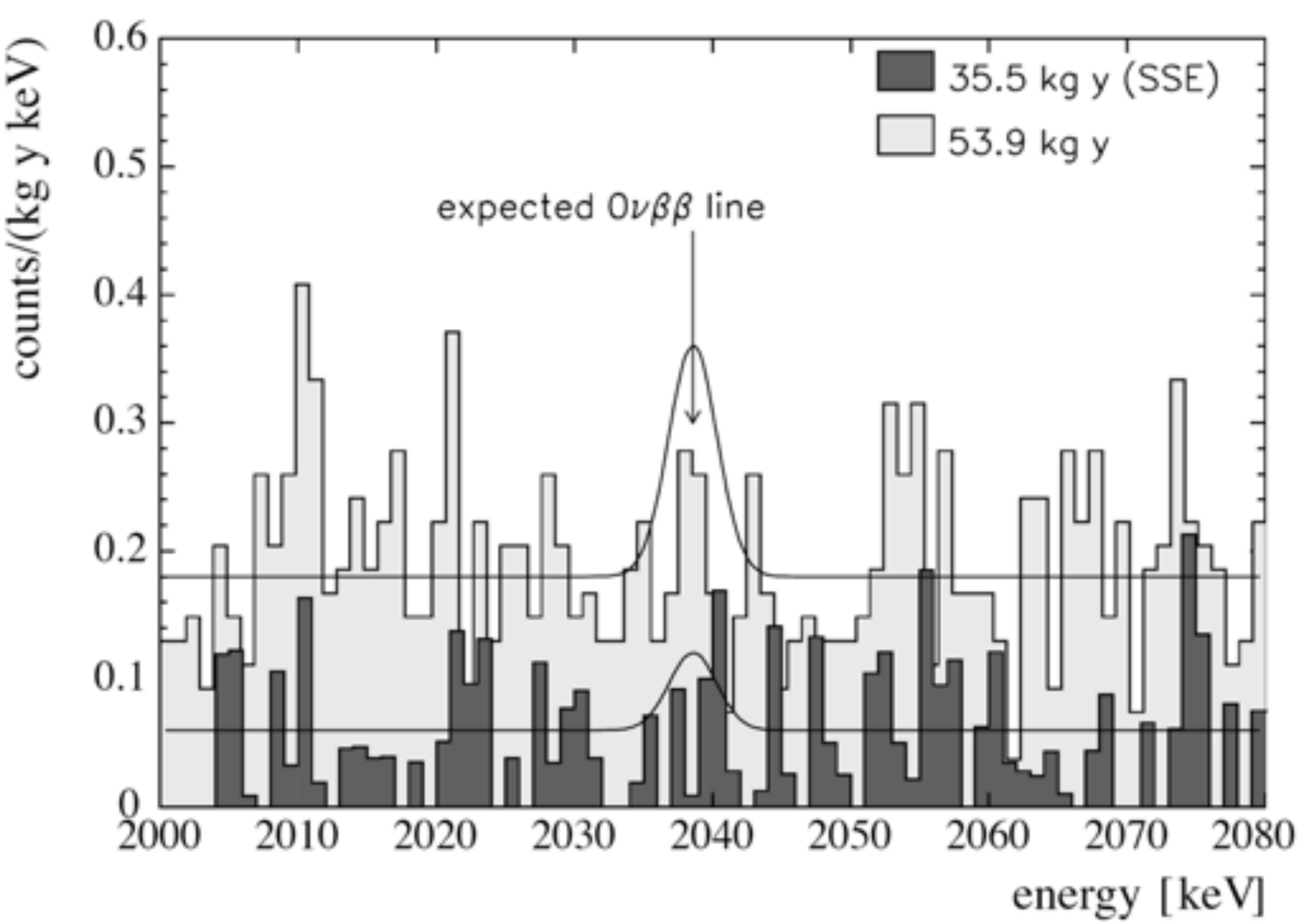
- ✦ 3σ discovery potential for current (red dots) and future (black dots) experiments
  - bands are due to uncertainties in nuclear matrix elements



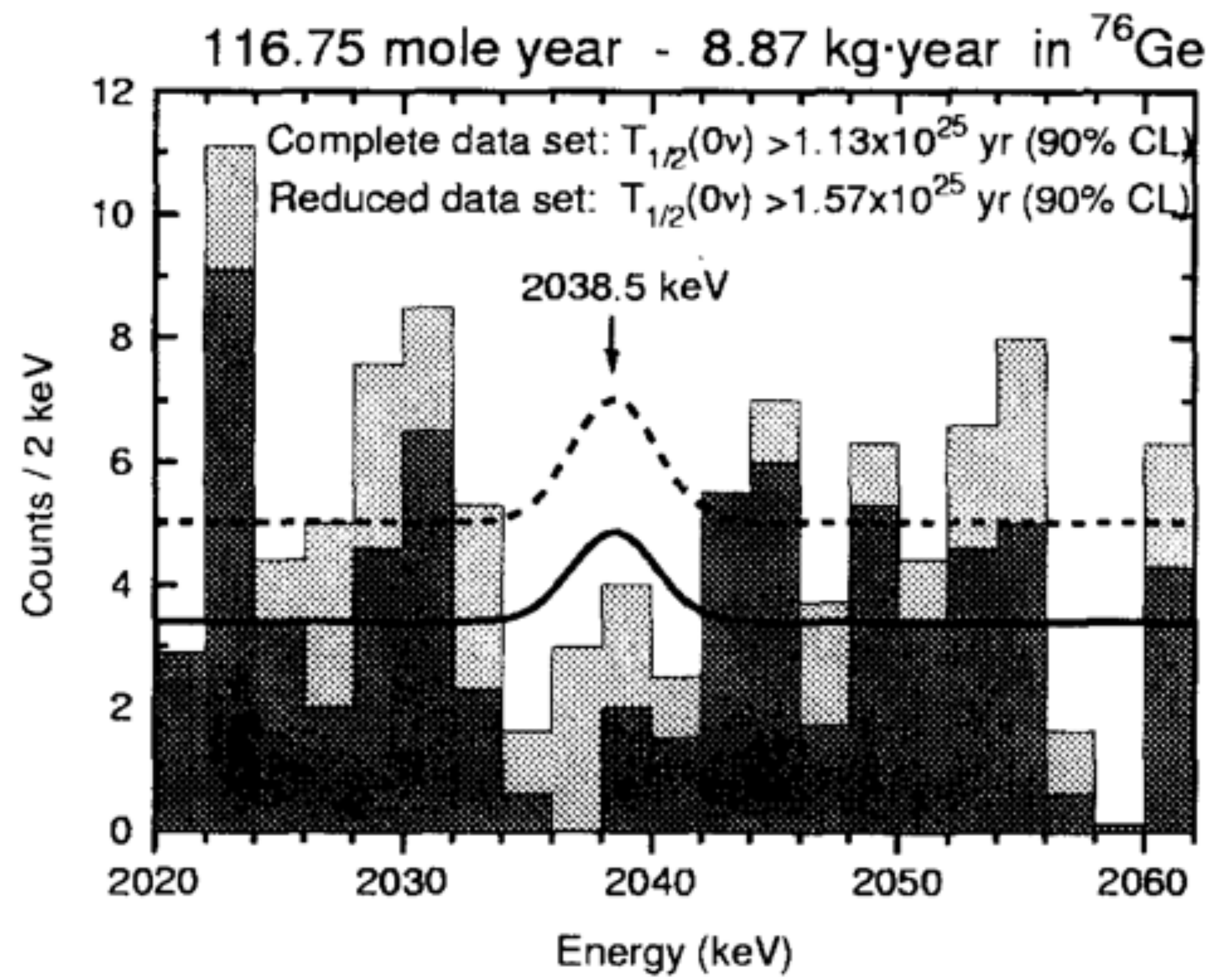
[Agostini, Benato, Detweiler (2017) arXiv:1705.02996v3]

Heidelberg-Moscow & IGEX

35.5 kg y: $T_{1/2}^{0\nu} > 1.9 \times 10^{25}$ y

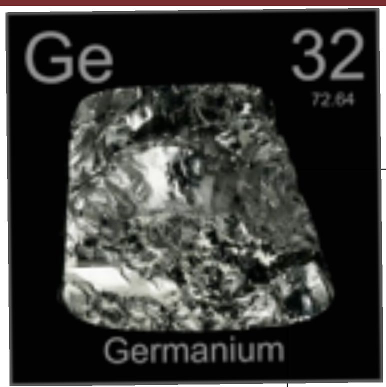


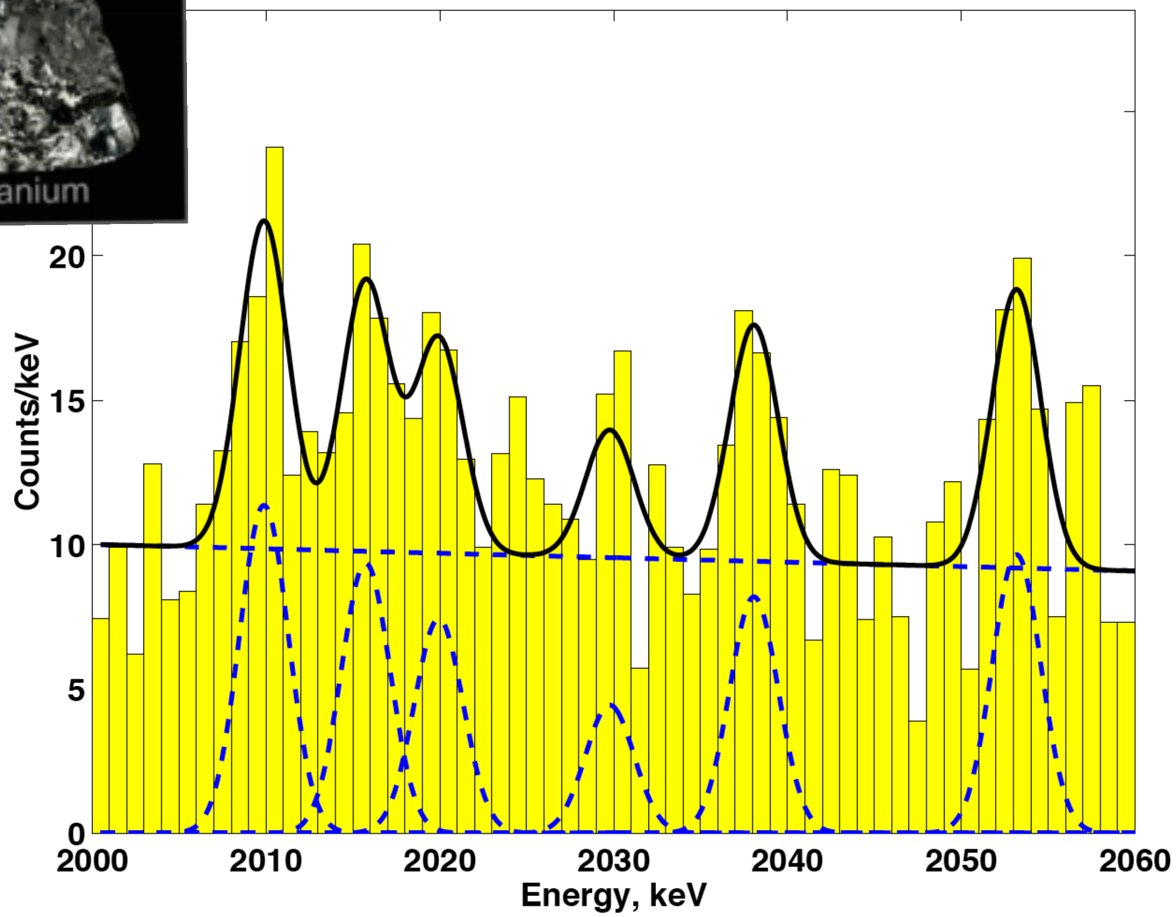
H.V. Klapdor-Kleingrothaus *et al.*, Eur. Phys. J. A **12**, 147 (2001).



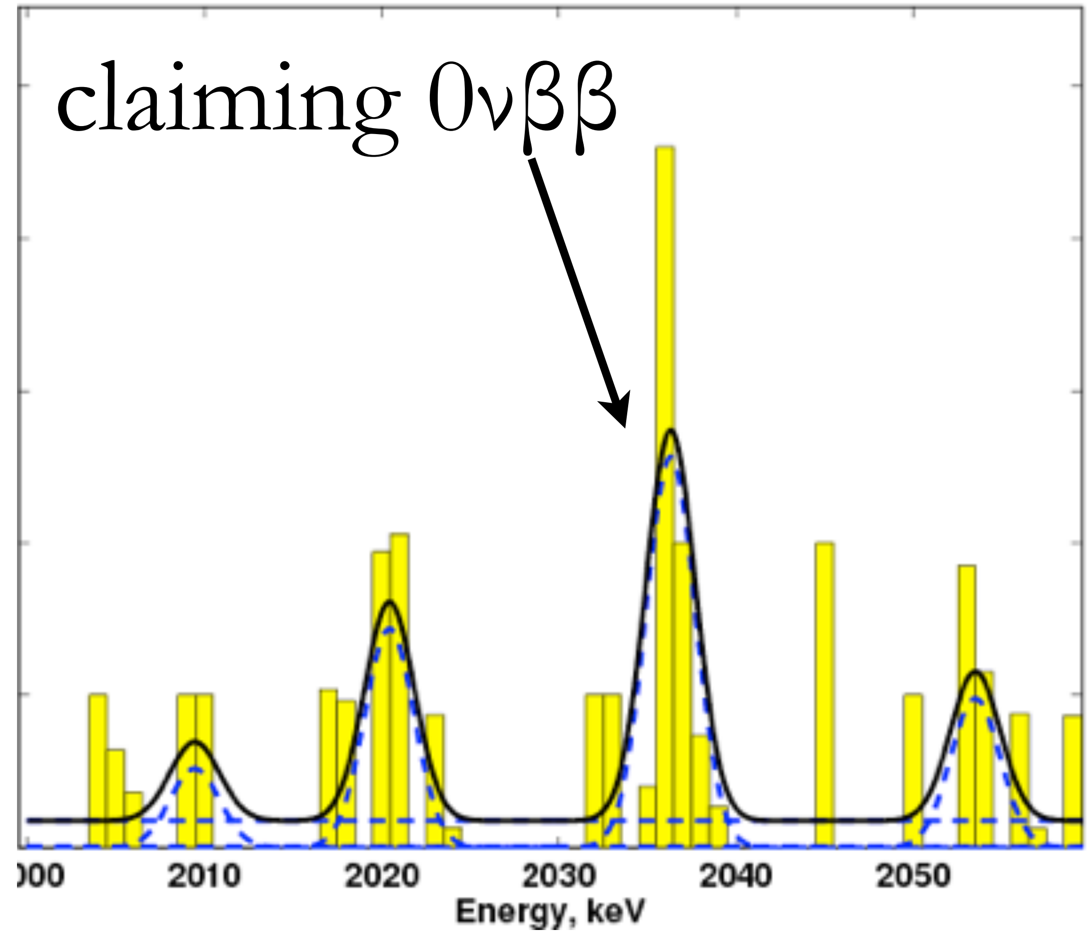
D. Gonzales *et al.*, Nucl. Phys. B. Proc. Suppl. **87**, 278 (2000)

Subset of the H-M group





71.7 kg y exposure



pulse shape selected events

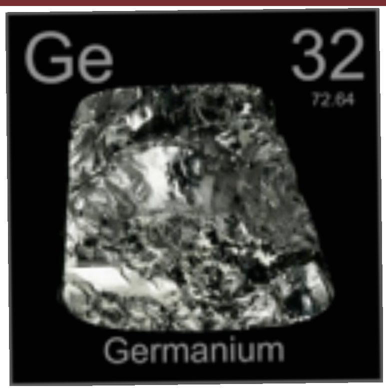
$T_{1/2}^{0\nu}$ = 1.2 x 10^{25} y significance: 4.2σ

✦ Problem:

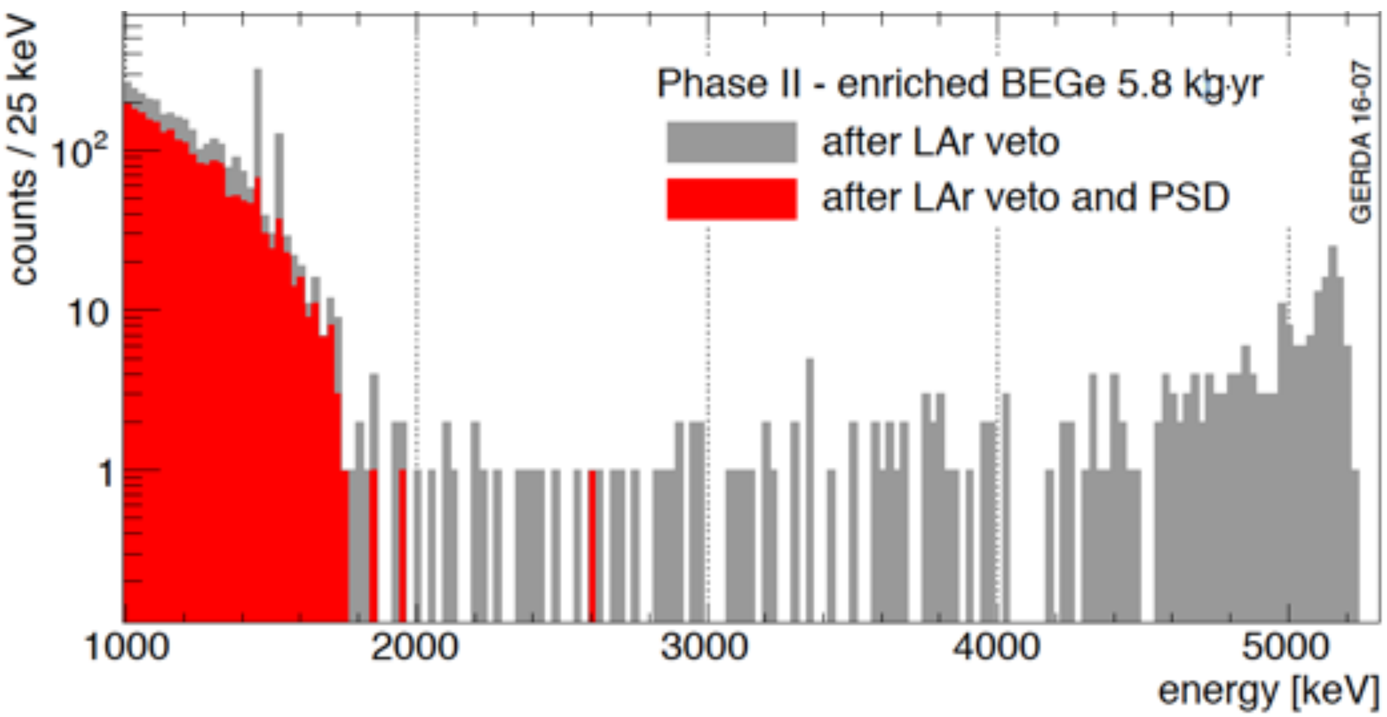
- Claimed signal is weak and a repeat test takes a long time
- Some uncertainty in background model
- Some lines not identified

H.V. Klapdor-Kleingrothaus *et al.*, Phys. Lett. B **586**, 198 (2004).

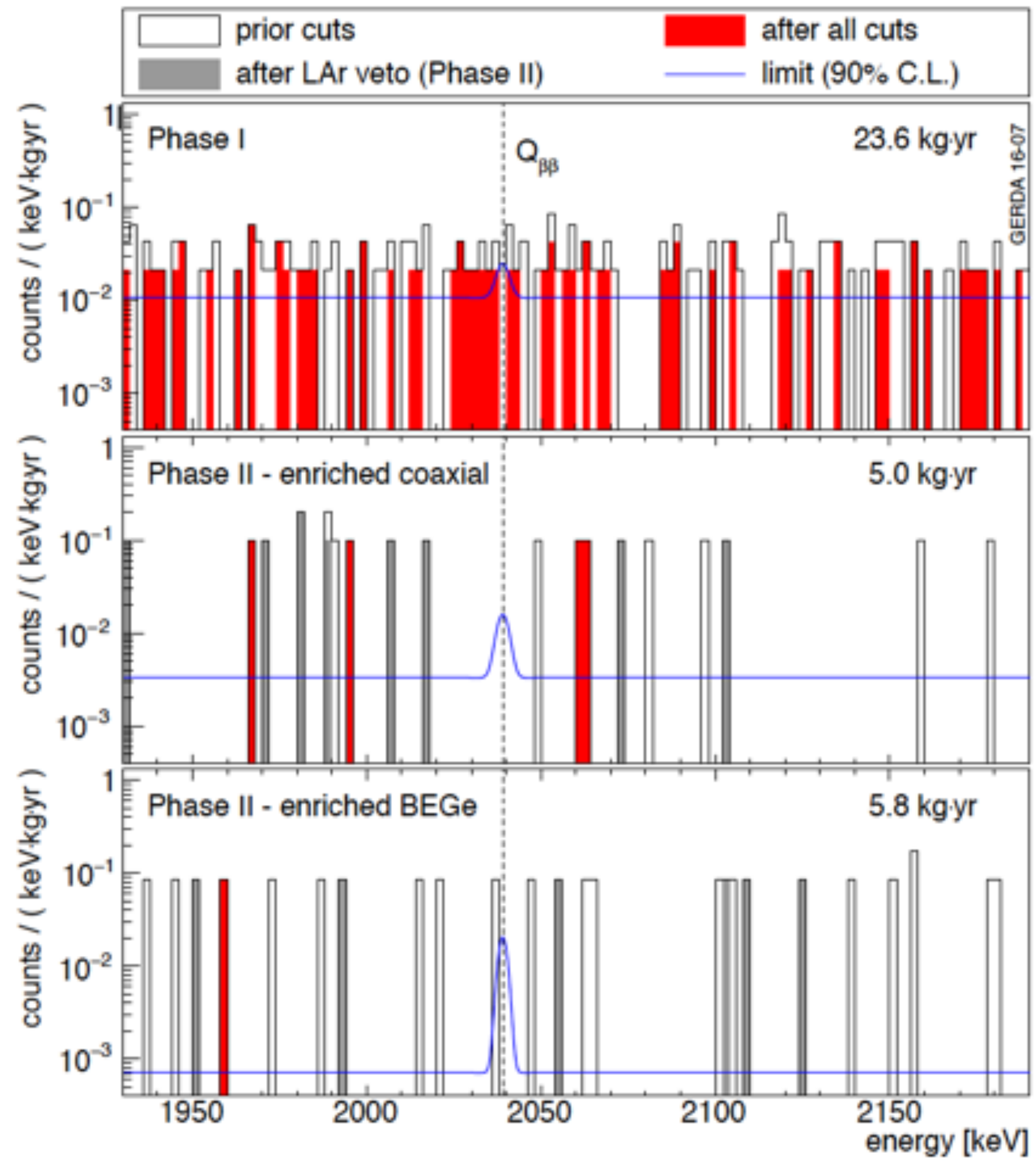
GERDA



Phase 1 & II Combined Results



$T_{1/2} > 5.3 \times 10^{25}$ yr

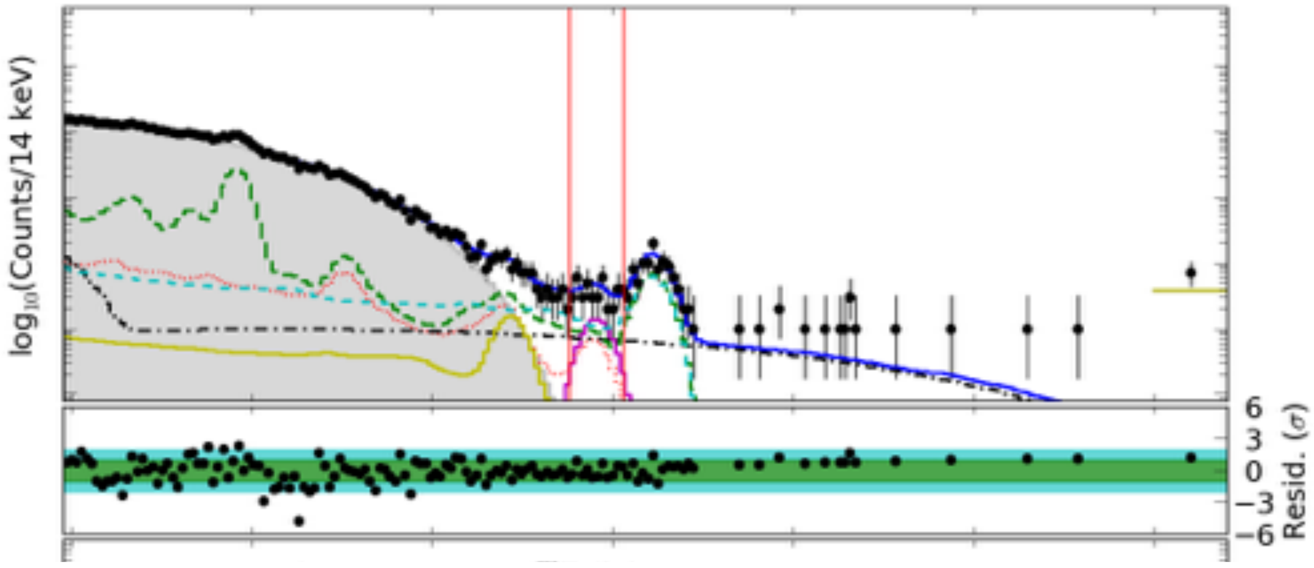


[arXiv:1703.00570v2 & M. Agostini *et a*

EXO & KamLAND-Zen

EXO-200

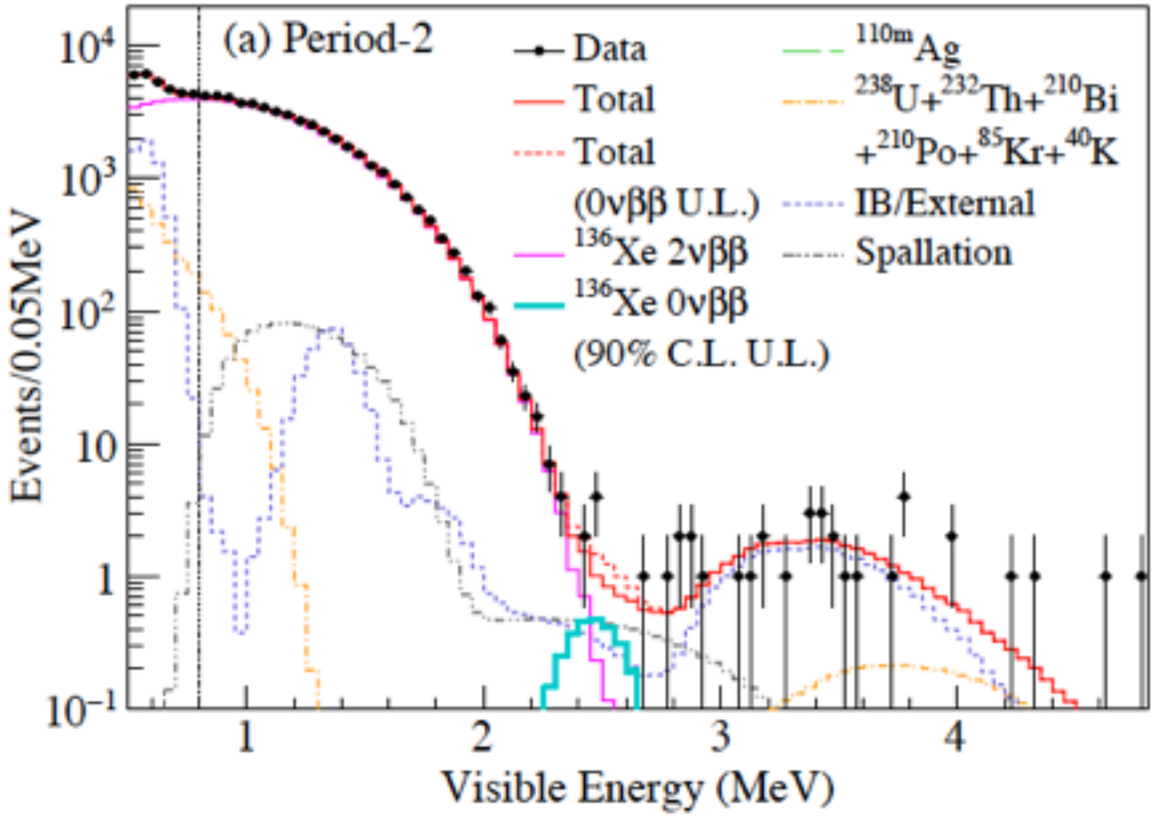
$T_{1/2} > 1.1 \times 10^{25}$ yr (90% CL)



J.B.Albertet al., Nature 510 (2014) 299

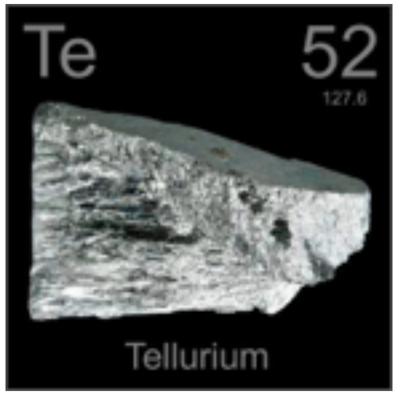
KamLAND-ZEN

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

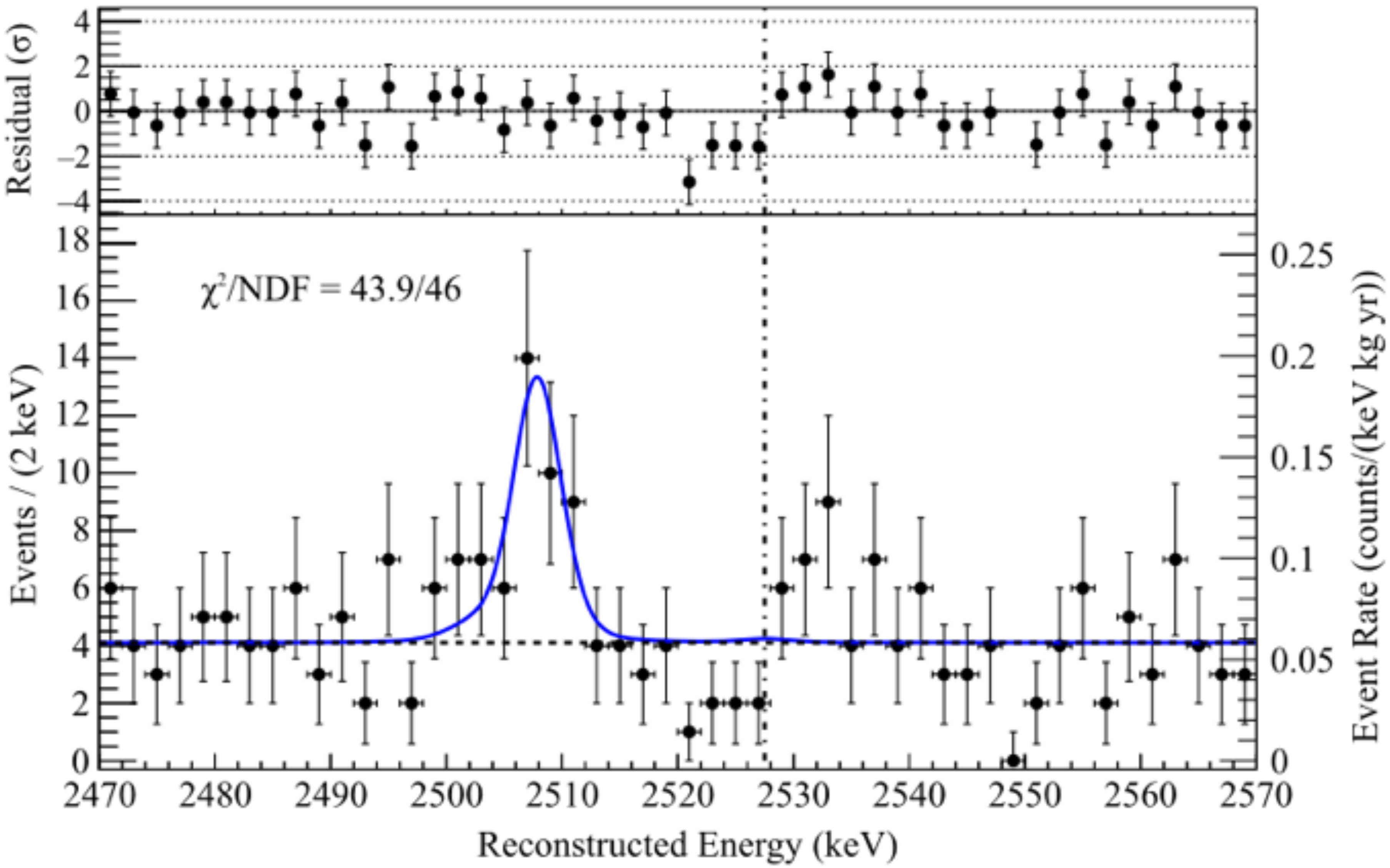


A. Gando et al.
Phys. Rev. Lett. 117, 082503

COURE



CUORE-0 + Cuoricino limit:
$T_{1/2} > 4.0 \times 10^{24}$ yr

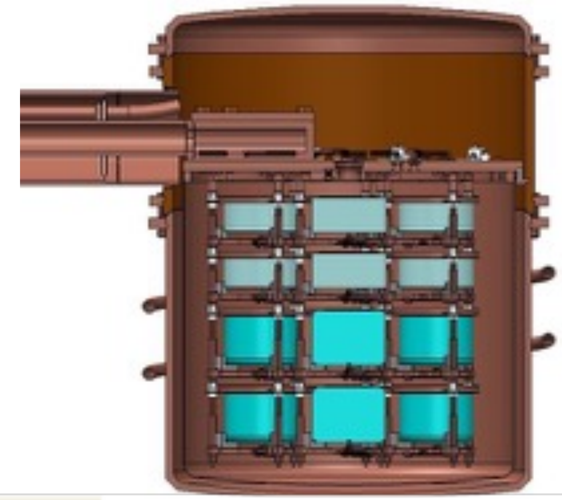


[Physical Review Letters 115, 102502 (2015)]

The MAJORANA DEMONSTRATOR

Funded by DOE Office of Nuclear Physics, NSF Particle Astrophysics, NSF Nuclear Physics
with additional contributions from international collaborators.

Goals: - Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Searches for additional physics beyond the standard model.



Operating underground at 4850′ Sanford Underground Research Facility

Background Goal in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV)
3 counts/ROI/t/y (after analysis cuts) Assay U.L. currently ≤ 3.5
44.1-kg of Ge detectors

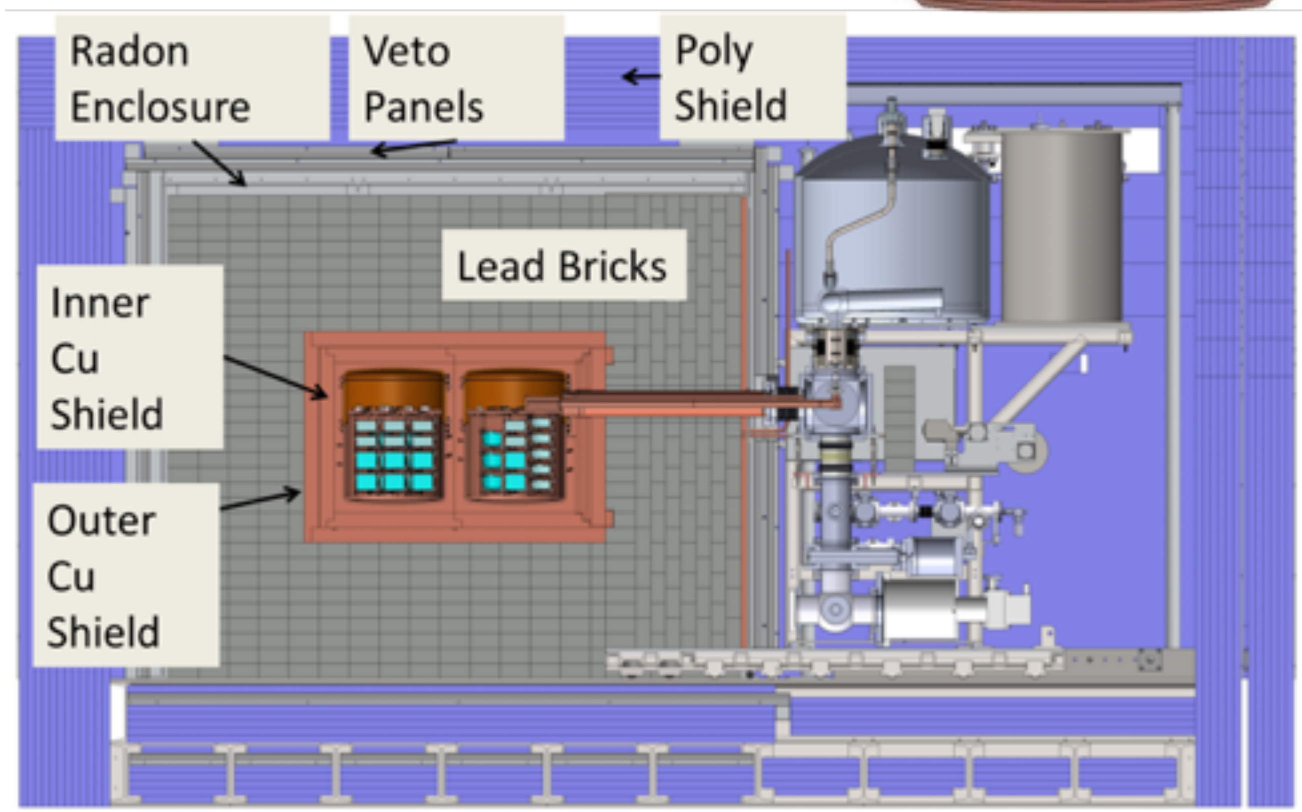
- 29.7 kg of 88% enriched ^{76}Ge crystals
- 14.4 kg of ^{nat}Ge
- Detector Technology: P-type, point-contact.

2 independent cryostats

- ultra-clean, electroformed Cu
- 22 kg of detectors per cryostat
- naturally scalable

Compact Shield

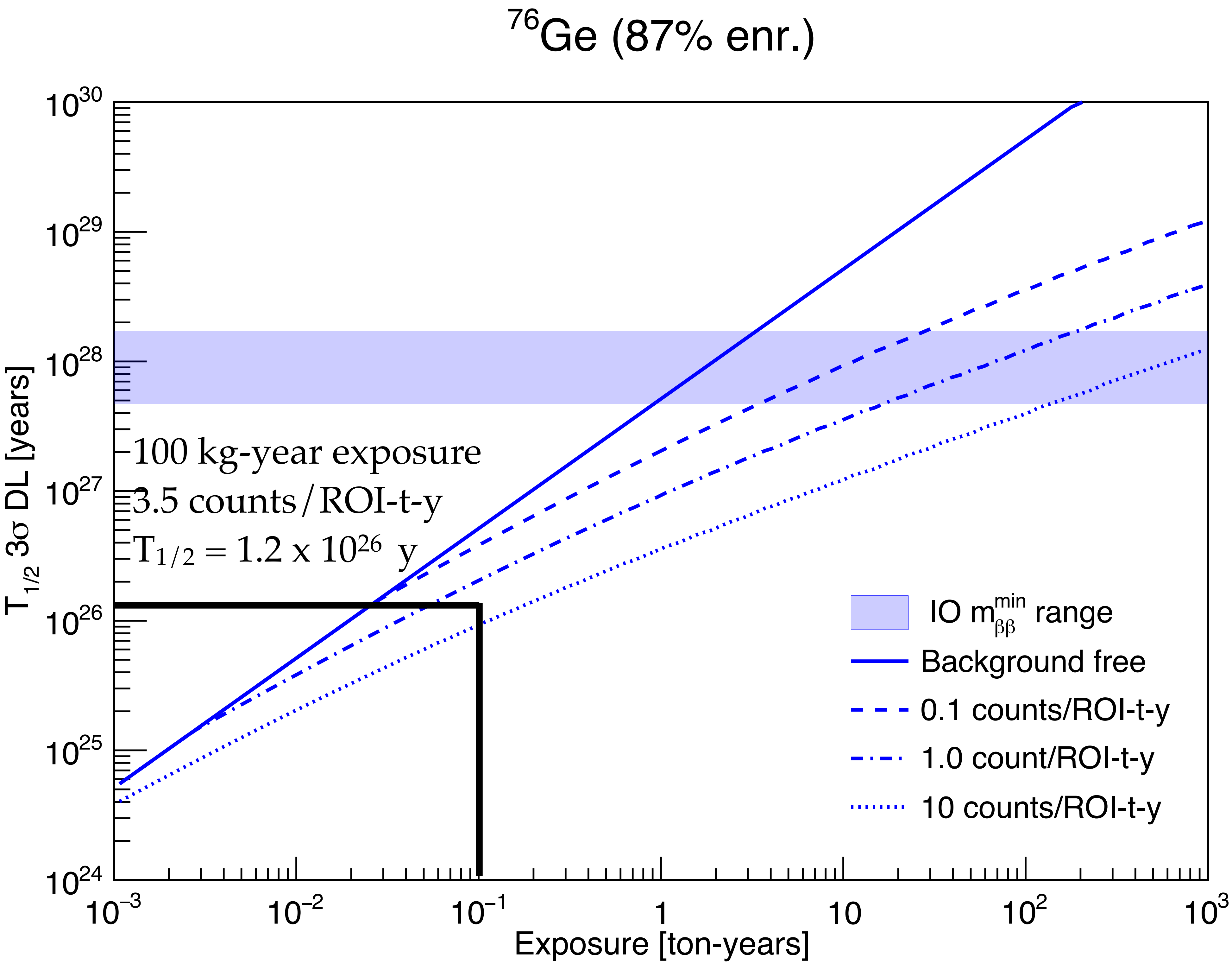
- low-background passive Cu and Pb shield with active muon veto



N. Abgrall et al. Adv. High Energy Phys **2014**, 365432 (2014)

3σ Discovery vs. Exposure for ^{76}Ge

J. Detwiler



Inverted Ordering (IO)

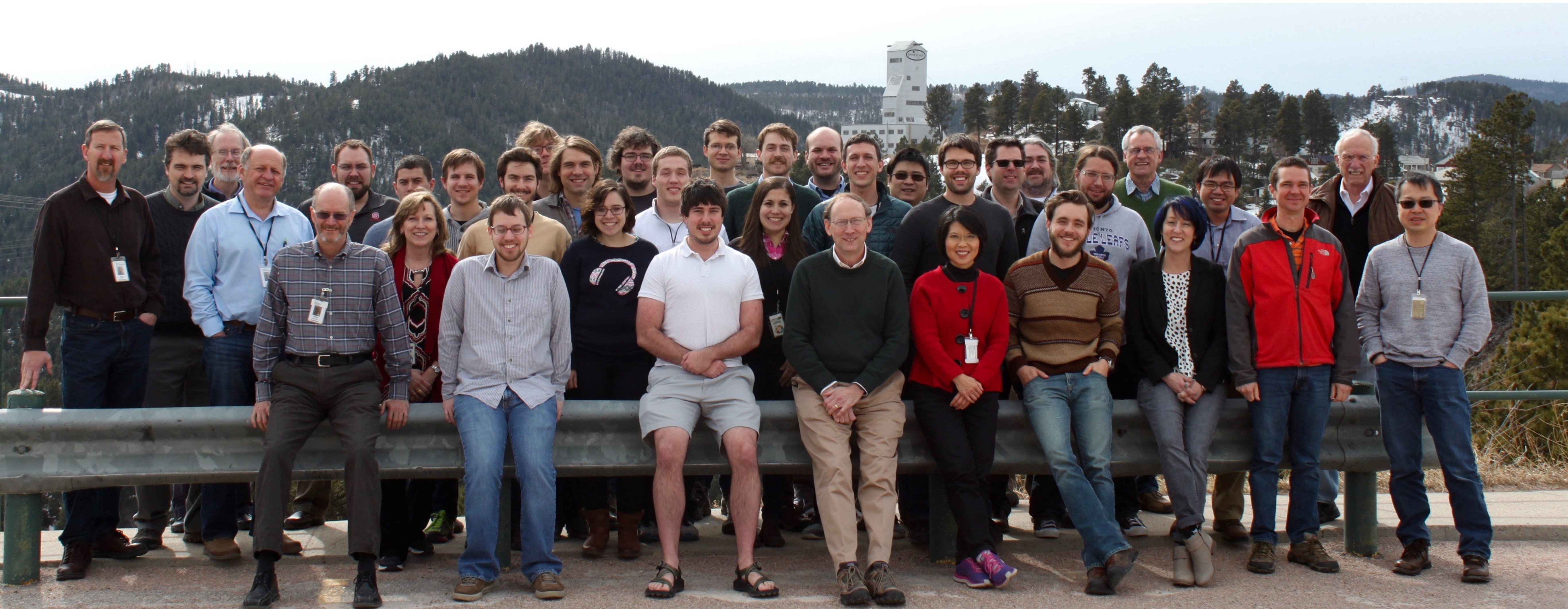
Minimum IO $m_{\beta\beta}$=18.3 meV, taken from using the PDG2013 central values of the oscillation parameters, and the most pessimistic NME for the corresponding isotope among QRPA, SM, IBM, PHFB, and EDF

Note : Region of Interest (ROI) can be single or multidimensional (E, spatial, …)

Assumes 75% efficiency based on GERDA Phase I. Enrichment level is accounted for in the exposure

The MAJORANA Collaboration

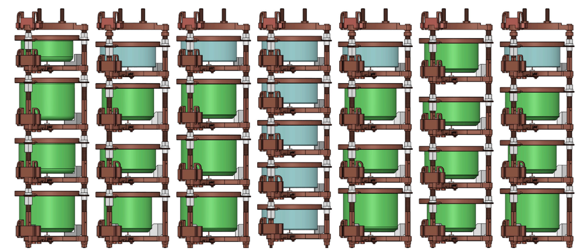
Black Hills State University
ITEP
BERKELEY LAB
Joint Institute for Nuclear Research
Duke University
The University of North Carolina at Chapel Hill
Oak Ridge National Laboratory
Los Alamos National Laboratory
South Dakota School of Mines & Technology
Tennessee Tech
Technische Universität München
University of South Carolina
The University of Tennessee Knoxville
TUNL
NC State University
W
大阪大学 Osaka University
University of South Dakota
Pacific Northwest National Laboratory — Proudly Operated by Battelle Since 1965
Princeton University
Queen's University
Max-Planck-Gesellschaft



MAJORANA DEMONSTRATOR Implementation

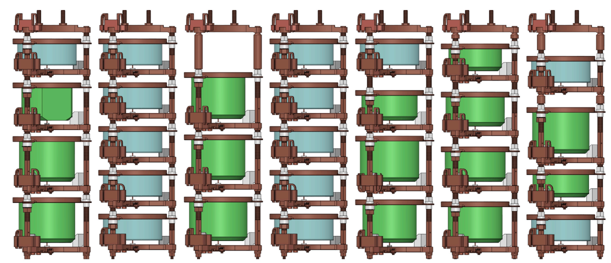
In shield Operation

✦Module 1: 16.9 kg (20) ^{enr}Ge
5.6 kg (9) ^{nat}Ge

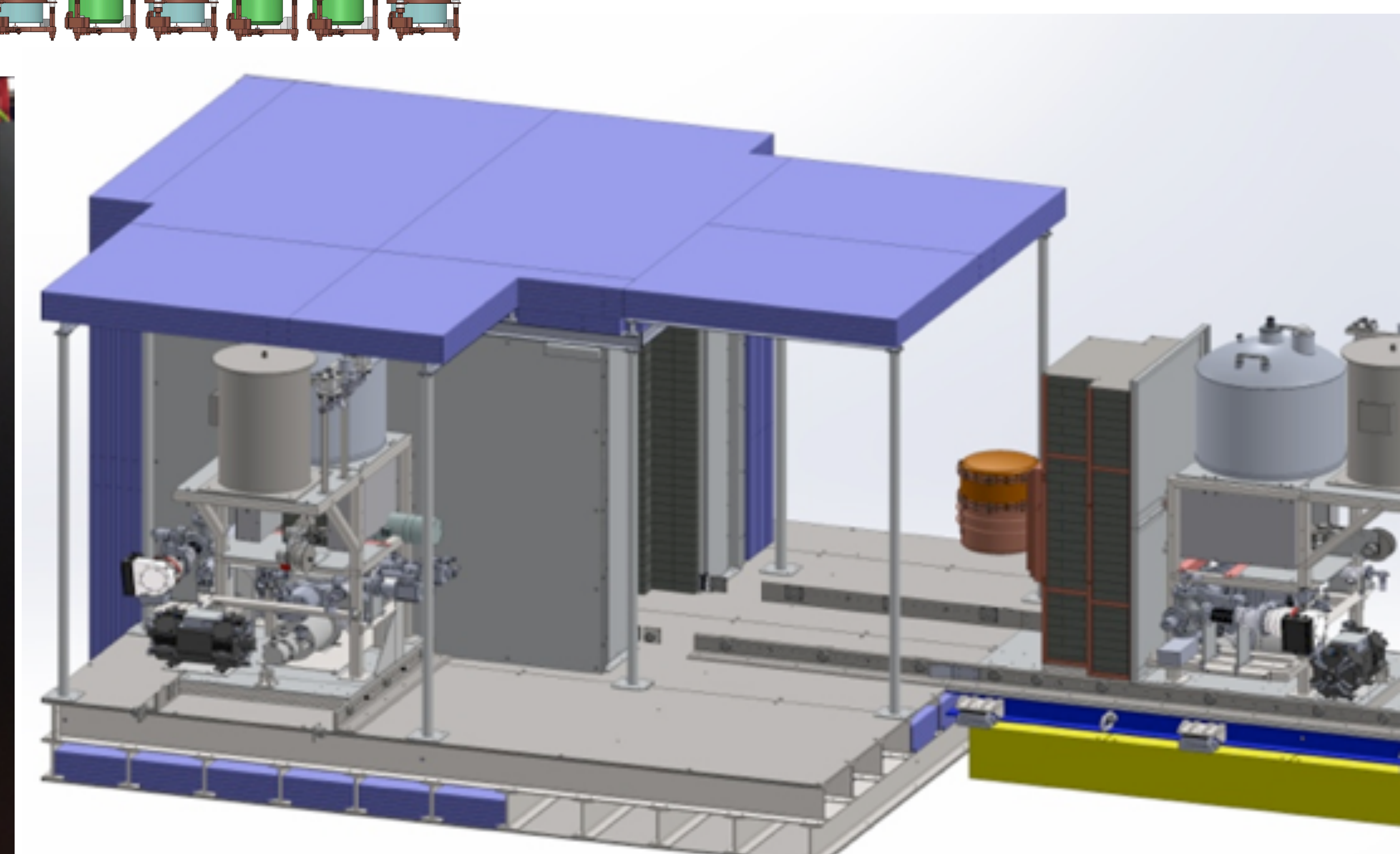


May – Oct. 2015,
Final Installation,
Dec. 2015 — ongoing

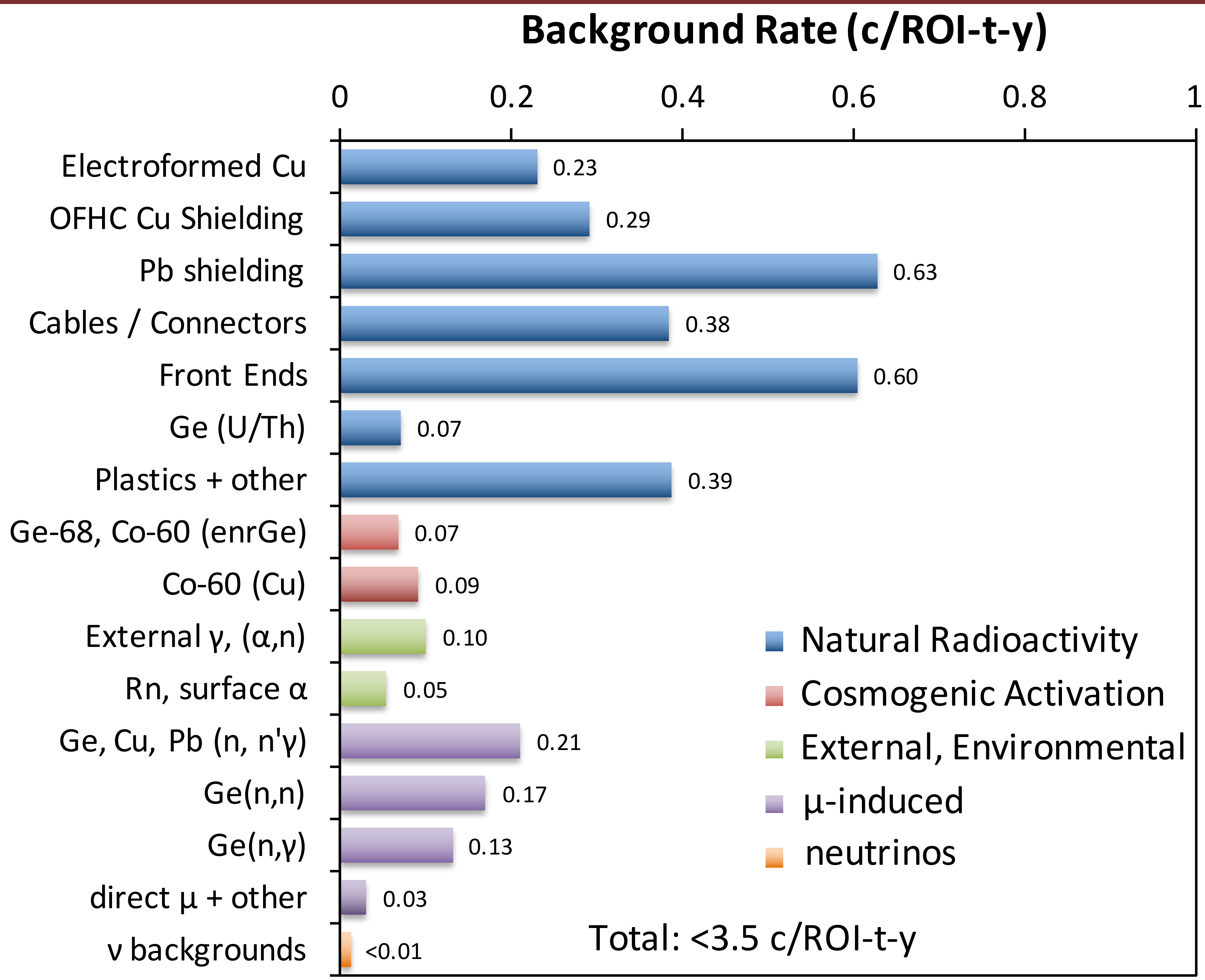
✦Module 2: 12.9 kg (15) ^{enr}Ge
✦ 8.8 kg (14) ^{nat}Ge



July 2016 — ongoing



DEMONSTRATOR Background Model



Background based on assay of materials.

Where an upper limit exists, use upper limit as contribution

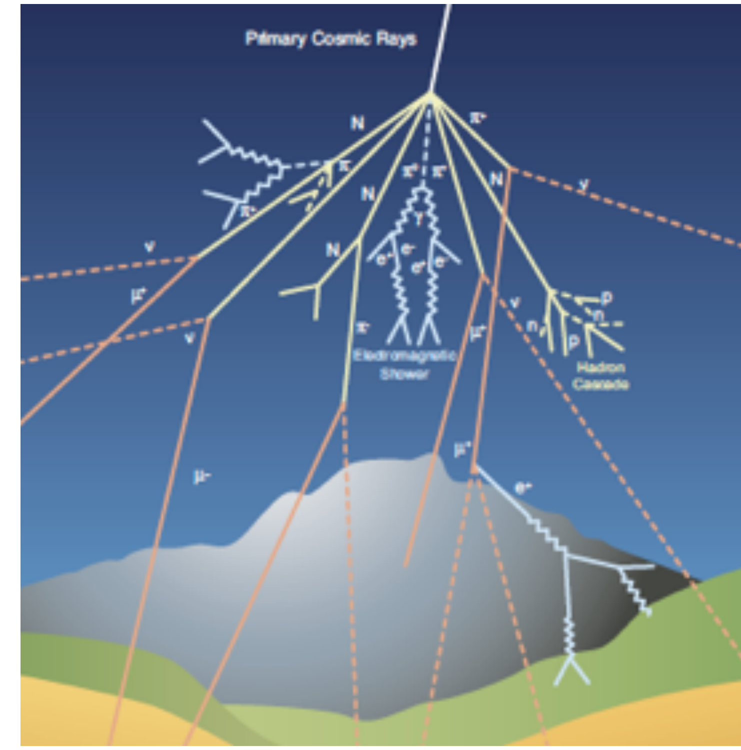
NIMA **828** (2016) 22–36 arXiv:1601.03779 [physics.ins-det]

Background Sources

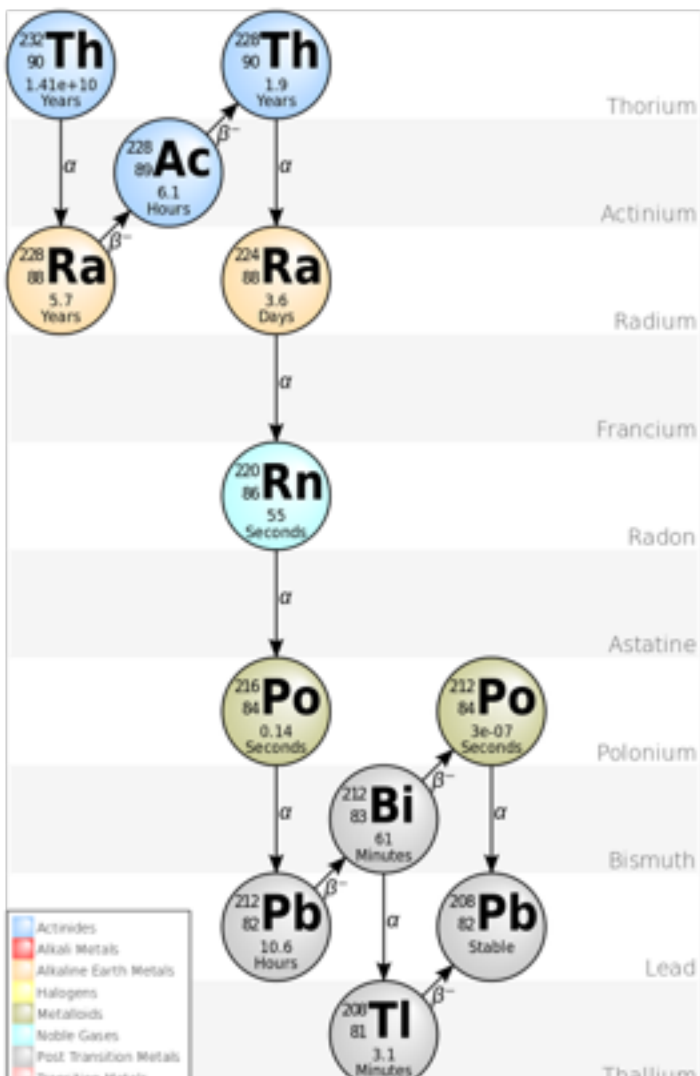
Our background sources are primarily naturally occurring radioactivity or cosmogenic-induced reactions

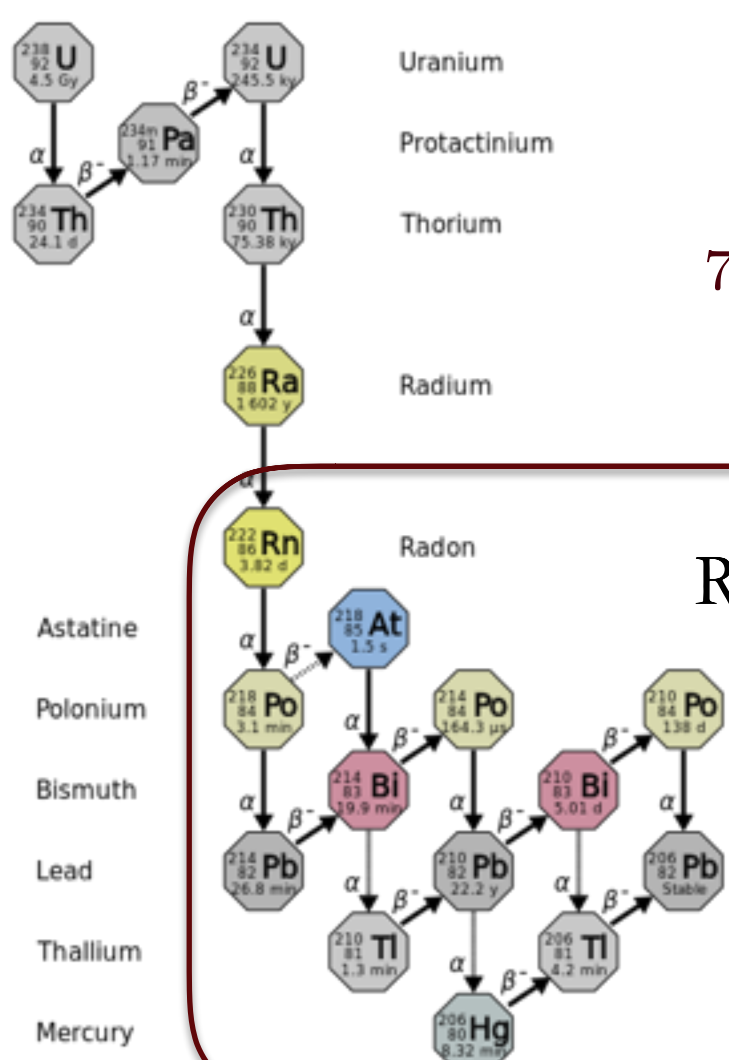
Perspective: 200,000 β decays/min in you body from ^{40}K

Expect < 3.5 cts/(ROI ton yr)



Natural Th and U decay chains





Radon and its long-lived progeny

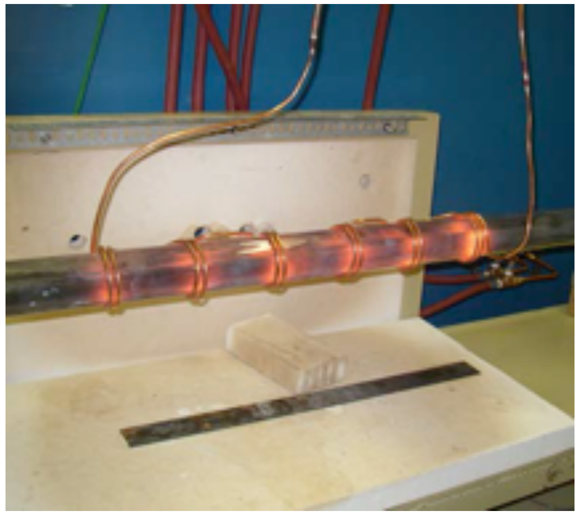
Cosmogenics, muon-induced neutrons

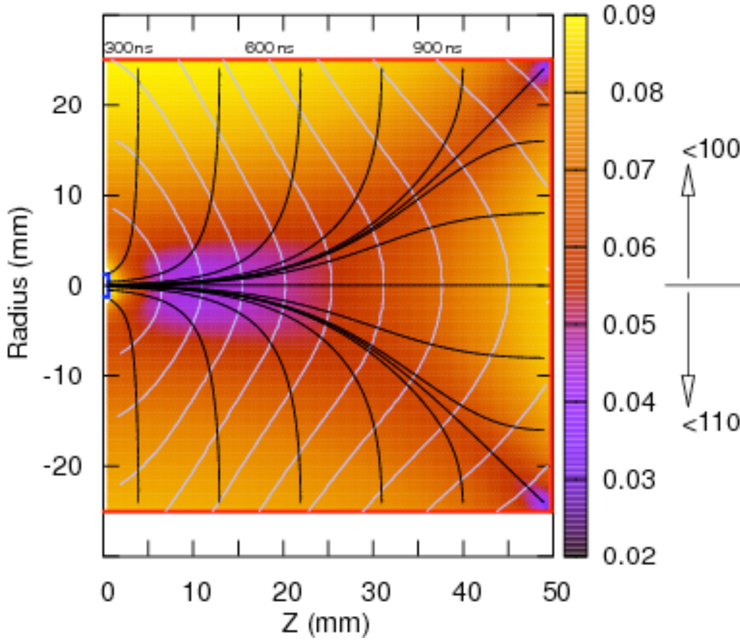
$$^{76}\mathrm{Ge}(n, n'\gamma)^{76}\mathrm{Ge}$$

$$^{63}\mathrm{Cu}(n, \alpha)^{60}\mathrm{Co}$$

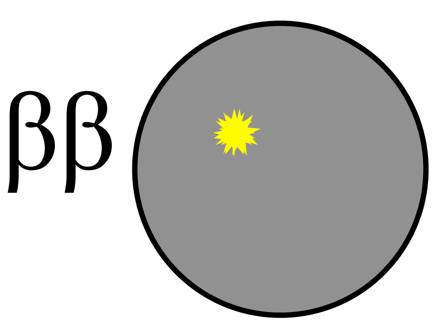
MAJORANA Approach to Backgrounds

- The detector: P-type point contact
  - ^{enr}Ge metal zone refined and pulled into a crystal that provides purification
  - Limit above-ground exposure to prevent cosmic activation
  - Slow drift velocity and localized weighting potential: separation of multi-site events
- Rejection of backgrounds
  - Granularity: multiple detectors hit
  - Pulse shape discrimination: multiple hits in a detector
  - Alpha events near surface: based on response

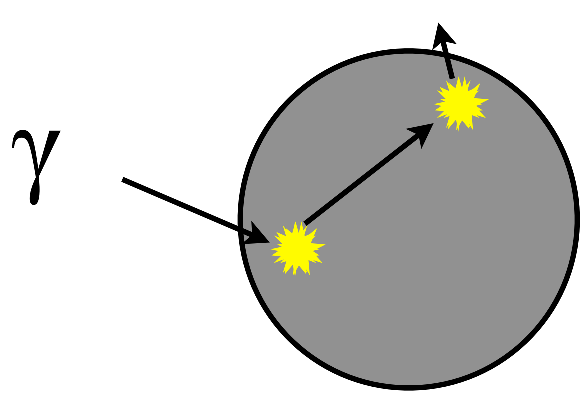


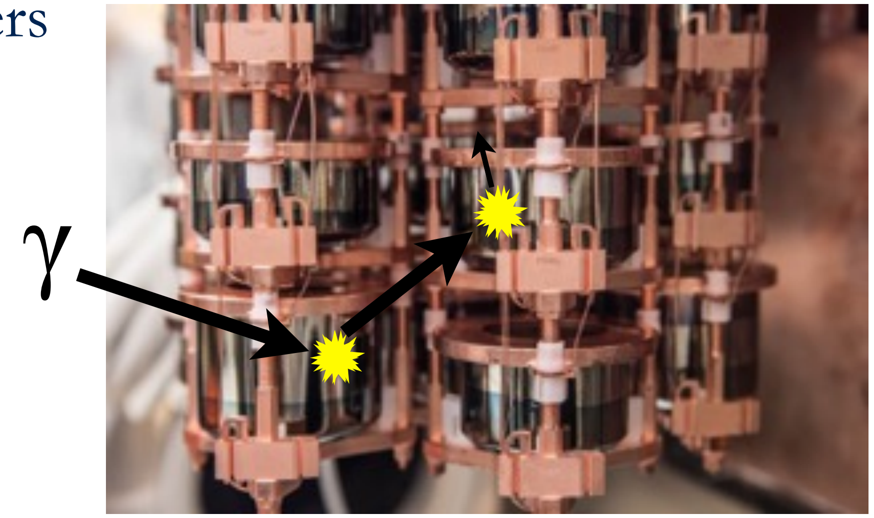


Single-site event



Multiple scatters





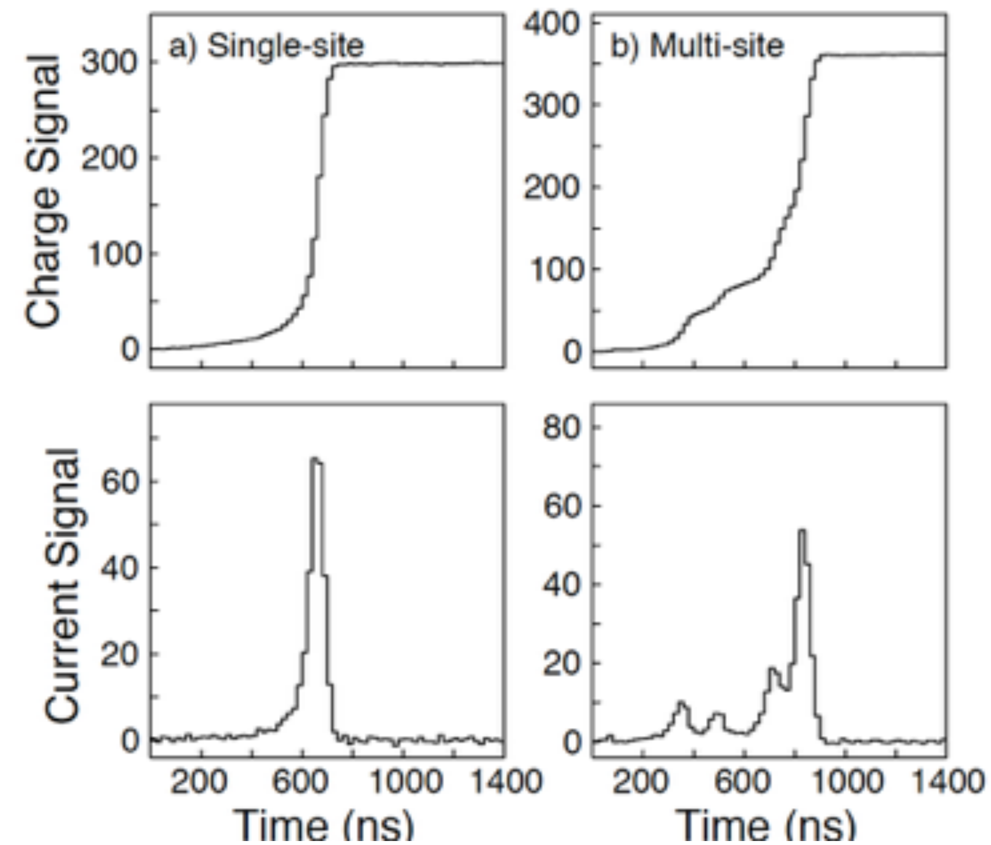
Pulse Shape Analysis

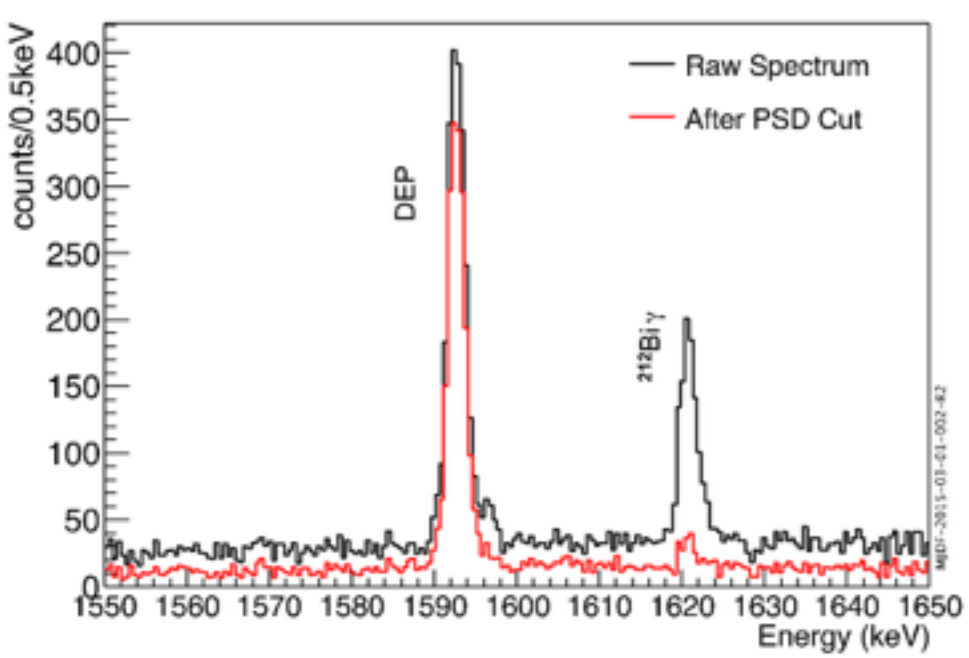
✦Use a pulse shape analysis (PSA) rejection of multi-site gamma events

✦Benefit of P-type Point-Contact (PPC) detectors for background rejection:

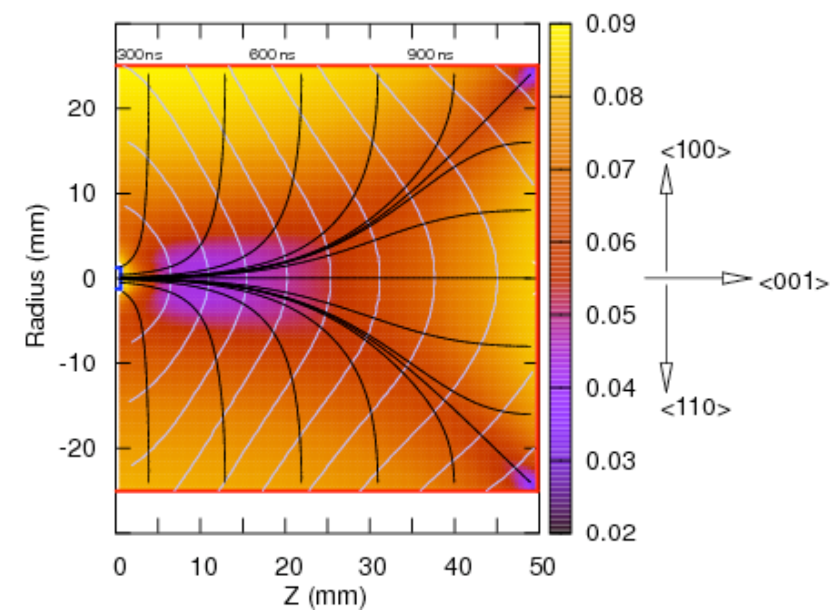
- Slow drift time of the ionization charge cloud
- Localized weighting potential gives excellent multi-site rejection

Rising edge "stretched" in time ⇒ improved PSA





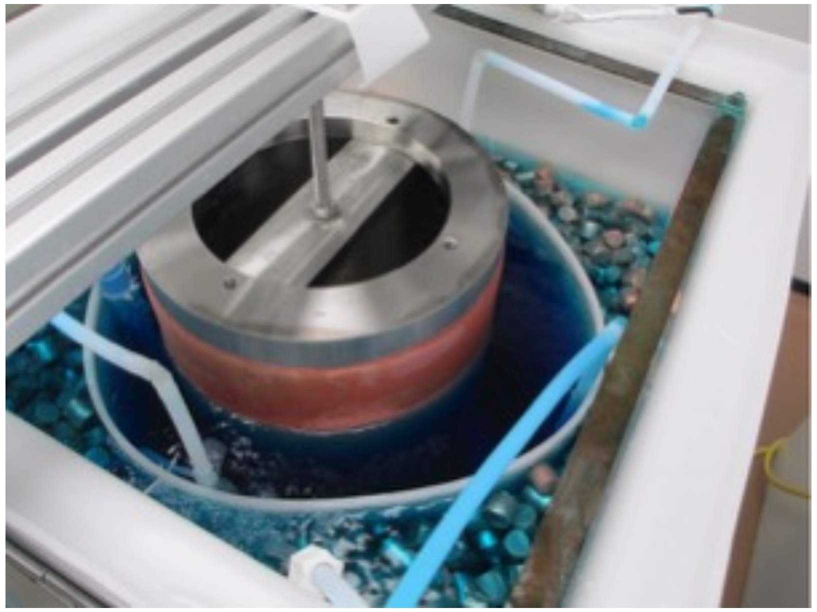
Luke et al., IEEE trans. Nucl. Sci. 36 , 926 (1989)
Barbeau, Collar, and Tench, J. Cosm. Astro. Phys. 0709 (2007).



Hole v_{drift} [mm/ns] with paths and isochrones

Majorana Approach to Backgrounds

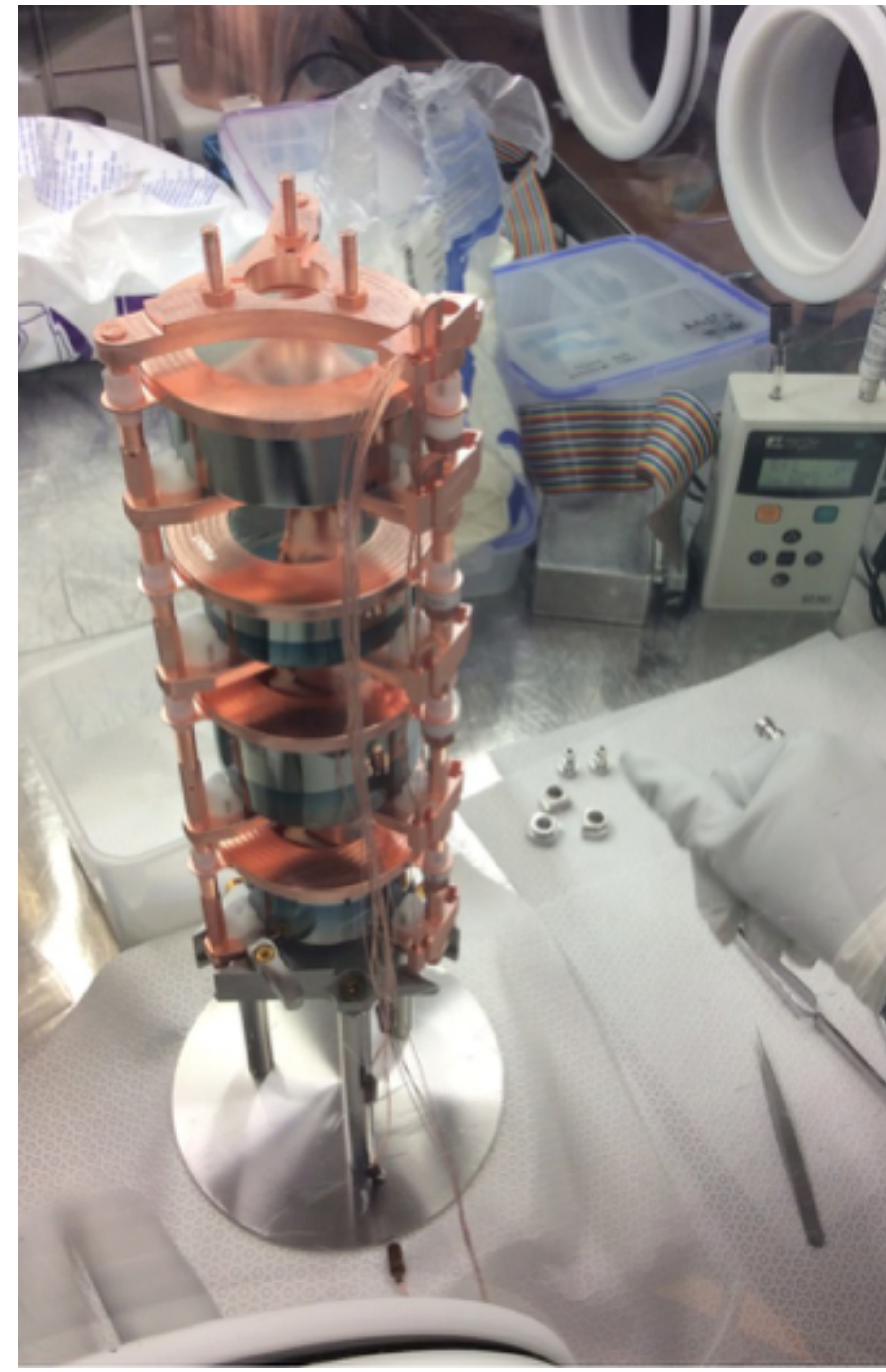
- Ultra-pure materials
  - Low mass design
  - Custom cable connectors and front-end boards
  - Carefully selected plastics & fine Cu coax cables
  - **Underground Electro-formed Cu**
    - 10 baths at SURF, 6 baths at PNNL
    - 2474 kg of electroformed copper produced.
    - Th decay chain (ave) ≤ 0.1 μBq/kg
    - U decay chain (ave) ≤ 0.1 μBq/kg

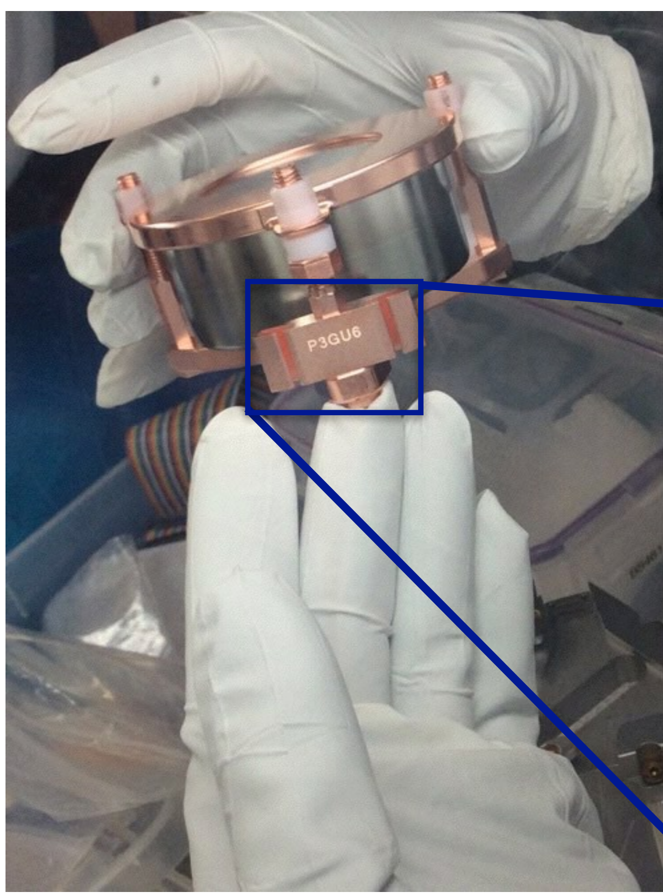


- Machining and Cleaning
  - Cu machining in an underground clean room
  - Cleaning of Cu parts by acid etching and passivation
  - Nitric leaching of plastic parts

Detector Units and Strings

Detector parts stored and assembled inside radon-reduced, dry N_2 environment storage and glove boxes.





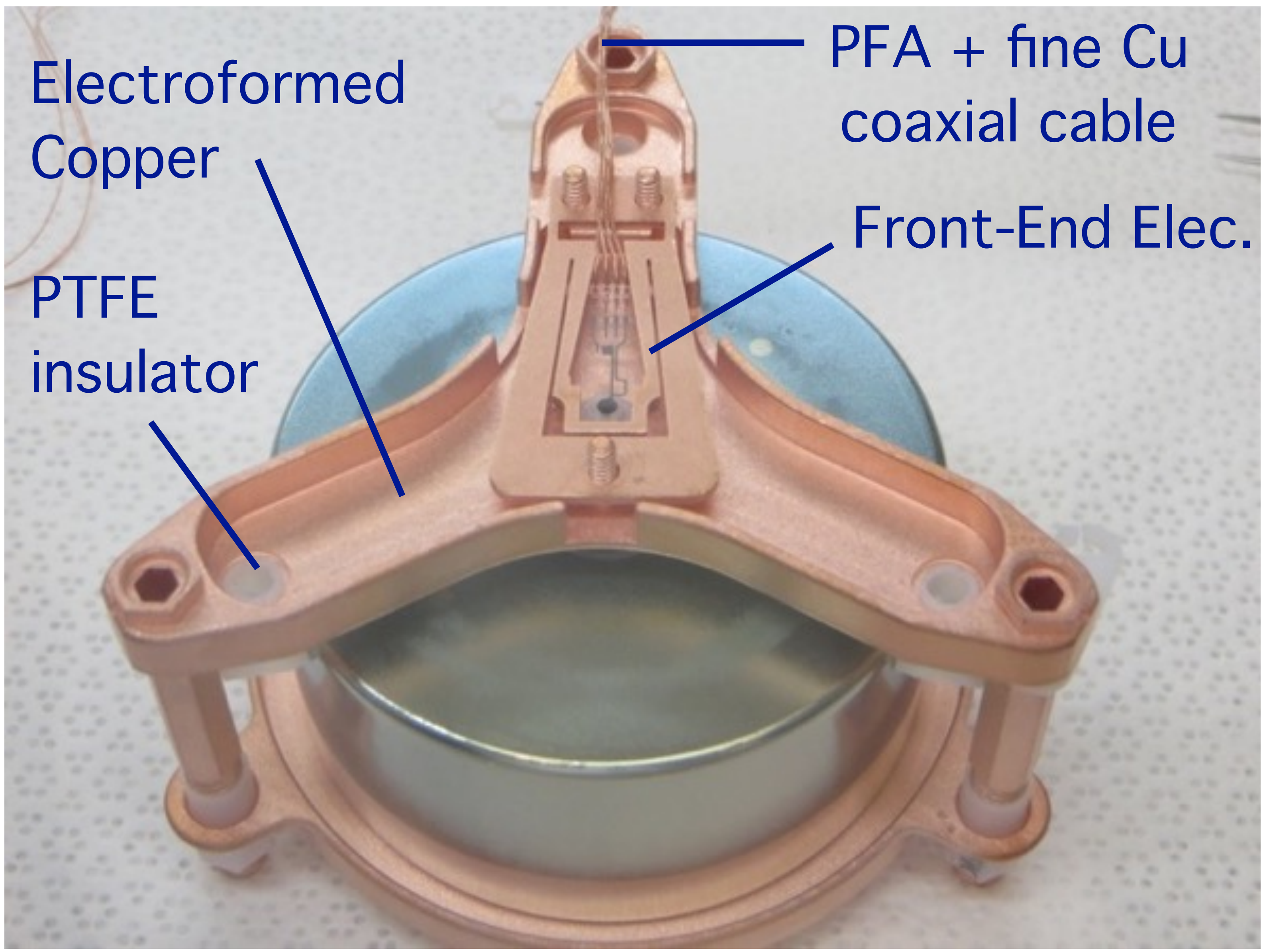
All parts are uniquely tracked through machining, cleaning, and assembly by a custom-built database.

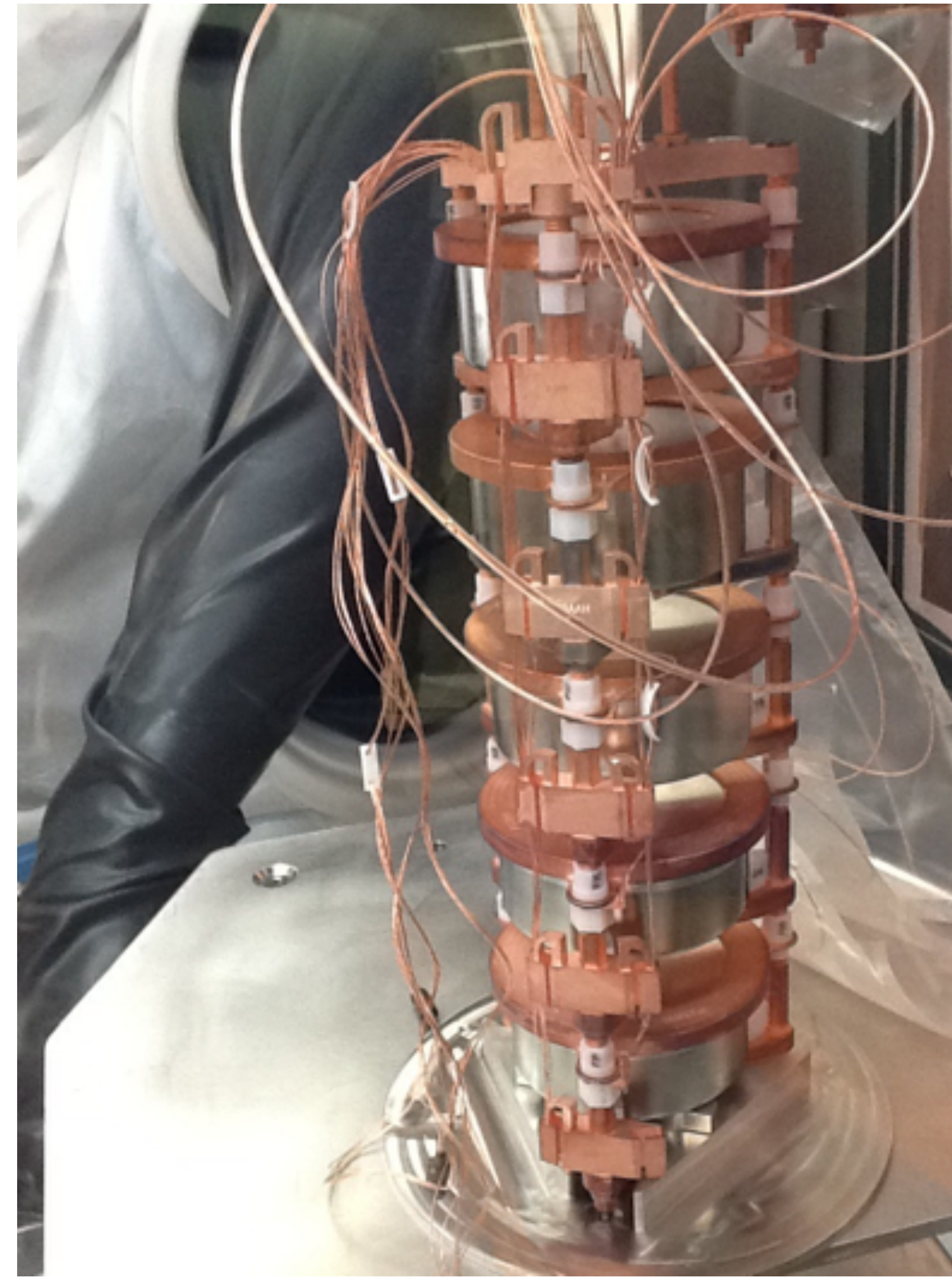
Assembled Detector Unit and String

AMETEK (ORTEC) fabricated enriched-Ge PPC detectors

- 35 enriched detectors: 29.7 kg, 88% ^{76}Ge.

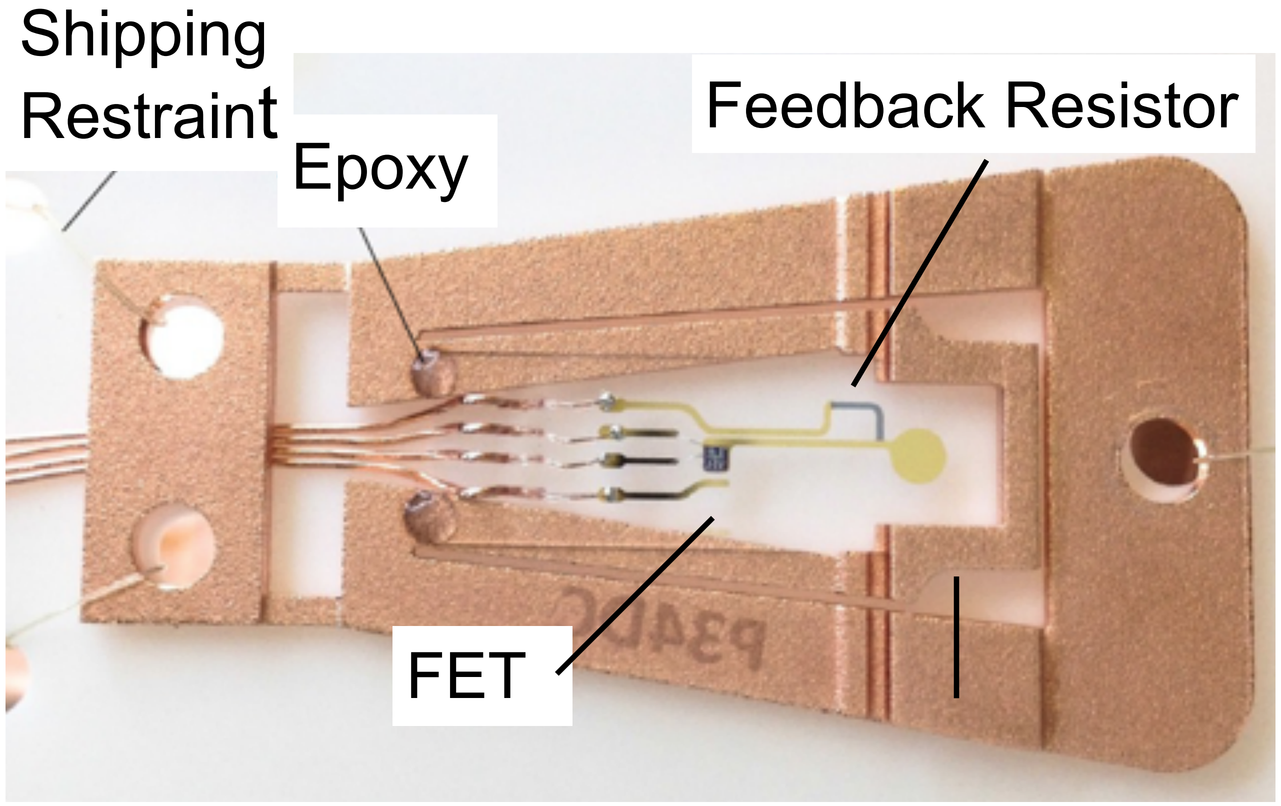
Canberra fabricated natural-Ge BEGe detectors



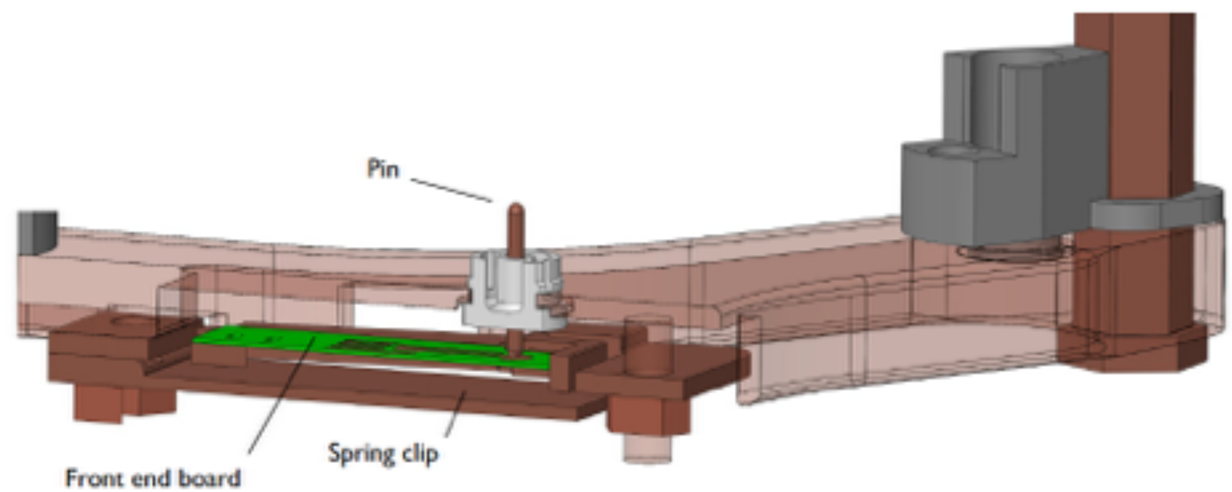


String Assembly

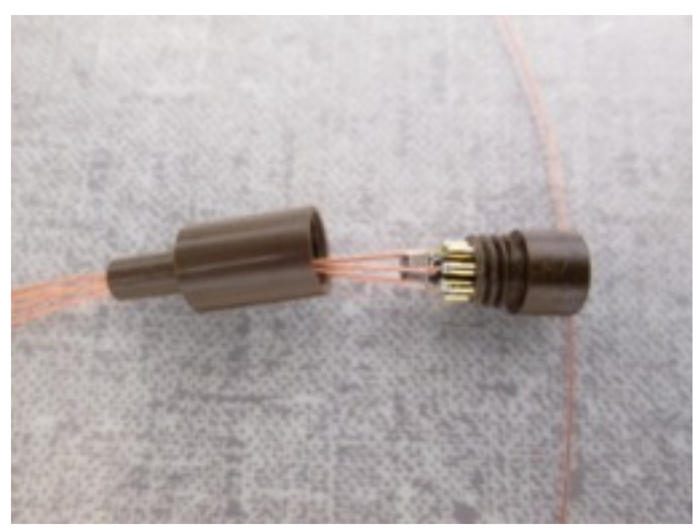
Detector Readout Components



Custom low mass front-end boards
Clean Au+Ti traces on fused silica
Amorphous Ge resistor
FET mounted with silver epoxy
EFCu + low-BG Sn contact pin



Fine Cu coaxial cable and clean connectors



Connectors reside on top of cold plate.
In-house machined from Vespel.
Axon' pico co-ax cable.
Low background solder and flux.

Detector Module

- A self contained vacuum and cryogenic vessel
- Contains a portion of the shielding
- Can be transported for assembly and deployment

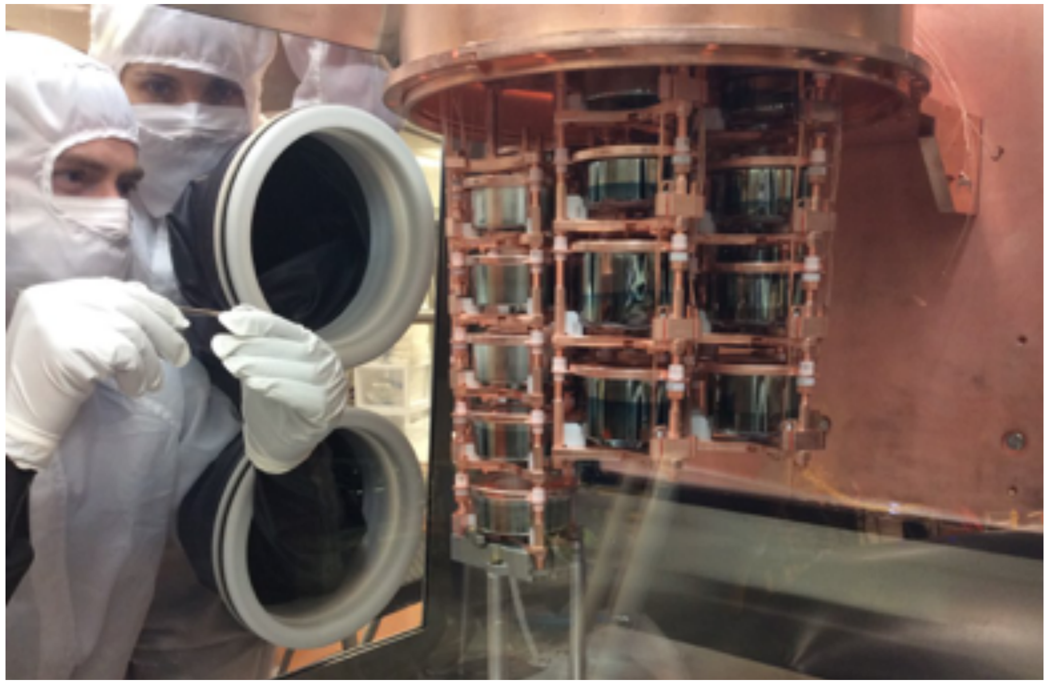
Module mated to the glovebox for string installation

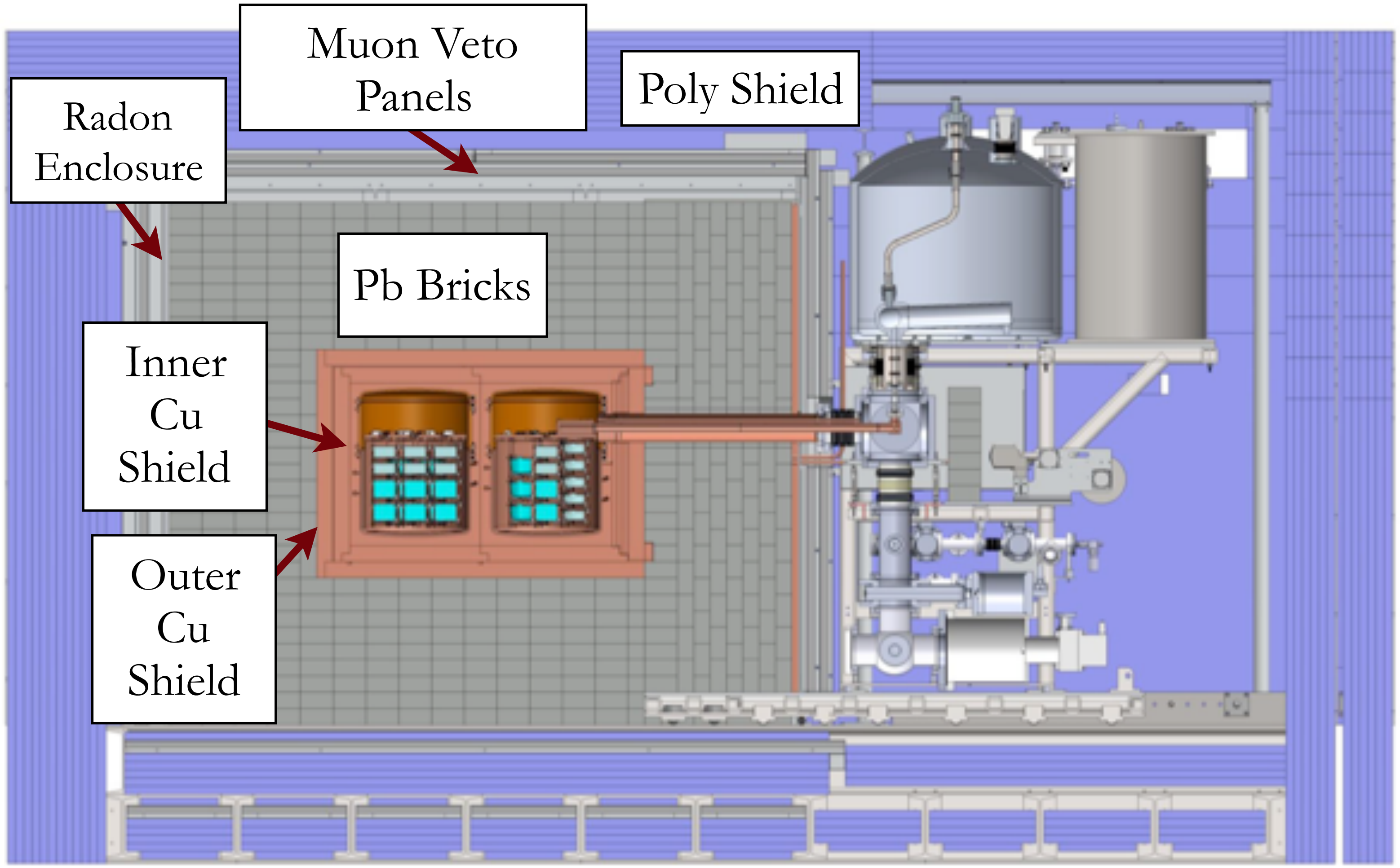
Module moving to/from transporter

Module and Shield

Pb and outer Cu shield

Loading of ^{enr}Ge in Cryostat 2



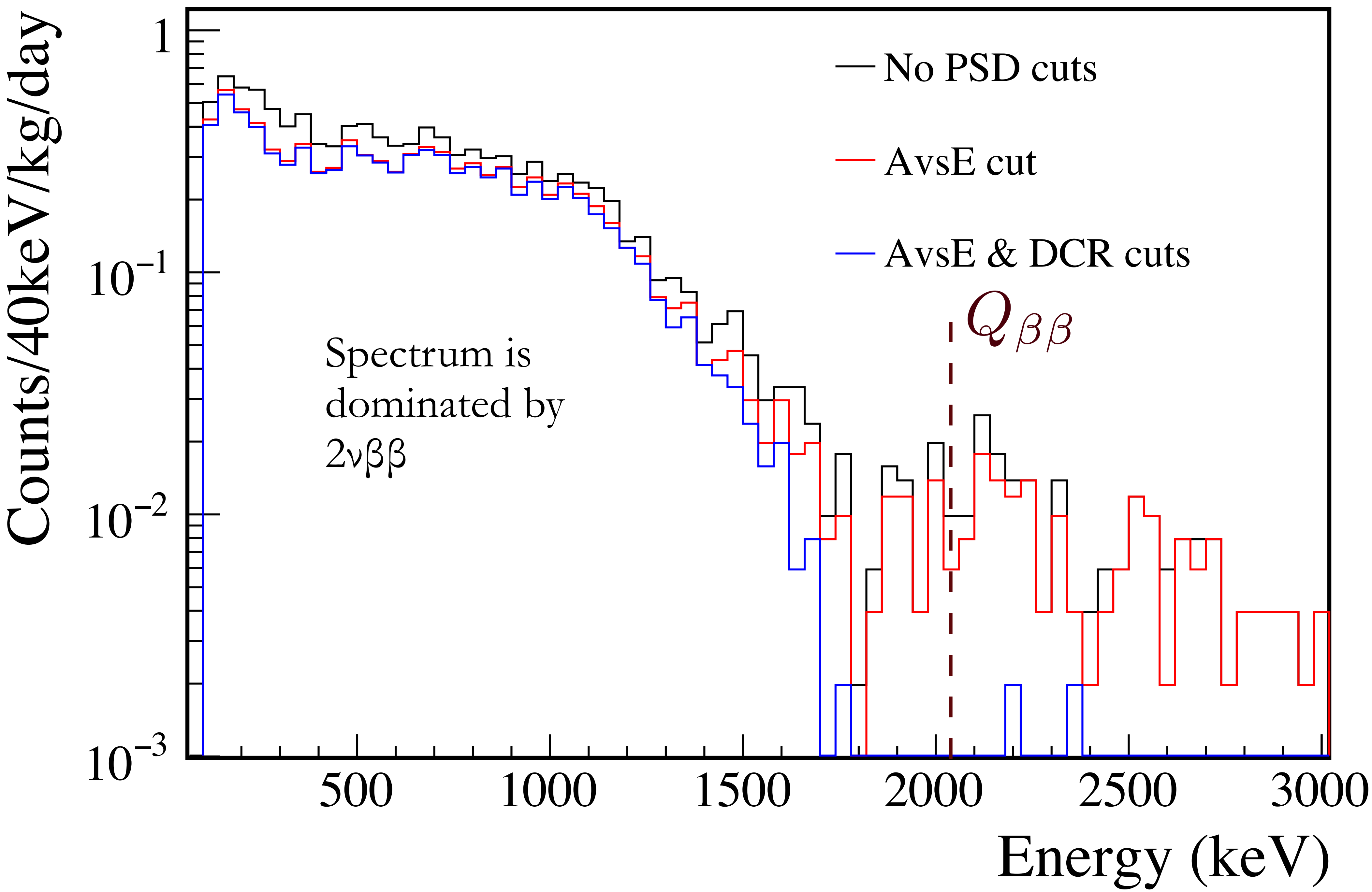


Module deployment

Background Spectrum (DS3 & DS4)

Lowest background configuration with both modules in shield.

Enriched detectors in Modules 1 & 2 , before and after PSD cuts

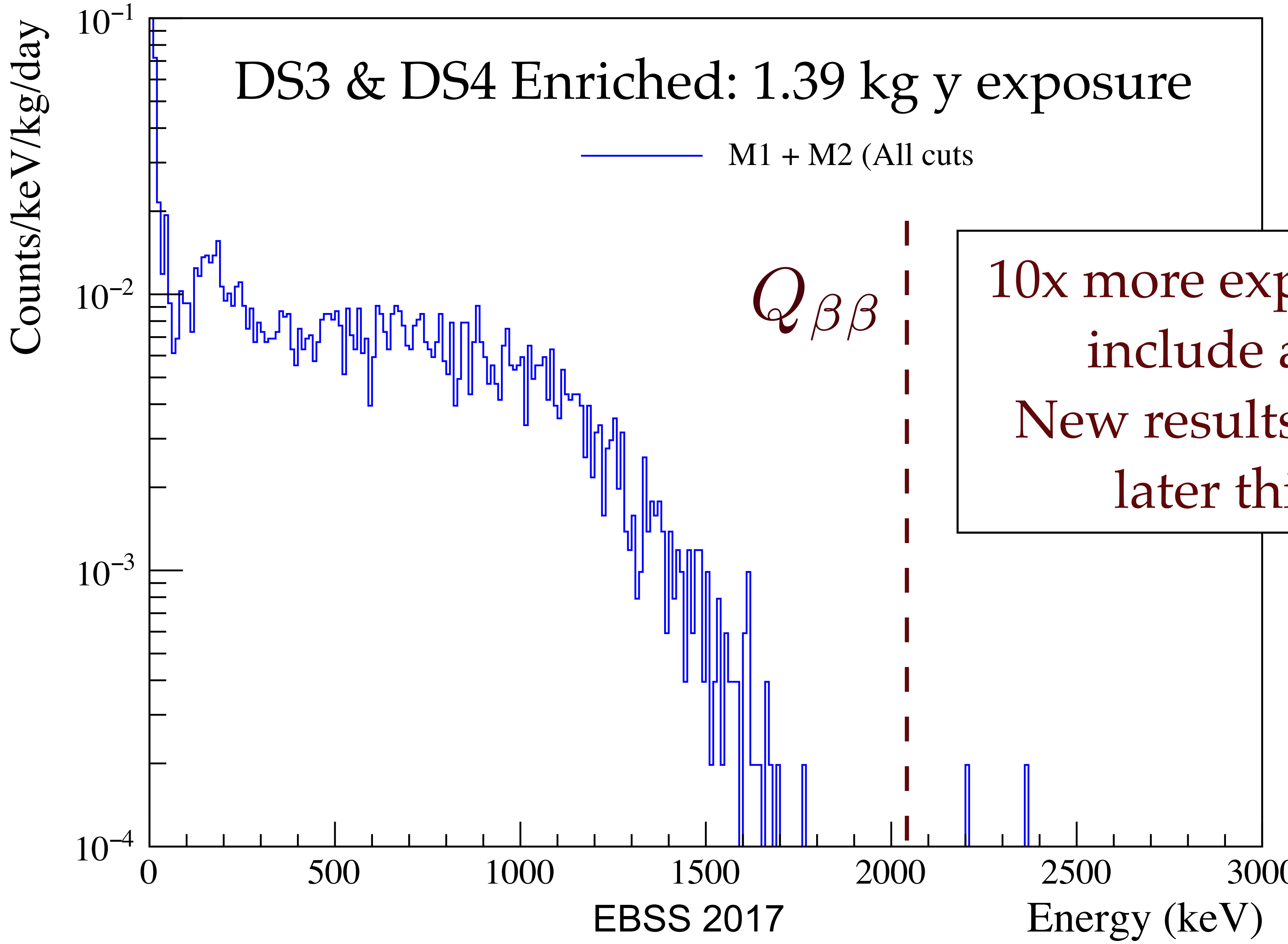


Background Spectrum (DS3 & DS4)

After cuts, 1 count in 400 keV window centered at 2039 keV (0νββ peak)

- Projected background rate is $5.1^{+8.9}_{-3.2}$ c /(ROI t y)
  - using a 2.9 (M1- DS3) & 2.6 keV (M2 - DS4) keV ROI (68% CL).
- Background index of 1.8 x 10^{-3} c/(keV kg y)

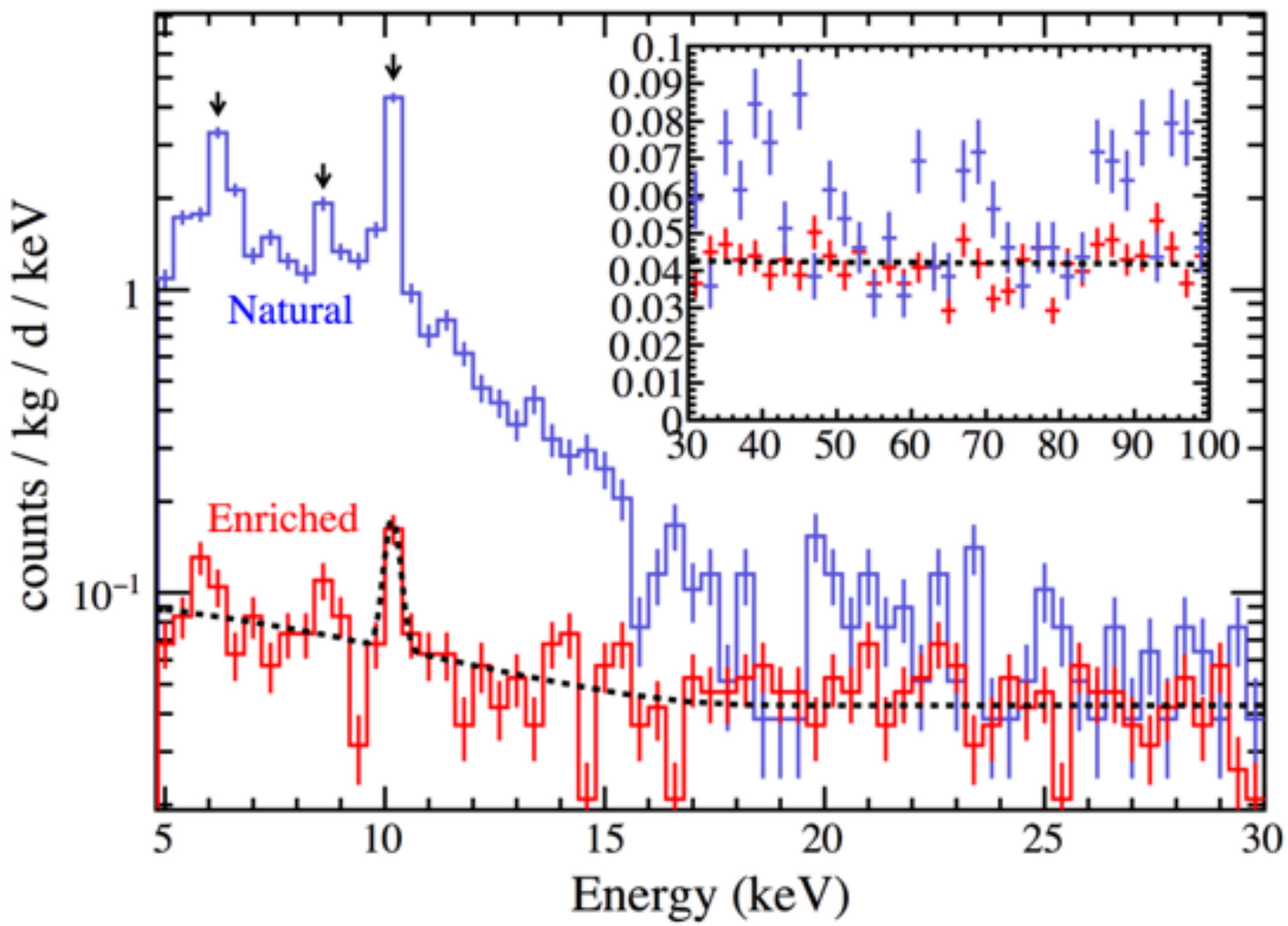
Analysis cuts are still being optimized.



10x more exposure when we include all data sets.
New results to be released later this summer.

Low Energy Spectrum

- Controlled surface exposure of enriched material to minimize cosmogenics
- Significant reduction of cosmogenics in the low-energy region.
  - Low-energy rate is improved in subsequent data sets
- Enriched Detectors: ~0.04 cts/(kg-keV-d) near 20 keV
- Efficiency below 5 keV is under study.



Phys. Rev. Lett. 118, 161801 (2017).

Permits Low-Energy physics

Pseudoscalar dark matter

Vector dark matter

14.4-keV solar axion

$e^- \Rightarrow 3\nu$

Pauli Exclusion Principle

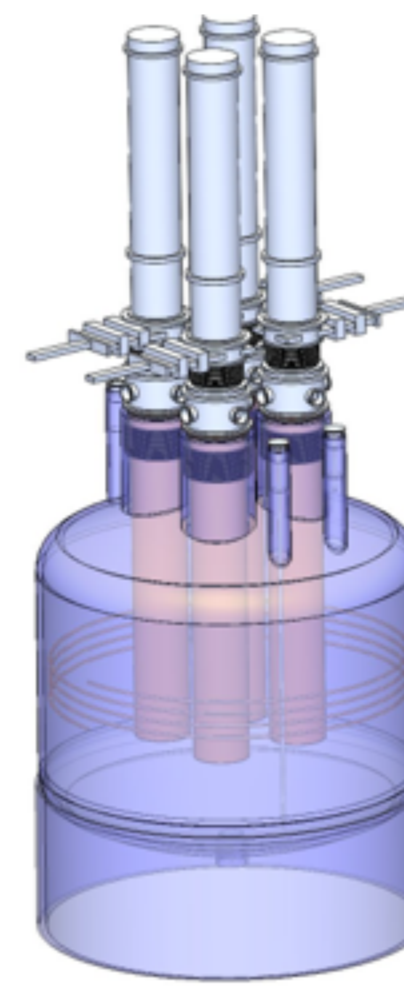
(LEGEND)

The collaboration aims to develop a phased, Ge-76 based double-beta decay experimental program with discovery potential at a half-life significantly longer than 10^{27} years, using existing resources as appropriate to expedite physics results

- Combine the strengths of the GERDA and the MAJORANA DEMONSTRATOR

First phase:
- (up to) 200 kg
- modification of existing GERDA infrastructure at LNGS
- BG goal (x5 lower) 0.6 c /(FWMH t y)
- start by 2021

Subsequent stages:
- 1000 kg (staged)
- timeline connected to U.S. DOE down select process
- BG: goal (x30 lower) 0.1 c /(FWHM t y)
- Location: TBD
- Required depth under investigation



Outlook

- The neutrino history is filled with important discoveries
- The future is even more exciting
  - What is the absolute mass scale?
  - Which hierarchy is correct?
  - Are they their own anti-particle?
  - Is Lepton # violated
  - Is there Leptonic CP-invariance violation
  - Leptogenesis
- Neutrinoless double-beta decay experiments are poised to help unlock the remaining secrets of the neutrino