# Neutrinoless double-deta decay and The MAJORANA DEMONSTRATOR


Wenqin Xu, LANL
For the MAJORANA collaboration


**Santa Fe Summer Workshop**

**Implications of Neutrino Flavor Oscillations**

INFO 2013

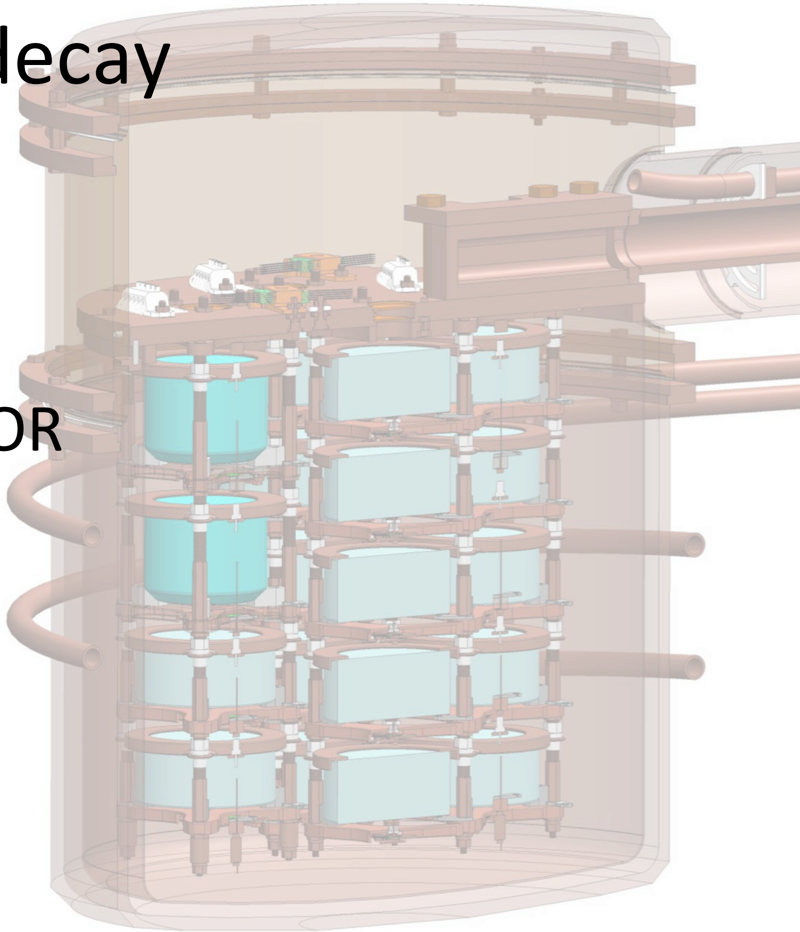
# Outline of the talk

- Neutrinoless double-beta decay

  the physics

  the experiments

- The MAJORANA DEMONSTRATOR



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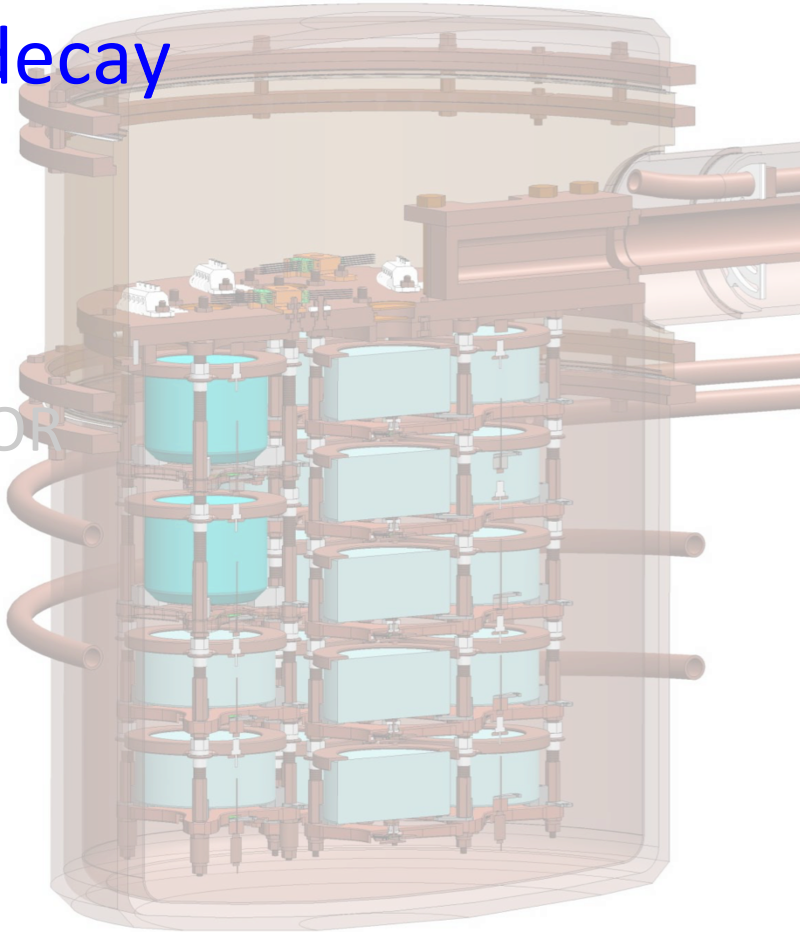
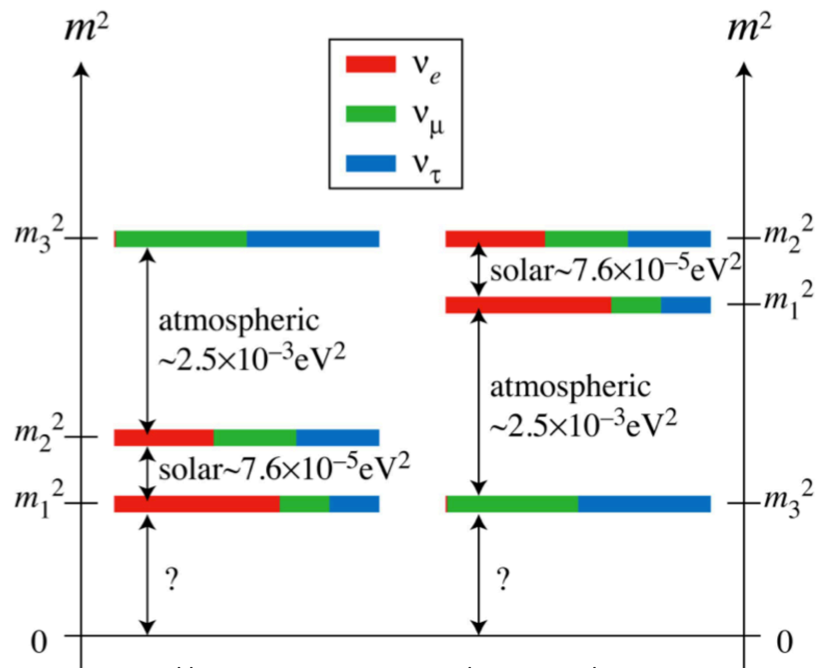


# Questions for neutrino physics




http://hitoshi.berkeley.edu/neutrino/

**Neutrinoless double beta decay:**

- **Is neutrino its own antiparticle (i.e. Majorana Particle)?**
  $0\nu\beta\beta$ **is the only practical way to test this.**

- **Is lepton number violated?**

- **Leptogenesis as a way to produce the excess of matter?**

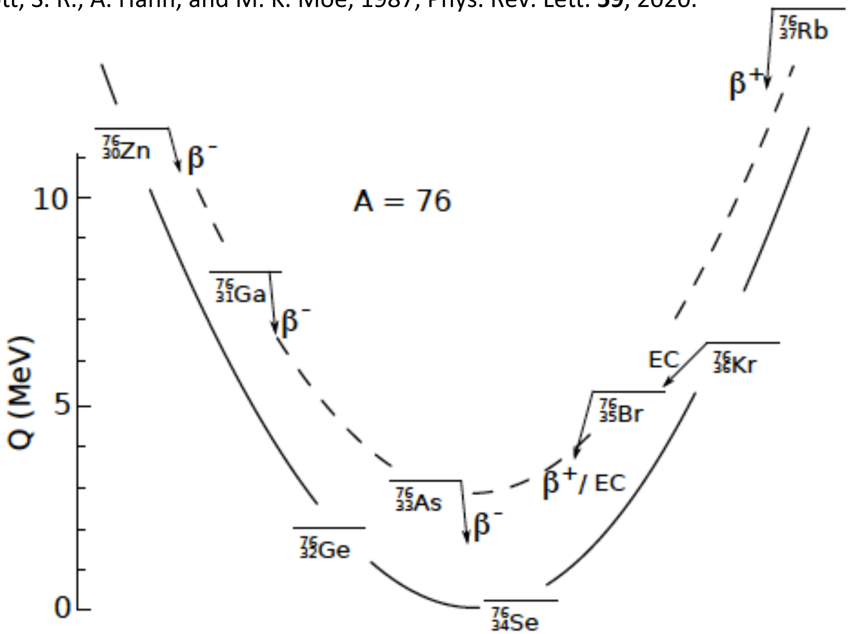
- **Neutrino mass hierarchy ?**

- **Absolute neutrino mas scale?**

# 2-neutrino double beta decay

First direct observation by Steve Elliott et al in 1987

Elliott, S. R., A. Hahn, and M. K. Moe, 1987, Phys. Rev. Lett. **59**, 2020.



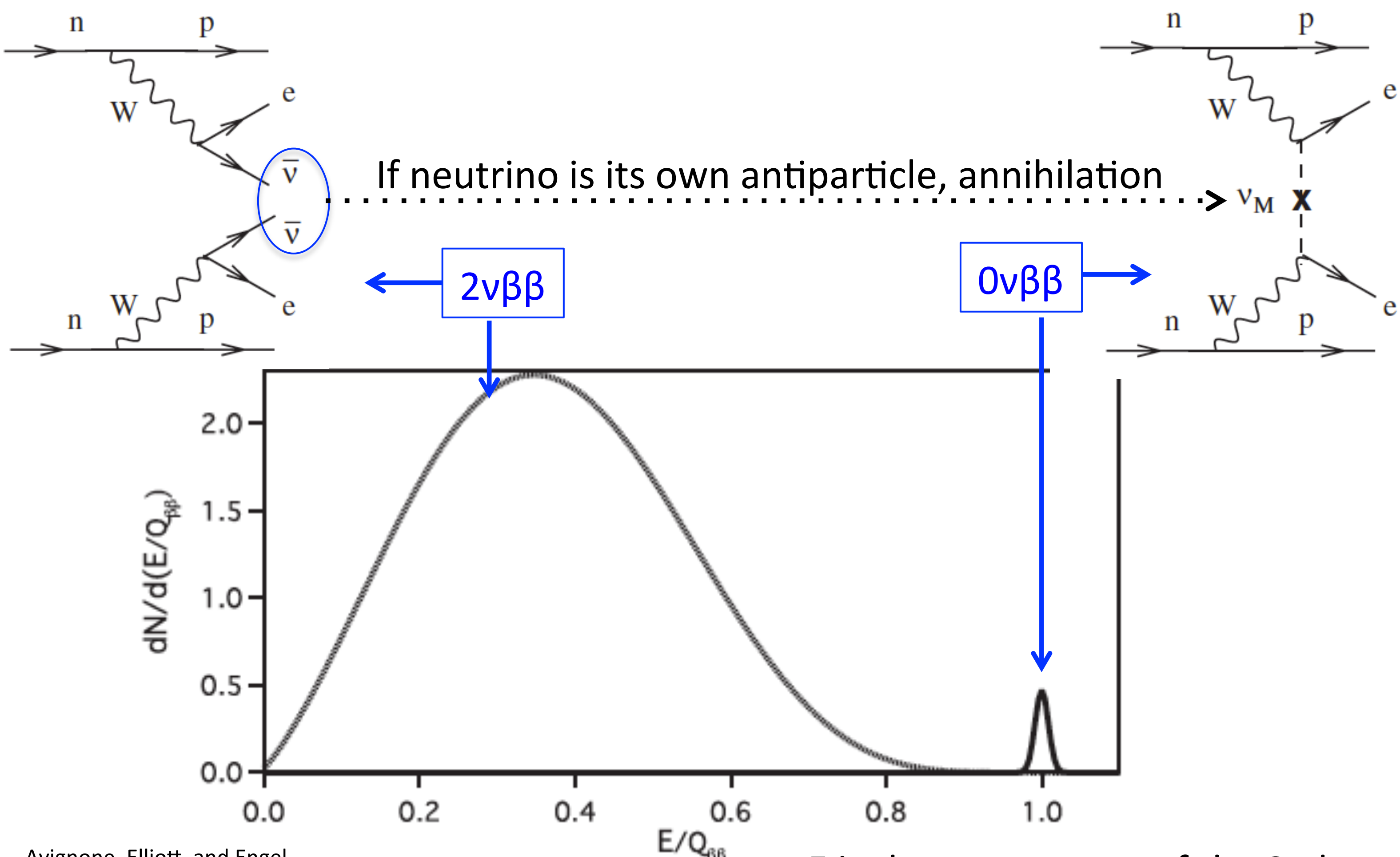

- Only possible if single beta decay is energetically forbidden.
- Observed for some nuclei with even numbers of protons and neutrons

2[nd] order weak decay, very long half life

| Isotope | $T_{1/2}(2\nu)$, yr |
|---|---|
| $^{48}$Ca | $4.3^{+2.1}_{-1.0} \times 10^{19}$ |
| $^{76}$Ge | $(1.5 \pm 0.1) \times 10^{21}$ |
| $^{82}$Se | $(0.92 \pm 0.07) \times 10^{20}$ |
| $^{96}$Zr | $(2.0 \pm 0.3) \times 10^{19}$ |
| $^{100}$Mo | $(7.1 \pm 0.4) \times 10^{18}$ |
| $^{100}$Mo–$^{100}$Ru$(0^+_1)$ | $(6.2^{+0.9}_{-0.7}) \times 10^{20}$ |
| $^{116}$Cd | $(3.0 \pm 0.2) \times 10^{19}$ |
| $^{128}$Te | $(2.5 \pm 0.3) \times 10^{24}$ |
| $^{130}$Te | $(0.9 \pm 0.1) \times 10^{21}$ |
| $^{150}$Nd | $(7.8 \pm 0.7) \times 10^{18}$ |
| $^{150}$Nd–$^{150}$Sm$(0^+_1)$ | $1.4^{+0.5}_{-0.4} \times 10^{20}$ |
| $^{238}$U | $(2.0 \pm 0.6) \times 10^{21}$ |
| $^{130}$Ba; ECEC$(2\nu)$ | $(2.2 \pm 0.5) \times 10^{21}$ |

A. S. Barabash, ISSN 1063-7788, Physics of Atomic Nuclei, 2010, Vol. 73, No. 1, pp. 162–178.

# Neutrinoless double beta decay
# ( 0νββ )




Avignone, Elliott, and Engel,
Rev. Mod. Phys., Vol. 80, No. 2, April–June 2008

E is the sum energy of the 2 electrons

# 0νββ half life is related to mass

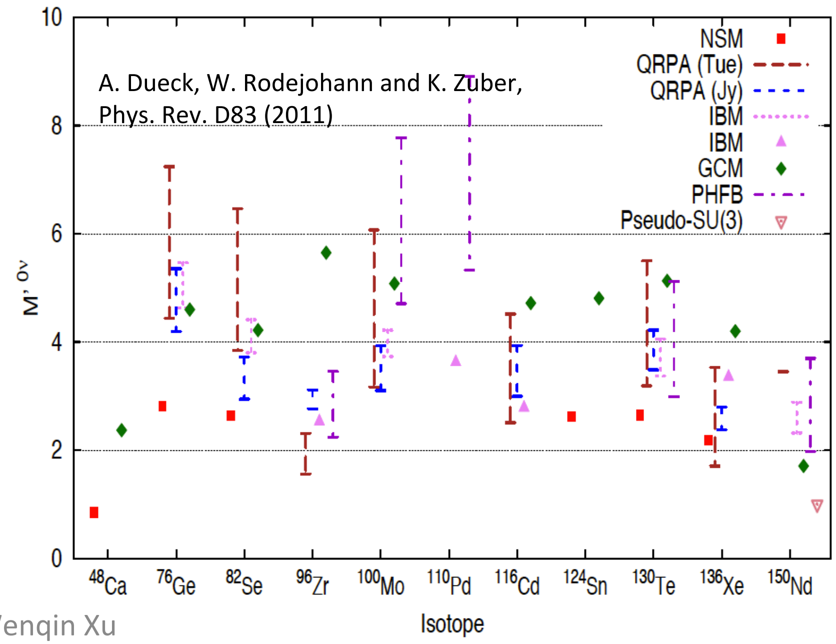
$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}\,|M_{0\nu}|^2 \left(\frac{\langle m_{\beta\beta}\rangle}{m_e}\right)^2$$

$\langle m_{\beta\beta}\rangle = \left|\sum_{i=1} U_{ei}^2 m_i\right|$ : Effective Majorana neutrino mass

$G^{0\nu}$ : Phase factor

$M_{0\nu}$ : Nuclear Matrix Element

Half life can be directly translated to effective majorana neutrino mass, although large uncertainties exist on NME calculation



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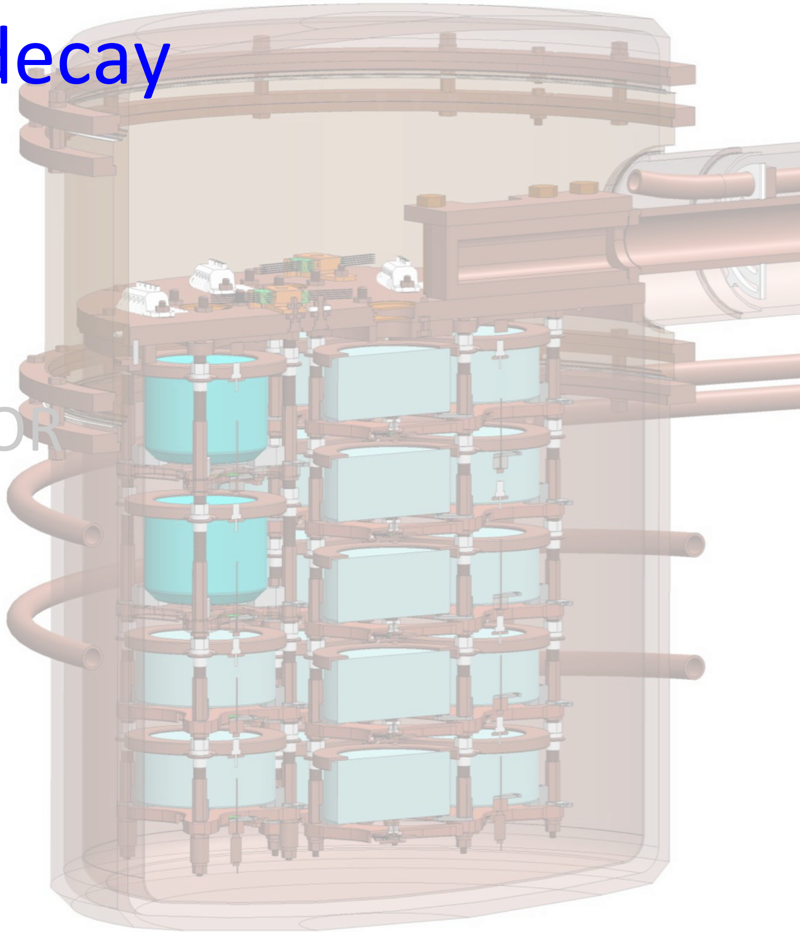


# Recent List of 0νββ experiments

| Isotope | $G^{0\nu}$ $\left[\frac{10^{-14}}{yr}\right]$ | $Q_{\beta\beta}$ [keV] | Nat. ab. [%] | $T^{2\nu}_{1/2}$ [$10^{20}$ yr] | Experiments |
|---|---|---|---|---|---|
| $^{48}$Ca | 6.3 | 4273.7 | 0.187 | 0.44 | CANDLES |
| $^{76}$Ge | 0.63 | 2039.1 | 7.8 | 15 | GERDA, MAJORANA DEMONSTR. |
| $^{82}$Se | 2.7 | 2995.5 | 9.2 | 0.92 | SuperNEMO, Lucifer |
| $^{100}$Mo | 4.4 | 3035.0 | 9.6 | 0.07 | MOON, AMoRe |
| $^{116}$Cd | 4.6 | 2809.1 | 7.6 | 0.29 | Cobra |
| $^{130}$Te | 4.1 | 2530.3 | 34.5 | 9.1 | CUORE |
| $^{136}$Xe | 4.3 | 2457.8 | 8.9 | 21 | EXO, Next, Kamland-Zen |
| $^{150}$Nd | 19.2 | 3367.3 | 5.6 | 0.08 | SNO+, DCBA/MTD |

B. Schwingenheuer, Ann. Phys. (Berlin) 525, No. 4 (2013)

# The Choice of Ge

Steven R. Elliott, Petr Vogel, Ann.Rev.Nucl.Part.Sci.52:115-151,2002

Excellent energy resolution: crucial in distinguishing 2νββ (the ultimate background) from 0νββ near the end point

$F = \frac{7Q\delta^6}{m_e}$ is roughly the fraction of 2νββ decays ends up in the 0νββ peak region, δ=ΔE/Q

$\frac{S}{B} = \frac{m_e}{7Q\delta^6}\frac{\Gamma_{0\nu}}{\Gamma_{2\nu}} = \frac{m_e}{7Q\delta^6}\frac{T^{2\nu}_{1/2}}{T^{0\nu}_{1/2}}$. depends on the half life of 2νββ and 0νββ, element dependent

Half life ratio and $(\Delta E)^6$ decides the S/B, thus the ultimate sensitivity.

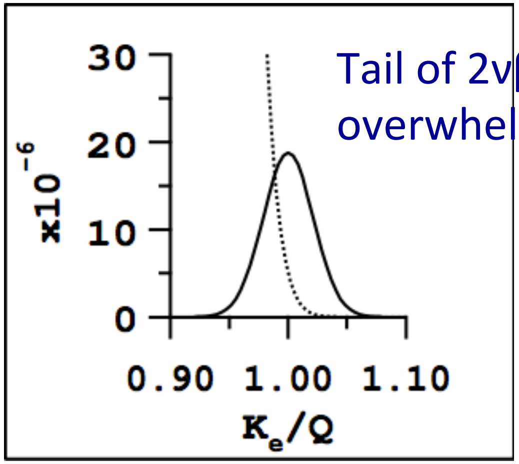
ΔE is crucial

Ge detector has ΔE/E~0.2% at $Q_{\beta\beta}$

i.e. 4 keV Region of Interest (ROI) @2039keV

2νββ is estimated to be negligible of the final background in ROI for the **DEMONSTRATOR**

Assumes 5% energy resolution, $\Gamma_{0\nu}$=1e-6 $\Gamma_{2\nu}$ →



# Good reasons for Ge

- ✓ Excellent Energy resolution (~0.2% at 2039keV)
- ✓ Source is detector
- ✓ Can be enriched in $^{76}Ge$ to 86%
- ✓ Low level of radio-impurities can be achieved during processing
- ✓ Technology is well understood
- ✓ Easy to operate (LN temperature, volume is small)
- ✓ Large Q-value puts $0\nu\beta\beta$ peak above most backgrounds

# Previous Ge experiment

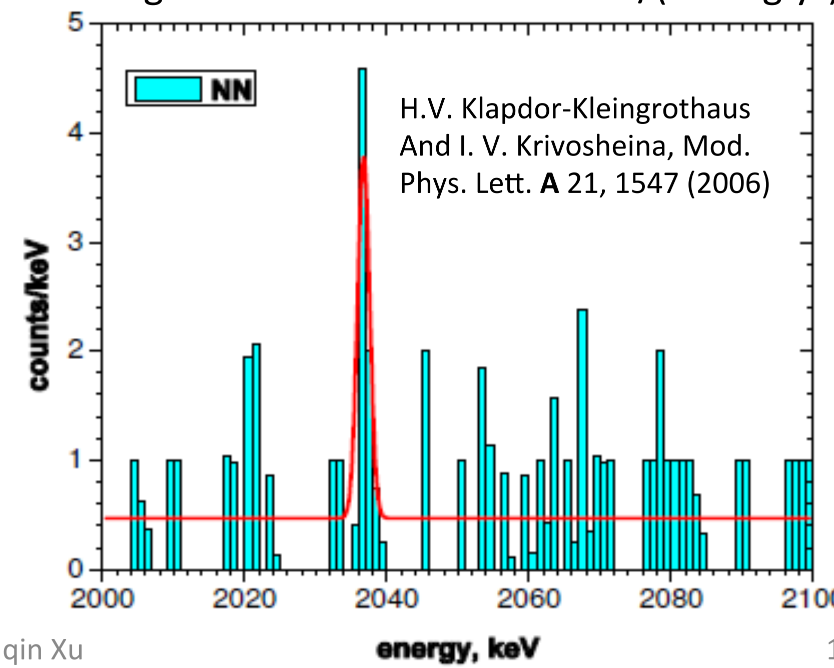
The upper limits on 0νββ half-life:
Heidelberg-Moscow:
$T_{1/2}$ ($^{76}$Ge)>1.9x10$^{25}$ years (90% CL)
Eur. Phys. J. A. 12, 147-154 (2001)

IGEX (International Germanium Experiment):
$T_{1/2}$ ($^{76}$Ge)>1.57x10$^{25}$ years (90% CL)
Phys. Rev. D, 65, 092007 (2002)
They are the most sensitive limits until recently.

Recent Non-Ge experiments:
EXO-200: $T_{1/2}$ ($^{136}$Xe)>1.6x10$^{25}$ years (90% CL)
Phys. Rev. Lett. 109, 032505 (2012)
and
KamLAND-Zen: $T_{1/2}$ ($^{136}$Xe)>1.9x10$^{25}$ years (90% CL)
Phys.Rev.Lett. 110, 062502 (2013)

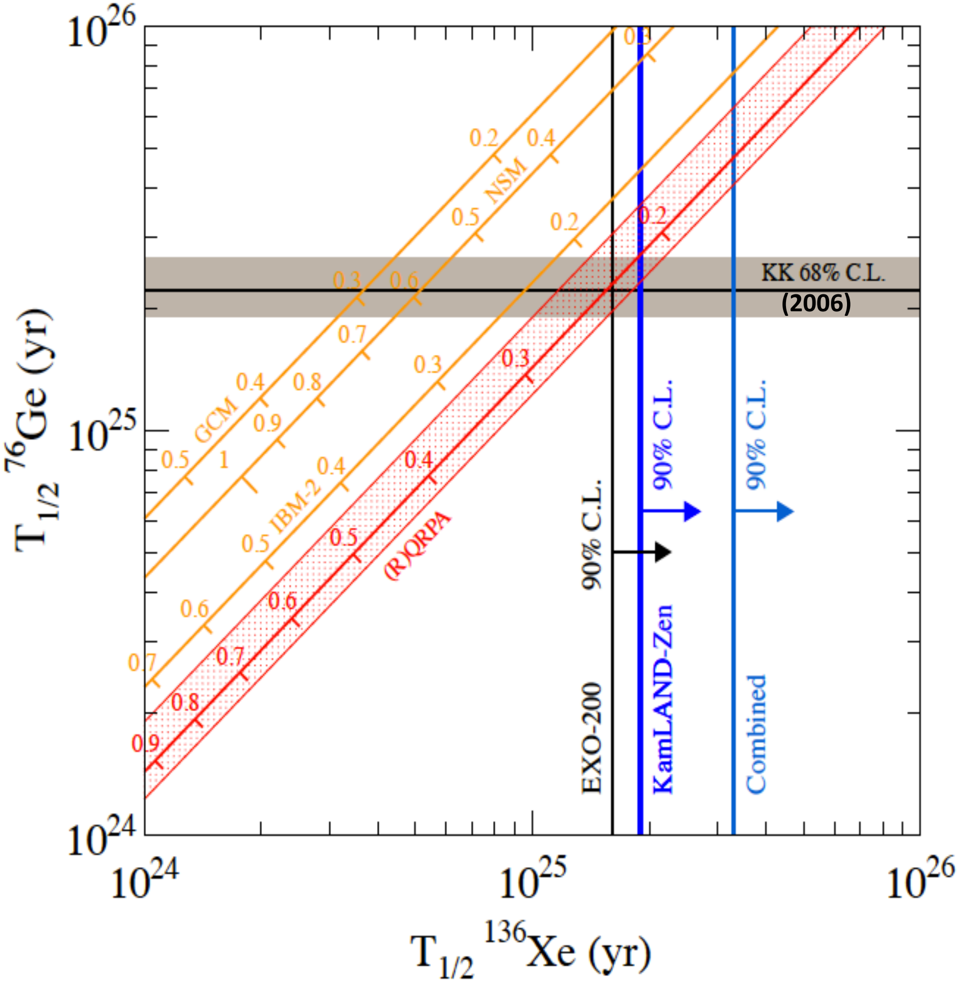
The (2004) 4.2σ 0νββ claim: $T_{1/2} = 1.19^{+0.38}_{-0.22}$ x10$^{25}$y
Total exposure 71.8kg*yr
H.V. Klapdor-Kleingrothaus, et al, PLB 586 (2004) 198-212

The (2006) 6.4σ 0νββ claim: $T_{1/2} = 2.23^{+0.44}_{-0.31}$ x10$^{25}$y
Reanalysis with Pulse Shape Decimation (PSA) used
Double-peak structure reported at $Q_{\beta\beta}$
Low background after PSD: 0.015 cnts/(keV·kg·yr)

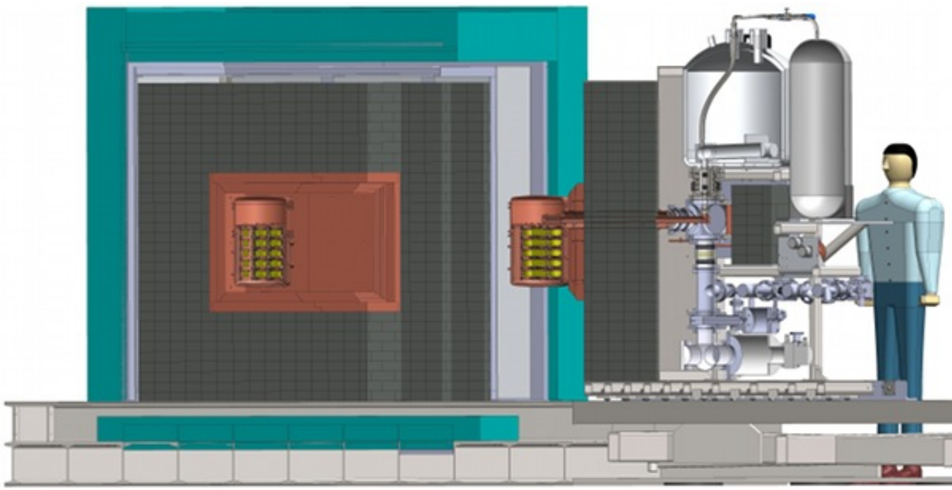


# Status prior to GERDA and MJD

KamLAND-Zen 2013, Phys.Rev.Lett. 110, 062502 (2013)



# GERDA &
# MAJORANA DEMONSTRATOR



**GERDA**

**Detectors inside a liquid argon shield**
**high-Z material budget is small, relaxing depth requirement**

**MAJORANA DEMONSTRATOR**

**Detectors are inside lays of compact shield**
**Effectively shield against natural radioactivity**

# GERDA: experimental setup

Eur. Phys. J. C (2013) 73:2330
arXiv:1212.4067

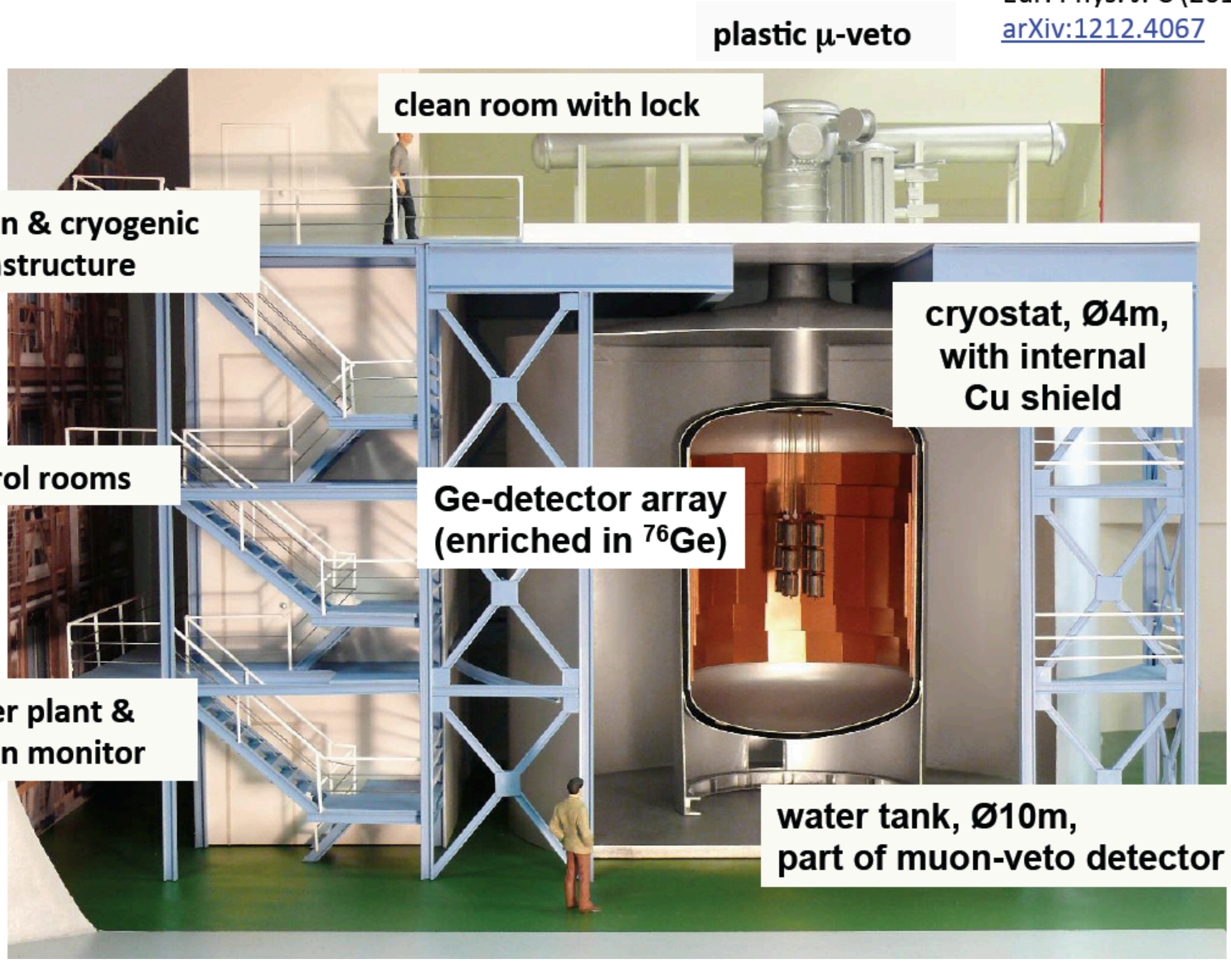
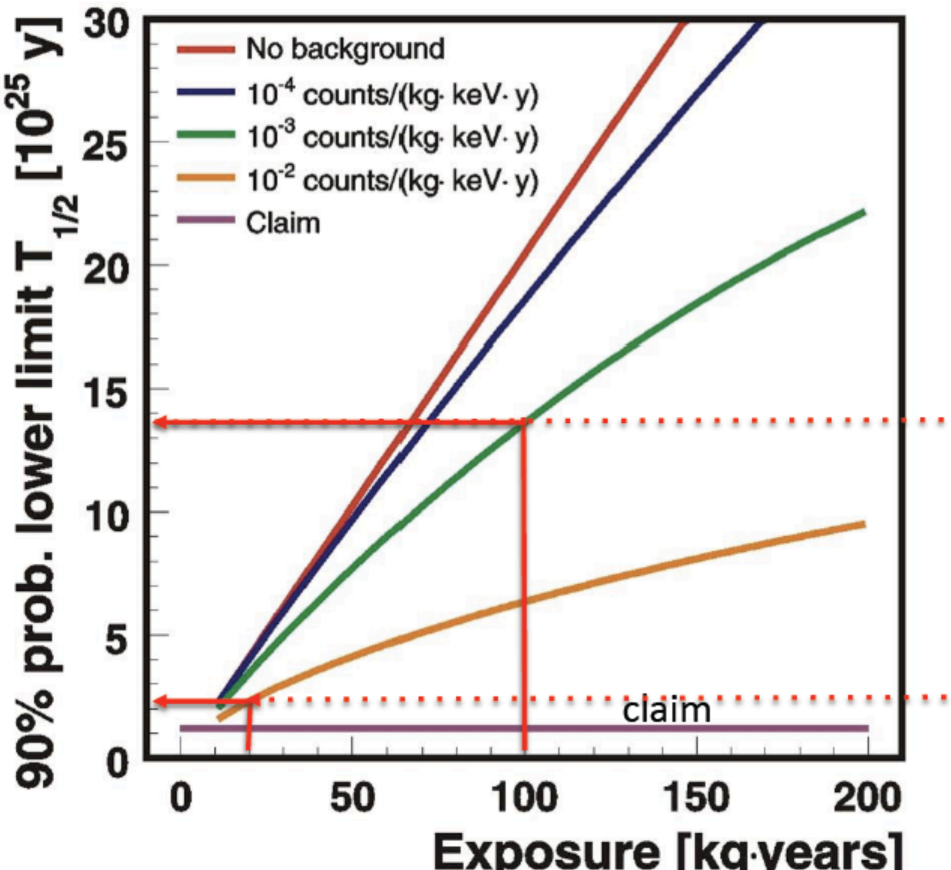



Figure adapted from:
Stefan Schönert
(for the GERDA collaboration)
LNGS Seminar, July 16, 2013

# GERDA phase I background

GERDA: "background index ranging from 17.6 to 23.8x10$^{-3}$ cts/(keV*kg*yr)", arXiv:1306.5084
Final results with PSD: background index ranging from 5 to 30x10$^{-3}$ cts/(keV*kg*yr), arXiv:1307.4720




Phase II:
Add new enr. BEGe detectors (20 kg)
BI ≈ 0.001 cts / (keV kg yr) i.e. 1ct/keV t yr
Sensitivity after 100 kg yr

Phase I:
Use refurbished HdM & IGEX (18 kg)
BI ≈ 0.01 cts / (keV kg yr) i.e. 10 cts/keV t yr
Sensitivity after 20 kg yr

Figure adapted from:
Stefan Schönert
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LNGS Seminar, July 16, 2013

# GERDA phase I results

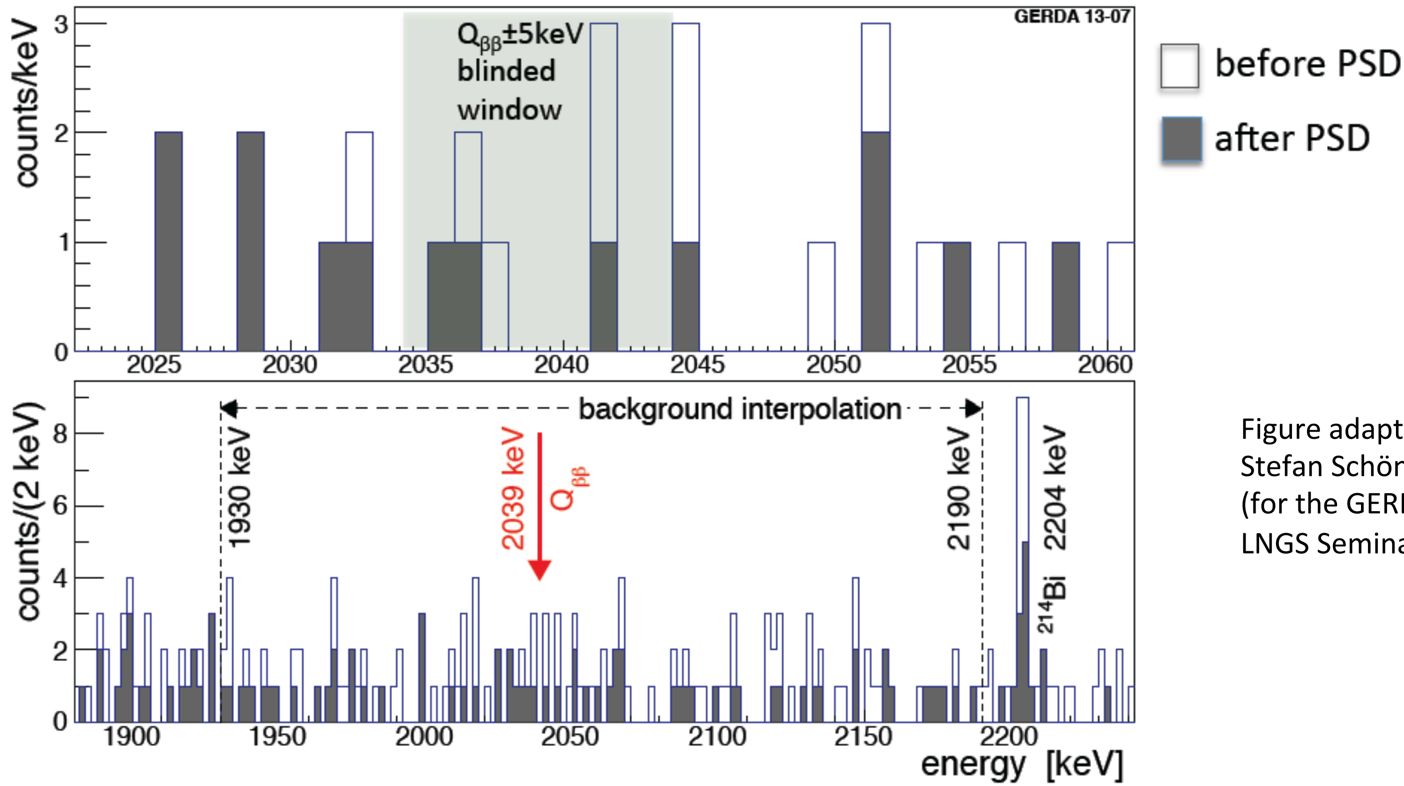


Figure adapted from:
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LNGS Seminar, July 16, 2013

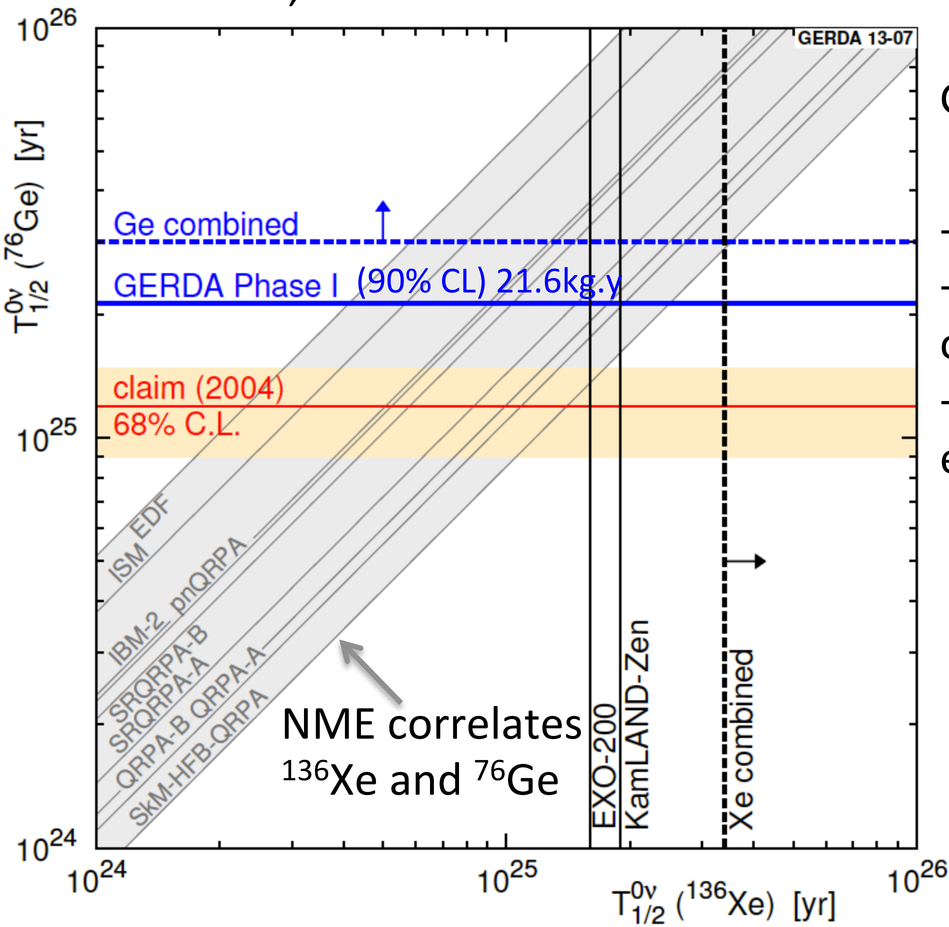
| | | |
|---|---|---|
| Full data set: | 7 event in blinded window | Expect 5.1 background |
| | 3 event survive PSD cut | Expect 2.5 background |

**No 0νββ**

S. Schönert (TUM): First GERDA results results on 0νββ decay search - LNGS, July 16, 2013 50

# GERDA phase I results

GERDA, arXiv:1307.4720




GERDA didn't compare with the 2006 claim due to "inconsistencies in the latter reference"

- The fit error on the signal count is too small.
- Expected background doesn't match observed (fluctuation probability ~ $5*10^{-7}$)
- Inconsistence with the signal detection efficiency

B. Schwingenheuer, Ann. Phys. (Berlin) 525, No. 4 (2013)

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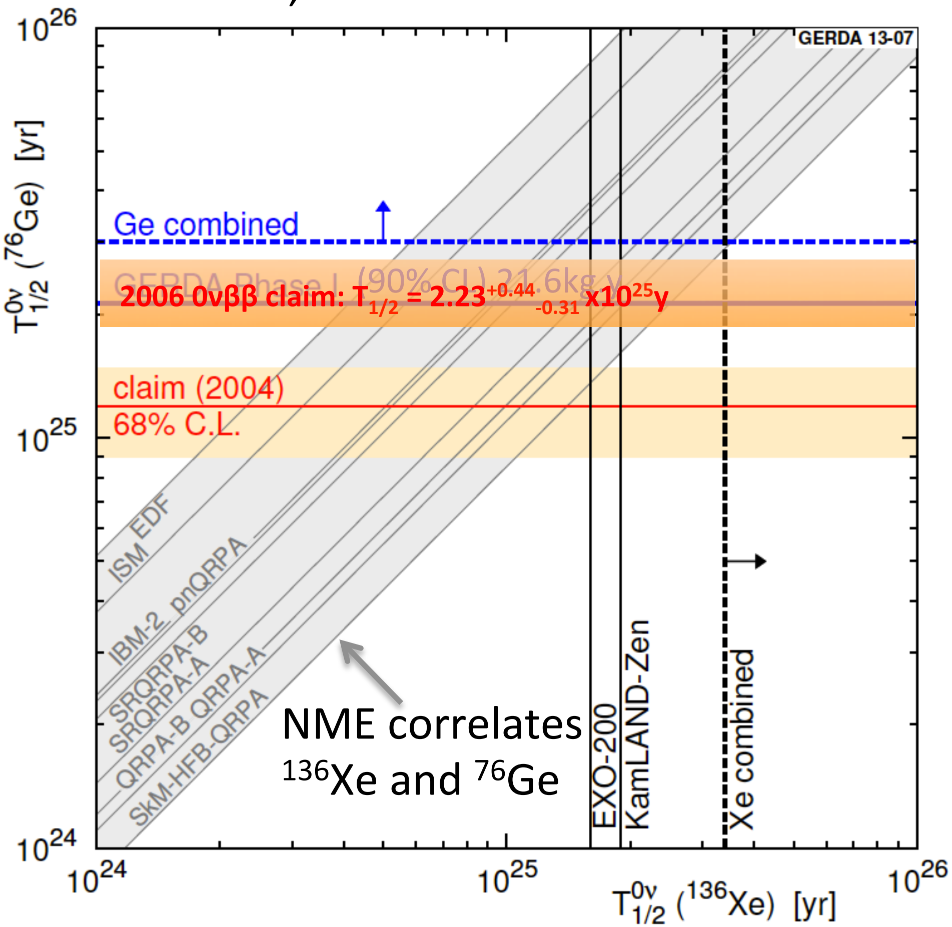
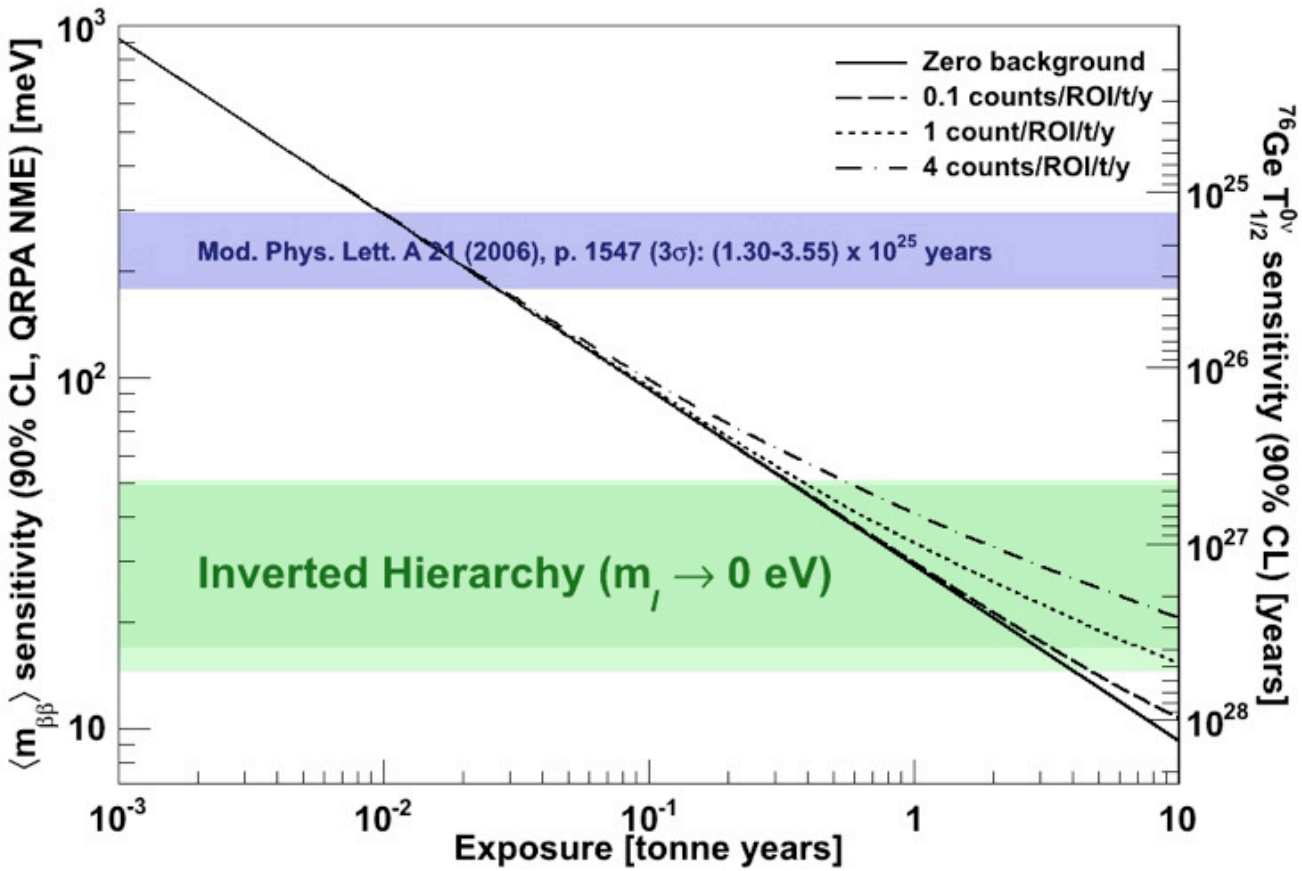
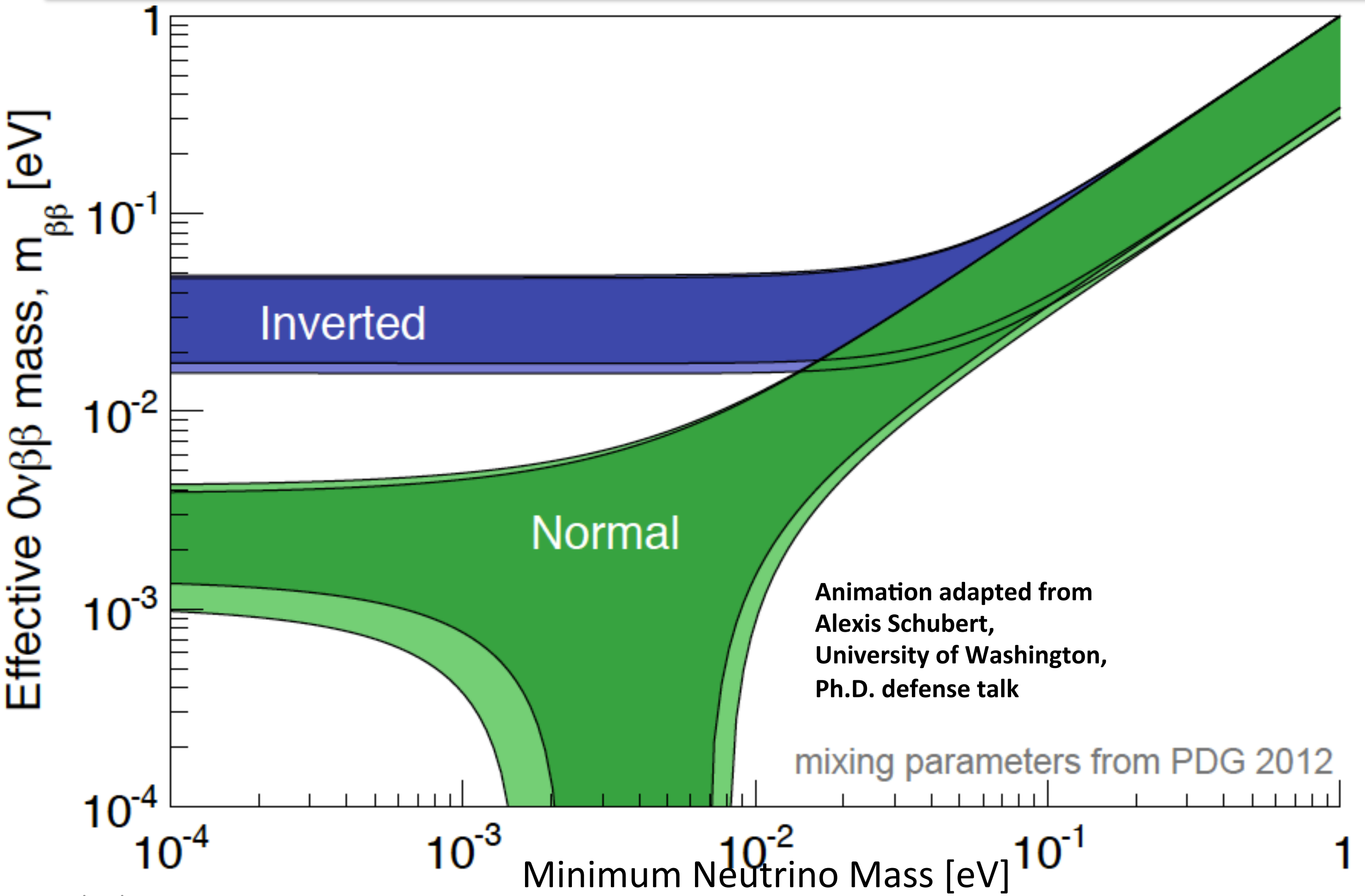
GERDA, arXiv:1307.4720



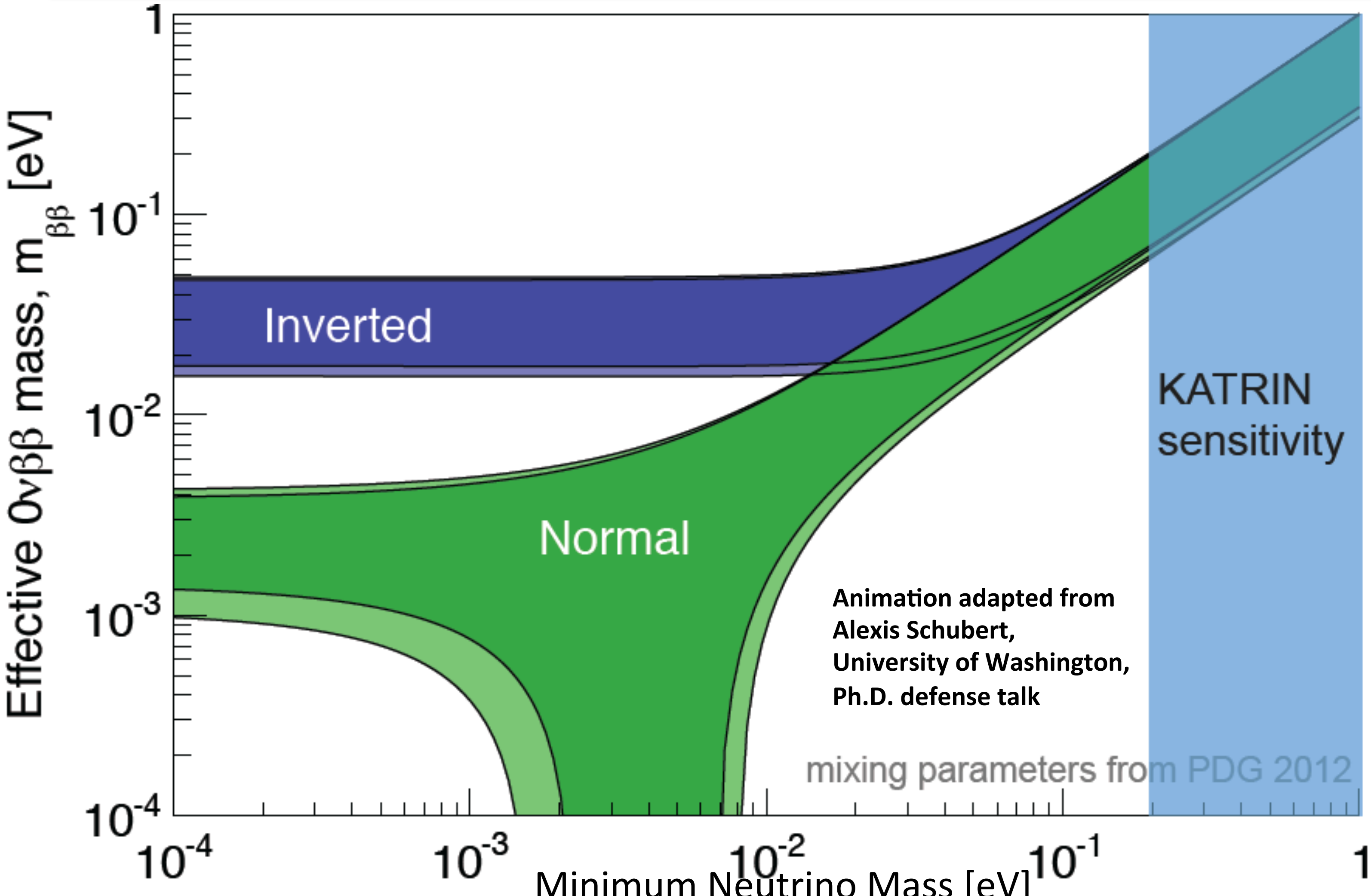
# MAJORANA DEMONSTRATOR sensitivity



# The mass plot



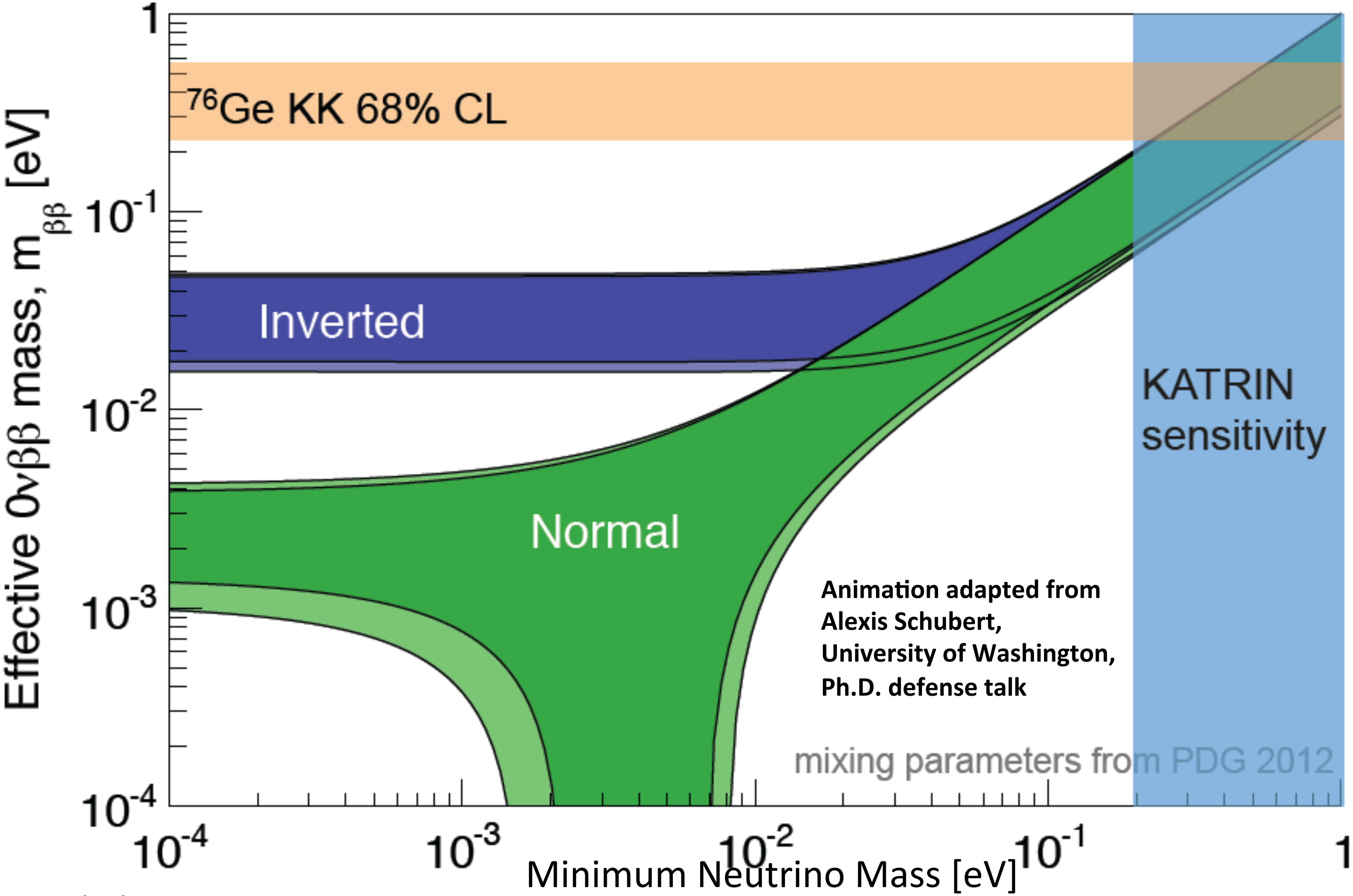
# KATRIN sensitivity




**Animation adapted from Alexis Schubert, University of Washington, Ph.D. defense talk**

https://www.katrin.kit.edu/128.php

# Neutrinoless double beta decay



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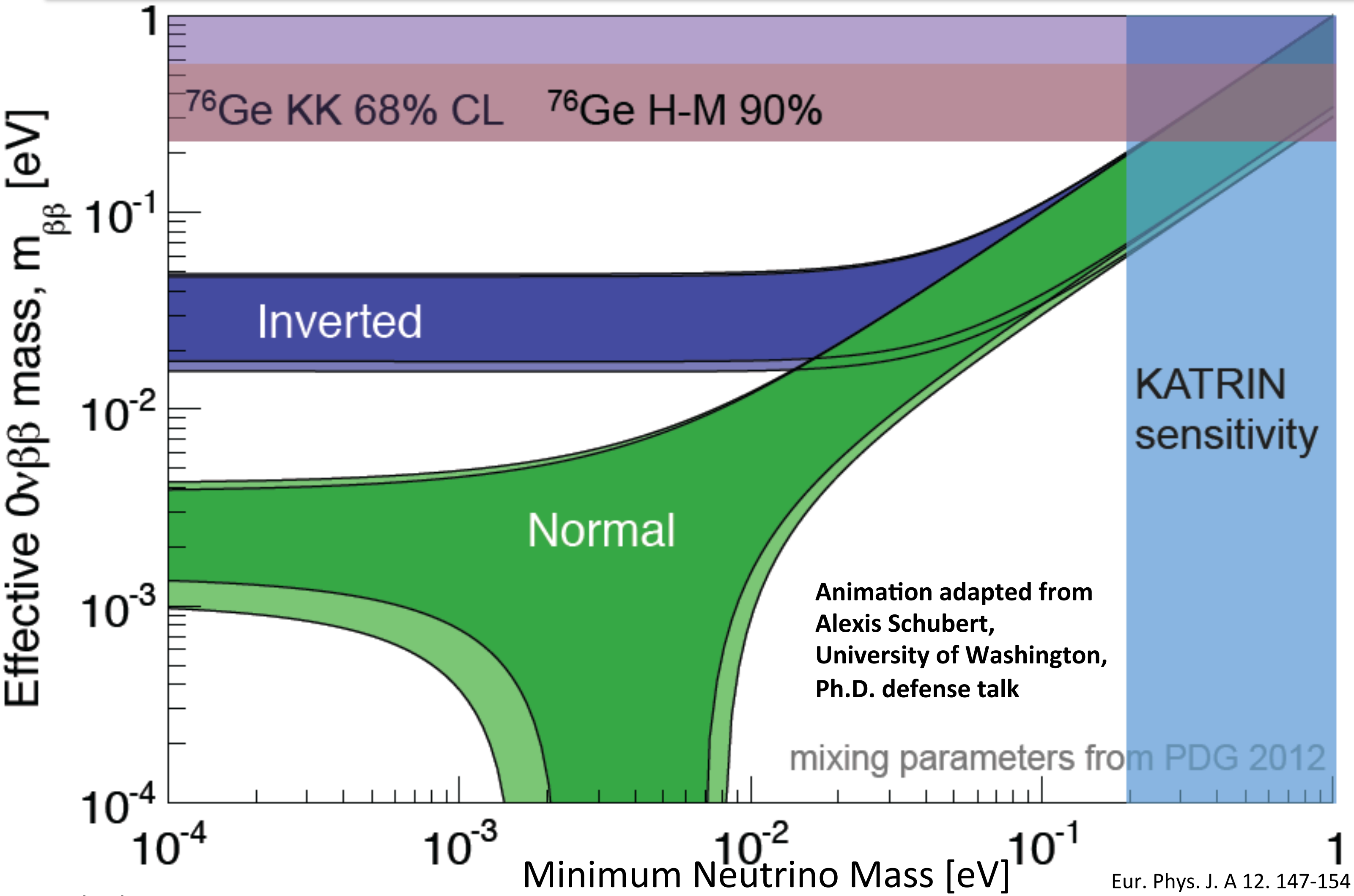
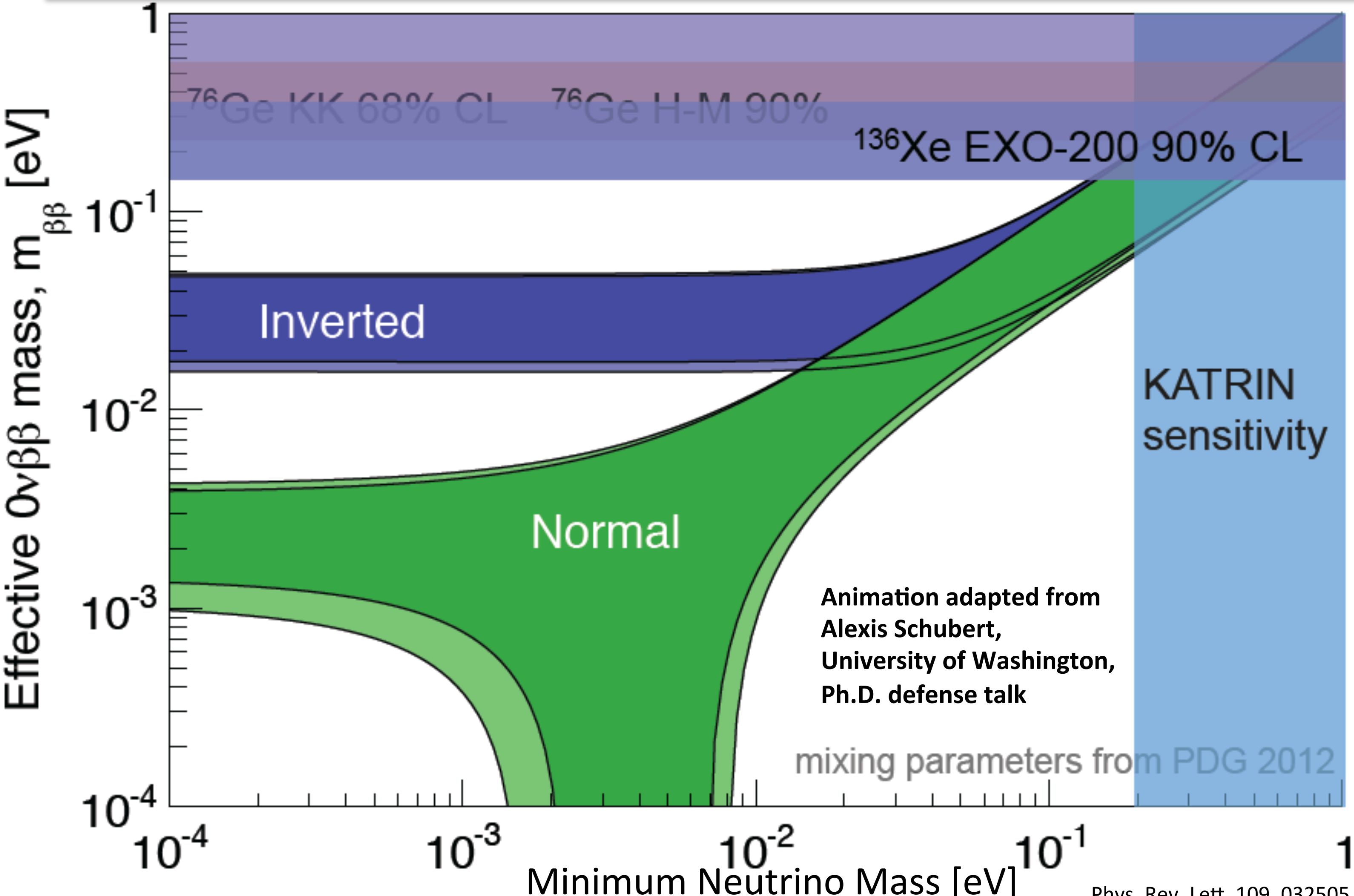



Upper limit of $<m_{\beta\beta}>$, if Majorana particle. The band uncertainty mainly comes from nuclear matrix Element.

# Neutrinoless double beta decay

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Phys. Rev. Lett. 109, 032505 (2012)

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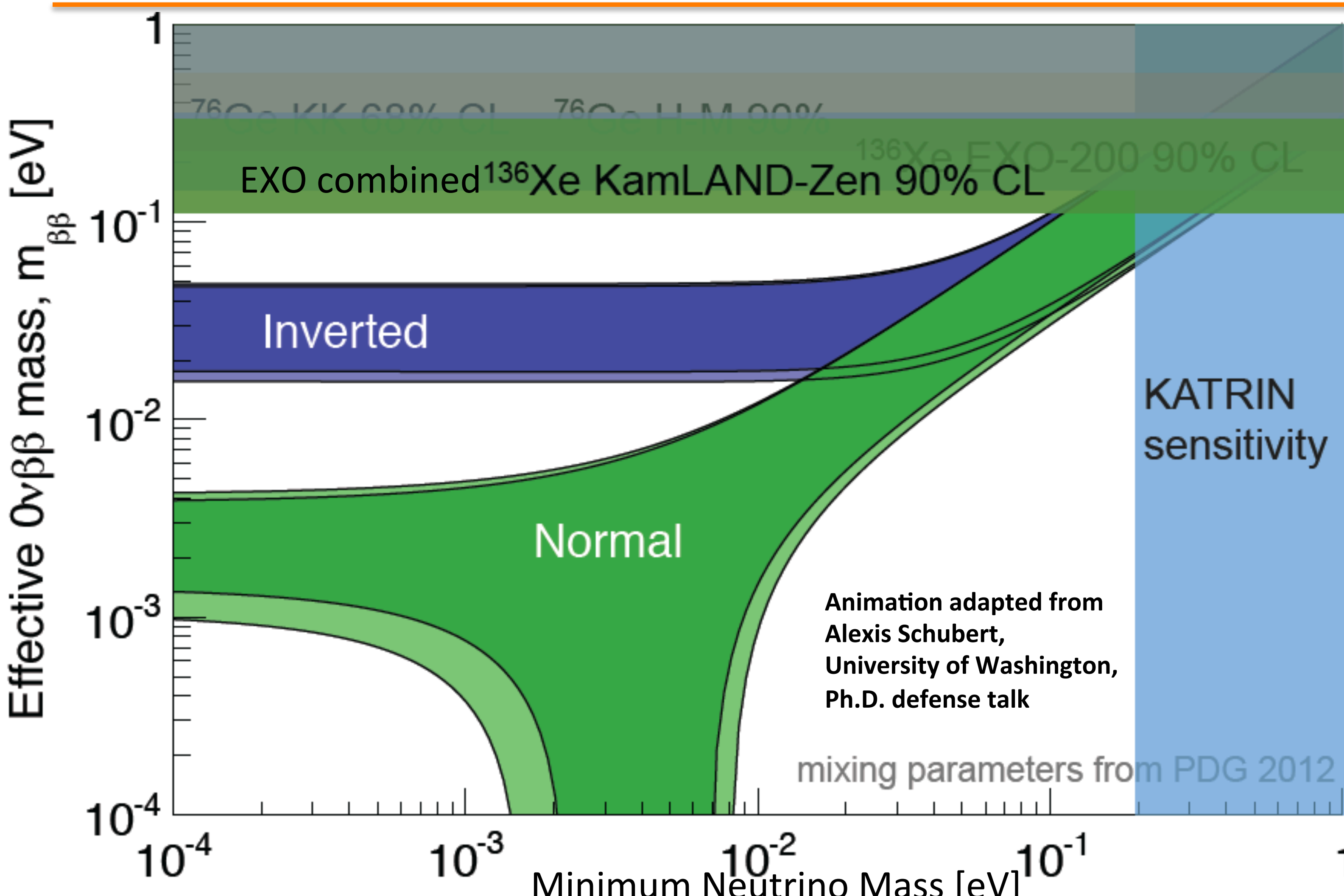


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Phys.Rev.Lett. 110, 062502 (2013)

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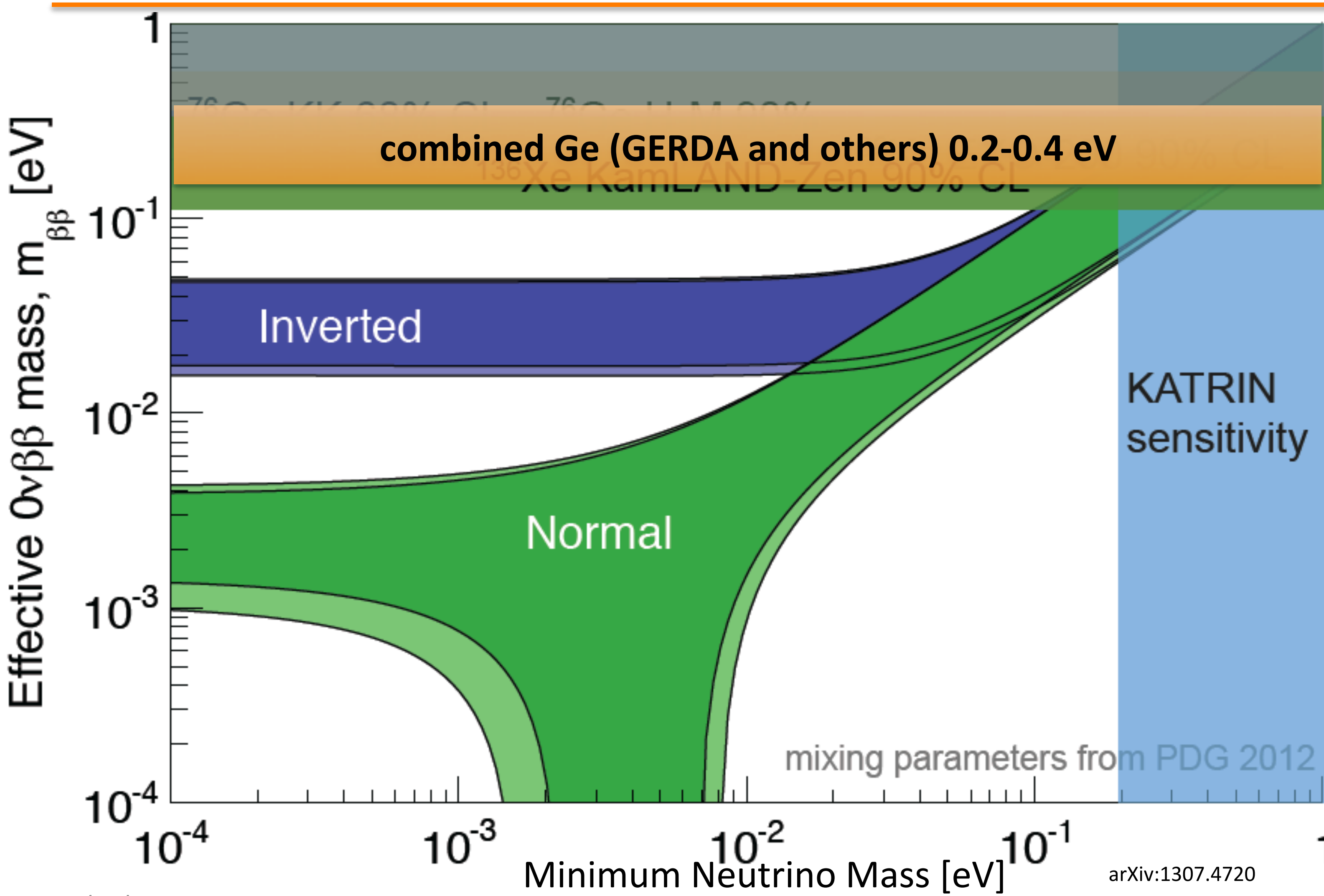


arXiv:1307.4720

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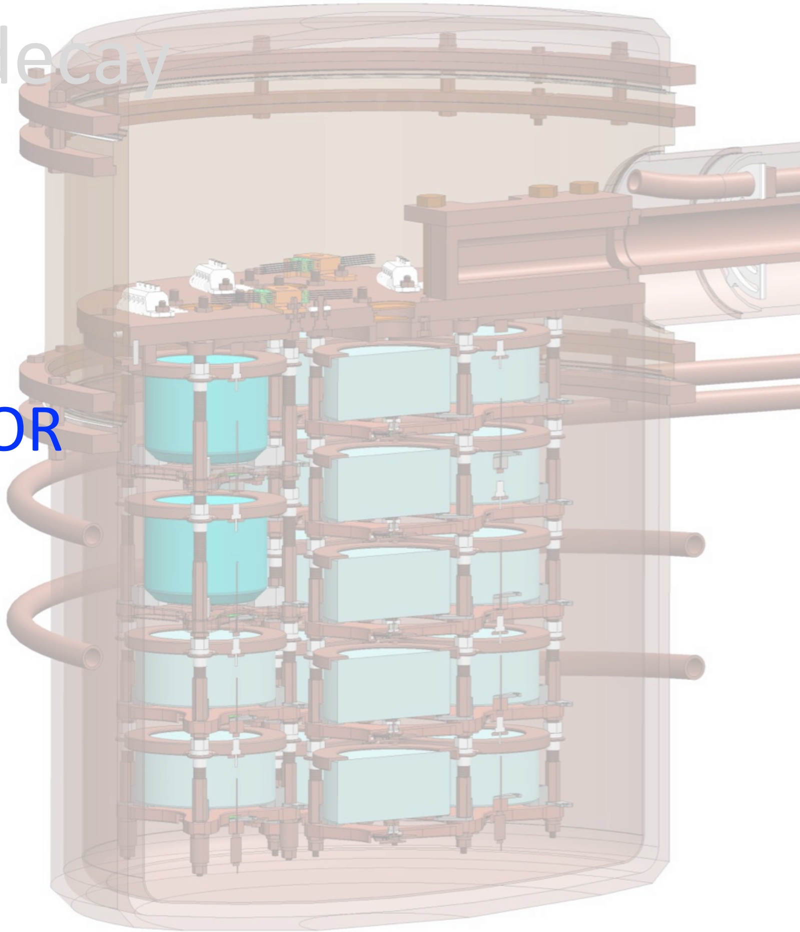
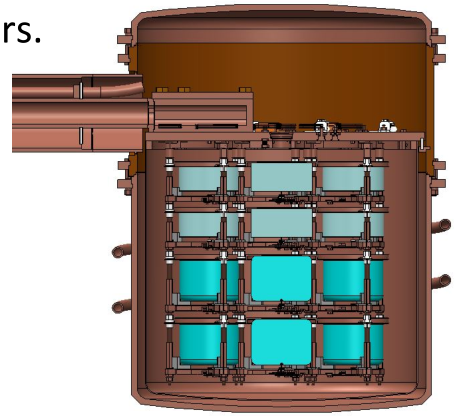


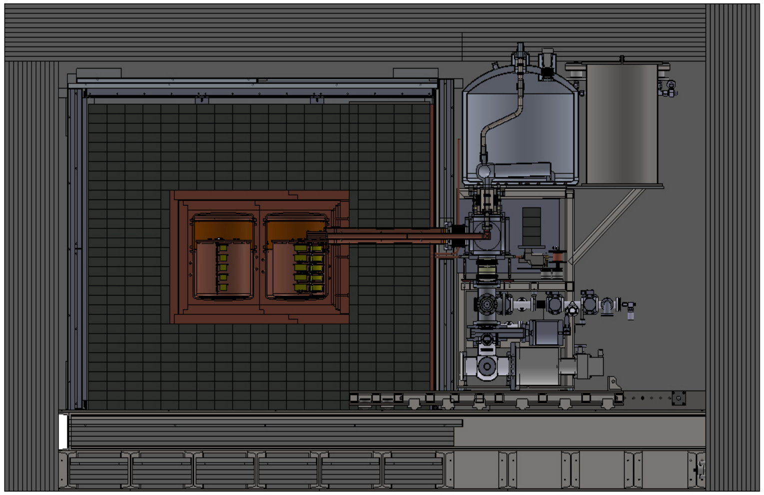
# The MAJORANA DEMONSTRATOR

Funded by DOE Office of Nuclear Physics and NSF Particle Astrophysics,
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.
- Test Klapdor-Kleingrothaus claim.
- Low-energy dark matter (light WIMPs, axions, ...) searches.

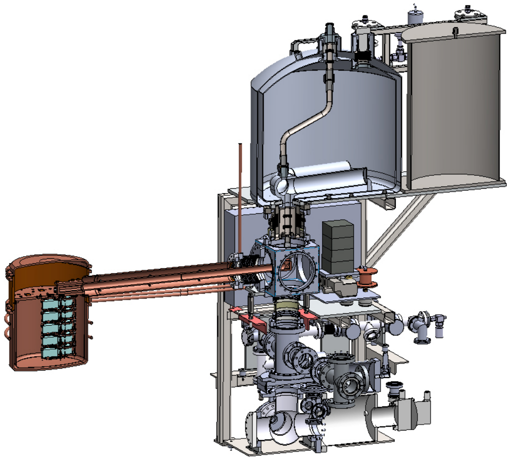


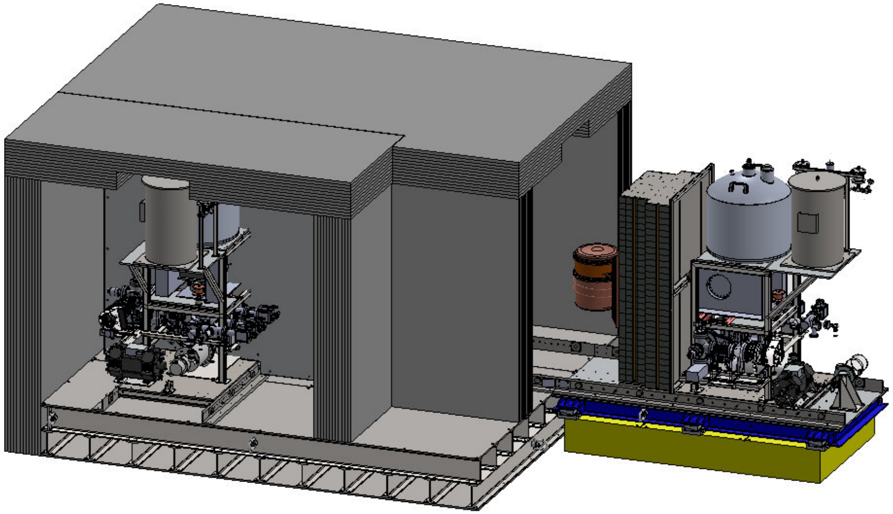
- Located underground at 4850' Sanford Underground Research Facility
- Background Goal in the 0νββ peak region of interest (4 keV at 2039 keV)
  3 counts/ROI/t/y (after analysis cuts)
  scales to 1 count/ROI/t/y for a tonne experiment
- 40-kg of Ge detectors
  - 30 kg of 86% enriched $^{76}$Ge crystals & 10 kg of $^{nat}$Ge
  - Detector Technology: P-type, point-contact.
- 2 independent cryostats
  - ultra-clean, electroformed Cu
  - 20 kg of detectors per cryostat
  - naturally scalable
- Compact Shield
  - low-background passive Cu and Pb shield with active muon veto



# MJD Implementation

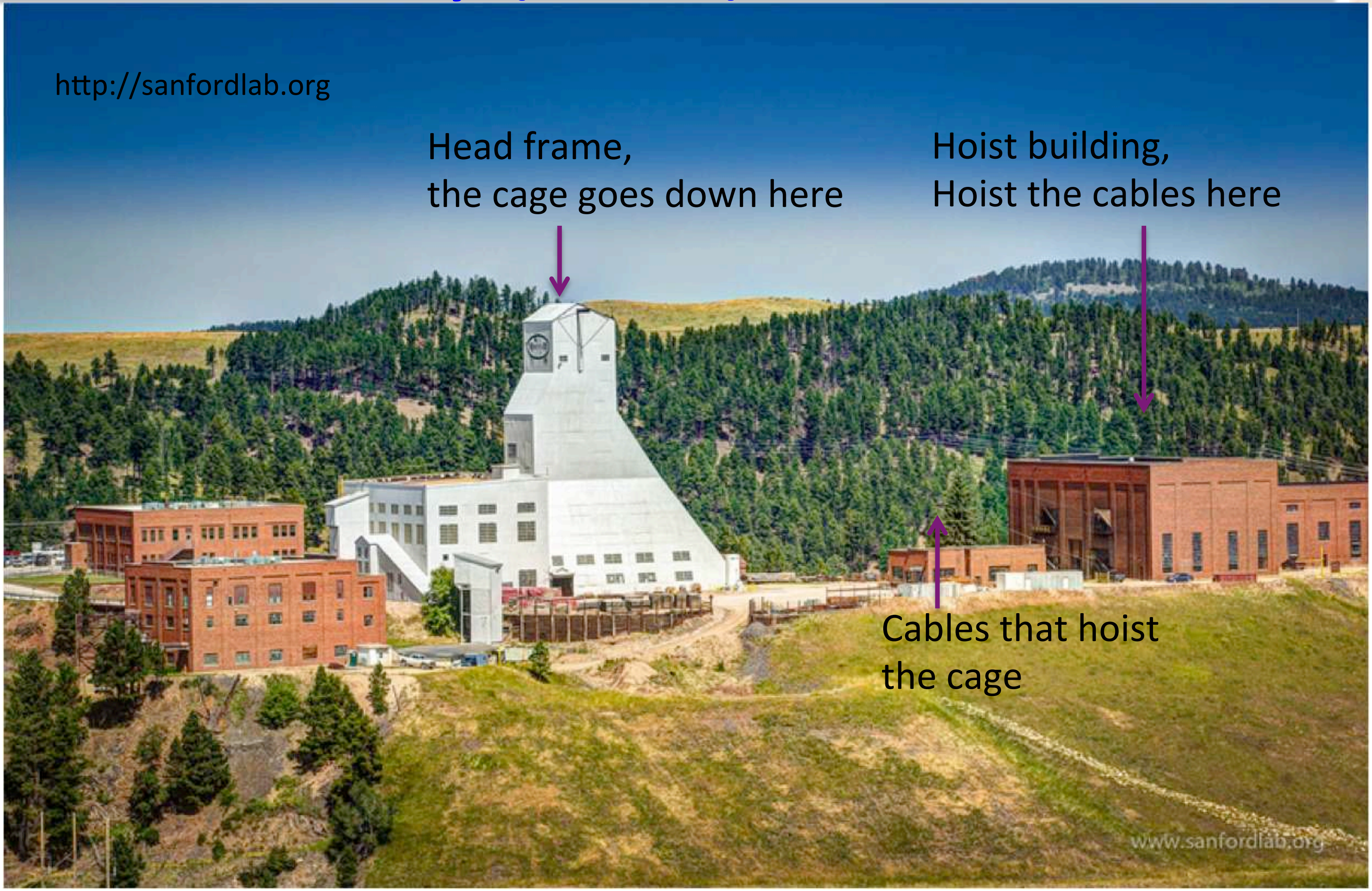
- Three Steps
  - Prototype Cryostat* (2 strings, $^{nat}Ge$)
  - Cryostat 1 (3 strings $^{enr}Ge$ & 4 strings $^{nat}Ge$)
  - Cryostat 2 (7 strings $^{enr}Ge$)





* Same design as Cryos 1 & 2, but fabricated using OFHC Cu (non-electroformed) components.

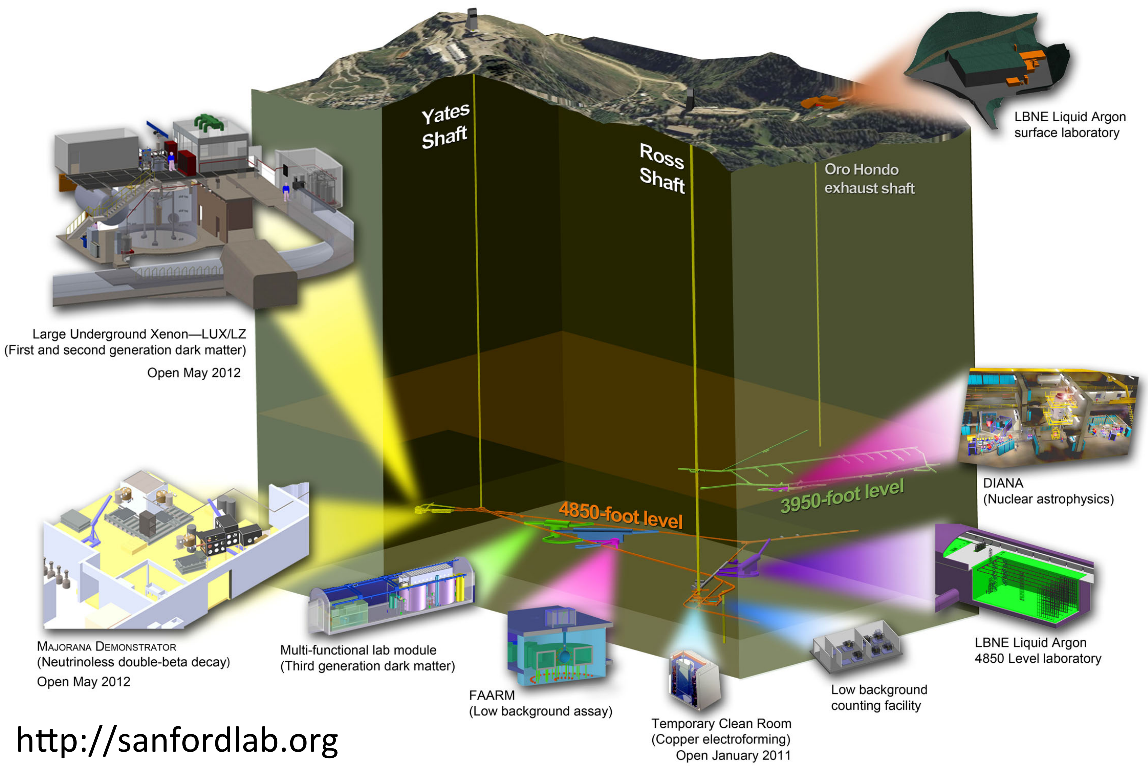
# Sanford Underground Research Facility (SURF), Lead, SD



# Sanford Underground Research Facility (SURF), Lead, SD

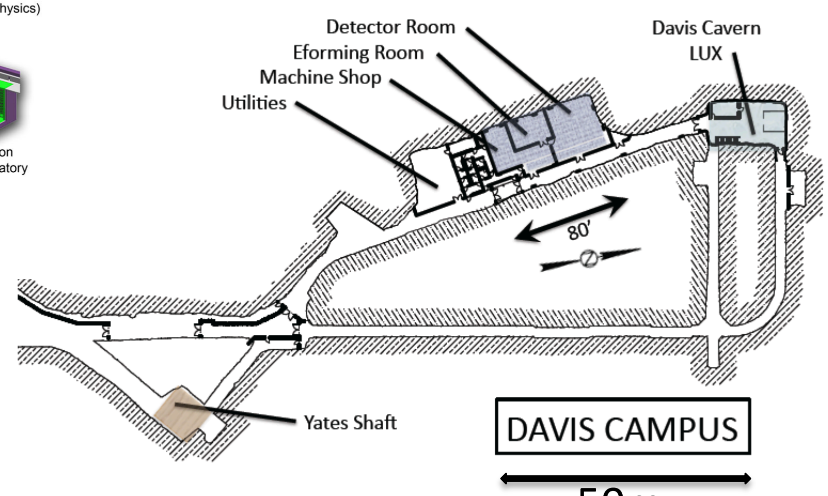
Photo Courtesy of R. Martin

# Sanford Underground Research Facility (SURF), Lead, SD

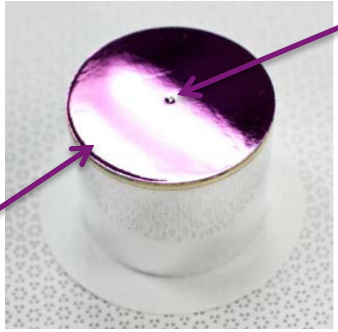



http://sanfordlab.org

4850 foot ~ 4260 m.w.e

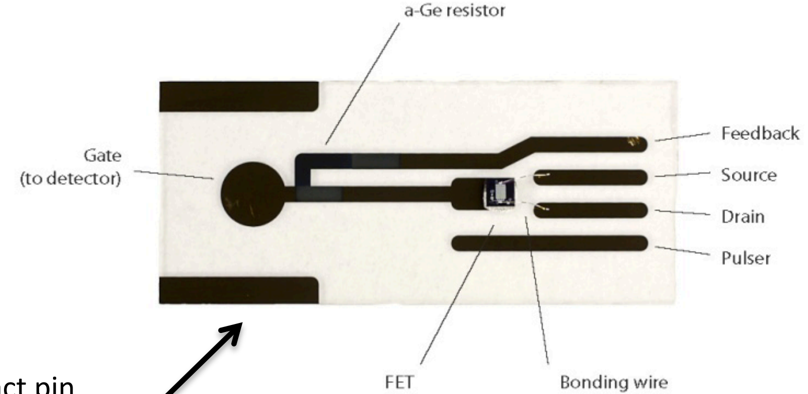


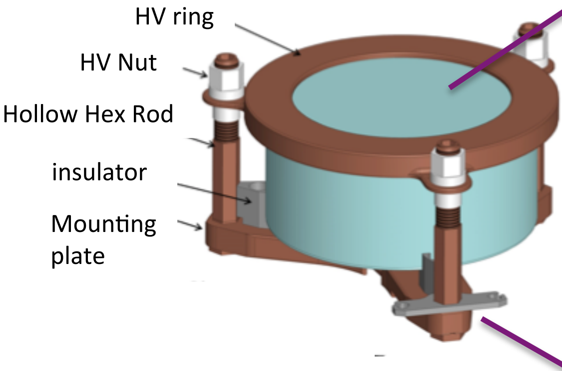
# Detector Unit Assemble

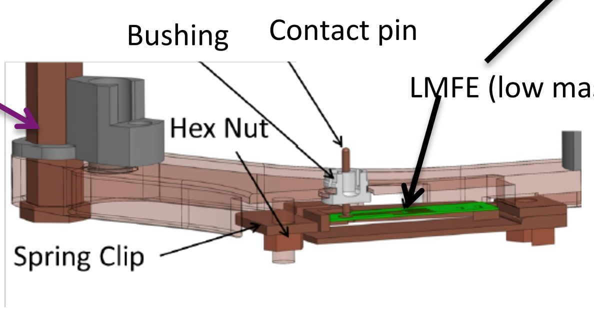


Point Contact Dimple,
the contact pin touches here

20.5mm x 7mm; total weight ~80mg



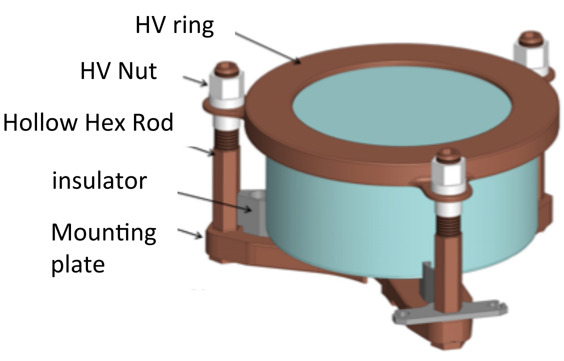

LMFE (low mass front end board)

Fused silica substrate

- Au-Cr traces
- Amorphous-Ge resistor
- Low background
- Low noise

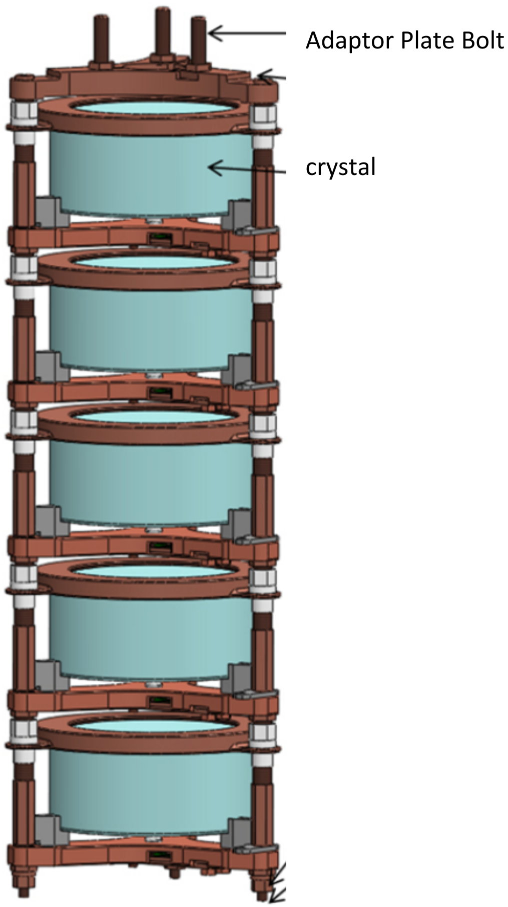
Natural or enriched
Ge crystal,
Detector unit

# Modular approach



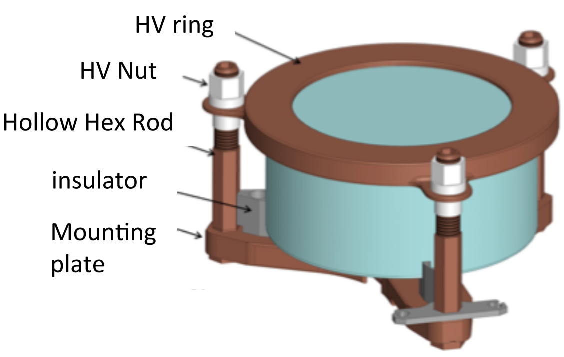

X 4 or 5

Natural or enriched
Ge crystal,
Detector unit



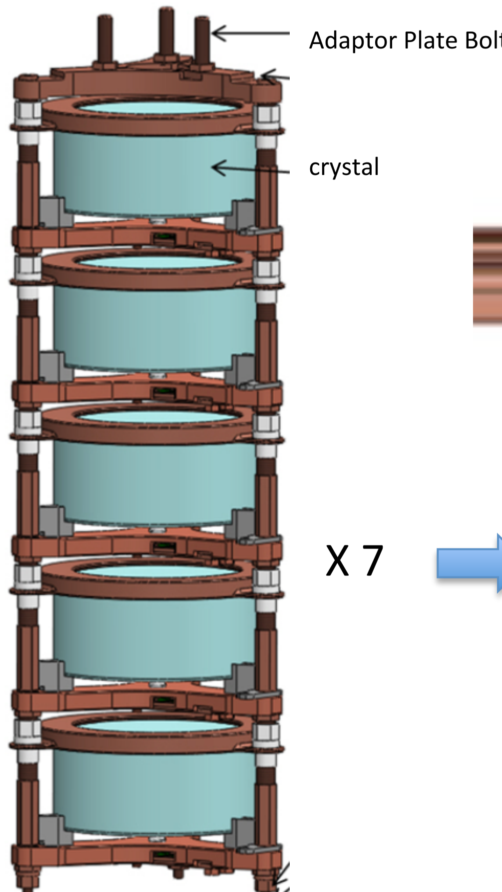

String assembly

# Modular approach



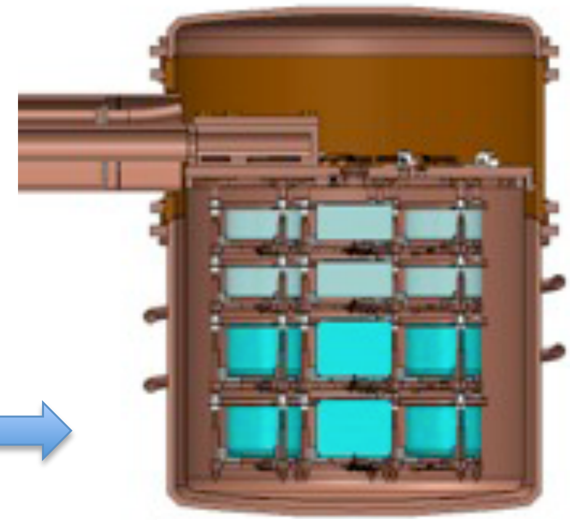

X 4 or 5

Natural or enriched Ge crystal, Detector unit



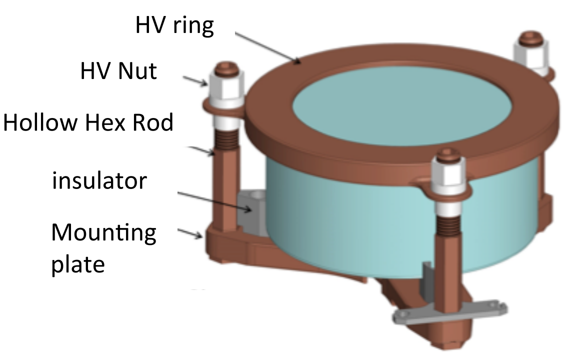

String assembly

X 7



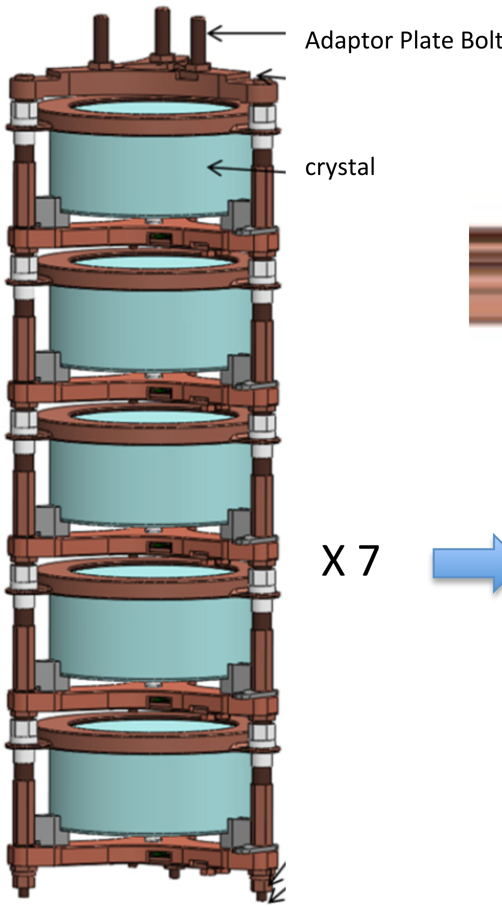
Module assembly in its own cryostat

# Modular approach



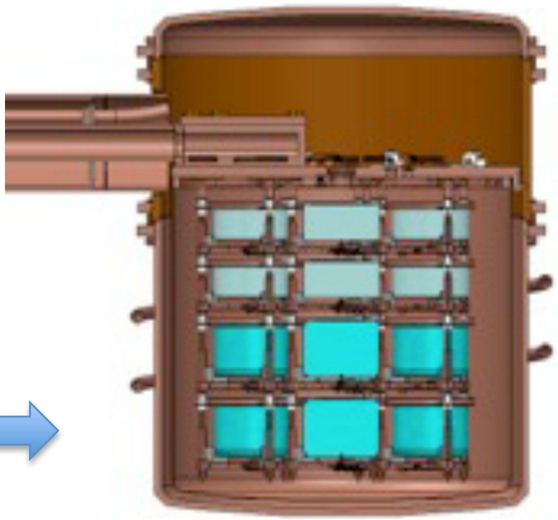

X 4 or 5

Natural or enriched
Ge crystal,
Detector unit




String assembly

X 7

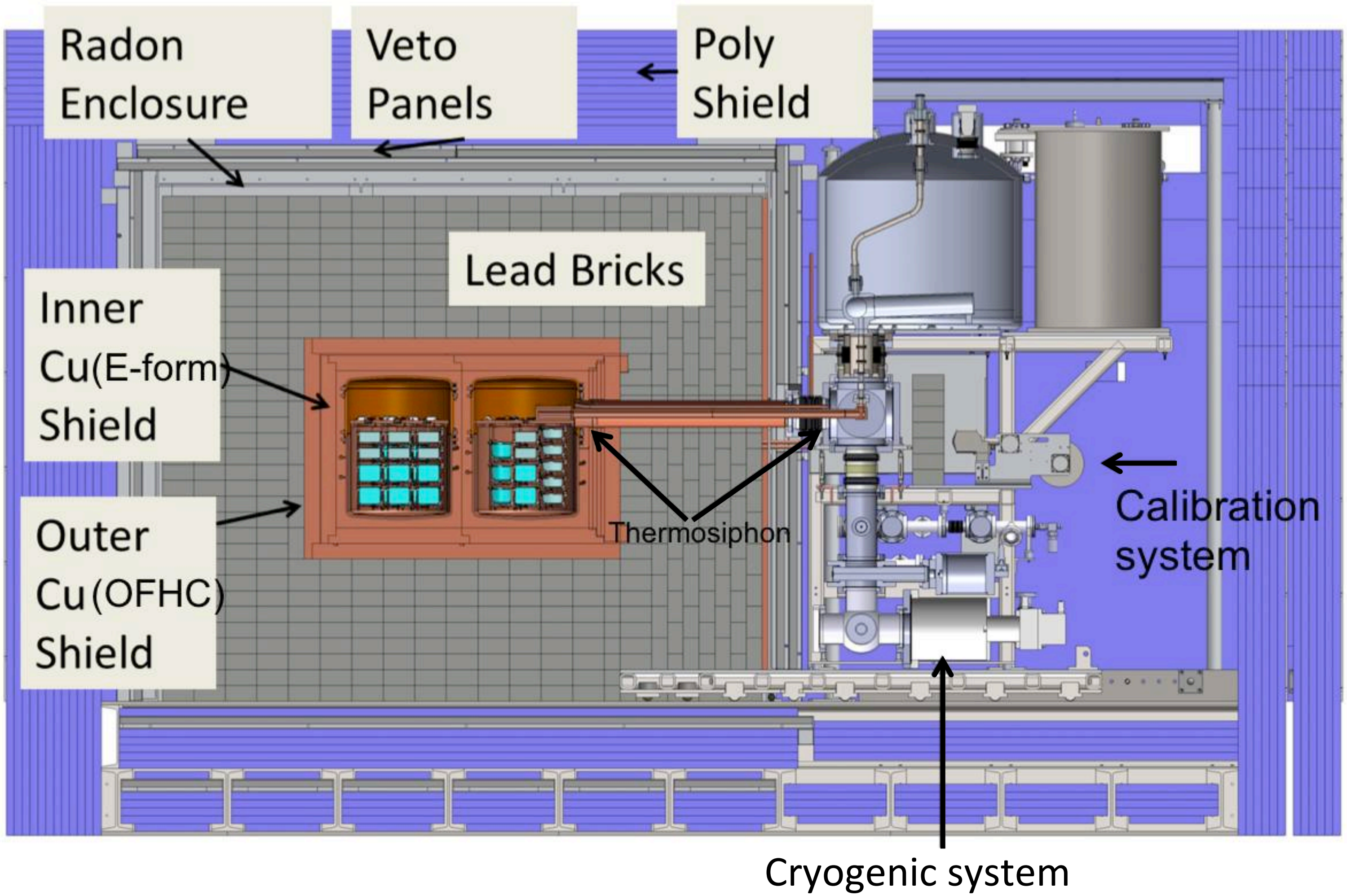


Module assembly
in its own cryostat

X 2

The Demonstrator

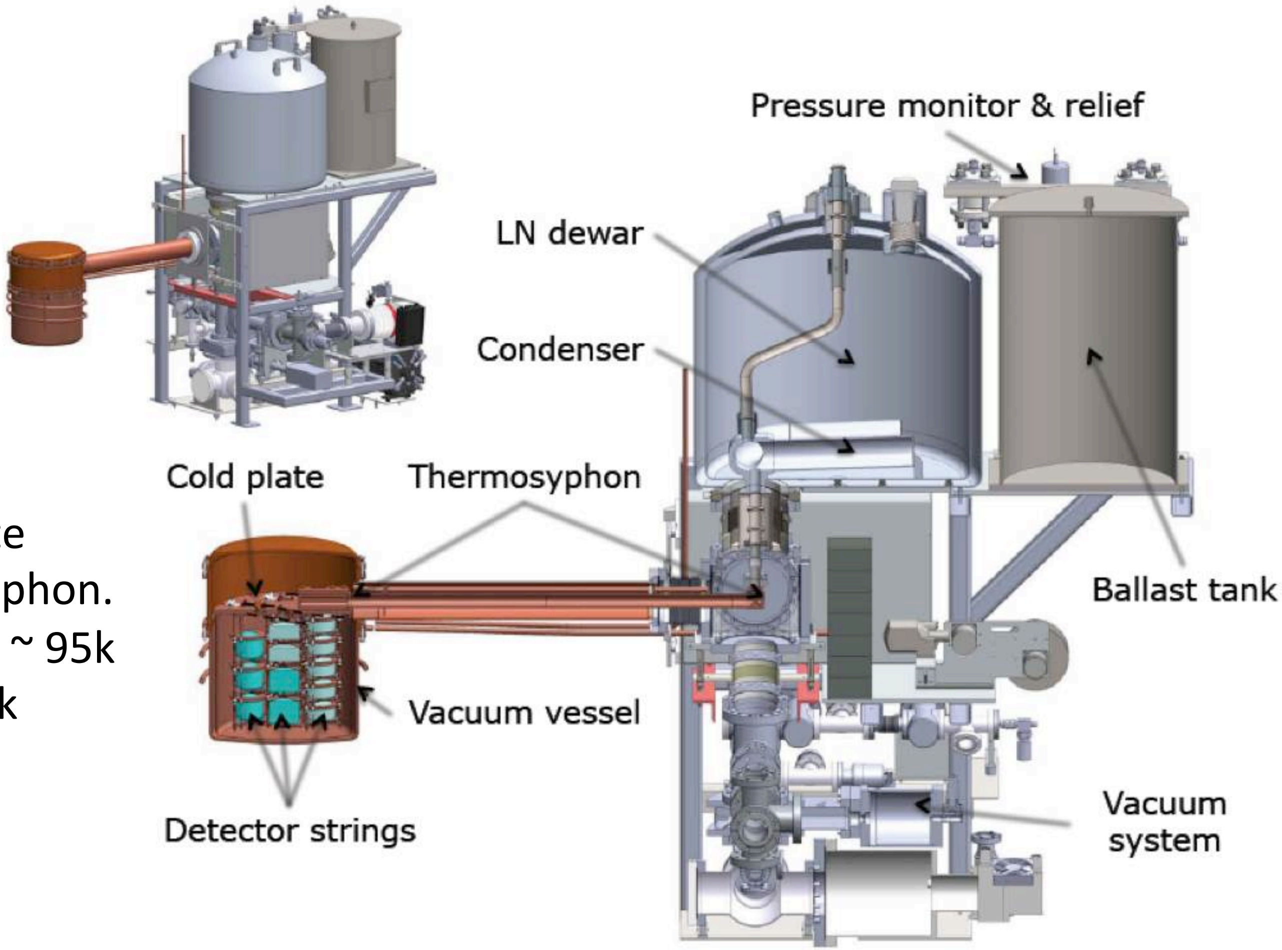
# The shielding




The veto panels (scintillating acrylic 2 layers, 2.54cm): active shielding.

The others are passive:
Poly shield - 30cm;
Radon enclosure - 0.32-0.635cm Al (purged with $N_2$);
Lead - 45 cm;
Outer Cu - 5 cm;
Inner Cu 4 layers - 1.25 cm each.

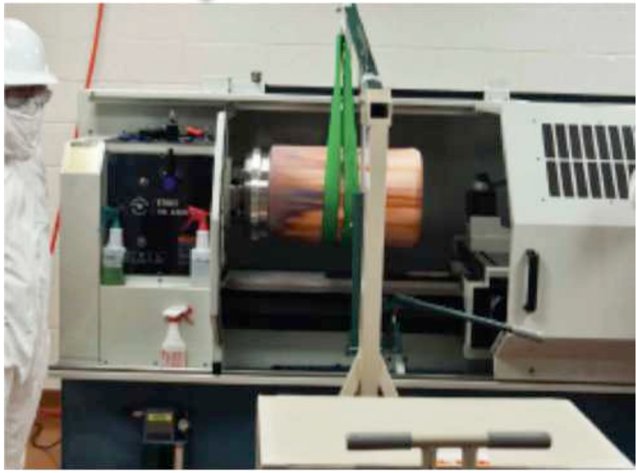
# Cryogenic System




Cooling to the cold plate provided by a thermosiphon.
Detectors temperature ~ 95k
FET temperature ~ 150k (self-heating)

# Electroformed copper (EFCu)

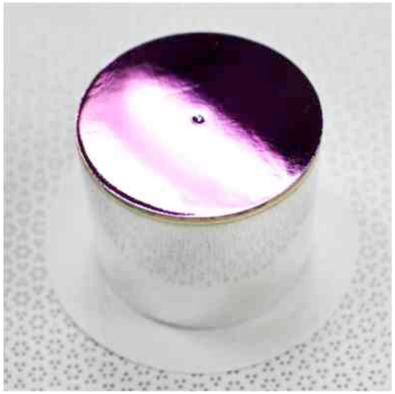

Max thickness 1.40cm

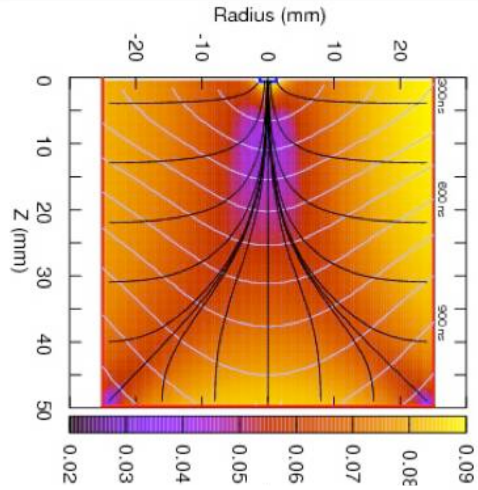


Assay results for e-form copper $^{232}$Th: 0.7 ± 0.3 μBq/kg. $^{238}$U: <1.3 μBq/kg

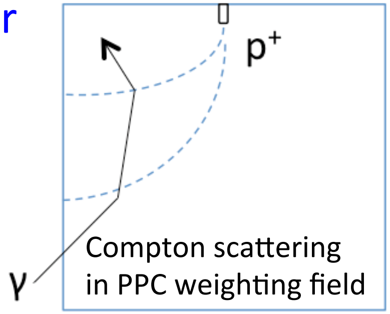
One order of magnitude better than the cleanest commercial copper

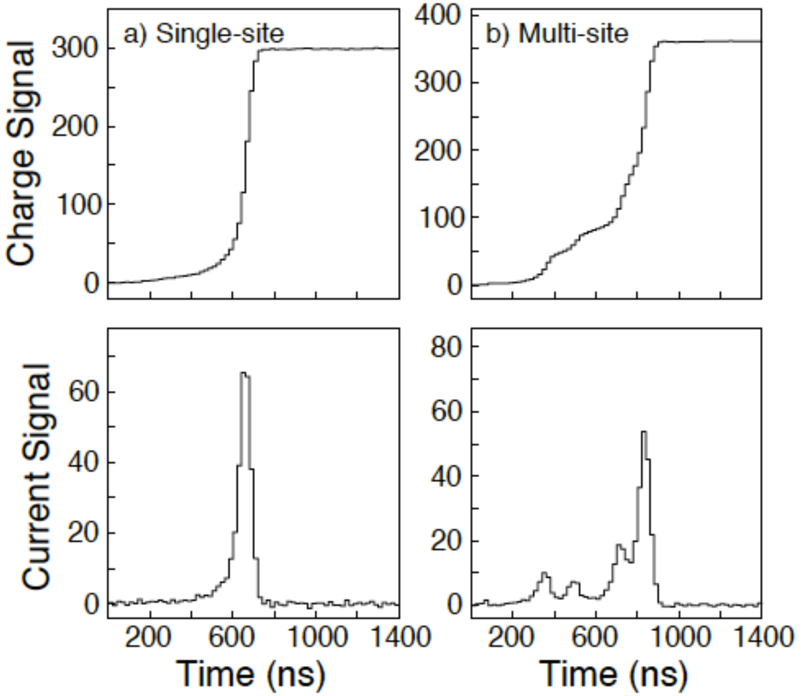
# Point Contact Detector






P-type Point Contact Detector (PPC)




Pulse-Shape-Discrimination (PSD)

Point Contact Detector:

- Relatively low electrical fields
- Larger time spreads for spatially distinct energy depositions
- Crucial in distinguishing multi-site γ background from single-site β signals

# Pulse-Shape-Discrimination

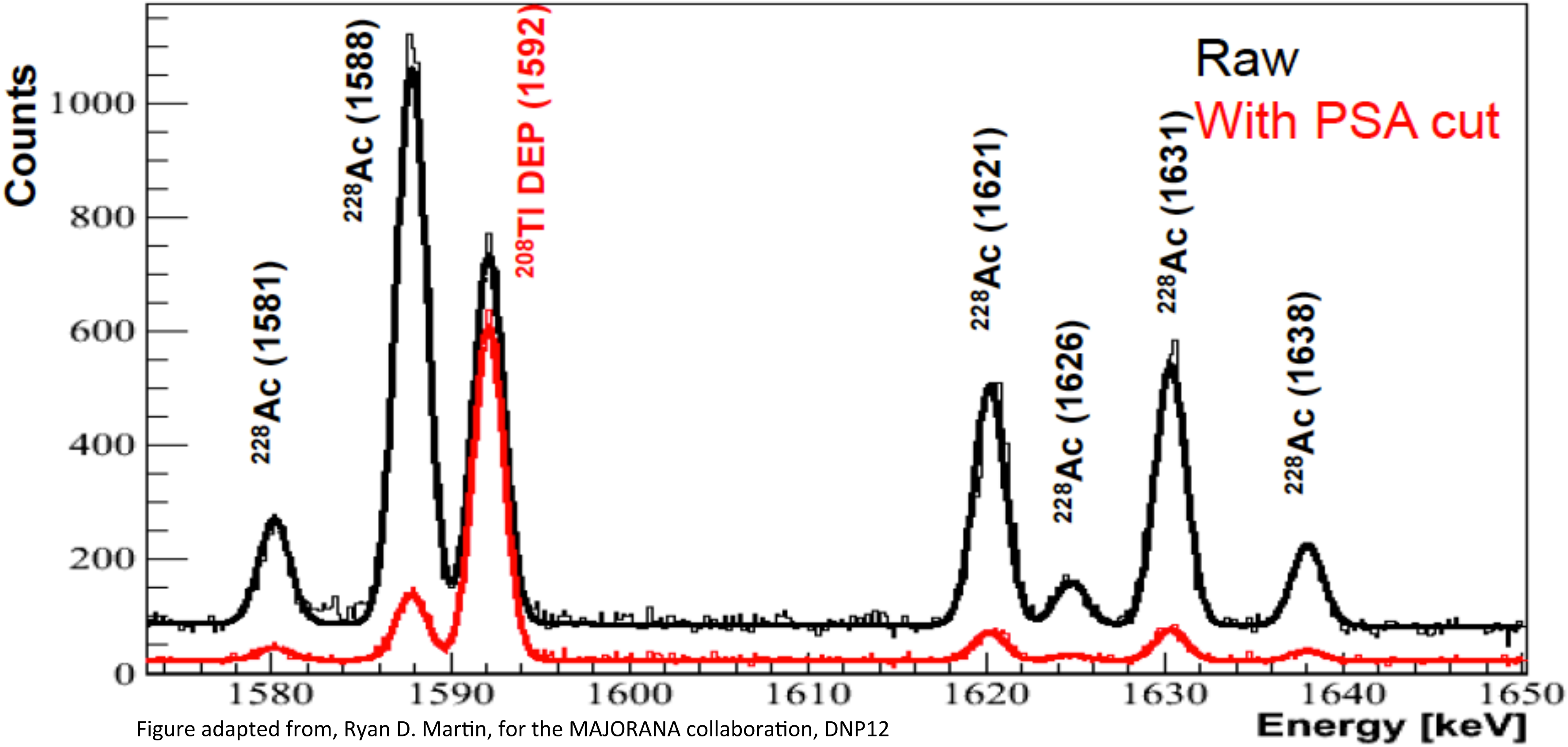



Figure adapted from, Ryan D. Martin, for the MAJORANA collaboration, DNP12

Retain 90% Double Escape Peak: single-site events, similar to $0\nu\beta\beta$ and $2\nu\beta\beta$

Reject 89% Full Energy Peaks: multi-site events, background-like

# Low background is the key

**Natural radioactivity:**

- **Pure material** (e.g. EFCu, clean plastic and others)
- **Shielding**
- **Analysis cuts** (PSD, granularity cuts)

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- **Deep underground**
- **Muon veto**

Combined efficiency of two layers of veto panel~99.9%,
Un-vetoed direct muon background<0.03 counts/ROI/t/y.

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- **Limit surface time of Ge** (shielded shipping and storage)

# Low background is the key

Delivery of enriched $GeO_2$
from Russia to Oak Ridge
~1 month by sea

- **Limit surface time of Ge** (shielded shipping and storage)

# Low background is the key

**Natural radioactivity:**

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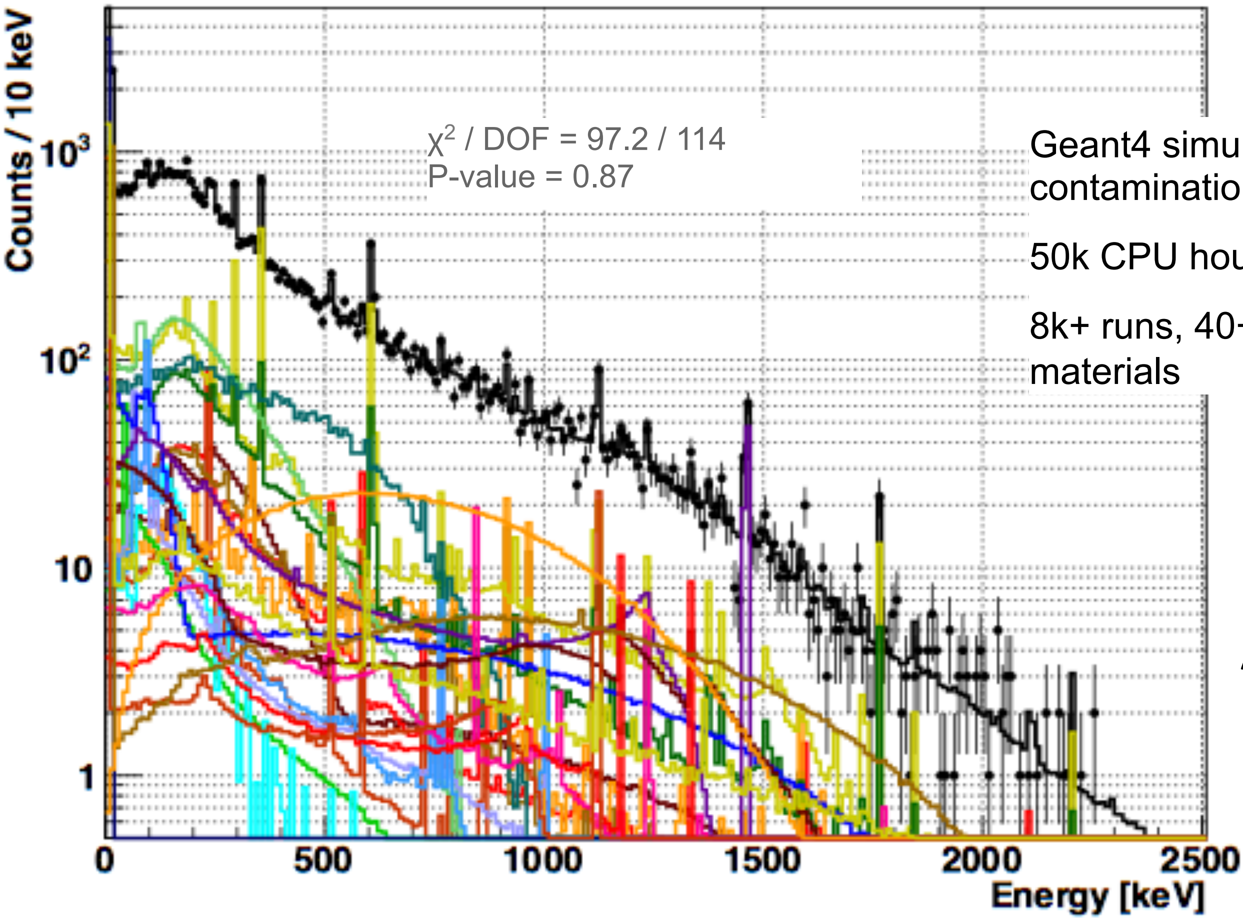
- **Limit surface time of Ge** (shielded shipping and storage)
- **E-form Cu underground**
- **Analysis cuts** $^{68}$Ge tag Single-Site Time Correlation Cut

# Background model fit of R&D Detector (MALBEK)




Geant4 simulations to determine efficiencies for contamination to deposit energy in our detectors

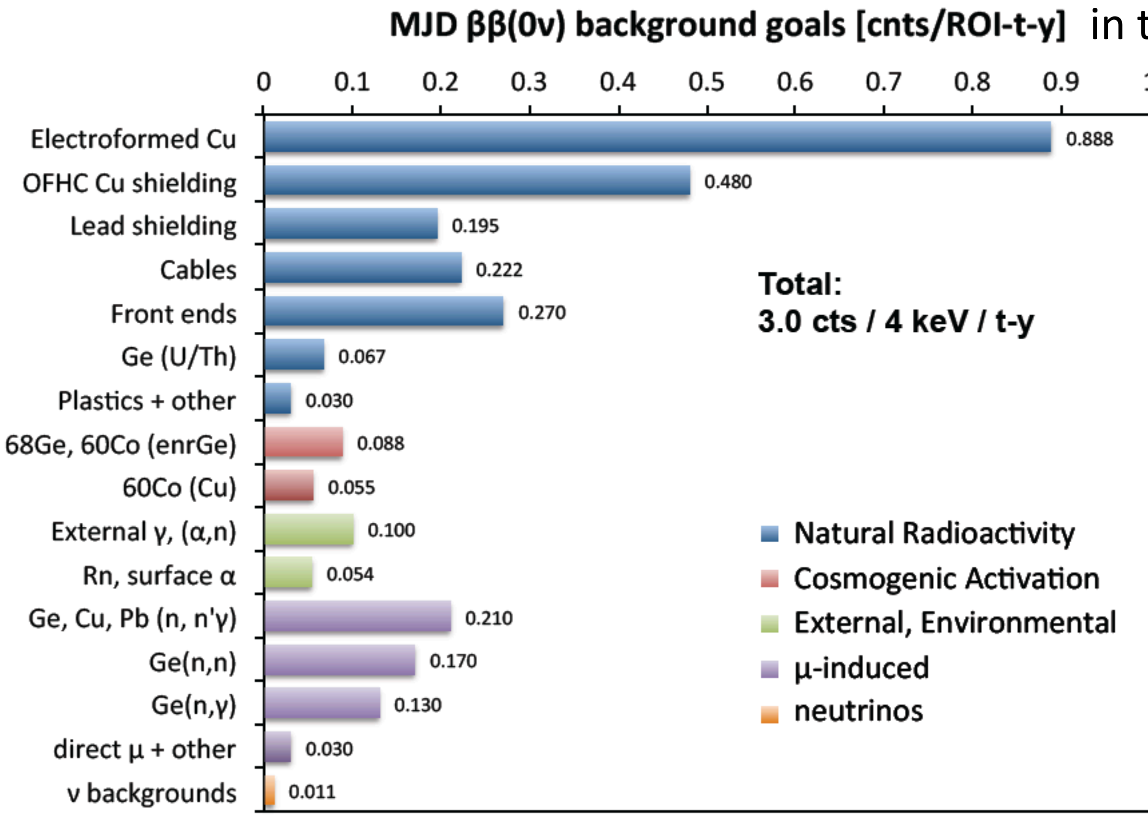
50k CPU hours

8k+ runs, 40+ contaminants, 56 components, 21 materials

A. Schubert,
Univ. Washington,
PhD Dec. 2012

# **DEMONSTRATOR background budget**

Based on assays of materials being used in MJD




in the 4keV Region of Interest near 2039keV

$2\nu\beta\beta$ background is negligible due to excellent energy resolution

# Simulated Background near $Q_{\beta\beta}$ after all cuts

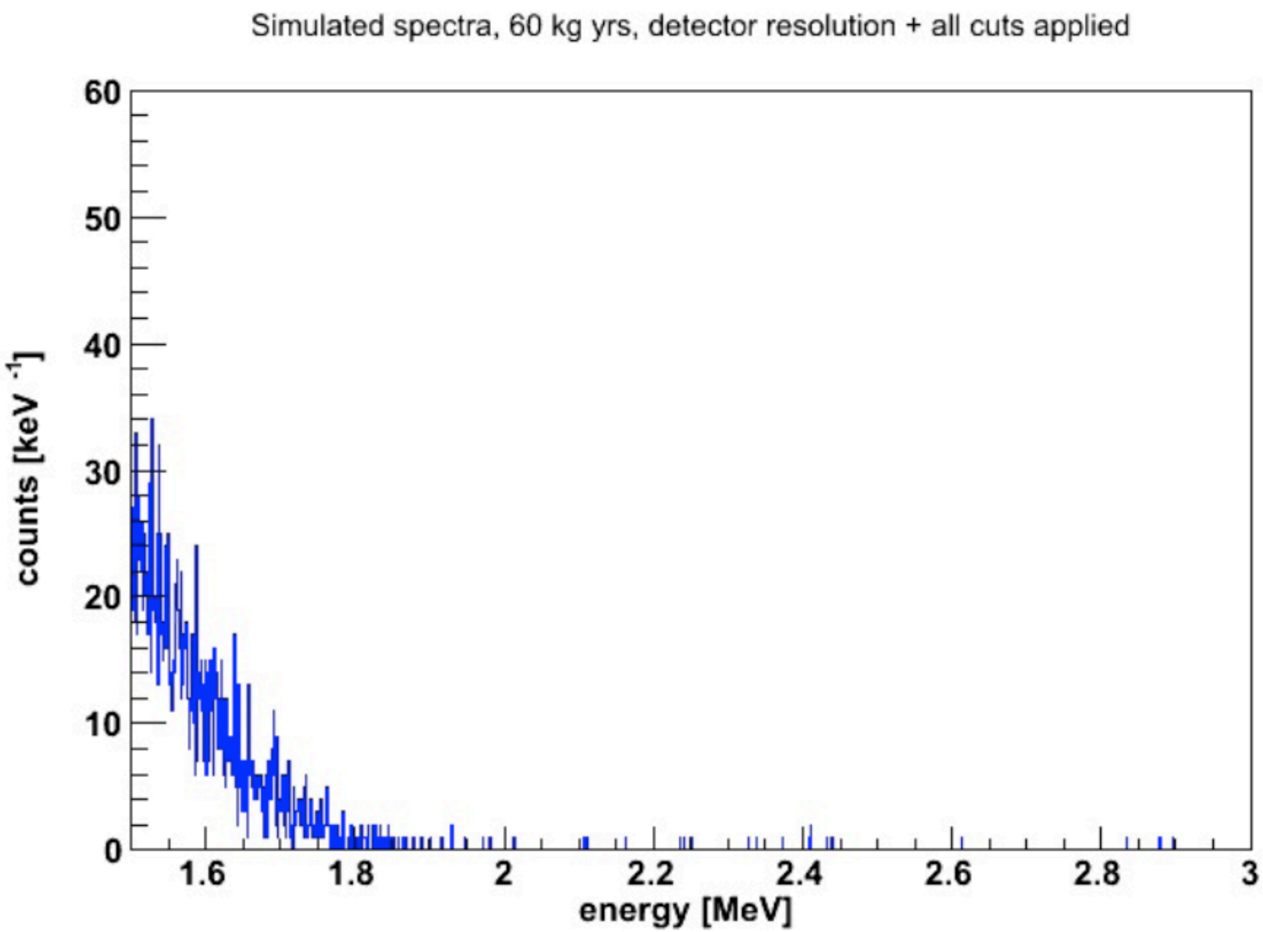
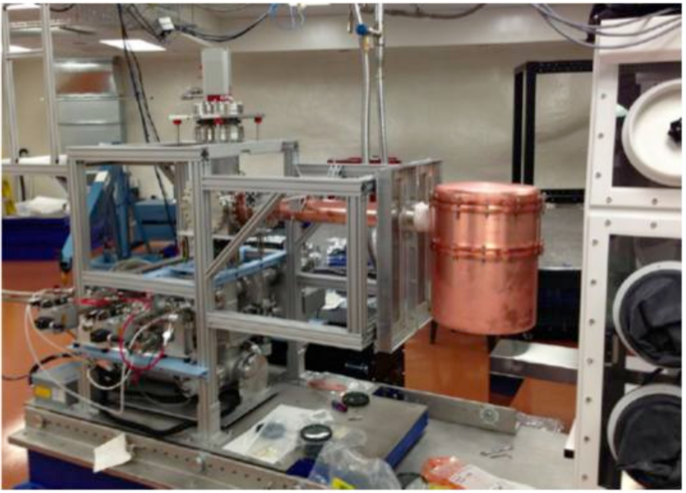
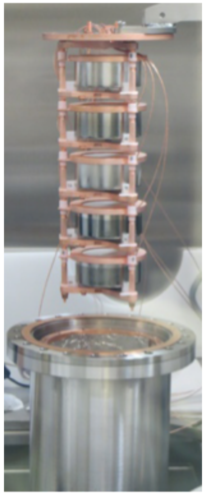



Figure adapted from
J.F.Wilkerson,
DOE ONP Comparative Review
June 25, 2013

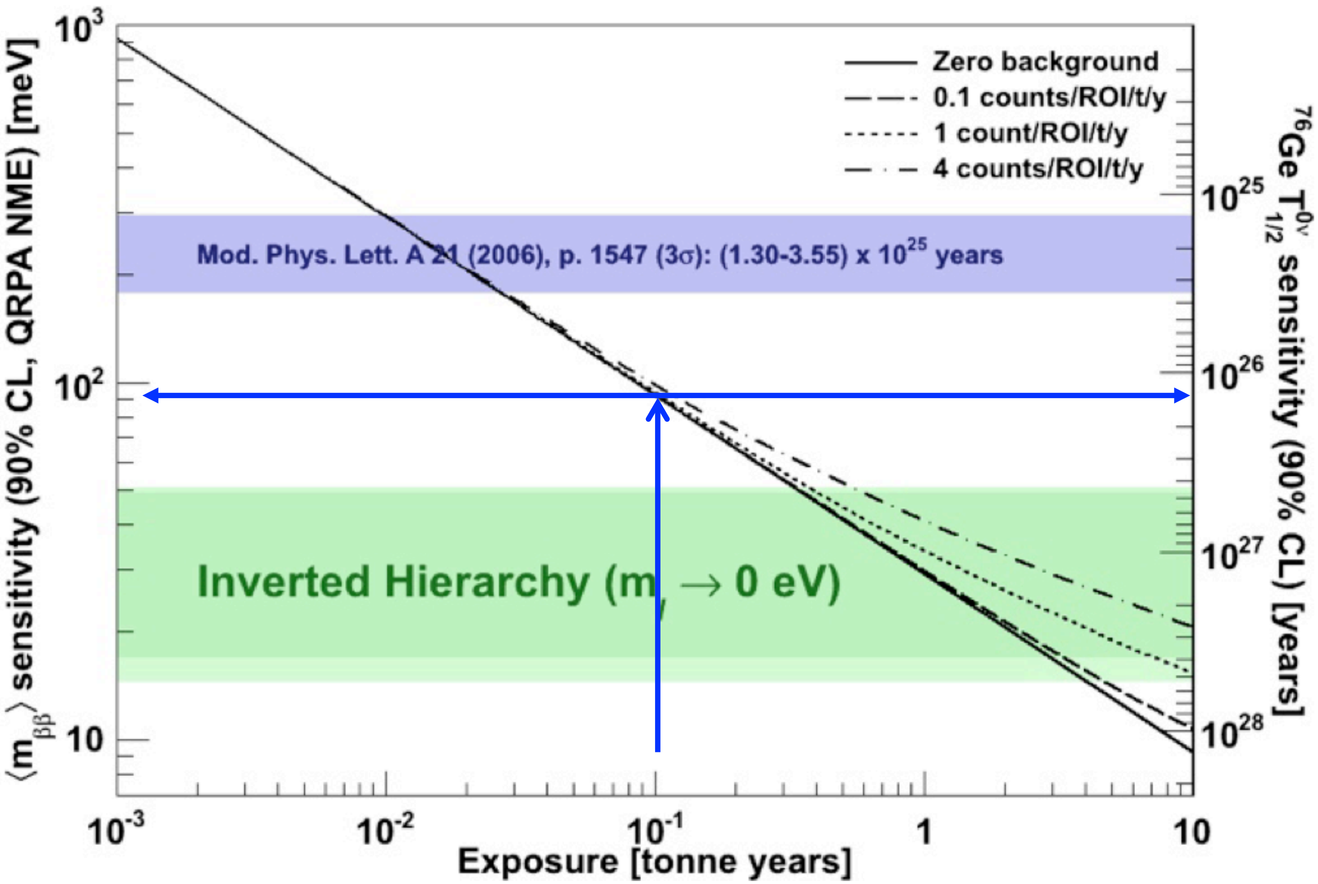
# DEMONSTRATOR Status





- ✓ Infrastructure and cleanliness established
- ✓ Assayed all materials
- ✓ 75% required e-form copper produced
- ✓ 42.5 kg of 86% enriched 76Ge procured, refined to electronic grade with a 98% yield
- ✓ Accepted 10 enriched Ge det., 9.5kg in total
- ✓ Built two strings of natural Ge detectors built
- ✓ Fabricated prototype cryostat
- ✓ Built the associated vacuum system
- ✓ Shield construction in progress
- ✓ SlowControl and DAQ in use

# DEMONSTRATOR schedule



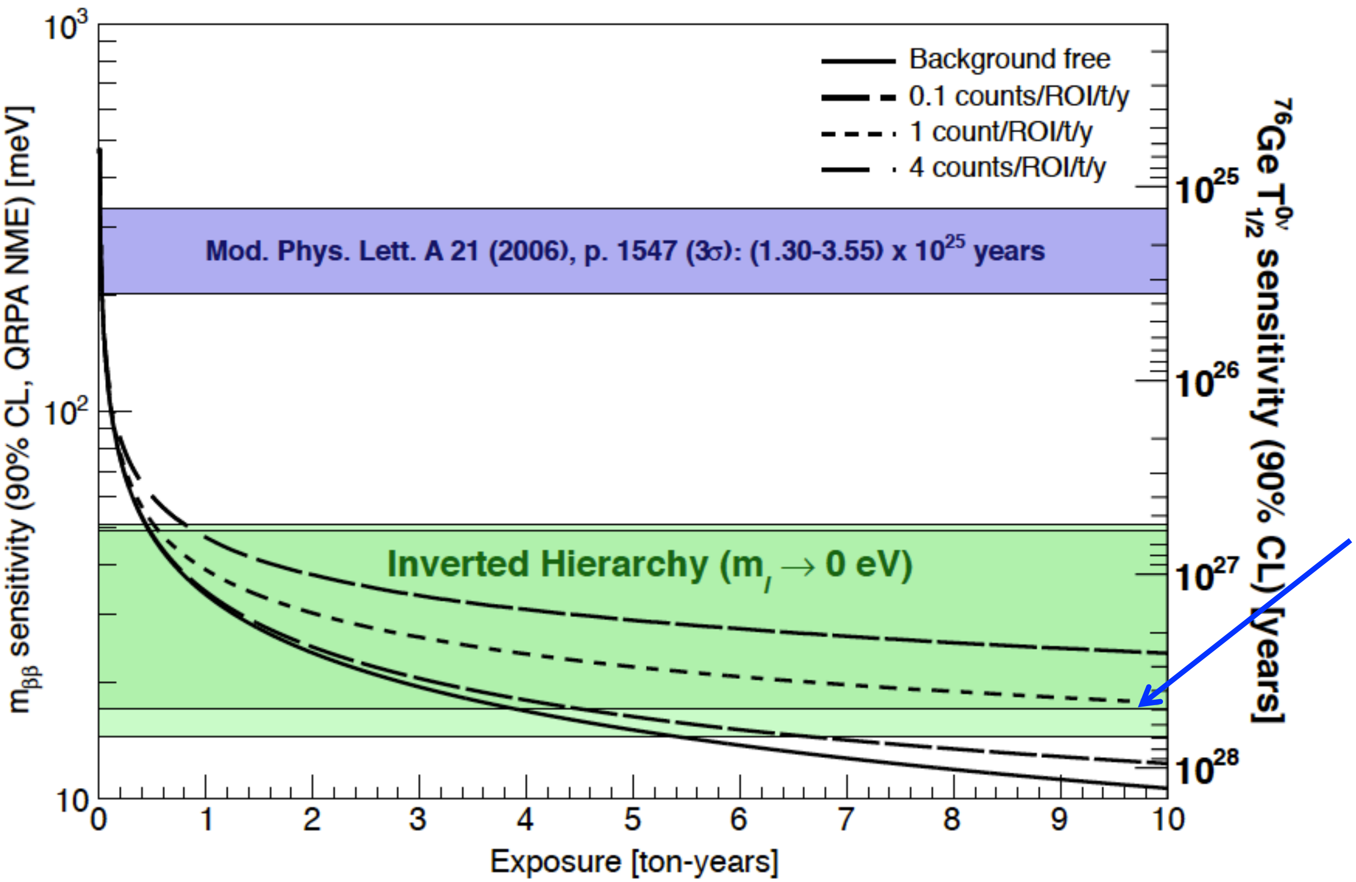

Prototype Cryostat:
summer 2013

Cryostat 1:
end of 2013

Cryostat 2:
end of 2014

Run for 3 years,
exposure~100kg*y
Sensitive to T ~ $10^{27}$ years

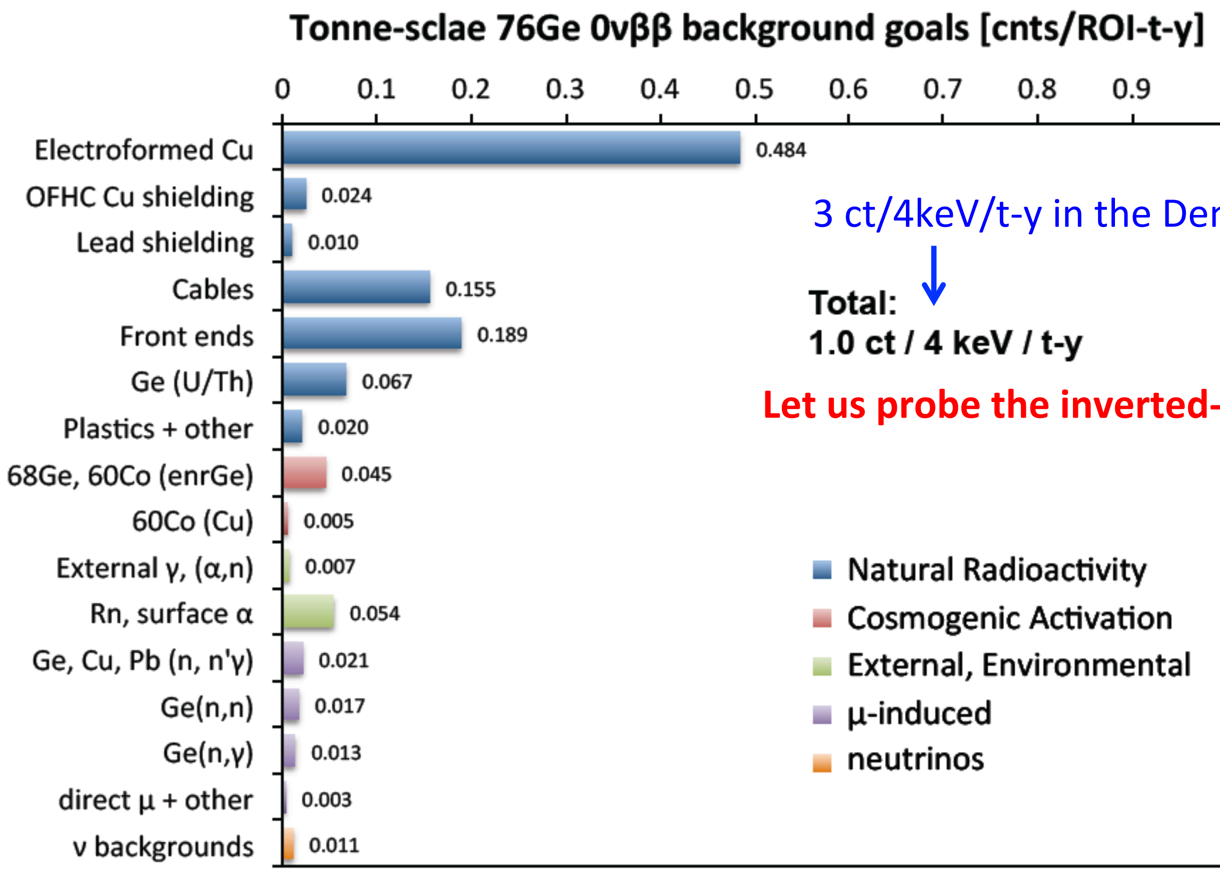
# Tonne scale sensitivity




Aim for background < 1count/ROI/t/y to probe the entire inverted-hierarchy region in a practical time period

# Background Projection for Tonne-scale

***Scaling from MJD projects***




3 ct/4keV/t-y in the Demonstrator

**Total:**
**1.0 ct / 4 keV / t-y**

**Let us probe the inverted-hierarchy region**

# The MAJORANA Collaboration

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*Duke University, Durham, North Carolina , and TUNL*
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Alexander Barabash, Sergey Konovalov, Vladimir Yumatov

*Joint Institute for Nuclear Research, Dubna, Russia*
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Frank Avignone, Vince Guiseppe, Clint Wiseman

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Nathan Snyder

*University of Tennessee, Knoxville, Tennessee*
Yuri Efremenko, Sergey Vasilyev

*University of Washington, Seattle, Washington*
Tom Burritt, Clara Cuesta, Jason Detwiler, Peter J. Doe, Julieta Gruszko, Greg Harper,
Jonathan Leon, David Peterson, R. G. Hamish Robertson, Alexis Schubert, Tim Van Wechel

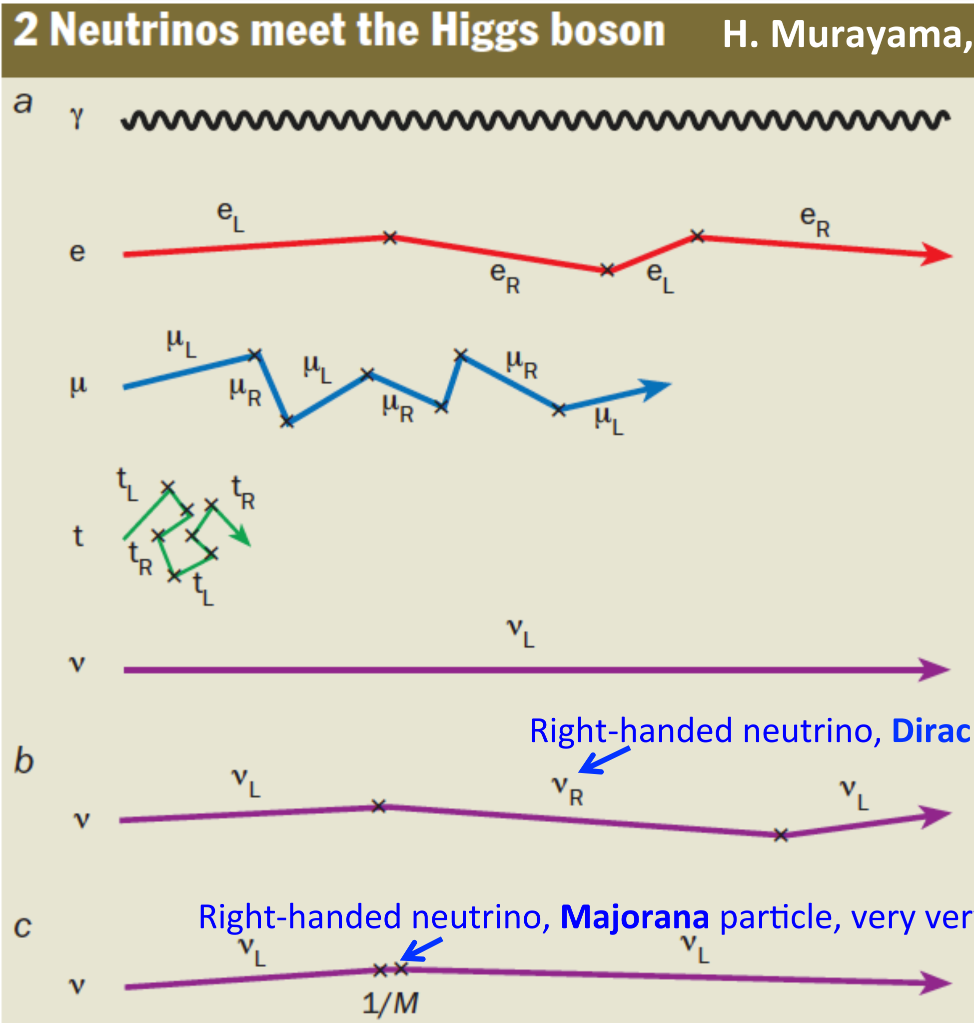

HOMESTAKE


# The END

**THANK YOU!**

# backup

# Seesaw mechanism: one motivation for majorana neutrinos




H. Murayama, **Physics World, May 2002**

Photons do not interact with Higgs, no mass

Other particles collider with Higgs, flipping the handedness, acquiring masses

No right-handed neutrino, so no coupling to H. Neutrinos having zero mass. Excluded

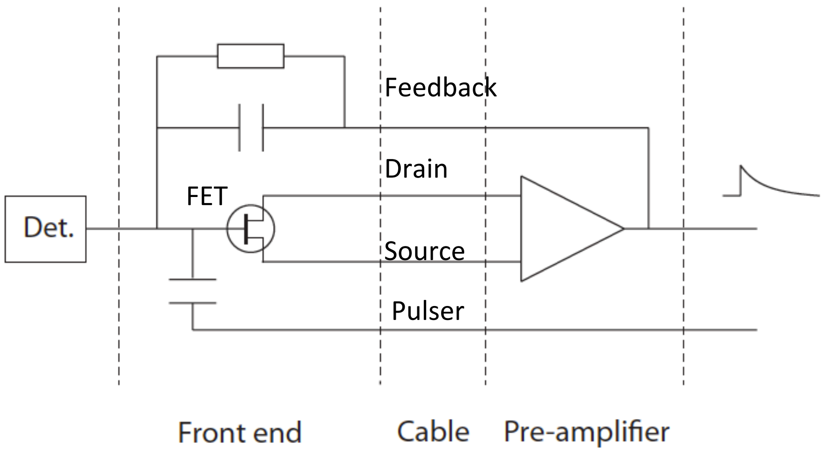
Right-handed neutrino, **Dirac** particle, similar mass, very very weak coupling to Higgs

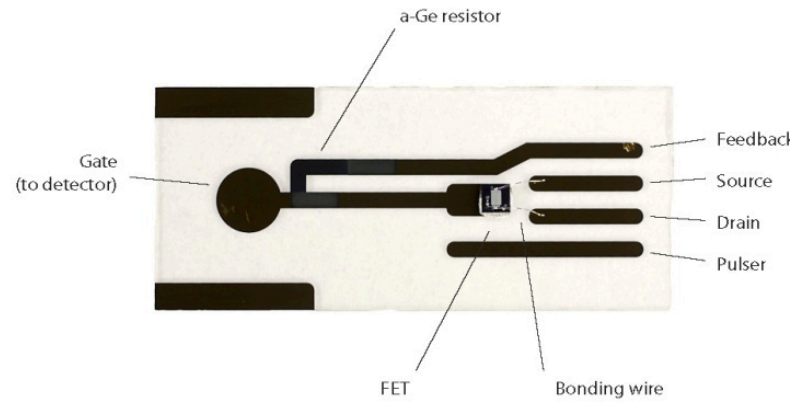
Neutrinos having Dirac masses.
Why the interactions of $\nu_R$ are so weak?

Right-handed neutrino, **Majorana** particle, very very heavy mass, can only exist here due to uncertainty principle

Neutrinos having Majorana masses.
No need for very very weak interactions

# Low Mass Front End

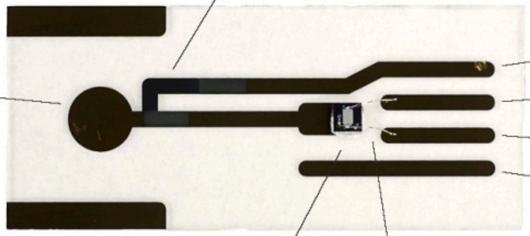



Fused silica substrate
- Au-Cr traces
- Amorphous-Ge resistor
- Low background
- Low noise

Self heating
Temperature can be Controlled by Drain to Source Voltage

# Low Mass Front End



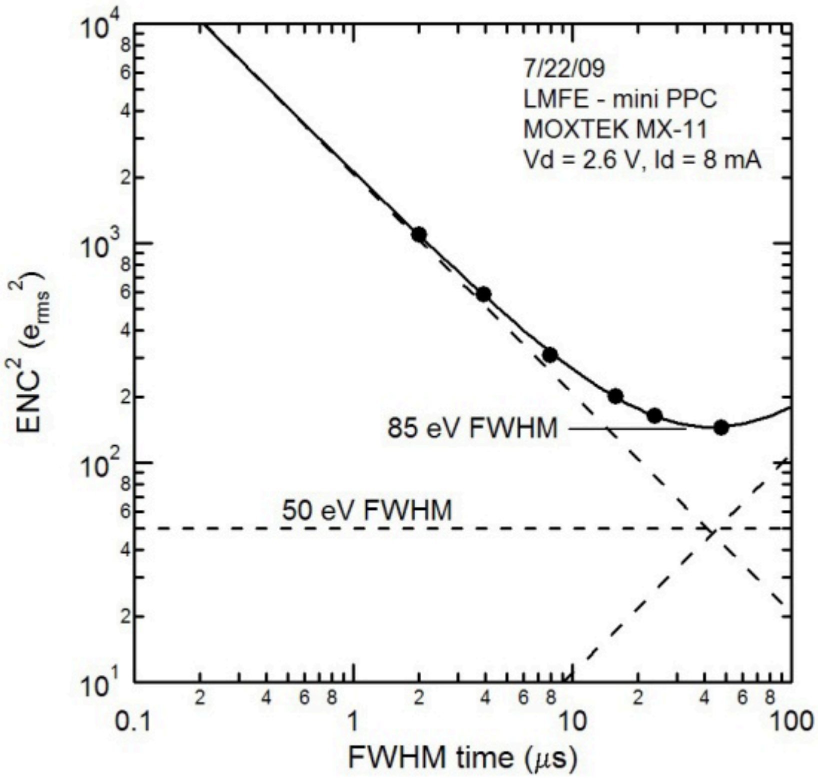

Fused silica substrate
- Au-Cr traces
- Amorphous-Ge resistor
- **Low background**
- Low noise

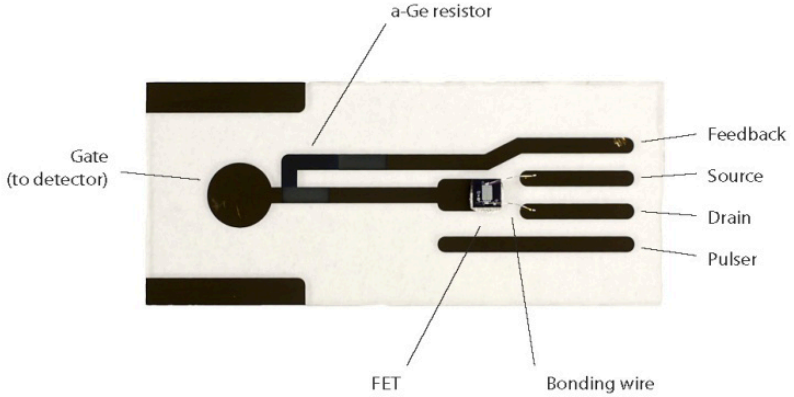
All material are selected to have low radioactivity

| Component | Material | Purity (g / g) | | Counts / ROI / t / y | | Ref. |
|---|---|---|---|---|---|---|
| | | $^{232}$Th | $^{238}$U | $^{232}$Th | $^{238}$U | |
| Substrate | Fused silica | $101\times10^{-12}$ | $284\times10^{-12}$ | 0.0259 | 0.0616 | MJ ICP-MS |
| Resistor | a-Ge | $5\times10^{-9}$ | $5\times10^{-9}$ | 0.0001 | 0.0001 | MJ ICP-MS |
| Traces | Au | $47(1)\times10^{-9}$ | $2.0(0.3)\times10^{-9}$ | 0.0421 | 0.0015 | MJ ICP-MS |
| Traces | Ti | $< 400\times10^{-12}$ | $< 100\times10^{-12}$ | $\sim 0$ | $\sim 0$ | MJ ICP-MS |
| FET | FET die | $< 2\times10^{-9}$ | $< 141\times10^{-12}$ | $< 0.0107$ | $< 0.0006$ | MJ ICP-MS |
| Bonding wire | Al | $91(2)\times10^{-9}$ | $9.0(0.4)\times10^{-12}$ | 0.0004 | $\sim 0$ | MJ ICP-MS |
| Epoxy | Silver epoxy | $< 70\times10^{-9}$ | $< 10\times10^{-9}$ | $< 0.0685$ | $< 0.0082$ | MJ gamma |
| Total | | | | $<0.1476$ | $<0.0720$ | |

Final Design Report, **The MAJORANA DEMONSTRATOR,** May 2012

# Low Mass Front End



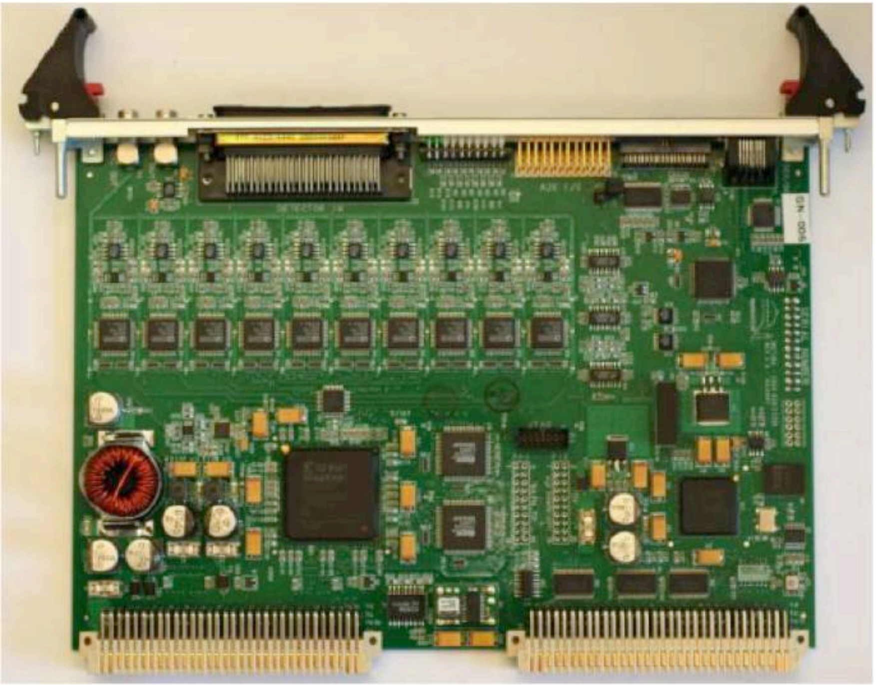




Fused silica substrate
- Au-Cr traces
- Amorphous-Ge resistor
- Low background
- **Low noise**

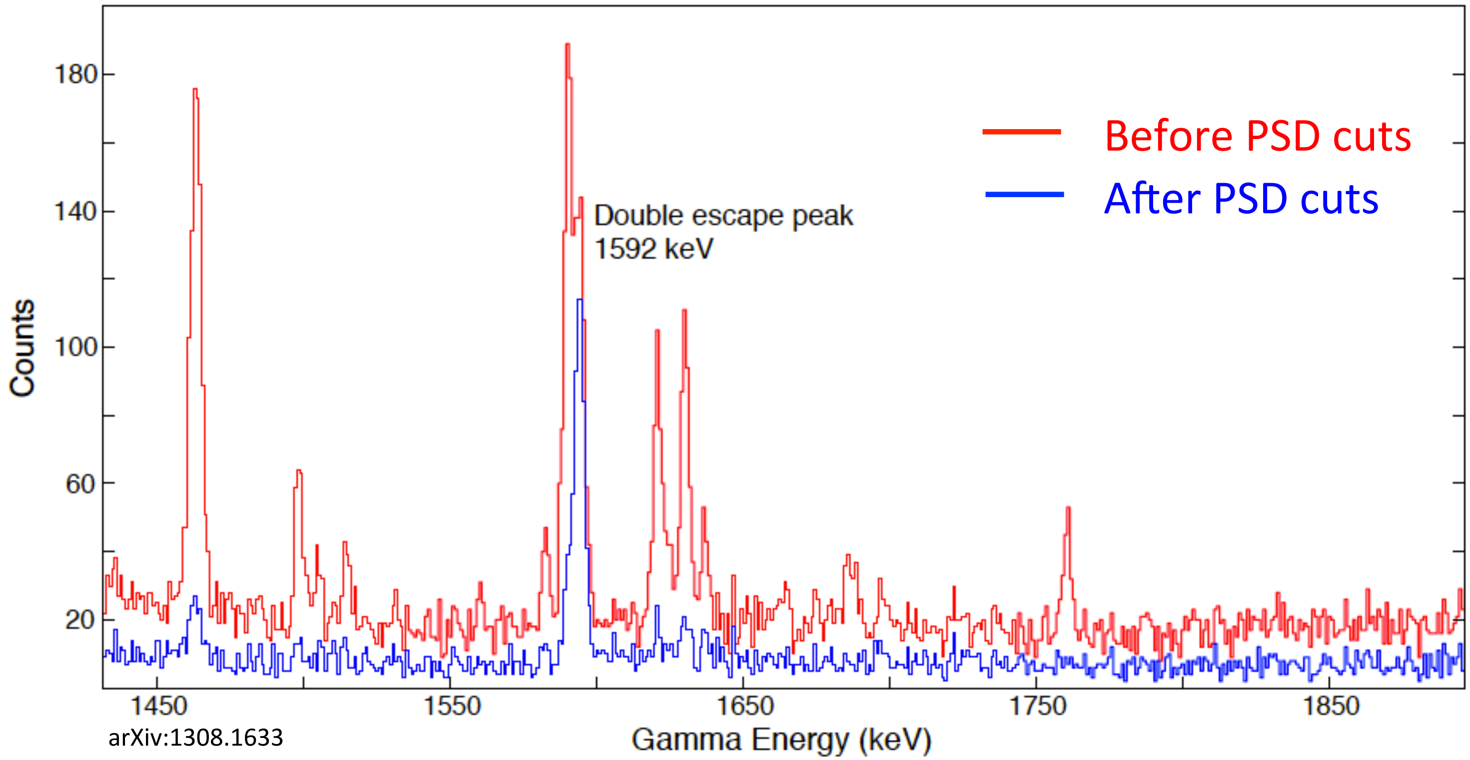
Equivalent noise:
55eV FWHM
without detector

85eV FWHM
with a small detector

# GRETINA digitizer card



# Pulse-Shape-Discrimination



# The most recent arguments

## Why is the Conclusion of the GERDA Experiment Wrong ?


H.V. Klapdor-Kleingrothaus[a], I.V. Krivosheina[b]
and S.N. Karpov[c]
[a] Heidelberg, Germany,
[b] Heidelberg, Germany and Nishnij Novgorod, Russia,
[c] JINR, Dubna, Russia


August 13, 2013




**Abstract**

The first results of the GERDA double beta experiment in Gran Sasso were recently presented. They are fully consistent with the Heidelberg-Moscow experiment, but *because of its low statistics cannot proof anything at this moment.* It is no surprise that the statistics is still far from being able to test the signal claimed by the Heidelberg-Moscow (HM) experiment. The energy resolution of the coaxial detectors is a factor of 1.5 worse than in the HM experiment. The *original goal* of background reduction to $10^{-2}$ counts/kg y keV, or by an order of magnitude compared to the Heidelberg-Moscow experiment, *has not been reached.* The background is only a factor 2.3 lower if we refer it to the experimental line width, i.e. in units counts/kg y energy resolution.

*With* pulse shape analysis (PSA) the background in the HM experiment around $Q_{\beta\beta}$ is $4 \times 10^{-3}$ counts/kg y keV [1], which is *a factor of 4 (5 referring to the line width) lower* than that of GERDA with pulse shape analysis.


arXiv:1308.2541
"The background model is oversimplified and not yet adequate.
It is not shown that the lines of their background can be identified.
GERDA has to continue the measurement further 5 years, until they can responsibly present an understood background."

… need much larger statistics/runtime

And
The 2006 claim was not excluded

# Effective mass formula

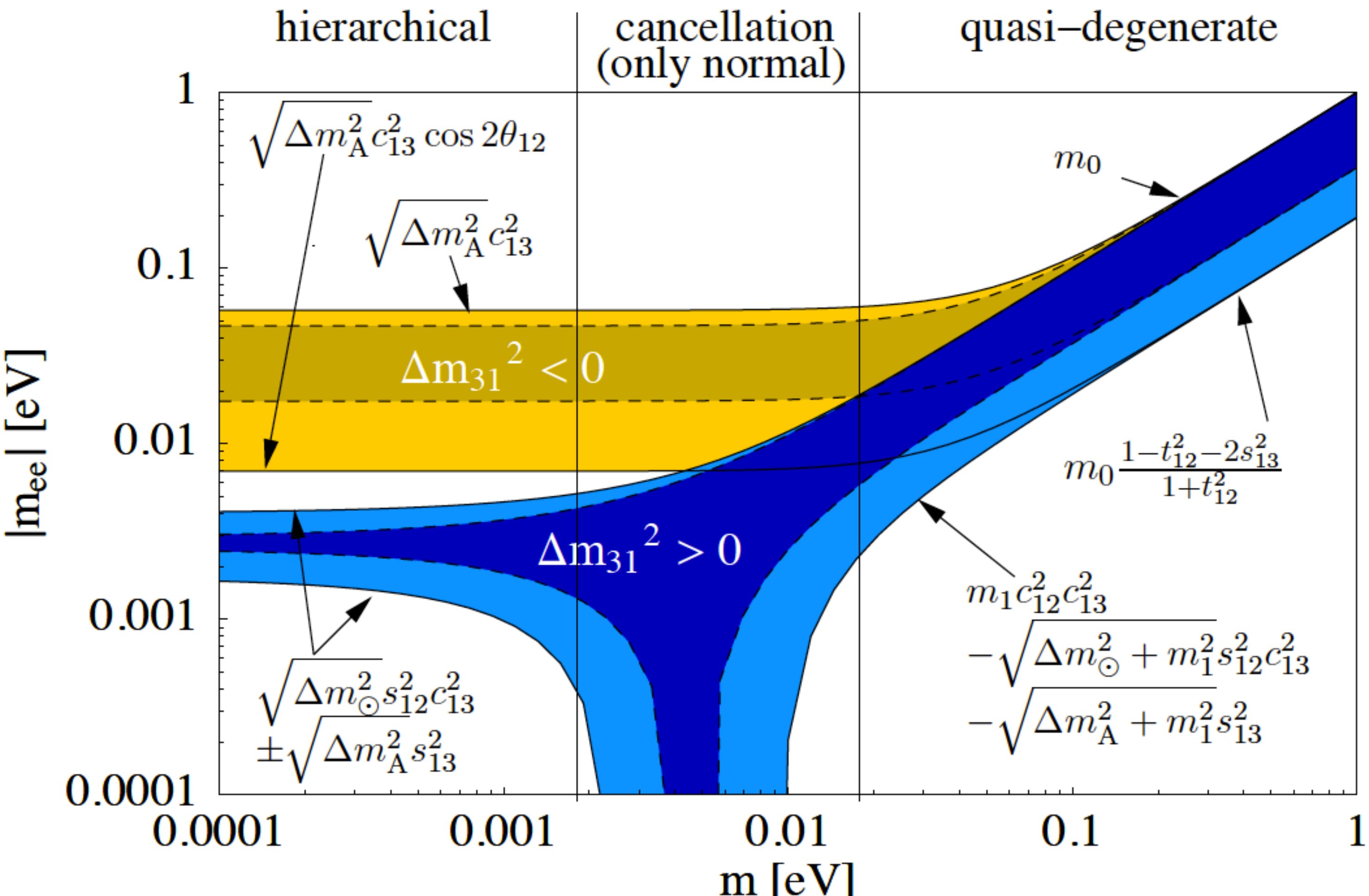
the sum. The prediction is insensitive to $\theta_{13}$ and $\delta m^2_{21}$ because they are small. Setting $\theta_{13} = 0 = \delta m^2_{21}$, the following relation between $M_{ee}$ and $\Sigma$ is obtained for both hierarchies [297]:

$$M_{ee} = \left(2\Sigma - \sqrt{\Sigma^2 + 3\delta m^2_{31}}\right) \left|c^2_{12} + s^2_{12} e^{i\phi}\right| /3, \qquad (7.8)$$

where $\phi$ is a Majorana phase. For a given measured value of $M_{ee}$ both upper (since $\theta_{12} \neq \pi/4$) and lower bounds are implied for $\Sigma$. These bounds are displayed in figure 7.2. The present upper limit on $M_{ee}$ is 0.35 eV at the 90% C.L. [301], with an overall factor of 3 uncertainty associated with the $0\nu\beta\beta$ nuclear matrix elements [302, 303]. A detection of neutrinoless double beta decay, corresponding to $M_{ee} = 0.39$ eV, has been reported [304], but this experimental result is highly controversial [305].

The physics of neutrinos, V Barger, D Marfatia, K Whisnant, 2012, Princeton University Press

# The mass plot




W. Rodejohann, arXiv:1106.1334

# Simulated Background near $Q_{\beta\beta}$

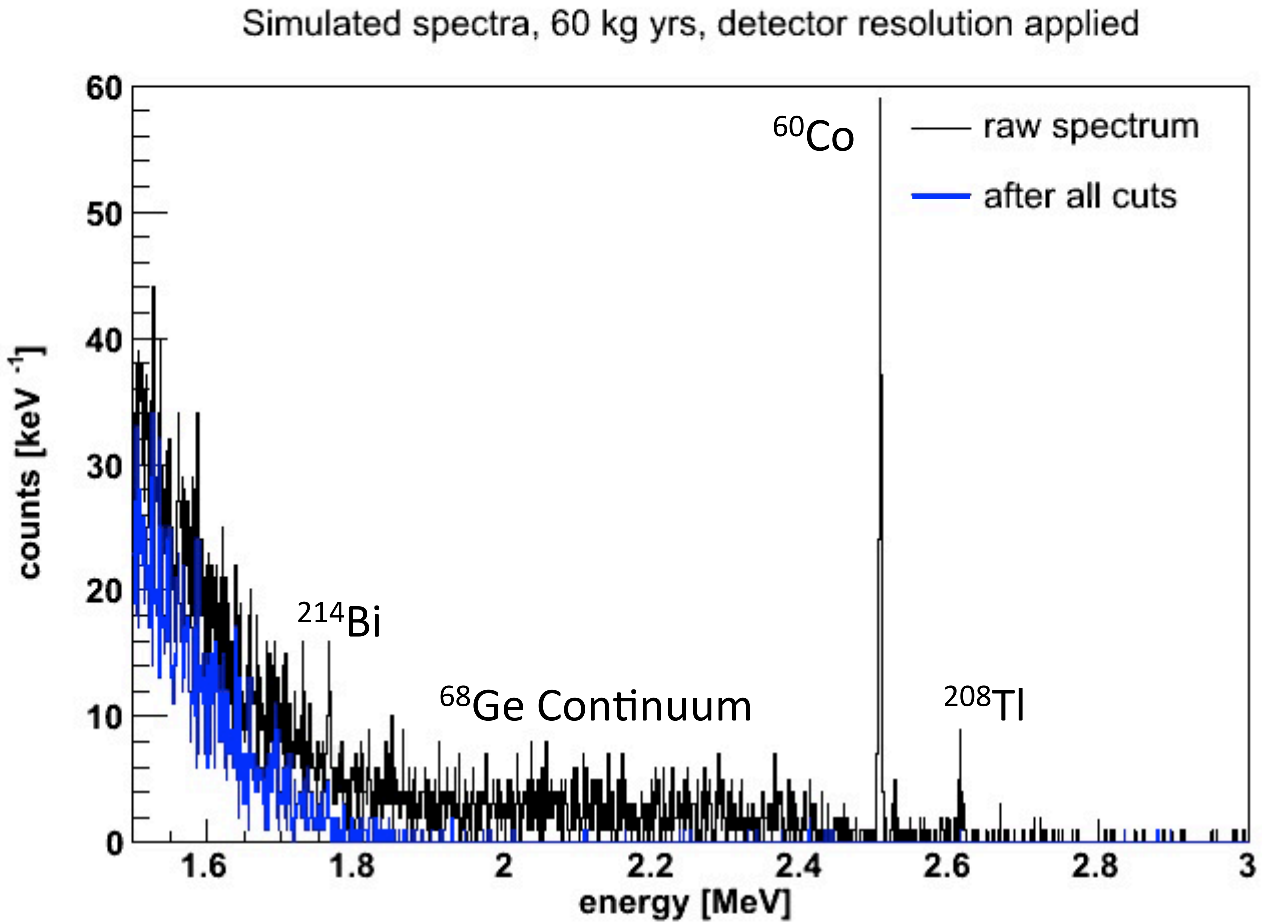



Figure adapted from
J.F.Wilkerson,
DOE ONP Comparative Review
June 25, 2013