Title: Recent results and future plans for the MAJORANA DEMONSTRATOR

Date: Oct 20, 2017 01:00 PM

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Abstract: <p>The MAJORANA DEMONSTRATOR (MJD) is a 44-kg array of low-background germanium detectors of which 30kg is made from detectors enriched to 88% in 76Ge. MJD is operating a mile underground in the Sanford Underground Research Laboratory in Lead, SD. Its main purpose is to search for the neutrinoless double-beta decay of 76Ge and to demonstrate the technical feasibility of a tonne-scale Ge-based neutrinoless double-beta decay experiment. It is also capable of direct searches of a variety of dark matter candidates and other physics beyond the Standard Model. In this talk I will review the motivation, design and construction of the MJD, as well as recent results for a the search for bosonic dark matter using commissioning data taken in 2015. I will also discuss the current status of MJD and conclude with a discussion of future plans for MJD and a proposed tonne-scale Ge-based experiment, LEGeND.</p>

THE UNIVERSITY
of NORTH CAROLINA
at CHAPEL HILL

Recent Results and Future Plans for the MAJORANA DEMONSTRATOR

Reyco Henning
U. of North Carolina and Triangle Universities Nuclear Laboratory

Perimeter Institute Seminar
October 20, 2017

Outline

Neutrinoless Double-beta decay:

History and Motivation

Majorana Experiment:

Overview

Construction

Other BSM Physics

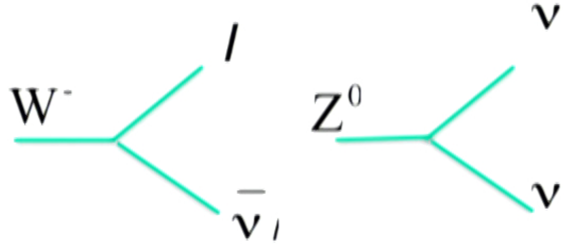
Recent Results

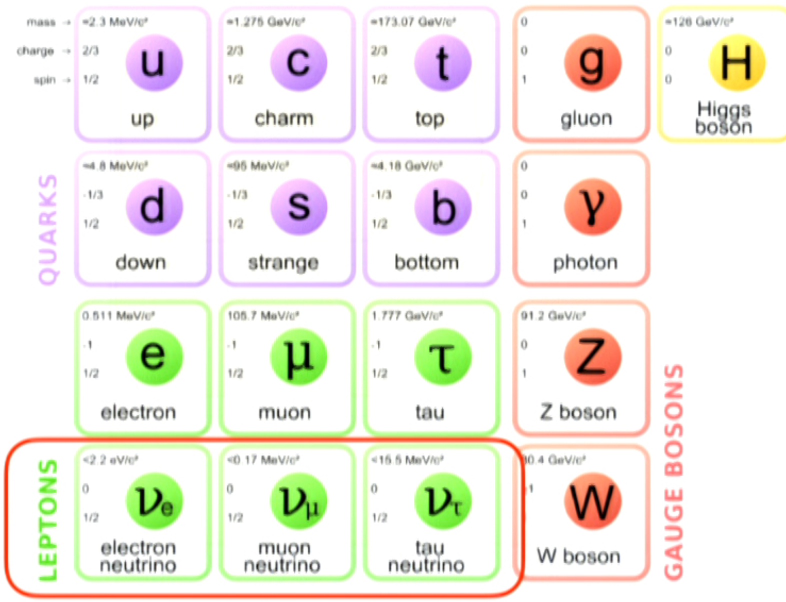
Current status and Plans

Towards a tonne-scale

Input: DVI - 1920x1080p@60Hz
Output: SDI - 1920x1080i@60Hz

The weak force and neutrinos





Wikipedia

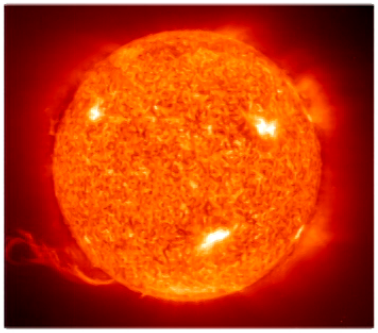
Three flavors that undergo only weak interactions

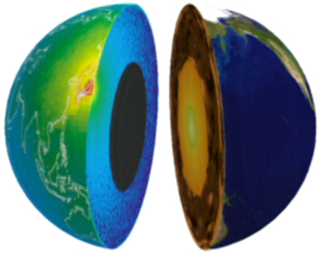
Electrically neutral

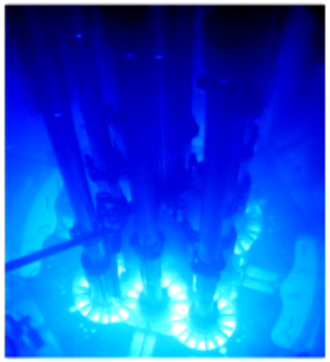
Neutrinos have mass, but very light

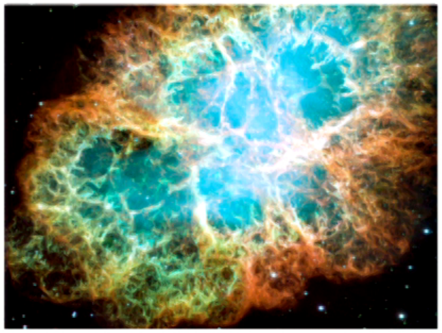
Compelling evidence neutrinos undergo flavor oscillations.

Neutrino Sources



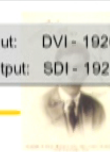






Most Abundant Particle in Universe!

Neutrino Flavor Mixing



Mass eigenstates different than flavor eigenstates.

⇒ Propagating neutrinos undergo flavor oscillations.

Mass to flavor relationship described by neutrino mixing matrix with 5 parameters.

Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.97
$\|\Delta m^2\|$ $[10^{-3}$ eV $^2]$	2.50 (2.46)	2.37 – 2.63 (2.33 – 2.60)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	0.437	0.379 – 0.616
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	0.569	0.383 – 0.637
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	0.0214	0.0185 – 0.0246
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	0.0218	0.0186 – 0.0248
δ/π	1.35 (1.32)	(0.92 – 1.99)
		((0.83 – 1.99))

pdg.lbl.gov

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{i\delta}s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$ $s_{ij} = \sin\theta_{ij}$

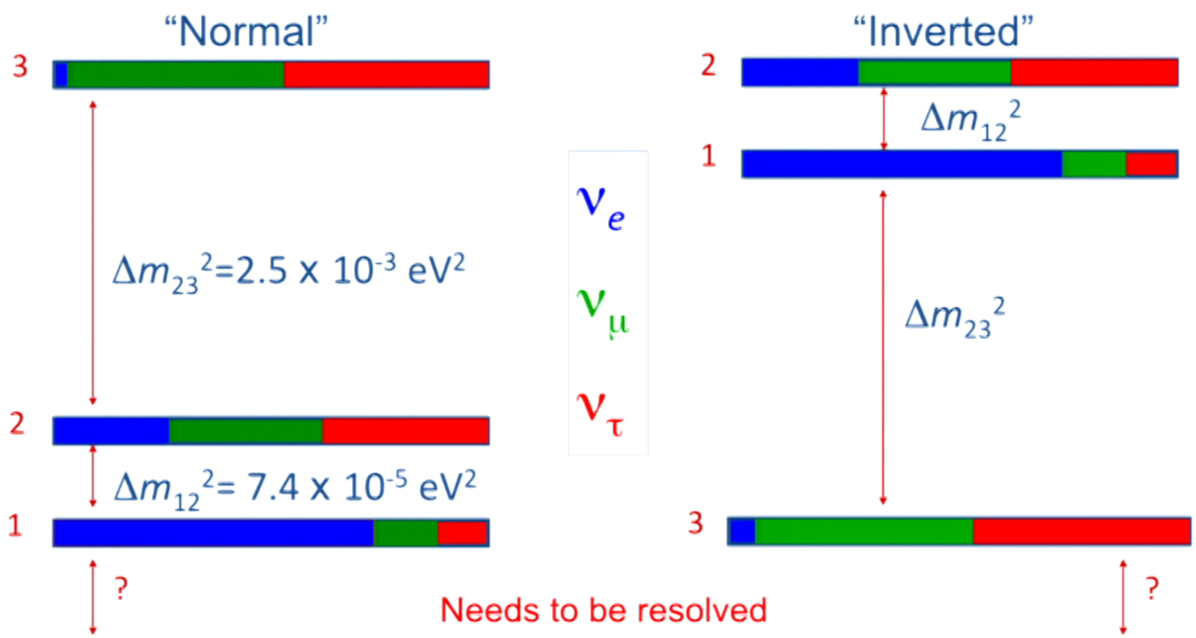
CP Phase

Neutrino Masses

Absolute masses weakly constrained, < 1eV.

Relative mass-squared differences known.

Three possible scenarios: Quasi-degenerate, also:



Majorana vs. Dirac

Majorana fermions are their own anti-particles.

Dirac fermions are not.

No fermions are known to be Majorana.

- Electrically charged fermions have good QM # to distinguish particle/anti-particles, hence are Dirac

Ettore Majorana

Experimental evidence consistent with both Majorana or Dirac neutrinos.

Verification difficult due to small neutrino masses and handedness of weak interaction.

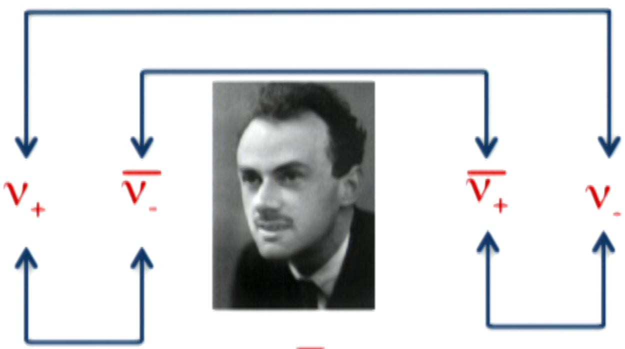
Paul Dirac

Neutrinoless double-beta decay is the only practical process that can resolve this mystery.

More about Majorana vs. Dirac

Note: Only valid if neutrinos are massive.

Lorentz Boost



CPT

$\nu \neq \bar{\nu}$

CPT

Lorentz Boost

CPT

$\nu = \bar{\nu} = \nu^M$

Original argument by Kayser, 1985

Origin of Matter

Majorana neutrinos

Required by

See-Saw mass-generating mechanism

Required (in general) by

Leptogenesis

Matter dominated universe?

What is neutrinoless double-beta decay ($0\nu\beta\beta$)?

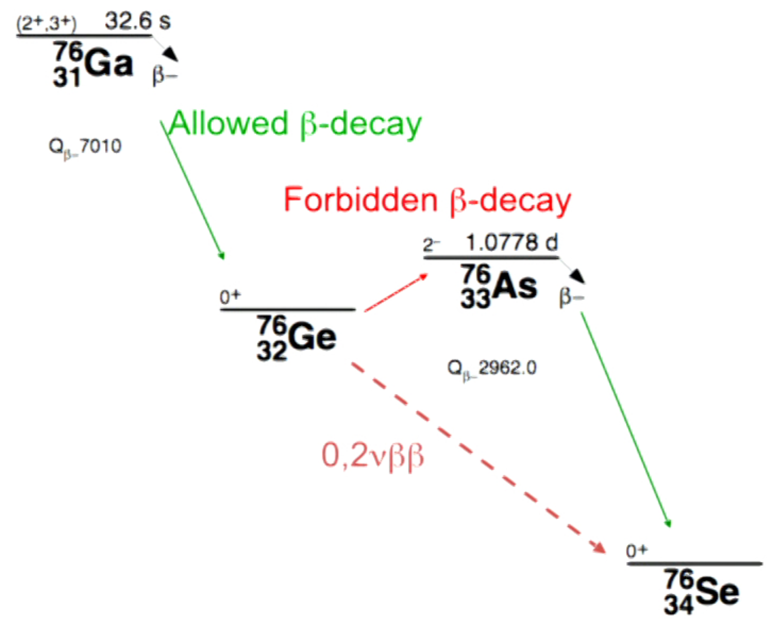
$$^{Z}A \Rightarrow {}^{Z+2}A + 2e^-$$

Energetically allowed in many nuclei.

Prefer nuclei stable against β-decay (about 30)

$2\upsilon\beta\beta$: Observed 2nd order weak process.

$$^{Z}A \Rightarrow {}^{Z+2}A + 2e^- + 2\bar{\nu}_\epsilon$$



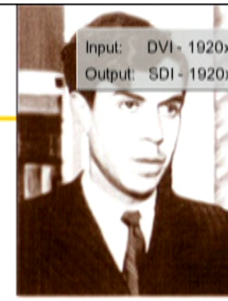
History

1935: Double beta decay postulated by Maria Goeppert-Mayer *Phys. Rev. 48 (1935) 512*

1937: Ettore Majorana formulates theory with no distinction between ν and anti-ν.
Nuovo Cimento 14 (1937) 171

1937: Giulio Racah suggests zero-neutrino double-beta decay as test for Majorana's theory. *Nuovo Cimento 14 (1937) 322*

Motivation for $0\upsilon\beta\beta$ Search



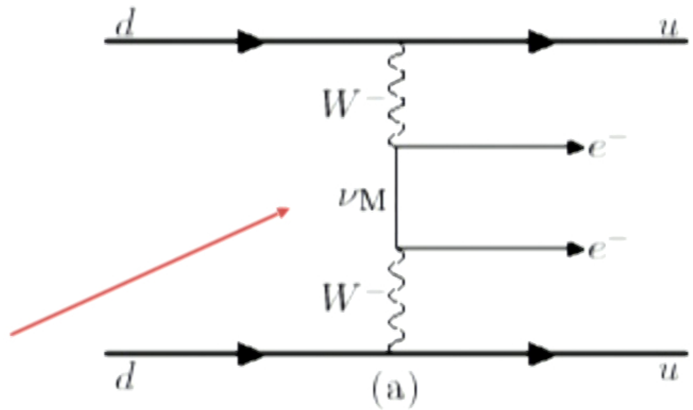
Majorana

Implications of discovery:

- Neutrino is Majorana* (own antiparticle)
- Total lepton number is not conserved
- Neutrinoes have mass* (known)
- Absolute neutrino mass.

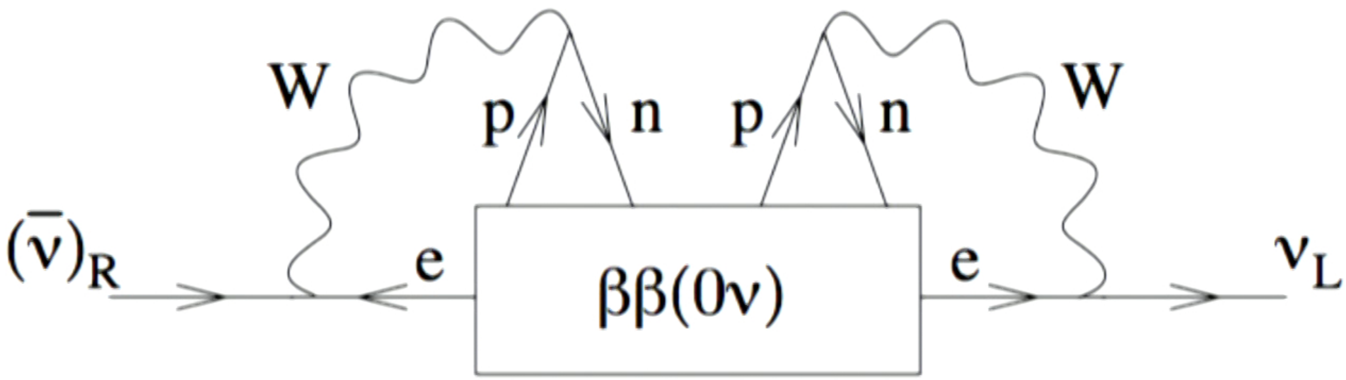
$0\upsilon\beta\beta$ nuclear decay may occur via several processes (SUSY, RH currents, etc)

Canonical example: Exchange of virtual Majorana neutrino + helicity flip



* Schechter et al, Phys. Rev. D**25**, 2951 (1982)

$0\nu\beta\beta$–decay and Majorana Neutrinos



Schechter et al, Phys. Rev. D**25**, 2951 (1982)

Majorana nature verification ***independent*** of process that mediates $0\nu\beta\beta$ decay!

$0\nu\beta\beta$ Rate and Neutrino Mass

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}(E_0,Z)\left|\langle m_{\beta\beta}\rangle\right|^2\left|M^{0\nu}\right|^2$$

$T_{1/2}^{0\nu}$: Half-life

$G^{0\nu}$: Phase Space (Known)

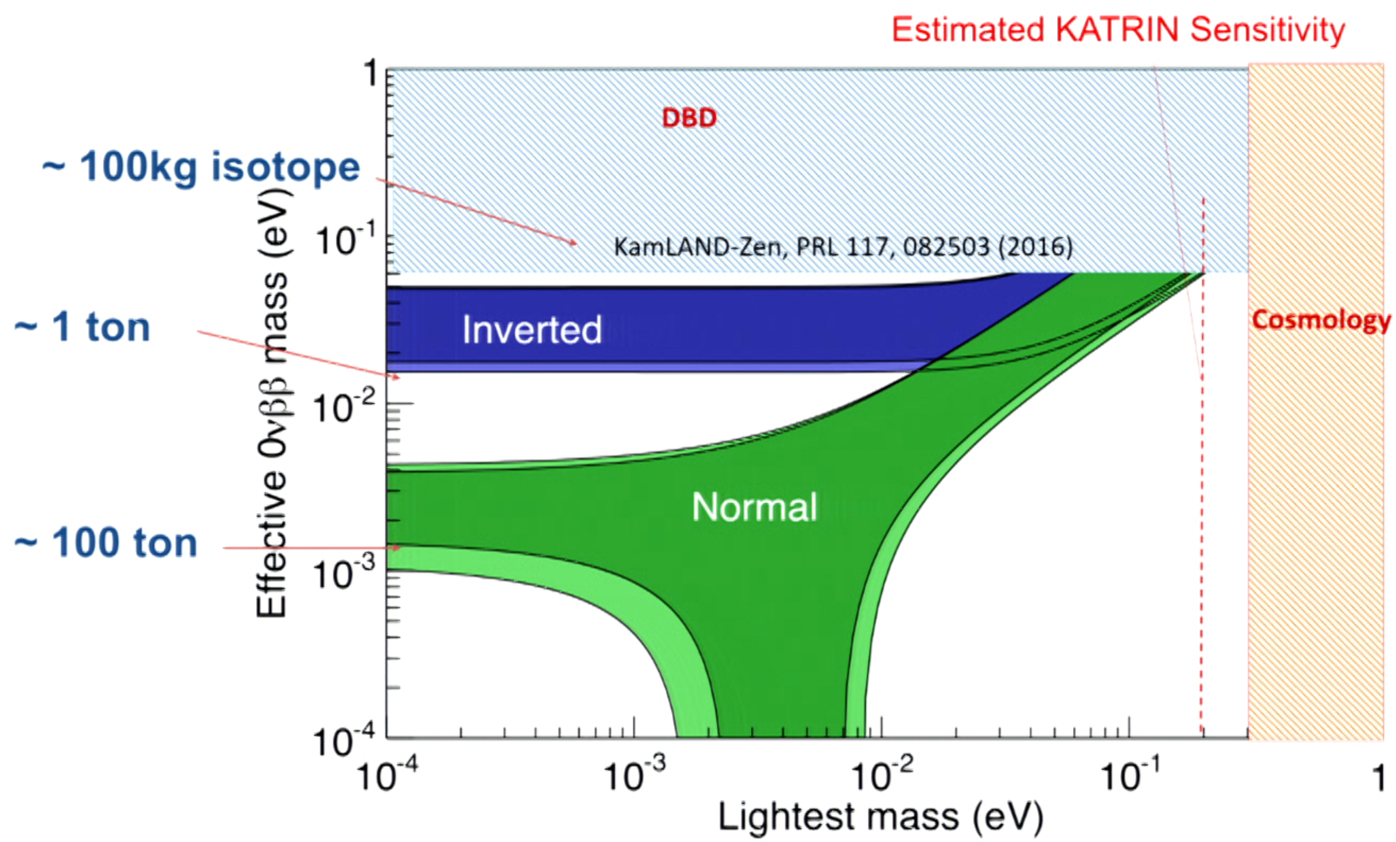
$M^{0\nu}$: Nuclear Matrix Element (large uncertainty)

$$\left|< m_{\beta\beta} >\right| = \left|\sum_i \left|U_{ei}\right|^2 m_{\nu_i} e^{i\alpha_i}\right|$$ Effective Majorana electron neutrino mass*

- $0\upsilon\beta\beta$ decay can probe **absolute** neutrino mass scale and mixing.
- Current neutrino experiments measure mass squared differences: Δm^2.

* Assumes ν_m exchange

Combined Mass Limits



First Experimental Search for DBD Decay

Phys. Rev. 74 (1948) 1248 (conference proceedings)

Artificial Radioactive Substances

T1. Double Beta Decay.* E. FIREMAN, *Princeton University.*—There exist a number of stable isobaric nuclei that differ by two in charge and may differ by several Mev in mass. The heavier should decay into the lighter with simultaneous emission of two electrons. The decay probability depends markedly upon whether or not the two electrons are accompanied by two neutrinos. No neutrinos are emitted if they obey the Majorana equation or if the interaction is composed of linear combinations of the usual interactions. Furry's calculations using Majorana wave functions have been extended to linear combinations that arise from symmetry considerations and meson theories. Isobars belonging to a triple set are the most promising for double beta decay since the middle one is near the minimum of the isobaric mass defect curve. Therefore, $_{40}Zr^{96}$ and $_{50}Sn^{124}$ were investigated with a Geiger counter coincidence arrangement. Their activity was compared with elements that are stable against all types of decay. No difference was detected. On the basis of these measurements and the assumption of two-Mev mass difference, the lifetime of $_{50}Sn^{124}$ is greater than $3\cdot 10^{15}$ years. This result rules out the polar vector, axial vector, and tensor interactions with Majorana wave functions and the more important linear combinations.

* This work was supported in part by Navy contract.

Searched for coincident betas from target materials using Geiger tubes

A Measurement of the Half-Life of Double Beta-Decay from ${}_{50}Sn^{124}$ *

E. L. Fireman
Department of Physics, Princeton University, Princeton, New Jersey
November 29, 1948

Followed by "discovery"!

In all situations specimen *A* gives 2 coincidence counts/hr. more than specimen *B*. By repeating this type of measurement with Al absorbers over one side of each specimen an absorption curve is obtained. This absorption curve is similar to that of electrons from a spectrum with an energy end point between 1.0 Mev and 1.5 Mev. The single counts from specimens *A* and *B* both give 6.5 ± 0.3 counts/min. If one interprets this effect as double beta-decay from Sn^{124}, one obtains a half-life between $0.4 \cdot 10^{16}$ yr. and $0.9 \cdot 10^{16}$ yr. Other alternative explanations for these observations have been considered but none have been found to be plausible. This result would indicate that double beta-decay is unaccompanied by neutrinos. A further consequence of these results pointed out to the author by Professor J. R. Oppenheimer is that the neutron-proton charge difference is exactly equal to the electron charge.

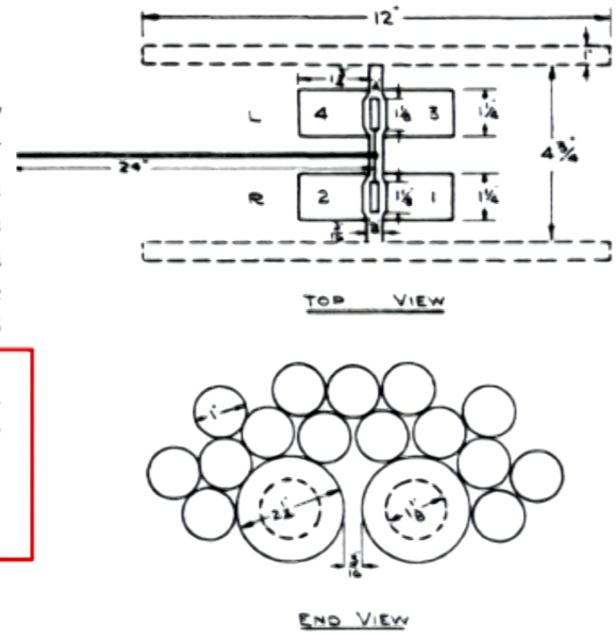


FIG. 1. Experimental arrangement.

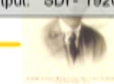
2.6 sigma effect

Ruled out by subsequent measurements, though. Astropart. Phys. 31 (2009) 412) $T_{1/2}(^{124}Sn, 0n) > 2.0 \times 10^{19}$yr

Likely due to radioactive contamination, uncontrolled systematics (no discussion of calibrations), sample thickness

Limited handles on data

First use of lead/Fe shield, enriched sources (54% enriched Sn source)



Still no conclusive evidence for the existence of DBD.

About 10 "claims" in literature, all debunked

Three explanations:

- Unknown backgrounds
- Statistical fluctuations
- Systematics / unknown detector response

Experimental Considerations in Modern Experiments

Measure ***extremely*** rare decay rates :

$T_{1/2} \sim 10^{26}$-10^{27} years ~ few decays per tonne per year.

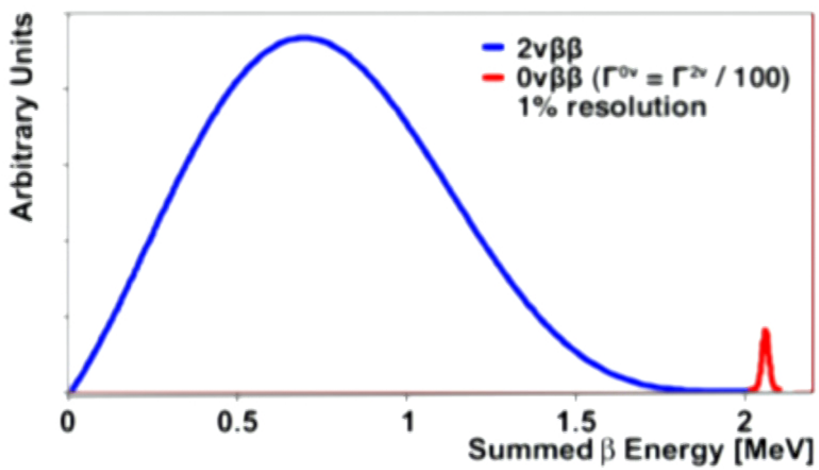
Large, highly efficient source mass.

Extremely low (near-zero) backgrounds in the 0νββ peak region-of-interest (ROI)

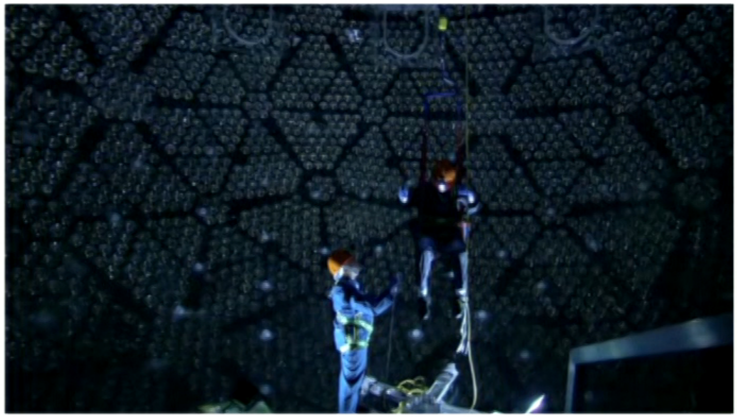
1. High *Q* value
2. Best possible energy resolution

   Minimize 0νββ peak ROI to maximize S/B

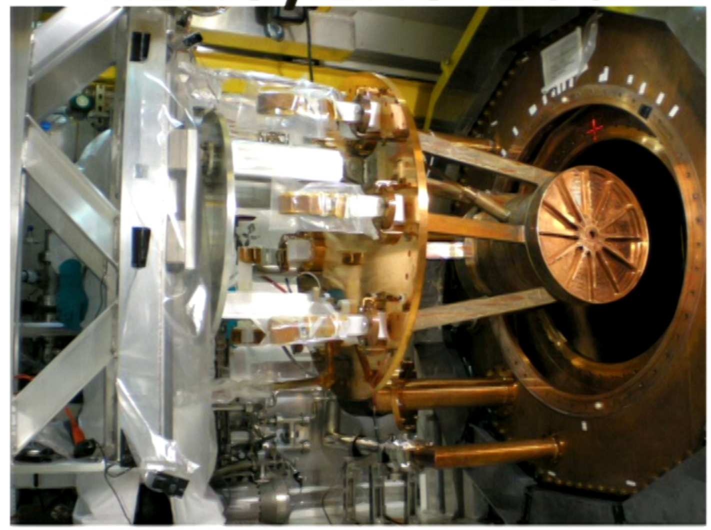
   Separate 2νββ/0νββ



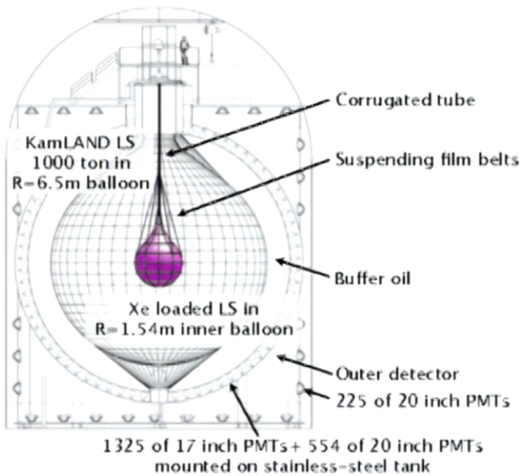
SNO+



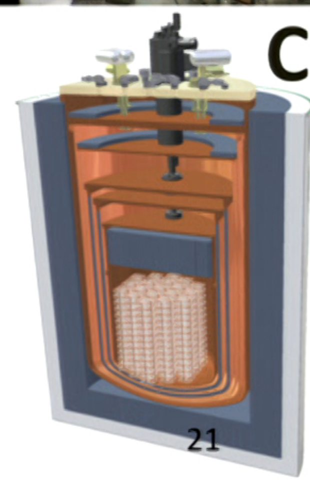
nEXO/EXO-200



KAMLAND-ZEN



CUORE



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Current Limits on selected isotopes

Isotope	$\beta\beta(0\nu)$ Half-life limit (years)	Natural Abundance [%]	Q-value (MeV)
^{48}Ca	$> 1.4 \times 10^{22}$	0.187	4.2737
^{76}Ge	$> 5.3 \text{ x} 10^{25}$	7.8	2.0391
^{82}Se	$> 1.0 \times 10^{23}$	9.2	2.9551
^{100}Mo	$> 1.1 \times 10^{24}$	9.6	3.0350
^{130}Te	$> 4.0 \times 10^{24}$	34.5	2.5303
^{136}Xe	$> 1.07 \text{ x} 10^{26}$	8.9	2.4578
^{150}Nd	$> 1.8 \times 10^{22}$	5.6	3.3673

Sensitivity, Background and Exposure

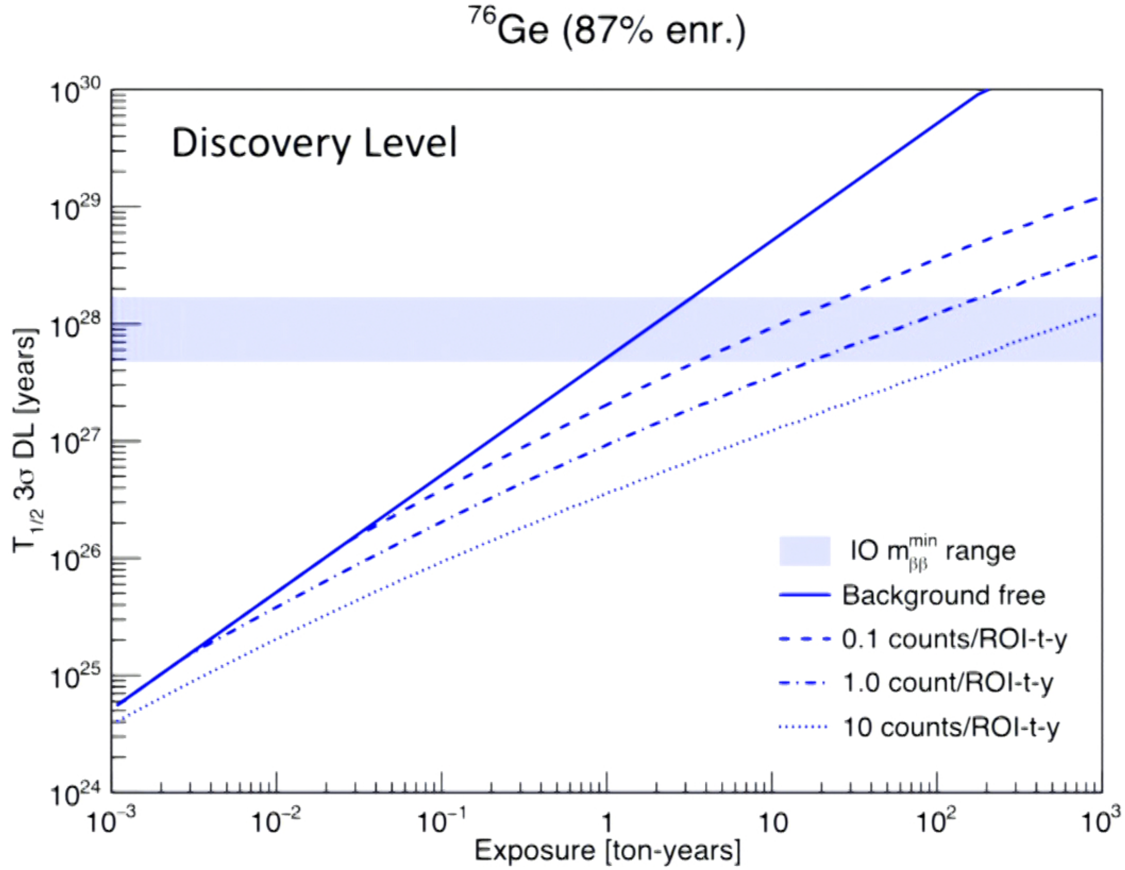


Fig: Courtesy J. Detwiler

Background Identification

Natural isotope chains:

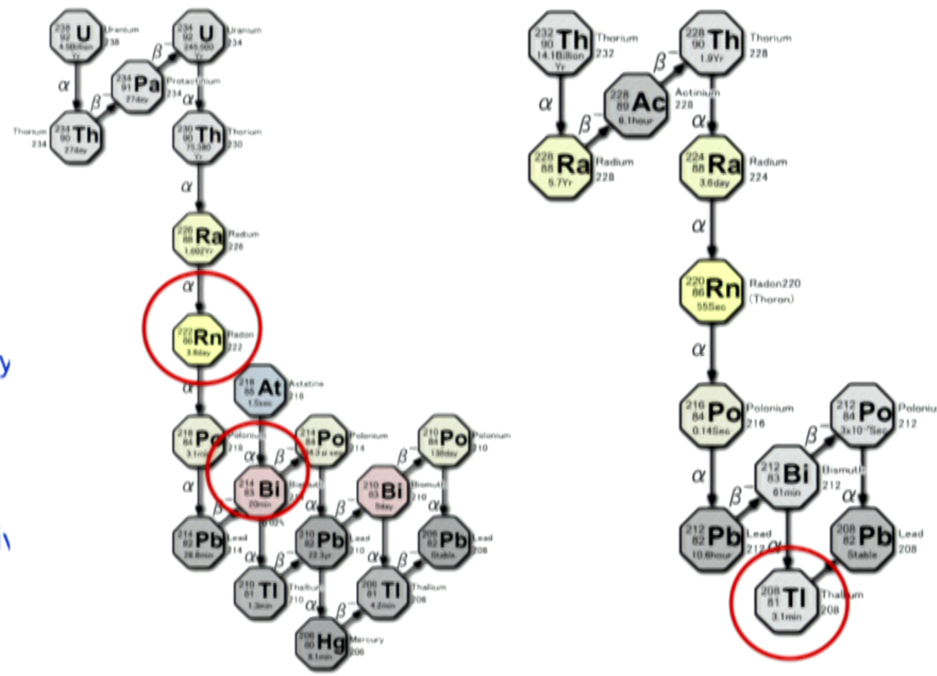
^{232}Th, ^{235}U, ^{238}U, Rn

$2\nu\beta\beta$-decays

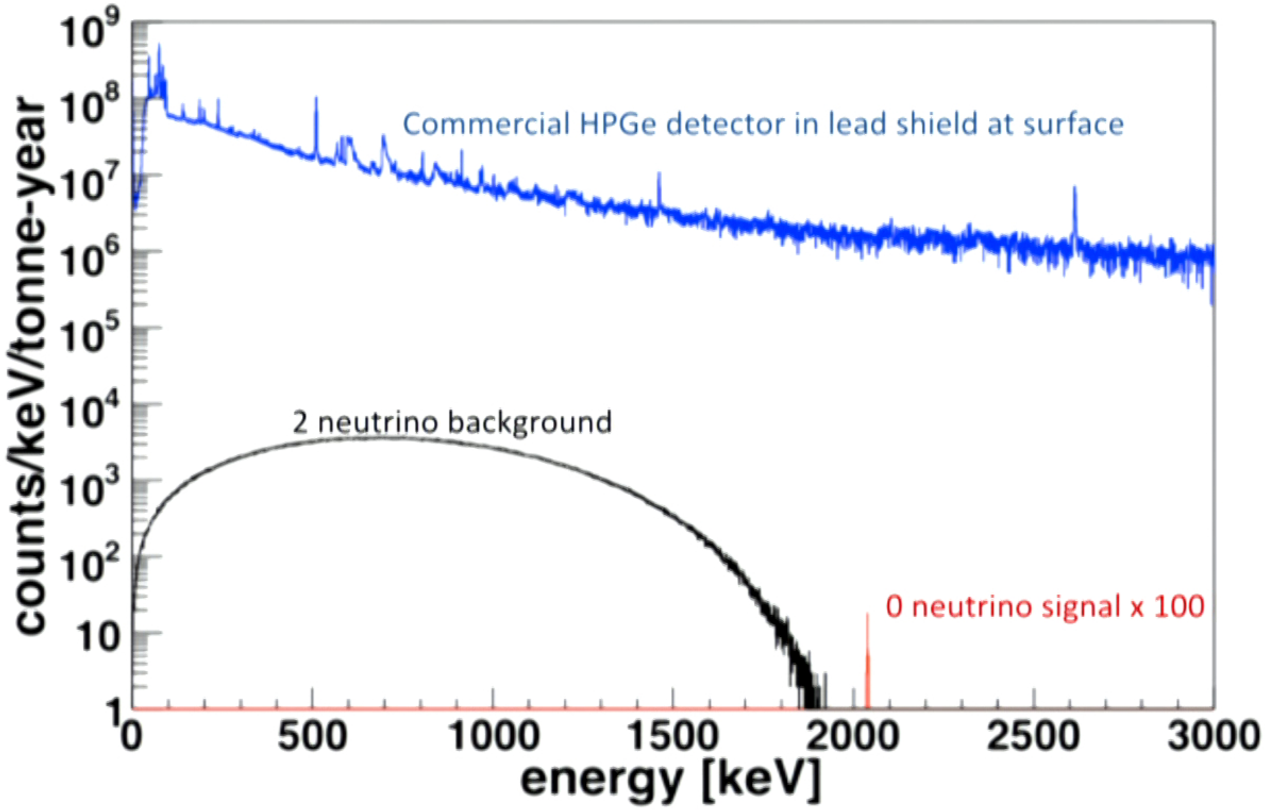
Cosmic Rays:

- Activation at surface creates ^{68}Ge, ^{60}Co.
- Hard neutrons from cosmic ray in rock and shield.

Pushing limits in ICP-MS, materials science, radio-assay. Ie. Ultra-low radioacti background, fast, low-noise electronics



Background Reduction Challenges

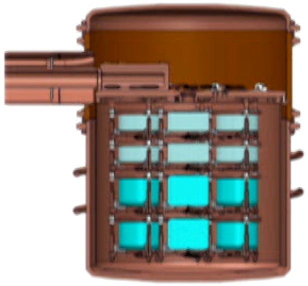


The MAJORANA DEMONSTRATOR

Input: DVI - 1920x1080p@60Hz
Output: SDI - 1920x1080i@60Hz

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

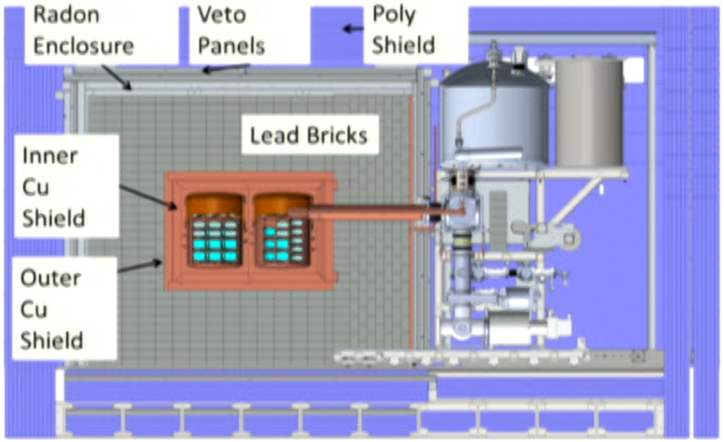
- 29.7 kg of 87% enriched ^{76}Ge crystals
- 14.4 kg of ^{nat}Ge
- Detector Technology: P-type, point-contact.

2 independent cryostats

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

Compact Shield

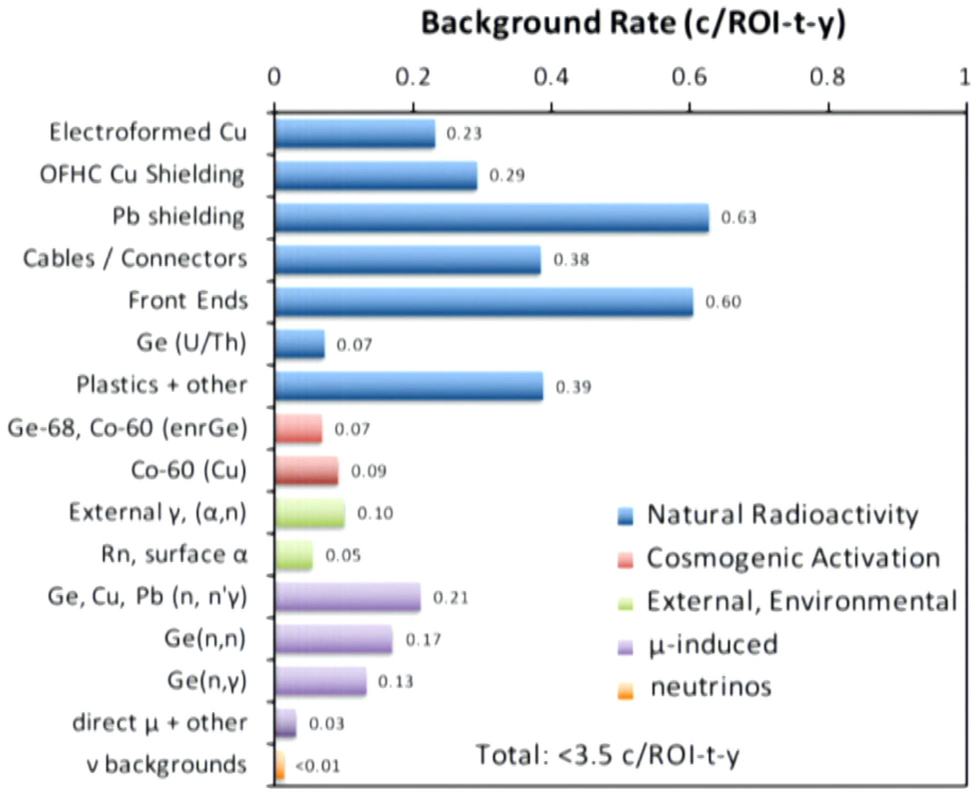
- low-background passive Cu and Pb shield with active muon veto



Sensitivity, Background and Exposure

Based on assays of materials; When UL, use UL as the contribution

NIMA 828 (2016) 22–36



Ge Detection Principle

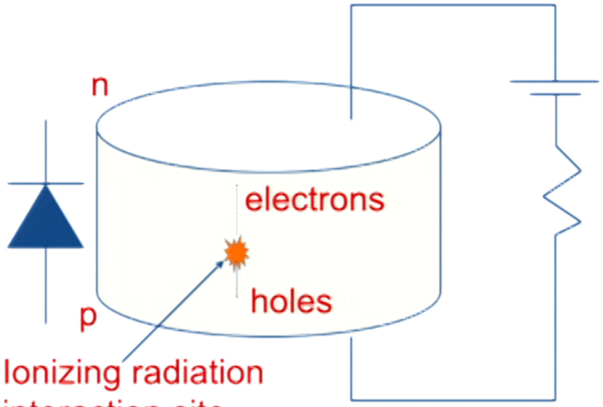
>50 years of experience

Ge is semiconductor -- Diode.

Ionizing radiation creates electron-hole pairs.

Signal generated by collecting electrons and holes.

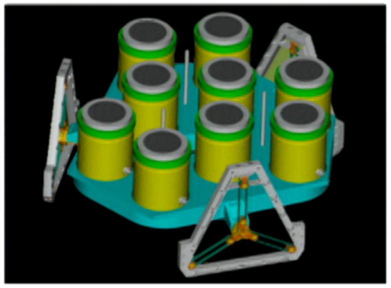
Gamma-ray spectroscopy



Mature Technology

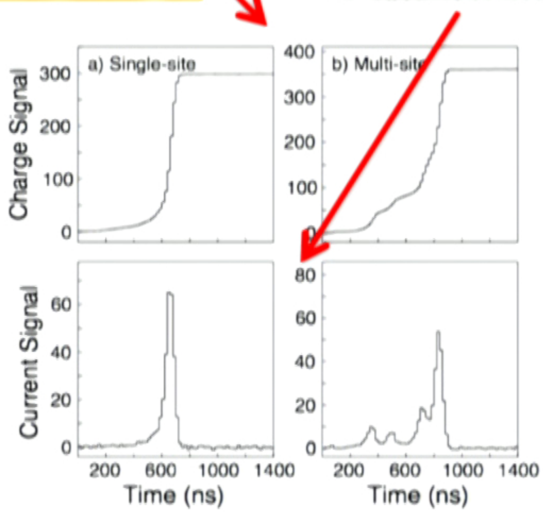
Gammasphere
GRETINA/AGATA

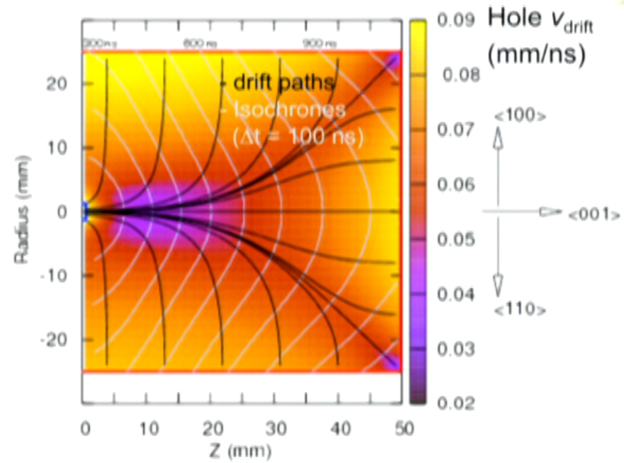
RHESSI

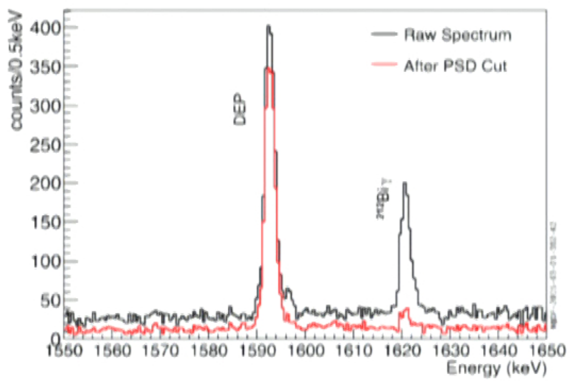


Canberra
(Commercial)

0νββ with Point Contact Detectors







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

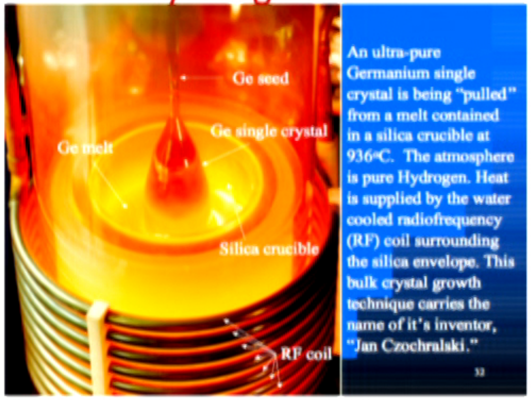
Enriched Crystal Production

Input: DVI - 1920x1080p@60Hz
Output: SDI - 1920x1080i@60Hz

Enrichment (86% ^{76}Ge)

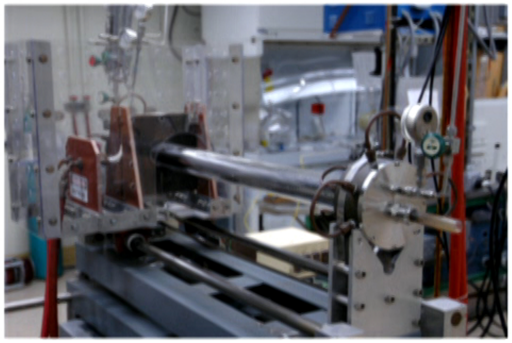
E.E Haller

Crystal growth



Polycrystalline bars

Zone refinement



Ge Processing and Recovery

Better than 98% yield from original 42.5-kg of ^{enr}Ge (61.7 kg of GeO_2)

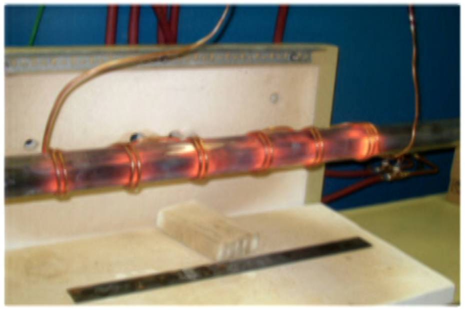
Recovered Ge from processing detector manufacturing waste

- 8.4-kg of "scrap" reprocessed
  - 2.87 kg of metal from detector manufacturer reject
  - 5.87 kg of Ge with >47 Ω-cm recovered from the manufacturing effluent and kerf
- Mixed with 3.22 kg of remaining Ge material to yield 9.1 kg of Ge >47 Ω-cm

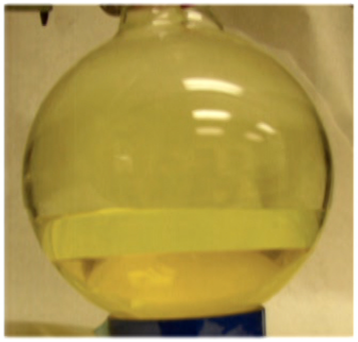
Resulted in 74% yield of operating detectors, best to date for Ge experiments

Ge reduced in Cl gas

Zone refining of Ge metal

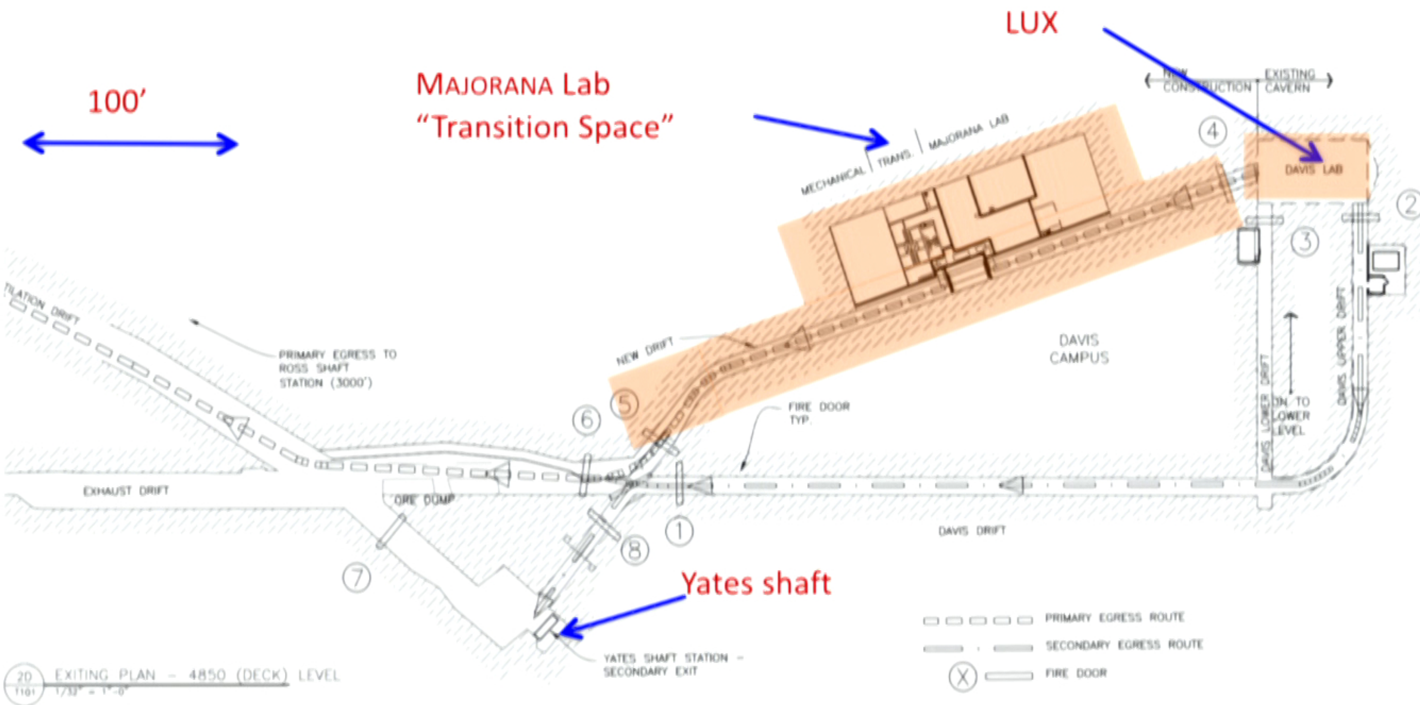


$GeCl_4$ with cover liquid



Sanford Underground Research Facility: Lead, South Dakota

Underground Location of MAJORANA Laboratory



Davis Campus, 4850' level, near Yates shaft

Early Activities

Underground Electroforming facility

Main underground Lab

Inside Electroforming Lab

Underground machine shop

Vacuum System Assembly

From electroformed Cu and enriched Ge

- electro-formed underground
- Th decay chain (ave) ≤ 0.1 μBq/kg
- U decay chain (ave) ≤ 0.1 μBq/kg
- ~1.1 tons used in MJD

Electroformed Cu and enriched Ge

- electro-formed underground
- Th decay chain (ave) ≤ 0.1 μBq/kg
- U decay chain (ave) ≤ 0.1 μBq/kg
- ~1.1 tons used in MJD

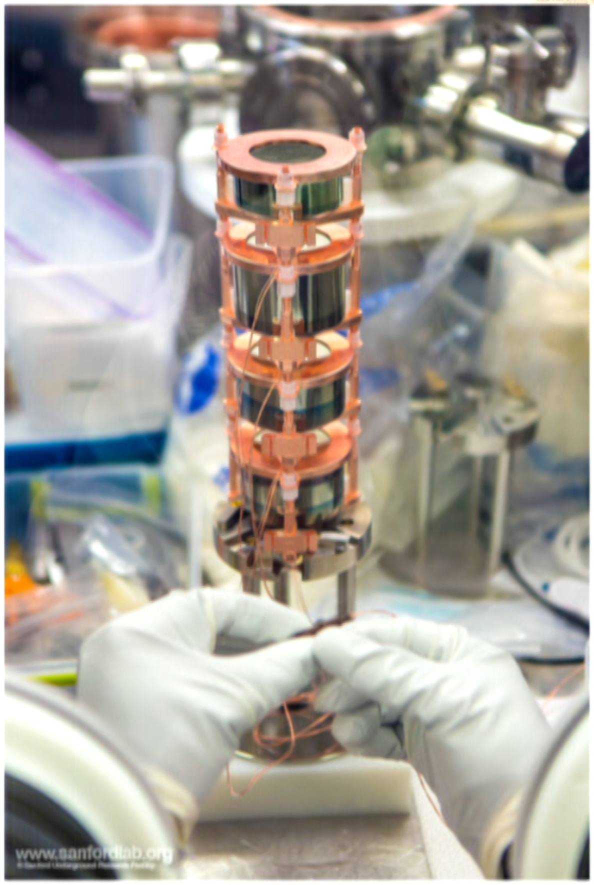
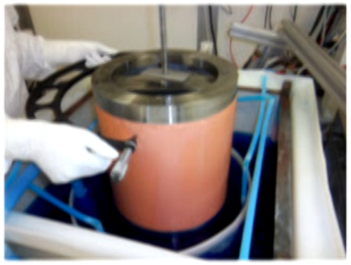
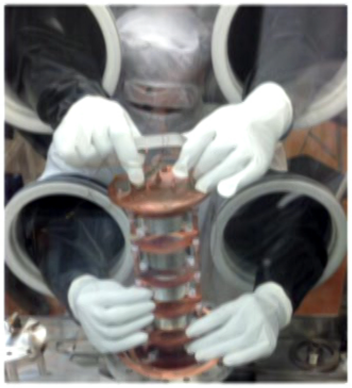
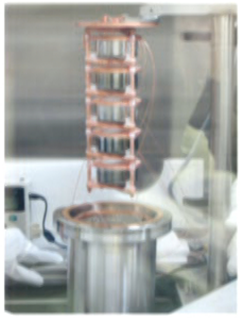


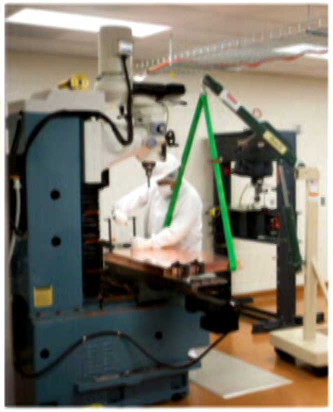
Fig: Courtesy M. Kapust

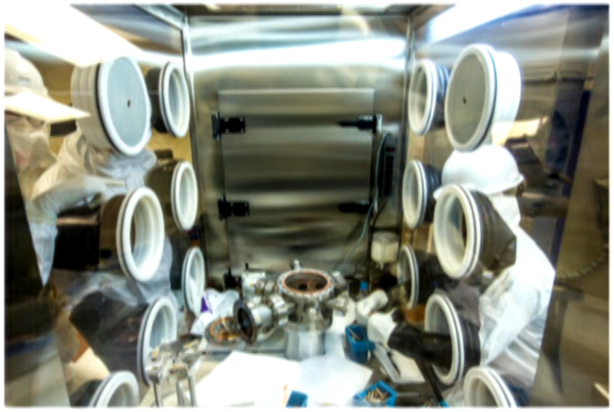
MJD Construction











Electroformed Cu and enriched Ge

Fig: Courtesy M. Kapust

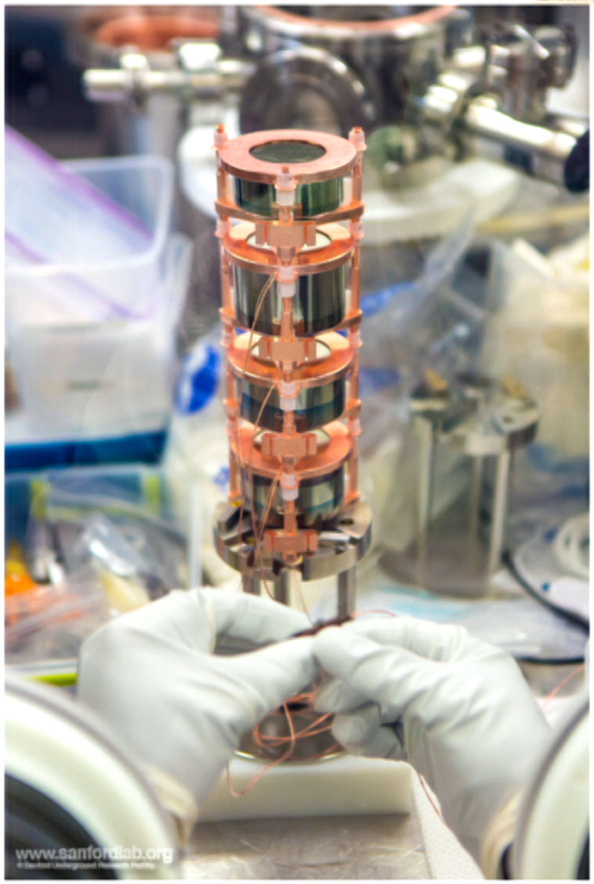


Fig: Courtesy M. Kapust

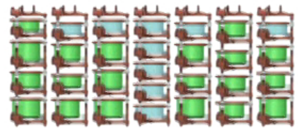
The MJD Shield

Input: DVI - 1920x1080p@60Hz
Output: SDI - 1920x1080i@60Hz

Module Implementation

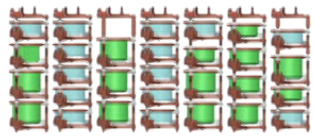
In shield Operation

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

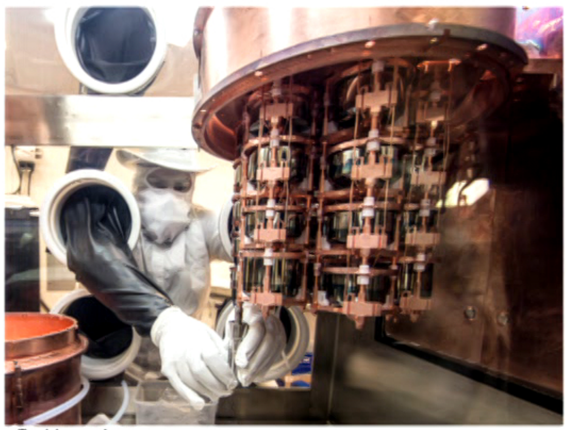


May – Oct. 2015, Final Installation, Dec. 2015 — ongoing

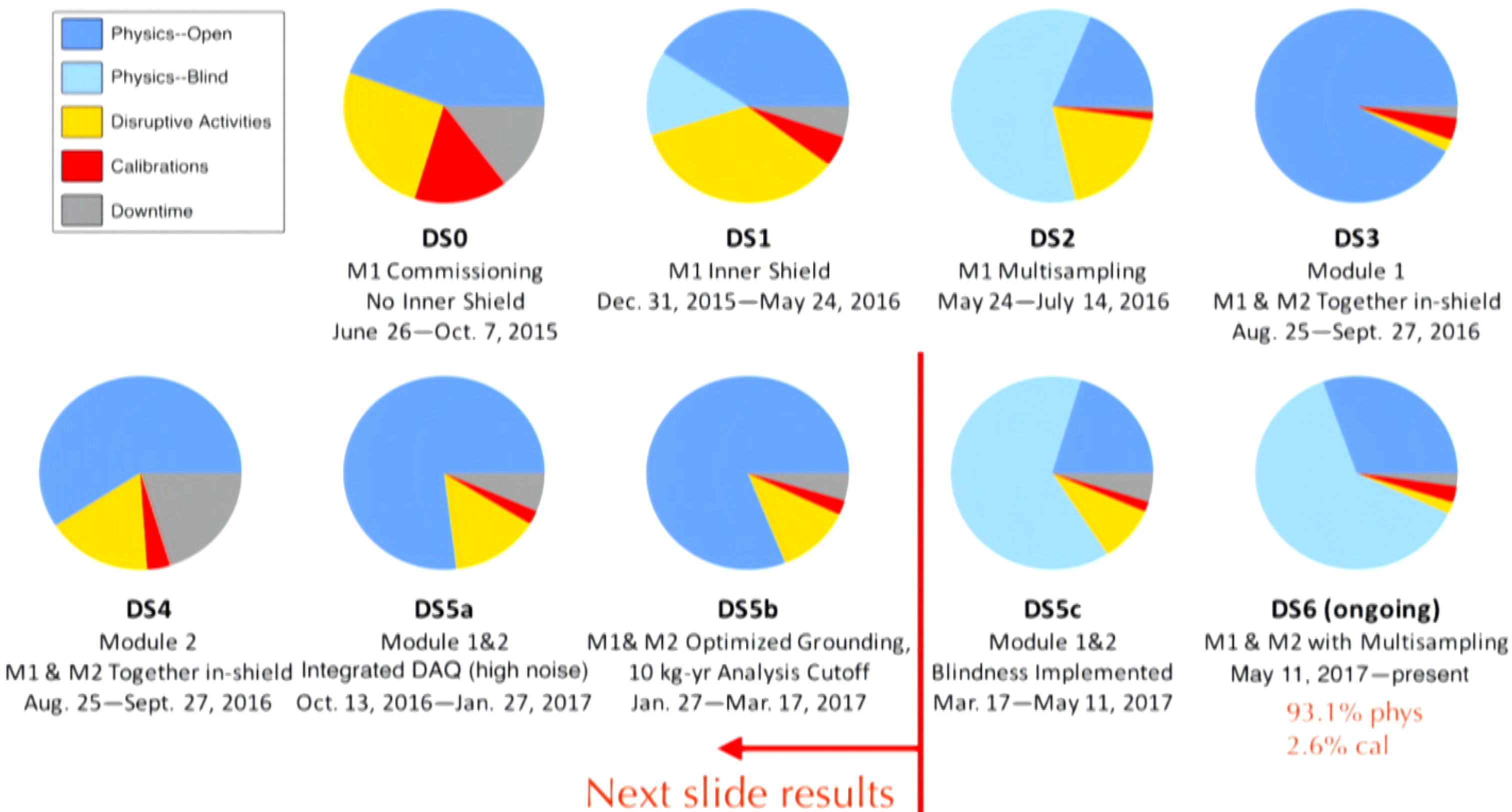
Module 2: 12.9 kg (15) ^{enr}Ge, 8.8 kg (14) ^{nat}Ge



July 2016 — ongoing



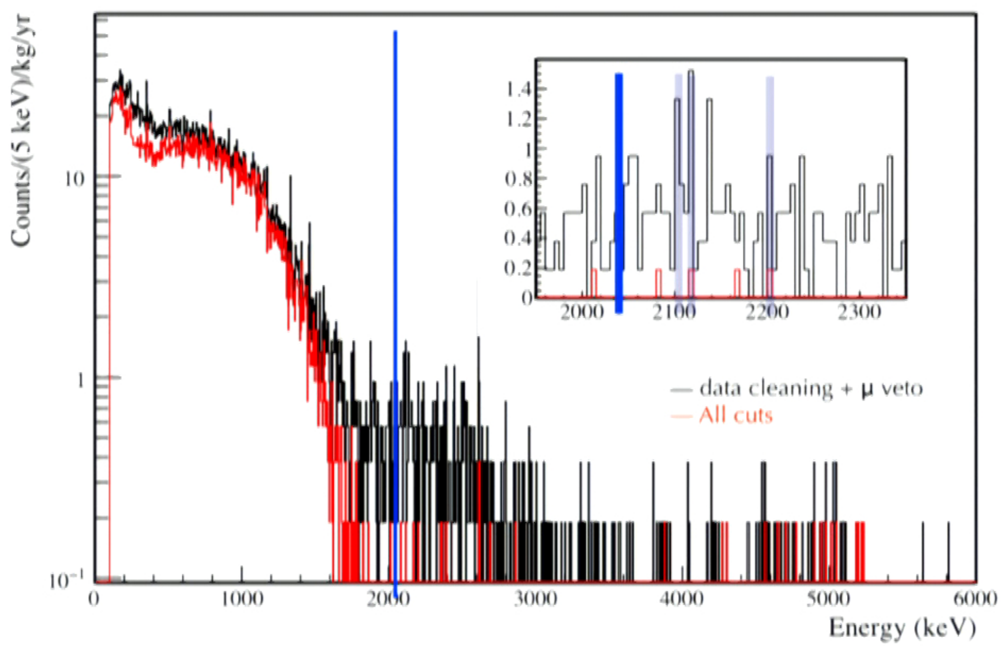
Data Sets and Duty Cycles



Low-Background Data: DS1-4,5b

Lowest background configuration, with both modules in shield.

- Active Exposure: 5.29 kg y (^{enr}Ge)
- Background after cuts: 3 counts in 360 keV window
- Background rate: $4.0^{+3.0}_{-2.5}$ c/(FWHM t y), $1.6^{+1.2}_{-1.0}$ c/(keV t y)



Other Physics with MJD

- Low-E thresholds of PPC design opens new possibilities for experiments:
  - Direct Dark Matter Searches
  - Coherent neutrino nuclear scattering (an initial goal of PPCs)
  - Solar Axions
  - Low momentum transfer neutrino-electron scattering
  - Fractionally charged Particles in cosmic-rays
  - Pauli Exclusion Principle Violation
  - Lorentz Violation
  - …
- **Enrichment reduces low-E backgrounds**

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Other Physics with MJD

- Low-E thresholds of PPC design opens new possibilities for experiments:
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  - ...
- **Enrichment reduces low-E backgrounds**

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Example: Light (1-100 keV-scale) Bosonic DM

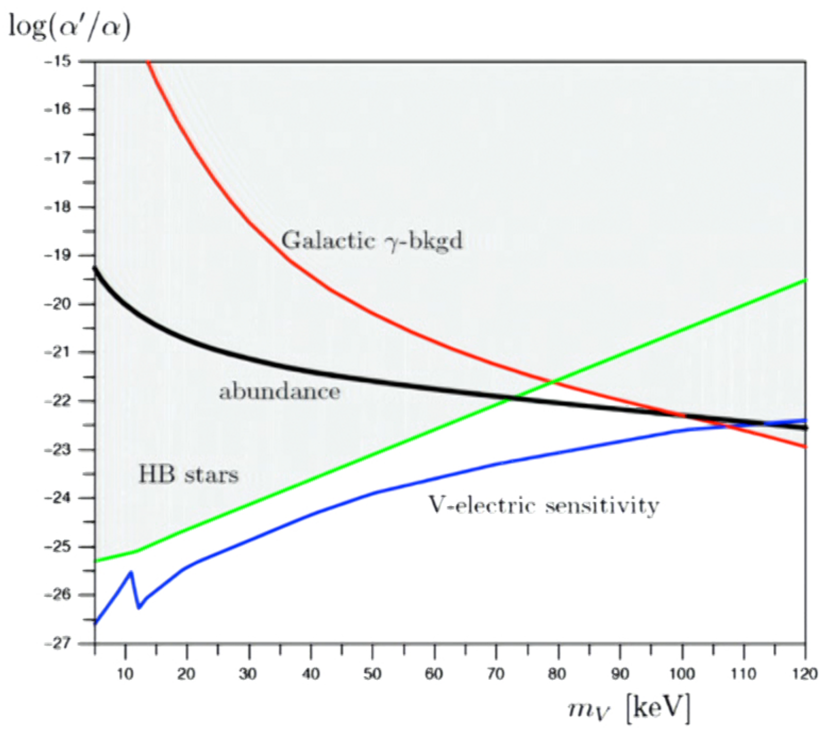
PHYSICAL REVIEW D **78**, 115012 (2008)

Bosonic super-WIMPs as keV-scale dark matter

Maxim Pospelov,[1,2] Adam Ritz,[1] and Mikhail Voloshin[3,4]

[1] *Department of Physics and Astronomy, University of Victoria, Victoria, British Colombia, V8P 1A1 Canada*
[2] *Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2J 2W9, Canada*
[3] *William I. Fine Theoretical Physics Institute, University of Minnesota, Minneapolis, Minnesota 55455, USA*
[4] *Institute of Theoretical and Experimental Physics, Moscow, 117218, Russia*

(Received 15 August 2008; published 16 December 2008)



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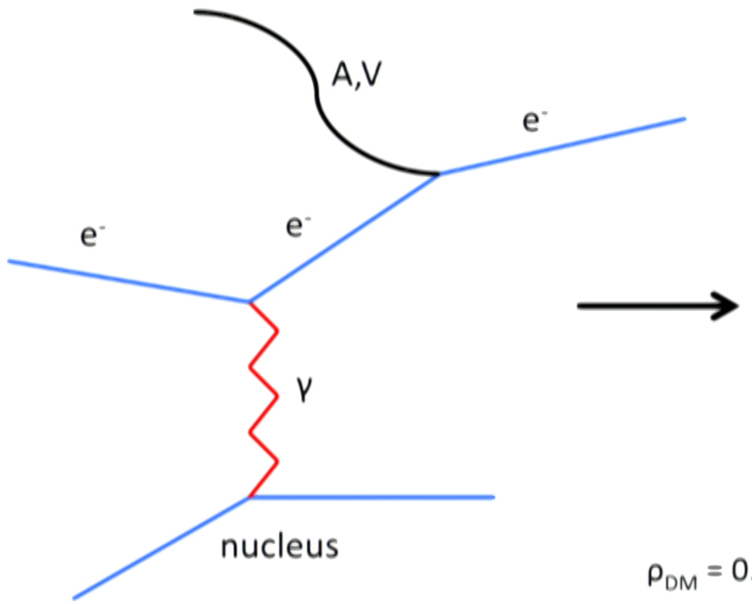
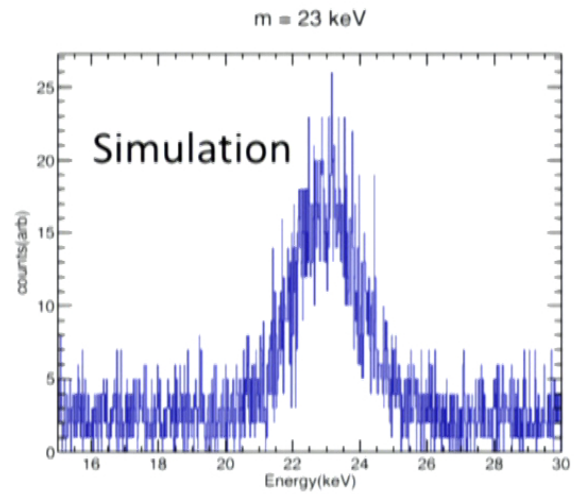
Example: Light (1-100 keV-scale) Bosonic DM

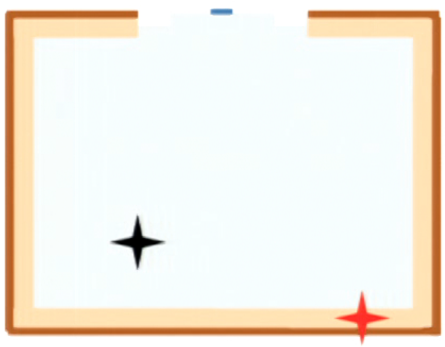




$\rho_{DM} = 0.3\ \mathrm{GeV/cm^3}$ $\beta = v/c \sim 0.001$

- Low threshold PPC Ge detectors well suited for keV-scale DM search
- Pseudoscalar (ALPs) or Vector DM could deposit rest mass-energy in detector

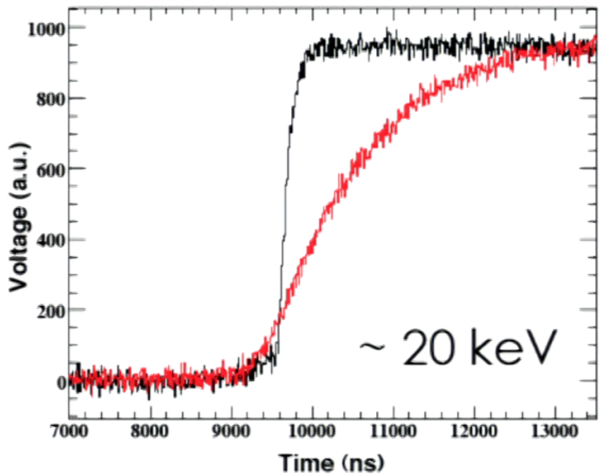
Slow Surface Events Near Detector Surface



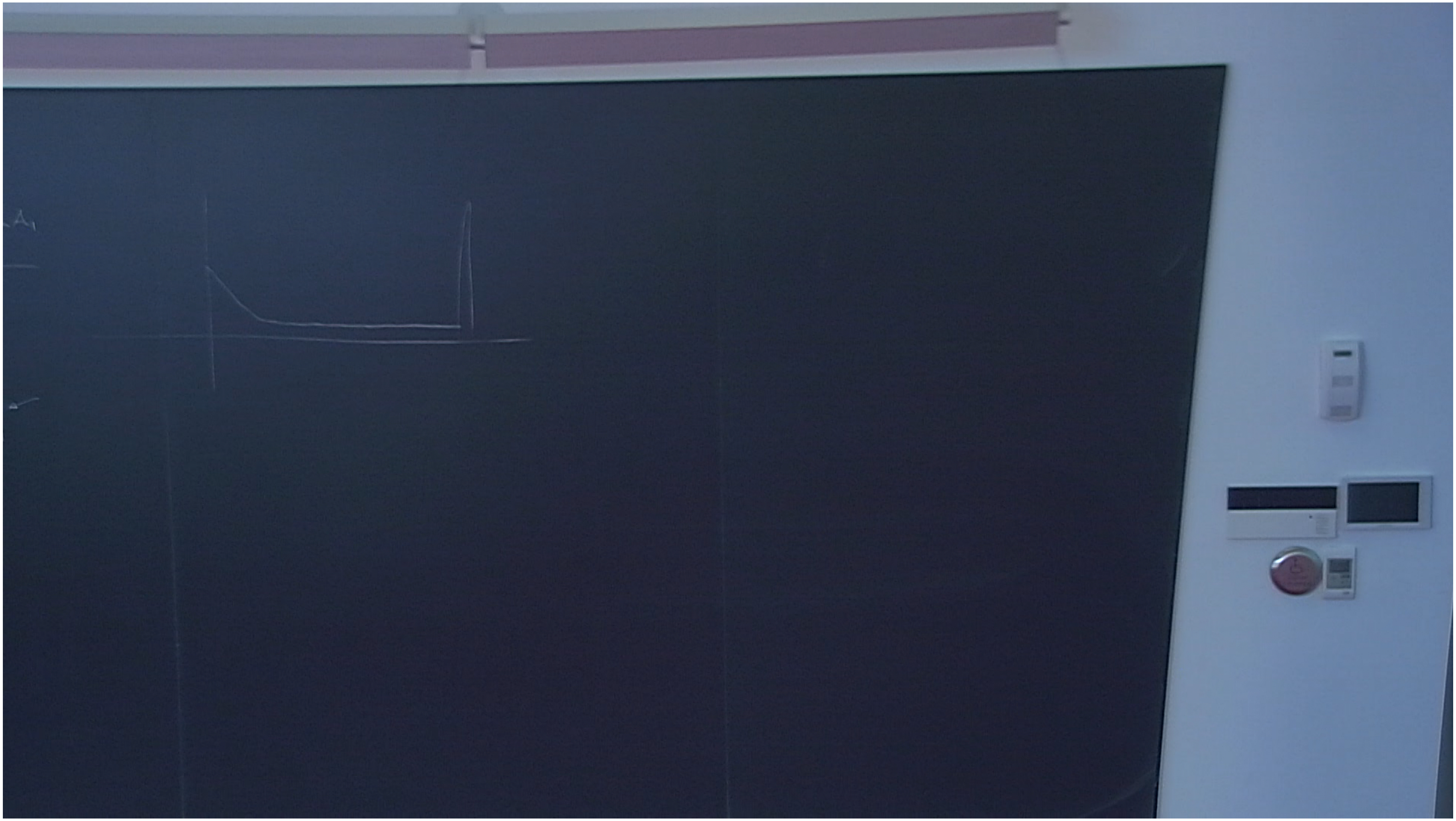
active volume

n+ dead layer

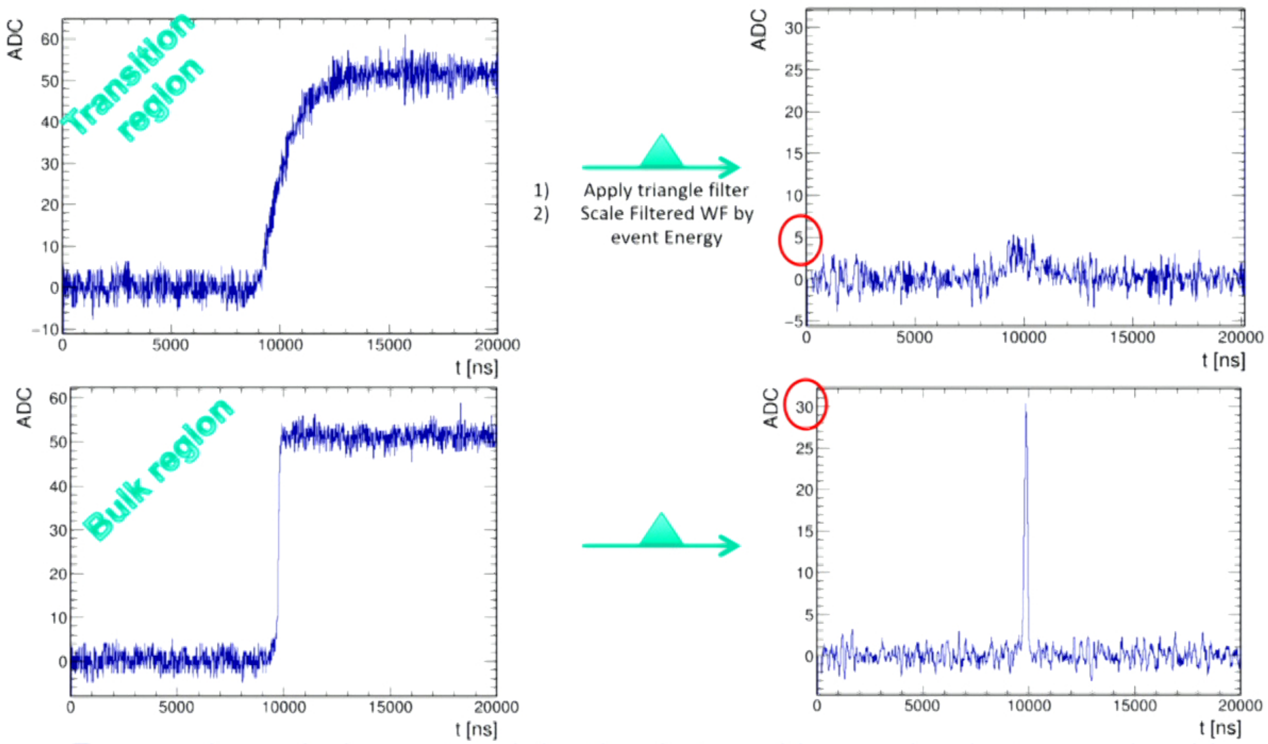
transition region – partial charge collection



Also energy-degraded



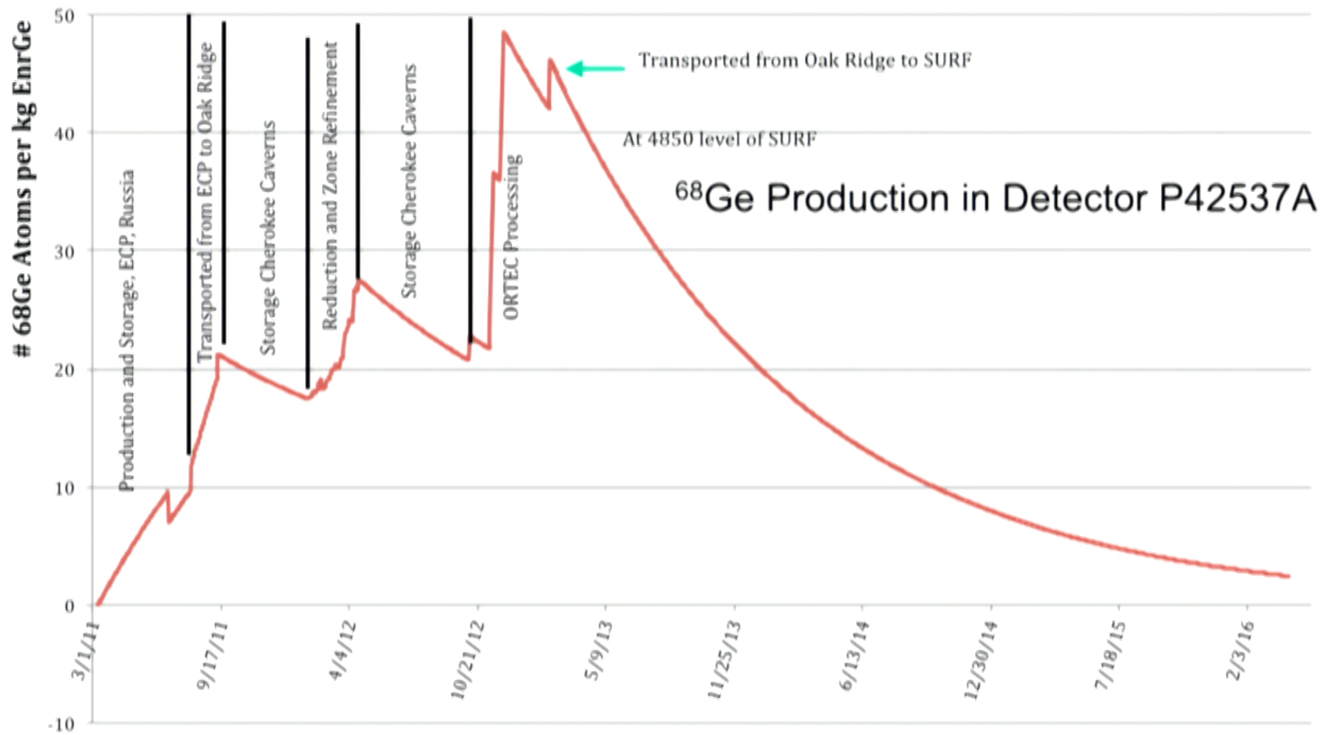
Transition Region Event Tagging



- Energy degraded events originating in transition region between dead layer and bulk region are a major background in low energy Ge experiments

G. Giovanetti et al., A Physics Procedia, **61**, 2015, 77, C. E. Aalseth et al., Phys. Rev. D **88,** 012002, 2013

Tracked and Minimized Cosmic-ray exposure



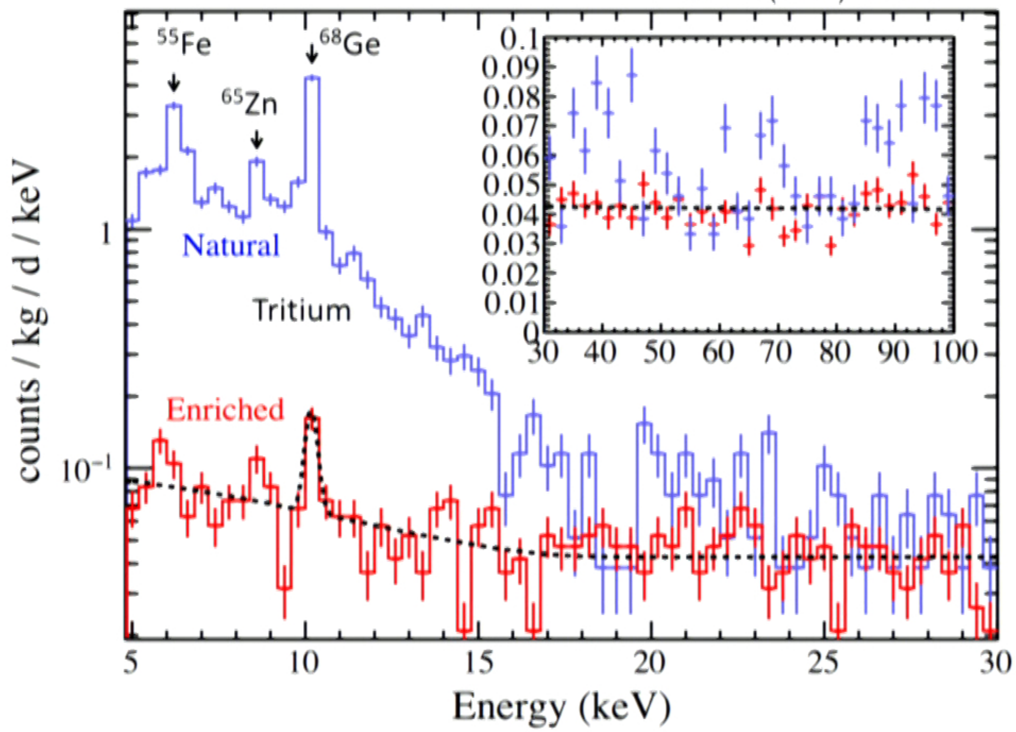
Low-Energy Spectrum in M1 Commissioning Data

Input: DVI - 1920x1080p@60Hz
Output: SDI - 1920x1080i@60Hz

Much lower background in enriched detectors, due to tight exposure control

- Exposure, enriched: 478 ± 6 kg-days, natural: ~195 kg-days
- From 20-40 keV: **~0.04** cts/kg-d-keV **(Best in world for Ge)**

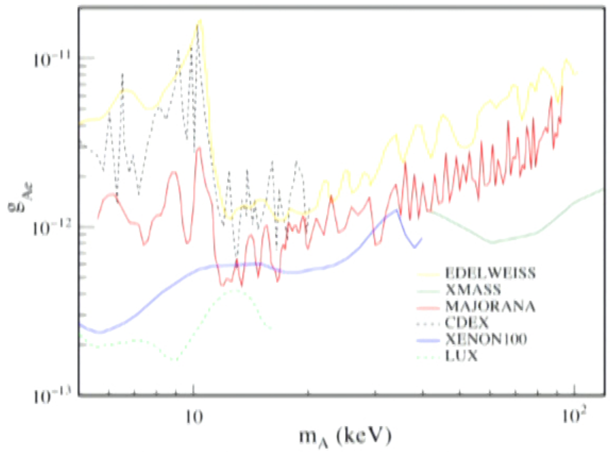
PRL 118 (2017) 161801



Dark Matter Results

For DS-0, 13 enriched detectors and a 478 kg-day exposure:

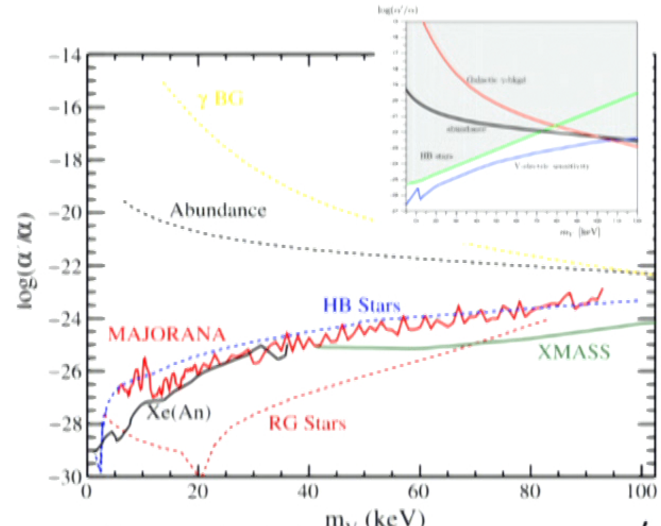
- Most stringent limit is for pseudoscalar axion-like particles (mass 11.8 keV)
- 90% upper limit for the coupling constants based on the expected event rate



Pseudoscalar ALP-like DM

$$g_{Ae} < 4.5 \times 10^{-13}$$

$$S(E) \approx g_{A_e}^2 \left(\frac{m_A}{\text{keV}}\right)\left(\frac{\sigma_{pe}}{\text{barn}}\right)\frac{1.2 \times 10^{-19}}{A}$$



Vector DM electron coupling α'

$$\left(\frac{\alpha'}{\alpha}\right) < 9.7 \times 10^{-28}$$

$$\Phi_{\text{DM}}(m_V)\sigma_{Ve}(m_V) = \frac{4 \times 10^{23}}{m_V}\left(\frac{\alpha'}{\alpha}\right)\frac{\sigma_{pe} m_V}{A}$$

Additional Low-Energy Results

Three additional limits obtained from DS-0:

- **Solar axion coupling** (14.4 keV ^{57}Fe M1)

  Low-mass limit. 90% UL.

  $$g_{AN}^{\text{eff}} \times g_{Ae} < 3.8 \times 10^{-17}$$

- **Non-Paulian transition** in Ge:

  $$a_i a_j^\dagger - q\ a_j^\dagger a_i = \delta_{ij}$$
  $$q = -1 + \beta^2$$

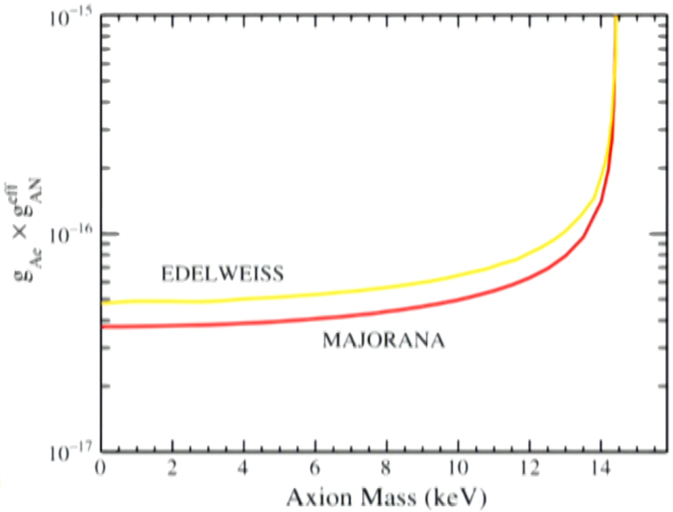
  Binned likelihood study for peak at 10.6 keV

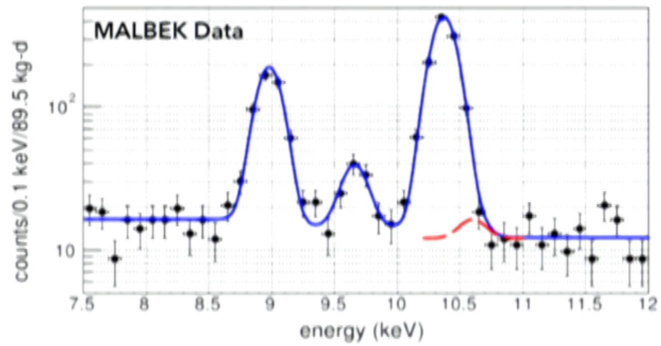
  $$1/2\ \beta^2 < 8.5 \times 10^{-48}$$ (90% CL UL)

- **Electron decay**

  Binned likelihood for peak at 11.1 keV

  $$e^- \rightarrow \nu\ \bar{\nu}\ \nu$$
  $$\tau_e > 1.2 \times 10^{24}\ \text{yr}$$ (90% CL UL)





Ref. MALBEK, arxiv:1610.06141

What's next?

Current backgrounds factor 2-3 lower

Will collect 5-10x stats.

- Updated bosonic DM search
- Solar axions
- Light WIMP w/ bremsstrahlung
- Charged Excitations
- Other

PRL 118, 031803 (2017) PHYSICAL REVIEW LETTERS week ending 20 JANUARY 2017

Probing Sub-GeV Dark Matter with Conventional Detectors

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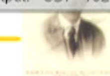
(Received 17 July 2016; revised manuscript received 28 November 2016; published 20 January 2017)

PRL 109, 251302 (2012) PHYSICAL REVIEW LETTERS week ending 21 DECEMBER 2012

Direct Constraints on Charged Excitations of Dark Matter

Haipeng An,[1] Maxim Pospelov,[1,2] and Josef Pradler[3]
[1]Perimeter Institute, Waterloo, Ontario N2L 2Y5, Canada
[2]Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia V8P 5C2, Canada
[3]Department of Physics and Astronomy, Johns Hopkins University, Baltimore, Maryland 21210, USA
(Received 9 October 2012; published 20 December 2012)

LEGEND



Large Enriched Germanium Experiment for Neutrinoless Decay

Working cooperatively with GERDA and other interested groups toward the establishment of a next-generation 76Ge 0vBB decay experimental collaboration, to build an experiment to explore the inverted ordering region of the effective mass.

37 institutions in 14 countries: North America, Europe, and Asia

The MAJORANA Collaboration

Acknowledgment

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, the Particle Astrophysics and Nuclear Physics Programs of the National Science Foundation, and the Sanford Underground Research Facility.