Results of the MAJORANA DEMONSTRATOR's search for neutrinoless double-beta decay

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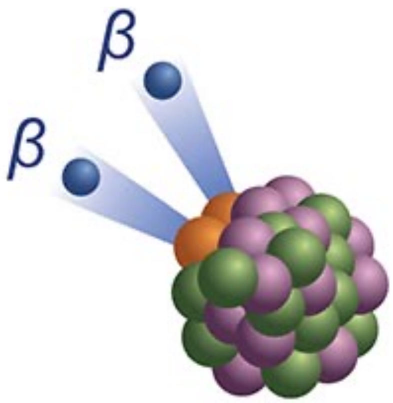
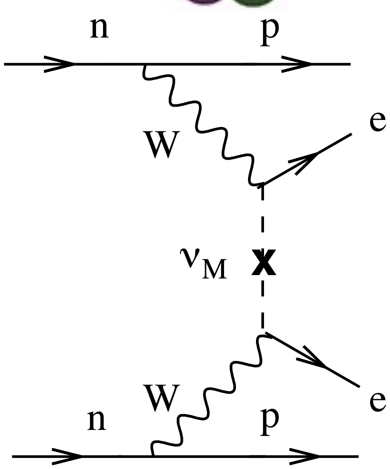
On behalf of MAJORANA collaboration
IPA 2022

Sanford Underground Research Facility
U.S. DEPARTMENT OF ENERGY | Office of Science
NSF

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





Searching for theoretical process:

$$(\mathbf{A}, \mathbf{Z}) \rightarrow (\mathbf{A}, \mathbf{Z}+\mathbf{2}) + \mathbf{2e^{-}}$$

Contrast with observed $2\nu\beta\beta : (A, Z) \rightarrow (A, Z+2) + 2e^{-} + 2\bar{\nu}_e$

$0\nu\beta\beta$ necessarily requires new physics

Lepton number is not conserved

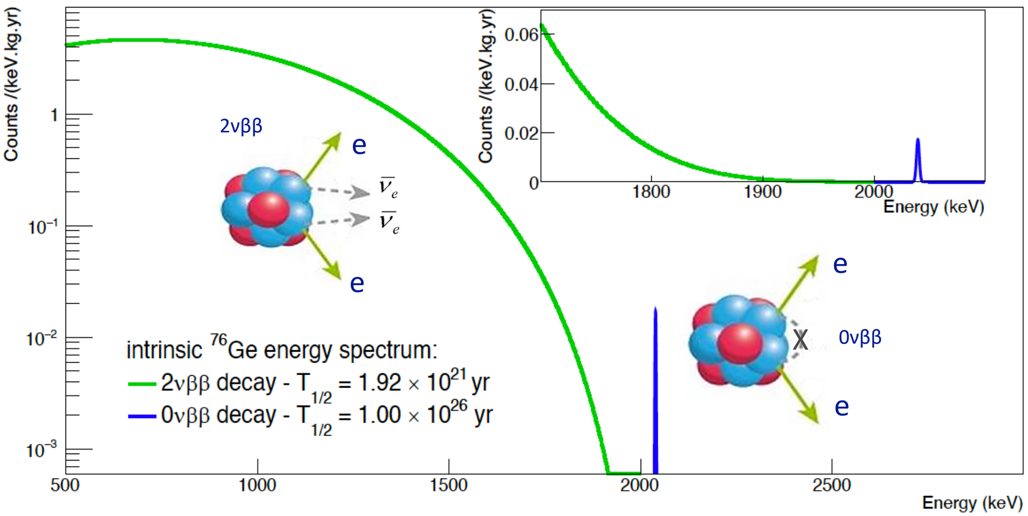
Fundamental Majorana particles exist

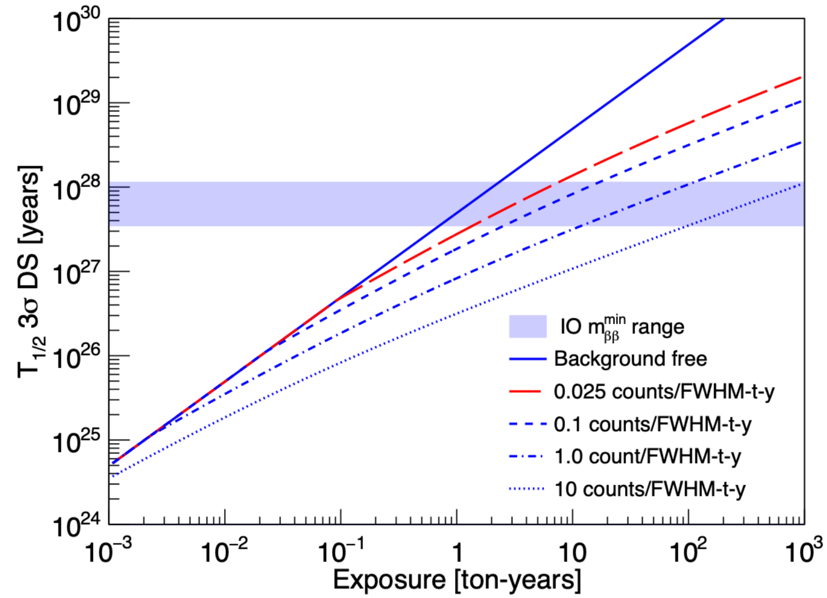
$0\nu\beta\beta$ related to other exciting physics

Small observed neutrino mass scale Majorana neutrinos help explain small observed neutrino masses via see-saw mechanism

Leptogenesis as ingredient for explaining matter-antimatter asymmetry

Neutrinoless Double Beta Decay





Signature of 0νββ is monoenergetic peak at Q-value

- Half-life greater than 1.8×10^{26} yr (^{76}Ge)

Intrinsic background from continuous 2νββ spectrum at lower energy

- Half-life of 1.9×10^{21} yr (^{76}Ge)

Effective Neutrino Mass

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

Nuclear Matrix Element

MAJORANA DEMONSTRATOR

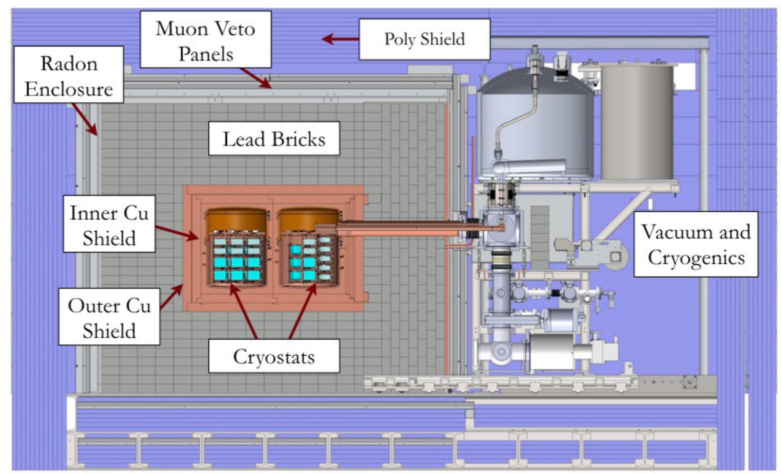
Searching for neutrinoless double-beta decay of ^{76}Ge in HPGe detectors, probing additional physics beyond the standard model, and informing the design of the next-generation LEGEND experiment

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

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

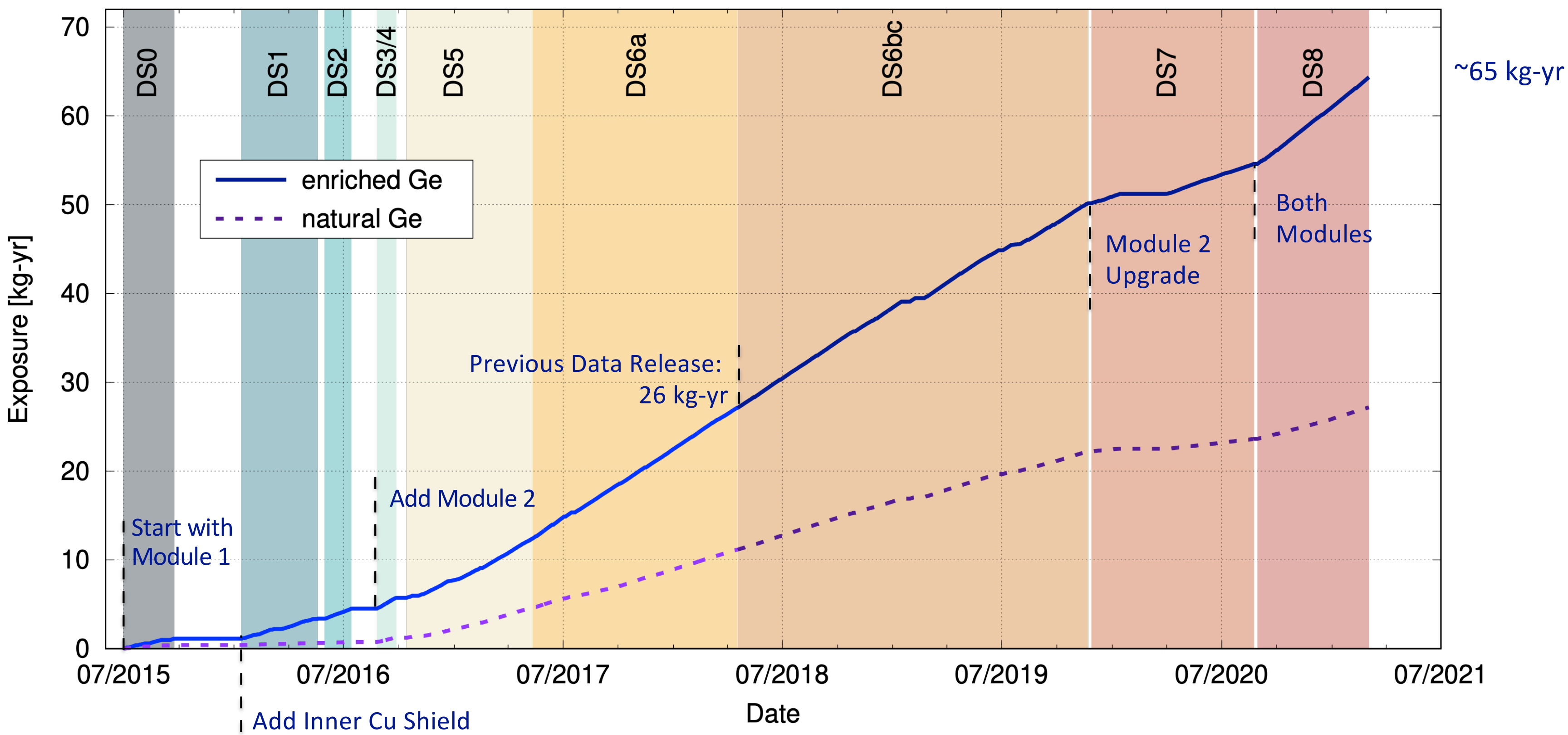
Low Background: 2 modules within a compact graded shield and active muon veto using ultra-clean materials

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



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

MAJORANA Total Exposure



MAJORANA Approach to Backgrounds

P-type point contact detectors low intrinsic backgrounds, excellent energy resolution, pulse-shaped based background suppression

PRC **100** 025501 (2019)

Ge enrichment, zone-refining and crystal pulling processes enhance purity

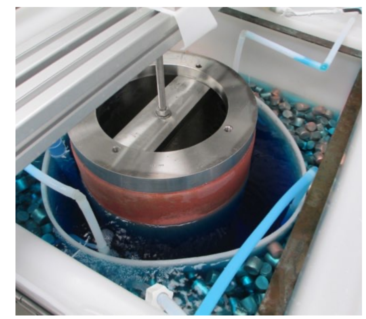
NIM A **877** 314 (2018)

Limit above-ground exposure to prevent cosmic activation.

Slow drift of ionization charge carriers allows separation of multiple interactions inside a detector.

Array components and passive shielding fabricated from ultra-pure materials with extremely low radio-isotope content

NIM A **828** 22 (2016)



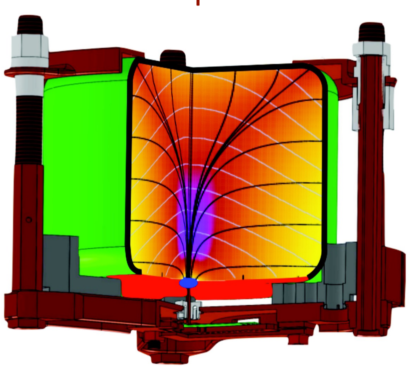
Rejection of backgrounds

Muon Veto: reject events coincident with muons

Astropart. Phys. **93** 70 (2017)

Granularity: multiple detectors hit

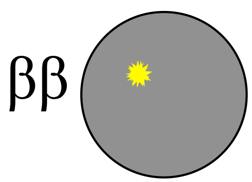
Pulse shape discrimination: no multiple hits, reject surface events



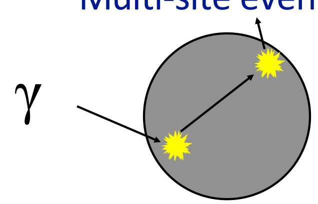
PRC **99** 065501 (2019)

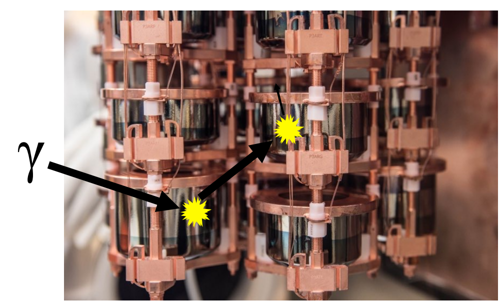
Eur. Phys. J. C **82,** 226 (2022)

Single-site event



Multi-site event





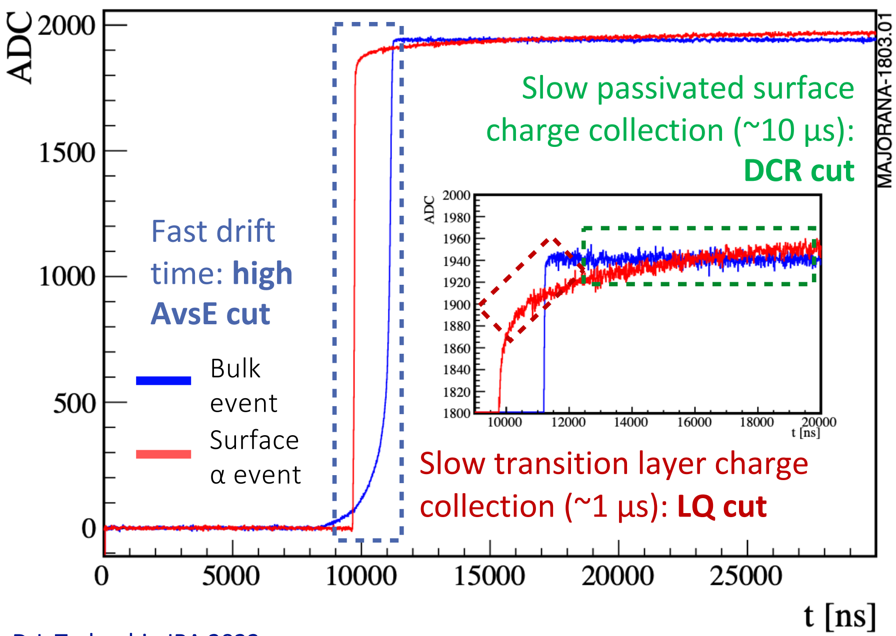
Analysis Techniques for Reducing Backgrounds

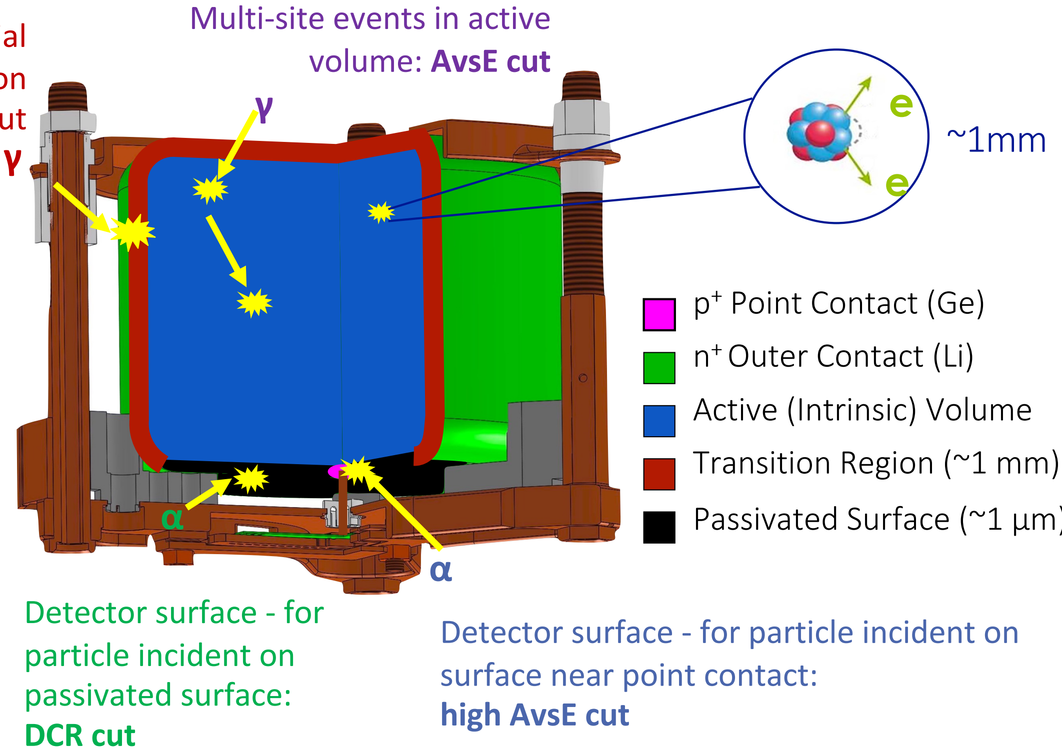
0νββ is most likely single-site and located in the bulk of the detector.

Many backgrounds are multi-site or located near detector surfaces.
Pulse-shape discrimination is used to distinguish between these event topologies.

PRC **99** 065501 (2019)

EPJC 82 (2022) 226





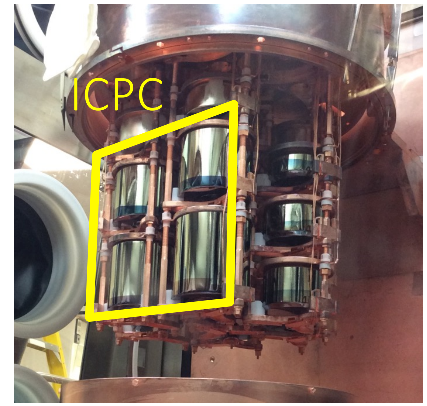
Inverted Coaxial Point Contact Detectors

Inverted coaxial point contact (ICPC) detectors are larger (>3 kg) than PPC detectors (up to 1.2 kg). MAJORANA operated 4 ICPCs from Aug. 2020 to Mar 2021

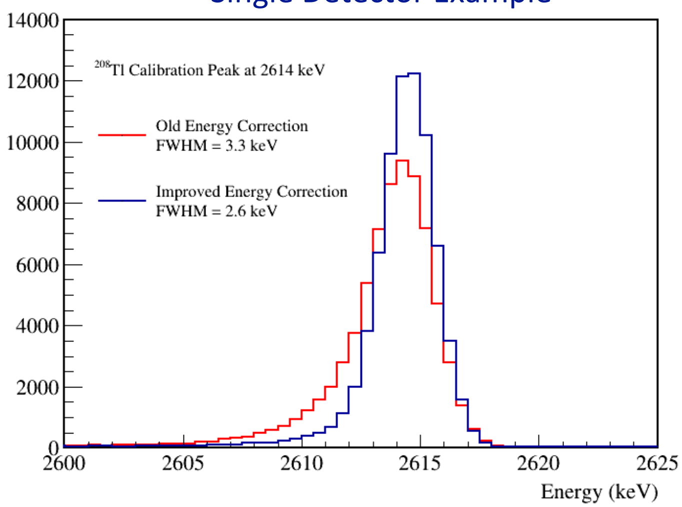
Beneficial for background reduction in LEGEND

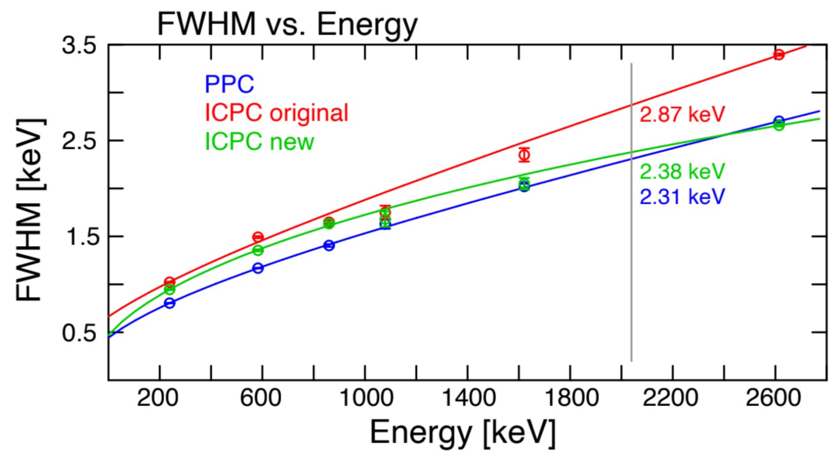
Larger range of drift times requires more refined analysis techniques

MAJORANA has demonstrated comparable performance with ICPCs and PPCs. Best energy resolution for ICPCs to date!



Single Detector Example

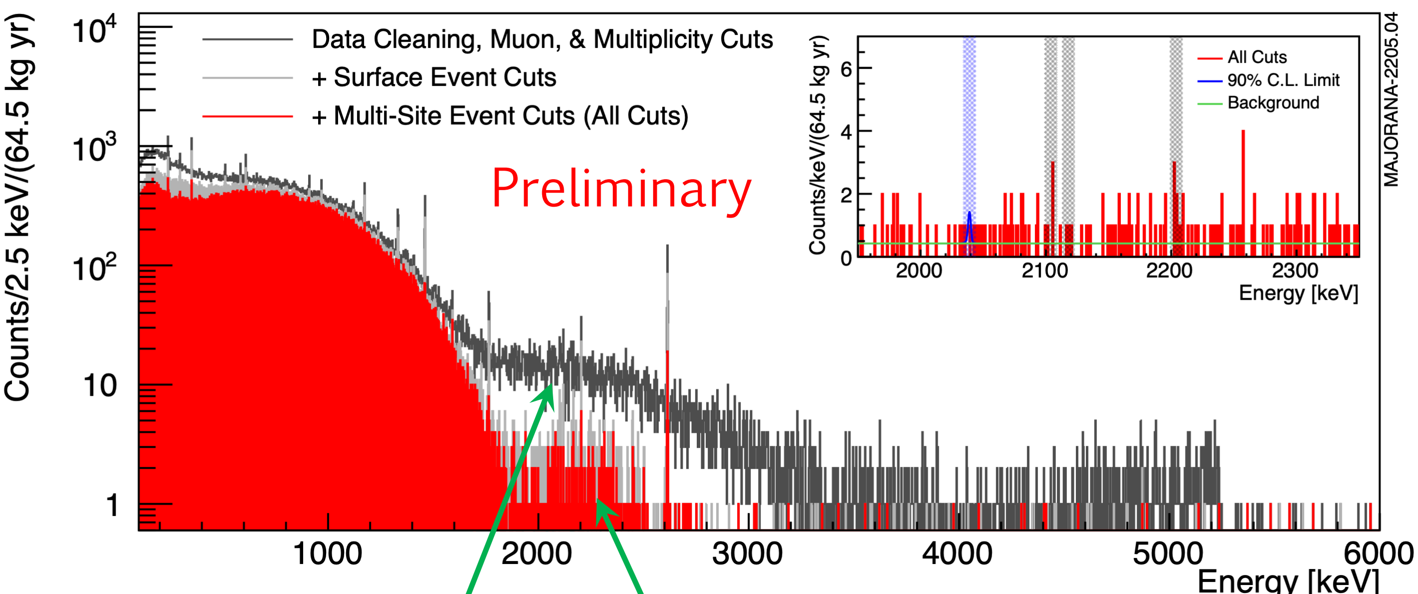




New analysis techniques improve combined energy resolution of ICPCs

MAJORANA DEMONSTRATOR 2022 0νββ Result

Operating in a low background regime and benefiting from excellent energy resolution



arXiv:2207.07638 (2022)

Dominated by surface alphas before cuts

^{208}Tl (^{232}Th)-like after cuts

Final enriched detector active exposure:

64.5 ± 0.9 kg-yr

Background index at 2039 keV in low-background configuration

15.7 ± 1.4 cts/(FWHM t yr)

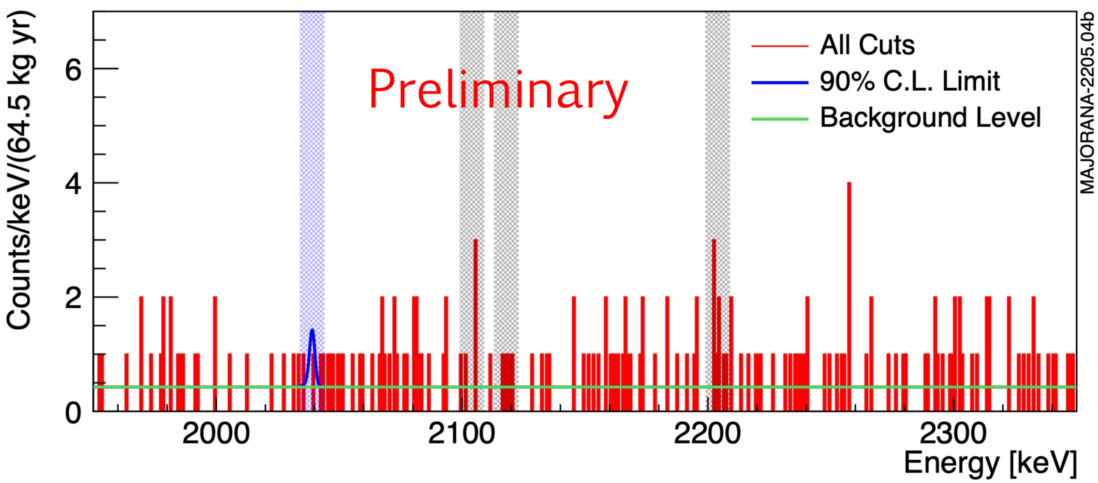
Background index in Module 1

18.6 ± 1.8 cts/(FWHM t yr)

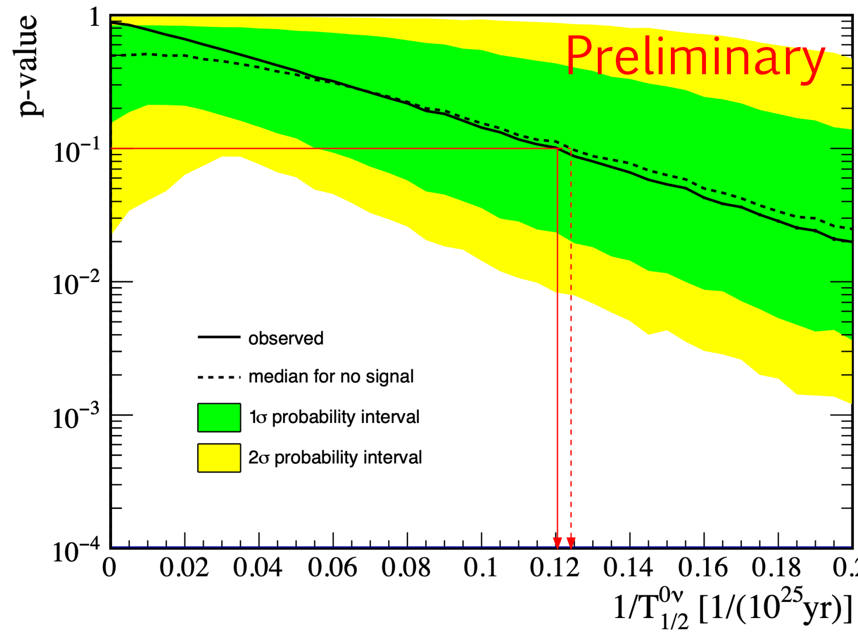
Background index in Module 2

$8.4^{+1.9}_{-1.7}$ cts/(FWHM t yr)

MAJORANA DEMONSTRATOR 2022 0νββ Result



arXiv:2207.07638 (2022)



Background Index:

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

Energy resolution: 2.5 keV FWHM @ $Q_{\beta\beta}$

Frequentist Limit:

Median $T_{1/2}$ Sensitivity: 8.1×10^{25} yr (90% C.I.)

65 kg-yr Exposure Limit: $T_{1/2} > 8.3 \times 10^{25}$ yr (90% C.I.)

Bayesian Limit: (flat prior on rate)

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

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

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

Rich and Broad Physics Programs

Tests of Fundamental Symmetries and Conservations

- Lepton number violation via $0\nu\beta\beta$
- Baryon number violation
- Pauli Exclusion Principle violation

arXiv:2207.07638 (2022)

PRC **100** 025501 (2019)

PRD **99** 072004 (2019)

arXiv:2203.02033 (2022)

Standard Model Physics

BSM Physics

Standard Model Physics, particular backgrounds

- $2\nu\beta\beta$ to excited states
- In situ cosmogenics
- (alpha, n) reactions

PRC **103** 015501 (2021)

PRC **105** 014617 (2022)

PRC **105** 064610 (2022)

MAJORANA DEMONSTRATOR

Excellent energy performance & low backgrounds across broad energy regions

Low-mass dark matter signatures

- Pseudoscalar dark matter
- Vector dark matter
- Fermionic dark matter
- Sterile neutrino
- Primakoff solar axion
- 14.4-keV solar axion

PRL **118** 161801 (2017)

PRL **129** 081803 (2022)

arXiv:2206.10638 (2022)

Exotic Physics

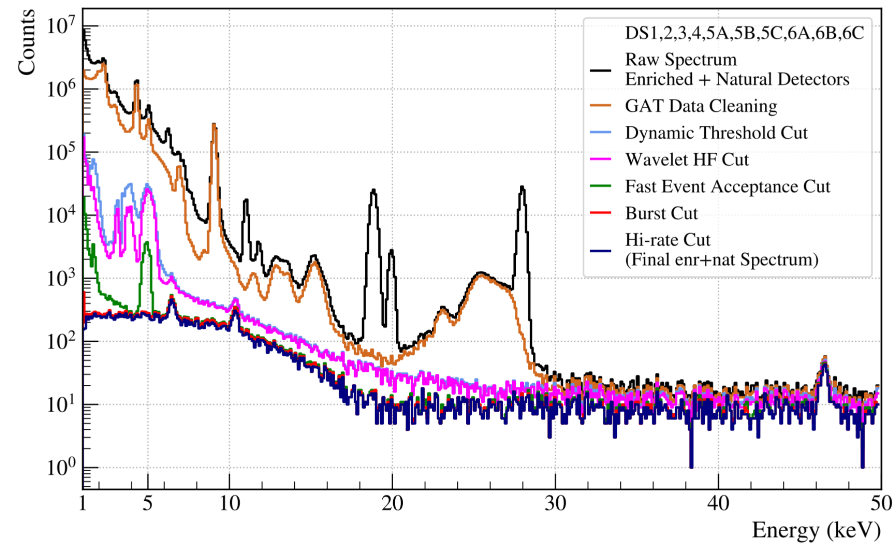
- Quantum wavefunction collapse
- Lightly ionization particle

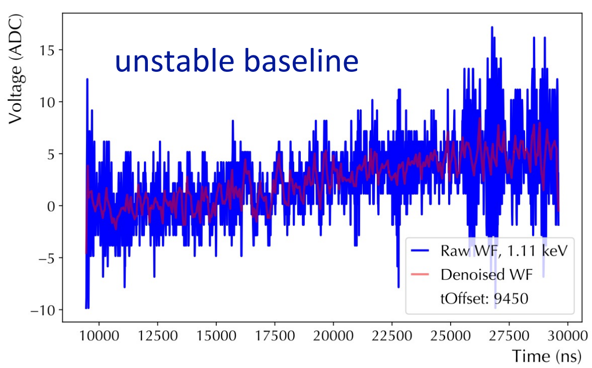
PRL **129** 080401 (2022)

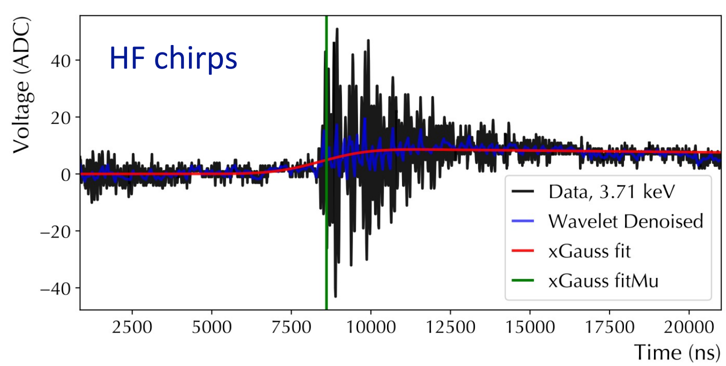
PRL **120** 211804 (2018)

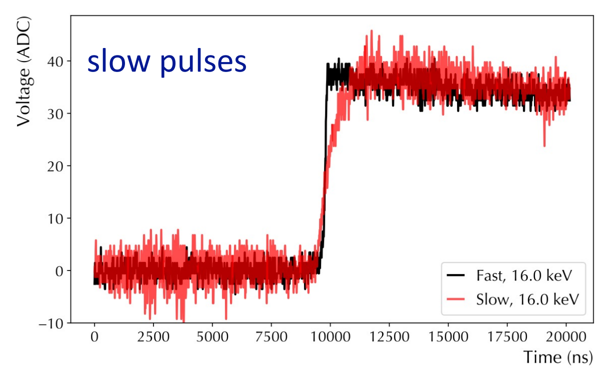
Cleaning up the Low Energy spectrum (1-100 keV)

- Many populations of low-energy noise initially obscured spectral features under 100 keV.
- Careful cuts based on waveform fitting, wavelet denoising, and other parameters were trained on ^{228}Th calibration data.
- Data taking milestones:
  - **June 2015:** commissioning dataset taken
  - **Nov 2019:** End of the "Low-E" data set (6C)
  - **2021:** ^{enr}Ge detectors removed, ^{nat}Ge detectors running
- After 4 years of operation, our analysis achieves a
- **5 order of magnitude noise reduction** in the low E spectrum!



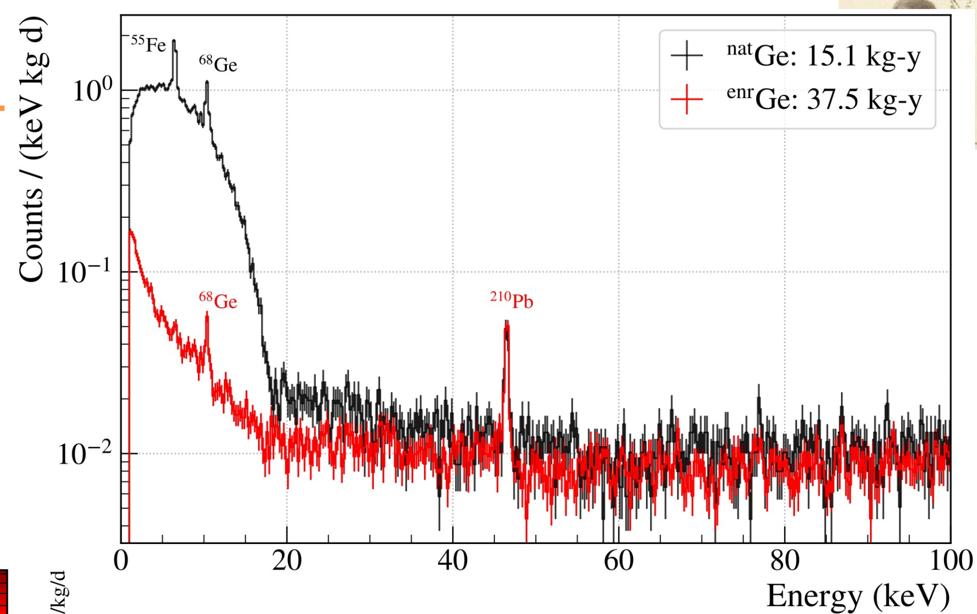


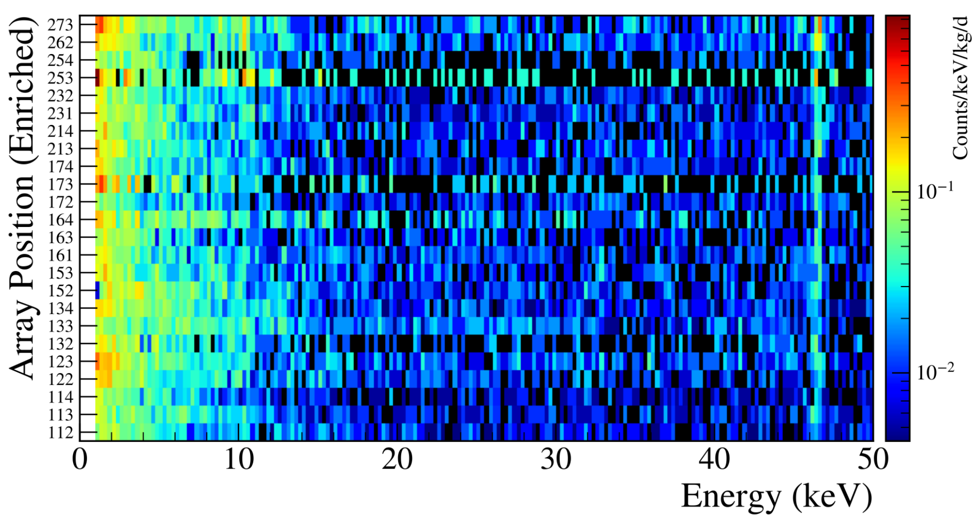


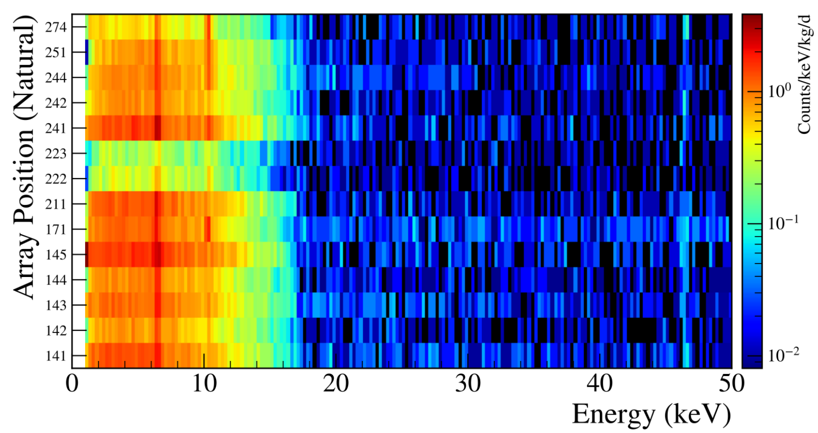


The Low-E spectrum

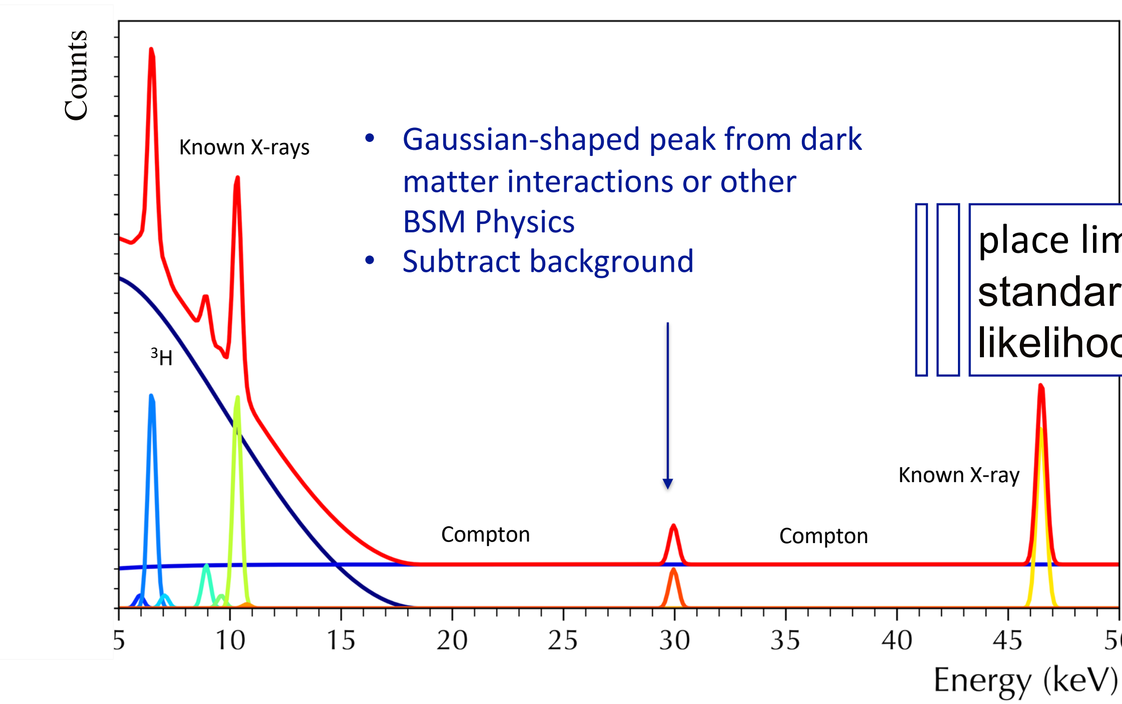
- After spectrum is cleaned:
  - 37.5 kg-y ^{enr}Ge, 15.1 kg-y ^{nat}Ge
  - ^{210}Pb line at 46 keV @ same rate in both sets
  - Minimal cosmogenic activation in ^{enr}Ge
  - ^{enr}Ge rising shape likely from Rn progeny
  - Reduced cosmogenics in two ^{nat}Ge detectors







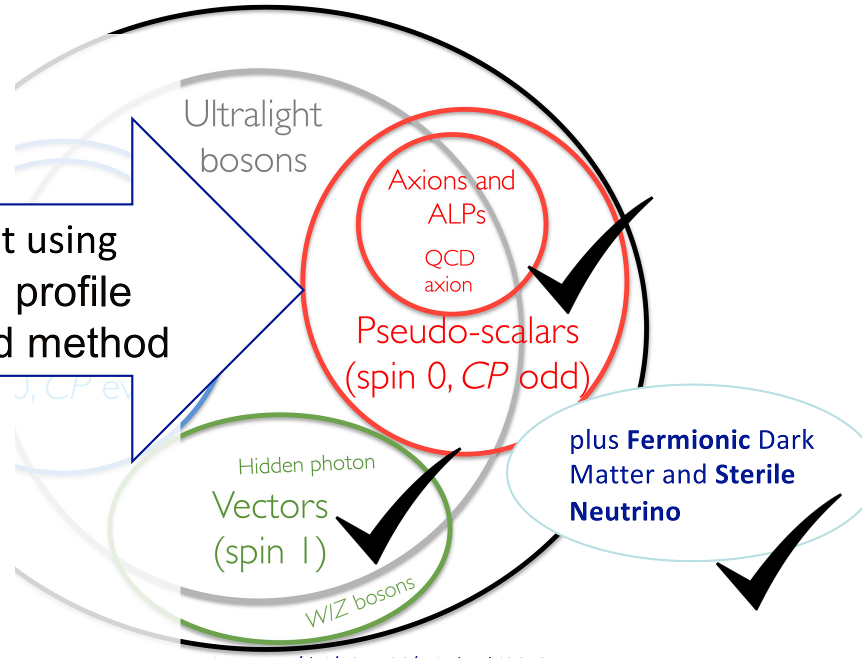
Common Theme: BSM Peak Searches in Energy Spectrum



- Gaussian-shaped peak from dark matter interactions or other BSM Physics
- Subtract background

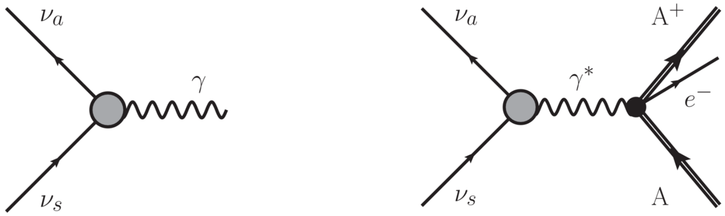
place limit using standard profile likelihood method

Dark Matter candidates



science.org/doi/10.1126/sciadv.abj3618

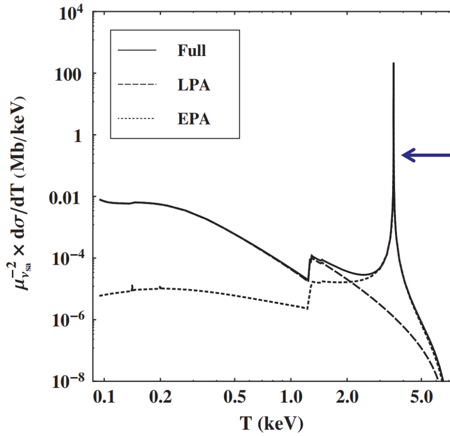
$\nu_s - \nu_a$ Sterile-to-Active Transition Magnetic Moment



- Transition magnetic moment (TMM) could induce a sterile-to-active transition
- DM sterile neutrinos can ionize atom A: *[Phys. Rev. D 93, 093012 (2016)]*

$$\nu_s + A \rightarrow \nu_a + A^+ + e^-$$

- Cross section enhanced greatly at energy transfer of $m_s/2$, leading to a peak-like signature.
- MAJORANA searched for sterile neutrino DM peak-like signature
- **<u>The limit established by MAJORANA is the best limit so far</u>**
- The local galactic halo is considered as the source of incoming ν_s
- Implication: If the DM halo consists of the keV-scale sterile neutrinos, then the μ_{sa} is too weak to produce the XENON1T excess

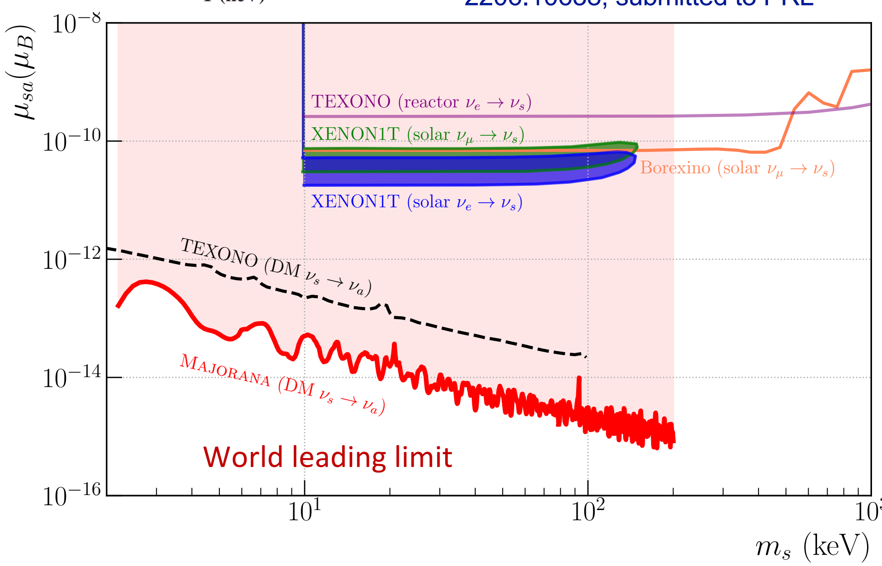


PRD **93**, 093012 (2016)

$$\frac{d\sigma(m_s, v)}{dT} \approx \left(\frac{\mu_{sa}}{2m_e}\right)^2 \frac{\alpha}{2n_A} \frac{m_s^2}{|v|^2}$$

v^{-2} amplification

2206.10638, submitted to PRL

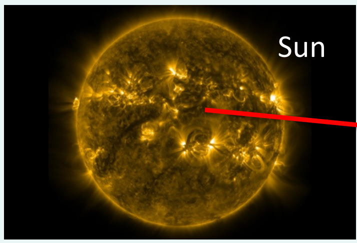


Solar Axion Search via Photon Coupling

BSM Physics

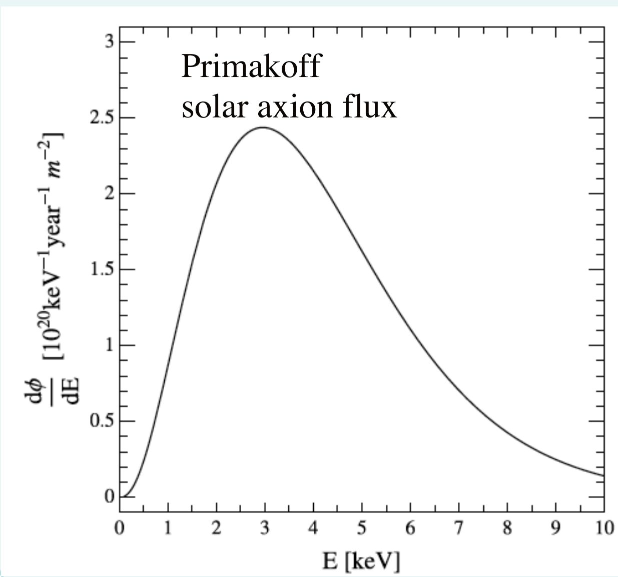
Energy-Time 2-D analysis

Production



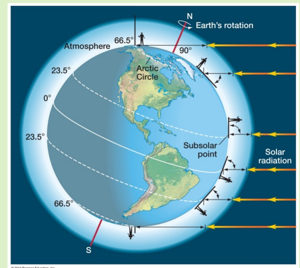
$\gamma + \gamma \rightarrow Axion$ Primakoff axions

axion-photon coupling (reverse Primakoff effect)



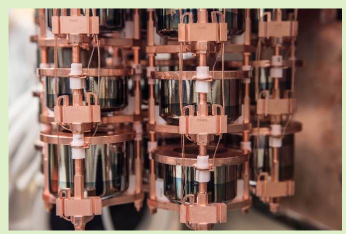
Progress in Particle and Nuclear Physics
102 (2018) 89–159

Detection



$Axion + \gamma_{virtual} \rightarrow \gamma$

- axion-photon coupling (Primakoff effect)
- enhanced by coherent Bragg diffraction



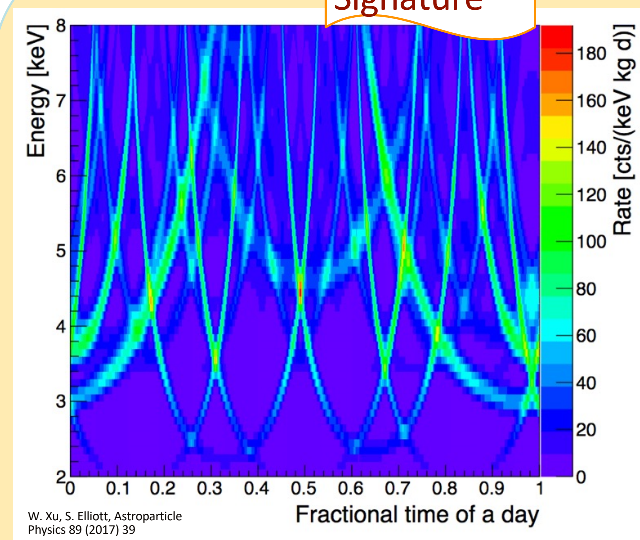
Axion signals:

- enhanced at certain incident angles for certain energy --- the Bragg condition
- follow Sun's movement over time

R. J. Creswick, et al., PLB 427, 235-240 (1998)

R. Battesti et al. Lect. Notes Phys. 741, 199–237 (2008)

Signature



plot for $g_{A\gamma} = 10^{-8} GeV^{-1}$, $g_{Ae} = 0$

- ➢ Distinct time dependence is a key strength for discovery
- ➢ Reduced sharpness if crystal orientations on the horizontal plane are unknown, but still good for analysis

Solar Axion Search

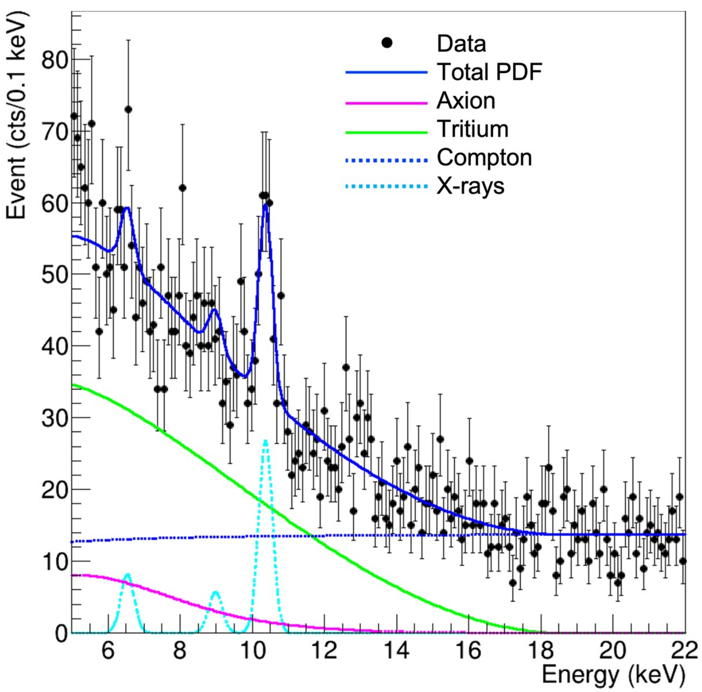
Combine time and energy into a 2-dimensional analysis

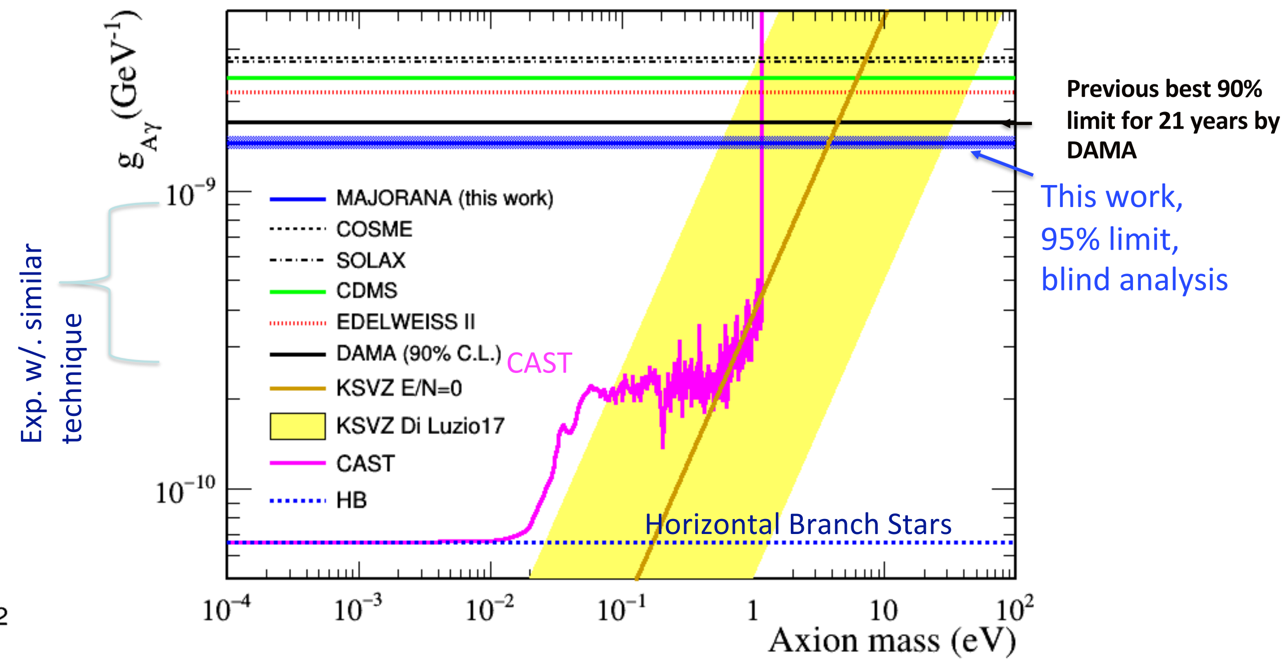
All PDFs have both energy and time dependence
(5-min precision over 3 years)

Only the energy dimension shown
Solar axion flux consistent with zero within 2.1σ

PRL **129**, 081803 (2022)

$g_{A\gamma} < 1.45\times10^{-9}\mathrm{GeV}^{-1}$ (95% Bayesian CI) improves the best lab-based limit between 1.2 eV and 100 eV solar axion mass





SOLAX, Phys. Rev. Lett., 81:5068, 1998, DAMA, Phys. Lett. B, 515:6, 2001 , COSME, Astropart. Phys., 16:325, 2002, CDMS, Phys. Rev. Lett., 103:141802, 2009 EDELWEISS II, JCAP11 (2013) 067

MAJORANA DEMONSTRATOR Summary and Outlook

- Started taking data with first module in 2015 and has completed enriched Ge data-taking in 2021
  - Excellent energy resolution of 2.5 keV FWHM @ 2039 keV, best of all 0νββ experiments
  - **Latest limit on 0νββ of $T_{1/2} > 8.3 \times 10^{25}$ yr (90% C.I.) from 64.5 kg-yr exposure**
  - Leading limits in the search for double-beta decay of ^{76}Ge to excited states
- Background model being investigated and refined
  - Initial background fits are informing possible distribution of background sources
- Low background + energy resolution + multiple years of high-quality data allows for broad physics program, yielding many new results
  - BSM physics results extracted in wide energy range with various analysis techniques
  - Search for neutron and cosmogenic signatures at high energy
- Continuing operation with natural detectors for background studies and other physics
- The technologies, analysis techniques, and people involved in MAJORANA will continue to play a major role in searching for 0νββ with LEGEND

Walter C. Pettus

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U.S. DEPARTMENT OF ENERGY | Office of Science

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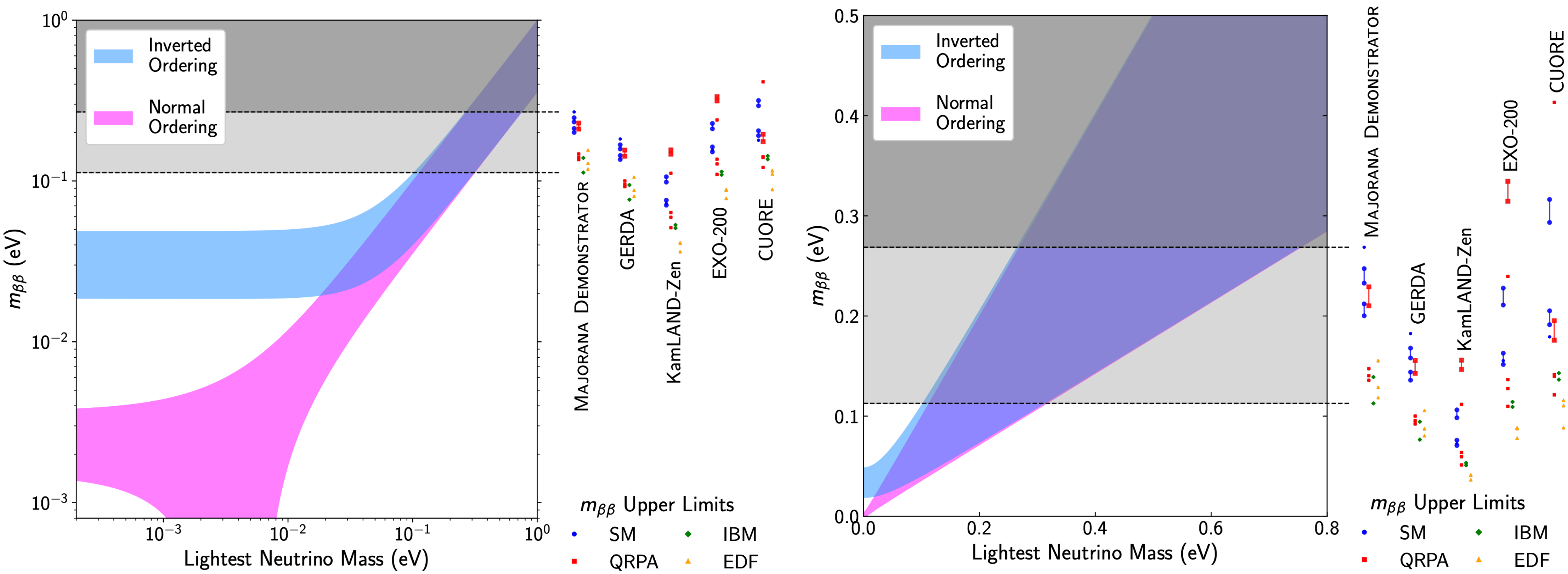
Backup

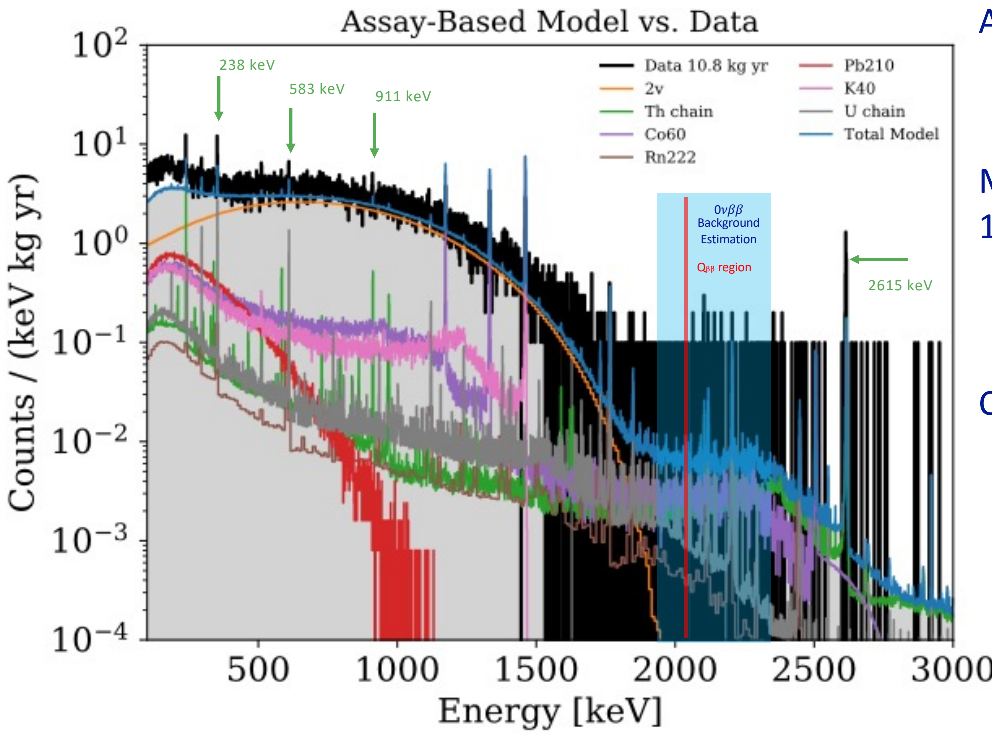
MAJORANA DEMONSTRATOR 2022 0νββ Result

Allowed values of the effective Majorana mass (mββ) for the Normal and Inverted Ordering



Best-fit values of neutrino oscillation parameters from 2022 PDG [PTEP **2022** 083C01 (2022)]

Background Modeling and Investigation



Assay-based prediction: 2.9 ± 0.14 cts/ (FWHM t y)

Updated to match as-built geometry, new assay information, and more refined uncertainties

Measured Background in lowest background configuration: 15.7 ± 1.4 cts/(FWHM t y) [PRELIMINARY]

Module 1: 18.6 ± 1.8 cts/(FWHM t yr)

Module 2: 8.4 $^{+1.9}_{-1.7}$ cts/(FWHM t yr)

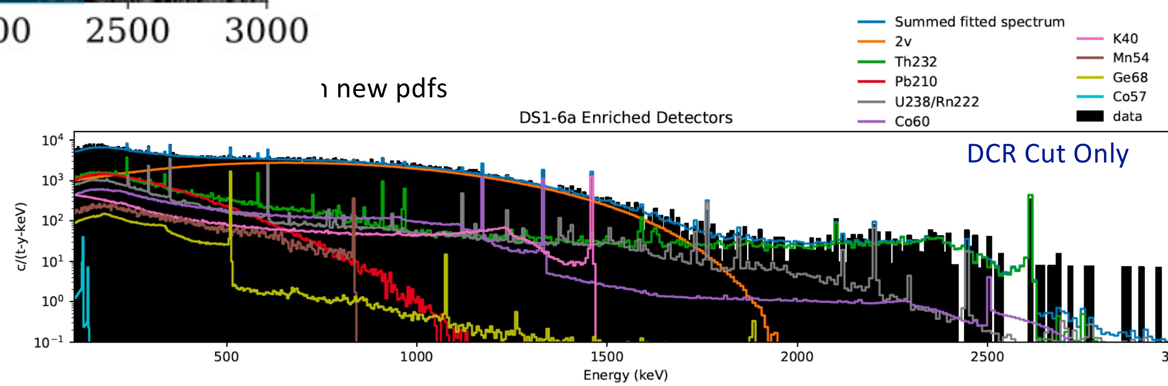
Characteristics of background excess:

Dominated by ^{232}Th decay chain — excess apparent at ^{208}Tl, especially 238 keV and 2615 keV

Does not indicate a source within the Ge detector array (front end electronics, detector holders, etc.).

ı new pdfs

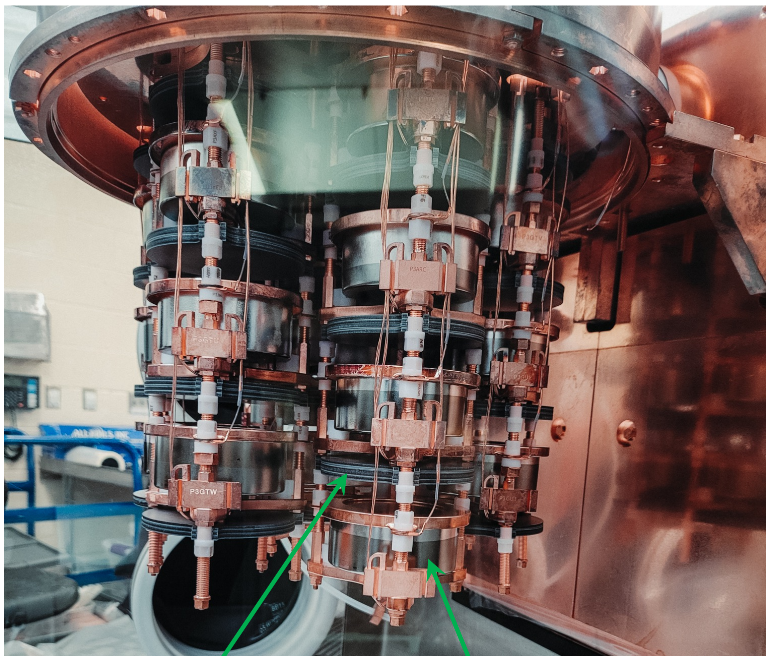
Improved Frequentist and Bayesian fitting efforts underway in order to more precisely locate source of excess ^{232}Th background and complete the background model



Tantalum: The Next DEMONSTRATOR Chapter

MAJORANA DEMONSTRATOR has been reconfigured with single module of only natural detectors only

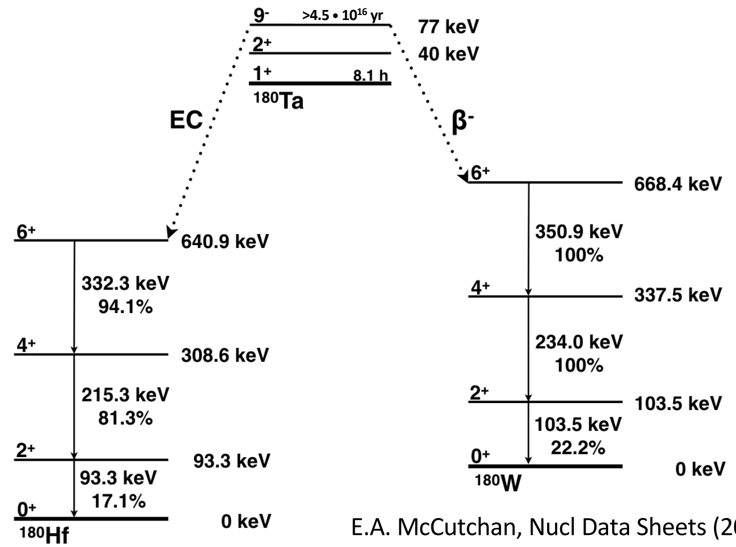
Searching for decay of ^{180m}Ta, nature's longest lived metastable isotope



17 kg tantalum disks

2 g ^{180m}Ta

23 ^{nat}Ge BEGe detectors



E.A. McCutchan, Nucl Data Sheets (2015)
B. Lehnert *et al.* Phys. Rev. C (2017)

MAJORANA search will be sensitive to theory-favored half-lives of 10^{17}–10^{18} yr

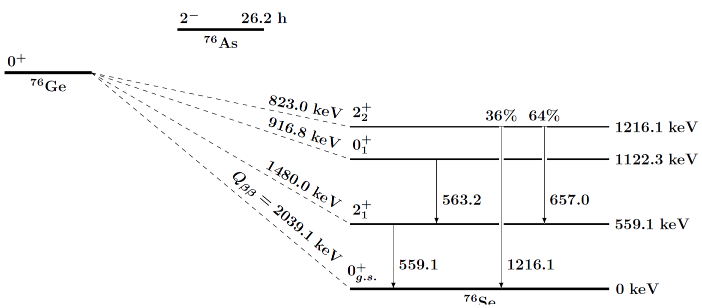
- Order of magnitude more ^{180m}Ta than previous searches
- Many more detectors for coincidence gammas
- Ultra-low background DEMONSTRATOR environment
- Two orders of magnitude improvement in sensitivity

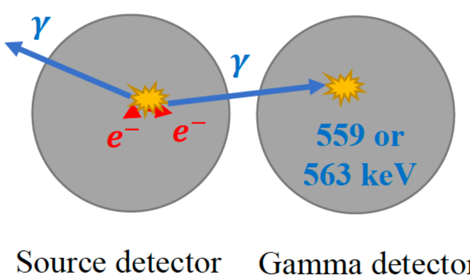
Double Beta Decay to Excited States

- **Sensitive to neutrino properties**: e.g. if the neutrino has a bosonic component, the ββ half-life to the 2_1^+ state would be sensitive

- ββ to Excited States is inherently multi-site. Look for **events with multiple detectors**:
  - The "source" detector will have a broad energy spectrum from the ββ-site
  - The "gamma" detector will measure energy peaked at the γ energies

- **Perform a peak search**, utilizing information from the source detector to reduce backgrounds and improve sensitivity





Example of $2\nu\beta\beta$ to the 0_1^+ state

New Half-Life Limits Set

PRC **103** 015501 (2021)

Decay Mode	Det. efficiency (M1, M2)	$T_{1/2}$ prev. limit (90% CI)	$T_{1/2}$ new limit (90% CI)	$T_{1/2}$ sensitivity (90% CI)
$0^+_{g.s.} \xrightarrow{2\nu\beta\beta} 0^+_1$	2.4%, 1.0%	$> 3.7 \cdot 10^{23} y$ [1]	$> \mathbf{7.5 \cdot 10^{23} y}$	$> \mathbf{10.5 \cdot 10^{23} y}$
$0^+_{g.s.} \xrightarrow{2\nu\beta\beta} 2^+_1$	1.4%, 0.6%	$> 1.6 \cdot 10^{23} y$ [1]	$> \mathbf{7.7 \cdot 10^{23} y}$	$> \mathbf{10.2 \cdot 10^{23} y}$
$0^+_{g.s.} \xrightarrow{2\nu\beta\beta} 2^+_2$	2.2%, 0.8%	$> 2.3 \cdot 10^{23} y$ [1]	$> \mathbf{12.8 \cdot 10^{23} y}$	$> \mathbf{8.2 \cdot 10^{23} y}$
$0^+_{g.s.} \xrightarrow{0\nu\beta\beta} 0^+_1$	3.0%, 1.2%	$> 1.3 \cdot 10^{22} y$ [2]	$> \mathbf{39.9 \cdot 10^{23} y}$	$> \mathbf{39.9 \cdot 10^{23} y}$
$0^+_{g.s.} \xrightarrow{0\nu\beta\beta} 2^+_1$	1.6%, 0.7%	$> 1.3 \cdot 10^{23} y$ [3]	$> \mathbf{21.2 \cdot 10^{23} y}$	$> \mathbf{21.2 \cdot 10^{23} y}$
$0^+_{g.s.} \xrightarrow{0\nu\beta\beta} 2^+_2$	2.3%, 1.0%	$> 1.4 \cdot 10^{21} y$ [4]	$> \mathbf{9.7 \cdot 10^{23} y}$	$> \mathbf{18.6 \cdot 10^{23} y}$