The MAJORANA DEMONSTRATOR

An R&D project towards a germanium-based tonne-scale neutrinoless double-beta decay search

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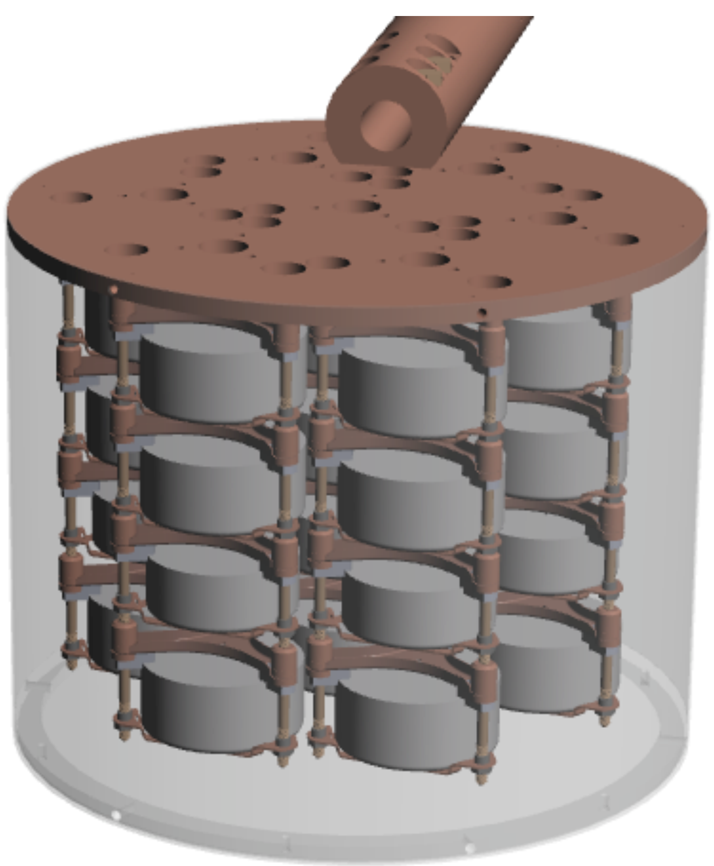
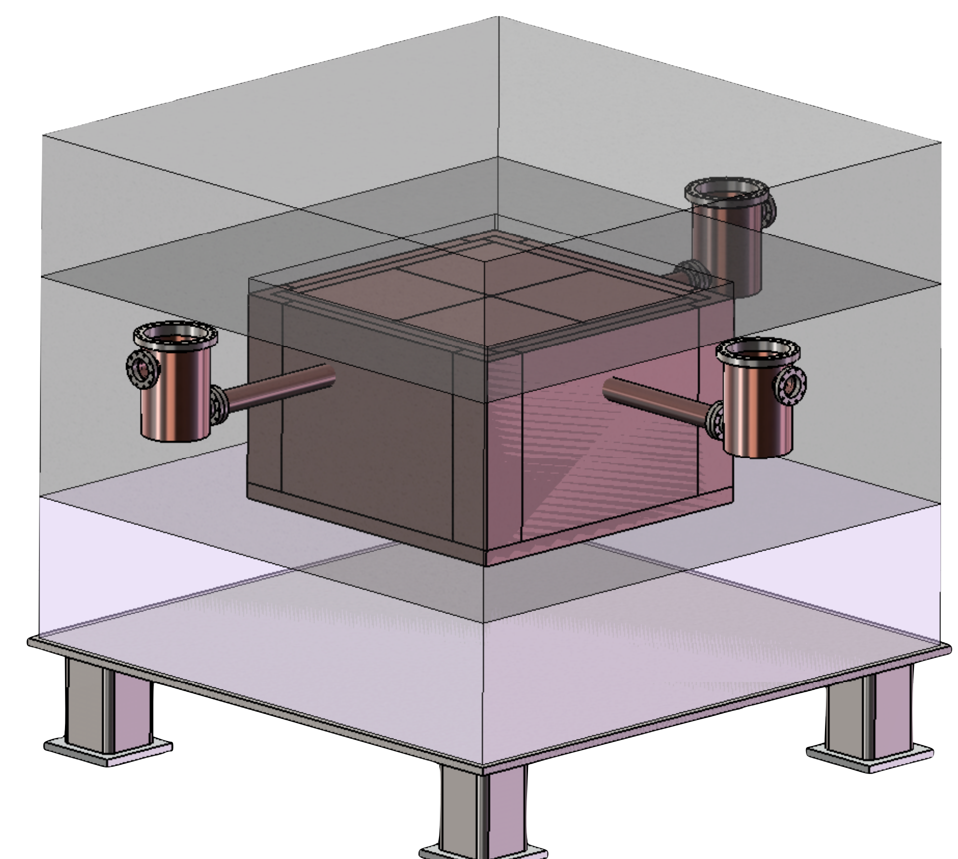
On behalf of the MAJORANA Collaboration



NDM 2009
31 August, 2009
Madison, WI

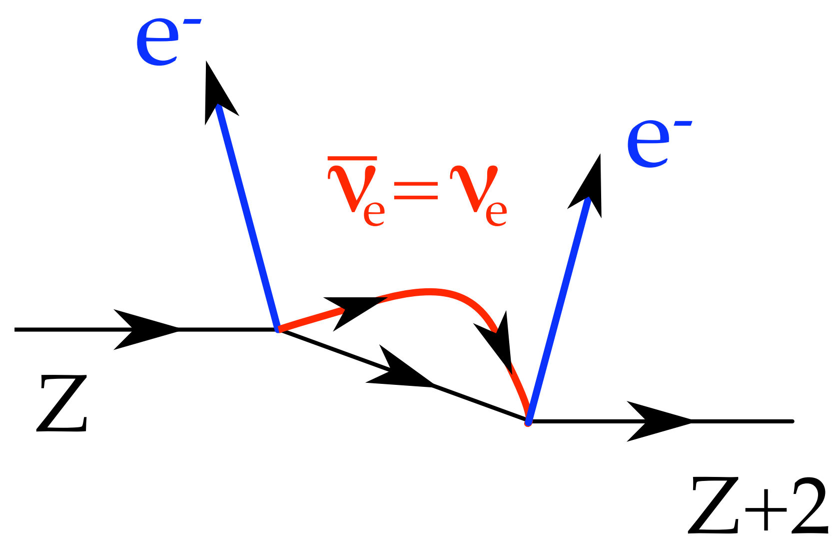


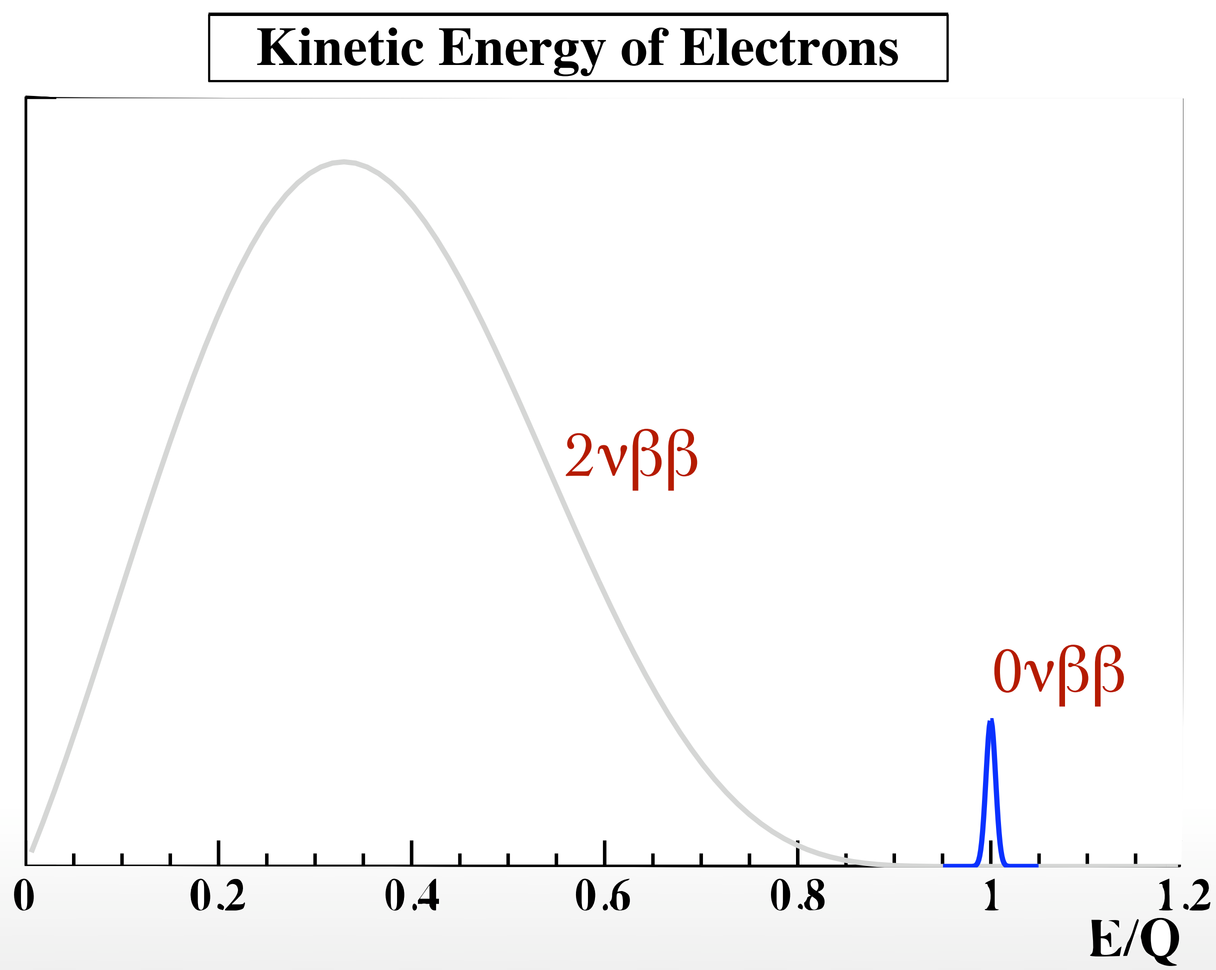
Outline

- Towards a 1-tonne ^{76}Ge $0\nu\beta\beta$ experiment
- The MAJORANA DEMONSTRATOR Overview
- P-type Point Contact (P-PC) HPGe Detectors
- Current status of project and R&D

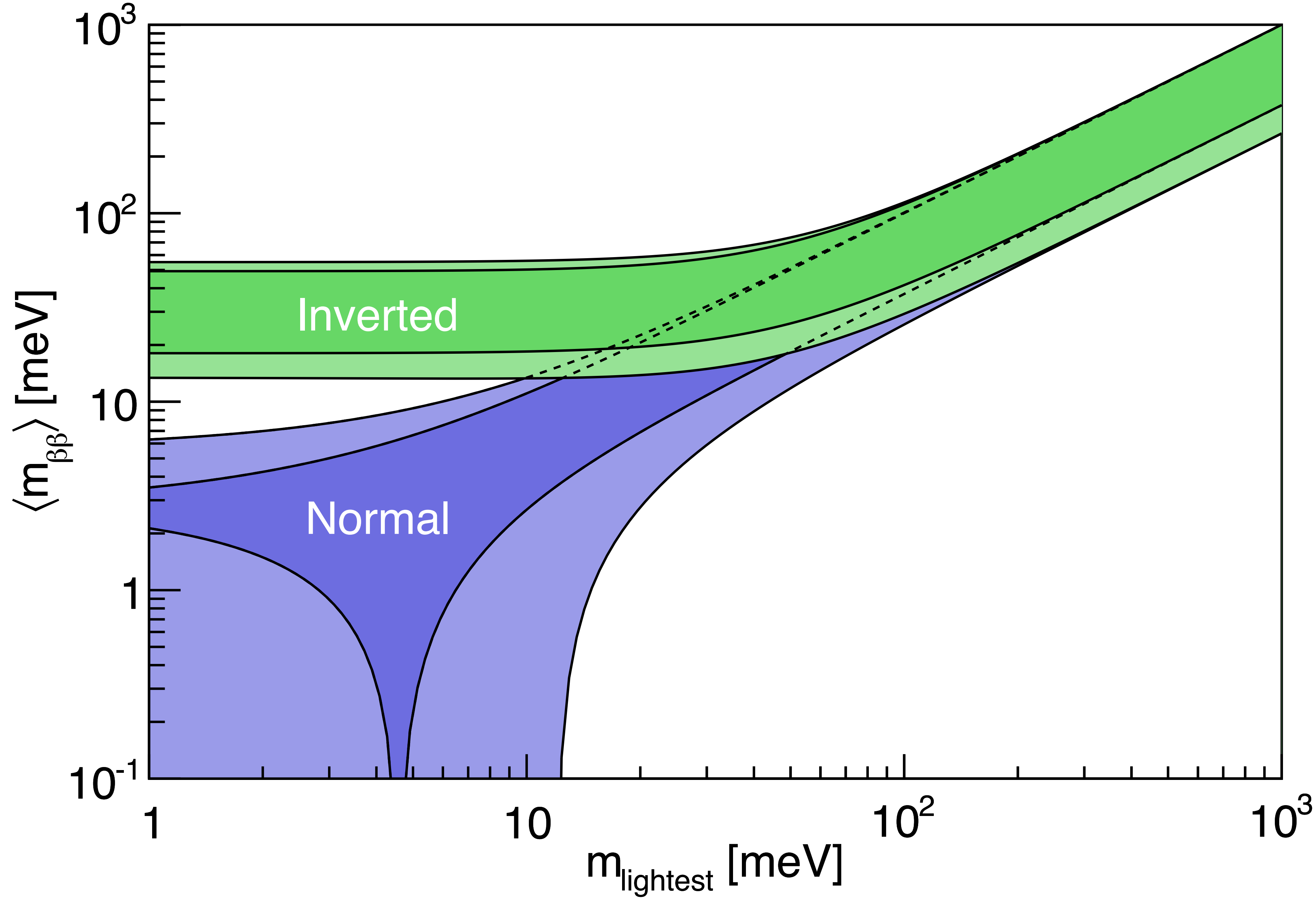
Experimental Criteria for 0νββ Search

- Source material
  - Amount, efficiency, enrichment
- Extremely low backgrounds in the 0νββ peak region-of-interest (ROI)
  - Ultra-clean materials
  - Background discrimination
  - Deep-underground setting
- High Q value
- Best possible energy resolution
  - Minimize background counts in region-of-interest
  - ONLY way to separate 2νββ from 0νββ





Majorana Mass Limits



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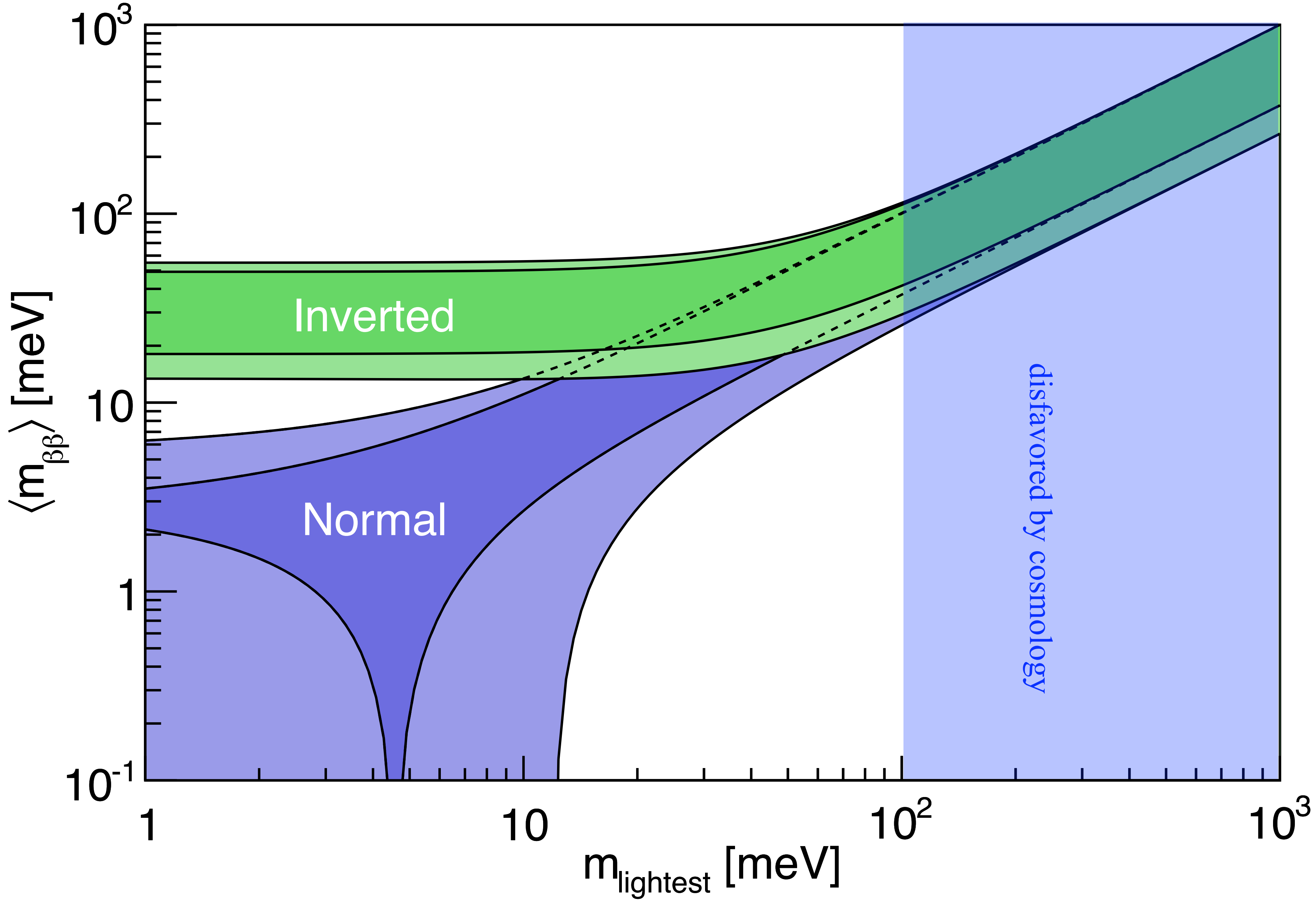

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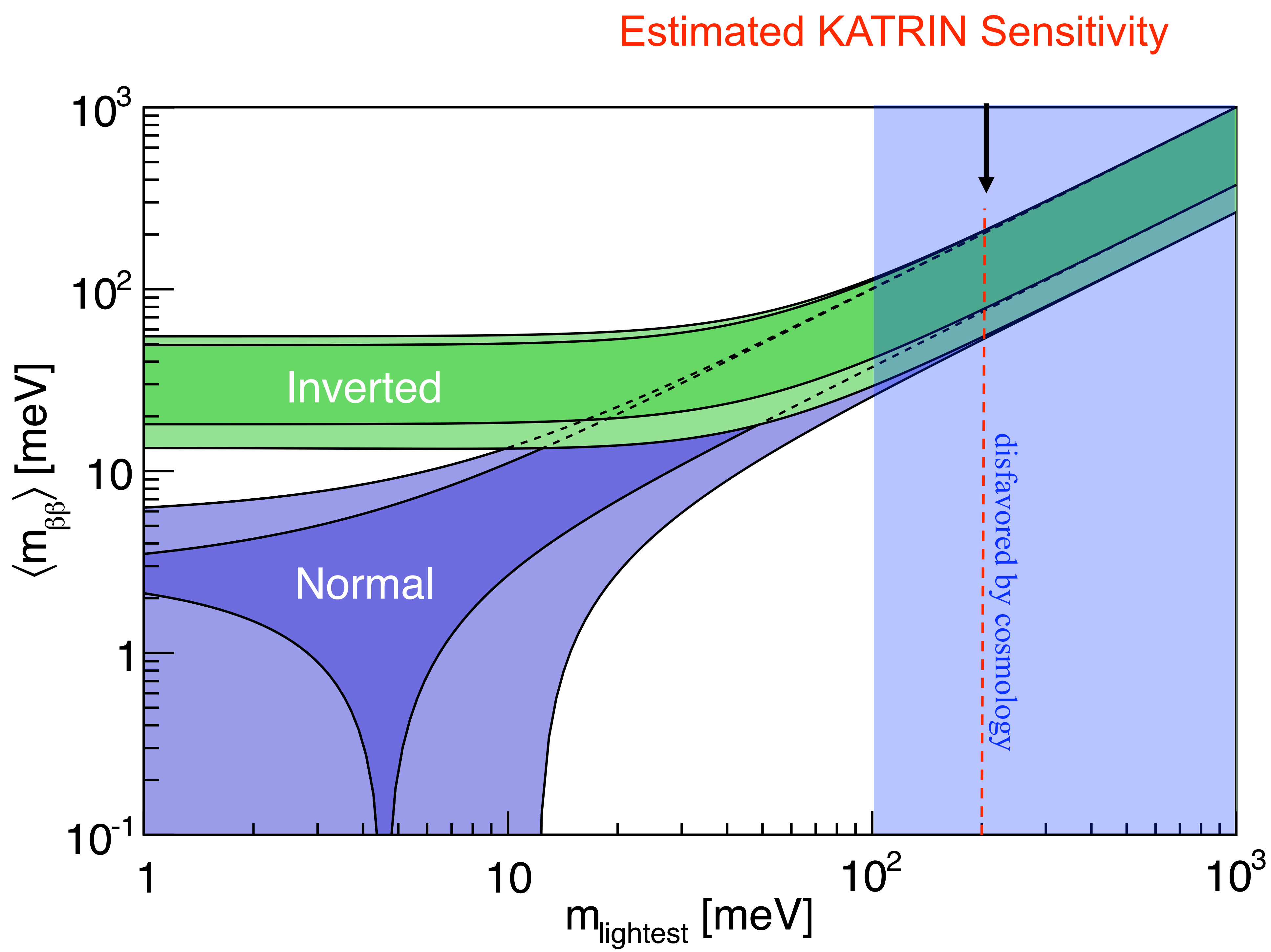

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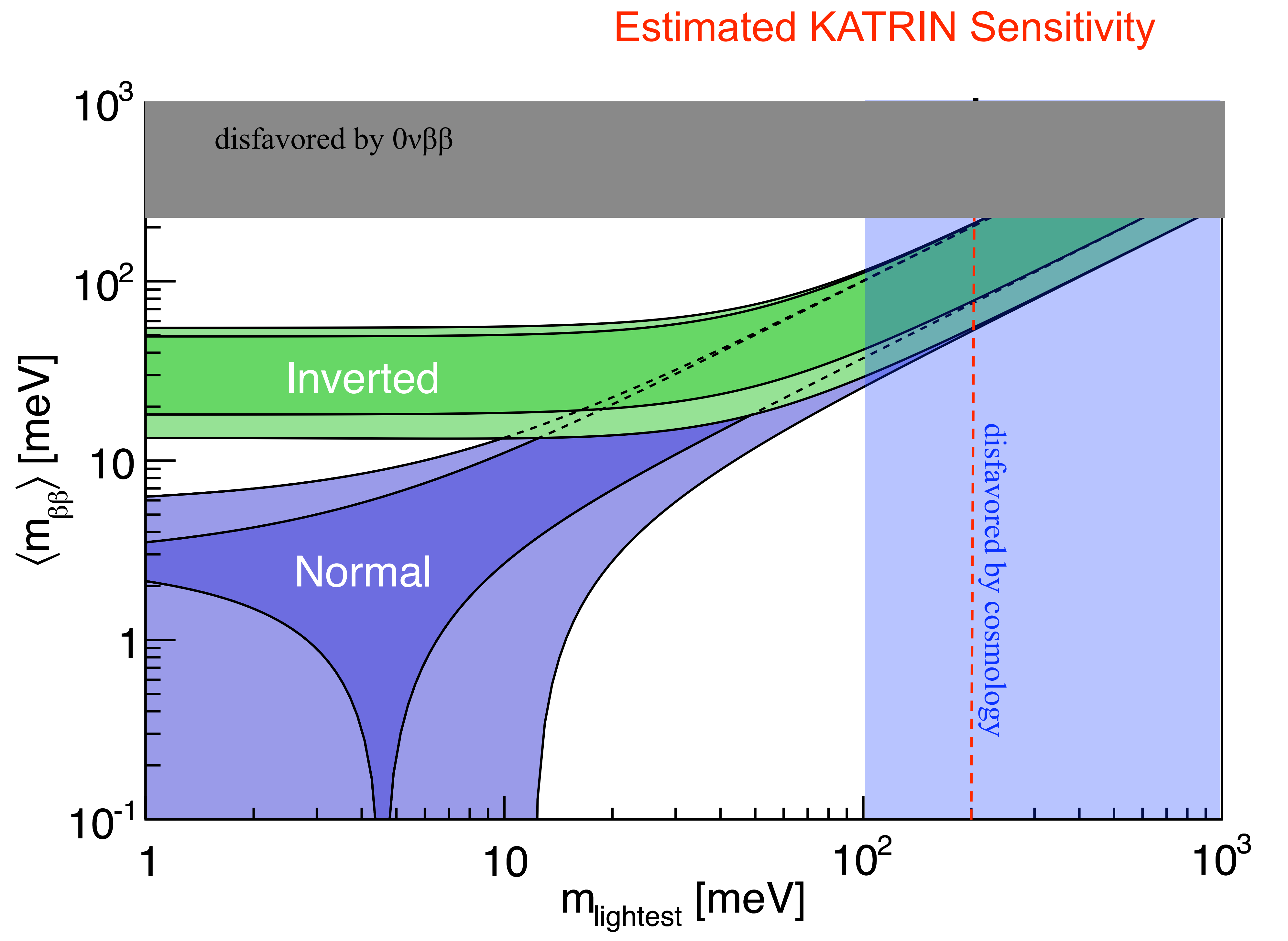
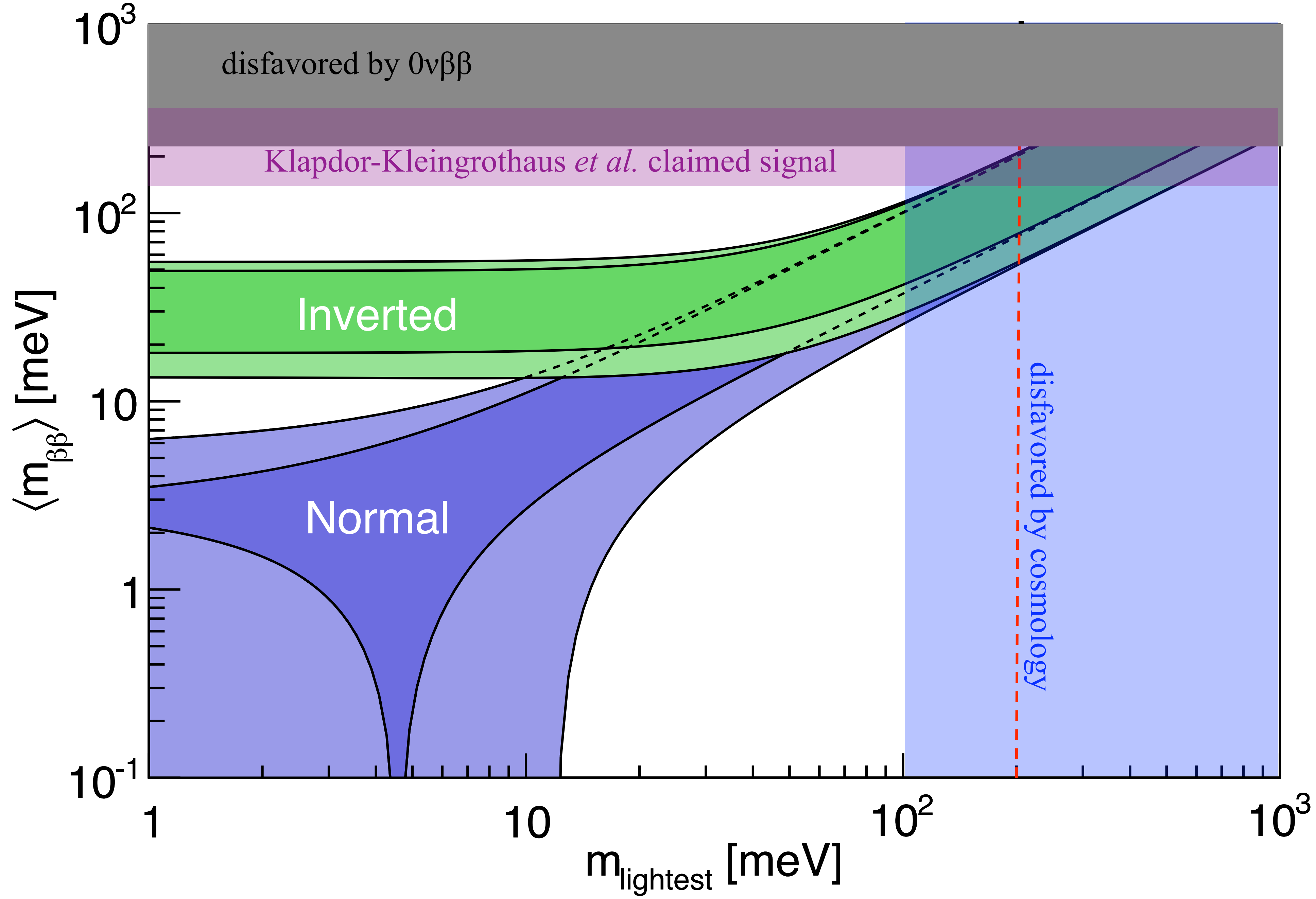


Majorana Mass Limits

Estimated KATRIN Sensitivity



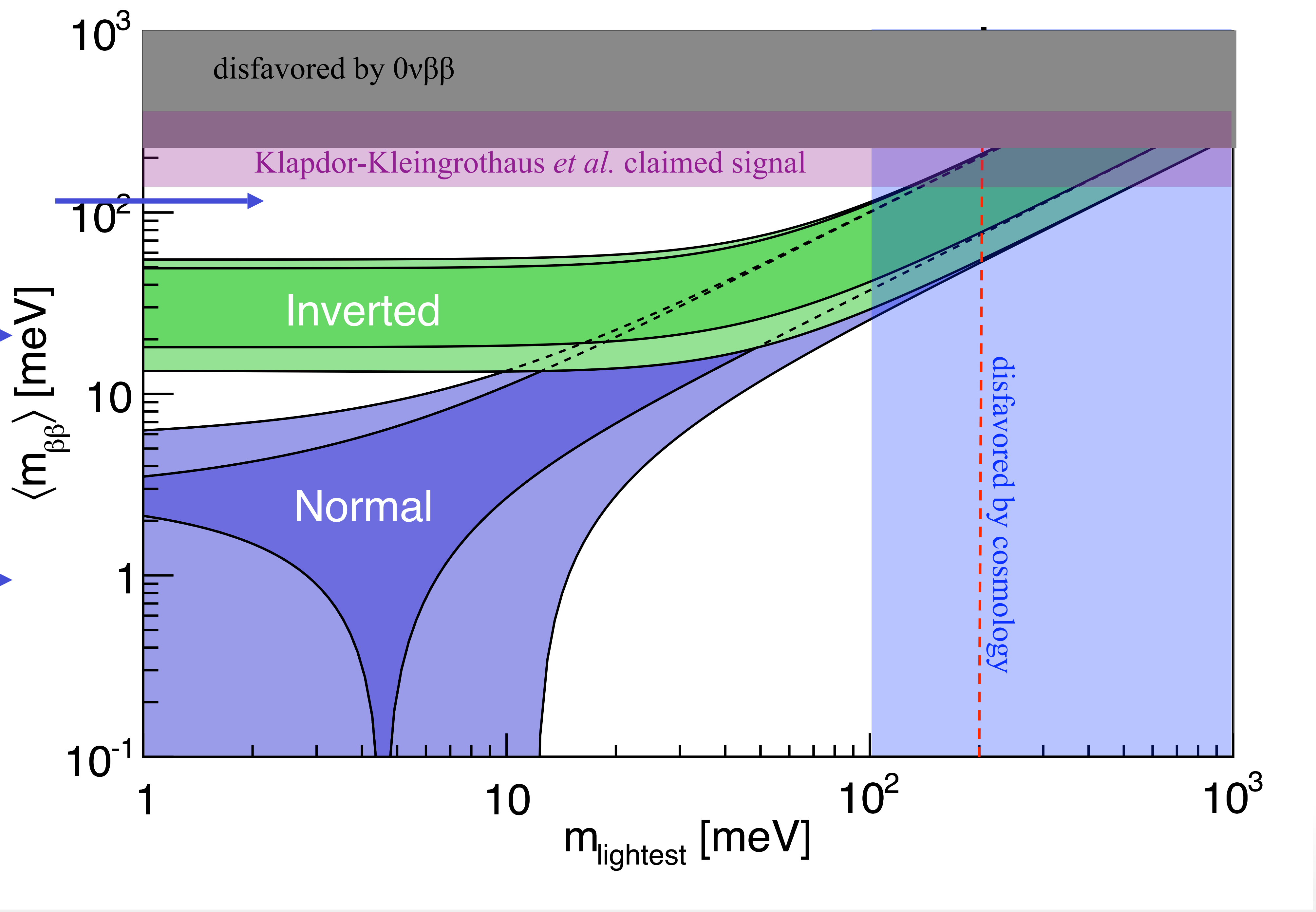
Majorana Mass Limits

Estimated KATRIN Sensitivity

~ 100kg isotope

~ 1 ton

~ 100 ton



^{76}Ge: Capabilities and Sensitivities

- Efficient use of source material
  - Source is the detector
  - Enrichment to 86% ^{76}Ge (from 7.44%)
- Well-established technologies
  - Commercially available
  - Easily scalable
- Intrinsically clean detectors
- Excellent energy resolution
  - 0.16% at 2039 keV
- Background rejection
  - Event timing, position sensitivity, pulse-shape analysis
- Best 0νββ half-life sensitivity to date
  - $T_{1/2}^{0\nu} > 1.9\times10^{25}$ y[1]

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

The MAJORANA Collaboration (Aug. 2009)

Note: Red text indicates students

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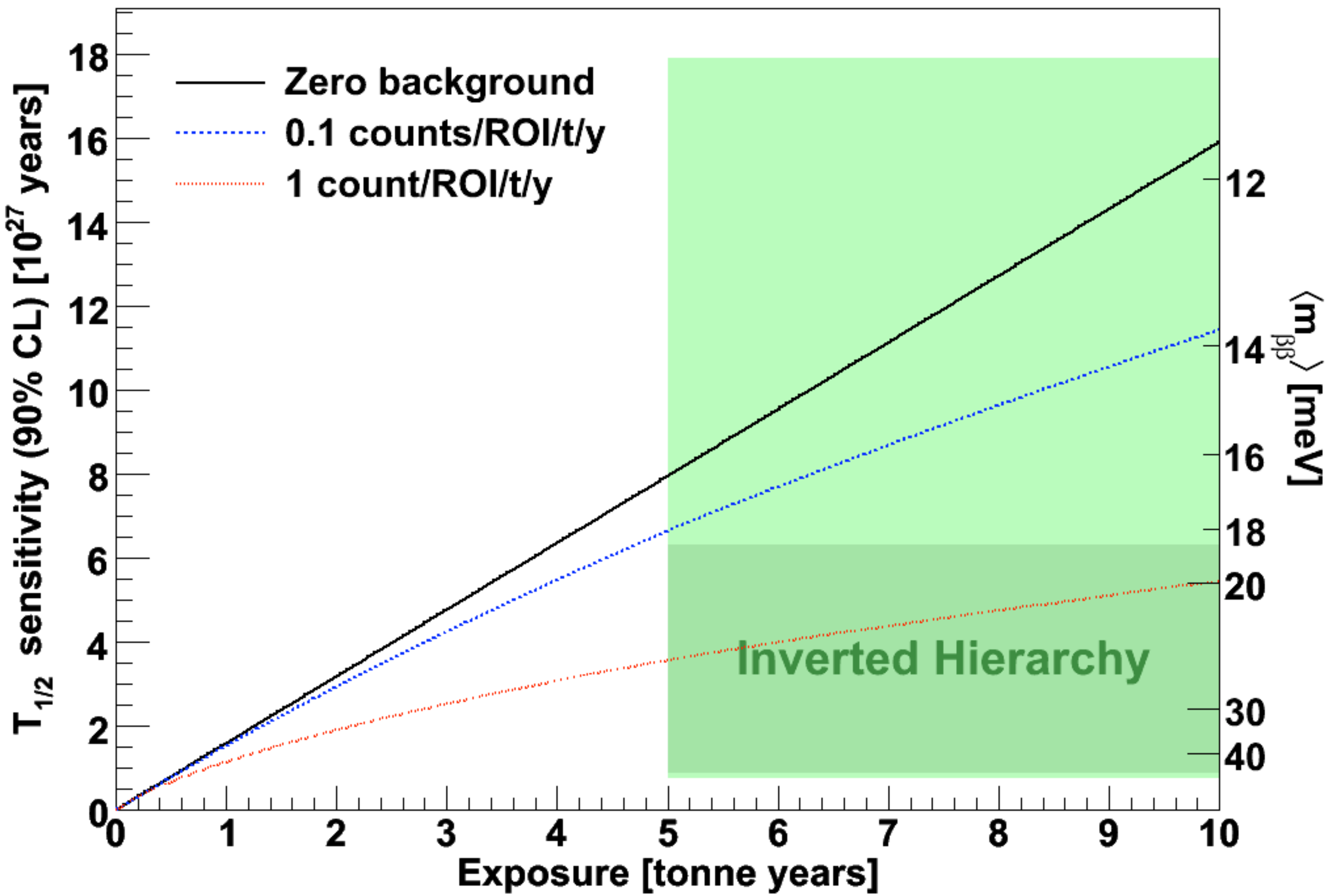
MAJORANA Goals

Actively pursuing the development of R&D aimed at a ~1-tonne scale ^{76}Ge 0νββ-decay experiment.

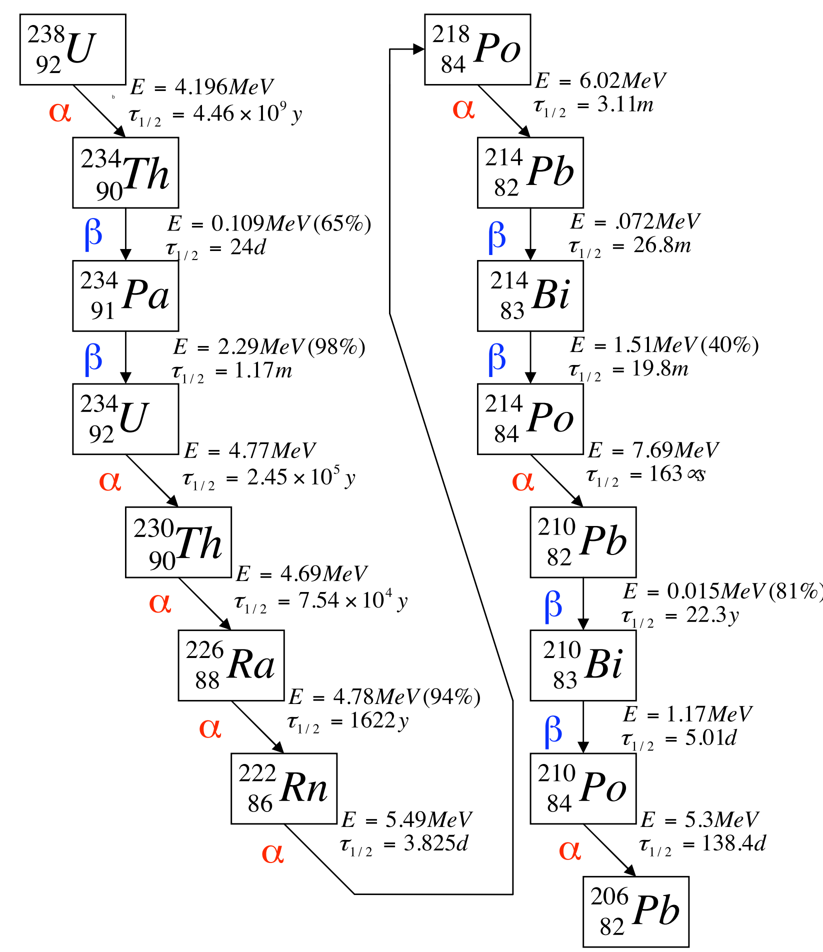
- Technical goal: Demonstrate background low enough to justify building a tonne-scale Ge experiment
- Science goal: Build a prototype module to test the recent claim of an observation of 0νββ.
- Working cooperatively with GERDA Collaboration
  - Prepare for a single international tonne-scale Ge experiment
  - Combine the best technical features of GERDA and Majorana

Tonne-Scale ^{76}Ge: Sensitivity vs. Background

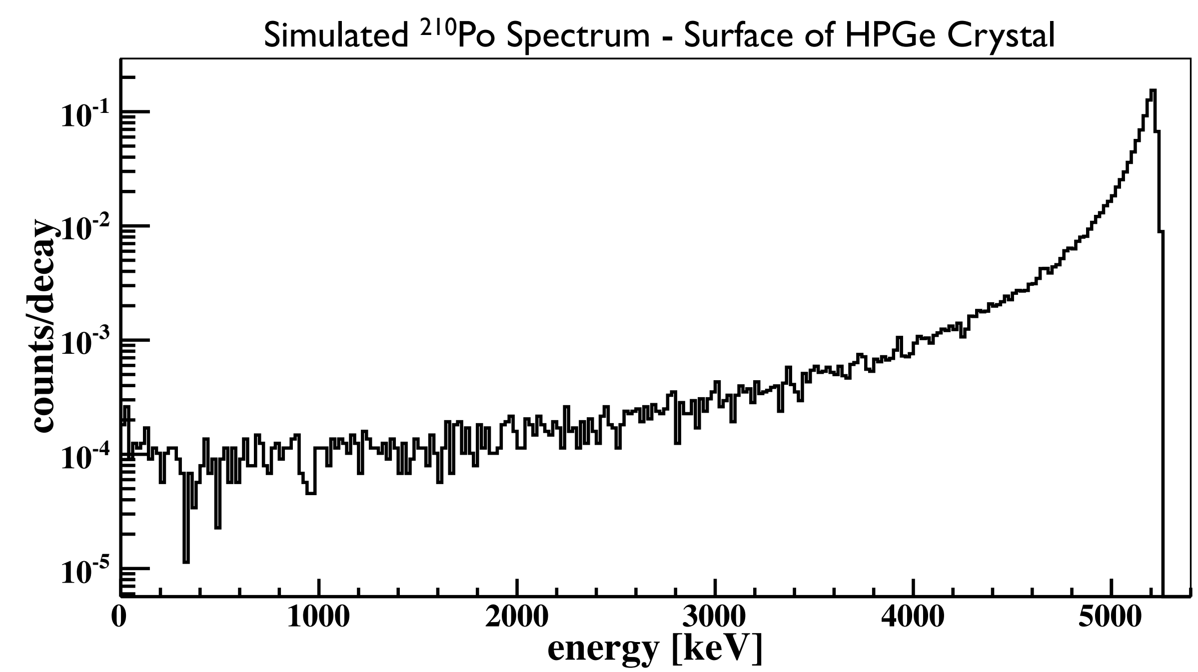


The MAJORANA DEMONSTRATOR

- Towards a tonne-scale ^{76}Ge Experiment
  - Background reduction is the name of the game
    - α, β, γ (U & Th decay chains, cosmogenic)
    - Cosmic Rays
    - Neutrons
    - 2νββ

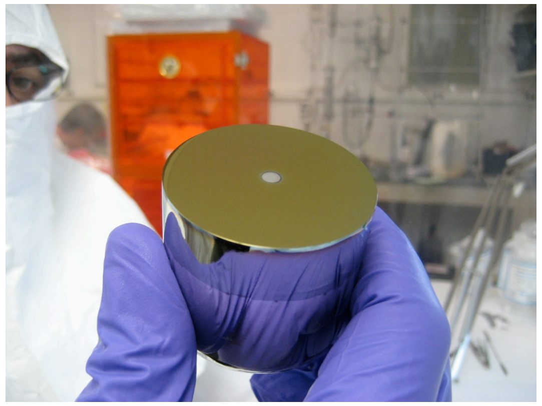


- Physics reach
  - 0νββ
    - Test recent claim of an observation of 0νββ
    - Sensitive to the quasi-degenerate scale
  - Other physics
    - 2νββ excited-state decays
    - Low-mass WIMP search

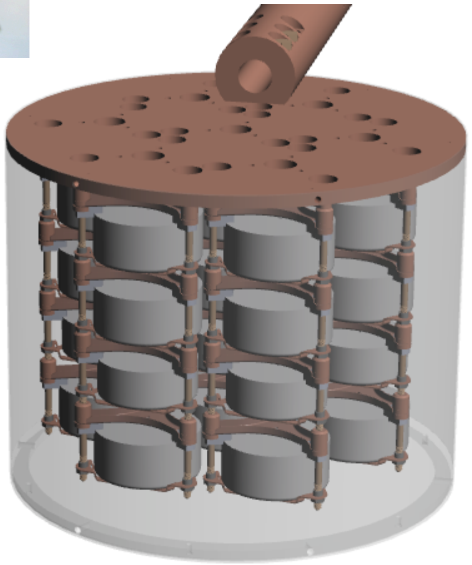


The MAJORANA DEMONSTRATOR

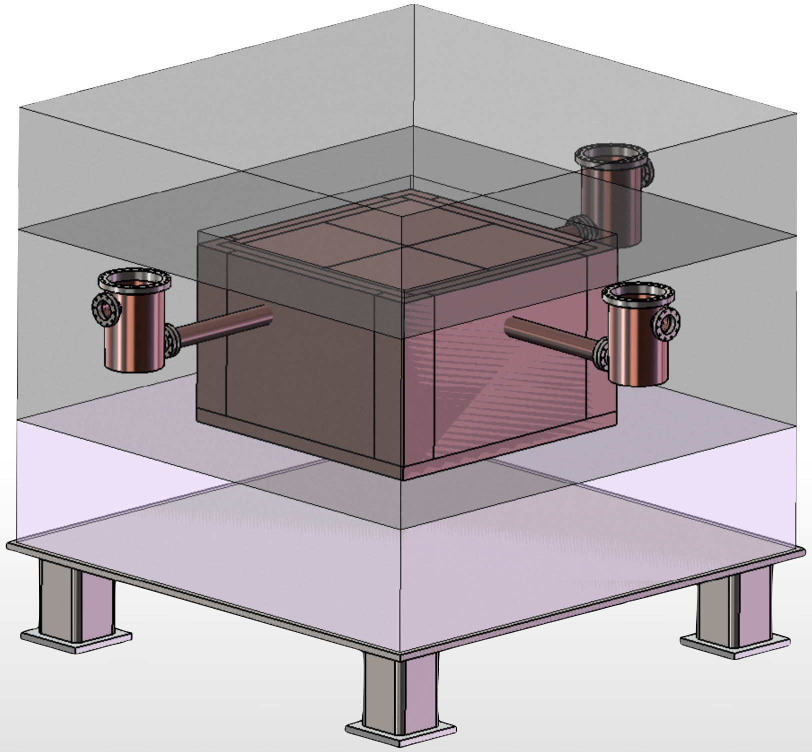
- 60-kg of Ge detectors, 3 cryostats
  - 30-kg of 86% enriched ^{76}Ge crystals
  - 30-kg natural Ge
  - Examine detector technology options



- Low-background cryostats & shield
  - Ultra-clean, electroformed Cu
  - Compact, low-background passive Cu and Pb shield with active muon veto



- Lab is being prepared at 4850' level at Sanford Lab / Homestake



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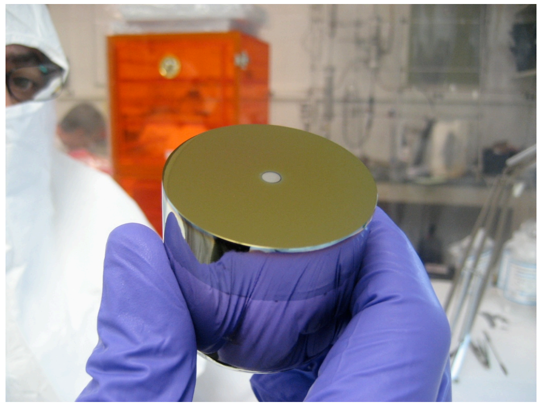

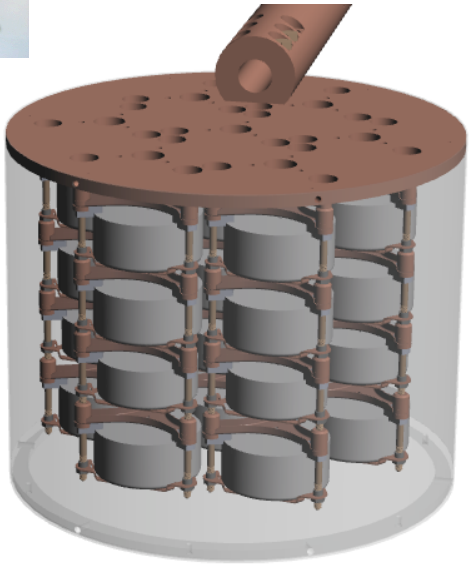

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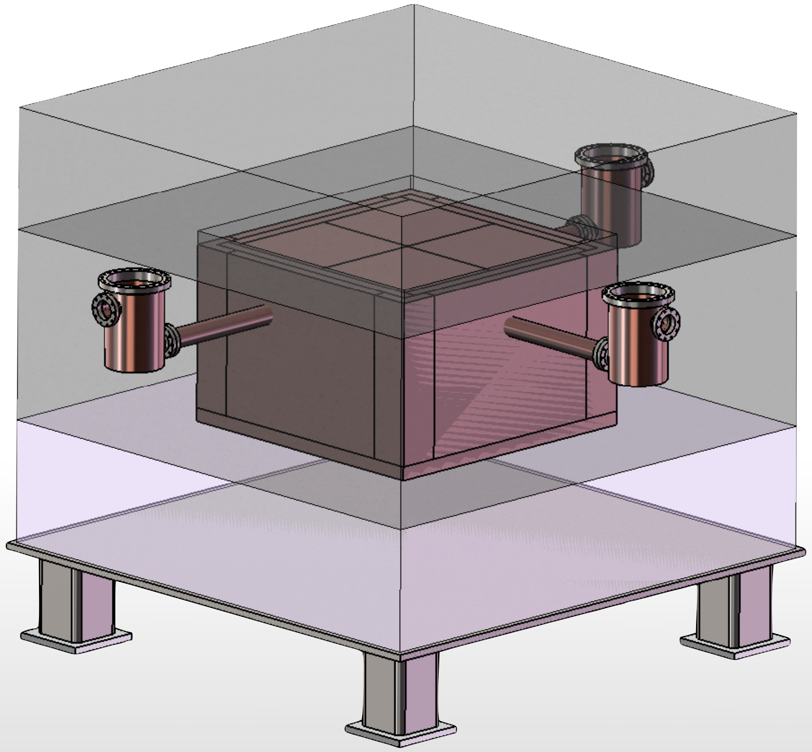

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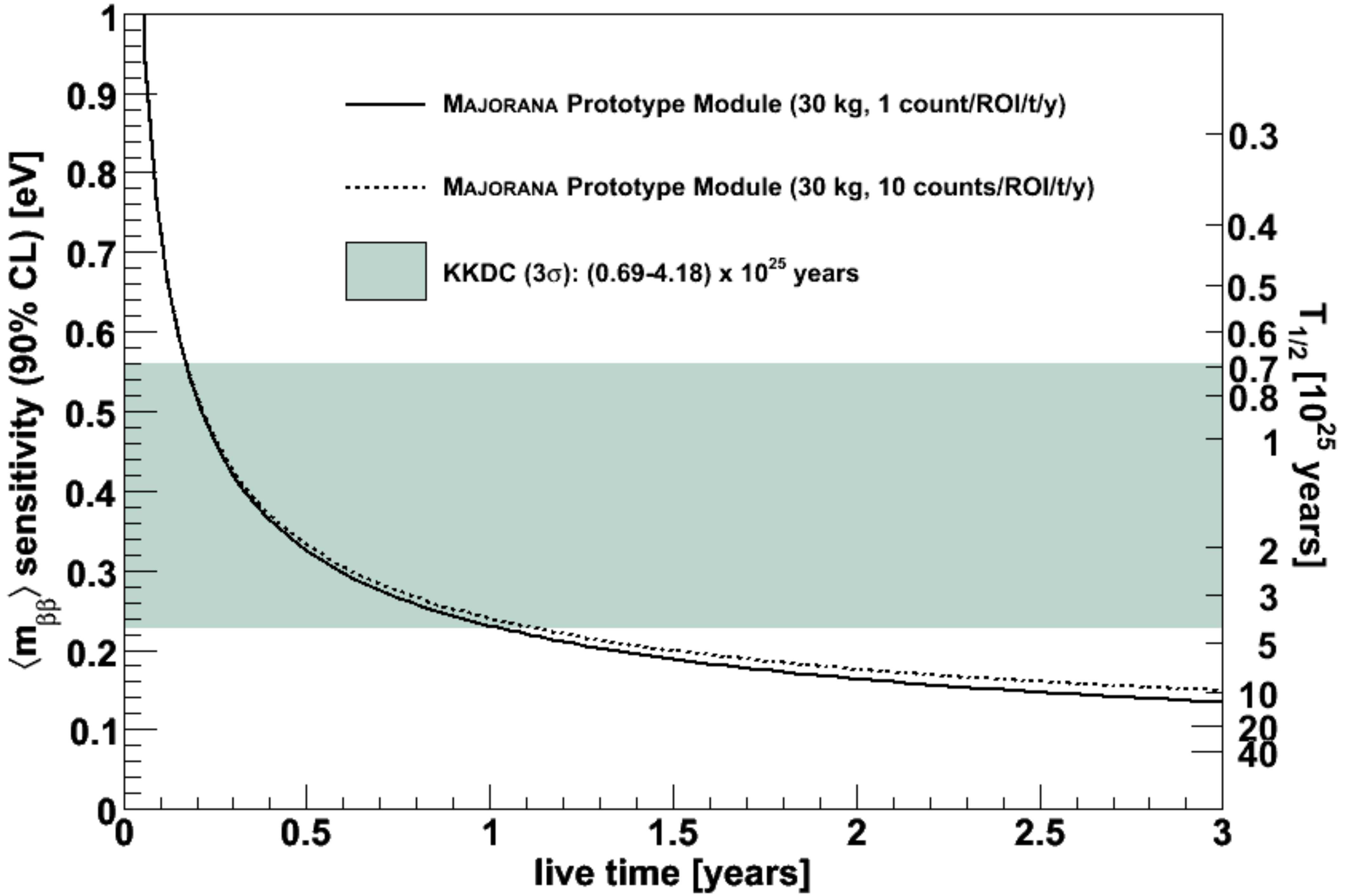
ROI: 4 keV at 2039 keV

MAJORANA DEMONSTRATOR Sensitivity

Expected Sensitivity to 0νββ

(30 kg enriched material, running 3 years, or 0.09 t-y of ^{76}Ge exposure)

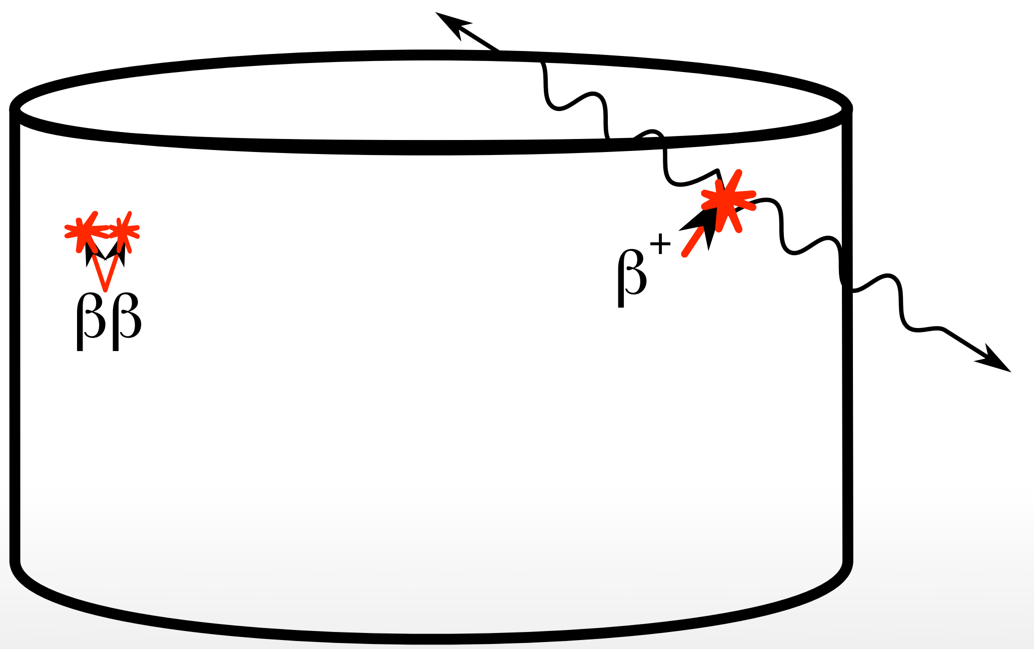
$T_{1/2} \geq 10^{26}$ y (90% CL).Sensitivity to <m_ν> < 140 meV (90% CL)[1]



[1] V. A. Rodin, A. Faessler, F. Simkovic, and P. Vogel, Nucl. Phys. A766, 107 (2006), nucl- th/0503063, see also the Erratum arXiv:0706.4304.

Background Rejection
Single-site vs. Multi-site Events

- Single-site events
  - Localized energy deposition
  - Examples
    - Double-Beta Decay
    - Double-Escape Events
- Multi-site events
  - Extended energy depositions
  - Examples
    - Compton scatters
    - Single-Escape Events



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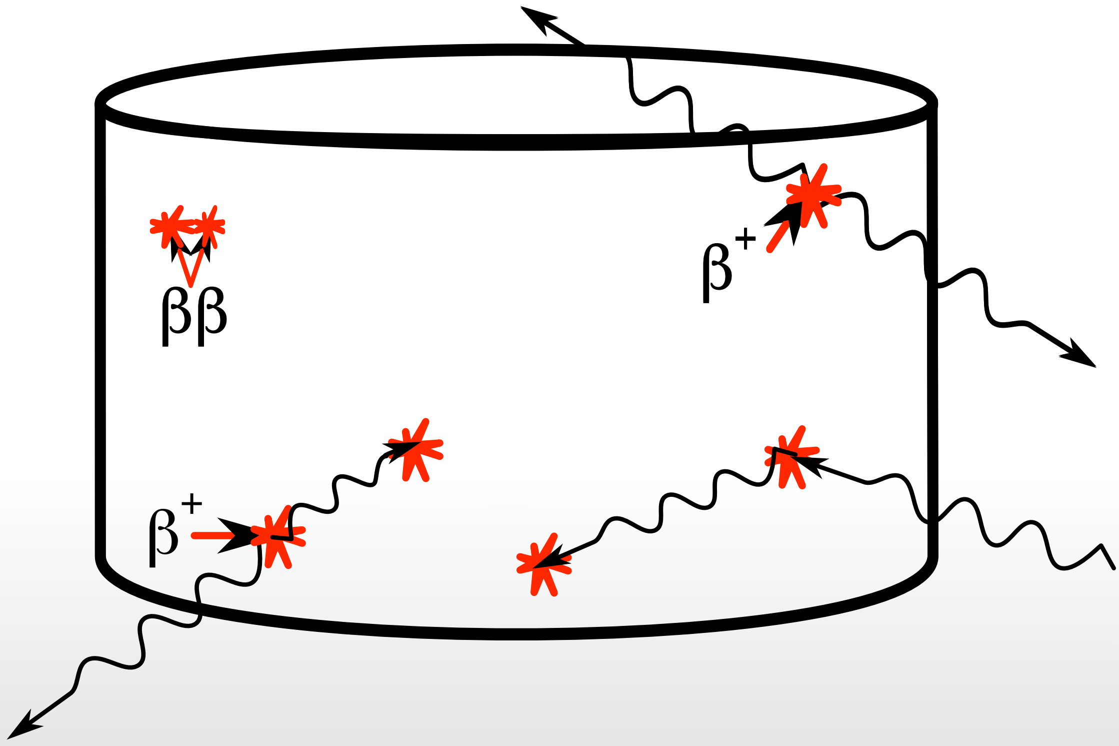

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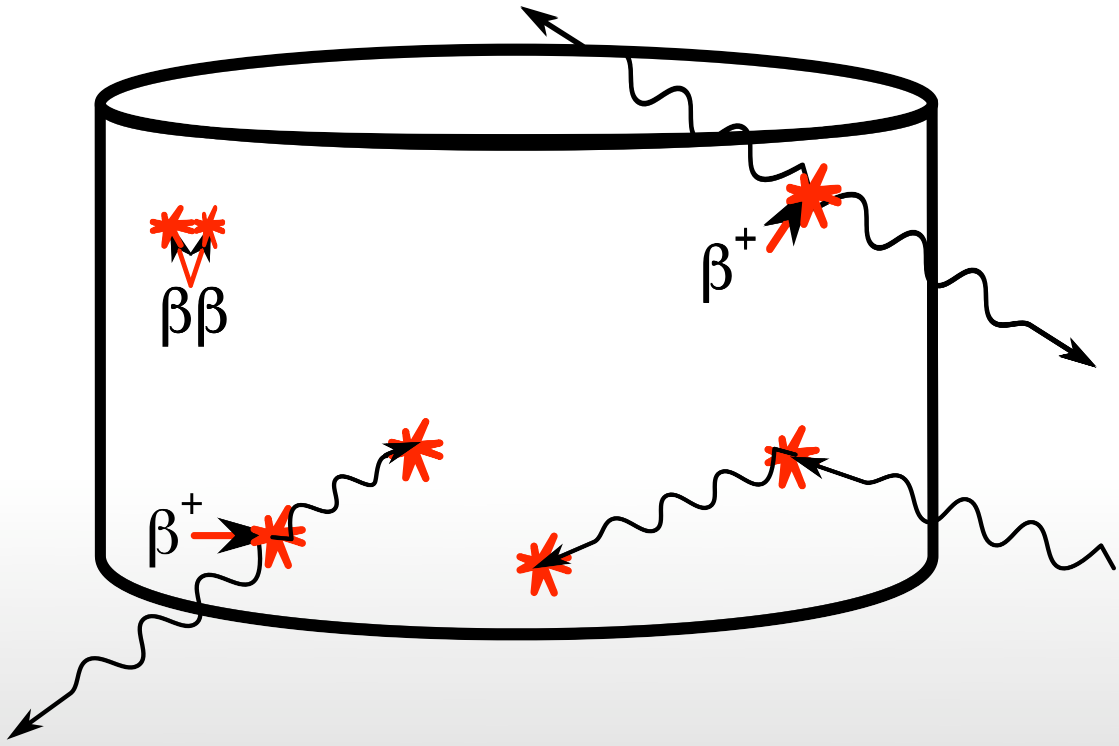
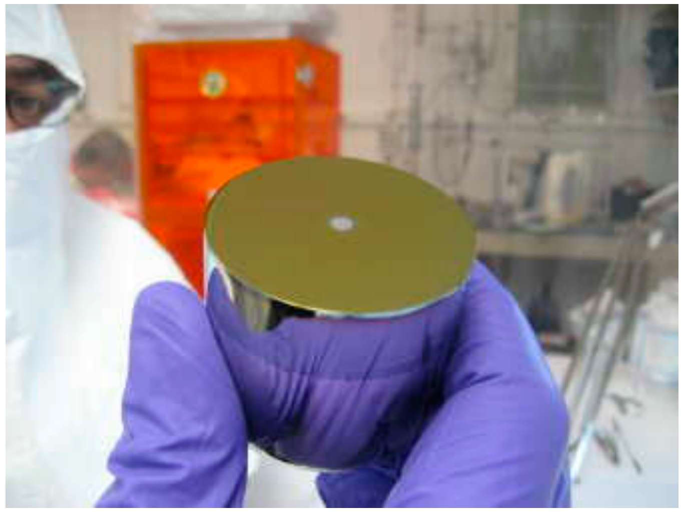
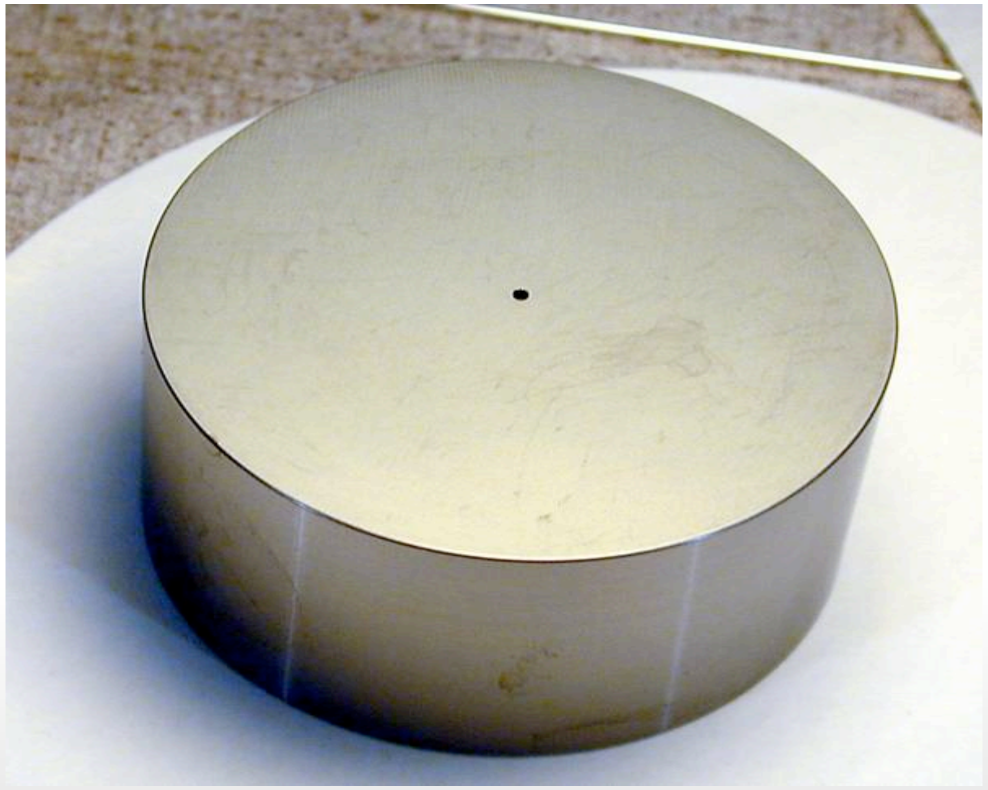
Discrimination of single-site vs. multi-site events is a key to background rejection



P-type Point Contact (P-PC) Detectors



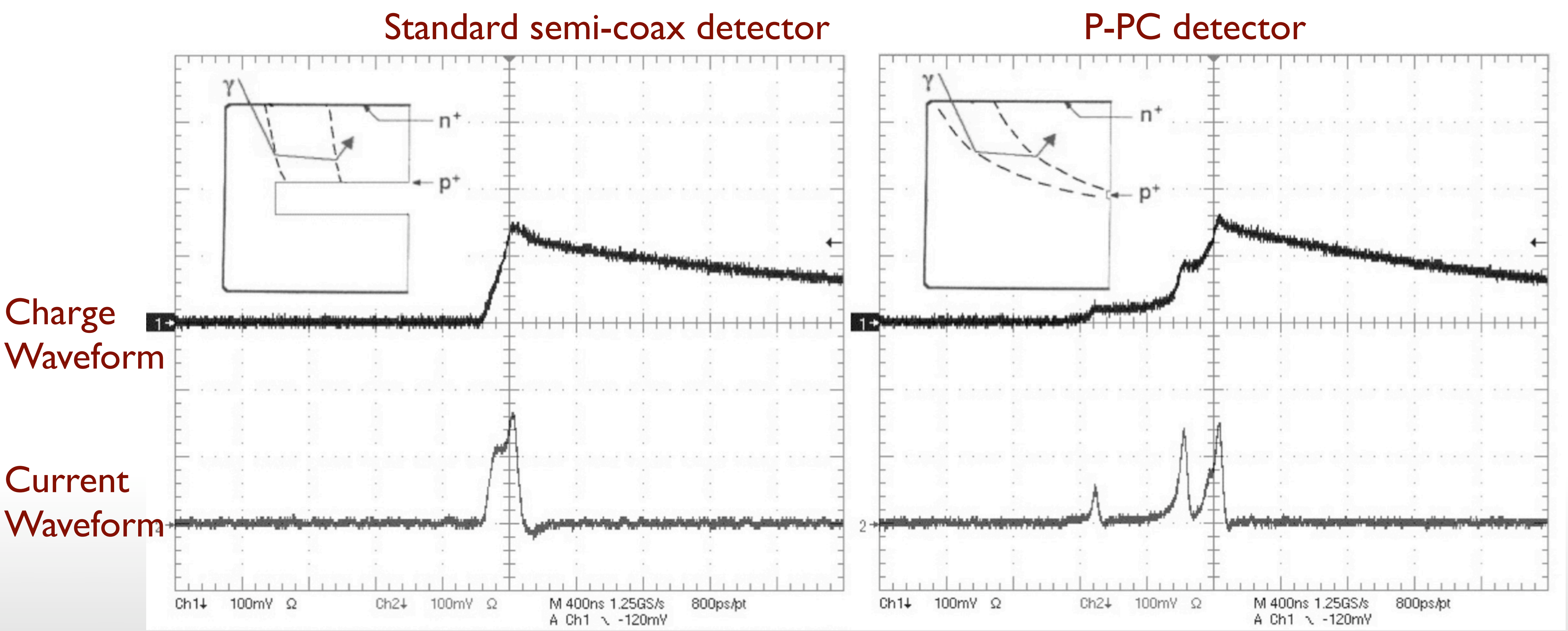
- Geometry
  - Small, point-like central contact (no hole)
- Impurity gradient
  - Increased drift times
  - Superb pulse-shape sensitivity: distinguish single-site events from multi-site events
- Noise characteristics
  - Very low capacitance (~1pF)
  - Excellent low-energy resolution
  - Low energy threshold
- Thick (~0.5 mm) outer Li contact
  - Reduces alpha background
- Fewer cables / parts
  - Less background, less complexity



P-PC Detectors

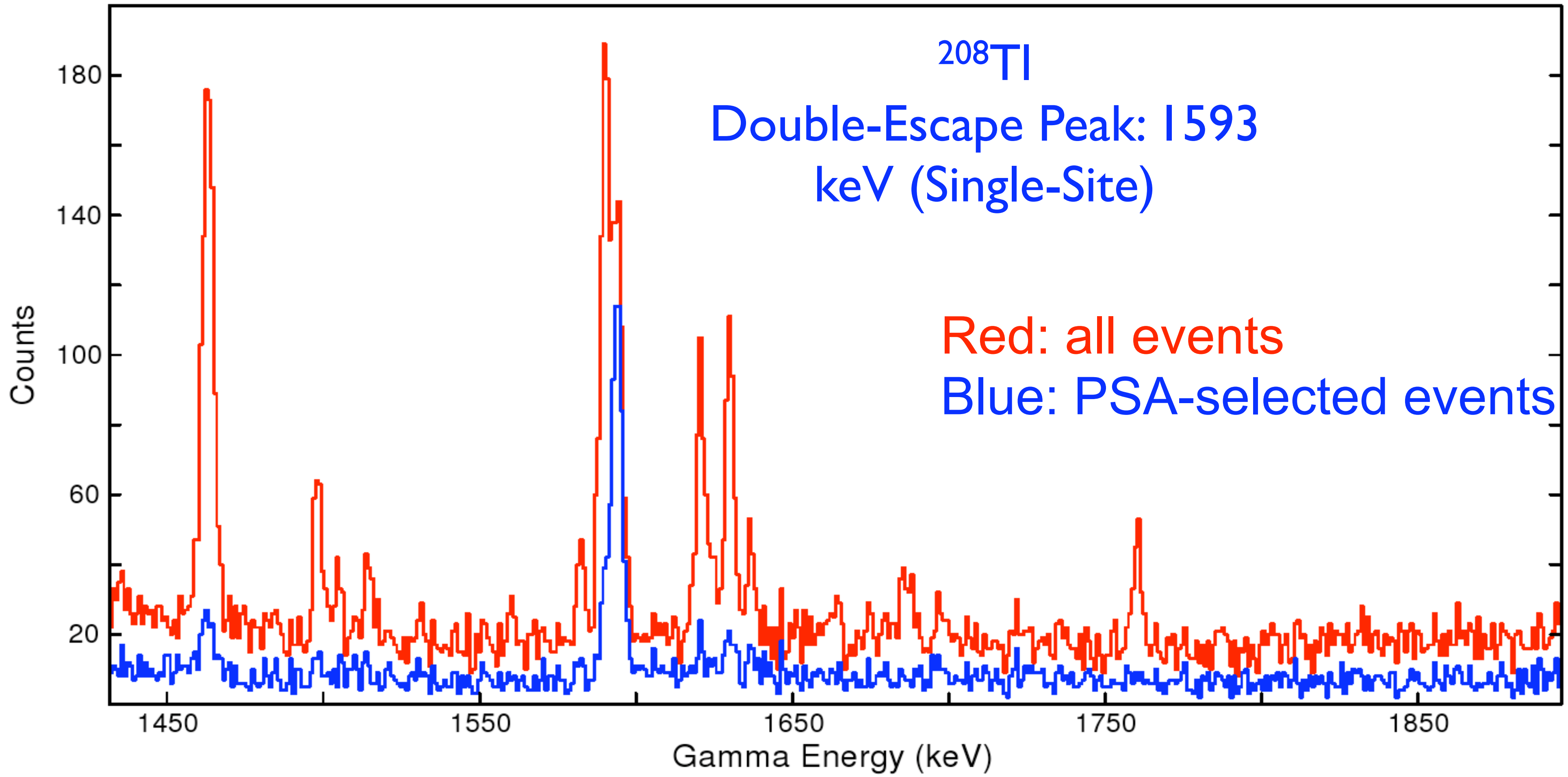
Increased range in drift times

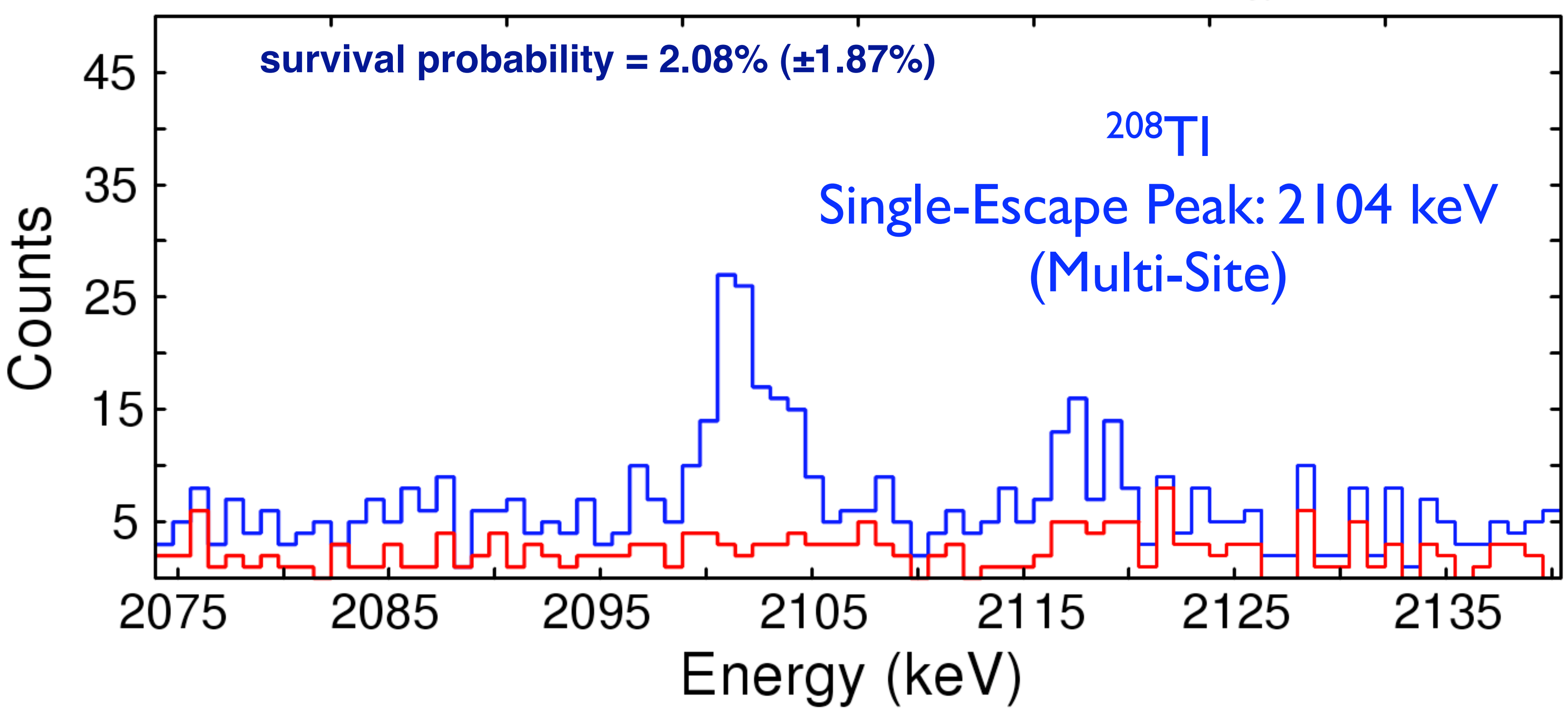
- Separation of features in waveforms
- Better spatial resolution
- Enhanced multi-site rejection



Barbeau et al., JCAP 09 (2007) 009; Luke et al., IEEE trans. Nucl. Sci. 36 , 926(1989).

P-PC Detectors: Signal Discrimination





- Data from PPC Detector
- PSA parameters
  - Adjusted for 95% efficiency for double-escape peak survival (single-site)
  - Results in 2.08% survival for single-escape peak(multi-site)

R. Cooper, D. Radford, ORNL

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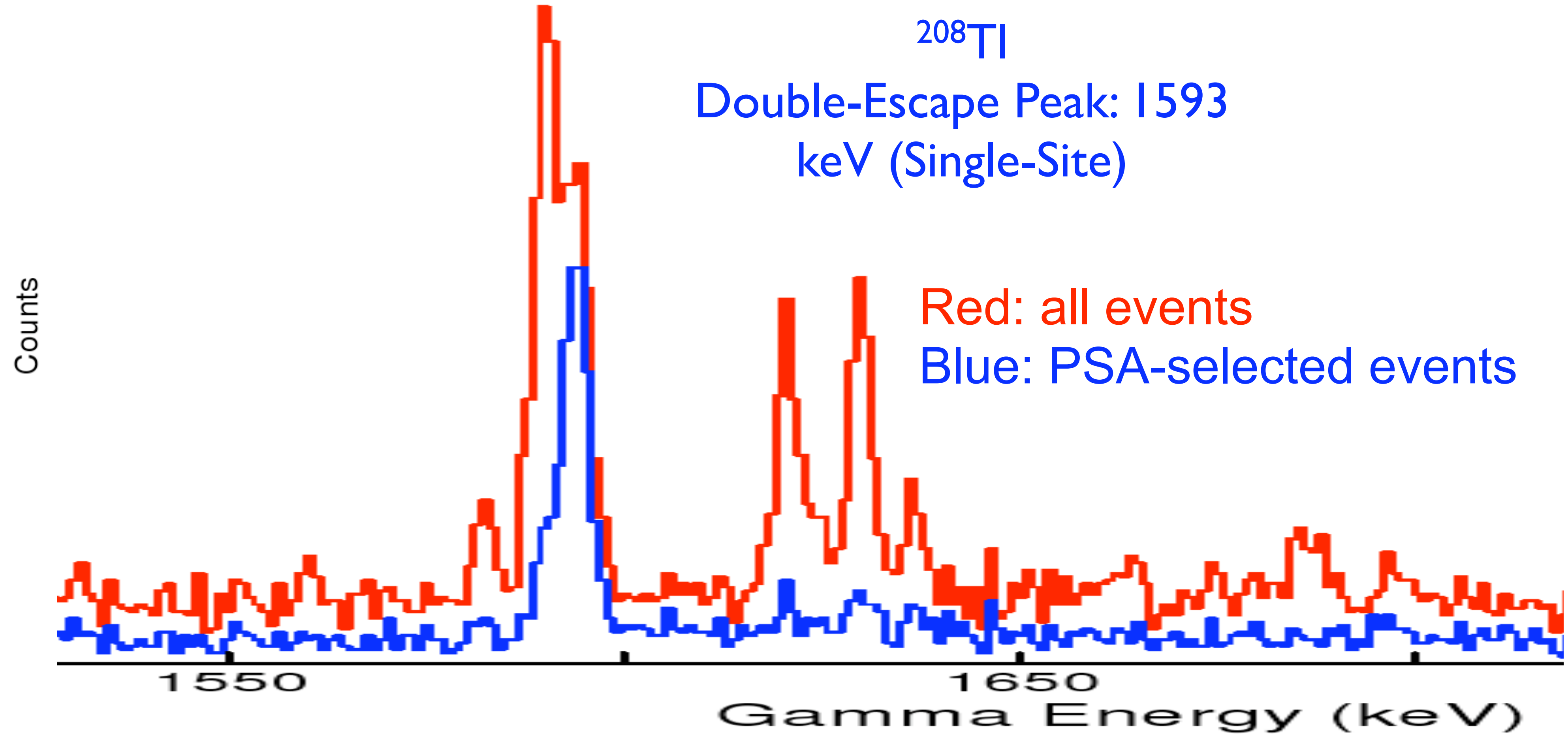

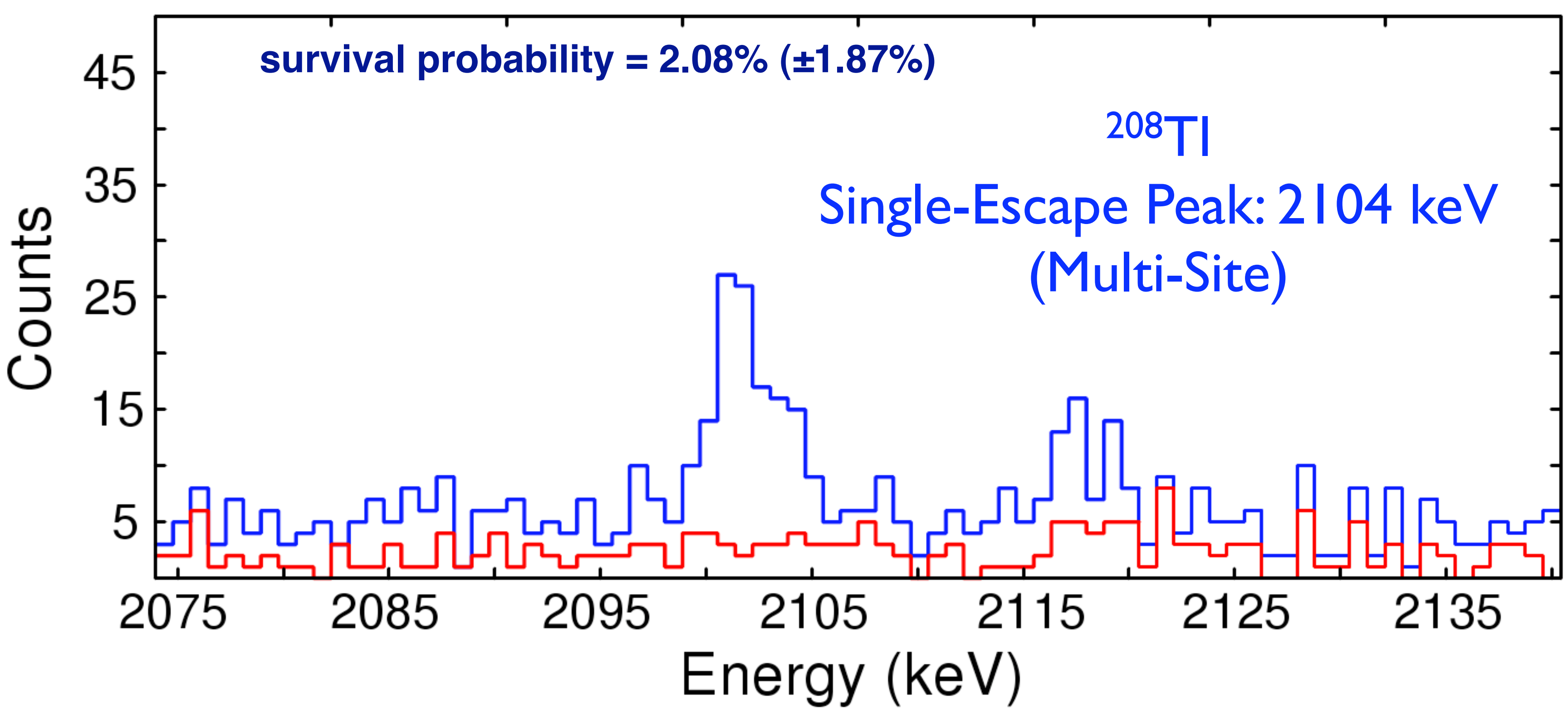

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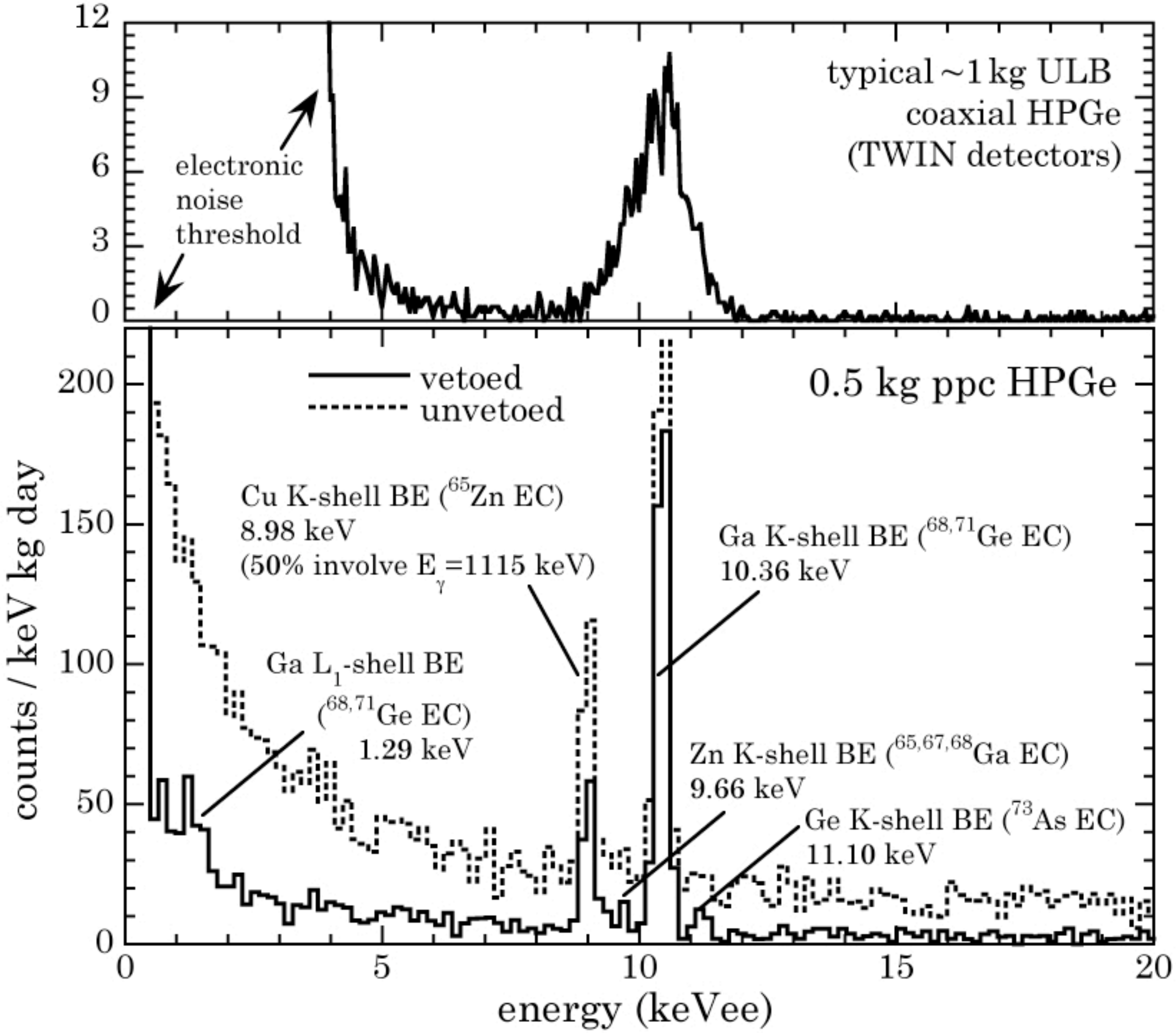
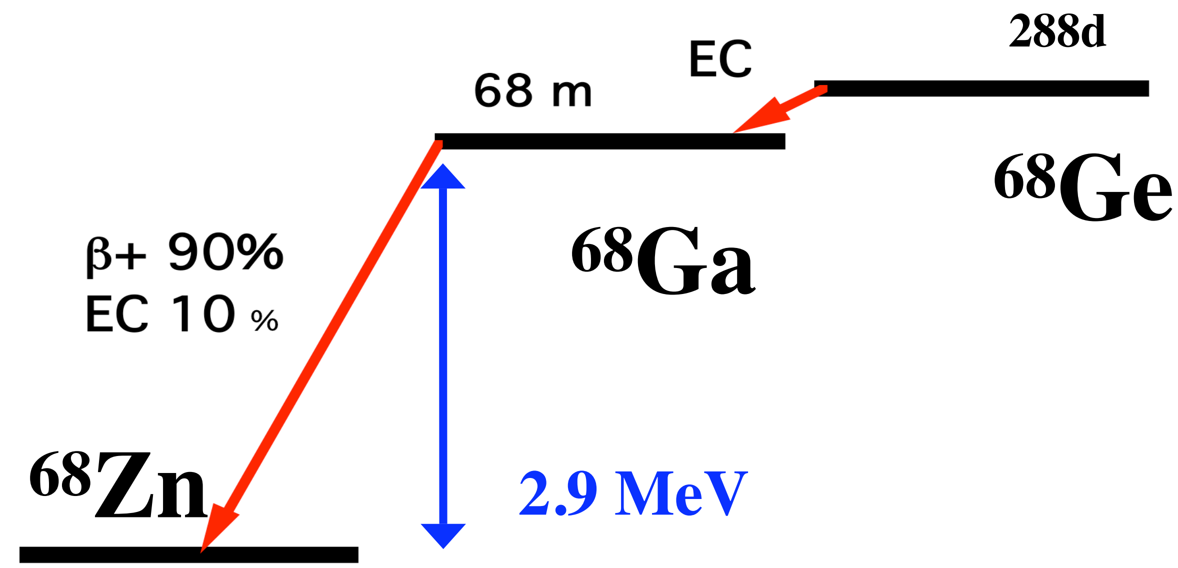
P-PC Detectors: Low-energy resolution



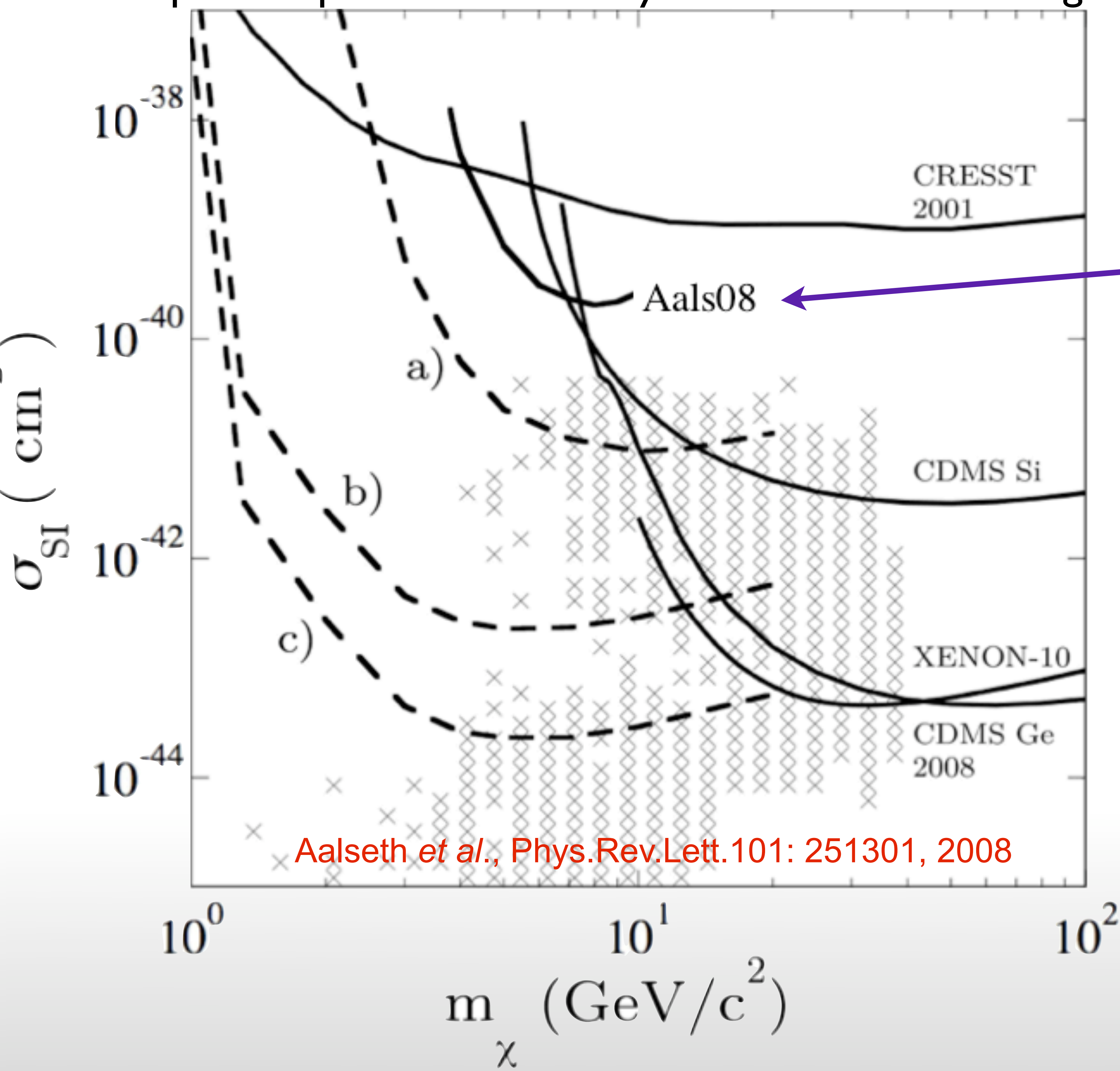


- ^{68}Ge: cosmogenic background
  - Characteristic x-rays from ^{68}Ga (10.4 keV & 1.3 keV)
  - Timing correlation analysis cut

Barbeau et al., JCAP 09 (2007) 009; Luke et al., IEEE trans. Nucl. Sci. 36 , 926(1989).

P-PC Detectors: Dark Matter Prospects

Spin-independent sensitivity in low-mass WIMP region



CoGeNT Collaboration:
Very low Threshold
HPGe Detectors
Sensitivity to light
WIMPS
(8.4 kg-days)

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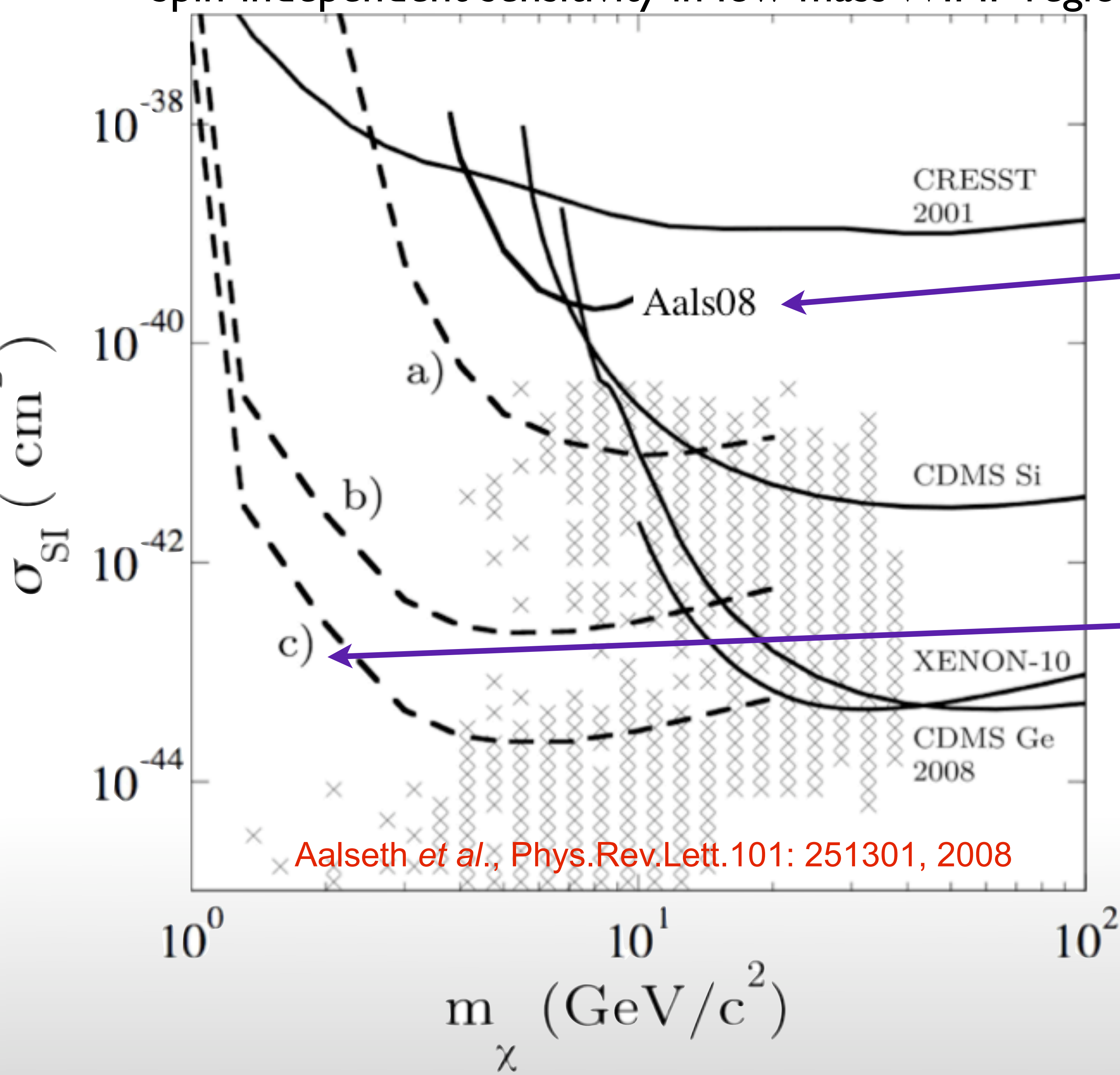


CoGeNT Collaboration:
Very low Threshold HPGe Detectors
Sensitivity to light WIMPS
(8.4 kg-days)

MAJORANA DEMONSTRATOR can probe this region further

Background Simulations

- Background modeling
  - Major background sources for detector components using MaGe*
  - Calculated total backgrounds
    - For each detector technology under consideration
- Results
  - Cu purity of ~0.3 mBq/kg is required
    - Sizeable contribution from ^{208}Tl in the cryostat and shield.
  - Higher rejection of segmented designs is roughly balanced by introduction of extra readout components.
- P-PC appears to achieve the best backgrounds with minimal readout complexity.

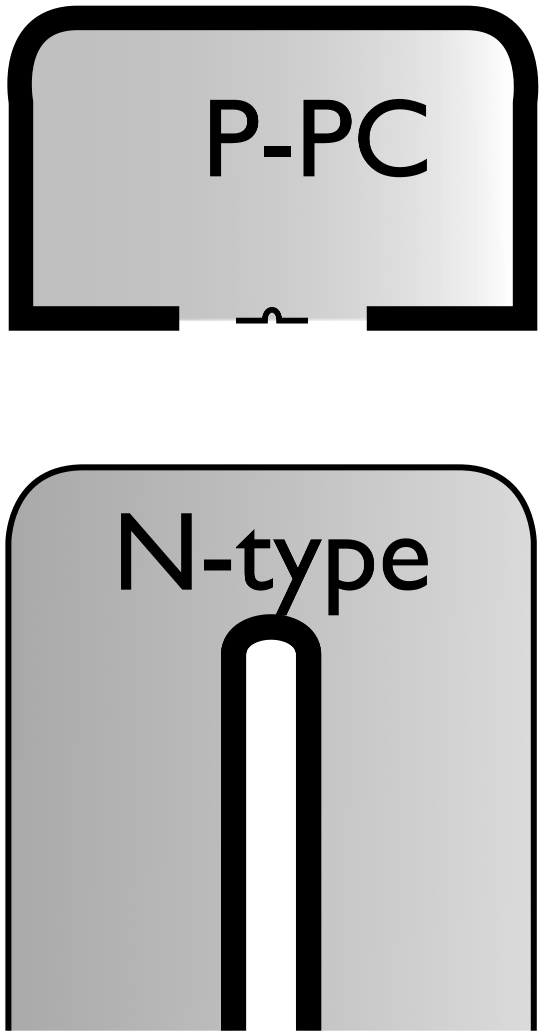
*MaGe: Joint simulation package of GERDA and MAJORANA collaborations

MAJORANA Background budget

Background Source	Radioactive Isotope [counts/t/y/ROI]			Total Background [counts/t/y/ROI]
Germanium Crystals	^{68}**Ge**	^{60}**Co**	^{232}**Th**/^{238}**U**	
Gross:	4.88	0.612	0.218	5.71
Net:	0.215	0.110	0.198	0.523
Detector Supports	^{208}**Tl**	^{214}**Bi**		
Gross:	0.0416	0.0277		0.0693
Net:	0.0181	0.00693		0.0250
Front End Boards	^{208}**Tl**	^{214}**Bi**		
Gross:	0.524	0.373		0.897
Net:	0.351	0.186		0.537
Cabling	^{208}**Tl**/^{214}**Bi**			
Gross:	0.220			0.220
Net:	0.150			0.150
Copper Cryostat/Shield	^{208}**Tl**	^{214}**Bi**	^{60}**Co**	
Gross:	1.47	1.09	0.001716	2.54
Net:	1.20	0.687	0.0000099	1.89
Lead Shield	^{208}**Tl**	^{214}**Bi**		
Gross:	0.151	0.277		0.428
Net:	0.123	0.174		0.297
Neutrino Scattering	**Solar**	**Atmospheric**	**Geoneutrinos**	
Gross:	0.000924	0.010296	0.0000099	0.0112
Net:	0.000924	0.010296	0.0000099	0.0112
			Total Gross:	**9.88**
			Total Net:	**3.43**

After analysis cuts → Total Net

Example Background: Surface Alphas



Surface contacts for HPGe

n^+:~0.5 mm (diffused lithium)

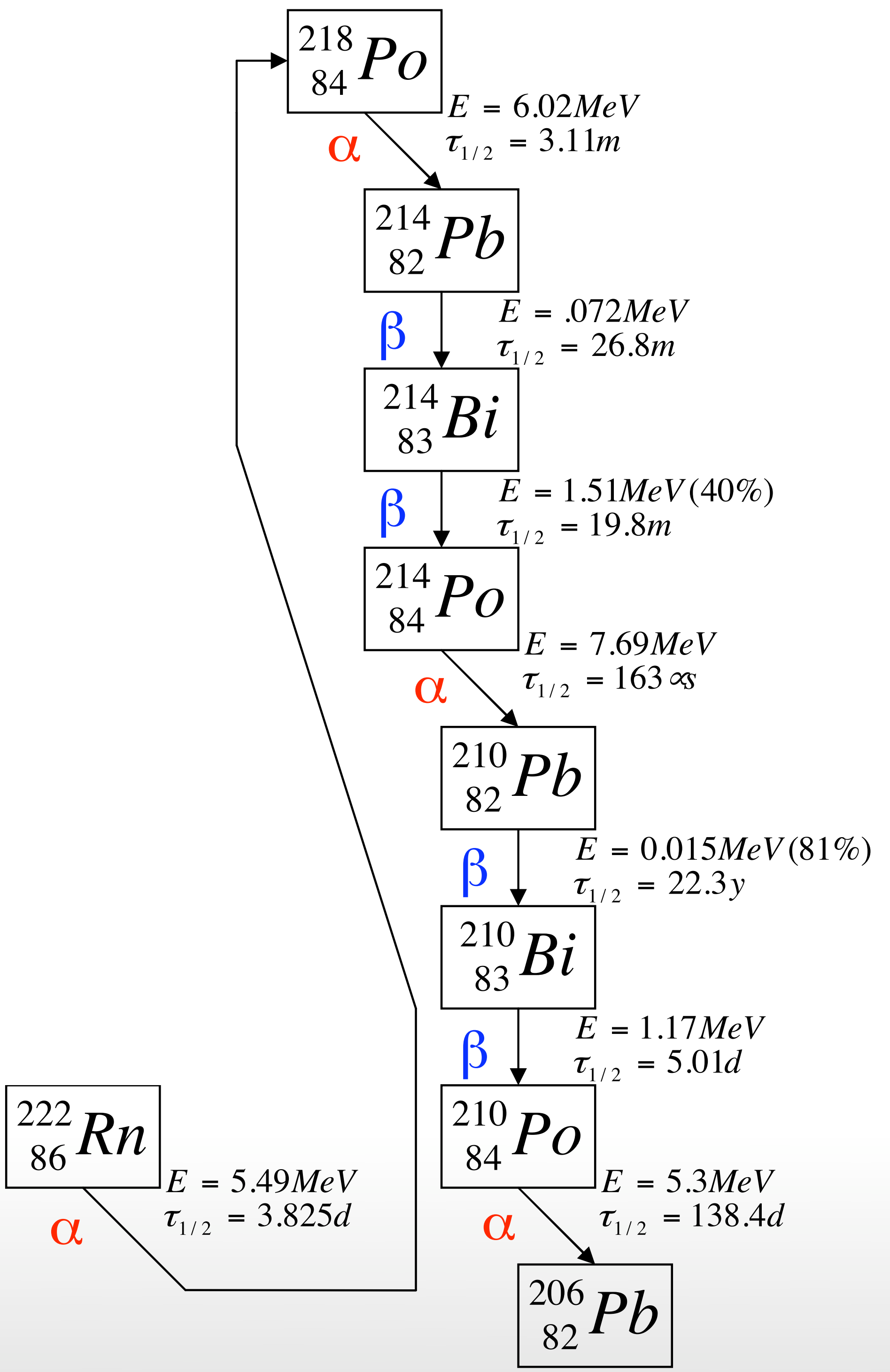
p^+: ~0.3 μm (implanted boron)

Range of α in Ge: 13-40 μm (3.9-8.8 MeV)

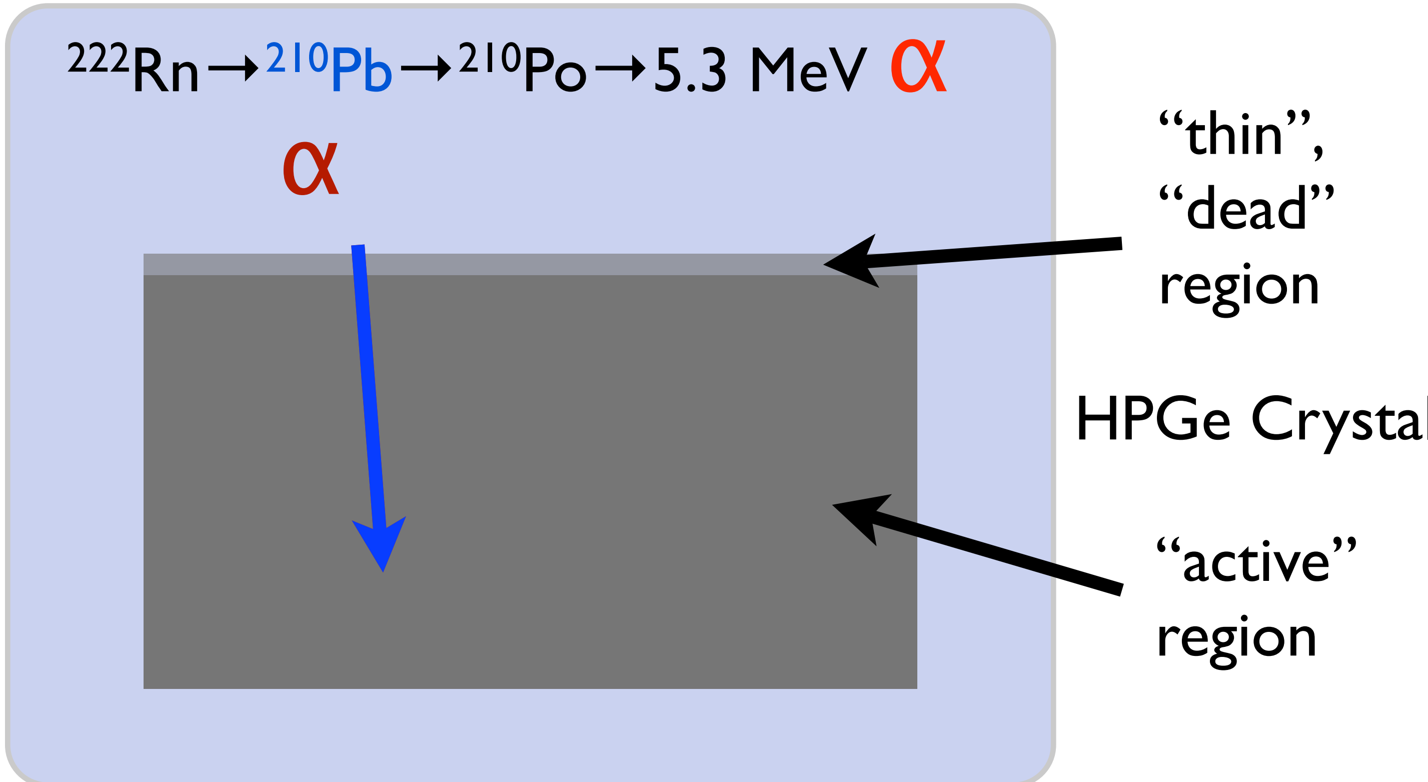
Contacts act as "dead regions" - energy lost by particle is not collected

- Alphas can get through p^+ layer (thin), but not n^+ (thick)
- P-PCs have drastically lower amount of "thin" surface area compared to N-types.

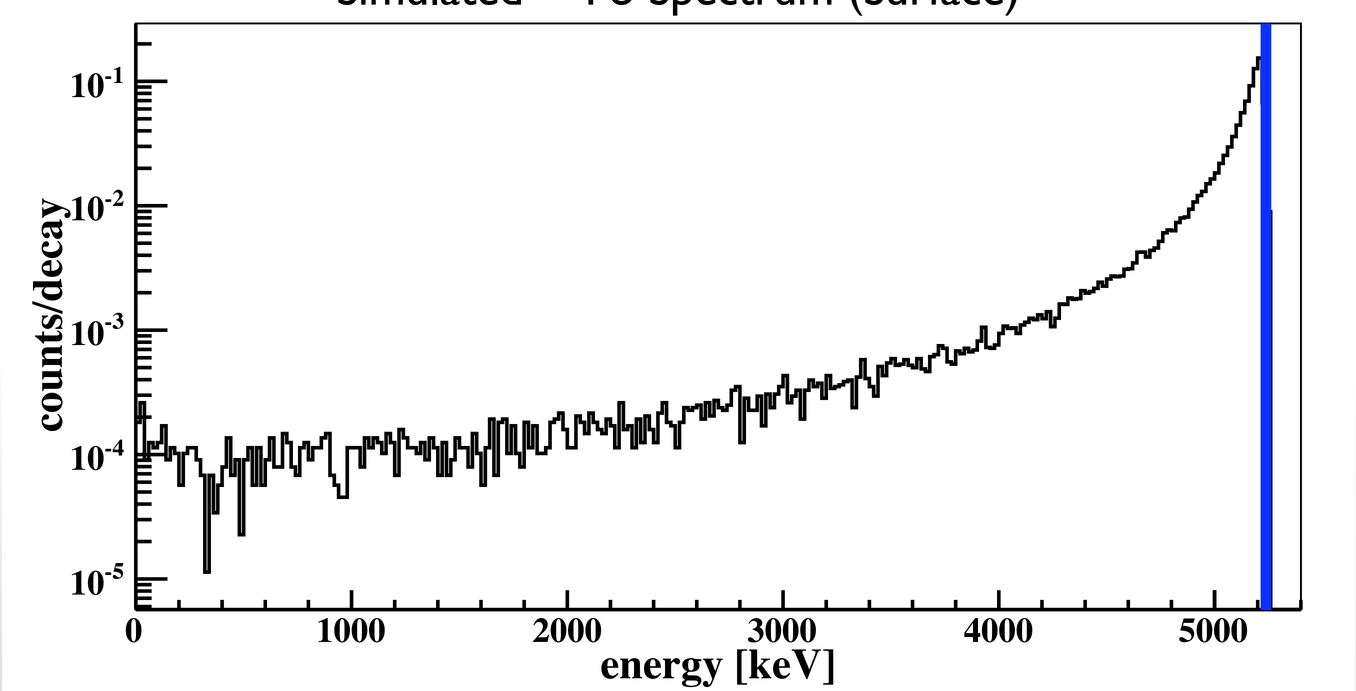
Example Background: Surface Alphas



α decay on surface (^{210}Pb plate-out)



Simulated ^{210}Po Spectrum (Surface)



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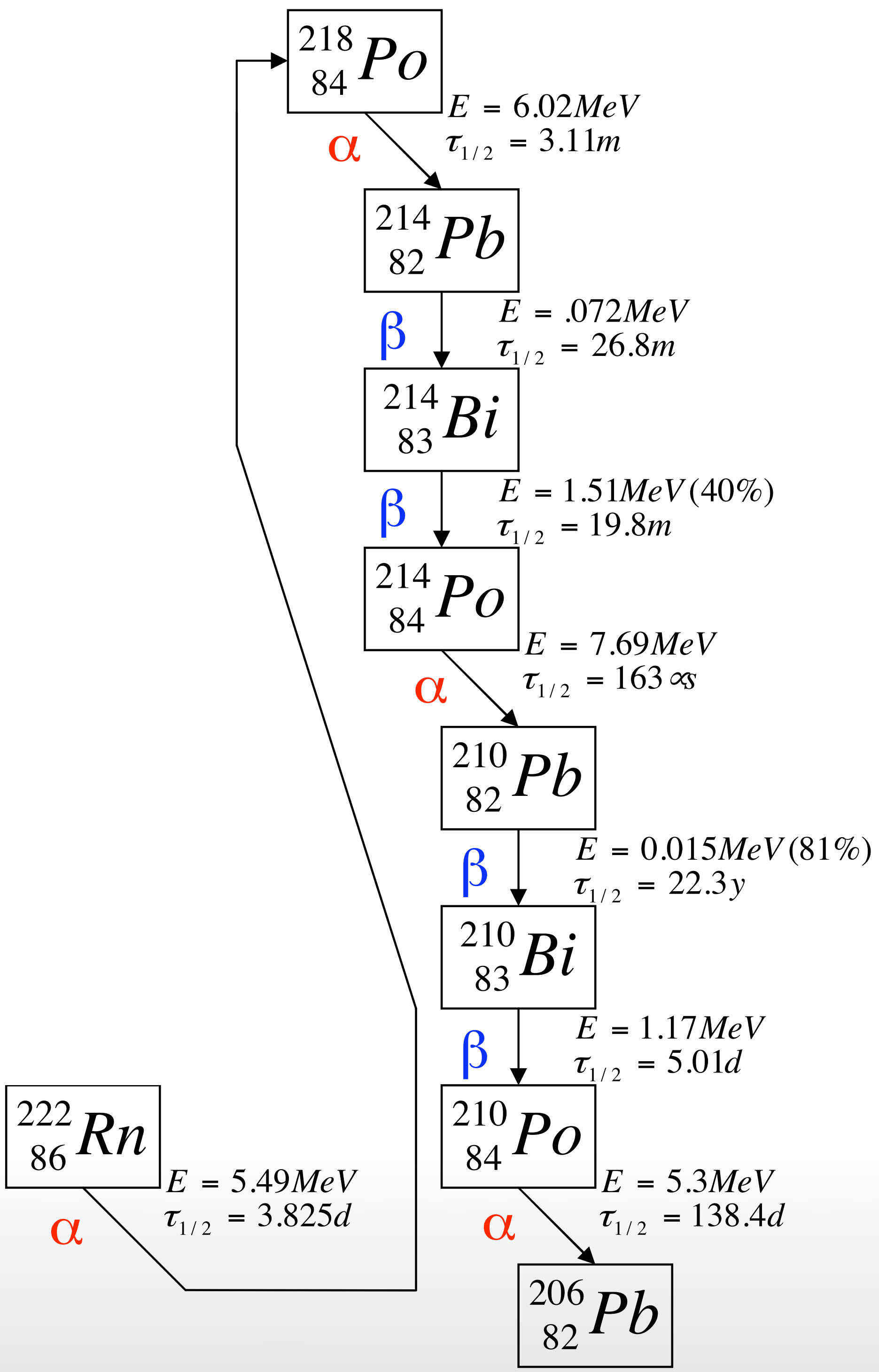

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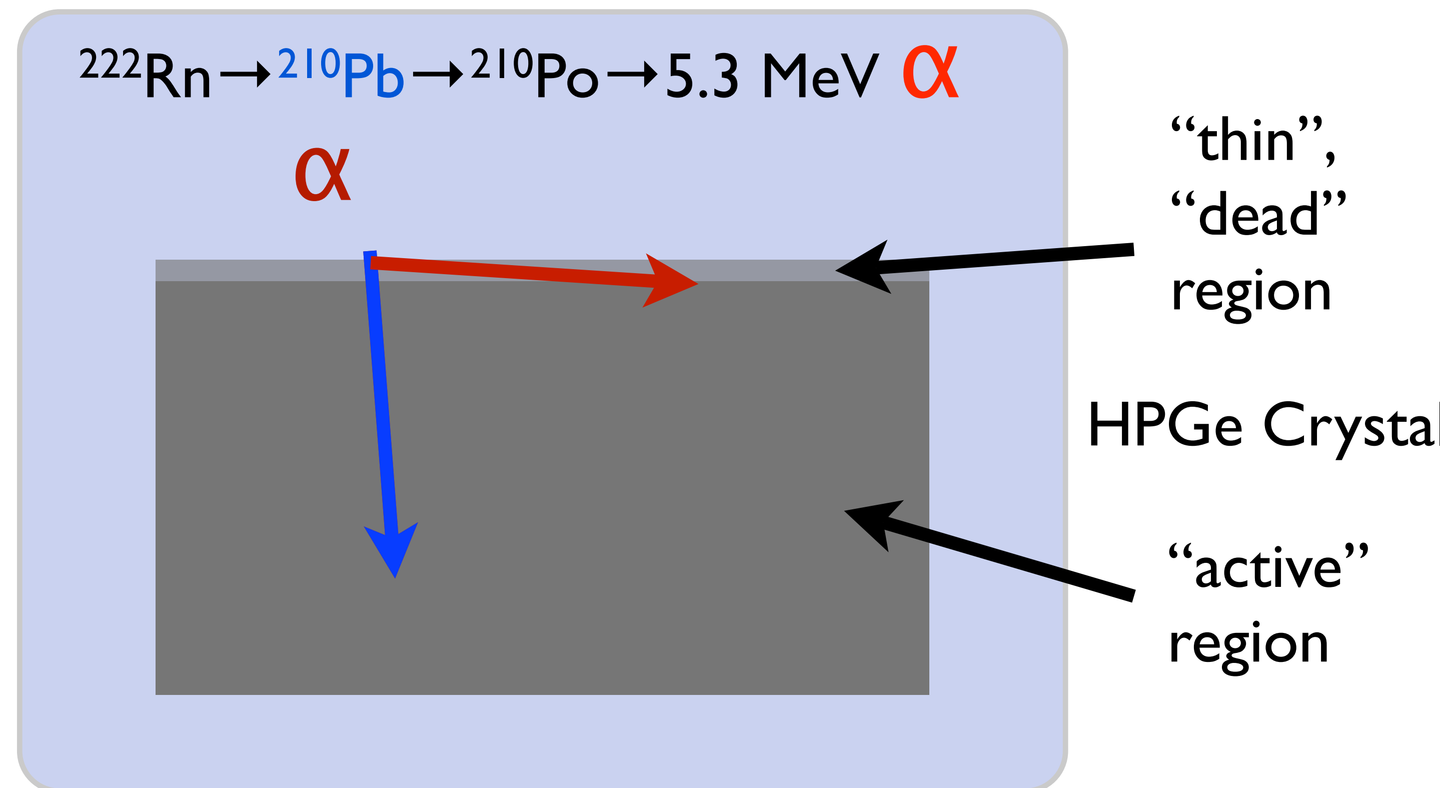

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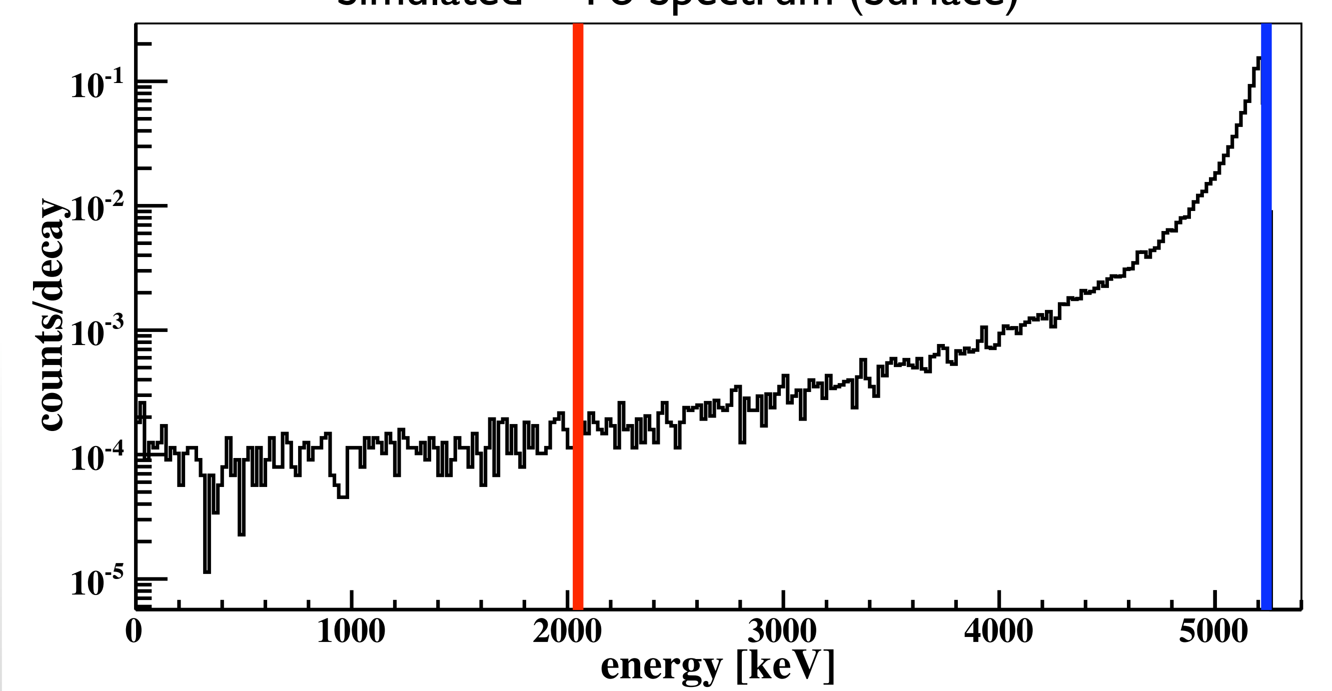


Example Background: Surface Alphas

- Brief exposure to Rn
  - ^{210}Pb plateout
  - 22-year half-life
- How much ^{210}Pb plateout is too much?
- MaGe Simulations
  - Allowable surface activity for P-PCs ~ 1000 greater than for N-types
  - Not a large background for P-PCs in the MAJORANA DEMONSTRATOR

Example Background: Surface Alphas

- Brief exposure to Rn
  - ^{210}Pb plateout
  - 22-year half-life

- How much ^{210}Pb plateout is too much?

- MaGe Simulations
  - Allowable surface activity for P-PCs ~ 1000 greater than for N-types
  - Not a large background for P-PCs in the MAJORANA DEMONSTRATOR

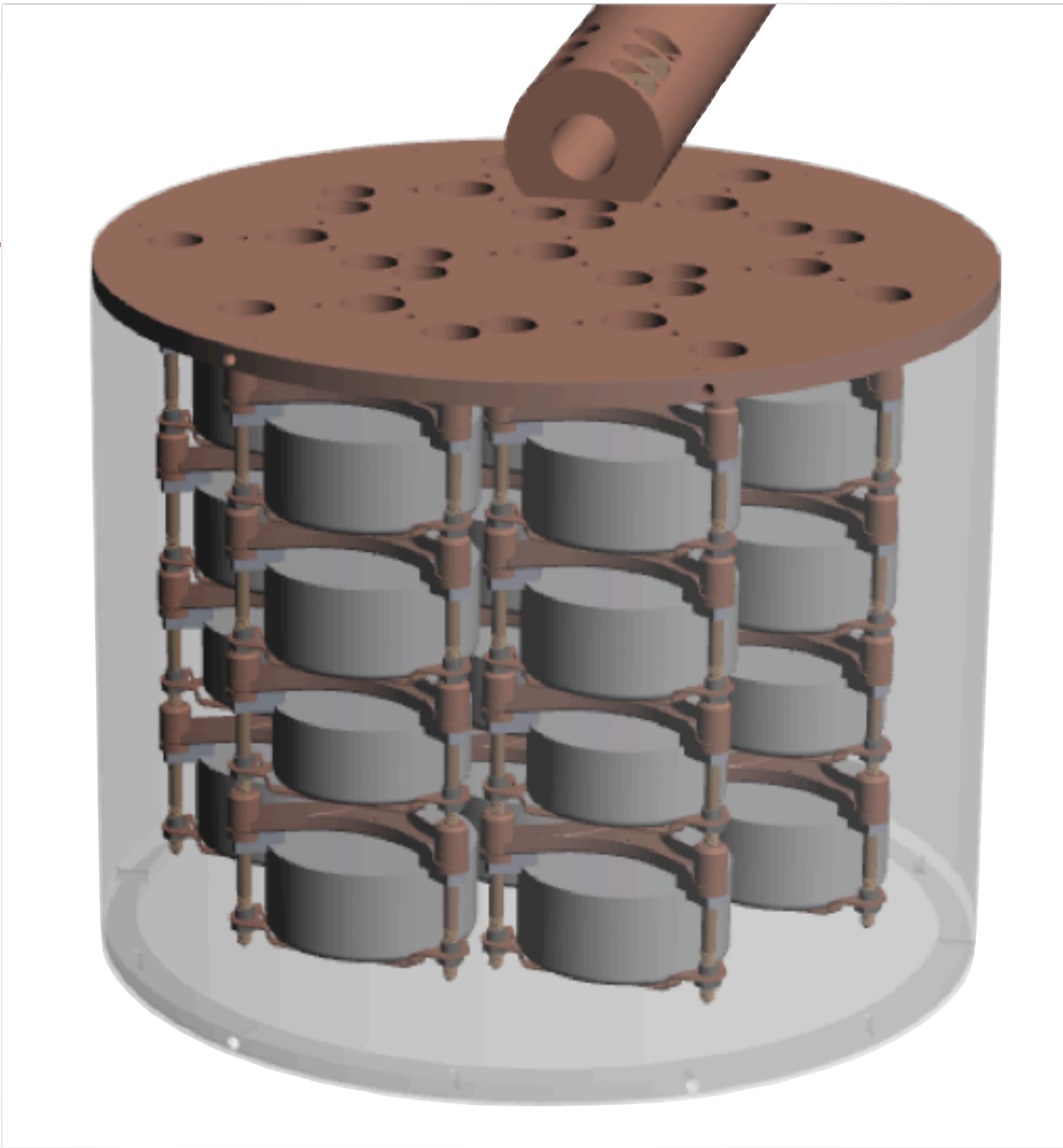
P-PC detectors have lots of nice attributes!

MAJORANA Recent Developments

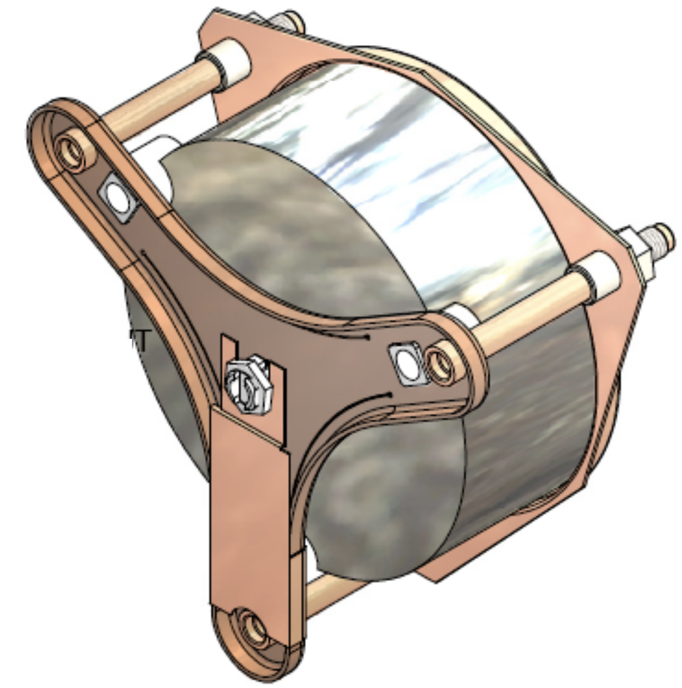
- Funding from DOE ONP, NSF MPS, and Institutional support
  - DOE ONP support as R&D project
  - DUSEL R&D from NSF and DOE
  - NSF MRI for establishing an UG electroforming facility at Sanford Lab
  - NSF S4 for developing 1-tonne Ge experiment
  - Operational support from DOE and NSF
- Majorana Demonstrator DOE ONP R&D Project
  - With participation by NSF PNA
  - Major review scheduled late October, 2009
- First module is under construction
  - 18 natural-Ge PPC Canberra Broad Energy Ge (BEGe) detectors now arriving at Los Alamos
  - Detector mounting designs being finalized

First Module

- 18 natural-Ge Canberra BEGe's now being delivered to Los Alamos
  - Detector acceptance lab constructed at LANL
  - 4 to 6 crystals per string
  - 70 mm x 30 mm
  - 579 g of active mass per detector
- Some current R&D
  - Detector mount / string design
  - Preamp front end prototyping
  - Data acquisition
- Design of Pb/Cu shield underway
  - Already procured material and shipped to Homestake
- Full-scale demonstration of MAJORANA configuration



Detector Mount / String Design

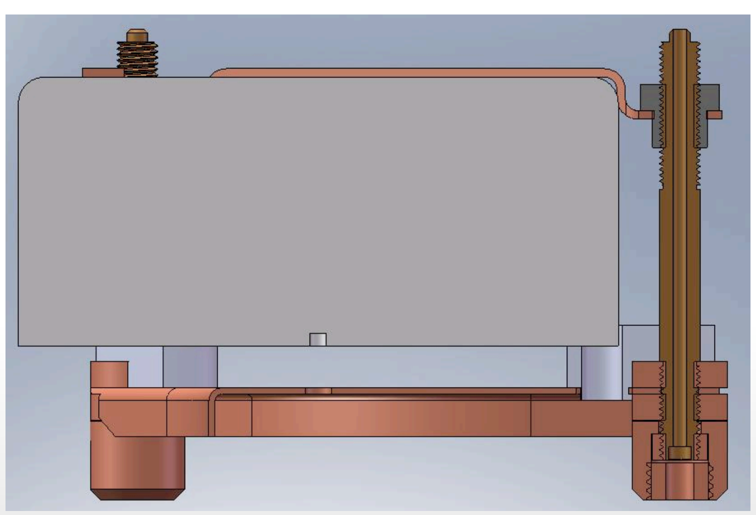


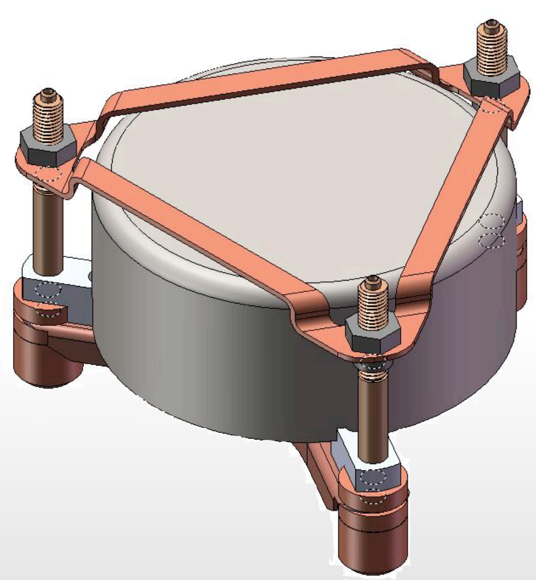
Different designs under consideration

Common to all:

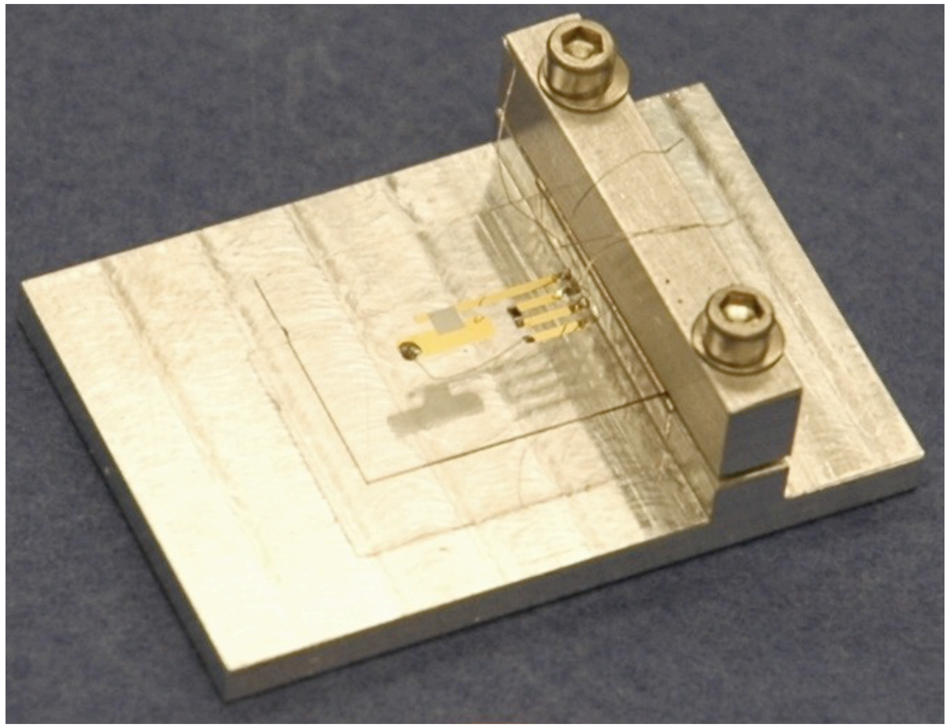
- Electroformed copper
- Low-background plastic
- Minimization of part count / mass

- Currently: iterating, prototyping, testing



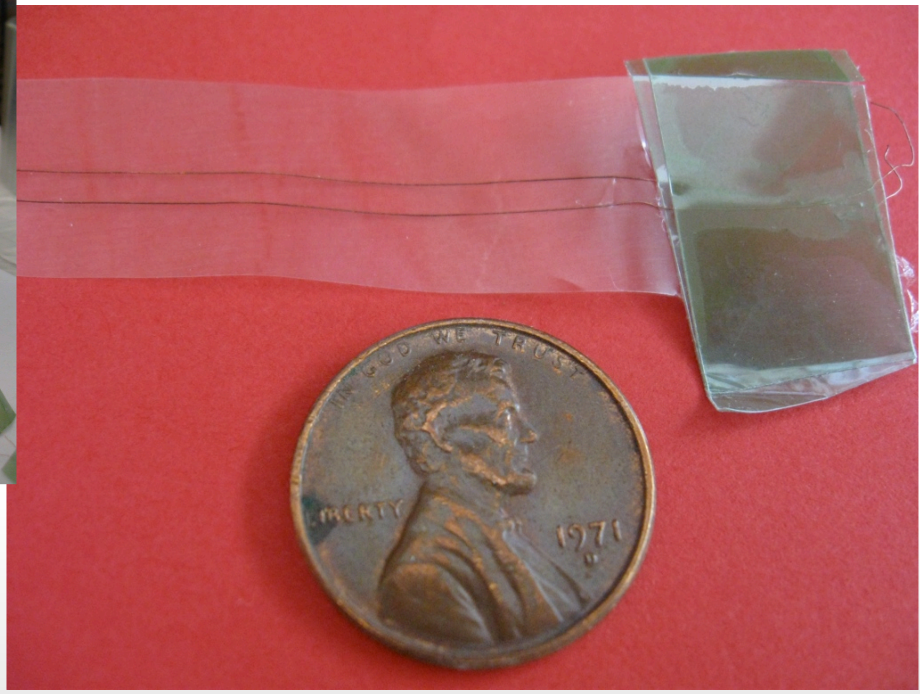


Front-End Electronics



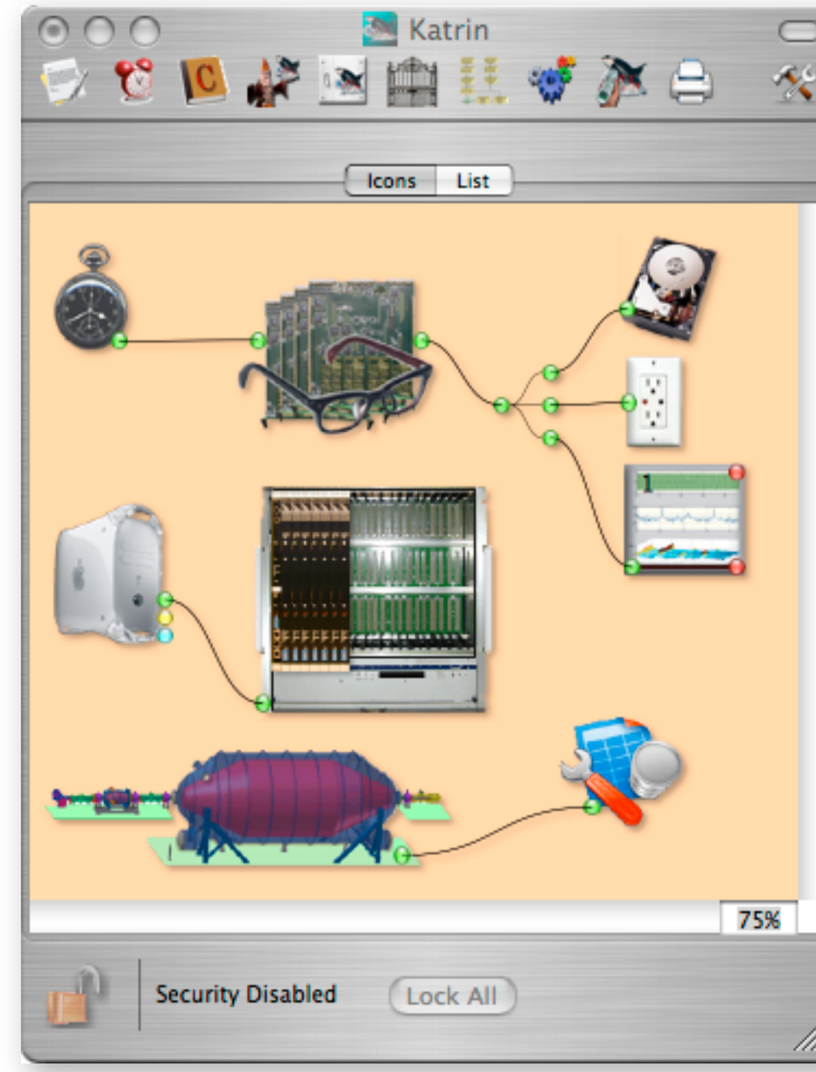
- Low-background, low-noise preamp
  - Mounted < 1” from point contact (for noise)
  - Small footprint
  - 100 eV noise-threshold goal
  - Evaluating pulsed-reset and resistive feedback designs

- Low-background, low-mass cables
  - Handmade Parlyene-coated wire, ribbon cable prototypes
  - Low mass: .4 g/km Cu, ~0.02 g/km Parylene (wire)
  - Low-background: present upper limit, parylene < 30 - 50 ppt U, Th



DAQ R&D Detector: Soudan, MN

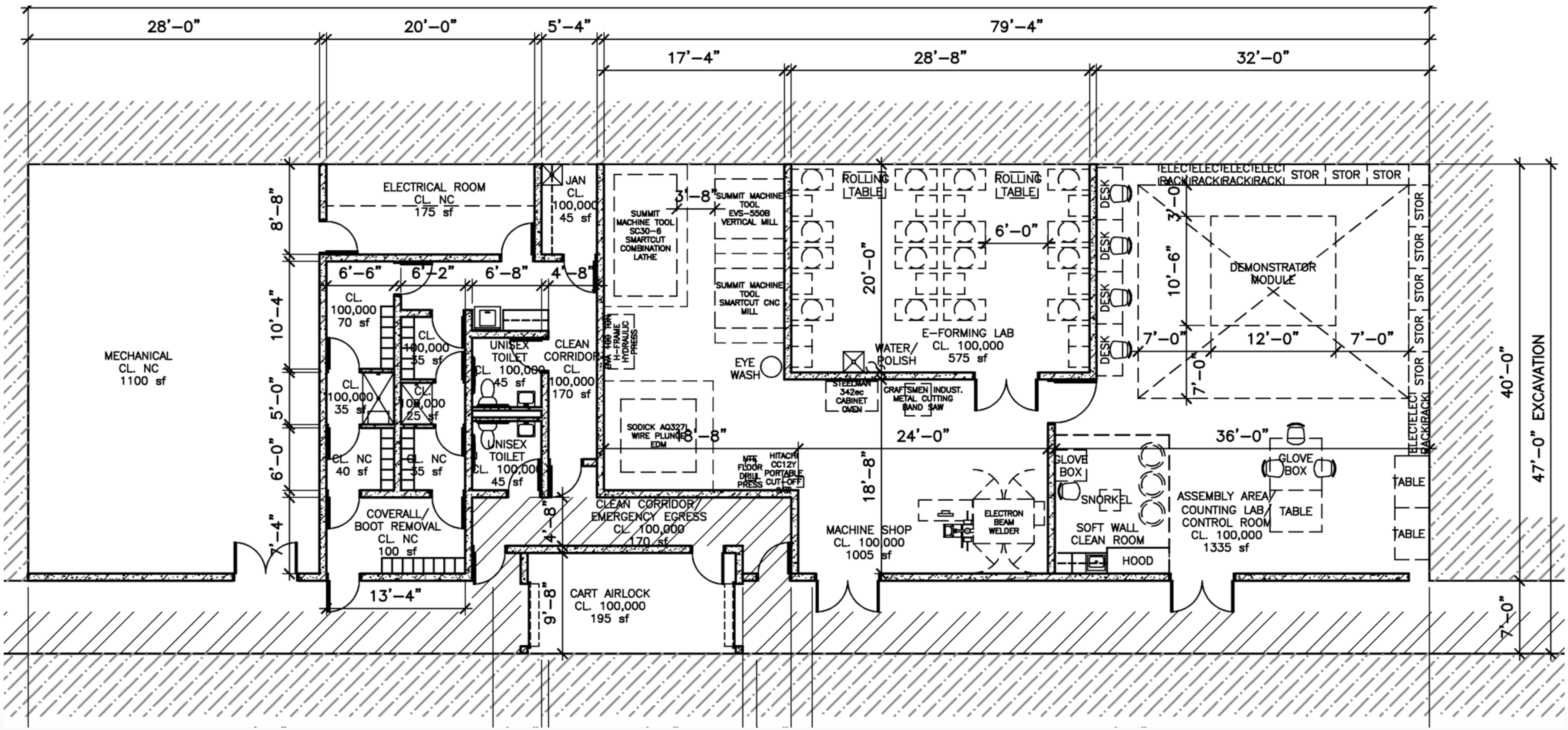
- Deployed underground in Soudan, MN (Sept 2008)
  - 0.5 kg PPC, 200 eV electronic noise (FWHM)
  - Lead shield, inner copper shield, muon veto
- Goals:
  - Testing stability of fully digital DAQ/analysis chain in a deployed (remote, underground) system
  - Concurrently take digitized pulses at low-energy (≤ 100 keV) and high-energy (≤ 10 MeV)
- ORCA Running stably for >100 days
  - Object-oriented Real-time Control and Acquisition[1]
  - Large catalog of data acquisition hardware, tools
  - Drag & Drop to create data acquisition chain
  - Runtime configuration, data monitoring, data broadcast
  - Used in SNO NCD phase, KATRIN, UW, LANL, MAJORANA



[1] Howe *et al.* IEEE Transactions on Nuclear Science, 51 (3), 878-83

MAJORANA Lab Space

Draft of lab space, 4850’ level of Sanford Lab / Homestake



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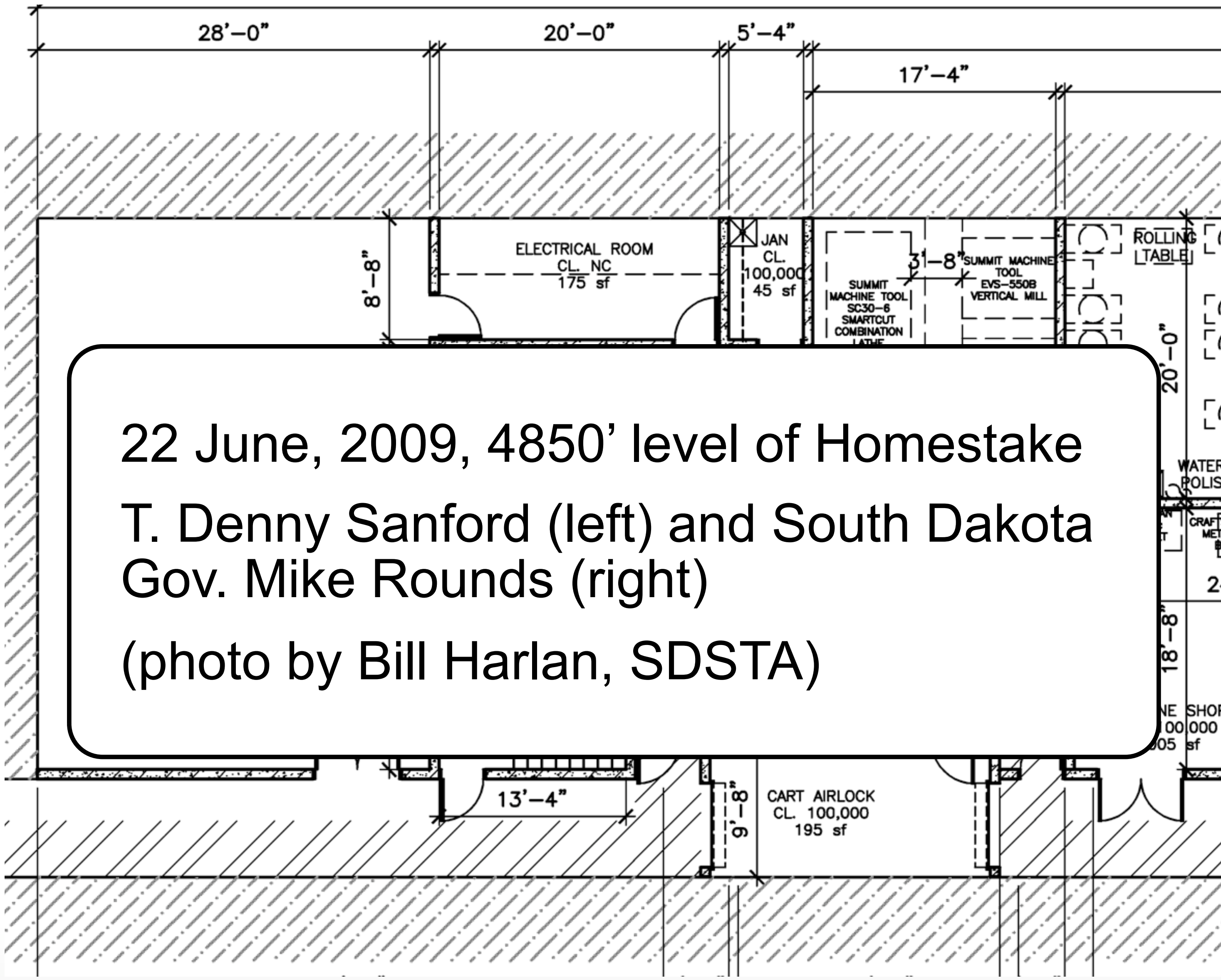


22 June, 2009, 4850’ level of Homestake

T. Denny Sanford (left) and South Dakota Gov. Mike Rounds (right)

(photo by Bill Harlan, SDSTA)

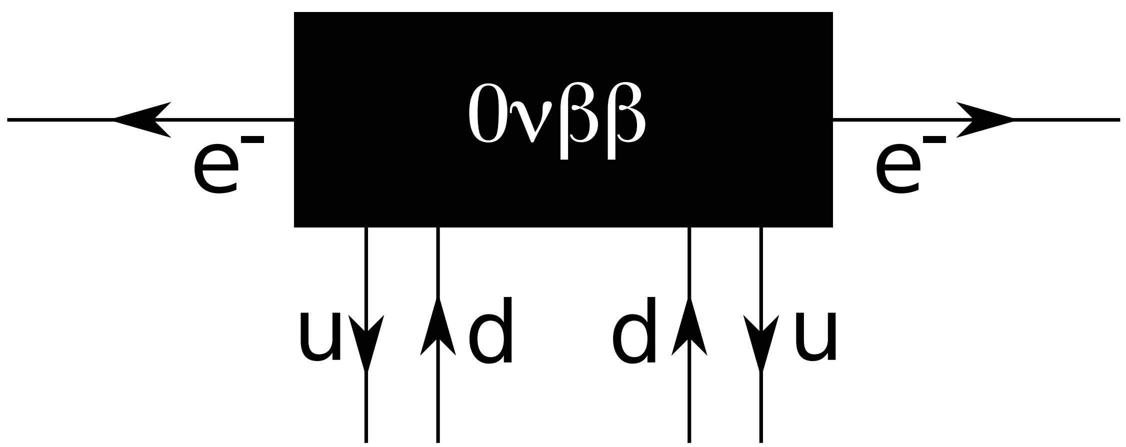
MAJORANA Summary

- The MAJORANA DEMONSTRATOR is a 0νββ R&D project using 60-kg of Ge: aimed at tonne-scale experiment
  - Technical goal: Demonstrate low-enough background to justify a tonne-scale experiment
  - Science goal: Confirm or refute the recent discovery claim of 0νββ
- Primary focus is on first module, first BEGe (P-PC) detectors have arrived.
- Much design work and prototyping in progress.
- Sanford Lab preparations are proceeding rapidly
  - Installation of electroforming facility in late 2009
  - Installation of DEMONSTRATOR lab in 2010

Thanks for your attention!

Backup Slides

$0\nu\beta\beta \Rightarrow$ Majorana Neutrino



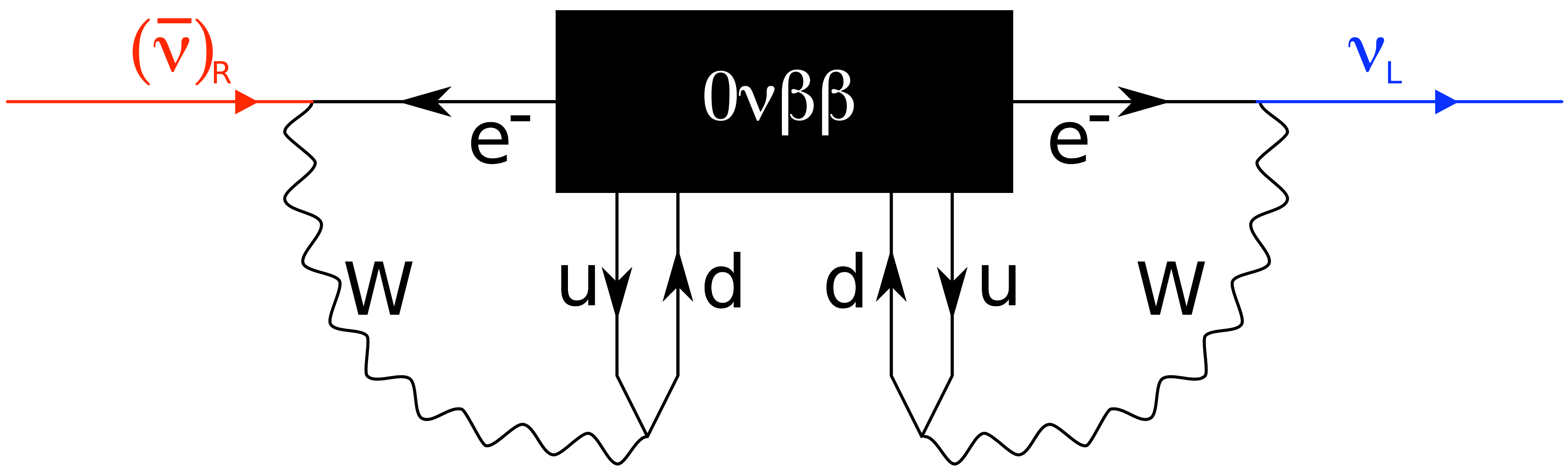
Schechter and Valle

Phys. Rev. D 25, 2951 - 2954 (1982)

Neutrinoless double-β decay in SU(2)×U(1) theories

$0\nu\beta\beta \Rightarrow$ Majorana Neutrino

$(\bar{\nu})_R \longrightarrow \nu_L$



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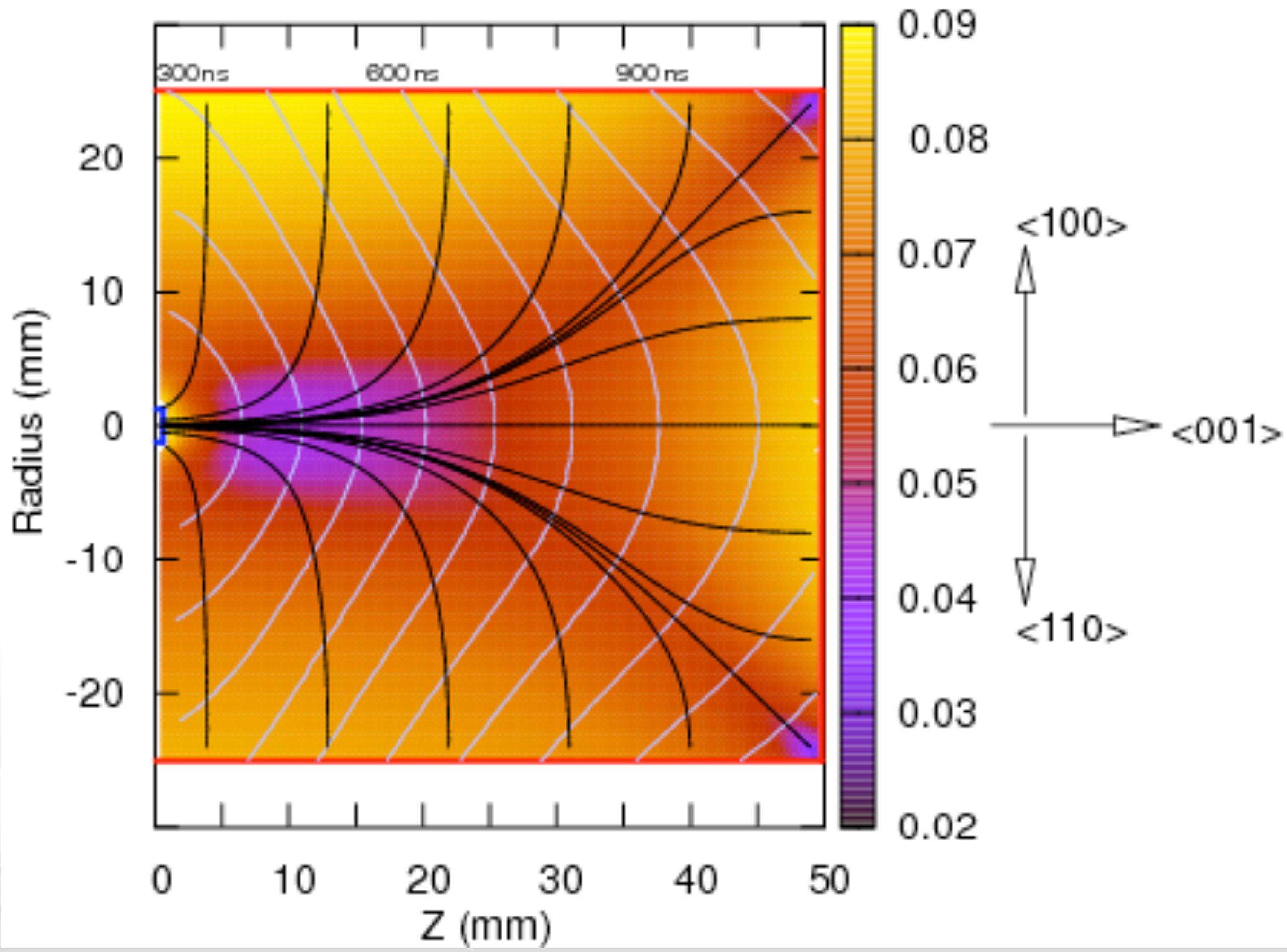
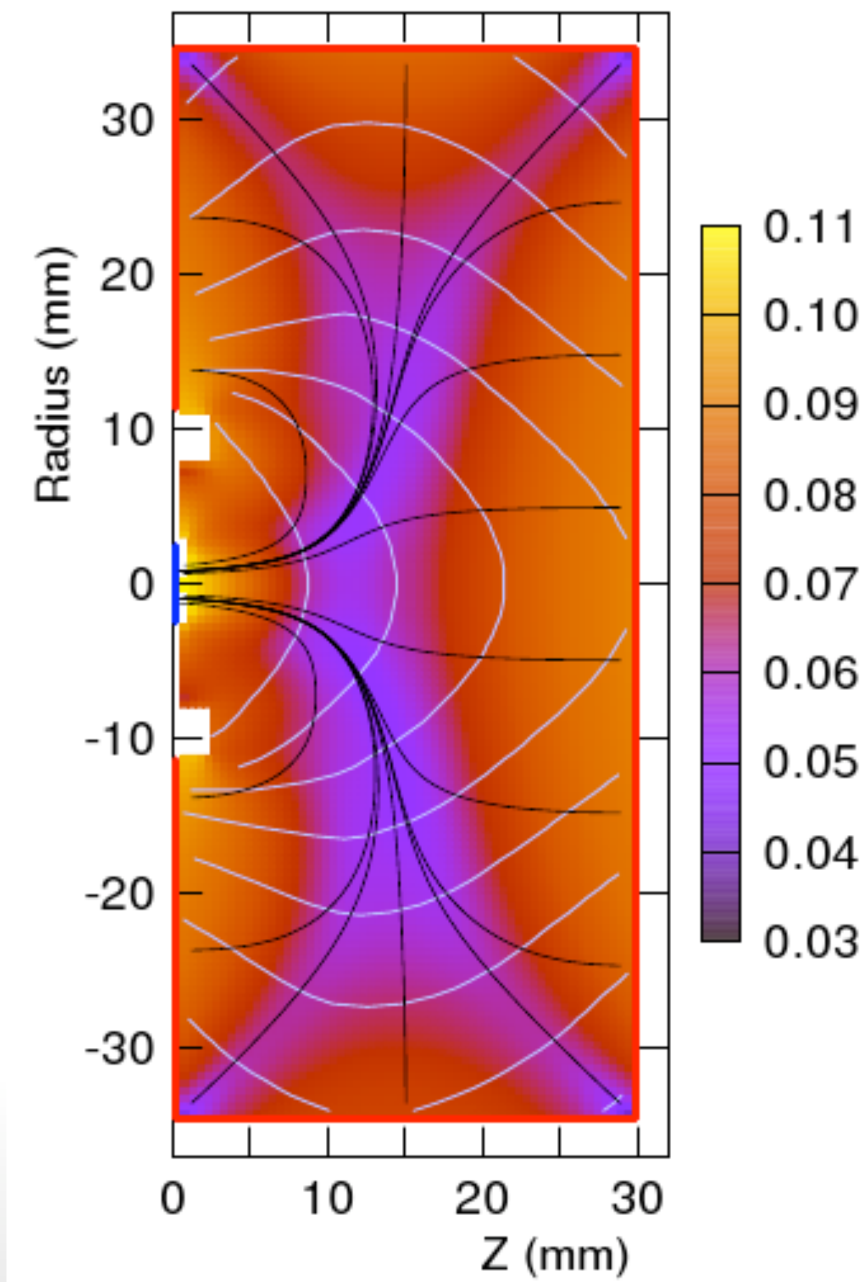
P-PC Detectors

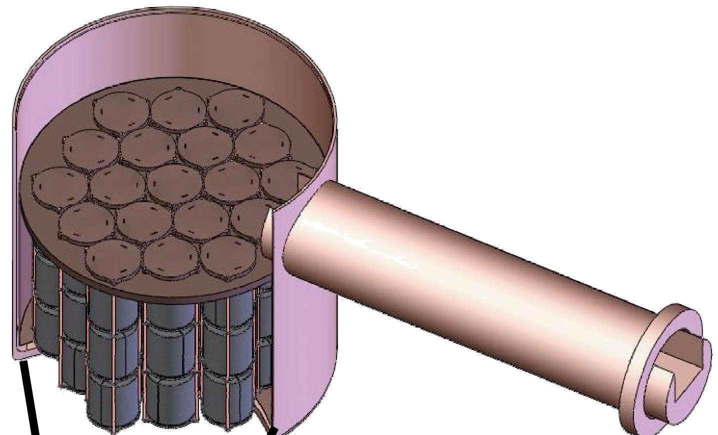
Calculated hole drift in typical PPC-style detectors

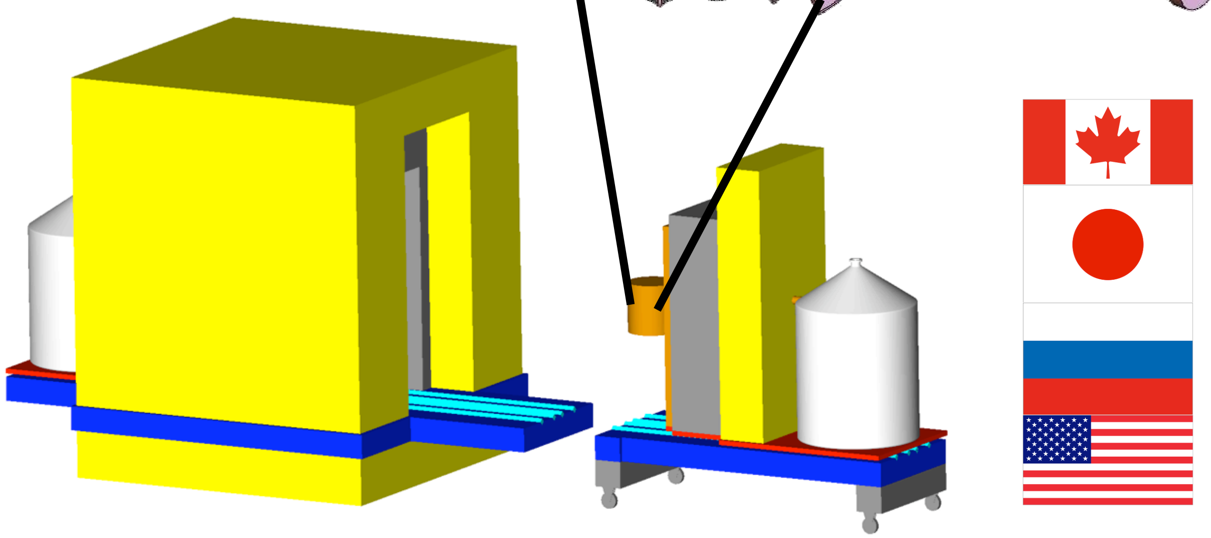
- Velocity of hole charges (mm/ns; color scale)
- Example drift paths (black lines)
- Isochrones (grey lines): Constant drift time, 100 ns/line

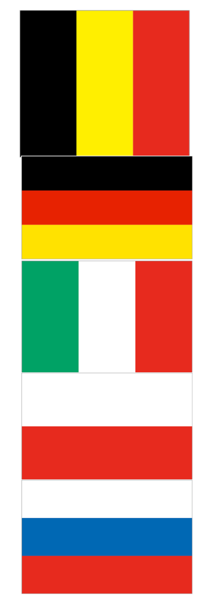


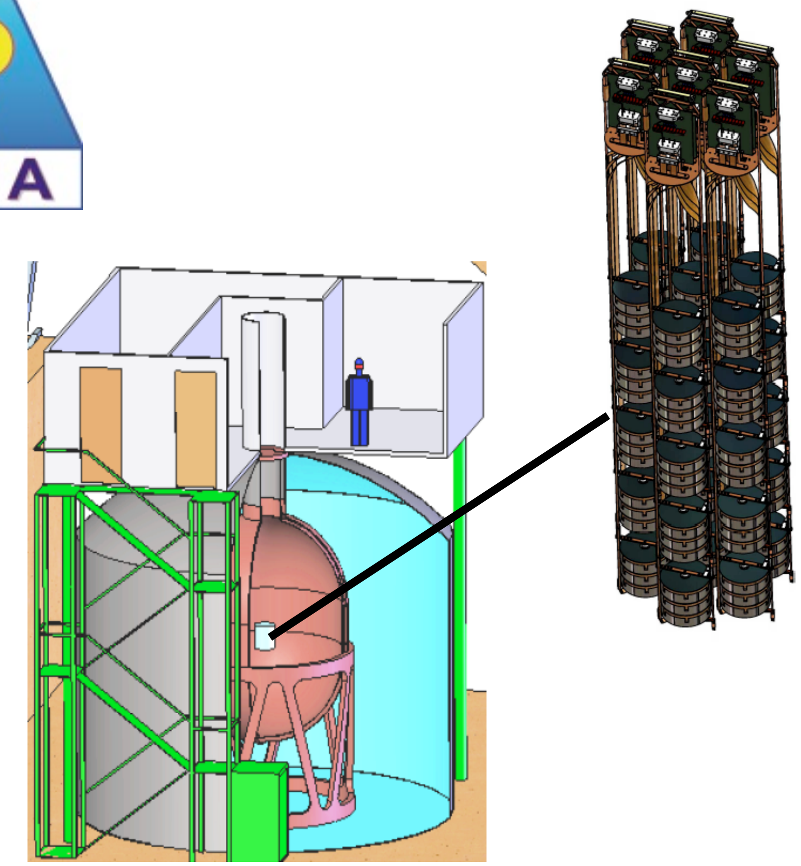


MAJORANA and GERDA









- Modular ^{enr}Ge arrays in electroformed Cu cryostats
- E-formed Cu / Pb passive shielding
- 4π plastic scintillator μ veto

- ^{enr}Ge array submersed in LAr (bare)
- Water cherenkov μ veto
- Phase I: ~18 kg (H-M/IGEX crystals)
- Phase II: +20 kg segmented crystals

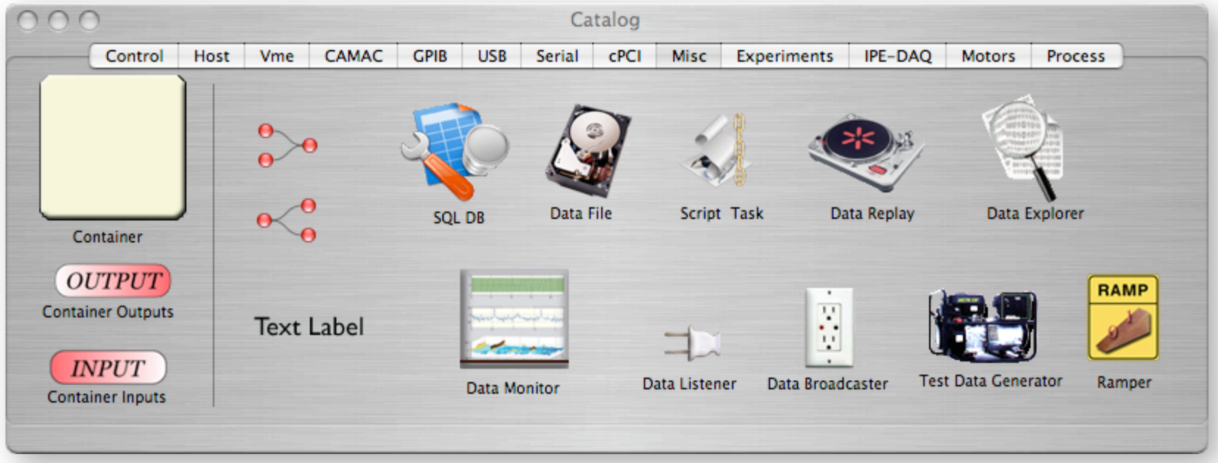
Open exchange of knowledge and ideas (e.g. MaGe MC)
Intend to merge for 1-tonne experiment using the best techniques

ORCA

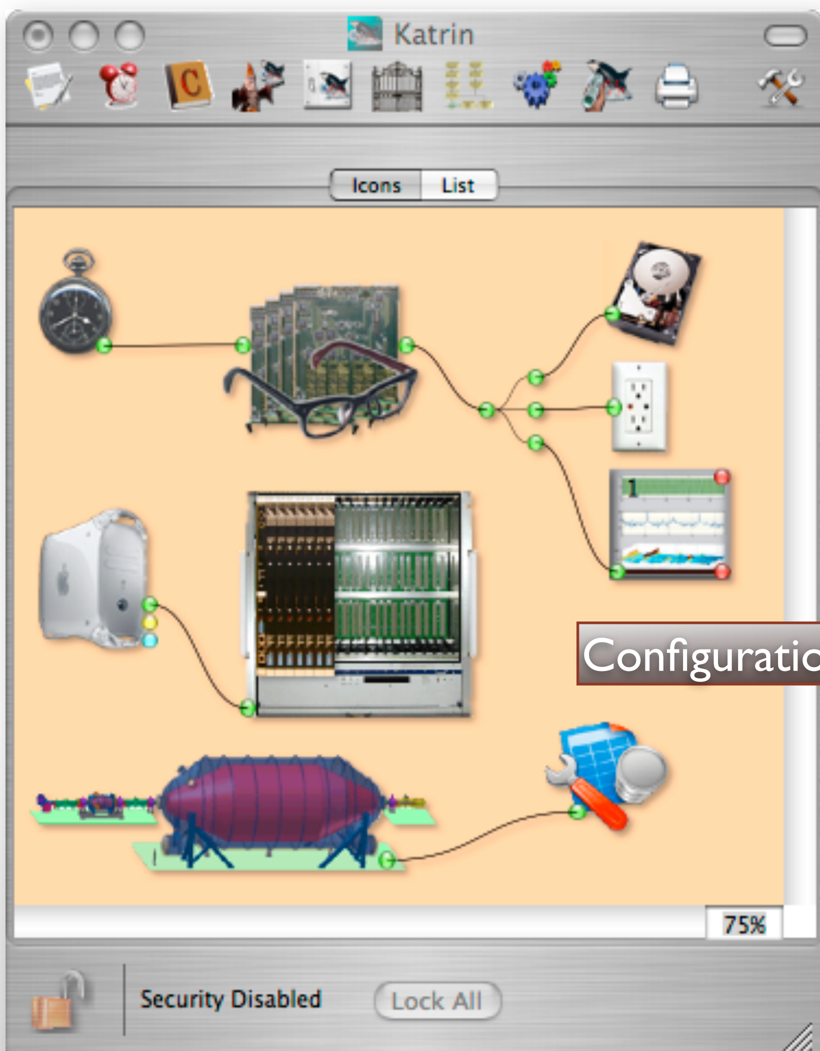
Object-Oriented Real-time Control and Acquisition

Howe *et al.* IEEE Transactions on Nuclear Science, 51 (3), 878-83

Object Catalog



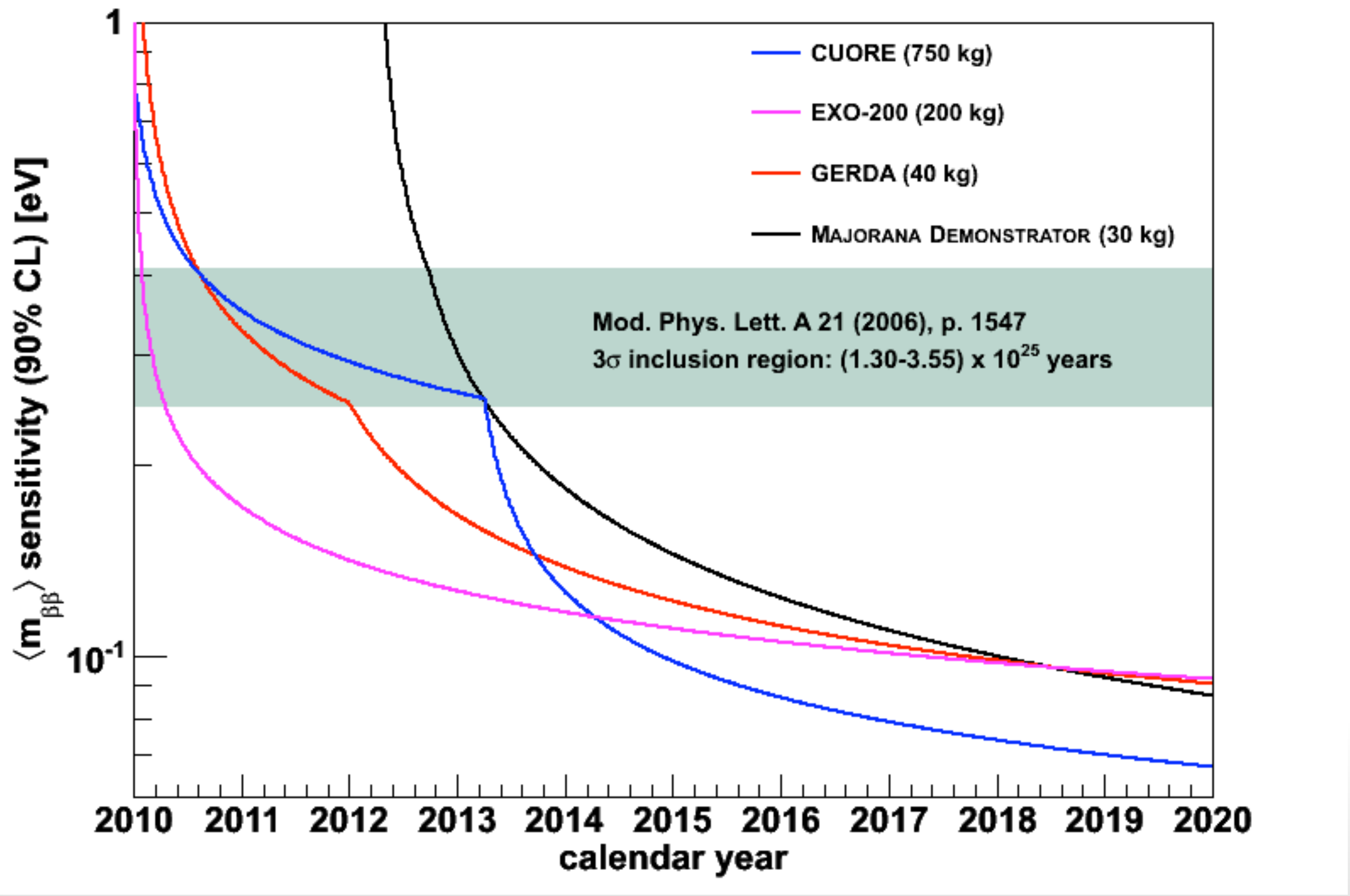
Drag 'n Drop to Place Objects



Configuration View

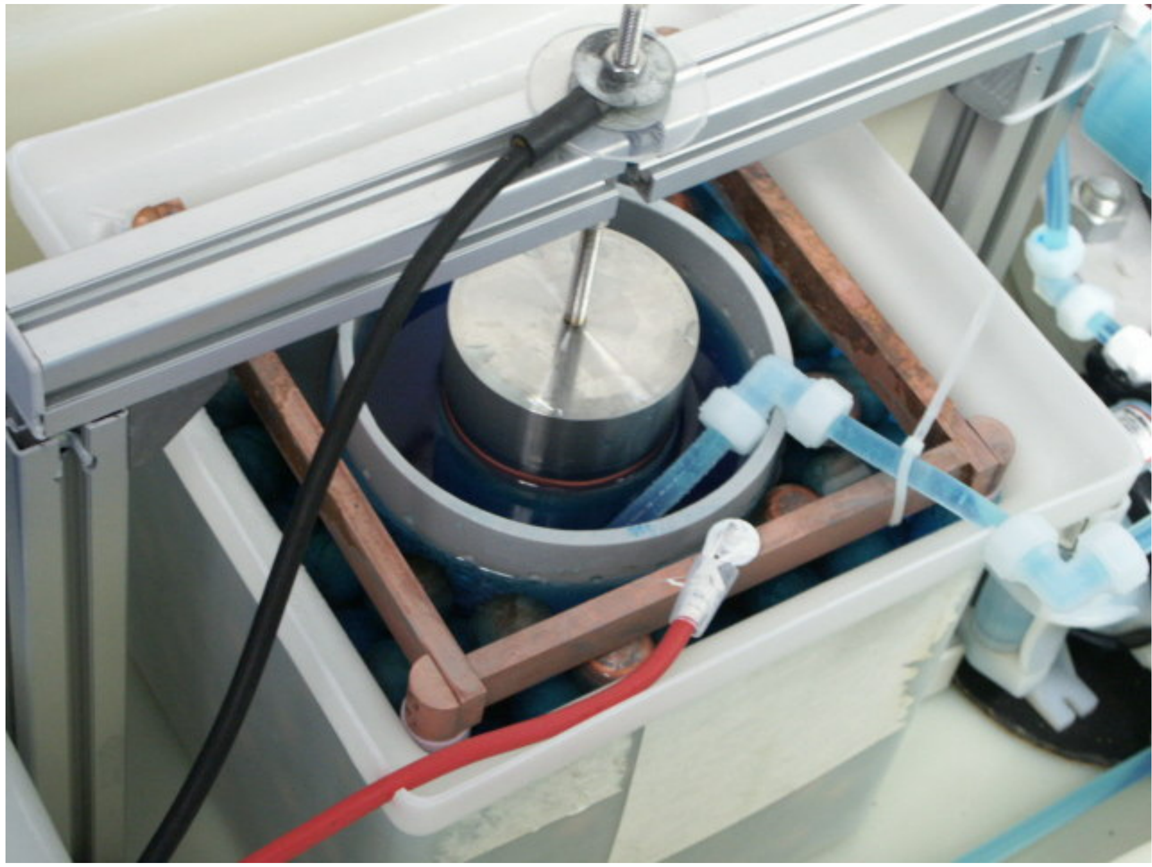
- Object-oriented
  - Plug & Play
  - Large catalog of acquisition hardware, analysis tools
  - Drag & Drop to create data acquisition chain
- Run
  - Runtime configuration
  - Data monitoring / replay
  - ROOT support
  - Data stream can be broadcast to remote applications/machines Support
- Usage
  - SNO NCD, KATRIN pre-spectrometer, UW accelerator, UW test stands, UW Radiology, MAJORANA(development), Los Alamos

Global 0νββ Efforts



Underground electroforming

- Electroforming underground
  - Start from pure copper stock
  - Sacrificial copper anode material, $CuSO_4$ bath, current
  - Plate-out on cathode
  - Remove ^{60}Co, Th, U



- First underground part e-formed at Waste Isolation Pilot Plant (WIPP)
  - Carlsbad, NM
  - 655 m, 1585 m.w.e. (meters water equivalent)
  - D.O.E. facility w/ space set aside for fundamental science research

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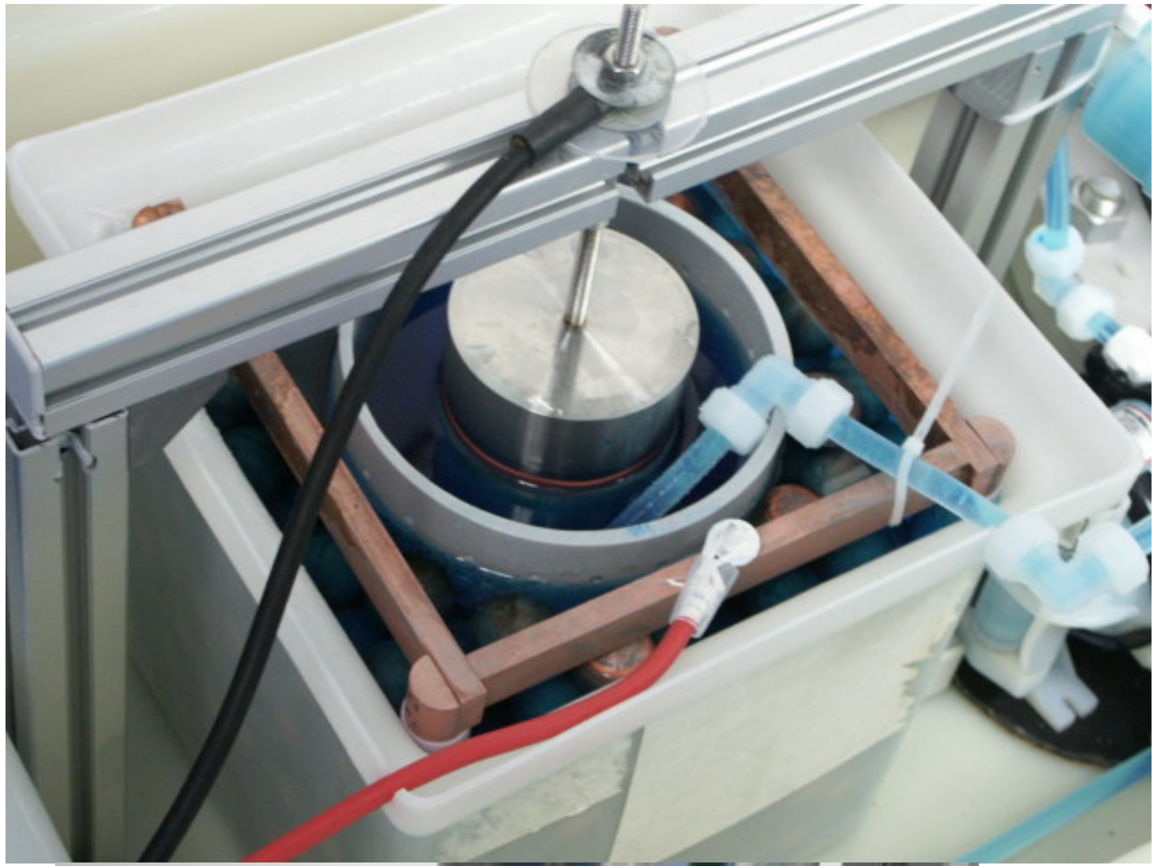

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