THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

A search for bosonic dark matter with the MAJORANA DEMONSTRATOR

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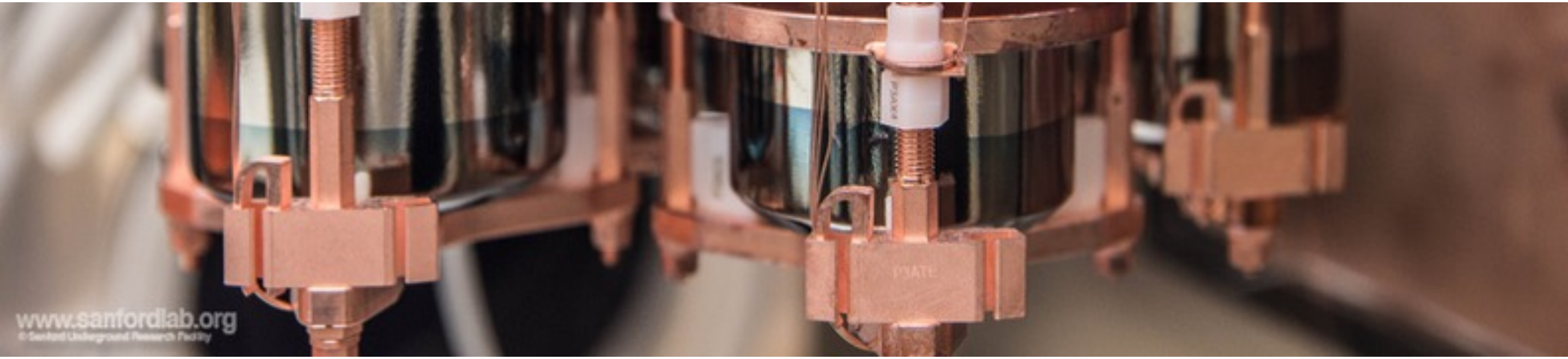
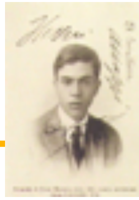
University of North Carolina
and
Triangle Universities Nuclear Laboratory



Patras Workshop
Jeju Island, South Korea
June 23, 2016

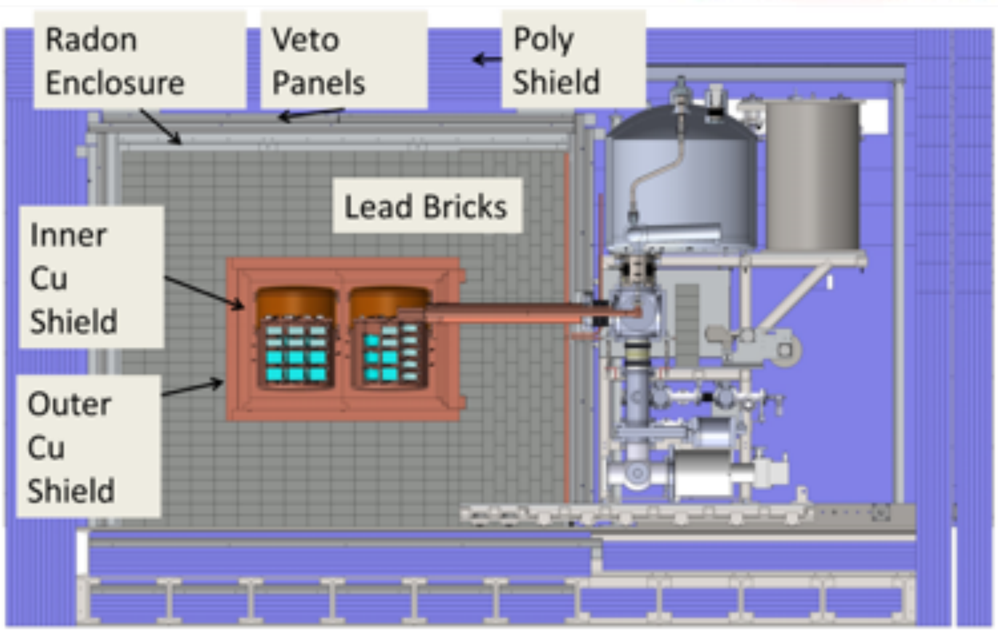
The MAJORANA DEMONSTRATOR



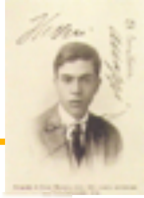
Funded by DOE Office of Nuclear Physics, NSF Particle Astrophysics, & NSF Nuclear Physics with additional contributions from international collaborators.

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

- Located 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
  scales to 1 count/ROI/t/y for a tonne experiment
- 44-kg of Ge detectors
  - 29 kg of 87% enriched ^{76}Ge crystals
  - 15 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



Sensitivity, Background and Exposure



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

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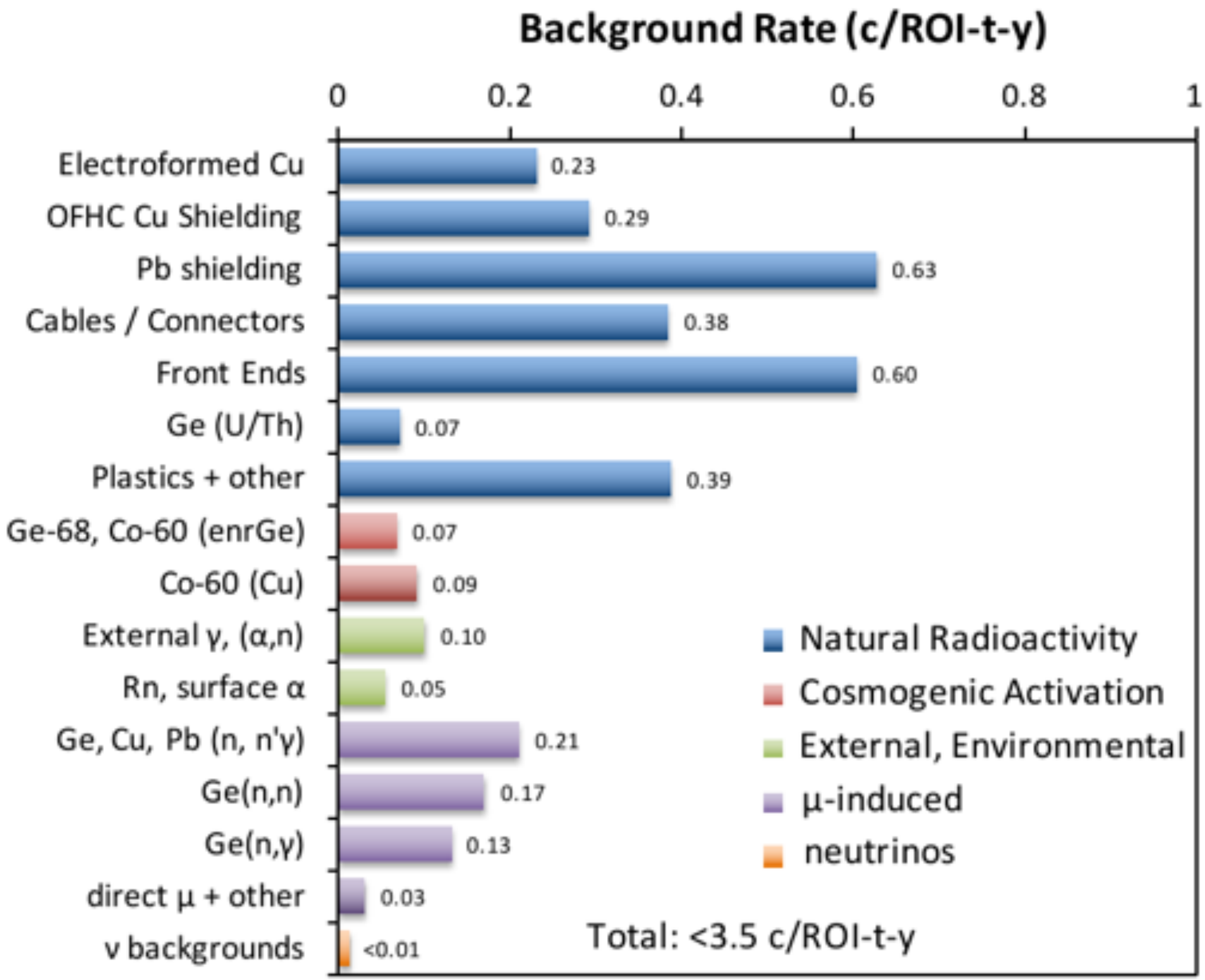

From electroformed Cu and enriched Ge

- 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

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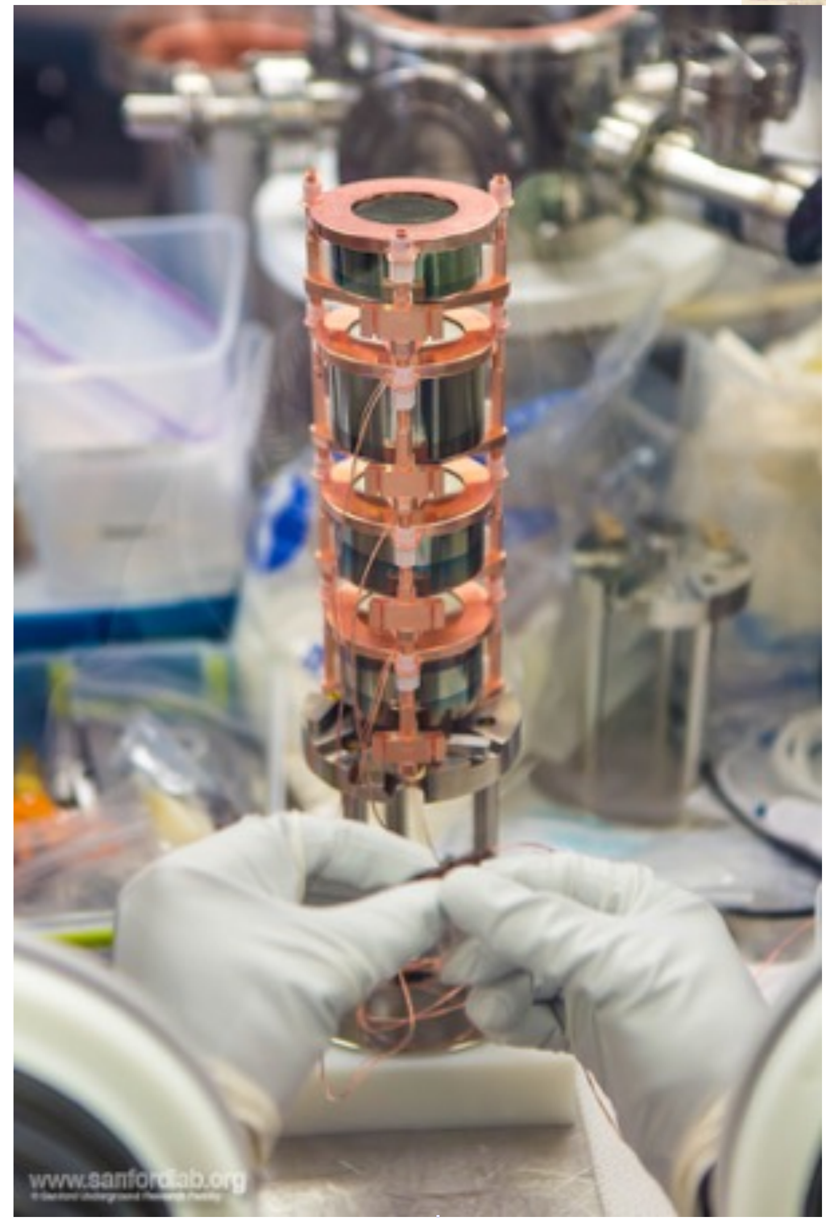


Fig: Courtesy M. Kapust

Electroformed Cu and enriched Ge

Fig: Courtesy M. Kapust

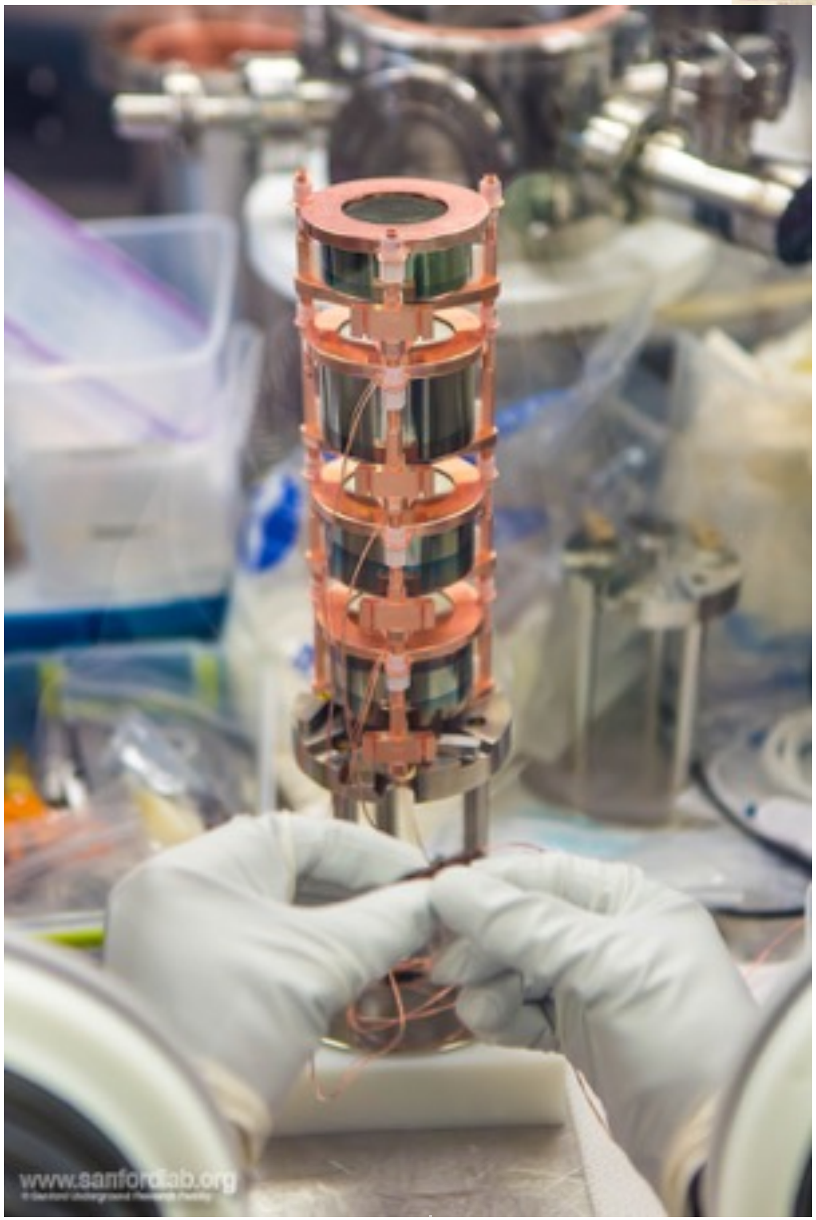
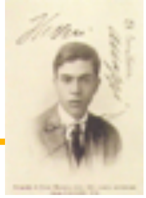


Fig: Courtesy M. Kapust

DEMONSTRATOR Implementation

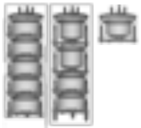


Three Steps

In-shield Running

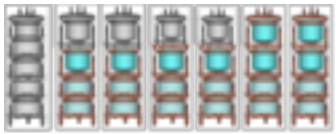
Prototype Module : 7.0 kg (10) ^{nat}Ge

Same design as Cryos 1 & 2, but fabricated using OFHC Cu.



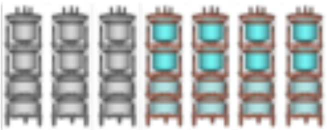
June 2014 - June 2015

Module 1 : 16.8 kg (20) ^{enr}Ge, 5.7 kg (9) ^{nat}Ge

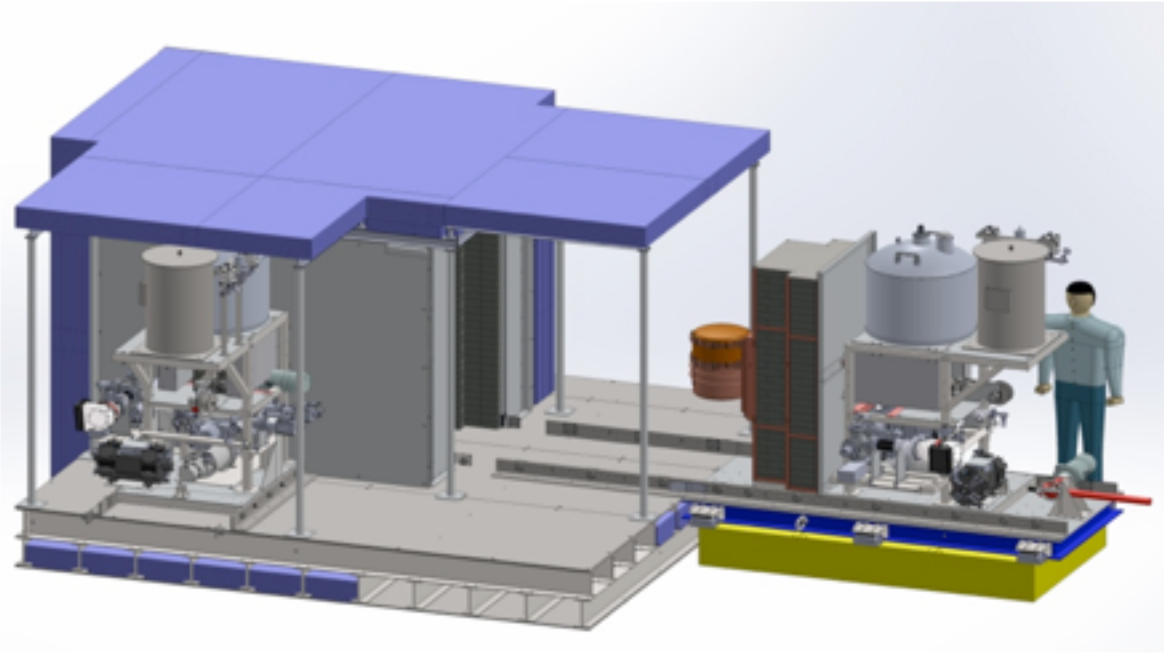


May 2015 - Oct. 2015
Final Installations,
Jan. 2016 - on going

Module 2 : 12.8 kg (14) ^{enr}Ge, 9.4 kg (15) ^{nat}Ge

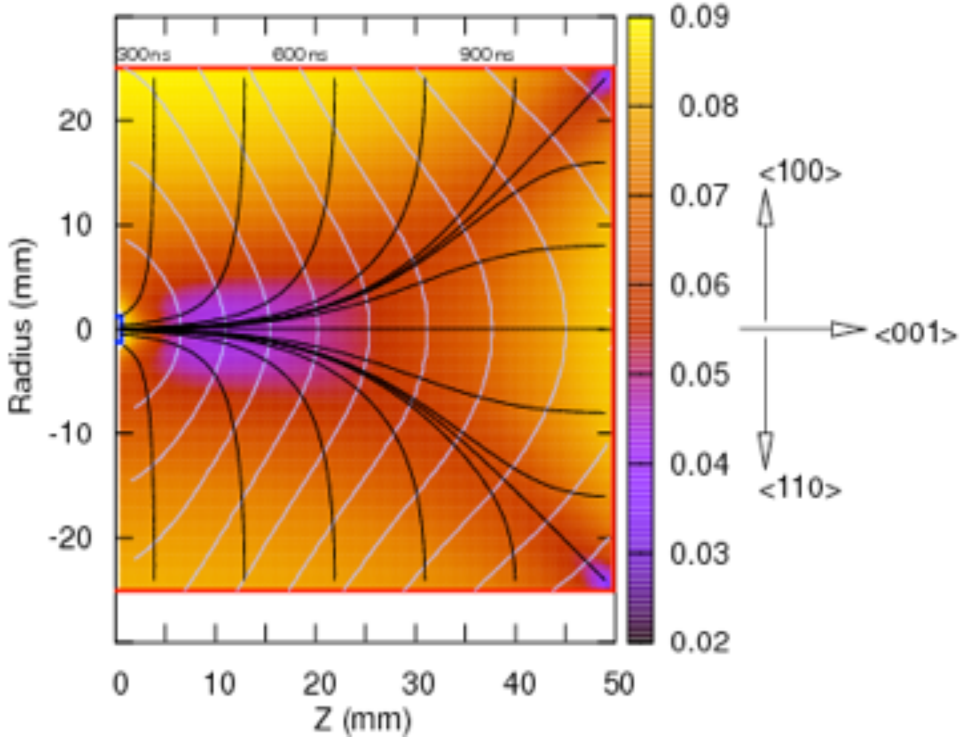


July 2016



Low-energy physics with P-PC detectors

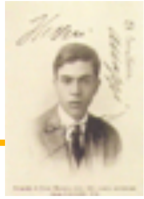
- Low-energy Thresholds (<500eV) of P-PC detectors and excellent energy resolution provides powerful tag of ^{68}Ge decays via K and L-Shell lines
- Also allows other science goals.
- **Isotopic enrichment and control of exposure to cosmic-rays reduces low-E backgrounds**



Low-energy physics with P-PC detectors

- Light (<10 GeV/c2) WIMP searches
  - Low energy nuclear recoil, excess events < 2-2.5 kev_{ee}
- Solar Axions
  - Primakoff Conversion, Axioelectric effect, ^{57}Fe, ^{169}Tm M1 transitions
- Pauli-Exclusion Principle Violation
  - Distortions in $2\nu\beta\beta$ spectrum,
  - Downshifted Ge x-ray rate (peak at 10.6 keV)
- Electron Decay $e^- \rightarrow \nu_e \overline{\nu}_e \nu_e$
  - Upshifted Ge x-ray rate (peak at 11.1 keV)
- Bosonic Superweak Dark Matter
  - Anomalous peak (< 100 keV)
- Lorentz Violation
  - Distortions in spectral shape (Maximum sensitivity at 810 keV)
- Majoron Emmission
  - Distortions in $2\nu\beta\beta$ spectral shape

Updates and status



After commissioning run of Module 1 in Fall 2015, we....

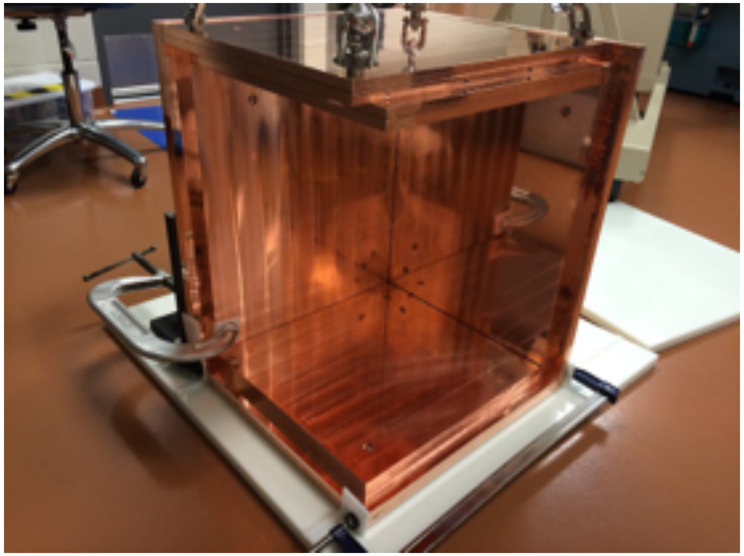
... installed the inner electroformed copper shield.

... added additional shielding in the crossarm.

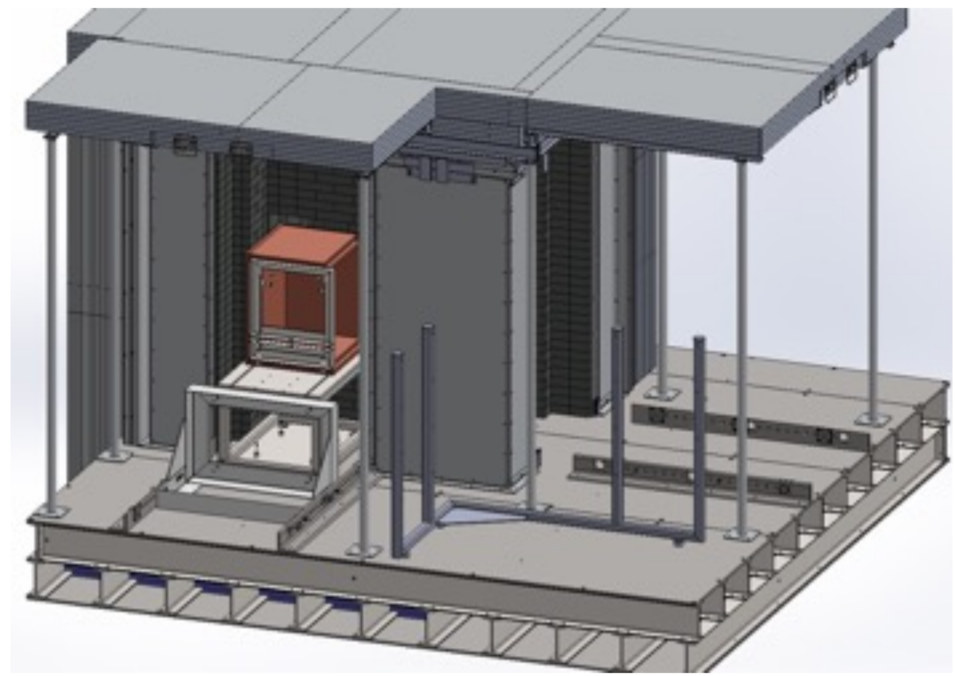
... replaced the cryostat seals with low radioactivity versions.

... repaired non-operating channels.

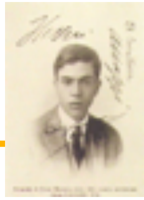
Inner Cu shield



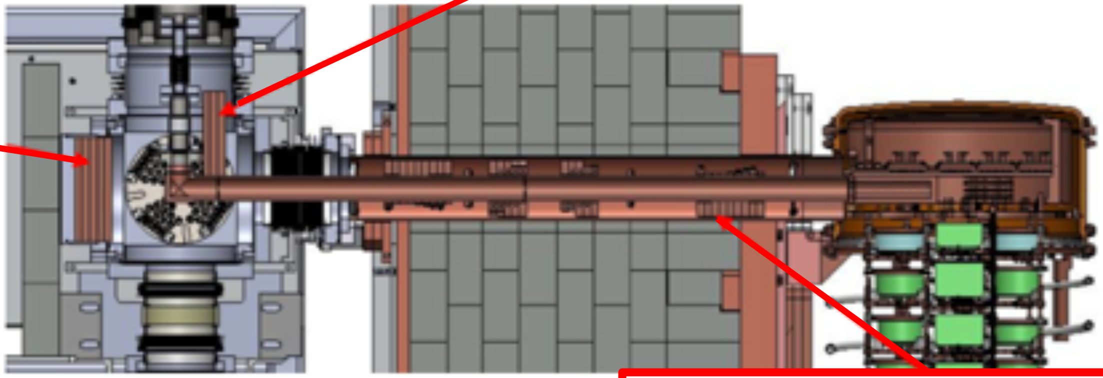
- Extensive time to electroform the Cu parts.
- String parts higher priority for machining.
- Hence installed after shield constructed.
- Installed in two parts in Nov. 2015.
- Expect x10 reduction in background from other shield materials.



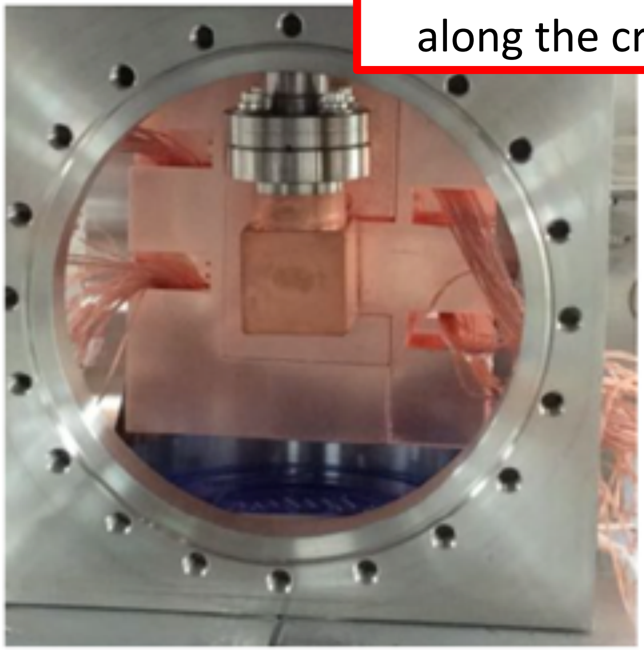
Extra shielding through shield penetration



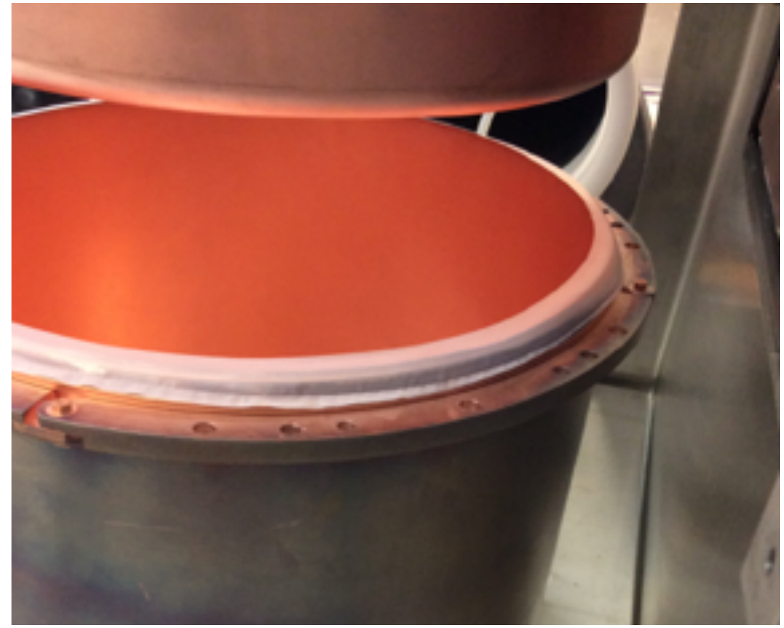
extra shield plates at the backside



extra shield plates along the cross arm



Cryostat seals



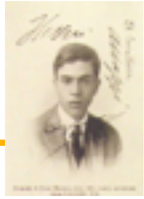
Kalrez:

- reusable
- high mass
- activity 27.8 counts / ROI /t /year

PTFE:

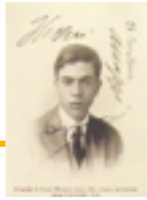
- single use
- low mass (only 0.002” thick)
- activity 0.013 counts / ROI /t /year

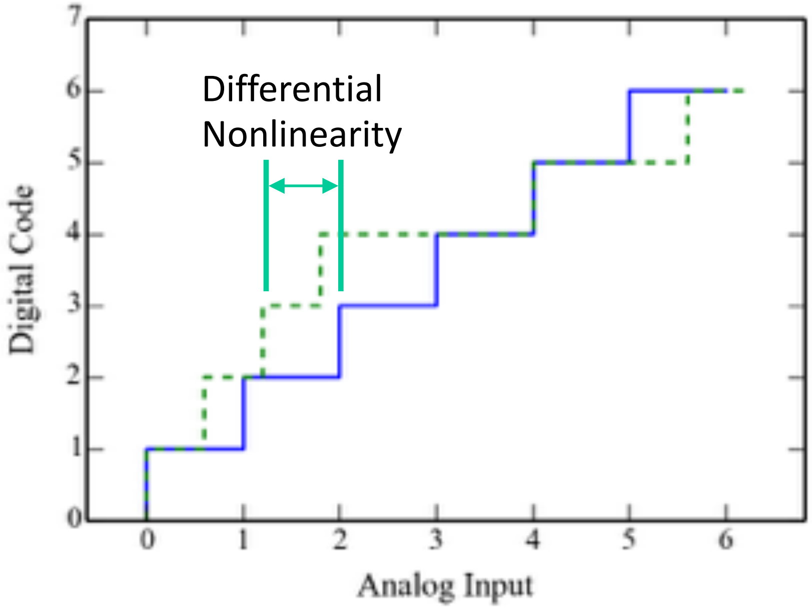
Data Processing

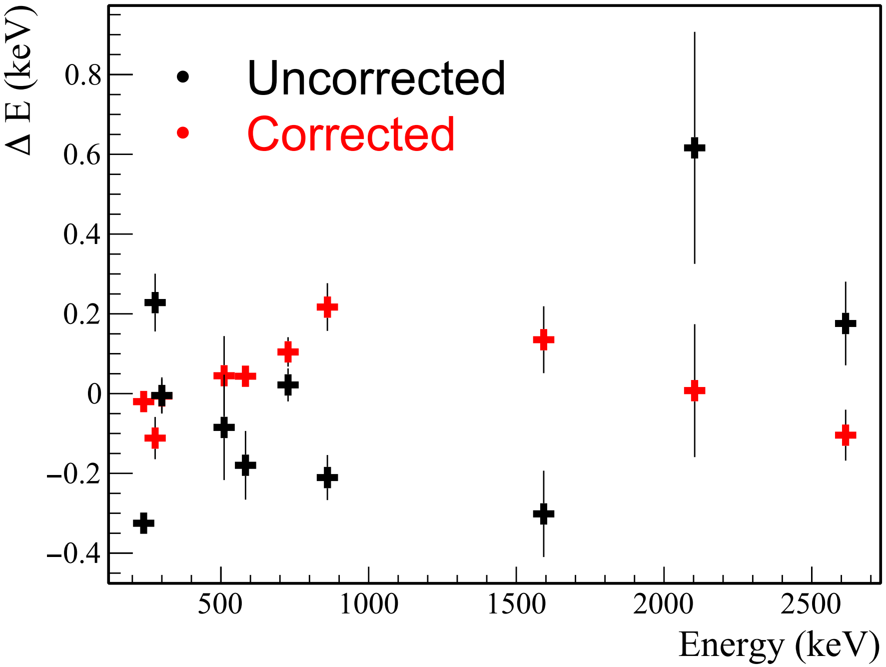


- Event Building
  - Group waveforms into events based on timing
  - Build ROOT trees from the event structure
- Germanium Analysis Toolkit ‘gatification’
  - Apply filters, calculate waveform level parameters
- Data Cleaning
  - Remove noise, pulsers, saturated events, etc…
- Non-linearity Corrections
- Energy Calibration
- Slow Pulse Removal

ADC Nonlinearity Correction

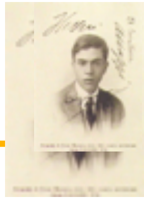


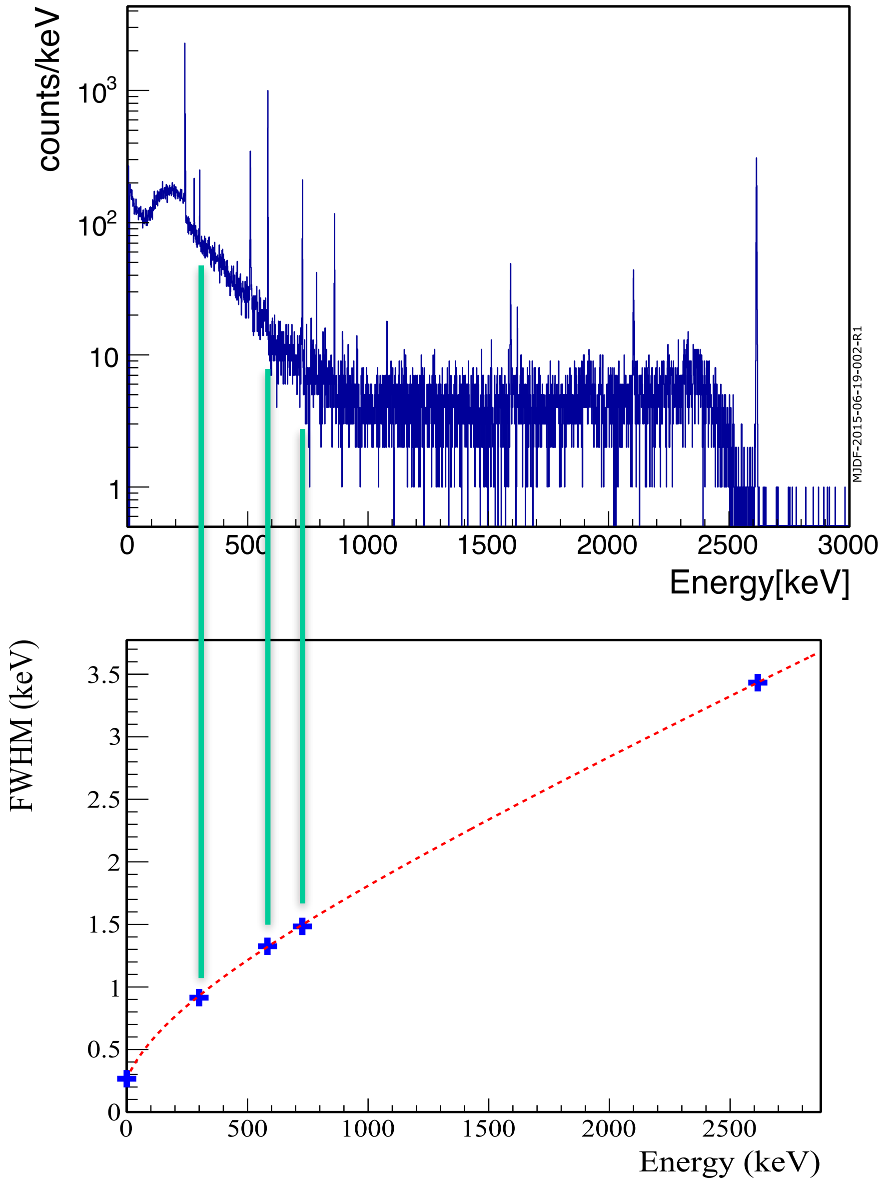




- Left: Differential nonlinearity in a single ADC channel can generate measurable integrated non-linearities.
- Right: Peak energy residuals in ^{228}Th source data from a single detector. Black is uncorrected, Red is after the correction is applied.

^{228}Th Calibration Spectrum in Module 1



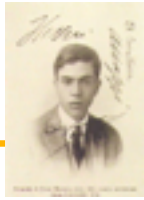


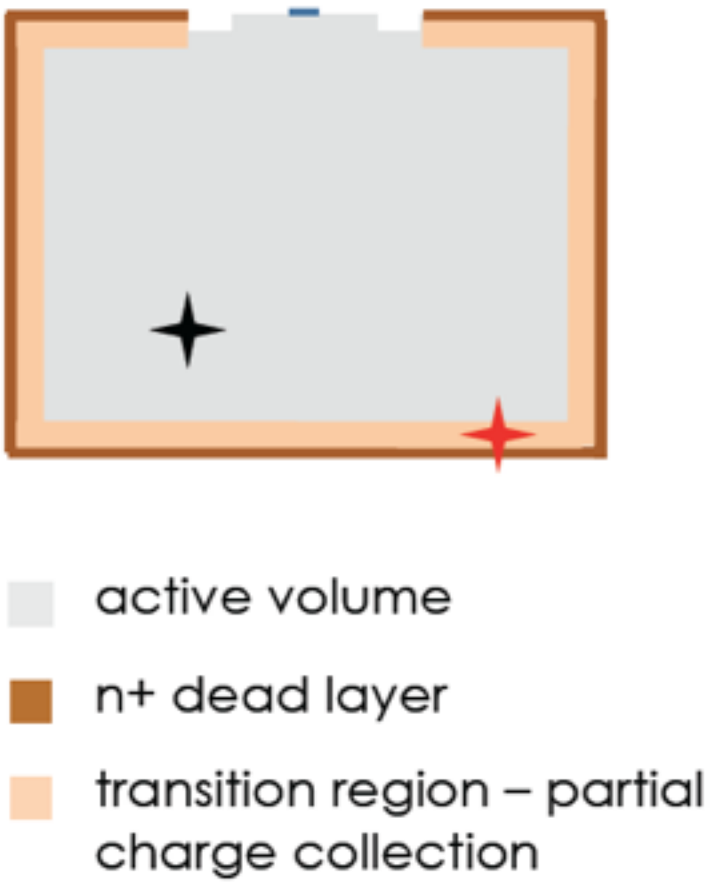
- Standard Energy Calibration based on ^{228}Th lines
- The energy resolution fits a functional form:

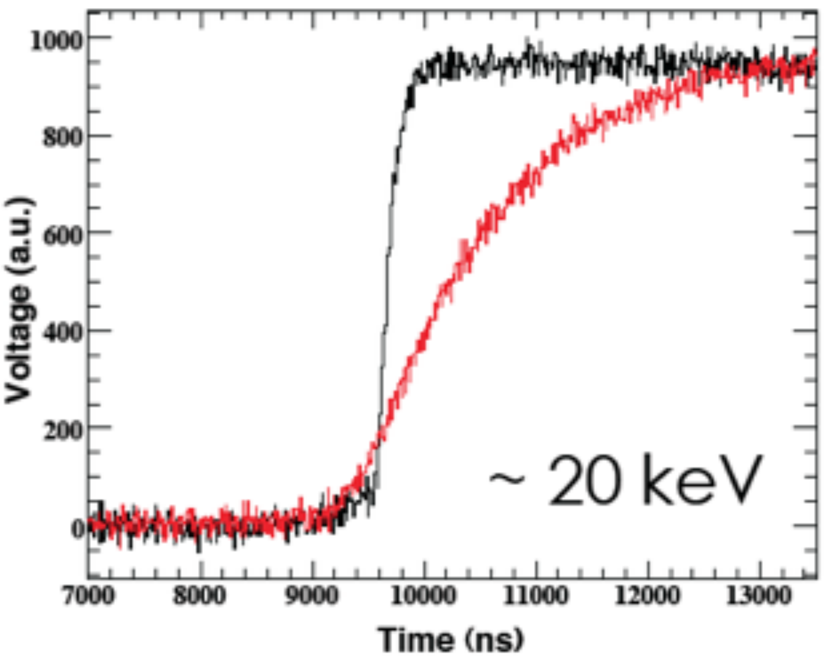
$$\mathrm{FWHM}(E) = \sqrt{p_0^2 + p_1^2 E + p_2^2 E^2}$$

- Calibration for Low-E taken from two-point: 0 keV, 300 keV

Slow Surface Events Near Detector Surface

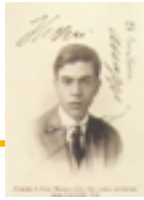


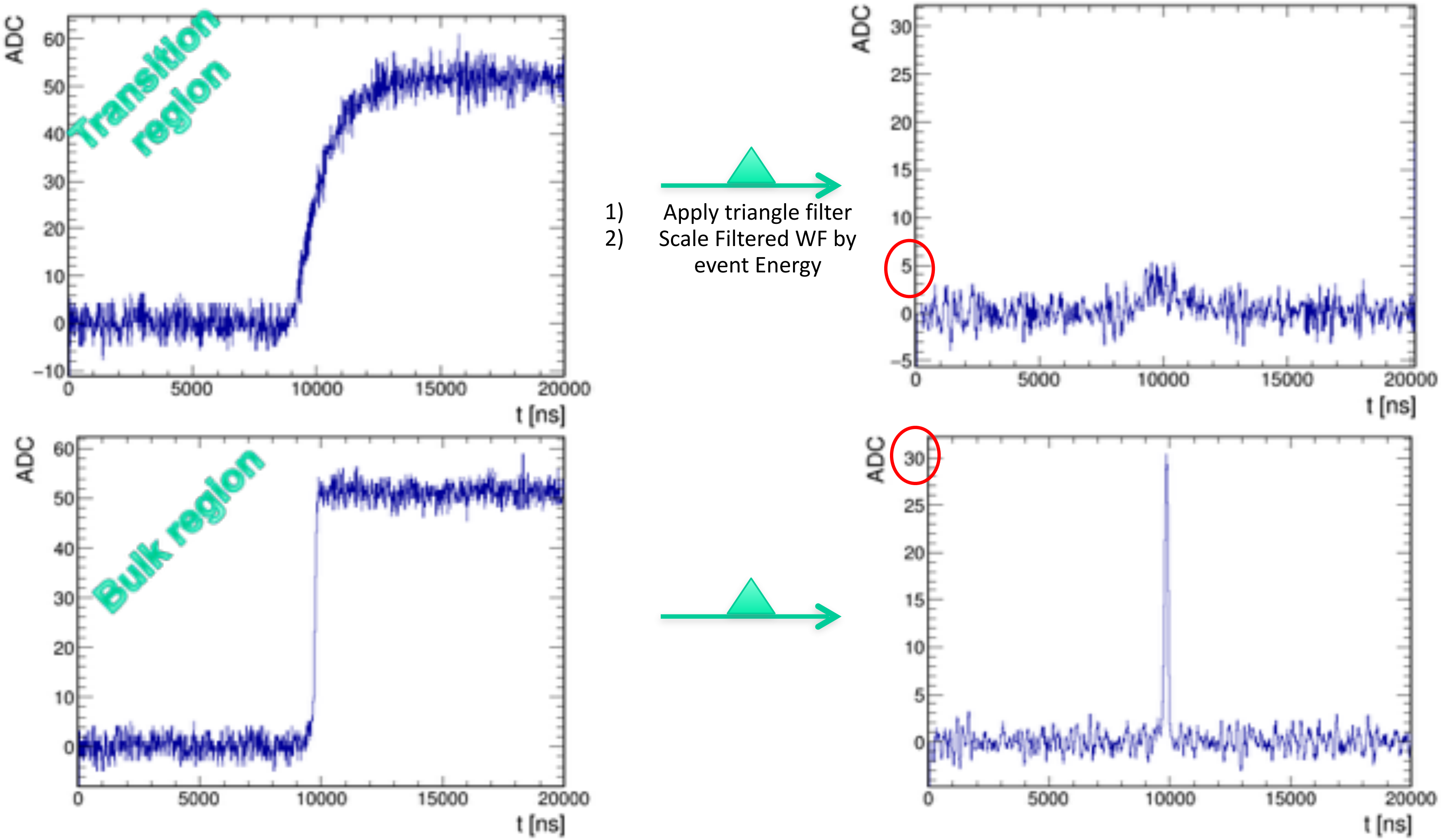




Also energy-degraded

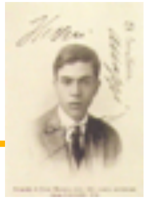
Transition Region Event Tagging

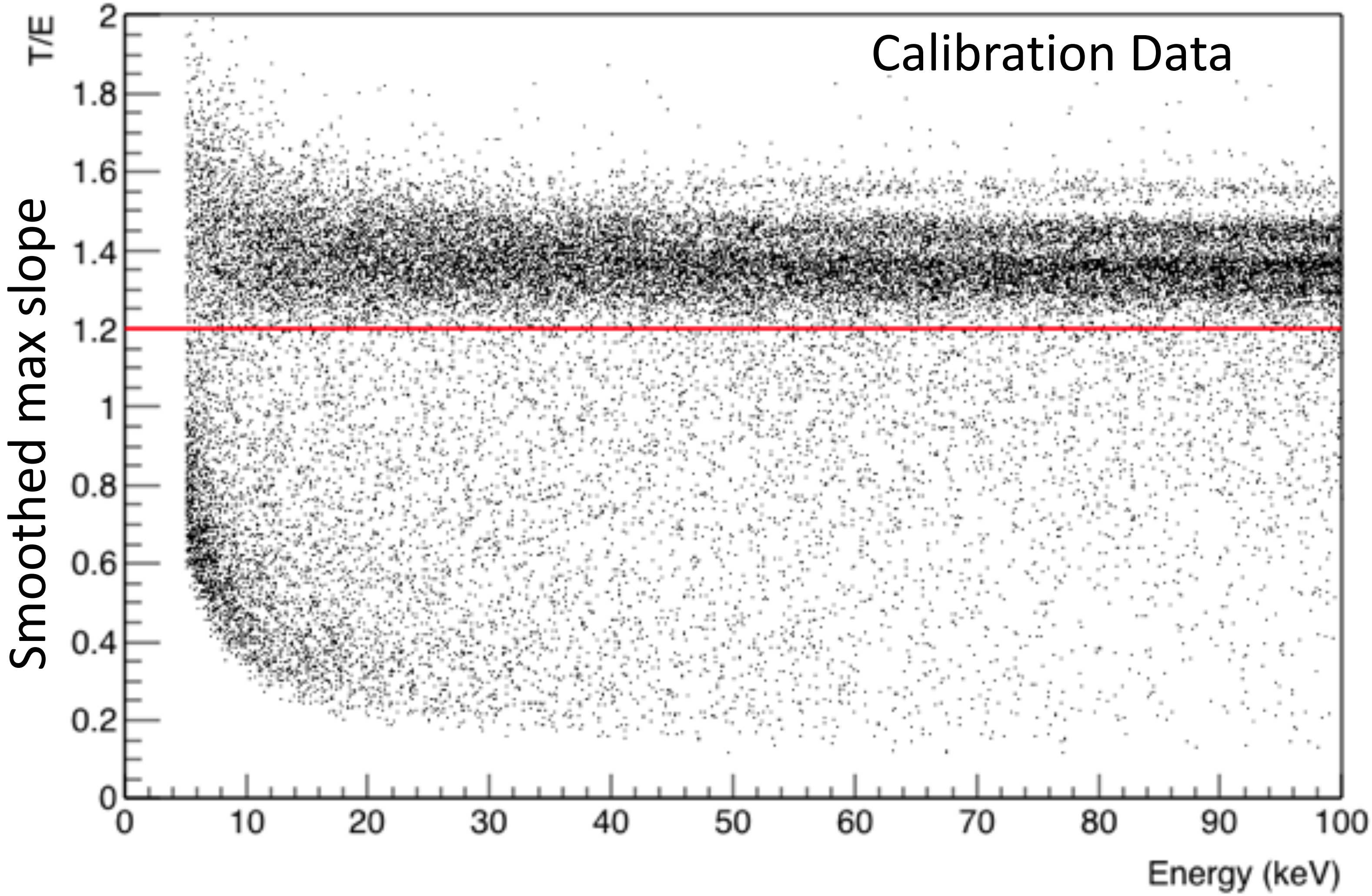




- Energy degraded events originating in transition region between dead layer and bulk region are a major background in low energy Ge experiments
- G. Giovanetti et al., A Physics Procedia, **61**, 2015, 77, C. E. Aalseth et al., Phys. Rev. D **88,** 012002, 2013

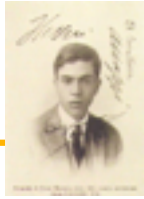
Transition Region Event Cut



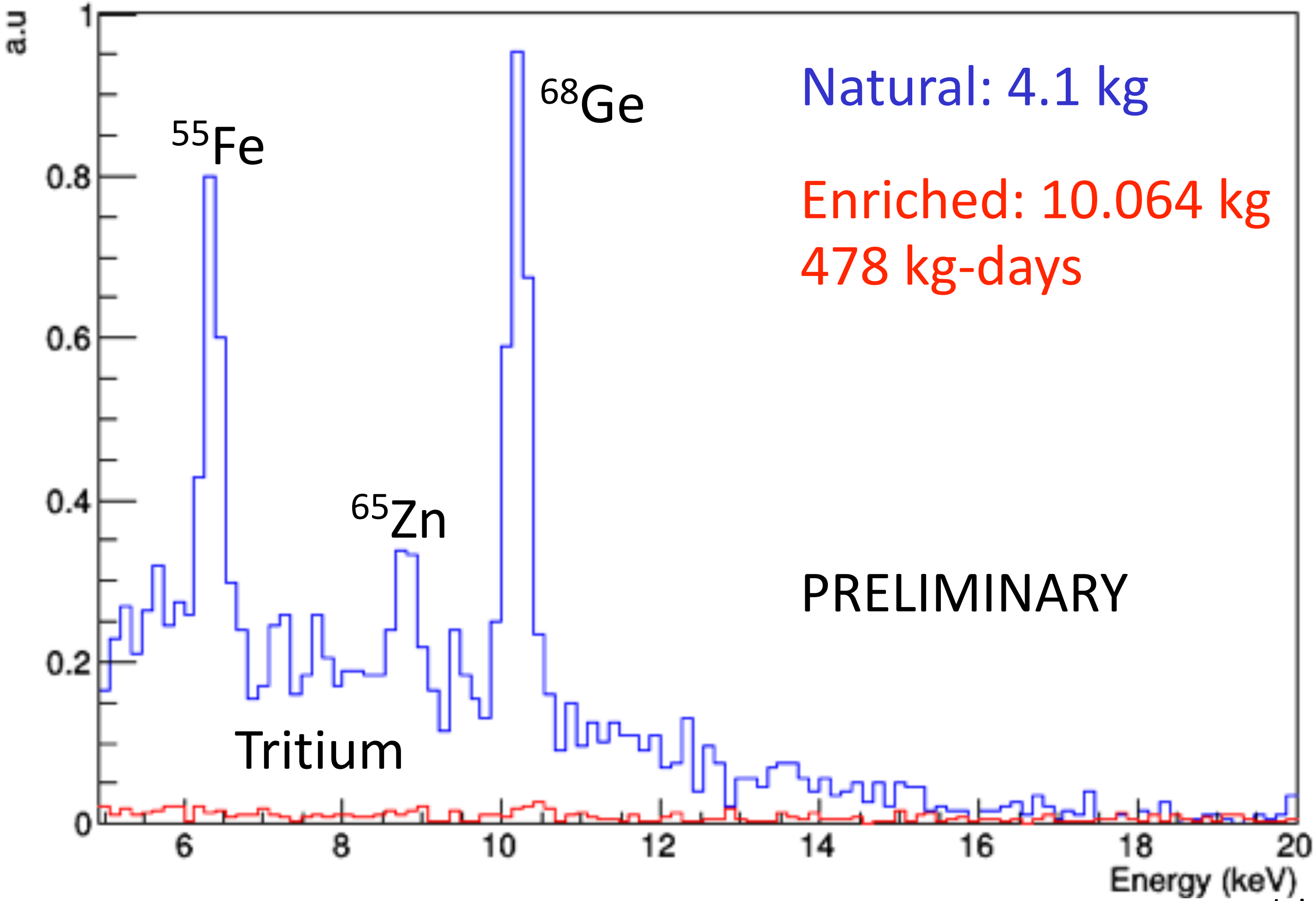


- Accept events above red line (T/E = 1.2)
- Determined acceptance via attenuated external pulser calibration
  - 96% acc at 5 keV
  - >99% acc for E > 10 keV

Low-Energy Spectrum Commissioning Data



- Controlled surface exposure of enriched material.
  - The enriched detector ^{68}Ge rate is low enough that an SSTC cut will not be nec
- Significant reduction of cosmogenics in the low-energy region.
- Tritium is obvious and dominates in natural detectors below 20 keV.
- June 26-Oct 7, 2015 Data, improved shielding lowers BG factor of ~ a few.



Upcoming Results

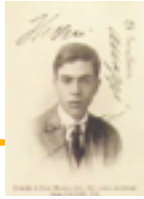
Limits to be presented in upcoming papers

- Pseudoscalar dark matter coupling, g_{Ae}
- Vector dark matter coupling, α'/α
- 14.4 keV solar axion, $g_{AN}^{eff} \times g_{Ae}$
- 11.1 keV electron decay
- 10.6 keV Pauli Exclusion violating decay

Production rate of Tritium and other isotopes.

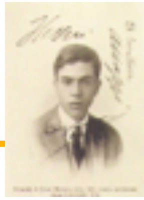
Reduction in background and increased exposure will result in more stringent limits soon

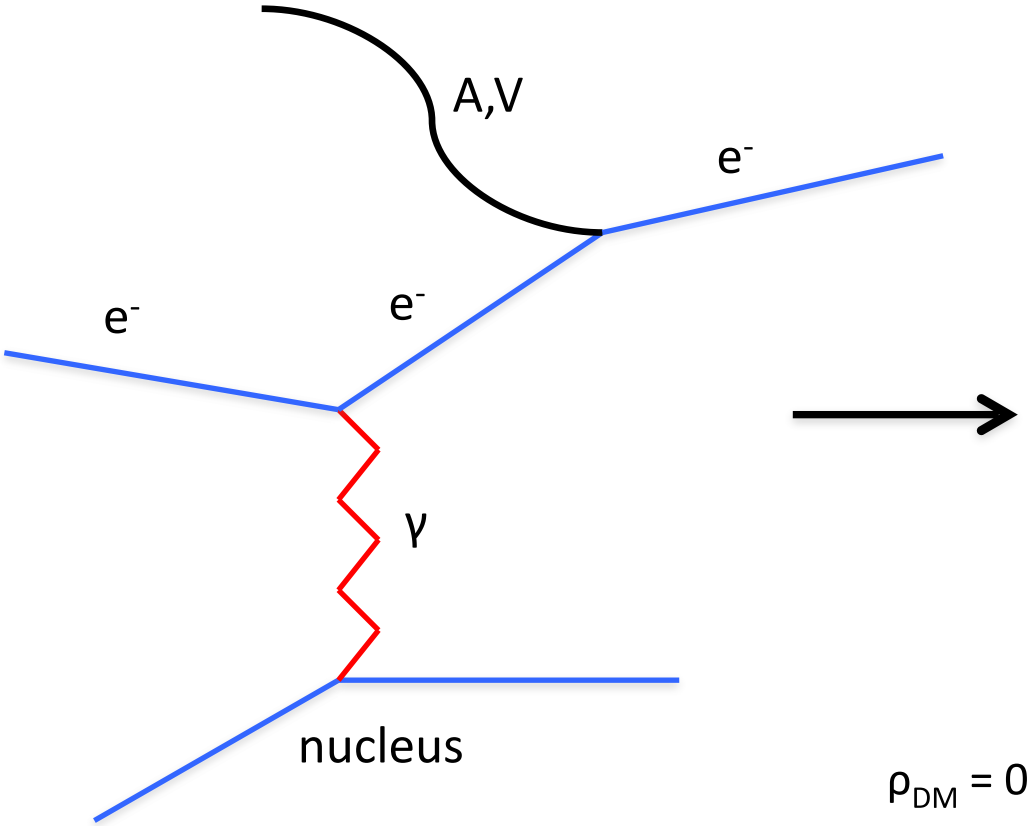
Systematic Considerations

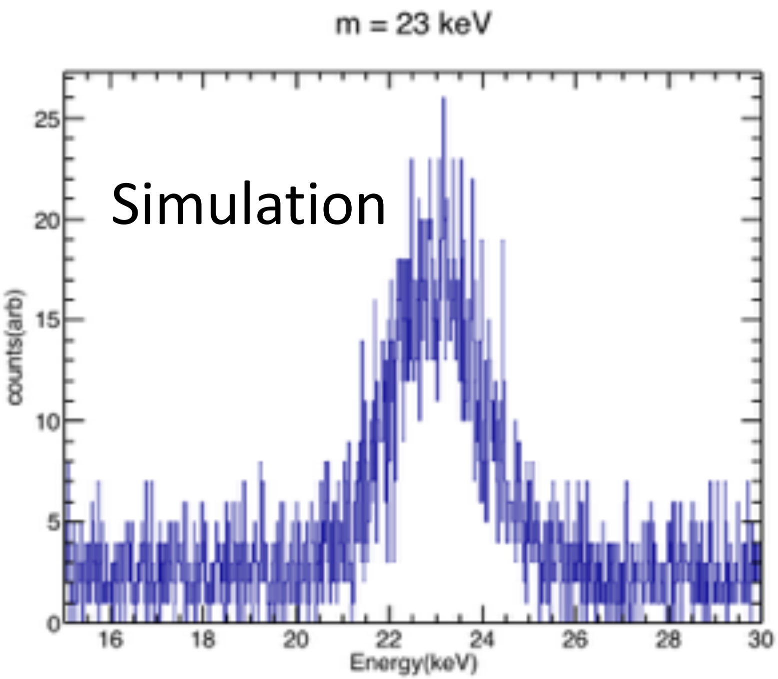


- Energy calibration
  - ^{228}Th source + zero-point noise measurement
- Resolution
  - Fit resolution curve from sources, zero-point noise measurement
- Cut acceptances
  - Measured from external pulser data
- Quantification of systematics nearly complete

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





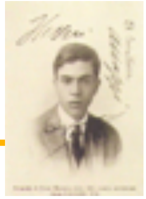


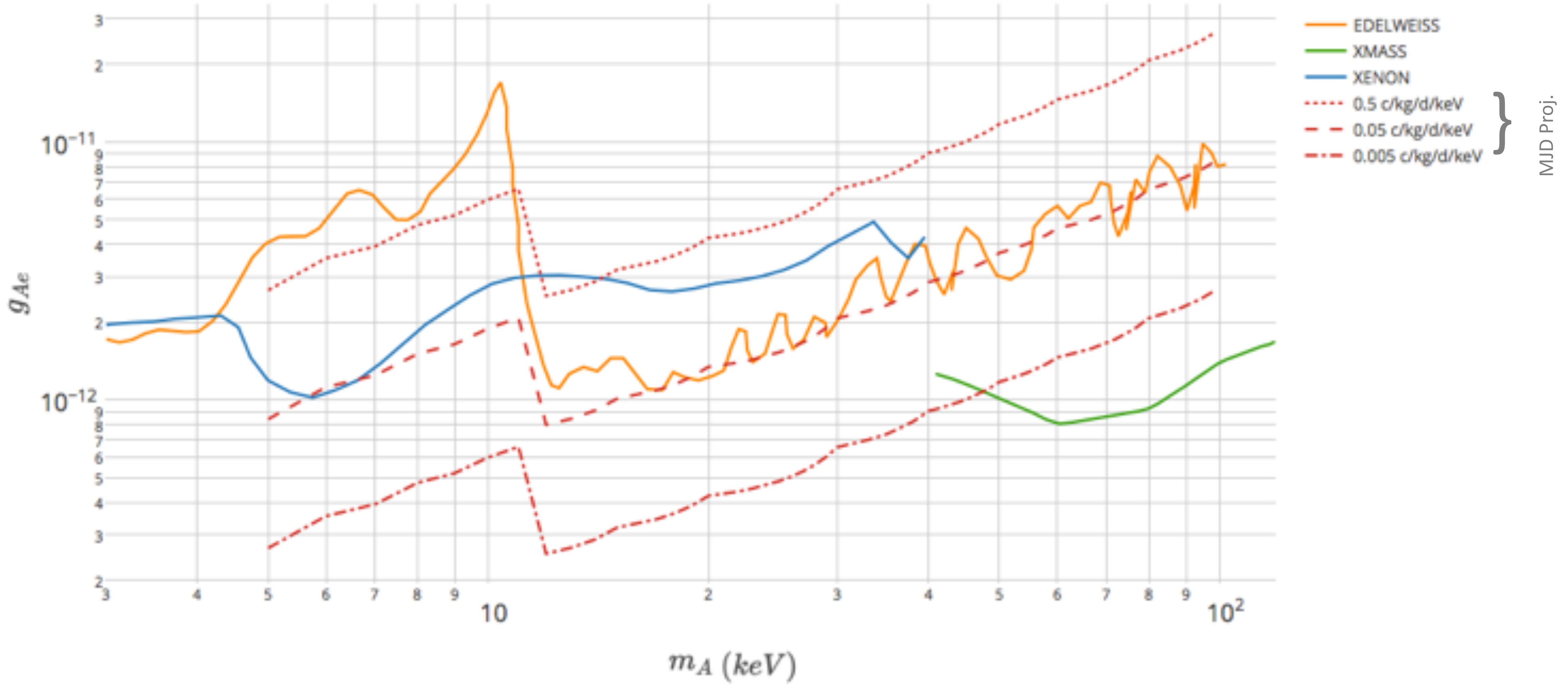
$\rho_{DM} = 0.3$ GeV/cm^3 $\beta = v/c \sim 0.001$

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

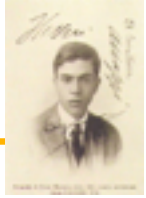
See: M. Pospelov, A. Ritz, and M. Voloshin, Phys. Rev. D, 78, 115012 (2008).

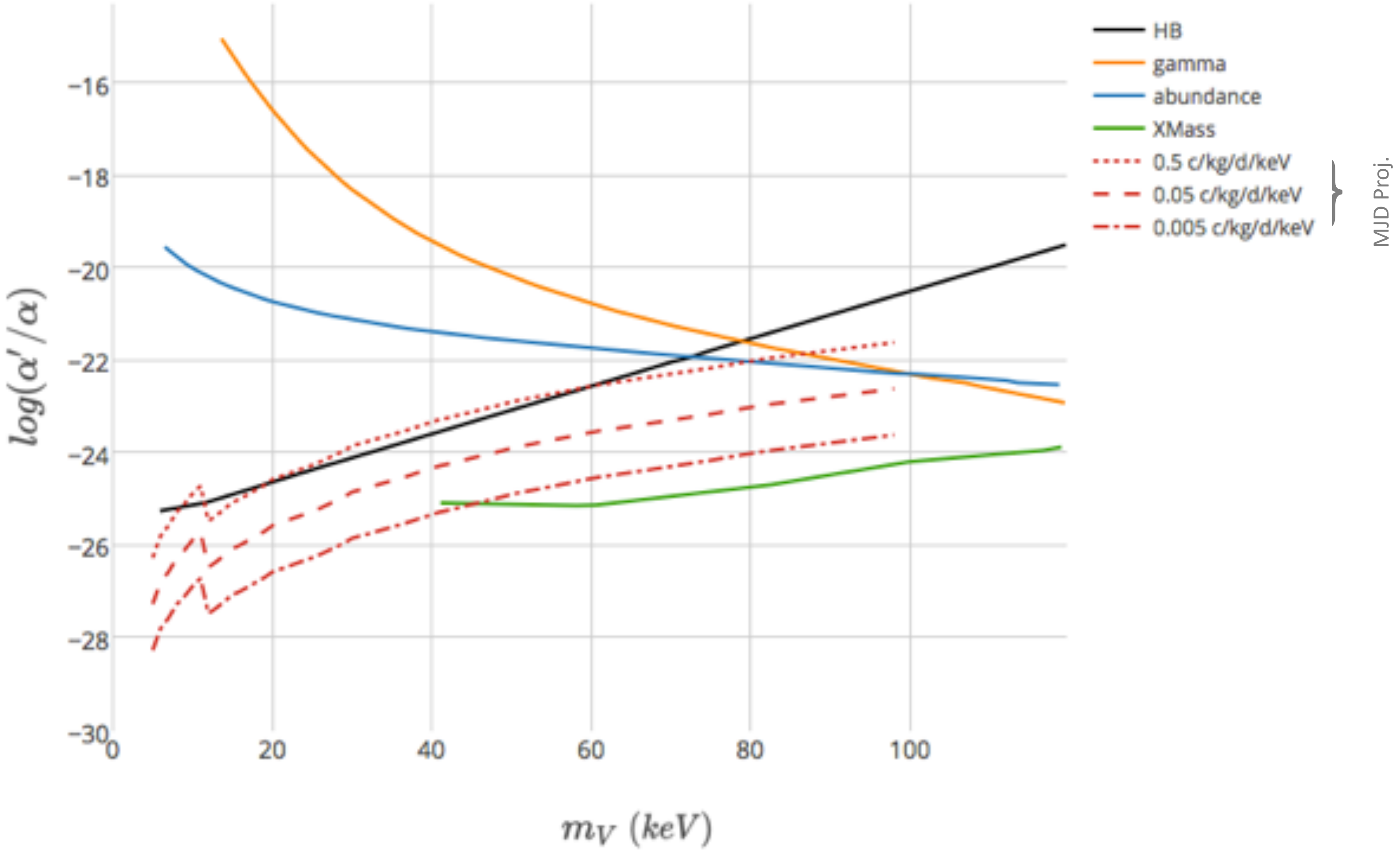
Pseudoscalar U.L. Projection





Vector U.L. Projection





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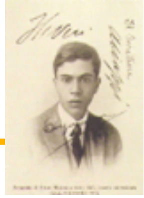

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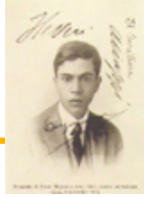
MAJORANA DEMONSTRATOR Progress

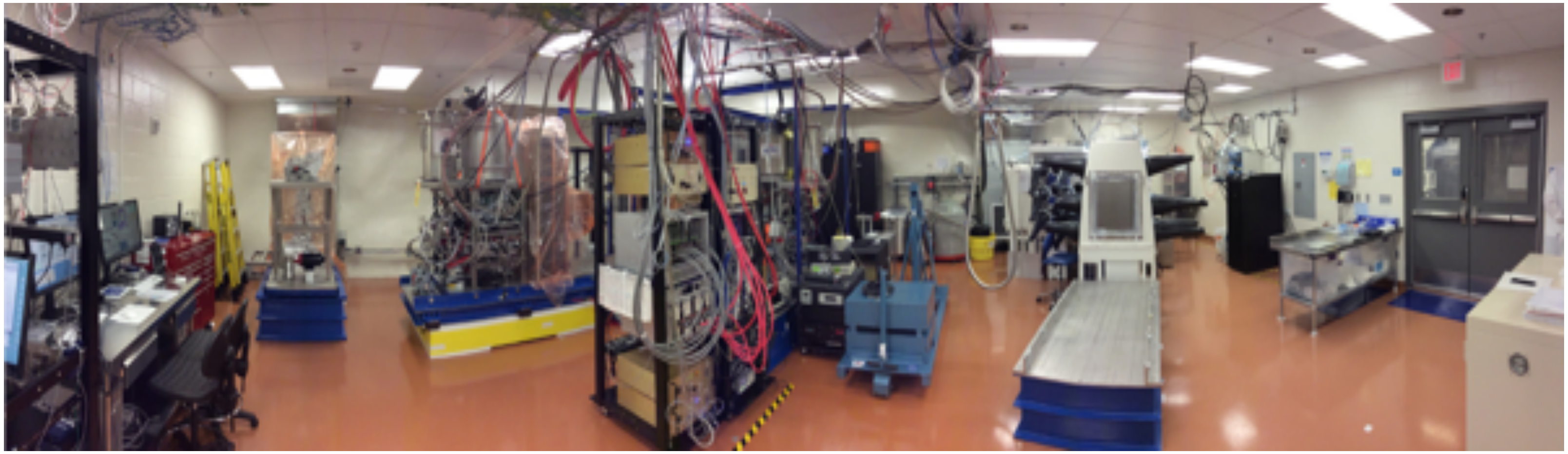


Goal:
- Demonstrate backgrounds needed for a tonne scale 0νββ experiment.
- 5 year run (108 kg-years): $T_{1/2} > 1.6\ 10^{26}$ years (90 % CL)
  $T_{1/2} = 4.3\ 10^{25}$ years (5σ discovery)

Configuration:
- 44-kg of Ge detectors, in two independent cryostats
- 29 kg of 87% enriched ^{76}Ge crystals; 15 kg of ^{nat}Ge, P-type point-contact detectors

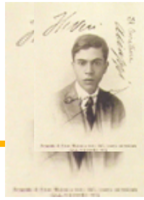
Module One:
- installed in-shield and taking low background data since January 2016.
- end-to-end analysis underway from July - Oct. 2015 dataset to shake down data cleaning and analysis tools.
- expect to have first background information from 2016 run in the summer.
- low energy spectrum producing physics results: pseudoscalar & vector DM, 14.4 keV axion, $e^- \rightarrow 3\nu$, Pauli exclusion principle

Module Two:
- construction and assembly proceeding on schedule, in-shield commissioning started ~ May 2016



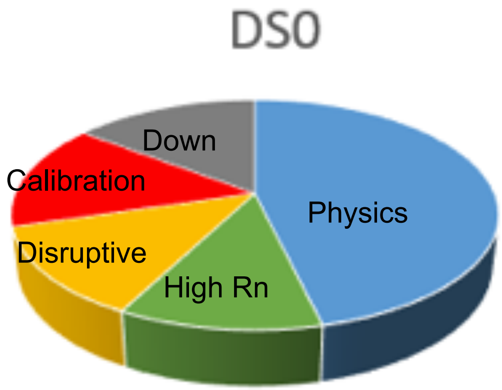
Backups

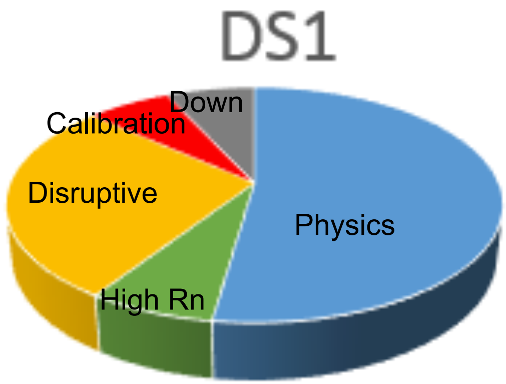
Module 1 Data Set Duty Cycles



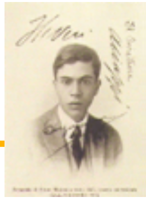
		DS0 (days) No inner shield June 26, – Oct. 7, 2015	DS1 (days) with inner shield Dec. 31, 2015 – Apr. 14, 2016*
Total		103.15	104.68
Total acquired		87.93	97.52
Physics	(blue)	47.70	54.73
High radon	(green)	11.76	7.32
Disruptive Commissioning tests	(yellow)	13.10	28.61
Calibration	(red)	15.44	6.86
Down time	(grey)	15.21	7.16

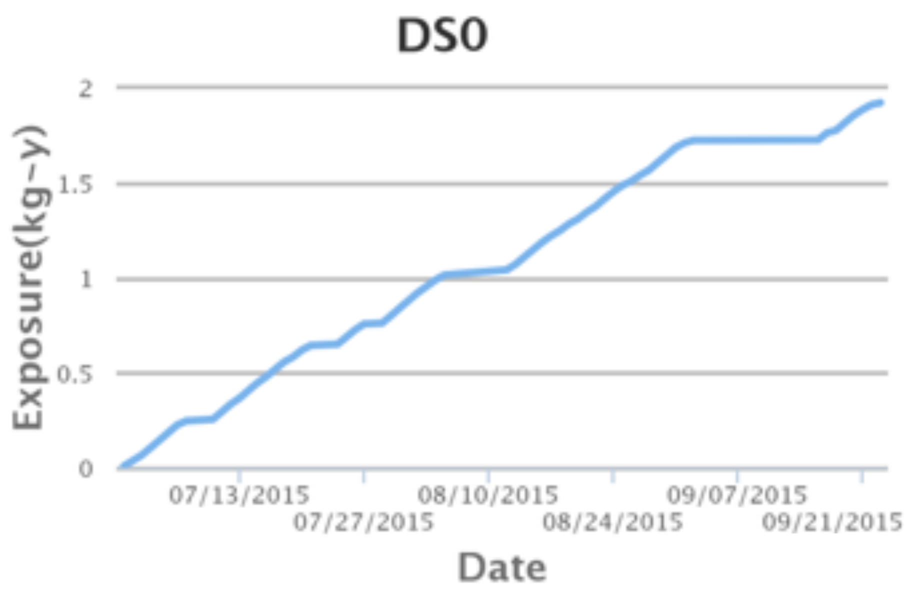
*Data taking ongoing

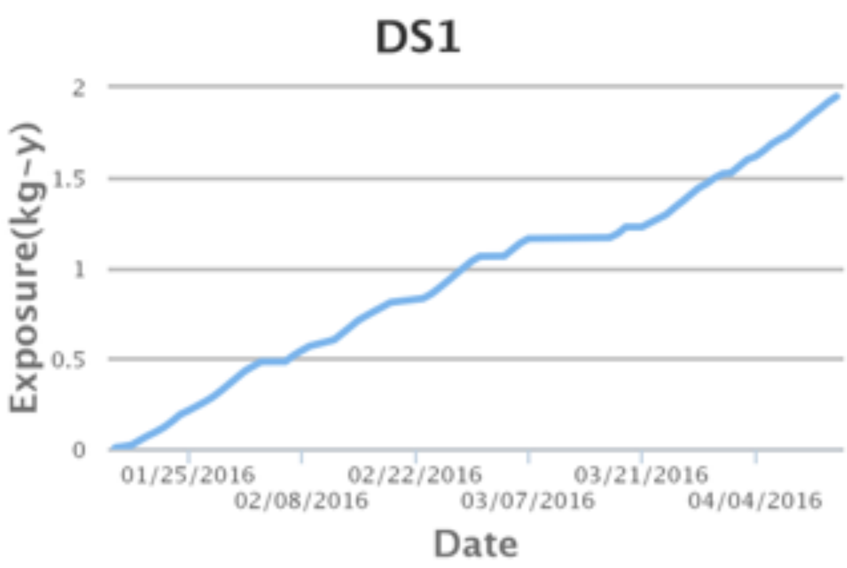




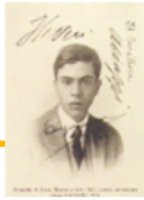
Exposure Module 1

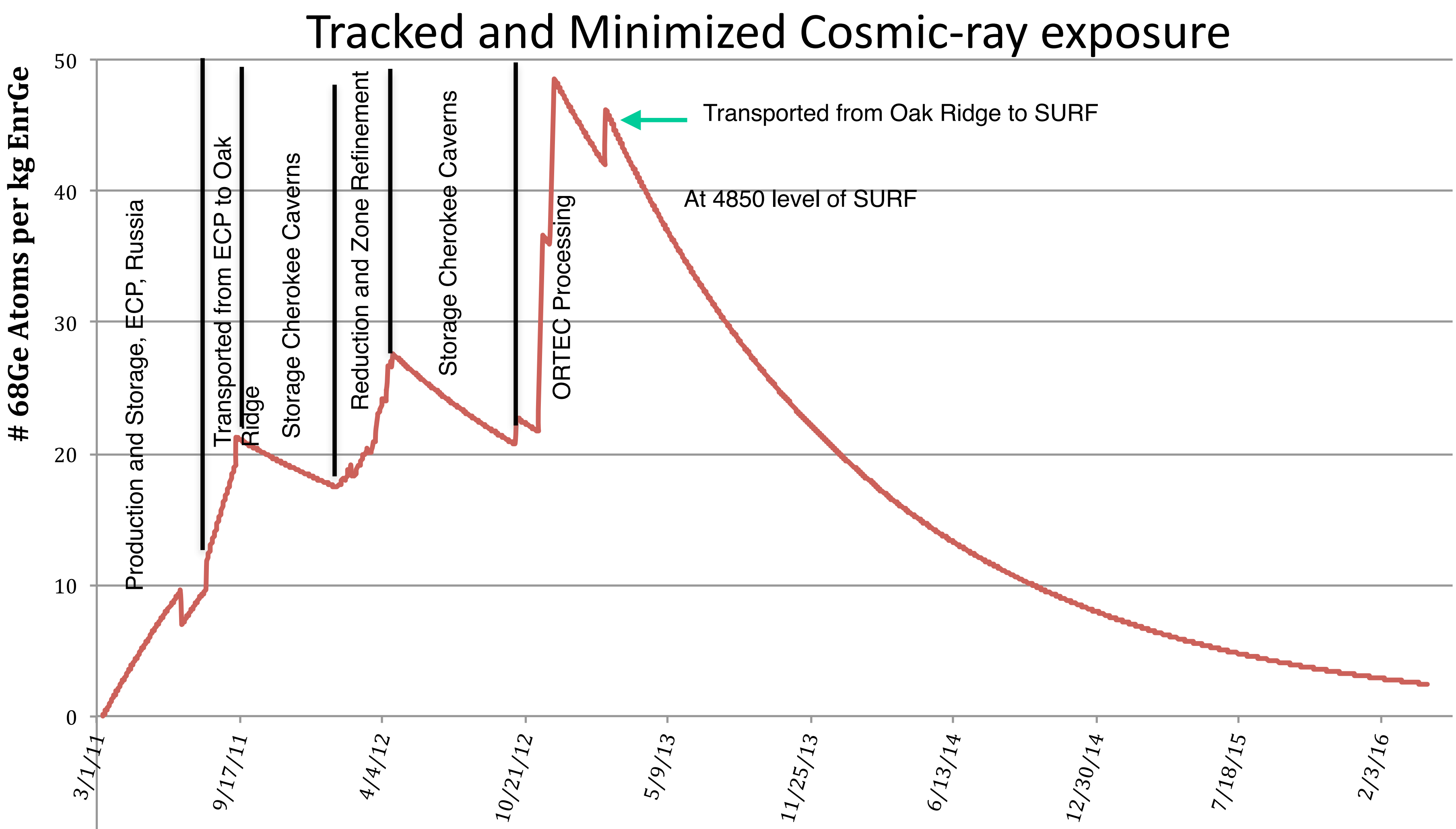




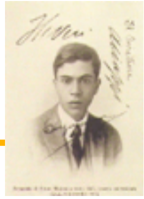


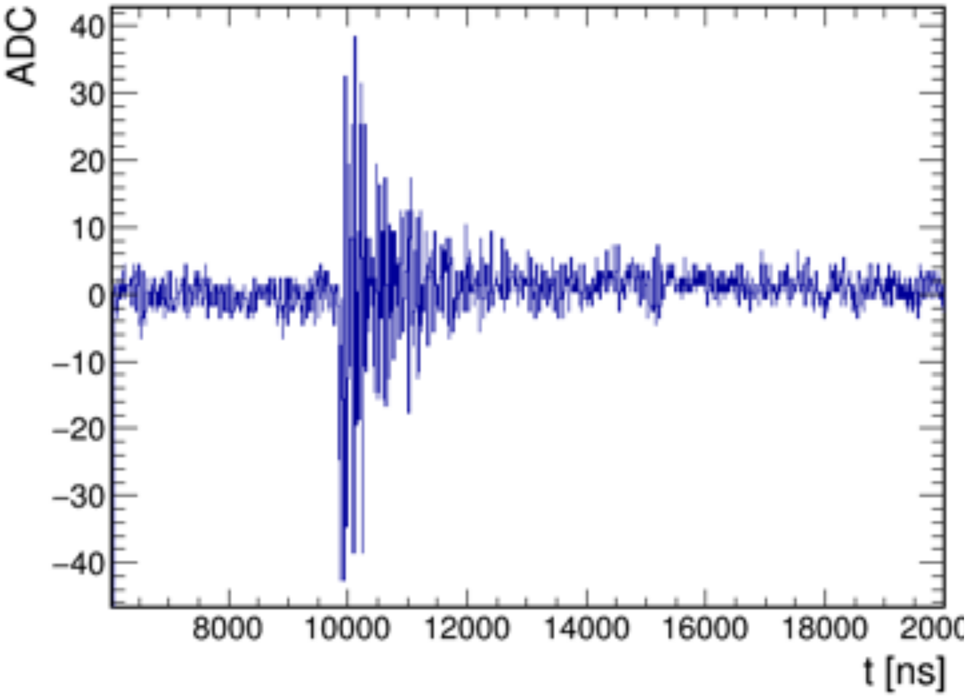
^{68}Ge Production in Detector P42537A

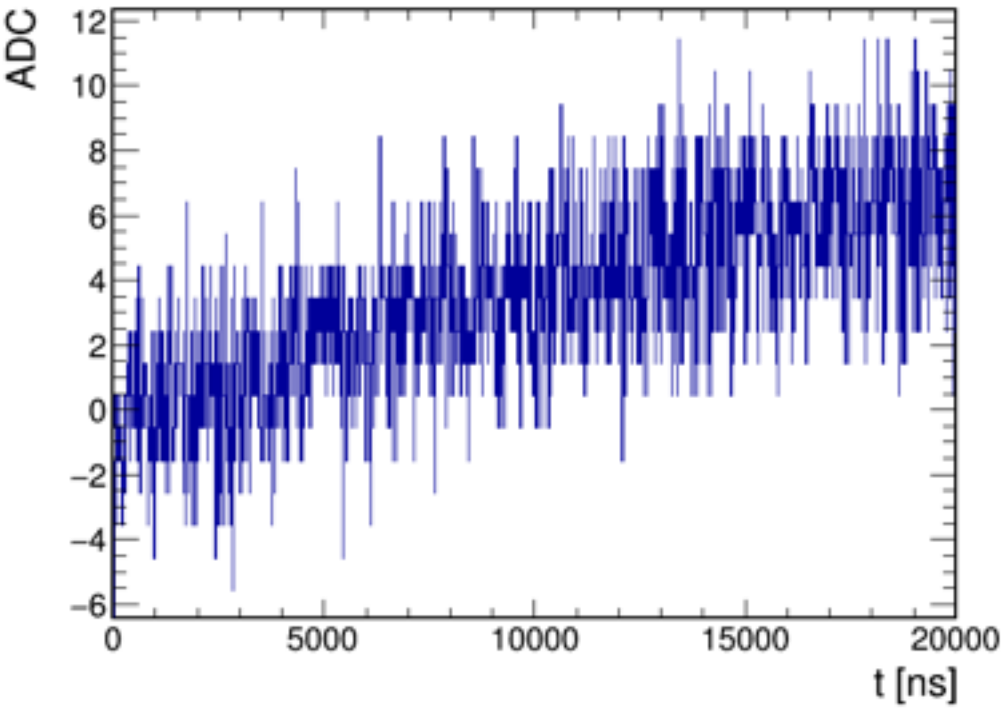




Electronic Noise Removal at low-E

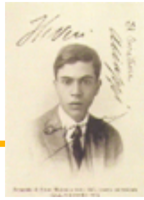


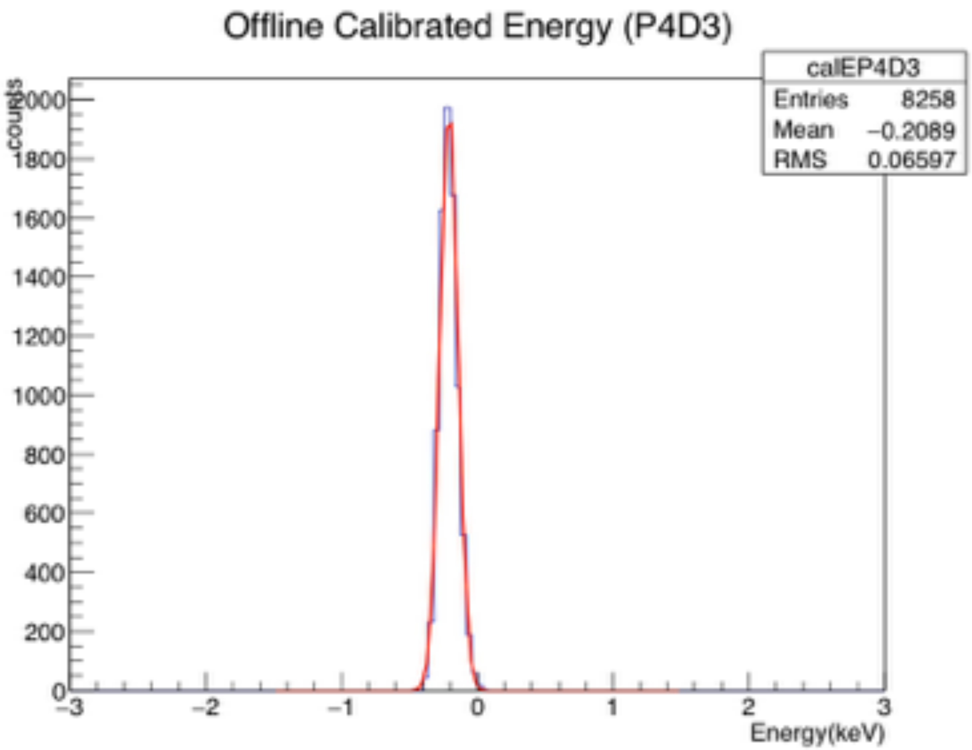


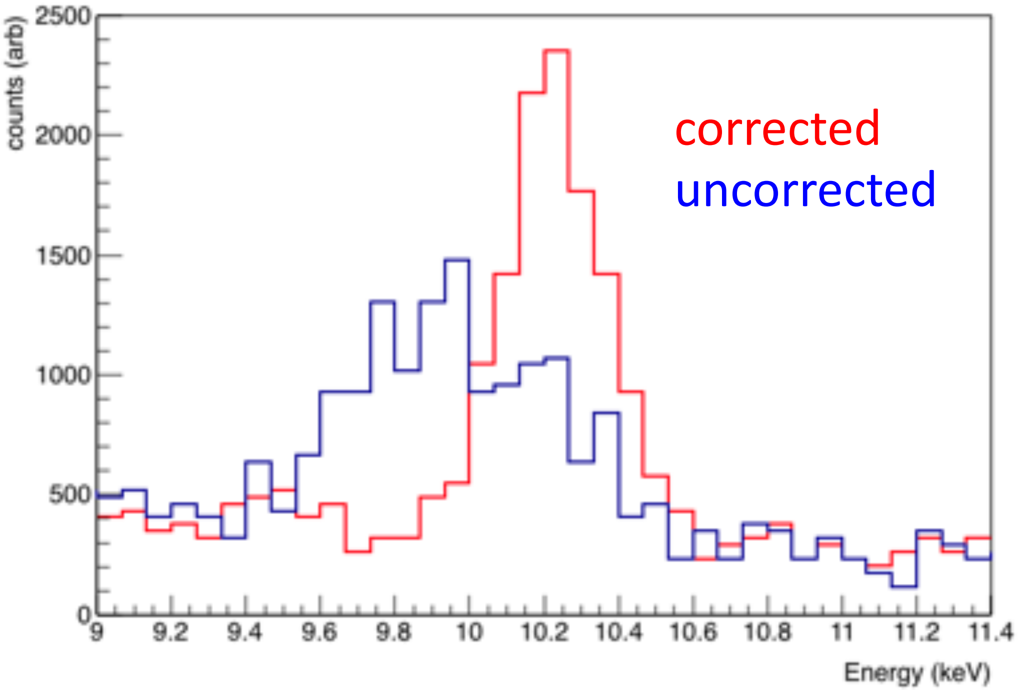


- Left: Transient noise (removed by considering only single detector events)
- Right: Internal pulser recovery events (very low E, <3 keV)
- Pulse shape analysis provides additional suppression

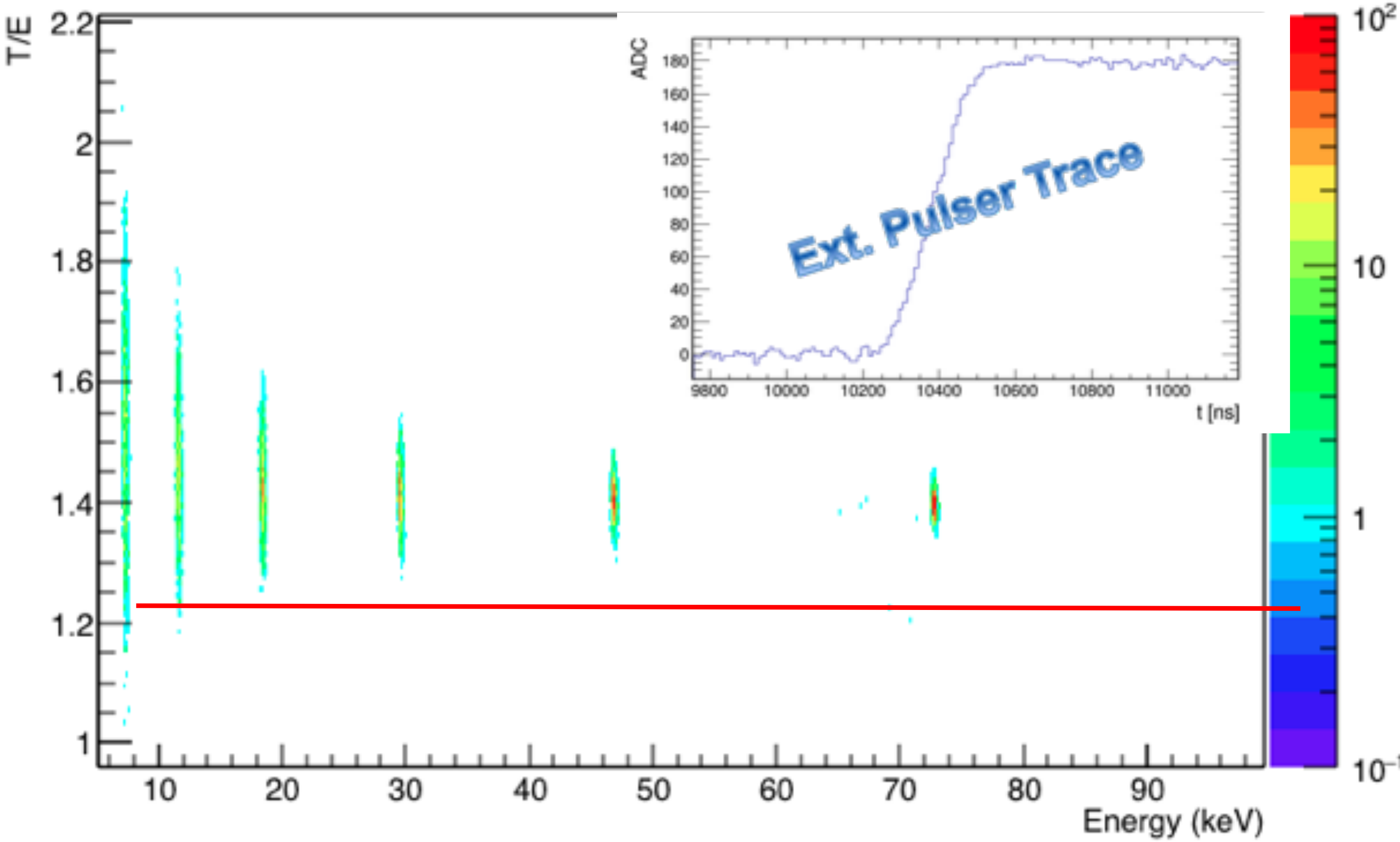
Determining Offset







T/E Acceptance



For some detectors, hardware allowed external pulsing

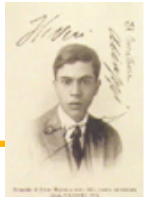
Used external pulsers with precision attenuators tuned to BG T/E vs E to estimate T/E vs E accptance

Module 1 Commissioning Data

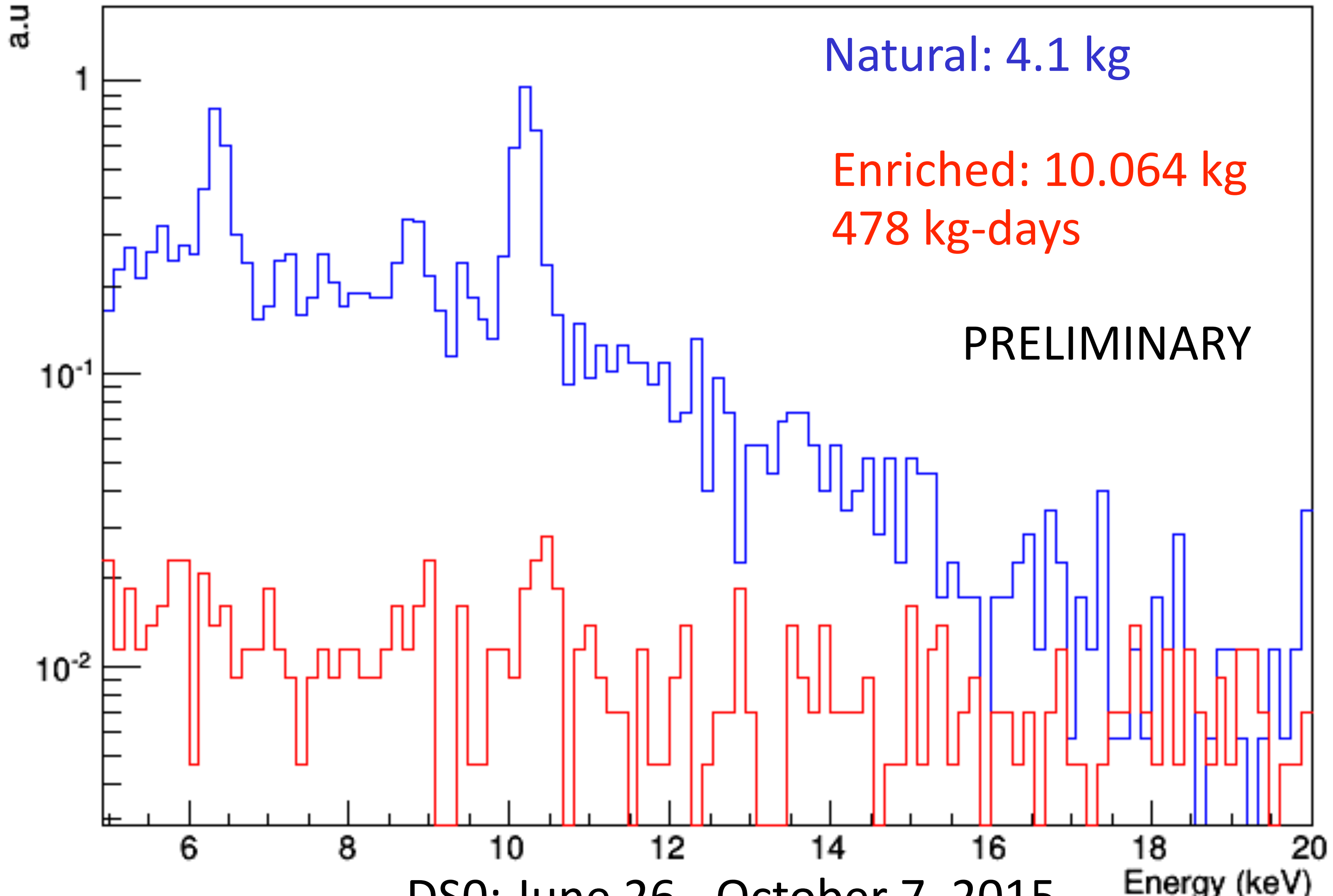
- Analyzed data from Module 1 commissioning
  - June 26 – Oct 7, 2015
- Analyzing Low-E BG data from 13 enriched detectors (10.064 kg)
- Analysis exposure: 478 kg d
- Innermost electroformed copper shield installed AFTER this run
- Roughly 25% coverage on neutron shield
- Rn purge not fully optimized
- Shield blank installed in Module 2 port

Module 1
Photo: M. Kapust

Low-energy spectrum (log scale)

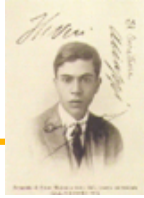


Significant reduction in low-E background in enriched detectors!



DS0: June 26 - October 7, 2015

Pseudoscalar General Formula



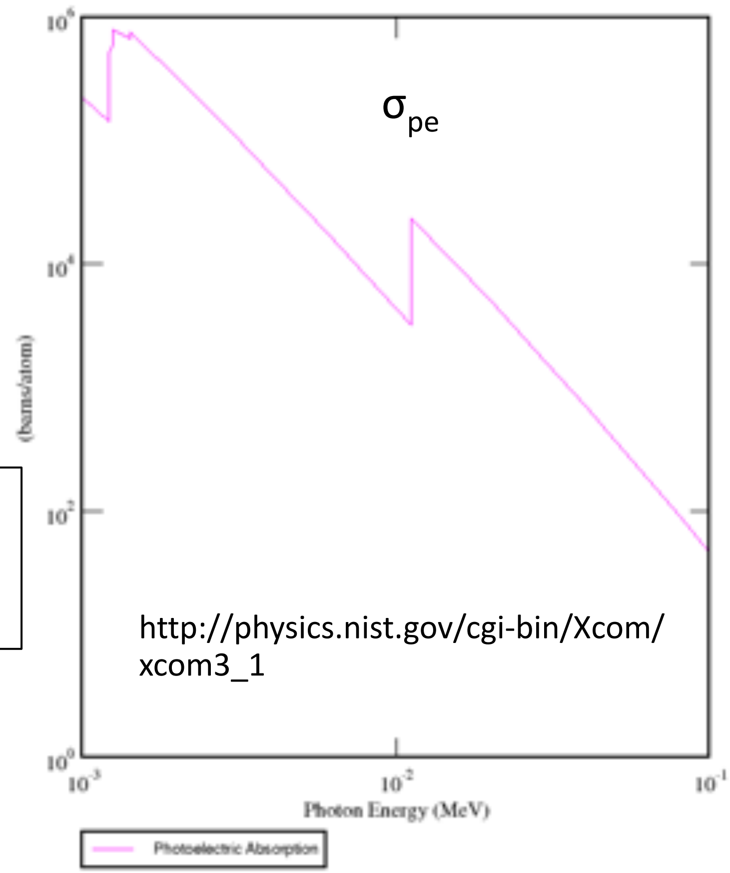
Get UL on counts, solve for this…

$$\sigma_{Ae}(E) = \sigma_{pe}(E)\frac{g_{Ae}^2}{\beta}\frac{3E^2}{16\pi\alpha m_e^2}\left(1-\frac{\beta^{\frac{2}{3}}}{3}\right)$$

$$\Phi_{DM}[/\mathrm{cm}^2/\mathrm{s}] = \rho_{DM}\cdot \mathrm{v_A}/\mathrm{m_A} = 9.0\times 10^{15}\left(\frac{\mathrm{keV}}{\mathrm{m_A}}\right)\cdot\beta$$

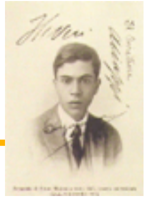
E. Armengaud et al., Journal of Cosmology and Astroparticle Physics, 2013, 067 (2013)

Pospelov M, Ritz A, and Voloshin M. Physical Review D 78, 115012 (2008)



Here β = v/c ~ .001 based on galactic halo models, though terms cancel when multiplying formulas

Module 1 – commissioning



Rn purge-off test Sept. 2015, during Module 1 commissioning (DS0).
Model with a 1-D convection diffusion model.
Shield Rn tracks room with purge off, but is unobserved with purge on.