Modeling Background Results from the MAJORANA DEMONSTRATOR

Tom Gilliss

Lake Louise Winter Institute
February 14, 2019

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

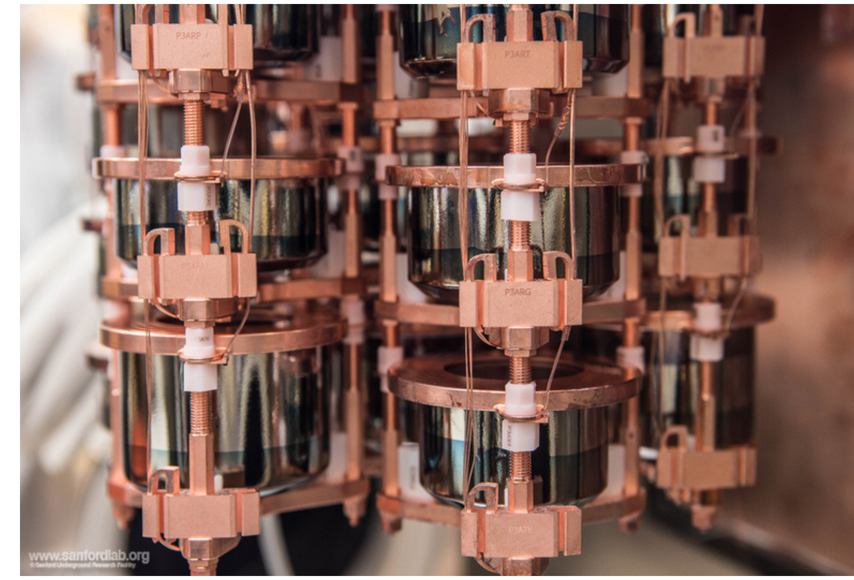
MAJORANA DEMONSTRATOR

Searching for neutrinoless double-beta decay ($0\nu\beta\beta$) of ^{76}Ge in HPGe detectors and additional physics beyond the standard model

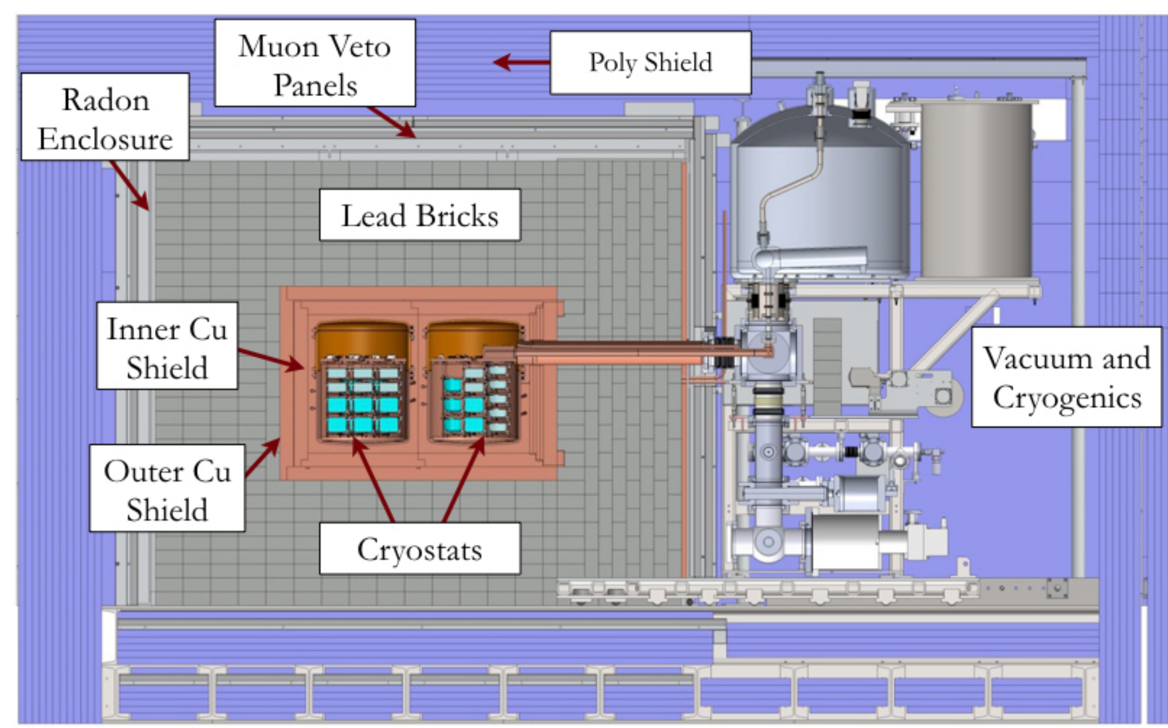
Source & Detector: Array of p-type, point contact detectors
29.7 kg of 88% enriched ^{76}Ge crystals

Excellent Energy resolution: 2.5 keV FWHM @ 2039 keV

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



Operating underground at the 4850' level of the Sanford Underground Research Facility



MAJORANA DEMONSTRATOR Results

2017 Release

9.95 kg-yr open data

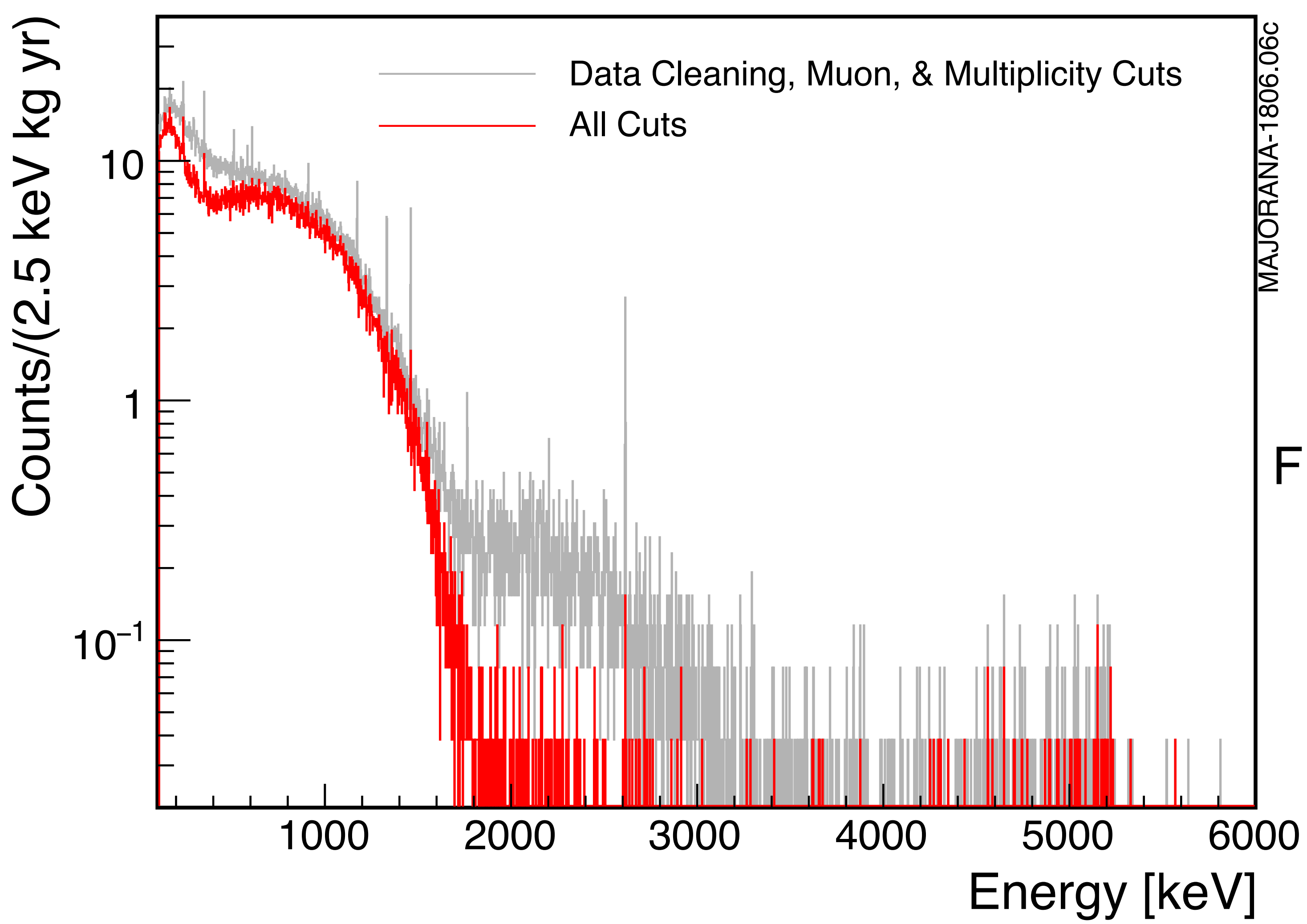
PRL **120** 132502 (2018)

2018 Release

26 kg-yr open+blind

Neutrino 2018

DOI:10.5281/zenodo.1286900



Median half-life sensitivity (90% CL): yr

$$4.8 \times 10^{25}$$

Full exposure limit (90% CL): yr

$$2.7 \times 10^{25}$$

Final configuration background: cts/(FWHM t yr)

$$11.9 \pm 2.0$$

Higher than prediction from initial background model: cts/(FWHM t yr)

$$< 2.2$$

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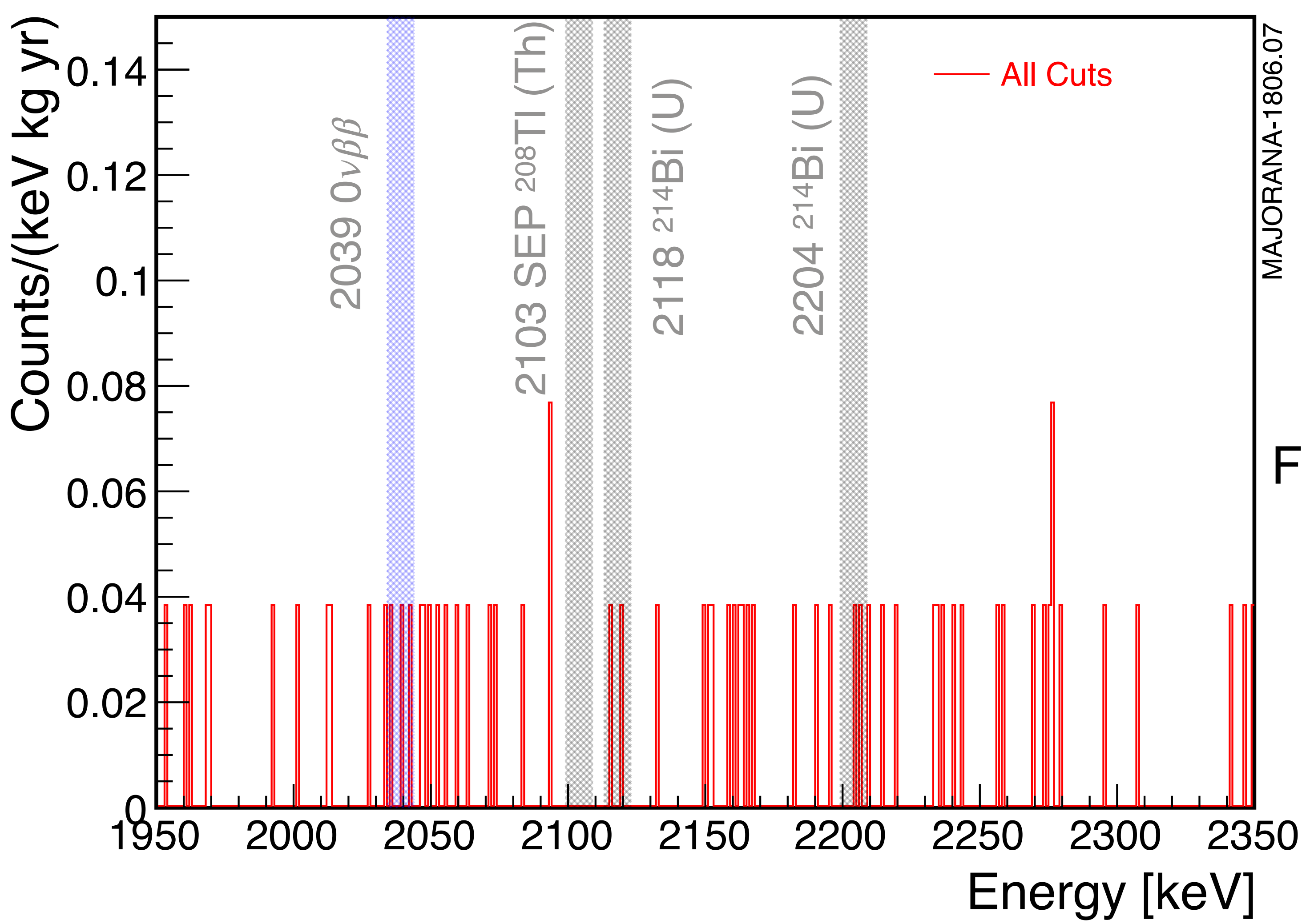

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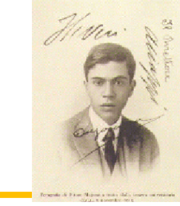


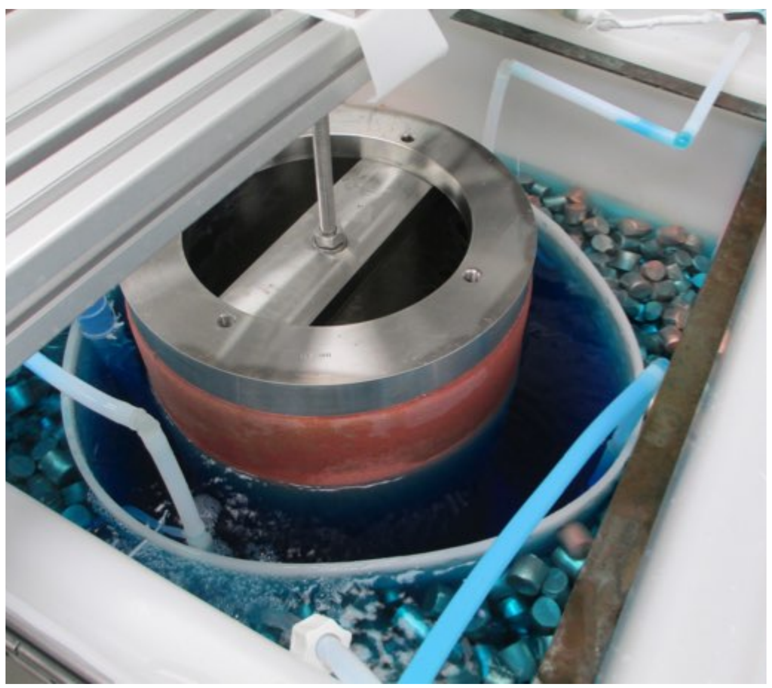
Control of Backgrounds

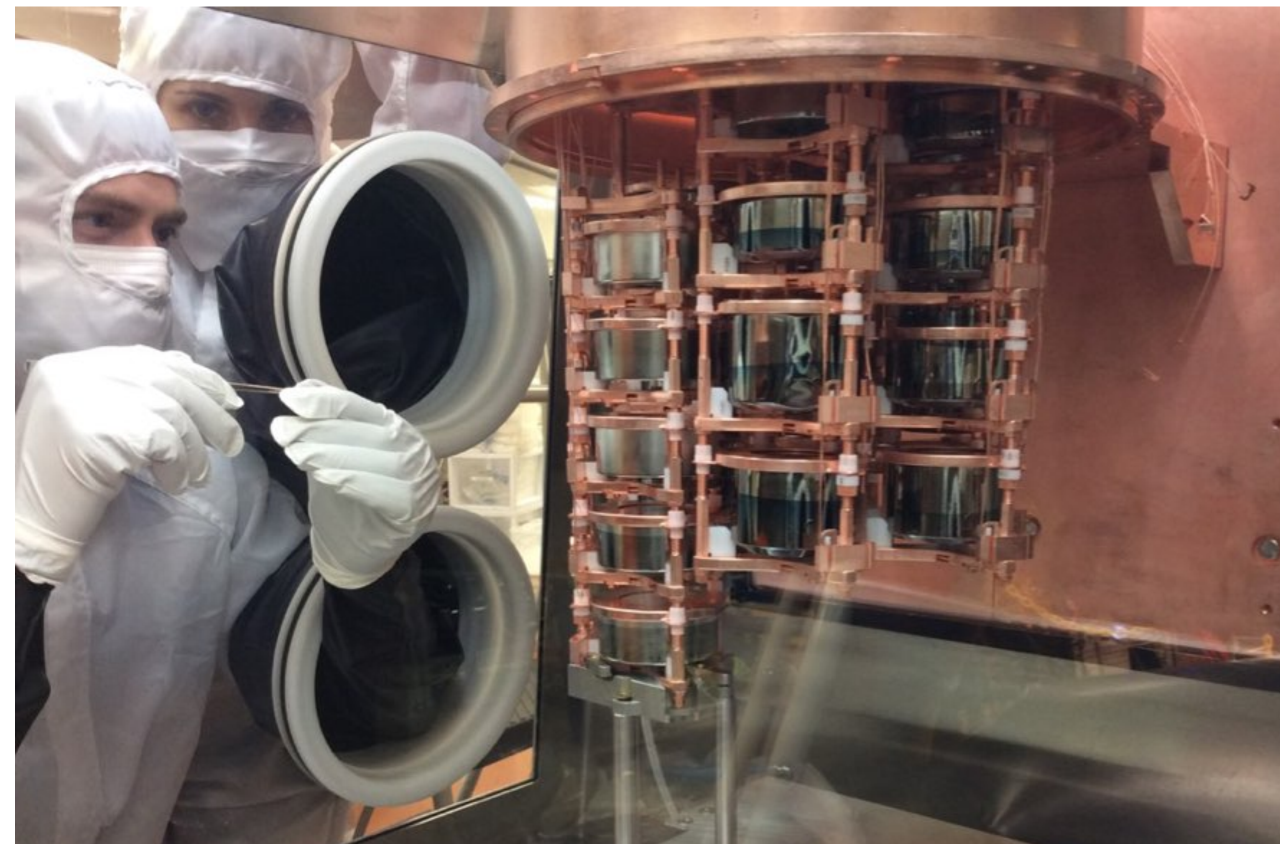
Ultra-pure materials

- Low mass design
- Custom cable connectors and front-end boards
- Selected plastics & fine Cu coax cables
- Underground Electro-formed Cu

Detector assembly

- Dedicated glove boxes with a purged N_2 environment

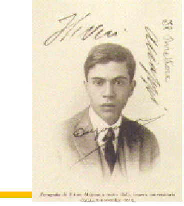




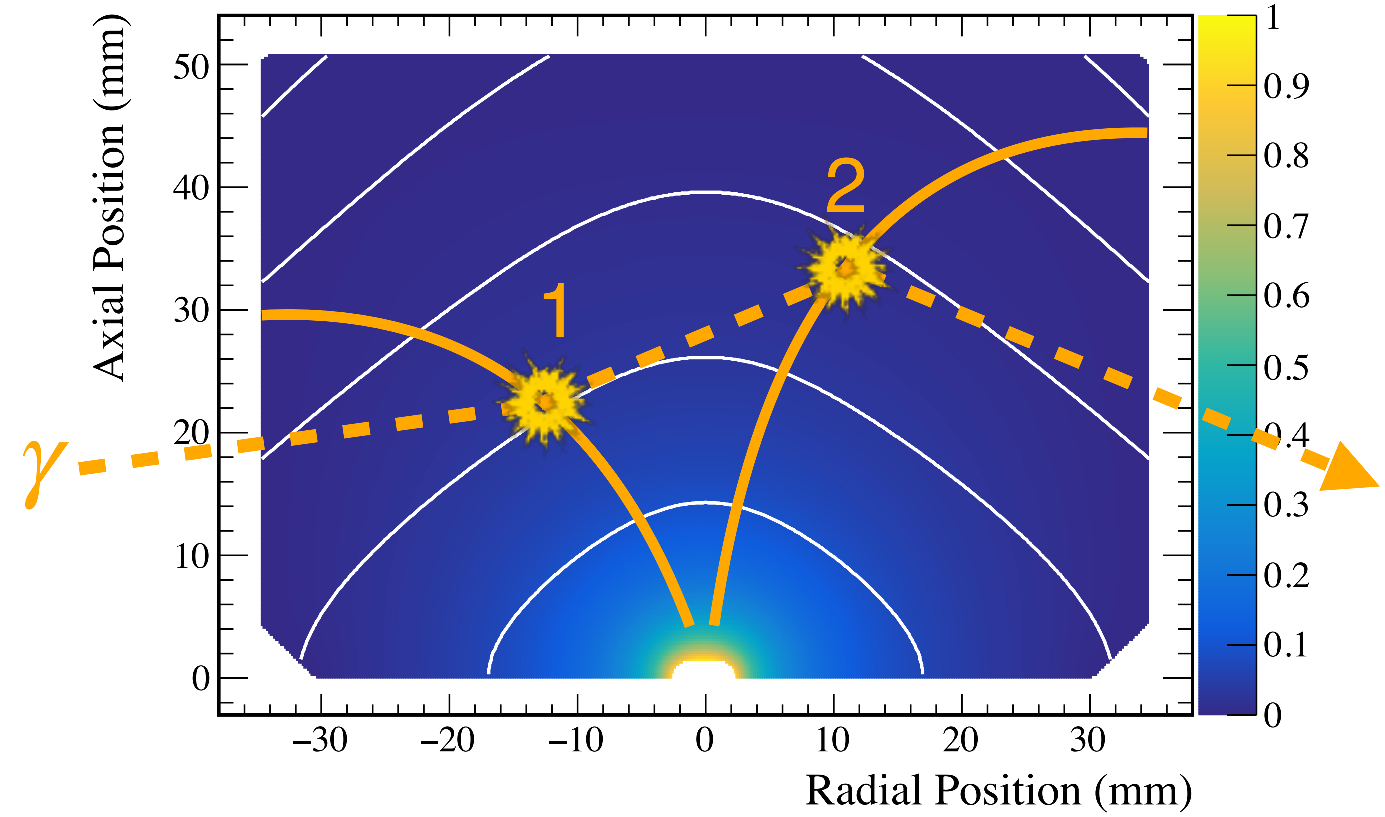
Machining and Cleaning

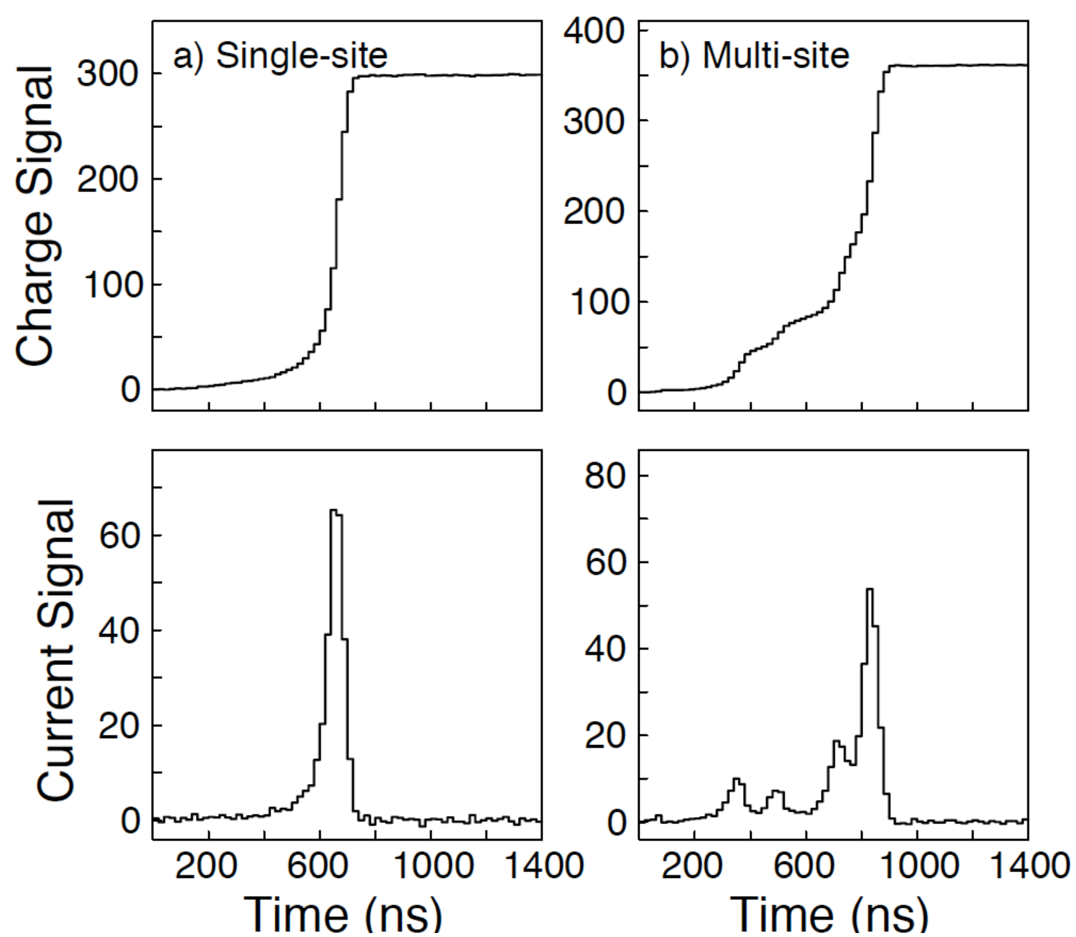
- Cu machining in an underground clean room
- Cleaning of Cu parts by acid etching and passivation
- Nitric leaching of plastic parts

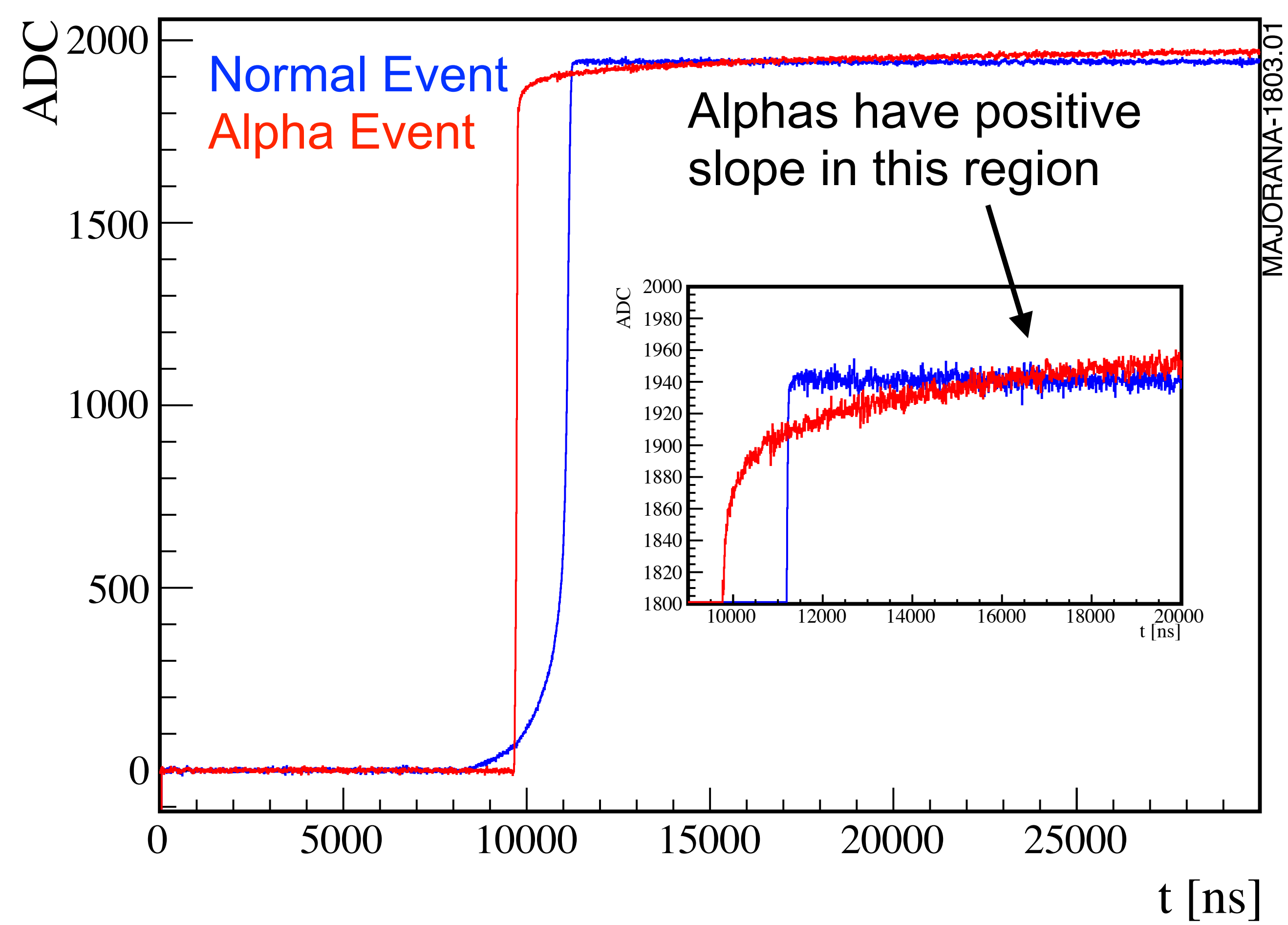
Multi-Site Event Discrimination



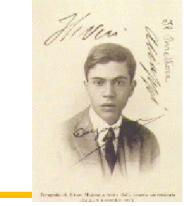
- P-type point contact detectors: slow drift, localized potential
- $0\nu\beta\beta$ events appear single-site
- Max current versus energy rejects multi-site (AvsE) arXiv:1901.05388 [physics.ins-det]
- Delayed charge recovery rejects alphas on passivated surface (DCR)







Multi-Site Event Discrimination



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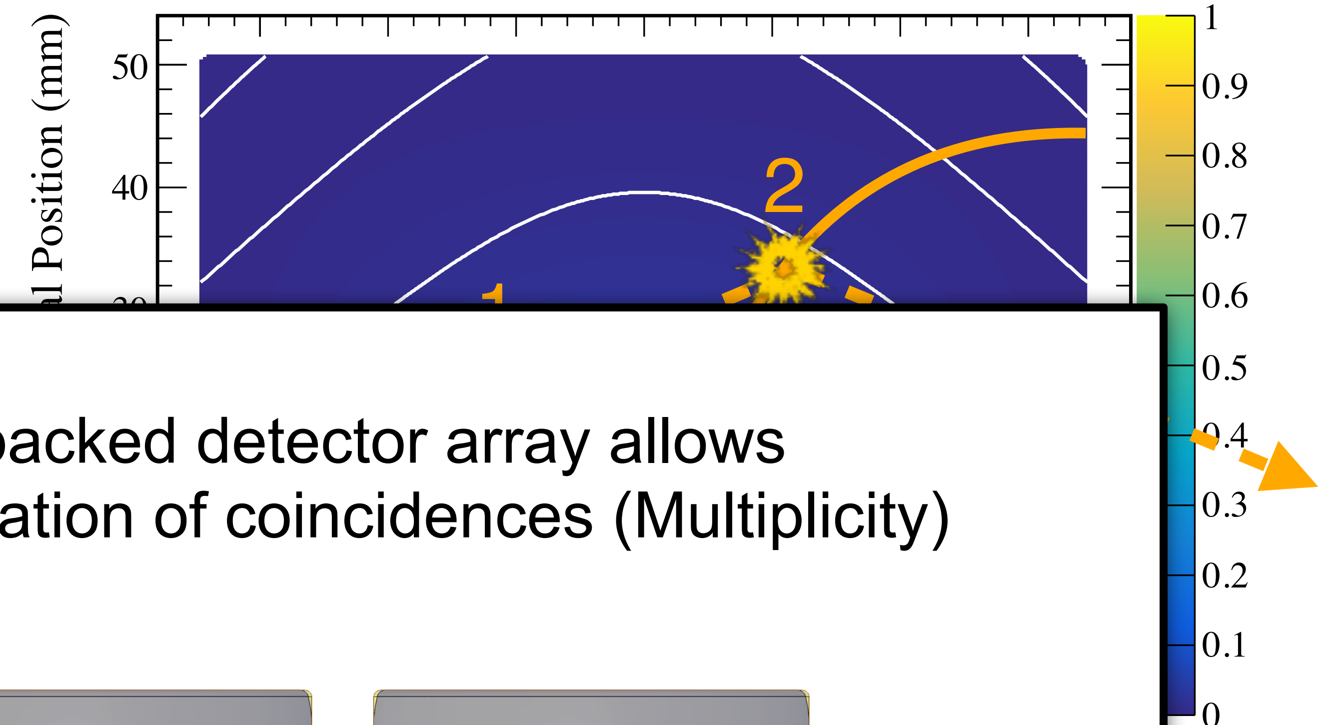
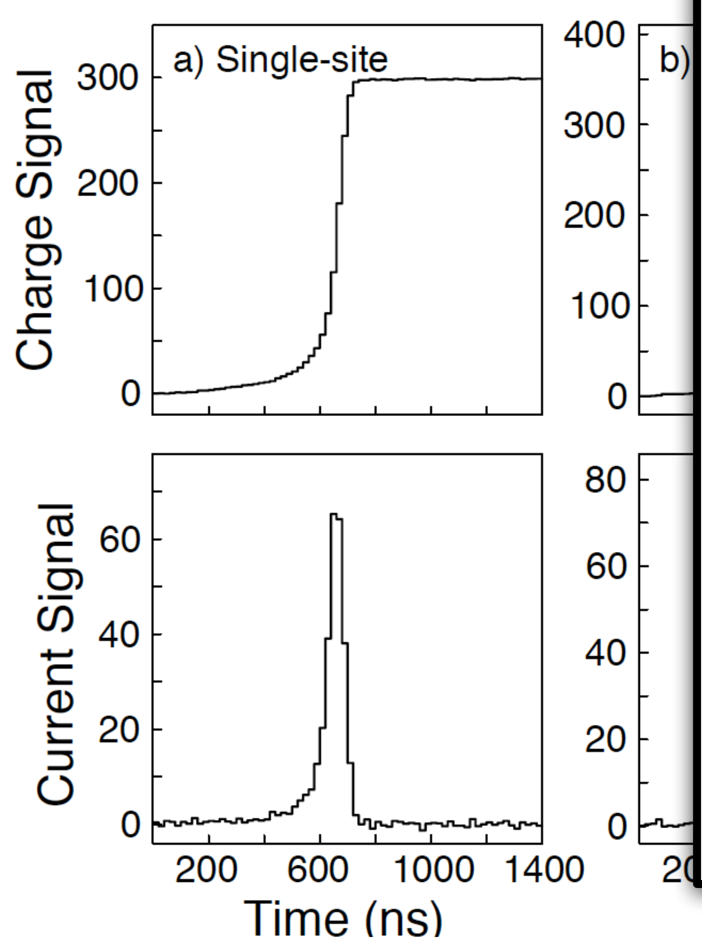
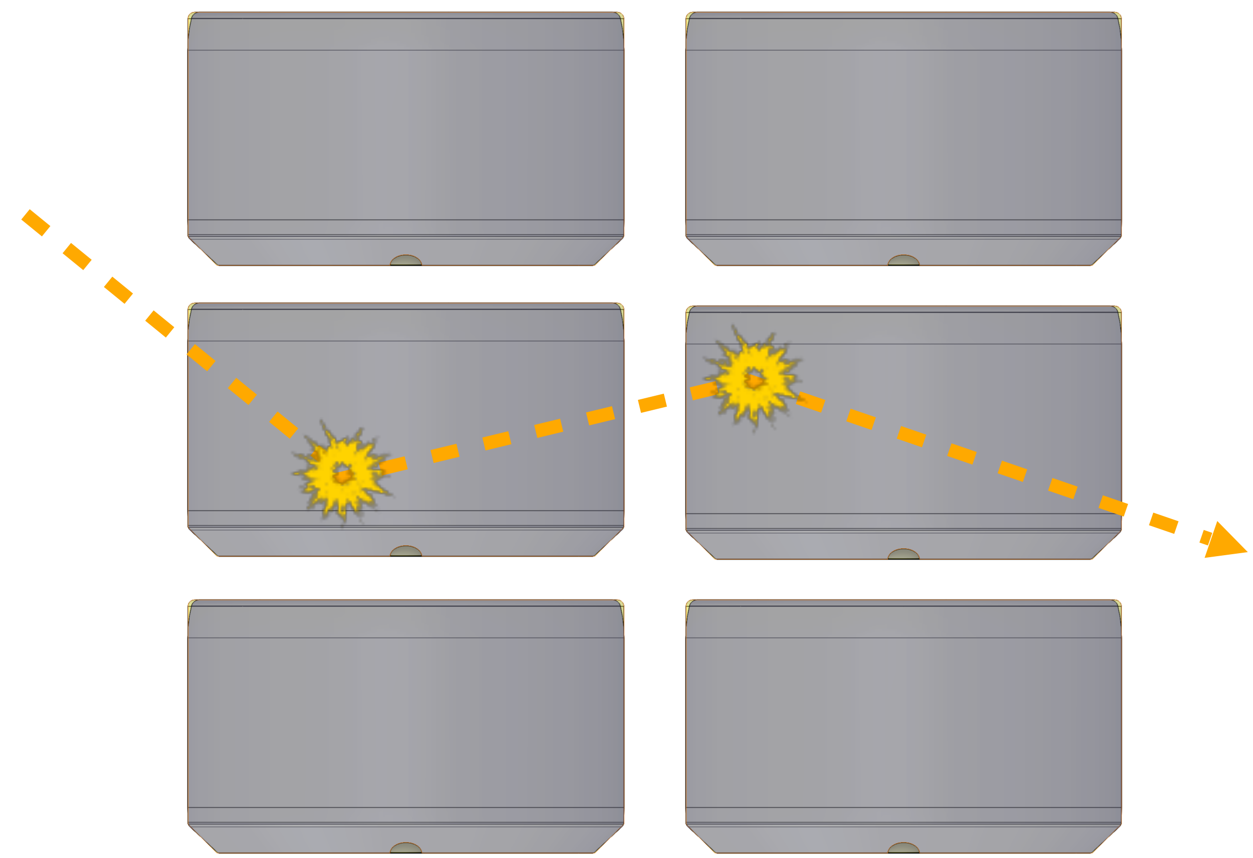
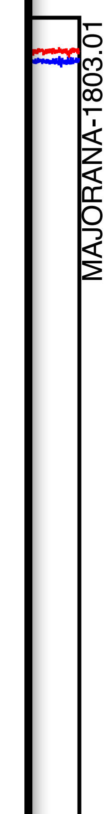




- Closely packed detector array allows discrimination of coincidences (Multiplicity)

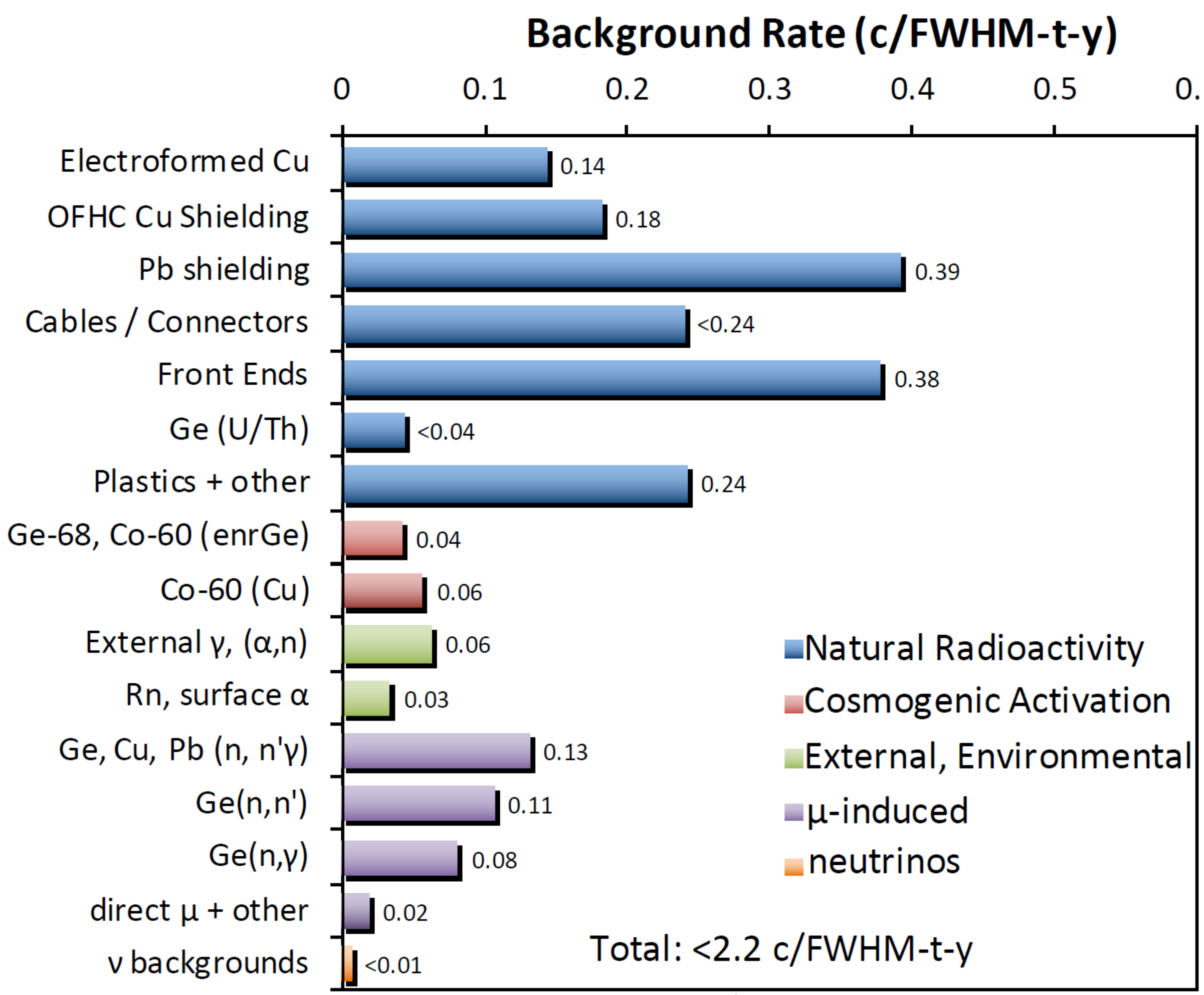




Assays, Expected Backgrounds

- Hundreds of assayed materials and parts
- Sub-ppt sensitivity assay techniques
- Calculate expected rate from assay and simulations

NIM A **828 22** (2016)

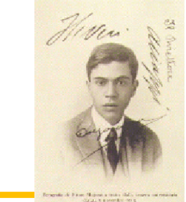


Underground electroformed Cu:
Th < 0.1 uBq/kg
U < 0.1 uBq/kg
~3 decays/kg/yr

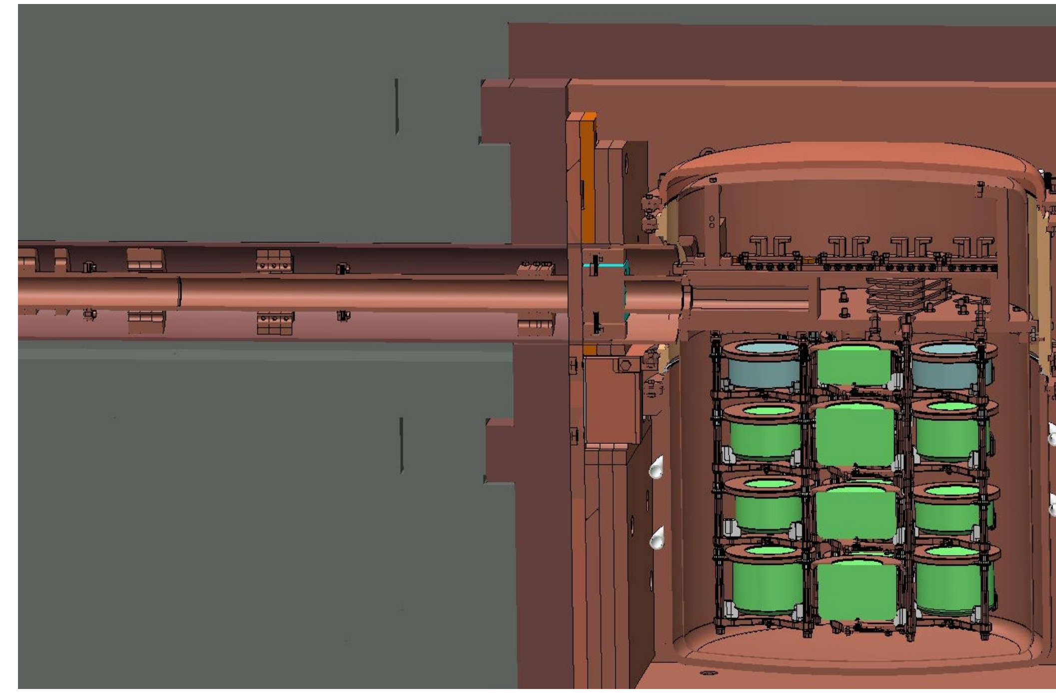
Observed final configuration background: cts/(FWHM t yr)

$$11.9 \pm 2.0$$

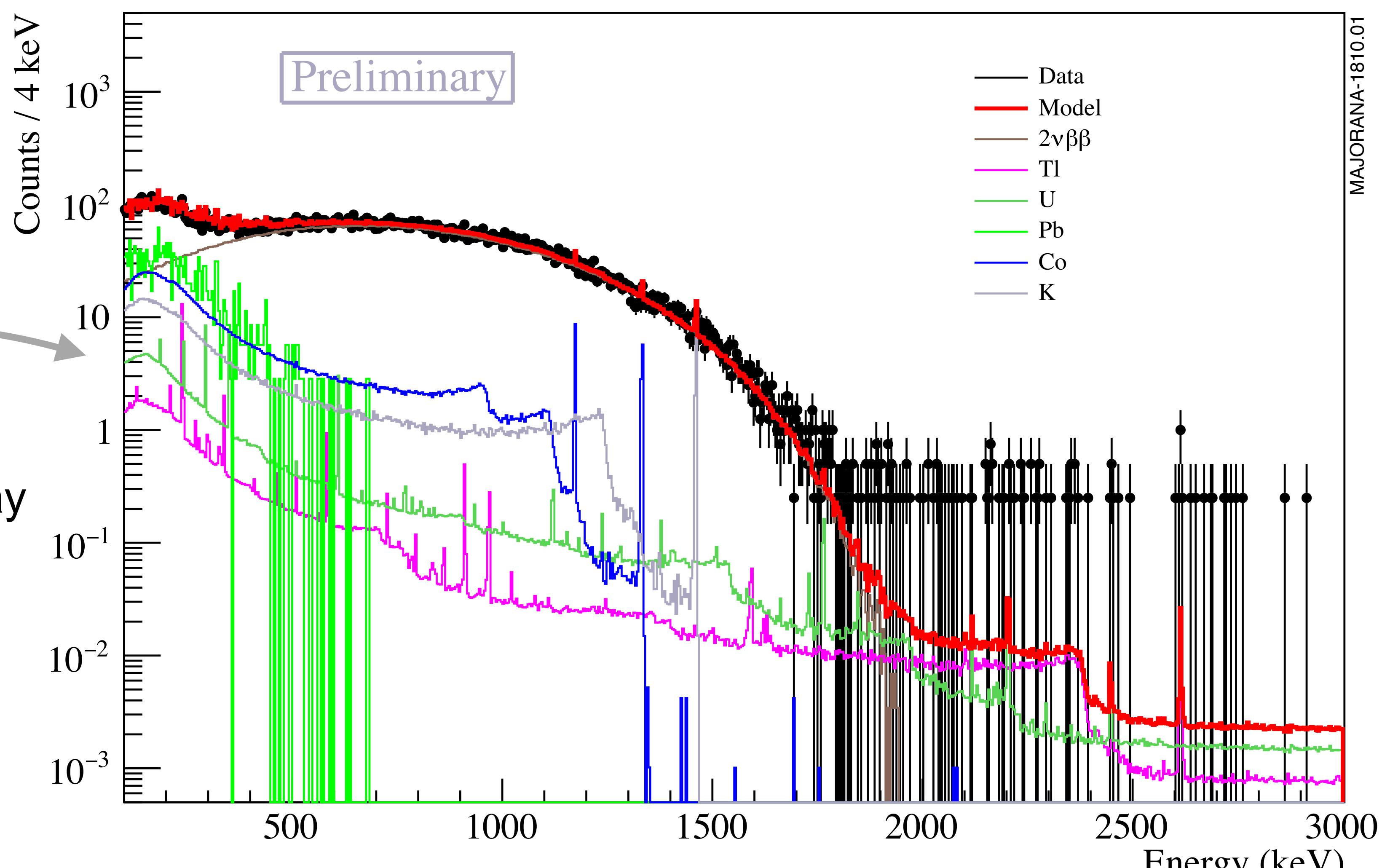
Observed Backgrounds



- Initial analysis suggests source of excess is not nearby the detectors
- Ratio of ^{208}Tl 2614 keV to low-energy peaks suggests missing activity in far components
- Coincidences between 583 and 2614 keV gammas (^{208}Tl → ^{208}Pb): One observed, Factor of 5-10 more expected for source nearby detectors



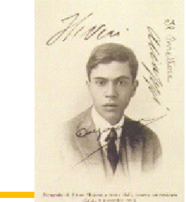
All cuts, components fixed to assay estimate



Sum over components for decay chain contributions

Assume secular equilibrium

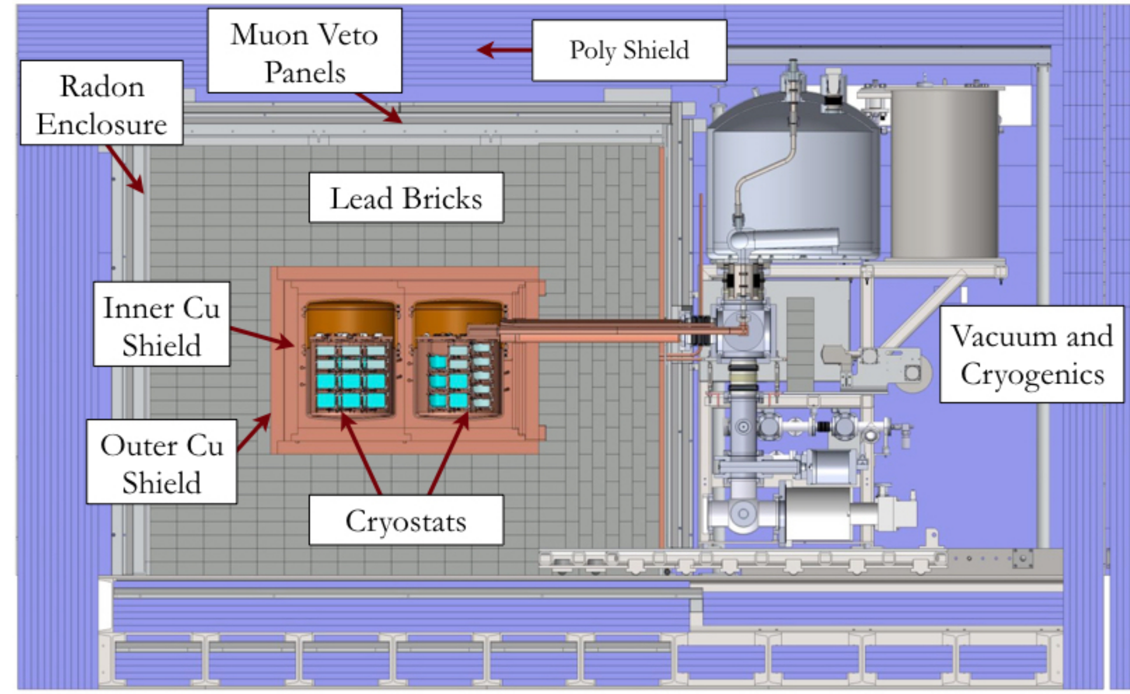
Under-predicted backgrounds seem attributable to ^{232}Th

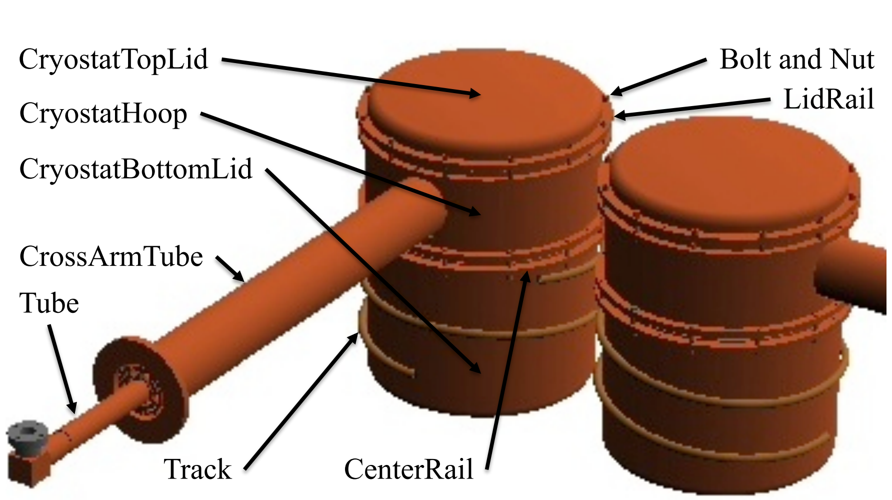


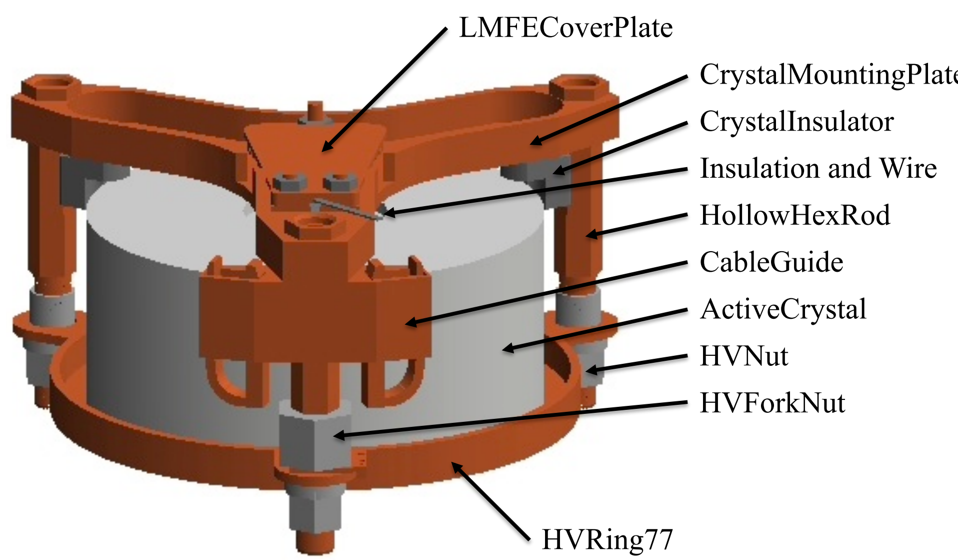
Updated Background Model

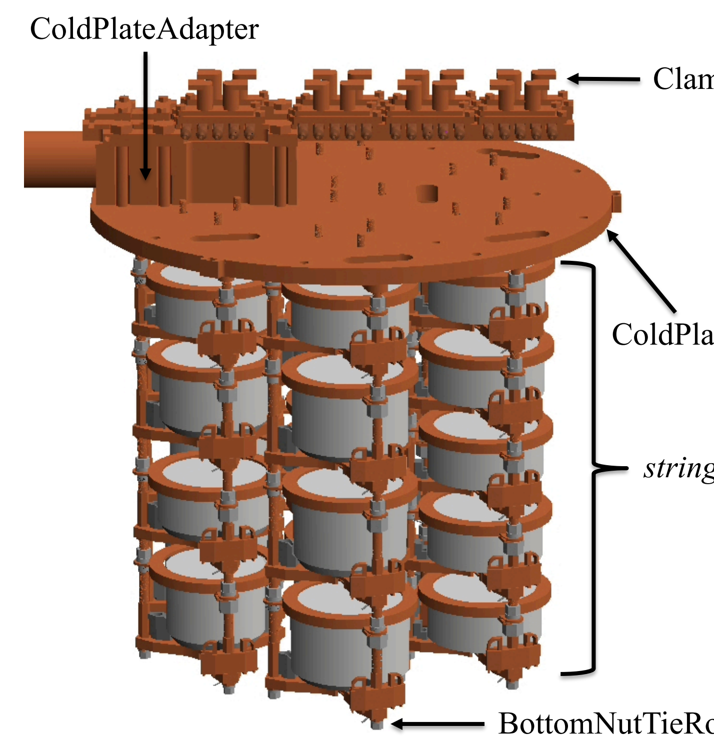
- MaGe/Geant Monte Carlo simulations

  IEEE Trans Nucl Sci **58** 1212 (2011)
- Model as-built geometry of experiment
  - ~4000 parts, ~70 unique designs
  - ~40 component groups of related parts
- Cuts and crystals are modeled in simulations



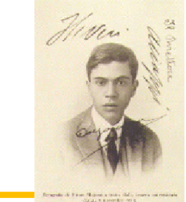






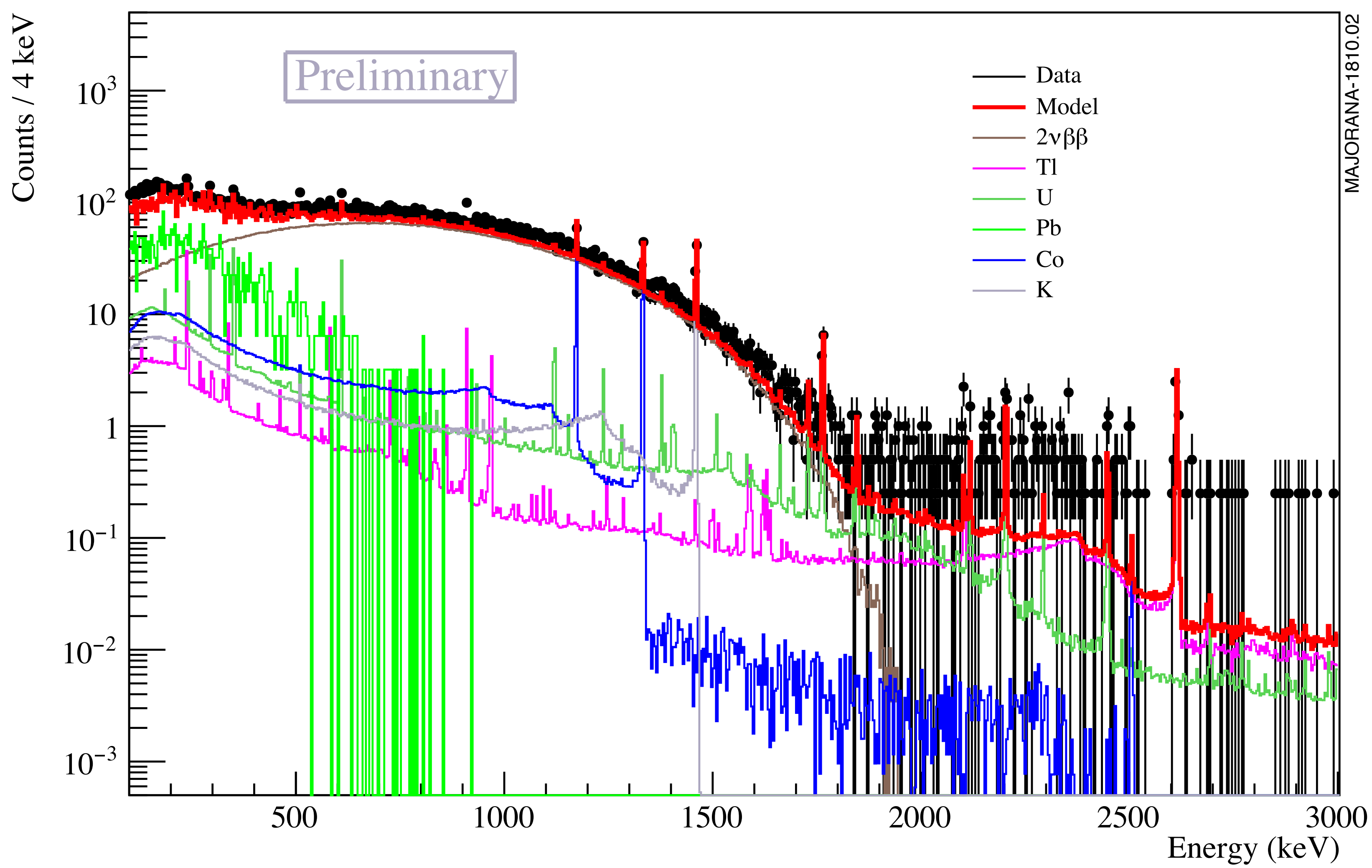
- National Energy Research Scientific Computing Center

Background Model Inference



- Tune activities of model components to best fit the data
- Bayesian model
  - prior information from assay campaign

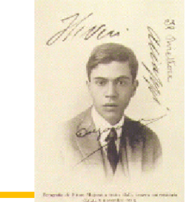
No AvsE cut, activities fit to background spectrum



$$\Pr(\mathrm{M}|\mathrm{D}) = \frac{\Pr(\mathrm{D}|\mathrm{M}) \times \Pr(\mathrm{M})}{\Pr(\mathrm{D})}$$

MCMC procedure approximates marginal posteriors for components

D = Data, M = Model

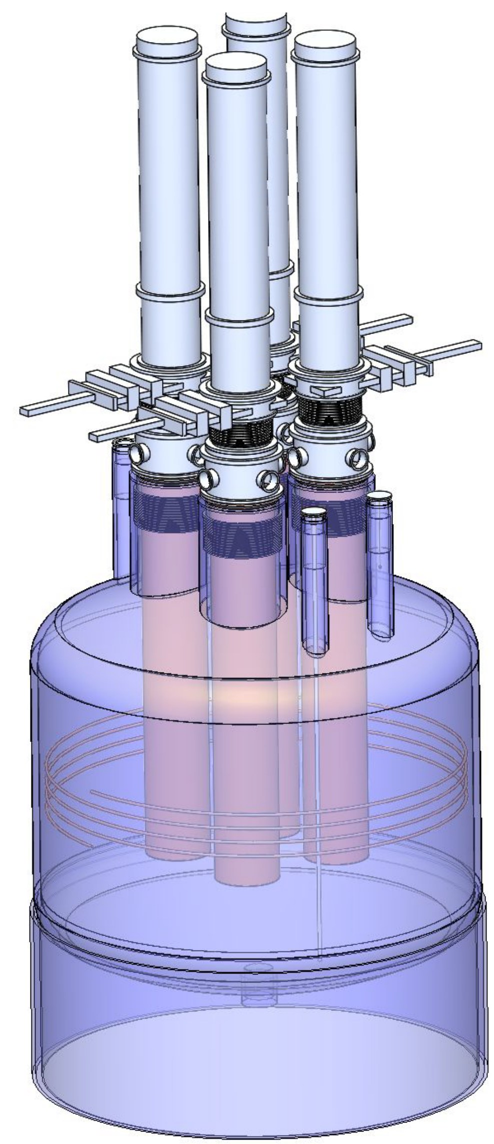


LEGEND

- Updated background model will inform design and procedures for next-generation in ^{76}Ge

Next Talk: Oliver Schulz
https://indico.cern.ch/event/760557/contributions/3262504/

Next Generation ^{76}Ge: LEGEND — Large Enriched Germanium Experiment for Neutrinoless ββ Decay (52 Institutions, ~250 Members)



The MAJORANA Collaboration

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Osaka University, Osaka, Japan:
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Additional Slides

Beyond the Standard Model Searches

The low backgrounds, low threshold, high resolution spectra allows additional searches

- Controlled surface exposure of enriched material to minimize cosmogenics

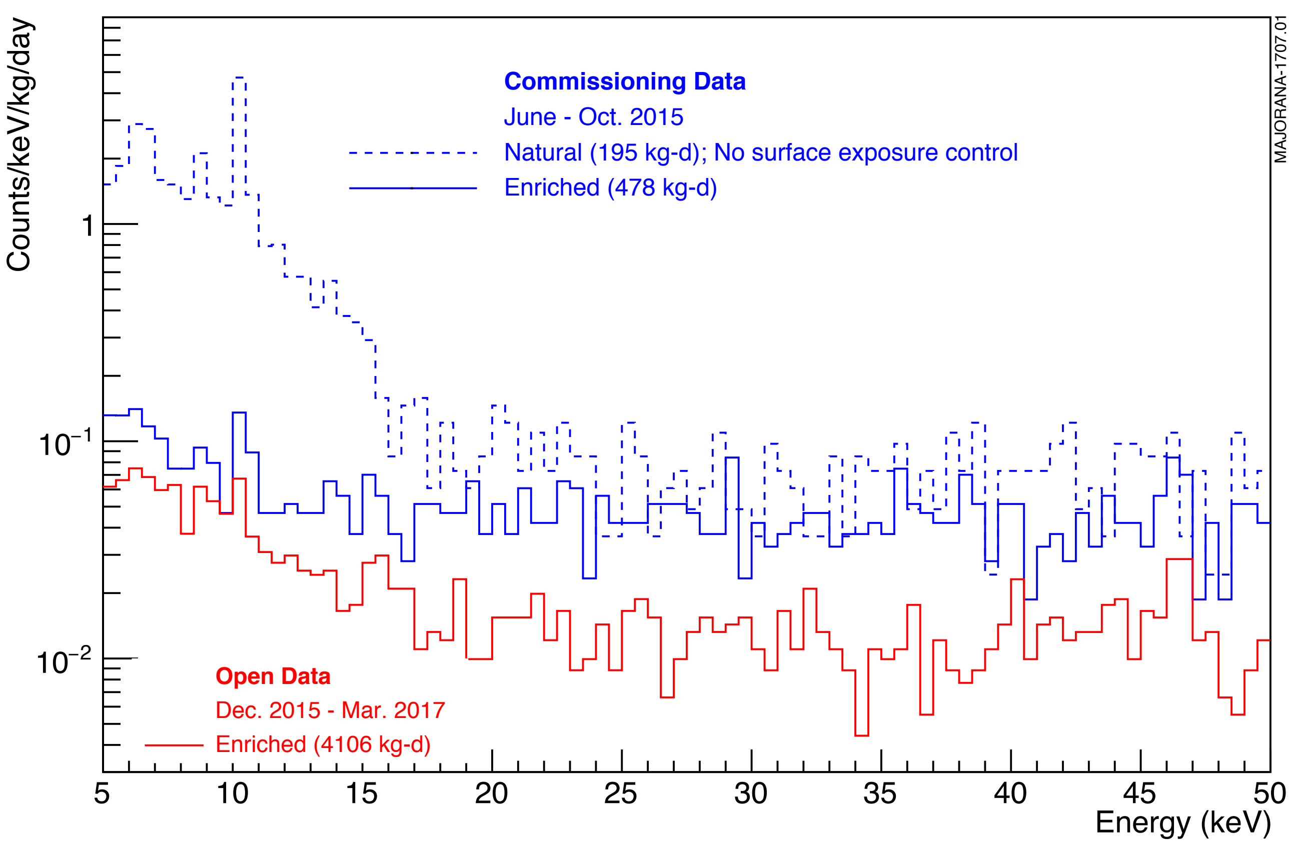
Excellent energy resolution: 0.4 keV FWHM at 10.4 keV

- Ongoing effort on:
  - low energy data cleaning, de-noising
  - low energy cut development & efficiencies

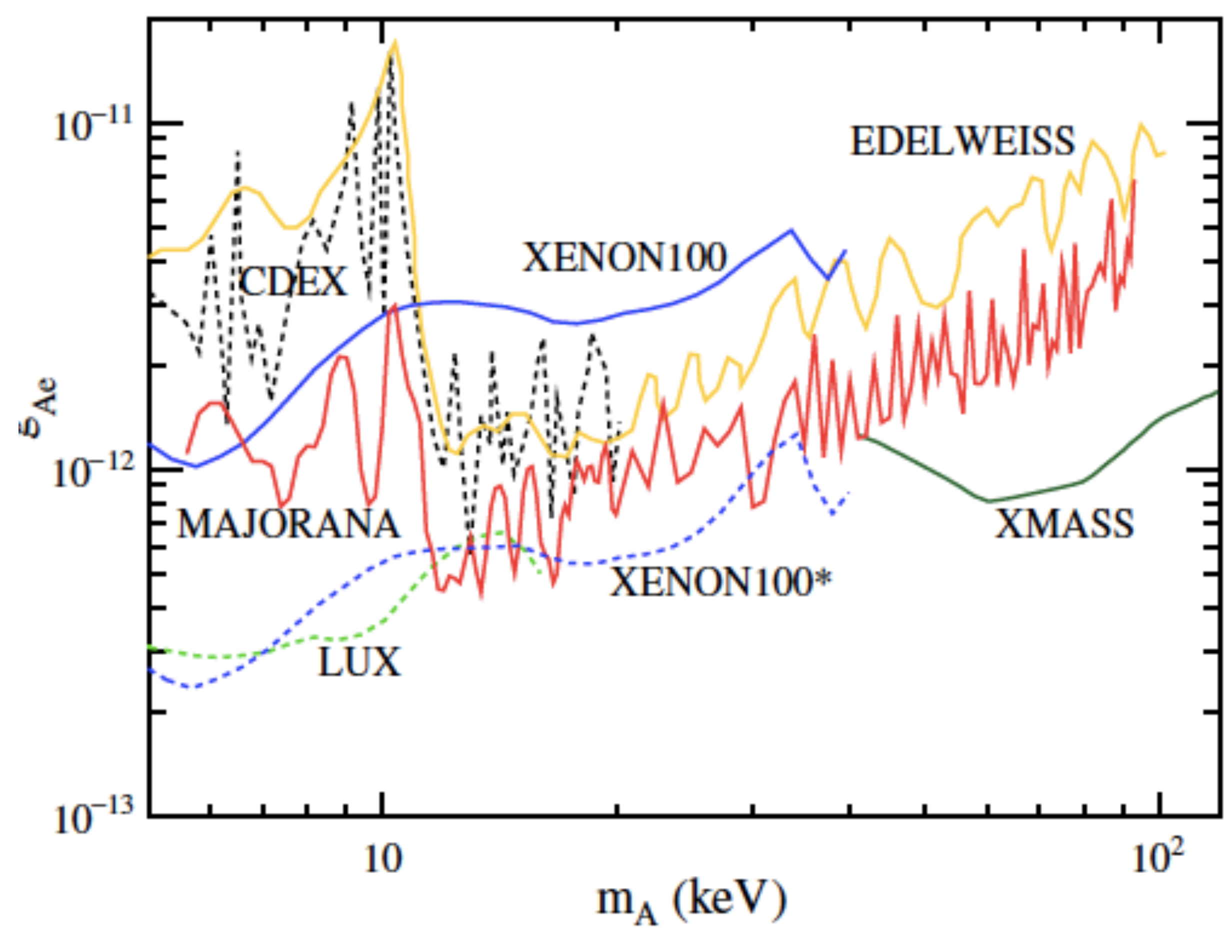
Permits low-energy physics

- pseudoscalar dark matter, vector dark matter, 14.4-keV solar axion, $e^- \rightarrow 3\nu$, Pauli Exclusion Principle

PRL **118** 161801 (2017)



Low energy spectra during commissioning (blue) and first low-background physics running (red)



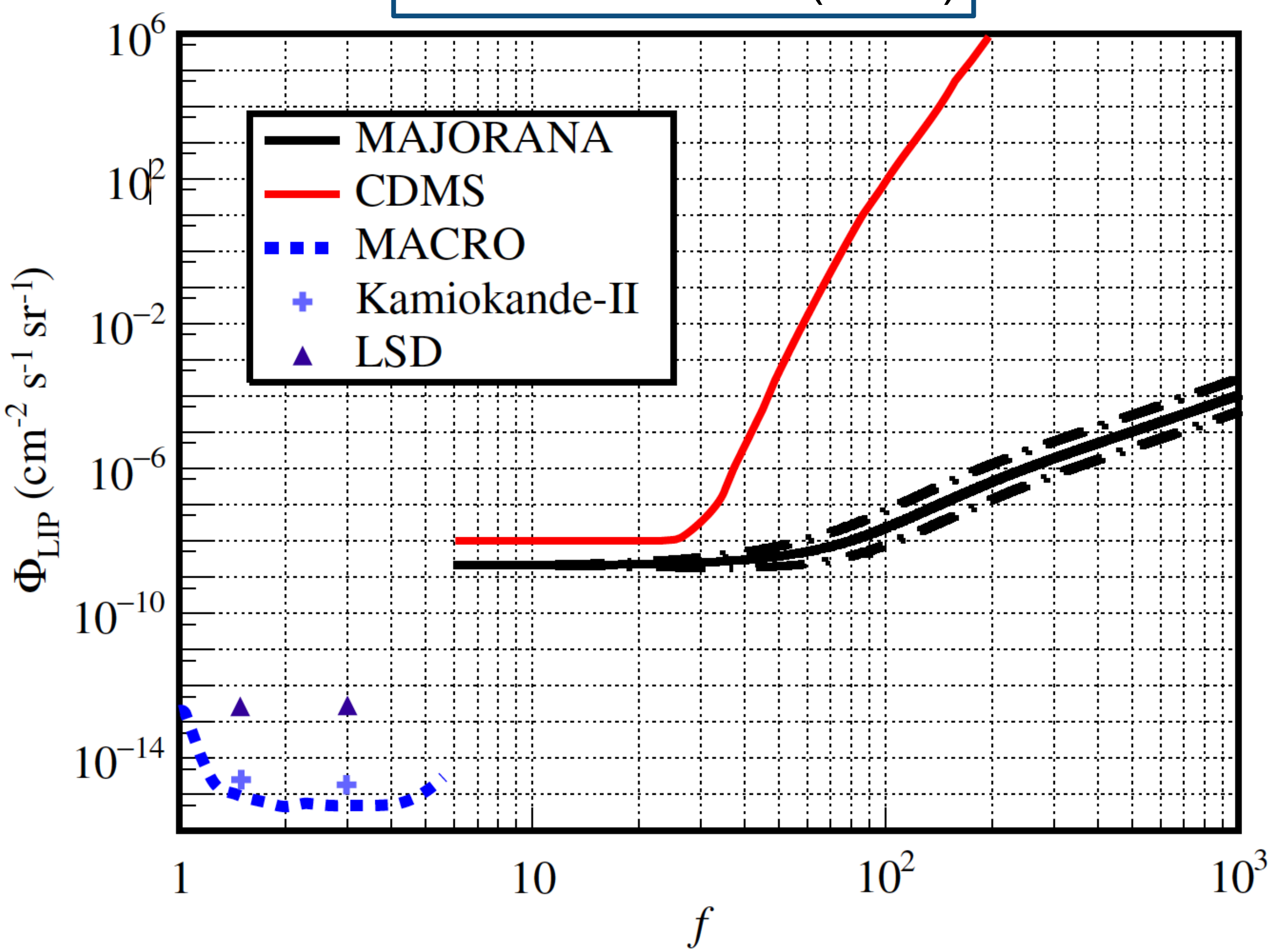
The 90% UL on the pseudoscalar axionlike particle dark mater coupling

Beyond the Standard Model Searches

The low backgrounds, low threshold, high resolution spectra allows additional searches

First Limit on the direct detection of Lightly Ionizing Particles for Electric Charge as Low as *e*/1000

PRL **120** 211804 (2018)



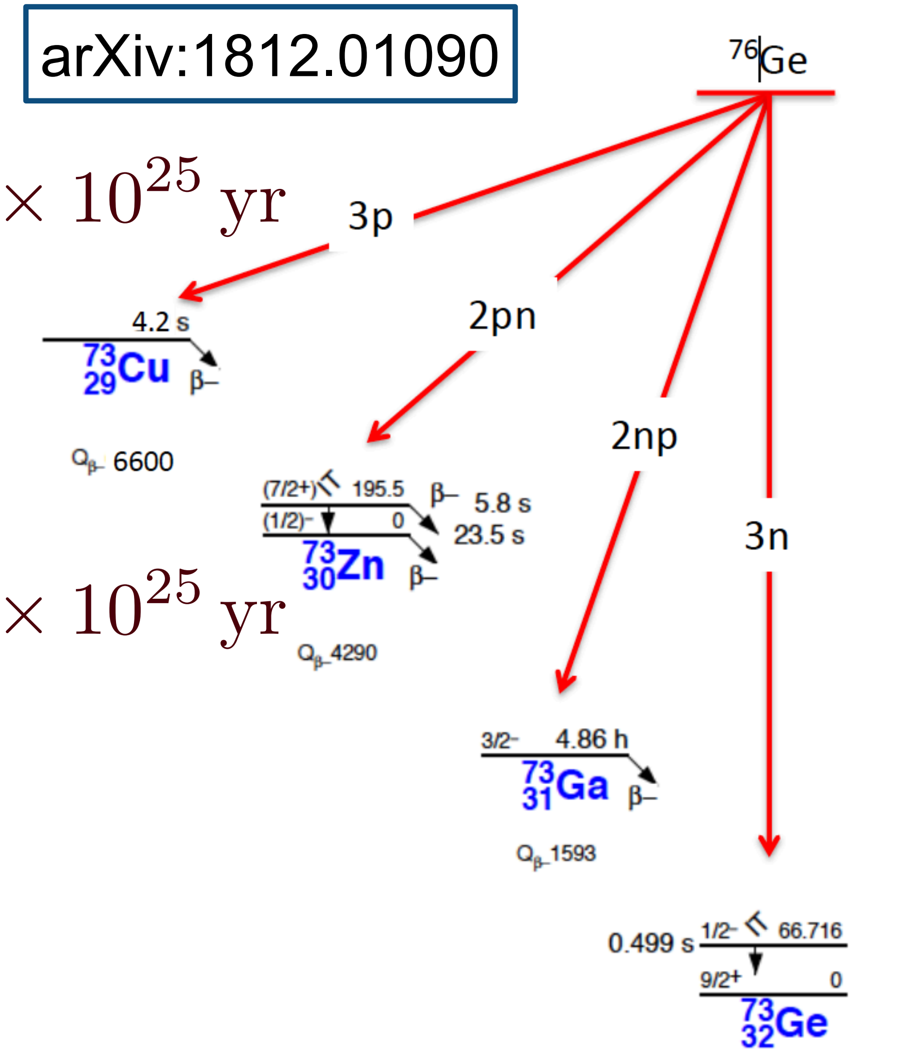
The 90% UL on the Lightly Ionizing Particle flux with 1σ uncertainty bands

Search for Tri-Nucleon Decay: A test of baryon number violation

arXiv:1812.01090

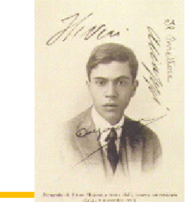
$$T_{1/2} > 4.7 \times 10^{25}\ \text{yr}$$

$$T_{1/2} > 4.9 \times 10^{25}\ \text{yr}$$



The 90% UL for two tri-nucleon decay-specific modes

Cable and Connector Improvements

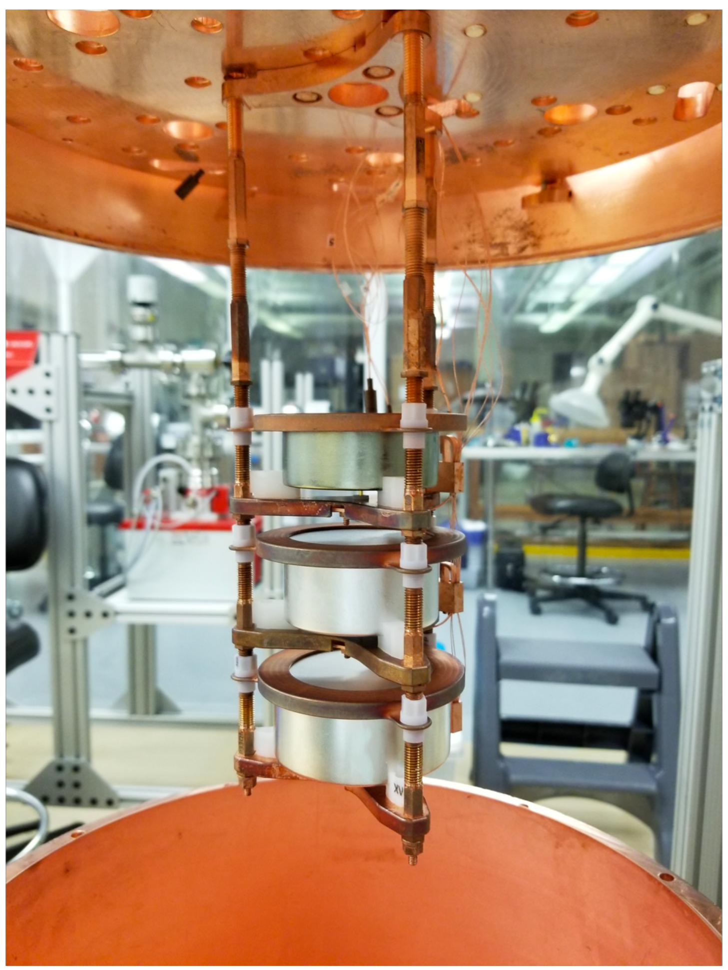


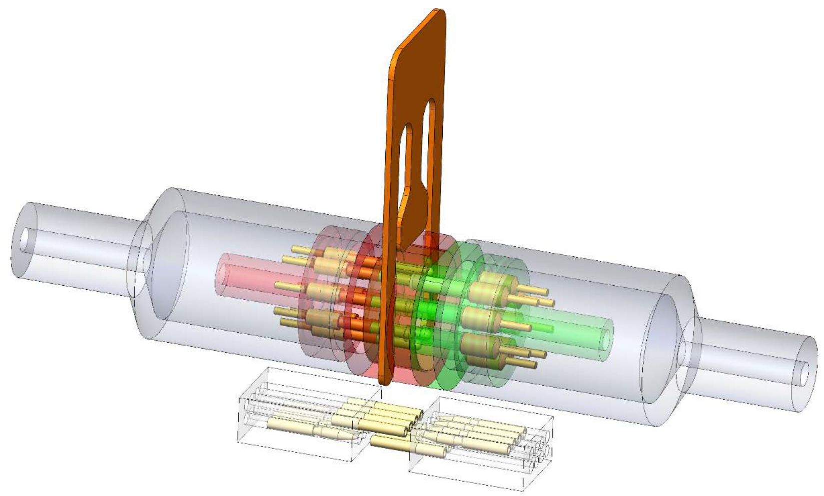
Operating with only 40/58 detectors due to cable/connector issues

- Testing and developing options to upgrade both signal and HV cables and connectors
  - Requires new designs that are ultra-clean, low-mass, better reliability

A string of three natural Ge detectors has been assembled and installed at UNC

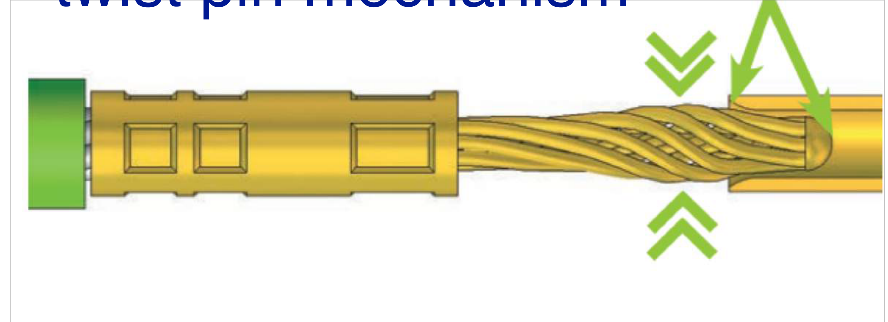
- Evaluating cables and connectors in their final configuration

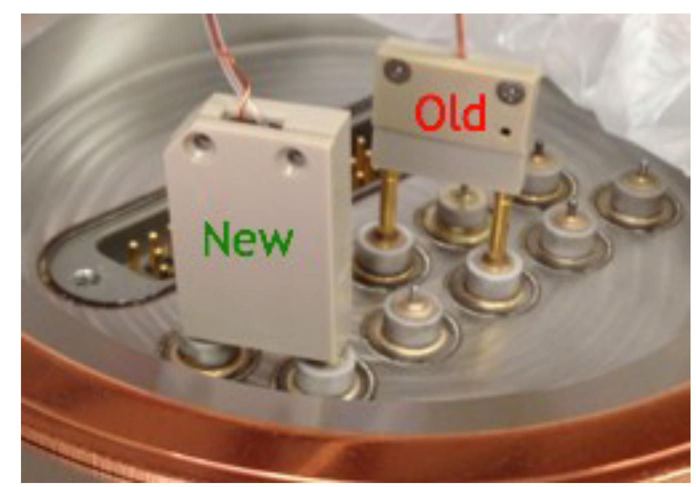




Improve protection of cables

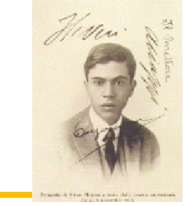
Custom connectors that incorporate a twist pin mechanism





Better HV crimp at the detector and flange

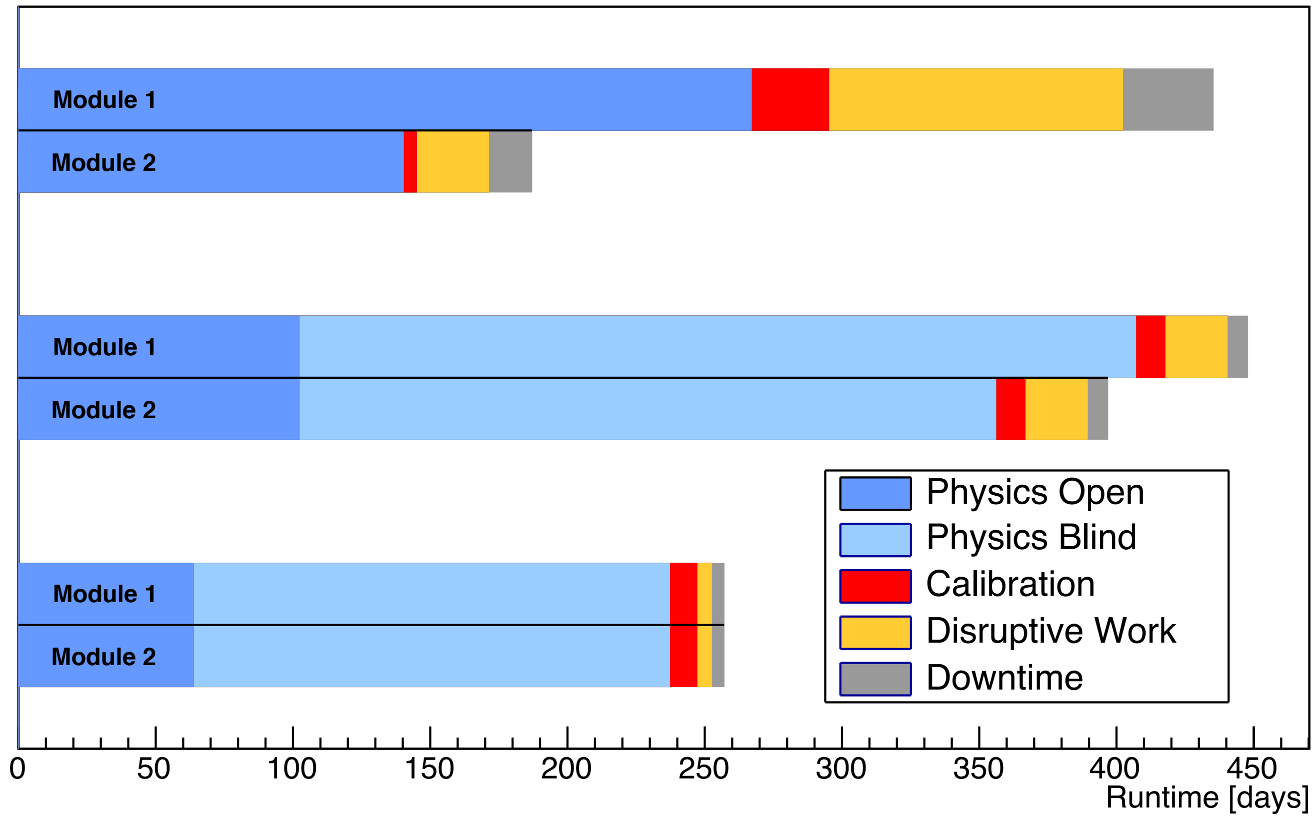
Runtime and Exposure



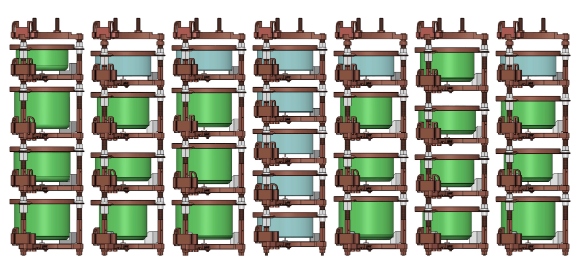
Open data: Jun. 2015 - Mar. 2017
9.95 kg-yr

All blind data: Jan. 2016 - Apr. 2018
New Open Data: Mar. 2017 - Apr. 2018
+16.1 kg-yr

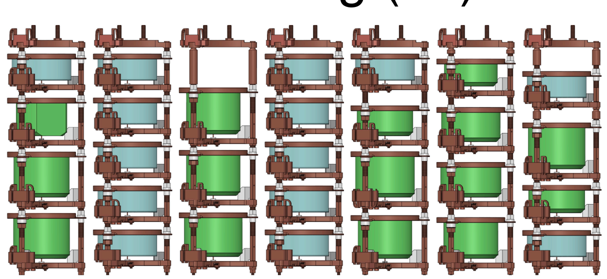
April 2018 - Present*
*As of Dec. 31, 2018



Jun. 2015 - Module 1: 16.9 kg (20) ^{enr}Ge
5.6 kg (9) ^{nat}Ge



Aug. 2016 - Module 2: 12.9 kg (15) ^{enr}Ge
8.8 kg (14) ^{nat}Ge



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PRL **120** 132502 (2018)

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Neutrino 2018
DOI:10.5281/zenodo.1286900

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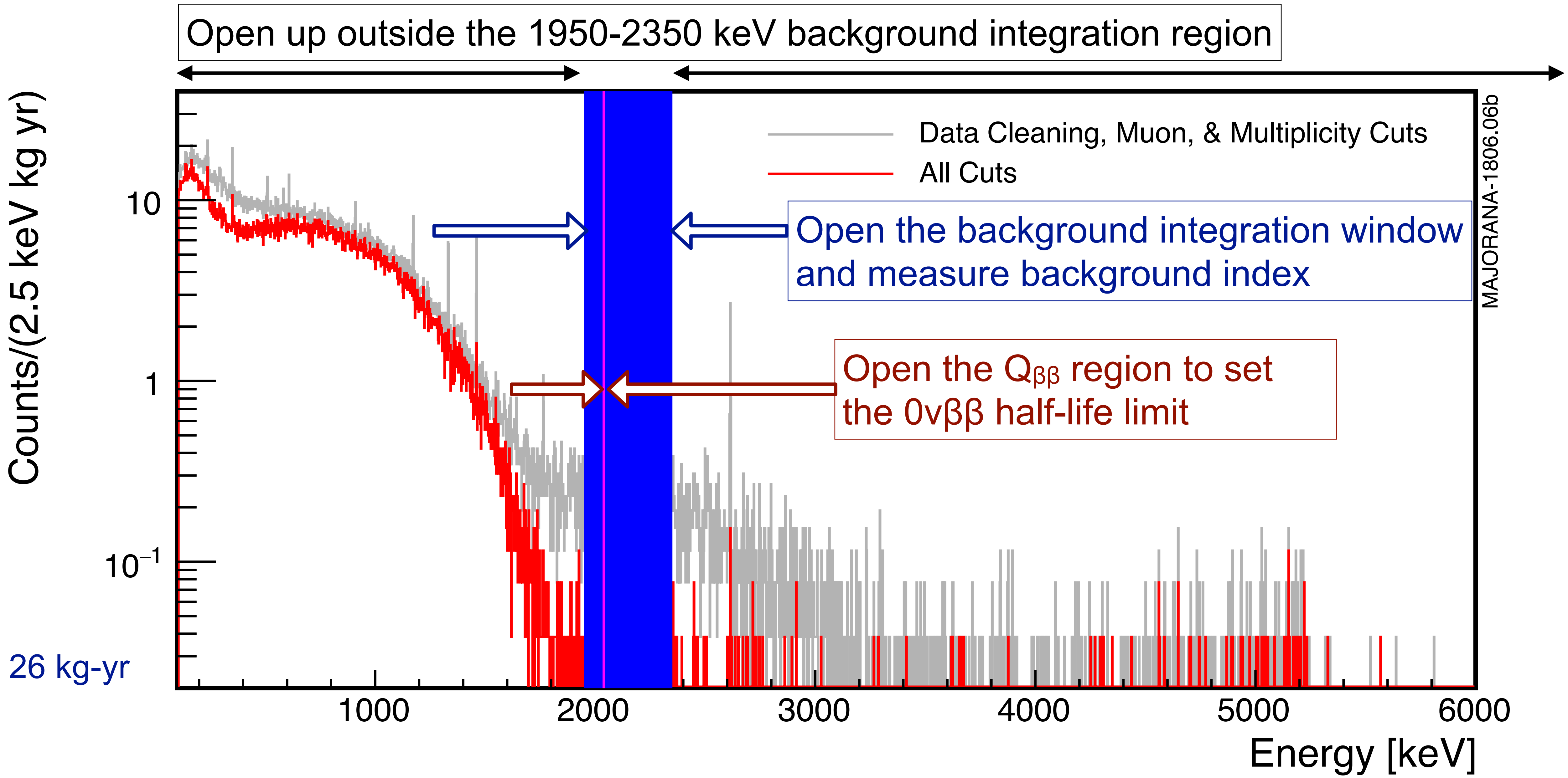
Blindness Implementation

Data is split for statistical blindness, analysis cuts developed on open data

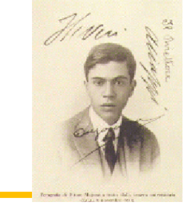
Each 31 hours of open data is followed by 93 hours of completely blind data

Unblinding in phases to perform data quality and consistency checks

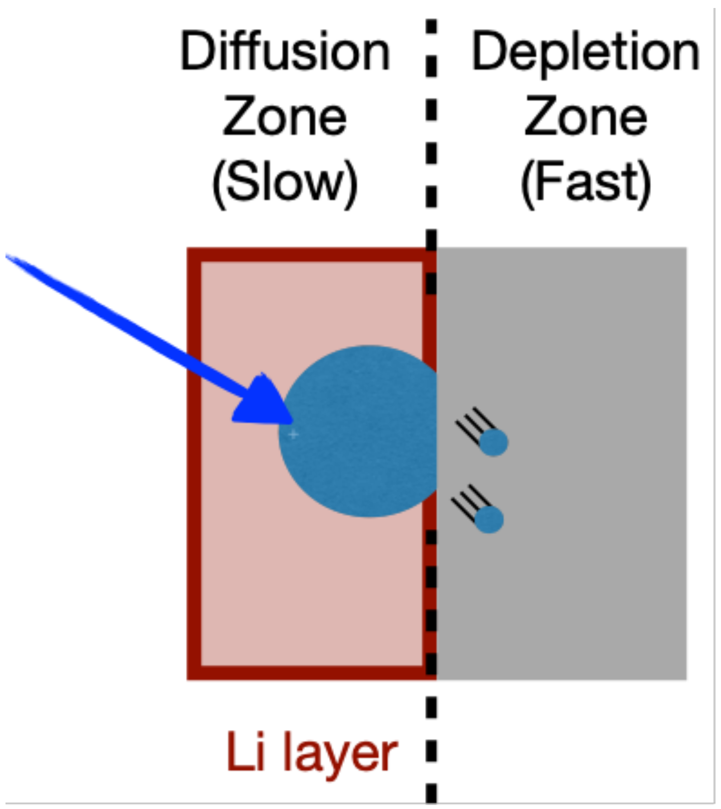
(<100 keV and multiple-detector events remain blind for other studies)

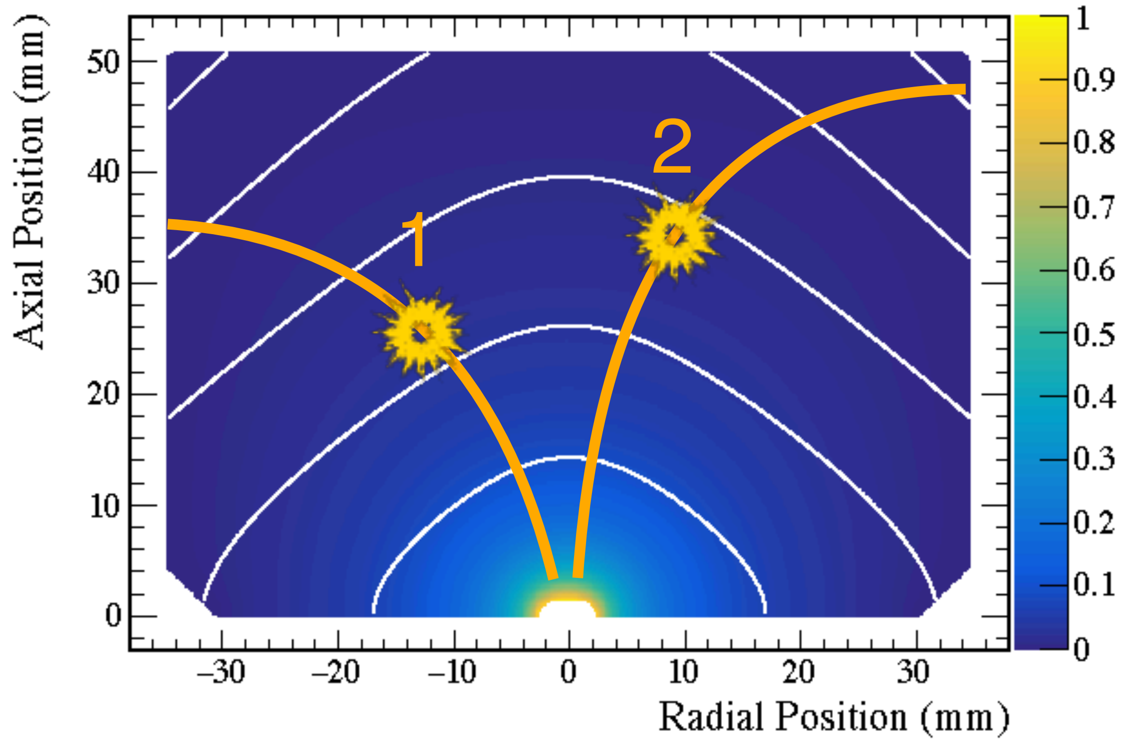


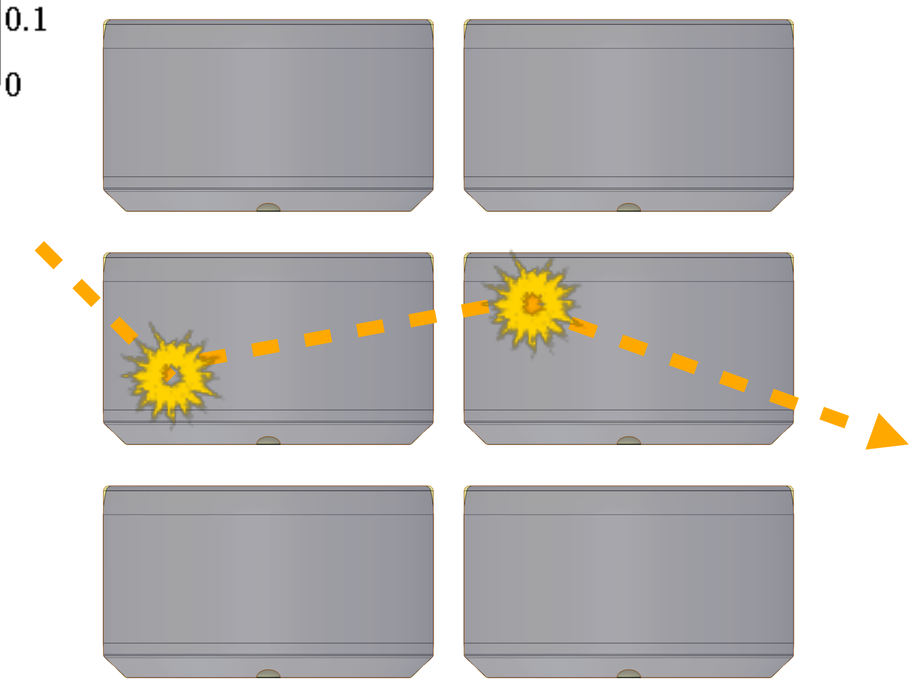
Cuts and Crystals Modeled in Simulations



- Energy degradation of events incident in lithiated outer layer of crystals
- Multi-site events based on energy-dependent Δt heuristic
- Coincidences based on as-built active detector lists

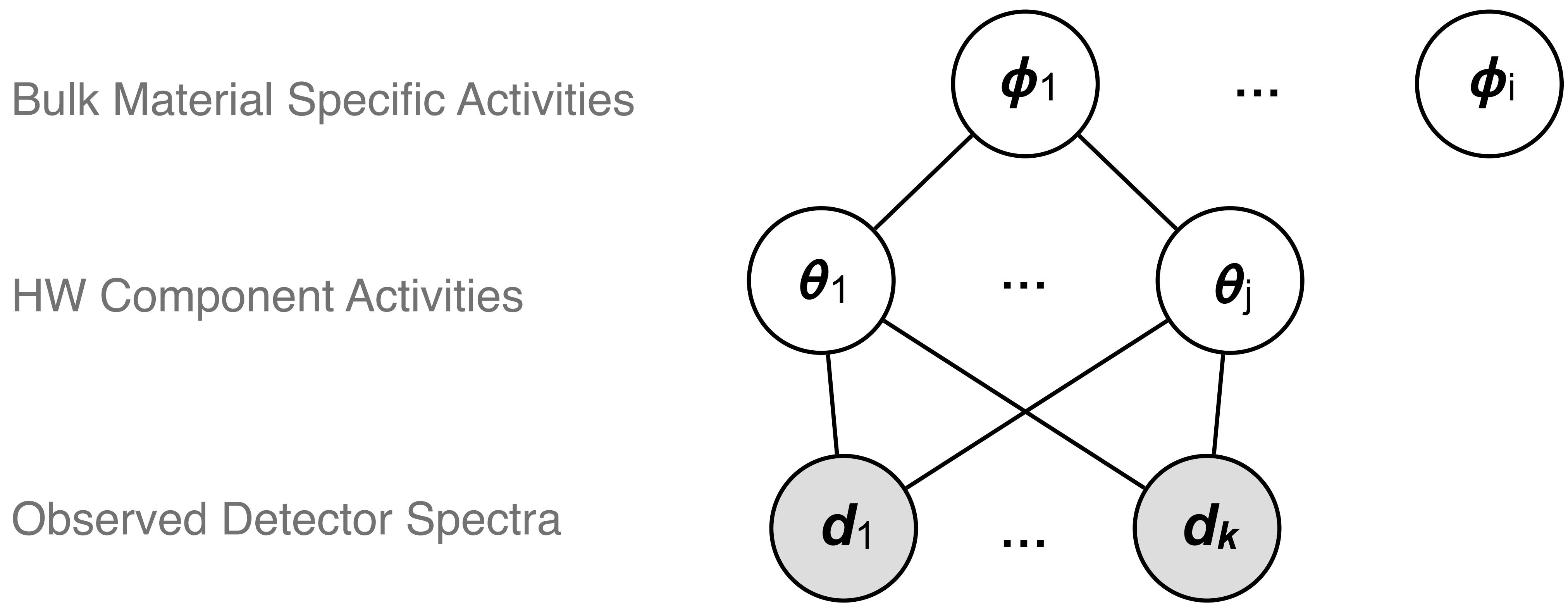






Background Modeling

- Graphical model for activities of components as seen by detectors
- Assuming uniformly distributed backgrounds, pool individual detectors together

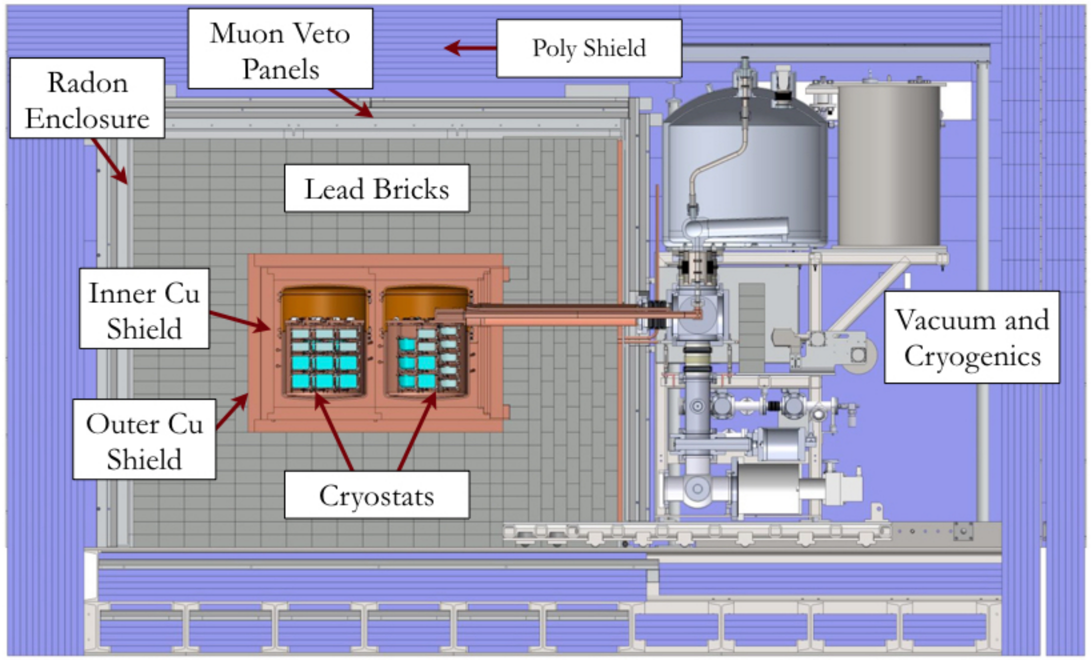


P(Material, Component, Detector) =

P(Detector | Component, Material) × P(Component | Material) × P(Material)

Challenges in Background Modeling

- Low statistics of the data (that was the goal…)
- High dimensionality of parameter space: O(100)



- One option for model selection, better than grid search through parameter space:

  Markov chain Monte Carlo Model Composition (MC^3)

  1. Begin chain at some model M
  2. Define neighborhood of M, including models that differ by only one parameter
  3. Draw a random next step M' from the neighborhood and accept with probability

$$\min\left\{1, \frac{\mathrm{P}(M'|D)}{\mathrm{P}(M|D)}\right\}$$

D. Madigan et al "Strategies for Graphical Model Selection" Selecting Models from Data **89** (1994)