

Measuring cosmogenic activation rates in active detector material

21st May 2019

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(Presented by Ariel Matalon)

Cosmogenic Activation

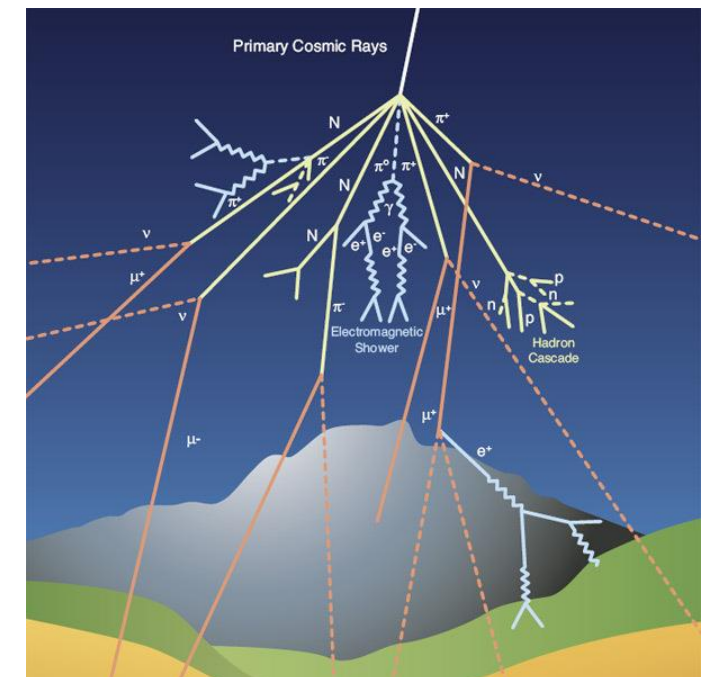
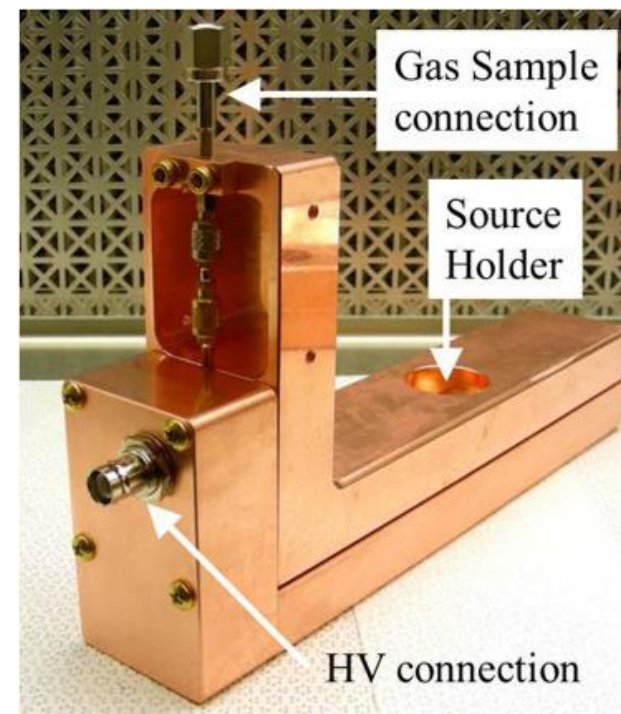
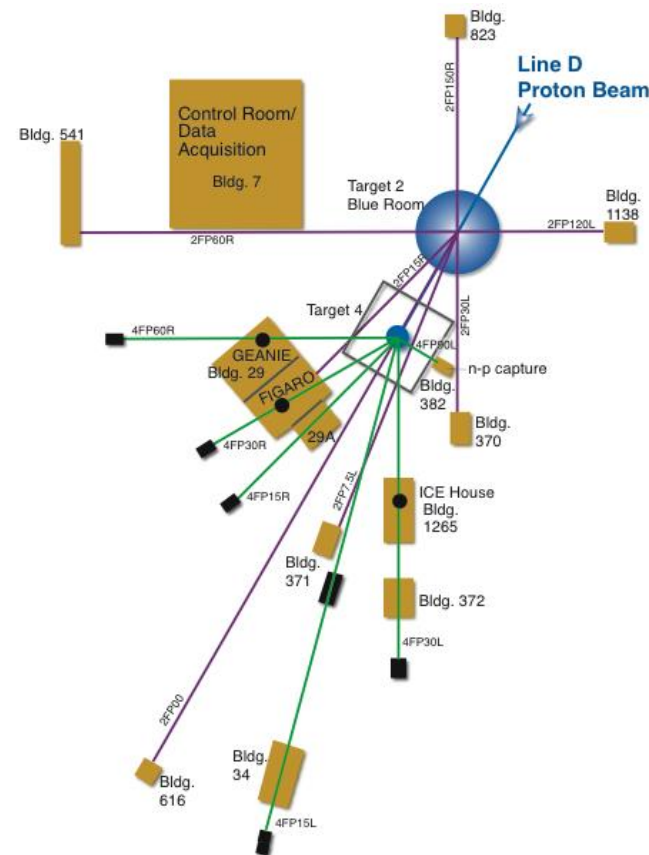
- Radioactive isotopes produced by cosmogenic particle interactions in detector materials can be one of the leading sources of backgrounds in rare event searches
- Understanding the production rate of these isotopes is extremely important in order to evaluate the total surface residency time, transportation options, and storage requirements for low background detector components
- Small production rates and low energy decays of interest for next generation dark matter experiments (**tritium**, ^{39}Ar) make it difficult to measure sea-level activation without building a full-scale experiment

Measurement Technique

Use high intensity neutron beam to increase production rate compared to sea-level cosmic rays

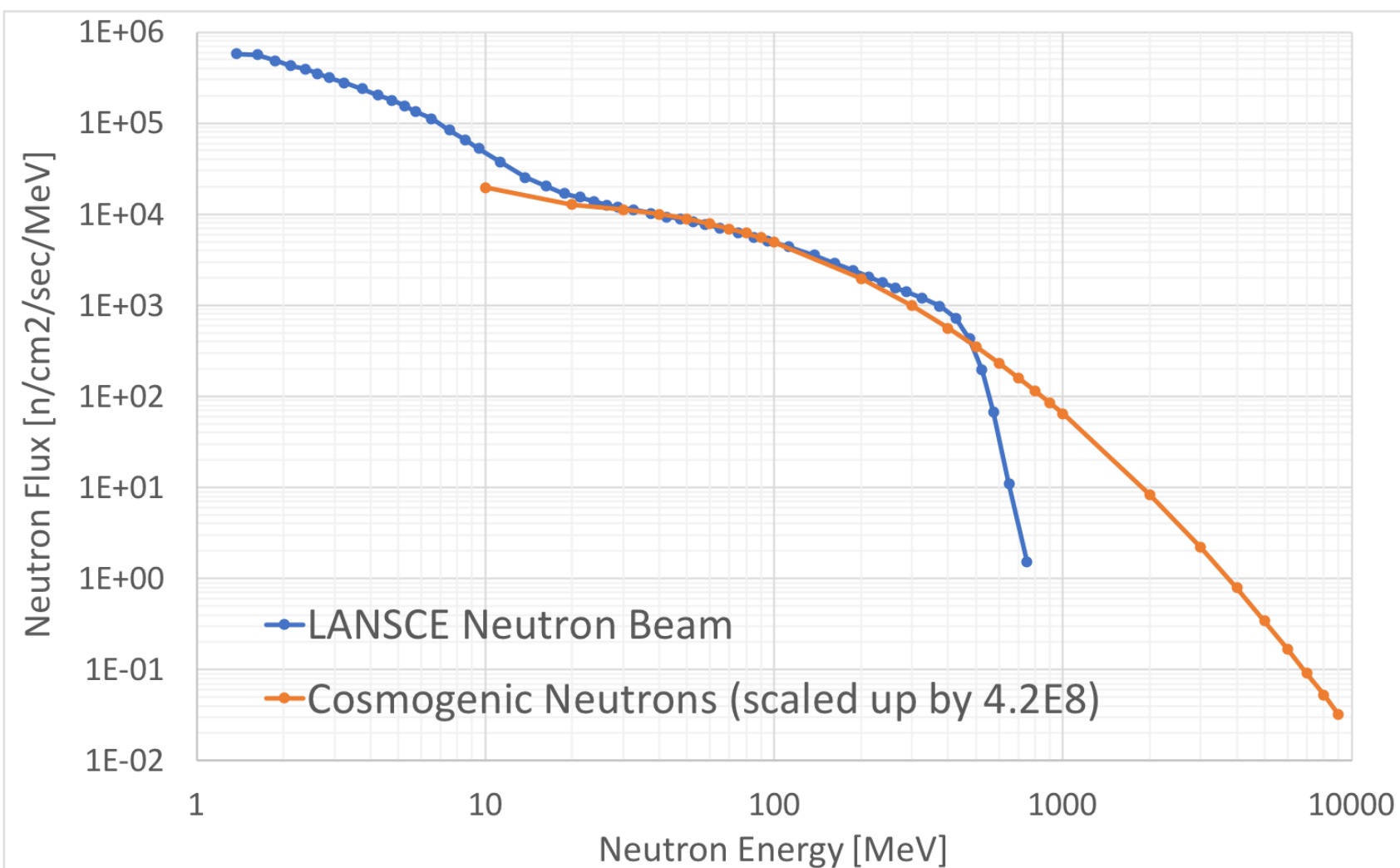
Irradiate active detector materials and use self-counting techniques to measure low-energy beta decays and x-rays

Extrapolate from measured activity to expected sea-level cosmogenic production rate



LANSCE ICE-HOUSE Neutron Beam

Los Alamos Neutron Science Center (LANSCE) Weapons Neutron Research (WNR) Facility
has a neutron beam (4FP30R ICE-HOUSE II)
that is very similar in spectral shape to the cosmic ray spectrum



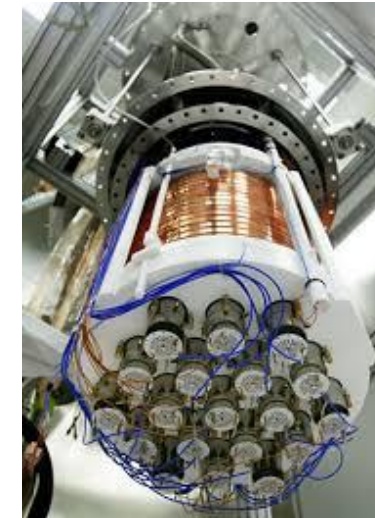
The good agreement in spectral shape between 10–500 MeV allows for low-uncertainty extrapolations to cosmic ray activation rates

The neutron flux is roughly **4.2×10^8 times larger** than the sea-level cosmic neutron flux

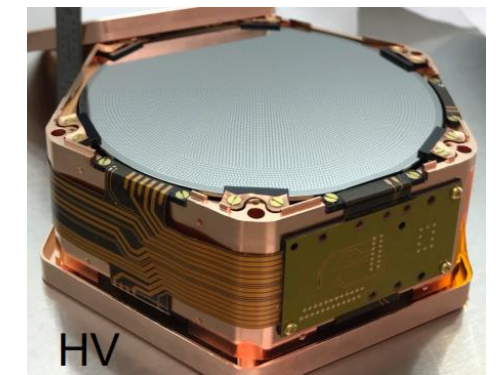
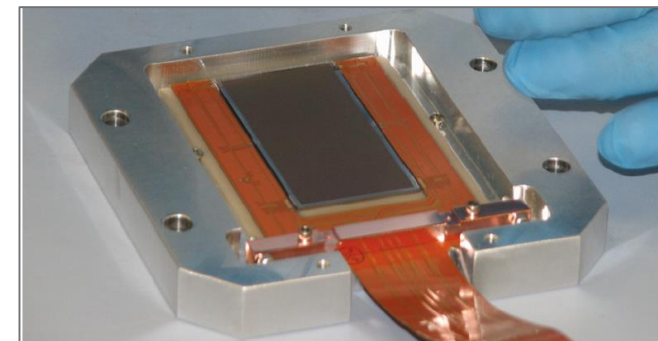
1 second on beam
~ 13 years on the surface

Activation Measurements for Dark Matter Experiments

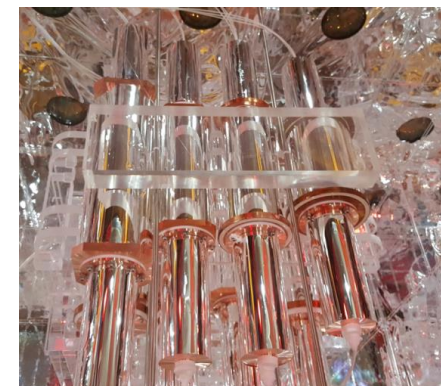
^{39}Ar , ^{37}Ar in Argon



^3H (Tritium), ^7Be , ^{22}Na in Silicon

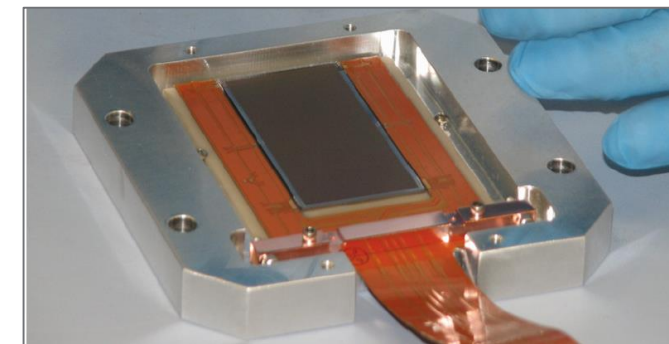
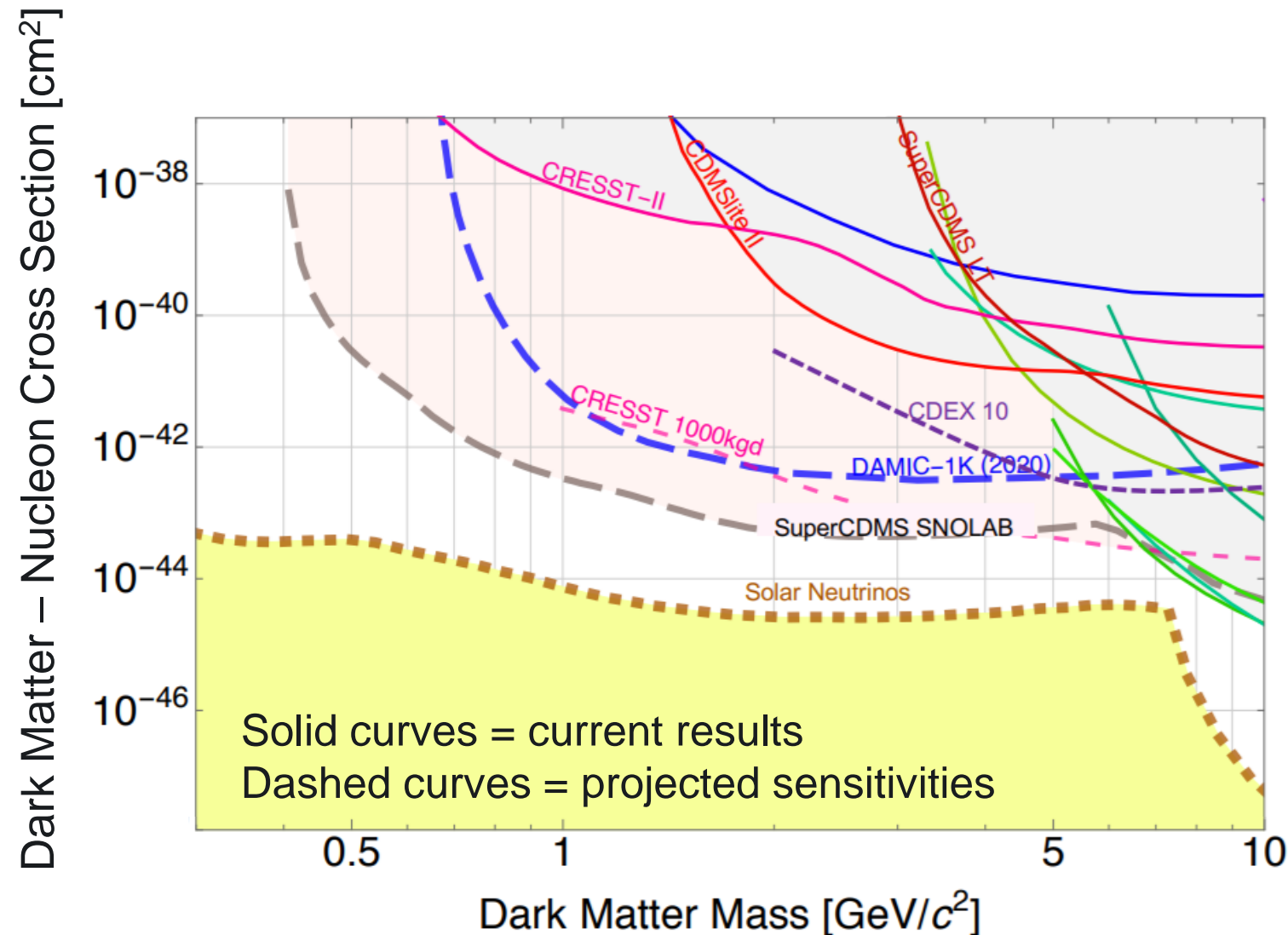


^3H (Tritium), ^{109}Cd in Sodium Iodide

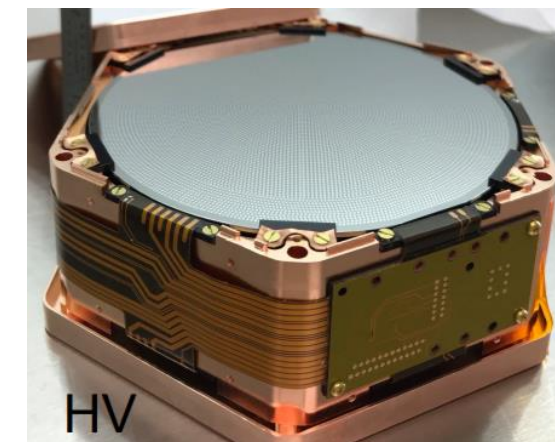


Silicon-Based Dark Matter Detectors

Silicon detectors are poised to make a huge leap in sensitivity to low mass dark matter



DAMIC CCDs



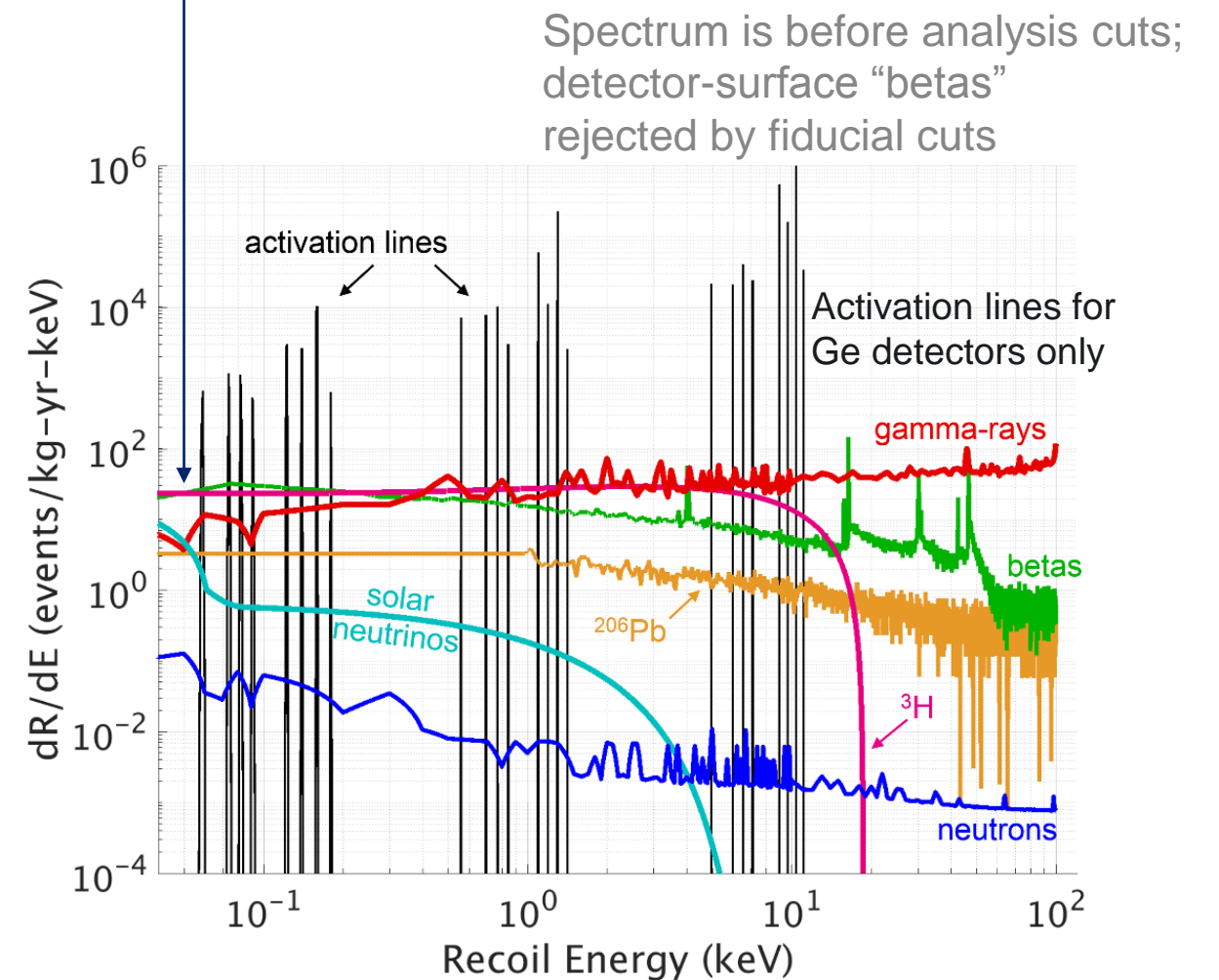
SuperCDMS (phonons)

*Talk on May 23
15:50-16:10 !*

Tritium Background in Silicon

- ▶ Tritium is spallation product from cosmic-ray neutrons.
- ▶ Produced in detectors during above-ground detector fabrication prior to installation underground.
- ▶ New SuperCDMS “High Voltage” detectors and DAMIC CCDs do not reject electron-recoil backgrounds for nuclear-recoil searches.
- ▶ Possible dark matter signals also in electron-recoil channel.

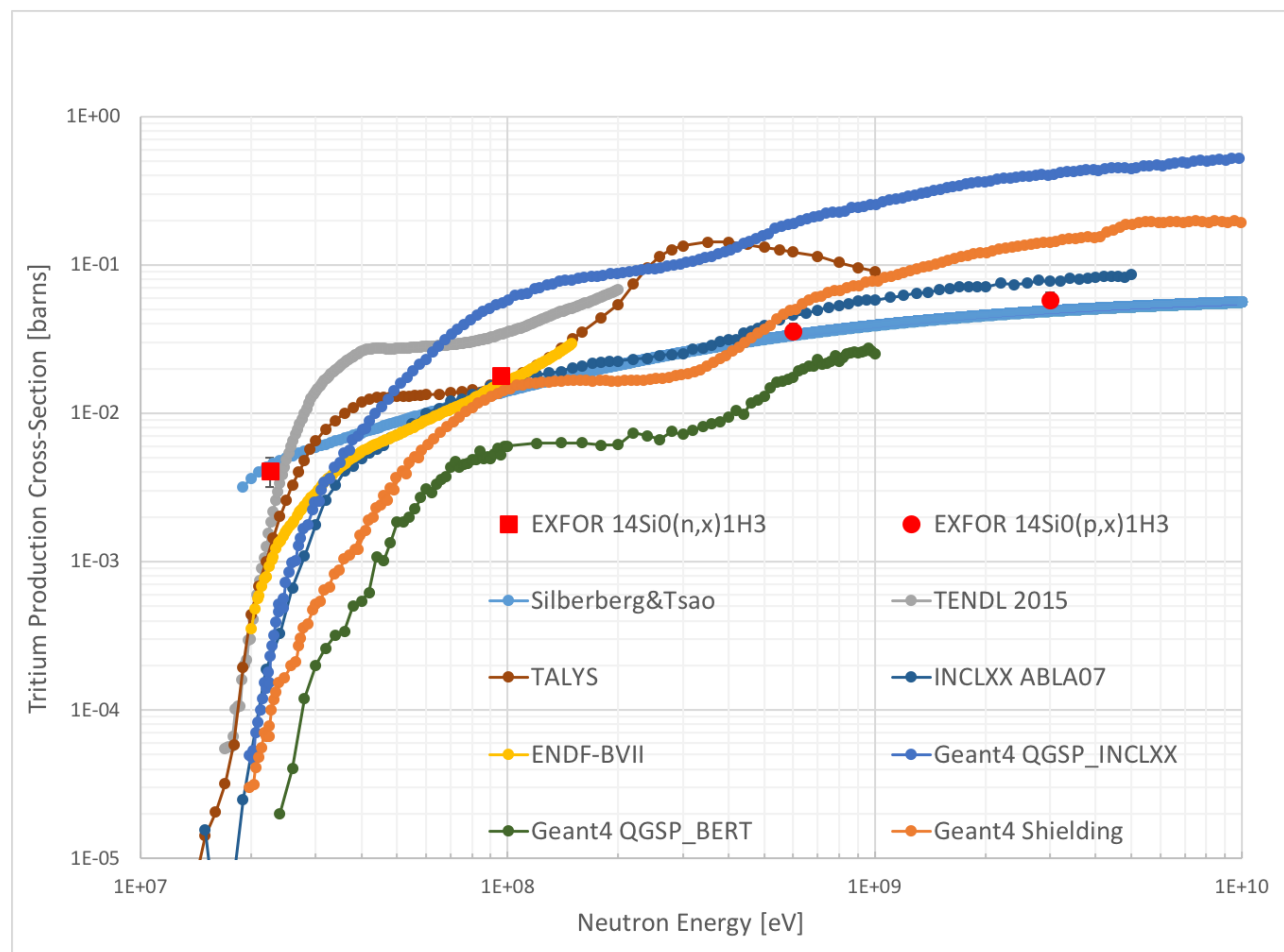
Tritium betas are dominant source of background in low-energy signal region!



Tritium beta decay is a very important background consideration.

^{22}Na and ^7Be are also relevant

Tritium Production Cross-Sections



Very limited experimental cross-section measurements for tritium production

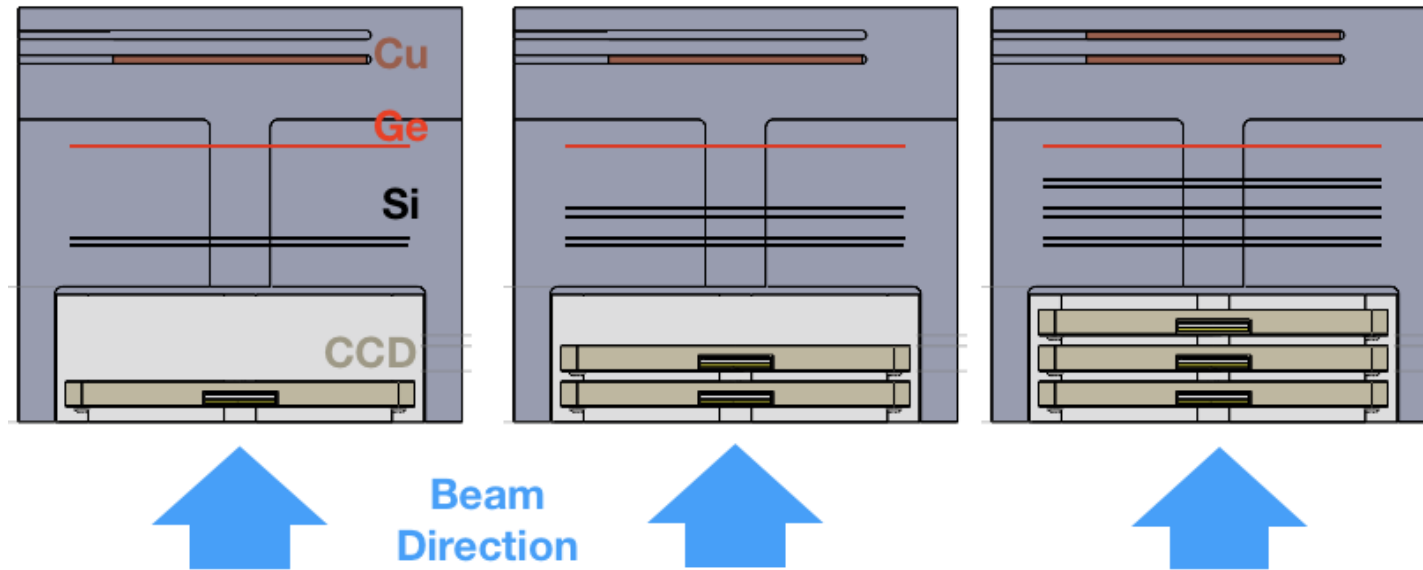
Estimates from nuclear databases and empirical calculations show significant spread
~8x variation in predicted tritium production rate

Can we directly measure the production rate through detection of low energy ($Q = 18.6$ keV) tritium beta decays?

Experimental Plan:

Irradiate silicon CCDs on LANSCE neutron beam and then self-count tritium activity in CCD bulk

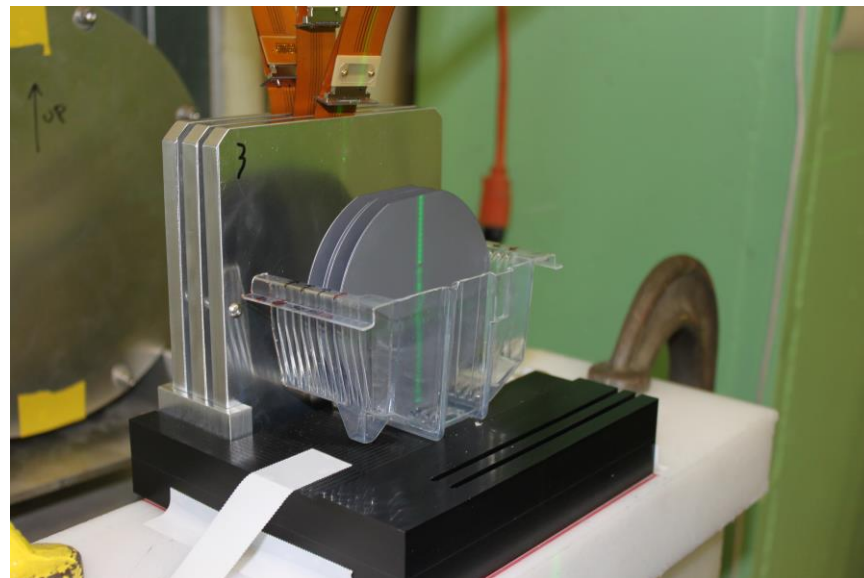
CCD Beam Irradiation



CCD and readout can undergo radiation damage in beam affecting dark current and charge transfer

Based on previous tests with SNAP CCDs* we aimed to keep maximum dose $< 2 \times 10^8$ MeV/g

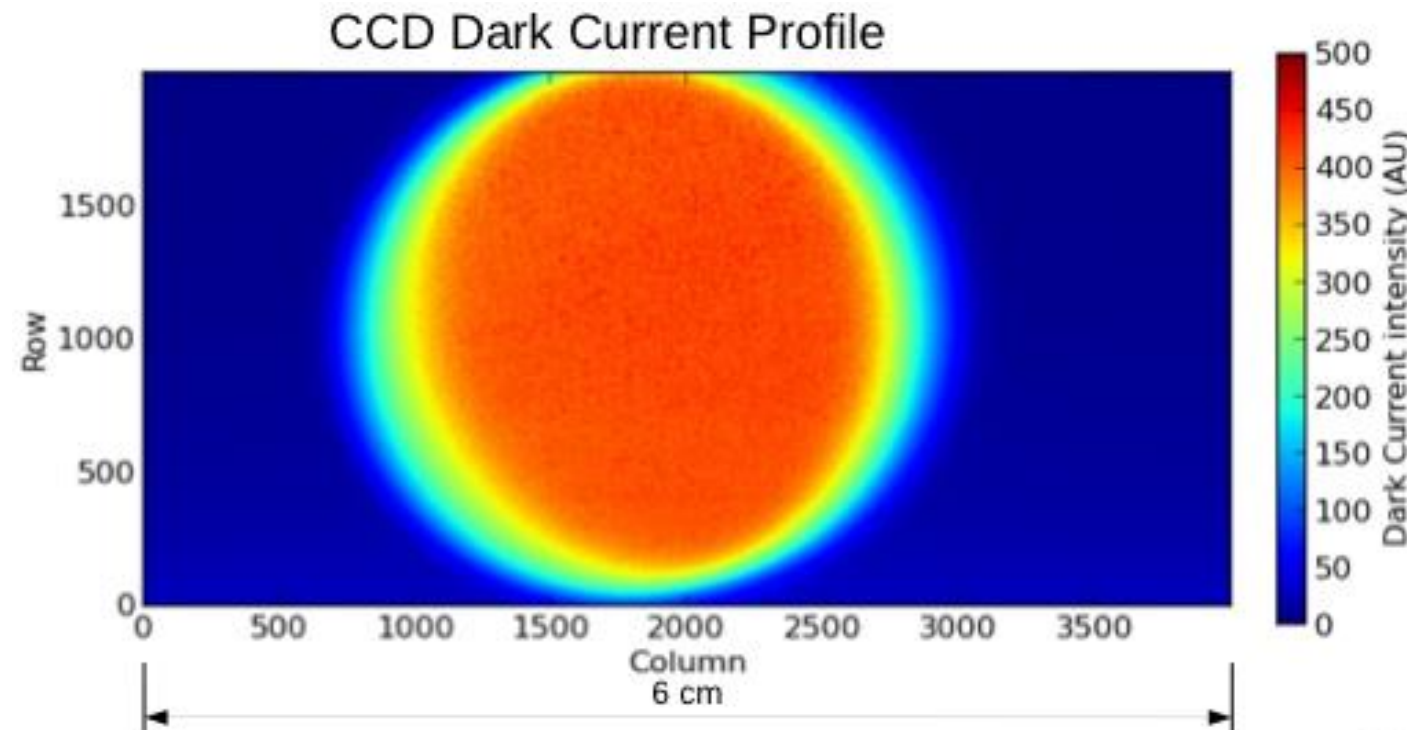
1" beam profile was chosen to minimize irradiation of registers at CCD edges



	Number of neutrons	Beam Time
CCD #1	6.16E+12	109.4 hrs
CCD #2	3.68E+12	62.7 hrs
CCD #3	1.34E+12	22.8 hrs

We used 3 CCDs with staggered exposures to ensure we had at least one CCD that survived

CCD Beam Irradiation



Beam spot region shows higher activity in CCD images

Dark Current matches neutron beam profile

Dark Current

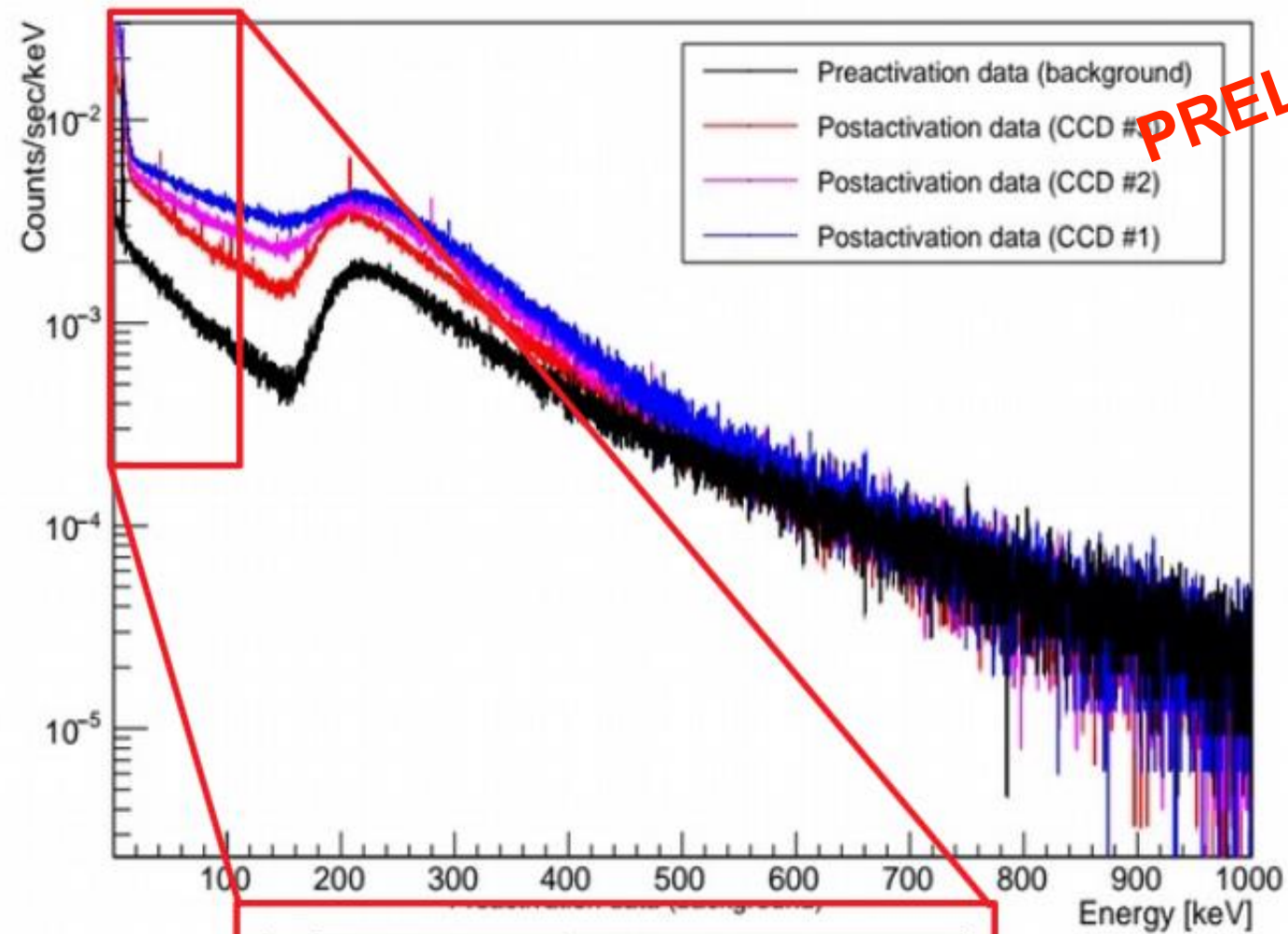
Before Activation: $< 3 \times 10^{-5}$ e-/pix/hr

After Activation: $\sim 1500-2000$ e-/pix/hr

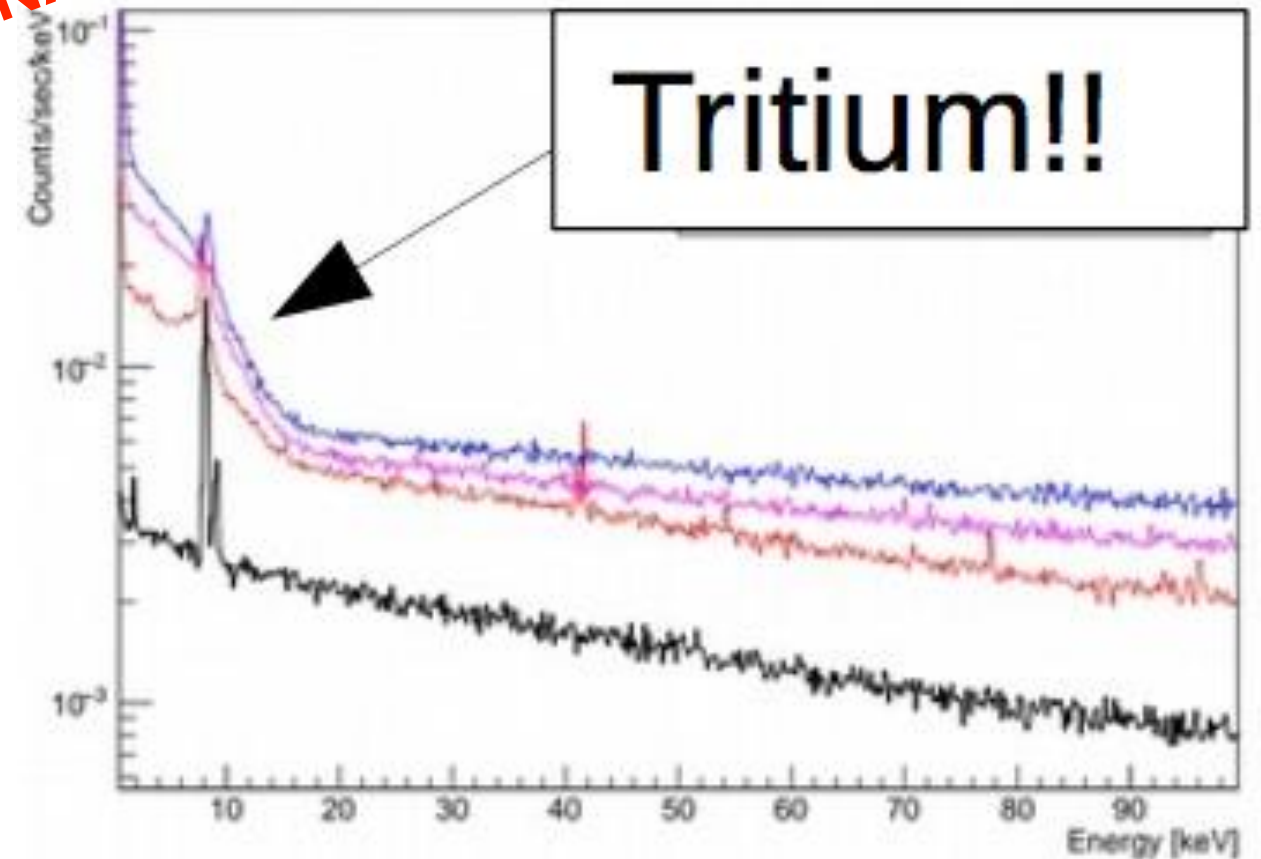


- Dark current forms a continuous "band" as CCD readout is nearly continuous (5 second exposure, 412 seconds of readout)

CCD Energy Spectra



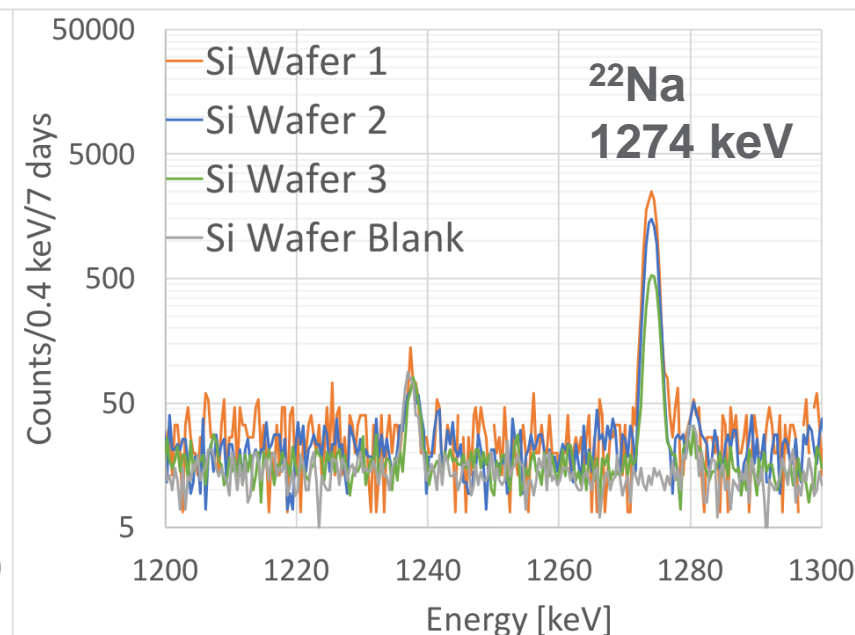
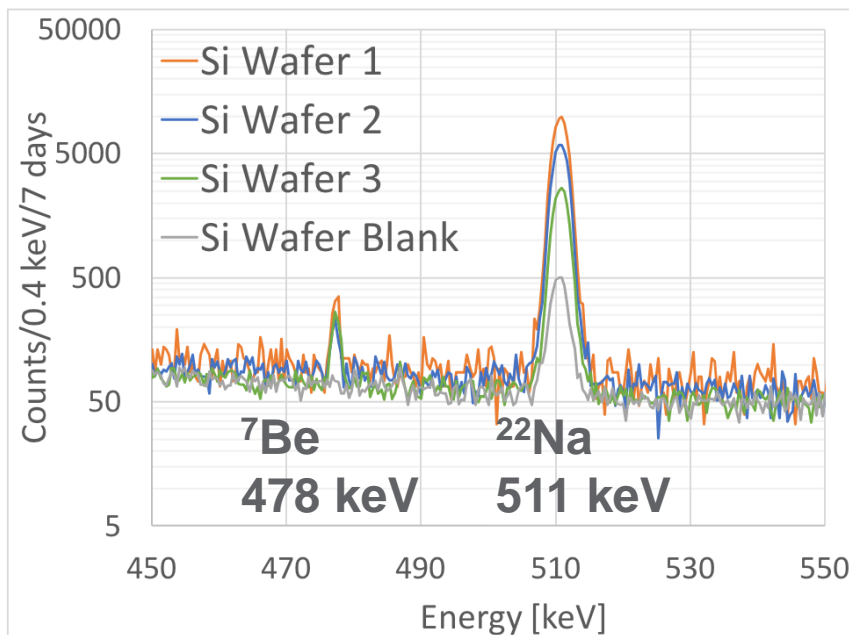
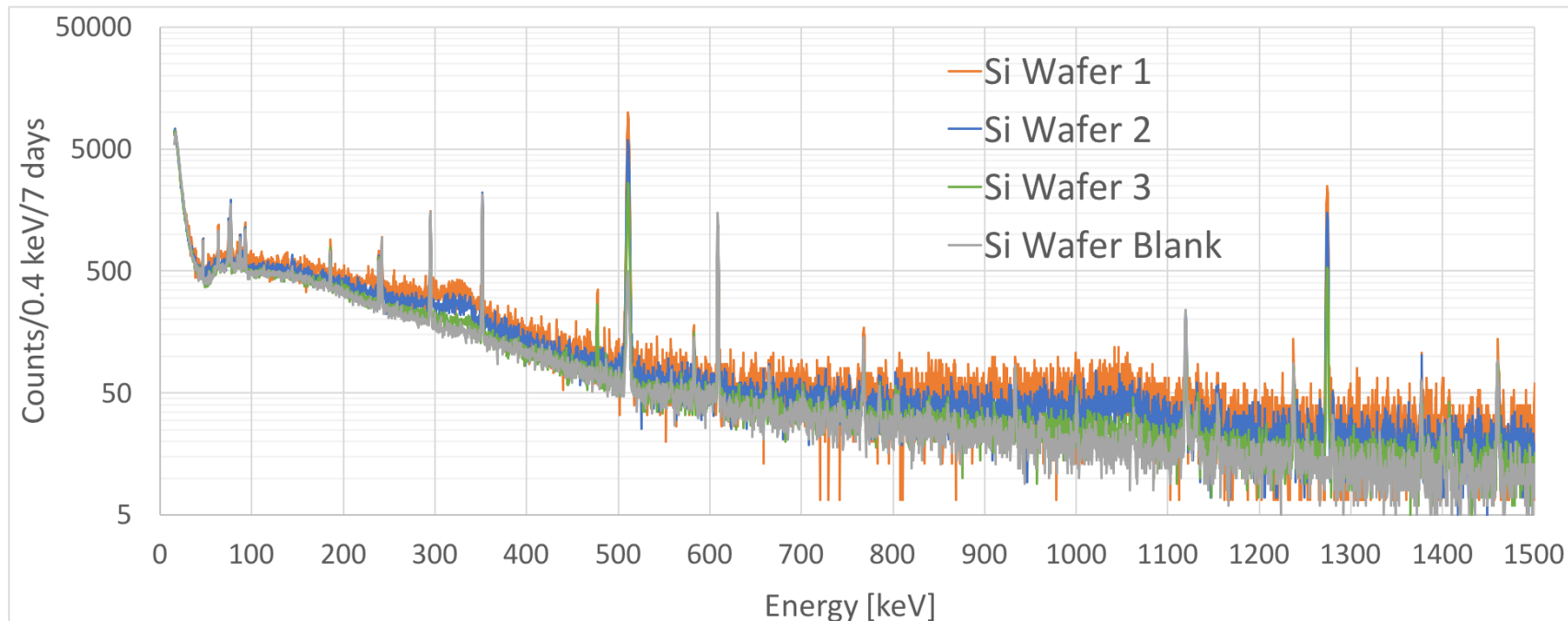
PRELIMINARY



Energy spectrum shows clear signs of 18 keV tritium beta spectrum
and 545 keV ^{22}Na positron spectrum
Detailed analysis and spectral fits to estimates rates is currently underway

Silicon Wafer Gamma Counting

Along with each CCD a pair of silicon wafers were irradiated with the same exposure in order to measure the ^{22}Na and ^7Be activation rates using low background Ge gamma counting



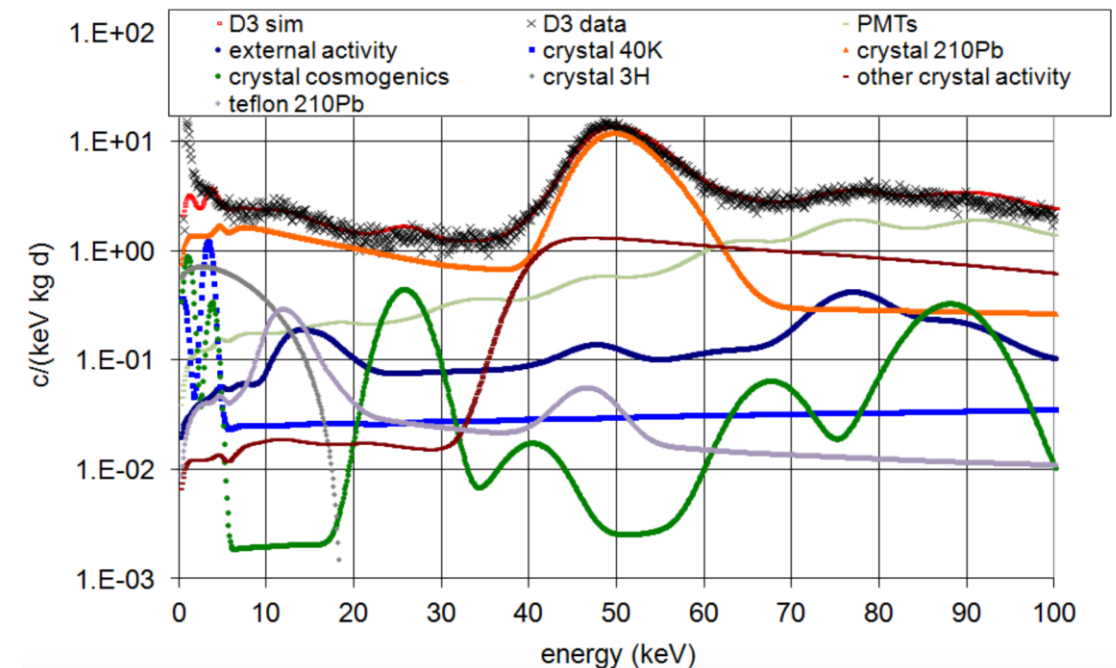
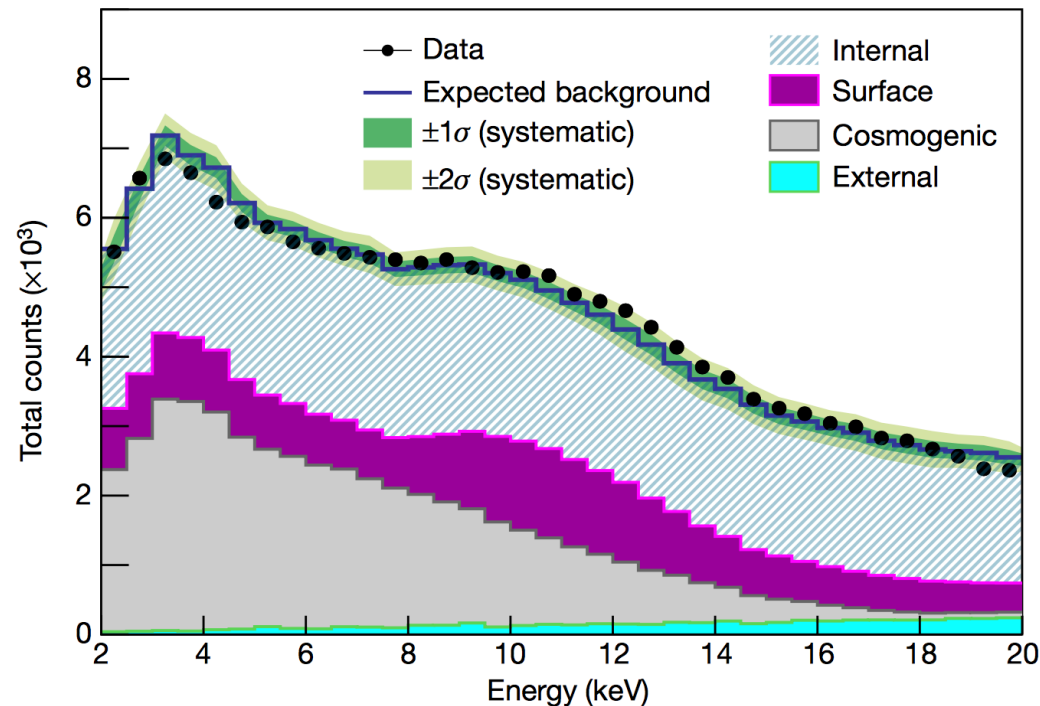
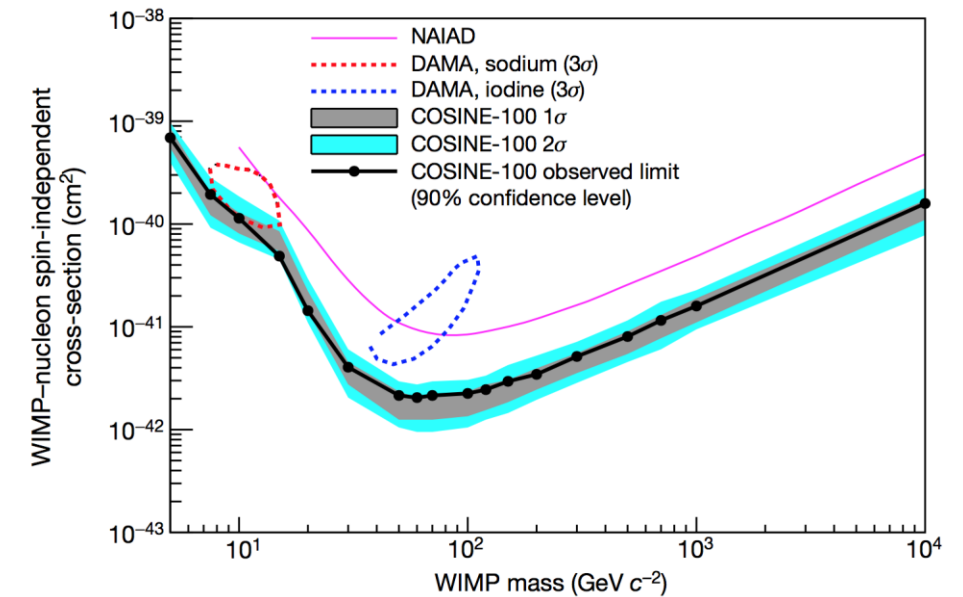
	Si Wafer 2/ Si Wafer 1	Si Wafer 3/ Si Wafer 1
Neutron Beam Flux*	0.598	0.218
^7Be from 478 keV	0.48 +/- 0.10	0.24 +/- 0.04
^{22}Na from 511 keV	0.59 +/- 0.05	0.20 +/- 0.02
^{22}Na from 1274 keV	0.61 +/- 0.04	0.21 +/- 0.01

Tritium and ^{109}Cd Production in NaI

Several NaI-based experiments are currently trying to verify the DAMA-LIBRA dark matter claim

Tritium and ^{109}Cd are the dominant cosmogenic backgrounds in the energy region of interest (2-6 keV_{ee})

We are setting up to make a measurement of NaI detectors irradiated in the LANSCE beam

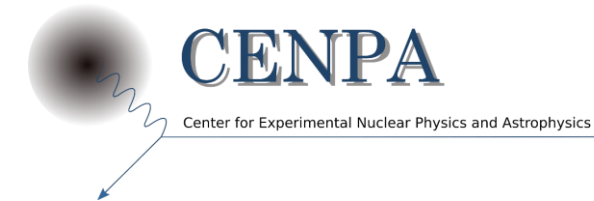


Summary

- ❖ Long-lived cosmogenic isotopes are a significant background for several dark matter experiments
- ❖ Activation rates of critical isotopes are not well known due to low production rates and low energy of decays
- ❖ We have used a method of irradiating active detector material in a high energy neutron beam and self-counting the activation products to estimate the production rates
- ❖ We are in the process of making the first measurement of tritium production in silicon
- ❖ We are getting ready to try and make the first measurement of tritium production in NaI



Collaboration (Tritium Background in Silicon)



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A. Myers (PNNL), J. O'Donnell (LANL), L. Rodrigues (LANL)



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ENERGY

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Science

Thank you

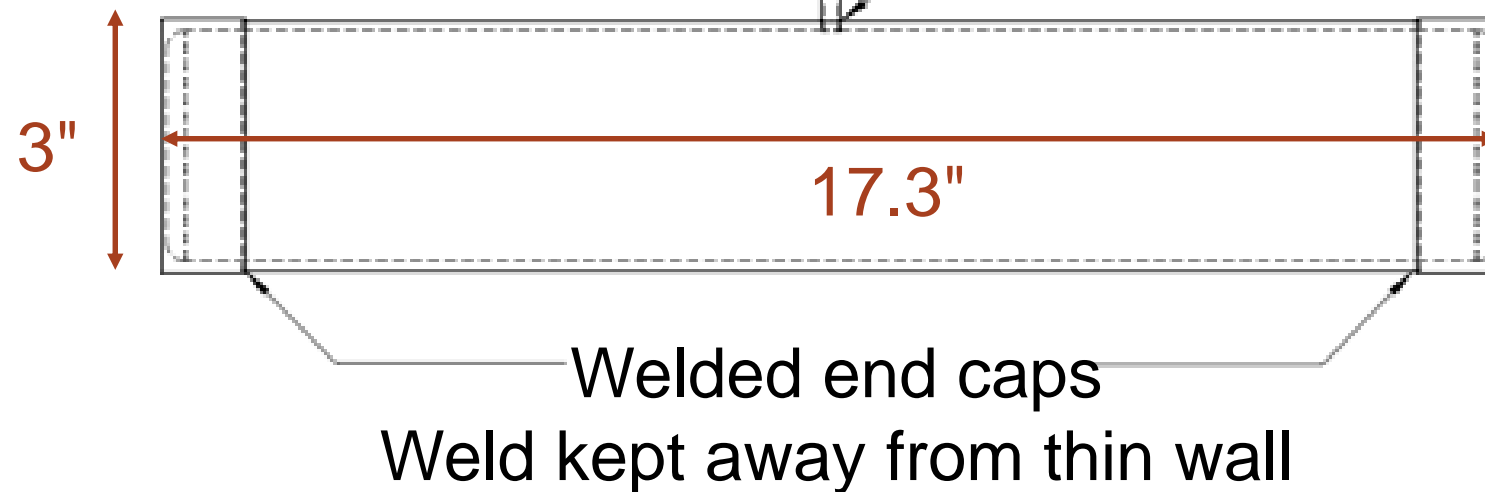
Irradiation Vessel

Double valved for safety

VCR Fitting for leak-tightness

Aluminum to SS transition

Welded pipe



End caps are
thinned down
to 1.5 mm
thick
in the central
2.5" diameter

Aluminium attenuation for 10 MeV neutrons ~ 1% per mm

Storage underground - how deep?

C. Johnson et al. / Journal of Environmental Radioactivity 140 (2015) 123–129

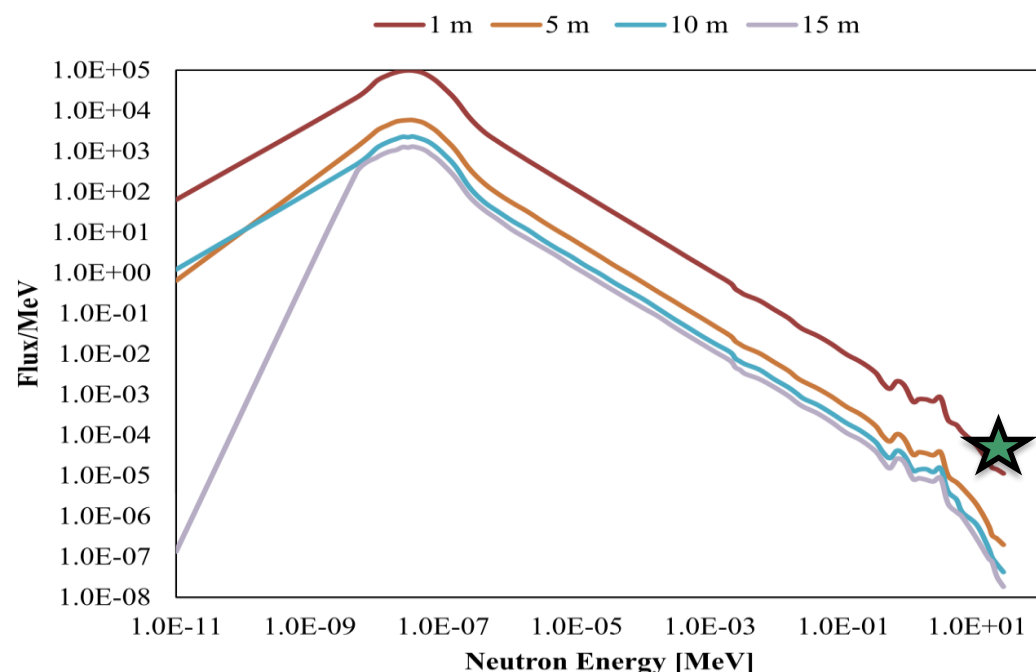


Fig. 8. Neutron flux in carbonate rock at various depths from 1 to 15 m as calculated by MCNP6 model.

Just 5 m depth reduces the neutron flux by about 2 orders of magnitude

Deep underground, the neutron flux "attenuation length" is about 860 m.w.e

PHYSICAL REVIEW D **73**, 053004 (2006)

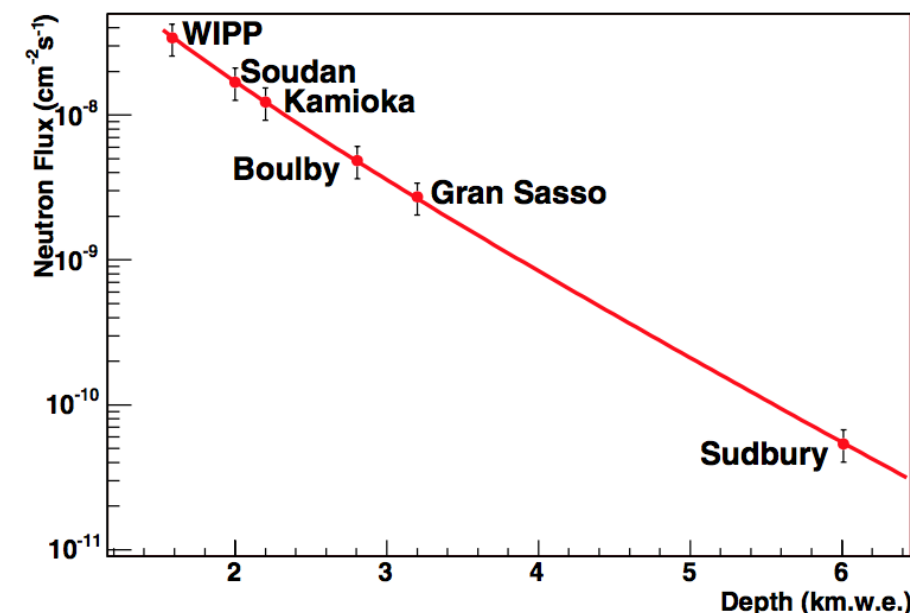


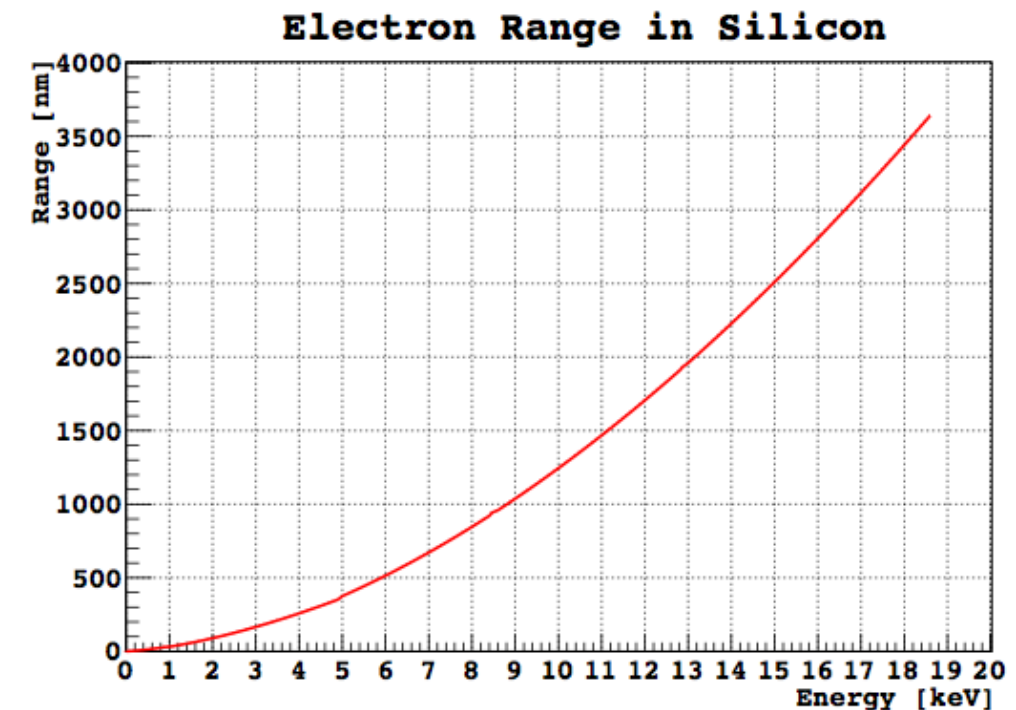
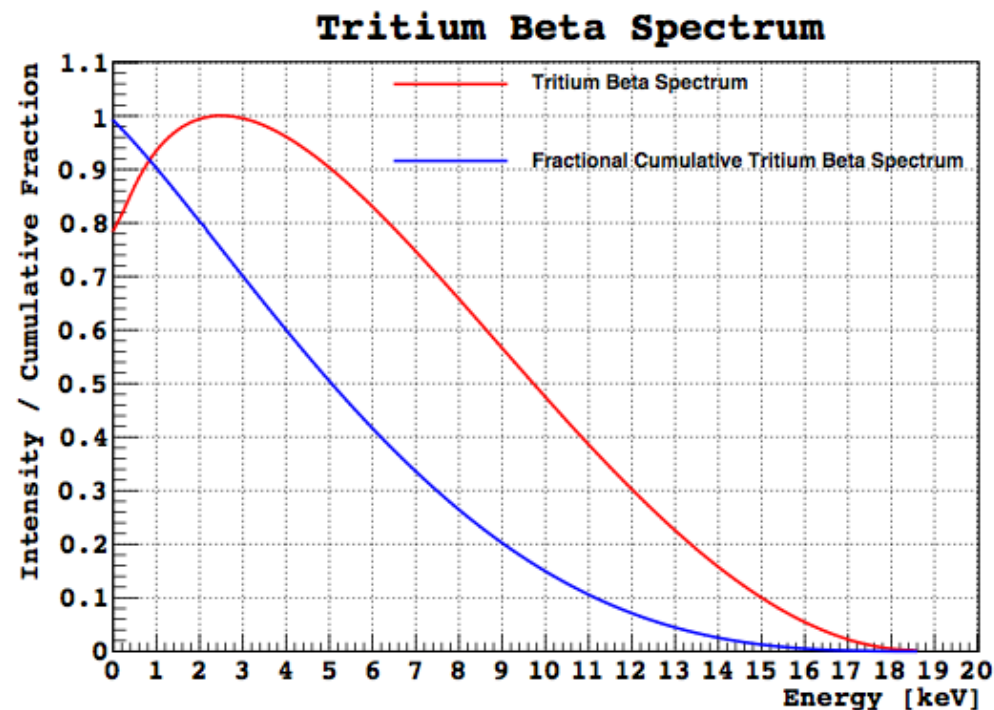
FIG. 14 (color online). The total muon-induced neutron flux deduced for the various underground sites displayed. Uncertainties on each point reflect those added in quadrature from uncertainties in knowledge of the absolute muon fluxes and neutron production rates based upon our simulations constrained by the available experimental data.

$$\phi_n = P_0 \left(\frac{P_1}{h_0} \right) e^{-h_0/P_1}, \quad (13)$$

where h_0 is the equivalent vertical depth (in km.w.e.) relative to a flat overburden. The fit parameters are $P_0 = (4.0 \pm 1.1) \times 10^{-7} \text{ cm}^{-2} \text{ s}^{-1}$ and $P_1 = 0.86 \pm 0.05 \text{ km.w.e.}$

Tritium Beta Decay Spectrum and Range

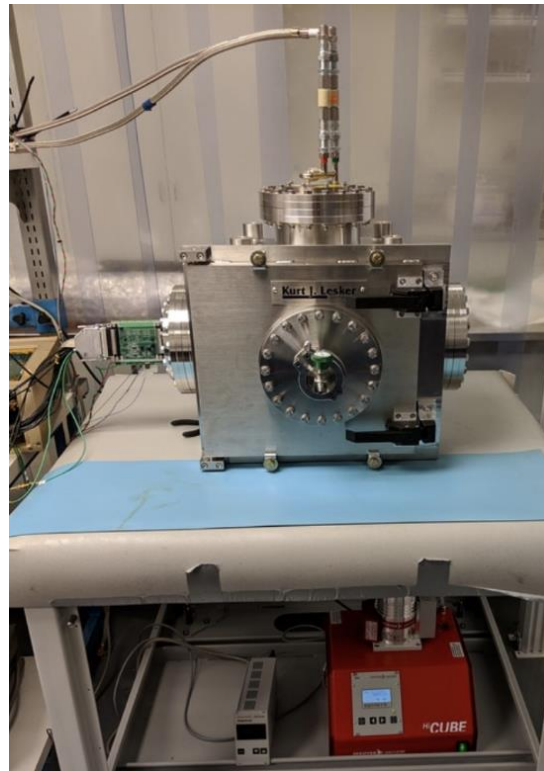
Lack of tritium cross-section measurement is probably due to the difficulty in measuring tritium, a pure low-energy beta decay



The **low Q-value** of the tritium beta decay and the **small range of electrons** in silicon, means that only a small fraction of betas make it to the surface

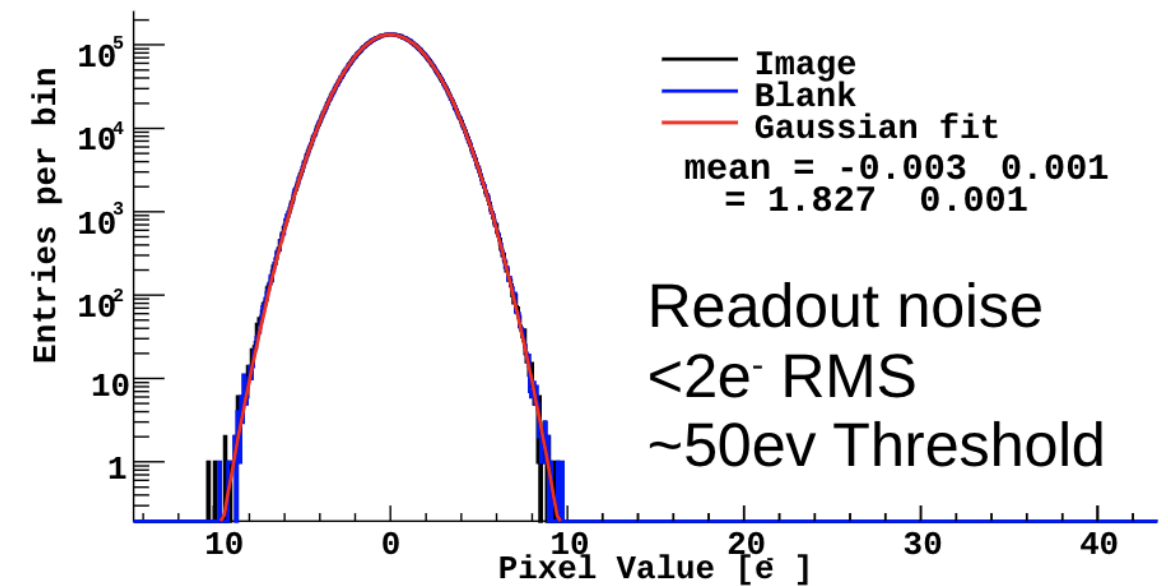
CCD Setup

CCD Test Chamber at the University of Chicago

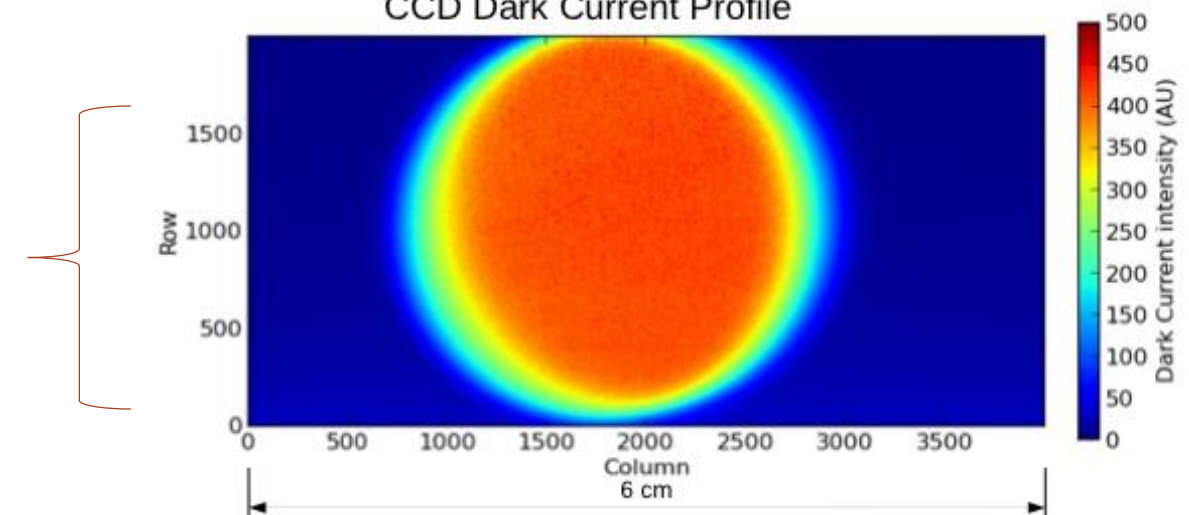


Remove analog baseline, mask hot pixels;
construct profile by taking median dark current
of several 600 s exposures and subtracting
median of 0 s exposures

Current DAMIC at SNOLAB CCDs



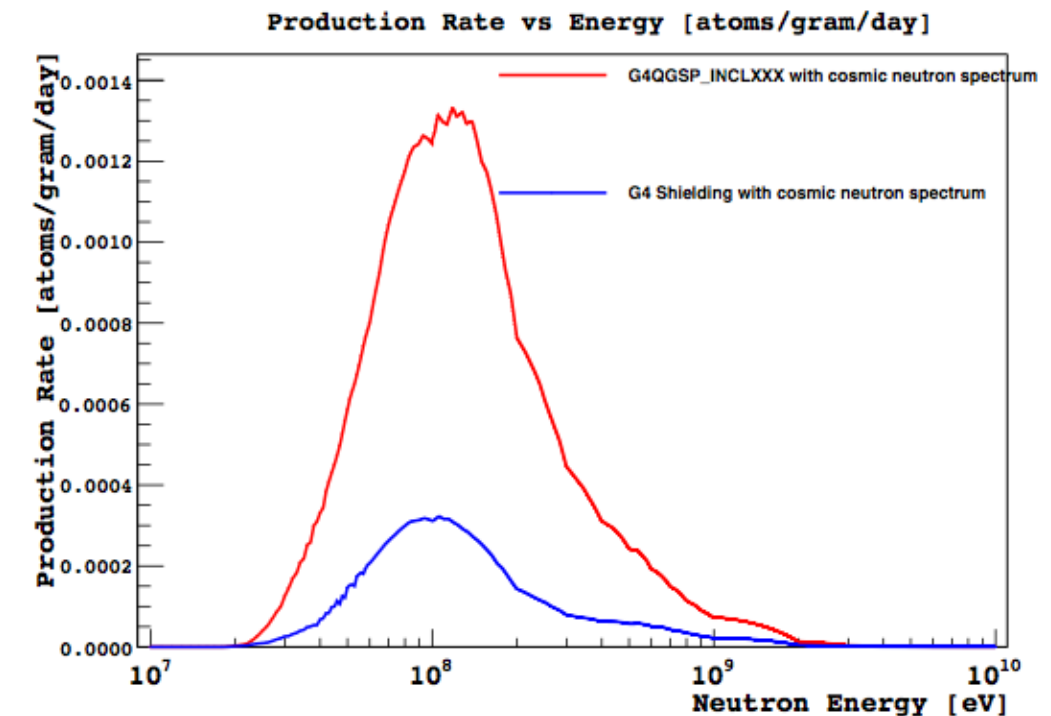
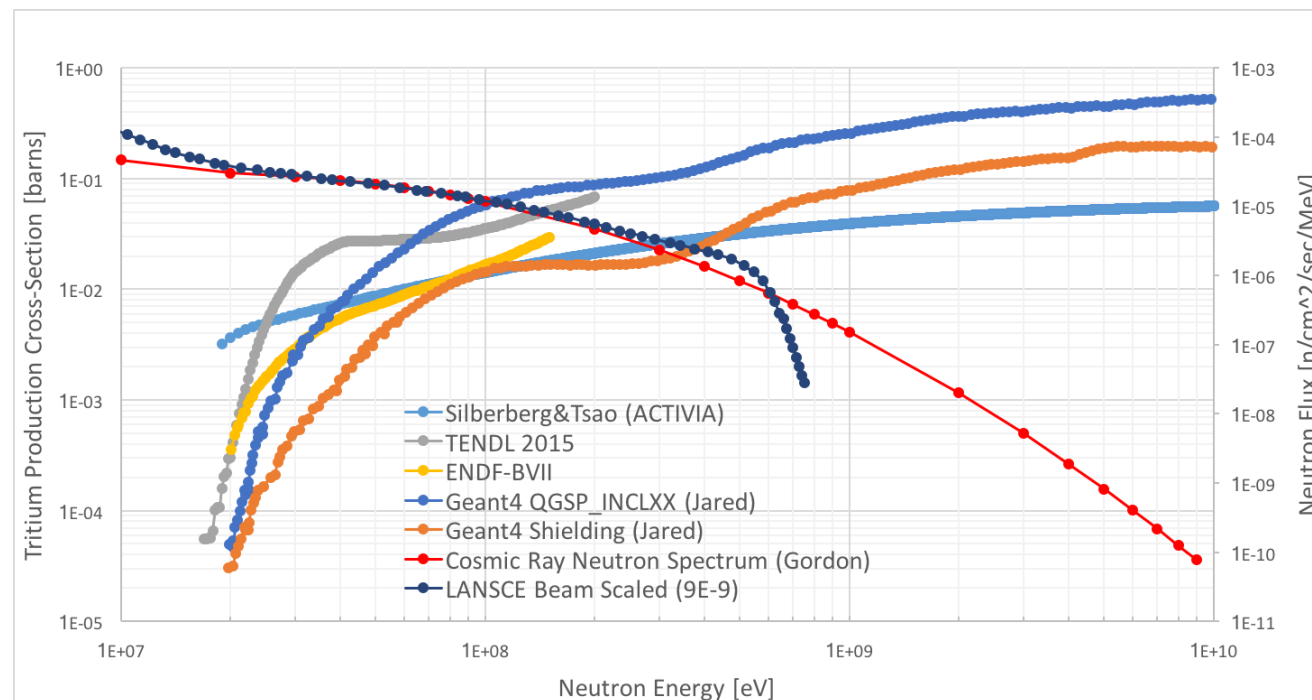
CCD Dark Current Profile



LANSCCE Neutron Beam vs Cosmic Ray Neutrons

Does the high energy cut-off matter?

Cross-sections are still rising above 600 MeV,
but the cosmic ray neutron flux is dropping



The production rate depends on the product of the neutron flux and the cross-section

Depending on the cross-section model, the difference between the production rate due to cosmic rays and the LANSCE beam varies between 0-20%

Displacement damage dose

Displacement damage dose D :

$$D = \frac{\Phi}{\rho} \frac{dE_{de}}{dx}$$

where

D : Displacement damage dose [$MeV g^{-1}$]

Φ : Particle fluence [cm^{-2}]

ρ : Target density [$g cm^{-3}$]

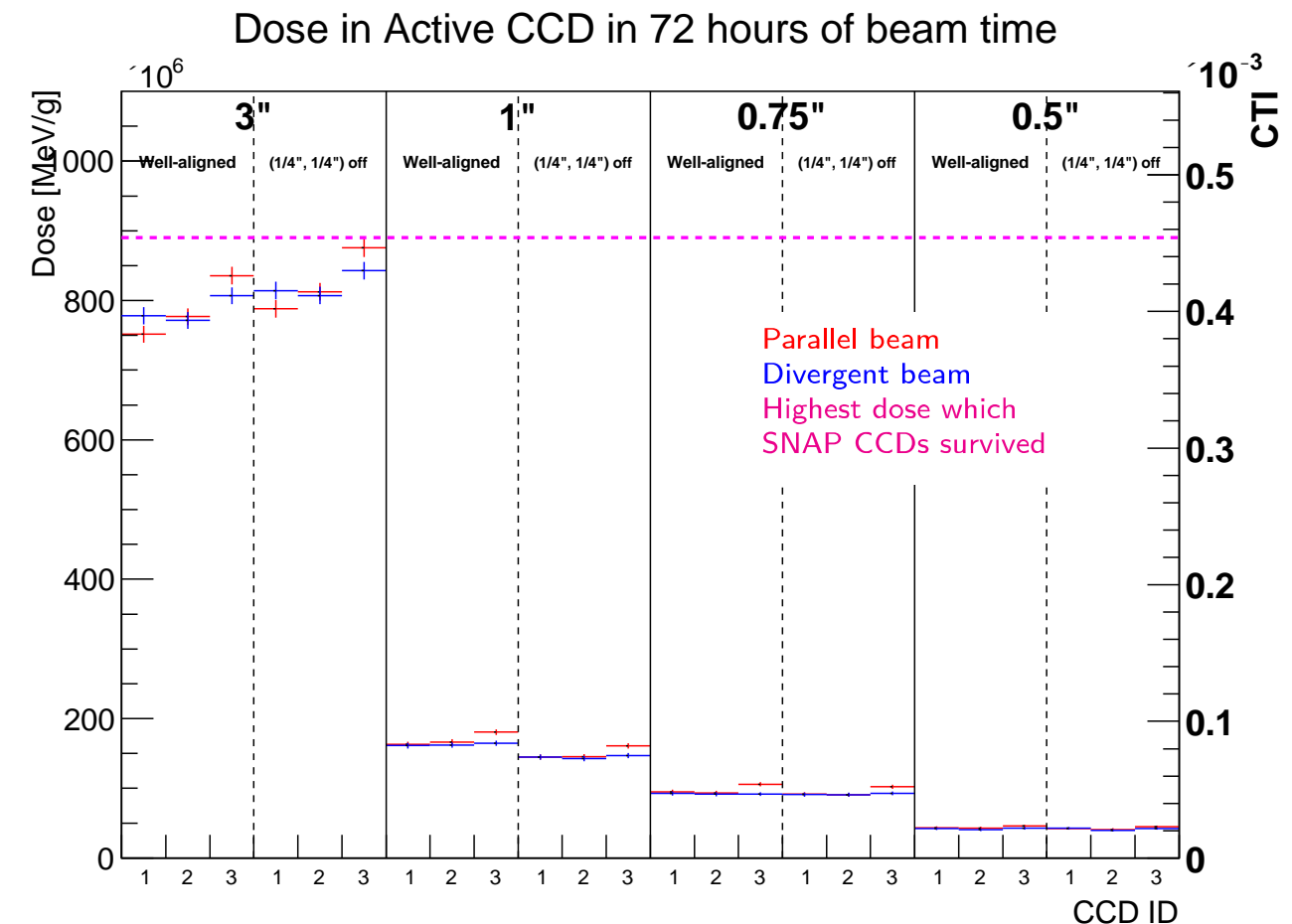
$\frac{dE_{de}}{dx}$: Displacement stopping power [$MeV cm^{-1}$]

For a thin target,

$$D = \frac{\Phi}{\rho} \frac{E_{de}}{x}$$

“NIEL factor”: $S_{NIEL} := \frac{D}{\Phi} = \frac{E_{de}}{\rho x}$

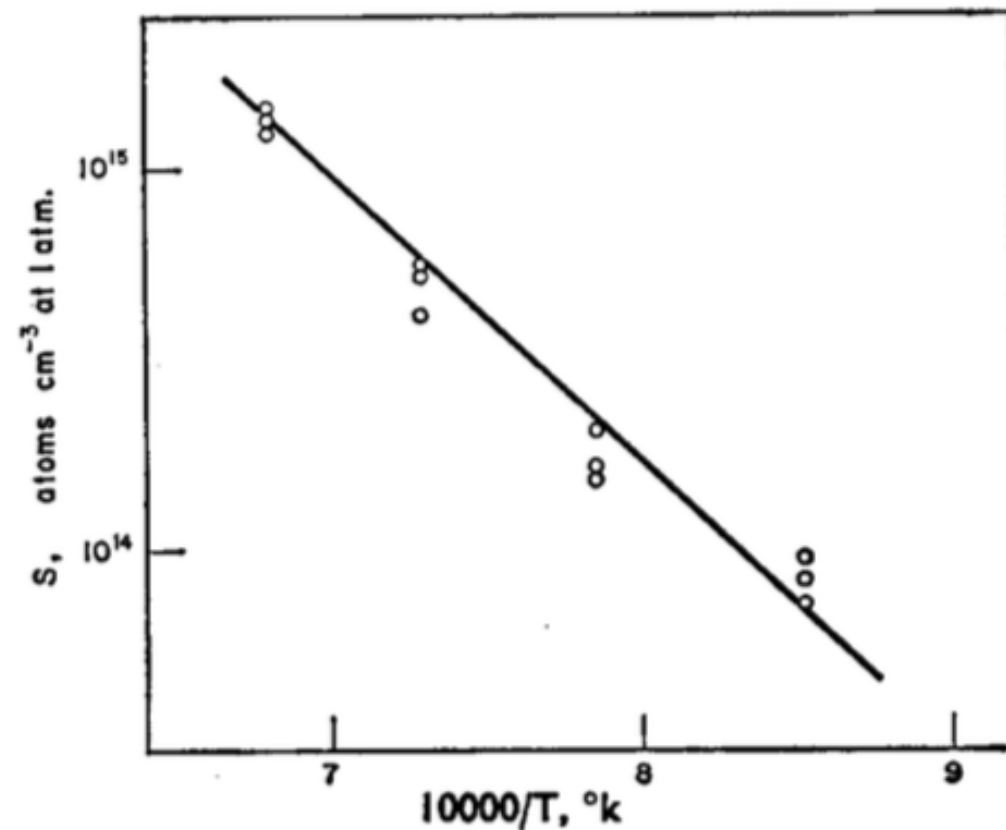
Ref: <http://www.sr-niel.org/index.php/niel-and-displacement-stopping-power>



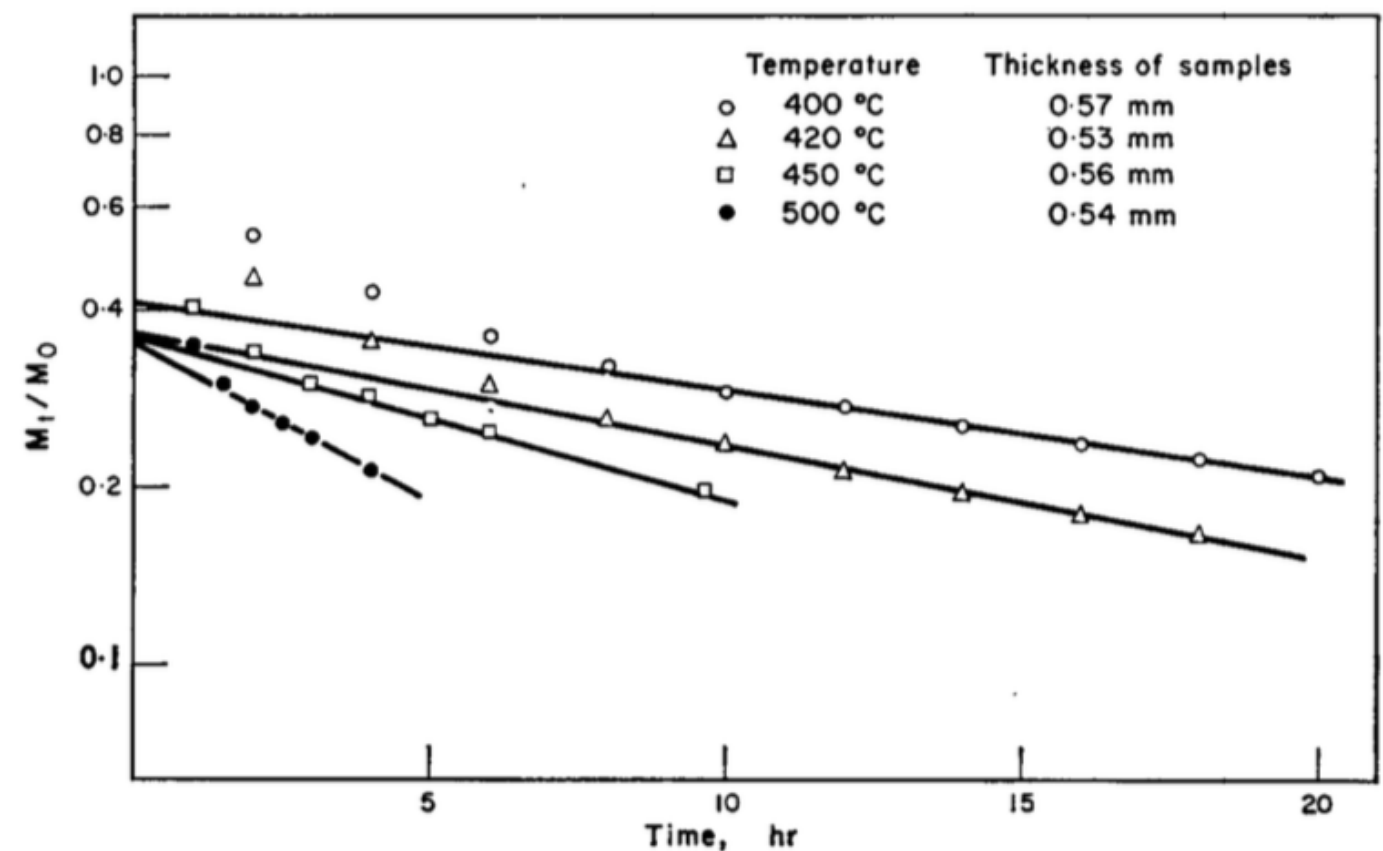
Baking ^3H out

Past studies on the solubility and diffusion of tritium in silicon could open the door for further background reduction

Solubility



Relative quantity after baking



Ichimiya, T. et al., *The International Journal of Applied Radiation and Isotopes* 19.7(1968) 573-578.