



# Benchmarking and validating cosmogenic activation models (NDIAWG project)

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**WANDA 2026**

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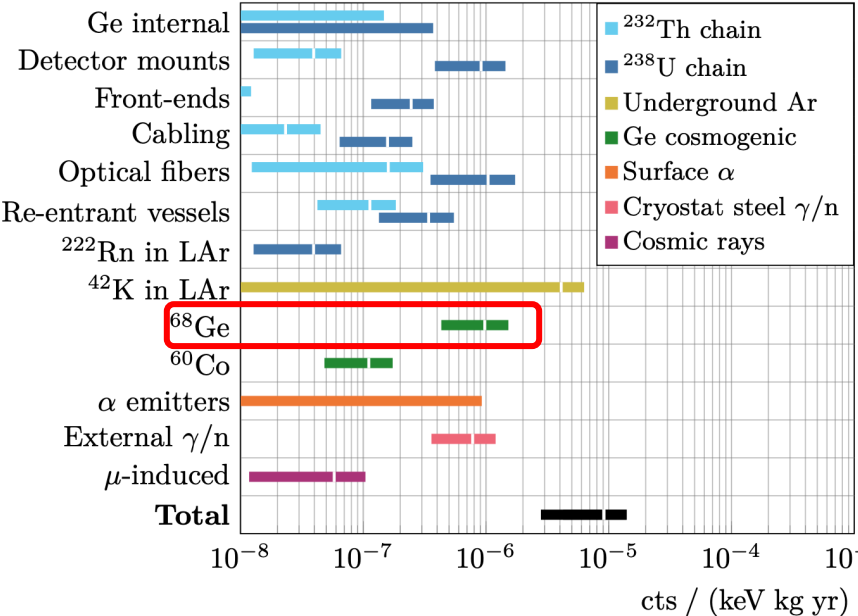
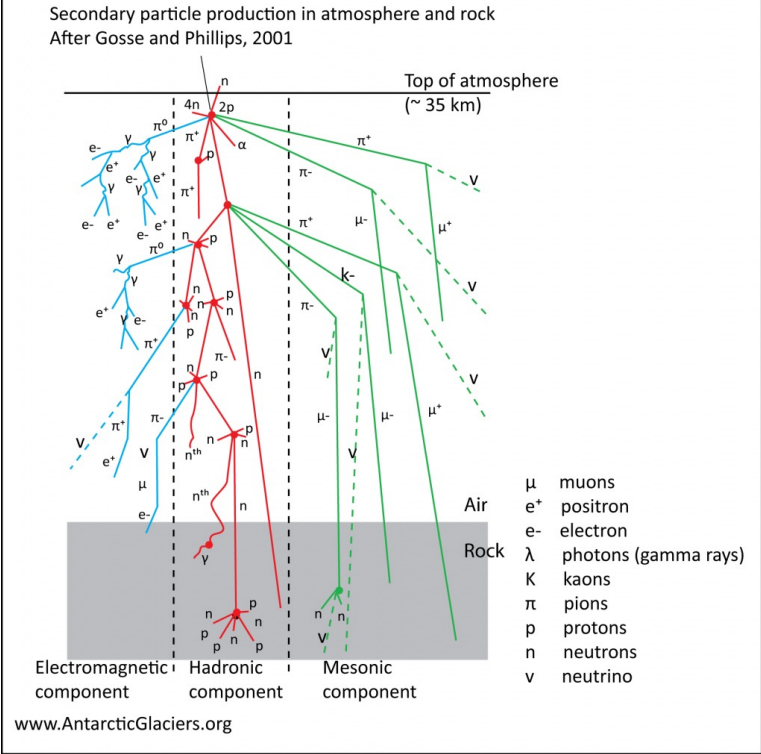
# Motivation

At or near the Earth's surface, high energy secondary particles (neutrons, protons, etc.) can interact with materials producing radioactive isotopes in otherwise stable material

Rare event searches, such as neutrinoless double beta decay have very stringent requirements on the radioactivity levels of all detector components

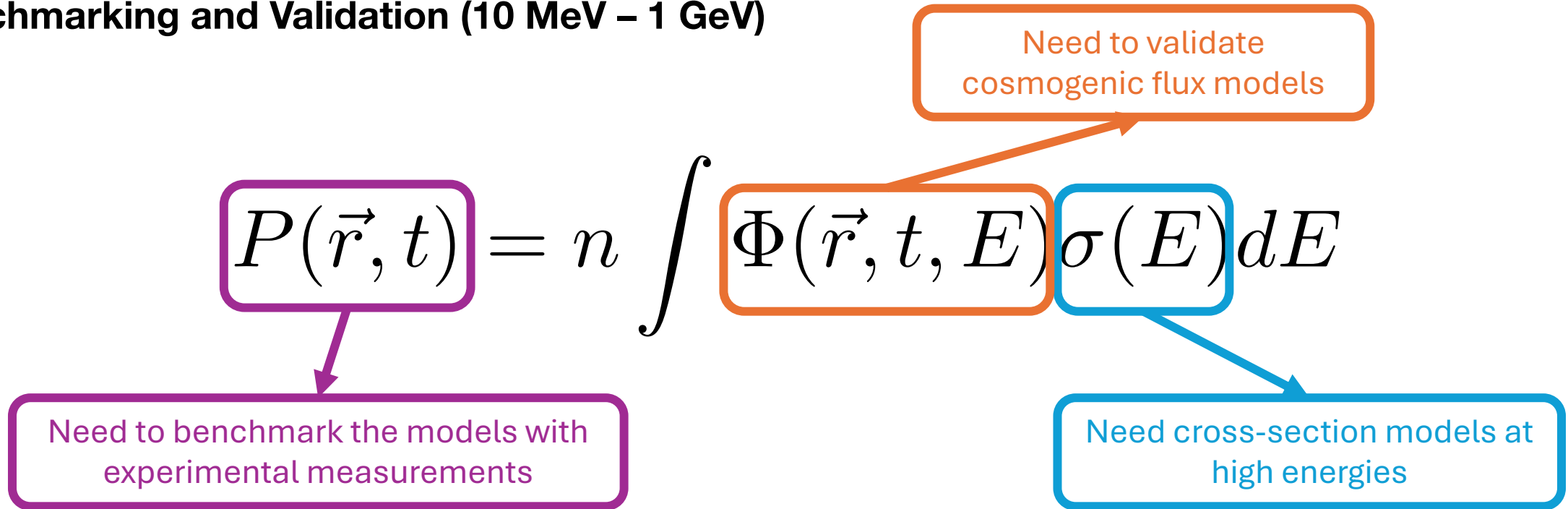
Understanding the production rate of these isotopes is extremely important in order to evaluate the total surface residency time, transportation options, and storage requirements for low background detector components

## Enable rare-event experiments to carefully plan and mitigate cosmic activation



# Production Rates

## Benchmarking and Validation (10 MeV – 1 GeV)



## GOALS

- Create a user-friendly benchmarked software package (**ACTIVATE**) to calculate the expected cosmogenic activation rate given a material and exposure history (latitude, longitude, altitude, duration)
- Develop a system of witness samples that can be transported with detector material to experimentally validate the exposure

# Witness Samples

Witness samples: Specifically chosen materials that can be measured for induced activity to determine the cosmogenic exposure of detector parts

## Advantages:

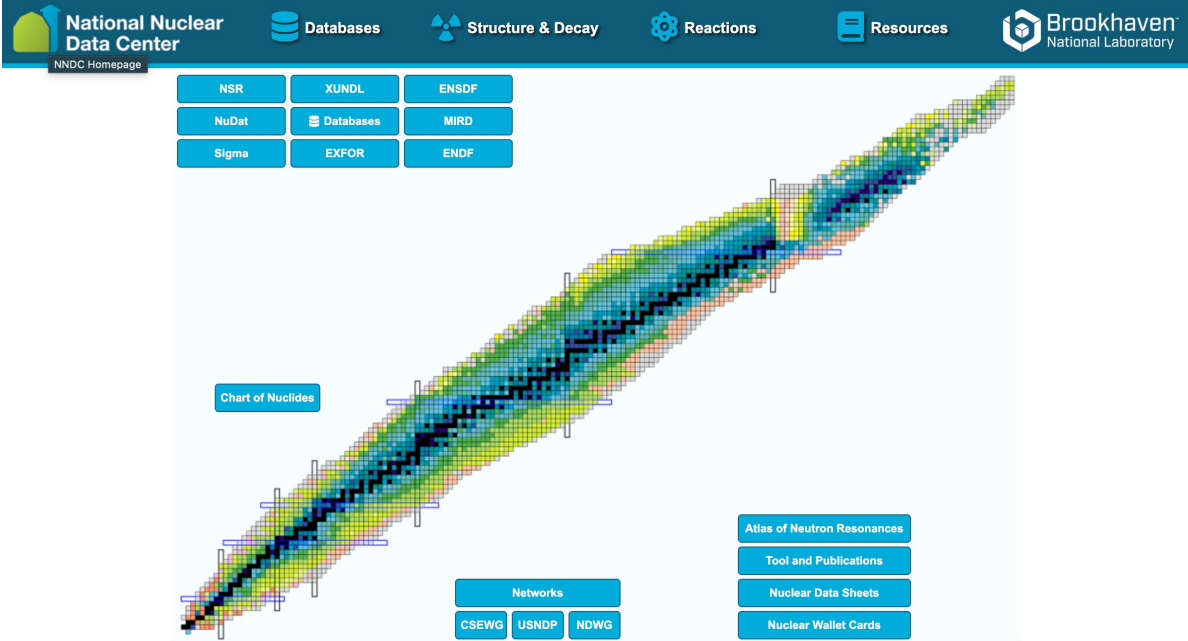
- Simple, passive system, easily deployed
- Direct measurement of the relevant particle flux (compared to muon flux counters)
- Can be tailored to the specific reactions of interest

## Disadvantages:

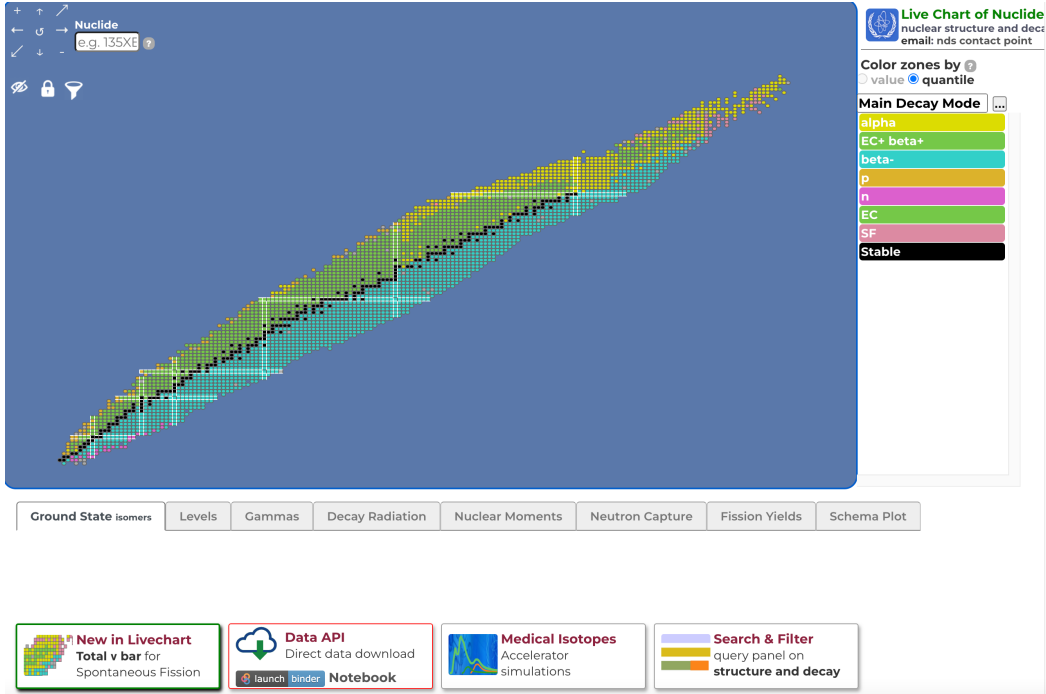
- Production rates for cosmogenic-induced reactions is low.
  - Cannot be used as a live monitor. Must be transported to a facility to be analyzed. Exposure and radioactive decay during transport must be taken into account

# Identifying Witness Materials

## BNL National Nuclear Data Center



## IAEA Nuclear Data Services



Use existing isotope databases to collect full set of possible isotope for witness materials  
Downloaded all relevant isotope data and saved in dataframe for subsequent work  
~ 1600 isotopes  
~ 190,000 decay schemes

# Identifying Witness Materials

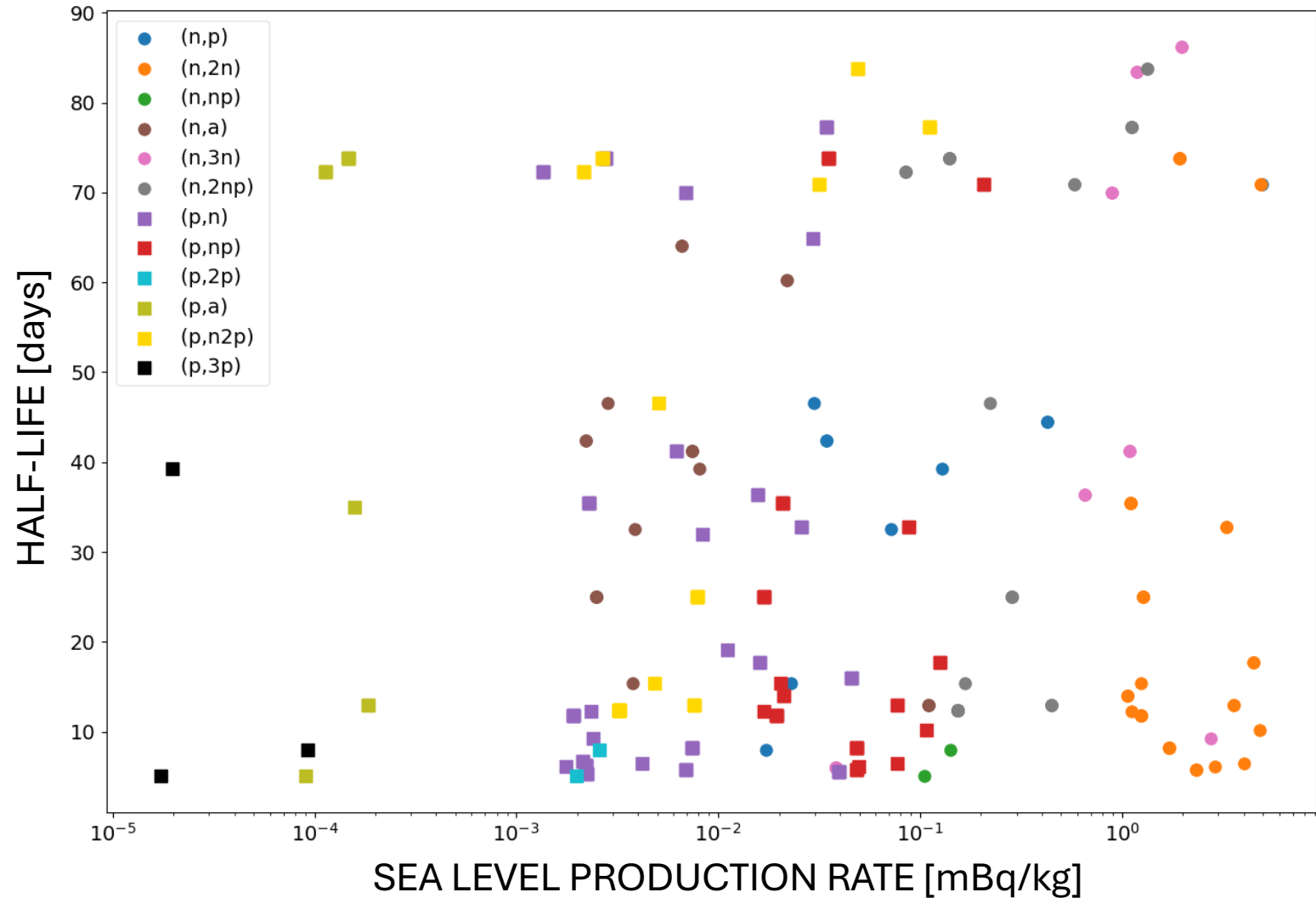
Select radioisotopes with suitable half-lives

Select isotopes with gamma rays above a threshold energy and intensity

For each reaction select target isotopes above a threshold natural abundance

Extract reaction cross-sections from TENDL

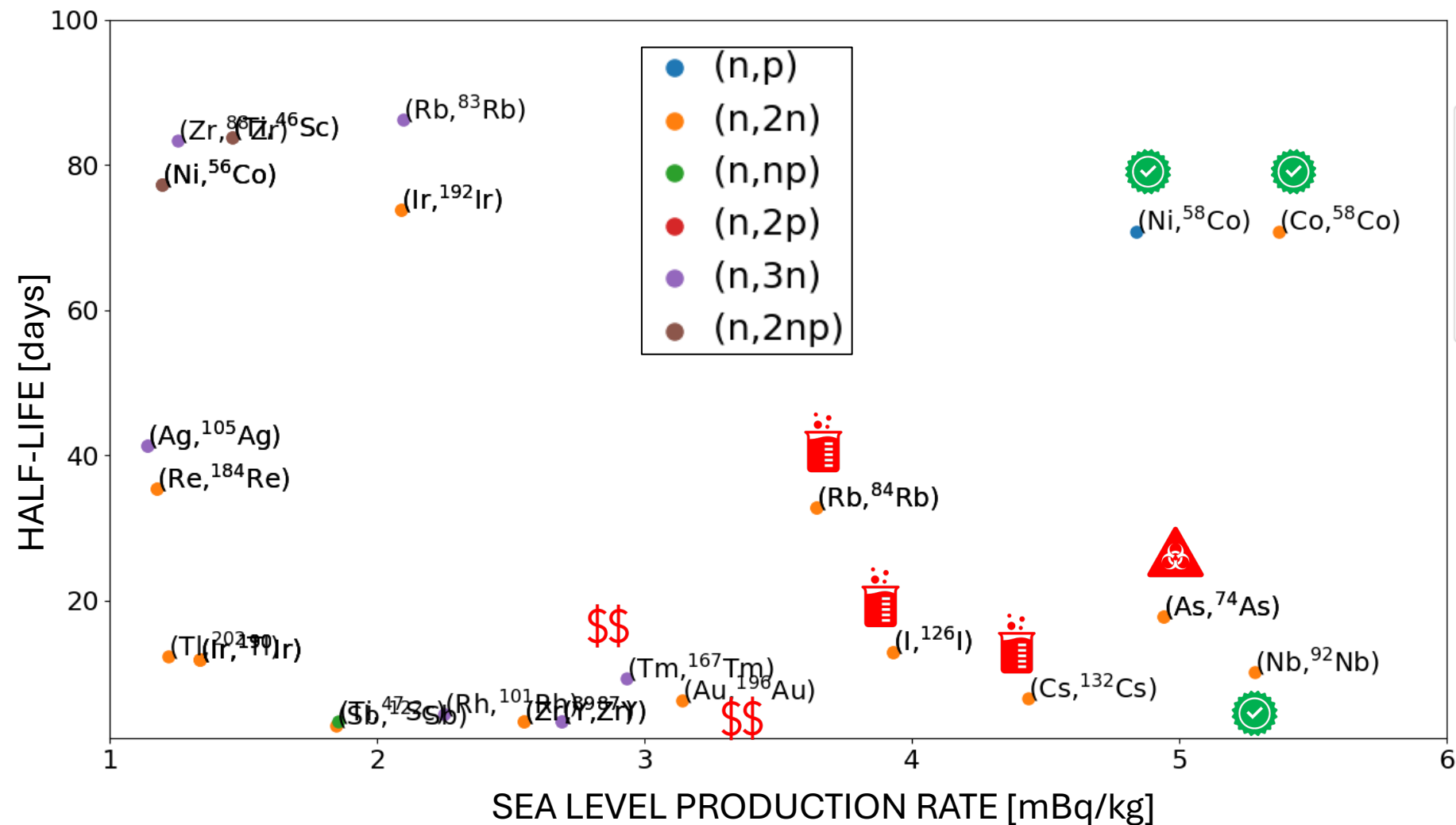
Integrate cross-section with particle flux (EXPACS) to calculate production rates



(n,2n) reactions typically have highest production rates

Proton-induced reactions having lower rates due to the lower flux at sea-level

# Candidate Witness Materials



Measuring production rates below 1 mBq/kg through Ge counting is difficult

Besides production rates and half-lives, one also needs to take into account toxicity, chemical reactivity, price, etc.

Good candidates:

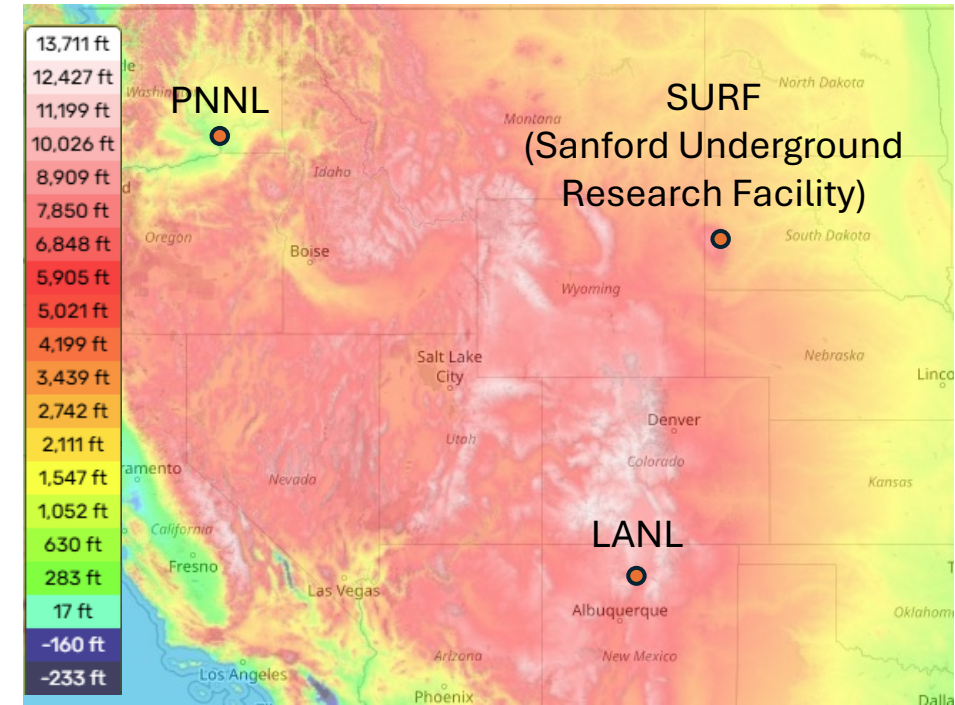
- <sup>58</sup>Ni (n,p) <sup>58</sup>Co
- <sup>59</sup>Co (n,2n) <sup>58</sup>Co
- <sup>93</sup>Nb (n,2n) <sup>92m</sup>Nb

# Witness Sample Deployment

Deploying high purity niobium, nickel and cobalt pellets at 3 different locations

Samples were deployed for more than 5-half-lives to ensure that any pre-existing activity decays away and that the measured activity is the same as the production rate

The predicted activities were calculated using the ACTIVATE code, with EXPACS predicted neutron flux and TENDL cross-sections



Source: <https://en-us.topographic-map.com/>

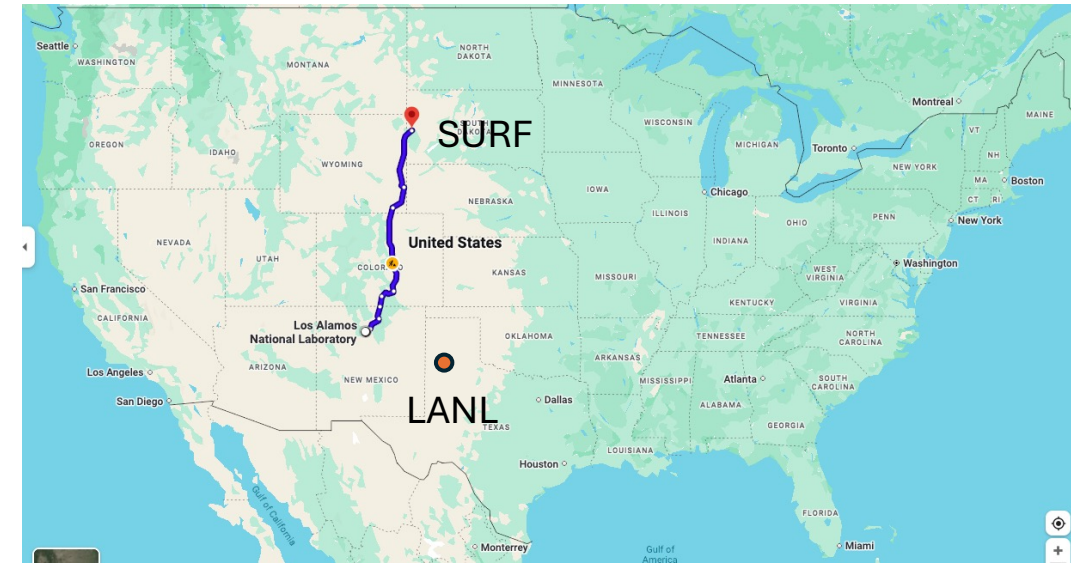
Target	Product	Half-life (days)	Time to saturation (days)	PREDICTIONS		
				PNNL Saturation (mBq/kg)	LANL Saturation (mBq/kg)	SURF Saturation (mBq/kg)
Cobalt	$^{58}\text{Co}$	70.88	354.4	4.4	24	17
Nickel	$^{58}\text{Co}$	70.88	354.4	5.2	28	19
Niobium	$^{92m}\text{Nb}$	10.12	50.6	2.2	11.6	7.3



3.6 kg of high-purity Nb deployed at PNNL

# Witness Sample Deployment: Nb at LANL, counted at SURF

- 2 lbs (0.9 kgs) of Nb was positioned at LANL for 122 days
- Witness sample was then driven from LANL to SURF for Ge counting, accompanied by a GPS tracker (~1.5 days)
- The estimated activity during the entire exposure was calculated by the ACTIVATE code using EXPACS for the neutron flux and TALYS for the cross-sections



ACTIVATE - Atmospheric Cosmic Ray Transport

Introduction Materials Cross Sections Products Flux History Analysis

Results Analysis

Calculate Production & Activity

Activity Evolution by Location

Location	Production Rate	Exposure Time	Inventory Start	Inventory End	Activity	Notes
LANL	1.159e-02	1.0e+01 d	0.200e+00	1.480e+04	1.159e-01	Initial exposure: ~1.47e+04 from production
SURF	1.159e-02	1.01 d	1.400e+04	1.480e+04	1.159e-01	+8.76e+02 from production
LANL	1.151e-02	1.00 min	1.400e+04	1.480e+04	1.151e-01	
SURF	1.151e-02	1.00 min	1.400e+04	1.480e+04	1.151e-01	
LANL	1.164e-02	2.00 min	1.400e+04	1.480e+04	1.164e-01	+1.68e+03 from production
SURF	1.172e-02	1.00 min	1.400e+04	1.480e+04	1.172e-01	
LANL	1.087e-02	2.00 min	1.400e+04	1.480e+04	1.108e-01	
SURF	1.085e-02	1.00 min	1.400e+04	1.480e+04	1.108e-01	
LANL	1.026e-02	1.00 min	1.400e+04	1.480e+04	1.026e-01	
SURF	1.016e-02	1.00 min	1.400e+04	1.480e+04	1.016e-01	
LANL	8.843e-03	1.00 min	1.400e+04	1.480e+04	8.843e-02	

Calculation completed successfully! Scenario: stationary, Locations: 376

$$N(t) = \left( N(0) + \int_0^t P(\vec{r}, t') e^{t'/\tau} dt' \right) e^{-t/\tau}$$

Predicted saturation activity at LANL:

11.6 mBq/kg

Predicted activity at SURF:

11.4 mBq/kg



0.9 kg of high-purity Nb loaded on the Ge detector at SURF

# Witness Sample Results: Nb

Sample was taken underground and counted on low-background Ge detector in the Black Hills State University Underground Campus (BHUC)

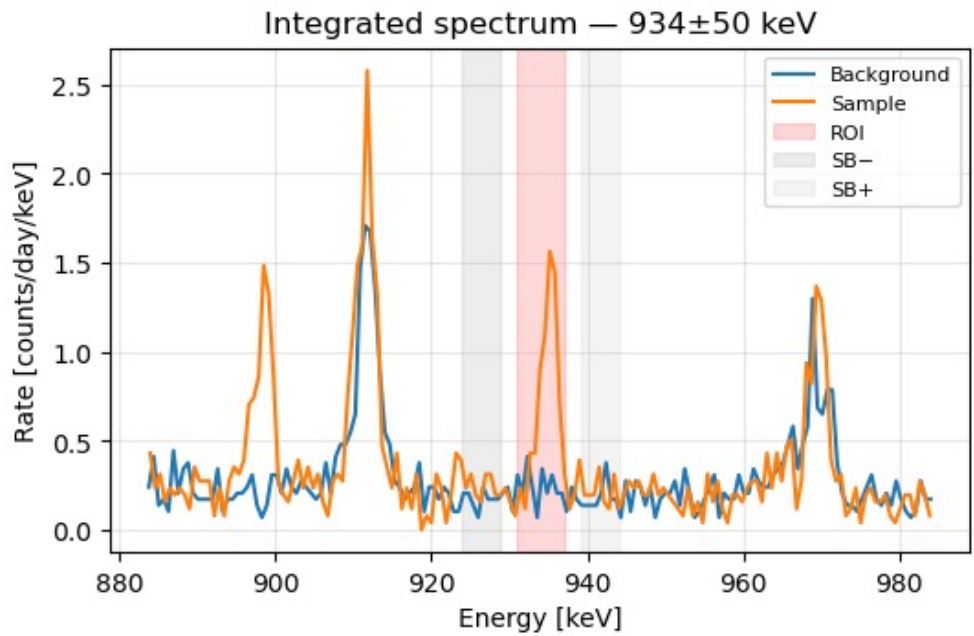
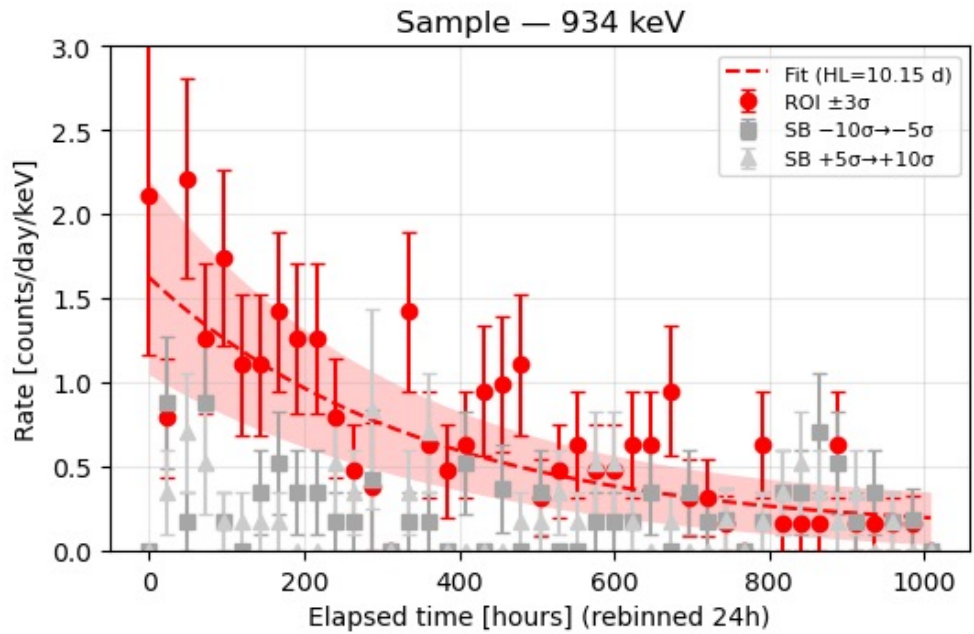
**PRELIMINARY**

Location	Measured Activity [mBq/kg]	Predicted Activity [mBq/kg]
PNNL	$2.3 \pm 0.3$	2.2
LANL	$8.4 \pm 1.6$	11.6
SURF	Currently counting	7.3

Initial results indicate reasonable agreement between predictions and measured activity, though more detailed analysis and uncertainty evaluation is on-going

Predictions depend on both flux and cross-section

How accurate are the cross-sections?



# Cross-Section Verification: Nb

No experimental cross-sections above 30 MeV.

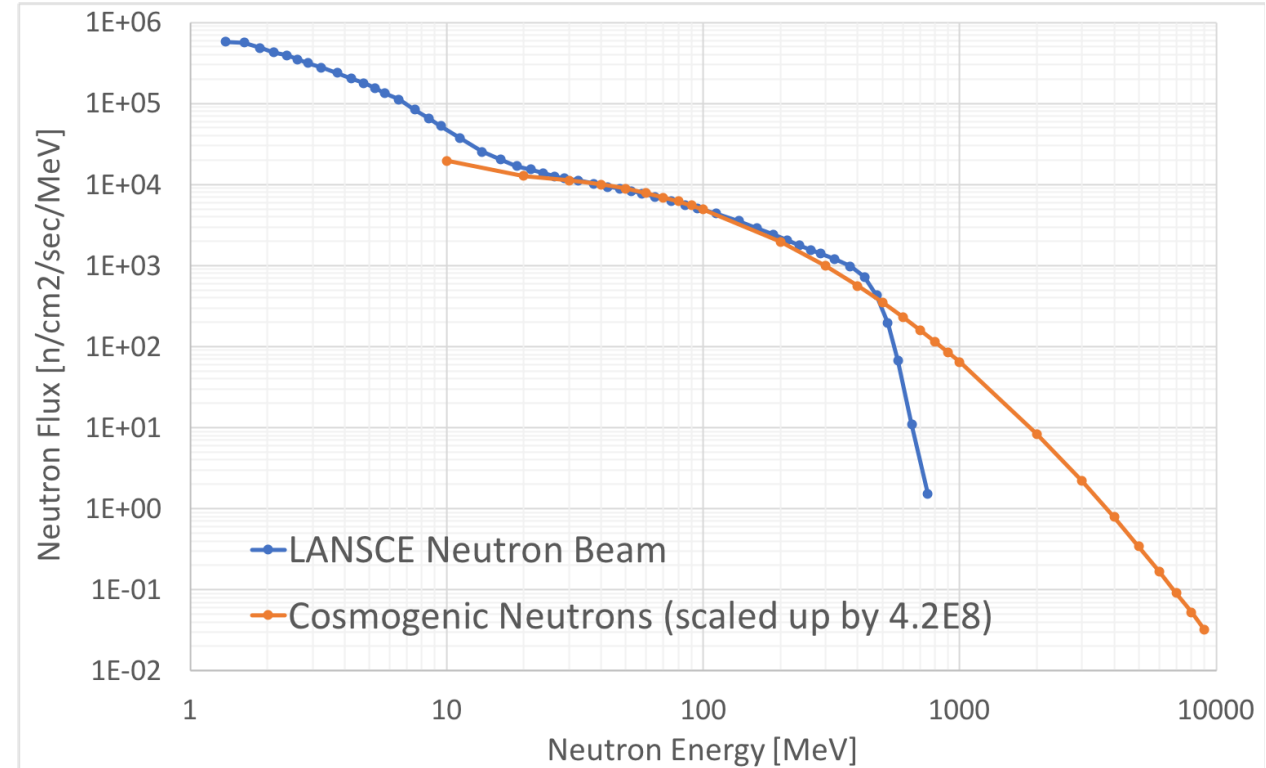
Limited nuclear libraries for high energy neutron cross-sections

Can verify models using LANSCE neutron beam that has very similar spectrum to cosmogenic neutrons

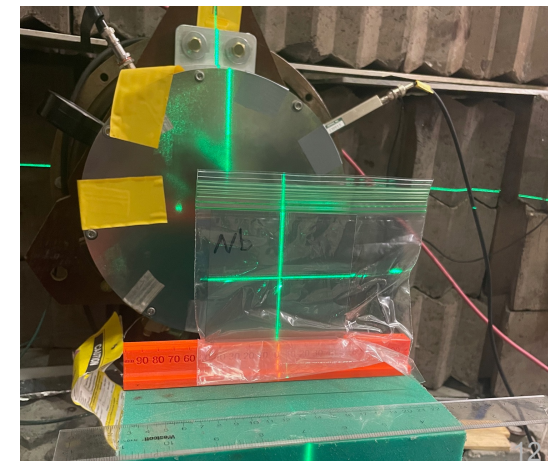
Irradiated thin (~0.5 mm) target foils of different candidate materials on the LANSCE ICE-HOUSE 60R beam

After exposure, foils were counted on a Ge detector to measure the beam-induced activity.

Analysis in progress



Target	Neutrons > 1 MeV	Neutrons > 10 MeV
Nb	4.57E+14	1.79E+13
Ni	5.00E+14	1.95E+13
Co	1.06E+15	4.15E+13
Cu	1.92E+15	7.51E+13
Zr	3.11E+14	1.22E+13



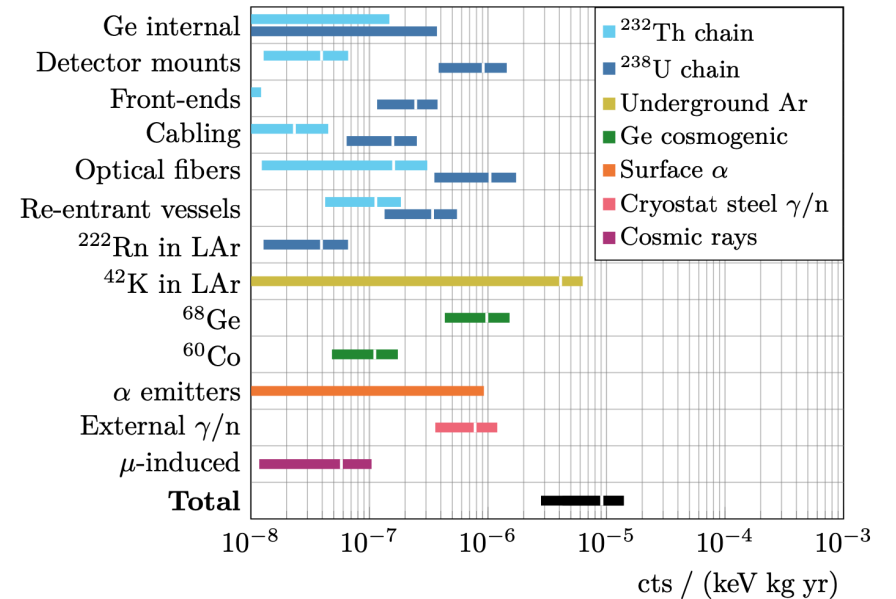
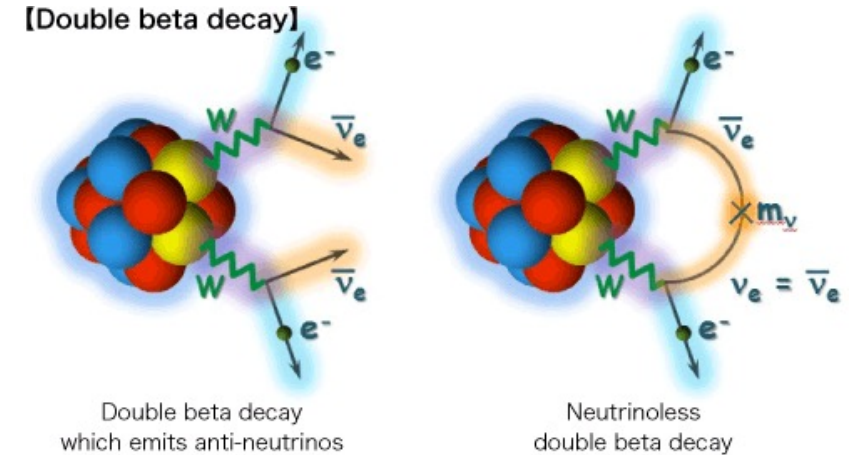
# Summary

- We have identified suitable materials for witness samples that can be deployed to measure the cosmogenic exposure of detector components
  - Samples deployed at multiple locations
  - Counting and analysis in progress – initial results match expectations
- We have exposed these sample materials to the LANSCE neutron beam to validate the cross-section models
  - 6 different target materials placed on beam
  - Post-beam activity has been measured with Ge detectors
  - Analysis in progress
- We have developed a user-friendly open-source software (ACTIVATE) that combines cosmogenic flux models and cross-section databases to evaluate the activation of materials given a specific exposure
  - Software release coming soon!

# Backup

# Neutrinoless Double Beta Decay Experiments

- The search for neutrinoless double beta decay (NLDBD) is one of the most interesting experimental efforts on-going in nuclear and particle physics, with deep consequences for our understanding of the Standard Model and the origin of matter in the universe
- Tonne-scale NLDBD has been recognized as the highest priority for new construction in the 2023 Nuclear Physics Long Plan
- Experiments like LEGEND-1000 are currently in the design and planning stage
- Planning for cosmogenic activation of detector materials is an important ingredient for limiting the radioactive backgrounds in the experiment



# Goals

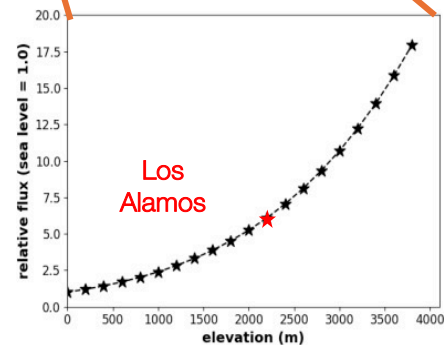
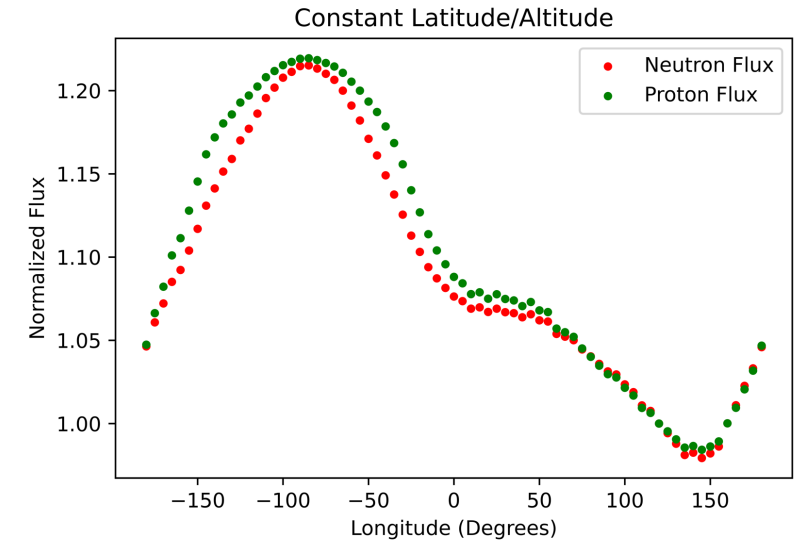
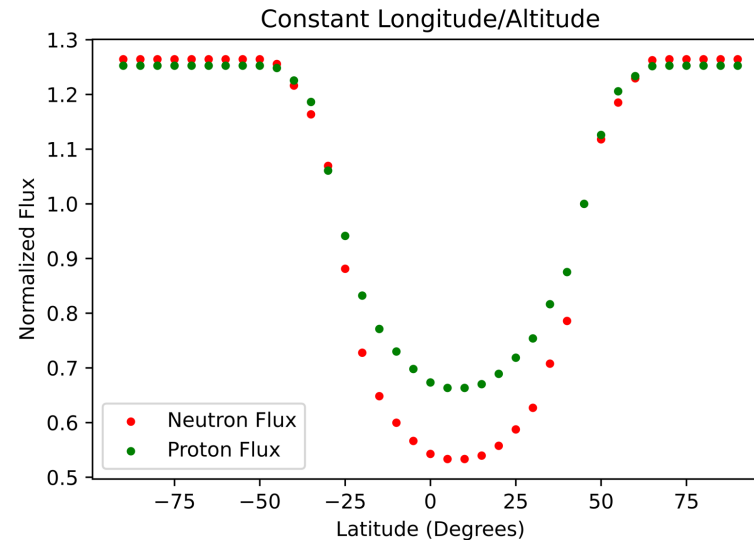
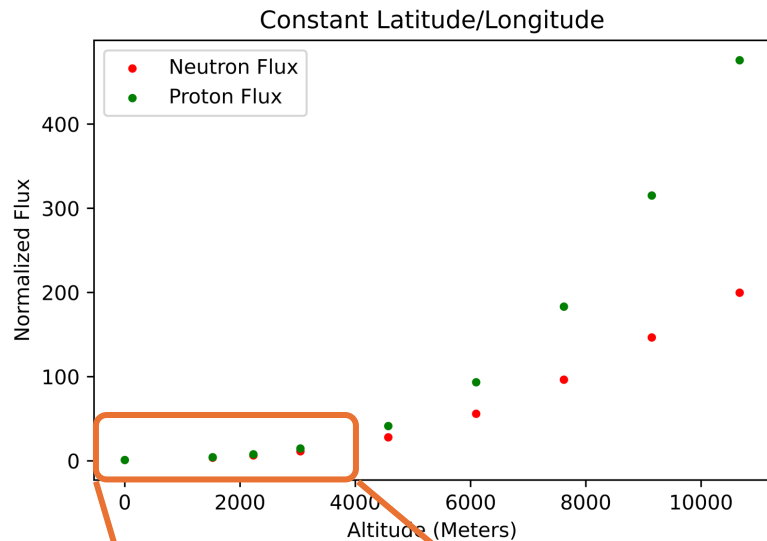
- Create a user-friendly benchmarked software package (**ACTIVATE**) to calculate the expected cosmogenic activation rate given a material and exposure history (latitude, longitude, altitude, duration)
- Develop a system of witness samples that can be transported with detector material to experimentally validate they exposure

## **Benchmark and Validation (10 MeV – 1 GeV neutrons)**

- Cosmic Flux: Witness material exposures at different locations
- Cross-sections: Irradiations at LANSCE

# Cosmogenic Flux Variation

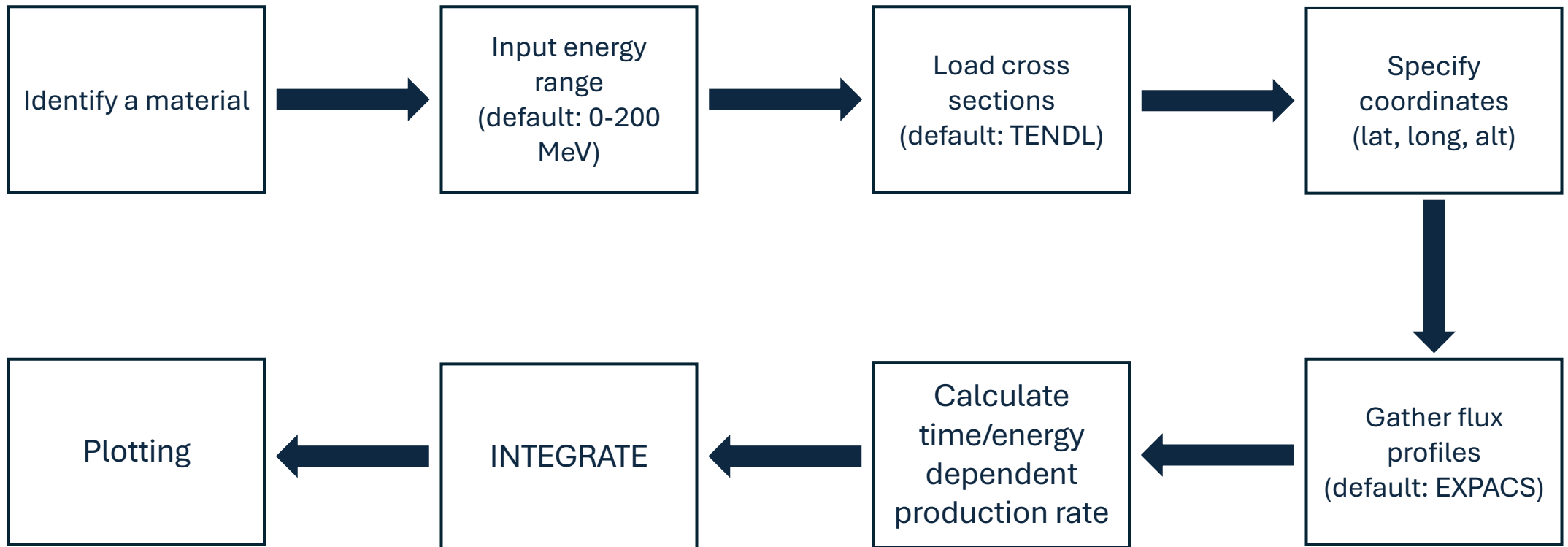
Flux of cosmogenic neutrons and protons varies by altitude, latitude, and longitude



With large international collaborations, detector components often travel across the globe before finally being assembled in deep underground sites

Careful tracking is needed to calculate the activation of components during transportation and shielding

# ACTIVATE: How does it work?

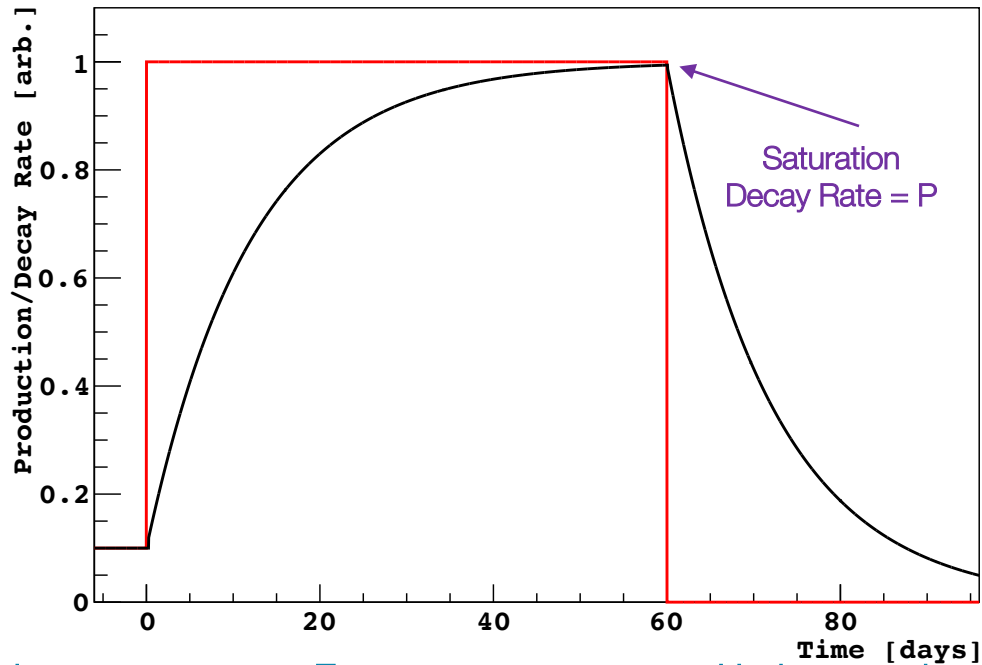


# Activation Time Profiles

Assumed constant production rate during 60-day exposure

$$N(t) = \left( N(0) + \int_0^t P(t') e^{t'/\tau} dt' \right) e^{-t/\tau}$$

Mean-Life = 0.2x Mission Time

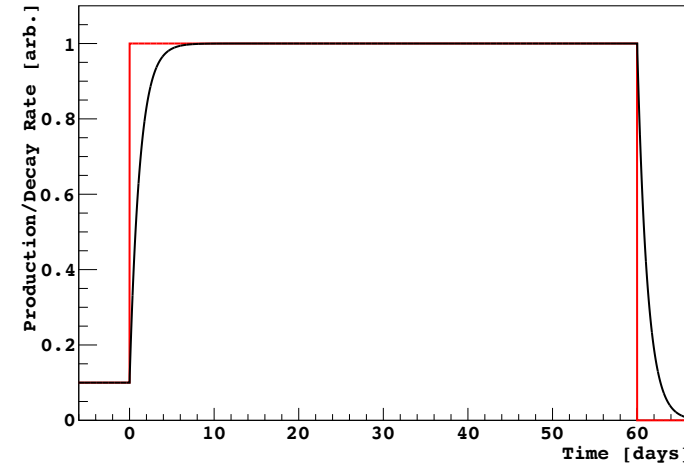


Unknown history

Exposure Period

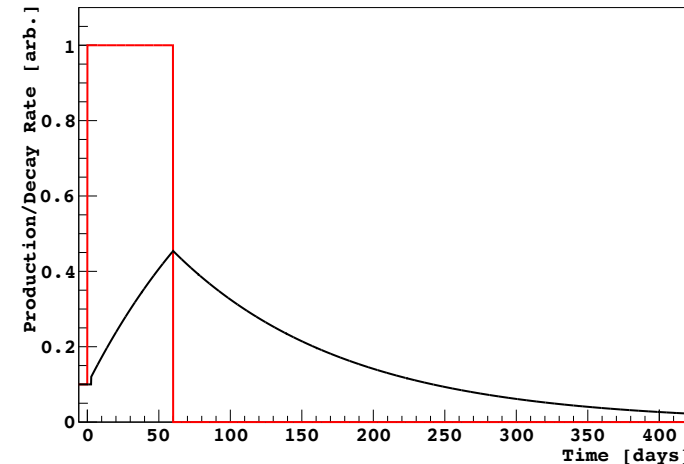
Underground storage and measurement

Mean-Life = 0.02x Mission Time



Isotope half-life very short: Extra time does not increase activity. Could make it hard to measure before it decays away

Mean-Life = 2x Mission Time



Isotope half-life very long: Does not reach maximum activity

**IDEAL: Isotope half-life is ~ 1/5<sup>th</sup> exposure period**