# Tritium Production in SuperCDMS

**Sagar S. Poudel**[*], Lekhraj Pandey, Rob Calkins, Ben Loer,
Tina Cartaro, Spencer Keller, John Orrell
(on behalf of the SuperCDMS Collaboration)

[*] South Dakota School of Mines & Technology

LRT2024

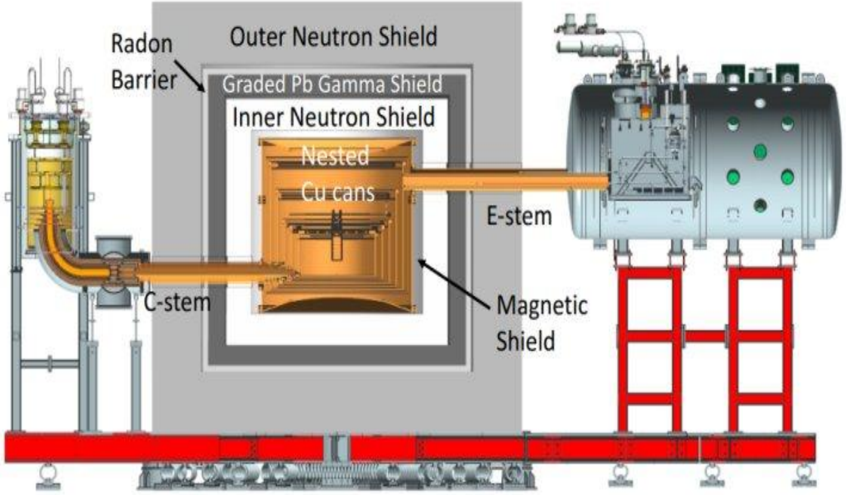
SUPER
CDMS
Cryogenic Dark Matter Search

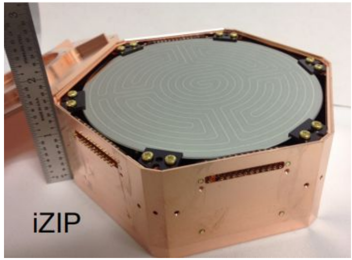
# SuperCDMS experiment and Ge (and Si) HV detectors

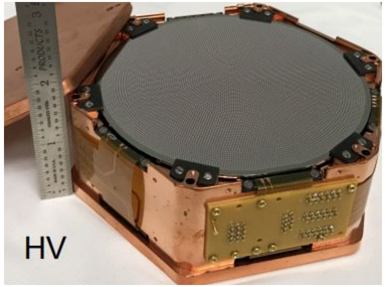
- The SuperCDMS experiment is under installation at SNOLAB, Canada

- SuperCDMS uses two targets (Ge and Si) and two detector technologies:
  - **iZIP**: phonon and charge readout with keV scale threshold and ER/NR discrimination

  - **HV**: phonon-only signal with low energy threshold (can probe much lower-mass dark matter interactions) and little or no ER/NR discrimination



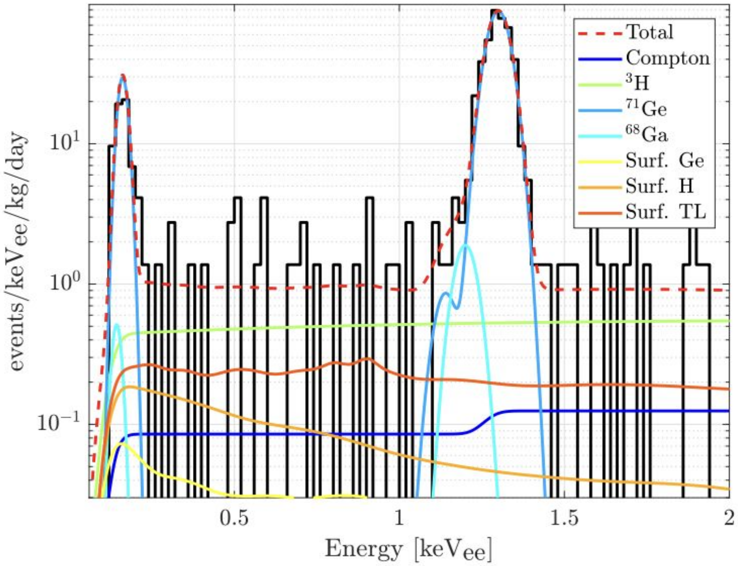




4 detector towers:
12 HV detectors: 8 Ge + 4 Si
12 iZIP detectors: 10 Ge + 2 Si

# Cosmogenic activation

- Cosmic-ray neutrons are the major contributors to tritium production in Ge and Si.
- Tritium (Beta-emitter, Q = 18.6 keV), produced in Ge and Si, is a big issue due to its presence in the detectors, its long half-life (half-life = 12.32 y), and.
- Tritium decays dominant backgrounds in Ge HV detectors



CDMSLite Run3 spectrum

[Agnese et al, Phy. Rev. D, 2019]

# SuperCDMS efforts: Mitigating cosmogenic activation

- No transport of detector materials by flights
- Use of underground sites for various purposes including detector storage
- Transport of detector/crystals in GERDA/MAJORANA container
  (a factor of 10 suppression of tritium production)
- Detailed tracking of exposure history of detector and Cu materials

| Underground sites | Description | Depth |
|---|---|---|
| Hades Storage Area Brussels,Belgium | Crystal storage | ~ 600 mwe |
| SUF Tunnel A | Detector etching and polishing | 15-20 mwe |
| SUF Tunnel C | Detector storage | 15-20 mwe |
| SLC South Adit Storage | Detector tower storage | 50-60 mwe |
| MINOS facility, Fermilab | Storage of cryostat can copper sheets | ~ 300 mwe |
| SNOLAB | Experiment | ~ 6000 mwe |

~ 14.5 ton stainless cylinder
(1.4 m (D) x 1.26 m (H)
~ 15 cm thick at the bottom

GERDA/MAJORANA (GM) container shipping crystals/detectors

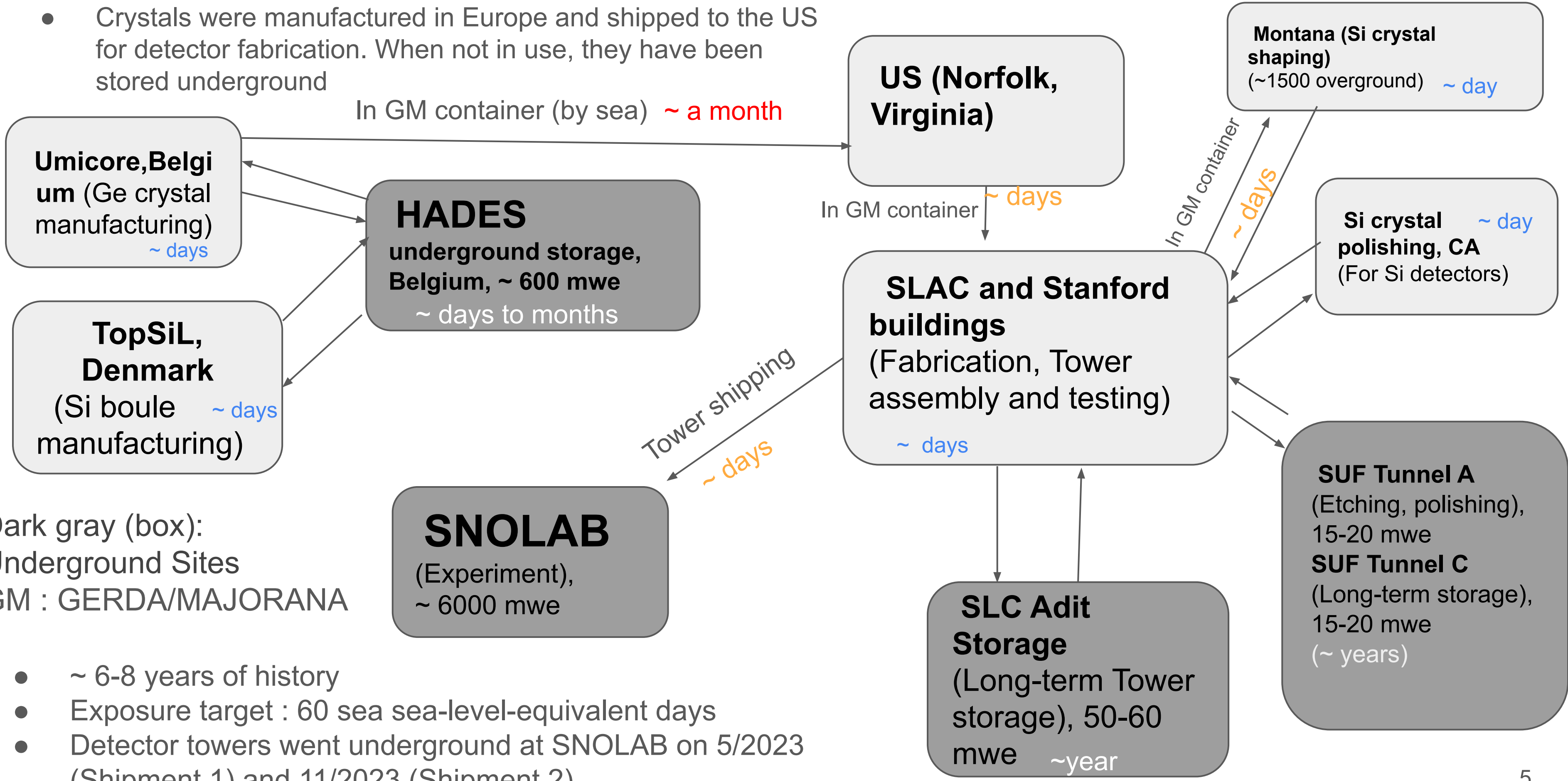
[Barabanov et al. NIM B, 2006]

CDMS eTraveler

SLAC maintained database used to record the entire history of detectors as well the (tower and housing) materials

# Exposure history of SuperCDMS Ge (Si) HV crystals/detectors

- Crystals were manufactured in Europe and shipped to the US for detector fabrication. When not in use, they have been stored underground



In GM container (by sea) ~ a month

**Umicore,Belgium** (Ge crystal manufacturing)
~ days

**HADES**
**underground storage, Belgium, ~ 600 mwe**
~ days to months

**TopSiL, Denmark**
(Si boule manufacturing)
~ days

**US (Norfolk, Virginia)**

In GM container ~ days

**Montana (Si crystal shaping)**
(~1500 overground) ~ day

In GM container ~ days

**Si crystal polishing, CA**
(For Si detectors)
~ day

**SLAC and Stanford buildings**
(Fabrication, Tower assembly and testing)
~ days

Tower shipping ~ days

**SNOLAB**
(Experiment),
~ 6000 mwe

**SLC Adit Storage**
(Long-term Tower storage), 50-60 mwe ~year

**SUF Tunnel A**
(Etching, polishing),
15-20 mwe
**SUF Tunnel C**
(Long-term storage),
15-20 mwe
(~ years)

Dark gray (box): Underground Sites
GM : GERDA/MAJORANA

- ~ 6-8 years of history
- Exposure target : 60 sea sea-level-equivalent days
- Detector towers went underground at SNOLAB on 5/2023 (Shipment 1) and 11/2023 (Shipment 2)

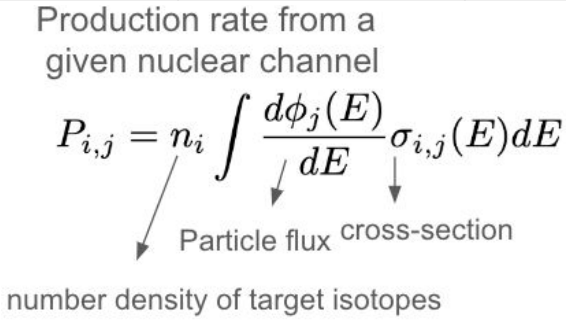
# Tritium production in Ge (and Si) at sea-level

- Experiments can measure tritium decays, but measured production rate has also uncertainties.

- Gordon's neutron spectrum (NYC, 2003) and TALYS + INCL cross-section model, reproduce measured tritium production (within ~ 25 %)

- No measurement exists for shallow depths. For shallow depths, we will obtain neutron flux and spectrum , and choose the TALYS + INCL model to estimate tritium production

| **Activation** | **Production (atoms/kg/day), at sea-level** | **Reference** |
|---|---|---|
| Tritium in Ge | 74±9<br>82±21<br>94 | CDMSLite, 2019 (Measurement)<br>EDELWEISS-III, 2017(Measurement)<br>TALYS (< 100 MeV) + INCL (A. Robinson, U.of Montreal) |
| Tritium in Si | 112±24<br>125 | Richard et al. 2020<br>TALYS (< 100 MeV) + INCL (A. Robinson, U.of Montreal) |


Production rate from a given nuclear channel

$$P_{i,j} = n_i \int \frac{d\phi_j(E)}{dE} \sigma_{i,j}(E) dE$$

Gordon et al. IEEEE, 2004

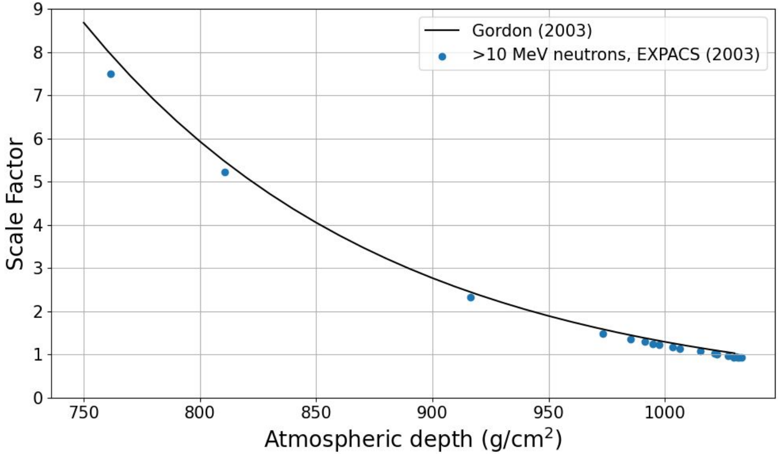
# Gordon’s scale factors

- > 10 MeV neutron flux (and tritium production) depends strongly on altitude.

- Since, the shape of the > 10 MeV neutron energy spectrum doesn’t change up to significant altitude,Gordon’s flux factor can be used as the tritium production scale factors for overground sites

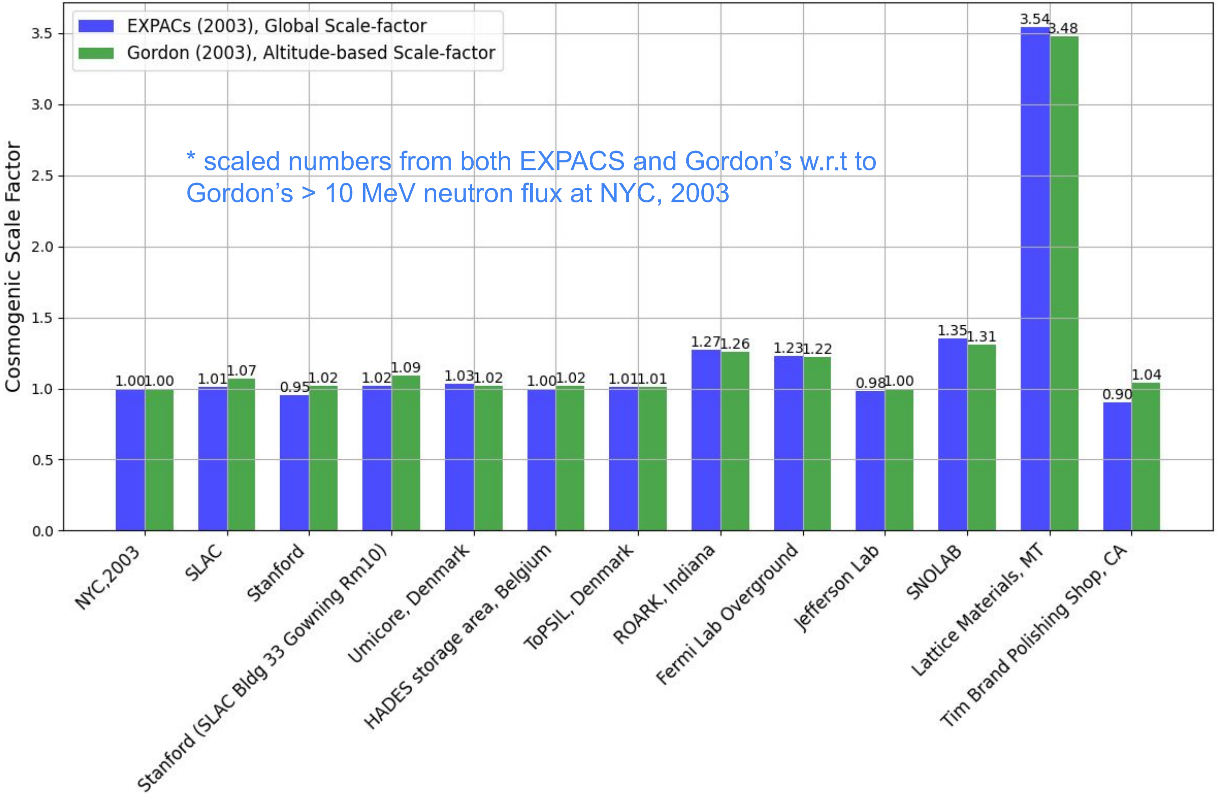
- Gordon’s scale factor :
neutron flux (> 10 MeV) at an altitude ⁄ neutron flux (> 10 MeV) at sea-level

[Gordon et al. IEEEE, 2004](#)
[Tatsuhiko Sato. PlOS One, 2015](#)



- Good to consider also an alternative tool like EXPACs (that considers altitude, latitude, longitude, and solar cycle) to identify if factors other than altitude matter for overground sites
- ~ 5 % difference in Gordon’s flux factor vs EXPACS’s for NYC, 2003.

# Scale factors at SuperCDMS overground sites



* scaled numbers from both EXPACS and Gordon's w.r.t to Gordon's > 10 MeV neutron flux at NYC, 2003

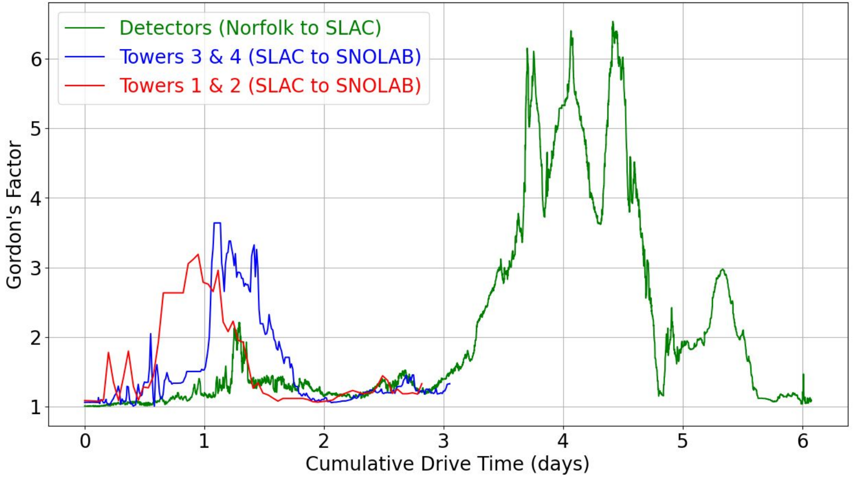
- Comparing EXPACS and Gordon in the same solar cycle (shown left) shows us that apart from altitude, location is a sub-dominant effect. We have thus adopted the Gordon parameterisation for these studies.
- Comparing EXPACS data from 2003 and 2020 to understand the impact of the solar cycle, we see a ~10% increase, indicating that the solar cycle is a non-trivial effect. We are working to incorporate this in future analysis

# Effective Gordon’s scale factor for land trips

- We use available (GPS/route) information on the road trips
  : Extract altitude information
  : Obtain atmospheric depth

- A time-weighted effective production scale factor per trip can be used in tritium production calculation

- 1/10 suppression factor from the use of GERDA/MAJORANA container for some trips

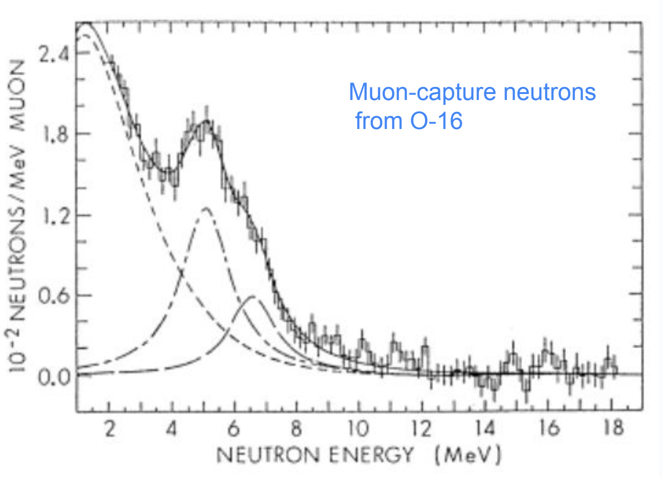


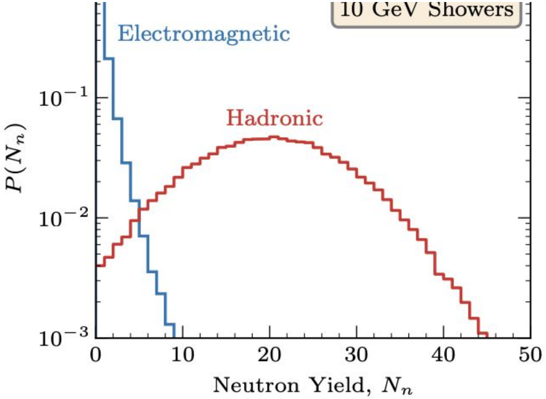
| Road trips | Purpose | Effective scale factor |
|---|---|---|
| Norfolk-SLAC | Transport of detector/crystals | 1.73/10 |
| SLAC-Montana (and back) | Slicing and Shaping of Si crystals | 3.8/10 (SLAC-Montana),<br>3.0/10 (Montana-SLAC) |
| SLAC to SNOLAB (two shipments) | Transport of detector towers to SNOLAB | 1.55<br>1.58 |

# Neutron production at shallow depths

- Neutron spectrum and flux for the shallow-depth sites of interest require simulations.
- Radiogenic neutrons – neutrons from U, Th SF and (alpha,n) – are irrelevant for tritium production in Ge (and Si).
- Cosmic-ray neutrons are sub-dominant at depths greater than 5 m.
- Only cosmogenic (muon-induced) neutrons become relevant at depths > 5 m (~ 15 mwe).
- Various neutron production processes from muon-induced interactions
  - i) Negative muon-capture
  - ii) Direct muon spallation
  - iii) Hadronic showers and Electromagnetic showers

D.F. Measday Physics Reports,2001

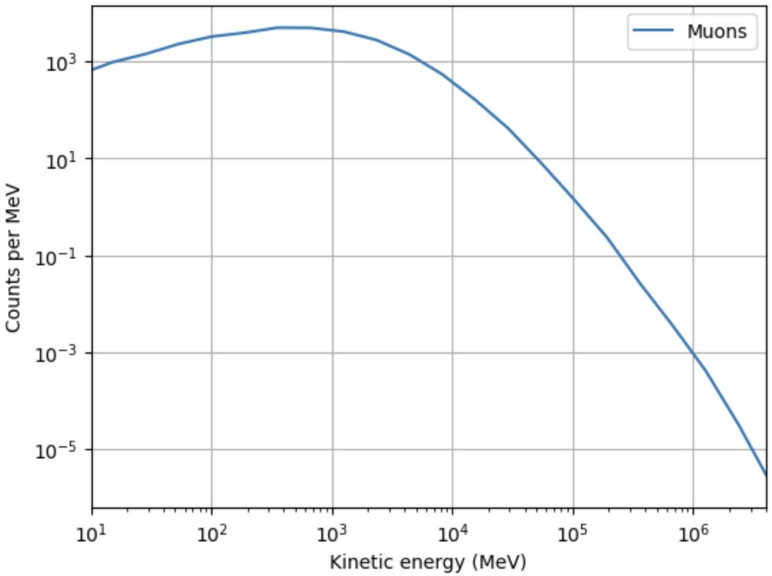




Obada Nairat et al. 2024, arXiV

# Cosmic-ray muon generator and particle transport

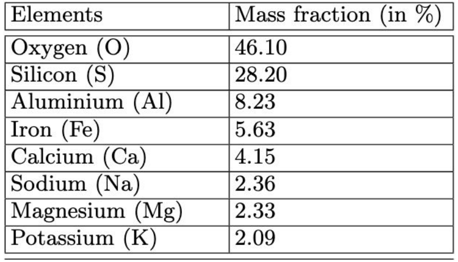
- CRY as a cosmic-ray generator (muons generated in 100 m x 100 m plane above the modelled rock), muon energy and angular distribution considered
- Particle Transport code FLUKA used to propagate CRY's muons and muon-induced secondaries through the modelled rock turning on all the relevant physics models for neutron production.
- We obtain the neutron flux and the energy spectrum at various shallow-depths from simulations to use them for calculating tritium production at relevant shallow-depth sites.



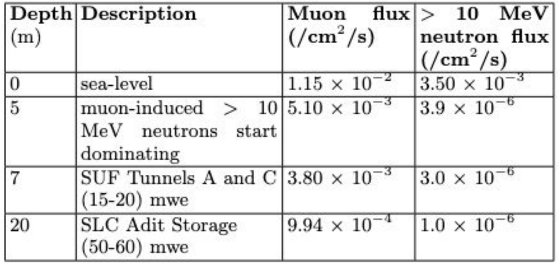
[Hagmann et al. IEEE, 2007](#)
[Battistoni et al. Annals of N.E, 2015](#)

# Muon flux and neutron flux at shallow depths

- Number of muons propagated: 1.74 billion
- Rock density = 2.7 g/cm^3



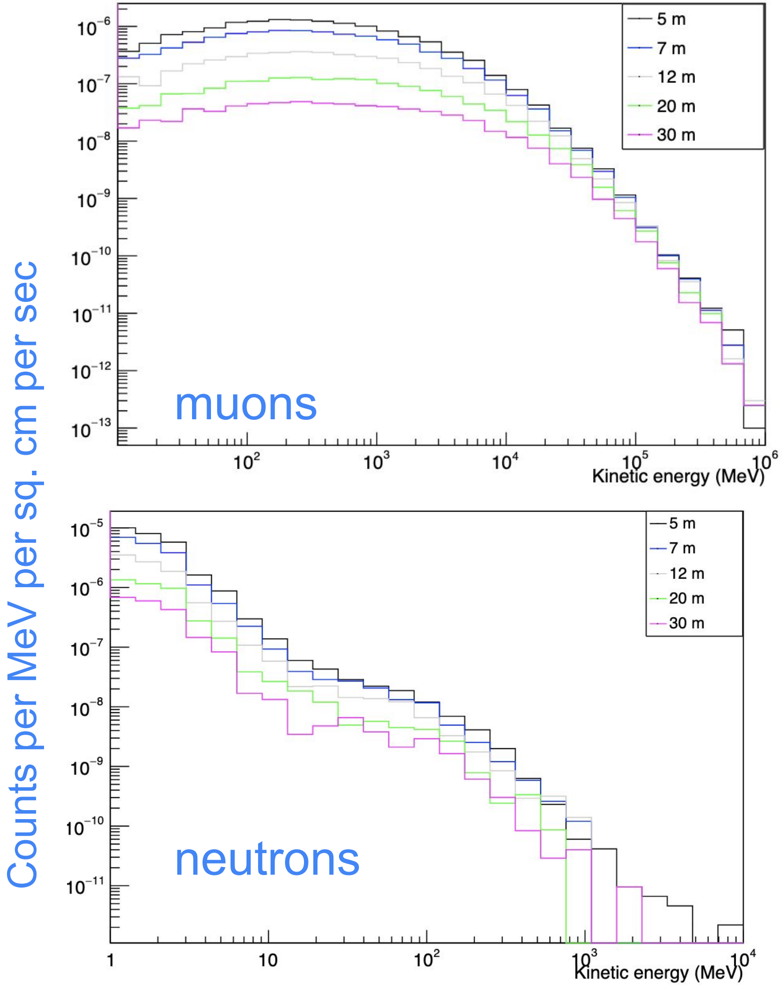
| Elements | Mass fraction (in %) |
|---|---|
| Oxygen (O) | 46.10 |
| Silicon (S) | 28.20 |
| Aluminium (Al) | 8.23 |
| Iron (Fe) | 5.63 |
| Calcium (Ca) | 4.15 |
| Sodium (Na) | 2.36 |
| Magnesium (Mg) | 2.33 |
| Potassium (K) | 2.09 |



| Depth (m) | Description | Muon flux ($/cm^2/s$) | > 10 MeV neutron flux ($/cm^2/s$) |
|---|---|---|---|
| 0 | sea-level | $1.15 \times 10^{-2}$ | $3.50 \times 10^{-3}$ |
| 5 | muon-induced > 10 MeV neutrons start dominating | $5.10 \times 10^{-3}$ | $3.9 \times 10^{-6}$ |
| 7 | SUF Tunnels A and C (15-20) mwe | $3.80 \times 10^{-3}$ | $3.0 \times 10^{-6}$ |
| 20 | SLC Adit Storage (50-60) mwe | $9.94 \times 10^{-4}$ | $1.0 \times 10^{-6}$ |

- Neutron flux measurements at SUF (Chen et al 1993) is reproduced well by our simulations
- (11.5-50) MeV neutron flux measured at SUF by Chen et al. (1993) was about (1.1 ± 0.4)E-6 n/cm$^2$/s
- Our simulations in that energy range produces 1.2 E-6 n/cm$^2$/s

Chen et al. NIMA, 1993



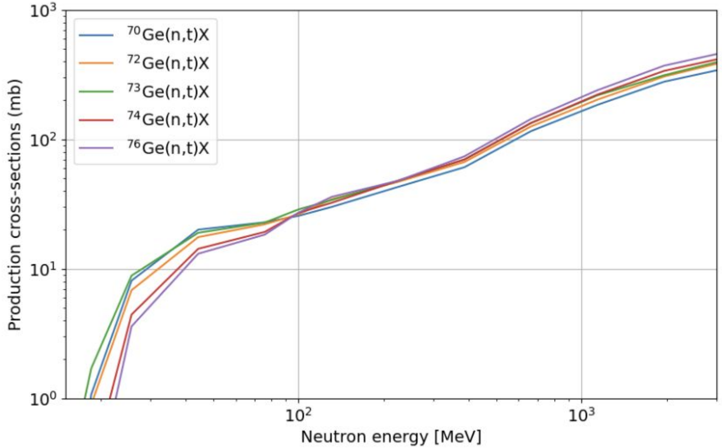
# Tritium production in Ge and Si at shallow depth

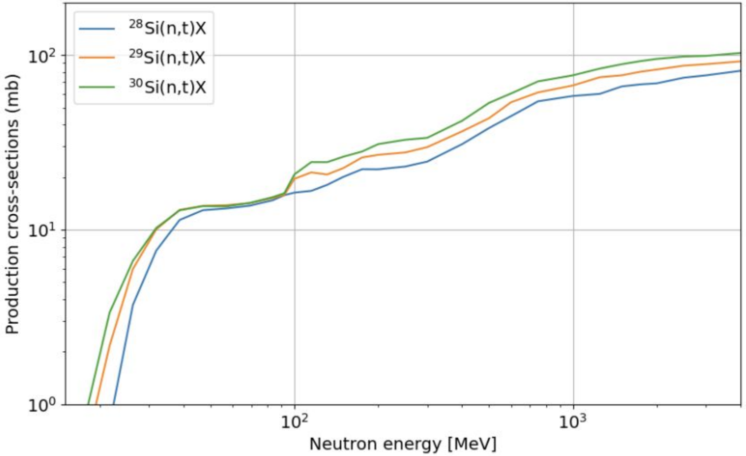
- TALYS (For < 100 MeV neutrons) + INCL (For >=100 MeV neutrons) reproduces overground measurements

- We use the same mix of models for shallow-depths and neutron spectrum obtained from the simulations to calculate tritium production in Ge and Si for SUF Tunnel A/C and SLC Adit storage

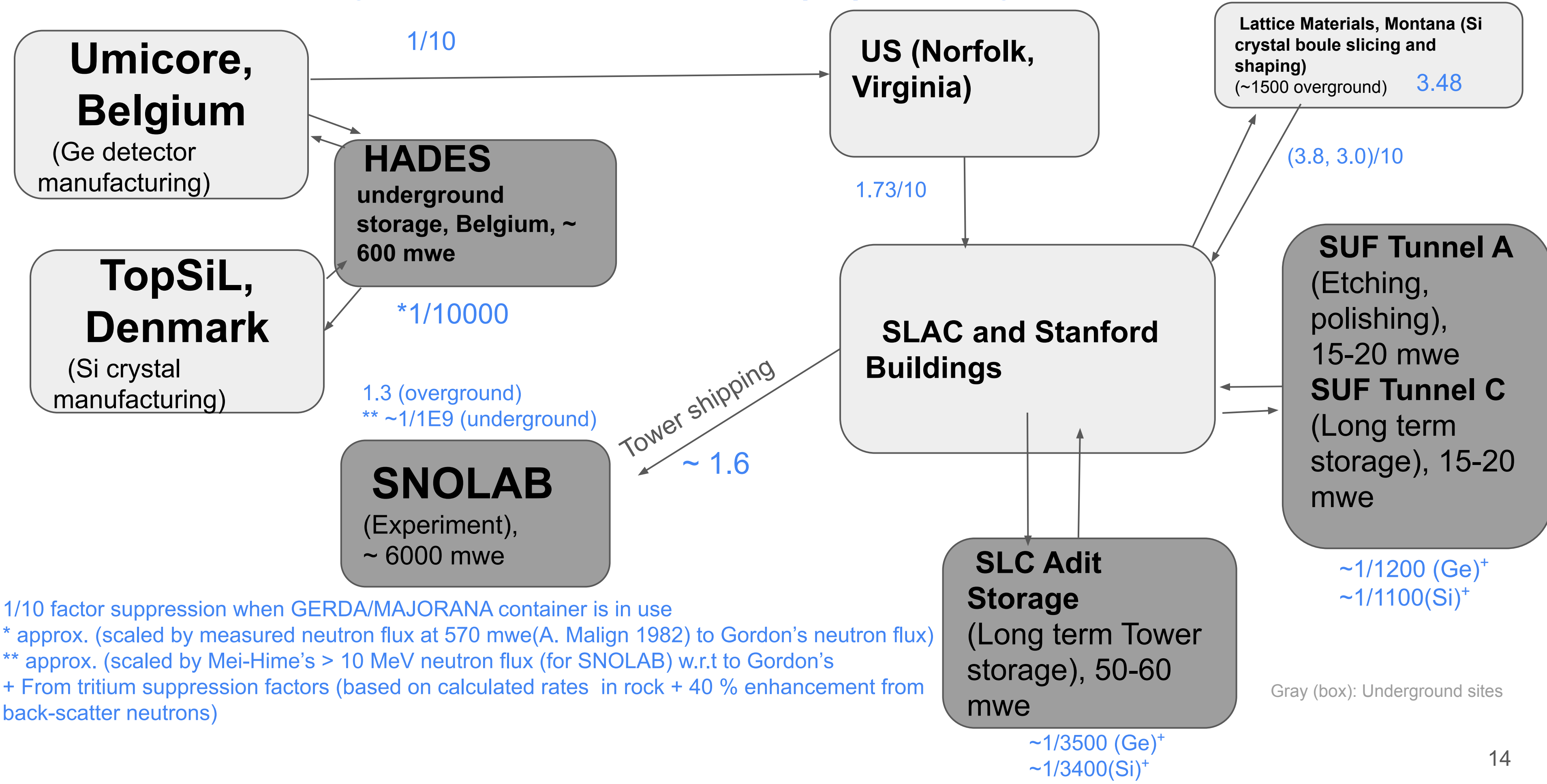
7 m (15 -20 mwe): SUF Tunnel A/C
20 m (50 -60 mwe) : SLC Adit Storage

| **Depth (m)** | **Tritium production in Ge (/kg/day)** | **Tritium production in Si(/kg/day)** |
|---|---|---|
| 0 | 94 | 125 |
| 5 | $6.7 \times 10^{-2}$ | $9.5 \times 10^{-2}$ |
| 7 | $5.7 \times 10^{-2}$ | $7.8 \times 10^{-2}$ |
| 20 | $1.9 \times 10^{-2}$ | $2.6 \times 10^{-2}$ |





# Exposure history of SuperCDMS Ge (Si) HV crystals/detectors



**Umicore, Belgium**
(Ge detector manufacturing)

**TopSiL, Denmark**
(Si crystal manufacturing)

**HADES**
**underground storage, Belgium, ~ 600 mwe**

*1/10000

1/10

**US (Norfolk, Virginia)**

1.73/10

**Lattice Materials, Montana (Si crystal boule slicing and shaping)**
(~1500 overground) 3.48

(3.8, 3.0)/10

**SLAC and Stanford Buildings**

**SUF Tunnel A**
(Etching, polishing), 15-20 mwe
**SUF Tunnel C**
(Long term storage), 15-20 mwe

~1/1200 (Ge)$^+$
~1/1100(Si)$^+$

Tower shipping
~ 1.6

1.3 (overground)
** ~1/1E9 (underground)

**SNOLAB**
(Experiment),
~ 6000 mwe

**SLC Adit Storage**
(Long term Tower storage), 50-60 mwe

~1/3500 (Ge)$^+$
~1/3400(Si)$^+$

1/10 factor suppression when GERDA/MAJORANA container is in use
* approx. (scaled by measured neutron flux at 570 mwe(A. Malign 1982) to Gordon's neutron flux)
** approx. (scaled by Mei-Hime's > 10 MeV neutron flux (for SNOLAB) w.r.t to Gordon's
\+ From tritium suppression factors (based on calculated rates in rock + 40 % enhancement from back-scatter neutrons)

Gray (box): Underground sites

# Summary and Conclusions

- SuperCDMS Tritium production calculated including overground/underground scale factors and known exposure at various locations.
- Tritium production during long-term underground storage is small.  Overground exposure dominates.
- Preliminary estimate of the tritium activity in the HV detectors is about 30-40 sea-level-equivalent days well within targeted 60 days sea-level-equivalent exposure (full-scale systematic study still ongoing, including calculation for tritium production from stopping muons at shallow depths).

| Detector | Sea-level-equivalent days | Specific activity (micro-Bq/kg) |
|---|---|---|
| Hypothetical unshielded Ge HV detector | ~2400 days (if no mitigation) | ~ 300 |
| G145 (Ge HV detector) | ~ 60 days (target) | ~ 10 |

Time exposure at a place

$$N(t_{exp}) = \tau A_0 \left[1 - e^{\frac{-t_{exp}}{\tau}}\right]$$

Production rate

Number of tritium atoms

- Need more study of muon-induced neutron production with modern particle transport codes and neutron flux measurements at shallow-depth sites.

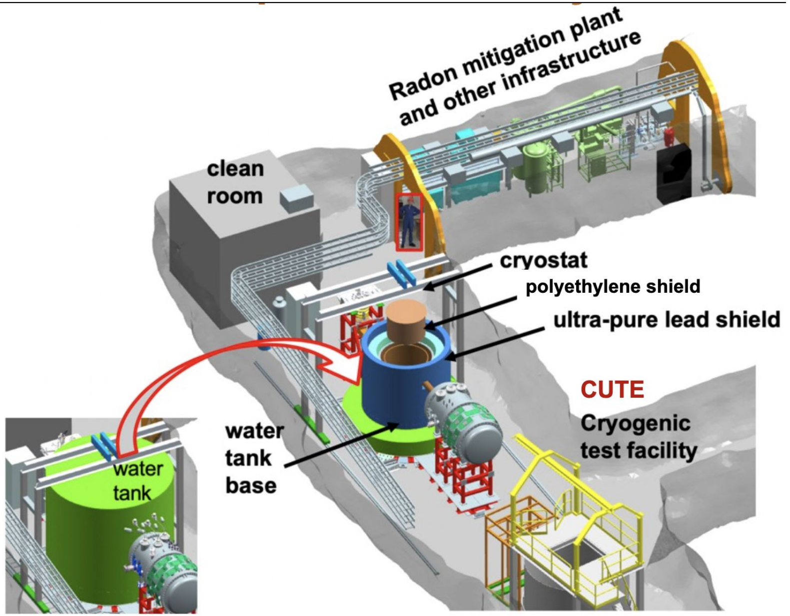
# Thanks!

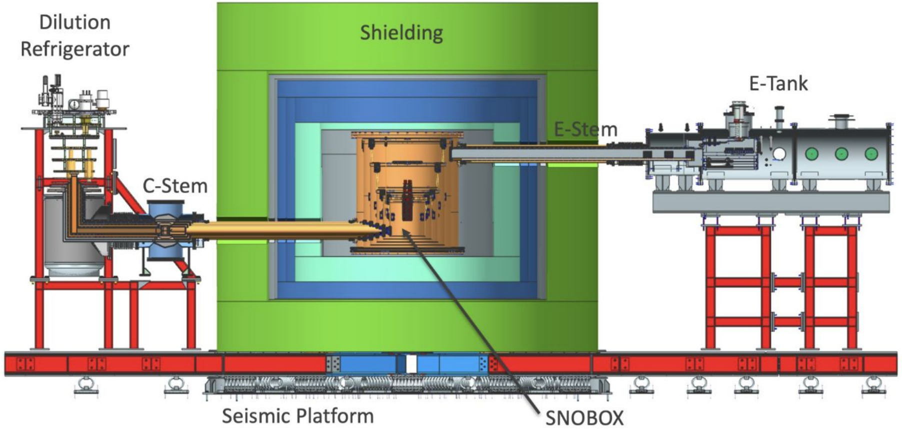

Francisco Ponce
Matt Wilson
Hanno Meyer zu Theen...
Mouli
Varchaswi Kashyap
Ruslan Podviianiuk
Sagar Sharma
Tina Cartaro
Richard Schnee
Kent May
Sukee (S. Dharani)
Wolfgang Rau
Belina von Krosigk (she...
Lauren Hsu
Kelsey, Michael H
Silvia Scorza
Steven Yellin
Huanbo Sun
David MacFarlane
Rob Cameron
Vijay Iyer
David Santiago Pedreros
Sasha (A. Zaytsev)
sudipta (he/him/his)
Qubit & Quark
Arts
science
Arts & Science
UNIVERSITY OF TORONTO
FACULTY of ARTS & SCIENCE
SUPER
CDMS
Cryogenic Dark Matter Search

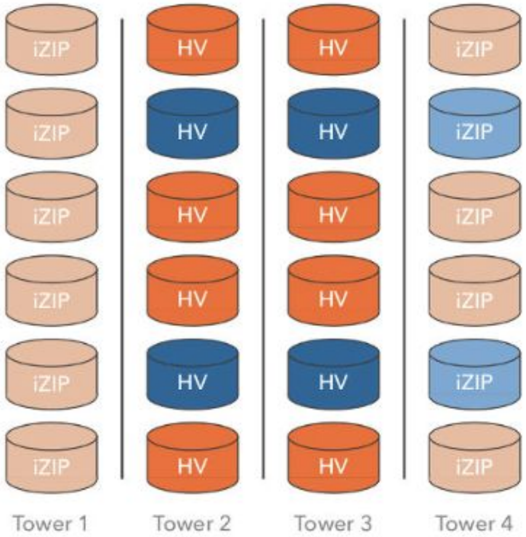
# Back up

# SuperCDMS experiment

- ~ 6 kmwe depth underground at SNOLAB
- Two iZIP towers and two HV towers
- Base temperature : 15 mK



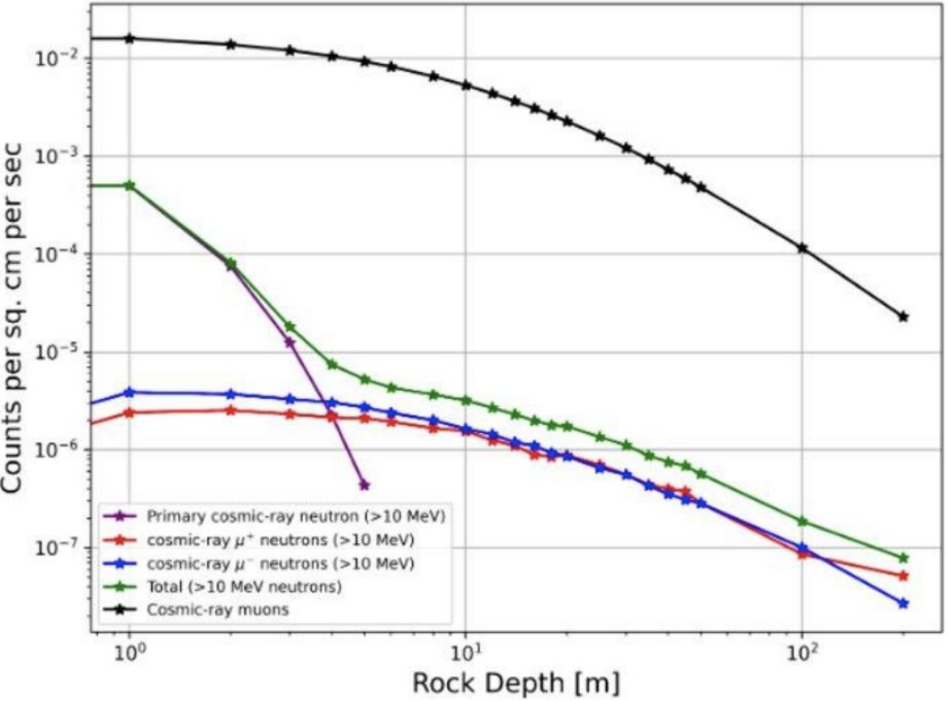


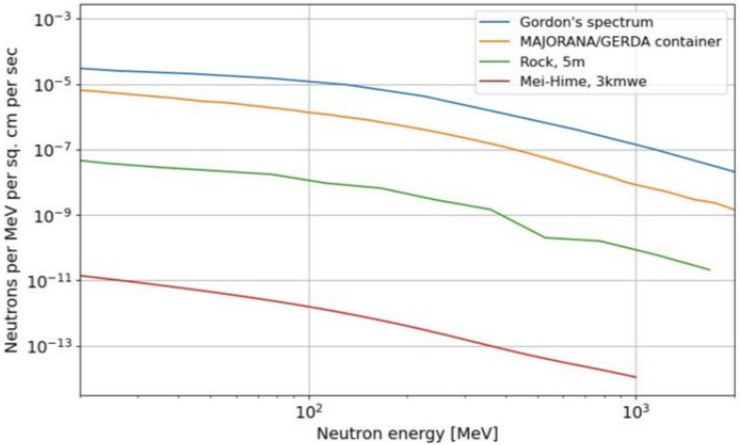


| Tower 1 | Tower 2 | Tower 3 | Tower 4 |
|---|---|---|---|
| iZIP | HV | HV | iZIP |
| iZIP | HV | HV | iZIP |
| iZIP | HV | HV | iZIP |
| iZIP | HV | HV | iZIP |
| iZIP | HV | HV | iZIP |
| iZIP | HV | HV | iZIP |

# Neutron flux as a function of depth

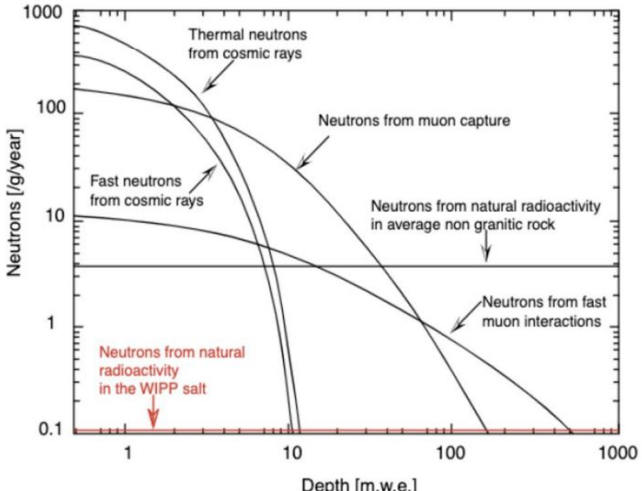
Omnidirectional muons and cosmic-ray neutrons (given by EXPACs) from overground incident vertically and propagated through rock (2.7 g/cm^3)





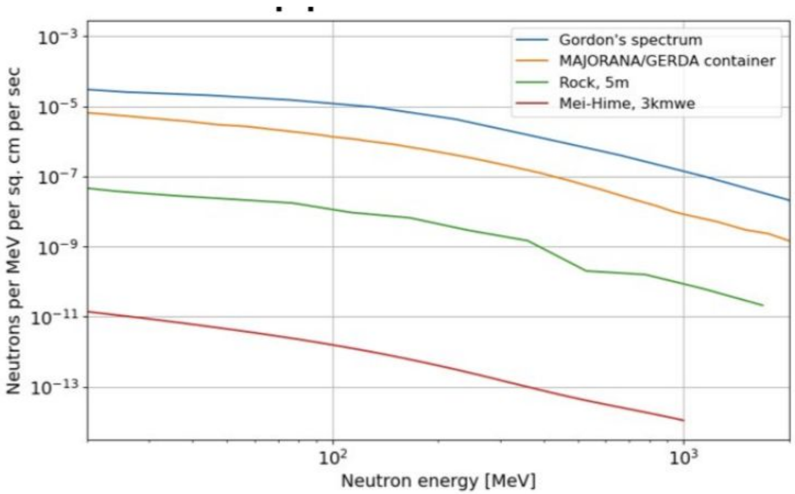
# Shallow depth vs deep depth

| **Shallow depths** | **Deep depths** |
|---|---|
| Constant ratio of Vertical muon intensity/Total muon flux , earth curvature is not important | Ratio of Vertical muon intensity/Total muon intensity increases with depth |
| Muon energy losses in rock is primarily by ionization | Muon energy losses through hadronic showers compete with ionization losses. |
| Several competing neutron-production processes | Hadronic showers dominate muon-induced neutron production |



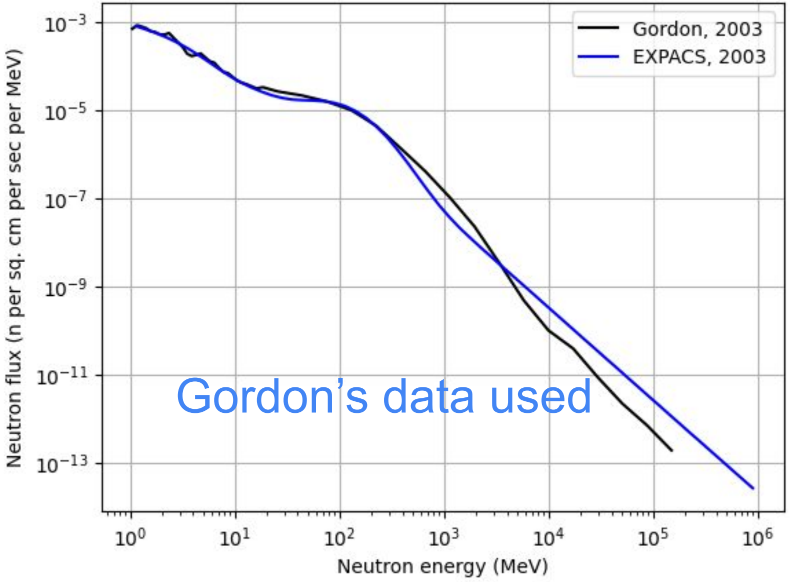
Esch, Ernst-Ingo. "Detector development for dark matter research." (2001).

# GERDA/MAJORANA neutron spectrum and comparison

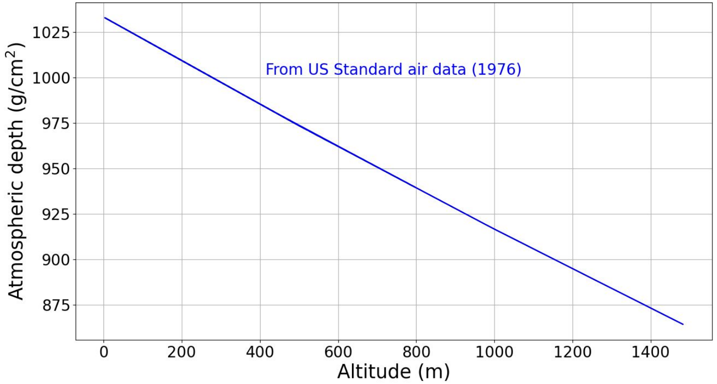


# EXPACs vs Gordon (comparison)

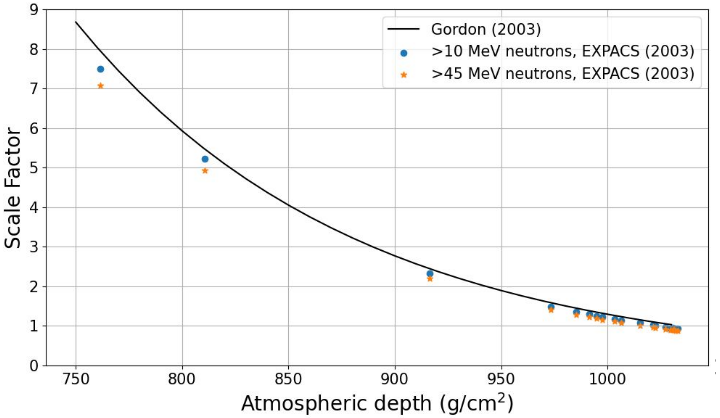
| Tool | Neutron flux (n per sq. cm per sec) at NYC, 2003 | Neutron flux (n per sq. cm per sec) at NYC, 2020 |
|---|---|---|
| Gordon's parameterization | 3.50E-3 | - |
| EXPACS | 3.33E-3 | 3.95E-3 (10-15 % larger) |



Gordon's data used



From US Standard air data (1976)



# TALYS vs TALYS+INCL

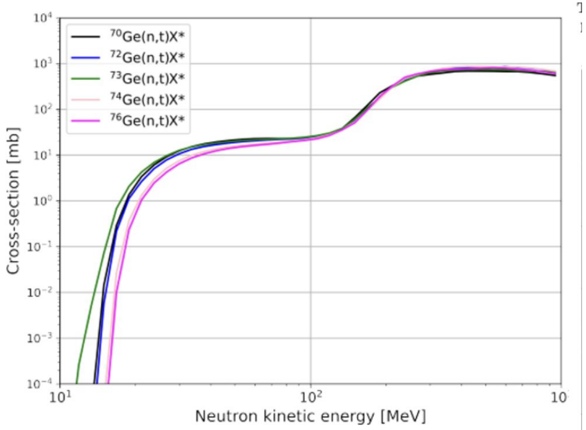


FIG. 8: Tritium production cross-sections as a functior of neutron kinetic energy in Germanium. Only neutron-induced nuclear reactions on most abundant Ge isotopes ($^{70}$Ge: 20.4%, $^{72}$Ge: 27.3%, $^{73}$Ge:7.8%, $^{74}$Ge: 36.7 %, $^{76}$Ge: 7.8%) are included.

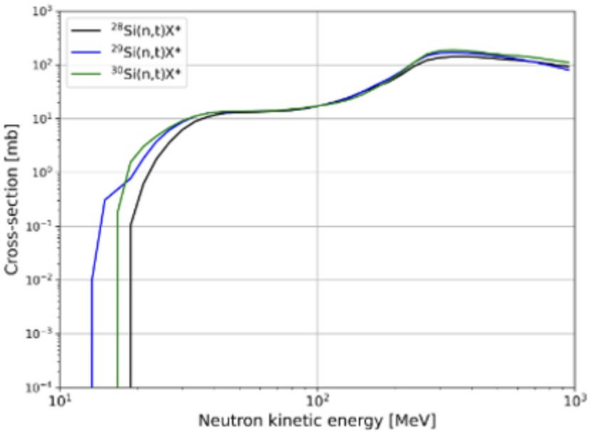
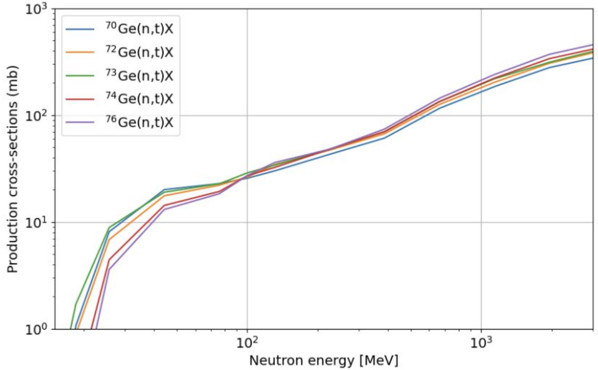
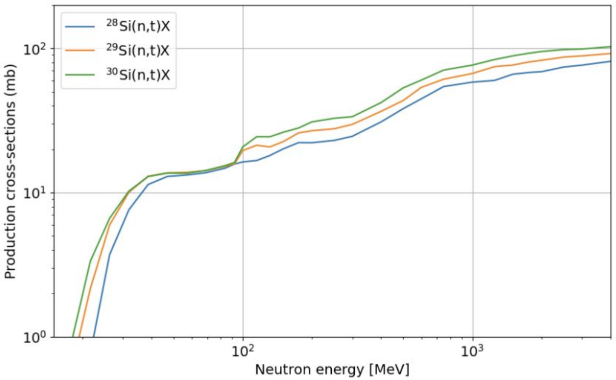
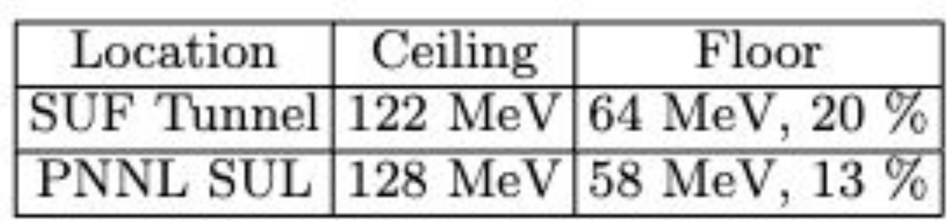


FIG. 9: Tritium production cross-sections as a function of neutron kinetic energy in Si. Only neutron-induced nuclear reactions on most abundant Si isotopes ($^{28}$Si: 92.2%, $^{29}$Si: 4.7%, $^{30}$Si:3.1%) are included.





# Back-scatter neutrons



| Location | Ceiling | Floor |
|---|---|---|
| SUF Tunnel | 122 MeV | 64 MeV, 20 % |
| PNNL SUL | 128 MeV | 58 MeV, 13 % |

Mean neutron kinetic energy and % of the
> 10 MeV neutrons entering from the ceiling and floor
for modelled SUF Tunnel and PNNL SUL.

# Neutron production

- Chen at al. 1993:
  38 % contribution from muon- capture neutrons to the neutron flux in the range (11.5-50) MeV" and the rest from muon-induced showers at the depth of SUF (7 m, ~20 mwe)

- Our calculation:  ~20% to the total tritium production in Ge(Si) from (11.5-50) MeV neutrons
- An indication that the hadronic shower neutrons may already be dominating muon-capture neutrons in producing tritium in Ge/Si even at even very shallow depths.
- More need of neutron production studies with modern tools (with improved hadronic models) necessary.