Project #3: GANDALF

Cosmogenic Activation in Si, Ge and NaI

Ry Cyna, Gulliver Milton, Beymar Quenallata, and Owen Stanley

Project #3:
Germanium N**A**I silico**N** **D**ark matter **A**nd 0vββ**L**ess **F**un

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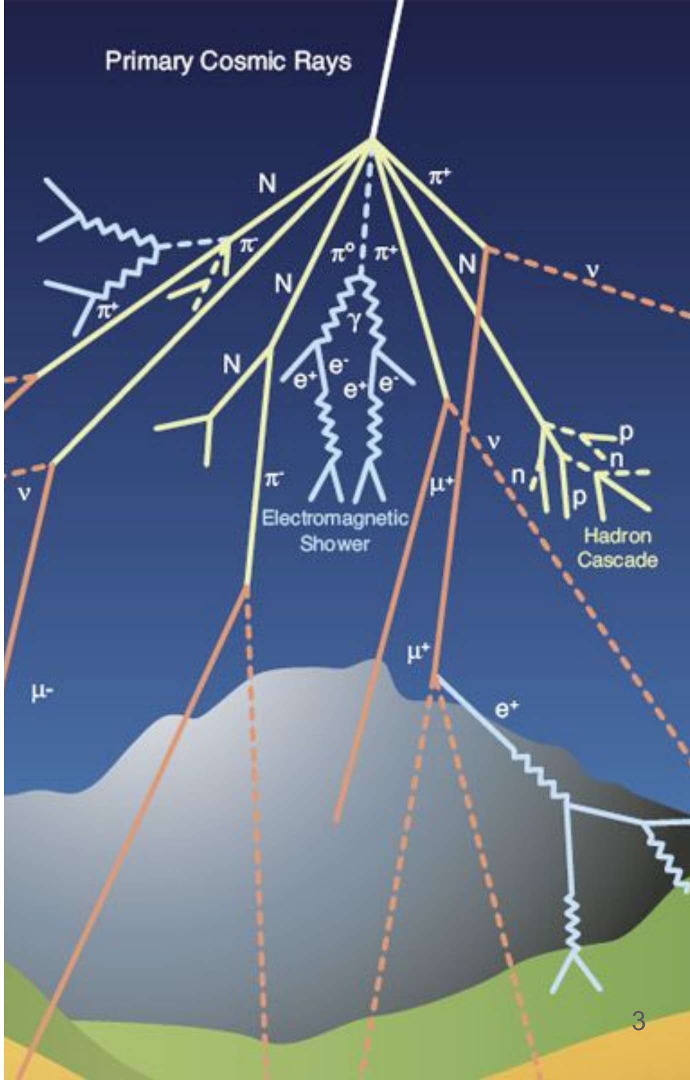
Cosmic rays

Cosmic rays hitting the upper atmosphere produces a large number of different neutral and charged particles. These particles results in the production of different phenomena

- Aurora,
- bitflip in CPU & RAM,
- **cosmogenic production of radionuclides.**

Also see Daniel Wenz & Jeanne Wilson - lectures

https://en.wikipedia.org/wiki/Radiation_hardening
A physical explanation for Aurora, W.Qiang



Cosmogenic Backgrounds

- Muons can interact with material in the detector producing n,p, radioactive isotopes
- Materials above ground experience higher activation rates
  - Source material
  - During construction
  - In transit

Isotopes produced with short (<1year) half-lives can be mitigated by allowing materials to ‘cool’ underground

- In-situ cosmogenic production
  - Can veto short-lived isotopes with time-cut after muon

Underground laboratories

- High energy protons hit $^{nat.}N$ and $^{nat.}O$ in upper atmosphere
  - **Spallation leads to production of neutron, proton, pions Kaons**
  - **K‘s and $\pi's$ decay further into muons via weak force e.g.**

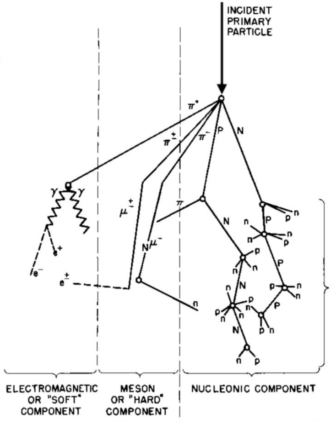
$$\pi^+ \rightarrow \mu^+ + \nu_\mu\,,\ \pi^- \rightarrow \mu^- + \overline{\nu_\mu}$$

- Rate at sea level is about $R_\mu \approx 0.01\ \mathrm{s^{-1}cm^{-2}sr^{-1}}$

*([sr] = steradian, unit of solid angle, full sphere is 4 pi)

➡ **About 1 μ/min/cm²** ➡ **1 m² detector about 170 μ/s**

- Typical energy scale of Muon’s GeV

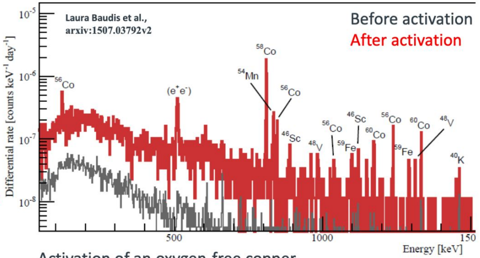


https://www.ngdc.noaa.gov/stp/image/shower.gif

Underground laboratories

- Why are muons so important to shield?
  - **The average μ energy of about 4 GeV at sea level shifts to higher energies for the remaining μs when going underground**
  - **Binding energy nucleons ~8 MeV per nucleon**

➡ **μ induced spallation and hadronic shower lead to neutrons and material activation!**



Activation of an oxygen-free copper sample after 345 days in 3470 m height.

- **Activation of detector materials lead to a whole range of different isotopes:**
  - **^{3}H, ^{39}Ar, ^{42}Ar, ^{60}Co, ^{68}Ge, ^{127}Xe, PTFE (C_2F_4) (^{19}F -> ^{17}N -> ^{17}O + β -> ^{16}O + n)**

Underground laboratories

- Why are muons so important to shield?
  - **The average μ energy of about 4 GeV at sea level shifts to higher energies for the remaining μs when going underground**
  - **Binding energy nucleons ~8 MeV per nucleon**

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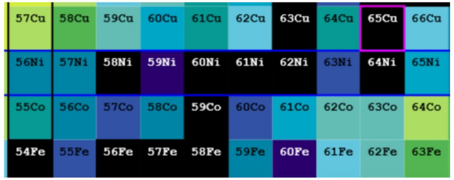


57Cu	58Cu	59Cu	60Cu	61Cu	62Cu	63Cu	64Cu	65Cu	66Cu
56Ni	57Ni	58Ni	59Ni	60Ni	61Ni	62Ni	63Ni	64Ni	65Ni
55Co	56Co	57Co	58Co	59Co	60Co	61Co	62Co	63Co	64Co
54Fe	55Fe	56Fe	57Fe	58Fe	59Fe	60Fe	61Fe	62Fe	63Fe

Image of nudat database nuclide chart https://www.nndc.bnl.gov/nudat3/

Which isotopes due to you expect to be harmful in case of copper? Do you know any of these isotopes from your lab courses?

Why do we care?

DM and 0νββ experiments try to minimise backgrounds (intrinsic and extrinsic).

- Produces intrinsic background within our target.
    - Can't be physically separated (ie, via shielding) or removed from material
- Result in increased rate:
    - Puts more strain on the DAQ system
    - Events may lie within our ROI (region of interest)
        - Typically ~keV for DM (~MeV 0νββ)
- Long lived. (Months - Years)
- Limits transportation, characterization methods.

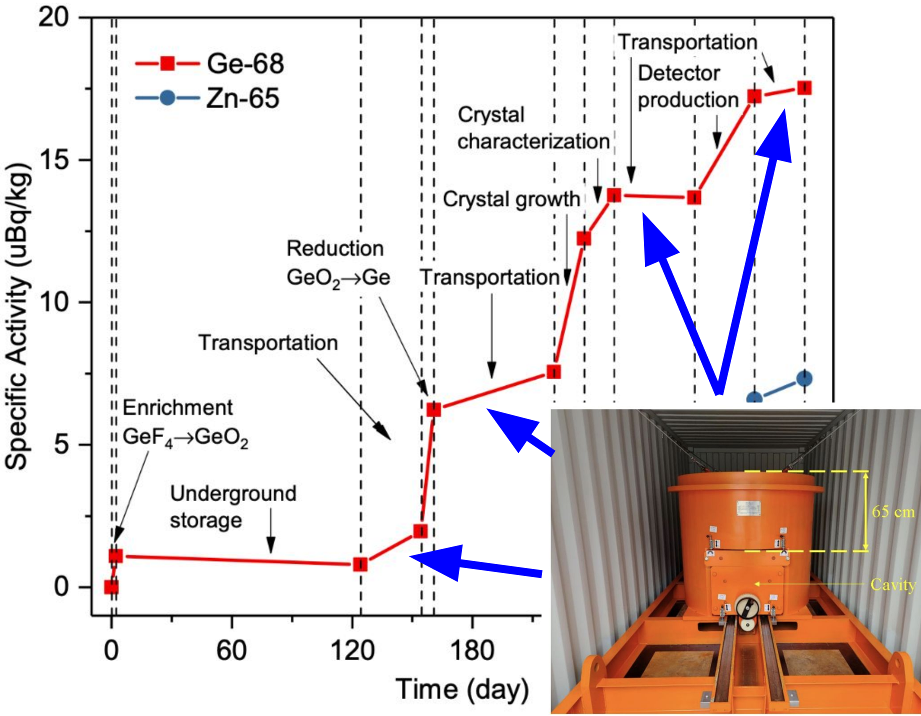


Figure 2: The transportation shield inside a shipping container.

Figure 3: The specific activities of cosmogenic radionuclides in germanium at different stages of the fabrication and transportation processes.

How do we mitigate

- Grow/Source target material with already low backgrounds

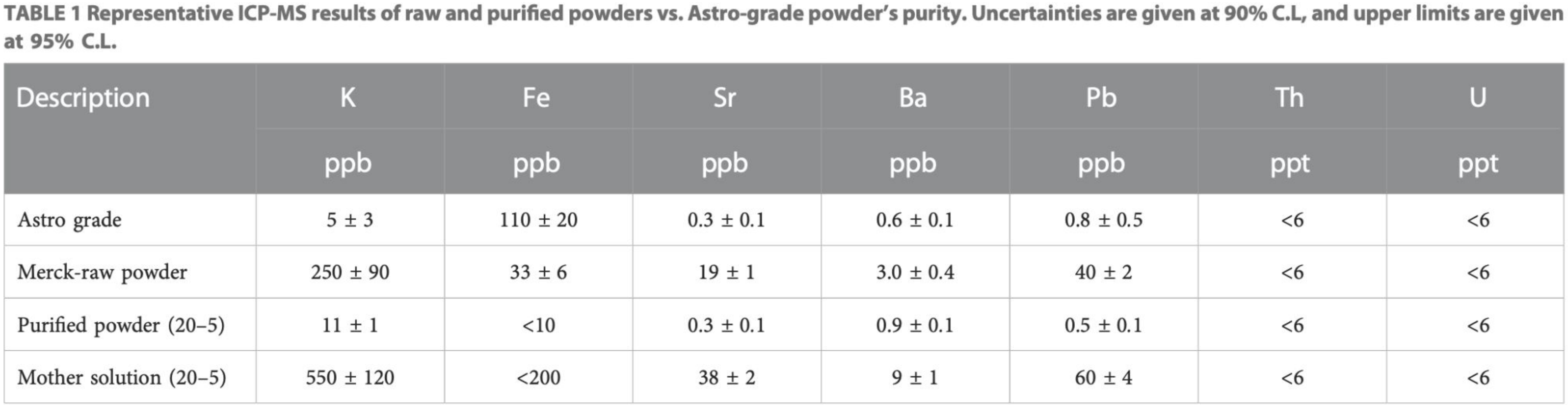


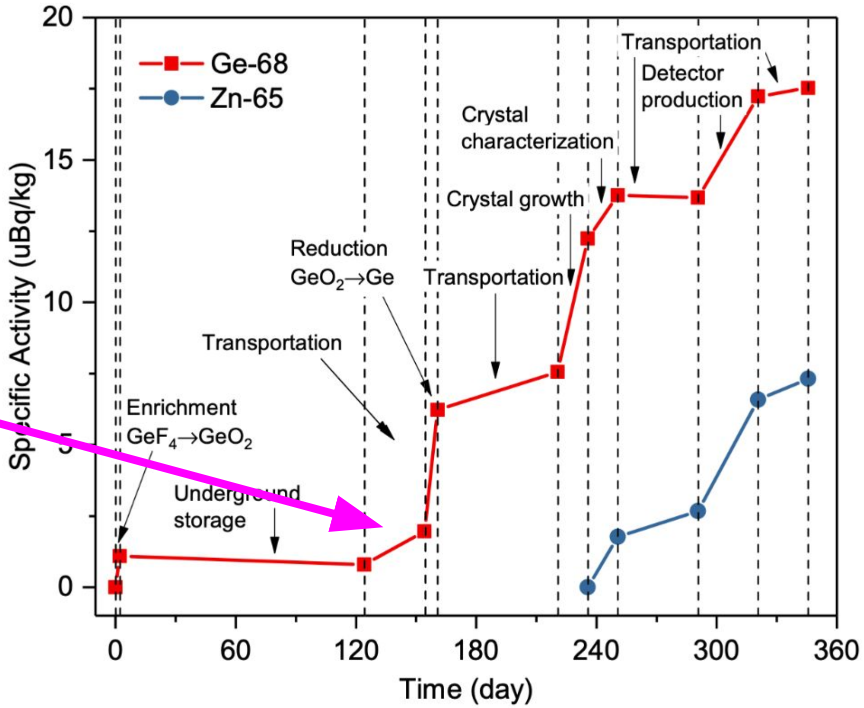
TABLE 1 **Representative ICP-MS results of raw and purified powders vs. Astro-grade powder's purity. Uncertainties are given at 90% C.L, and upper limits are given at 95% C.L.**

Description	K	Fe	Sr	Ba	Pb	Th	U
	ppb	ppb	ppb	ppb	ppb	ppt	ppt
Astro grade	5 ± 3	110 ± 20	0.3 ± 0.1	0.6 ± 0.1	0.8 ± 0.5	<6	<6
Merck-raw powder	250 ± 90	33 ± 6	19 ± 1	3.0 ± 0.4	40 ± 2	<6	<6
Purified powder (20–5)	11 ± 1	<10	0.3 ± 0.1	0.9 ± 0.1	0.5 ± 0.1	<6	<6
Mother solution (20–5)	550 ± 120	<200	38 ± 2	9 ± 1	60 ± 4	<6	<6

Purification of NaI powder for COSINE-200, Keon-Ah Shin
Mass production of ultra-pure NaI powder for COSINE-200

How do we mitigate

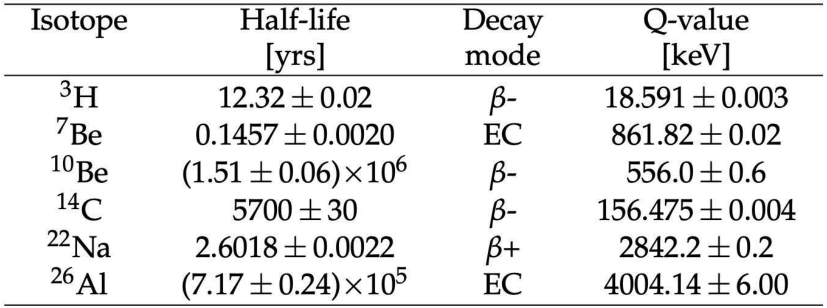
- Grow/Source target material with already low backgrounds
- Take care of how the material gets processed
- Choose low background target material dependant
- Shield the experiment
    - Maybe with a mountain ? or in the earth



How do we mitigate

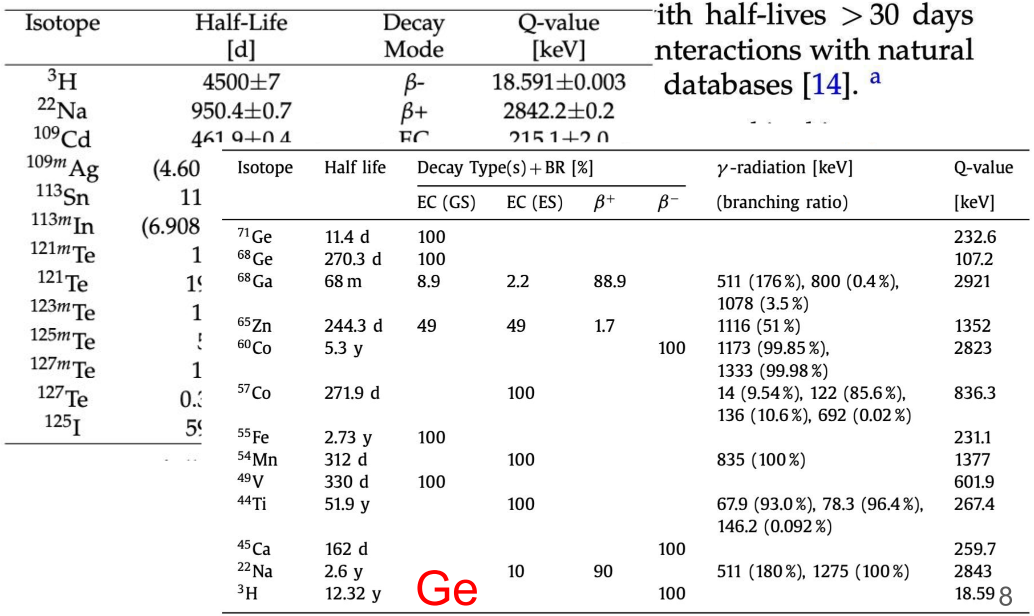
- Grow/Source target material with already low backgrounds
- Take care of how the material gets transported
- Choose low background target material dependant
- Shield the experiment
    - Maybe with a mountain ? or in the earth

Silicon



Isotope	Half-life [yrs]	Decay mode	Q-value [keV]
^{3}H	12.32 ± 0.02	β-	18.591 ± 0.003
^{7}Be	0.1457 ± 0.0020	EC	861.82 ± 0.02
^{10}Be	$(1.51 \pm 0.06) \times 10^{6}$	β-	556.0 ± 0.6
^{14}C	5700 ± 30	β-	156.475 ± 0.004
^{22}Na	2.6018 ± 0.0022	β+	2842.2 ± 0.2
^{26}Al	$(7.17 \pm 0.24) \times 10^{5}$	EC	4004.14 ± 6.00

NaI



Isotope	Half-Life [d]	Decay Mode	Q-value [keV]
^{3}H	4500±7	β-	18.591±0.003
^{22}Na	950.4±0.7	β+	2842.2±0.2
^{109}Cd	461.9±0.4	EC	215.1±2.0
^{109m}Ag	(4.60		
^{113}Sn	11		
^{113m}In	(6.908		
^{121m}Te	1		
^{121}Te	1		
^{123m}Te	1		
^{125m}Te	5		
^{127m}Te	1		
^{127}Te	0.		
^{125}I	5		

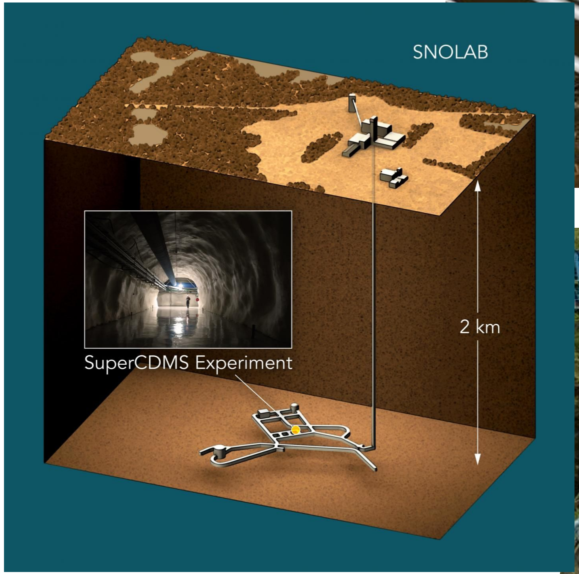
ith half-lives > 30 days
nteractions with natural
databases [14]. [a]

Isotope	Half life	Decay Type(s) + BR [%]				γ-radiation [keV] (branching ratio)	Q-value [keV]
		EC (GS)	EC (ES)	β^{+}	β^{-}		
^{71}Ge	11.4 d	100					232.6
^{68}Ge	270.3 d	100					107.2
^{68}Ga	68 m	8.9	2.2	88.9		511 (176 %), 800 (0.4 %), 1078 (3.5 %)	2921
^{65}Zn	244.3 d	49	49	1.7		1116 (51 %)	1352
^{60}Co	5.3 y				100	1173 (99.85 %), 1333 (99.98 %)	2823
^{57}Co	271.9 d		100			14 (9.54 %), 122 (85.6 %), 136 (10.6 %), 692 (0.02 %)	836.3
^{55}Fe	2.73 y	100					231.1
^{54}Mn	312 d		100			835 (100 %)	1377
^{49}V	330 d	100					601.9
^{44}Ti	51.9 y		100			67.9 (93.0 %), 78.3 (96.4 %), 146.2 (0.092 %)	267.4
^{45}Ca	162 d				100		259.7
^{22}Na	2.6 y		10	90		511 (180 %), 1275 (100 %)	2843
^{3}H	12.32 y				100		18.59

Ge

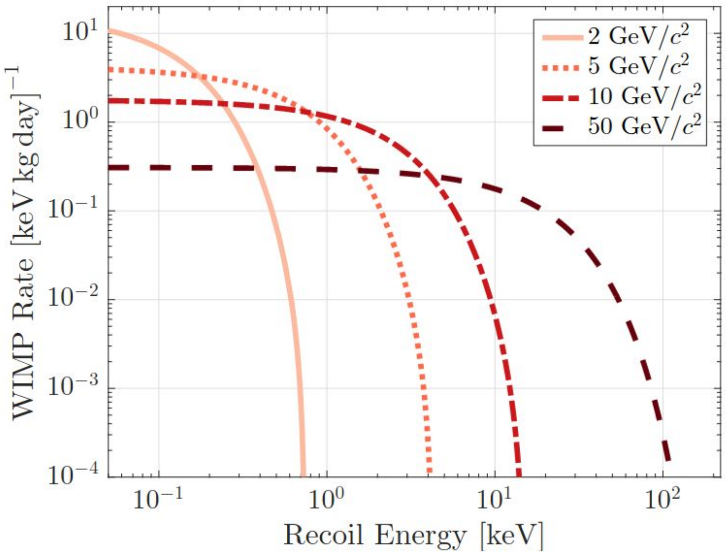
How do we mitigate

- Grow/Source target material with already low backgrounds
- Take care of how the material gets transported
- Choose low background target material dependant
- Shield the experiment
  - Maybe with a mountain ? or in the earth

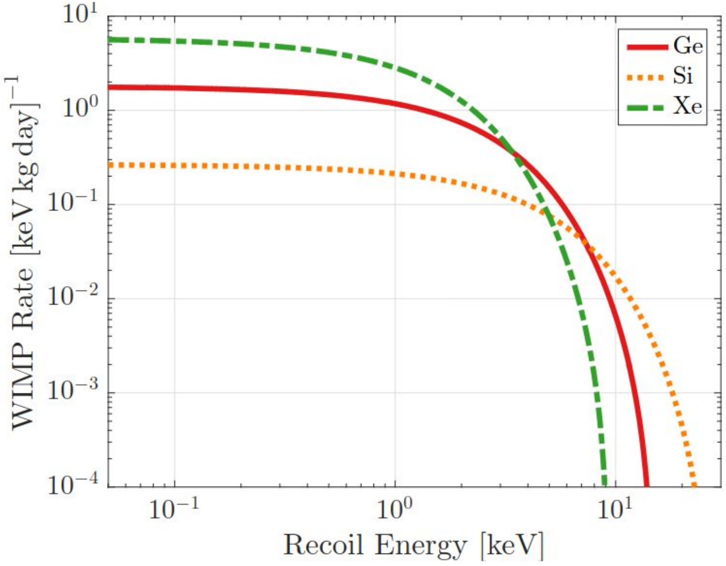


Impact on Dark Matter (based only in energy)

- Nuclear recoil energy
  - ~ 1-100 keV



Germanium target

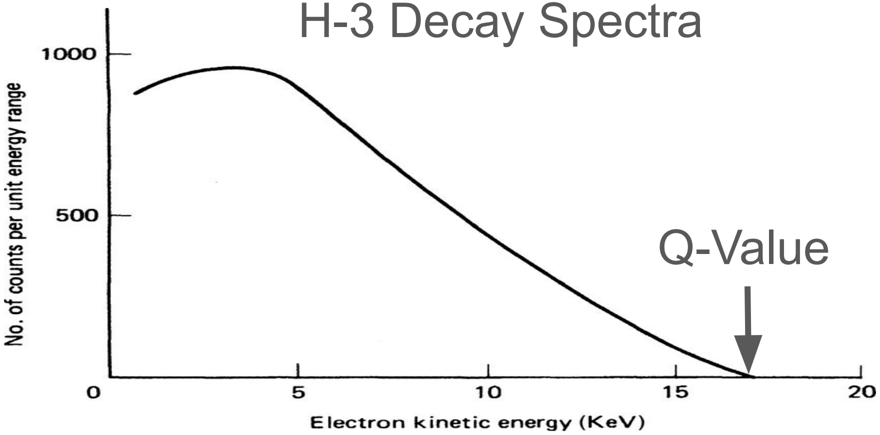


10 GeV/c^2 WIMP

Impact on DM searches

~ 1-100 keV

- Si



H-3 Decay Spectra

Q-Value

Isotope	Half-Life [years]	Decay Mechanism	Q-value [keV]
H-3	12.3	β-	18.6
Be-7	0.146	EC	861
Be-10	$1.51 \cdot 10^6$	β-	556
C-14	5700	β-	156
Na-22	2.602	β+	2840
Al-26	$7.17 \cdot 10^5$	EC	4000

Impact on DM searches

~ 1-100 keV

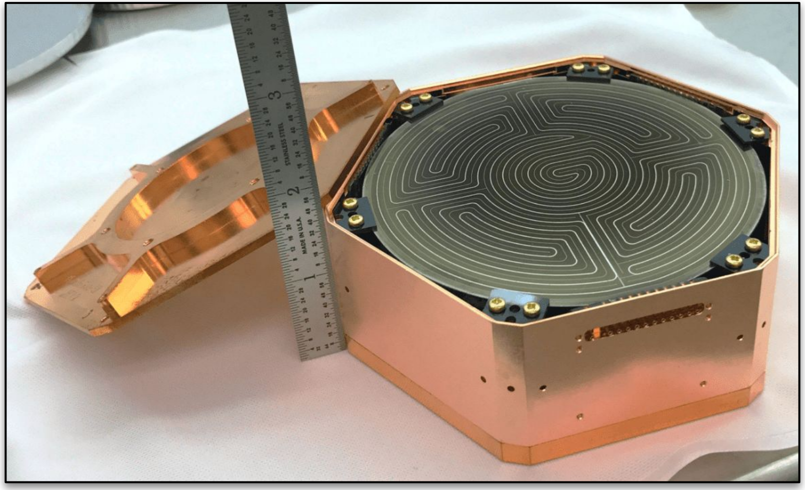
- NaI

Isotope	Half-Life [years]	Decay Mechanism	Q-value [keV]
H-3	12.32	β-	18.6
Na-22	2.6018	β+	2840
Cd-109	1.26	EC	215
Sn-113	0.31	EC	1040
Te-121m	0.45	IT	294
Te-123m	0.33	IT	247
I-125	0.16	EC	186
Sb-125	2.75856	β-	2360
Te-125m	0.157	IT	145
Te-127m	0.289	β-	703

Impact on DM searches

~ 1-100 keV

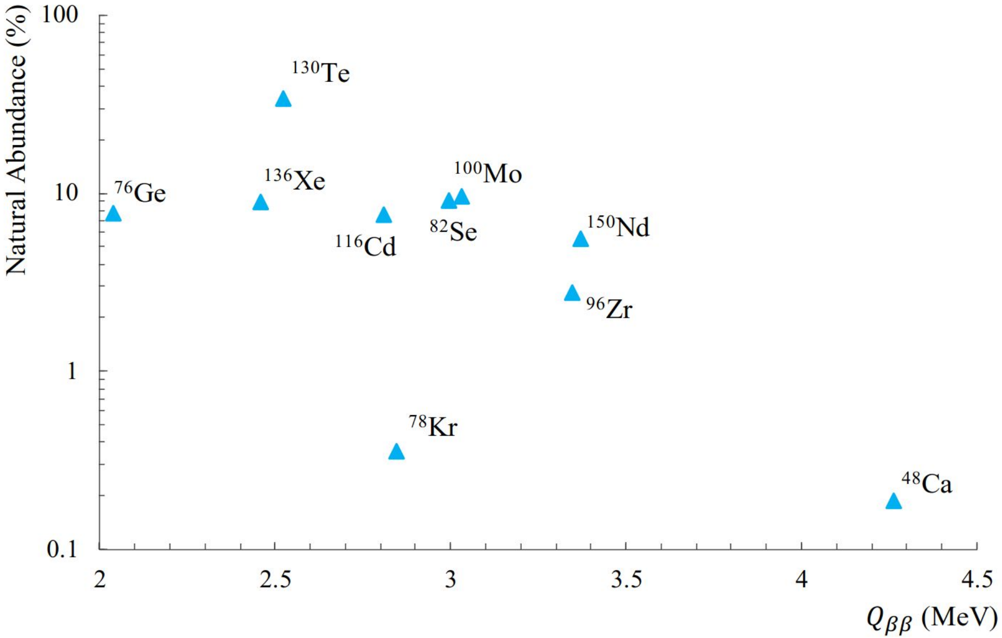
- Ge



Isotope	Half-Life [day]	Decay Mechanism	Q-value [keV]
V-49	330	EC	602
Mn-54	312.19	EC	542
Fe-55	1002.7	EC	231
Co-57	271.82	EC	836
Co-58	70.85	EC	2310
Co-60	1924.0	β-	2820
Ge-68	270.95	EC	107
Zn-65	244.01	EC	1350
H-3	4496.8	β-	18.6

Impact on $0\nu\beta\beta$ searches

Ge-76 can undergo $\beta\beta$ decay



Impact on $0\nu\beta\beta$ searches

$Q_{\beta\beta}$ value in Germanium is 2039 keV

Isotope	Half-Life [day]	Decay Mechanism	Q-value [keV]
V-49	330	EC	602
Mn-54	312.19	EC	542
Fe-55	1002.7	EC	231
Co-57	271.82	EC	836
Co-58	70.85	EC	2310
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Ge-68	270.95	EC	107
Zn-65	244.01	EC	1350
H-3	4496.8	β-	18.6

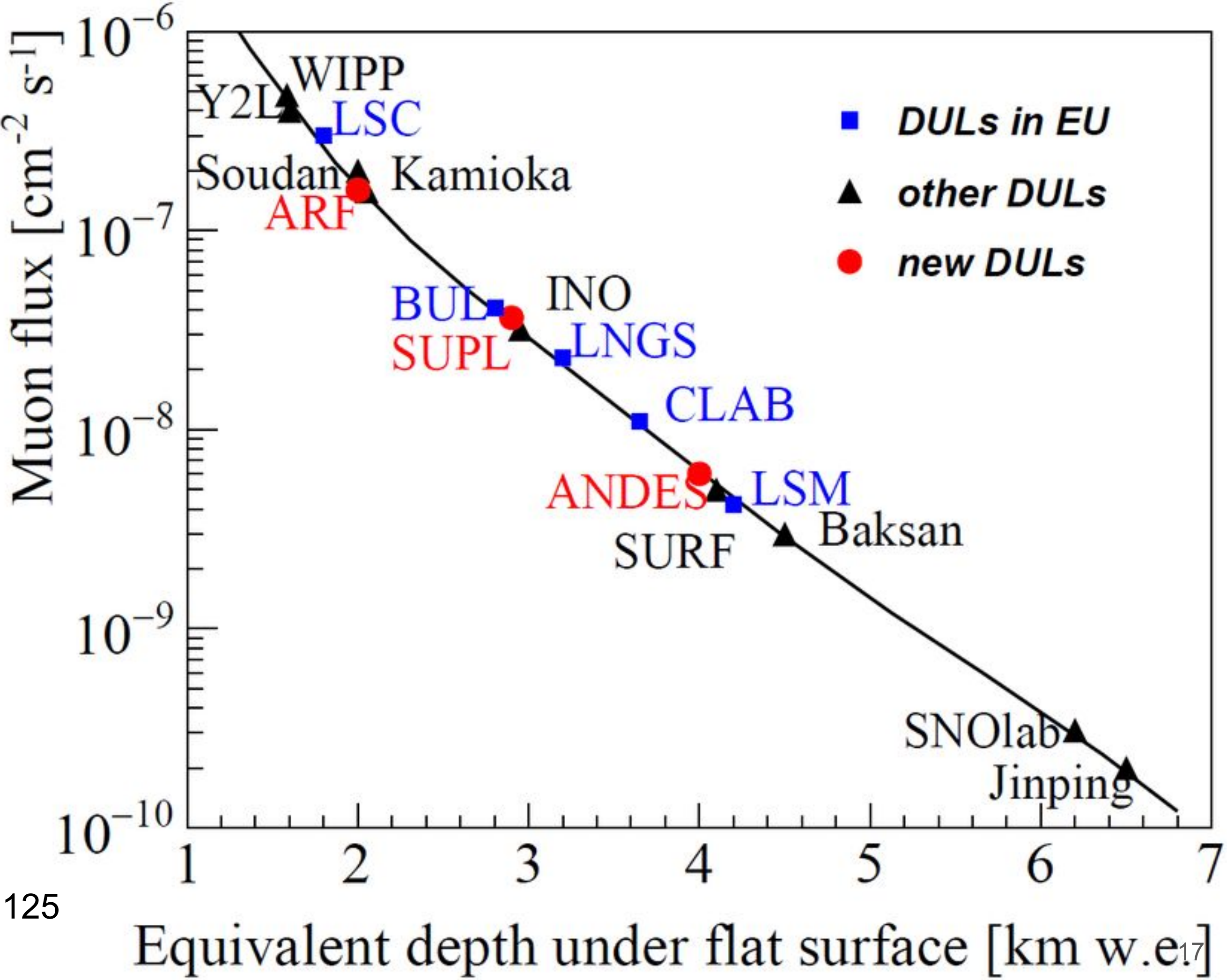
Impact on $0\nu\beta\beta$ searches

$Q_{\beta\beta}$ value in Germanium is 2039 keV

Isotope	Half-Life [day]	Decay Mechanism	Q-value [keV]
V-49	330	EC	602
Mn-54	312.19	EC	542
Fe-55	2.747 y	EC	231
Co-57	271.82	EC	836
Co-58	70.85	EC	2310
Co-60	1924.0 (~5 y)	β-	2820
Ge-68	270.95	EC	107
Zn-65	244.01	EC	1350
H-3	12.32 y	β-	18.6

Cosmic Ray Flux

- We approximate all cosmic ray flux as muon flux
- Modeled overburden flux as an exponential function



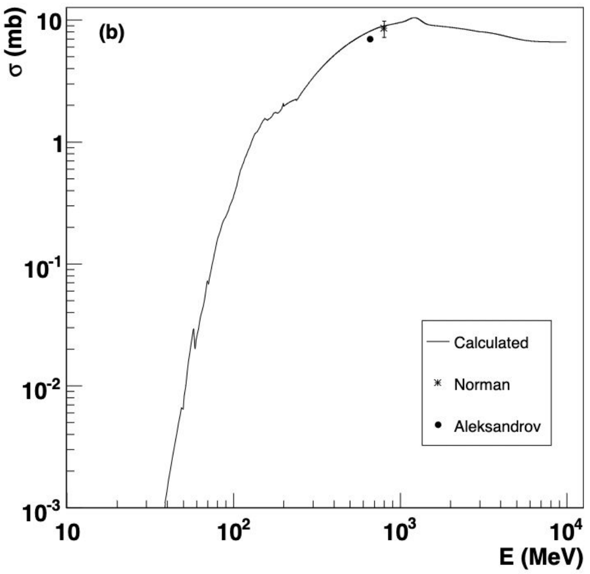
https://arxiv.org/pdf/astro-ph/0512125

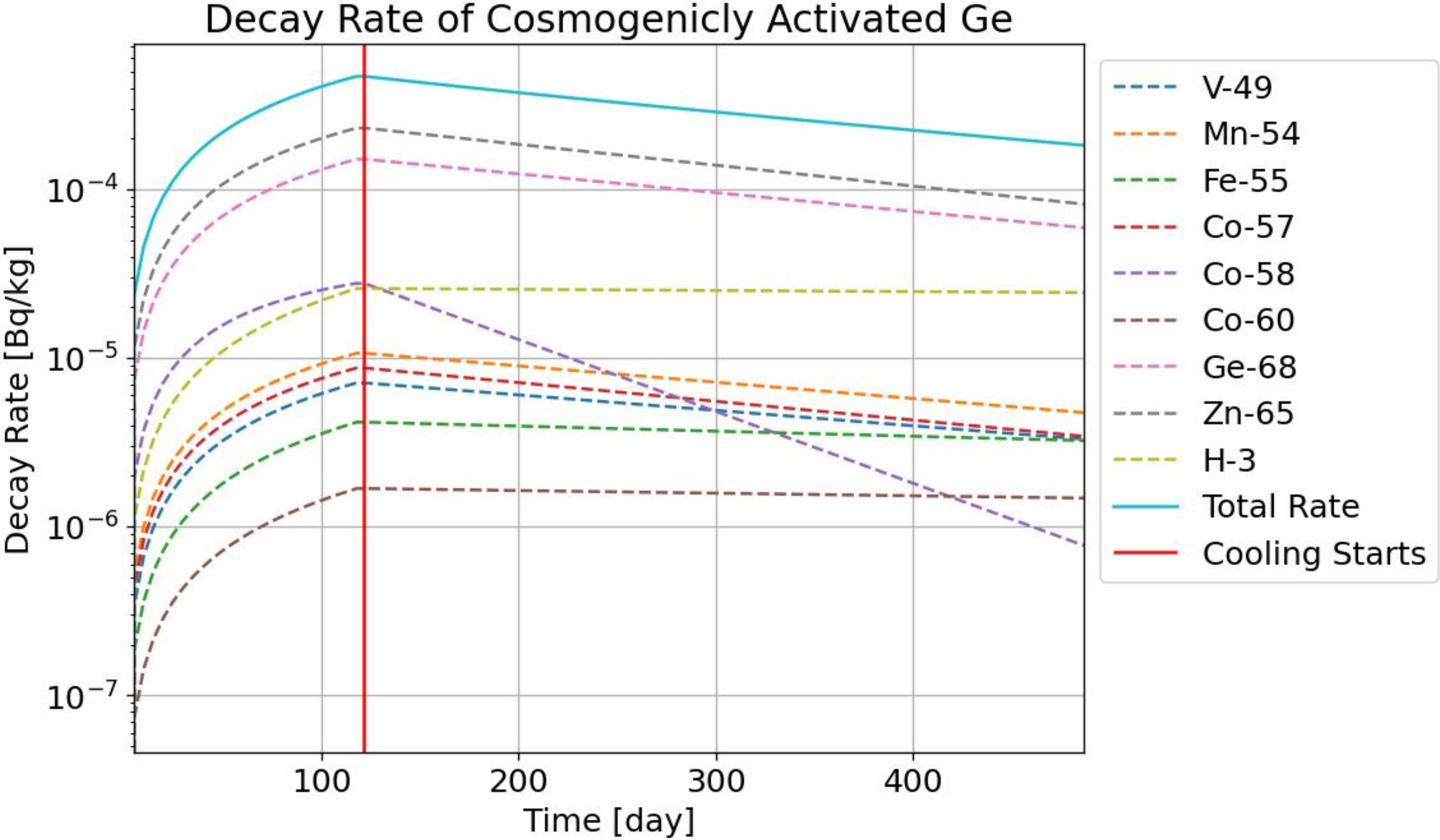
https://arxiv.org/pdf/0709.3472

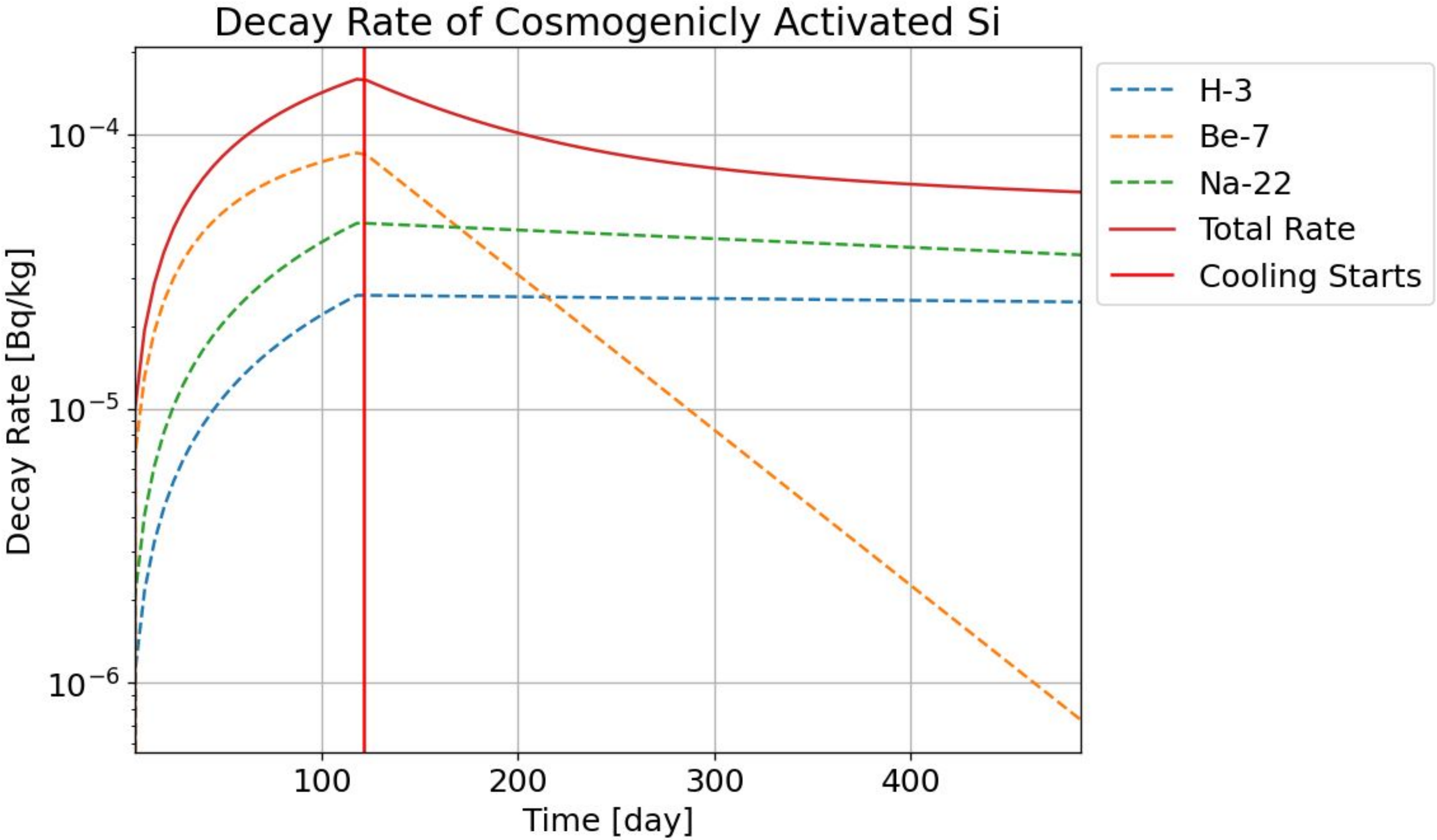
Modeling Cosmogenic Activation

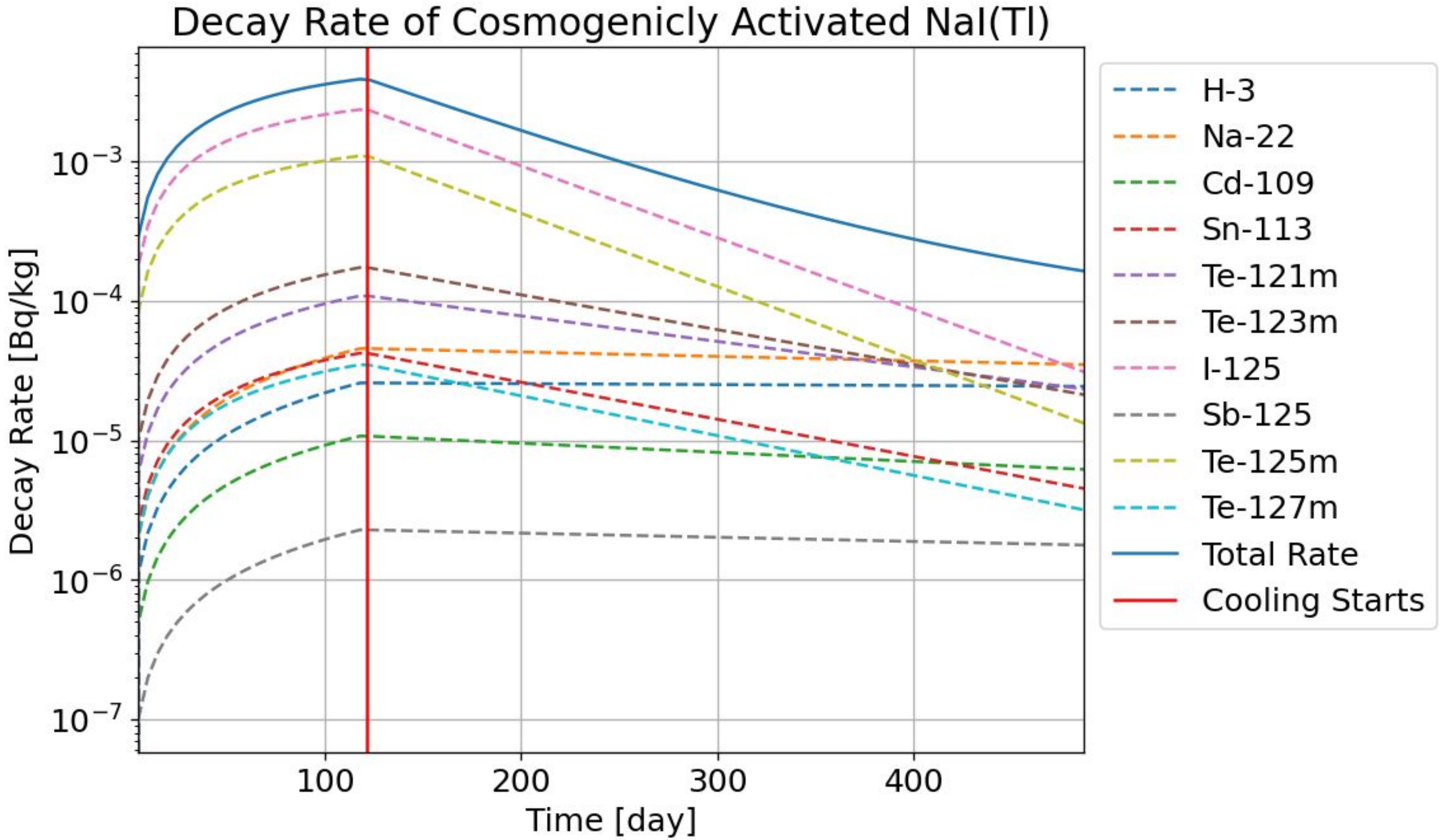
- Activation rate: $R(E,x) = \int \sigma(E) \frac{d\phi(E,x)}{dE} dE$
- Approximate a constant cross section for large energies $\longrightarrow R \propto \phi$
- Benchmarking assumptions:
  1. Detector crystal is grown/assembled, transported, and tested for 120 day (⅓ yr) - activation time
  2. Cooldown time occurs for 1 yr at 6 km w.e. (SNOLAB depth)

Proton production of Co-60 in nat. Ge




Decay Rate of Cosmogenicly Activated Ge
Decay Rate [Bq/kg]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
100
200
300
400
Time [day]
V-49
Mn-54
Fe-55
Co-57
Co-58
Co-60
Ge-68
Zn-65
H-3
Total Rate
Cooling Starts


Decay Rate of Cosmogenicly Activated Si
Decay Rate [Bq/kg]
10^{-4}
10^{-5}
10^{-6}
100
200
300
400
Time [day]
H-3
Be-7
Na-22
Total Rate
Cooling Starts


Decay Rate of Cosmogenicly Activated NaI(Tl)
Decay Rate [Bq/kg]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
100
200
300
400
Time [day]
H-3
Na-22
Cd-109
Sn-113
Te-121m
Te-123m
I-125
Sb-125
Te-125m
Te-127m
Total Rate
Cooling Starts

Comparing Results to Detector Rates

Overburden [km w.e.]	Si [dru]	Ge [dru]	NaI(Tl) [dru]
0	0.14(3)	0.19(3)	0.20(12)
1	0.056(5)	0.072(12)	0.07(4)
3	0.030(6)	0.038(6)	0.039(16)
6	0.029(6)	0.036(6)	0.037(14)

Simulated cosmogenic activities at various overburden during assembly. (120 days of assembly, 30 days travel at sea level, 365 day cool down at 6 km w.e.)

- dru = events/kg/keV/day
- Across various experiments (SuperCDMS, EDELWEISS, COSINE, SABRE) cosmogenic activation contributes O(0.1) dru
- Total backgrounds O(1) dru
- Cosmogenic background reduction is limited by travel

Code of Conduct

Purpose

- This policy aims to foster a community based on the principles of equity, diversity, and inclusivity to best support the scientific research carried out by the Collaboration

Key points:

- Professional Conduct
    - Discrimination
    - Inappropriate behaviour
- Ombudsperson

Code of Conduct

Professional Conduct

- All individuals are expected to treat each other with respect and professionalism
- Collaborators are expected to refrain from behaviours and actions that may lead to discrimination, harassment, or retaliation:
  - Ability status
  - Age
  - Educational background
  - Gender, gender identity, or gender expression
  - Political affiliation
  - Race, nationality, or ethnicity
  - Religious or philosophical beliefs
  - Sexual orientation or marital status

Code of Conduct

Ombudsperson

- The Ombudsperson(s) serves as a confidential point of contact for informal exploration of complaints and possible unofficial resolution of any issues

- 2 spokespersons, one early career (graduate student or postdoctoral researcher), and one faculty equivalent member. Efforts should be taken to vary the institution and gender identity of the candidates.

- The Ombudsperson(s) can either advise the complainant to address the situation by attempting to facilitate a conversation between those involved (with the permission of the complainant), provide information, or refer the complainant to appropriate resources to escalate the situation.

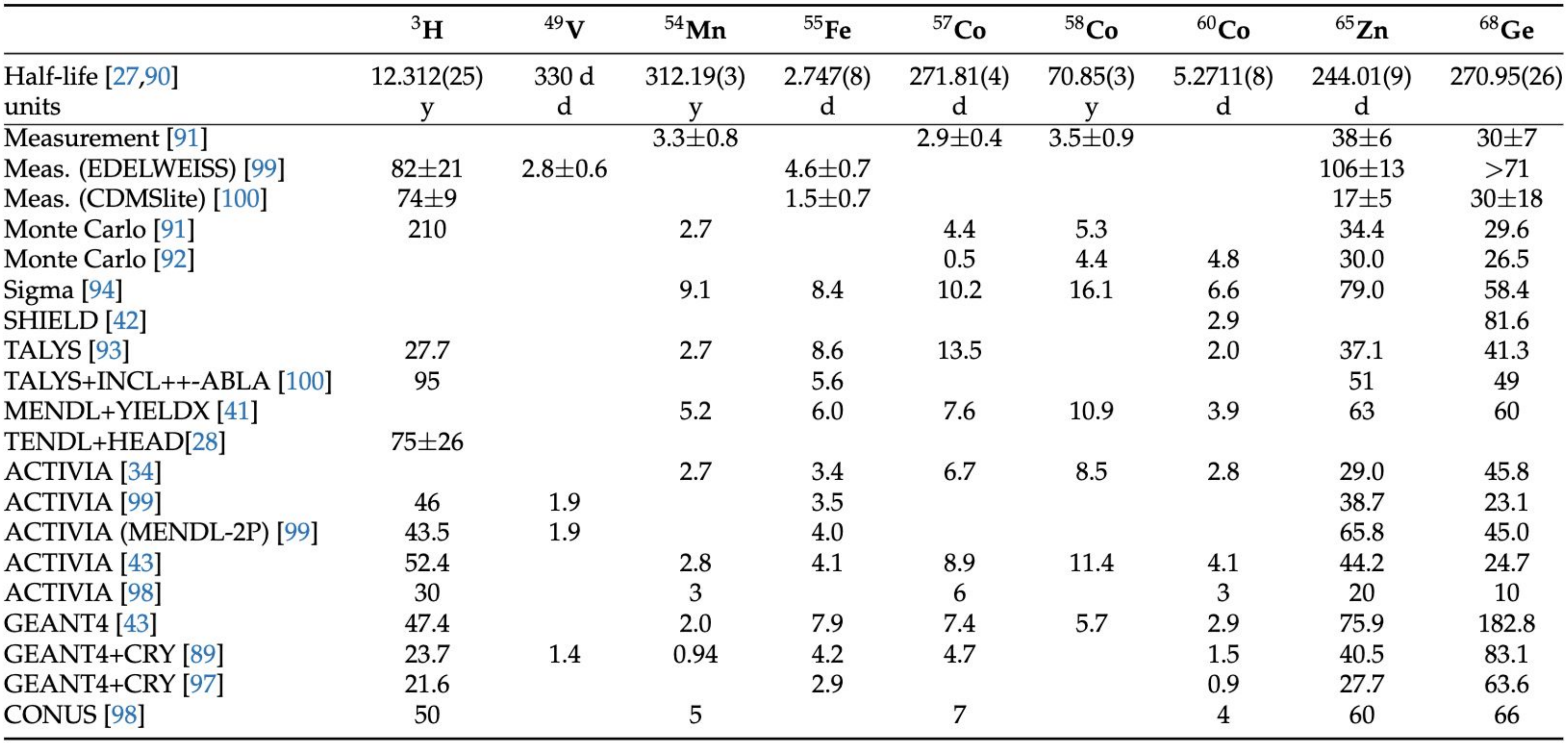
Summary

- Cosmogenic Backgrounds in 0vBB in Ge searches are dominated by Co-60
- Main cosmogenic backgrounds in
  - Ge are H-3, Co-60, Ge-68
  - Si are H-3, Na-22
  - NaI(Ti) are H-3, Na-22, Cd-109 (after cool time > 1yr)
- Constructing detector with overburden can reduce decay rate by an order of magnitude
- Future calculations should be done using ACTIVIA and GEANT4 to improve exposure accuracy.

Bonus Slides

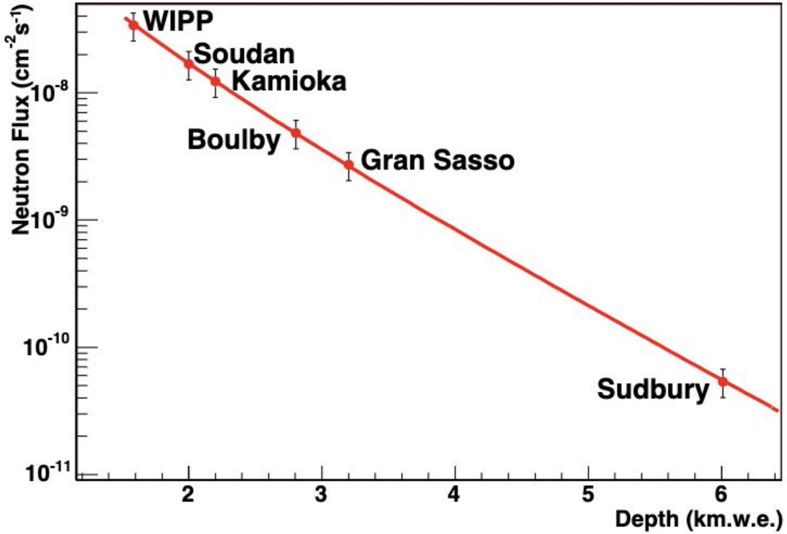
https://arxiv.org/pdf/2010.02381

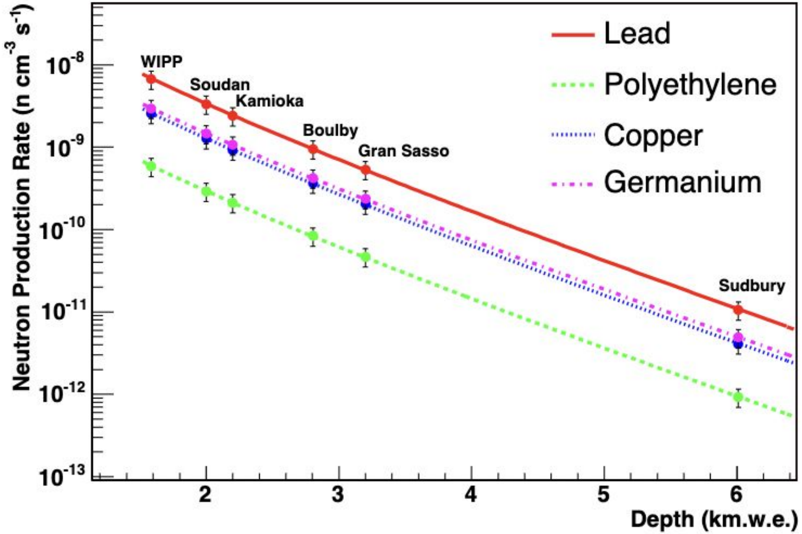
Cosmogenic Activation Systematics



	^{3}H	^{49}V	^{54}Mn	^{55}Fe	^{57}Co	^{58}Co	^{60}Co	^{65}Zn	^{68}Ge
Half-life [27,90]	12.312(25)	330 d	312.19(3)	2.747(8)	271.81(4)	70.85(3)	5.2711(8)	244.01(9)	270.95(26)
units	y	d	y	d	d	y	d	d	
Measurement [91]			3.3±0.8		2.9±0.4	3.5±0.9		38±6	30±7
Meas. (EDELWEISS) [99]	82±21	2.8±0.6		4.6±0.7				106±13	>71
Meas. (CDMSlite) [100]	74±9			1.5±0.7				17±5	30±18
Monte Carlo [91]	210		2.7		4.4	5.3		34.4	29.6
Monte Carlo [92]					0.5	4.4	4.8	30.0	26.5
Sigma [94]			9.1	8.4	10.2	16.1	6.6	79.0	58.4
SHIELD [42]							2.9		81.6
TALYS [93]	27.7		2.7	8.6	13.5		2.0	37.1	41.3
TALYS+INCL++-ABLA [100]	95			5.6				51	49
MENDL+YIELDX [41]			5.2	6.0	7.6	10.9	3.9	63	60
TENDL+HEAD[28]	75±26								
ACTIVIA [34]			2.7	3.4	6.7	8.5	2.8	29.0	45.8
ACTIVIA [99]	46	1.9		3.5				38.7	23.1
ACTIVIA (MENDL-2P) [99]	43.5	1.9		4.0				65.8	45.0
ACTIVIA [43]	52.4		2.8	4.1	8.9	11.4	4.1	44.2	24.7
ACTIVIA [98]	30		3		6		3	20	10
GEANT4 [43]	47.4		2.0	7.9	7.4	5.7	2.9	75.9	182.8
GEANT4+CRY [89]	23.7	1.4	0.94	4.2	4.7		1.5	40.5	83.1
GEANT4+CRY [97]	21.6			2.9			0.9	27.7	63.6
CONUS [98]	50		5		7		4	60	66

Neutron Flux

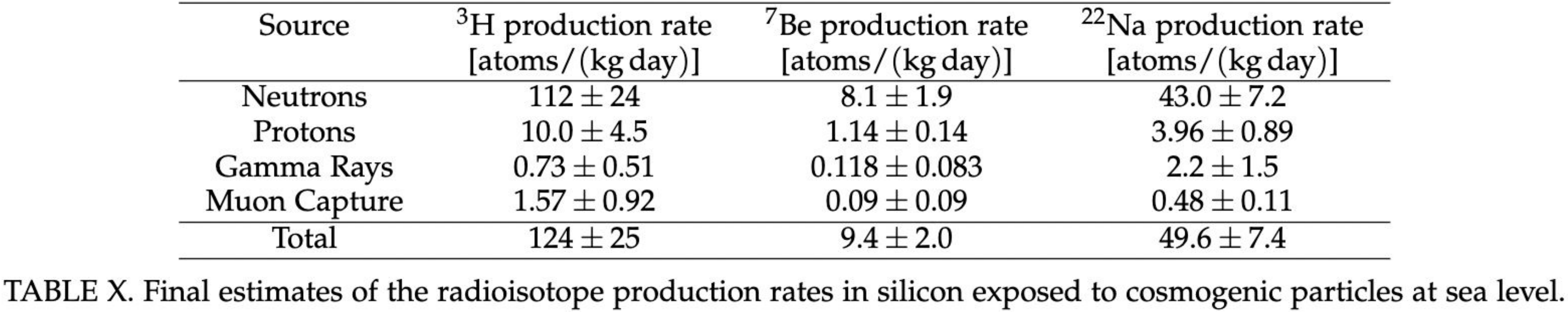




https://arxiv.org/pdf/astro-ph/0512125

https://arxiv.org/pdf/2007.10584

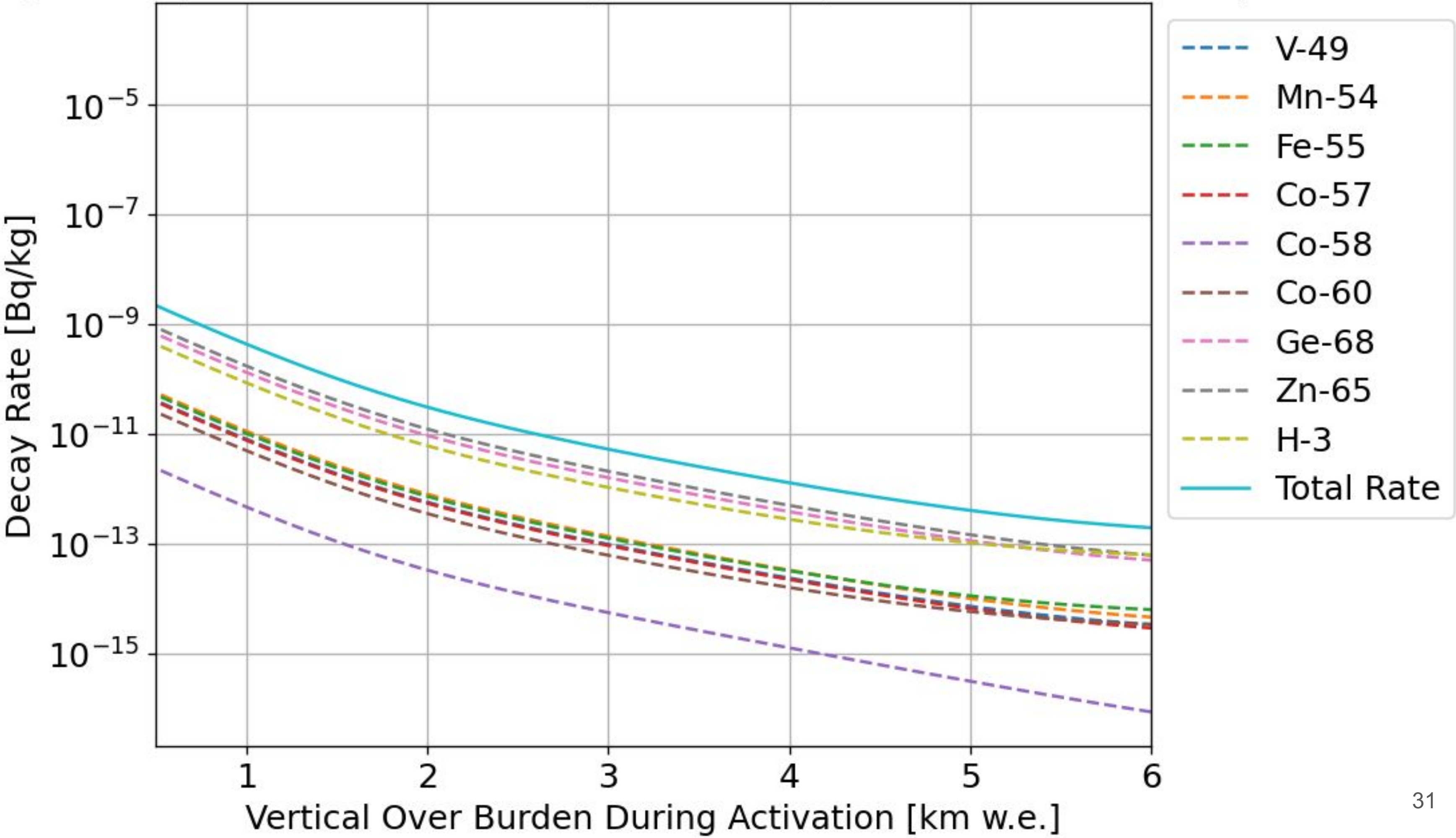
Cosmic Ray Production Breakup

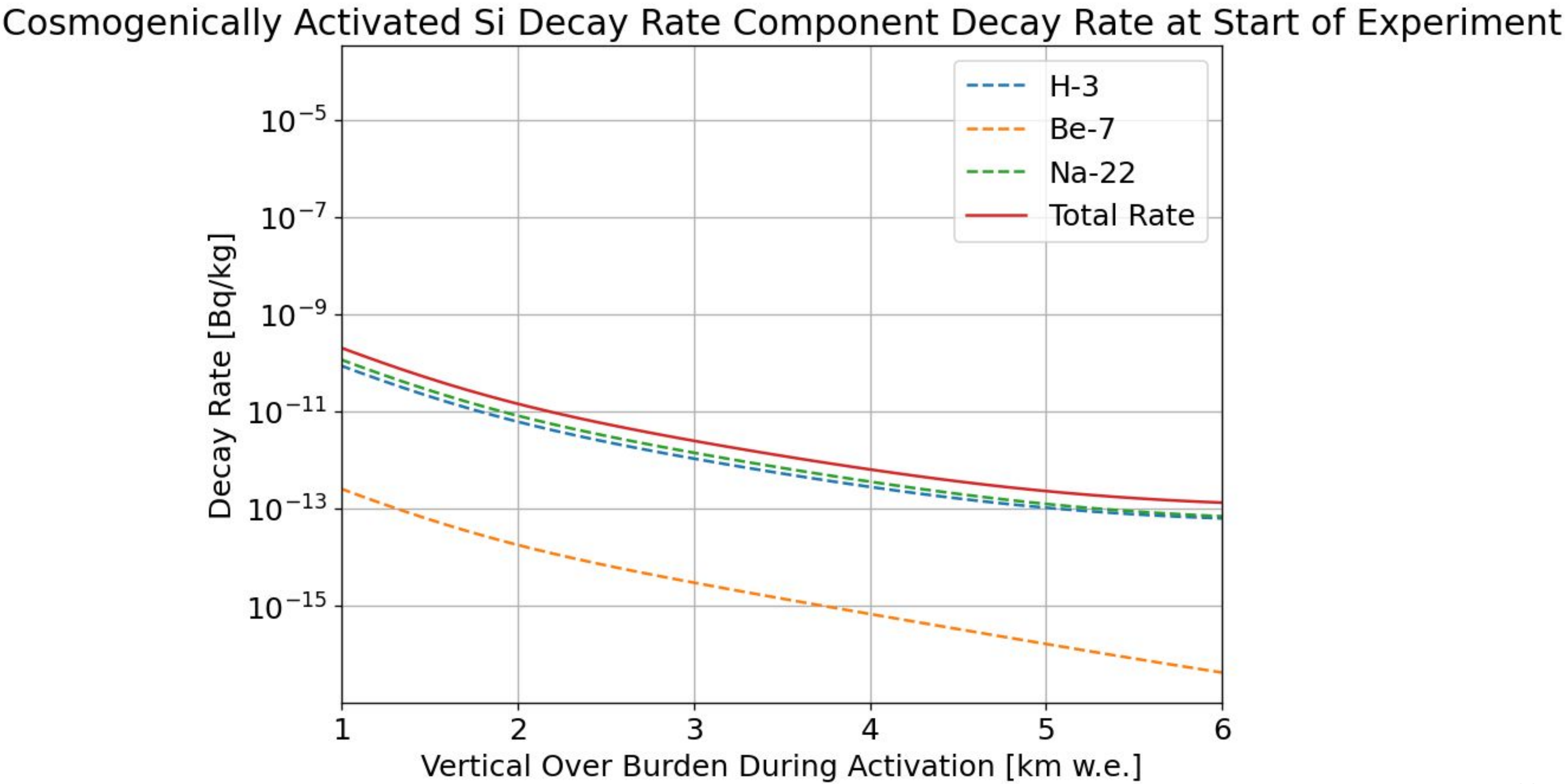


Source	^{3}H production rate [atoms/(kg day)]	^{7}Be production rate [atoms/(kg day)]	^{22}Na production rate [atoms/(kg day)]
Neutrons	112 ± 24	8.1 ± 1.9	43.0 ± 7.2
Protons	10.0 ± 4.5	1.14 ± 0.14	3.96 ± 0.89
Gamma Rays	0.73 ± 0.51	0.118 ± 0.083	2.2 ± 1.5
Muon Capture	1.57 ± 0.92	0.09 ± 0.09	0.48 ± 0.11
Total	124 ± 25	9.4 ± 2.0	49.6 ± 7.4

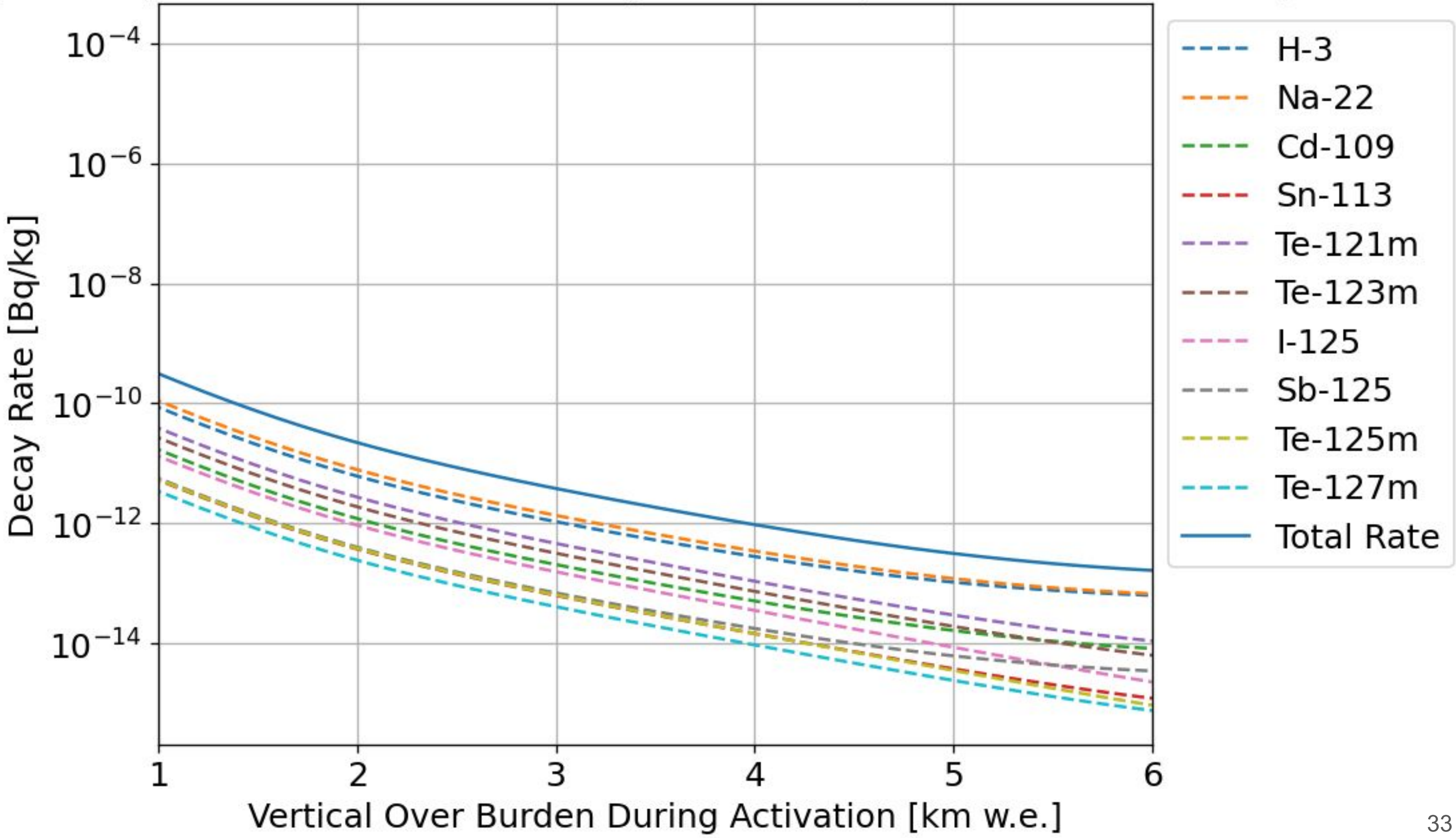
TABLE X. Final estimates of the radioisotope production rates in silicon exposed to cosmogenic particles at sea level.

Cosmogenically Activated Ge Decay Rate Component at Start of Experiment




Cosmogenically Activated Si Decay Rate Component Decay Rate at Start of Experiment
H-3
Be-7
Na-22
Total Rate
Decay Rate [Bq/kg]
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
1
2
3
4
5
6
Vertical Over Burden During Activation [km w.e.]

Cosmogenically Activated NaI(Ti) Decay Rate Component at Start of Experiment



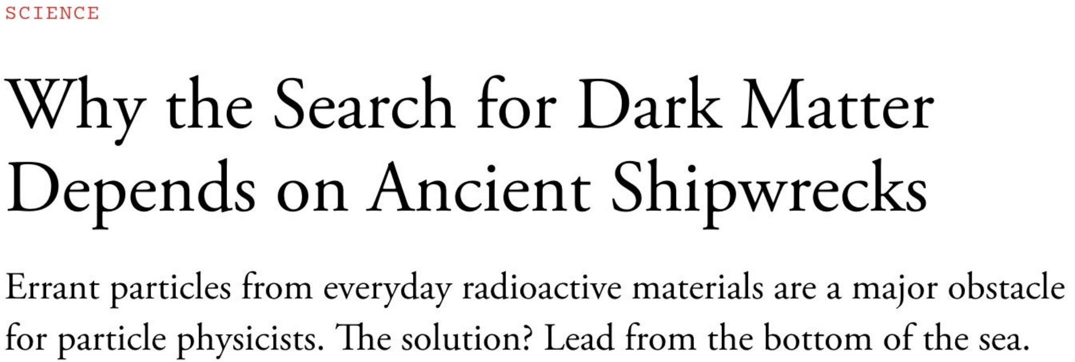
Cosmogenic Backgrounds

- Muons can interact with material in the detector producing n,p, radioactive isotopes
- Materials above ground experience higher activation rates
  - Source material
  - During construction
  - In transit

As was seen earlier in the week

Isotopes produced with short (<1year) half-lives can be mitigated by allowing materials to ‘cool’ underground

- In-situ cosmogenic production
  - Can veto short-lived isotopes with time-cut after muon



SCIENCE

Why the Search for Dark Matter Depends on Ancient Shipwrecks

Errant particles from everyday radioactive materials are a major obstacle for particle physicists. The solution? Lead from the bottom of the sea.

/ PLANET EARTH

Particle Physics Experiment Will Use Ancient Lead From a Roman Shipwreck

Discoblog

By Smriti Rao

Apr 16, 2010 5:28 PM | Last Updated Jul 13, 2023 11:16 AM

Ancient Lead Can Help Experimental Physics

MISIS National University of Science and Technology

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The National University of Science and Technology MISiS ⟶

Jun 21, 2019, 05:00 ET

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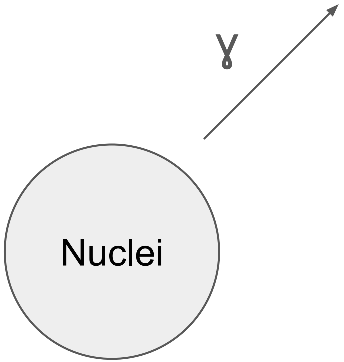
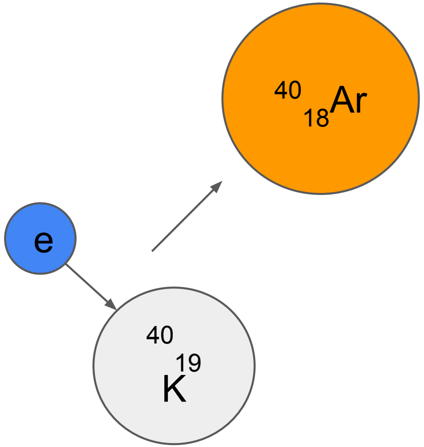
Radiogenic processes

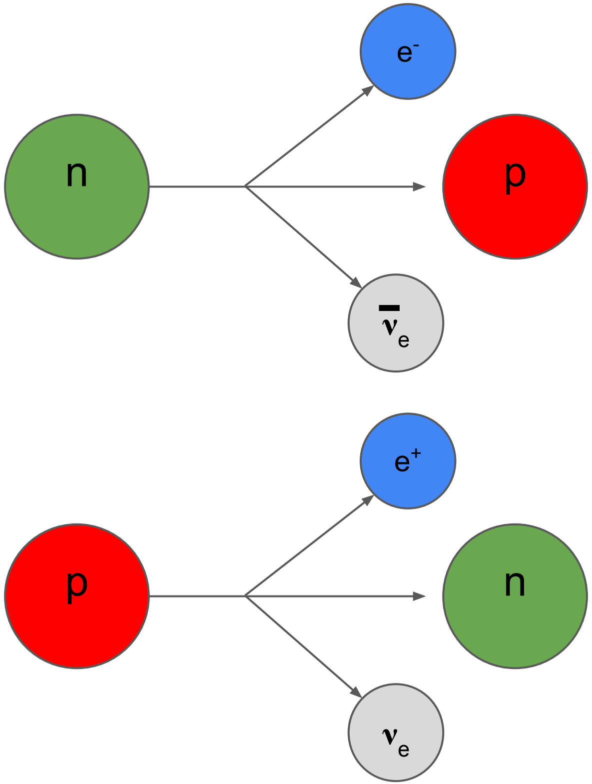


Isometric Transition:
Decay from excited state
$X^m \rightarrow X + \gamma$



Electron Capture:
Energy release by absorption

$^{40}_{19}K + {}^{0}_{-1}e \rightarrow {}^{40}_{18}Ar$



Beta decay:
Results in production of
electron/positron

Production process

Cosmic rays, largely result in the production of muons, neutrons and protons (amongst others).

Neutrons and Protons:

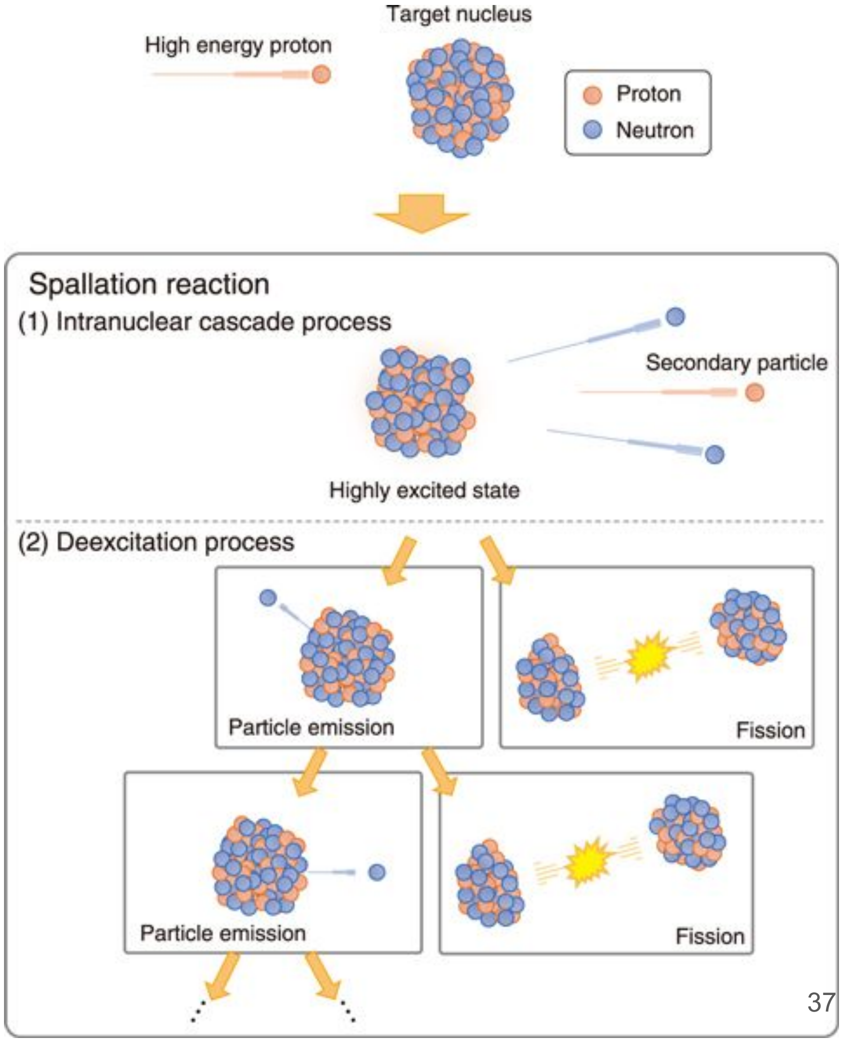
- Produces spallation within nucleons

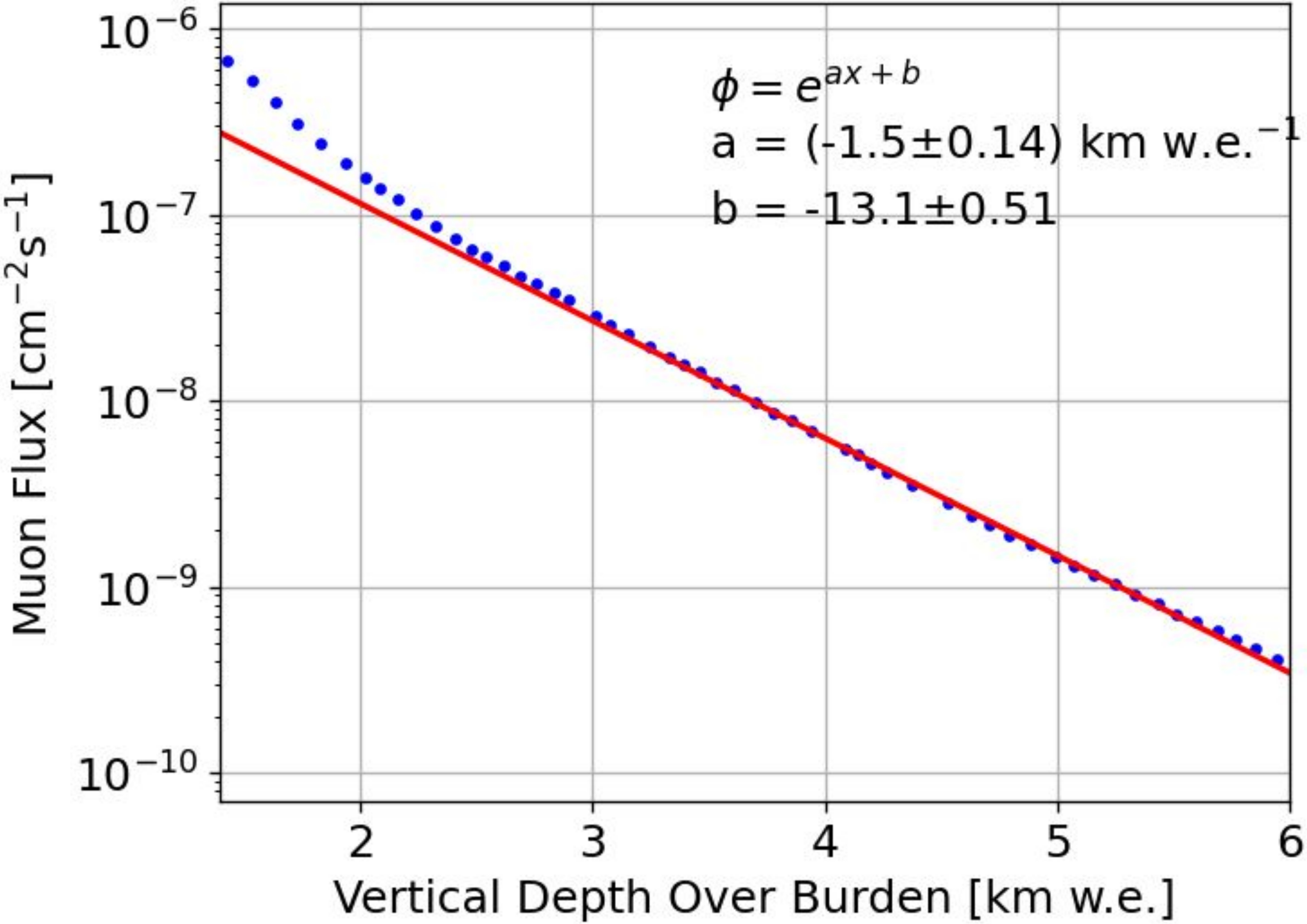
Muons:

- Can directly produce spallation or Induce spallation

Results in radiogenic particles.

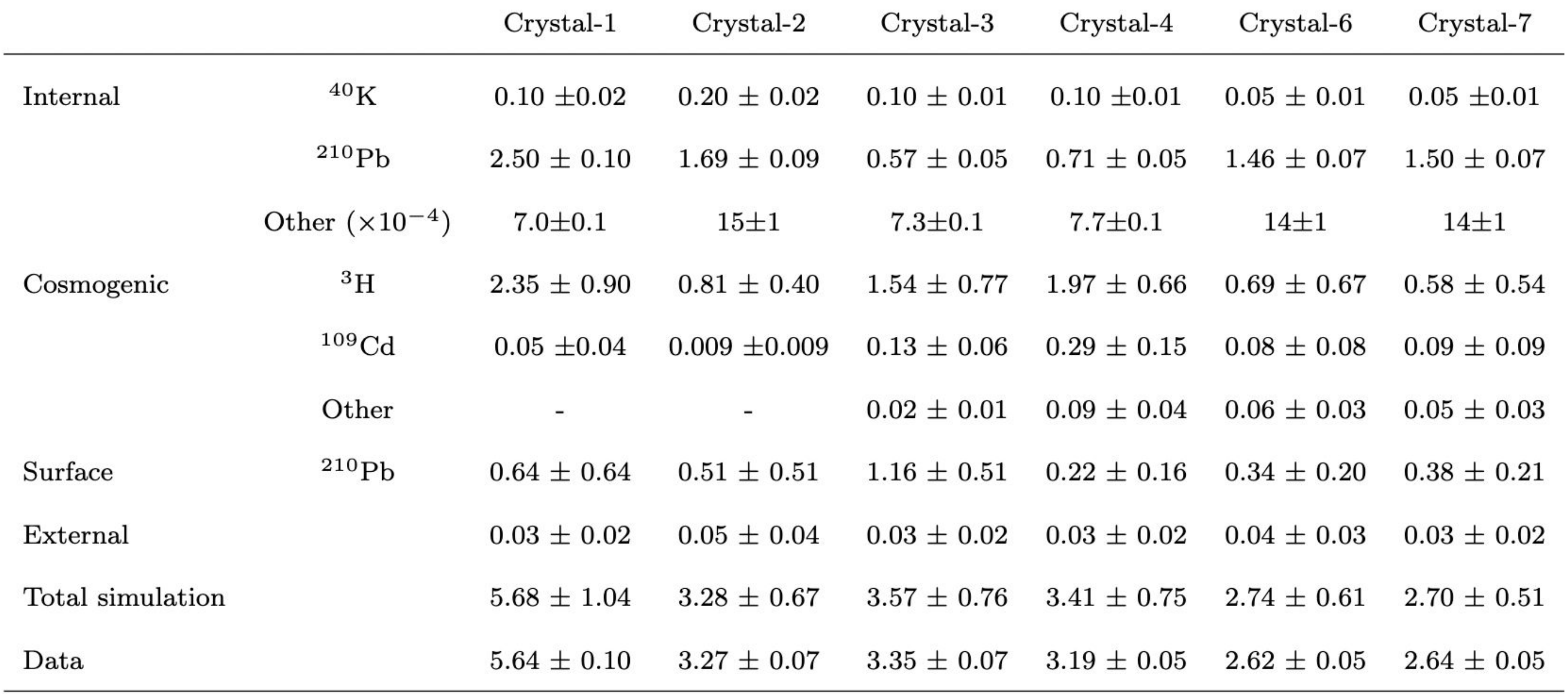
^{3}H, ^{14}C, ^{36}Cl, ^{32}Si, ^{10}Be and ^{7}Be




$\phi = e^{ax+b}$
a = (-1.5±0.14) km w.e.$^{-1}$
b = -13.1±0.51
Muon Flux [cm^{-2}s^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
2
3
4
5
6
Vertical Depth Over Burden [km w.e.]

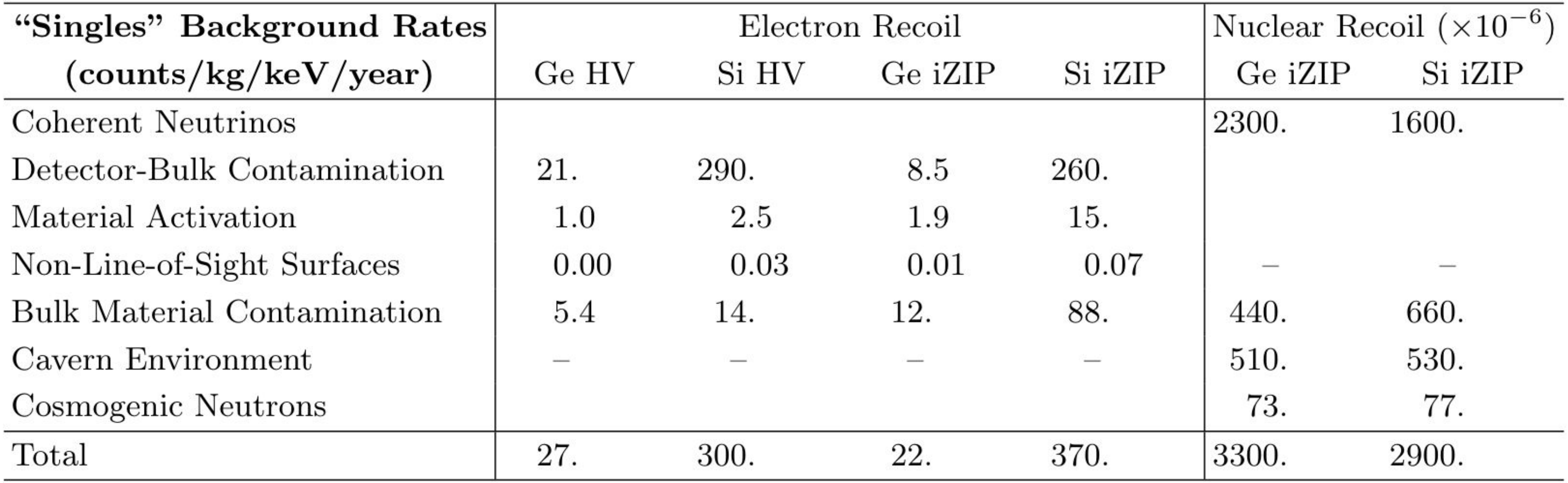
COSINE Background

https://arxiv.org/pdf/1804.05167



		Crystal-1	Crystal-2	Crystal-3	Crystal-4	Crystal-6	Crystal-7
Internal	^{40}K	0.10 ±0.02	0.20 ± 0.02	0.10 ± 0.01	0.10 ±0.01	0.05 ± 0.01	0.05 ±0.01
	^{210}Pb	2.50 ± 0.10	1.69 ± 0.09	0.57 ± 0.05	0.71 ± 0.05	1.46 ± 0.07	1.50 ± 0.07
	Other ($\times 10^{-4}$)	7.0±0.1	15±1	7.3±0.1	7.7±0.1	14±1	14±1
Cosmogenic	^{3}H	2.35 ± 0.90	0.81 ± 0.40	1.54 ± 0.77	1.97 ± 0.66	0.69 ± 0.67	0.58 ± 0.54
	^{109}Cd	0.05 ±0.04	0.009 ±0.009	0.13 ± 0.06	0.29 ± 0.15	0.08 ± 0.08	0.09 ± 0.09
	Other	-	-	0.02 ± 0.01	0.09 ± 0.04	0.06 ± 0.03	0.05 ± 0.03
Surface	^{210}Pb	0.64 ± 0.64	0.51 ± 0.51	1.16 ± 0.51	0.22 ± 0.16	0.34 ± 0.20	0.38 ± 0.21
External		0.03 ± 0.02	0.05 ± 0.04	0.03 ± 0.02	0.03 ± 0.02	0.04 ± 0.03	0.03 ± 0.02
Total simulation		5.68 ± 1.04	3.28 ± 0.67	3.57 ± 0.76	3.41 ± 0.75	2.74 ± 0.61	2.70 ± 0.51
Data		5.64 ± 0.10	3.27 ± 0.07	3.35 ± 0.07	3.19 ± 0.05	2.62 ± 0.05	2.64 ± 0.05

SuperCDMS Background



“Singles” Background Rates (counts/kg/keV/year)	Electron Recoil				Nuclear Recoil ($\times 10^{-6}$)	
	Ge HV	Si HV	Ge iZIP	Si iZIP	Ge iZIP	Si iZIP
Coherent Neutrinos					2300.	1600.
Detector-Bulk Contamination	21.	290.	8.5	260.		
Material Activation	1.0	2.5	1.9	15.		
Non-Line-of-Sight Surfaces	0.00	0.03	0.01	0.07	–	–
Bulk Material Contamination	5.4	14.	12.	88.	440.	660.
Cavern Environment	–	–	–	–	510.	530.
Cosmogenic Neutrons					73.	77.
Total	27.	300.	22.	370.	3300.	2900.

arXiv:1610.00006v1

Comparing Results to Detector Rates

Overburden [km w.e.]	Si [dru]	Ge [dru]	NaI(Tl) [dru]
0	0.12(2)	0.15(2)	0.16(11)
1	2.7(5)E-2	3.5(0.6)E-2	3.8(2.5)E-2
3	1.5(3)E-3	2.0(0.3)E-3	2.2(1.4)E-3
6	9.2(1.8)E-5	1.1(0.2)E-4	1.1(3)E-4

Simulated cosmogenic activities at various overburden during assembly. Travel is not considered

- dru = events/kg/keV/day
- Across various experiments (SuperCDMS, EDELWEISS, COSINE, SABRE) cosmogenic activation contributes O(0.1) dru
- Total backgrounds O(1) dru

Equations used to simulate decay rate

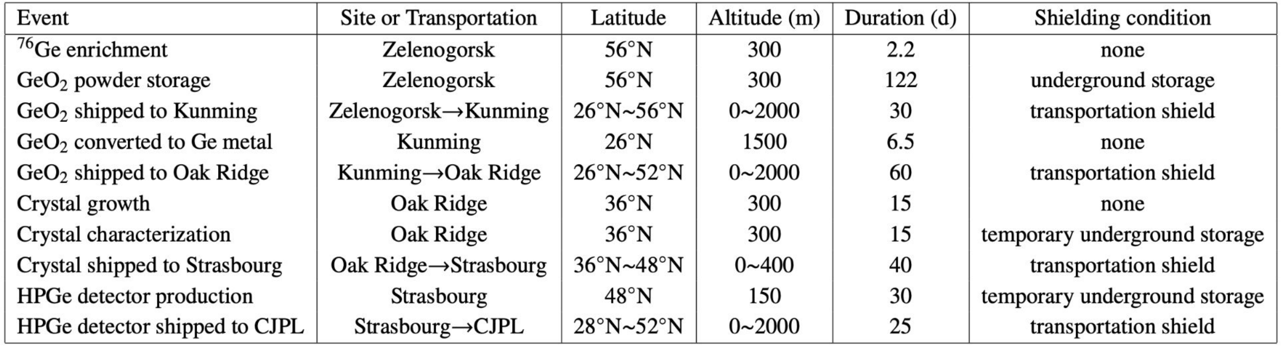
Activation rate:

$$R = Ae^{-\alpha x}, R(0) = R_0 = A$$

Decay rate:

$$R/R_0 = e^{-\alpha x_a}(1 - e^{-t_a/\tau})e^{-(t-t_a)/\tau} + e^{-\alpha x_t}(1 - e^{-t_t/\tau})e^{-(t-t_t)/\tau} + e^{-\alpha x_c}(1 - e^{-t_c/\tau})e^{-(t-t_c)\tau}$$

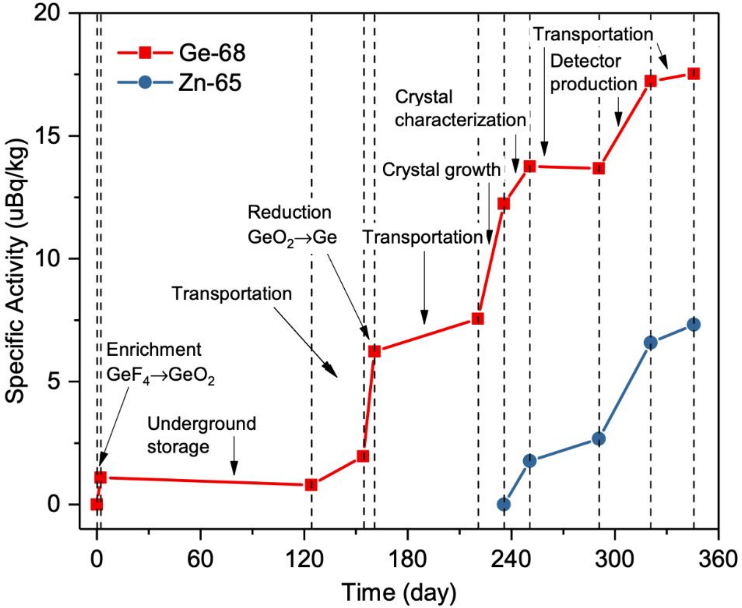
Table 1: Fabrication and transportation processes of germanium materials and detectors.



Event	Site or Transportation	Latitude	Altitude (m)	Duration (d)	Shielding condition
^{76}Ge enrichment	Zelenogorsk	56°N	300	2.2	none
GeO_2 powder storage	Zelenogorsk	56°N	300	122	underground storage
GeO_2 shipped to Kunming	Zelenogorsk→Kunming	26°N~56°N	0~2000	30	transportation shield
GeO_2 converted to Ge metal	Kunming	26°N	1500	6.5	none
GeO_2 shipped to Oak Ridge	Kunming→Oak Ridge	26°N~52°N	0~2000	60	transportation shield
Crystal growth	Oak Ridge	36°N	300	15	none
Crystal characterization	Oak Ridge	36°N	300	15	temporary underground storage
Crystal shipped to Strasbourg	Oak Ridge→Strasbourg	36°N~48°N	0~400	40	transportation shield
HPGe detector production	Strasbourg	48°N	150	30	temporary underground storage
HPGe detector shipped to CJPL	Strasbourg→CJPL	28°N~52°N	0~2000	25	transportation shield

https://arxiv.org/pdf/2312.06127

Figure 2: The transportation shield inside a shipping container.



Project #3:
0v**β**β **A**nd **L**ight **R**ecoils **O**bservations w/ **G**e,Si,NaI

Cosmogenic Activation in Si, Ge and NaI

Ry Cyna, Gulliver Milton, Beymar Quenallata, and Owen Stanley