UNIVERSITY OF SUSSEX

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Simulation results with full 10 kt geometry

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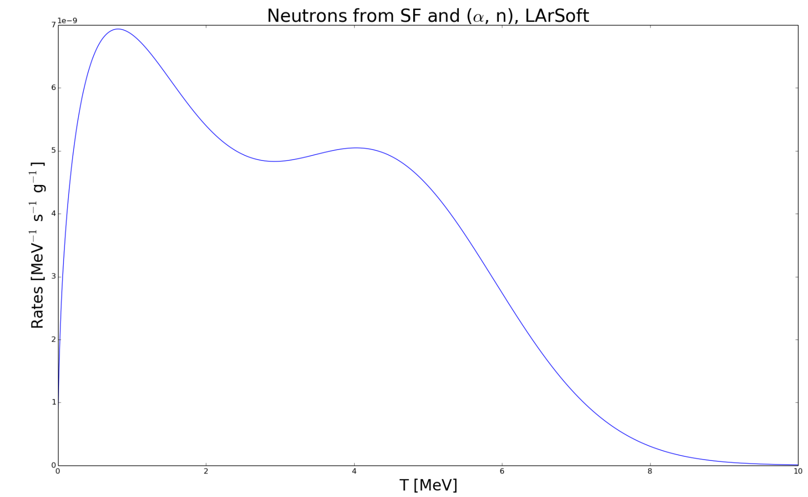
Neutron production in LArSoft

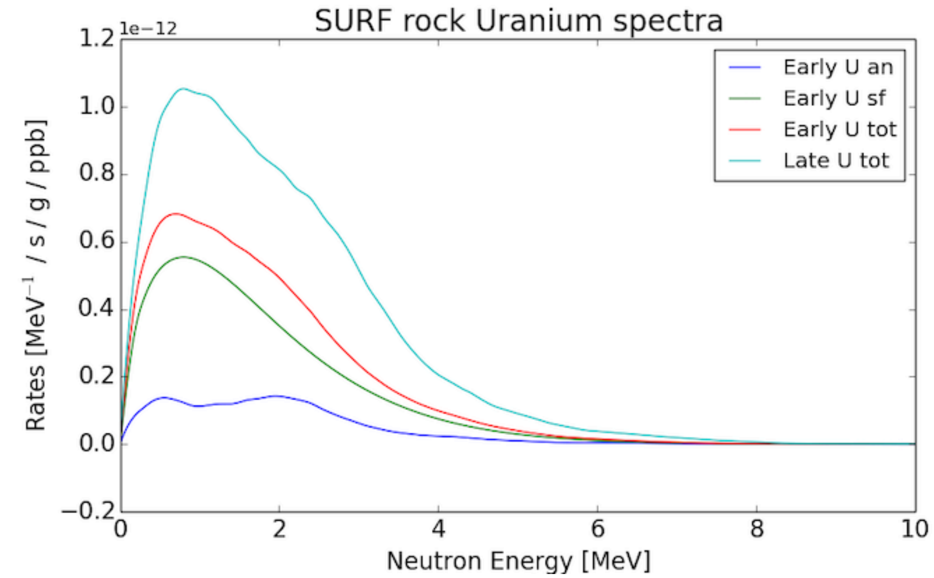
- **The LArSoft method**
  - Upper plot shows neutron spectrum in LArSoft
  - Represents a measured flux from a rock sample
  - Activity scaled assuming 10 neutrons/y/g per 10 ppm ^{238}U
  - We now know this is not totally representative of the real scenario

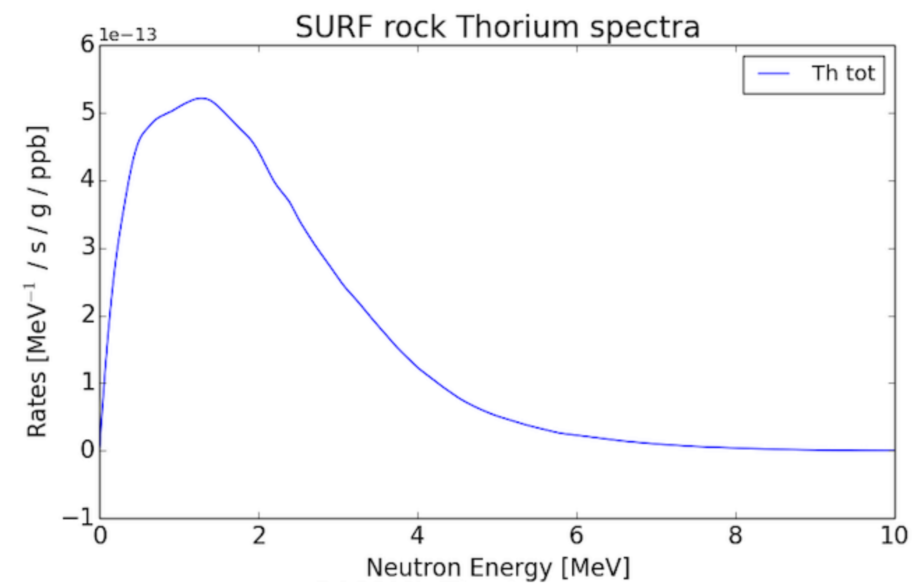


- **Updated production spectrum**
  - Material assays conducted at SDSMT evaluated the chemical composition of four rock samples from SURF
  - It was observed that the uranium decay chain was not in equilibrium
  - An averaged composition was used in SOURCES4 to produce neutron spectra for early and late chain uranium contributions and thorium contribution
  - New simulation time scaling required in this method:

$$t_{\text{sim}} = \frac{N_{\text{neutrons produced}}}{M_{\text{production material}} \times \int \Phi(E) dE \times C}$$

where $\Phi(E)$ is the neutron production spectrum and C is a concentration scaling factor to go from ppb to x ppm





Important simulation parameters

- **Radiological impurity concentration**
  - Relative concentrations of uranium and thorium vary in the different rock formations
  - General values uses for SURF rock (Poorman formation) are [1]
    - U: 3.43 ppm
    - Th: 7.11 ppm
  - Material assays yield similar results

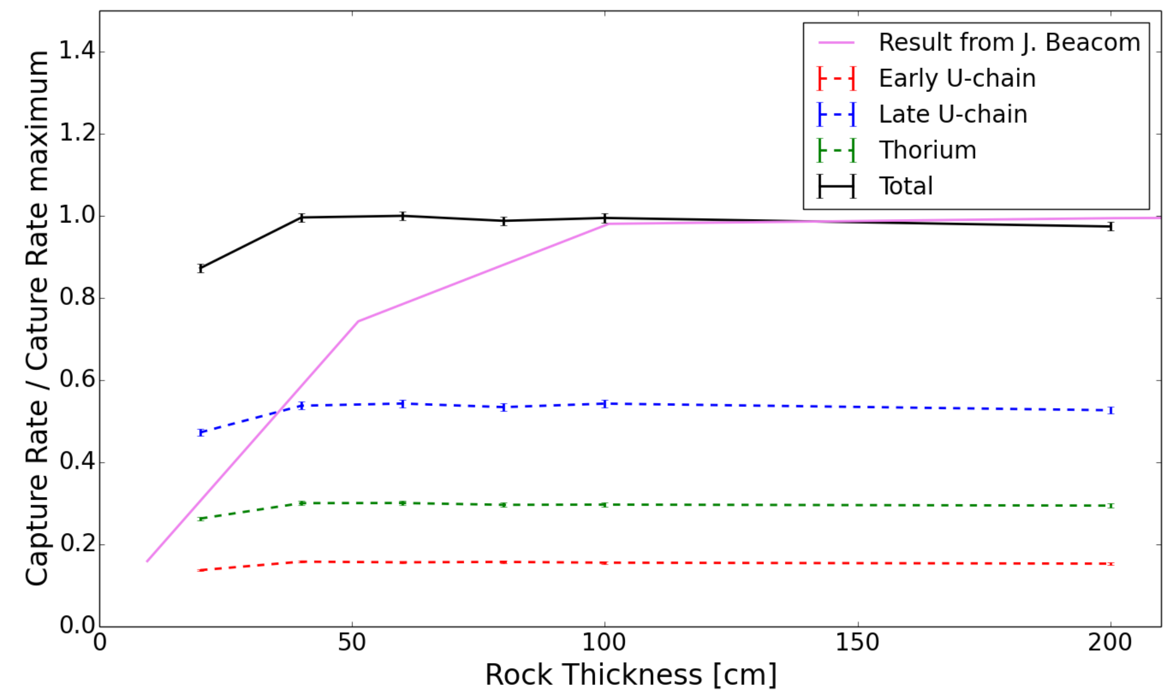
sample	description	U-238 [Bq/kg]	error [Bq/kg]	ppm U	err. [ppm]	Ra-226 [Bq/kg]	error [Bq/kg]	Th-232 [Bq/kg]	error [Bq/kg]	ppm Th	err. [ppm]	K-40 [Bq/kg]	error [Bq/kg]	% K	err. [%]
#1	DUNE Ross - #6 Winze	35.6	5.0	2.88	0.40	66.0	0.8	48.9	0.4	12.03	0.09	435.3	1.7	1.406	0.005
#2	DUNE Ross - Governor's Corner	24.4	6.9	1.98	0.56	79.1	1.1	20.5	0.4	5.05	0.10	420.6	2.4	1.358	0.008
#3	DUNE Ross - Test Blast Site	63.0	7.8	5.11	0.63	146.0	1.5	19.6	0.4	4.83	0.11	376.3	2.3	1.216	0.007
#4	DUNE Ross - #4 Winze	107.0	9.5	[illegible]	0.77	172.5	1.3	38.1	0.5	[illegible]	0.13	1429.7	4.0	4.618	0.013
mean		57.5	3.7	4.66	[illegible]	115.9	0.6	31.8	0.2	7.82	[illegible]	665.5	1.4	2.149	0.004
STDEV / sqrt(N)		18.4		1.5		25.8		7.1		1.8		255.0		0.8	
STDEV sample		36.7		3.0		51.5		14.2		3.5		510.1		1.6	

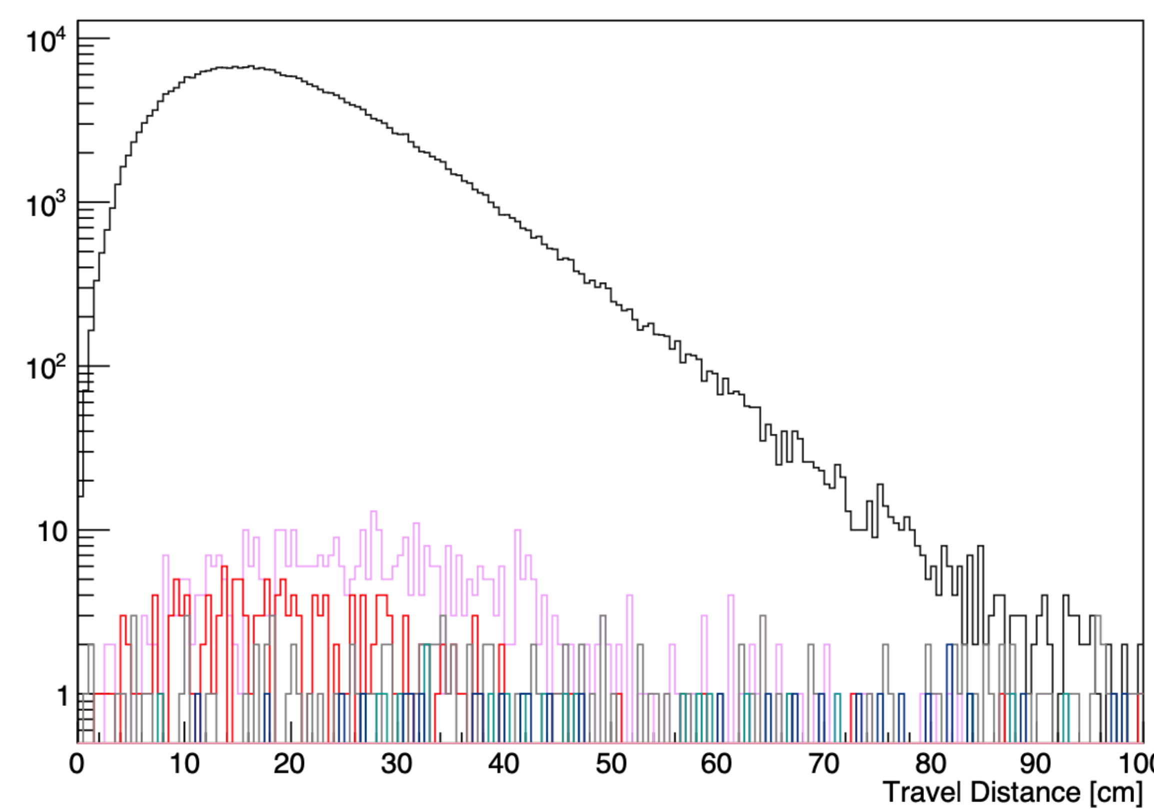
- **Thickness of rock layer**
  - Neutrons can travel ~10 - 30 cm in rock between scatters
  - They only tend to scatter a couple of times in rock, ~2 scatters per neutron
  - Thickness of the rock production layer needs to ensure accuracy w.r.t the real scenario

[1] H. Rogers, in Metallogeny of Gold in the Black Hills, South Dakota (Society of Economic Geologists, 1990) p. 204.

Rock thickness study: Simplified geometry

- **Geometry set-up**
  - Rock layer thicknesses from 20 cm to 200 cm
  - All geometries are very simplified
  - Essentially a 17 kt cuboid of LAr
- **What is a capture?**
  - Must occur within the y and z bounds of the APAs
  - Can occur anywhere within the x bounds of the cryostat
  - GEANT4 end process nCapture
  - Particle PDG code is 2112
  - End material must be LAr
- **Observations**
  - Results from J. Beacom paper (violet line) show rock is saturated at ~200 cm
  - LArSoft study shows at 20 cm we get 85% of the neutrons we should expect
  - Line plateaus at around 50 cm
  - This makes sense as >50 cm allows multiple scatters in rock
  - Good for simulations as thinner production volume means faster simulations and less computationally expensive





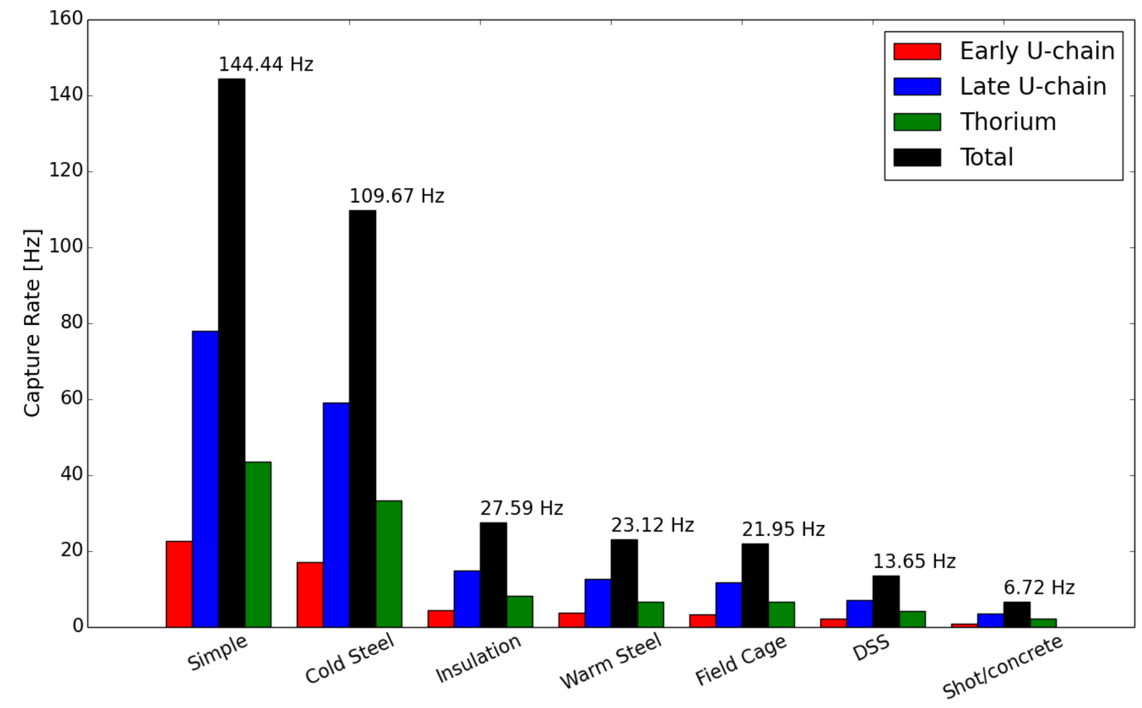
Passive shielding of cryostat components

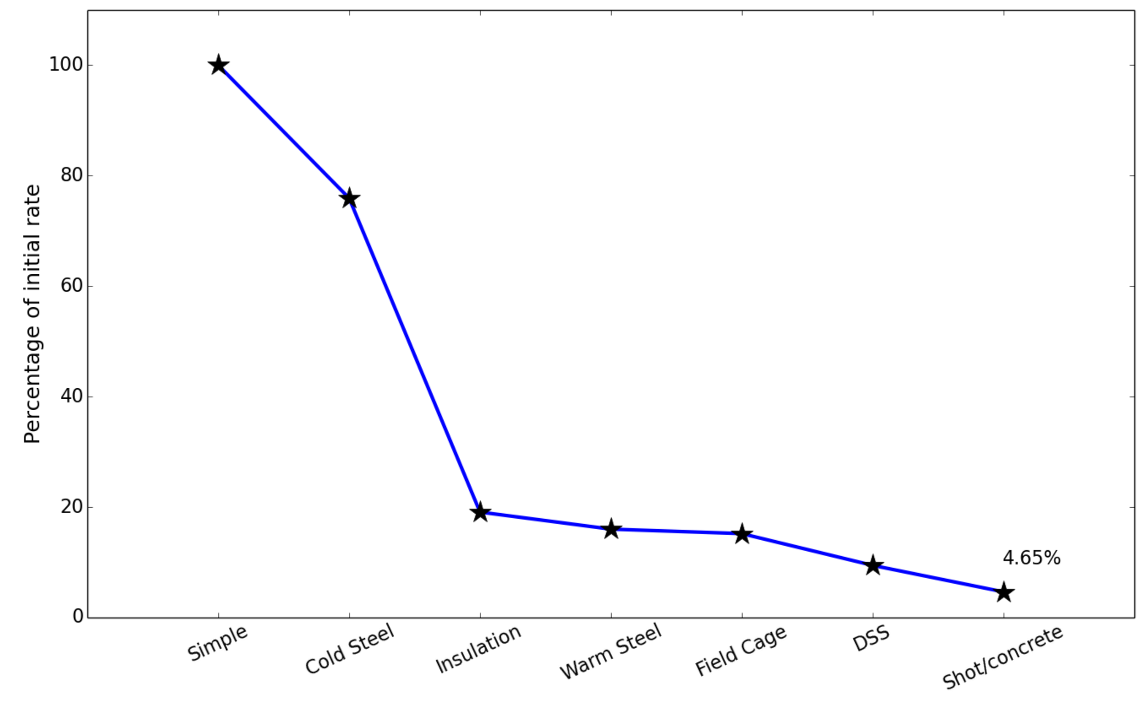
- **Including complex structures**
  - The DUNE FD modules aren't open cuboids of LAr
  - Hydrogen rich layers will act as neutron shields
    - Polyurethane foam: $C_{54}H_{60}O_{15}N_4$
    - Ply wood (cellulose): $C_6H_{10}O_5$
  - Also true to a lesser extent for ferrous layers

- **Quantifying the effect of adding layer by layer**
  - We can manipulate the geometry and add complexities in the following order:
    - Cold steel
    - Insulation layers
    - Warm steel shell
    - Field cage
    - Steel support structure
    - Shot/concrete on walls of cavern
  - Calculations roughly estimate a 2/3 reduction in capture rate only due to polyurethane so what else can we gain?

Passive shielding of cryostat components

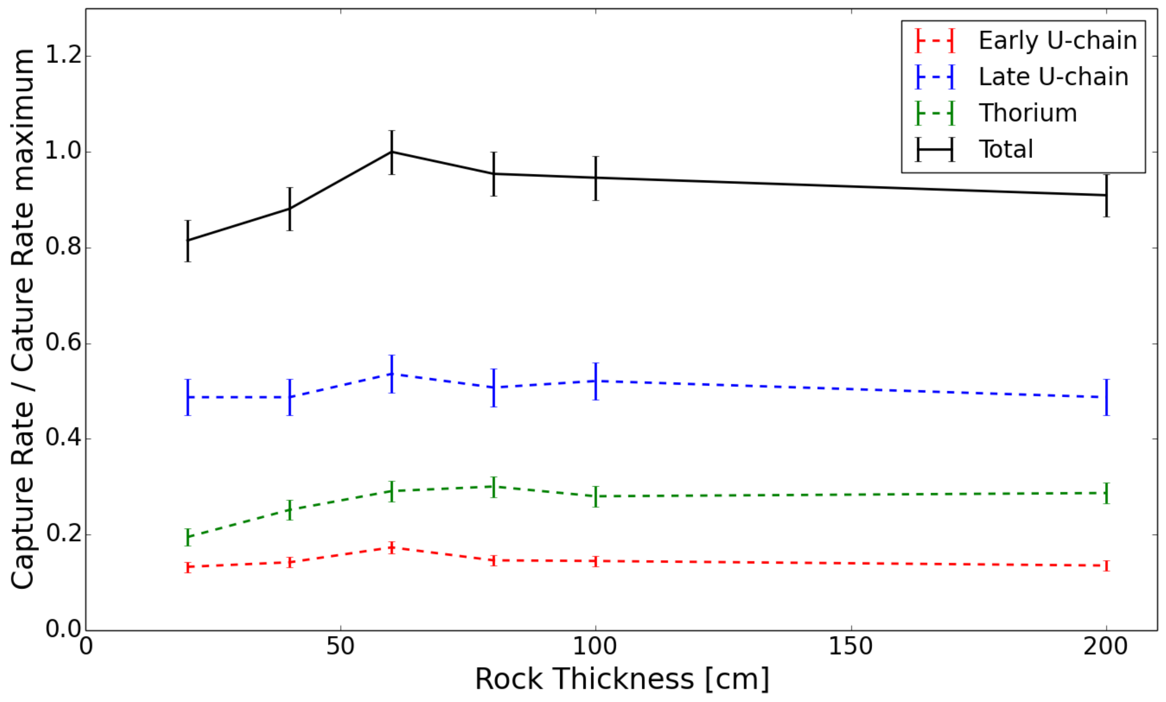
- **Geometry set-up**
  - Geometries were generated excluding specific layers
  - Each layer was added back in turn
  - Early and late uranium contributions and thorium contributions considered
- **Observations**
  - Simply containing the LAr in a steel box results in 24% improvement
  - Largest improvement seen with adding polyurethane foam and cellulose, as expected
  - Insulation layers result in 75% improvement over previous rate
  - 95% overall improvement when considering all features
  - NOTE: this is only considering neutrons emanating from the rock

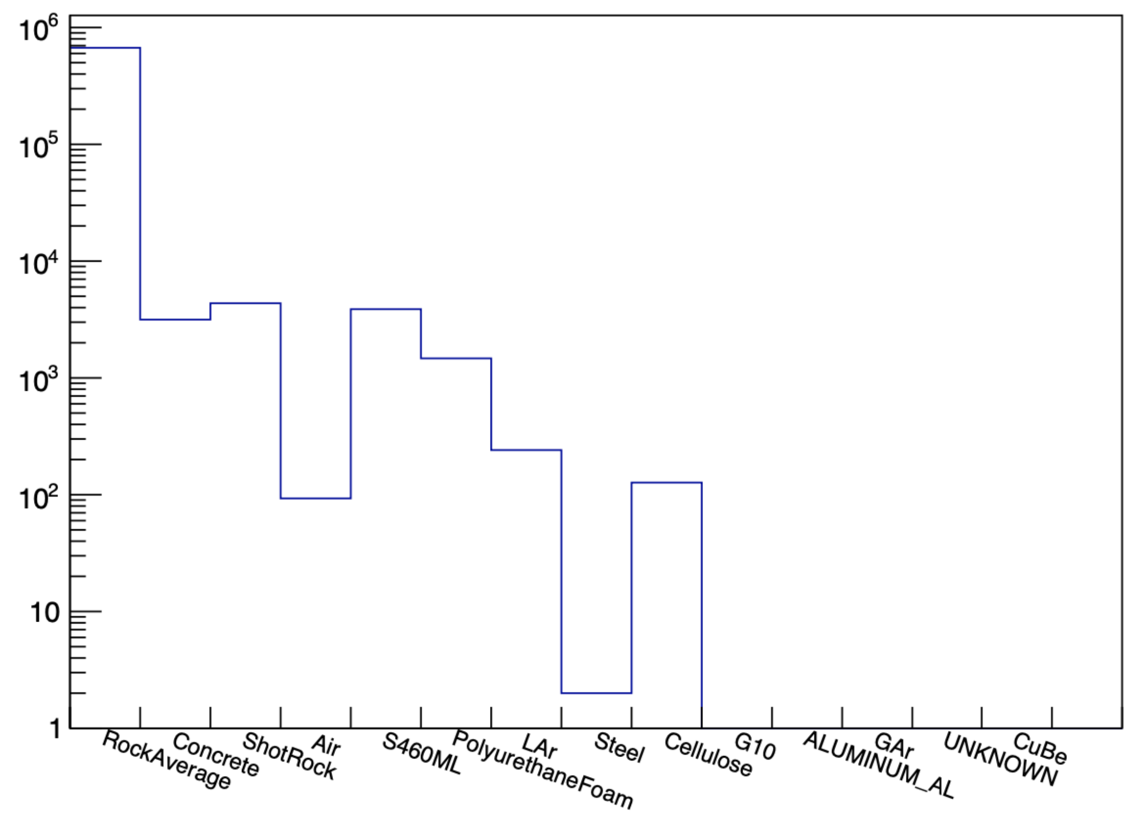




Rock thickness study: Full geometry

- **Setup**
  - Same as before but now considering all cryostat complexities
- **Observations**
  - At 20 cm we get ~80% of the neutrons we expect
  - Consistent plateau at >100 cm
  - Overall capture rate is 6.7 Hz as opposed to 144 Hz for the simplified geometry
  - Lower plot shows the distribution of materials captures occur within
- **Next steps**
  - Evaluate neutrons emanating from the steel support structure, shotcrete and concrete





Neutron from the shot/concrete

- **Simulation parameters**
  - For estimation purposes both layers are approximated as shotcrete
  - The spectra are calculated using SOURCES4
  - Impurity concentrations come from measurements from material assays
    - Uranium Early: 2.546 ppm
    - Uranium Late: 3.470 ppm
    - Thorium: 1.475 ppm

- **Observations**
  - Shotcrete volume is the more dominant source of neutrons
  - Concrete less imposing as half of the surface of the floor does not impinge on the detector module
  - Overall a reasonably low expected neutron background from these layers

Material	Capture rate Early	Capture rate Late	Capture rate Thorium	Capture rate Total [Hz]
Concrete	0.13 ± 0.02	0.08 ± 0.01	0.02 ± 0.00	0.23 ± 0.02
Shotcrete	0.73 ± 0.04	0.52 ± 0.03	0.10 ± 0.01	1.35 ± 0.05
Total				1.58 ± 0.06

Neutrons from the steel support structure

- **Steel is a radiologically active material**
  - Given the composition and neutron spectrum was evaluated using SOURCES4
  - Unfortunately the relative concentrations of Uranium and Thorium are not known
  - In this study I assumed a 1 ppm concentration
  - This can be easily scaled at a later date

Material	Capture rate Uranium	Capture rate Thorium	Capture rate Total [Hz]
Steel Support	0.95 ± 0.02	0.08 ± 0.001	1.03 ± 0.02

Total neutron background

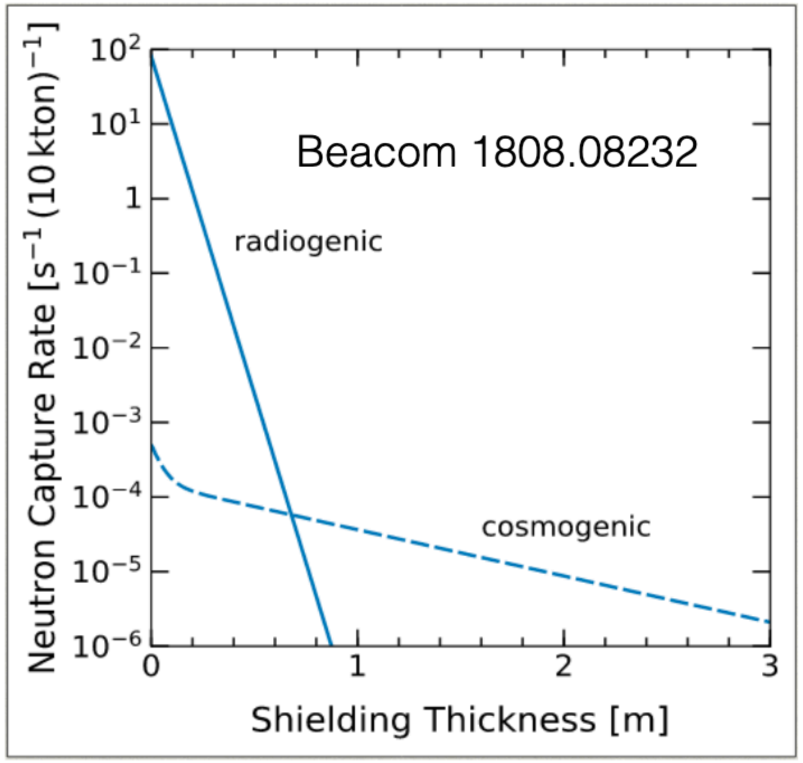
- **Total summed neutron capture rate**
  - Using the separation of the sources allows us to estimate the total neutron background we can expect in a DUNE FD module
  - Total capture rate is ~9 Hz which gives promise to Low-E studies in DUNE
  - This does not yet include radiological backgrounds from fibrous glass in the insulation; more results to come as spectroscopy studies continue

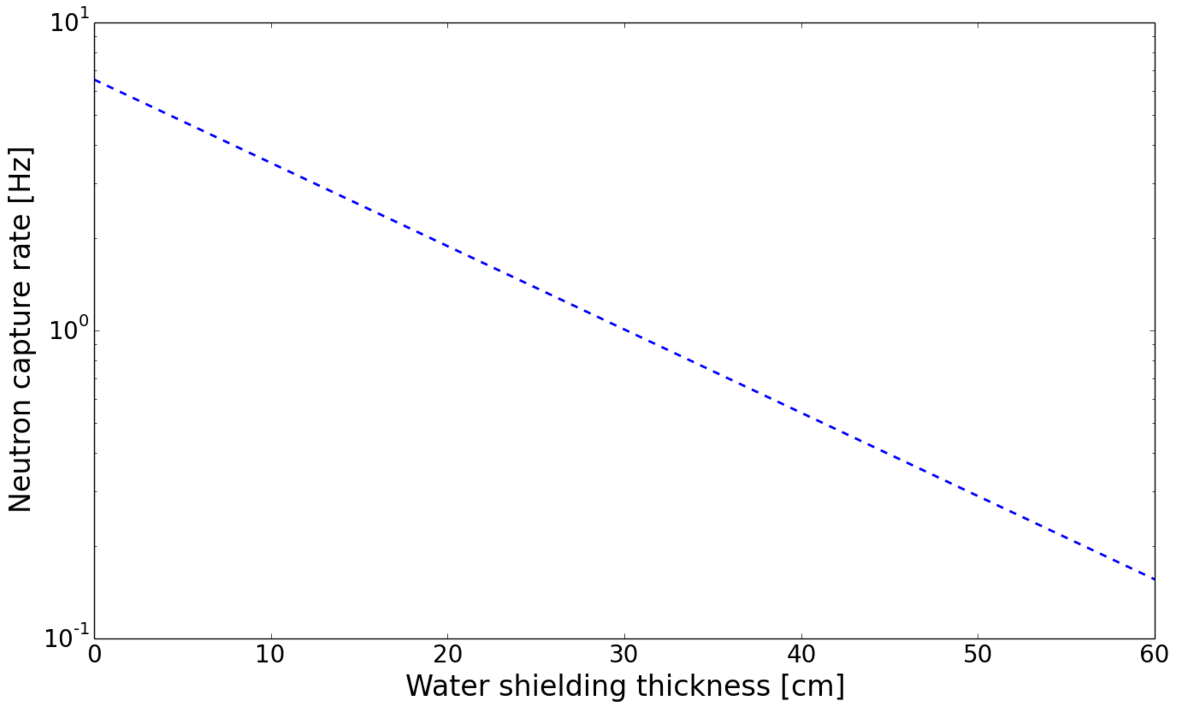
Source	Capture rate Early			Capture rate Late			Capture rate Thorium			Capture rate Total [Hz]		
Rock	1.00	±	0.08	3.60	±	0.28	2.12	±	0.16	6.72	±	0.33
Concrete	0.13	±	0.02	0.08	±	0.01	0.02	±	0.00	0.23	±	0.02
Shotcrete	0.73	±	0.04	0.52	±	0.03	0.10	±	0.01	1.35	±	0.05
DSS	0.95	±	0.02				0.08	±	0.00	1.03	±	0.02
Total										9.33	±	0.34

- **Can we take this one step further?**

Water shielding the cryostat

- **Water shielding prediction**
  - J. Beacom showed water is very effective at mitigating radiological neutron backgrounds
  - Roughly every 20 cm of water reduces the background rate by an order of magnitude
- **Simulation configuration**
  - Full detector geometry with all the complexities
  - Water layer around the cryostat
  - Water thickness increases in increments of 10 cm from 10 - 50 cm
  - Blue dashed line shows the best fit for the capture rate values with water shielding
  - Background rate is reduced by an order of magnitude with a 40 cm layer of water around the cryostat
  - Shielding will only effect the backgrounds from rock, shotcrete and concrete, however these are the dominant sources



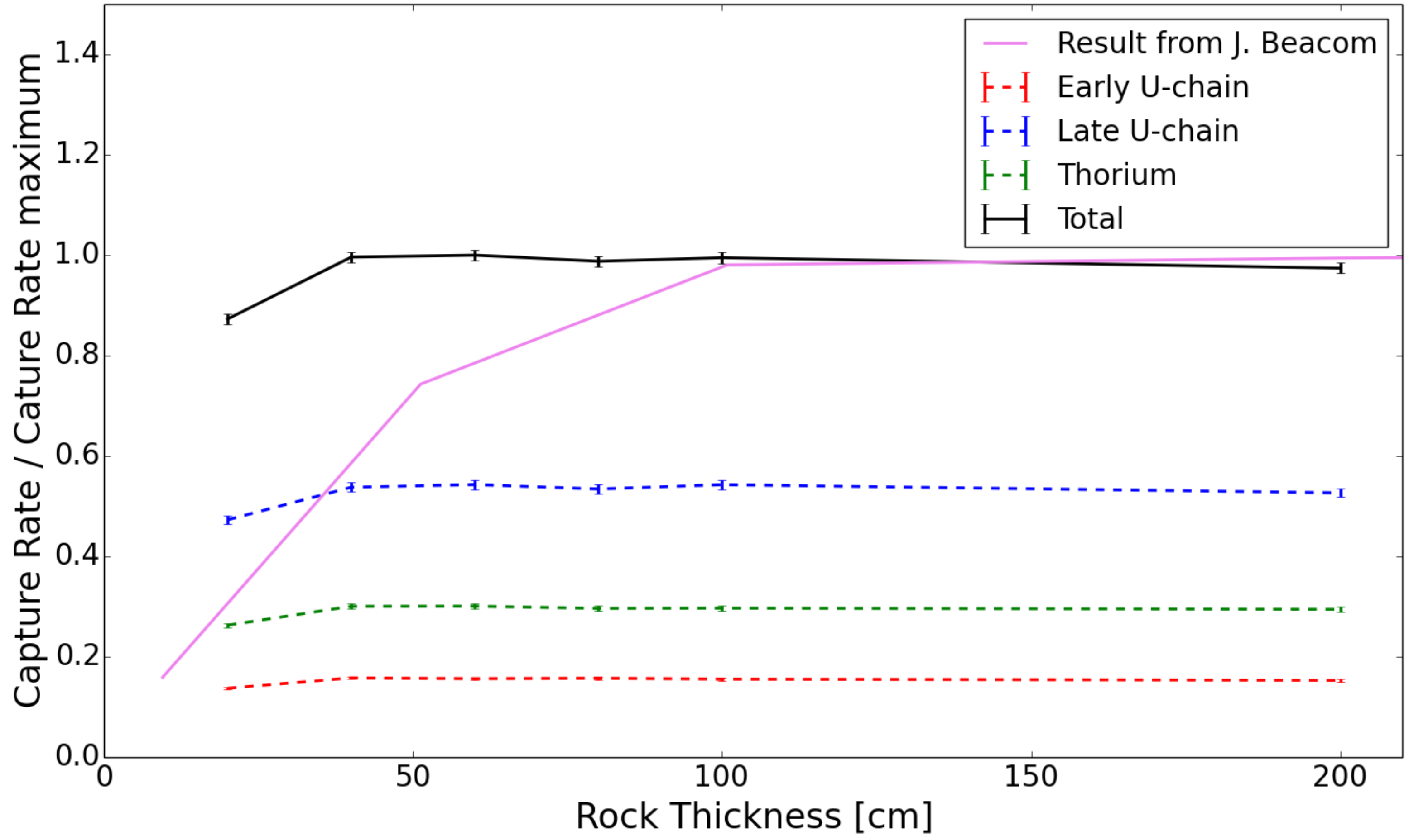


Conclusion

- **Simulation configurations**
  - New material assays and radiological activity studies provide excellent input for more accurate simulations
  - Complex geometry has provided realistic estimates for the background rate we can expect in the DUNE far detector
- **Background rate results**
  - The background rate for external neutrons from the rock, concrete, shotcrete and detector support structure is of the order 10 Hz
    - 1 Hz from the steel support structure
    - ~9 Hz from the rock, concrete and shotcrete combined
  - This shows good promise for the potential of low energy studies at DUNE
  - Background contributions from the insulation layers to be included as material and activity results arise
  - Preliminary water shielding studies show good neutron mitigation from the rock, shotcrete and concrete
- **Thank you for listening**

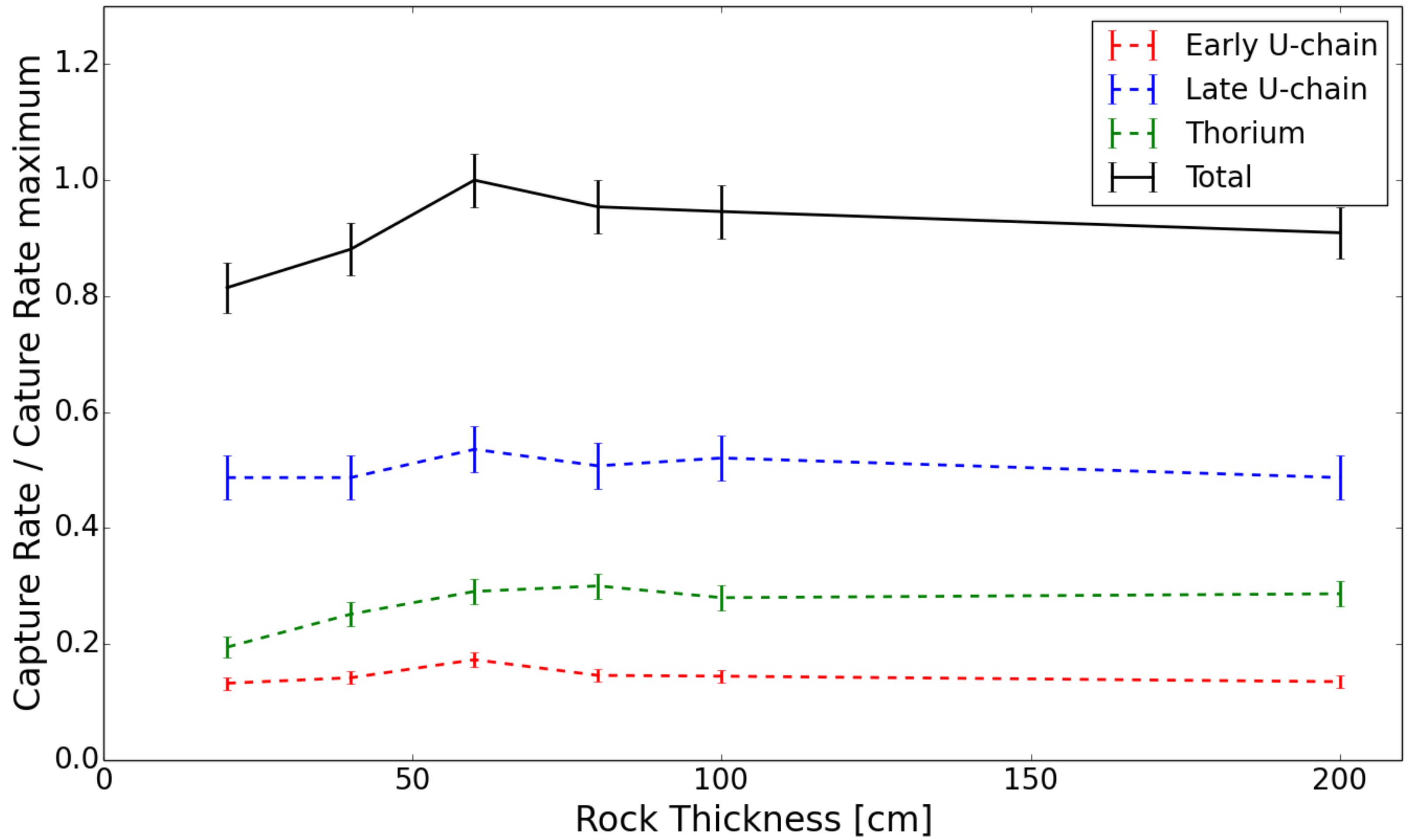
Backup slides

Rock thickness study (simplified geometry)



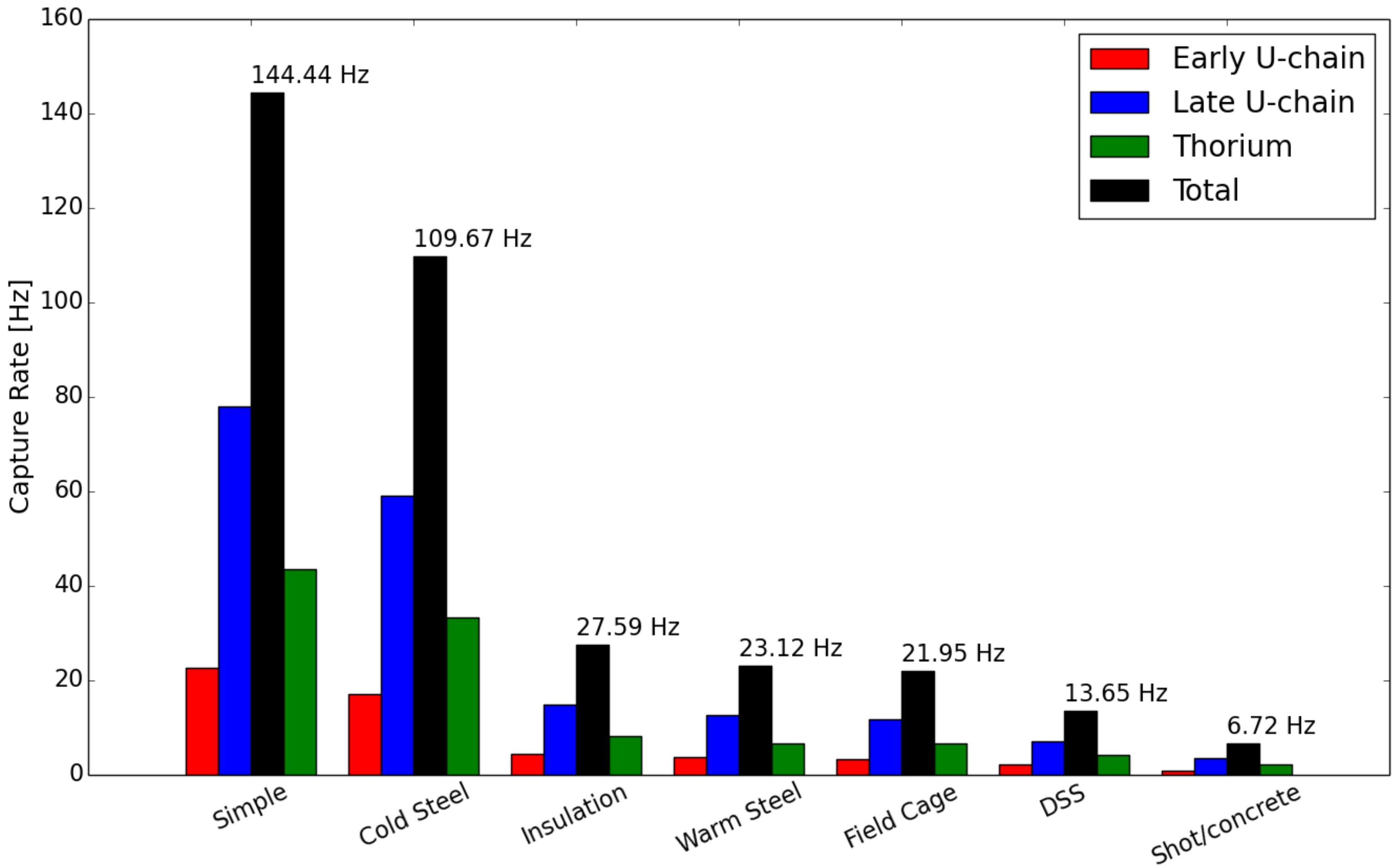
Layer Thickness [cm]	Capture rate Early	Capture rate Late	Capture rate Thorium	Capture rate Total [Hz]
20	20.35 ± 0.36	70.10 ± 1.24	38.98 ± 0.69	129.42 ± 1.46
40	23.42 ± 0.39	79.73 ± 1.39	44.55 ± 0.73	147.70 ± 1.62
60	23.18 ± 0.38	80.51 ± 1.33	44.60 ± 0.73	148.29 ± 1.57
80	23.33 ± 0.39	79.22 ± 1.32	43.93 ± 0.73	146.48 ± 1.56
100	23.05 ± 0.38	80.48 ± 1.33	44.01 ± 0.73	147.53 ± 1.56
200	22.69 ± 0.38	78.09 ± 1.31	43.66 ± 0.73	144.44 ± 1.54

Rock thickness study (complex geometry)



Layer Thickness [cm]	Capture rate Early	Capture rate Late	Capture rate Thorium	Capture rate Total [Hz]
20	0.98 ± 0.08	3.60 ± 0.28	1.44 ± 0.13	6.02 ± 0.32
40	1.05 ± 0.08	3.60 ± 0.28	1.86 ± 0.15	6.51 ± 0.33
60	1.28 ± 0.09	3.96 ± 0.29	2.15 ± 0.16	7.39 ± 0.34
80	1.08 ± 0.08	3.75 ± 0.29	2.22 ± 0.16	7.05 ± 0.34
100	1.07 ± 0.08	3.85 ± 0.29	2.07 ± 0.16	6.99 ± 0.34
200	1.00 ± 0.08	3.60 ± 0.28	2.12 ± 0.16	6.72 ± 0.33

Layer by layer study



Shot/ concrete	DSS	Field cage	Warm steel	Insulation	Cold steel inner	Capture rate Early U chain	Capture rate Late U chain	Capture rate Thorium	Capture rate Total [Hz]	Improvement w.r.t previous	Total improvement
X	X	X	X	X	X	22.69 ± 0.38	78.09 ± 1.31	43.66 ± 0.73	144.44 ± 1.54	0.00%	0.00%
X	X	X	X	X	✓	17.21 ± 0.33	59.22 ± 1.14	33.24 ± 0.63	109.67 ± 1.34	24.07%	24.07%
X	X	X	X	✓	✓	4.52 ± 0.17	14.85 ± 0.57	8.22 ± 0.32	27.59 ± 0.68	74.84%	80.90%
X	X	X	✓	✓	✓	3.74 ± 0.15	12.73 ± 0.53	6.65 ± 0.28	23.12 ± 0.62	16.20%	83.99%
X	X	✓	✓	✓	✓	3.38 ± 0.15	11.86 ± 0.51	6.71 ± 0.29	21.95 ± 0.61	5.06%	84.80%
X	✓	✓	✓	✓	✓	2.21 ± 0.12	7.16 ± 0.40	4.28 ± 0.23	13.65 ± 0.48	37.81%	90.55%
✓	✓	✓	✓	✓	✓	1.00 ± 0.08	3.60 ± 0.28	2.12 ± 0.16	6.72 ± 0.33	50.77%	95.35%