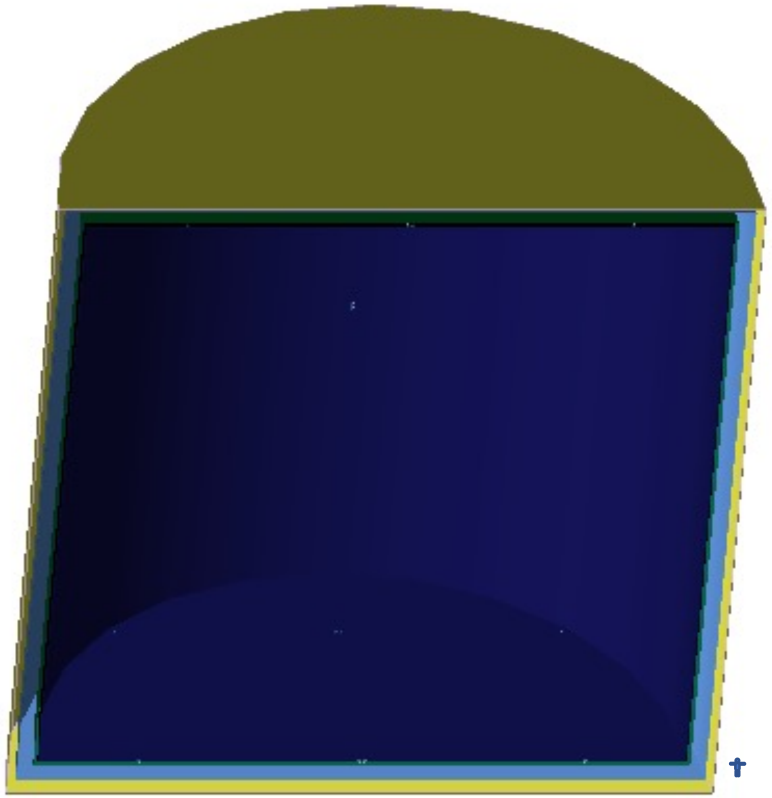
Scalability of Gd-doped-water Cherenkov reactor-antineutrino IBD detectors for nonproliferation



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Applied Antineutrino Physics Workshop
York, UK — September 18–20, 2023

LLNL-PRES-854315. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Formulation of the problem

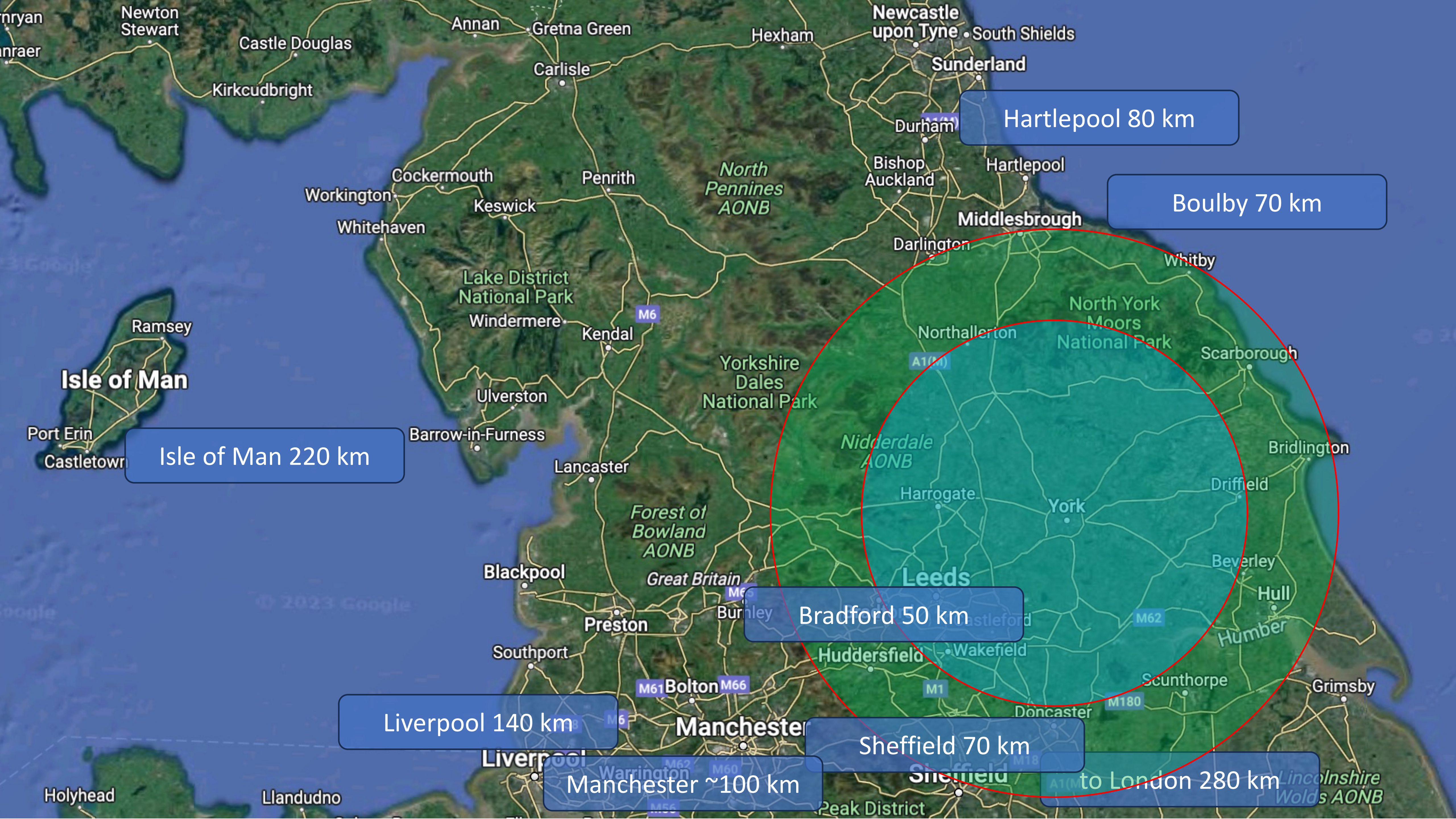
- In the past, claims have been made that reactors are detectable at very large distances using their antineutrino radiation. The question is if we include an accurate understanding of detector efficiencies and backgrounds, how scalable is this method?

- Detection technology: Gd-doped water-Cherenkov detector

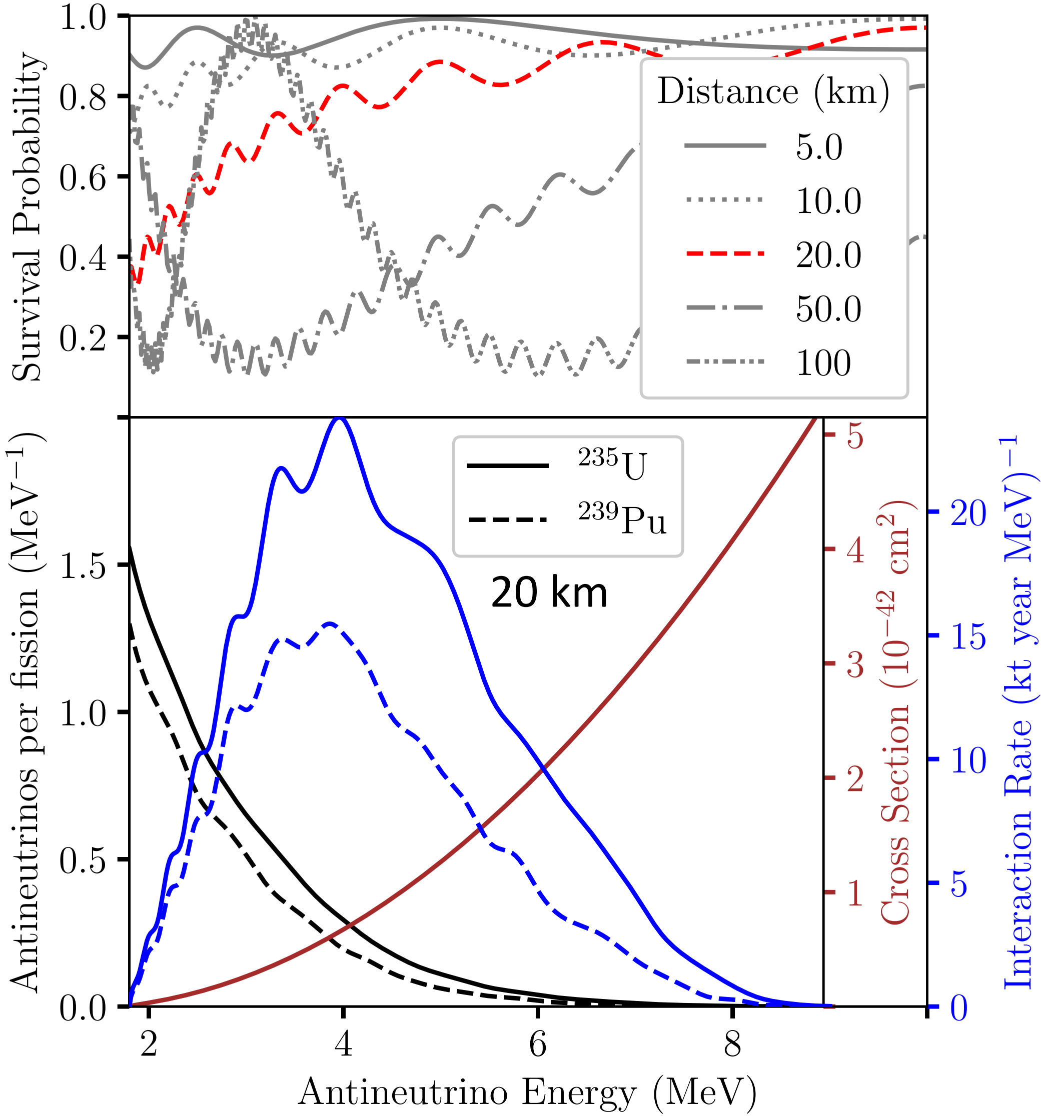
The actual question addressed in the paper:

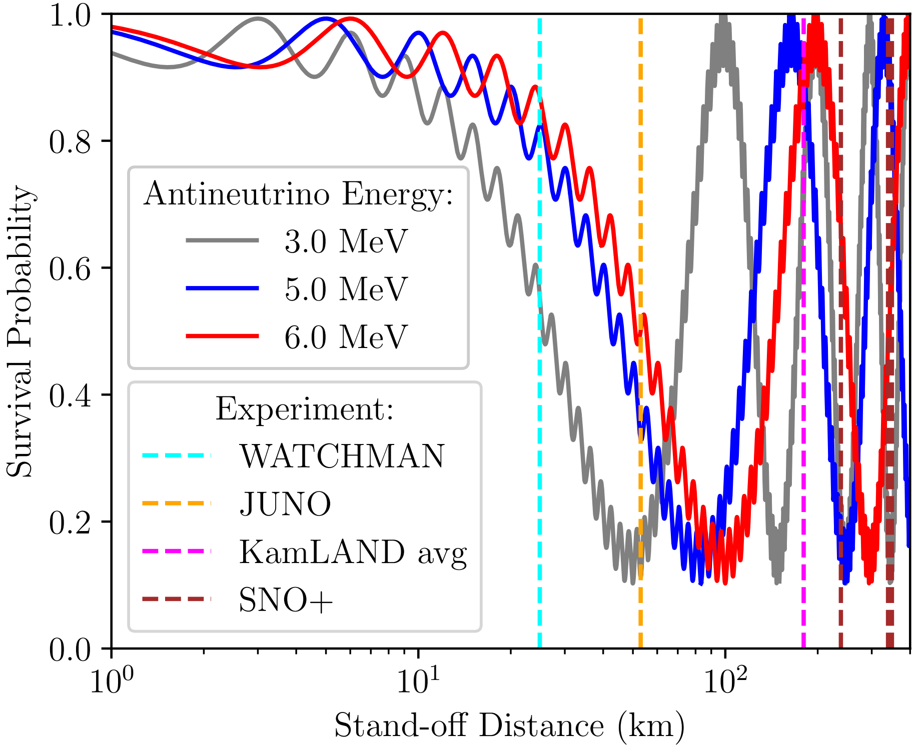
- **If we have an X-kt detector, what is the maximum range to detect a 50-MWt reactor in 1 year?**

Phys. Rev. Applied 18, 034059 (2022)


Hartlepool 80 km
Boulby 70 km
Isle of Man 220 km
Bradford 50 km
Liverpool 140 km
Sheffield 70 km
Manchester ~100 km
to London 280 km
Newton Stewart
Annan
Gretna Green
Hexham
Newcastle upon Tyne
South Shields
Castle Douglas
Sunderland
Carlisle
Kirkcudbright
Durham
Bishop Auckland
Hartlepool
Cockermouth
Penrith
North Pennines AONB
Workington
Keswick
Middlesbrough
Whitehaven
Darlington
Whitby
Lake District National Park
North York Moors National Park
Windermere
Kendal
Northallerton
Scarborough
Ramsey
Yorkshire Dales National Park
Isle of Man
Ulverston
Bridlington
Port Erin
Barrow-in-Furness
Nidderdale AONB
Castletown
Lancaster
Driffield
Harrogate
York
Forest of Bowland AONB
Beverley
Blackpool
Great Britain
Leeds
Hull
Burnley
Humber
Preston
Huddersfield
Wakefield
Southport
Bolton
Scunthorpe
Grimsby
Doncaster
Manchester
Liverpool
Warrington
Sheffield
Lincolnshire Wolds AONB
Holyhead
Llandudno
Peak District
M6
A1(M)
M62
M1
M180
M61
M66

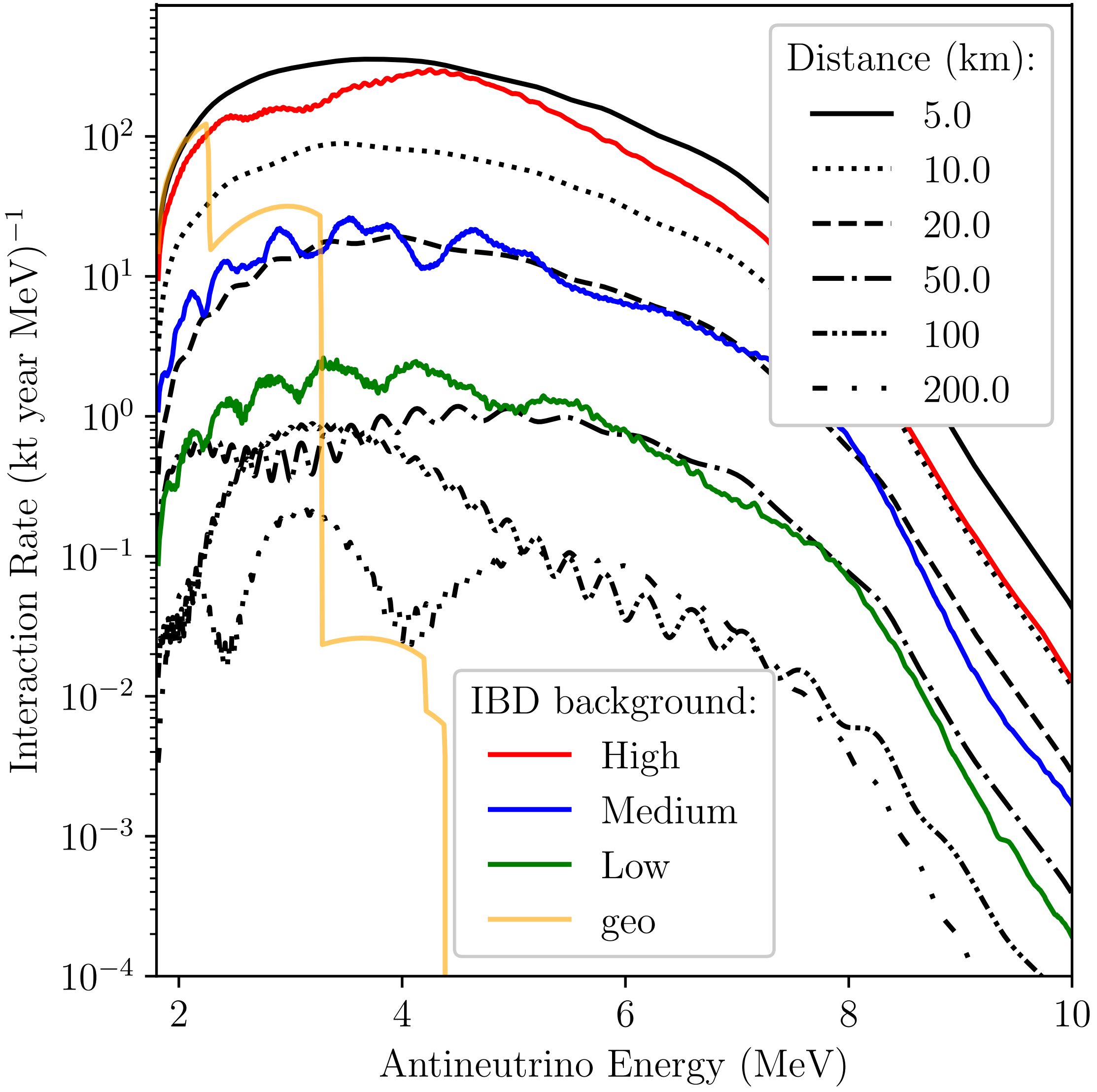
Neutrino oscillations make it more challenging to detect antineutrinos in the far-field





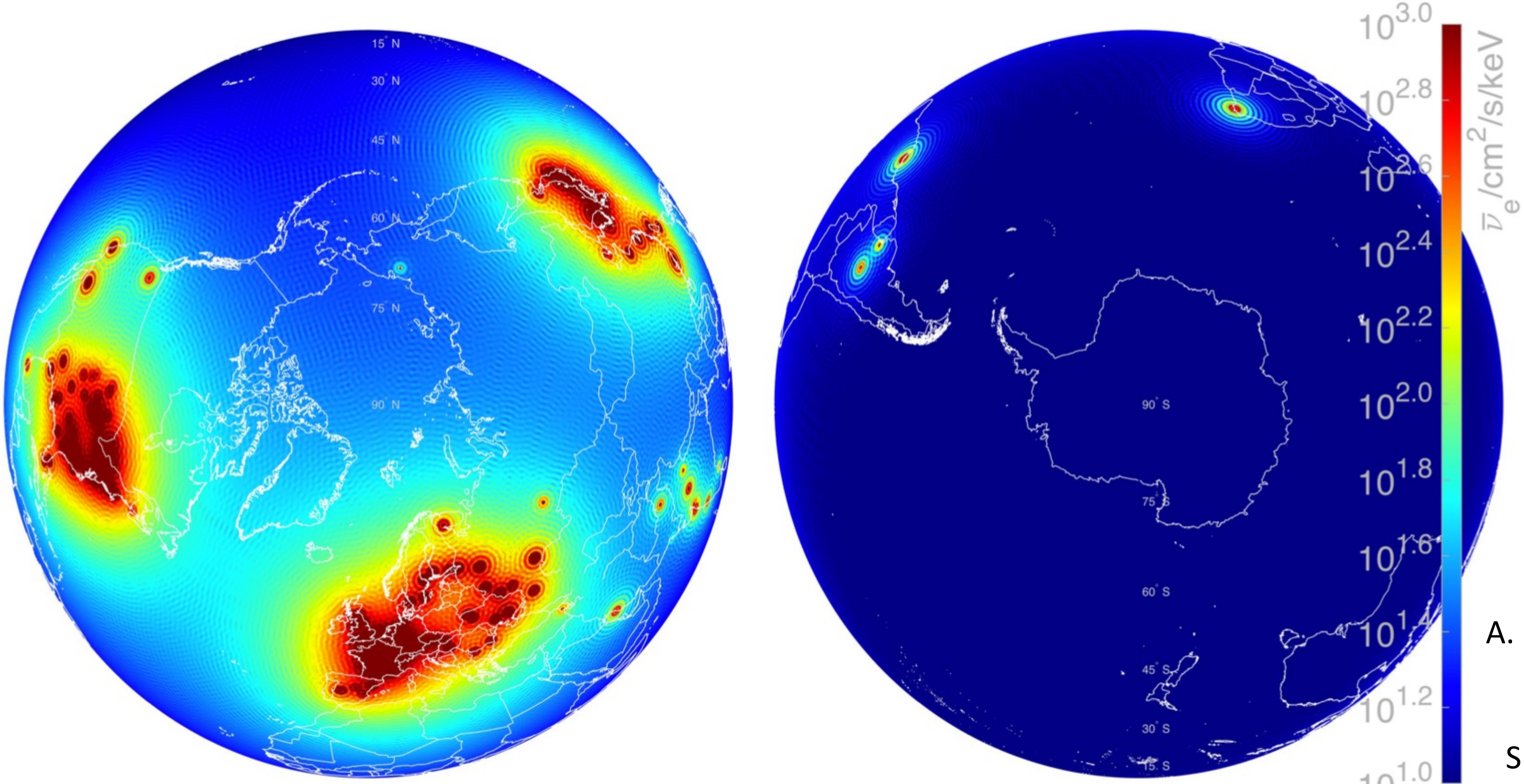
World reactors

We consider three distinct levels of world-reactor backgrounds (low, medium, and high)



Circles of different color indicate reactor types.

World as seen in reactor antineutrinos



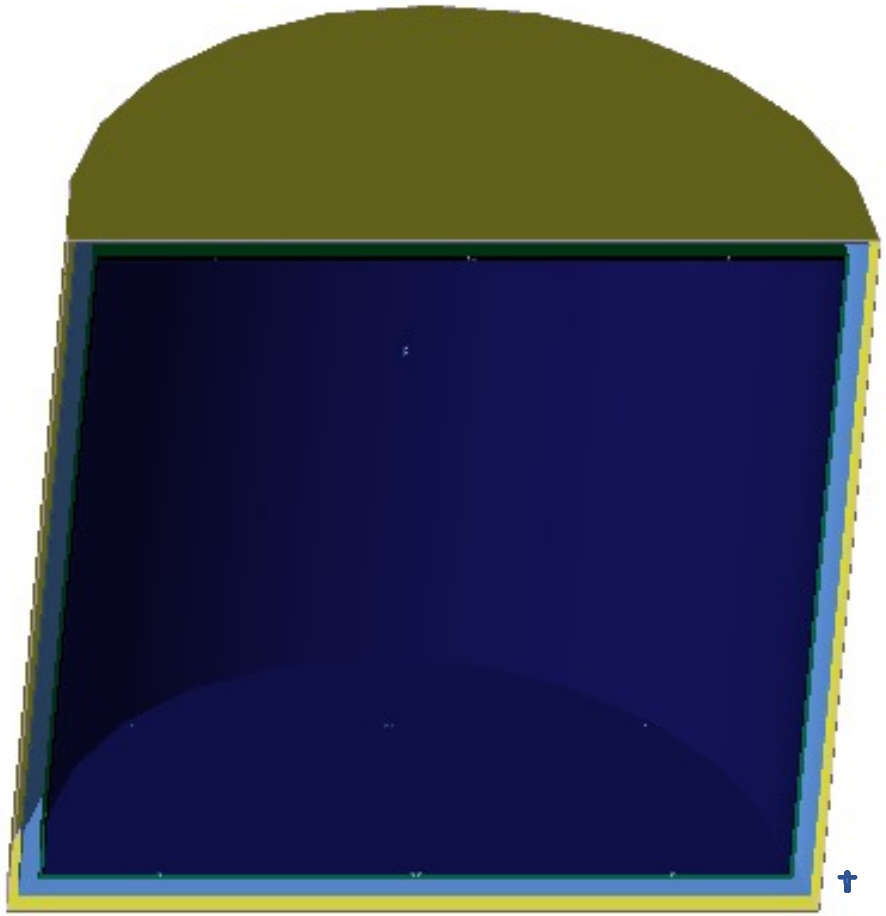
Northern Hemisphere

Southern Hemisphere

A. Barna and S. Dye, arXiv:1510.05633

S. M. Usman et al., Sci. Rep. 5, 13945 (2015)

Realistic detector performance

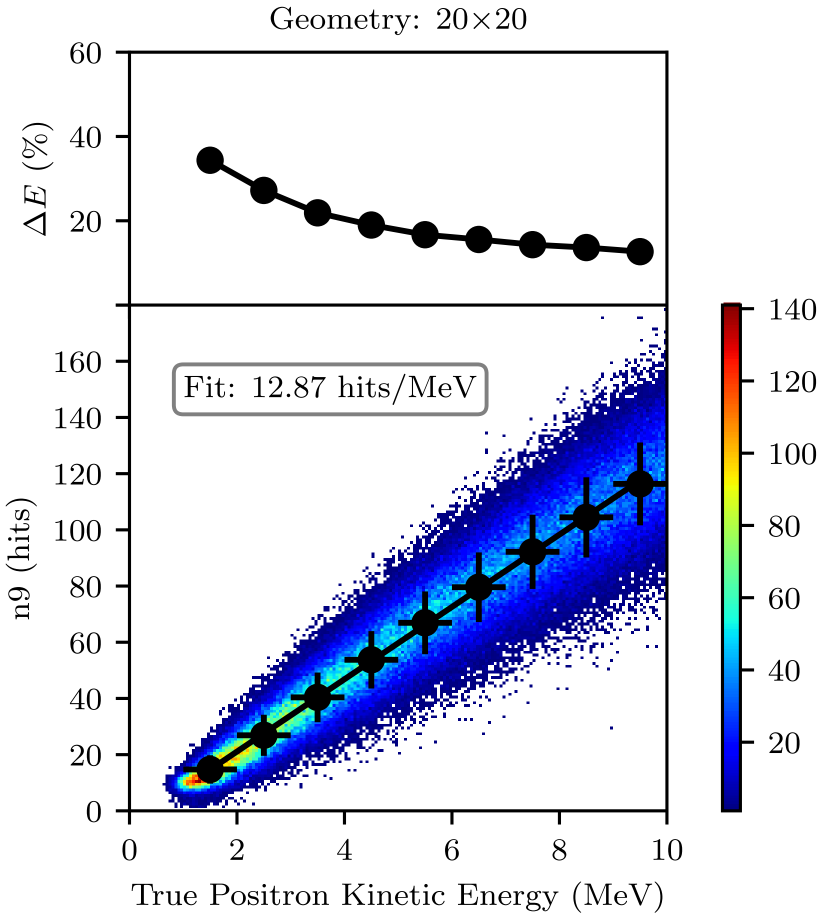


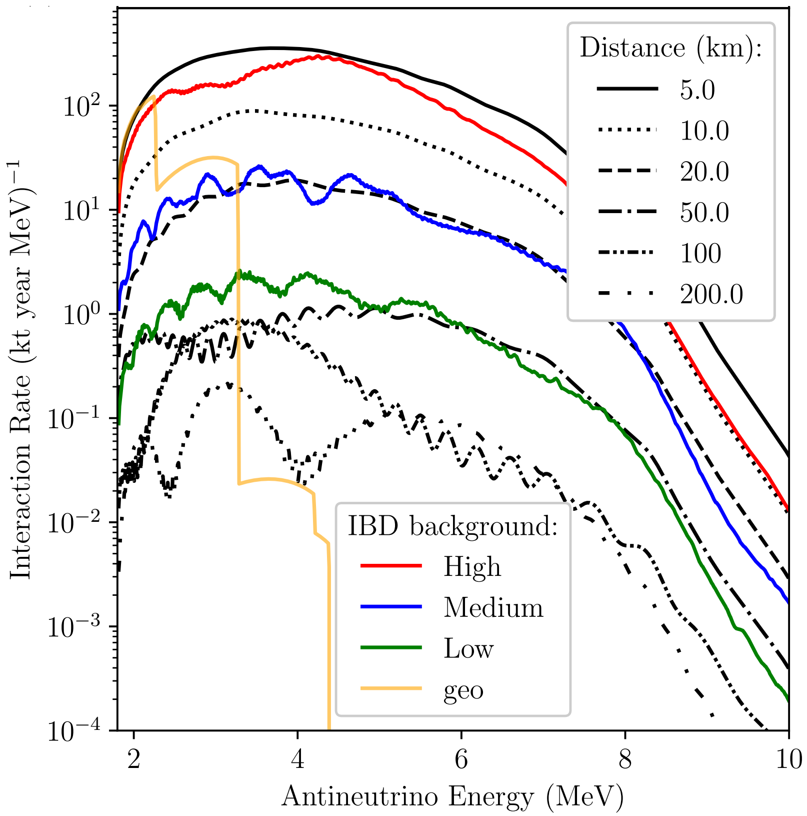
40% photo-coverage.

d (m) × h (m)	m (kt)	m_f (kt)	No. of 10-inch PMTs
15 × 15	2.7	0.3	4 512
20 × 20	6.2	1.4	9 516
30 × 30	21.2	8.4	25 182
40 × 40	50.3	25.7	48 258
50 × 50	98.2	58.2	78 856

The fiducial volume boundary is defined as 4 meters from the outer tank, or 2 meters from the PMTs.

Water-Cherenkov detectors are counters with limited energy resolution





"n9" is a technical term for the number of the PMT hits due to Cherenkov cone photons. All scattered or reflected photons are removed by employing a tight 9-nanosecond cut.

We can't resolve the "wiggles" in the spectrum using the water-Cherenkov detector (not enough photons to have a good energy resolution).

Backgrounds

- Accidental backgrounds due to radioactivity of detector components
- Cosmogenic backgrounds due to muons
- Radiopurity levels used in this study:

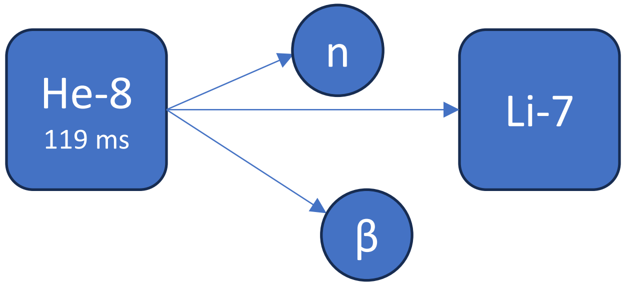
Medium	U-238	Th-232	K-40	Rn-222
Water (Bq/kg)	1e-6	1e-7	4e-6	1e-6
PMT (Bq/tube)	2.45e3	2.49e3	5.85e-1	—

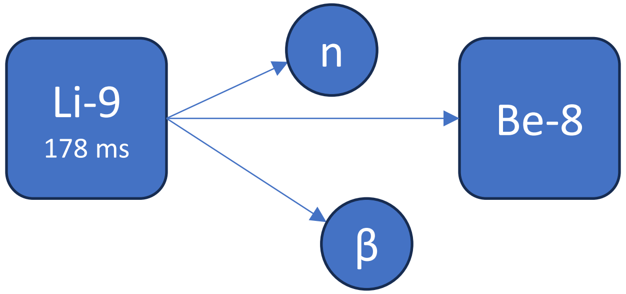
Depth

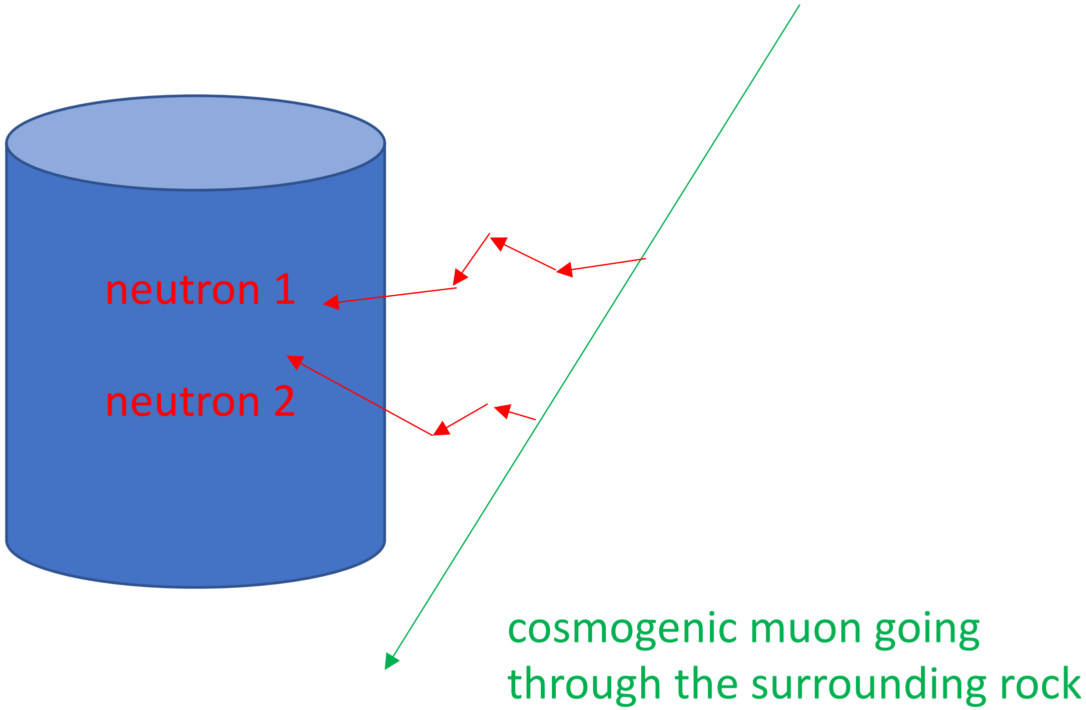
In this study, we assumed the same depth for all detector, causing the same flux of cosmogenics — scaled from the WATCHMAN detector.

Two types of cosmogenic backgrounds that mimic IBD:

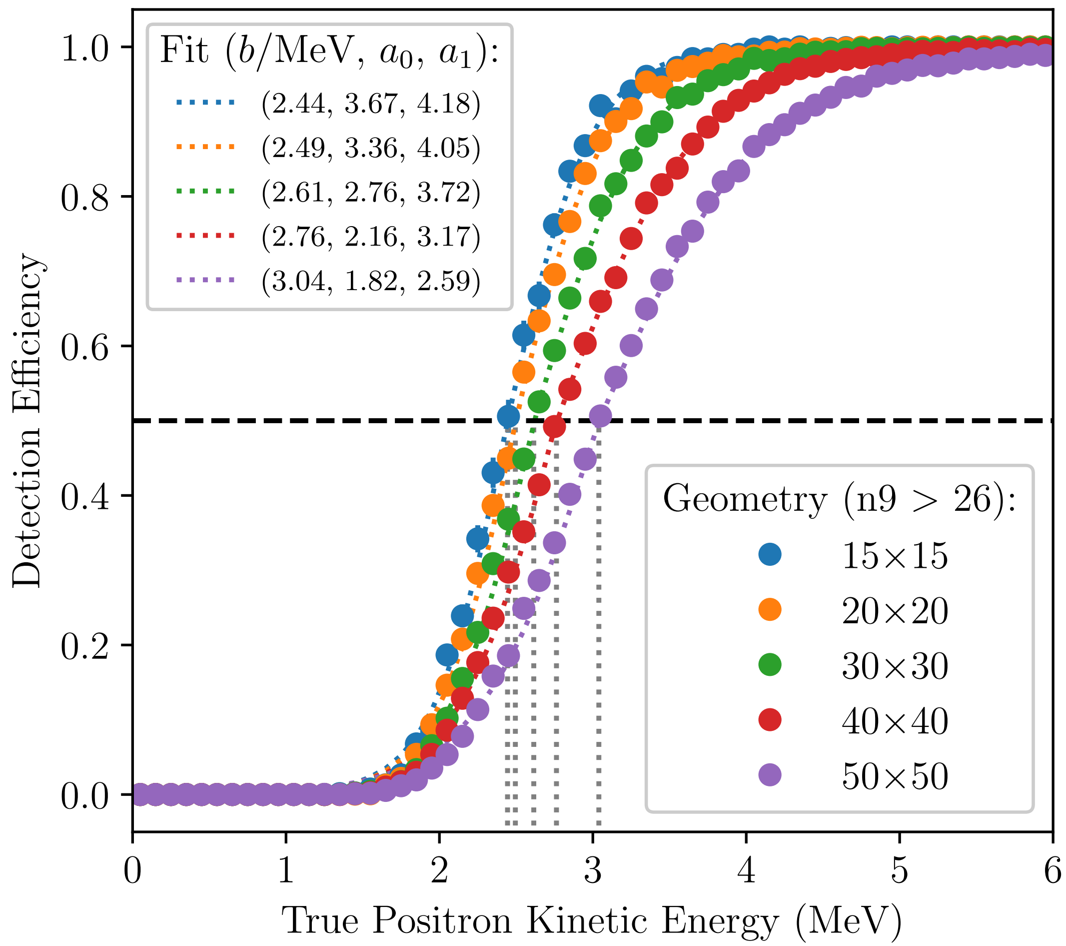
- ^{9}Li and ^{8}He long-lived isotopes
- Two correlated neutrons that penetrate to the inner volume of the detector from the rock

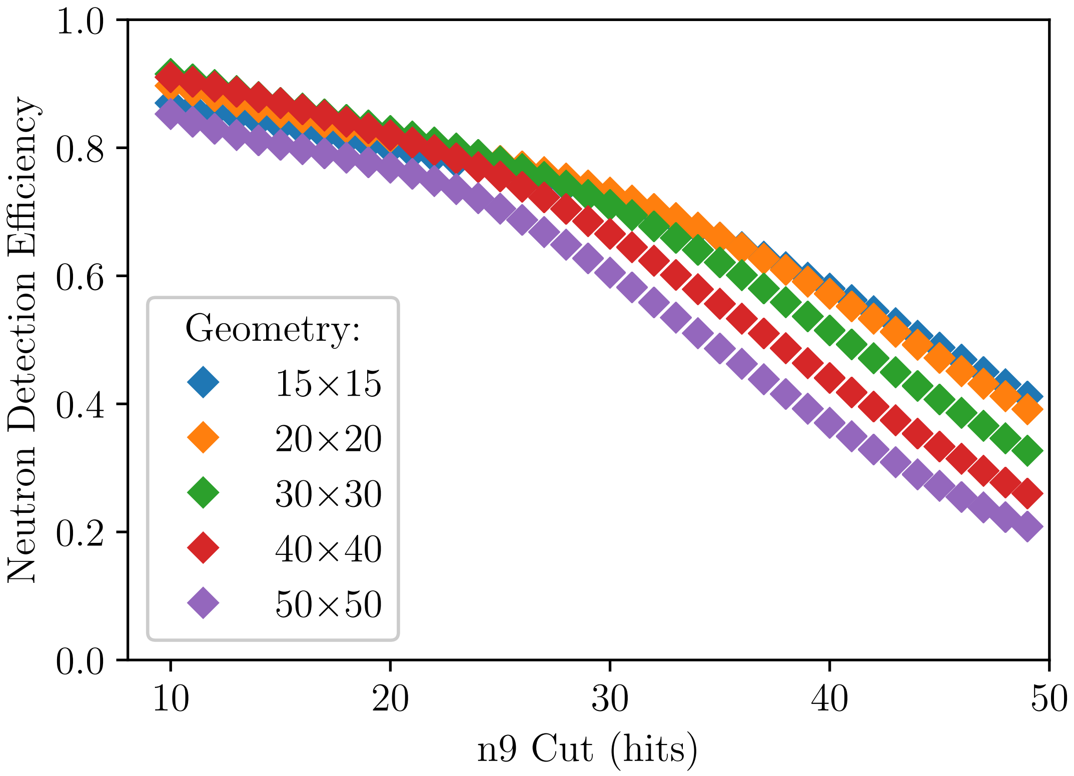




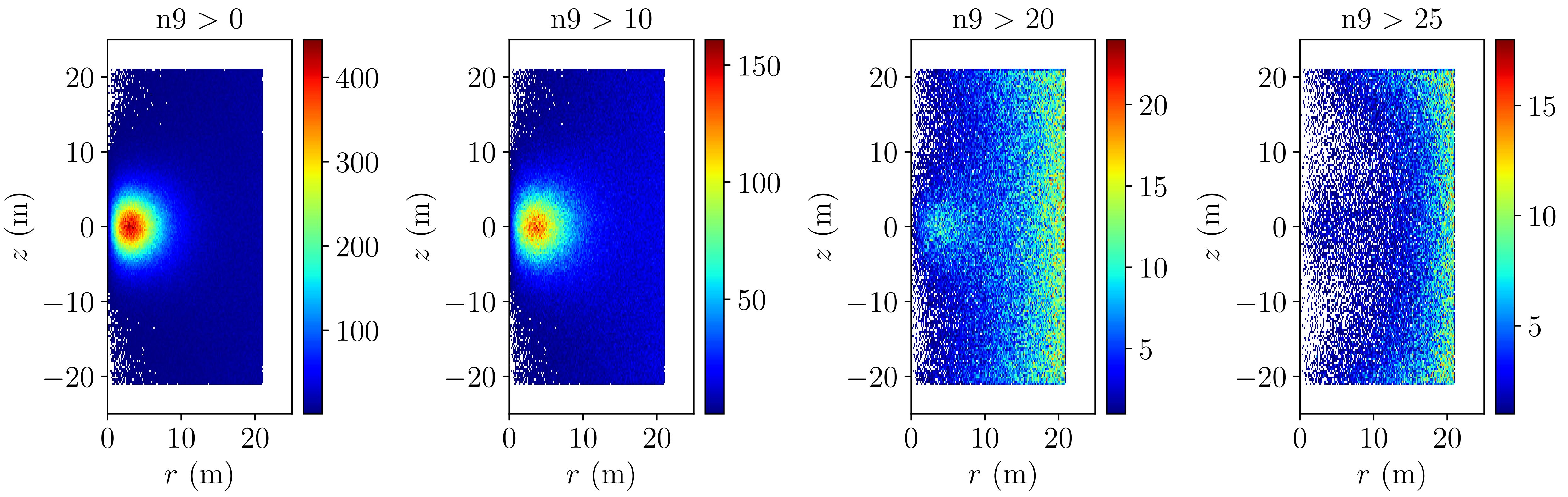


Positron and neutron detection efficiency



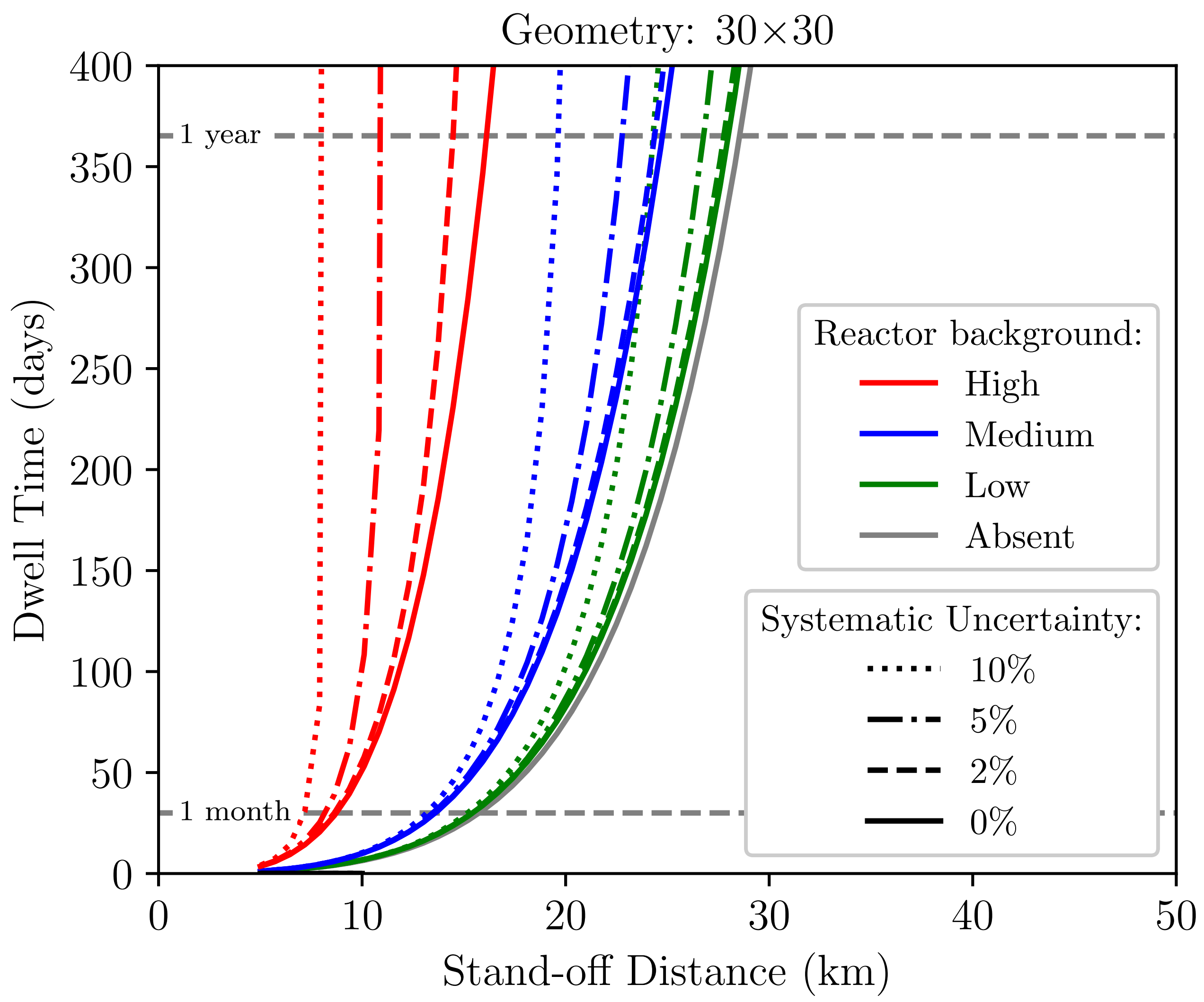


Problem of PMT dark rate and misreconstruction



Example: ^{208}Tl in PMTs, 50x50.

Dwell time to detect a 50-MWt reactor

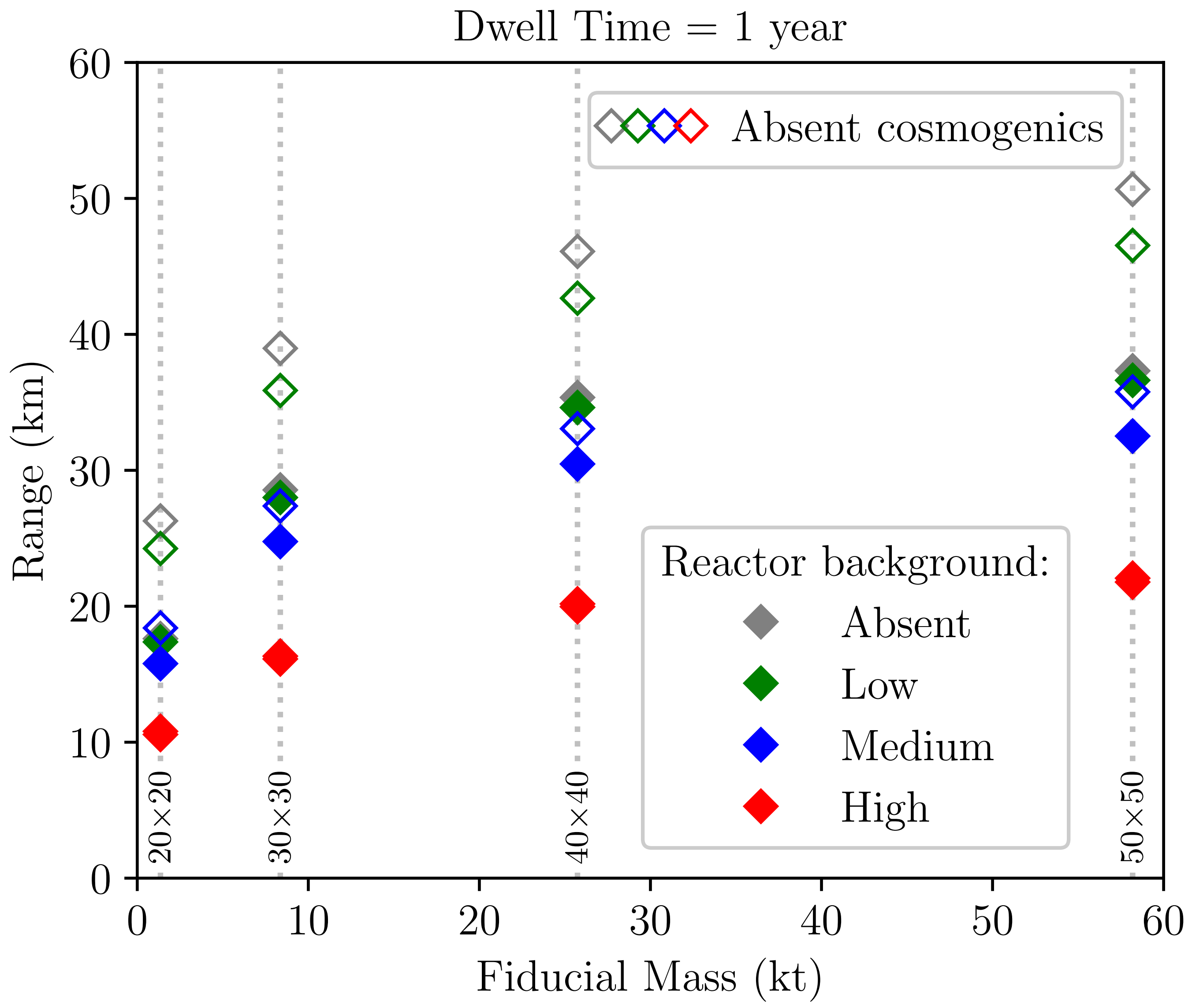


We solve this equation to find dwell time:

$$N_D = 4.653\sqrt{N_B}\sqrt{1 + N_B\delta^2} + 2.706$$

where N_D is the minimum number of counts from the source (antineutrinos from a 50-MWt reactor) required to ensure reliable detection in the presence of background, and N_B is the total background, including world reactors, uncorrelated detector backgrounds, cosmogenic fast neutrons, atmospheric neutrino interactions with oxygen, diffuse supernova antineutrinos, and geological antineutrinos.

Conclusion: Range to detect a 50-MWt reactor



For locations with a high world reactor background, the task of detecting a small 50-MWt reactor at a large distance depends primarily on the world reactor background at that location. This is the primary reason why the estimated range levels off as a function of detector size.

Notable publications on the subject since last AAP

- arXiv:2204.08618 — this study
- arXiv:2210.09391 — Exclusion and Verification of Remote Nuclear Reactors with a 1-Kiloton Gd-Doped Water Detector
- arXiv:2210.11224 — Sensitivity of an antineutrino monitor for remote nuclear reactor discovery
- arXiv:2008.13266 — Measurement of Muon-induced High-energy Neutrons from Rock in an Underground Gd-doped Water Detector
- arXiv:2305.05135 — Search for astrophysical electron antineutrinos in Super-Kamiokande with 0.01wt% gadolinium-loaded water

Backup slides

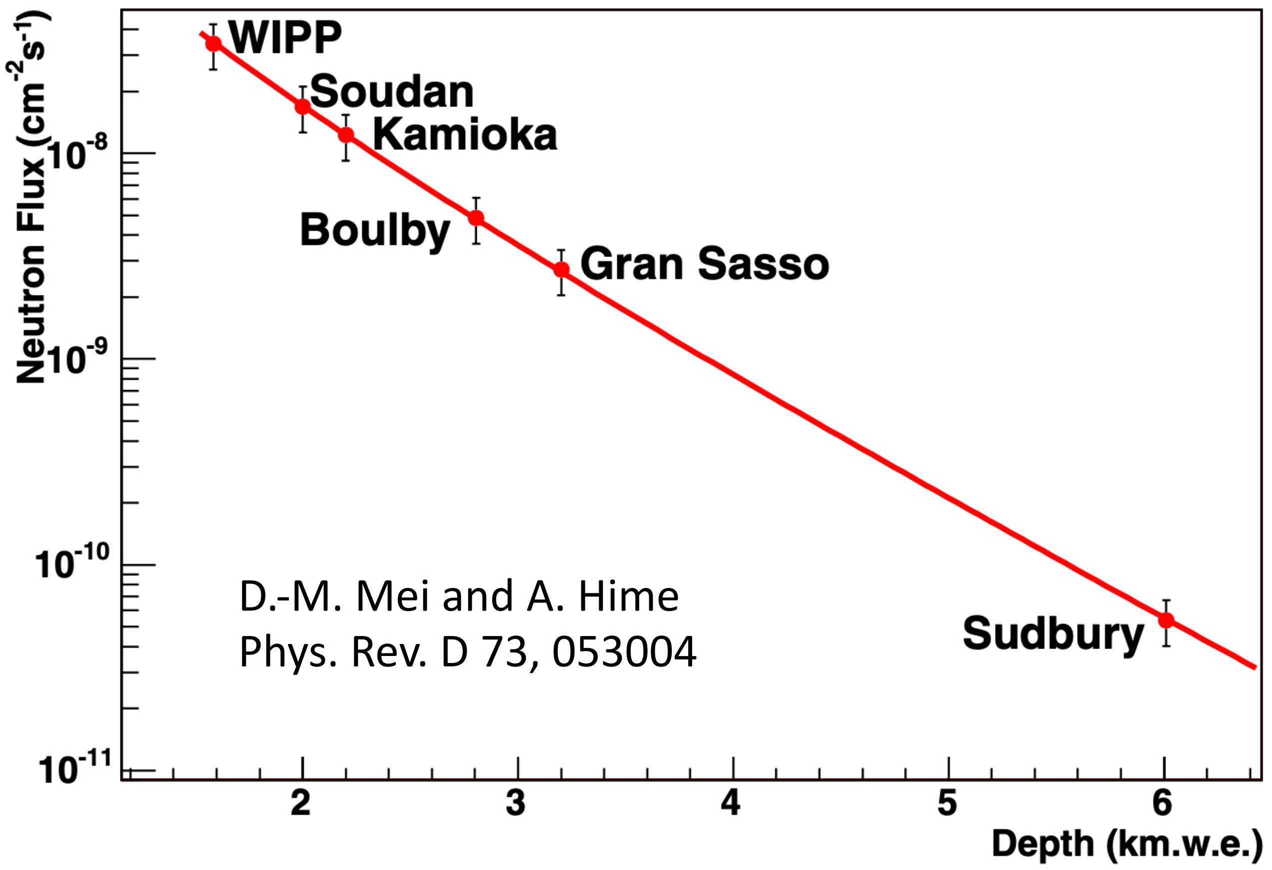
Backup: number of events

TABLE VII. Number of counts per year for signal and various backgrounds in the simulated detector geometries. The annual signal rates are reported for 10, 20, and 50-km baselines.

Detector		Signal (50 MWt)			Background						
$D \times H$	m_{fid}/kt	10-km	20-km	50-km	World reactor			Accidental	Cosmogenic	Exotic	Geo
					Low	Medium	High				
20×20	1.3	89	20	2	2	19	248	2	24	1	< 1
30×30	8.4	498	113	9	11	105	1388	7	81	5	2
40×40	25.7	1232	280	23	26	258	3397	17	165	15	3
50×50	58.2	1614	372	34	33	324	4017	2	247	35	3

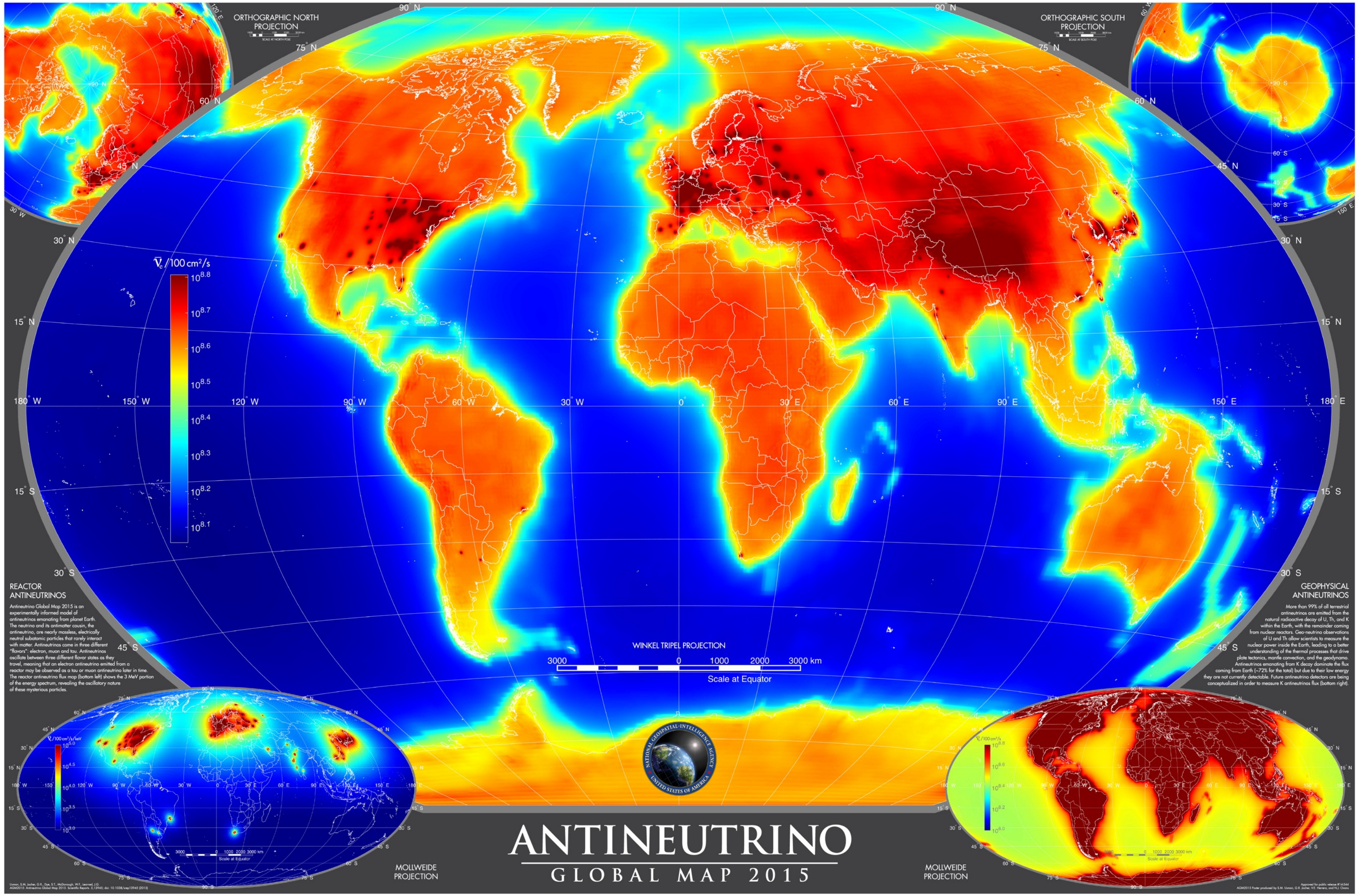
One can use this table/study to find dwell times for other reactor power (not 50 MWt) and various stand-off distances.

Cosmogenic neutron rates as function of depth

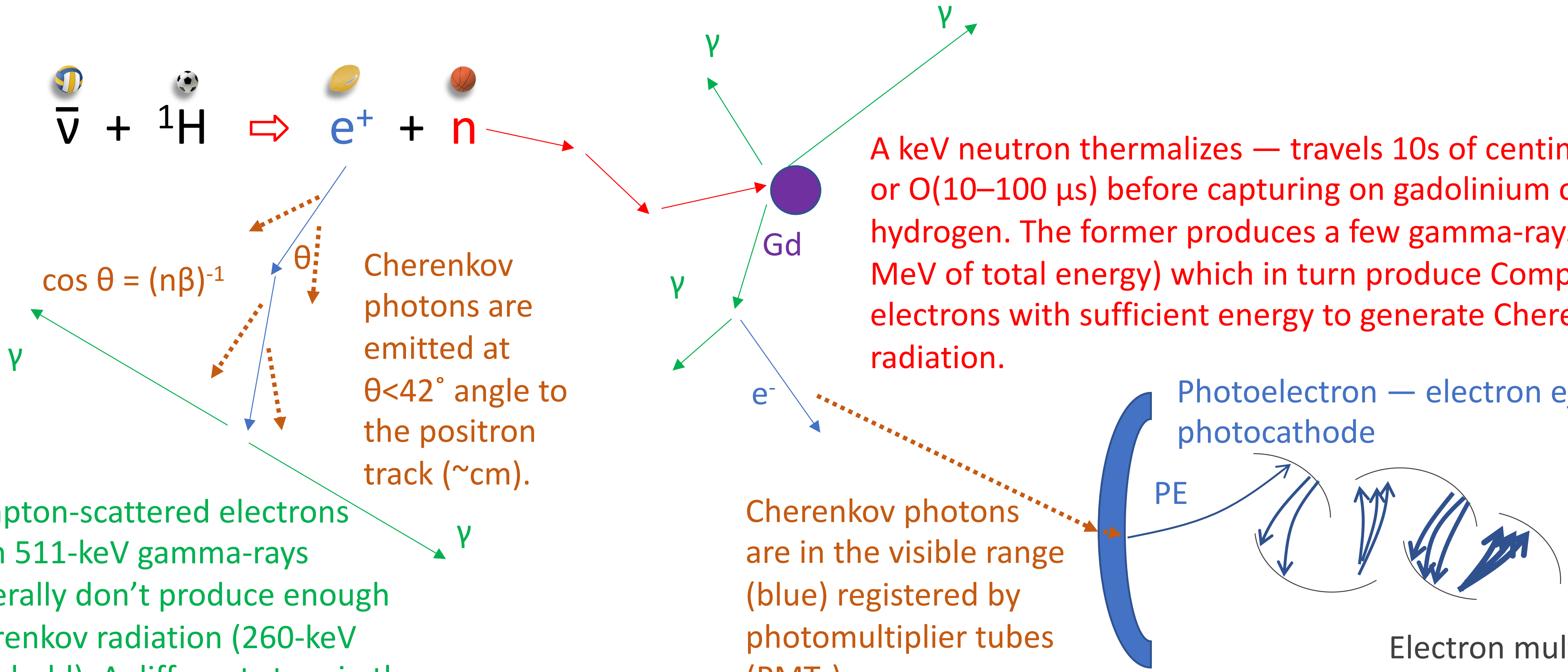


The detectors considered in this study are assumed to be placed at a depth roughly consistent with the proposed depth of the WATCHMAN experiment in the Boulby mine (approximately 2.8 km water equivalent). At this depth, and assuming that the detector fiducial volumes are protected by 4 m of veto and a PMT buffer as described above, cosmogenic fast-neutron backgrounds are expected to be subdominant.

Geoneutrinos are also included



How antineutrinos are detected (in this study)



A keV neutron thermalizes — travels 10s of centimeters or O(10–100 μs) before capturing on gadolinium or hydrogen. The former produces a few gamma-rays (~8 MeV of total energy) which in turn produce Compton electrons with sufficient energy to generate Cherenkov radiation.

Cherenkov photons are emitted at θ<42˚ angle to the positron track (~cm).

Photoelectron — electron ejected from photocathode

Compton-scattered electrons from 511-keV gamma-rays generally don't produce enough Cherenkov radiation (260-keV threshold). A different story in the scintillator.

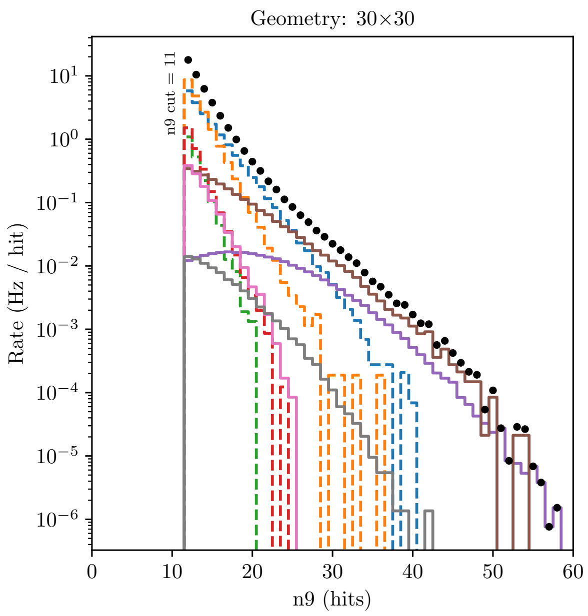
Cherenkov photons are in the visible range (blue) registered by photomultiplier tubes (PMTs).

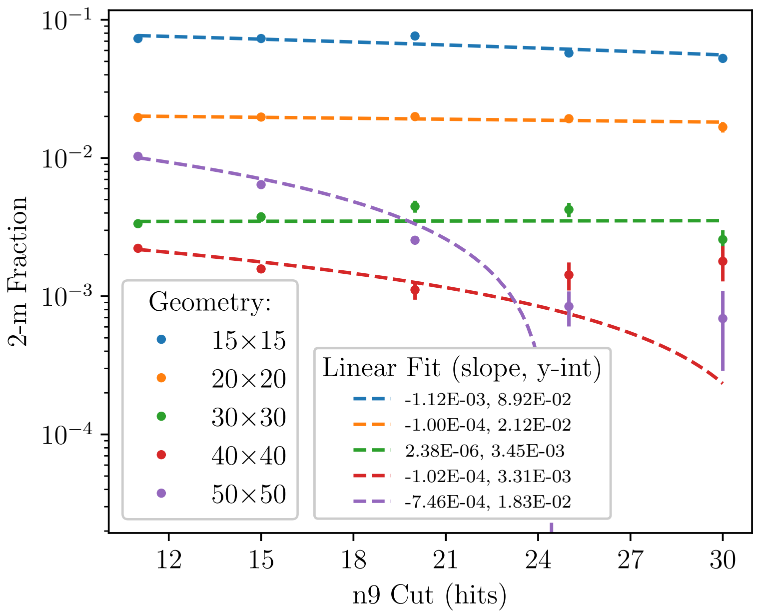
Electron multiplication: a single electron becomes ~10^{6} electrons, a macroscopic current possible to measure.

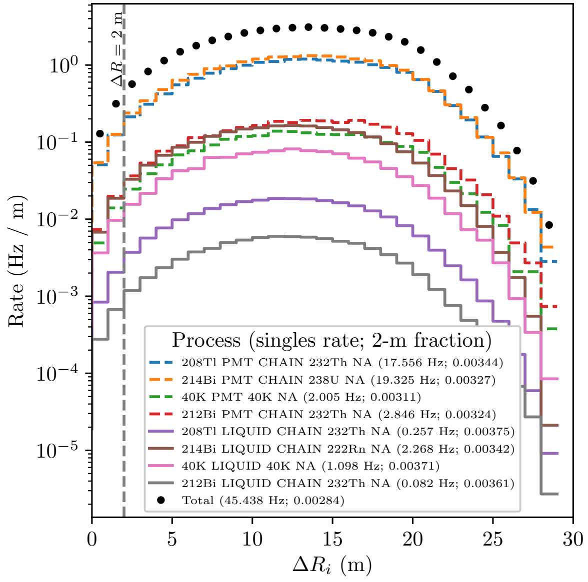
Positron, carries most of the antineutrino energy, travels a few centimeters before $e^{+}e^{-} \rightarrow \gamma\gamma$ annihilation.

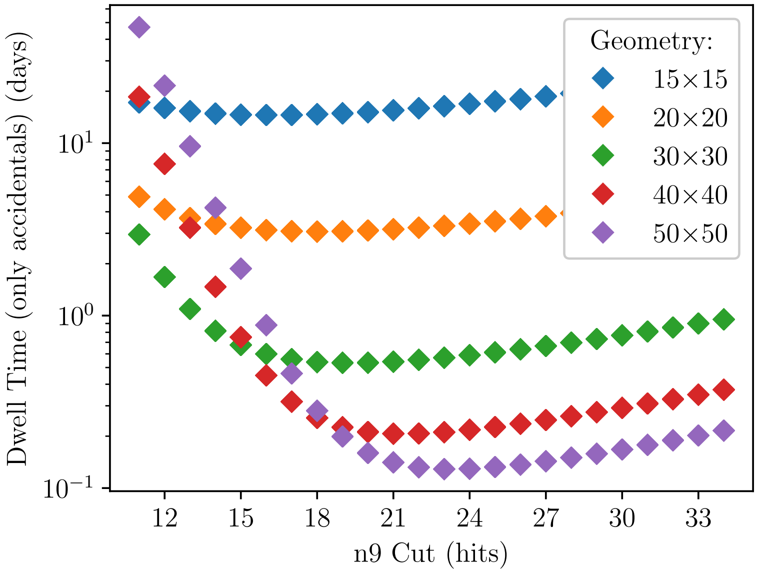
PMTs register Cherenkov light.

Backup:


Geometry: 30×30
n9 cut = 11
Rate (Hz / hit)
n9 (hits)


2-m Fraction
n9 Cut (hits)
Geometry:
15×15
20×20
30×30
40×40
50×50
Linear Fit (slope, y-int)
-1.12E-03, 8.92E-02
-1.00E-04, 2.12E-02
2.38E-06, 3.45E-03
-1.02E-04, 3.31E-03
-7.46E-04, 1.83E-02


ΔR = 2 m
Rate (Hz / m)
Process (singles rate; 2-m fraction)
208Tl PMT CHAIN 232Th NA (17.556 Hz; 0.00344)
214Bi PMT CHAIN 238U NA (19.325 Hz; 0.00327)
40K PMT 40K NA (2.005 Hz; 0.00311)
212Bi PMT CHAIN 232Th NA (2.846 Hz; 0.00324)
208Tl LIQUID CHAIN 232Th NA (0.257 Hz; 0.00375)
214Bi LIQUID CHAIN 222Rn NA (2.268 Hz; 0.00342)
40K LIQUID 40K NA (1.098 Hz; 0.00371)
212Bi LIQUID CHAIN 232Th NA (0.082 Hz; 0.00361)
Total (45.438 Hz; 0.00284)
ΔR_i (m)


Dwell Time (only accidentals) (days)
n9 Cut (hits)
Geometry:
15×15
20×20
30×30
40×40
50×50