Status update on a Far-field reactor monitoring demonstration at the Advanced Instrumentation Testbed

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On behalf of the WATCHMAN Collaboration

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LLNL-PRES-
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Lawrence Livermore National Laboratory

A working definition of far-field reactor monitoring

- **Monitor, discover or exclude the existence of operating reactors**
- **'Far': more than 1 km, out to ?? ... as far as possible** → see forthcoming R.M.P article https://arxiv.org/abs/1908.07113
  - 100 km requires ~100 kton detectors, 10-12 month dwell times
  - 1000 km → only with directionality in megaton detectors
- Varying degrees of access
- **Low statistics**: a few events per week, month, year
- **~50 MWt reactor power** – roughly generating 8 kg/one "Significant Quantity" of plutonium per year
- **Technology options**: variations on KamLAND, Super-Kamiokande, Borexino and other large water or oil-based detectors
- Explosive yield – difficult to achieve for less than 10 kton at reasonable standoff

This technology may be useful for cooperative remote monitoring, discovery or exclusion of operating nuclear reactors

25 km example

~25 km:

- ~20 kton detector would confirm absence of small reactors in 25 km radius—would have fulfilled US–Iran agreement requirement to exclude proliferant behavior and foster cooperation

- Site-wide monitoring for Fissile Material Cutoff Treaty

This scale to be demonstrated by WATCHMAN

100-1000 km

~100 km:

- Exclude new small reactors in a sector of a country

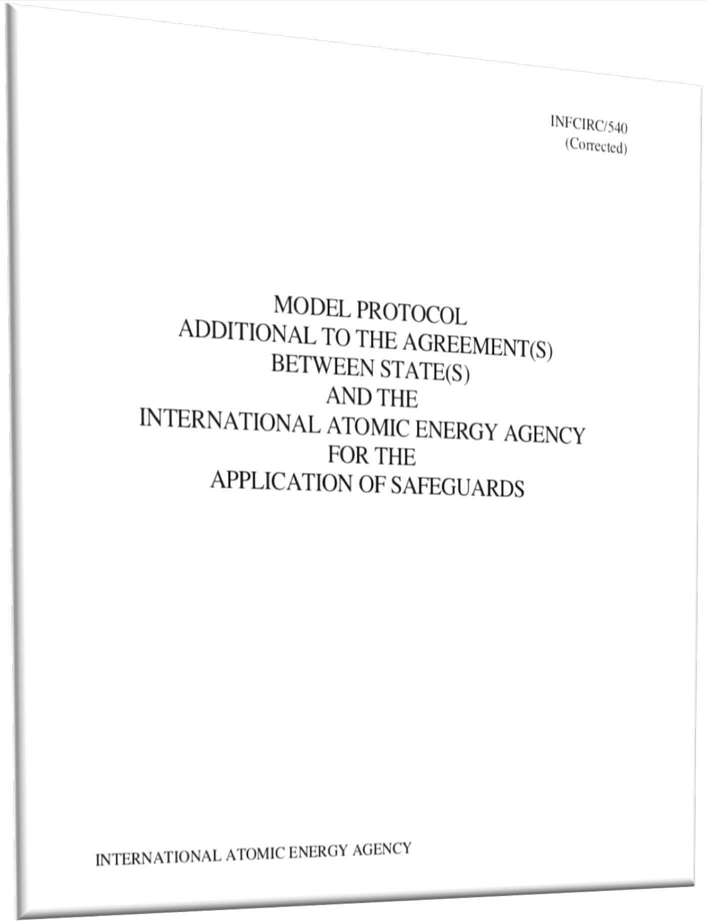
~1000 km:

- Exclude new small reactors across a border – difficult without large scale directional detectors

>100 km standoffs need directionality and/or 1–10 megaton detectors—AIT will permit study of these approaches

Small reactor standard ~50 MWt

Motivation: less intrusive nuclear monitoring techniques can help in treaty negotiations


INFCIRC/540
(Corrected)

MODEL PROTOCOL
ADDITIONAL TO THE AGREEMENT(S)
BETWEEN STATE(S)
AND THE
INTERNATIONAL ATOMIC ENERGY AGENCY
FOR THE
APPLICATION OF SAFEGUARDS

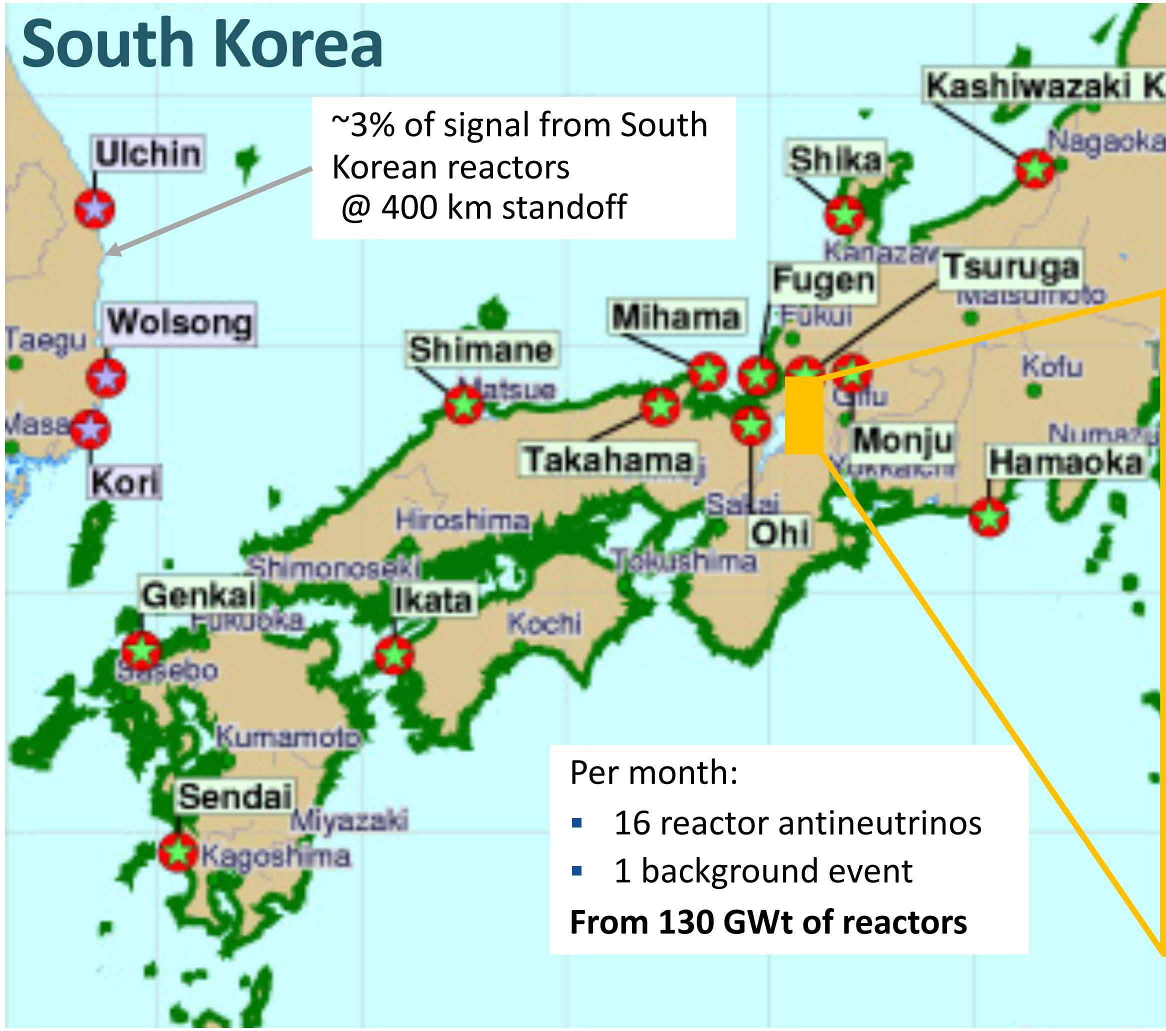
INTERNATIONAL ATOMIC ENERGY AGENCY

- Existing treaty language emphasizes minimizing intrusiveness and burden to the state being monitored:
  - "avoid hampering economic and technological development"
  - "avoid undue interference"
  - "take every precaution to protect commercial and industrial secrets and other confidential information coming to its knowledge and implementation of the Agreement"

(C. Jabarri, Center for Nonproliferation Studies, Monterey, CA)

100 km is considerably less intrusive than 25 meters – but what information remains in a large distant detector ?

Long-range reactor antineutrino detection has been demonstrated with the aggregate signal of relatively high-power reactors, and with an (arguably) hard-to-scale technology



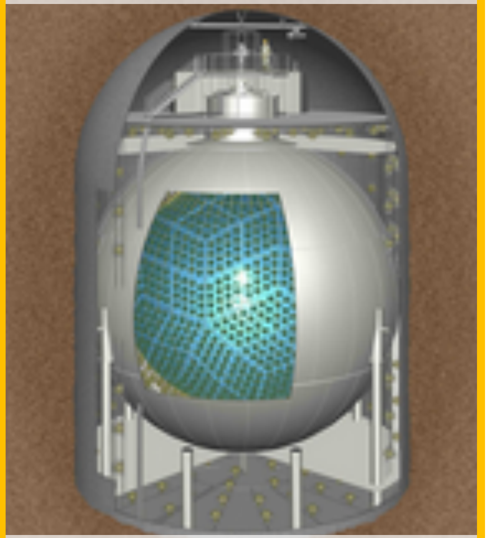
~3% of signal from South Korean reactors
@ 400 km standoff

Per month:

- 16 reactor antineutrinos
- 1 background event

From 130 GWt of reactors

The KamLAND detector



1000 tonnes scintillator
1000 m depth

Reactor power of interest for nonproliferation is ~50 MWt

KamLAND has performed rate and spectral analyses of reactor signals and background

Borexino has also studied reactor antineutrino sensitivity

sensitivity to the reactor signal is also the main focus of the planned **JUNO** experiment

Today's water Cherenkov detectors are 50x larger than scintillator detectors, but don't yet distinguish neutrino from antineutrino

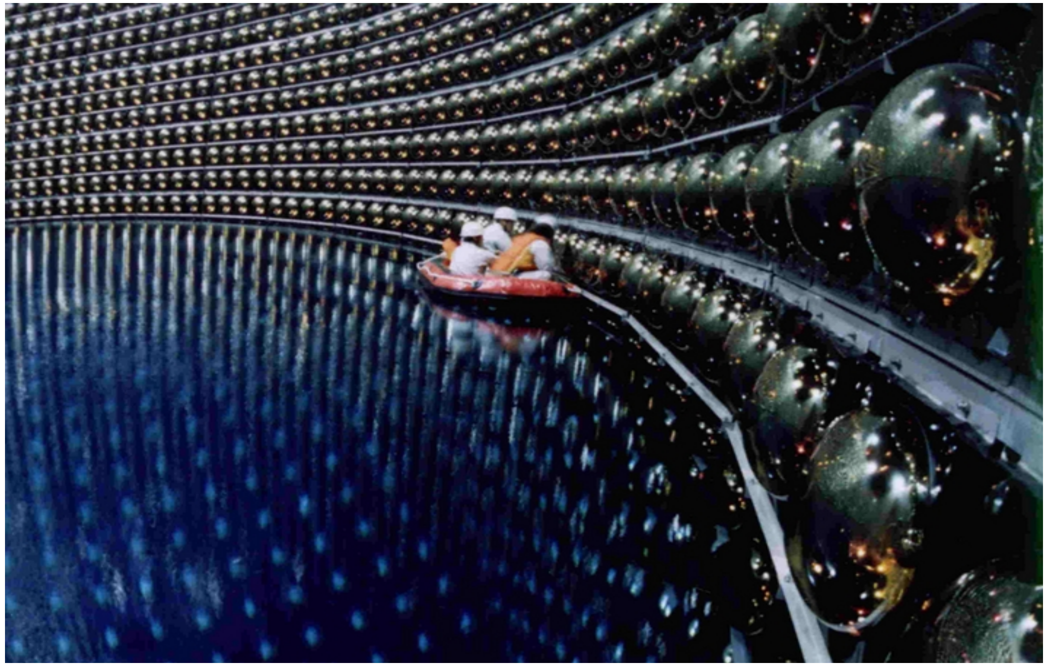
$\overline{\nu}_e + p = e^+ + n$ ←

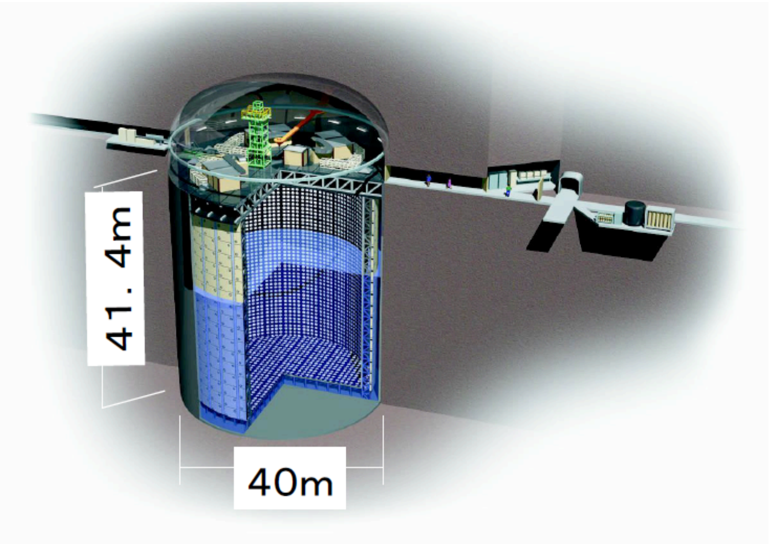
Inverse beta decay
from reactor $\overline{\nu}_e$

Identical signals from both processes:
a single flash of Cherenkov light

→ $\nu_e + e^- = \nu_e + e^-$

Elastic scatter
(solar neutrinos, reactors)





Super-Kamiokande water Cherenkov detector

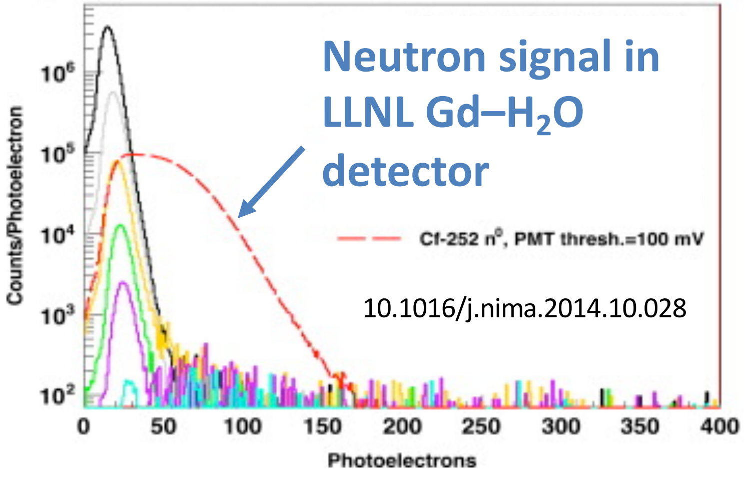
In 2009, LLNL and the Super-K collaboration both demonstrated water-based neutron detection using gadolinium as a trace additive

$$\overline{\nu}_e + p = e^+ + n$$

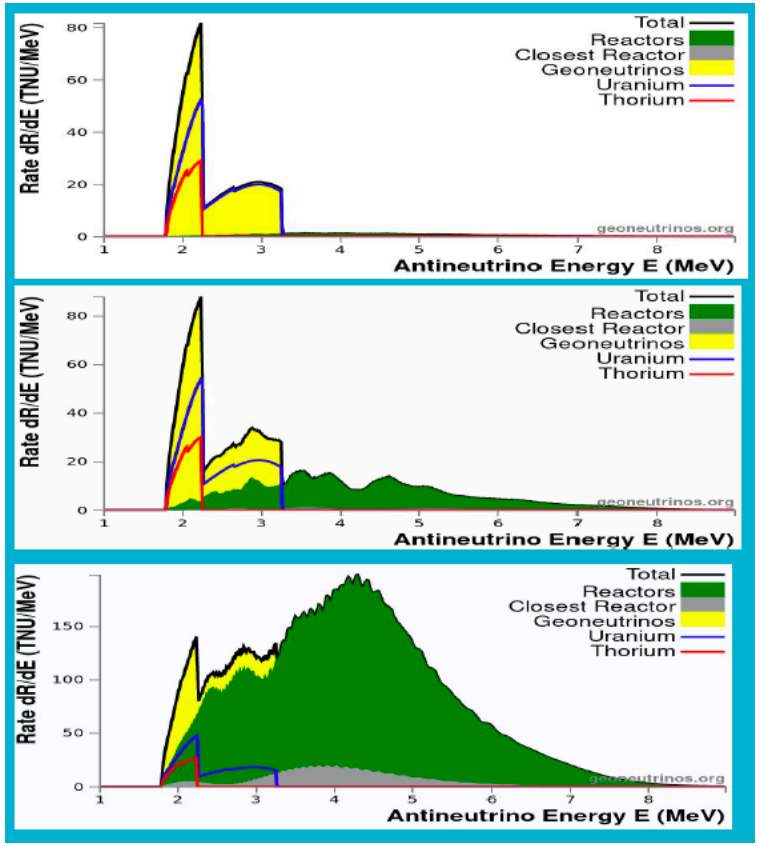
- Gadolinium nucleus captures neutrons with high efficiency and creates an intense flash of Cherenkov light
- The signal is two flashes of Cherenkov light, close in time (~100 μsec) and location (~5 cm)—the "antineutrino heartbeat"
- Reduces backgrounds by several orders of magnitude
- Gadolinium-doped Water Cherenkov technology offers path to 100–1000 kiloton antineutrino detectors
- First proposed by Bernstein in 2001
  Science & Global Security **9,** 235 (2001)
- Experimental verification in 2009

  LLNL: *NIMA* **607** (3), 21 (August 2009)

  Super-K: *Astroparticle Physics* **31**(4), 320–328 (May 2009)



Knowledge of global reactor backgrounds gives us partial insight into sensitivity to small reactors worldwide



Low reactor backgrounds

Medium

High

without directionality, reactor antineutrinos are an irreducible background
geoneutrinos.org/reactors (Dye, Barna)

idealized example: 50 MWt thermal reactor discovery;
3 sigma detection,100% efficient detector except: 3.3 MeV energy cut to remove geo-antineutrinos

Dwell time (months)	fiducial mass (kiloton)	standoff (km)	background level
1	1	10	low
4	1	10	high
		20	low
10-12	5	20	high
	10	50	low
	100	100	low
	1000	200	low

upcoming: expanded sensitivity studies in the UK and globally, including all known backgrounds and detector response - see T. Akindele presentation

A kiloton-scale demonstration will provide realistic backgrounds and signal efficiencies, and permit exploration of technology that can scale to even larger sizes

Main Project Goals:

1. demonstrate reactor discovery and exclusion
2. demonstrate verification of reactor operations
3. investigate the scalability and viability of detector concepts for far-field monitoring

- Cost and scalability arguments (and the work of KamLAND, Borexino and JUNO) have led us to focus on water-based detectors

Our current conceptual design is WATCHMAN: A WAter CHerenkov Monitor of Antineutrinos

Doping the water with gadolinium greatly increases sensitivity to inverse beta interactions of antineutrinos

$$\bar{\nu} + p \rightarrow e^{+} + n$$

HARTLEPOOL Reactors

- 2 cores
- 1.57 GWt per core
- 25 km standoff
- Relatively high power near an existing mine suits an initial demonstration

WATCHMAN detector at Boulby mine

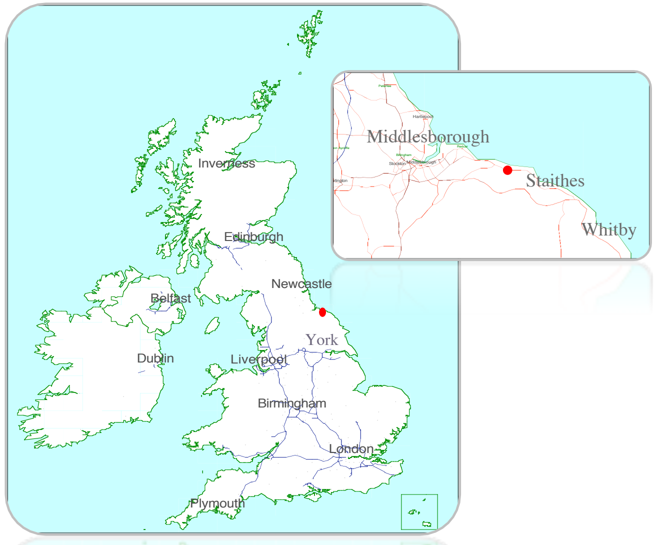
- ~ 6000 tons – 3500-4500 10" hemispherical light sensors
- Maximum size set by cavern geology and cost
- Baseline design to be determined in FY20

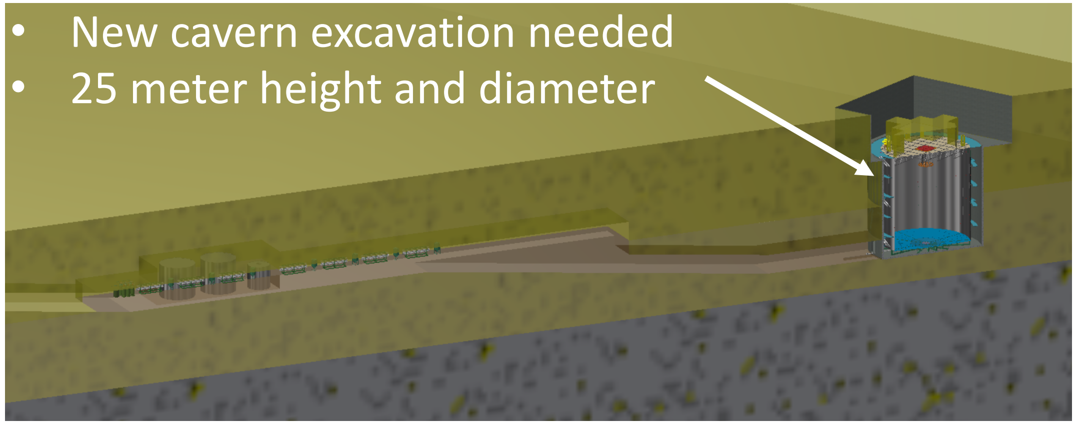
The WATCHMAN collaboration

122 collaborators
4 UK,13 US Universities
2 UK,3 US National Laboratories
recently added in the UK: Warwick University

The Advanced Instrumentation Testbed AIT will enable real-world, at-scale testing of antineutrino-based remote monitoring technologies for nuclear reactors

- UK's Underground Science Facility at Boulby has agreed to host AIT
- (AIT) will house the world's first experiment dedicated to exploring the viability and scalability of remote reactor monitoring technology
  - SK-GdH2O will measure aggregate reactor signals, AIT will measure individual reactor status and cycles
  - AIT permits studies of design variants specifically for nonproliferation sensitivity
- AIT will be designed to accommodate follow-on experiments aimed at increasing sensitivity to the reactor signal and related physics
- Depth is ~1100 m .. compares to ~1500 m (Homestake) and 2400 m (Jinping)
- Strong support from host mining company (ICL-UK) and the operators of the existing underground scientific laboratory





Timeline – indicative only, depends on outcome of ongoing cavern, tank, lab space conceptual design study

2021 – Final design for cavern, lab space and tank

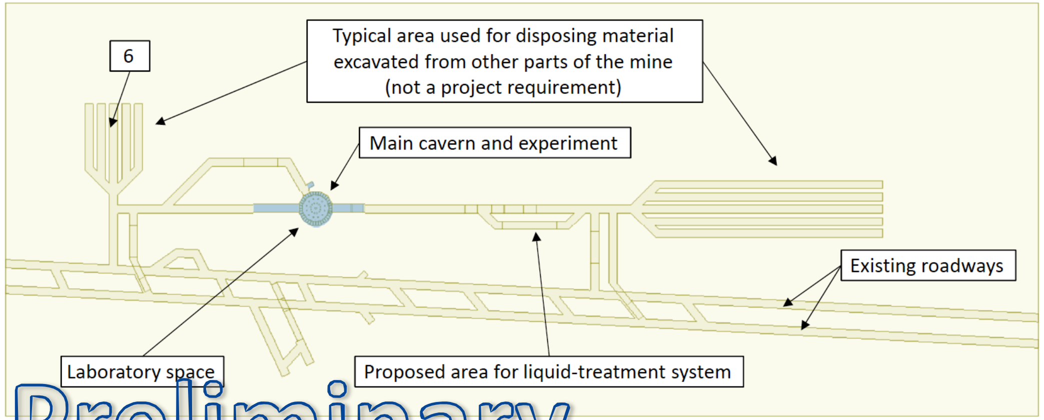
2024 – Beneficial occupancy for the detector installation

Preliminary Preliminary Preliminary

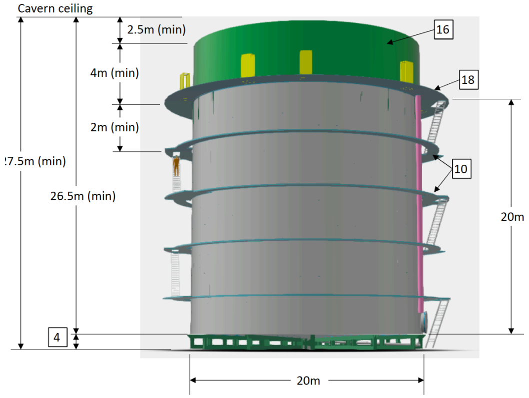
2025 – Baseline detector operational

2026 – Possible upgrades from baseline design ?

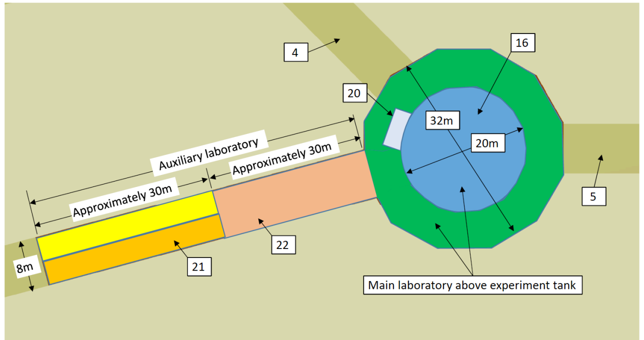
exemplary cavern and access design



exemplary tank design



exemplary lab space design



Collaboration focus in 2020 - evaluation and time-ordering of possible experiments at AIT

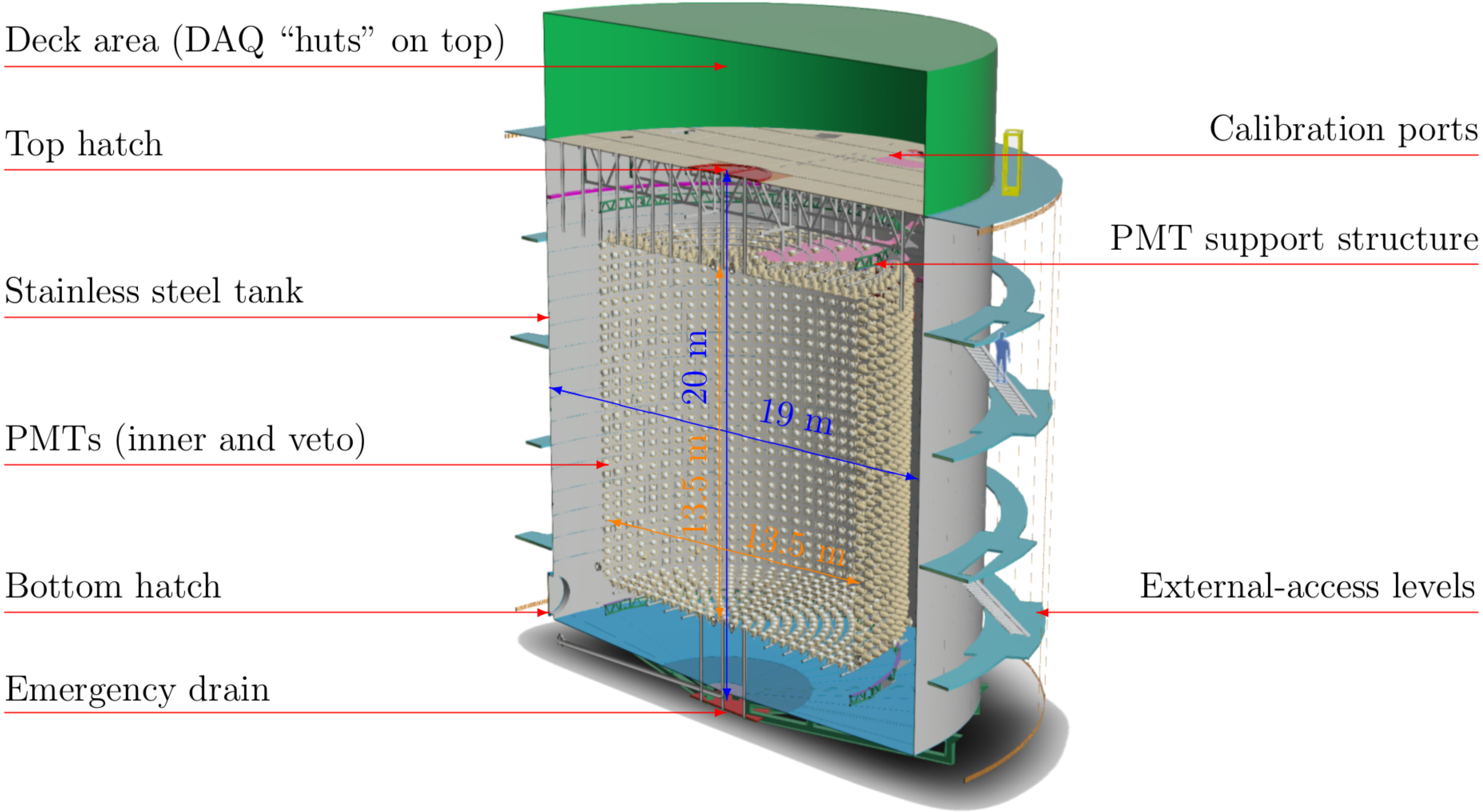
While we await our cavern conceptual design, US and UK sponsors have asked the collaboration to conduct a thorough study of design variants:

- **The WATCHMAN Gd-H_2O conceptual design is the best-understood option**
- variants include:
    - WbLS (with or without Gd)
    - wavelength shifting plates, dichroic filters, Winston cones, and other light collectors
    - LAPPDs or other fast photosensors
    - Alternative Data Acquisition approaches

Evaluation criteria: nonproliferation sensitivity, basic science/detector R&D potential, cost, schedule and risk

~May 2020: collaboration’s proposal for the first experiment at AIT, and for concepts for follow-on upgrades and experiments

The WATCHMAN Conceptual Design – a first look



- Cylindrical tank: 19-20 m diameter, 20 m tall
- Target region: 3600-4400 photomultiplier tubes
- ~1.5 m active buffer region around the fiducial volume
- 2.5 m – 3.5 m veto region outside of target

Sources of antineutrinos and radiological backgrounds

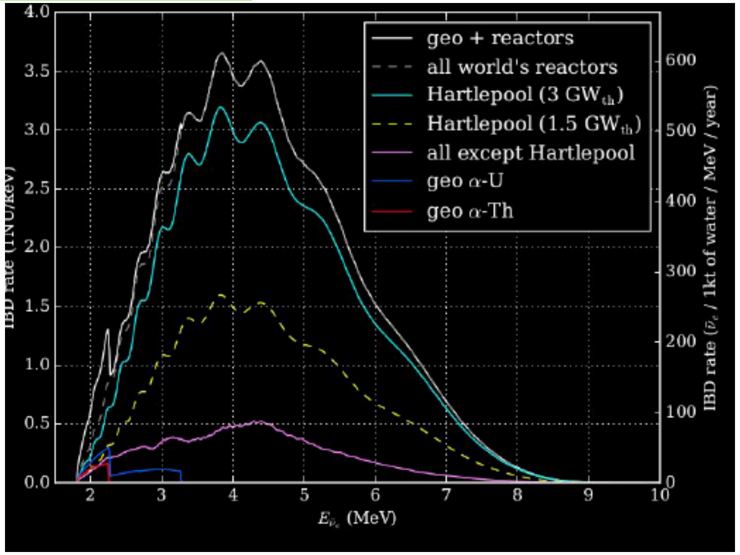
- Events modeled using RAT-PAC, a GEANT4 simulation based framework (UCB/LBL lead)
- Total reactor antineutrino and geoneutrino flux from Geoneutrinos.org
- Radiological backgrounds are based on estimated activity of detector components

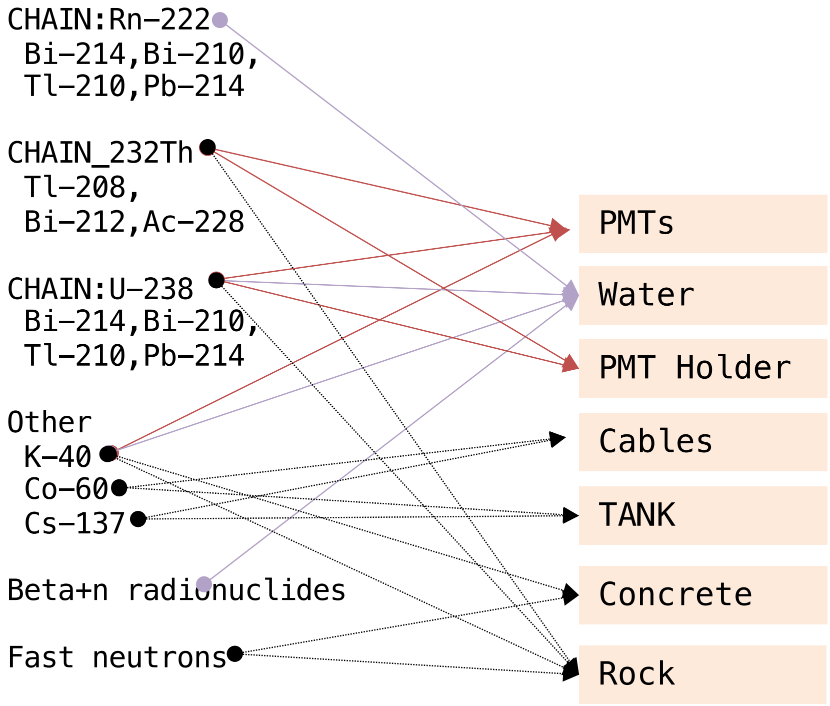
Backgrounds come in two flavors

- Accidental: two events form an IBD candidate by chance
- Correlated: IBD candidate is formed in a process that produces multilple neutrons or radionuclides with beta+n decays

Geoneutrinos.org

Both cores at max power





For 1kt Fiducial and 4401 Inner PMTS

Component	Events/week
Core 1	4.8
Core 2	4.8
World reactors	1.5
Accidentals	0.6
Fast neutrons	0.6
Radionuclides	0.1

Representative nonproliferation measurement scenarios

Discovery Scenarios (Mission Goal 1):

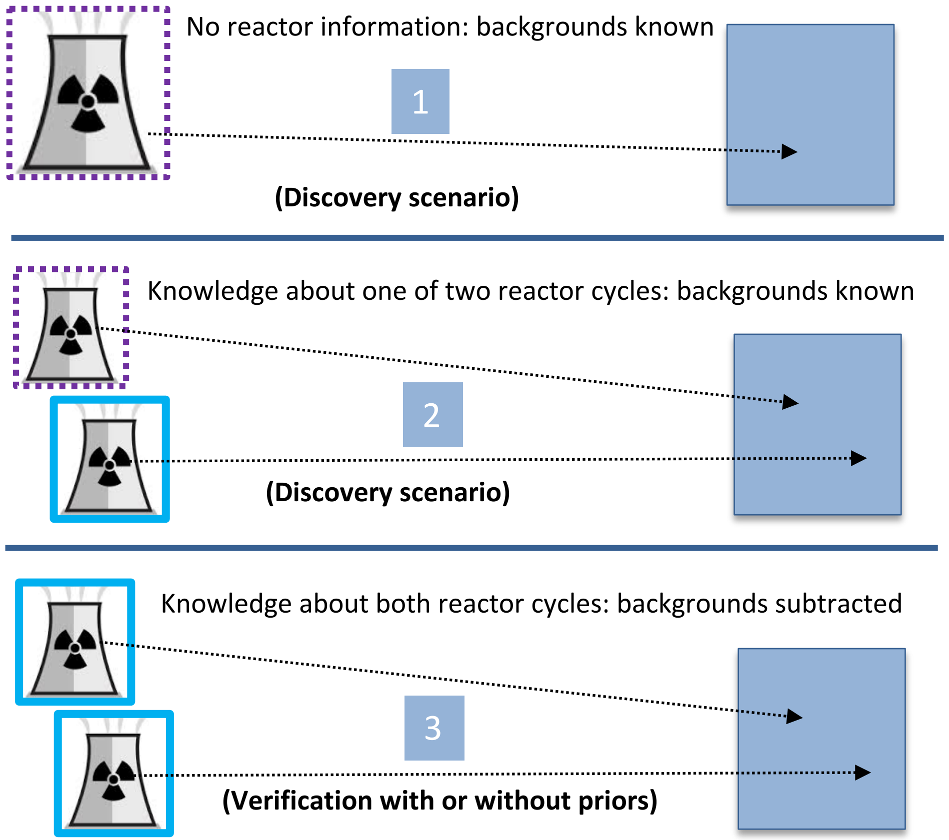
- Determine whether any reactor is present (case 1)
- Knowing that one reactor is operating, determine that a second reactor has turned on (case 2)

Verification Scenario: (Mission Goal 2)

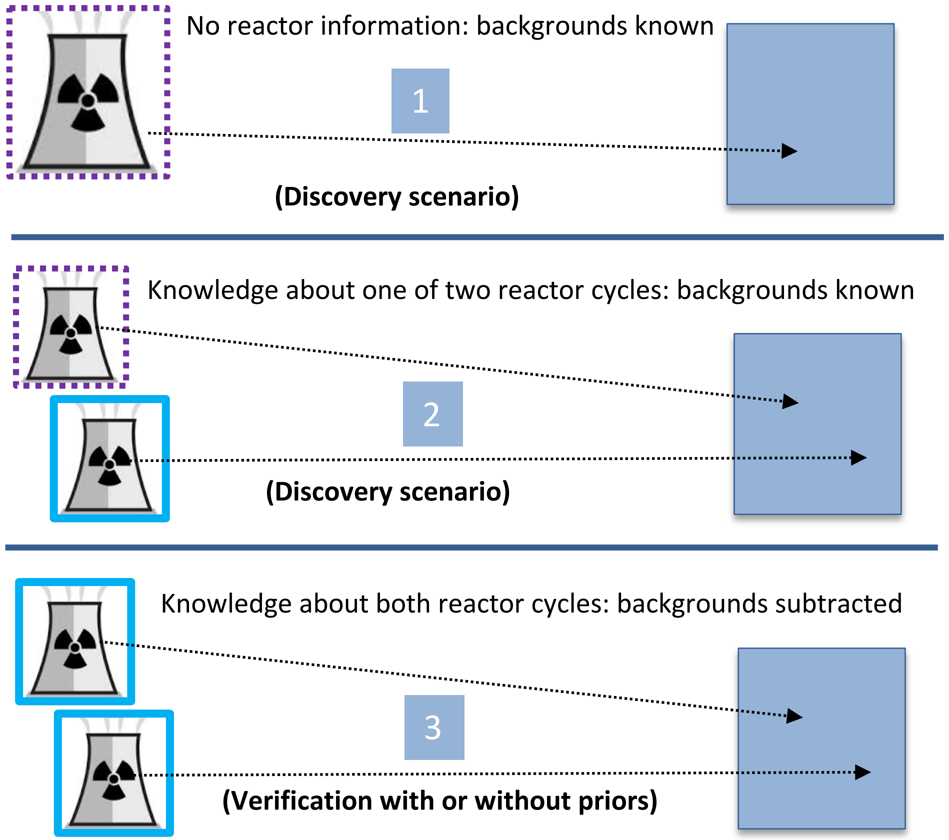
- Confirm operational status with or without prior knowledge of both reactor cycles. (case 3)

Nonproliferation use cases are in development within the collaboration. These will be further developed in consultation with sponsors and the broad nonproliferation community

The standardized scenarios defined above help us set detector performance requirements through simulation, and permit extrapolation in power and standoff



Expected dwell times for different scenarios

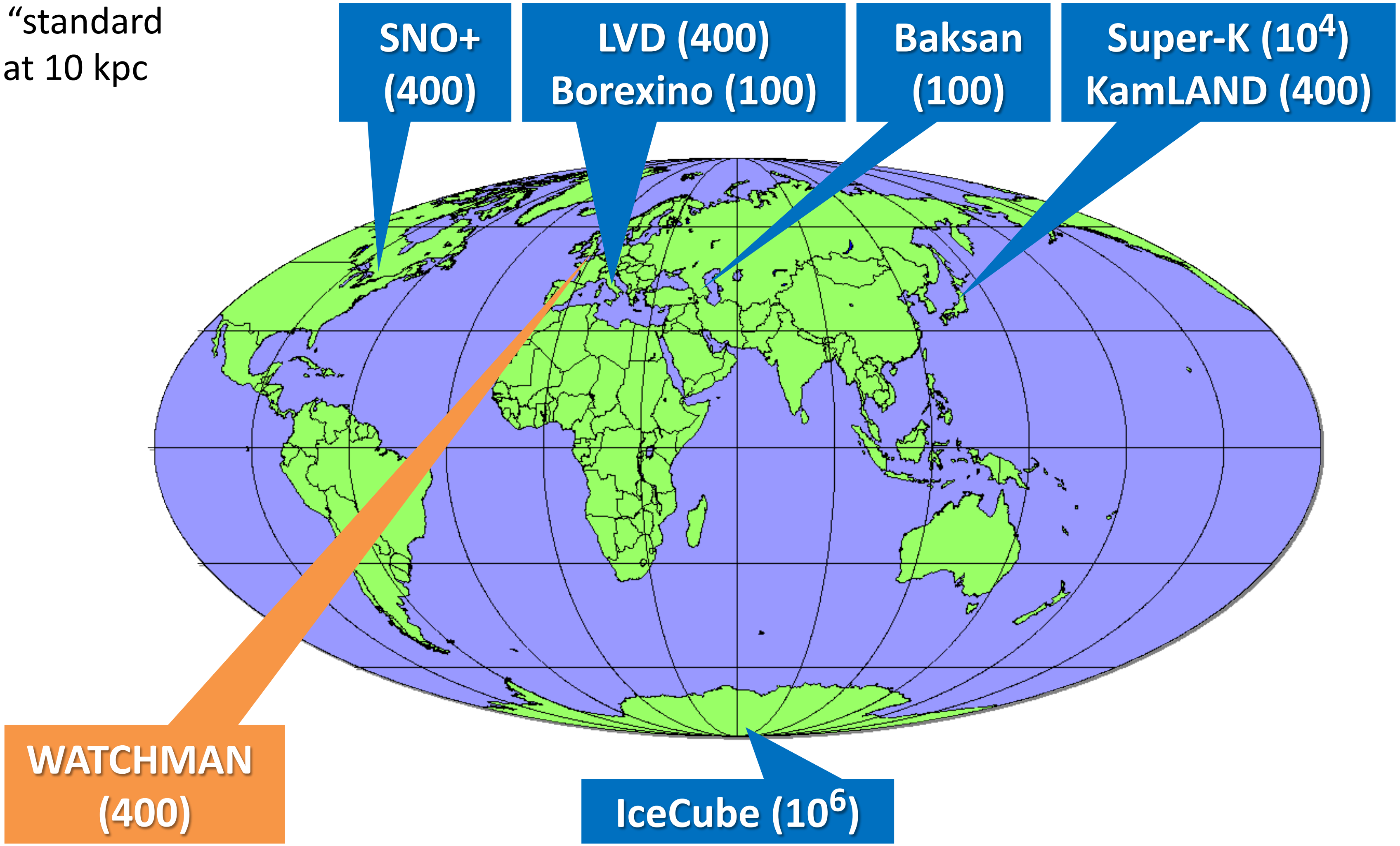


Scenario	Dwell Time	Metric
1	Two Core: 3-9 Days	TP/FP: 95%/9%
	One Core: 1-4 Weeks	TP/FP: 94%/7%
2	3-8 Weeks	TP/FP: 95%/7%
	2-4 Months	TP/FP: 99%/1%
3	6-18 Months	95% Confidence with prior cycle information

- Additional analysis may improve these dwell times
- Other studies are underway:
  - implied sensitivity to smaller, more distant reactors at this site
  - expected sensitivity with bigger detectors around the world

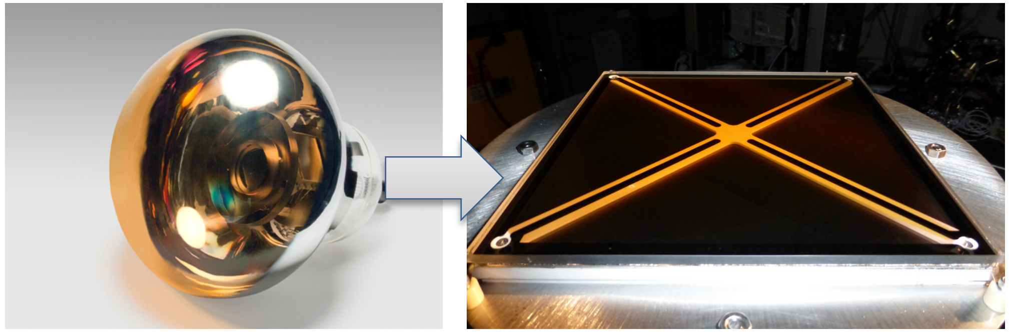
The first detector at AIT will join the handful of other large supernova neutrino/antineutrino detectors in the world

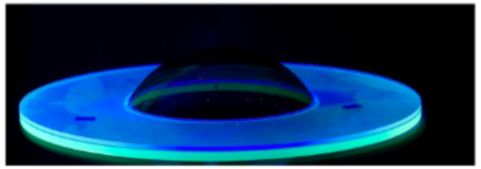
events for a "standard supernova" at 10 kpc

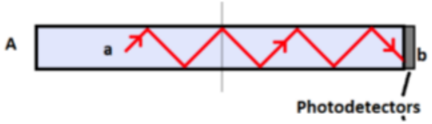


AIT will explore design variants to improve sensitivity to the reactor IBD signal

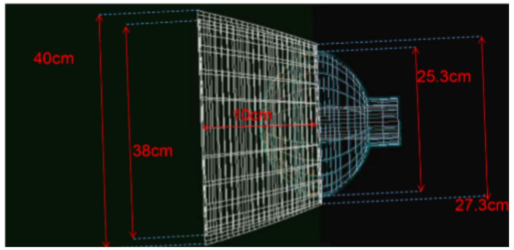
New (and old) Light Collection Tools

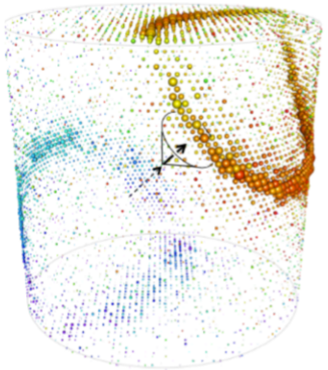




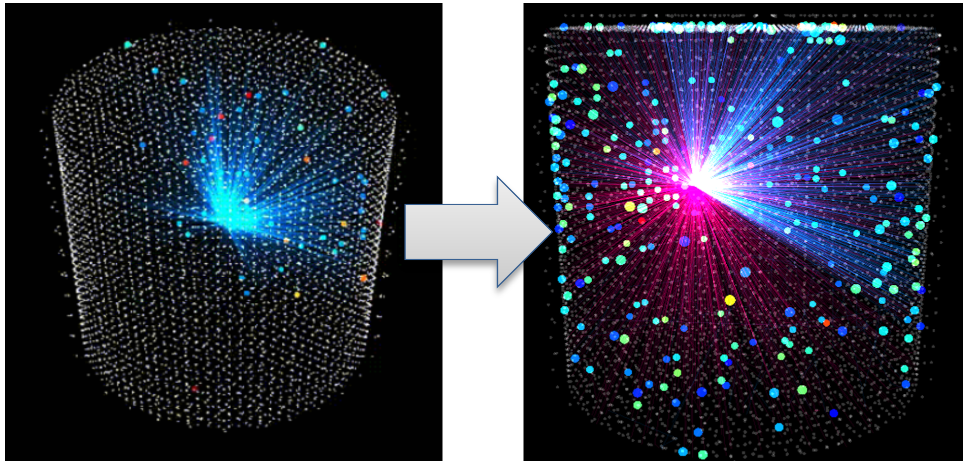


DESIGN, SIMULATION, AND PROTOTYPING OF WAVELENGTH-SHIFTING PLATE LIGHT COLLECTOR FOR A LARGE WATER CHERENKOV DETECTOR
William Albert Johnston , Colorado State University





New Light Generation Methods



Water-based liquid scintillator (WbLS) will increase light yield and *may* improve background rejection

Slide adapted from Minfang Yeh)

What is Water-based Liquid Scintillator (WbLS) ?

WbLS is a novel detector solvent bridging water and organic scintillator

In principle, the light yield is adjustable for different applications

- water-like WbLS: ~12% scintillator in water
- oil-like WbLS: ~40% water in scintillator cocktail

Cherenkov and scintillation detections in ONE detector

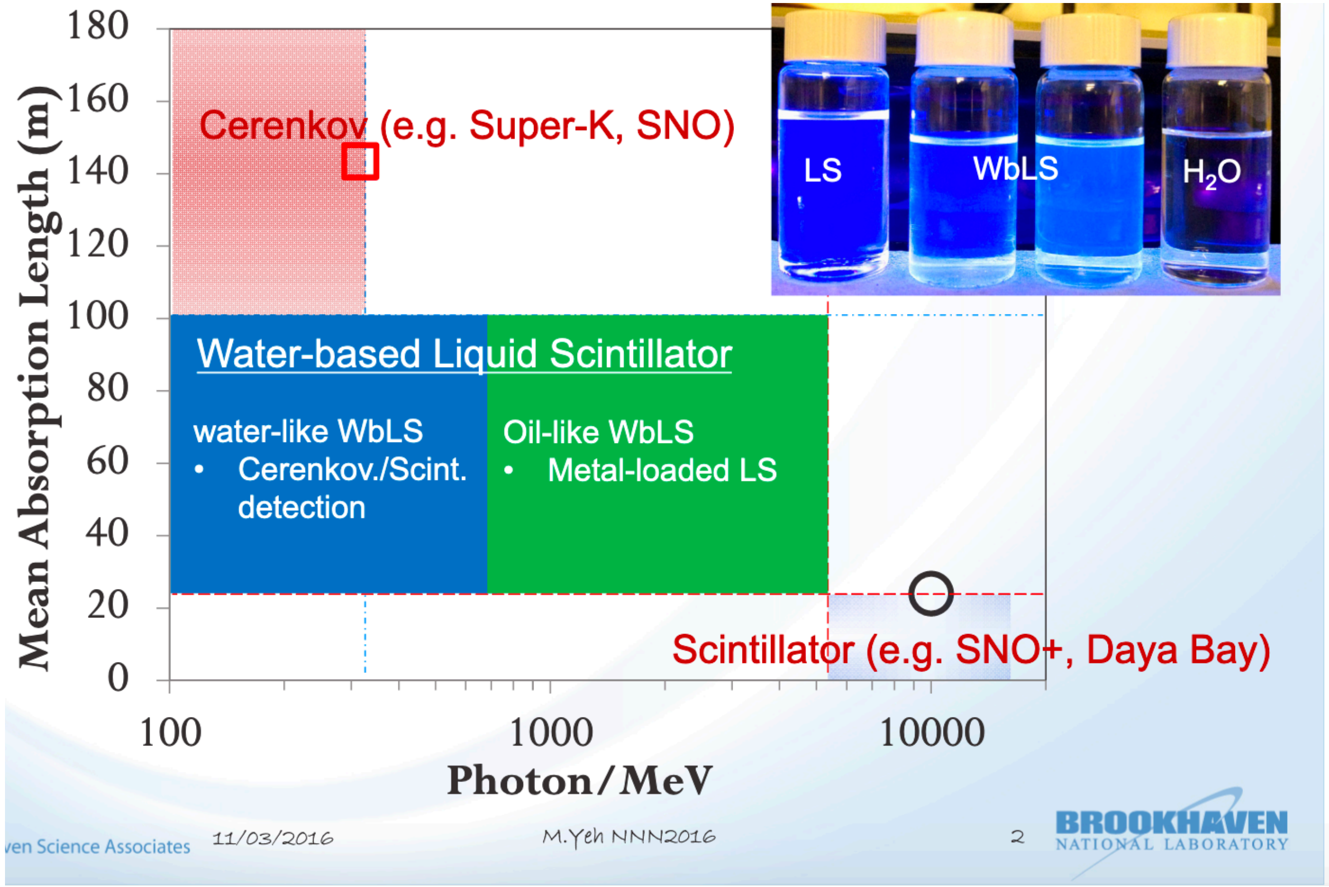
- a possible enhancement for future water Cherenkov detectors
- physics below Cherenkov threshold

Lower cost and better chemical safety compared to pure scintillator

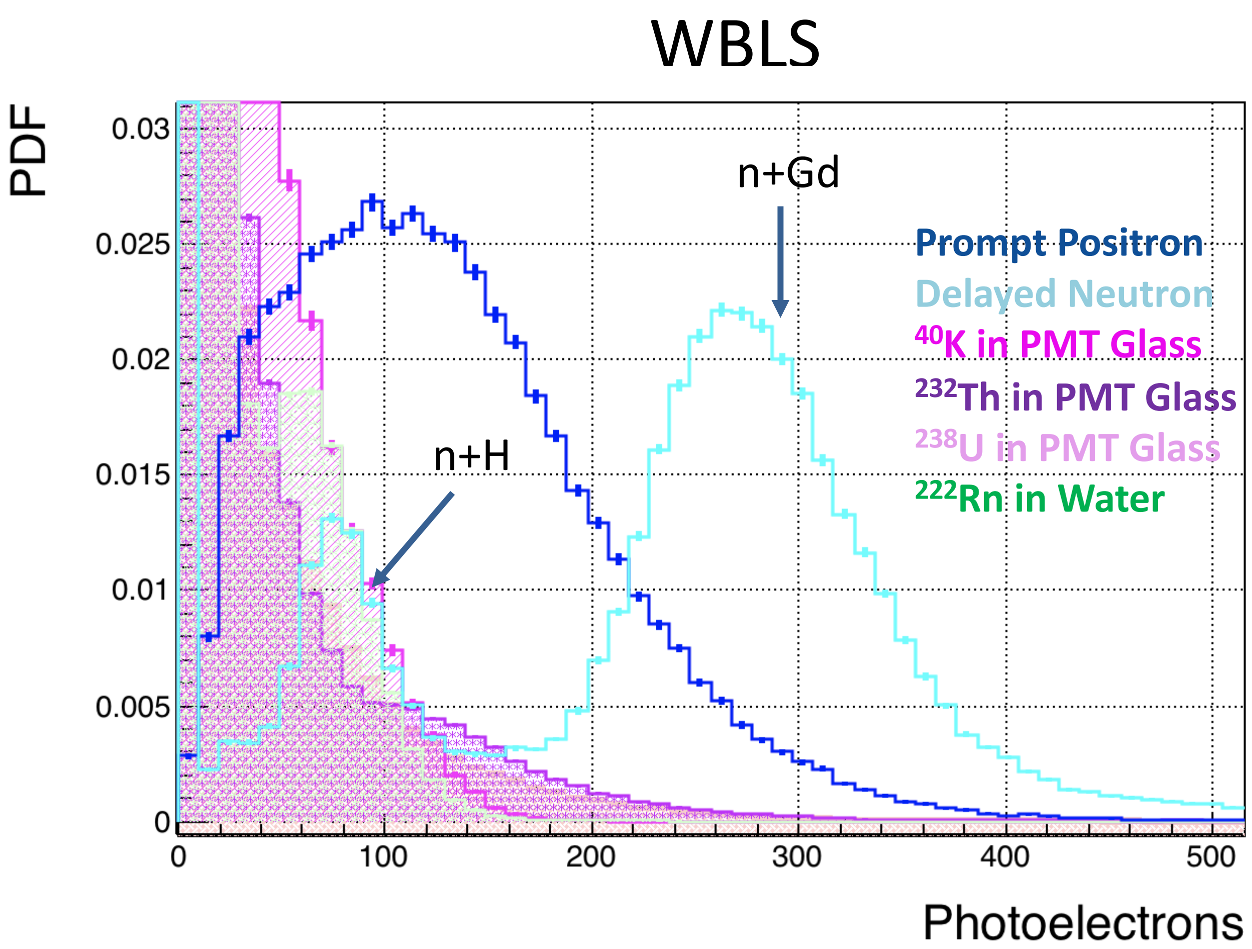
- (1%)WbLS~ \$30/ton (\$3,000 per ton for pure LS detector)

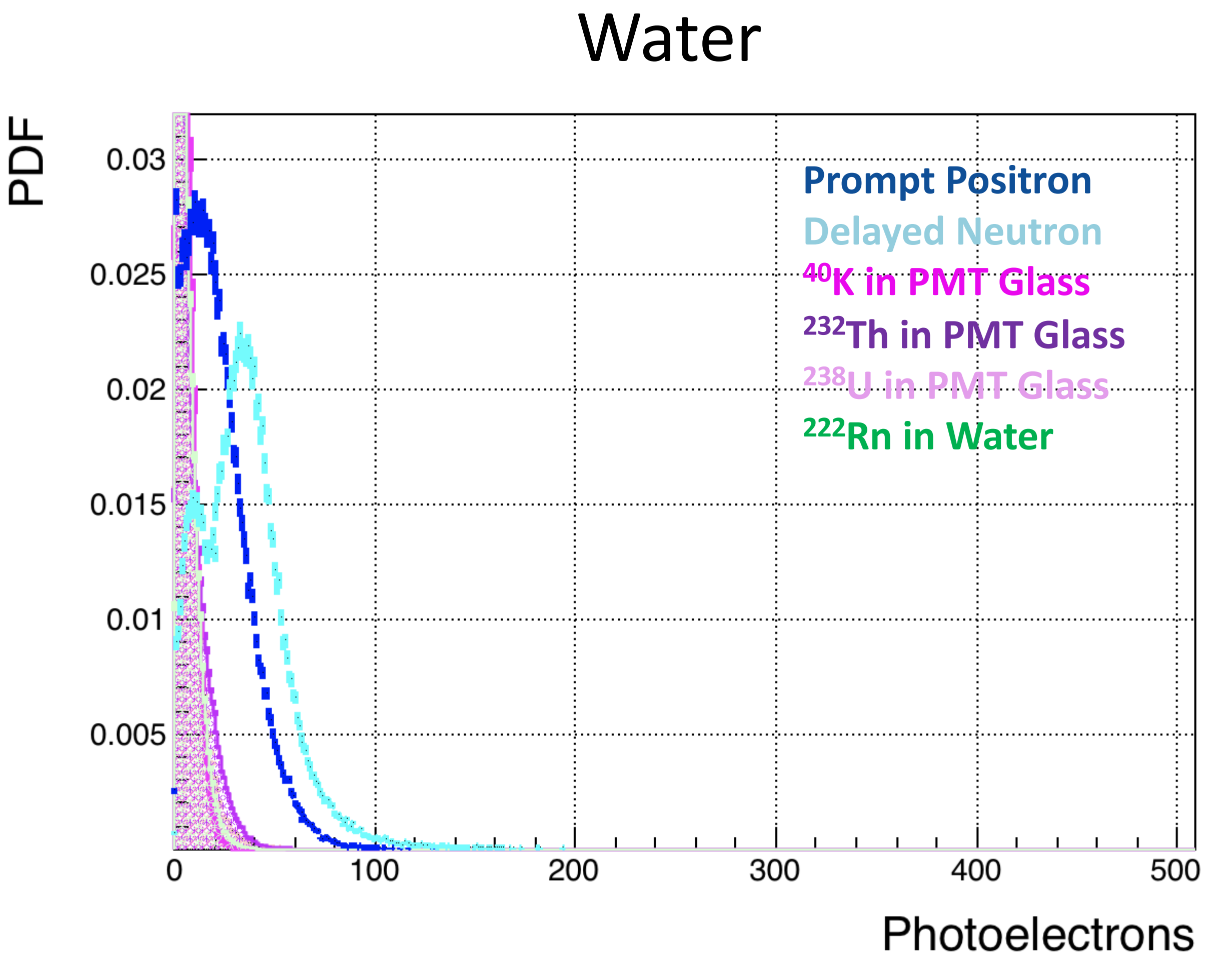
Capable of loading with metallic ions to enhance performance

- Gd, Li, B, etc.



Signal to Background Discrimination – do we need Gd in WbLS ?





As in pure water, Gd in WbLS helps reduce gamma backgrounds

The AIT long-term nonproliferation research program can help speed the development of detectors like THEIA and DUNE

$>10^1$ km → $>10^2$ km → $\sim10^3$ km

Standoff for observing small reactor operations in weeks to months

$\sim10^2$ ton
WATCHBOY, MARS, EGADS (complete)

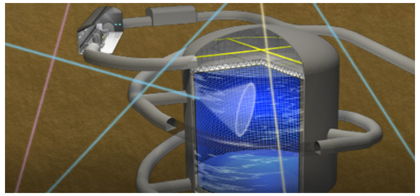
$\sim10^3$ ton
AIT-WATCHMAN Gd-H2O fill

$\sim10^3$ ton
AIT—"Proto-THEIA" WBLS fill

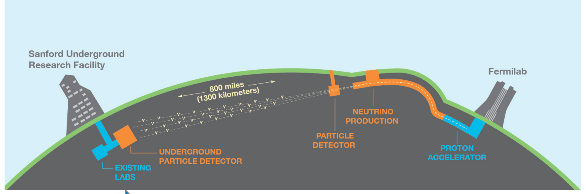
$\sim10^{4.8}$ ton
THEIA ~0.1 MT WBLS

$>\sim10^6$ ton
Megaton-scale detector with directionality

Hyperkamiokande



DUNE



2012–2017 activities → ~6 year lifecycle plan (this project) → Long-term vision consistent with fundamental science planning—THEIA, DUNE, Hyper-K

Summary

- The Advanced Instrumentation Testbed (AIT) will permit the study of far-field reactor monitoring in a succession of kiloton-scale experiments
- In 2020, WATCHMAN collaborators will perform an analysis of alternative designs for the first detector at AIT
- In about 4-5 years, a kiloton-scale detector will deployed in the Boulby mine in the Northeast of England, to detect reactor antineutrinos and demonstrate a scalable technology for reactor monitoring applications
- The design of the Cavern, Tank and Laboratory space is underway now !

THANK YOU!

akindele1@llnl.gov

Questions?

Lawrence Livermore National Laboratory

Timeline for Far-field monitoring and related concepts

relevant experiments

KamLAND

'03 - clearly demonstrates remote reactor monitoring with 1 kton of scintillator

EGADS

200 ton Gd-H2O engineering demonstrator

WATCHMAN:

1 kT Gd-doped water devoted to reactor monitoring

Super-K_Gd:

50 kT Gd-doped water

JUNO:

50 kT Liquid Scintillator

2000 2005 2010 2015 2020

relevant analyses

'01: Bernstein et. al.
Gd-doped water
for CTBT monitoring
applications

Conclusion: not worth it
for the 1 G$ price of entry

'03: Dreaming big: John Learned considers the benefits of a gigaton array of monitoring detectors

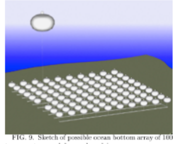


FIG. 9. Sketch of possible ocean bottom array of 100 ten-megaton modules anchored in a square array on the deep ocean bottom, typically 4-5km depths. One module is shown in retrieval/repair configuration. Array would be cabled to shore for power, command and control and data transmission.

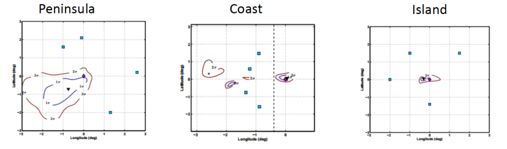
Neutrinos and Arms Control:
Thinking Big about Detection of Neutrinos from
Reactors at Long Distances

John G. Learned

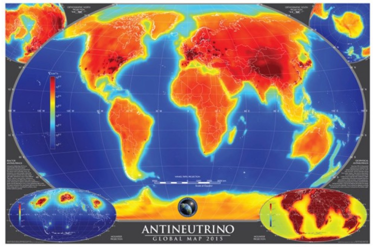
Department of Physics and Astronomy, University of Hawaii, Manoa

'08: Gullian –
Far-Field Monitoring of
Rogue Nuclear Activity

'10: Lasserre et. al – PRC
'Secret Neutrino Interaction Finder'
detailed treatment of
reactor and non-reactor backgrounds



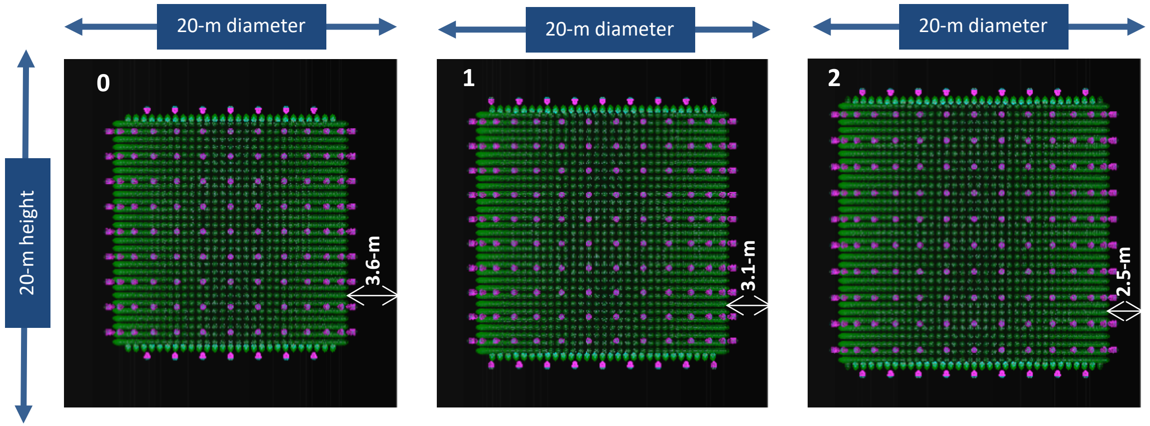
'17: Carr et. al – PR Appl. 10
'Seismically cued antineutrino detectors'
Modest improvement on '01 results



AGM 2015 Usman/Learned
geoneutrino.org/reactors S. Dye

We've explored trade-offs between PMT coverage and PMT distance from the fiducial

<u>Move PMTs</u> closer or farther away from a volume of interest (1 kton volume)



- Active volume decrease, less signal
- Fewer PMTs required to achieve desired photocoverage

- Volume increase, more signal
- More PMTs required to achieve desired photocoverage

<u>Vary photo-coverage.</u>

Vary photo-coverage from 15% to 35%.

More PMTs → better signal characterization

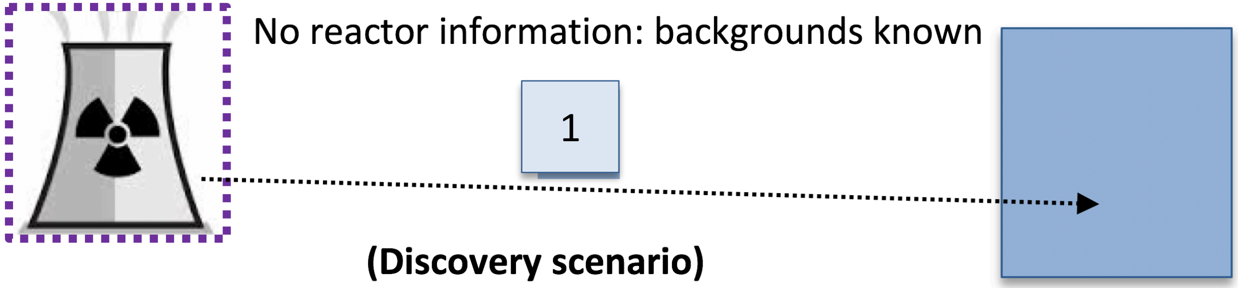
More PMTs → more radioactivity (more backgrounds)

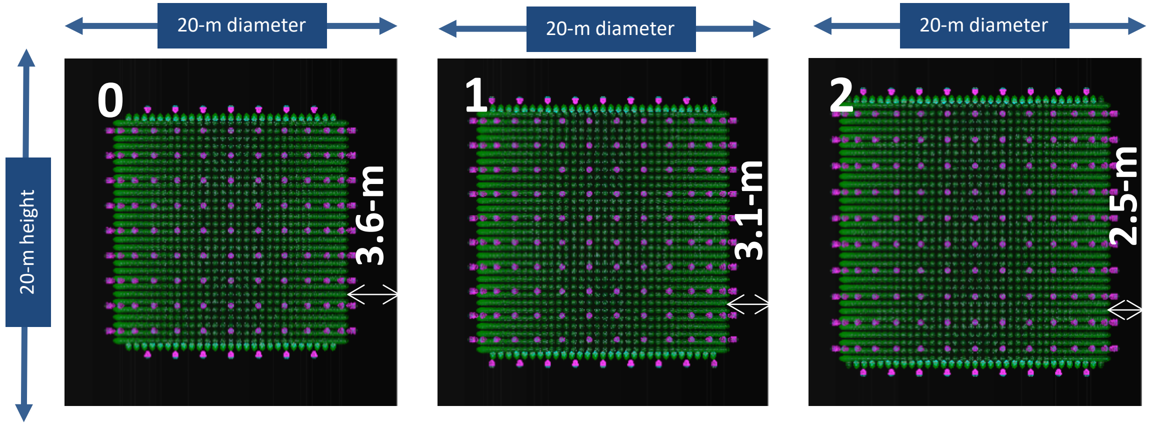
<u>PMT radioactivity is the main source of backgrounds impacting detector design</u>

<u>Inner</u> PMTs for each configuration

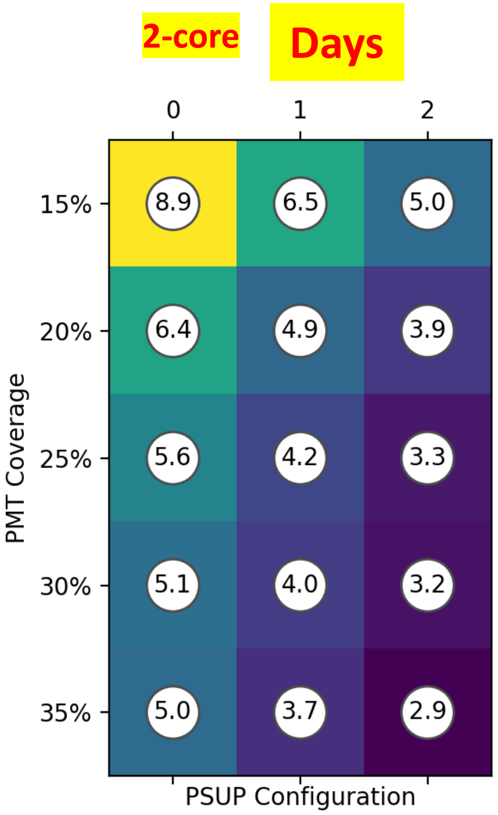
M. Bergevin

Discovery of any reactor activity above background

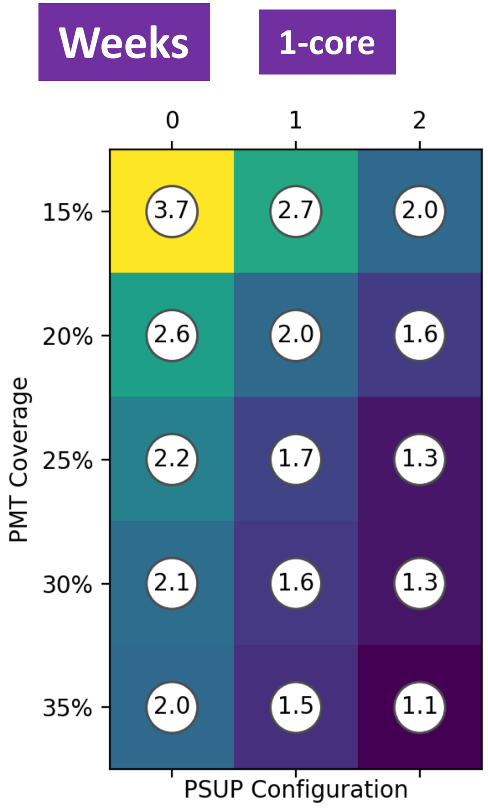




tank and fiducial volume (1 kiloton) fixed in these studies

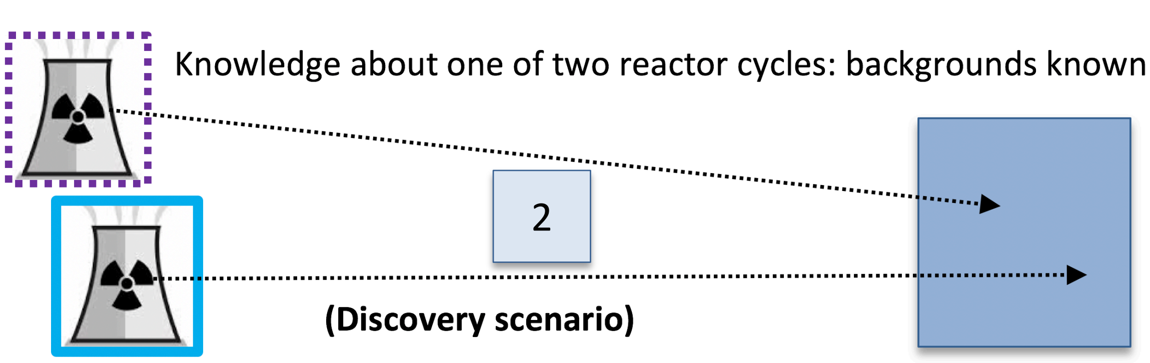


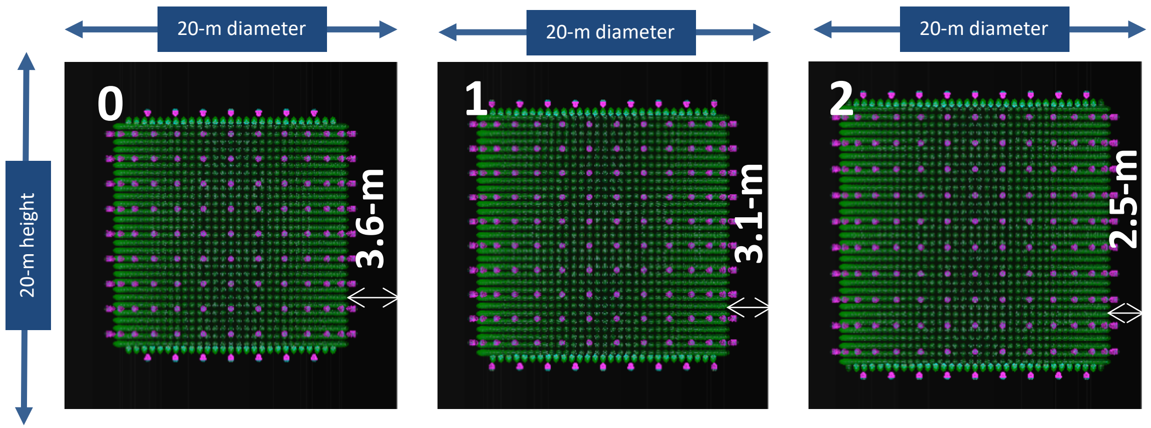
TP/FP: 95%/9%

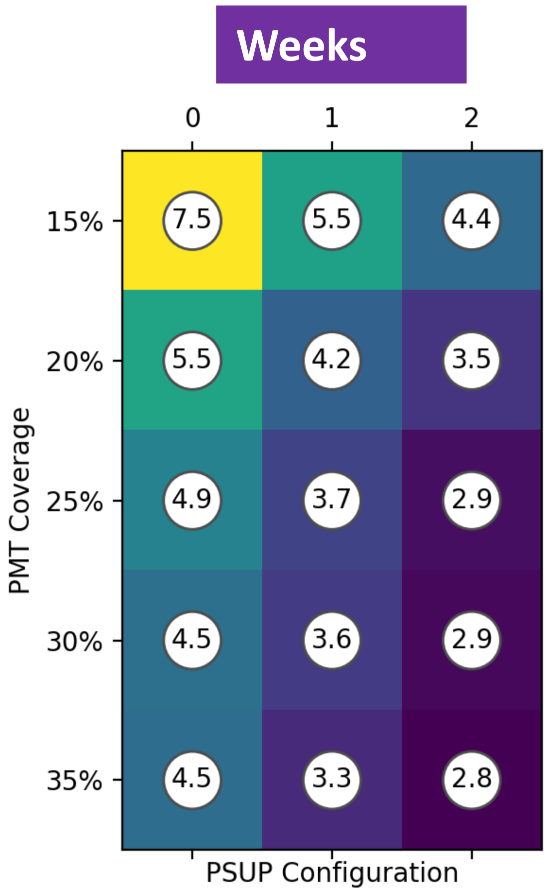


TP/FP: 94%/7%

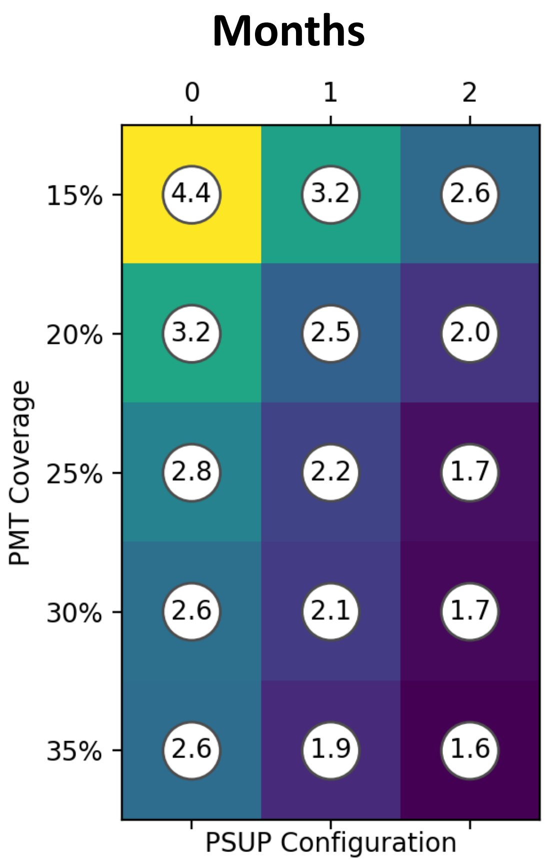
Discovery of an additional reactor





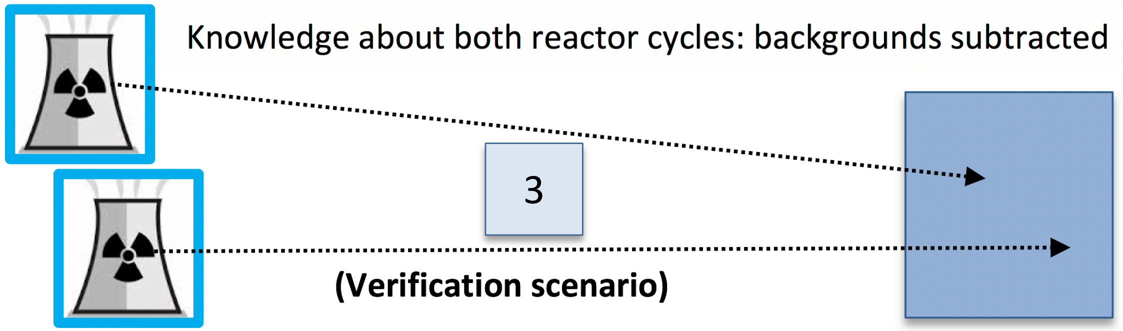


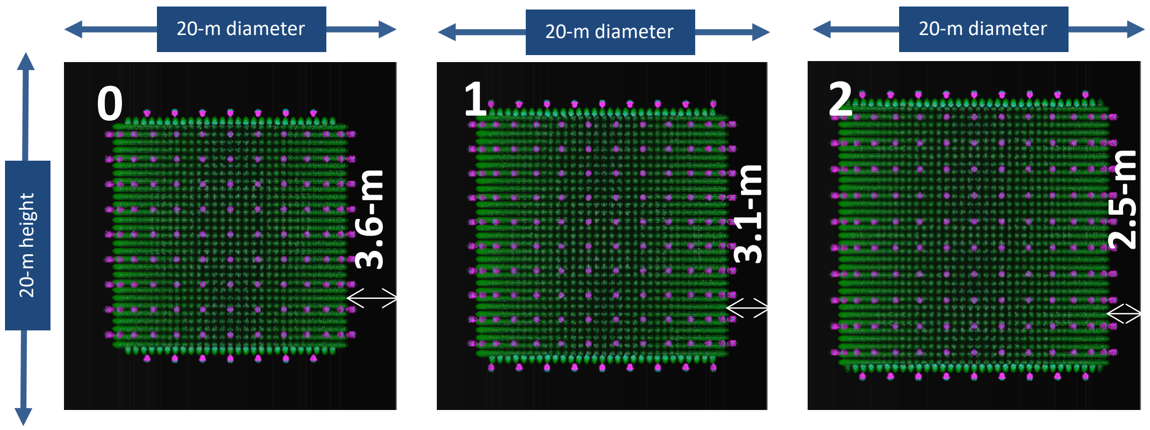
TP/FP: 95%/7%



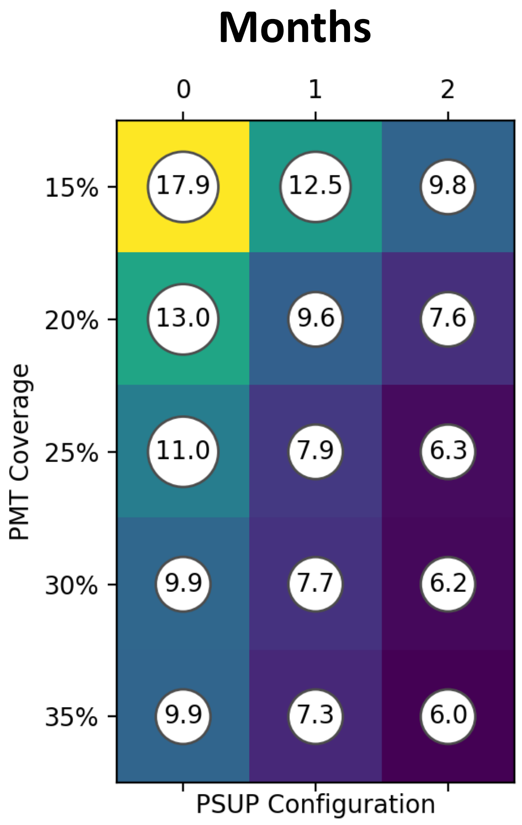
TP/FP: 99%/1%

Verification of reactor cycle



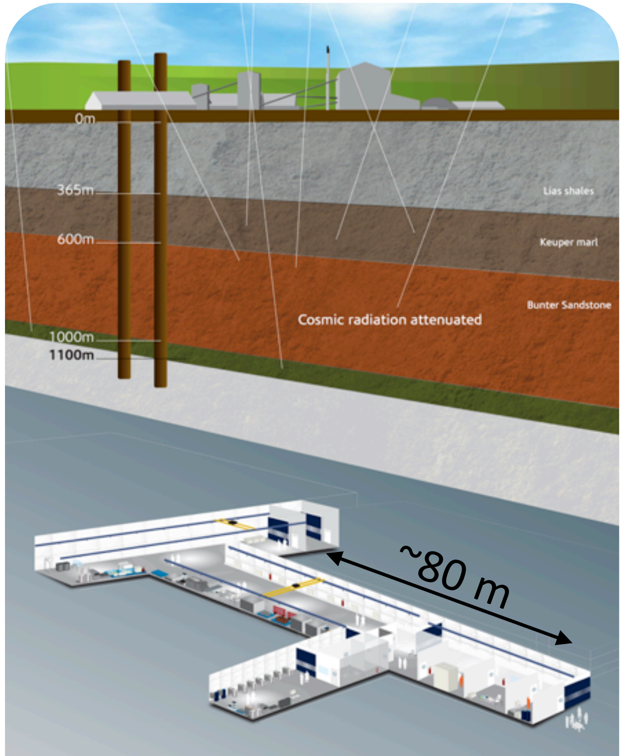


Observe **any** neutrinos over our backgrounds?

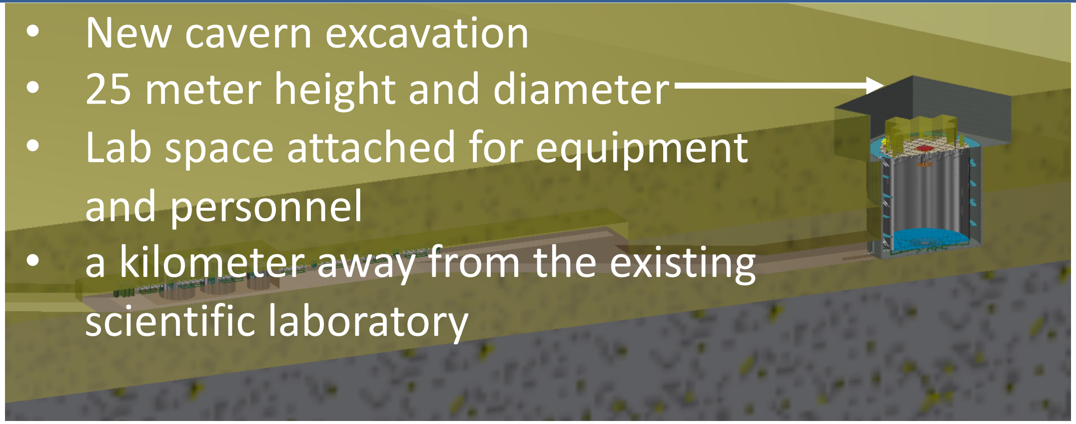


95% Confidence

AIT will be hosted at the Boulby Underground Laboratory



Existing Boulby lab space



What is it ?

- The Boulby Underground Laboratory is UK's deep underground (1.1 km, 2850 mwe) science facility, operated by the Science and Technology Facilities Council (STFC)

Why did we select Boulby for AIT ?

- Mature science and safety infrastructure
- 25 km standoff twice as far as U.S. alternative
- Opportunity for physics and nonproliferation collaboration with UK colleagues
- Strong support from host mining company (ICL-UK) and from the operators of the underground scientific laboratory

Rates (S,B) events (s,b) and dwell times (t) for 3 sigma detection of a 50 MWt reactor above background

Background	m (kt)	d (km)	B	S	b	s	t (yr)
High	1	10	280.1	110.4	92	36	0.33
High	5	20	1400.7	123.7	1487	131	1.06
High	1000	50	280136.9	1868.5	244116	1628	0.87
Low	1	10	1.7	110.4	0.14	9.17	0.08
Low	1	20	1.7	24.7	0.69	9.76	0.39
Low	10	50	17.4	18.7	18	19	1.02
Low	100	100	174.5	47.5	179	49	1.02
Low	1000	200	1744.6	161.4	1359	126	0.78

$$t = \left(3\frac{\sqrt{S + 1.2B}}{S}\right)^2$$