Strange Bedfellows:

Antineutrinos and Nonproliferation

FNAL seminar, June 18 2020

Lawrence Livermore National Laboratory

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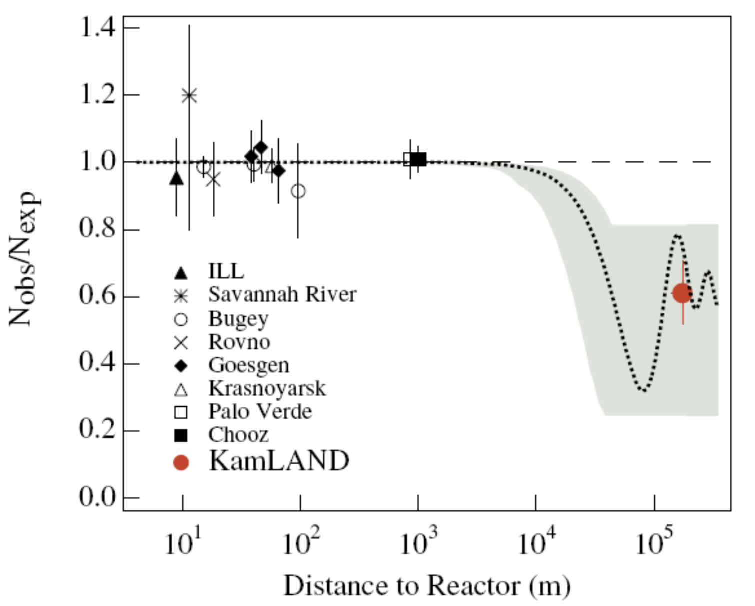
A working definition of near-field reactor monitoring

- Monitor reactor operational status, power and fuel consumption and composition
- ‘Near’: less than 1 km, typically 10-100 meters – site access granted by operators
- ‘High’ statistics: ~100-1000 events per day per ton, sufficient to populate a spectrum
- Reactor power > ~20 MWt, but main focus has been on > 1000 MWt

Rovno and numerous other detector provided detector technology even with null oscillation results



The origin of this idea: L.A. Mikaelyan – Neutrino '77 conference, Baksan

3. I want to talk about the development of the new technique of the remote reactor diagnostics by the neutrino radiation. Due to the novelty of the problem the consideration naturally will be incomplete and limited by two questions only:

- determination of the reactor power production and in prospect
- determination of the dynamics of the fissing isotopes burning-out and accumulation (mainly ^{235}U and ^{239}Pu).

The principle promises of the proposed technique seem to be the remote analysis and fixing the plutonium accumulation immediately in the place of its production. This technique (if developed successfully) will be sufficiently important from the point of view of the control on the leakage of fissing materials and on the non-proliferation of nuclear weapons, and also for the economics of nuclear fuel recycling. More detail consideration of these problems on this conference seems to be irrelevant.

The Nonproliferation Treaty and 'Safeguards'

The International Atomic Energy Agency - IAEA - applies nuclear safeguards – consisting of monitoring, inspection, information analysis, and other activities – to verify that nuclear activities remain peaceful and detect and deter their diversion, including to weapons-related purposes

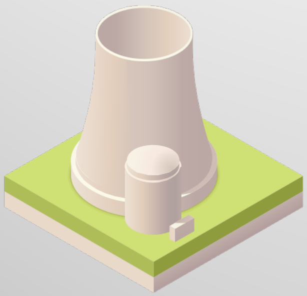
State Department website www.state.gov/iaea

Translation: the IAEA monitors nuclear facilities to detect diversion of fissile materials

IAEA
International Atomic Energy Agency

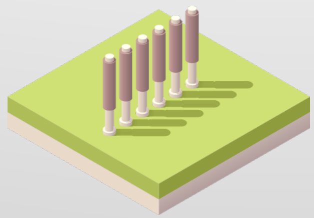
Current IAEA safeguards practice at reactors (220 worldwide)

Reactor
(1–1.5 years)



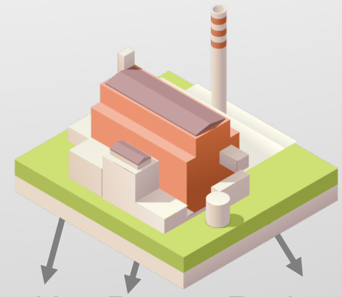
- Check declarations
- Item accountancy
- Containment and surveillance

Onsite Fuel Storage
(months to years)



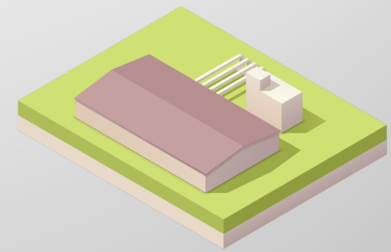
- Gross defect detection
- Item accountancy
- Containment and surveillance

Reprocessing
(months)



- Check declarations
- Bulk accountancy

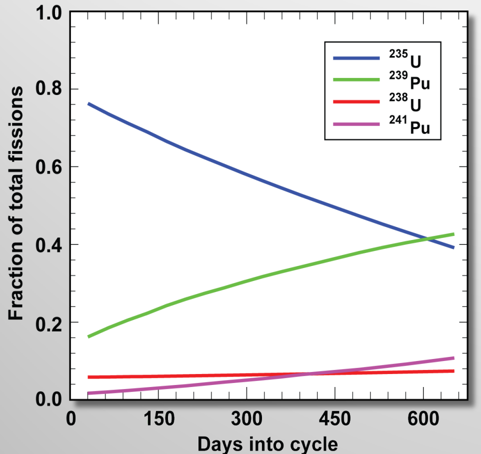
Waste Repository
(forever)



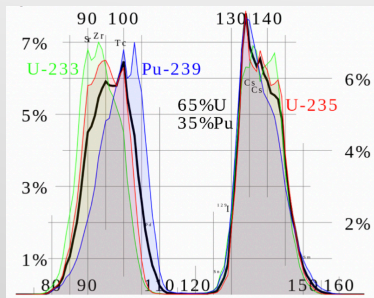
- Operators only declare fuel burn up and power history
- No direct Pu inventory measurement is made unless the fuel is reprocessed
- **Can antineutrino detectors provide real-time inventory estimates?**

From fission to antineutrinos – fuel inventory and the ‘burnup effect’

For each isotope, fission rates vary with time

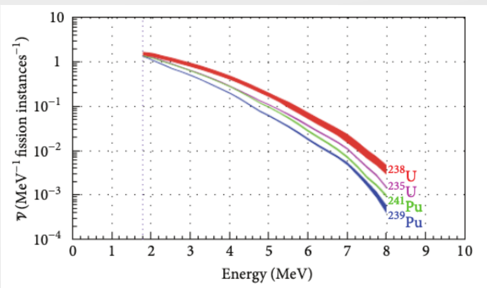


population of daughters varies with isotope



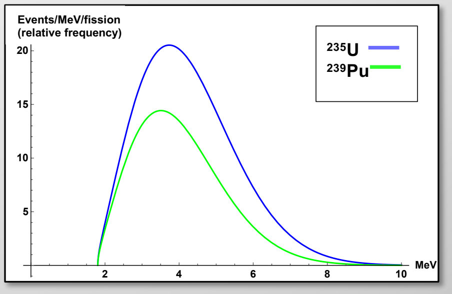
mass number

emitted antineutrino energy spectrum varies with isotope



emitted antineutrino spectrum (MeV)

Plutonium emits fewer detectable events for IBD interactions and spectrum is ‘softer’



detected spectrum (MeV)

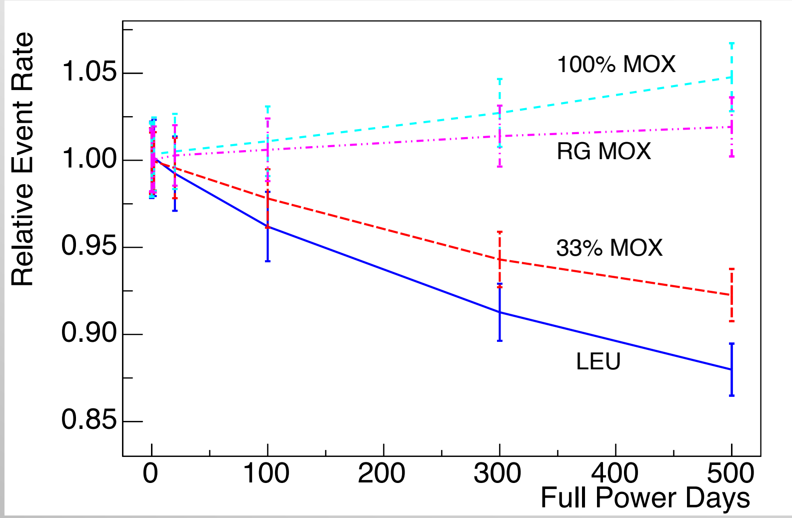
$$N_{\bar{\nu}} = \gamma \cdot (1 + k(t)) \cdot P_{th}(t)$$

← Zeroth order: reactor power

First order: ~10%
Varying contributions from Pu/U isotopes

Antineutrino rate and shape measurements reveal properties of the core

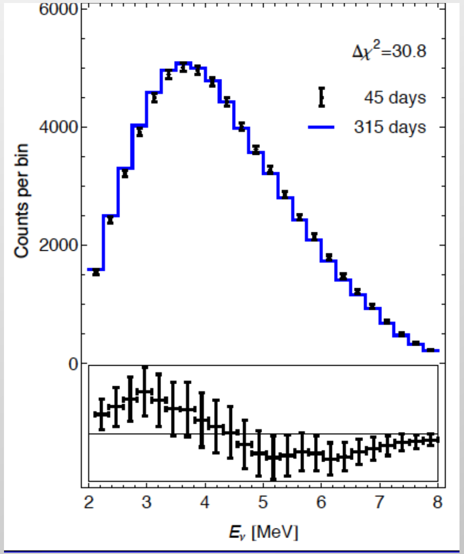
Comparison of relative nubar rates versus time for different core types



- 5 ton detector
- 3 GWt core
- 25 m standoff
- **Sensitive to an 8% change in MOX composition in 150 days**

arxiv:1612.00540

Comparison of two spectra with midpoints on cycle day 45 and day 315



- 5 ton detector
- 40 MWt core
- 17.5 m standoff
- **Sensitive to a change of 7 kg of Pu at > 5 sigma**

arxiv:1403.7065

R&D Timeline for Near-field Monitoring

2004:Early (the first ?) workshop on
Neutrinos and Arms control, UH

Applied Antineutrino Physics workshops
France, Japan, US, Brazil, India, UK,

1980 | 1990 | 2000 | 2010 | 2020

The Rovno era

All basic ideas explored

Birth of the idea:
Neutrino '77, Baksan
(maybe '75 ?)

Gd-scintillator
donated by
F. Boehm/Caltech/Palo
Verde experiment

SONGS

basic ideas re-explored
- minor simplifications and
attention of the IAEA

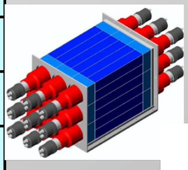
Theoretical case
studies (Huber, others)

SoLid,
CHANDLER,NuLat
PROSPECT… reactor
SBL expts.

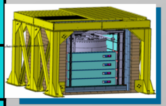
'Cambrian
explosion' for
monitoring
detectors

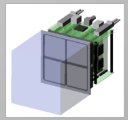
precursor
to reactor
short baseline
experiments

Group	Country
SNL/LLNL	USA
'PANDA'	Japan
'Mars'	UK
'CORMORAD	Italy
'Nucifer'	France
Tohoku U.	Japan
AECL	CA/US
Angra	Brazil
Niigata U.	Japan
U. Hawaii	USA
ISMRAN	India

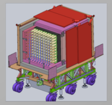

CORMORAD


PANDA


NUCIFER

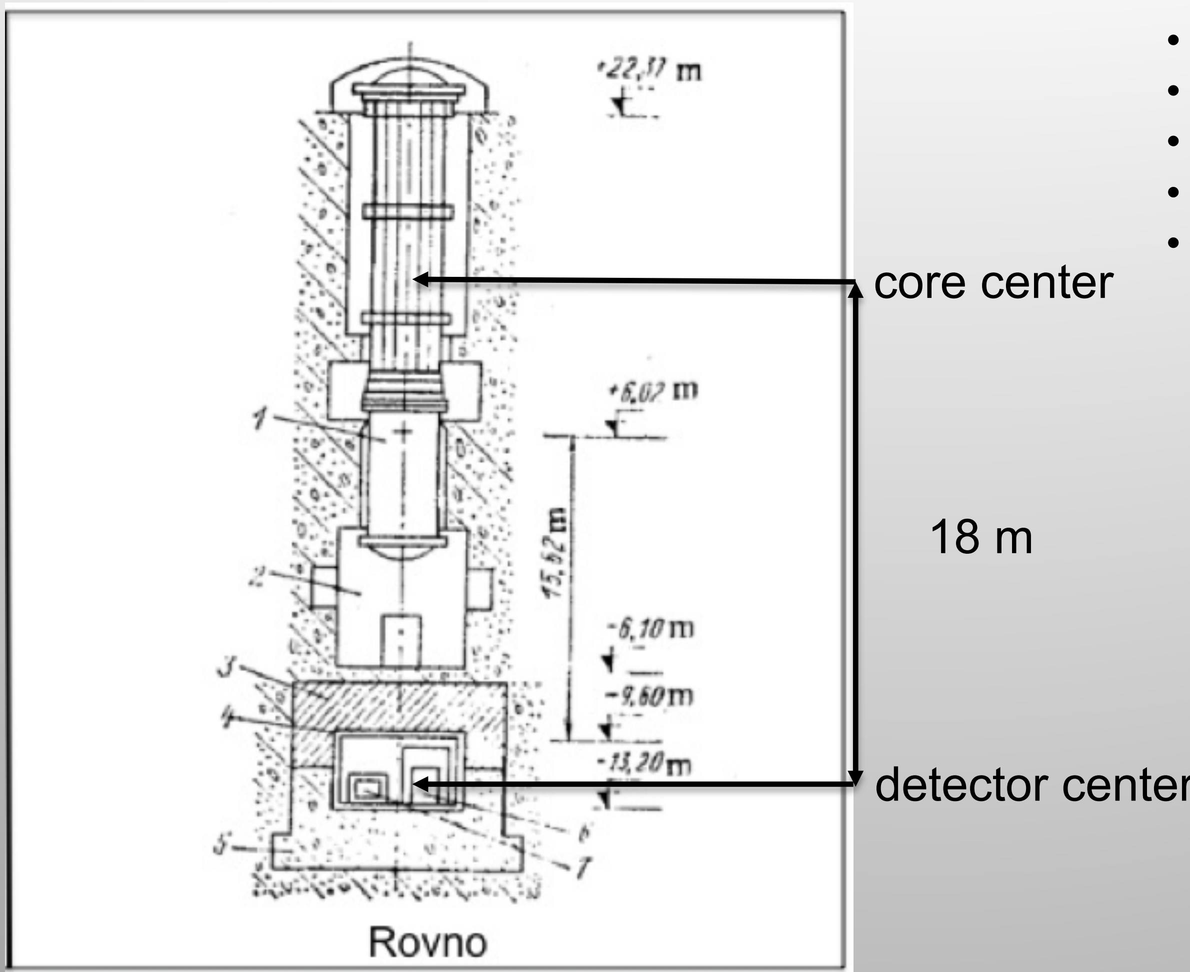

Mini-TimeCube


ANGRA


ISMRAN

IAEA workshops on antineutrino-based monitoring

1980s - the remarkable deployment at Rovno



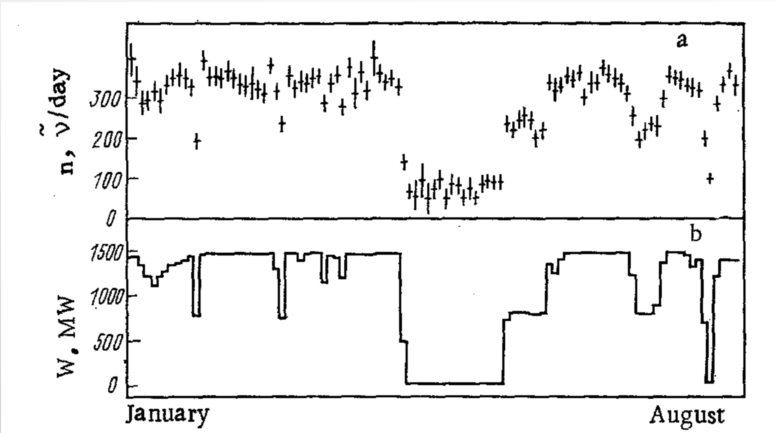
- 1400 MWt reactor (VVER 440)
- 18 m from core
- 18 m of overburden
- 500 l liquid scintillator (Gd-doped)
- 84 PMTs

The ideal monitoring experiment !

Reactor and Earth shield cosmics

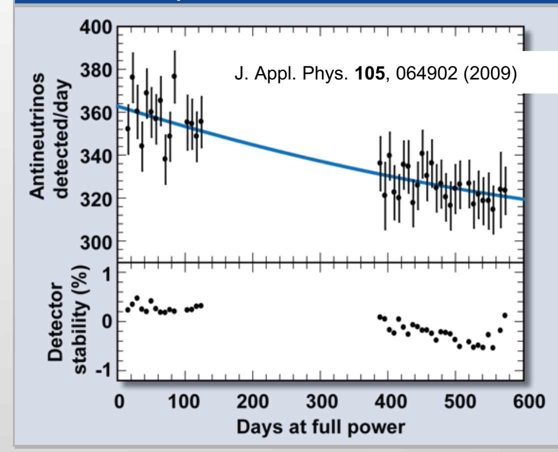
Detector is close to the core but in a relatively low radiation environment

The antineutrino rate measured over months and years) tracks power and fissile inventory “burnup effect”



2 months of data show reactor power/operational status tracking 2-3% precision – not so much worse than operator’s own estimates

Detect burnup of 250 kg U, 50 kg Pu with known power and initial fuel content



SONGS ‘06 (Rovno ’84 also measured this)

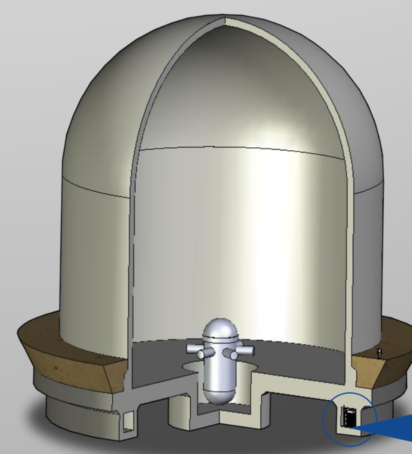
L. A. Mikaeiyan, "Neutrino laboratory in the atomic plant," in: Proceedings of the International Conference "Neutrino 77," Vol. 2, Nauka, Moscow (1978), pp. 383-385.

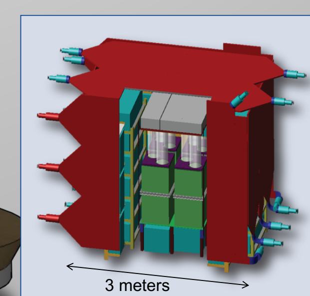
A. A. Borovoi and L. A. Mikaelyan, "Possibilities of practical applications of neutrinos," At. Energ., 44, No. 6, 508-511 (1978).

V. A. Korovkin, S. A. Kodanev, A. D. Yarichin, et al., "Measurement of nuclear fuel burnup in a reactor according to neutrino emission," At. Energ., 56, No. 4, 214-218 (1984).

V. A. Korovkin, S. A. Kodanev, N. S. Panashchenko, et al., "Measurement of power generation of a power reactor by the method of neutrino detection," At. I~nerg., 65, No. 3, 169-173 (1988).
Yu. V. Klimov, V. I. Kopeikin, L. A. Mika~lyan,, K. V. Ozerov, and V. V. Sinev, “Neutrino Method Remote Measurement of Reactor Power and Power Output, Atomic Energy, Vol. 76, No. 2, 1994

- 3640 MWt reactor
- 25 m from core
- 8/20 PMTs (detector/veto)
- 640 liters of scintillator





The LLNL-SNL antineutrino detector SONGS1

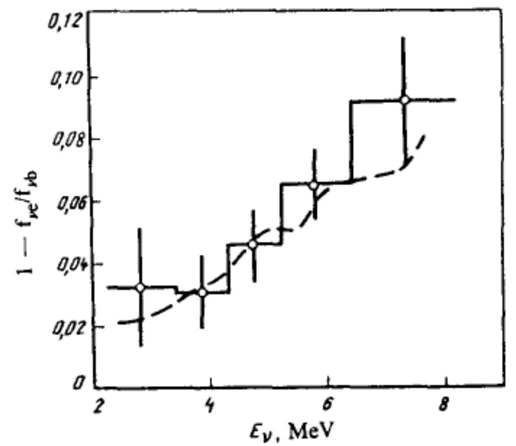
Antineutrino spectral evolution at measured at Rovno

Spectral information increases independence
from inputs (daily power levels) provided by the reactor operator

Plot shows the ratio of
energy spectra from beginning
and the end of the reactor cycle

Uranium hardens the spectrum, plutonium softens it

Klimov et. al, 1994, Atomic Energy



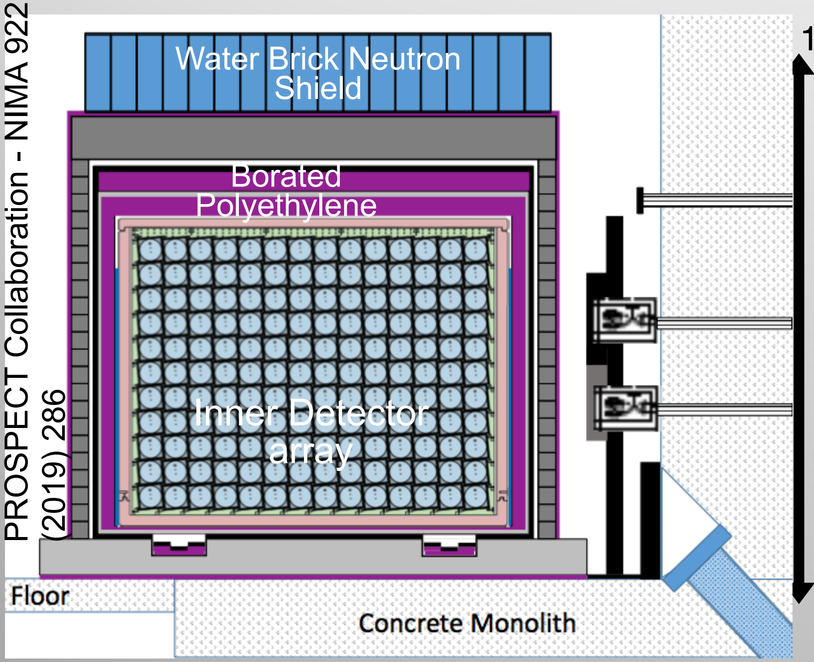
. 2. Ratio of the spectra of antineutrinos from the reactor at the beginning $f_{\nu b}$ and $f_{\nu e}$ of the period between reloadings.

Operational issue for safeguards: this data acquired in an inconvenient and unusual below-reactor detector gallery

Recent history and the near future: above-ground spectral sensitivity demonstrated in 2018

- Short baseline (5-10 m) oscillation searches demand near-surface operation – as does monitoring
- Highly segmented detectors, optimized shields permit above-ground rate and spectral measurements

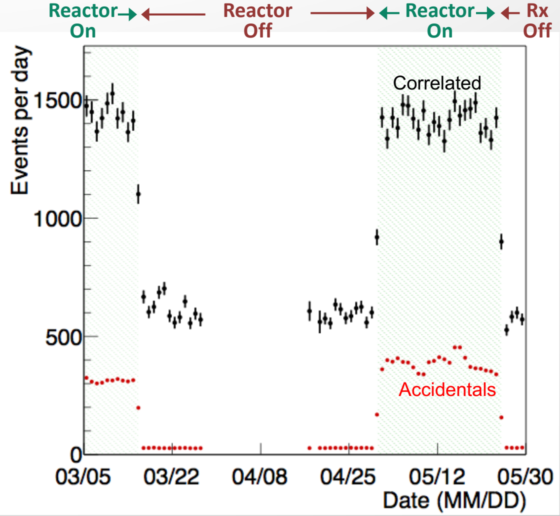
PROSPECT Collaboration - NIMA 922 (2019) 286



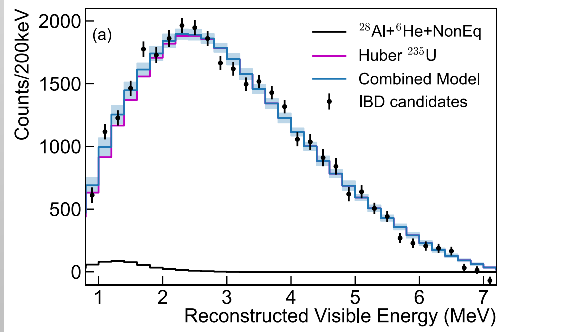
Talk: Thursday June 25 at 10am CDT by Bryce Littlejohn (IIT)

Posters:

- #158 Updated Event Selection for the PROSPECT Experiment
- #408 PROSPECT: Latest results for Sterile Neutrino Oscillation search
- #516 Measurement of the Uranium-235 Antineutrino Spectrum by PROSPECT
- #527 Detector characterization and calibration for PROSPECT
- #540 PROSPECT upgrade and science goals
- #556 Towards a Joint Measurement of the 235U Reactor Antineutrino Spectrum by the Daya Bay, PROSPECT, and STEREO Experiments



Phys. Rev. Lett. 121 (2018) 251802
PROSPECT Collaboration



Phys.Rev.Lett. 122 (2019) 251801
PROSPECT Collaboration

PROSPECT, NuLat, CHANDLER, SoLid and others will simplify monitoring deployments
The next logical step: a truck-mounted solid-state spectral detector

‘far-field’ or ‘remote’ reactor monitoring

- Discover, or exclude the existence of, operating reactors
- ‘Far’: more than 1 km, out to no more than 1000 km – varying degrees of access
- ‘low’ statistics: a few events per week month, or year
- Reactor power ~50 MWt – roughly generating 8 kg/one ‘Significant Quantity’ per year
- Explosive yield – difficult to achieve for less than 10 kton at reasonable standoff

Technology: Variations on KamLAND, Super-Kamiokande, Borexino and other large detectors used as models by a number of authors

Timeline for Far-field Monitoring 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

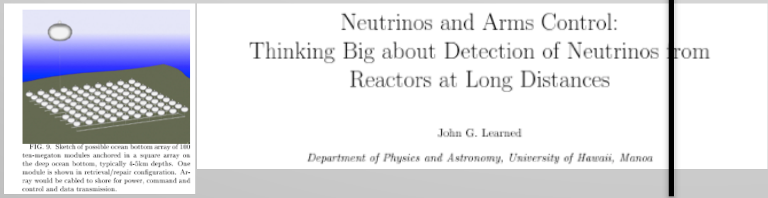
2000 2005 2010 2015 2020

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

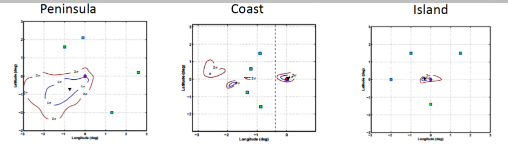

Neutrinos and Arms Control:
Thinking Big about Detection of Neutrinos from
Reactors at Long Distances

John G. Learned

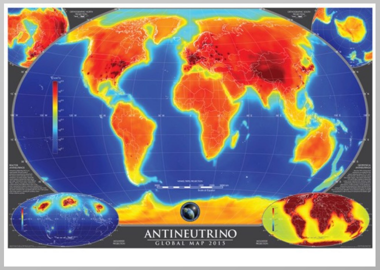
Department of Physics and Astronomy, University of Hawaii, Manoa

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

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

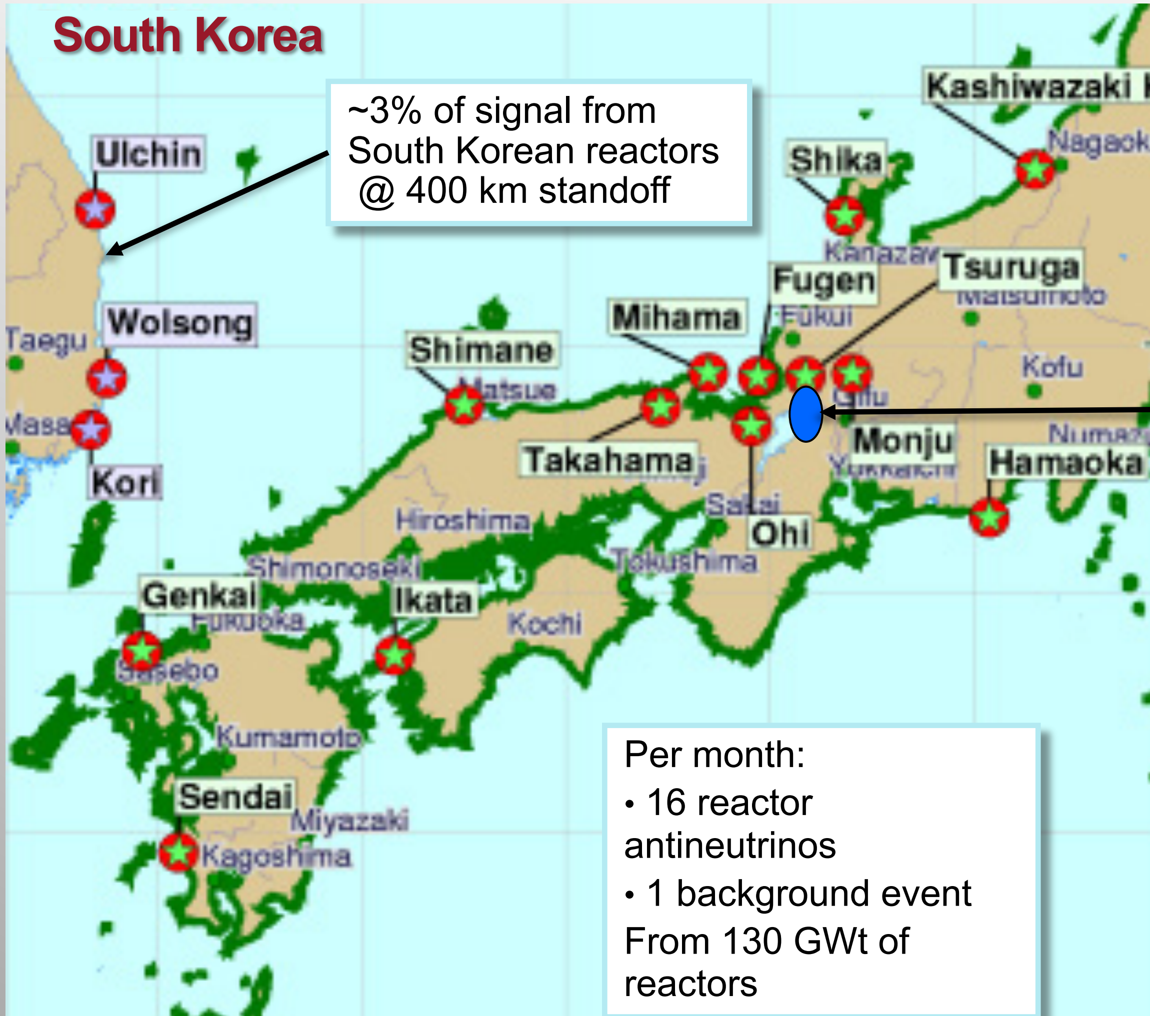


'17: Carr et. al – PR Appl. 10
'Seismically cued antineutrino detectors'
Modest improvement on '01 results



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

Long-range reactor antineutrino detection is feasible now but only for relatively high-power reactors and with a hard-to-scale technology



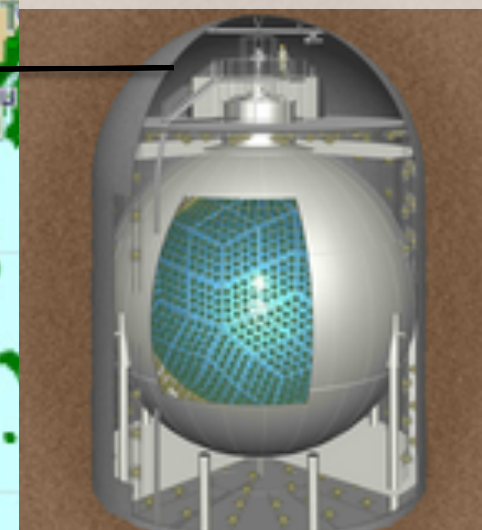
~3% of signal from South Korean reactors @ 400 km standoff

Per month:

- 16 reactor antineutrinos
- 1 background event

From 130 GWt of reactors

The KamLAND detector



1000 tonnes scintillator
1000 m depth

Today's Water Cherenkov detectors are 50x larger than scintillator detectors, but can't distinguish neutrino from antineutrino

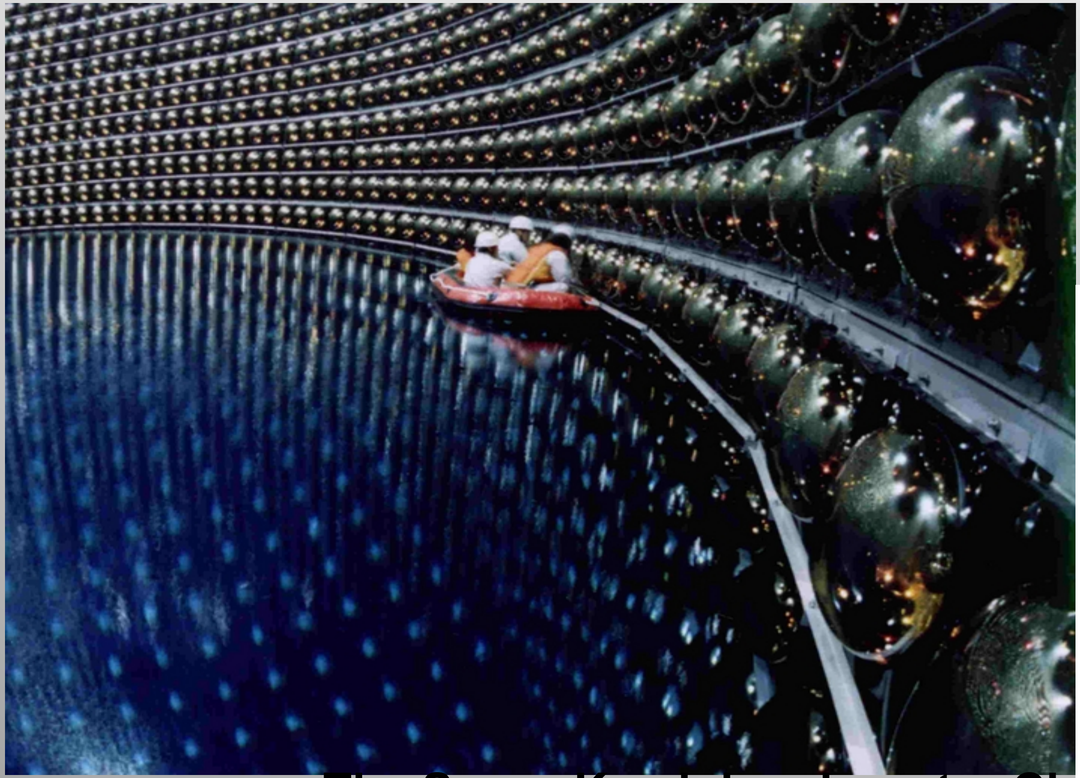
$\bar{\nu}_e + p = e^+ + n$

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

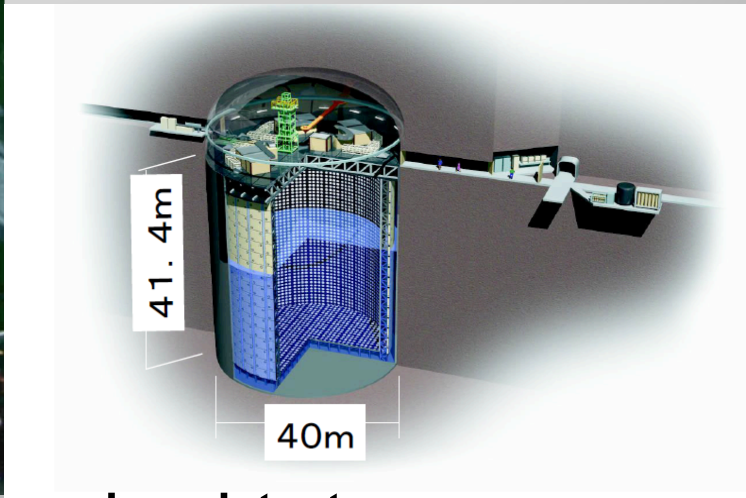
Identical signals from both processes:
a single flash of Cerenkov light

$\nu_e + e^- = \nu_e + e^-$

Elastic scatter (solar neutrinos, reactors)



backgrounds are also identical for both processes –
a flash of ~10-20 photons is a candidate antineutrino/neutrino

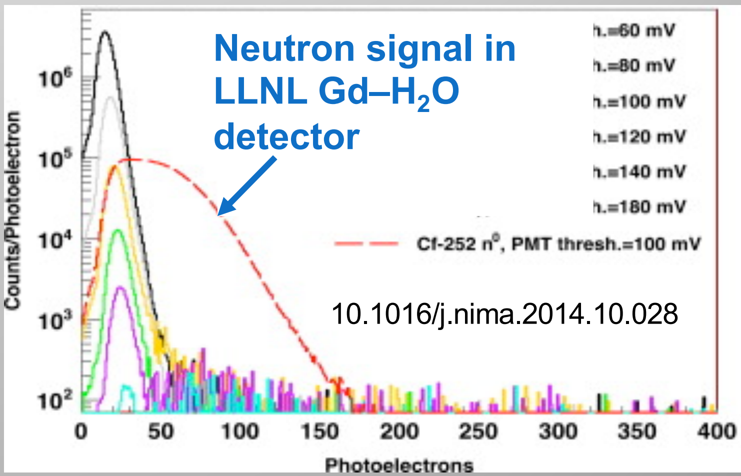


The Super-Kamiokande water Cherenkov detector

In 2009, LLNL and the Super-K collaboration both demonstrated water-based neutron detection using gadolinium as a trace additive – a natural extrapolation from Gd-scintillator

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

- 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"
- time-coincidence and ~4.5 MeV neutron Cherenkov flash reduces backgrounds by orders of magnitude
- Gadolinium-doped Water offers a path to 100–1000 kiloton antineutrino detectors
- First proposed by Bernstein, 2001
  Science & Global Security 9, 235 (2001)
- neutron signal verified, 2009
  LLNL: *NIMA* 607 (3), 21 (August 2009)
  Super-K: *Astroparticle Physics* 31(4), 320–328 (May 2009)
- Light transport and materials compatibility,
  EGADS, 2015

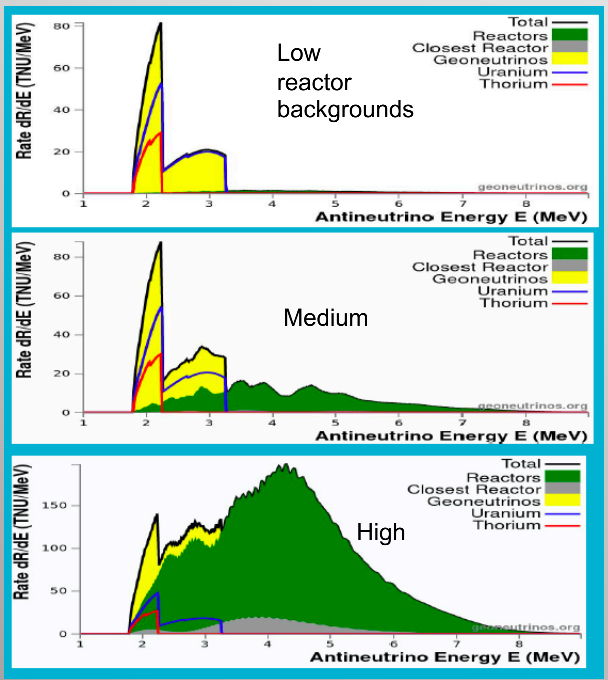


Best case sensitivity (monolithic hydrogenous detectors)

recent survey of the field: RevModPhys.92.011003

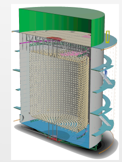
standoff distance for 3σ discovery

- 50 MWt reactor
- 100% efficient detector
- 3.3 MeV threshold removes all geoantineutrinos
- only world reactor backgrounds included in sensitivity estimate



geoneutrinos.org/reactors
A. Barna, S. Dye

detector



10 km – 1 kton, 0.25-4 months

20 km – 1-5 kton, 5-12 months

50 km – 10 kton, 12 months (low bg only)

WATCHMAN at AIT site would demonstrate capability to this standoff

100 km –
100- 1000 kton,
12 months (low-medium bg)

200 km – 1000 kton, 10 months (low bg only)

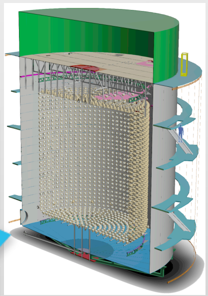
beyond 200 km
<u>directional methods required</u>
to reject other reactor signals

WATCHMAN: WATer CHerenkov Monitor of ANtineutrinos

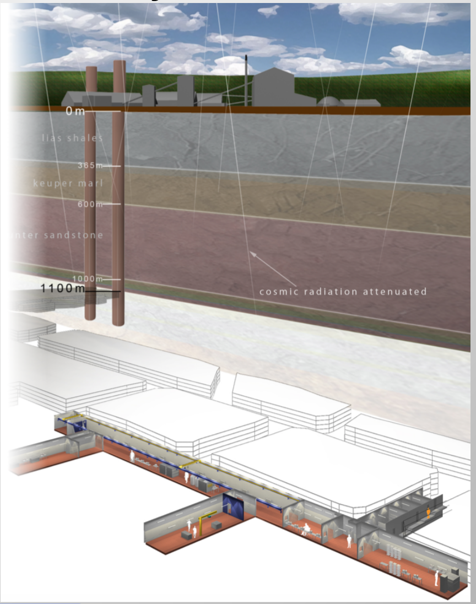
Hartlepool Reactors

- 2 cores
- 1570 MWt per core
- 25 km standoff

WATCHMAN Detector

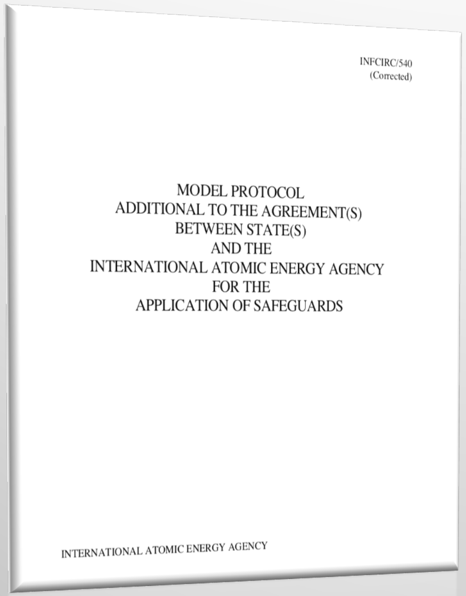


Boulby Underground Laboratory



- Selected site: **Boulby Underground Laboratory**
- Operated by UK-STFC
- 1100m underground
- Part of an operating polyhalite mine
- Candidate for deployment in the **Advanced Instrumentation Testbed**, a joint US-UK effort for studies of large-scale antineutrino detection methods
- Gd-H2O and WbLS under consideration for first fill

Possible first use after our demonstration: non-intrusive - but still cooperative - monitoring of an adversary



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

- likely focus on cooperative exclusion and discovery of reactors in tens of km geographical regions, not detailed monitoring

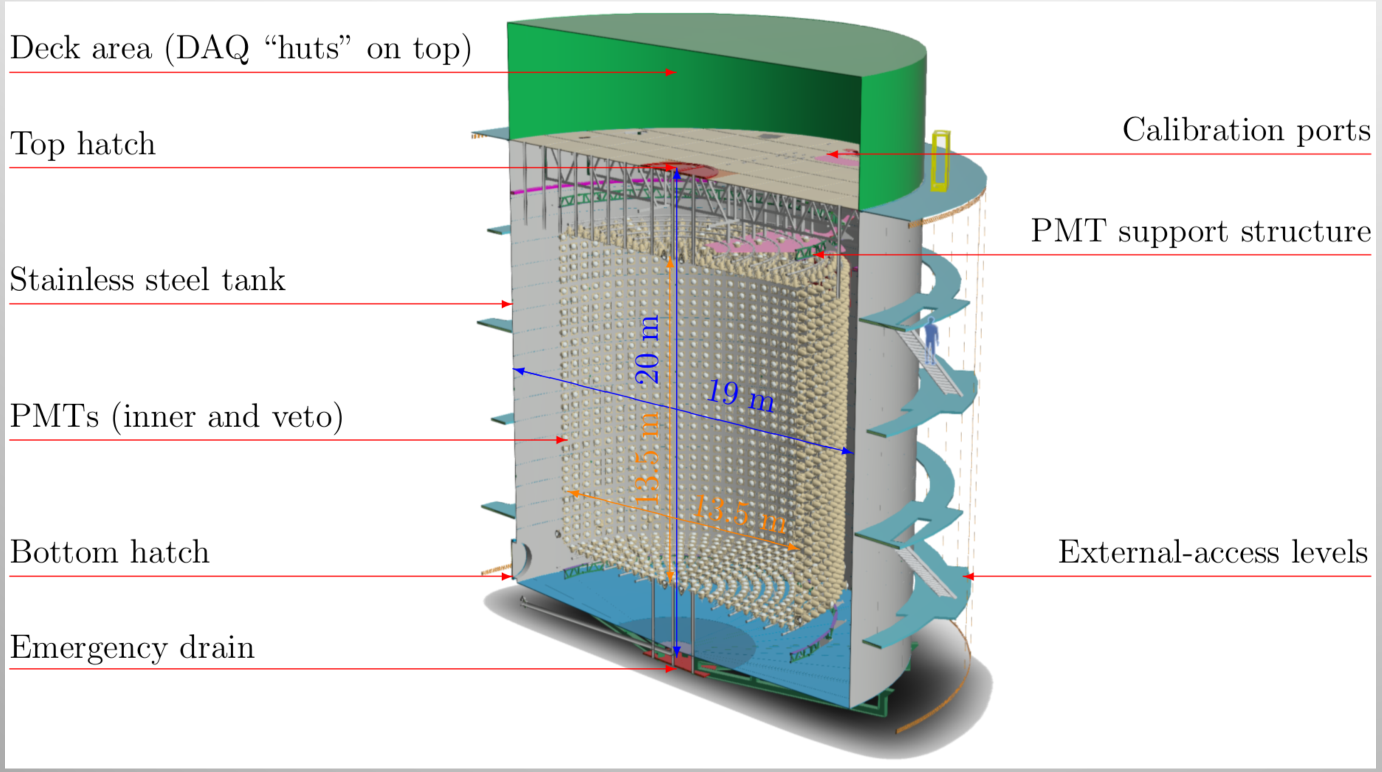
- a new tool for treaty negotiators

How does the adversary benefit ?

1. 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”
2. Large-scale neutrino experiment connects the scientific community into the global network of neutrino physics

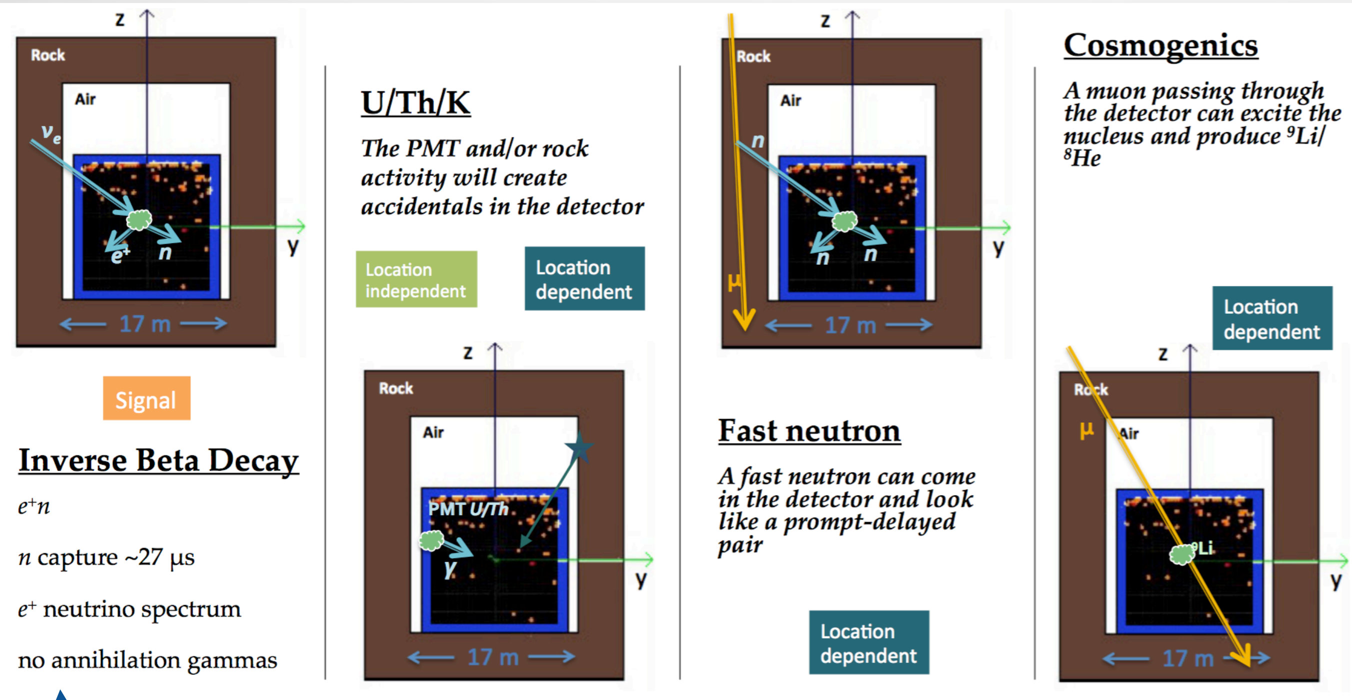
treaty language courtesy of C. Jabarri, Center for Nonproliferation Studies, Monterey, CA)

The WATCHMAN Gd—H2O 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

Description and quantification of signal and backgrounds (Gd-H2O only)



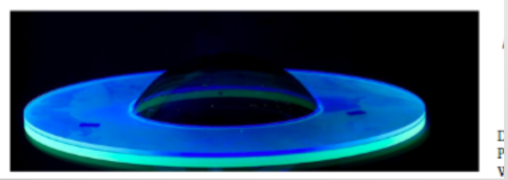
neutron capture on gadolinium for enhanced sensitivity
short capture time, high energy (~8 MeV) gamma-ray cascade

WATCHMAN baseline design

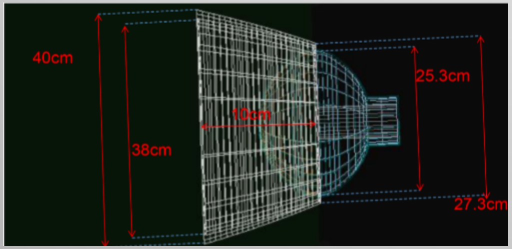
	detect 1 reactor	detect both reactors
Signal (#/day)	0.5	1
Total Bkg	0.9	0.4
Accidental	0.15	0.15
World reactors	0.7	0.2
Fast neutrons	0.01	0.01
Radionuclides	0.04	0.04
Spontaneous Fission	<<0.01	<<0.01
days to 3 sigma sensitivity $n\sigma = \frac{s\sqrt{t}}{\sqrt{s+b}}$	~50	~12

Can we get lower cost, higher performance, or both ?

Cost savings R&D



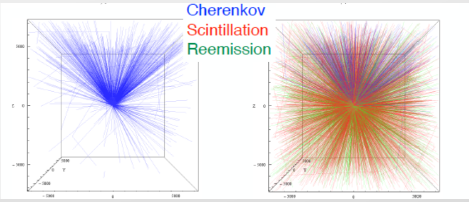
wavelength-shifting plates



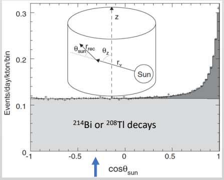
Winston cones

increase light collection
reduce number of PMTs
significant savings possible

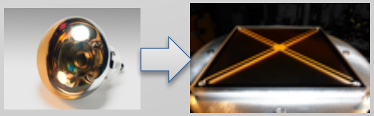
performance-enhancing R&D



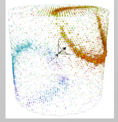
water-based scintillator



directionality via electron scattering



fast photo sensors

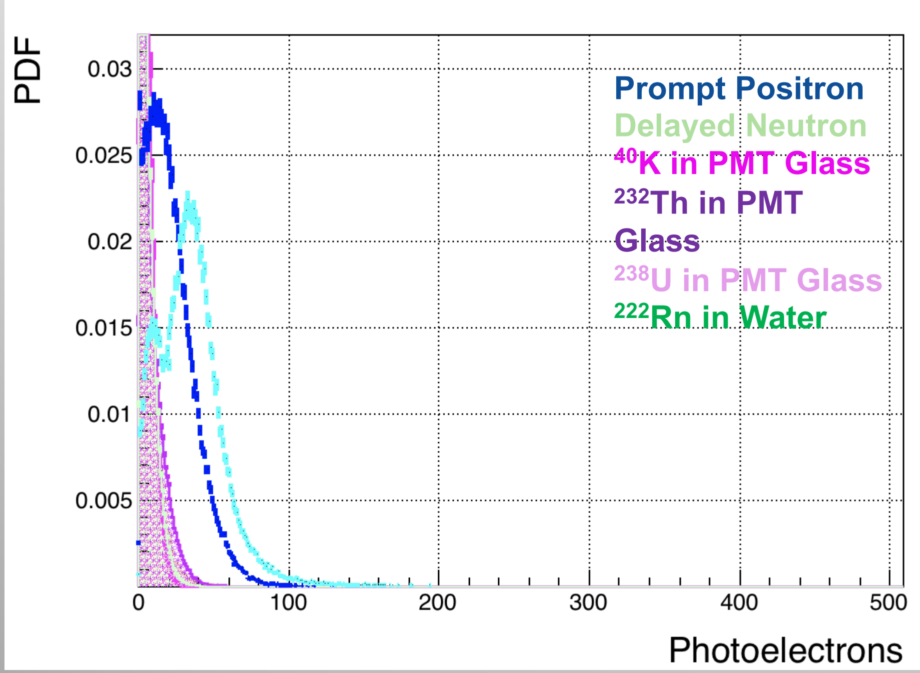


retroreflectors

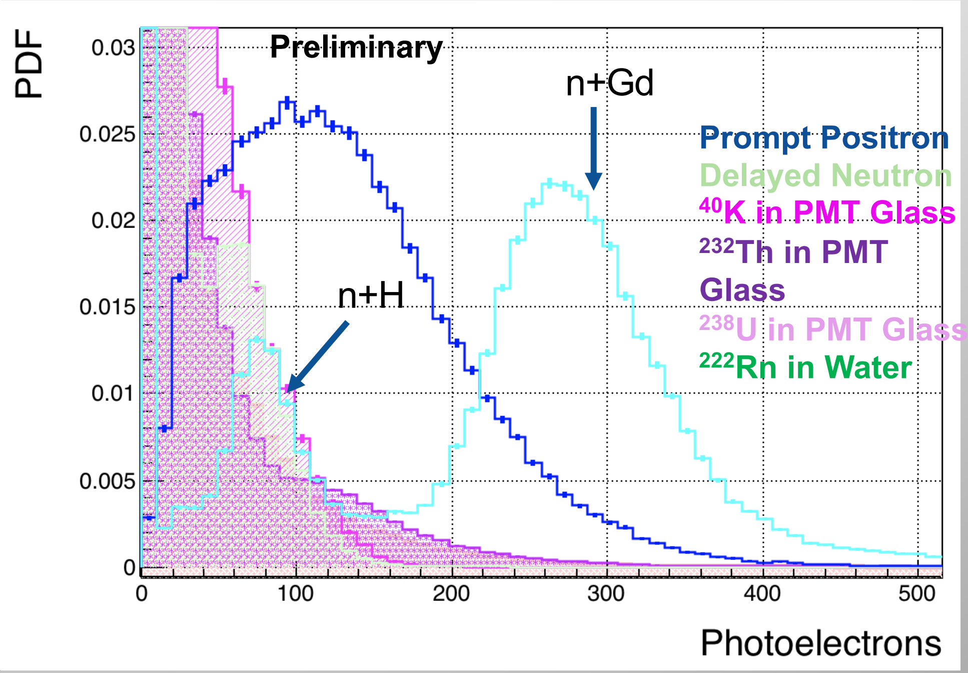
increase energy or vertex resolution
improve background rejection and/or signal efficiency
directionality (!)

Gd-WbLS and Gd-H2O comparison – (simulation, T. Akindele)

Water with Gd



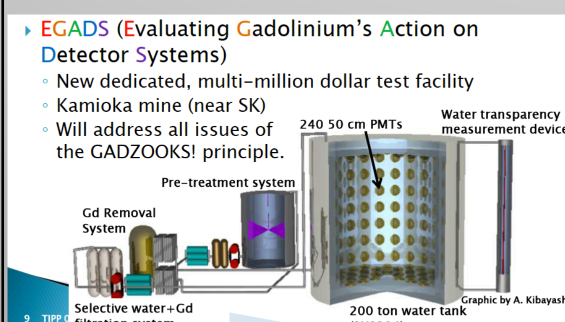
WBLS with Gd

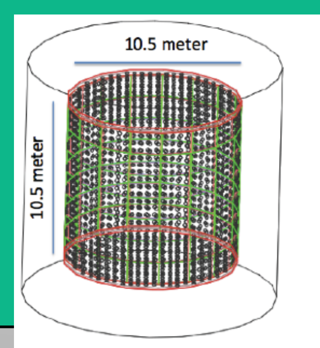


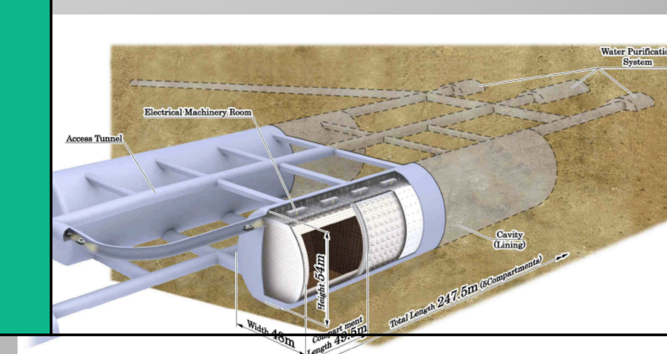
Key WbLS parameters must be measured for definitive sensitivity studies

Other relevant activities worldwide

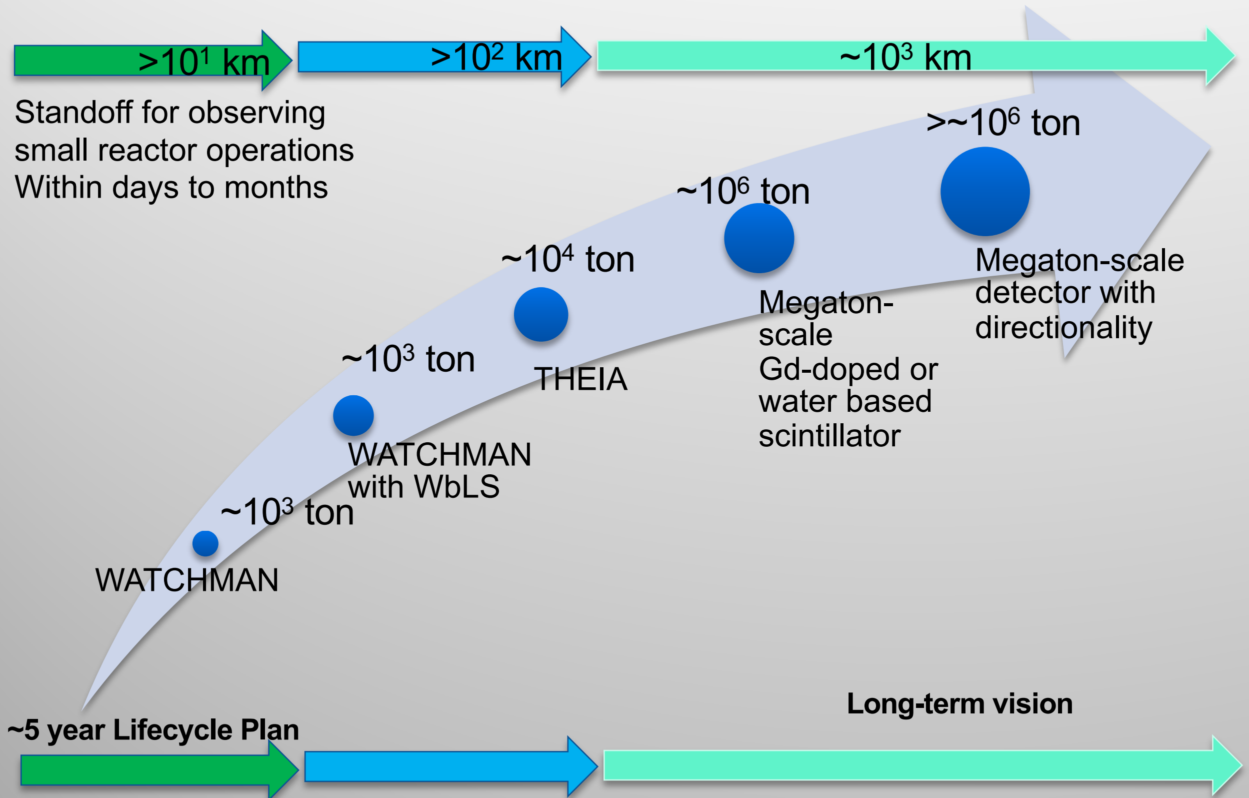
Detector	EGADS	WATCHMAN	Super-K-GD →Hyper-K
Status	Completed	2024	soon
Mass (ton)	200	5000	50,000 → 500,000
Type	Gd-WCD	Gd-WCD	Pure H2O or Gd-WCD
Purpose	Measure background materials,energy threshold Too small to see reactor antineutrinos	Remotely monitor reactor operations with antineutrinos	Neutrino oscillations, proton decay, supernovae… and maybe reactors and explosions

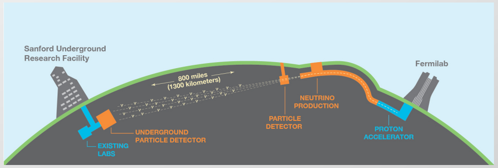






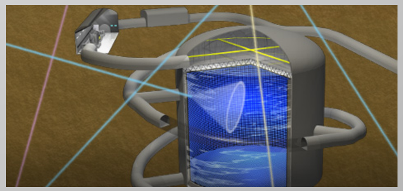
The long-term nonproliferation research arc will help speed the development of detectors like DUNE and Hyperkamiokande





DUNE

LLNL and the WATCHMAN collaboration will participate in the SNOWMASS planning process



Hyperkamiokande

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Summary

- In the near-field (<100 m or so) it has been proven since Rovno/1980's that antineutrino detectors can be used to determine issile inventories and power levels at reactors – easily deployable detectors are now approaching realization
- Far-field detection at hundreds of kilometers has already been demonstrated at one level by KamLAND – SuperK and WATCHMAN will demonstrate a more scalable water-based technology
- In all cases, the technology has a natural overlap with detection for particle physics and the two communities should plan accordingly
- Apologies to the many ideas and people I didn't talk about – coherent scatter, JUNO, fast photosensors/LAPPDs …
- Please see LLNL postdoctoral fellow Tomi Akindele's talk 'Antineutrino Monitoring of Reactors for Nuclear Nonproliferation' at Neutrino 2020, Thursday June 25 10:30 AM central time