Neutrinos for Nuclear Security

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How did we get here?

NEUTRINO DETECTORS

U.S. could value tamper resistance of neutrino signal, resilience of detectors

https://www.youtube.com/watch?v=emYo7edGUrM

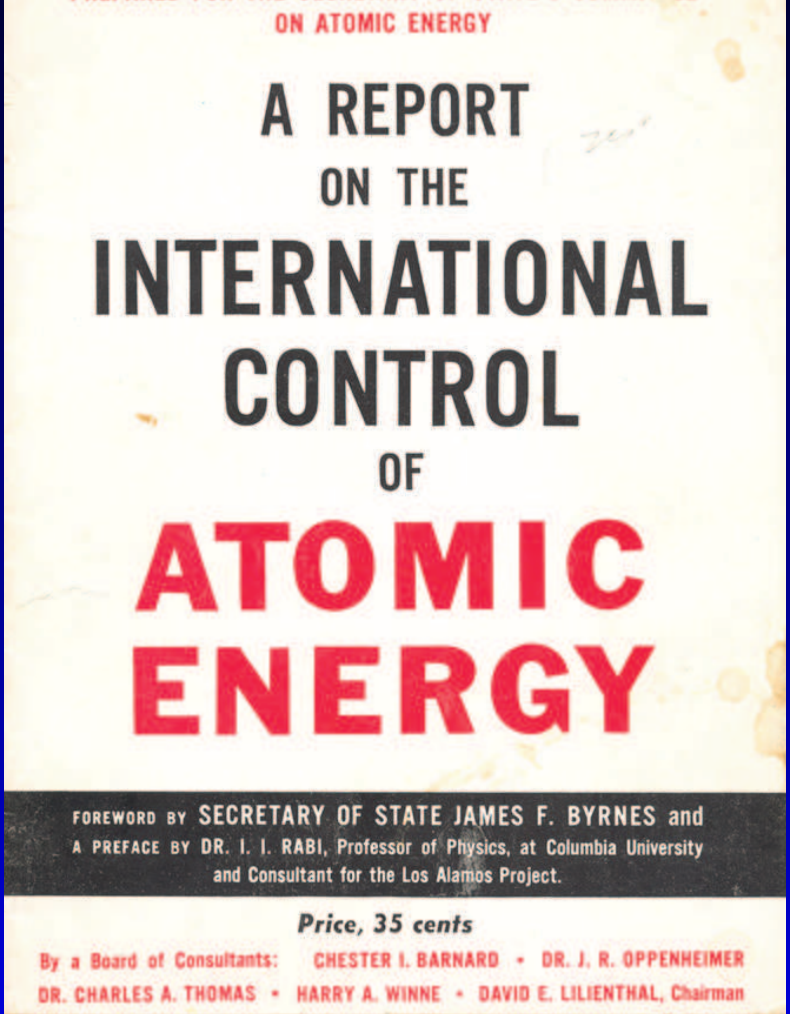
Two kinds of bombs

Both ^{239}Pu and ^{235}U have fast neutron fission cross sections of 1-2 barn.

A simple estimate of the critical mass is obtained from

$$\text{diameter} \simeq \text{mean free path} \Rightarrow m \propto (\rho\sigma)^{-3}$$

and yields about 10kg for ^{239}Pu and 50kg for ^{235}U.



PREPARED FOR THE SECRETARY OF STATE'S COMM[illegible]E
ON ATOMIC ENERGY

A REPORT
ON THE
INTERNATIONAL
CONTROL
OF
ATOMIC
ENERGY

FOREWORD BY SECRETARY OF STATE JAMES F. BYRNES and
A PREFACE BY DR. I. I. RABI, Professor of Physics, at Columbia University
and Consultant for the Los Alamos Project.

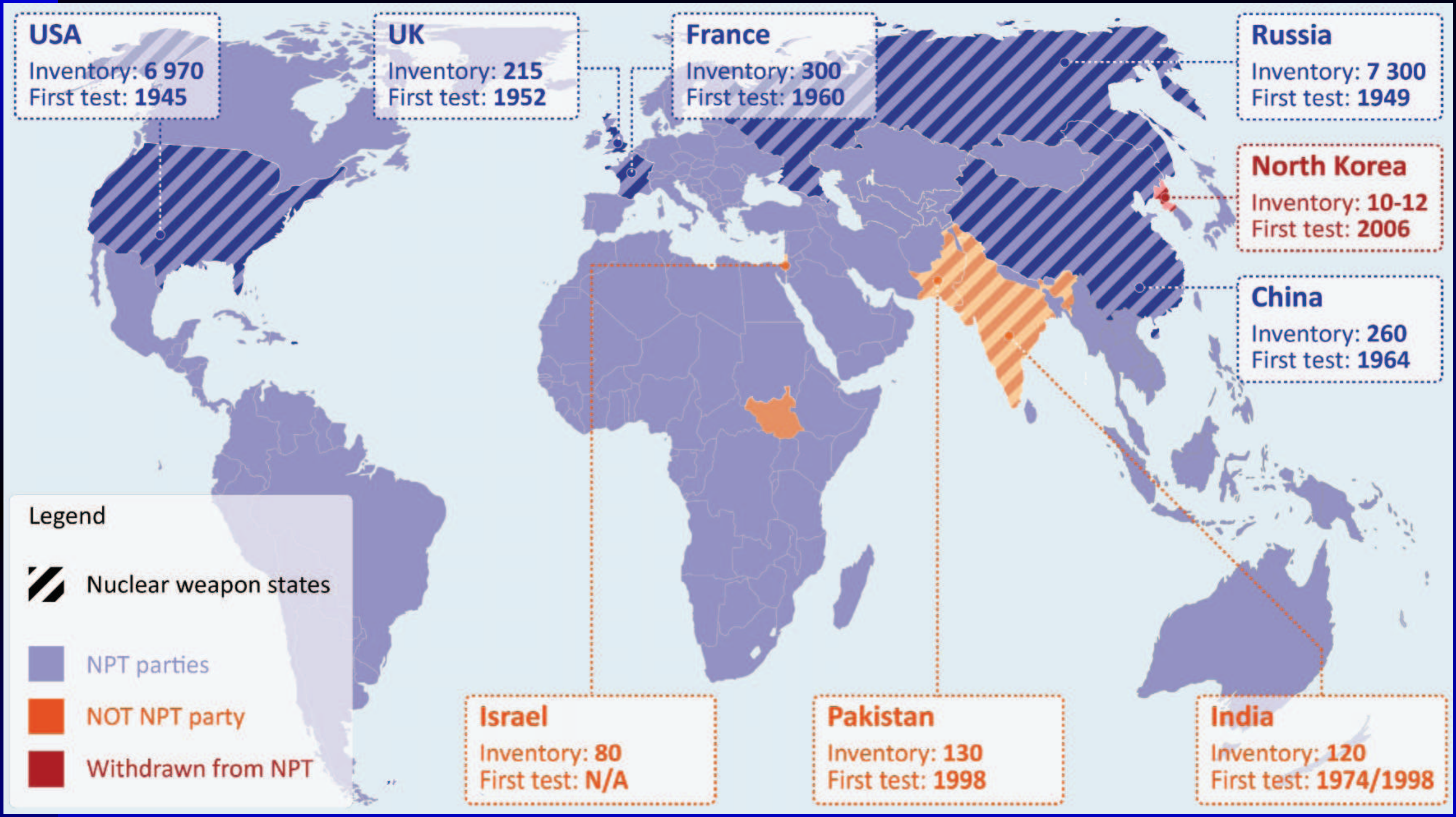
Price, 35 cents

By a Board of Consultants: CHESTER I. BARNARD • DR. J. R. OPPENHEIMER
DR. CHARLES A. THOMAS • HARRY A. WINNE • DAVID E. LILIENTHAL, Chairman

1946:

Control of special nuclear materials is **central** to prevent the proliferation of nuclear weapons.

This holds also today.



EPRS, 2016

NPT – Treaty for the Non-Proliferation for Nuclear Weapons
IAEA – International Atomic Energy Agency

IAEA Safeguards

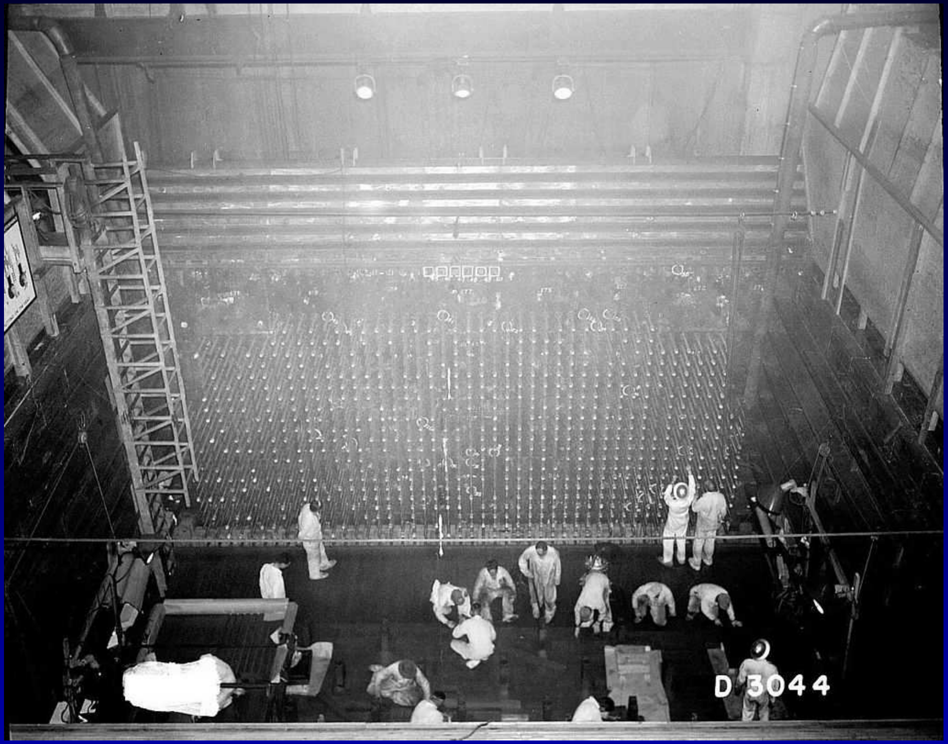
Each NPT non-weapons state enters a bilateral safeguards agreement with the IAEA – these are **cooperative** agreements based on:

- surveillance
- containment
- accounting

with the goal of a continuous chain of evidence – continuity of knowledge (CoK)

Path to nuclear weapons

U.S. – Hanford, graphite
Russia – Mayak, graphite
U.K. – Windscale, graphite
France – Marcoule, heavy water
China – uranium enrichment
Israel – Dimona, heavy water
South Africa – uranium enrichment
India – CIRUS, heavy water
Pakistan – uranium enrichment
DPRK – Yongbyon, graphite



Hanford, B reactor, making plutonium for the Trinity device and Little Boy

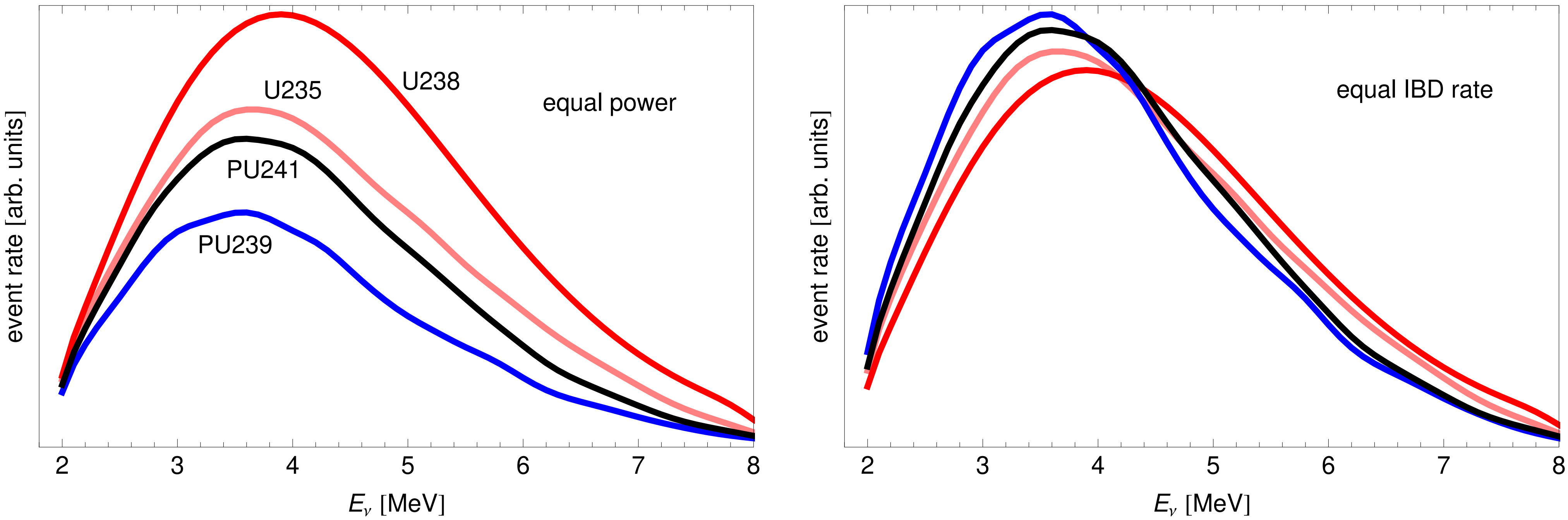
Out of 10 countries:
4 graphite, 3 heavy water, 3 uranium enrichment

Neutrinos for safeguards

Nuclear reactors produce enormous amounts of neutrinos and neutrinos, due to their high penetration capability, offer unique safeguards opportunities:

- measure reactor power
- detect undeclared production of fissile material
- independent verification of fuel burn-up

IBD event spectrum



Pu239 has a softer neutrino spectrum than U235 – as a consequence the neutrino spectrum becomes softer for higher burn-up

Fuel evolution

In a reactor the breeding reactions take place:

$$\begin{aligned} {}^{238}\mathrm{U} + n &\longrightarrow {}^{239}\mathrm{U} \xrightarrow{\beta^-} {}^{239}\mathrm{Np} \xrightarrow{\beta^-} {}^{239}\mathrm{Pu} \\ {}^{239}\mathrm{Pu} + n &\longrightarrow {}^{240}\mathrm{Pu} \longrightarrow {}^{241}\mathrm{Pu} \end{aligned}$$

And thus except for reactor fueled with only ^{235}U, eventually four isotopes contribute to fission with a time dependent fraction:

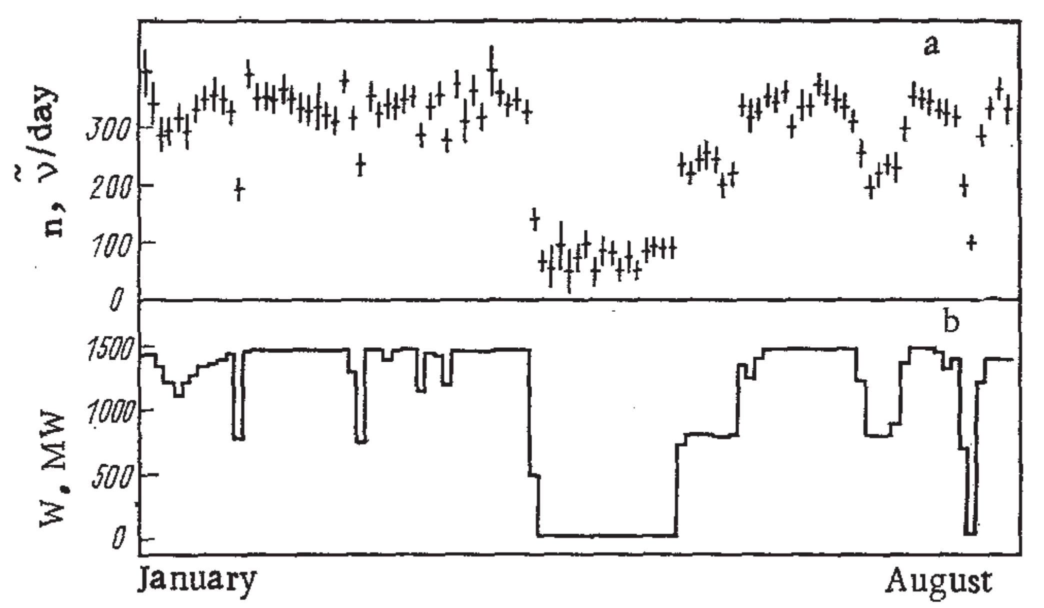
$$ {}^{235}\mathrm{U},\ {}^{239}\mathrm{Pu},\ {}^{238}\mathrm{U},\ {}^{241}\mathrm{Pu} $$

Reactor monitoring

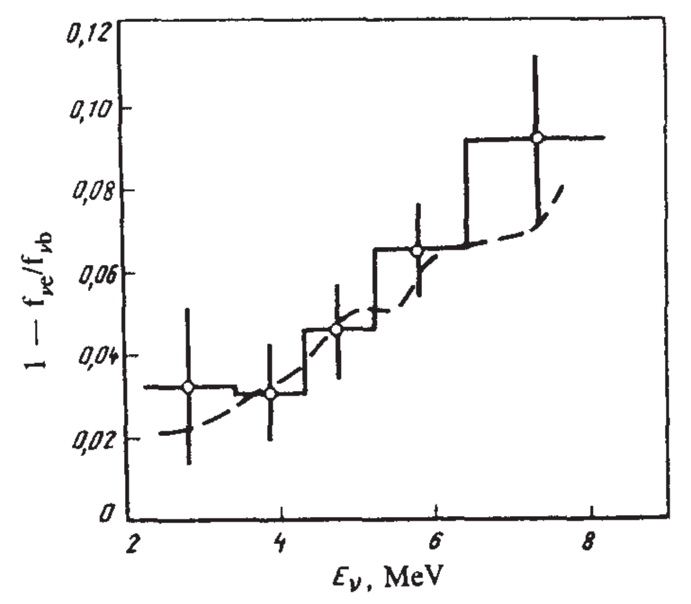
Pioneering work by a group at the Kurchatov institute lead by Lev Mikaelyan

Power monitoring

Fuel burn-up

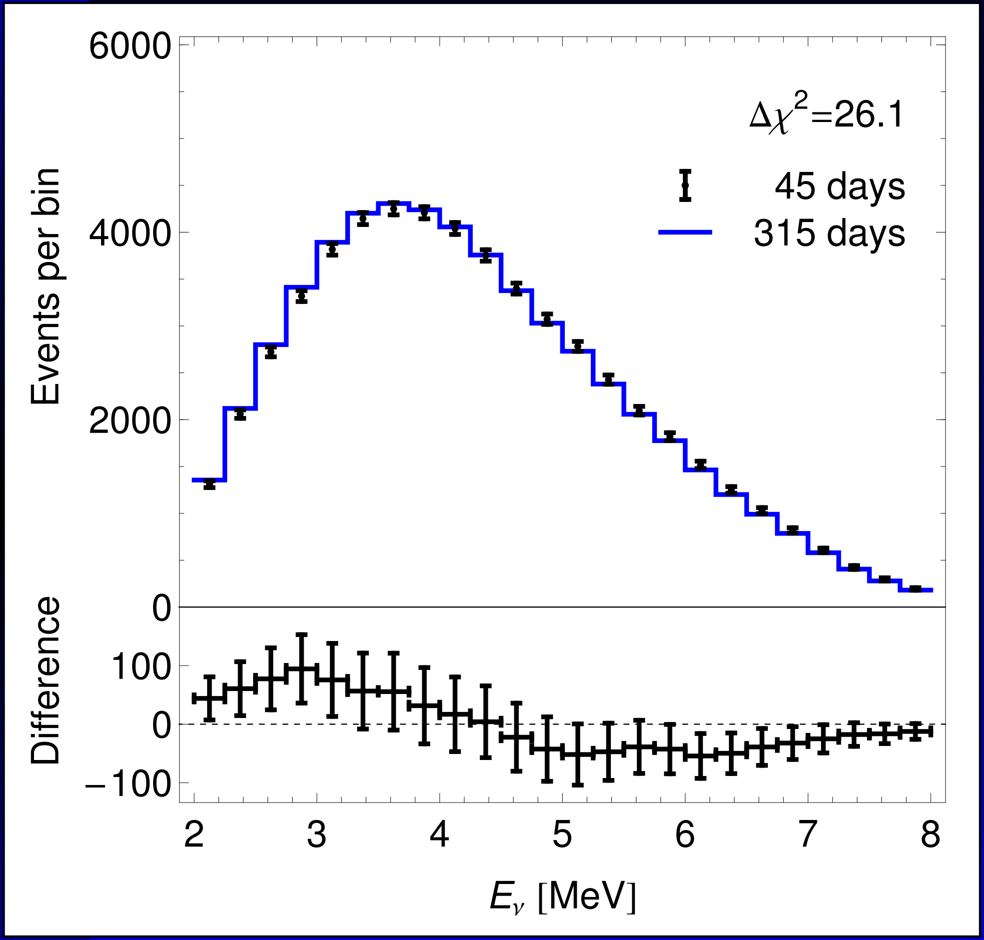


Korovkin *et al.*, 1988



Klimov *et al.*, 1994

Exploiting the energy spectrum

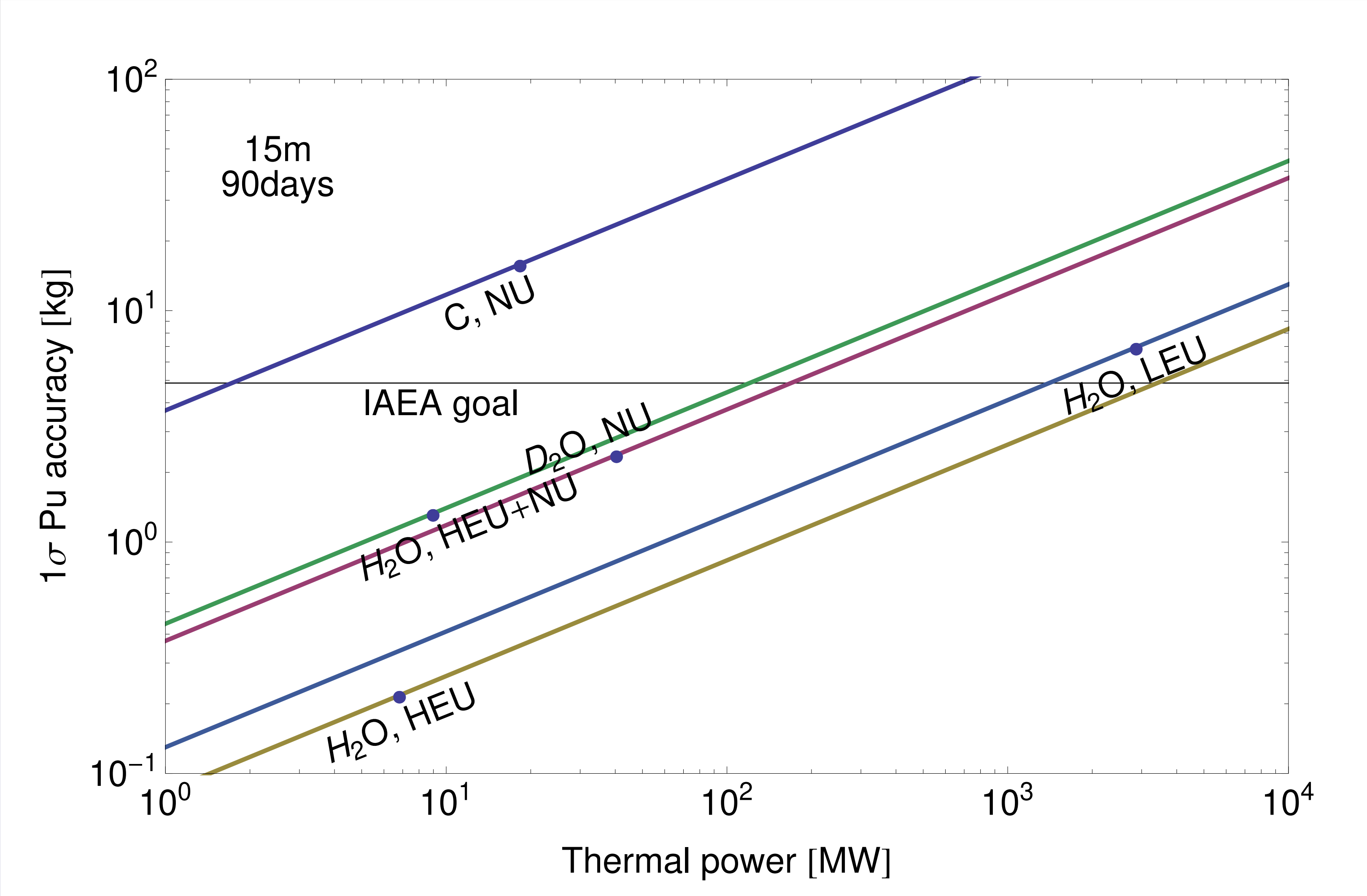


Comparing a reactor core at 45 days in the cycle to the same core at 315 days in the cycle

Corresponding to a difference in plutonium content of about 7 kg

Christensen, Huber, Jaffke, Shea, 2014

Different reactor types



Christensen, Huber, Jaffke, 2013

Iran – 2014

Arak – 40MW$_{\mathrm{th}}$ heavy water moderated, natural uranium fueled reactor

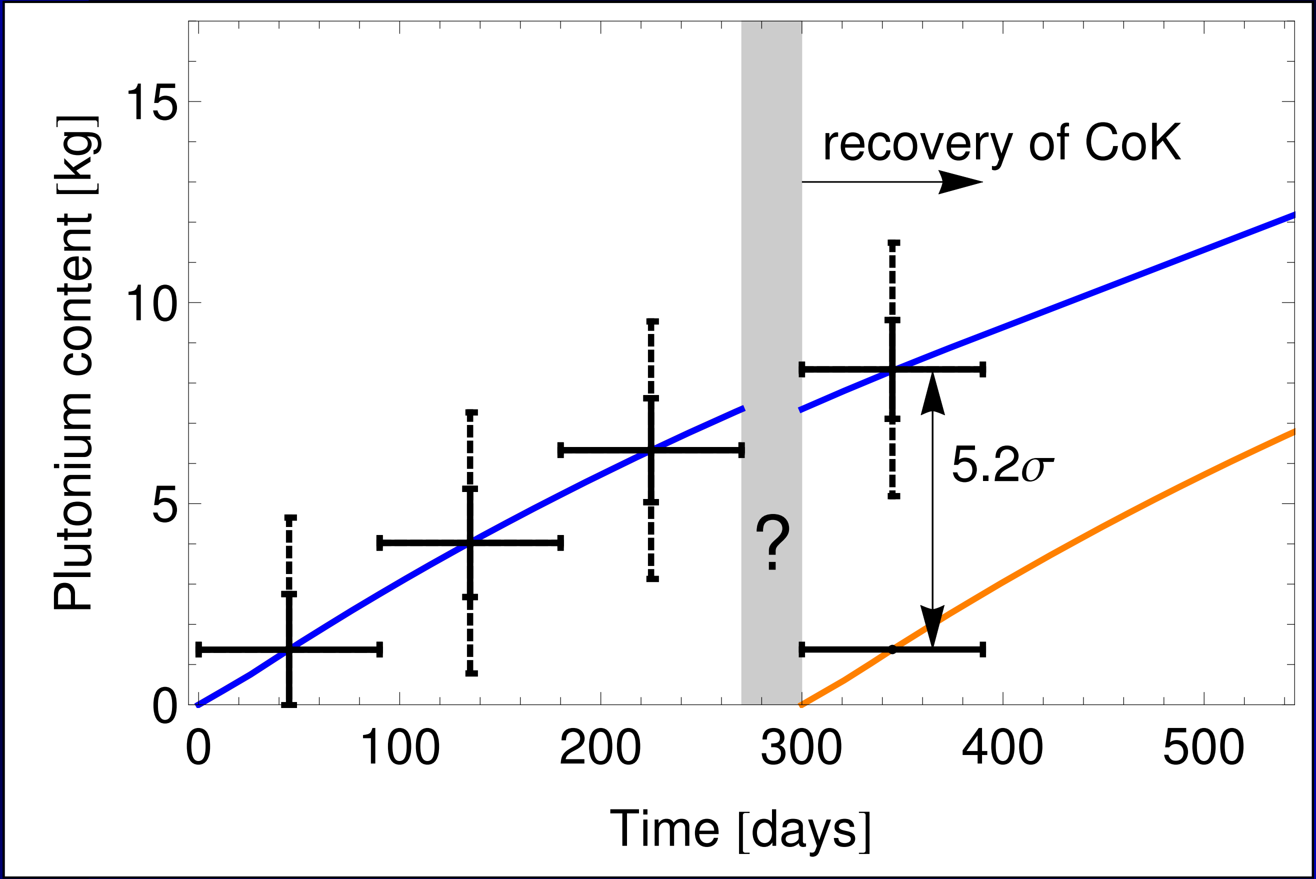
Once operational, produces 10 kg weapons-usable plutonium per year

The N$^{\mathrm{th}}$ month scenario

- Full inspector access for N-1 month
- Reactor shutdown in the N$^{\mathrm{th}}$ month
- Loss of the continuity of knowledge in the N$^{\mathrm{th}}$ month, for some reason:
    - Technical glitch
    - Diplomatic tensions (Twitter!)
    - Full scale diversion

Finding out which one is the true one can make the difference between war and peace.

Iran – results



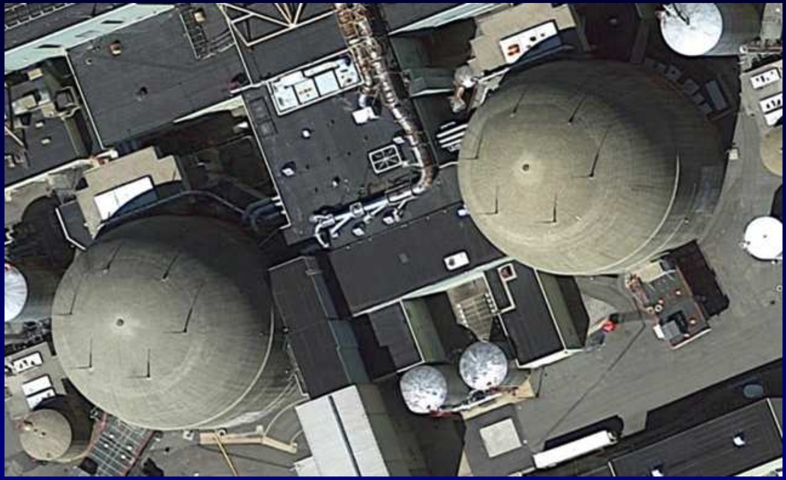
Christensen, Huber, Jaffke, Shea, 2014

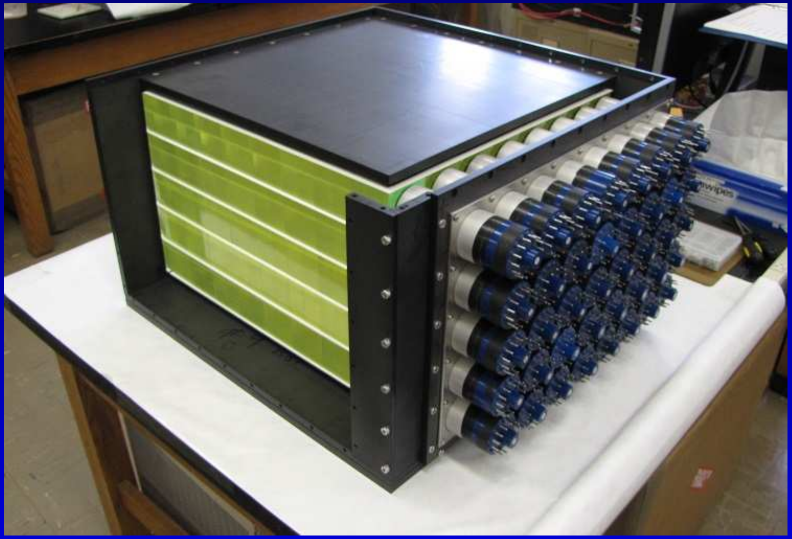
270 days corresponds to 93% plutonium-239

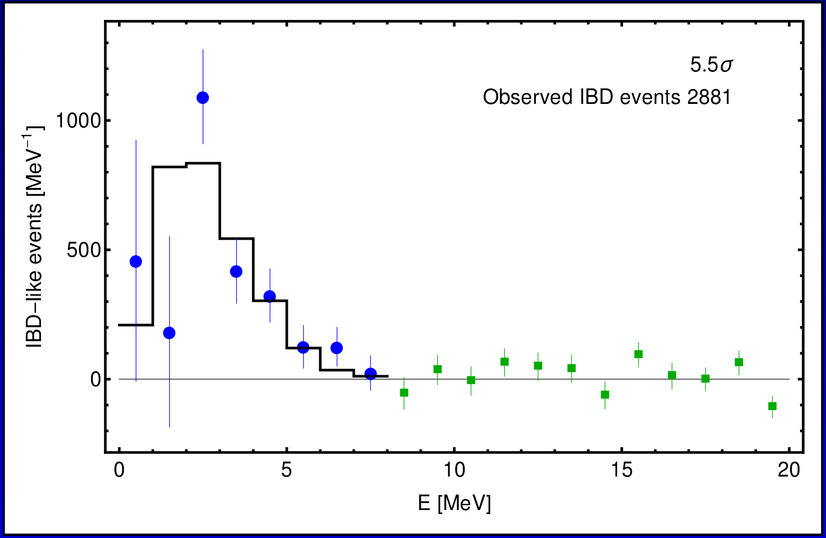
1.2 kg plutonium sensitivity

An undeclared refueling can be detected with 90% confidence level within 7 days.

CHANDLER



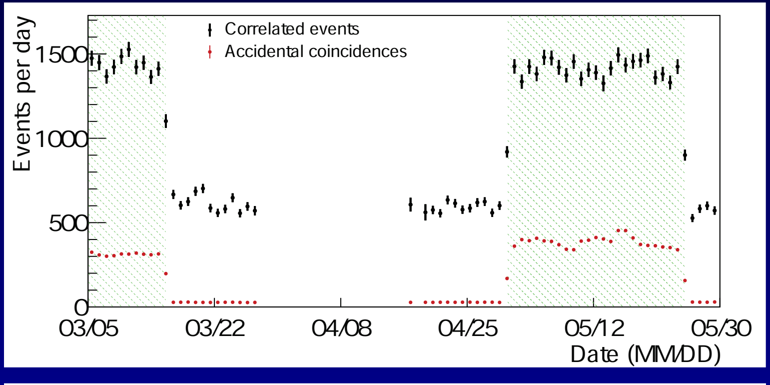


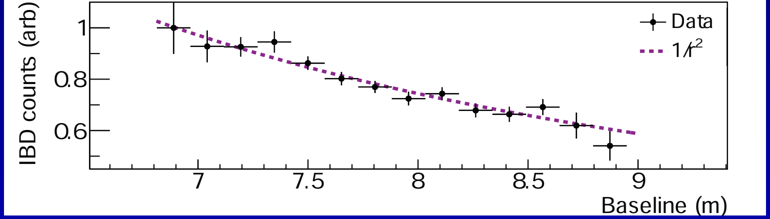


Haghighat *et al.*, 2018

PROSPECT

PROSPECT is a state-of-the-art neutrino detector, which works at the earth’s surface.

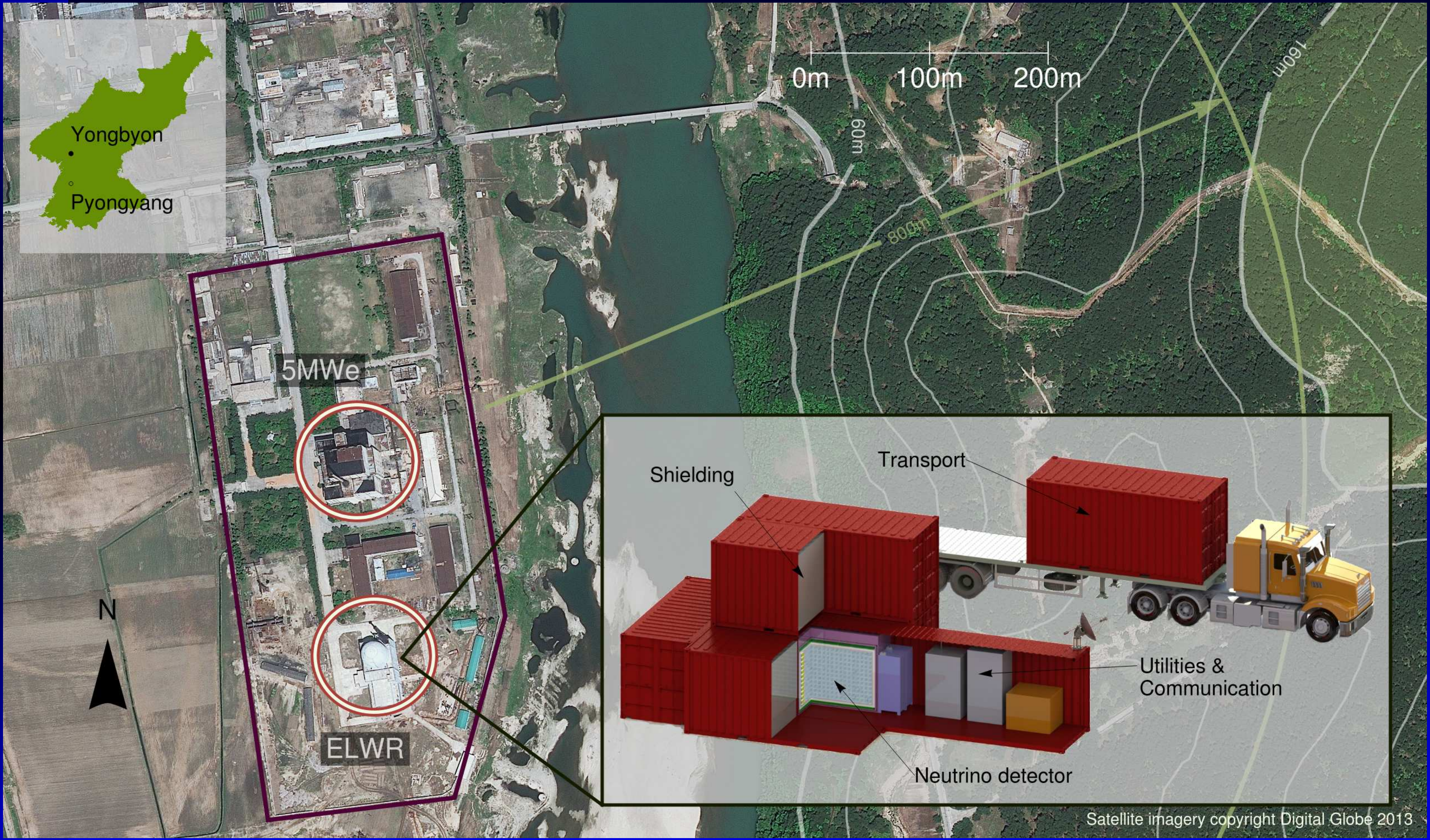




PROSPECT, 2018

We use it as yard stick in this talk for signal and background.

DPRK 2018



Carr *et al.*, 2019

Reactor status – near-field

Simplest thing to ask: Is the reactor on or off?

I use time to 95% C.L. detection based on a PROSPECT-sized detector with PROSPECT background, purely rate-based.

5MWe	IR40	ELWR
1.2d	8 h	1.5 h

Time to detection at 95% C.L.

⇒Can be done with a xerox copy of PROSPECT.

Reactor status – mid-field

1950 U.S. Army topographic map

Yongbyon – 300 m.w.e. overburden possible at around 1 km distance, similar to Daya Bay near detectors, scale from Daya Bay, 2012.

5MWe	ELWR
100 d	1 week

Time to detection at 95% C.L. for a 50 ton detector of Daya Bay-like detector performance.

Reactor core swap detection

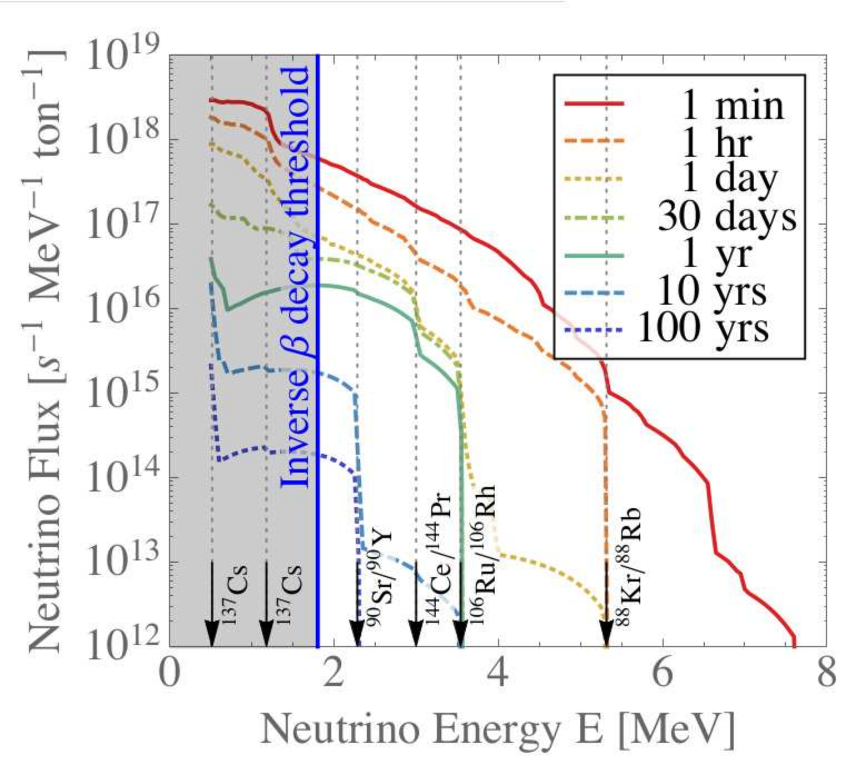
6 times PROSPECT
BG level 1 corresponds to PROSPECT.

BG level	ELWR	IR40	5MWe
1	134	109	1154
0.5	83	59	830
0.2	56	30	637
0	45	16	527

Days to detection at 95% C.L.

Modest background reduction yields $t < 90\,\mathrm{d}$,
but not for the 5MWe.

Spent fuel monitoring



Brdar, Huber, Kopp, 2017

High-energy neutrino flux decays within a day
Low-energy neutrino flux persists for decades

^{90}Sr has 28 year half-life and a direct fission yield of a few percent.

CEvNS may provide a real advantage here.
v. Raesfeld, Huber, 2022.

DPRK example

8 kg of plutonium (1 SQ) leaves about 2 mol of strontium-90 in the waste stream.

55 IBD events in BBD at 10 m in one year.

BG	1 SQ	10 SQ	100 SQ
0.01	1.7	0.024	0.00089
0.1	17	0.18	0.0024
1	170	1.7	0.018

Years to detection at 95% C.L.

Far field monitoring

Neutrino travel in straight lines over long distances. Can we exploit this?

- Undeclared plutonium production reactors
- Nuclear explosion identification

A 100 MW reactor at 1 000 km results in 5 events per year in a 250 kt detector.

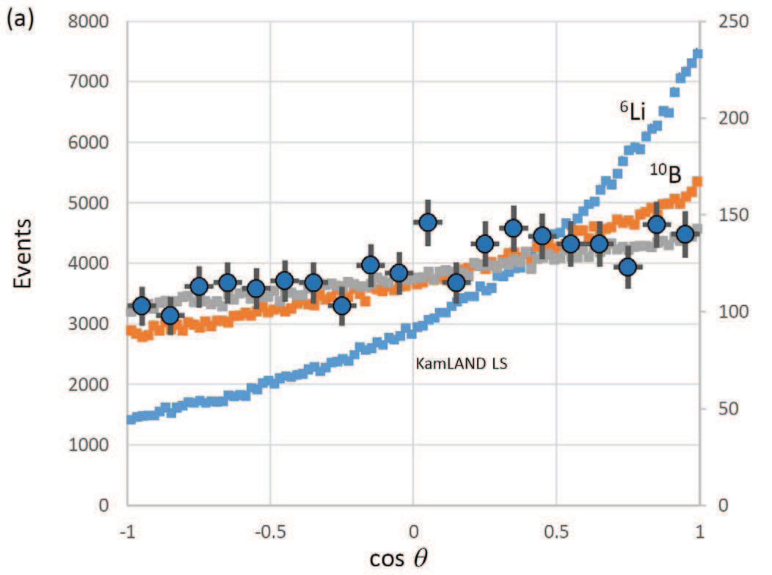
Far field considerations

Europe has about 350 GW$_{\mathrm{th}}$ in reactors at 5 000 km

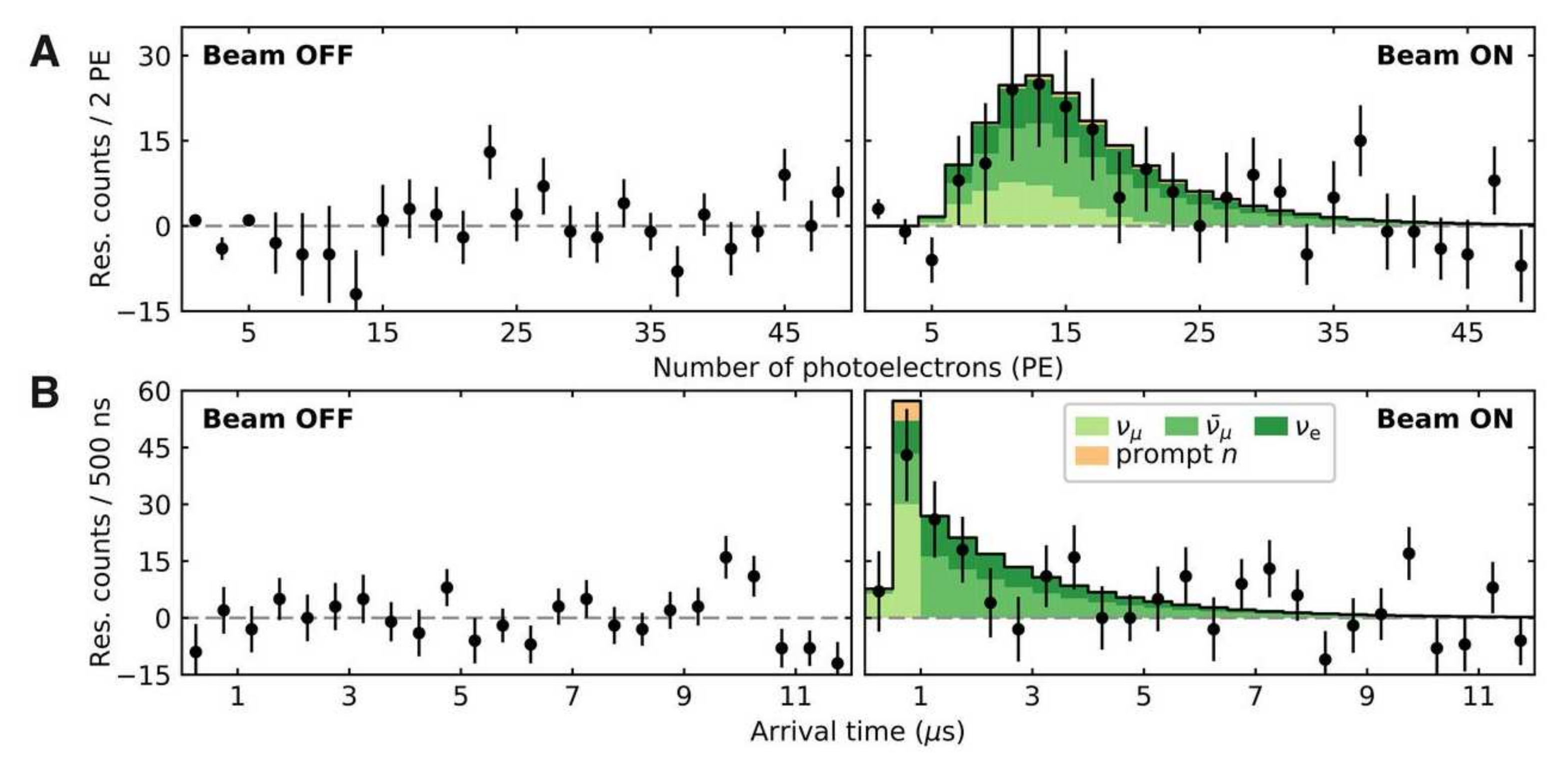
100 times brighter than neutrinos from one 100 MW$_{\mathrm{th}}$ reactor at 1 000 km. . .

Very difficult to get sufficient angular resolution with IBD in liquid scintillator

Tanaka, Watanabe, 2014



COHERENT observation

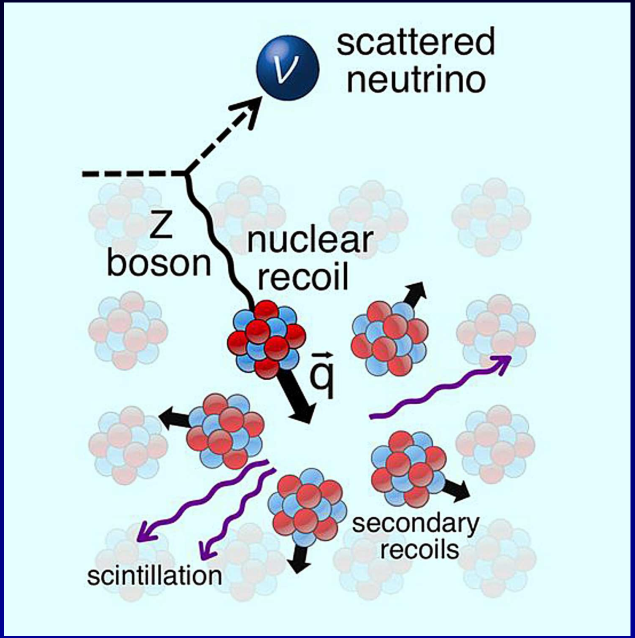


COHERENT 2017

50 MeV neutrino beam, $T_{\max} \propto E_\nu$
$\Rightarrow$ recoil energies at reactor 10 times smaller.

Coherent Neutrino Scattering

Coherent neutrino nucleus scattering (CENNS) is threshold-less.



$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} N^2 M_N \left(1 - \frac{M_N T}{2E_\nu^2}\right)$$

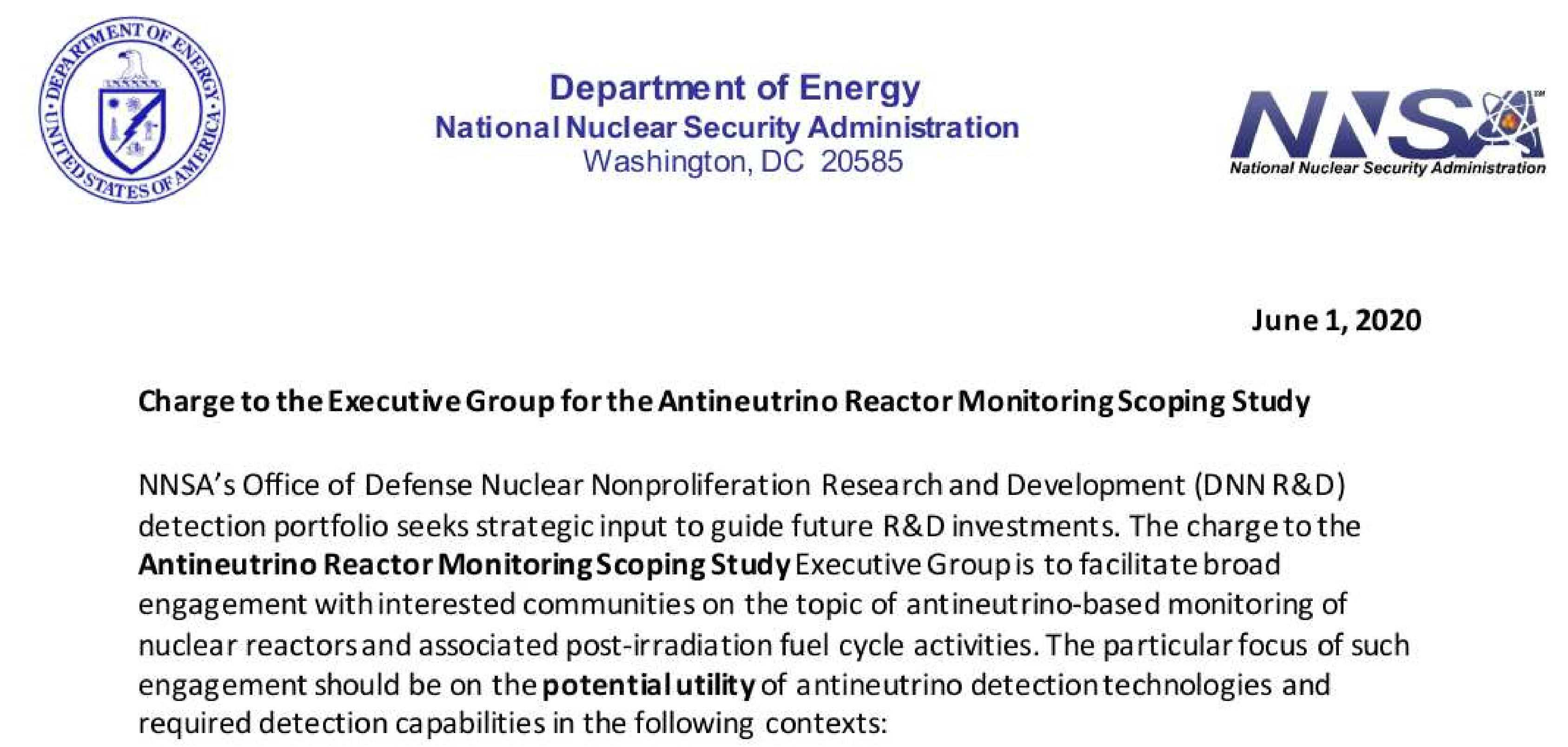
T recoil energy, N neutron number

Threshold in eV for parity in event rate per unit mass with IBD

^{12}C	^{20}Ne	^{28}Si	^{40}Ar	^{74}Ge	^{127}I	^{132}Xe	^{133}Cs
790	770	702	672	491	353	347	343

Bowen, Huber, 2021

NuTools



Department of Energy
National Nuclear Security Administration
Washington, DC 20585

June 1, 2020

Charge to the Executive Group for the Antineutrino Reactor Monitoring Scoping Study

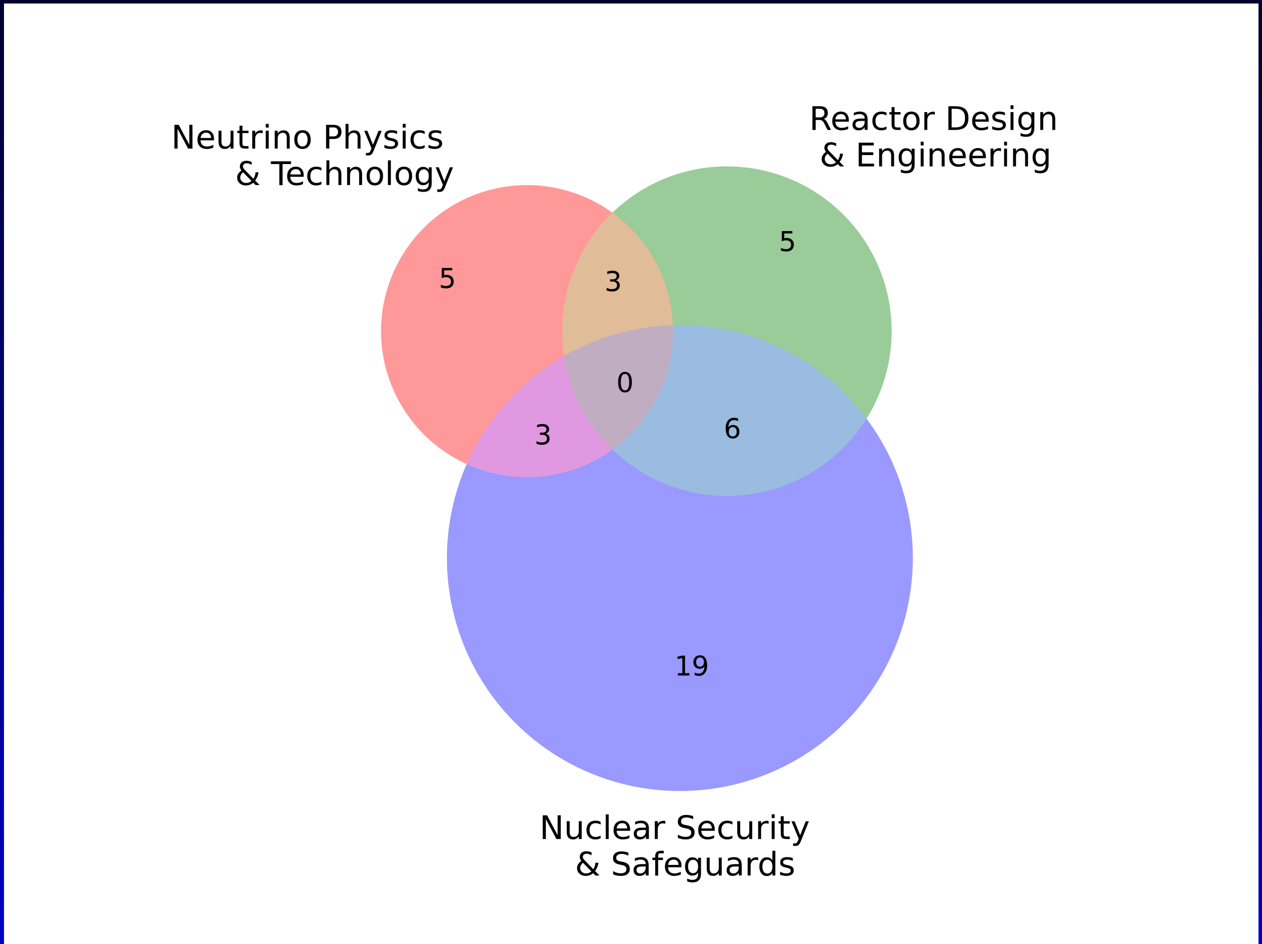
NNSA's Office of Defense Nuclear Nonproliferation Research and Development (DNN R&D) detection portfolio seeks strategic input to guide future R&D investments. The charge to the **Antineutrino Reactor Monitoring Scoping Study** Executive Group is to facilitate broad engagement with interested communities on the topic of antineutrino-based monitoring of nuclear reactors and associated post-irradiation fuel cycle activities. The particular focus of such engagement should be on the **potential utility** of antineutrino detection technologies and required detection capabilities in the following contexts:

- Focus on **utility**
- End-user engagement – not technical analysis

The executive group

Oluwatomi Akindele	Lawrence Livermore National Laboratory
Nathaniel Bowden	Lawrence Livermore National Laboratory
Rachel Carr	Massachusetts Institute of Technology
Andrew Conant	Oak Ridge National Laboratory
Milind Diwan	Brookhaven National Laboratory
Anna Erickson	Georgia Institute of Technology
Michael Foxe	Pacific Northwest National Laboratory
Bethany L. Goldblum	Lawrence Berkeley National Laboratory; University of California, Berkeley
Patrick Huber	Virginia Tech
Igor Jovanovic	University of Michigan
Jonathan Link	Virginia Tech
Bryce Littlejohn	Illinois Institute of Technology
Pieter Mumm	National Institute of Standards and Technology
Jason Newby	Oak Ridge National Laboratory

End-user engagement



41 interviews between May – September 2020

2 or more interviewers in each case

Notes from each interview approved by each interviewee

Interviewees had access to fact sheets prepared by the executive group, providing a high-level summary of neutrino capabilities prior to the interview.

Technical community input

Worskhop with 131 participants from 14 countries, with this agenda:

Nu Tools Overview
Ocean Bottom Detector
JUNO TAO
VIDARR
PROSPECT
Watchman
CONUS
Efforts at U. Chicago
RICOCHET
Angra/CONNIE
NuLAT

PANDA
LiquidO
Efforts in Turkey
CHANDLER
SANDD
ISMRAN
NUCLEUS
MINER
Nucifer
vIOLETA
NUDAR

Cross cutting findings

Three findings of this study apply across all potential applications of neutrino technology:

End-User Engagement: The neutrino technology R&D community is only beginning to engage attentively with end-users, and further coordinated exchange is necessary to explore and develop potential use cases.

Cross cutting findings

Technical Readiness: The incorporation of new technologies into the nuclear energy or security toolbox is a methodical process, requiring a novel system such as a neutrino detector to demonstrate sufficient technical readiness.

Cross cutting findings

Neutrino System Siting: Siting of a neutrino-based system requires a balance between intrusiveness concerns and technical considerations, where the latter favor a siting as close as possible.

Utility framework

1. Need for a new or improved capability
   → *Determined by end-user communities.*
2. Existence of a neutrino signal
   → *Determined by technology development community.*
3. Availability of a neutrino detection technology
   → *Determined by technology development community.*
4. Compatibility with implementation constraints
   → *Determined by end-user communities.*

A potential neutrino application is considered promising only if all four criteria are met or plausibly attainable.

Use case findings

Current International Atomic Energy Agency (IAEA) Safeguards: For the vast majority of reactors under current IAEA safeguards, the safeguards community is satisfied with the existing toolset and does not see a specific role for neutrinos.

Use case findings

Advanced Reactors: Advanced reactors present novel safeguards challenges which represent possible use cases for neutrino monitoring.

Use case findings

Future Nuclear Deals: There is interest in the policy community in neutrino detection as a possible element of future nuclear deals involving cooperative reactor monitoring or verifying the absence of reactor operations.

Use case findings

Reactor Operations: Utility of neutrino detectors as a component of instrumentation and control systems at existing reactors would be limited.

Use case findings

Non-Cooperative Reactor Monitoring or Discovery: Implementation constraints related to required detector size, dwell time, distance, and backgrounds preclude consideration of neutrino detectors for non-cooperative reactor monitoring or discovery.

Use case findings

Spent Nuclear Fuel: Non-destructive assay of dry casks is a capability need which could potentially be met by neutrino technology, whereas long-term geological repositories are unlikely to present a use case.

Use case findings

Post-Accident Response: Determining the status of core assemblies and spent fuel is a capability need for post-accident response, but the applicability of neutrino detectors to these applications requires further study.

Recommendations

Recommendation for End-User Engagement: DNN should support engagement between neutrino technology developers and end-users in areas where potential utility has been identified.

Recommendations

Recommendation for Technology Development: DNN should lead a coordinated effort among agencies to support a portfolio of neutrino detector system development for areas of potential utility, principally in future nuclear deals and advanced reactors.

Outlook

Antineutrinos may have some utility in a safeguards context.

Utility often lies in areas orthogonal to what physicists tend to expect.

Room for technology R&D, but needs to be informed by end-user needs, not just a better mousetrap.

Potential application space is large, did not touch on passive detectors, naval reactors, breeder reactors, explosion monitoring etc.