Nuclear non-proliferation with reactor neutrinos

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12th International Neutrino Summer School
August 5 – 16, 2019
Fermilab

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

Application to safeguards

Antineutrinos, due to their high penetration capability, offer unique safeguards opportunities based on spectral measurements:

- measurement of reactor power
- independent verification of fuel burn-up

These measurements are performed on the whole reactor core while the reactor is running.

Challenges

Power measurement can be done by established, simpler methods

Core-wide burn-up is not measured in current safeguards implementations

Automobile analogy

speed	thermal power
trip mileage	burn-up
used gas	produced plutonium

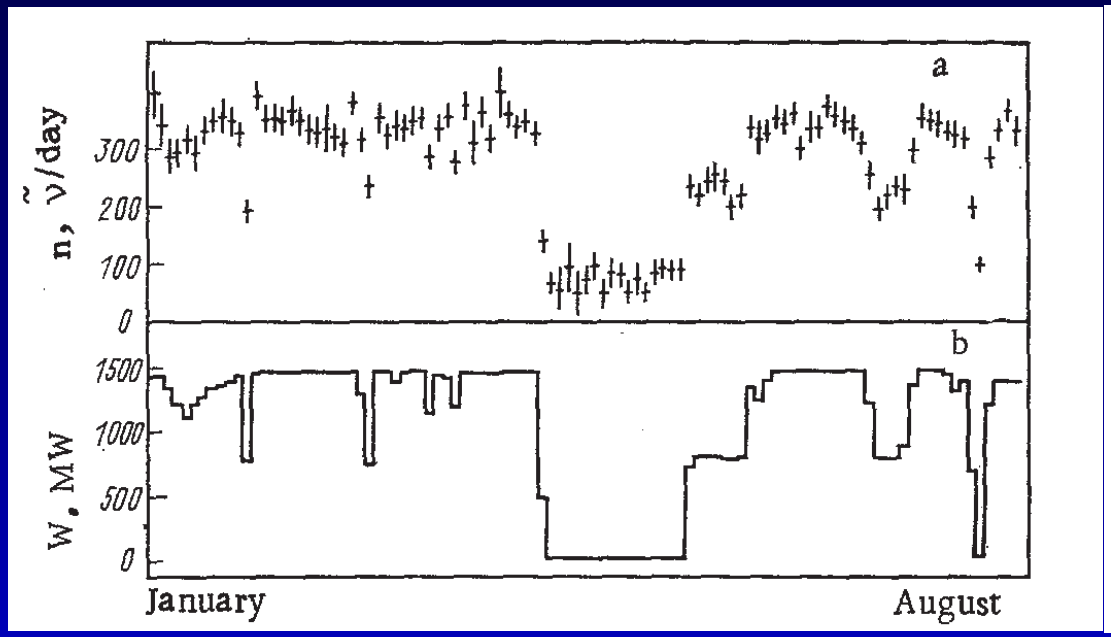
requires continuous speed measurement, discrepancies show up at refueling only

snapshot of used gas without prior record, discrepancies show up as you drive

Reactor monitoring

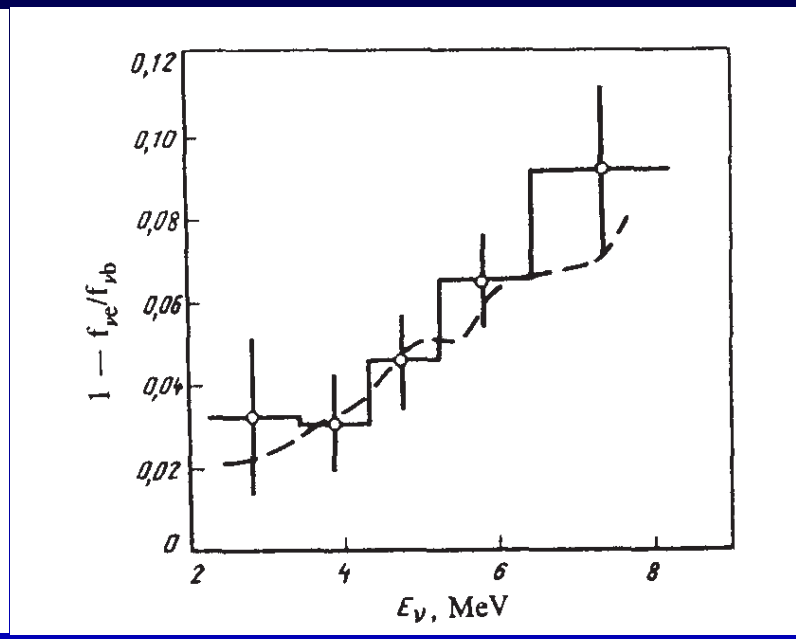
In th 1970s Mikaelyan *et al.* proposed this.

Power monitoring



Korovkin *et al.*, 1988

Fuel burn-up



Klimov *et al.*, 1994

Recent results on fuel evolution Daya Bay, 2017; RENO, 2018; DANSS, 2018 confirm our general understanding!

The standard detector

4.3E29 target protons

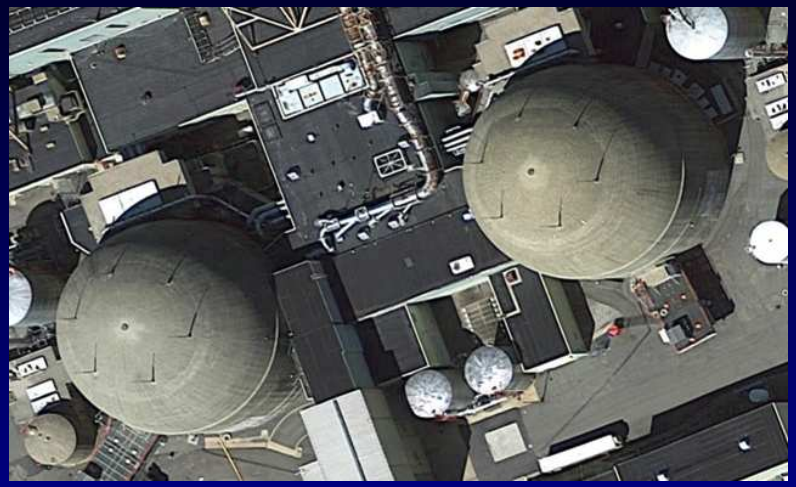
No overburden

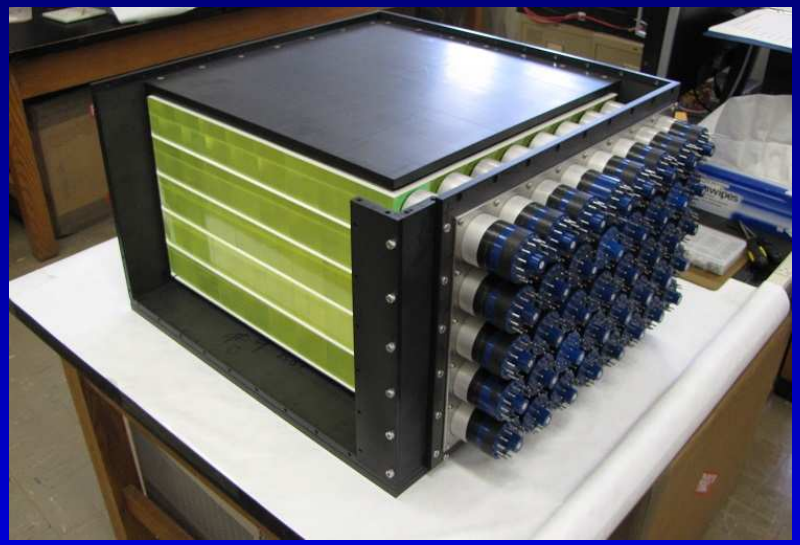
Irreducible cosmogenic background

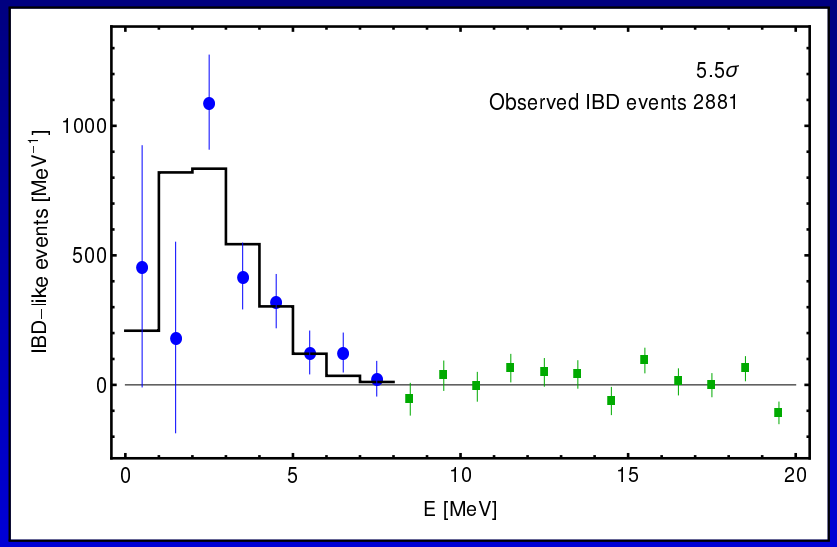
How far have we come with respect to the blue box detector (BBD)?

This is the “spherical cow” approximation…

CHANDLER



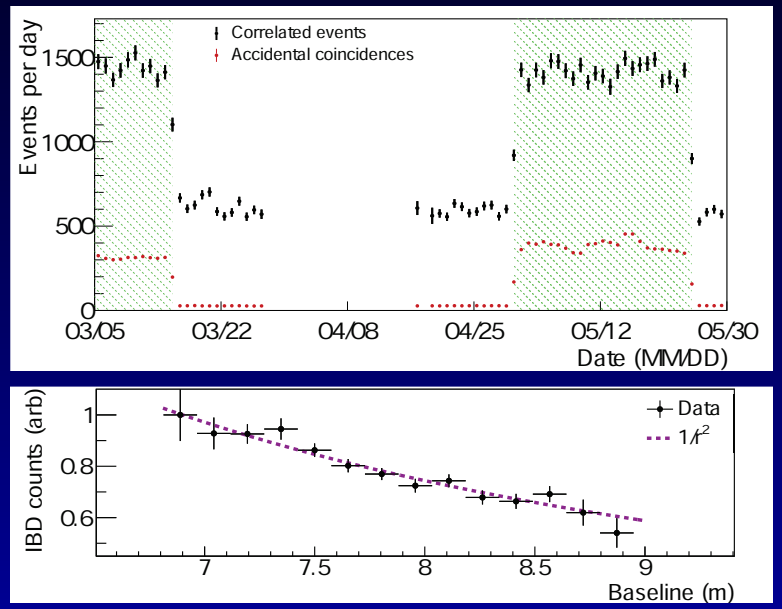




Haghighat *et al.*, 2018

PROSPECT

PROSPECT is a 2D segmented surface detector using Li-doped liquid scintillator. PSD to reject cosmogenic backgrounds, significant shielding.

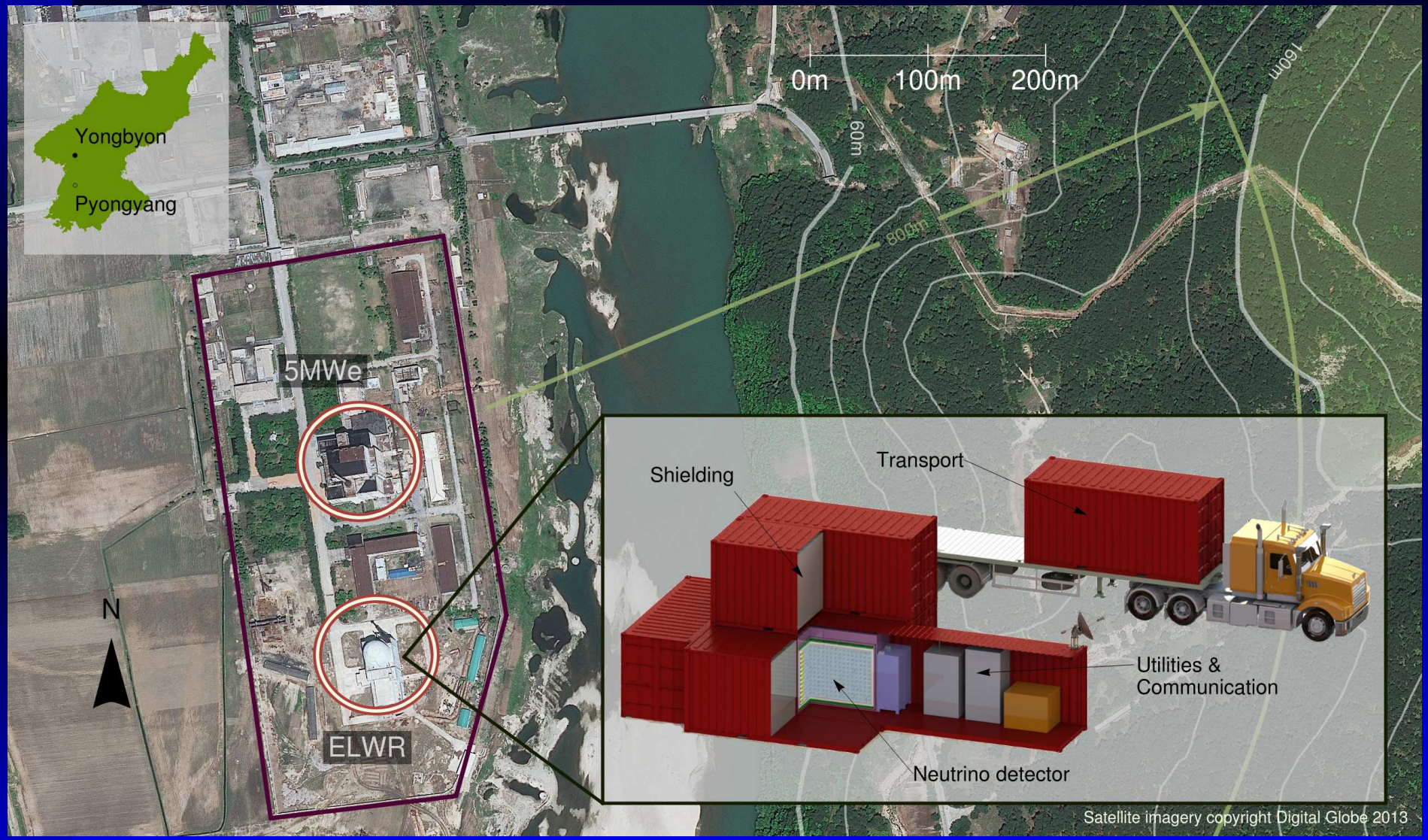


PROSPECT, 2018

$$S = 711 \left(\frac{m}{2\,[\text{ton}]}\right)\left(\frac{P}{85\,[\text{MWth}]}\right)\left(\frac{10\,[\text{m}]}{L}\right)^2 \text{d}^{-1}$$

$$B = \frac{711}{1.32}\left(\frac{m}{2\,[\text{ton}]}\right) \text{d}^{-1}$$

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.

NB – CEvNS: scaling from the CONUS presentation at Neutrino 2018 indicates 7.5 ton years (!) of exposure.

Reactor status – mid-field

1950 U.S. Army topographic map

Yongbyon

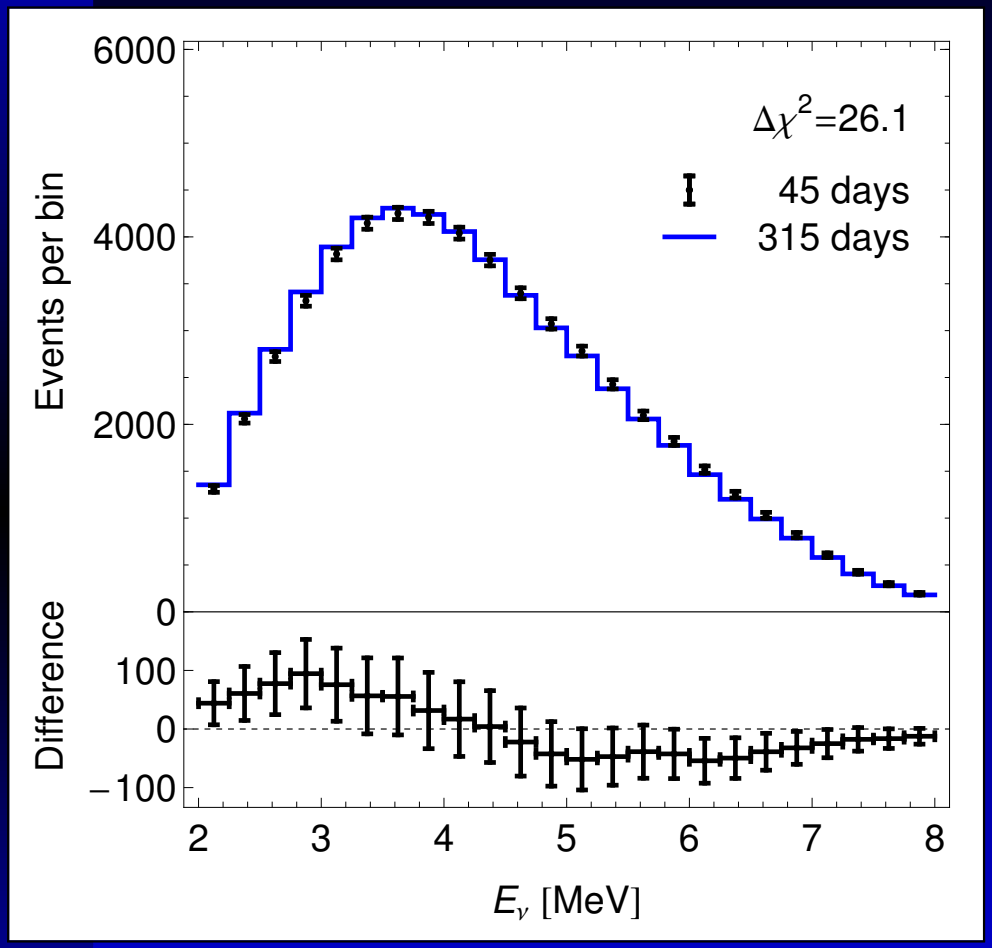
450 m mountain (Yak-san) at about 2 km from the reactors.

$\sim$ 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.

Exploiting the energy spectrum



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

This is based on the blue box detector with zero background.

Key to the capability to restore the continuity of knowledge, unique to antineutrinos...

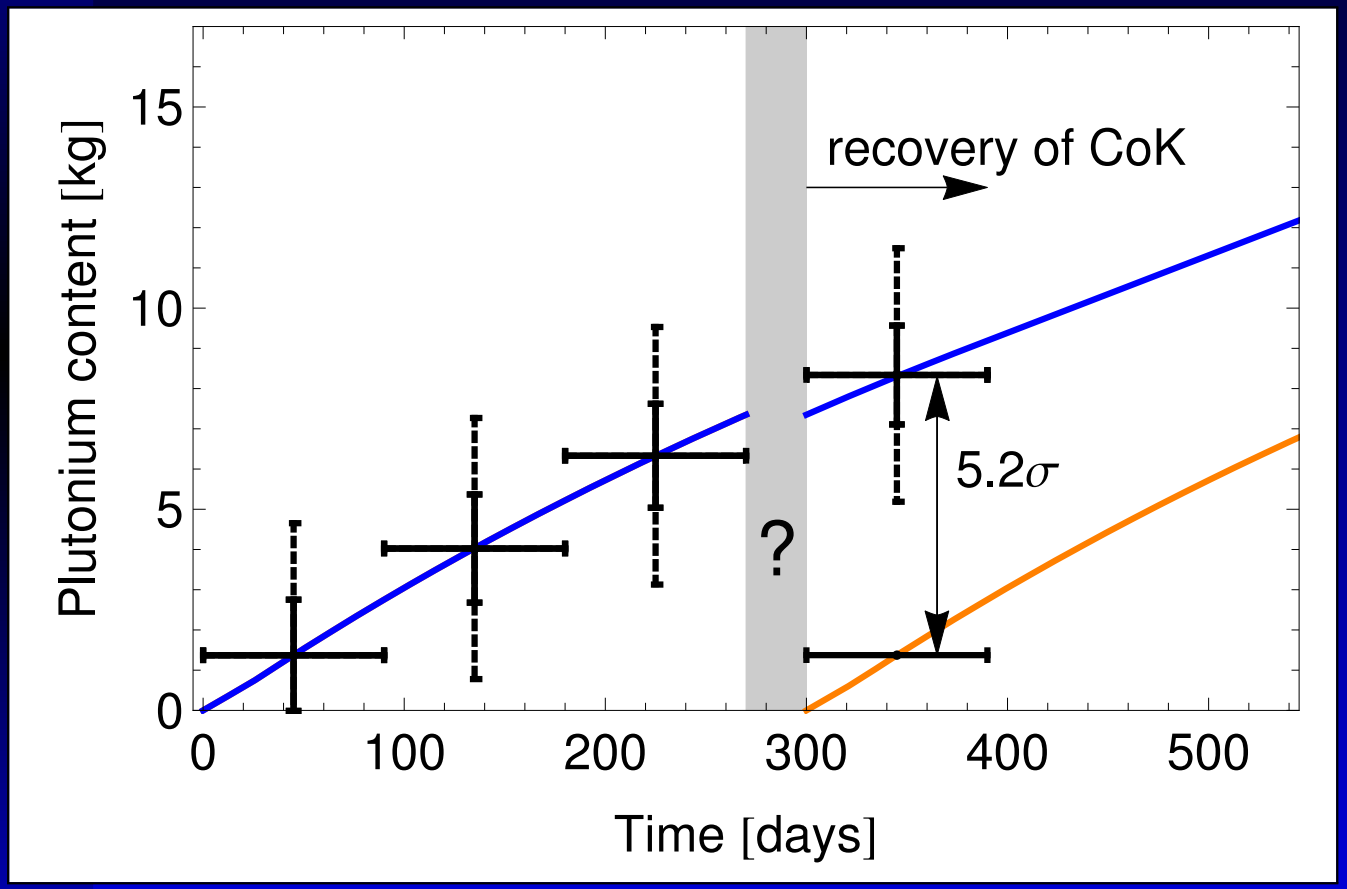
The Nth month scenario

- Full inspector access for N-1 month
- Reactor shutdown in the Nth month
- Loss of the continuity of knowledge in the Nth month

Reasons could range from technical glitch, over a diplomatic tensions (Twitter!) to full scale diversion – finding out which one is the true one can make the difference between peace and war.

Iran

IR40 is a 40MW heavy water cooled reactor.



270 days corresponds to 93% plutonium-239

An undeclared refueling can be detected at 90% C.L. within 7 days.

blue box detector, zero background

Reactor core swap detection

6 times PROSPECT $\simeq$ BBD, all times scale as m^{-1}.
BG level 1 corresponds to PROSPECT.

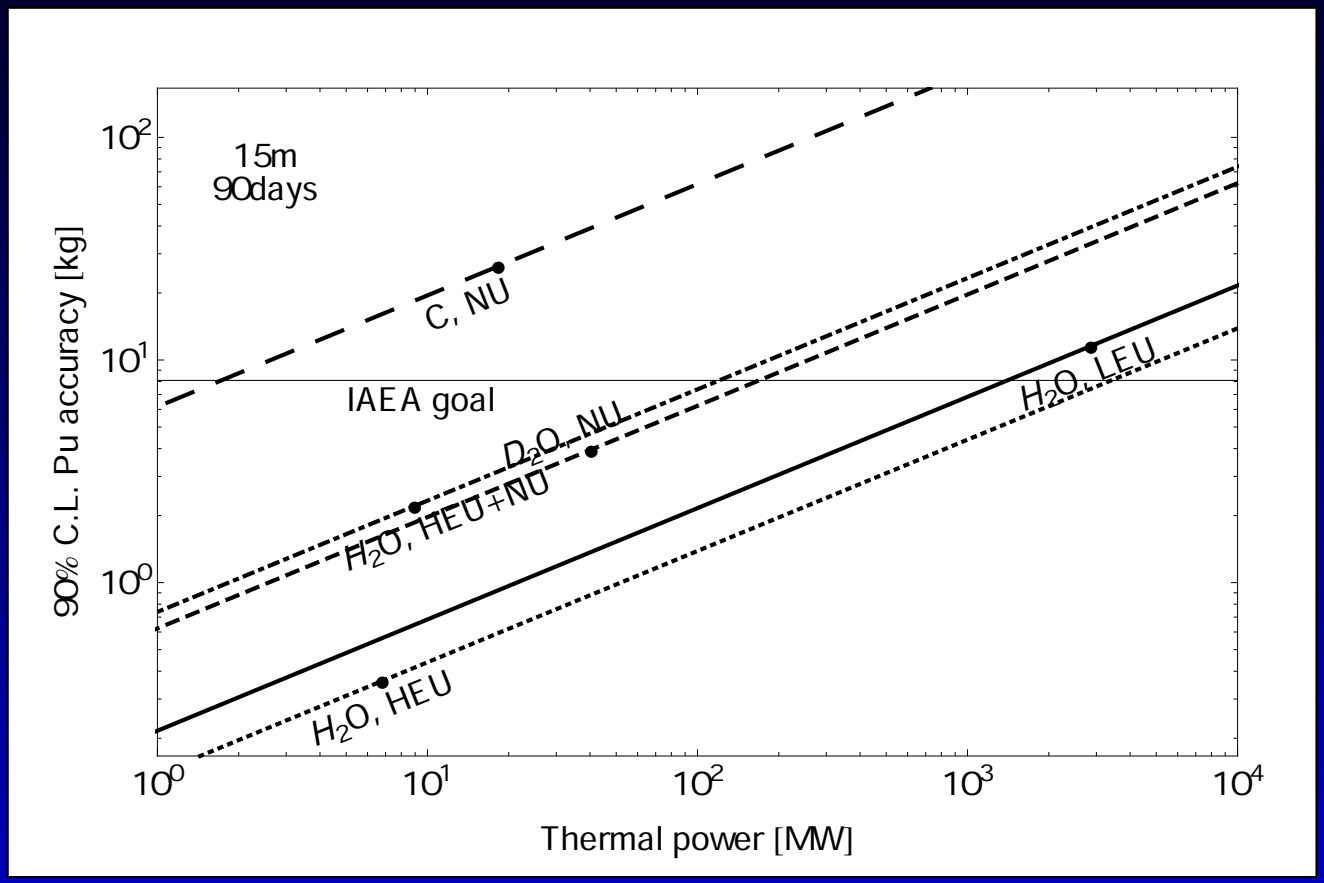
BG level	ELWR	IR40	5MWe
1	134	109	1154
0.5	83	59	830
0.2	56	30	637
0	45	16	527

Days to detection at 95% C.L.

This is based on a full spectral fit and uses the same analysis techniques as used in our prior DPRK and Iran papers.

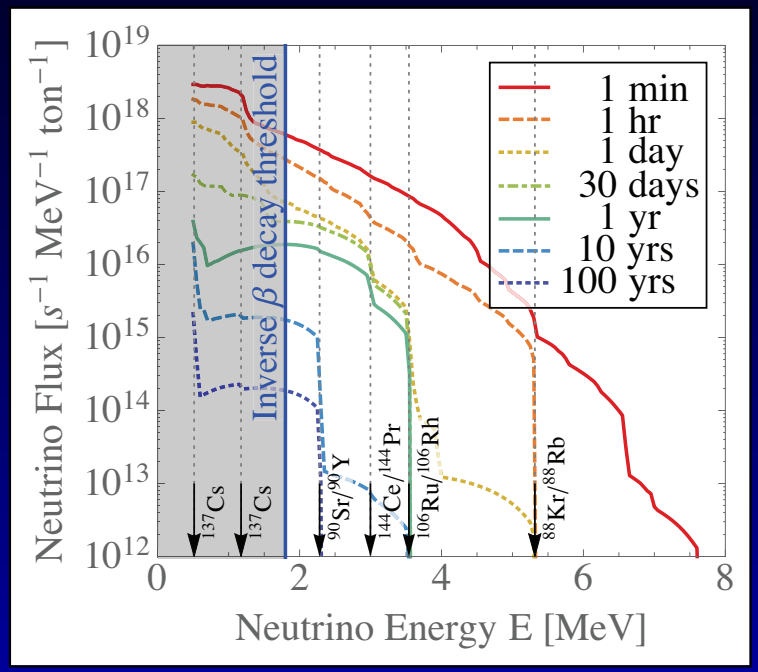
Modest background reduction yields $t < 90$ d,
but not for the 5MWe.

Measuring in-core Pu mass



The amount of neutrinos from plutonium per unit mass of Pu depends on neutron flux density: graphite moderated, NU-fueled reactors have a very low neutron flux density.

Spent fuel detection



There is flux from spent fuel above IBD threshold.

Even decades after discharge.

Nearly all in strontium-90.

This would be very useful to find reprocessing wastes $\rightarrow$ nuclear archeology, endgame of denuclearization.

Challenges:

rates are low and all signatures are below 3 MeV.

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.

Safeguards summary

Antineutrino monitoring can **detect a core swap within a few months, even with demonstrated background levels.**

Antineutrino monitoring is non-intrusive and can be performed *in situ* at a running reactor.

IAEA safeguards (INFCIRC/153 and 540) probably not the right context.

Regional nuclear deals offer a better case.

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