Lessons learned from case studies

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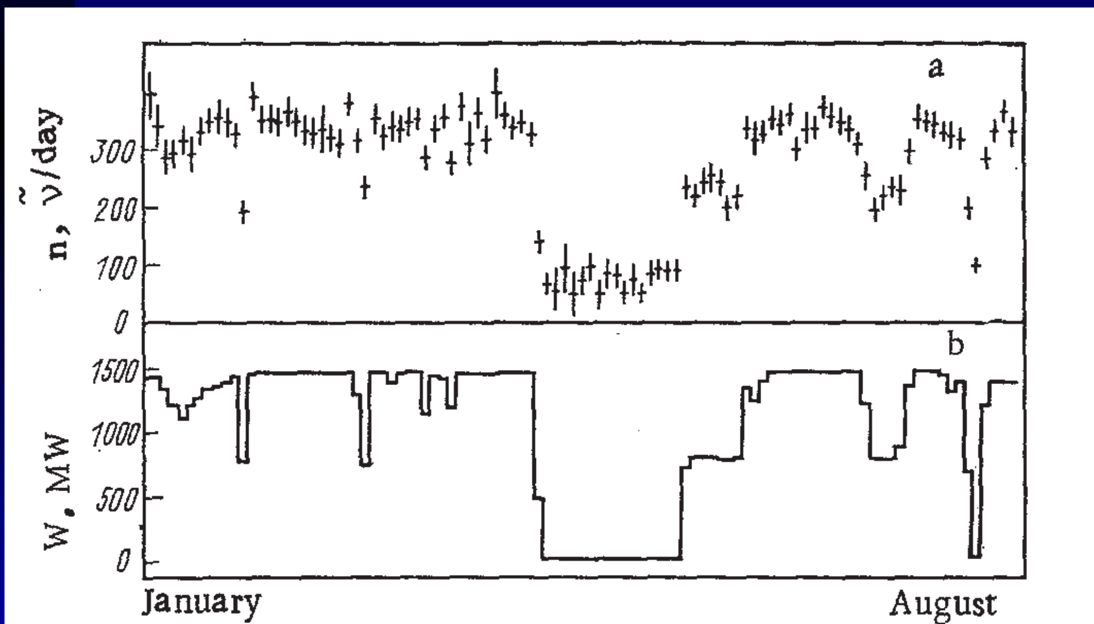
Reactor monitoring

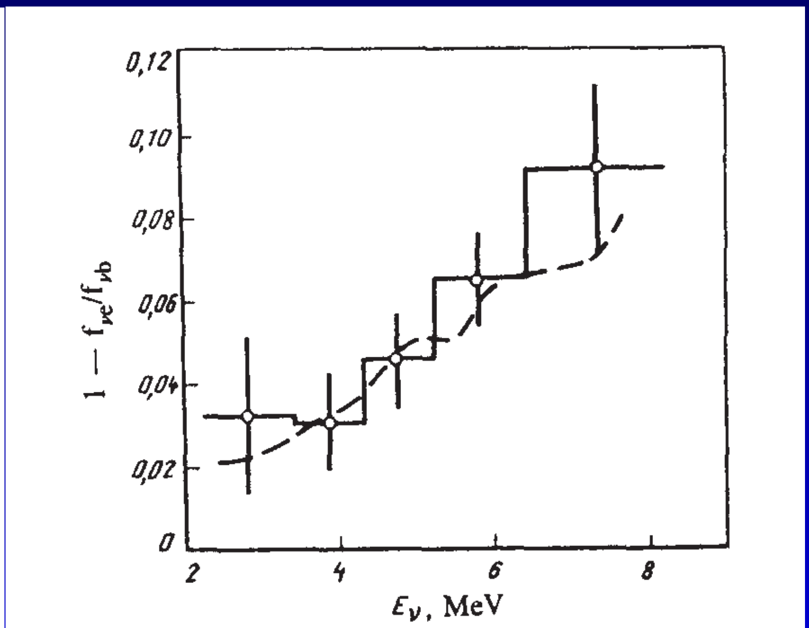
Pioneering work by a group at the Kurchatov institute lead by Lev Mikaelyan

Power monitoring



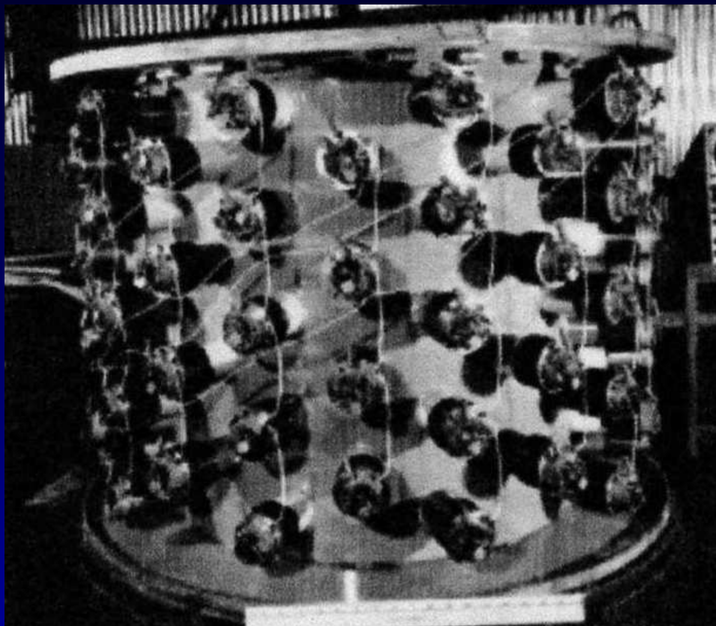
Korovkin *et al.*, 1988

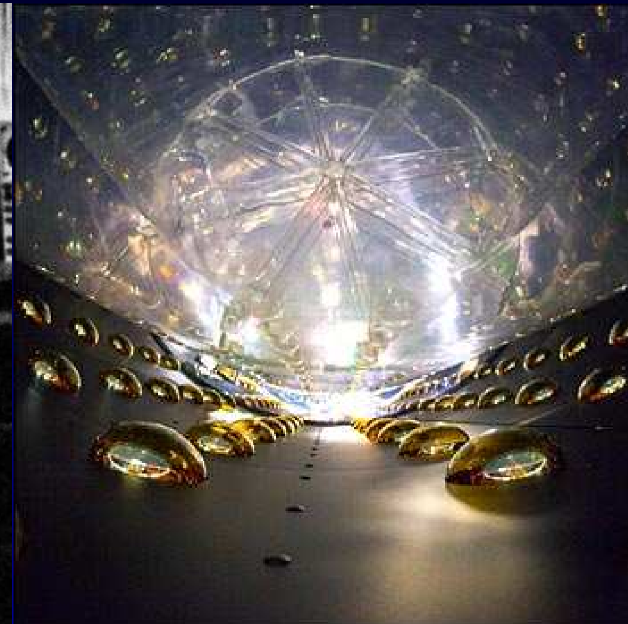
Fuel burn-up



Klimov *et al.*, 1994

The Poltergeist legacy





experiment	year	mass ton	efficiency	background $\text{day}^{-1}\ \text{ton}^{-1}$
Rovno 1	1994	0.5	20%	298
Bugey	1995	0.64	11%	4
Palo Verde	2001	11.3	10%	27
CHOOZ	2003	5	70%	0.24
SONGS 1	2008	0.64	10%	164
Daya Bay	2011	20	79%	0.17

The standard detector

4.3E29 target protons

10-20 metric tonne actual detector weight

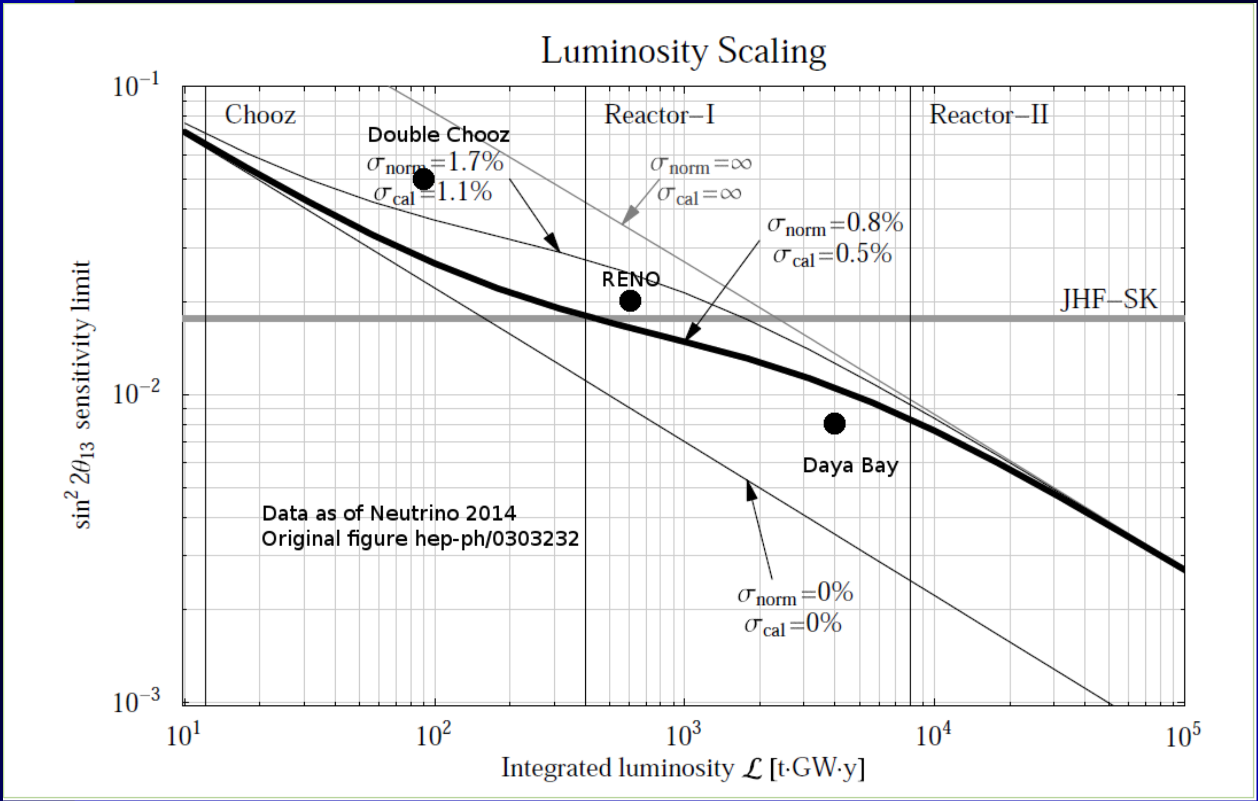
No overburden

Irreducible cosmogenic background

Detector mass depends on material and efficiency

Efficiency [%]	25	40	60	80
Liquid scintillator	20.1	12.5	8.4	6.3
Solid scintillator	34.0	21.3	14.2	10.6

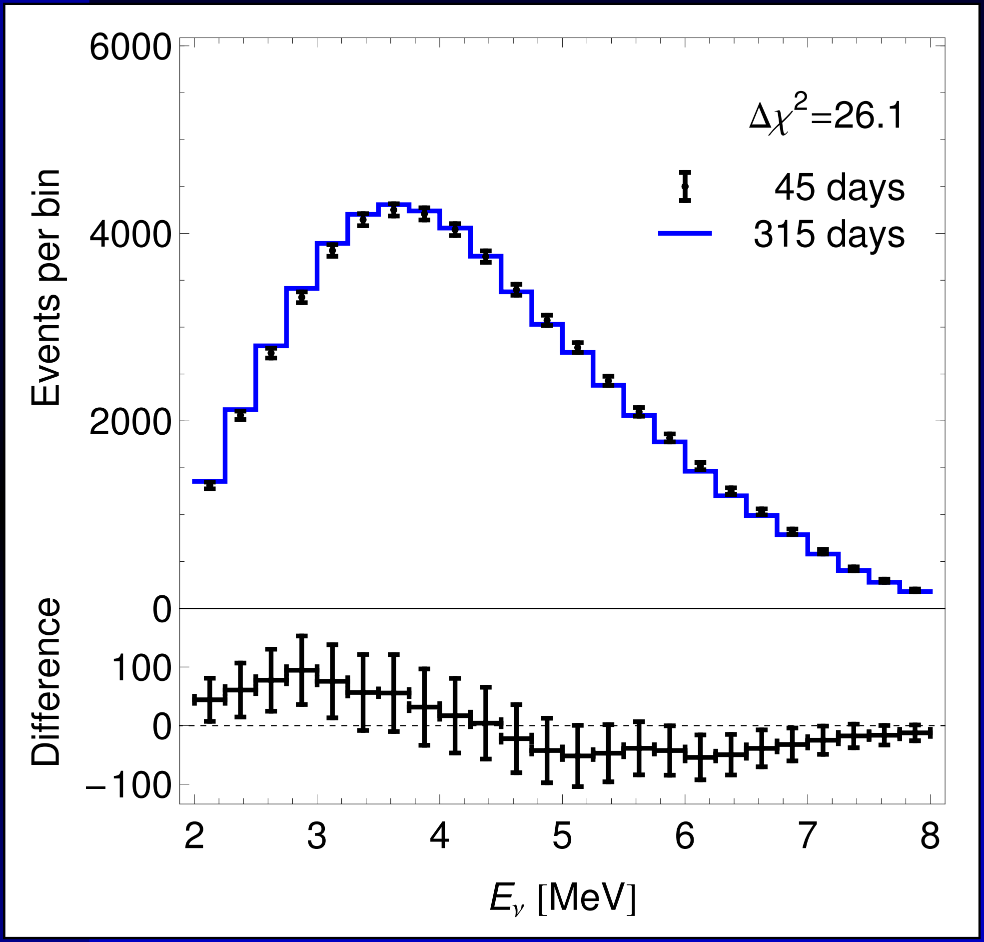
Feasibility



Shown is a 2003 prediction (PH, Lindner, Schwetz) of θ_{13} reactor experiment evolution and big dots show the actual status as of 2014

Based on the large number of short-baseline reactor experiments, which face much more difficult background conditions, there is reason for optimism to have working prototypes on a 12-24 months timescale

Exploiting the energy spectrum

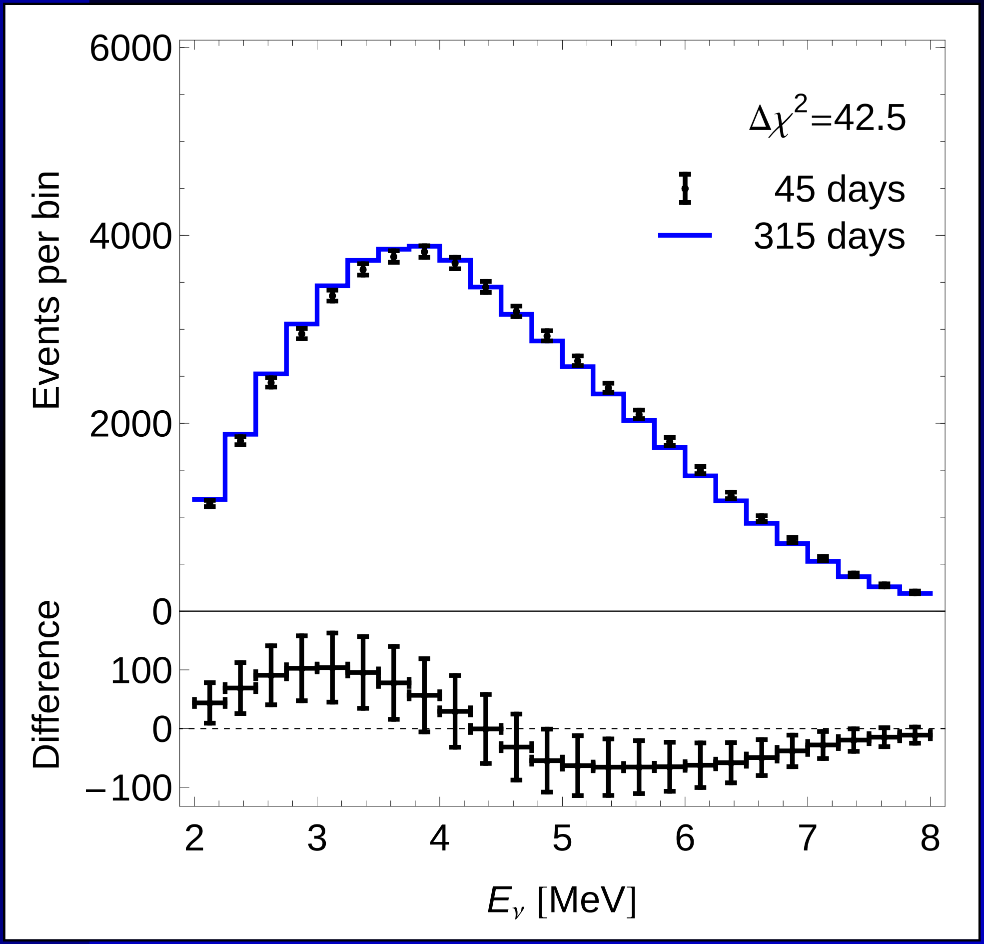


Comparing a reactor core at 45 days in the cycle to the same core at 315 days in the cycle

The later spectrum is indeed much softer and the difference is more than $5\,\sigma$

Corresponding to a difference in plutonium content of about 7 kg

What about the bump?

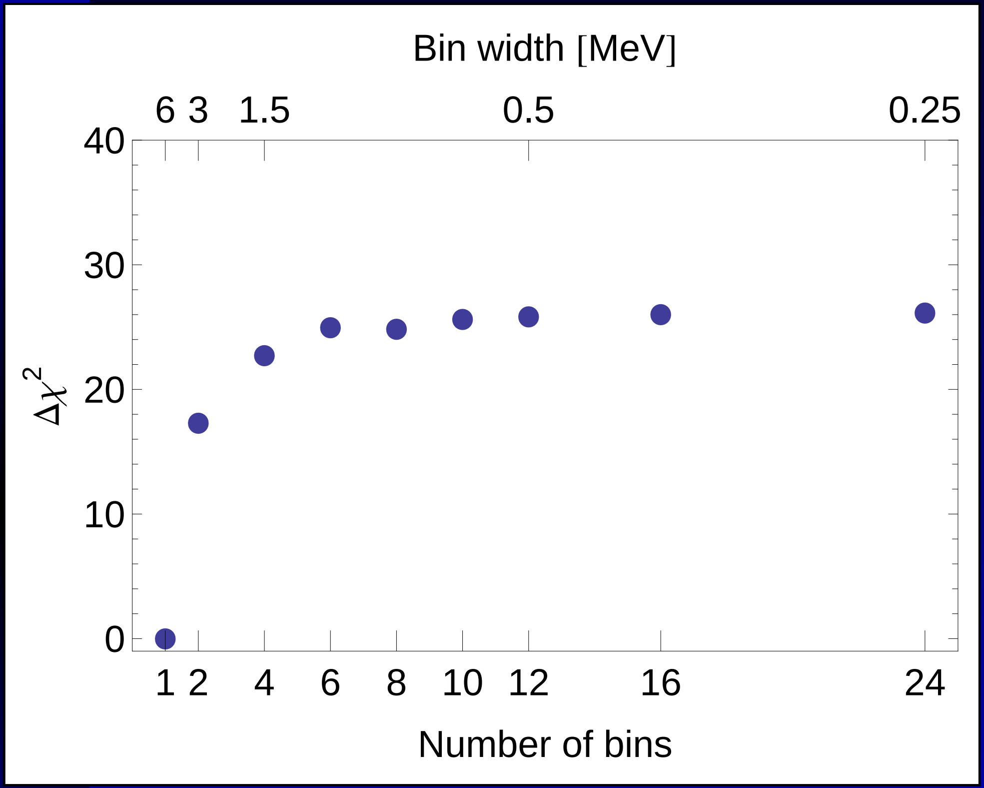


Same as before, but with Dwyer and Langford, 2014 antineutrino yields.

This would improve sensitivity by 30%

Clearly, accurate measurements of antineutrino yields from various reactors are a necessary input – see for instance PROSPECT

How much resolution is needed?

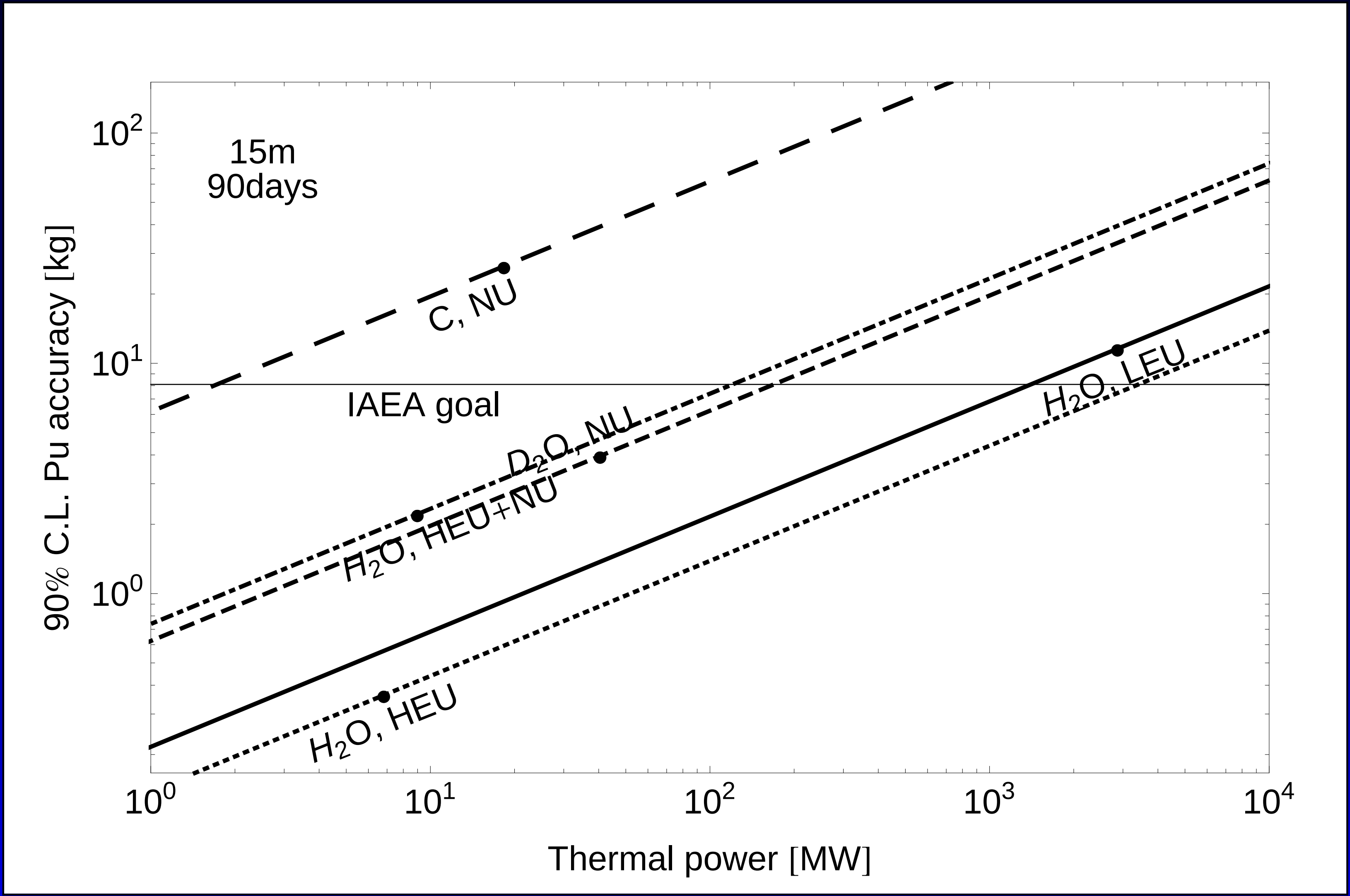


Statistical power is flat for bins smaller than 1 MeV

Even with only 2 bins, 2/3 of statistical power achieved

For comparison, the Daya Bay detectors have a resolution of about 0.65 MeV at an energy of 4 MeV
Daya Bay, 2013

Measuring in-core Pu mass



Fission fractions free in the fit. This is NOT based on a power measurement!

Diversion

Considering a diversion of plutonium from a known reactor, two separate problems have to be addressed

- the amount of plutonium produced – requires a continuous power history from antineutrinos or otherwise
- the amount of plutonium in the reactor core – can be measured ad-hoc using antineutrinos or by careful analysis of discharged fuel

A mismatch between these two quantities is indicative of a diversion.

Safeguards goals

The IAEA goal for in-core plutonium is detection of the diversion of 1 significant quantity or 8 kg within 90 days at 90% confidence level.

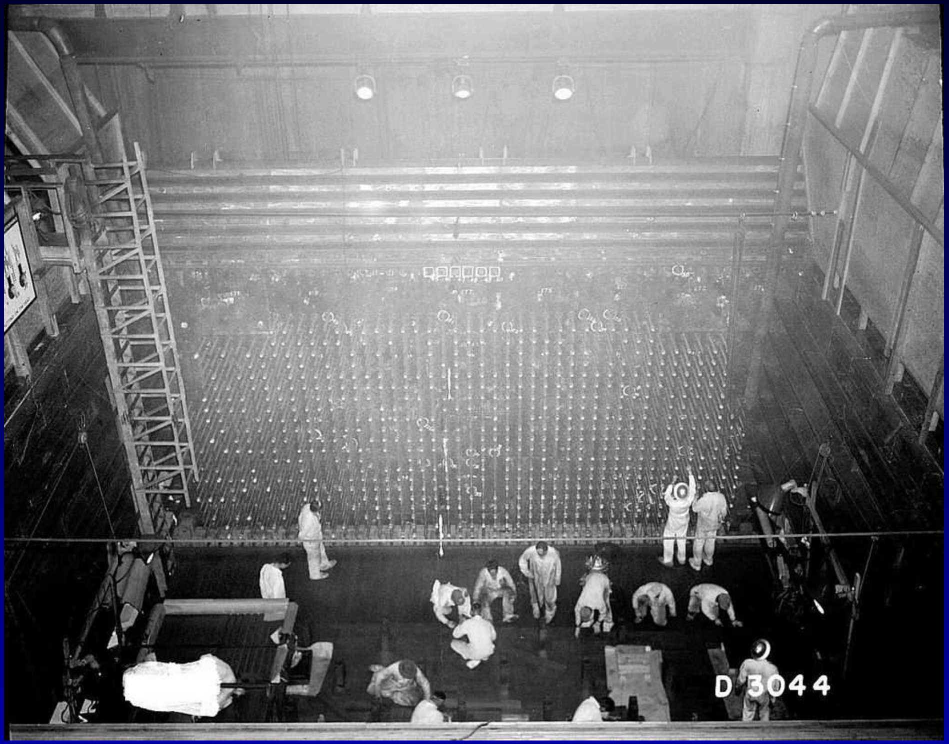
The produced plutonium in all practical applications will have a much smaller associated uncertainty, so it is the error on the in-core plutonium which drive the ability to detect a diversion.

For LWR, we should keep in mind that

- A PWR fuel assembly is 5 m long, weighs 500 kg and glows in the dark – easy to keep track of by item accountancy
- Not a single nuclear weapons program started from a safeguarded and/or light water reactor

Path to nuclear weapons

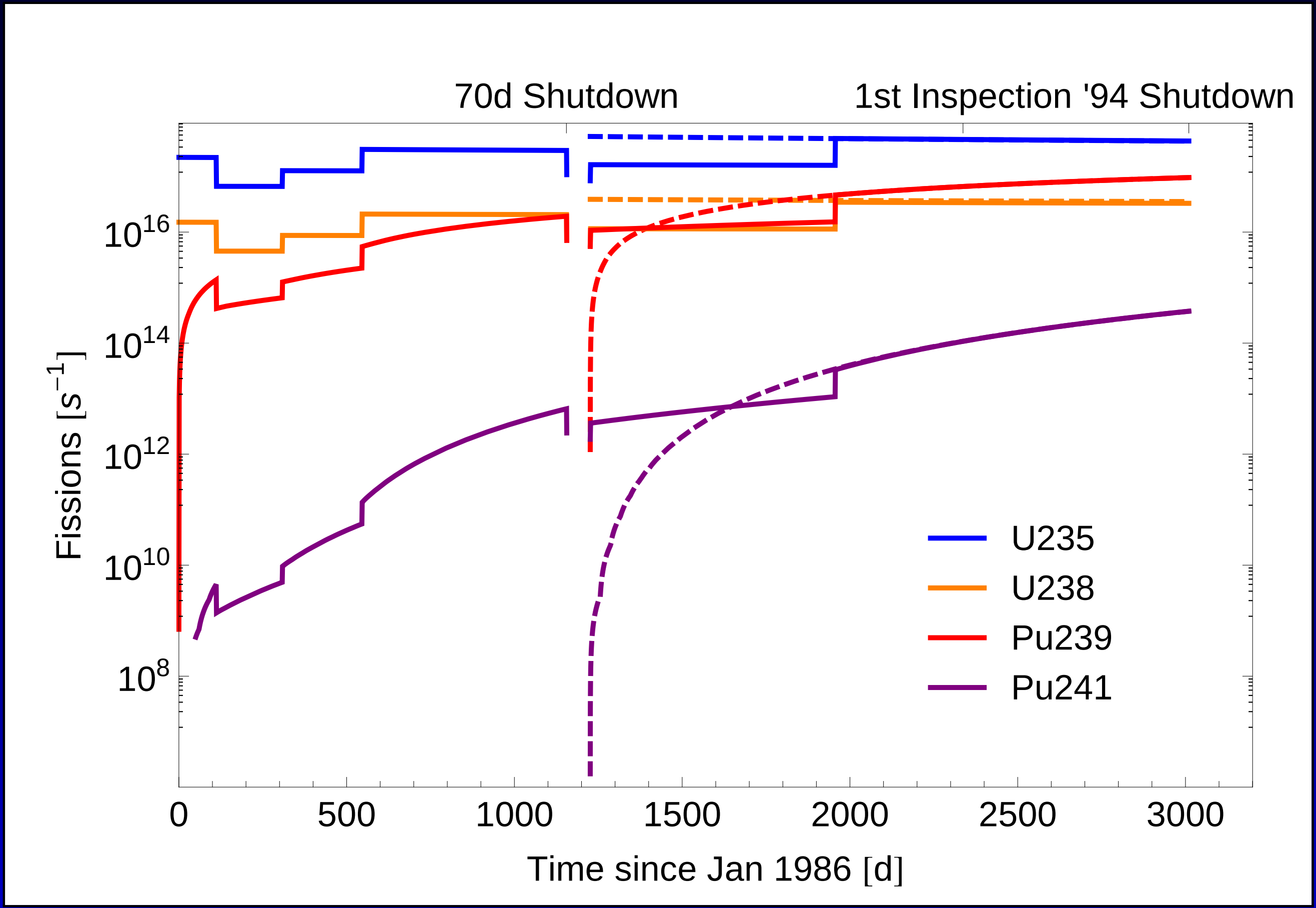
U.S. – Hanford, graphite
Russia – Mayak, graphite
U.K. – Windscale, graphite
France – Marcoule, heavy water
China – uranium enrichment
Israel – Dimona, heavy water
South Africa – uranium enrichment
India – CIRUS, heavy water
Pakistan – uranium enrichment
DPRK – Yongbyon, graphite



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

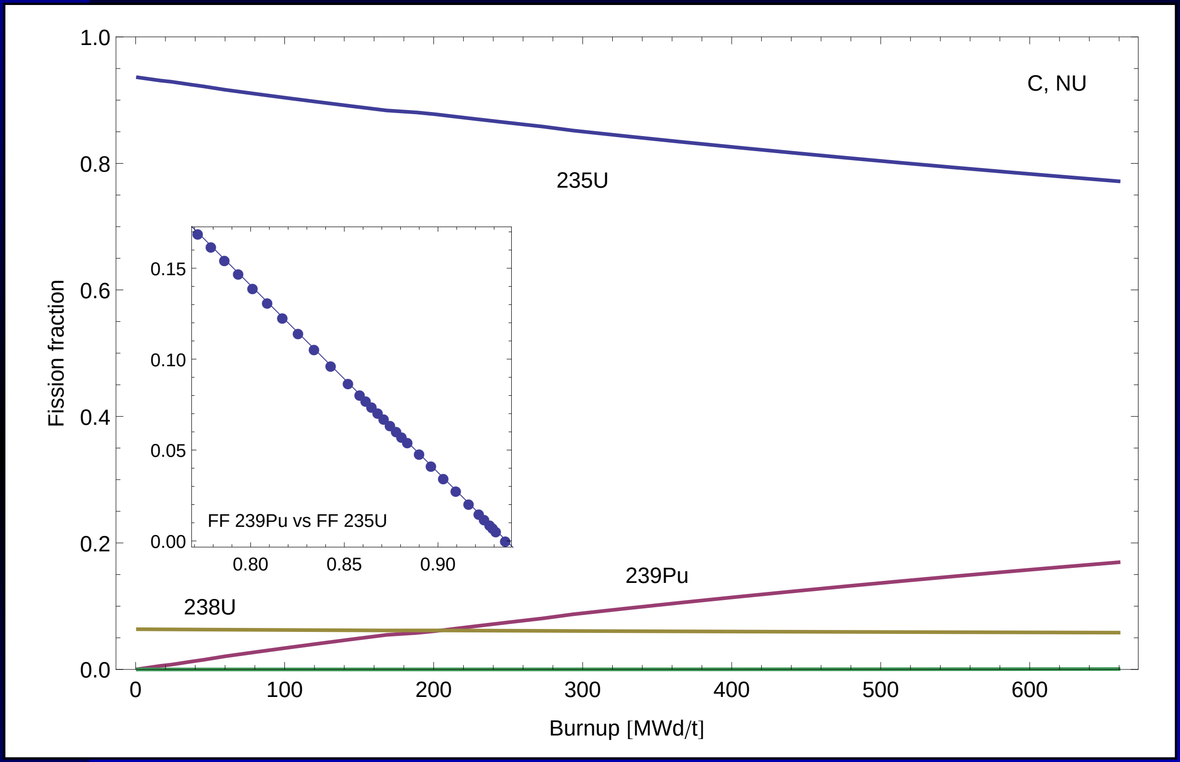
Out of 10 countries:
4 graphite, 3 heavy water, 3 uranium enrichment

Reactor simulation



Full SCALE calculation in 0-d using a detailed power history to predict fission rates. Results of 2-d and 3-d simulations tend to be very similar.

Burn-up



Reactor physics correlates fission fractions (FF)

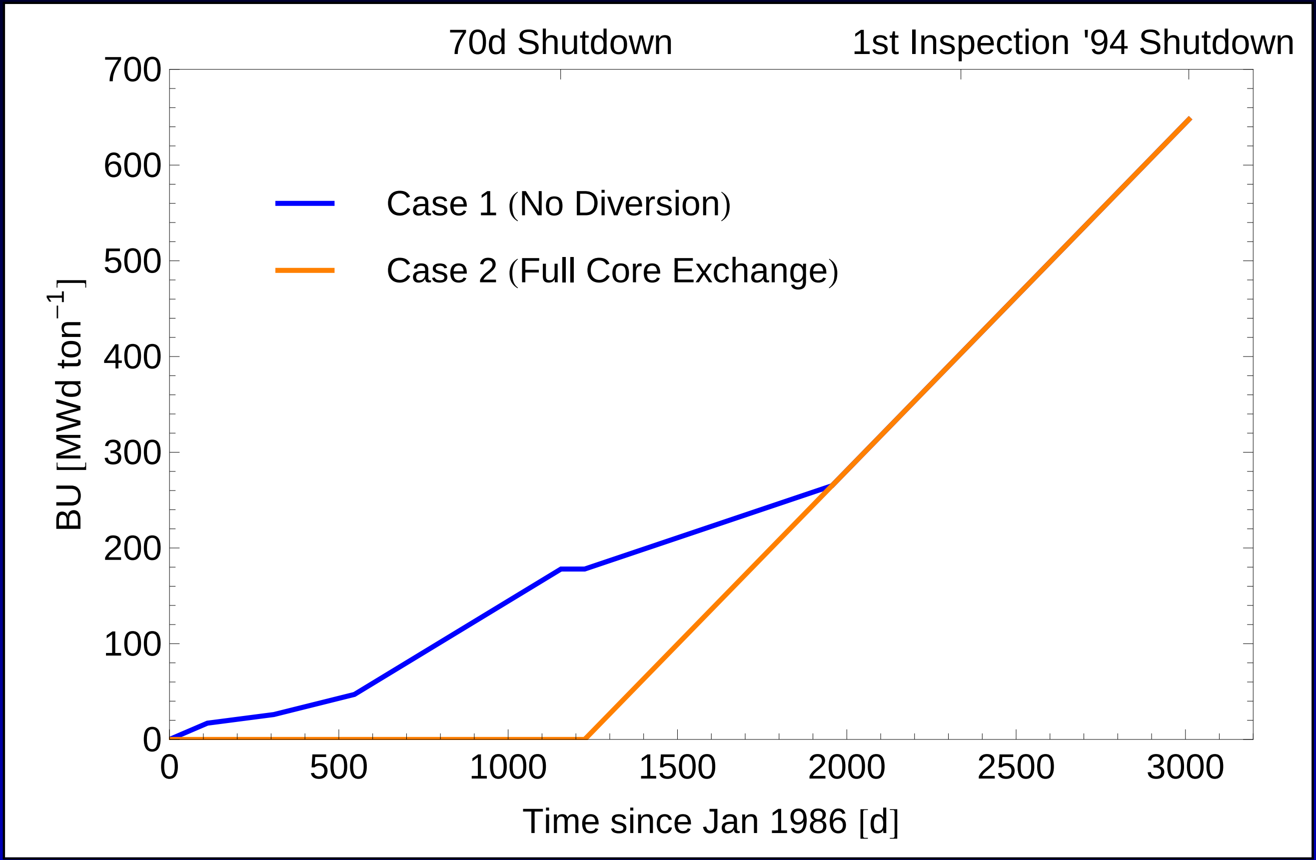
FF function of burn-up only (to very good accuracy)

⇒ use burn-up in the fit

Burn-up can be measured in two ways

Method 1: fit to FF – no prior history necessary
Method 2: antineutrino power measurement – complete history required

DPRK – the fate of the first core

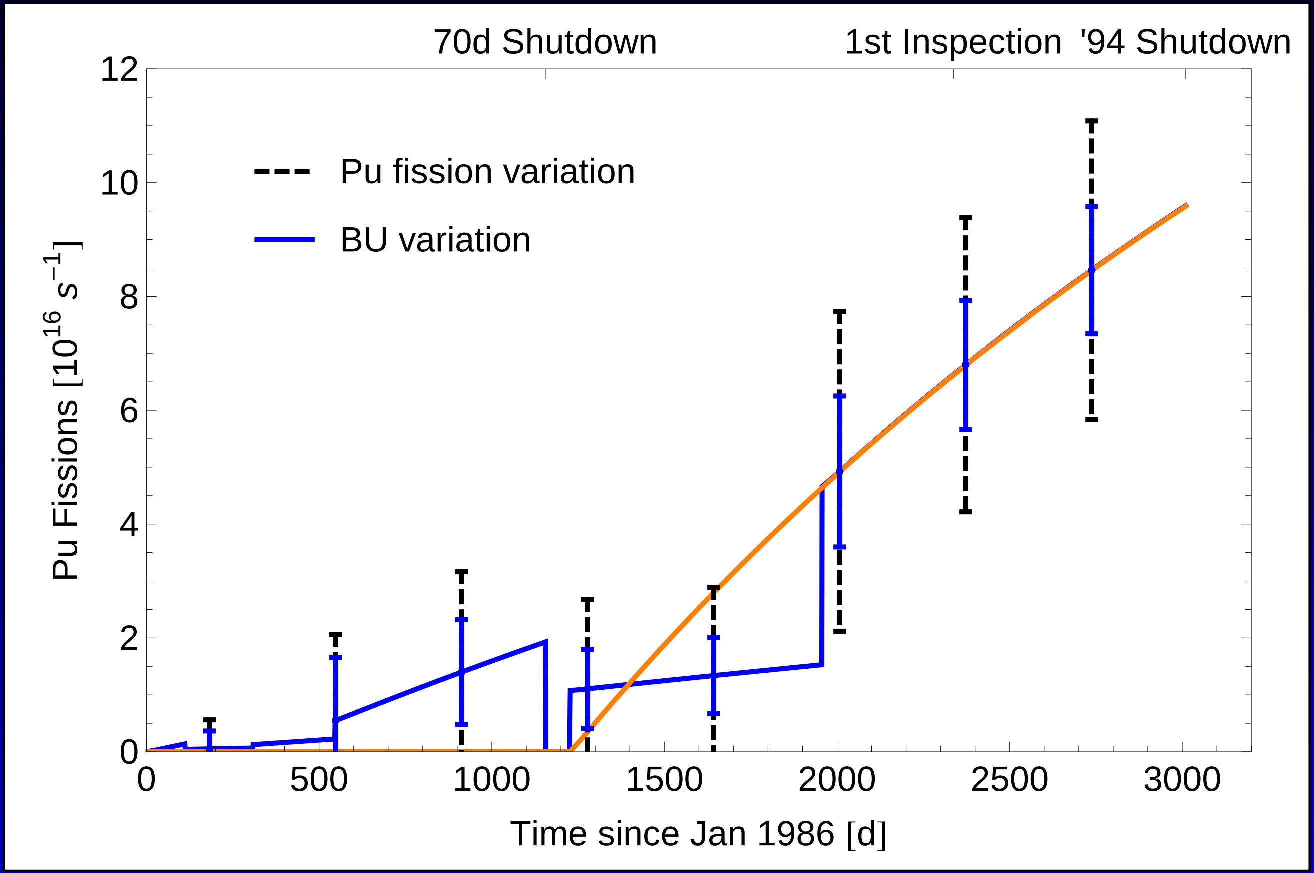


Albright, Solving the North Korean Nuclear Puzzle, 2000

All subsequent IAEA efforts centered around finding out whether the blue or orange curve was true.

In particular, in the diversion case, there has to be reprocessing waste somewhere.

Antineutrino measurement



This demonstrates the gain in accuracy from using reactor physics to constrain the variation of FF.

This observation would constitute a $2\,\sigma$ detection of the diversion of the first core without assuming a full power history (data points are independent)

Conventional methods

Measuring the γ-activity (esp ^{137}Cs) allows to determine the burn-up of a given SNF assembly. Mapping the burn-up distribution in the core by sampling a few hundred assemblies from known, carefully chosen sites in the reactor would have allowed to infer the presence of a second core. This is what IAEA tried to do in June 1994.

Certain trace elements present in the graphite change their isotope ratios due to neutron capture, thus these ratios record to the total local neutron fluence. Destructively sampling the graphite throughout the core allows to make a three dimensional fluence map, which then can be translated into the total produced Pu. Fetter, 1993

Both methods have an accuracy for burn-up around 5%, but can be applied only after the fact.

Iran – 2014

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

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

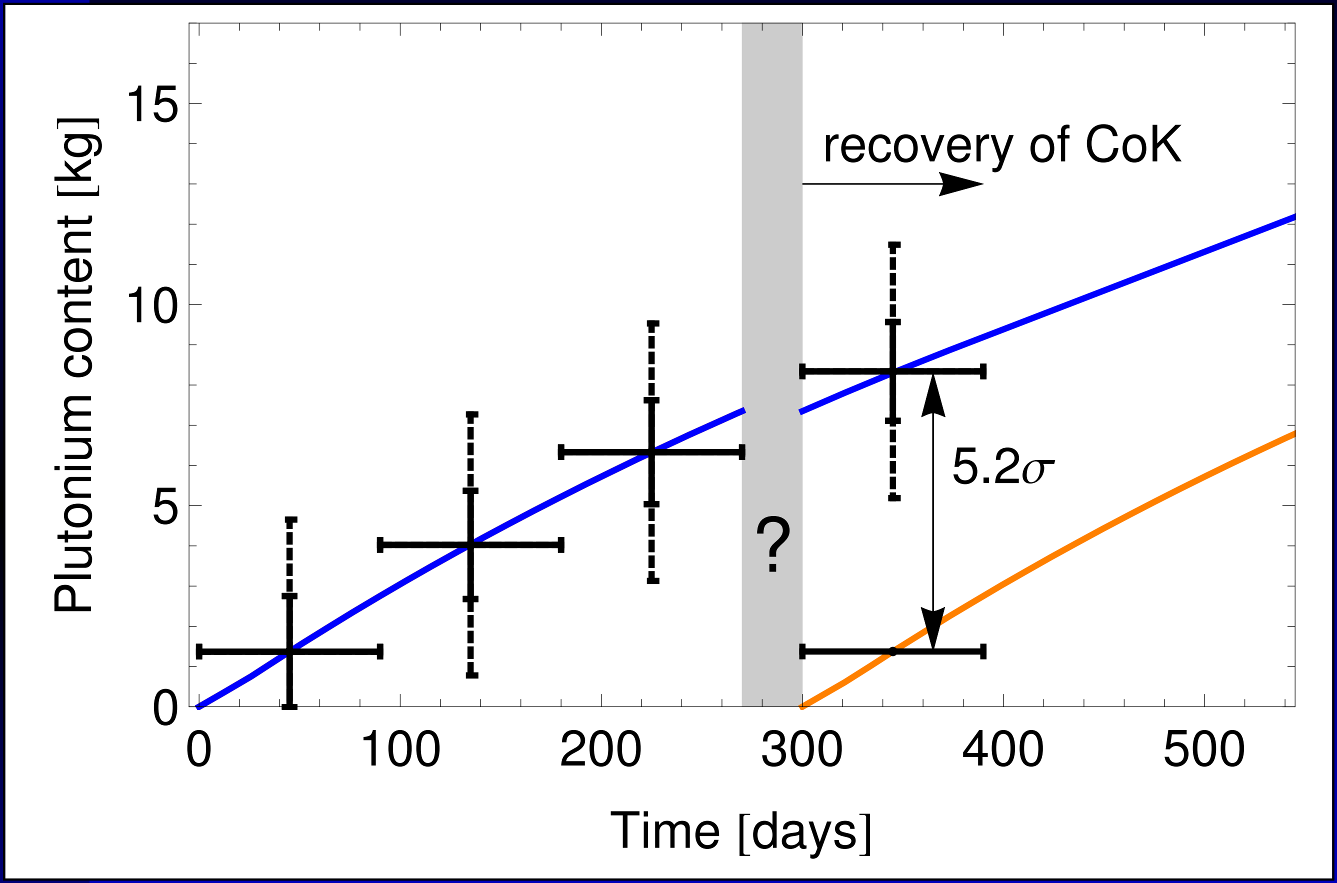
NB: most likely this reactor will be down-rated to $20\mathrm{MW}_{\mathrm{th}}$.

The N^{th} month scenario

- Full inspector access for N-1 month
- Reactor shutdown in the N^{th} month
- Loss of the continuity of knowledge in the N^{th} month

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

Iran – results

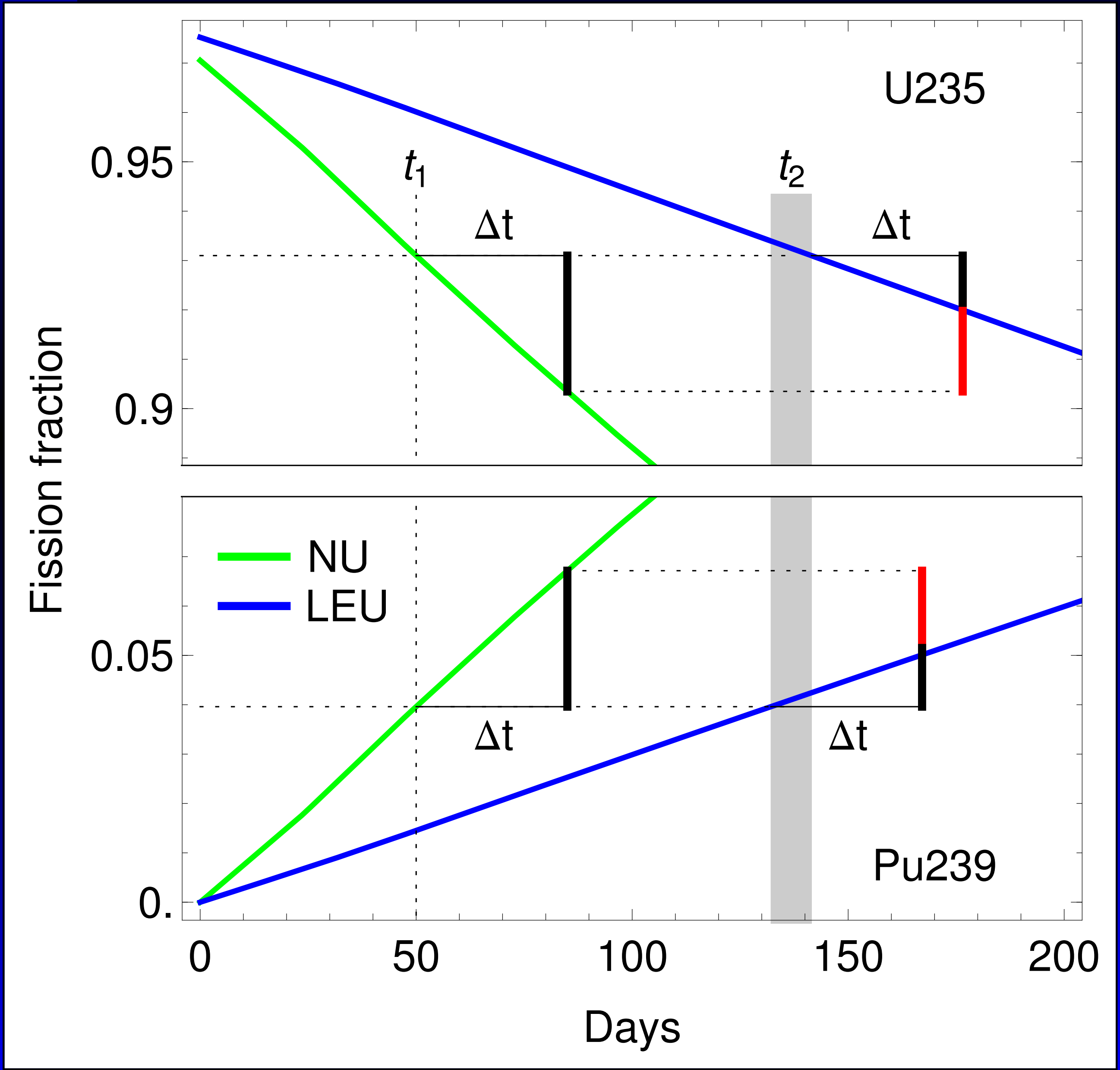


270 days corresponds to 93% plutonium-239

1.2 kg plutonium sensitivity

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

Differential burn-up analysis



- Rate of change in fission rates of U235 and Pu239 depends on enrichment
- Measure differential burn-up
- 90% confidence distinction after about 160 days

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.

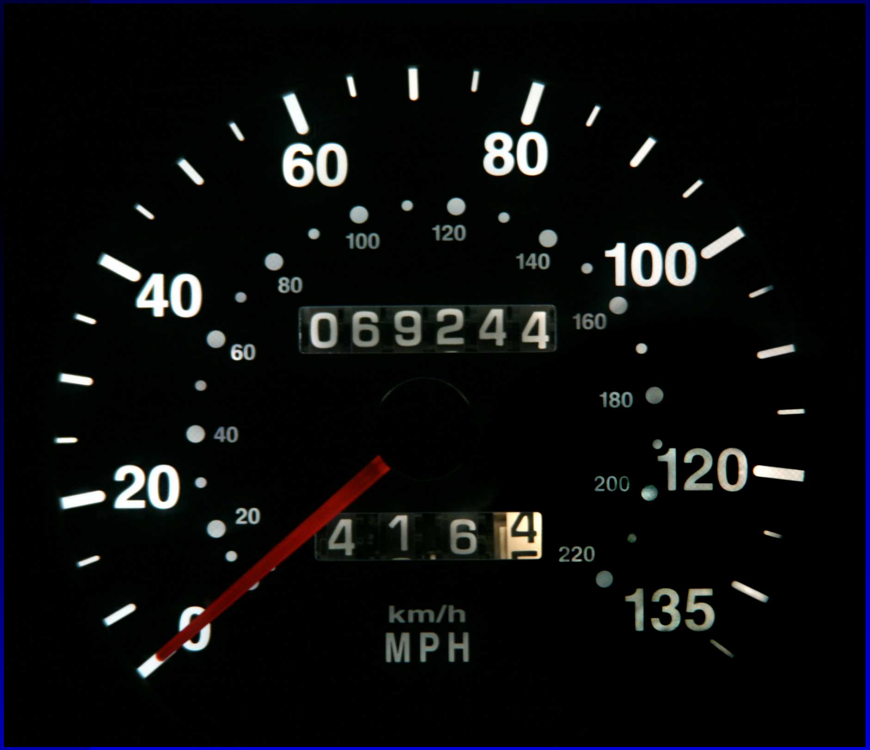
Challenges

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

Technical summary

- We have performed very detailed case studies for the DPRK and Iran
- Antineutrino monitoring provides good sensitivities for diversion for a wide range of small to medium sized reactors
- Detector capability is not yet existing, but significant R&D for short-baseline reactor experiments likely will resolve this on a 12-24 months timescale
- Neutrino sensitivities similar (within a factor two) to alternative, conventional methods
- Calibration of antineutrino yields crucial next step

Safeguards summary

- Antineutrino monitoring can determine the average fuel burn-up in a reactor with good precision within a few weeks of data taking.
- Antineutrino monitoring is non-intrusive and can be performed *in situ* at a running reactor.
- The resulting timeliness of information is a key advantage when dealing with a loss of the continuity of knowledge.

BUT

- None of the unique antineutrino capabilities have currently a corresponding part in safeguards as implemented by IAEA

Next steps, a proposal

with two pillars:

A permanent working group facilitating bi-directional information flow between the neutrino community and the IAEA

Antineutrino reactor monitoring demonstration experiment (ARME) – a full size demonstration of a mobile, surface-operating detector with sufficient efficiency, signal-to-noise and energy resolution deployed at one or more reactors of known core contents, funded by one or several national funding agencies

"I don't say that the neutrino is going to be a practical thing, but it has been a time-honored pattern that science leads, and then technology comes along, and then, put together, these things make an enormous difference in how we live" – Frederick Reines

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References

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