Reactor Neutrinos III: Applications

Patrick Huber

Center for Neutrino Physics – Virginia Tech

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“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

Fuel evolution

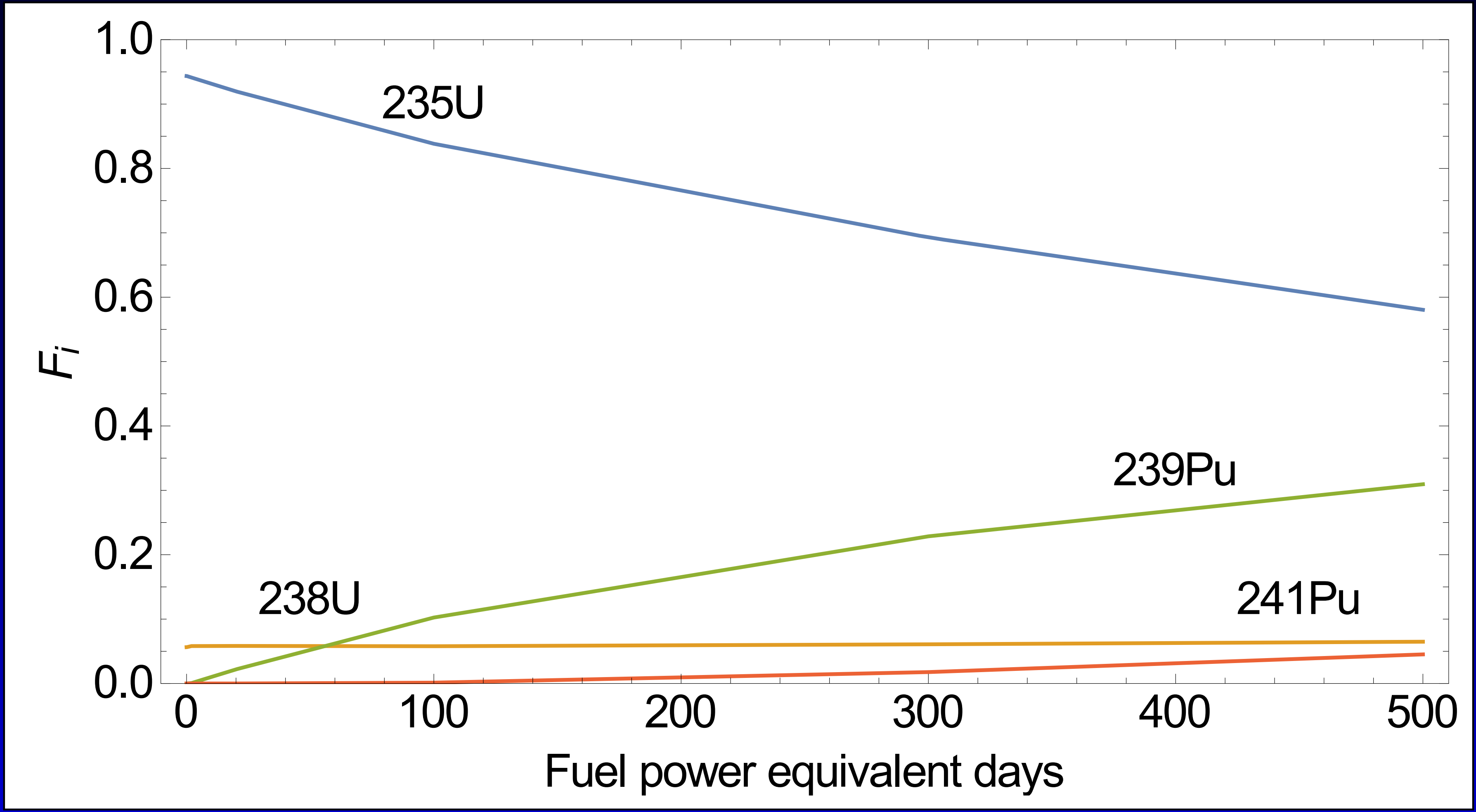
In a reactor the breeding reactions take place:

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

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

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

Burn-up



Typical 3.5GW commercial reactor.

Two kinds of bombs

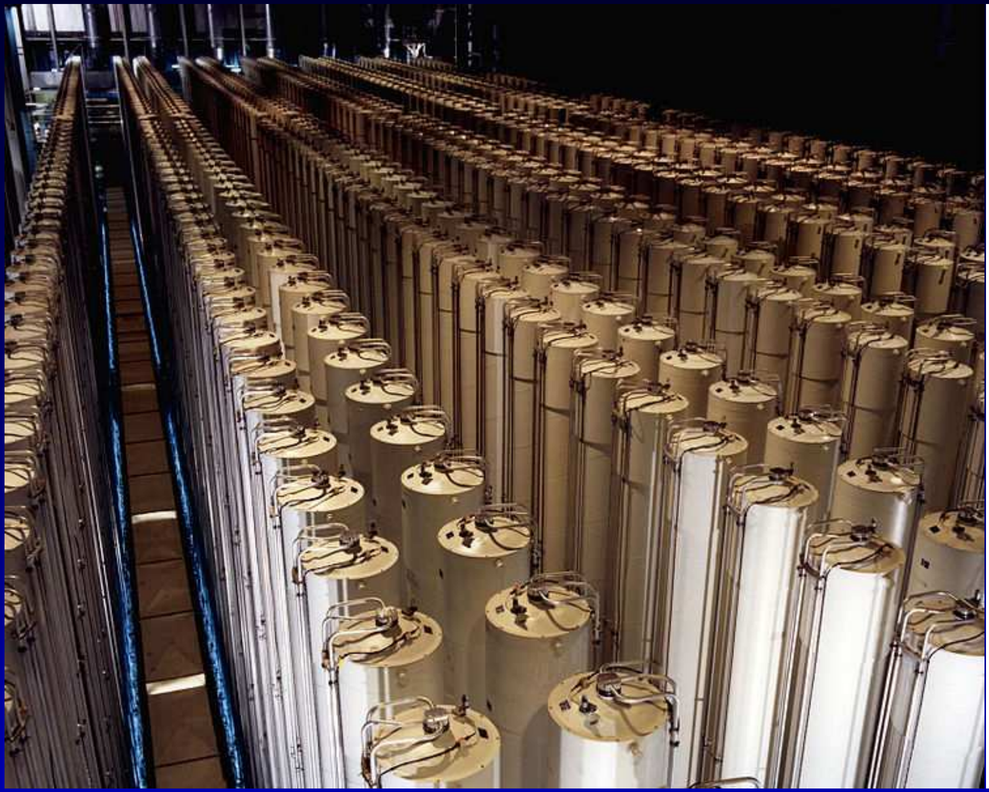
Both ^{239}Pu and ^{235}U have fast neutron fission cross sections of 1-2 barn. And hence both of them are suitable to build a bomb.

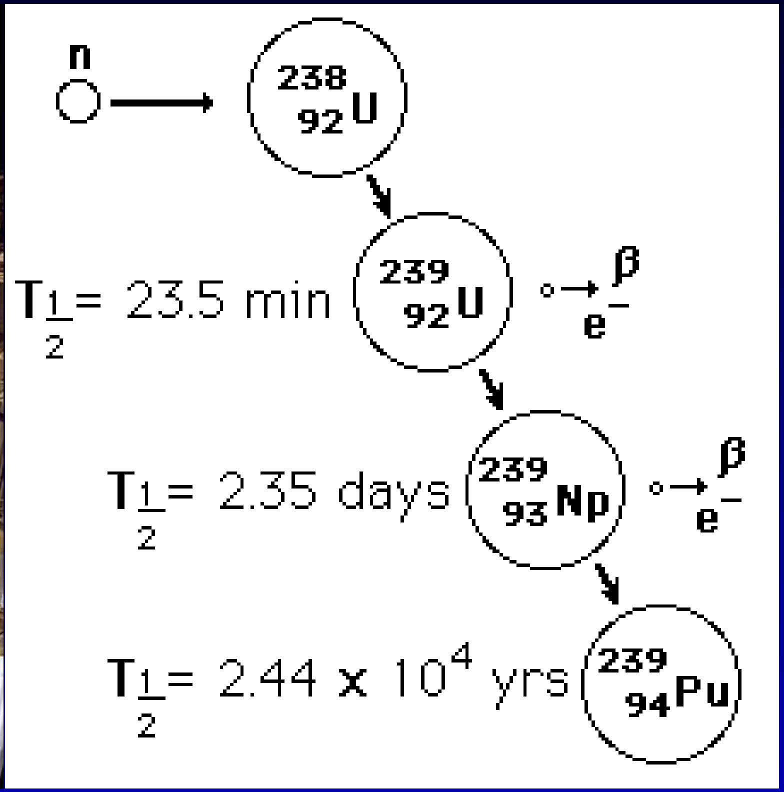
A simple estimate of the critical mass is obtained from

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

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

Enrichment vs Breeding





^{235}U
Gas centrifuges
High Tech
Energy intensive

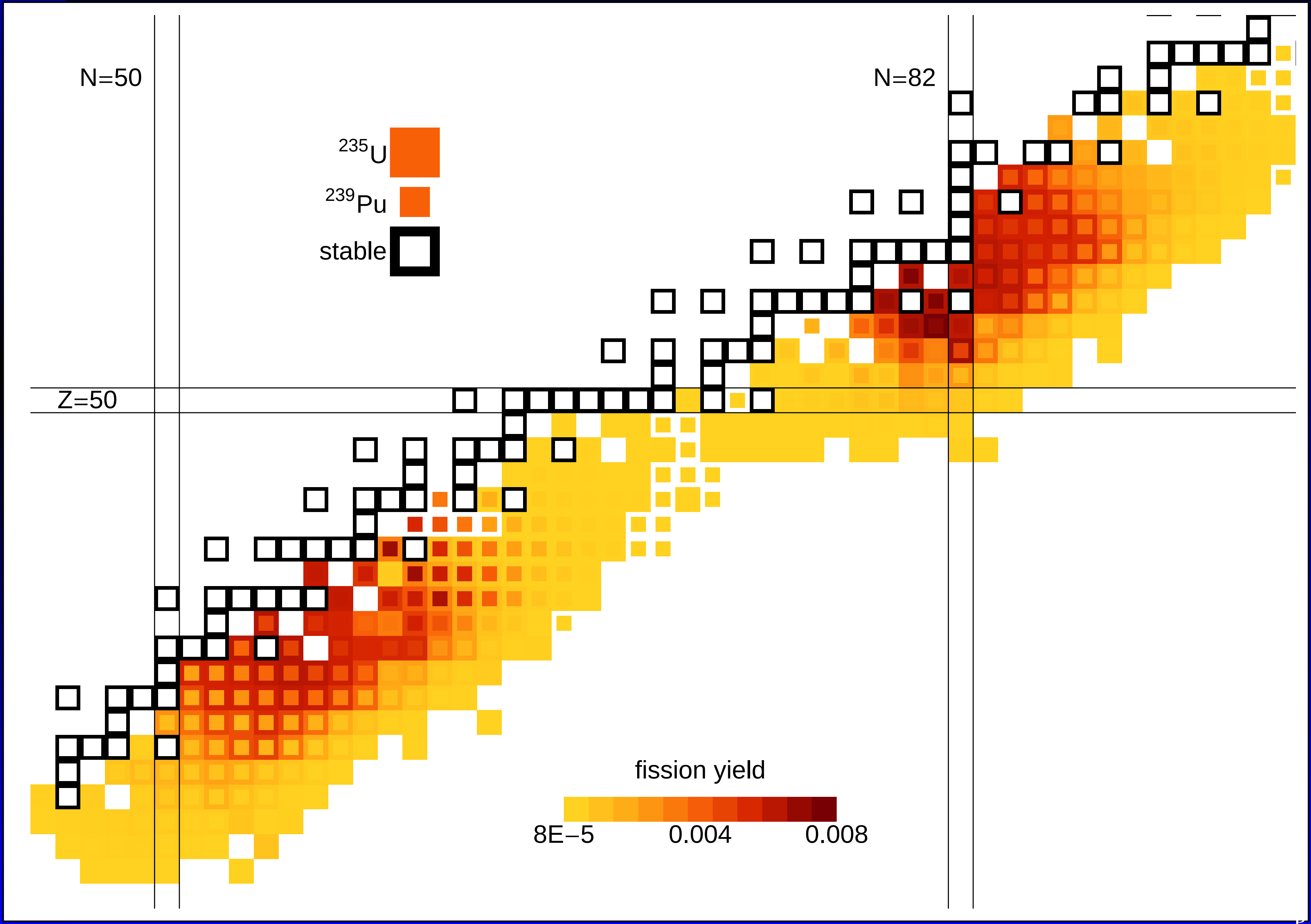
^{239}Pu
Nuclear reactor
Chemical processing
High levels of radioactivity

Application to safeguards

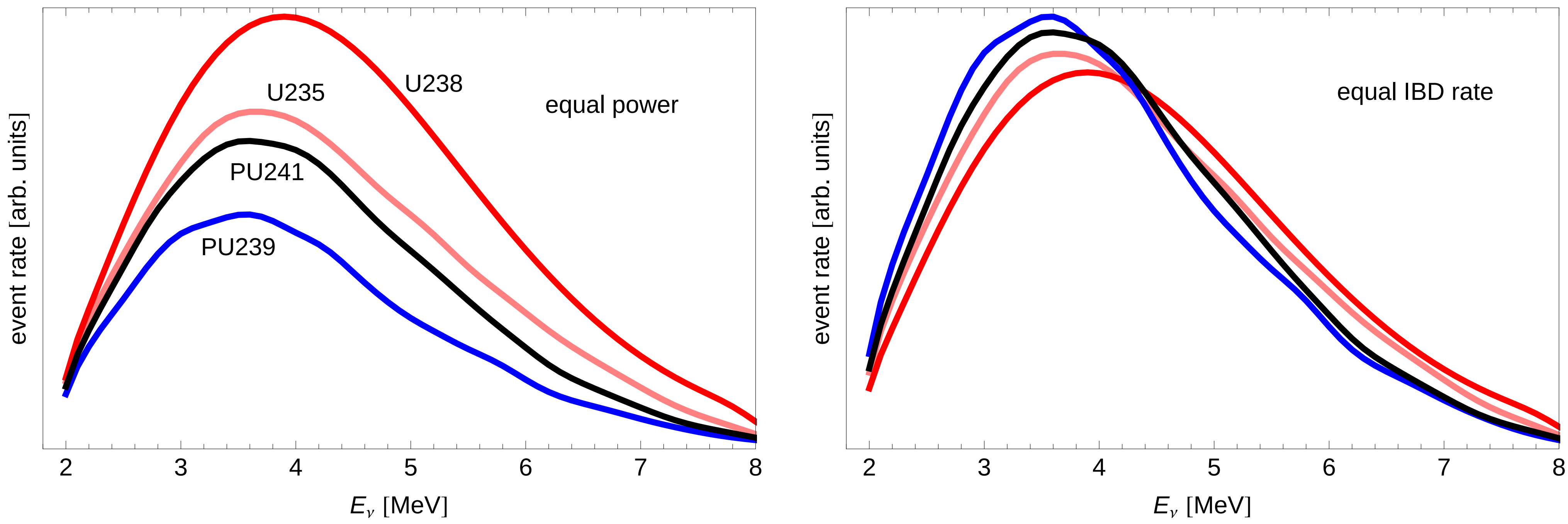
Neutrinos, due to their high penetration capability, offer unique safeguards opportunities. In particular, a measurement of the neutrinos spectrum allows to

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

Fission yields of β emitters



IBD event spectrum

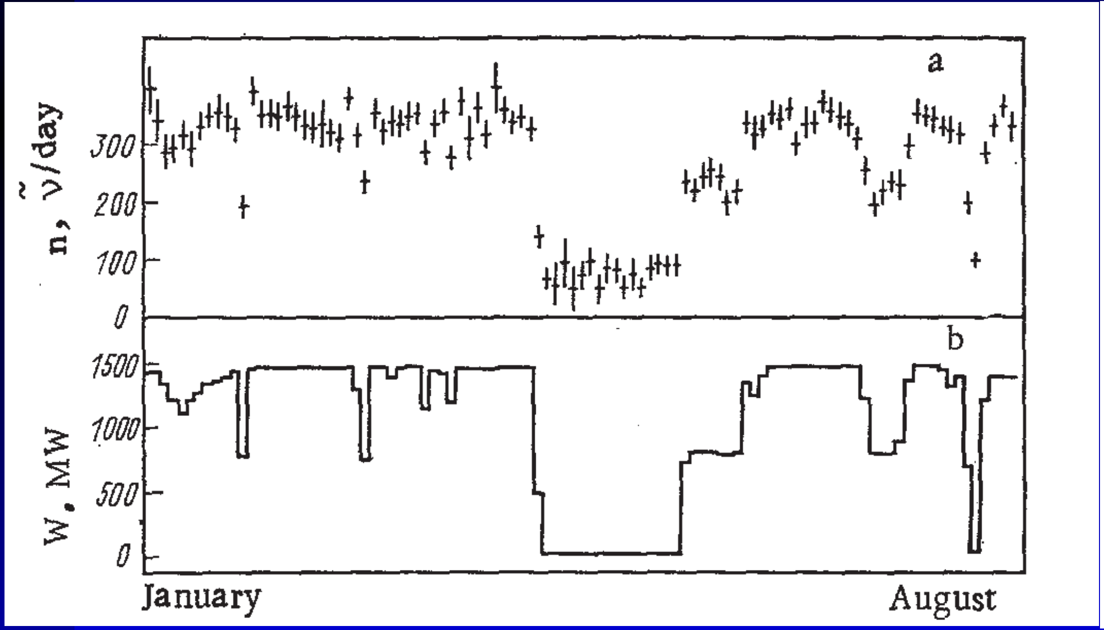


Pu239 has a softer neutrino spectrum than U235 – as a consequence the neutrino spectrum becomes softer for higher burn-up

Reactor monitoring

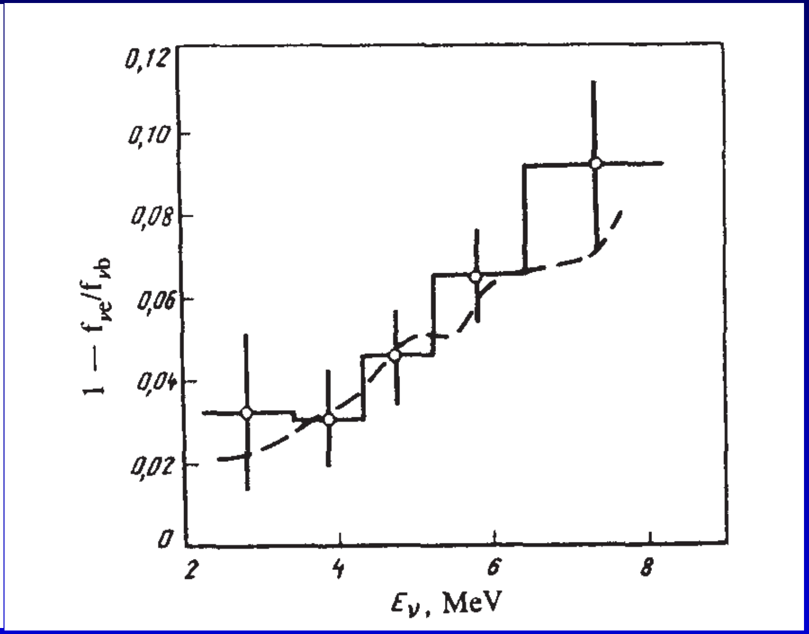
Pioneering work by a group at the Kurchatov institute lead by Lev Mikaelyan

Power monitoring



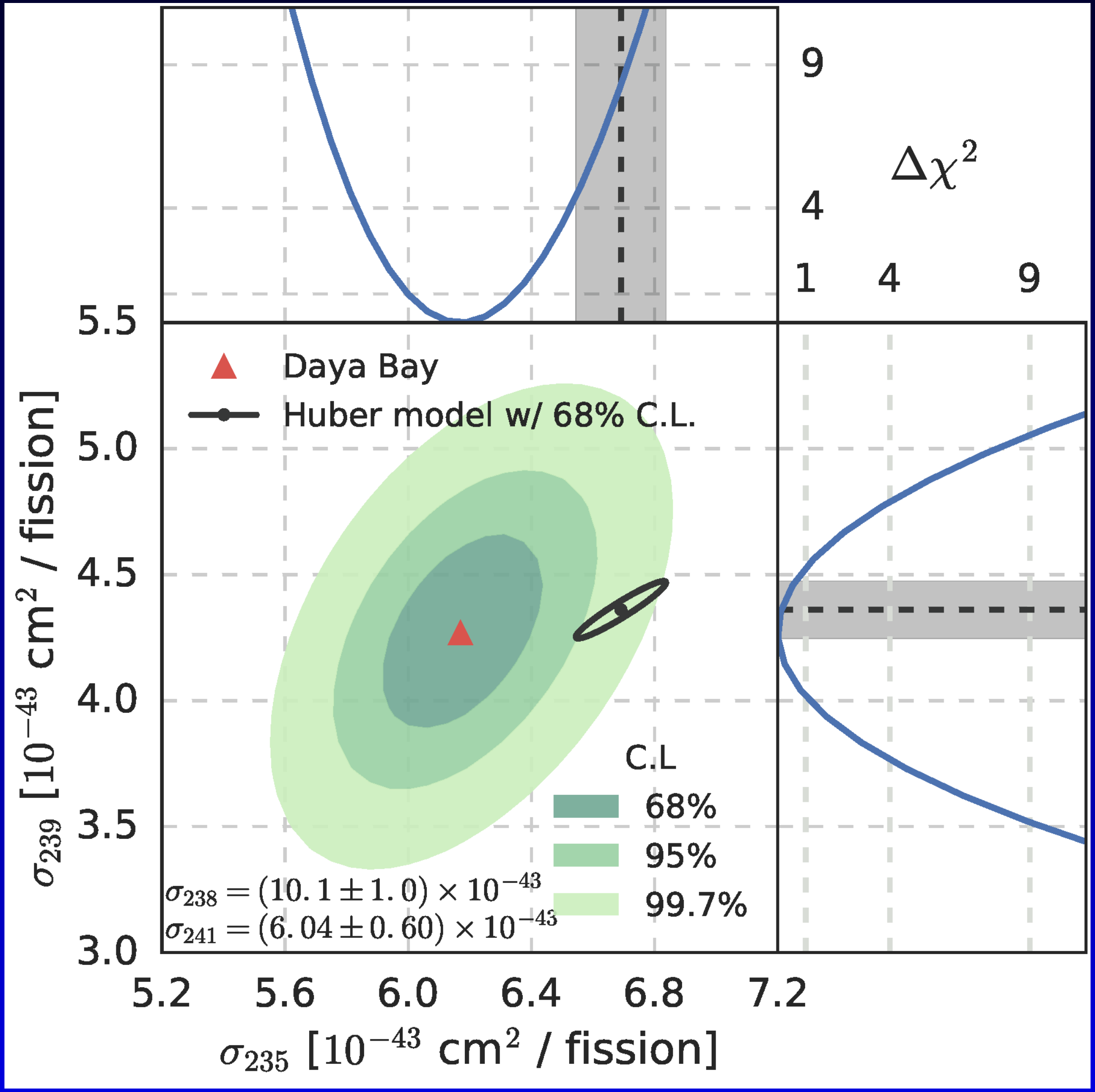
Korovkin *et al.*, 1988

Fuel burn-up



Klimov *et al.*, 1994

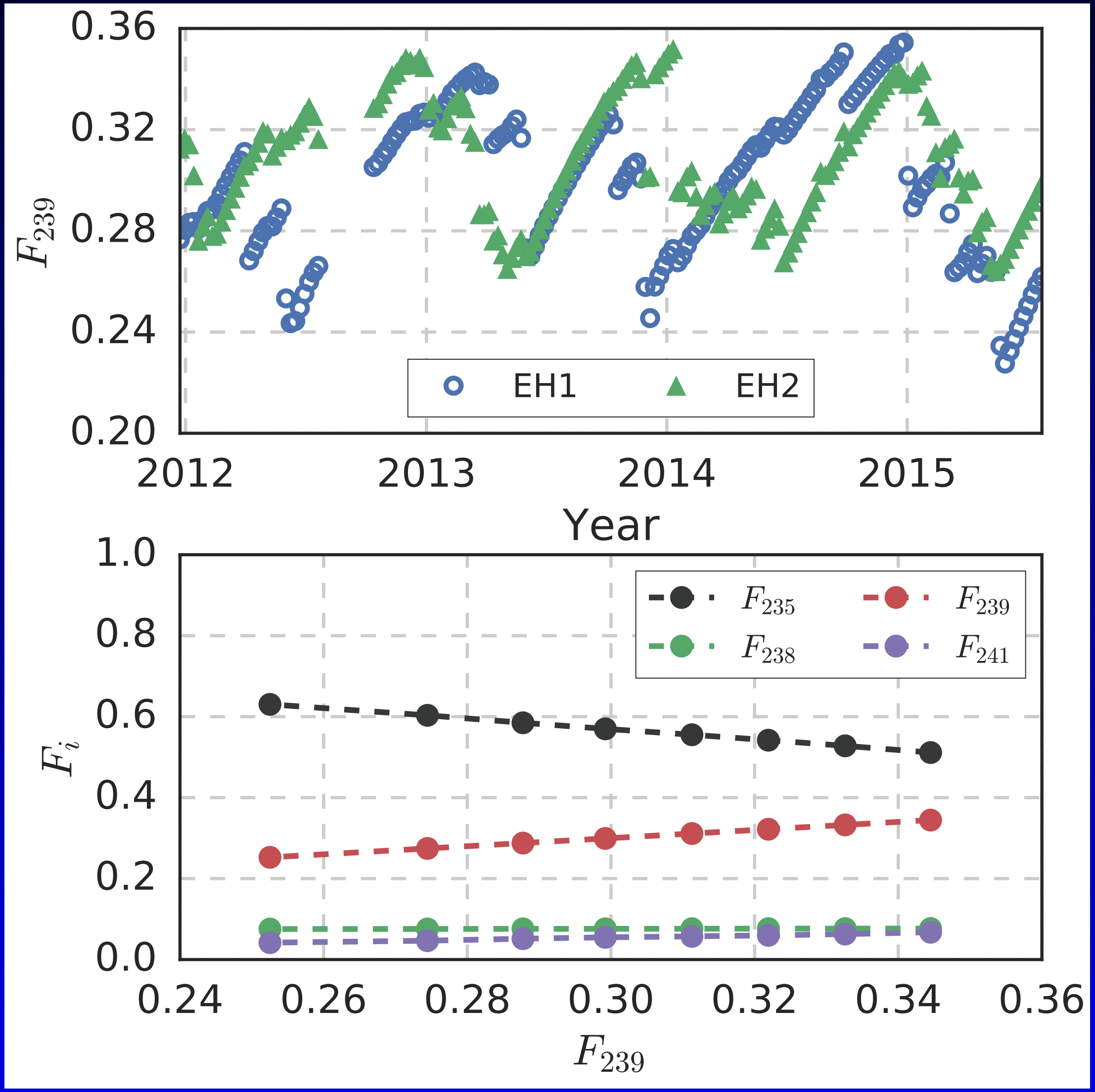
Flux evolution from Daya Bay



Daya Bay, 2017

Only an issue if the prediction of Pu239 in the Huber+Mueller model is correct. Hayes *et al.*, 2017

How does this work?



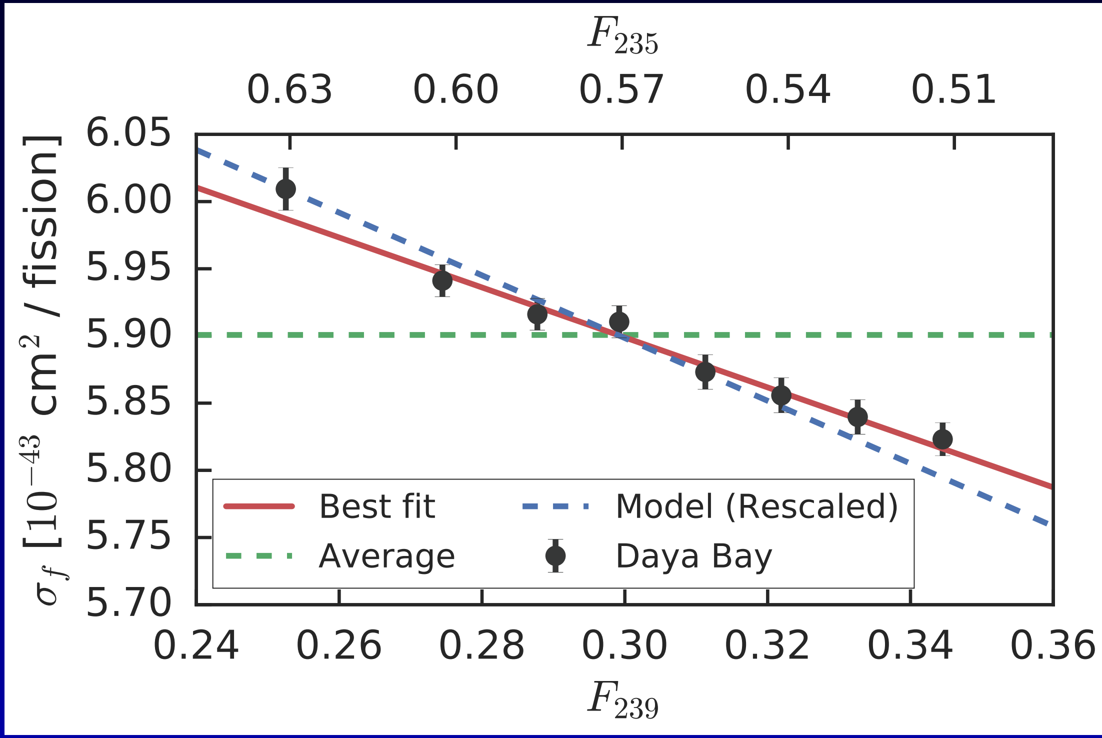
Daya Bay, 2017

Daya Bay has 6 reactor cores, small change in total burn-up

Data binned in burn-up, quantified by $F239$, fraction of fissions in ^{239}Pu.

$F239$ measures time since last refueling.

Daya Bay data



Daya Bay, 2017

Tiny mismatch between prediction and data of about 1%

Corresponds to about 3 σ

This only works if there are no other time or $F239$ dependent flux components at $\sim 0.5\%$ level.

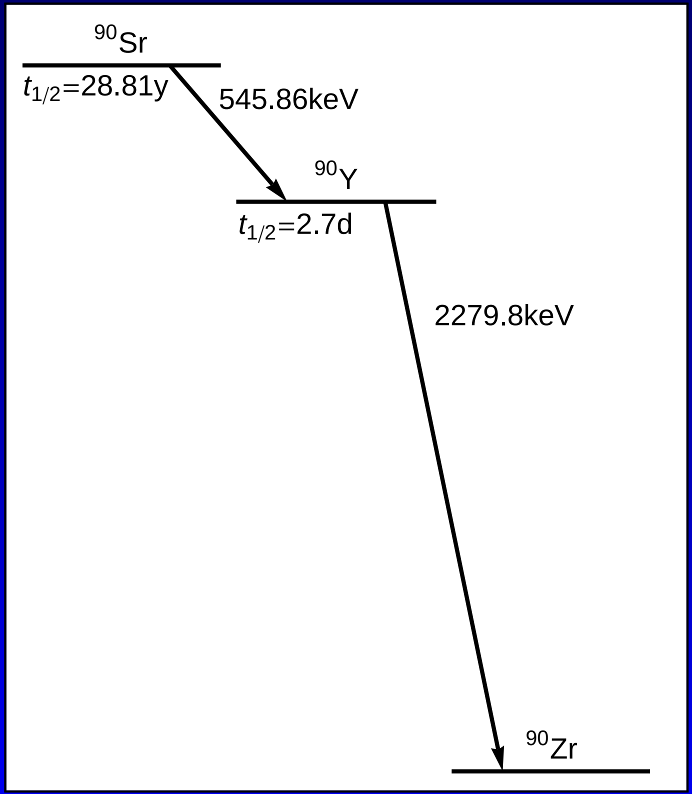
Disclaimer

- The following slides are NOT presented on behalf of the Daya Bay collaboration.
- Entirely based on publicly available data.
- The reactor model employed is of a vanilla pressurized water reactor.
- A detailed calculation based on the actual Daya Bay reactor data will yield a different quantitative result.
- There may be other contributions.

Long-lived decay chains

Some long-lived, $t_{1/2} > 12\,\mathrm{h}$, decay chains among fission fragments produce neutrinos above $1.8\,\mathrm{MeV}$.

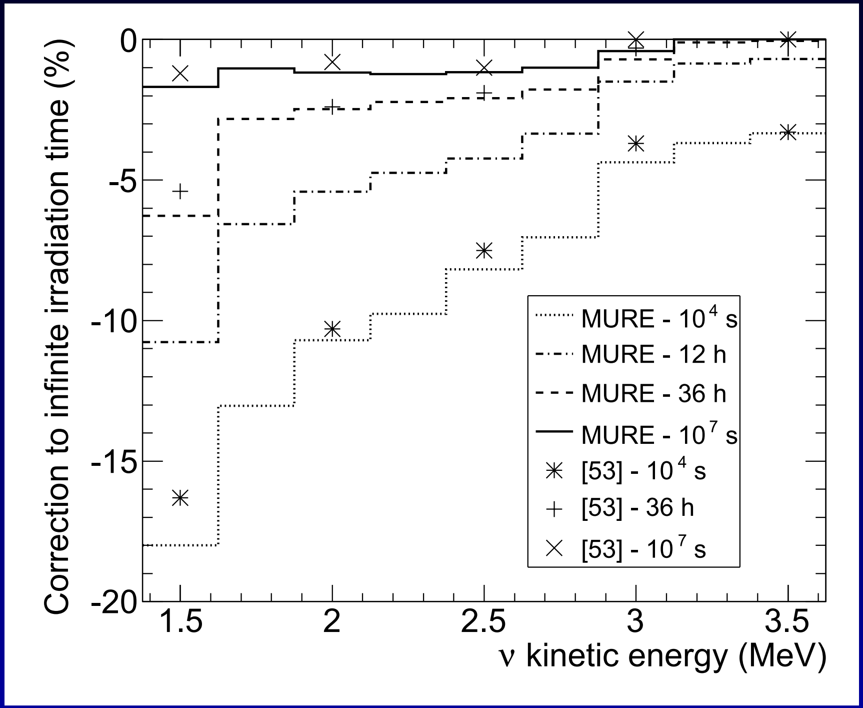
Isotope	^{90}Sr	^{106}Ru	^{144}Ce
Half life	29 y	372 d	285 d



Compute abundance using reactor burn-up codes and the associated nuclear data

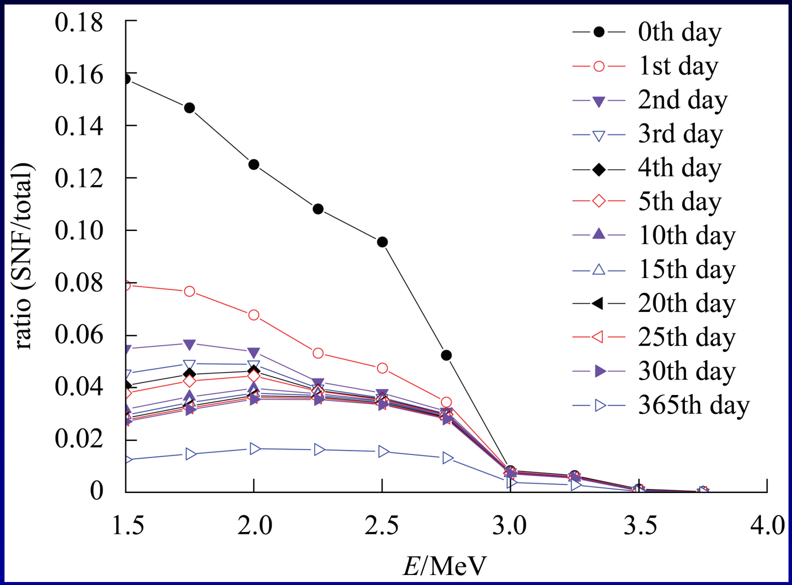
Compute ν-spectra using (well) known β-feeding functions and endpoints

Long-lived decay chains – cont.



Mueller *et al.*, 2011

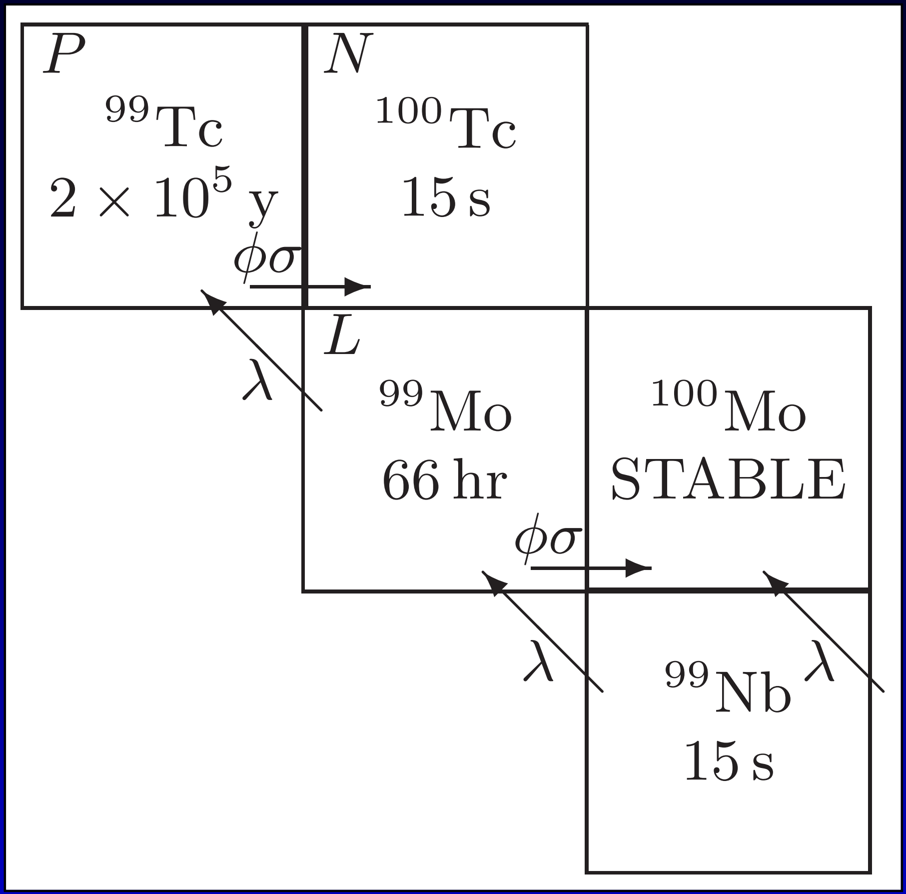
The β-spectra at ILL were taken for irradiation periods of 12-48 h, so long-lived isotopes never reached equilibrium, hence there is a so called "non-equilibrium correction". This is a 0.6 % correction with a 30% uncertainty.



Bin *et al.*, 2012

Spent nuclear fuel (SNF) present on-site in SNF ponds close to the reactor cores produces additional low energy neutrinos, overall a 0.3% rate effect with a 100% uncertainty.

Non-linear isotopes

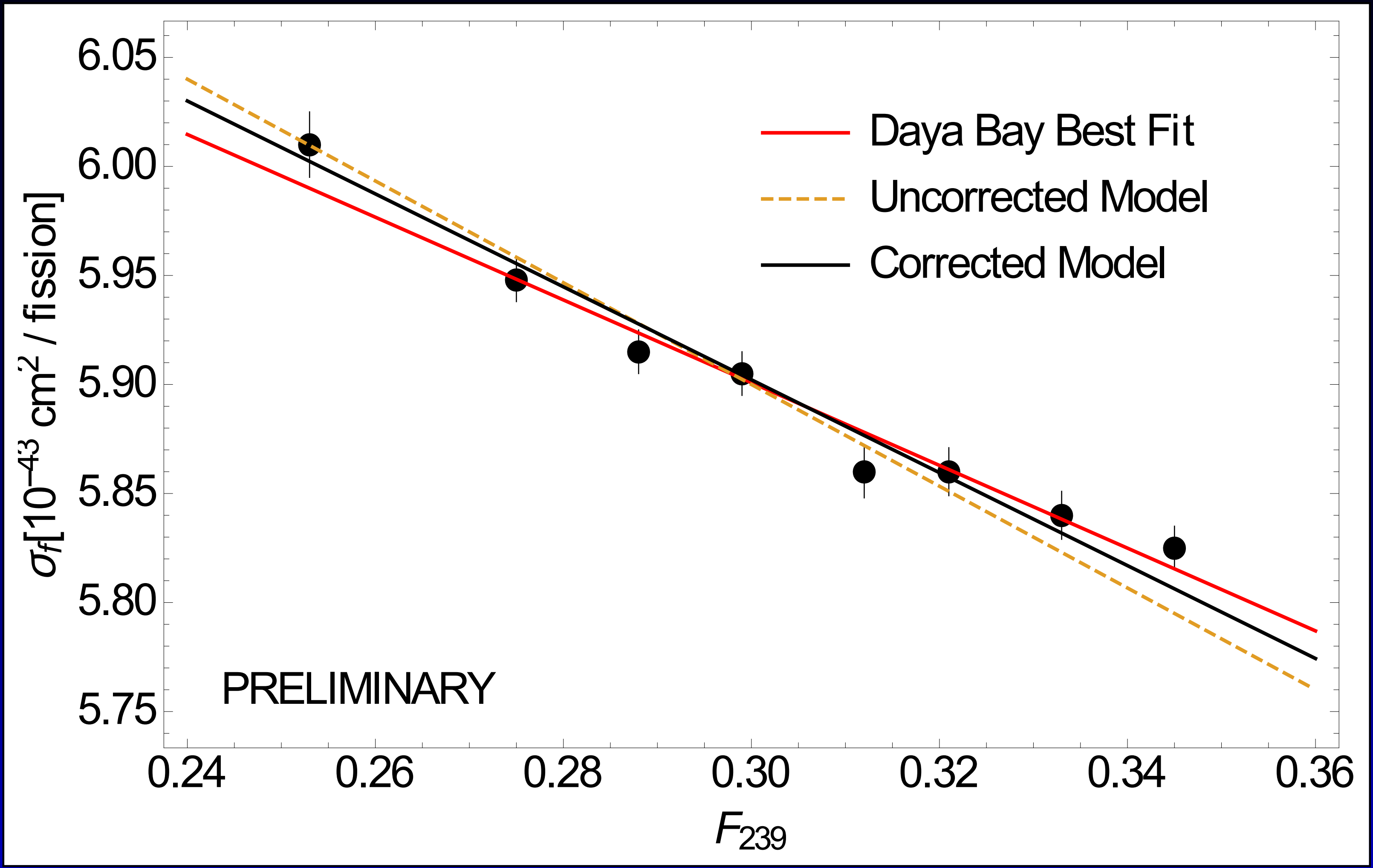


Jaffke, Huber, 2015

Out of 20 $\beta\beta$-isotopes made in fission, only 4 contribute to IBD rates in reactors:

^{100}Tc, ^{104}Rh, ^{110}Ag, ^{142}Pr

$$\Gamma_{nonlinear} \propto \underbrace{\Sigma_{\text{fiss}} \phi Z_P T_{\text{irr}}}_{\text{atoms of P}} \sigma^c_P \phi \propto T_{\text{irr}} \phi^2 \propto T_{\text{irr}}$$



Huber, in progress

	χ^2	$\sqrt{\Delta\chi^2}$
best fit	5.8	
uncorrected model	15.0	3σ
corrected model	8.5	1.6σ

The standard detector anno 2011

4.3E29 target protons

10-20 metric tonne actual detector weight

No overburden

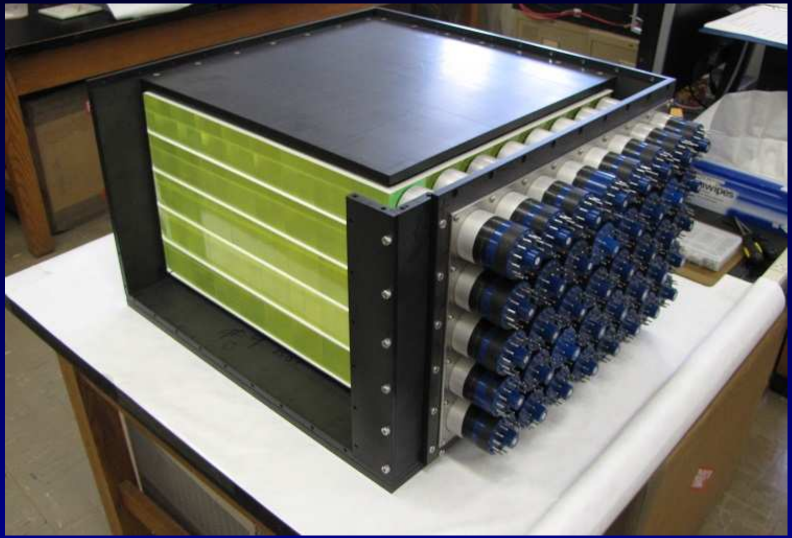
Irreducible cosmogenic background

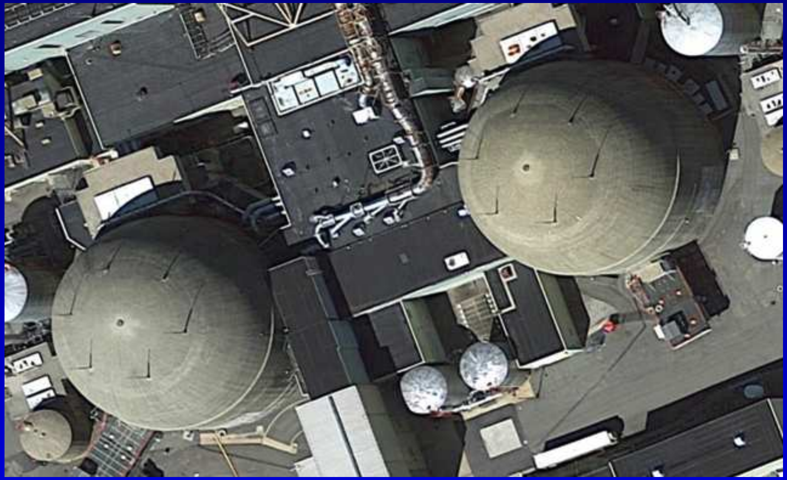
Detector mass depends on material and efficiency

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

CHANDLER anno 2017

Bug your experimental colleagues long enough...

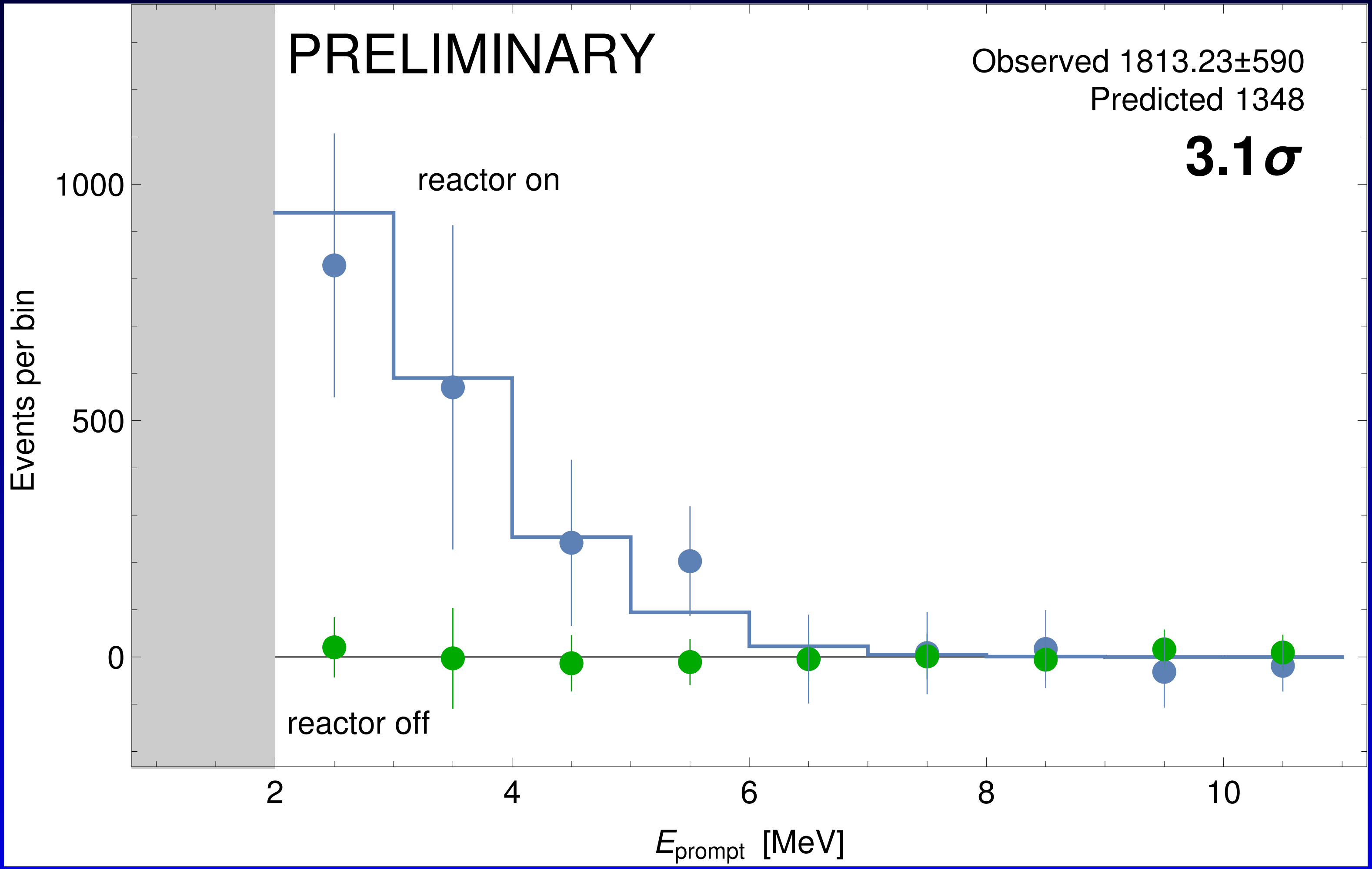




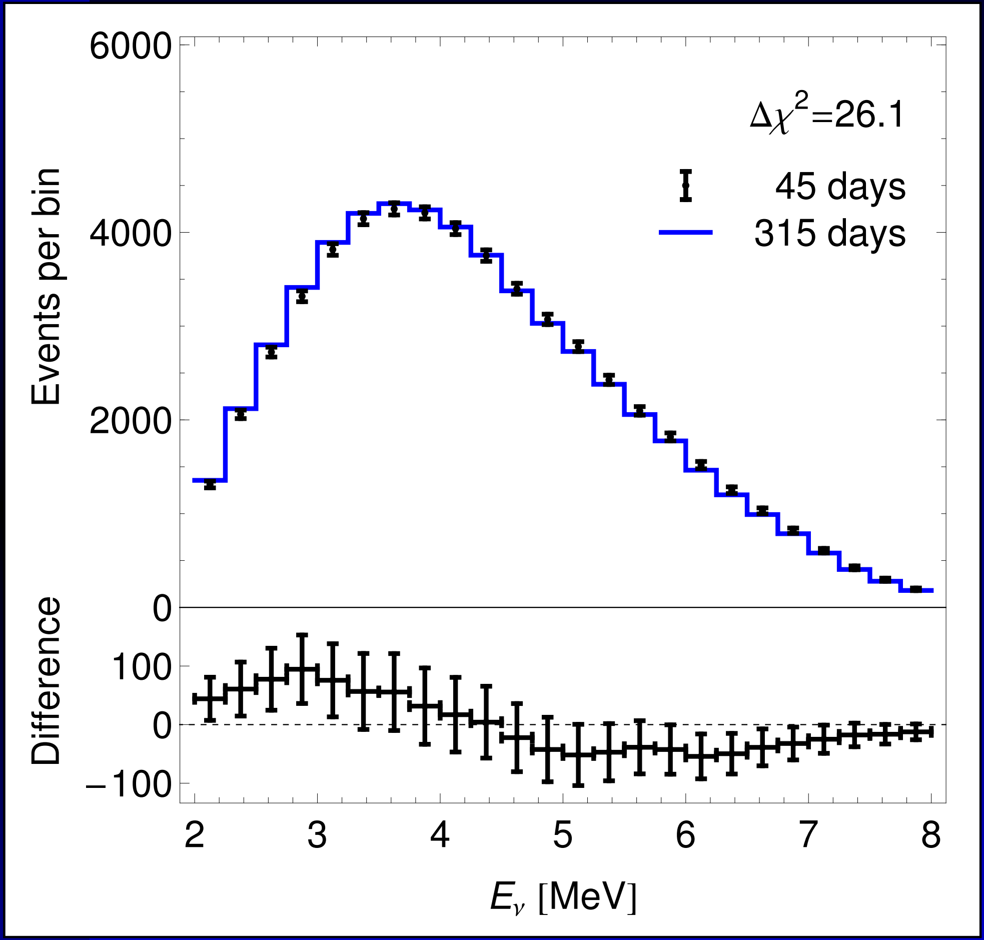
Developed by PH, C. Mariani, J. Link – pat. pend.

CHANDLER result

0.1 m water equivalent overburden.



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 σ

Corresponding to a difference in plutonium content of about 7 kg

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.

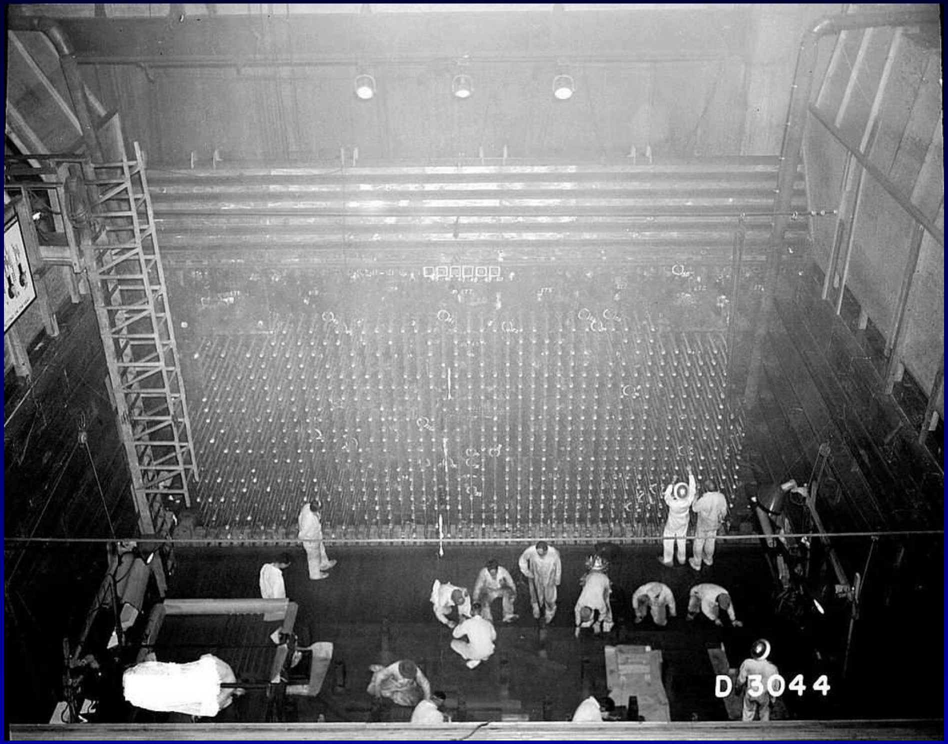
The produced plutonium in all practical applications will have a much smaller associated uncertainty, so it is the error on the in-core plutonium which drive the ability to detect a diversion.

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

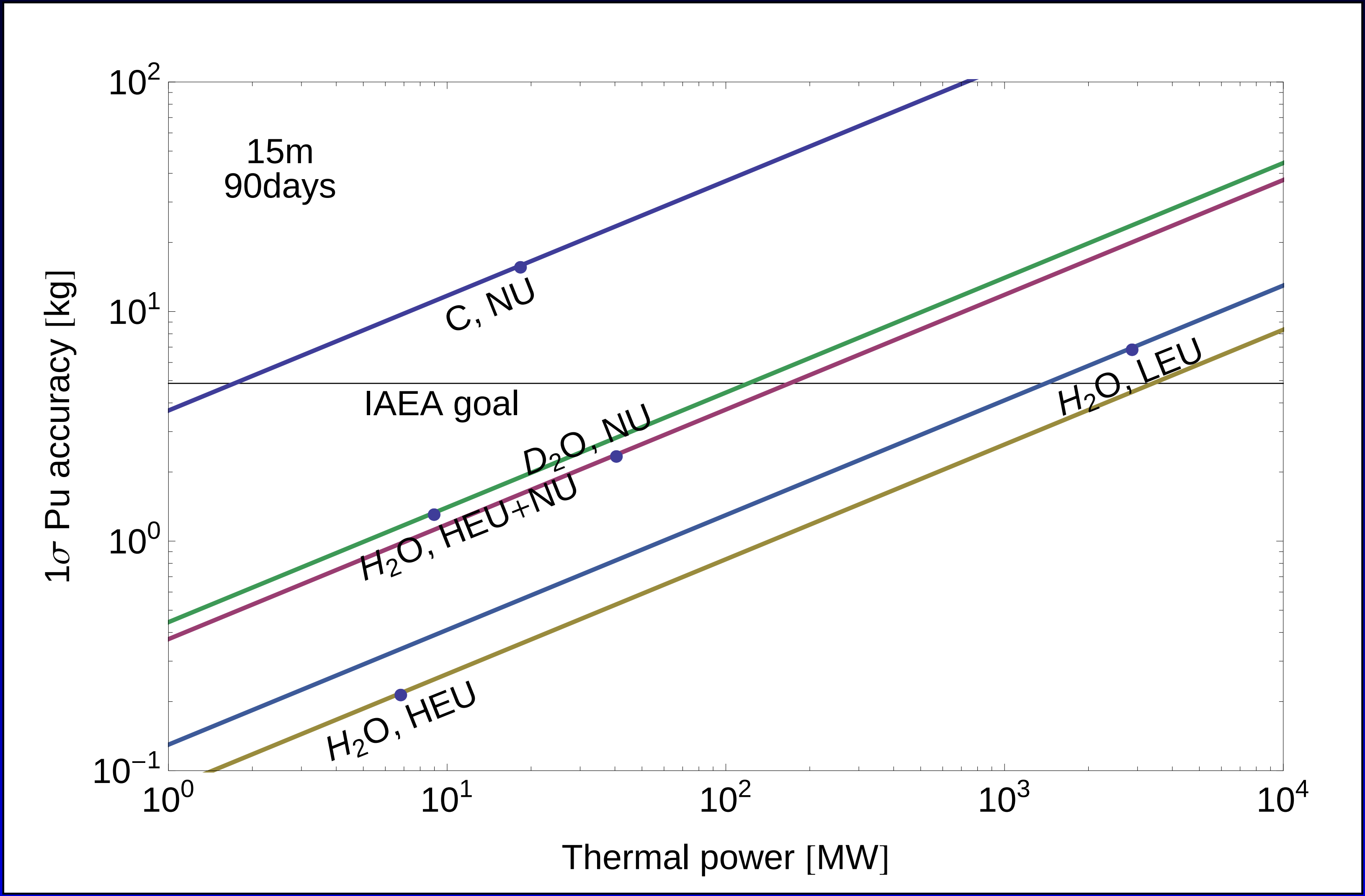
U.S. – Hanford, graphite
Russia – Mayak, graphite
U.K. – Windscale, graphite
France – Marcoule, heavy water
China – uranium enrichment
Israel – Dimona, heavy water
South Africa – uranium enrichment
India – CIRUS, heavy water
Pakistan – uranium enrichment
DPRK – Yongbyon, graphite



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

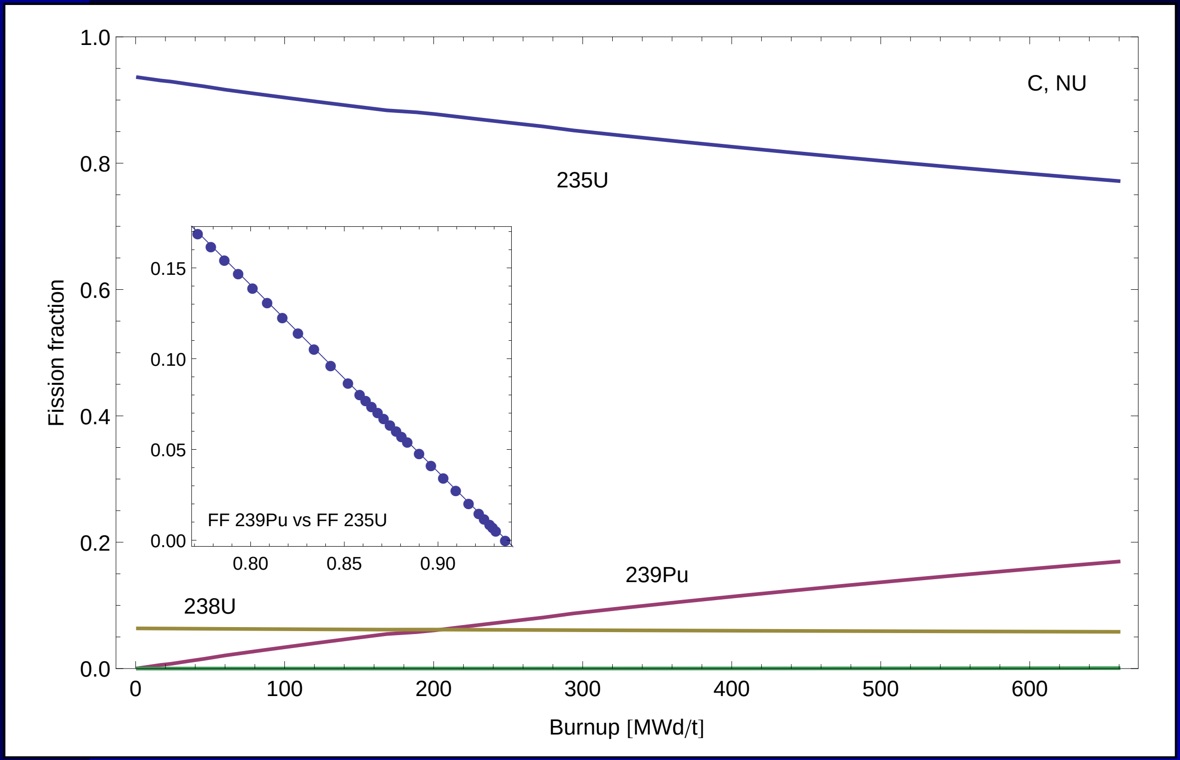
Out of 10 countries:
4 graphite, 3 heavy water, 3 uranium enrichment

Different reactor types



Standard detector – based on detailed SCALE calculations.

Burn-up



Reactor physics correlates fission fractions (FF)

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

$\Rightarrow$ use burn-up in the fit

Burn-up can be measured in two ways

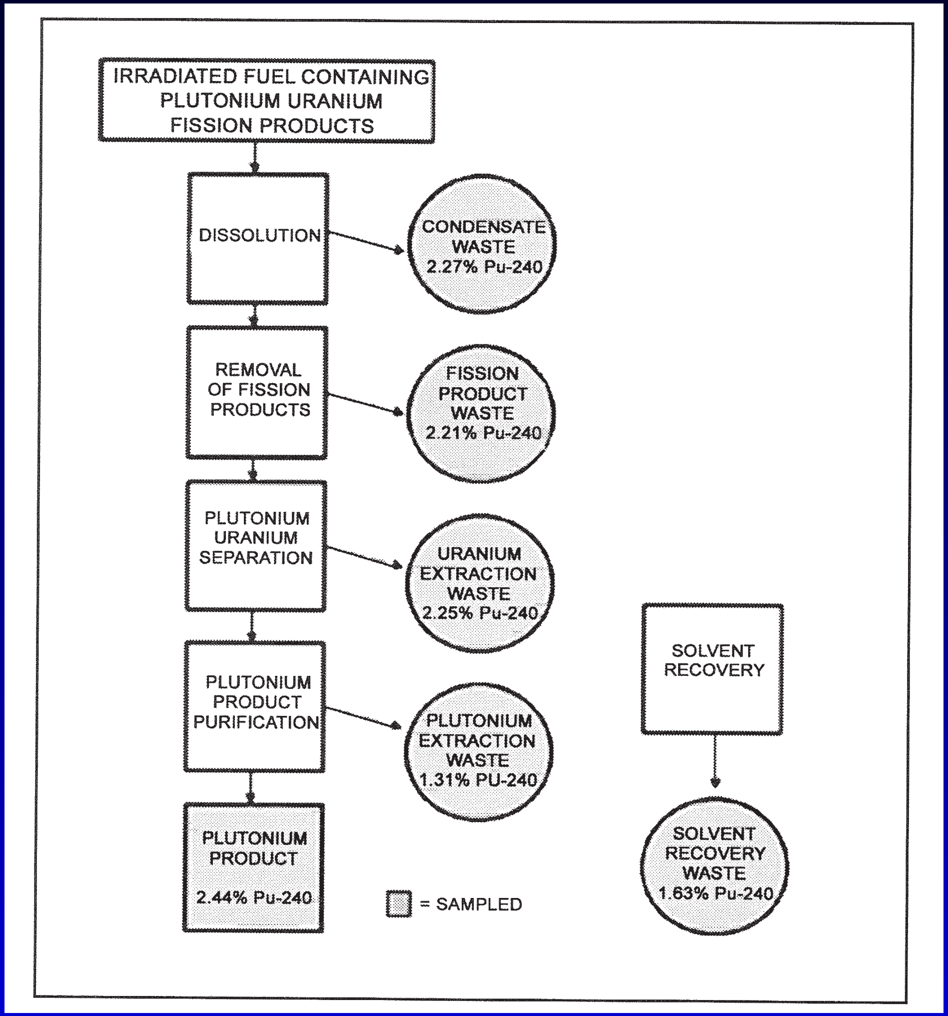
Method 1: fit to FF – no prior history necessary
Method 2: neutrino power measurement – complete history required

DPRK – The 1994 crisis

In its initial declaration to IAEA in May 1992, the DPRK stated:

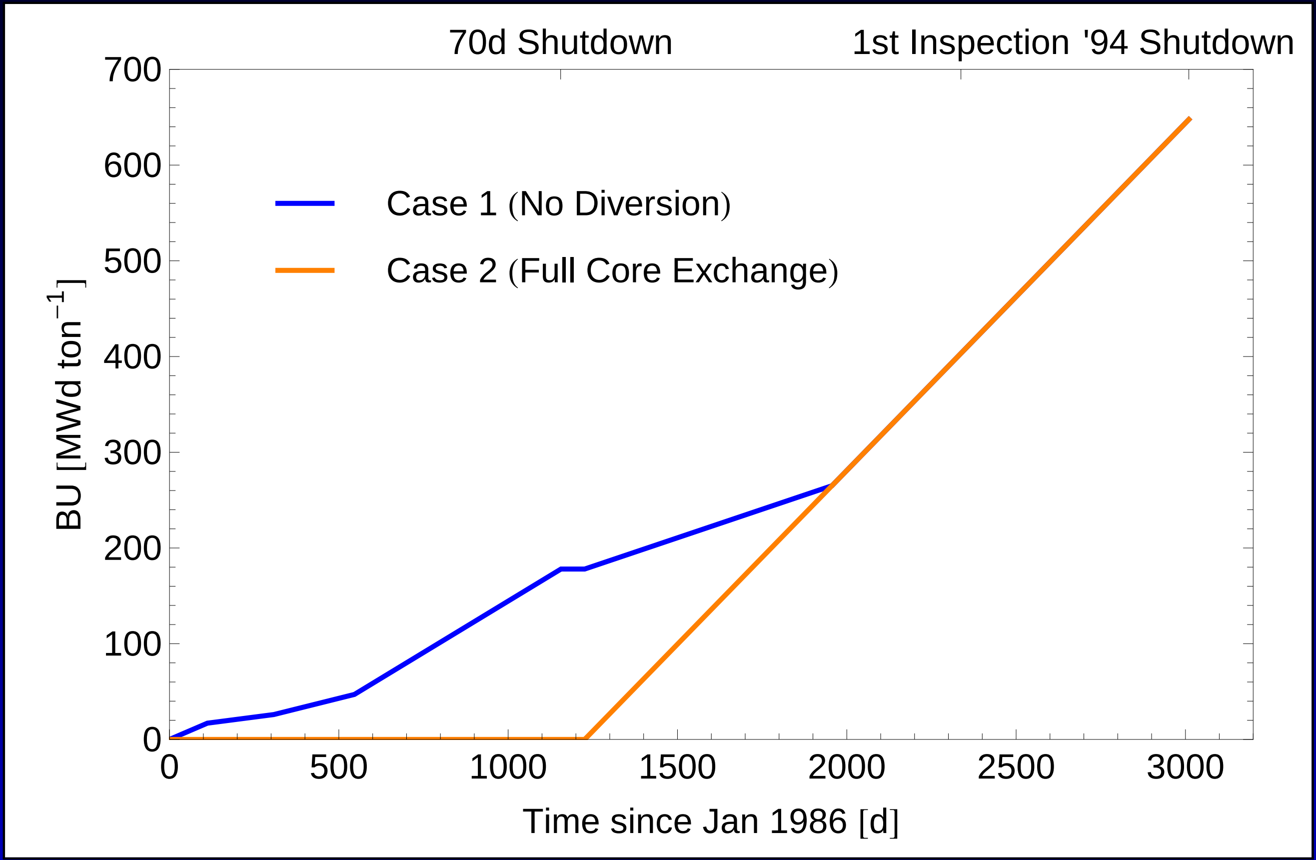
In 1989 during the shutdown of their 5MWe reactor a few hundred (out of 8 000 total) fuel elements were discharged

A part of the discharged fuel was reprocessed in a hot test of their reprocessing facility resulting in about 60 g of separated Pu.



Albright, Solving the North Korean Nuclear Puzzle, 2000

The fate of the first core

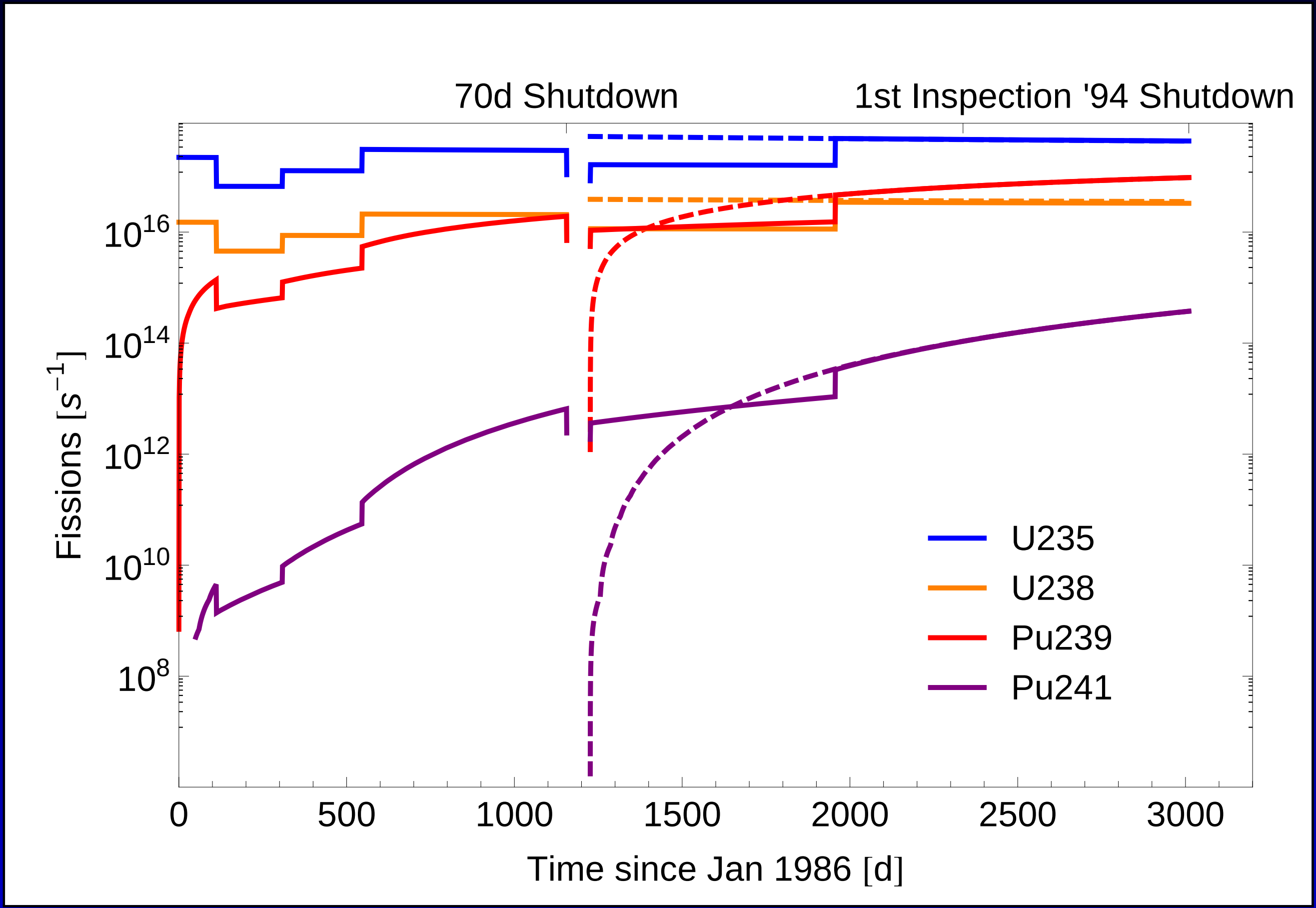


Albright, Solving the North Korean Nuclear Puzzle, 2000

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

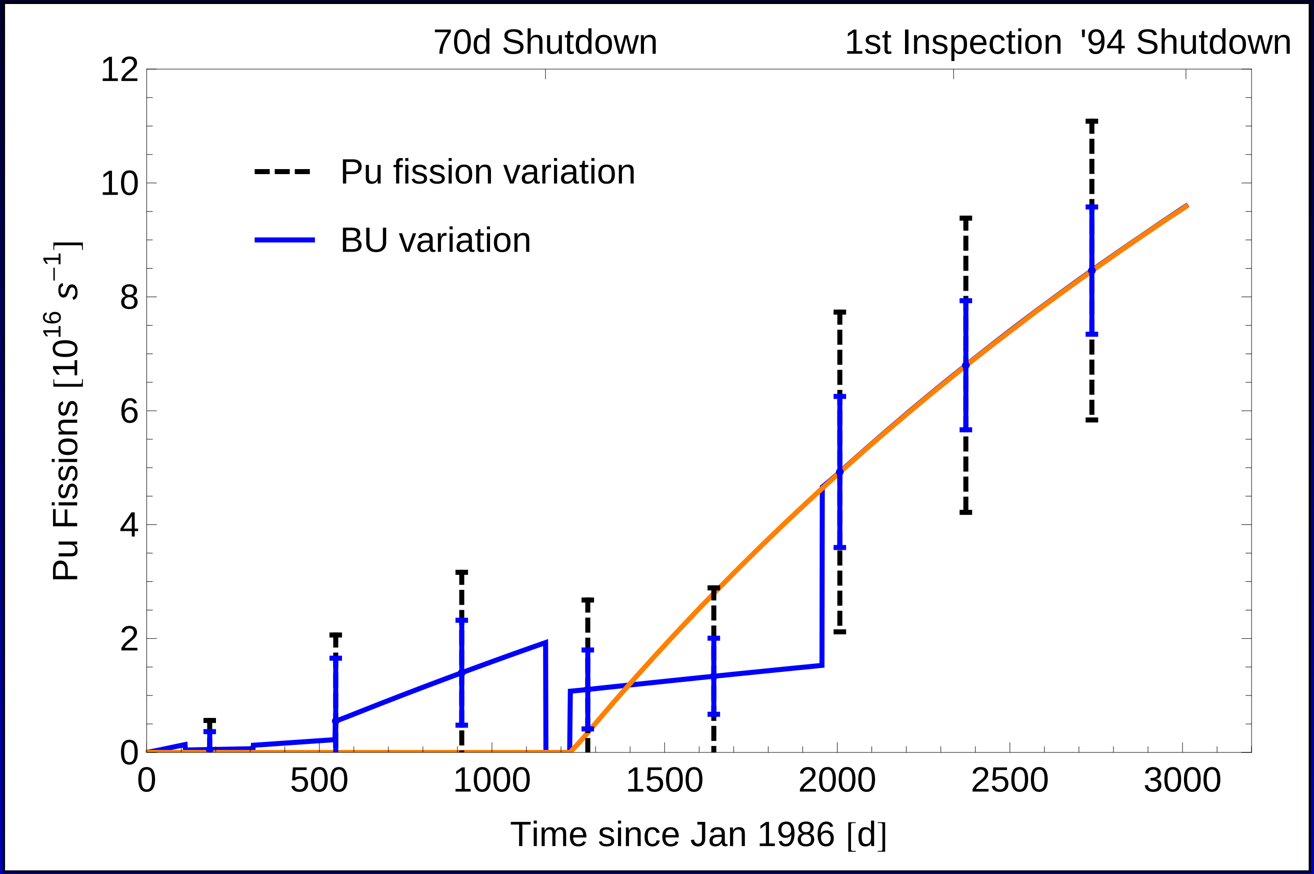
In particular, in the diversion case, there has to be reprocessing waste somewhere.

Reactor simulation



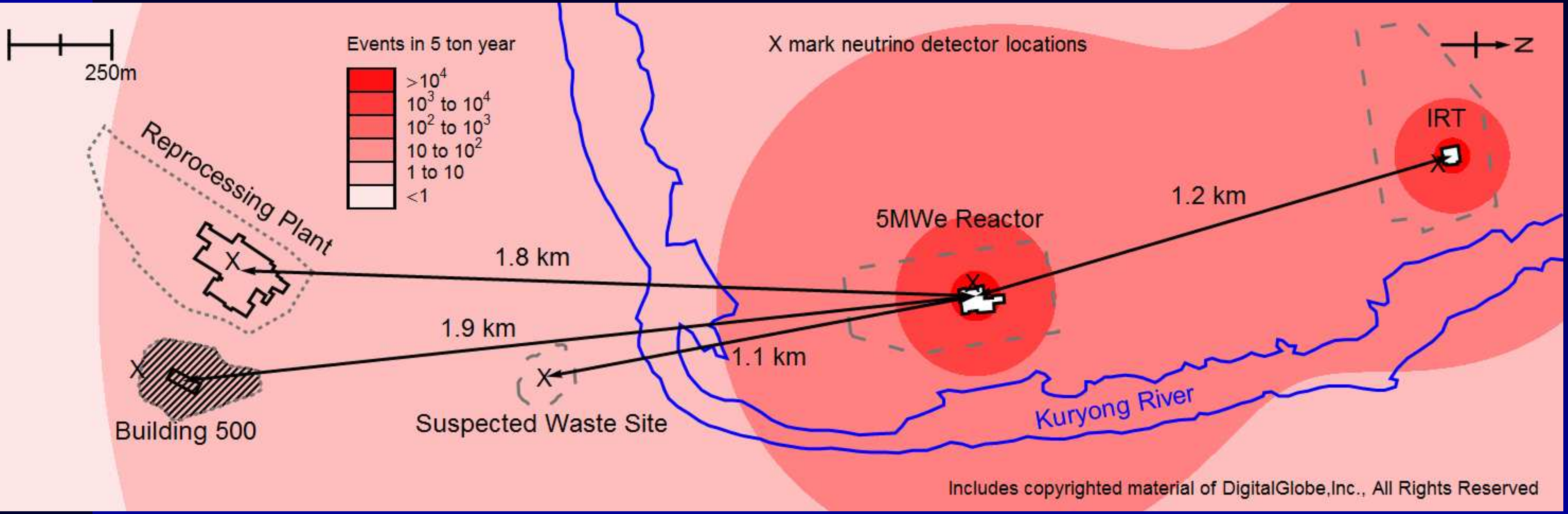
Based on a full SCALE calculation using a detailed power history and the magnox cross section libraries.

Neutrino 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)

Indirect means



The IRT is a small (6MWth) HEU reactor which has been under safeguards since 1977, neutrinos from the 5MWe will be visible at its site

We can look for reprocessing wastes since the long-lived isotopes (LLI), ^{90}Sr, ^{106}Ru and ^{144}Ce will still emit detectable neutrinos

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

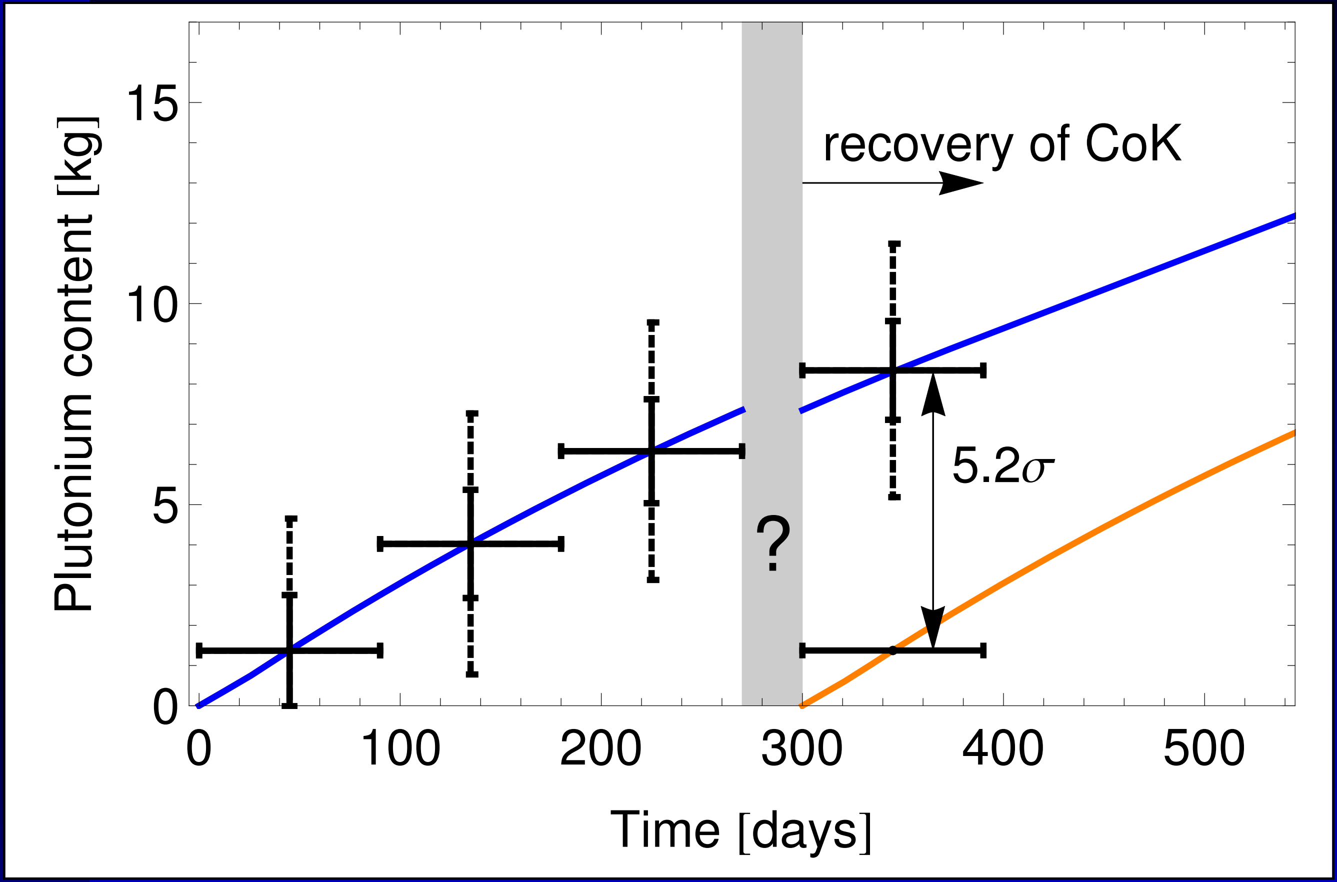
NB: most likely this reactor will be down-rated to $20\mathrm{MW}_{\mathrm{th}}$.

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 war and peace.

Iran – results

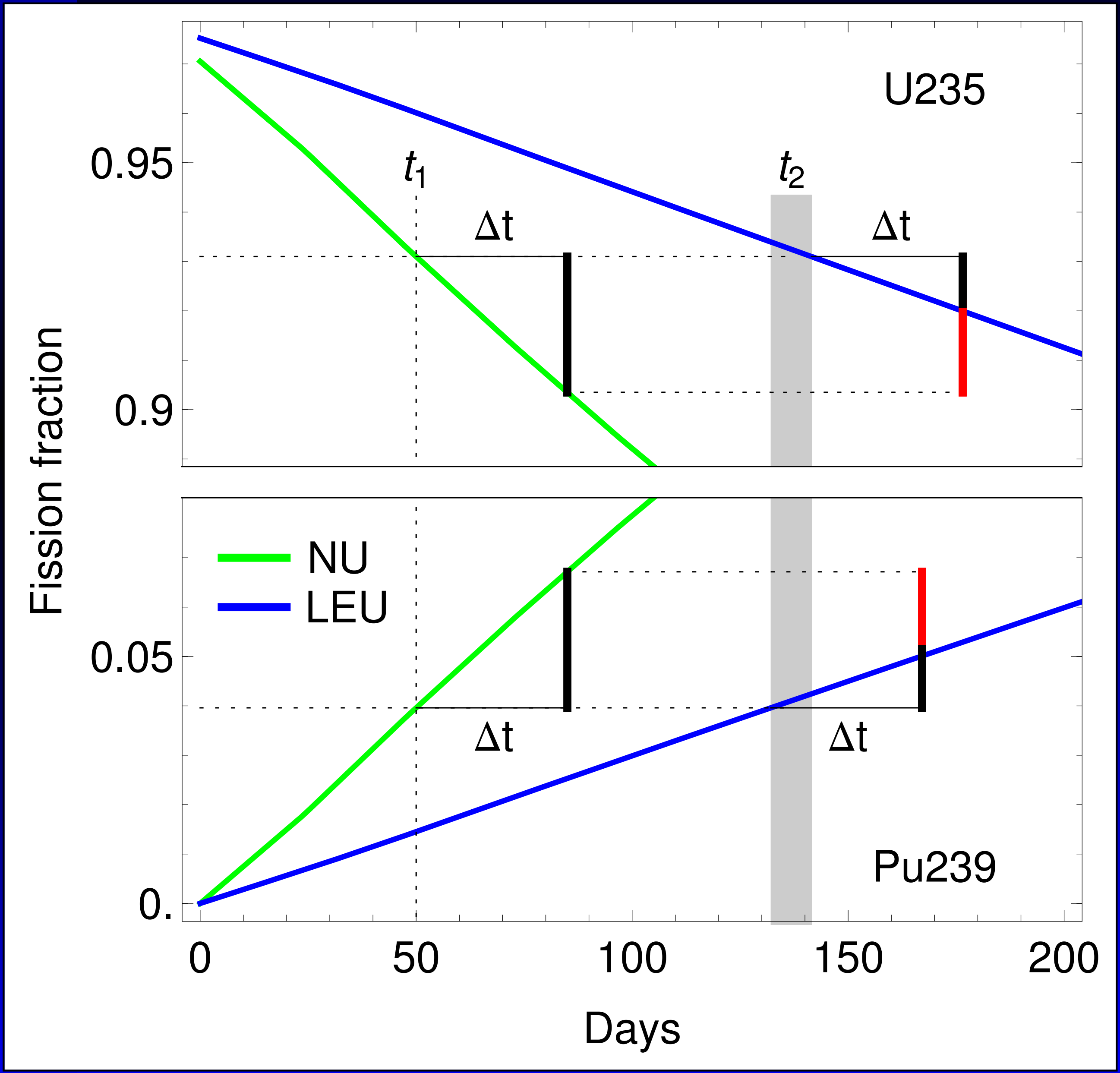


270 days corresponds to 93% plutonium-239

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.

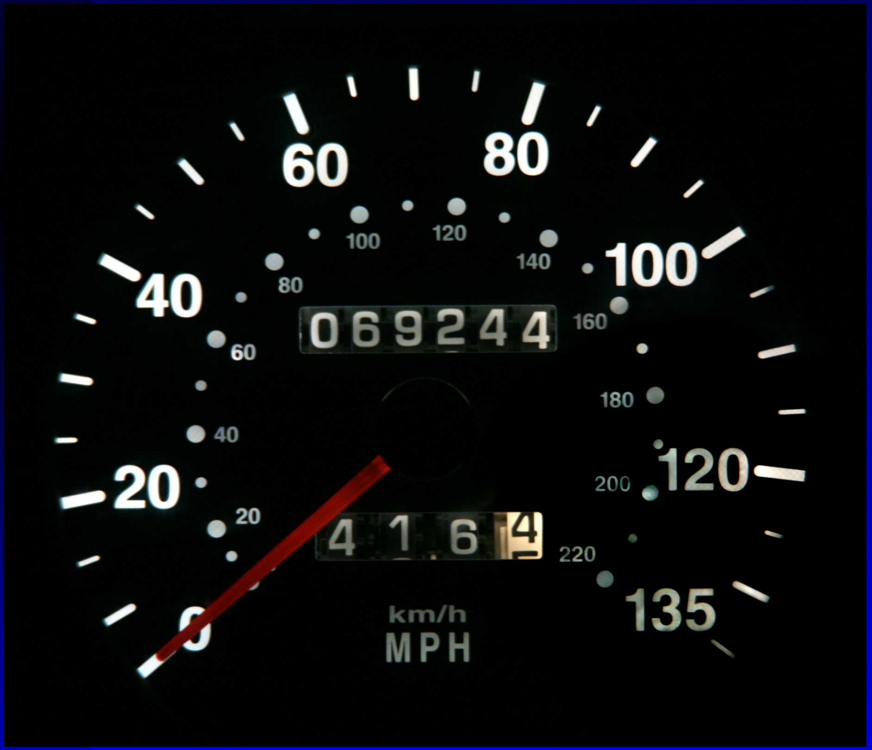
Challenges

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

The FMCT scenario

Assuming treaty-imposed limitations on the production of fissile materials, plutonium in spent fuel from nuclear power plants (and research reactors) becomes a much bigger proliferation risk.

Any safeguards regime for plutonium in SNF will need to include means to assess how much plutonium is contained in the SNF before it leaves the reactor facility.

In recognition of this, the NNSA has launched a research project on spent fuel nondestructive assay techniques, which are applied at the level of a single fuel assembly.

The FMCT scenario – neutrinos

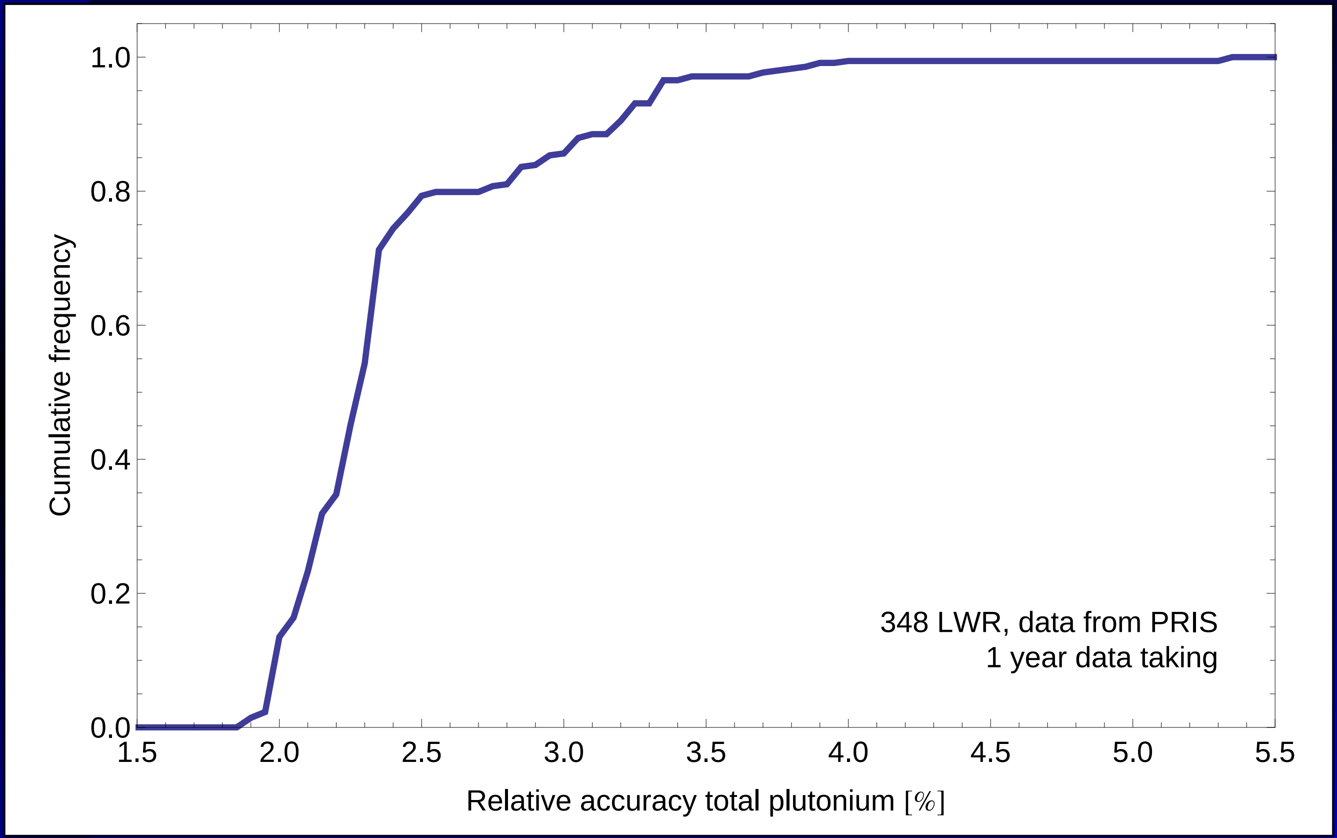
Neutrinos can provide a fissile plutonium (and fissile uranium) content determination for in-core fuel with percent level accuracy

This determination is made for the whole core (or for the total discharged batch)

At this stage, we do not know what the ultimate systematics limit for these measurements is or what would cause it

A specific example

A standard neutrino detector at each power reactor

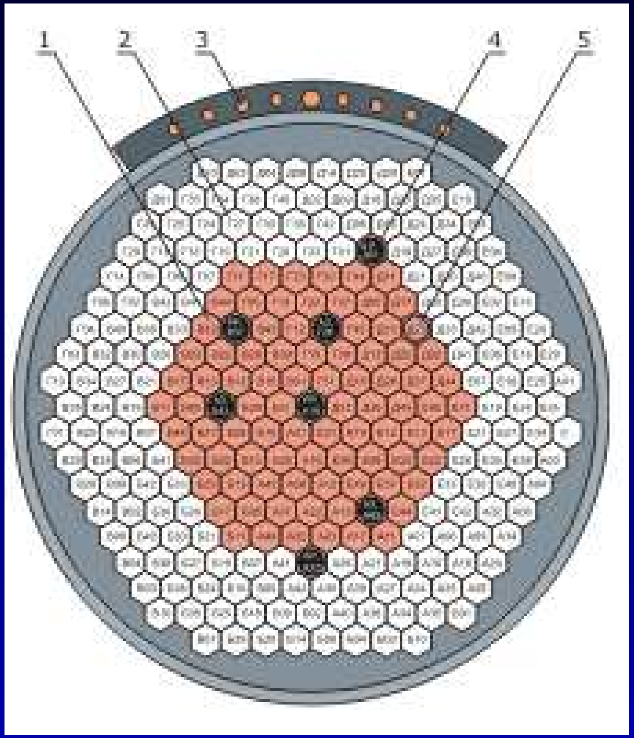


Median accuracy 13.3 kg (2.3%), single core

Combining individual reactors in quadrature, global annual plutonium production is measured to within 0.12%, neglecting systematics.

Breeding blankets

Breeder reactors generate more plutonium than they use fuel, but also can be used to burn weapons-grade plutonium.



The difference between making and destroying net plutonium stems from the presence/absence of a uranium-238 breeding blanket.

The problem is that the radiation from the fissions in the core outshine any radiation signature from the blanket.

Neutrinos to the rescue

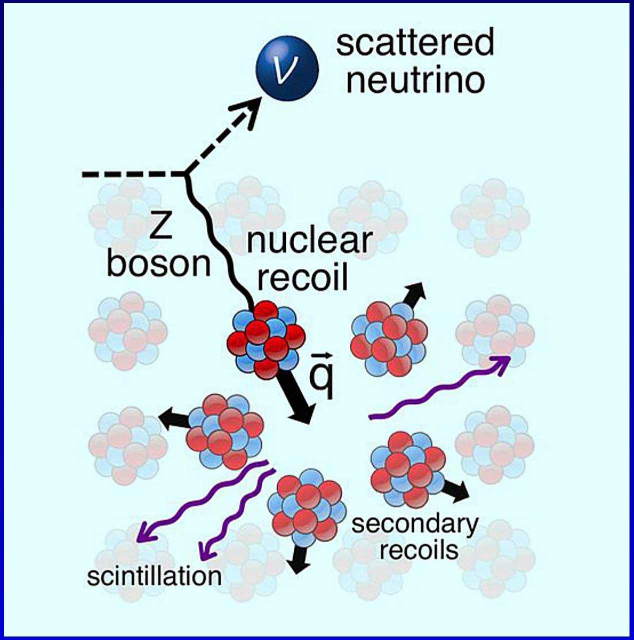
$$^{238}\mathrm{U} + n \longrightarrow {}^{239}\mathrm{U} \xrightarrow{\beta^-} {}^{239}\mathrm{Np} \xrightarrow{\beta^-} {}^{239}\mathrm{Pu}$$

The two beta-decay produce neutrinos with energies up to 1.2 MeV, which is below the IBD threshold.

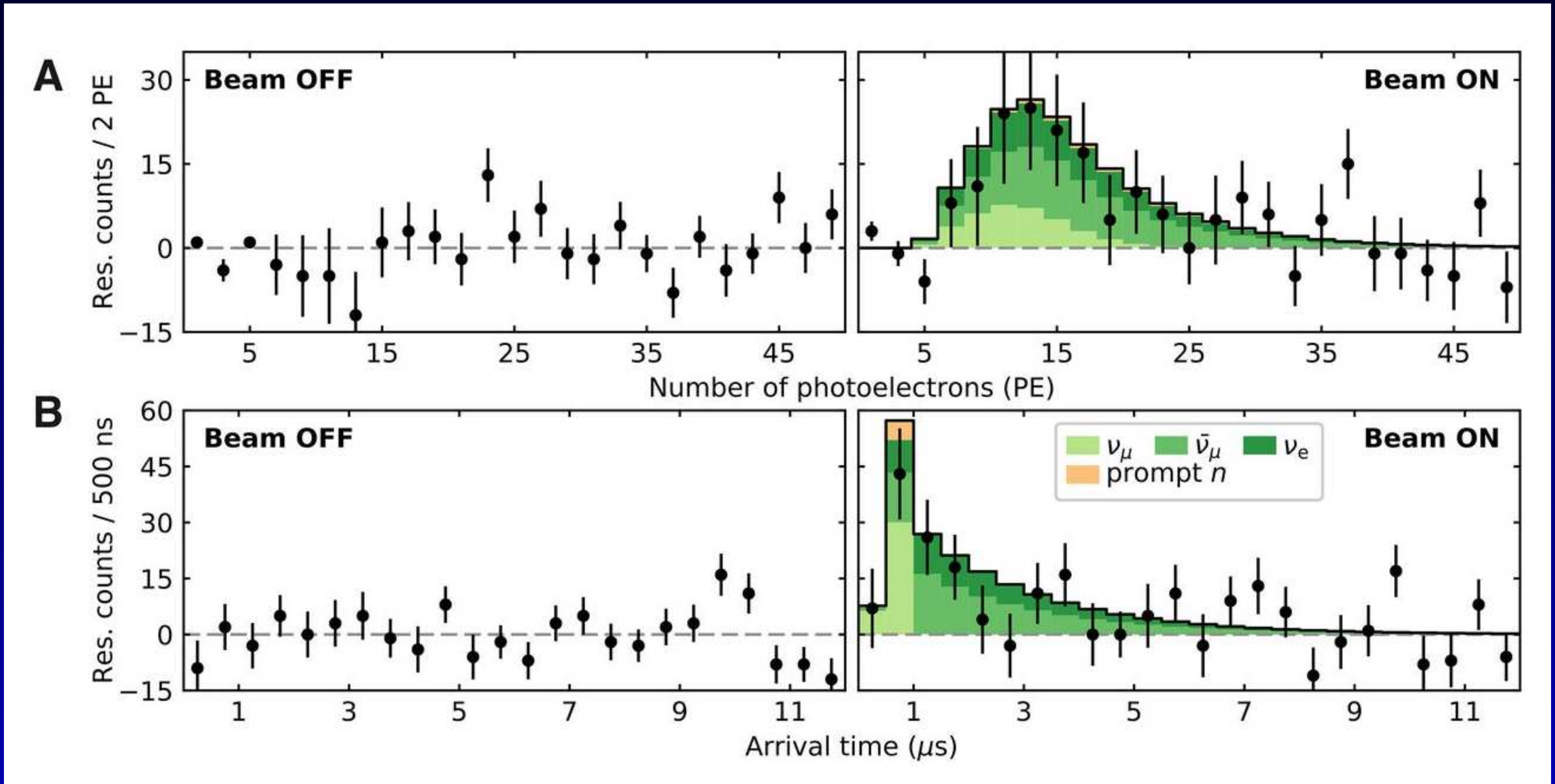
However coherent neutrino nucleus scattering (CENNS) is threshold-less.

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

T recoil energy, N neutron number



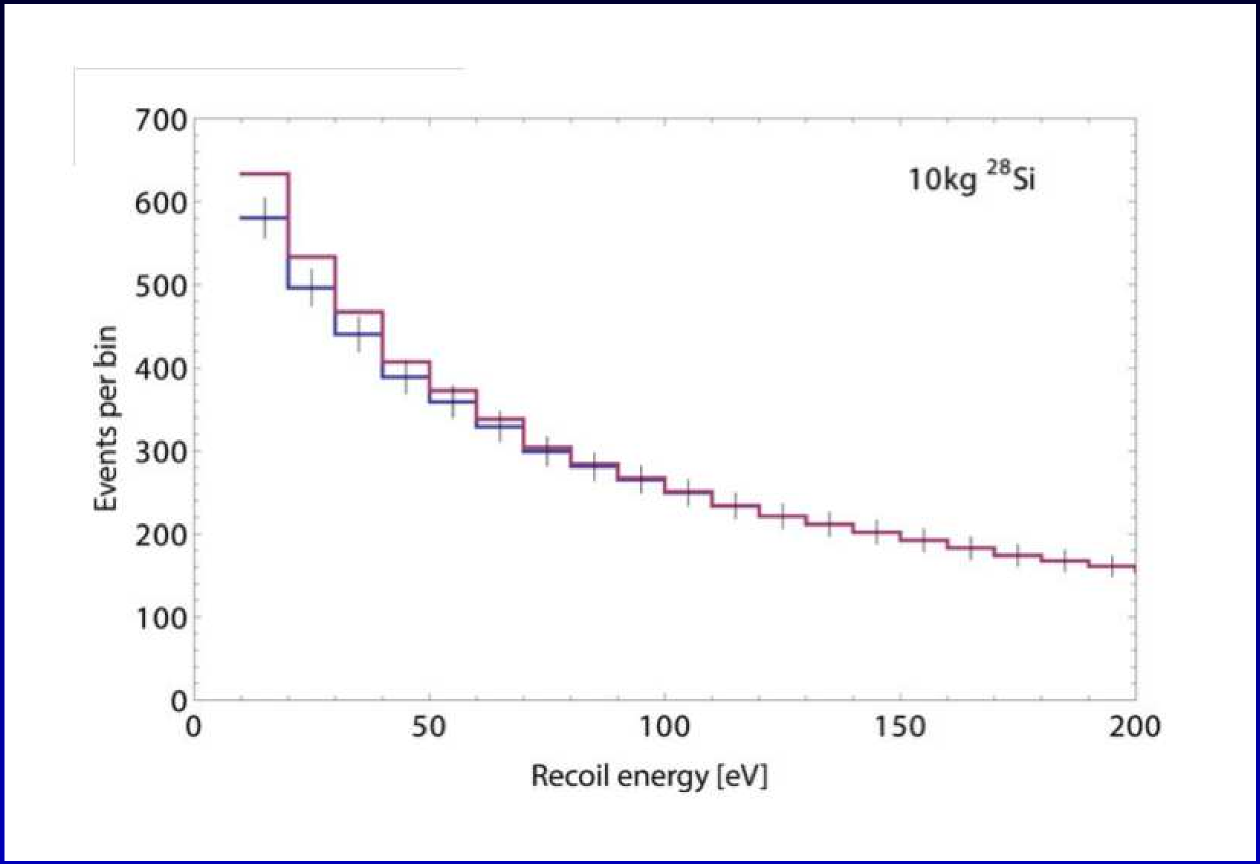
CENNS



COHERENT collab. 2017

First observation using a CsI scintillator detector using a pulsed 50 MeV neutrino beam.
Many detector ideas, most of them based on dark matter direct detection experiments.

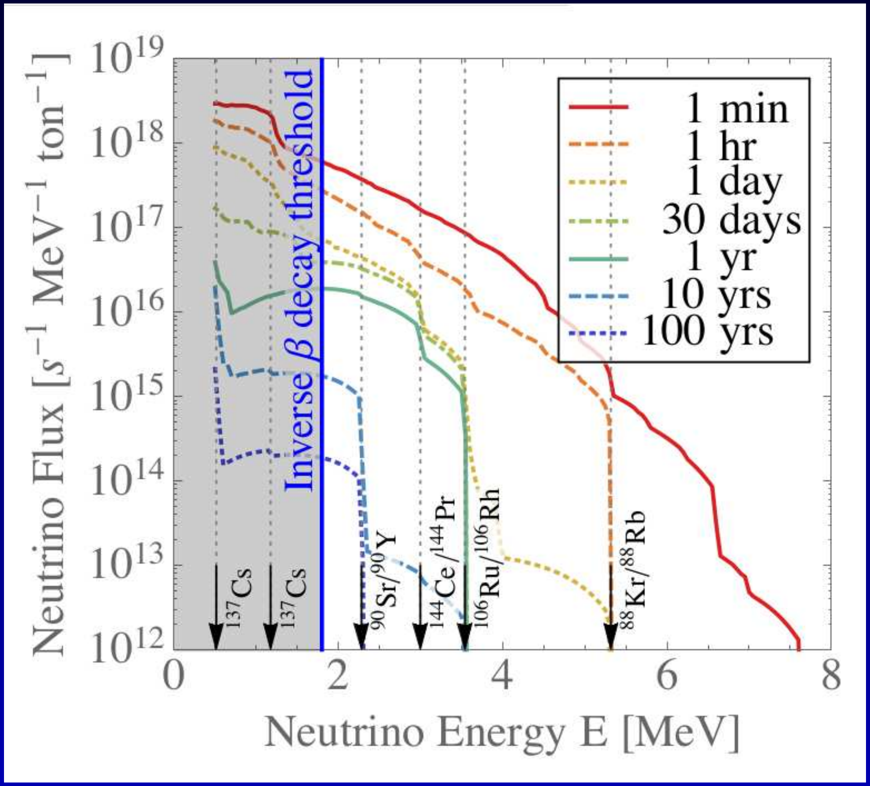
CENNS and breeding blankets



Cogswell, Huber 2016

Compare to the CONUS experiment, deploying a few kg of germanium detectors at a reactor.

Spent fuel monitoring

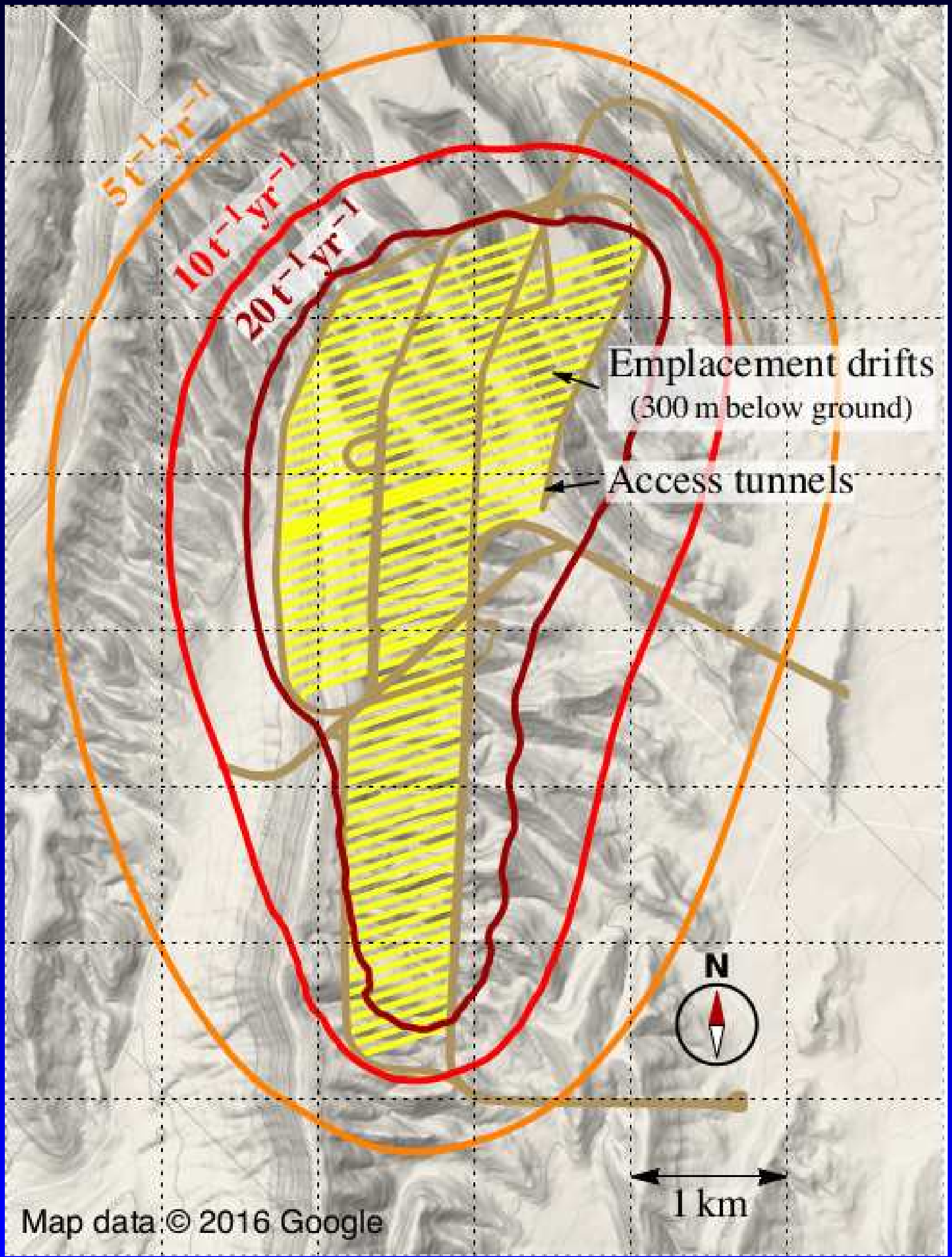


Brdar, Huber, Kopp, 2017

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.

Spent fuel monitoring



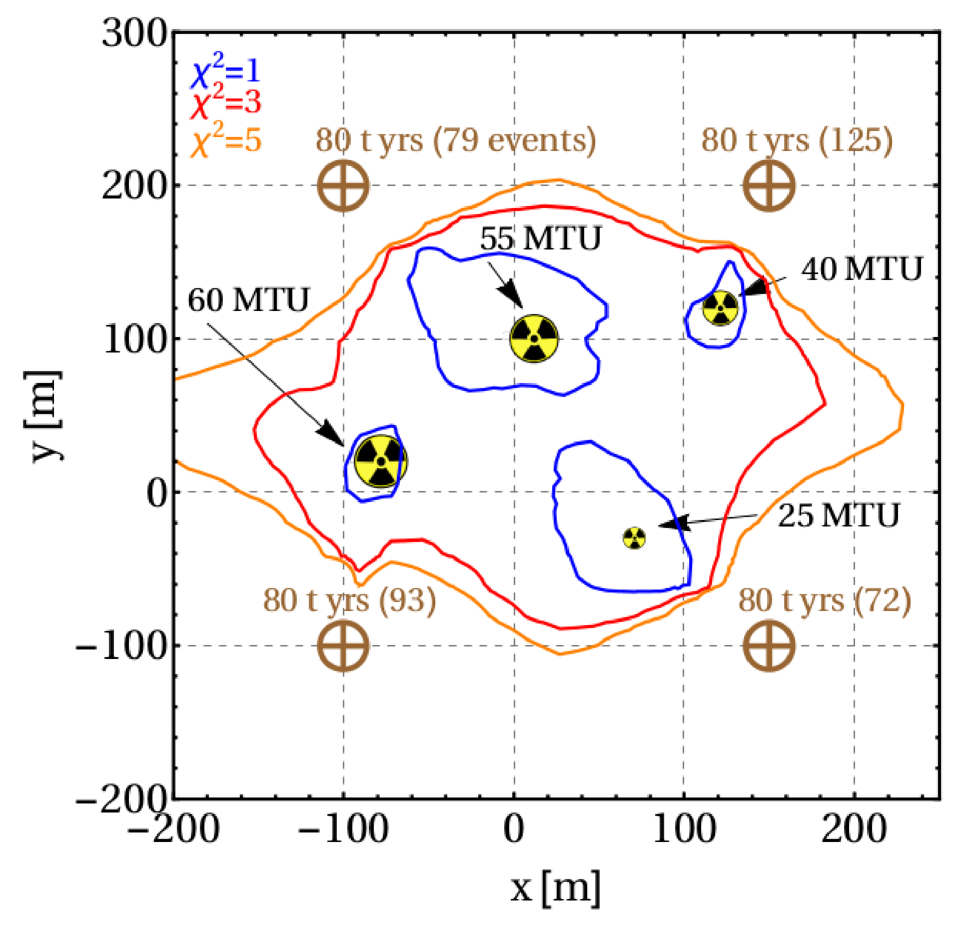
Geological final repository

Many 1,000 tons of spent fuel

Underground location

Reasonable statistics with KamLAND-size detector

Spent fuel monitoring



Clean-up after Cold War plutonium production

Locating underground tanks containing reprocessing waste

MTU: metric ton of uranium

Sites like this exits both in Russia and the U.S.

Far field monitoring

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

- Undeclared plutonium production reactors
- Nuclear explosion identification

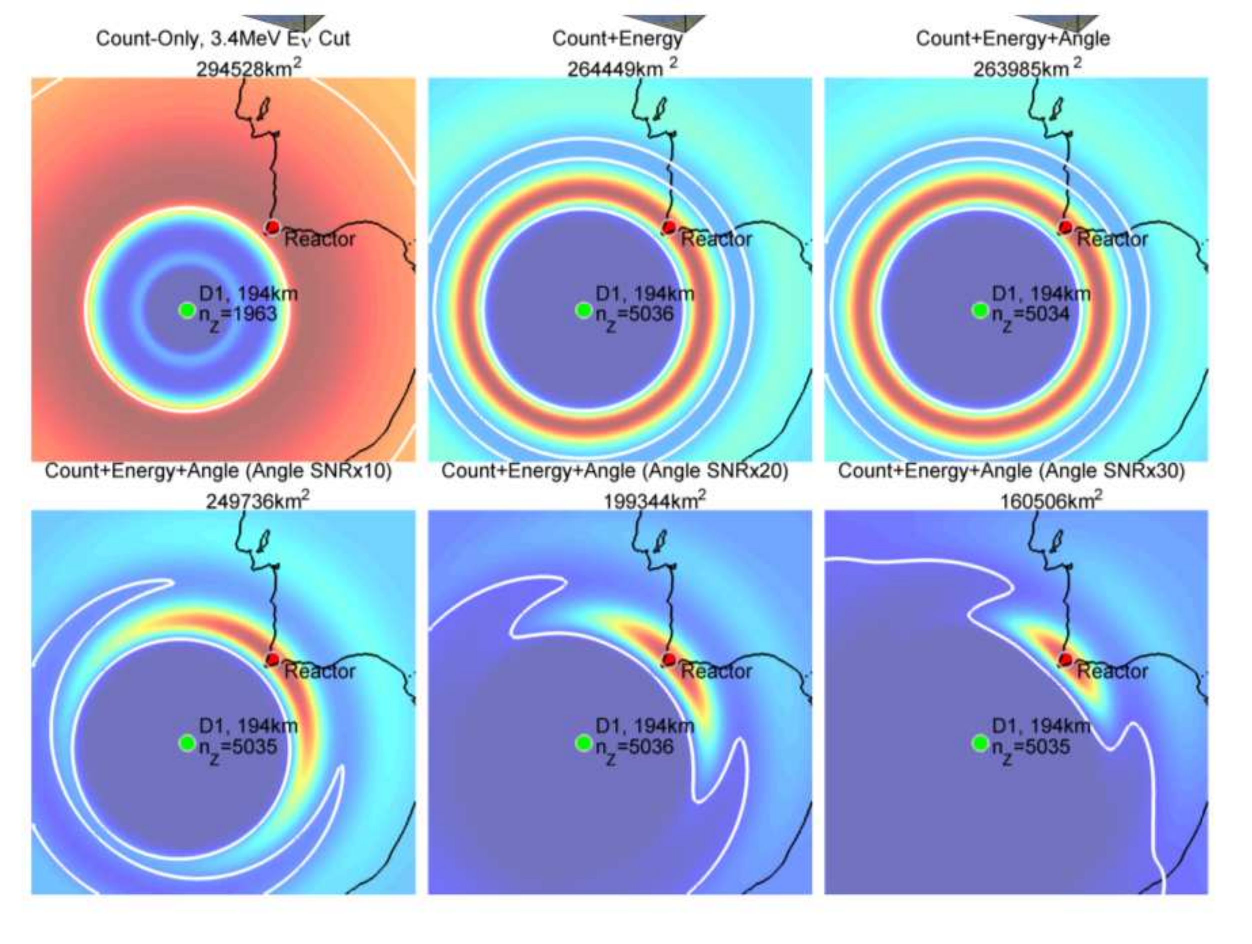
We have about 200 events per ton of detector, per year of measurement at 1 km distance for a 1GW reactor.

What size of detector is needed to see 5 events in a year for a 100MW reactor at 100 km distance? – 2.5 kt

This is of course a background-free scenario.

Far field example

138 kt liquid scintillator, 300 MW reactor.



Jocher, *et al.* 2013

Angular resolution far beyond current capabilities is required.

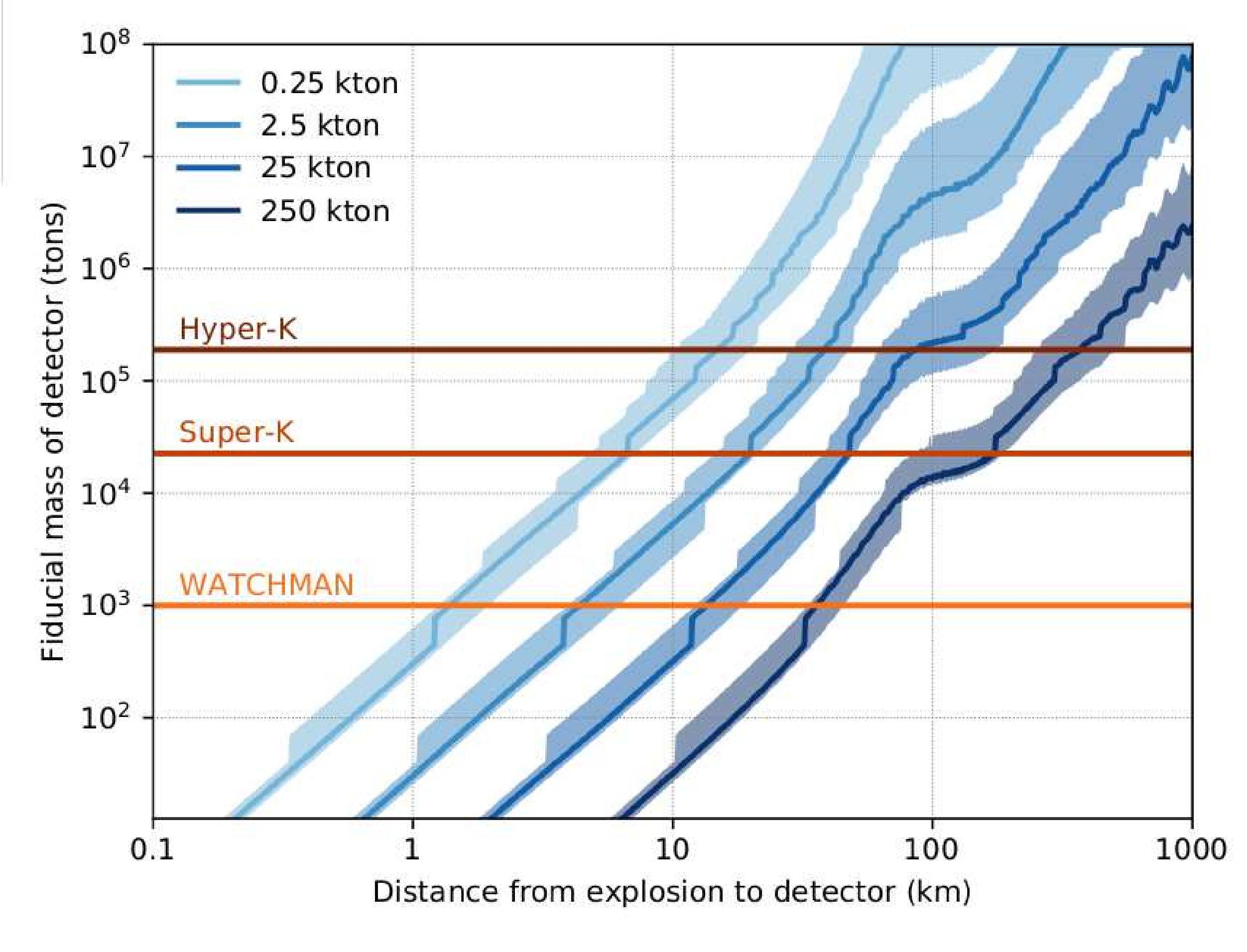
Far field comment

Out of 7 countries going the plutonium route:

U.S. – Hanford, graphite
Russia – Mayak, graphite
U.K. – Windscale, graphite
France – Marcoule, heavy water
Israel – Dimona, heavy water
India – CIRUS, heavy water
DPRK – Yongbyon, graphite

We know (and knew at the time) where the reactors are from overhead imagery, and the operational status can be inferred from heat signatures…

Nuclear explosion detection



To detect a single neutrino from a 20 kt fission device at 100 km at 10 kt detector is needed.

Carr, Dalnoki-Veress, Bernstein, 2017

However, the time of the event and rough location will be known from seismic observations.

Nuclear explosion detection

The CTBTO (comprehensive test ban treaty organization) uses seismic, infra-sound and radiochemical air sampling to monitor nuclear test.

DPRK tests courtesy F. Dalnoki-Veress

Date	Radionuclide detection	Source
2006	yes	CTBTO press release
2009	no	CTBTO press release
2013	after more than 50 days	CTBTO press release
01/2016	no	CTBTO press release
09/2016	no	CTBTO poster
2017	no	CTBTO personnel

There are many man-made large explosions and the only way to attribute a nuclear yield is radiochemical detection or neutrinos.

Summary

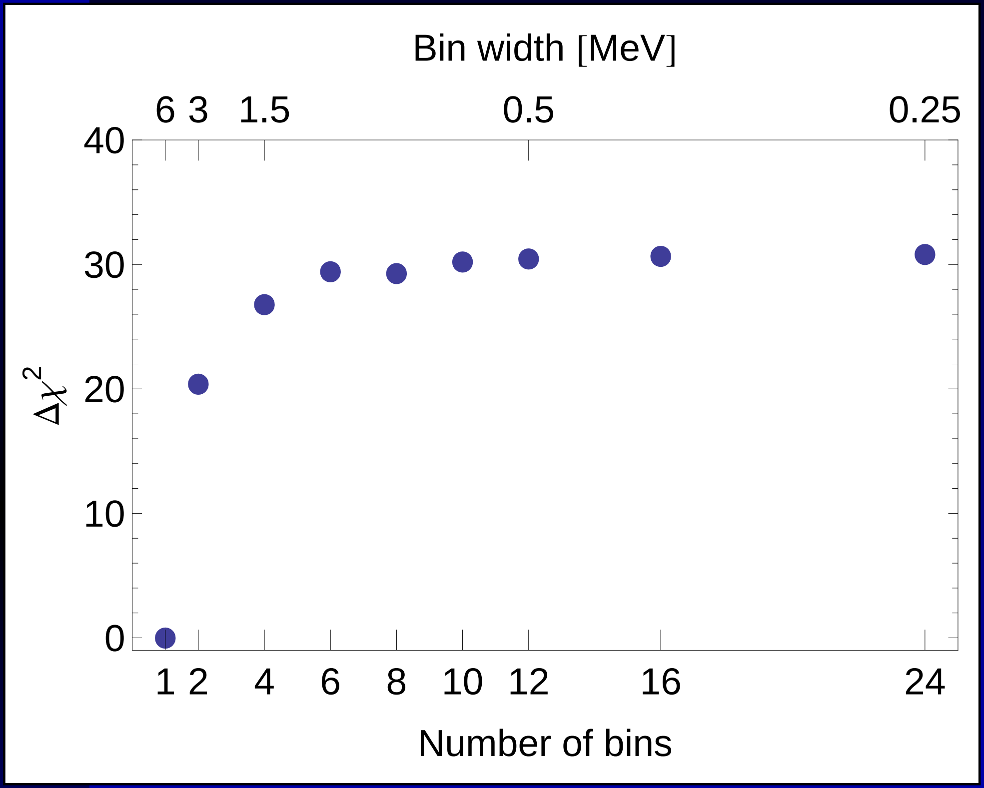
We have now a wide range of neutrino detectors which are essentially ready for being used in safeguards: large, liquid underground detectors, small solid surface detectors, CENNS etc.

Near-field monitoring offers a number of unique capabilities, but needs a much better understanding of reactor fluxes, SBL reactor program will help, but is likely insufficient.

Far-field applications are well within our technical capabilities, cost/benefit may be very good for nuclear explosion detection.

Backup Slides

How much resolution is needed?

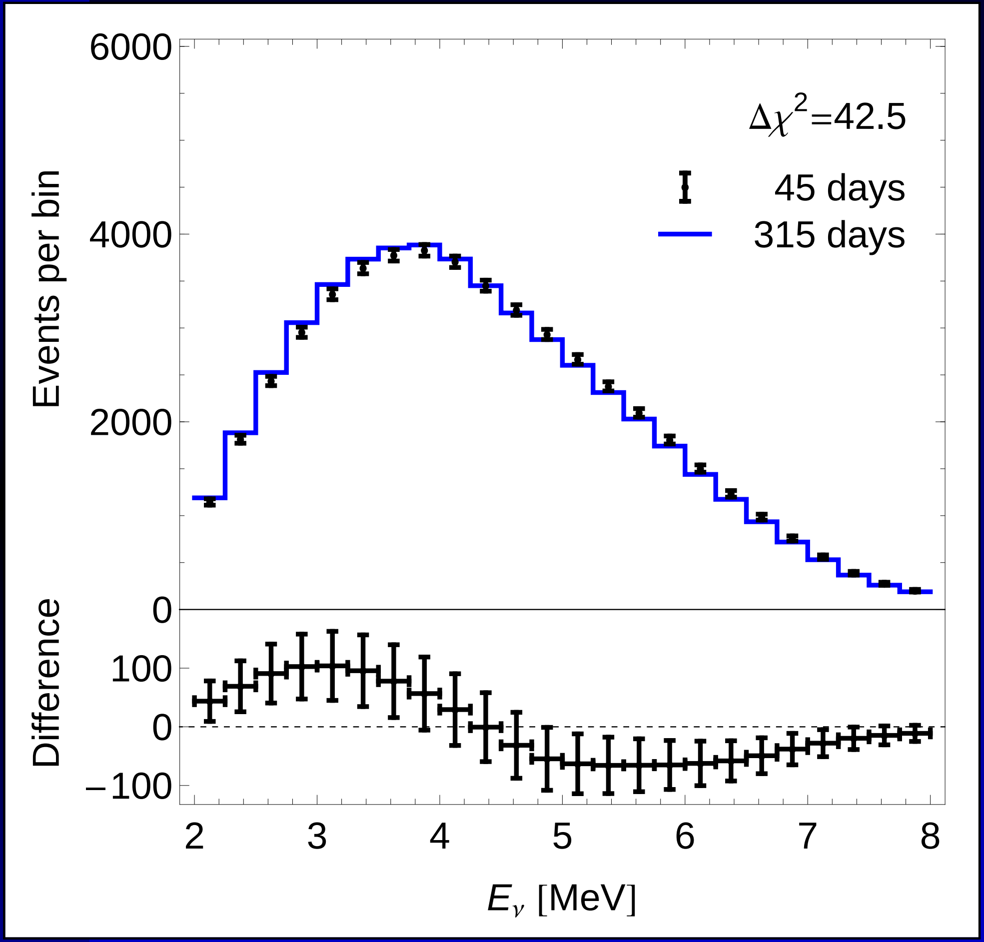


Statistical power is flat for bins smaller than 1 MeV

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

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