Neutrinos for Nuclear Security

Patrick Huber

Center for Neutrino Physics at Virginia Tech

Introduction and Motivation

Plutonium production is a critical step towards nuclear weapons

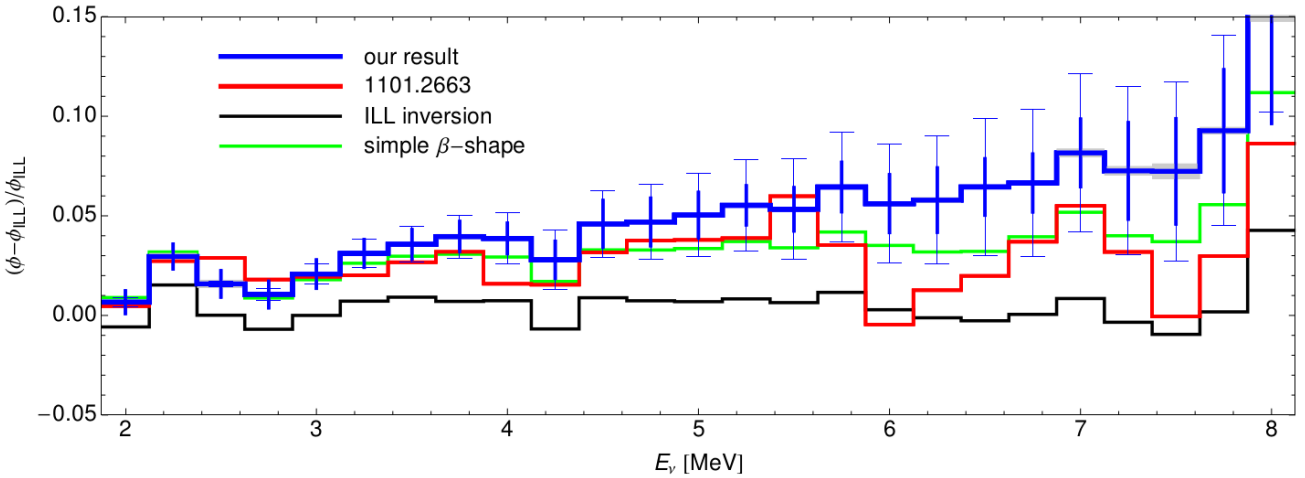
- Plutonium can only be produced in reactors: reactor monitoring and verification is a key element in preventing proliferation.
- The number and energy distribution of neutrinos carries direct information on reactor power and fuel burn-up, and thus plutonium content.
- Neutrinos can not be shielded or spoofed.
- Burn-up signatures remain detectable up to distances of ~100m.
- Deployment outside of reactor building → robust and non-intrusive.

Technical Approach

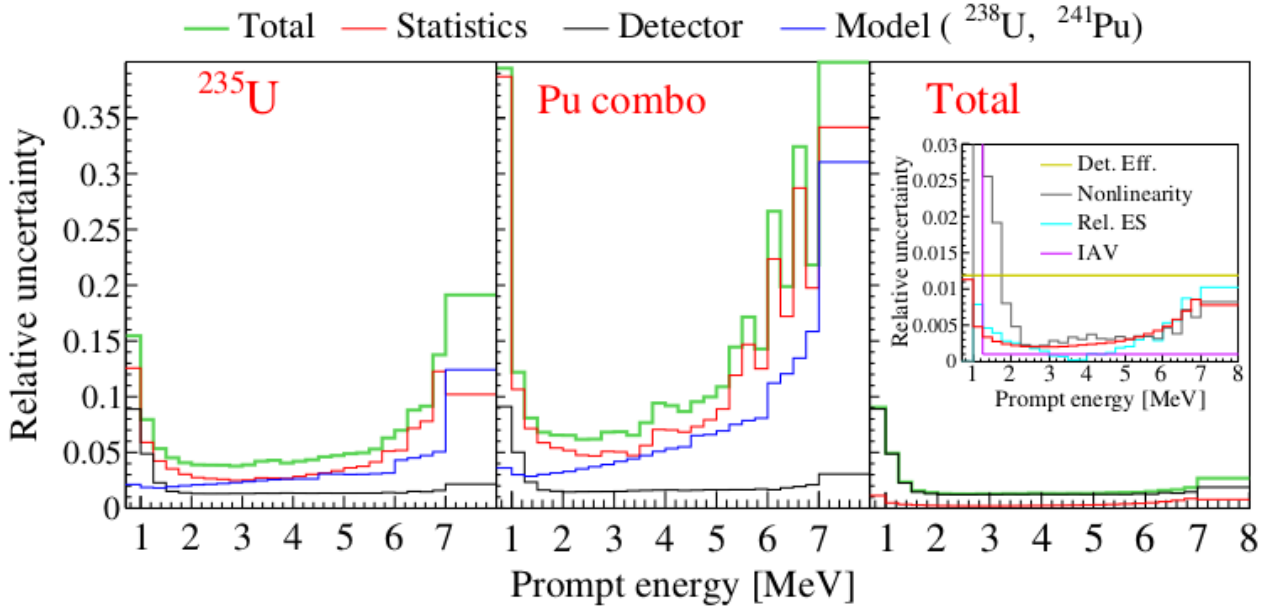
- Source term characterization: so-called Huber-Mueller model for reactor fluxes.
- Source term measurement: member of the Daya Bay experiment.
- Detector R&D: CHANDLER prototype, segmented plastic scintillator, surface deployable.
- Case studies: DPRK, Iran, PMDA (MOX and fast breeders), spent nuclear fuel, CEvNS.

Source term

To-date the most precise and widely used reactor neutrino flux for U-235 and Pu-239, Pu-241.



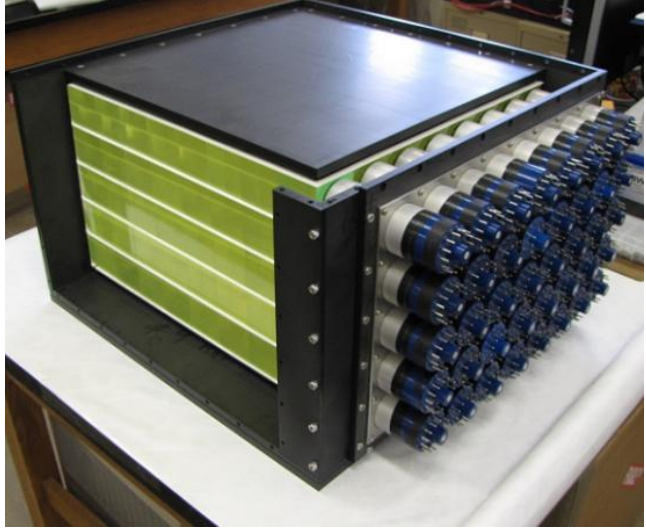
P. Huber, Phys. Rev. C 85 (2012) 029901.



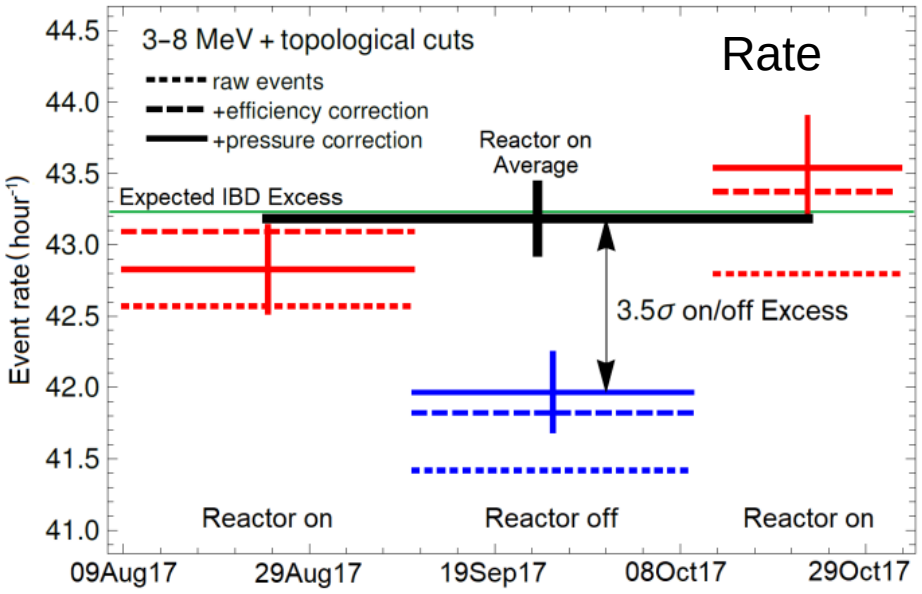
Most precise and accurate measurement of U-235 and Pu reactor fluxes by the Daya Bay experiment (3.2 million inverse beta decay events).

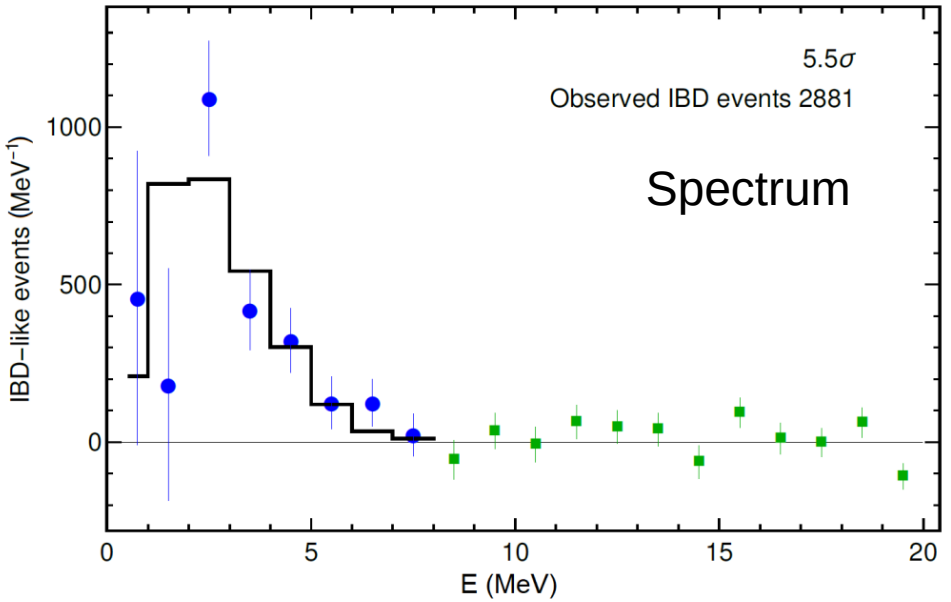
Daya Bay collaboration, arXiv:2102.04614

CHANDLER



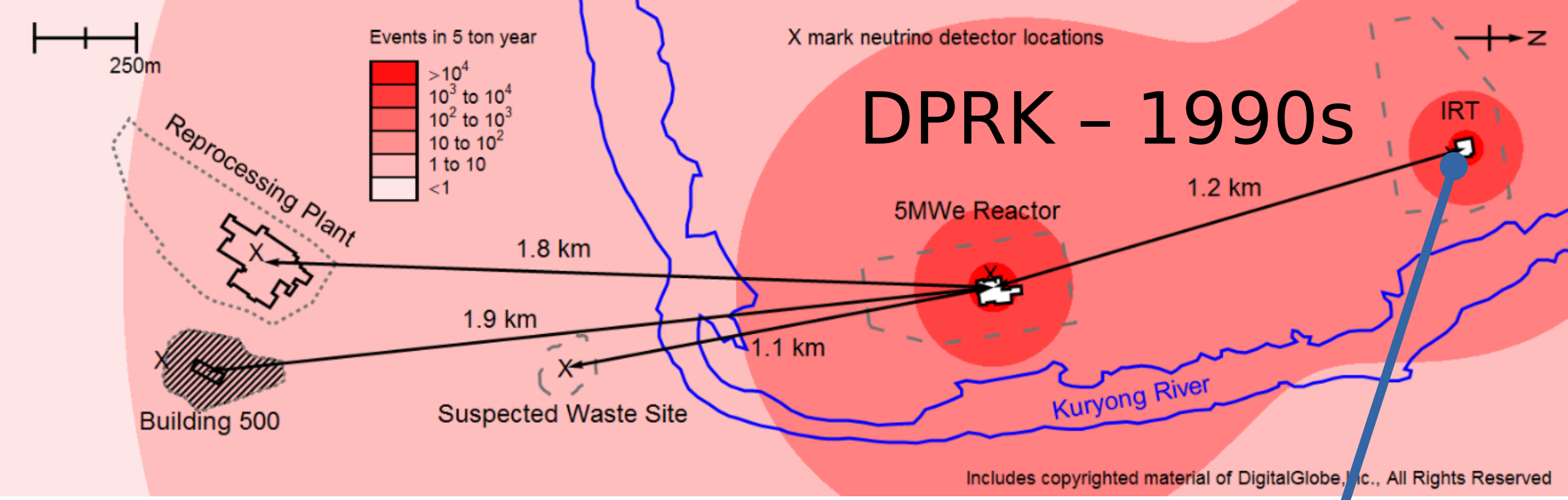
Based on commercially available scintillators EJ-426/260.
3D segmentation, very clean neutron ID.
One of the first detectors to show surface operation, spectral capabilities and high-efficiency.





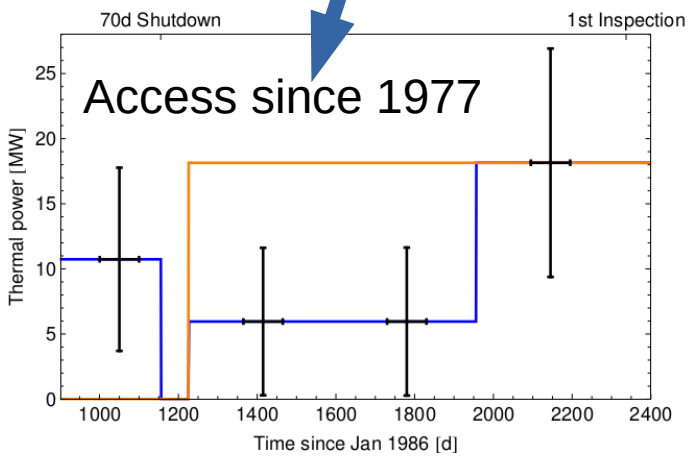
A. Haghighat, P. Huber, S. Li, J.M. Link, C. Mariani, J. Park, T. Subedi, Phys. Rev. Appl. 13 (2020) 3 034028.

DPRK – 1990s



Question: What happened with the reactor core during the 70d shutdown in 1989?

Indirect neutrino measurement from the IRT location would have answered with high confidence



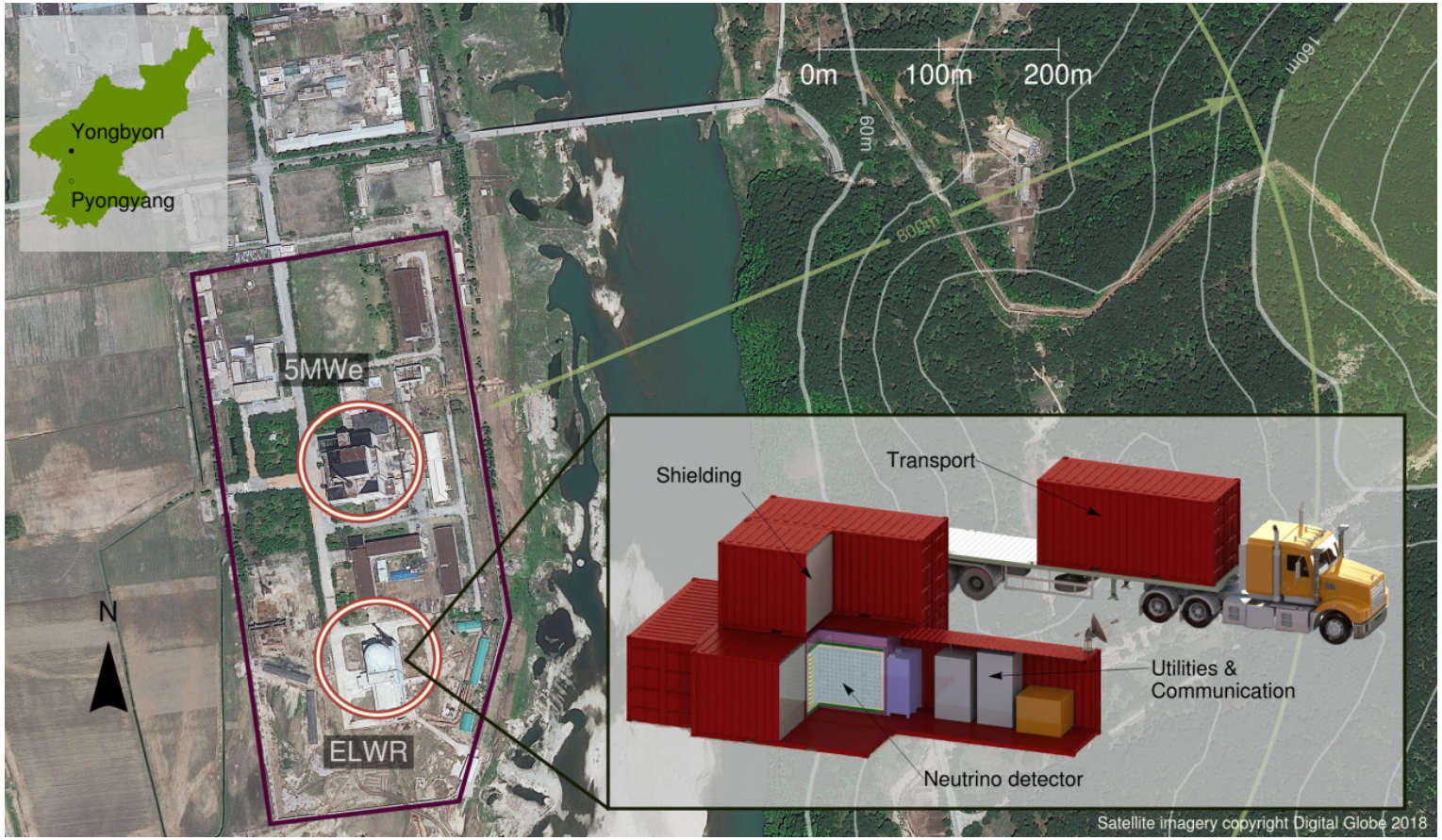
E. Christensen, P. Huber, P. Jaffke, Science & Global Security 23 (2015) 40.

DPRK – 2018

Together with R. Carr (MIT) we organized a study with a group of 20+ neutrino experts, including members from China, Korea, Russia, Japan.

Based on demonstrated detector performance.

Considered several deployment options.



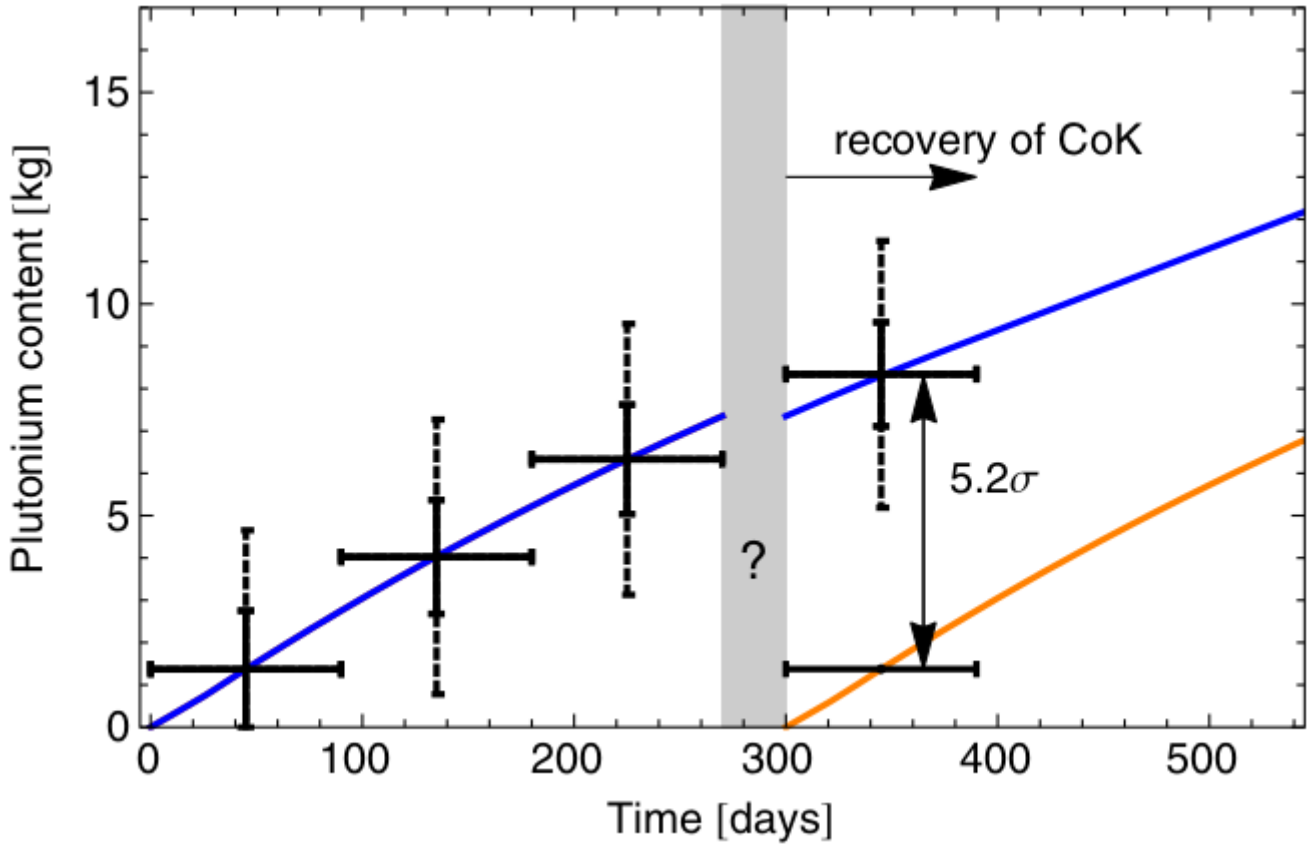
R. Carr *et al.*, Global Science & Security 27 (2019) 15.

Iran – IR40

N-th month scenario

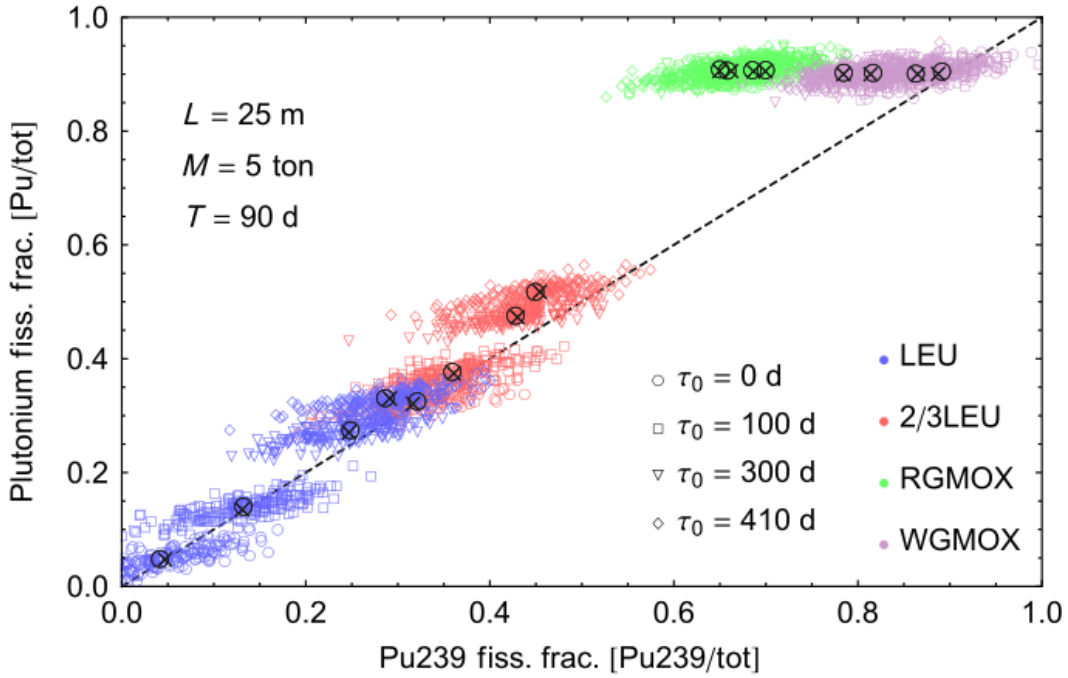
- Safeguards access for N-1 months
- Reactor shut-down in month N
- Loss of continuity of knowledge (CoK)

Neutrinos can restore CoK within a week.



E. Christensen, P. Huber, P. Jaffke, T. Shea, Phys. Rev. Lett. 113 (2014) 042503.

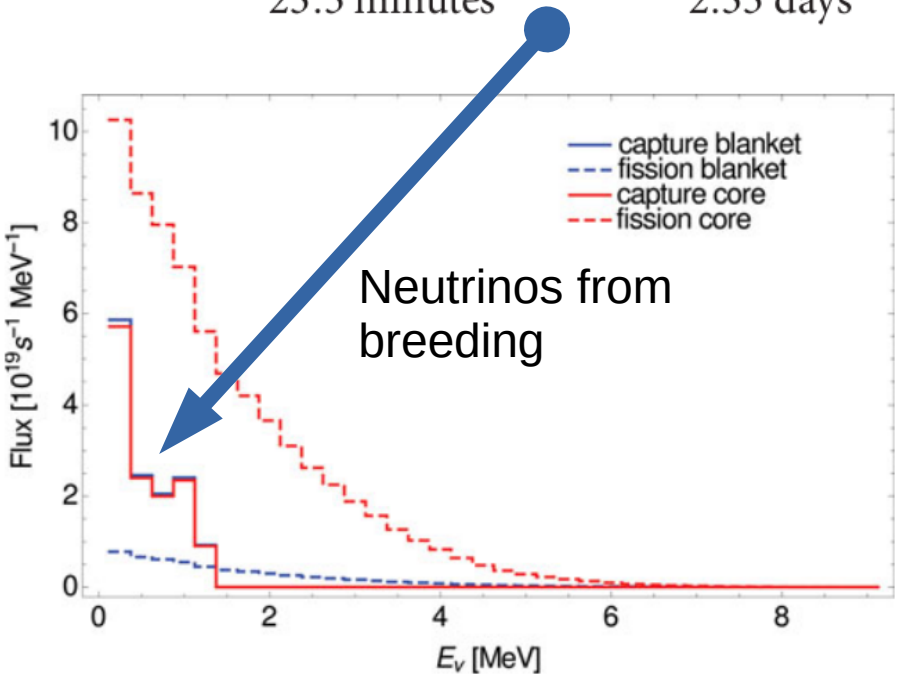
PMDA – MOX & breeders



P. Huber, P. Jaffke, Phys. Rev. Appl. 8 (2017) 034005

MOX fuel – plutonium vector from neutrino measurement

$$^{238}\mathrm{U} + n \rightarrow {}^{239}\mathrm{U} \xrightarrow[23.5\ \text{minutes}]{\beta-} {}^{239}\mathrm{Np} \xrightarrow[2.35\ \text{days}]{\beta-} {}^{239}\mathrm{Pu}$$



B. Cogswell, P. Huber, Science & Global Security 24 (2016) 114.

CEvNS

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

threshold-less reaction

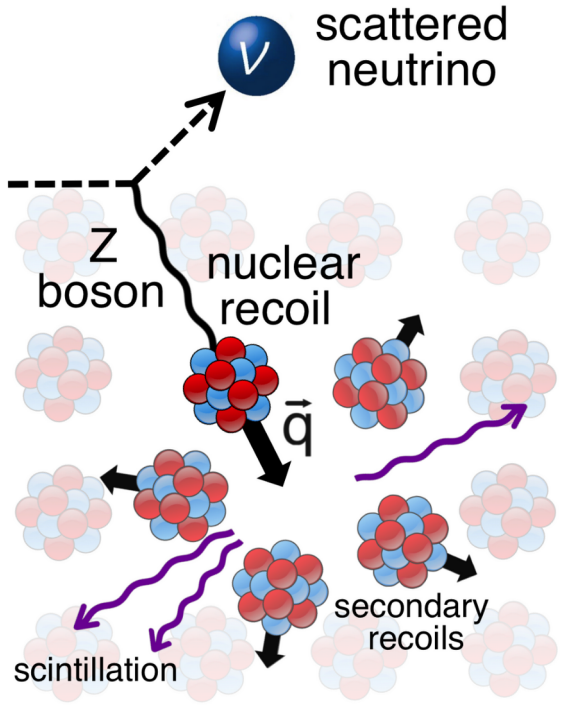


TABLE III. The recoil energy threshold at which IBD and the CEvNS detection result in the same neutrino event number.

Isotope	C	Ne	Si	Ar	Ge	Xe	W
$T_{\min}$ [eV]	791	782	707	677	496	352	281

Sub-keV recoil thresholds needed to be useful.

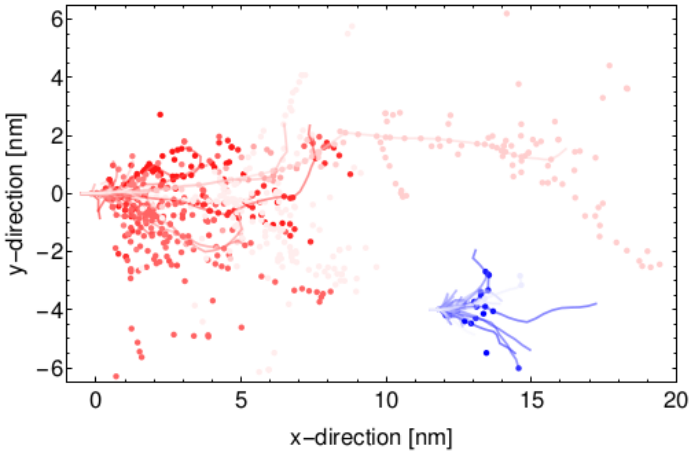
M. Bowen, P. Huber, Phys. Rev. D 102 (2020) 053008

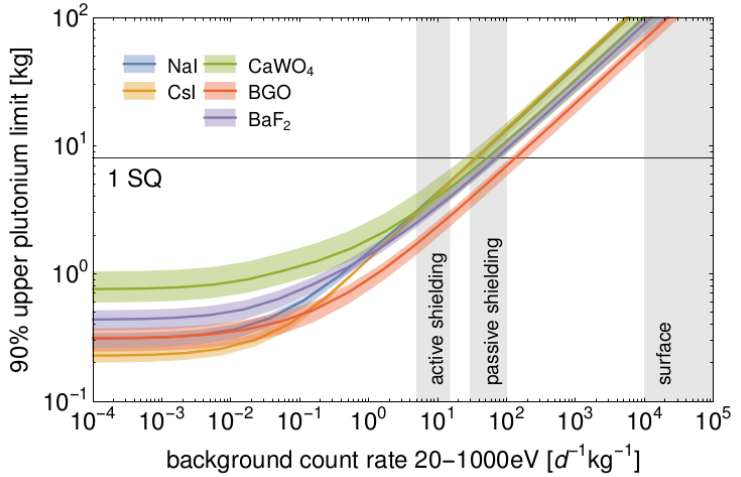
Crystal damage → color centers

20-50eV recoil threshold

Passive detectors with optical readout

100g (!) detector
20m standoff
90 days





B. Cogswell, A. Goel, P. Huber, to appear soon

Expected Impact

- Provide a solid science base for neutrino applications.
- Explore what capabilities neutrinos have in monitoring reactors.
- Motivate targeted detector R&D.
- Understand how these capabilities help to achieve safeguards objectives.

Conclusion and Next Steps

- Our research shows that neutrinos enable unique and relevant monitoring and verification capabilities.
- We are currently assessing our understanding of the source terms and determining steps to improve it.
- We would like to understand if passive detectors are possible and what new use cases this may open.
- We are always seeking input from safeguards practitioners.
- Interest in exploring machine learning for neutrino data fusion.