Science for Nuclear Arms Control

Lecture III: Verification

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CERN Academic Training, 8 February 2024

Safeguards

<u>Verifying declared nuclear materials</u>

Nuclear material accountancy

- On-site inspections in nuclear facilities
- Remote monitoring

Example remote monitoring at declared facilities: Online Enrichment Monitor

Measurement at (header) pipes

- NaI scintillation detector measures U-235 186 keV gamma peak of gas flowing past the device
- Pressure and temperature measurements to deduce density of gas

→ Obtain real-time enrichment

Undeclared nuclear facilities

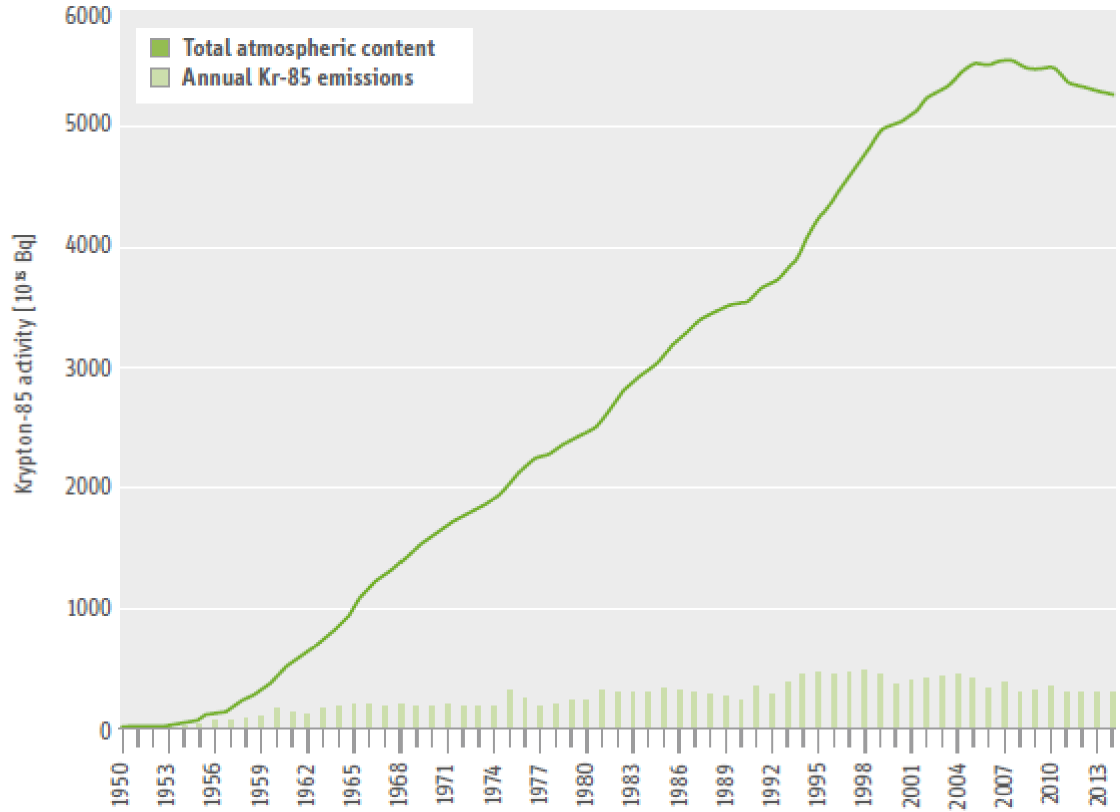
- On-site inspections (short notice, high threshold)
  - Swiping (e.g. undeclared presence of fissile material)
- “up-stream” verification to detect diversion
- Wide-area environmental sampling
  - U for enrichment, Kr-85 for reprocessing
- Open source information (signal-to-noise ratio)
  - Satellite imagery
  - News and other media
  - Research publications

Wide-area environmental sampling

Kr-85 (fission product, noble gas) is released in reprocessing plant

→ Detection indicates repro-cessing

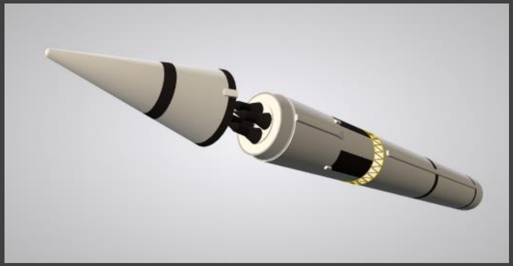
But: High background



International Panel on Fissile Materials

Nuclear disarmament verification

Delivery systems



Warheads

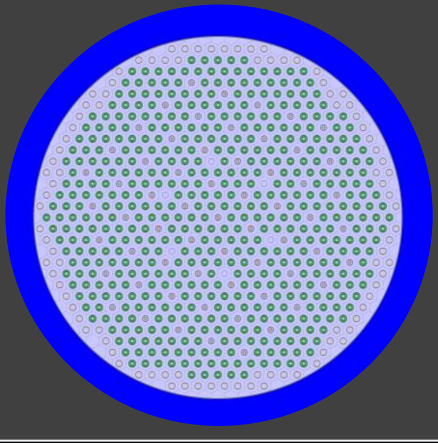
Fissile materials

My verification research

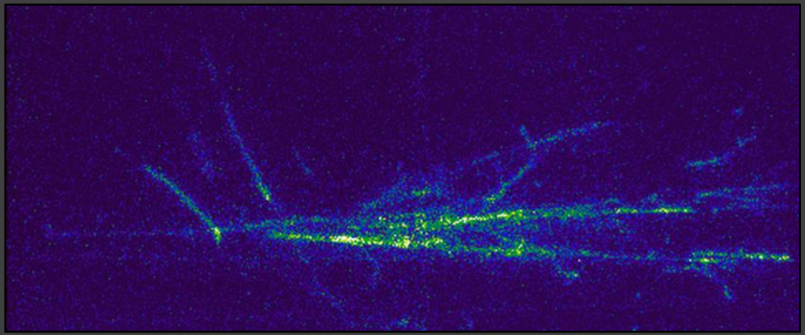
Gamma & neutron detection

A. Glaser

Computational nuclear archaeology



Antineutrino detection



K. Mavrokoridis


Nuclear Verification
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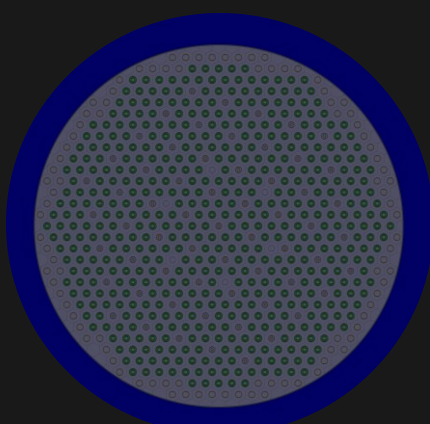

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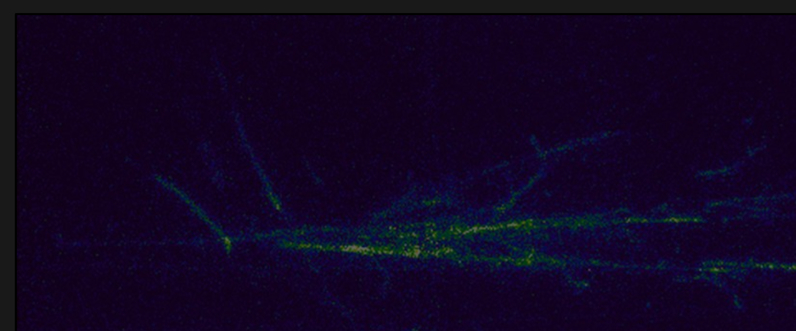

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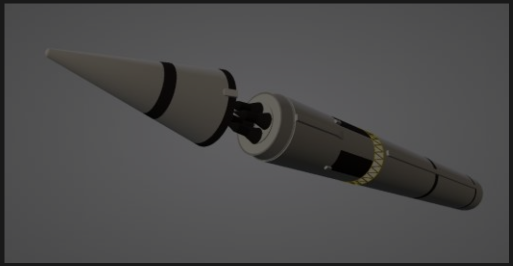
Nuclear disarmament verification

Delivery systems



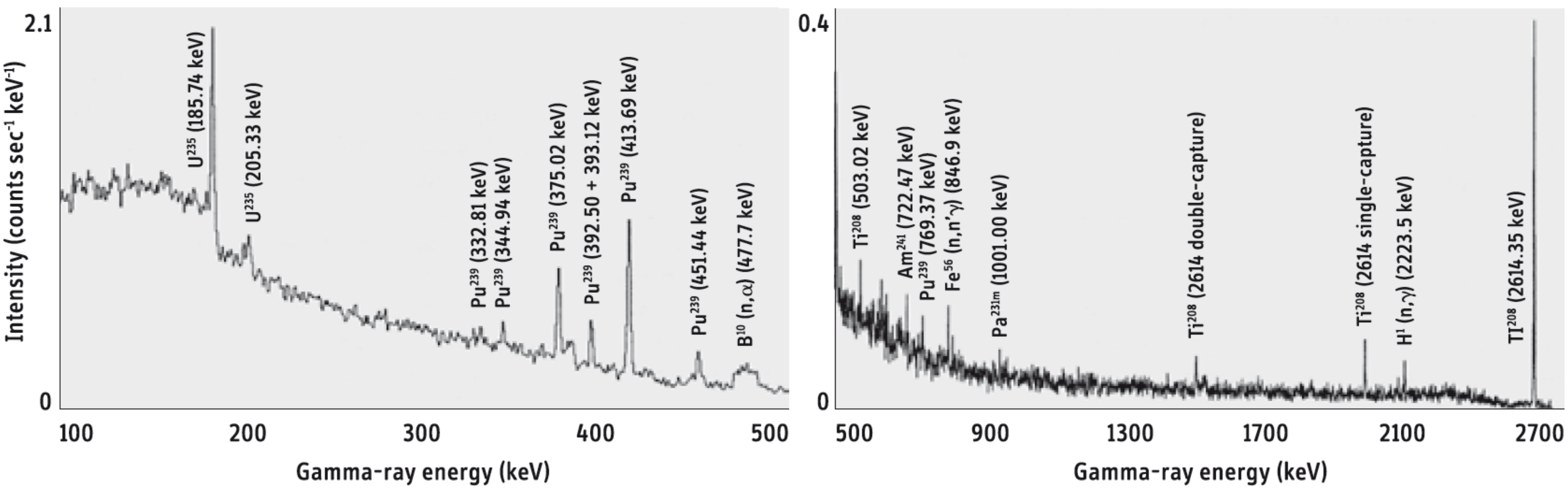
Warheads

Fissile materials

Warhead confirmation

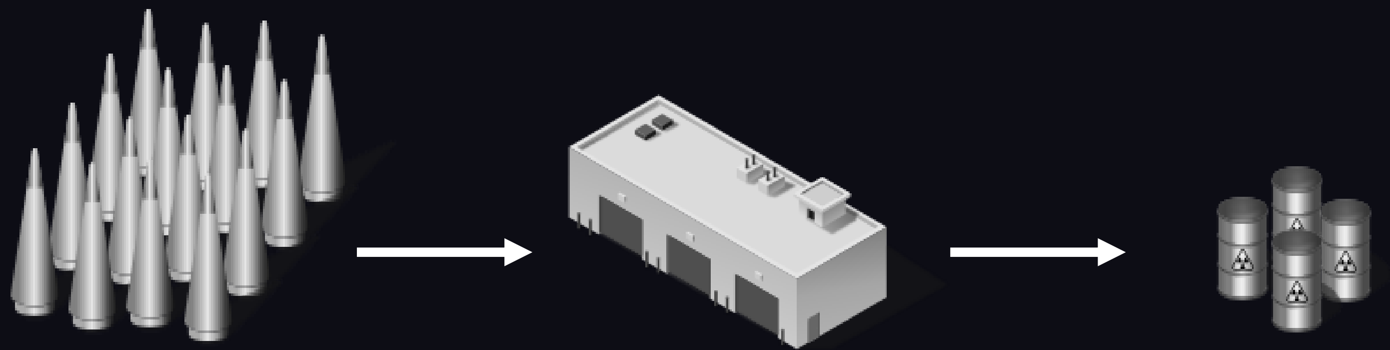
Black Sea Experiment 1989

US independent scientists at Soviet ship



Balyaev et al., Science & Global Security 17, 2009

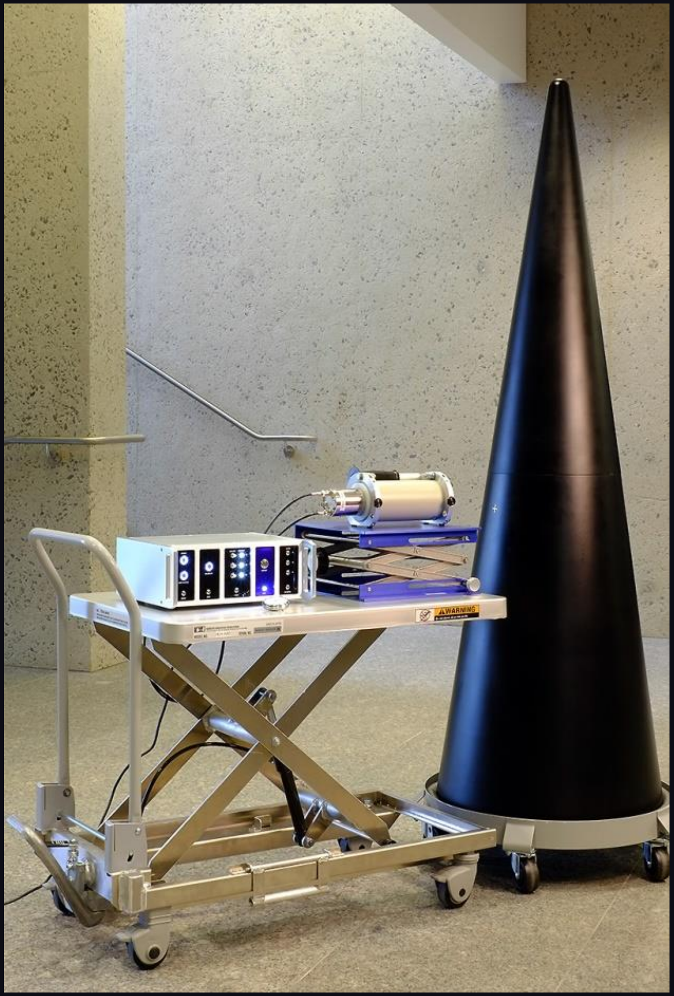
Verified warhead dismantlement



Warhead confirmation

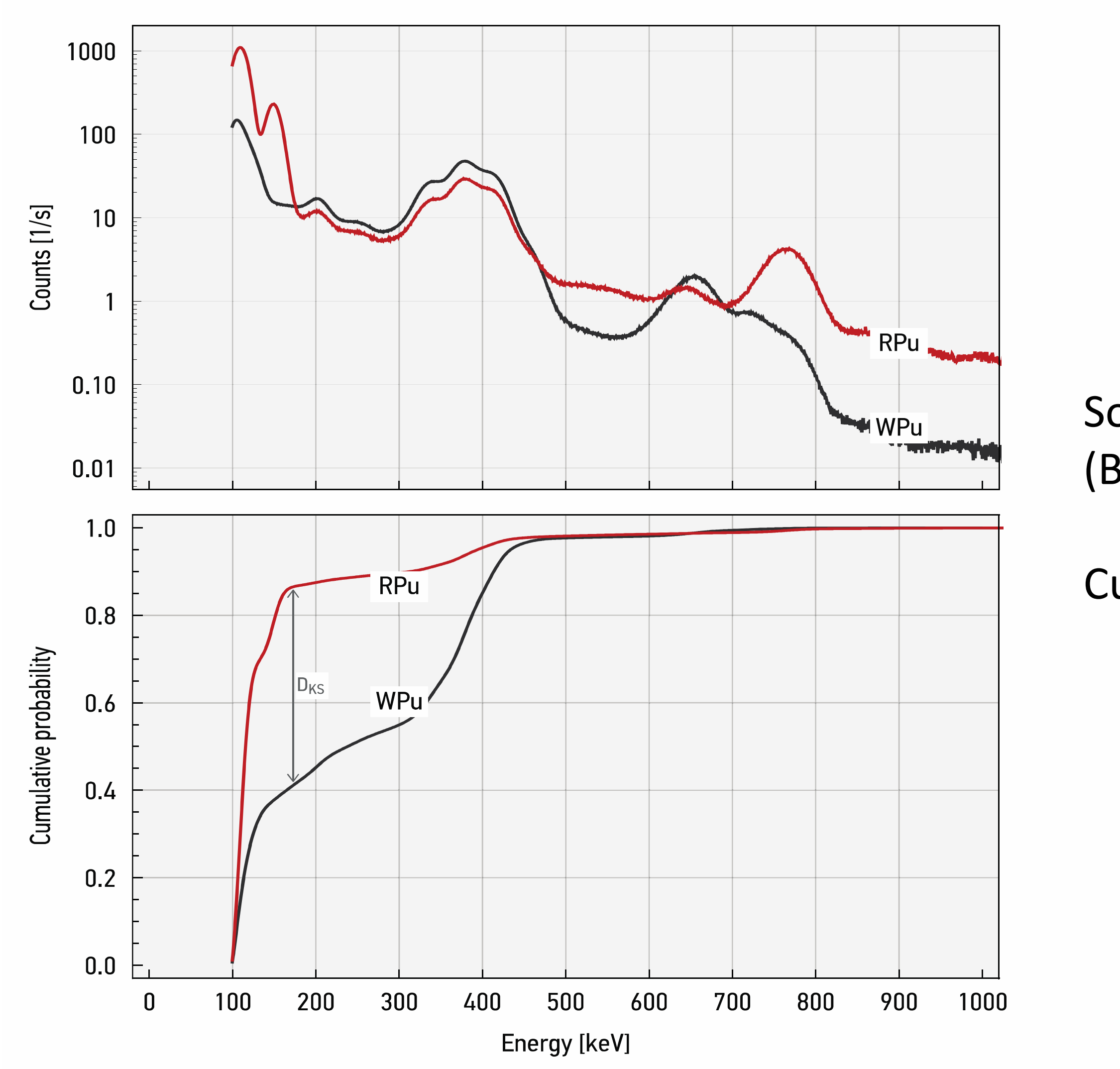
<u>Verify that an item is a nuclear warhead (without visual access)</u>

Acquiring a gamma spectrum (weapon-grade Pu?) or neutron counts (sufficient Pu mass?) can contain too much information



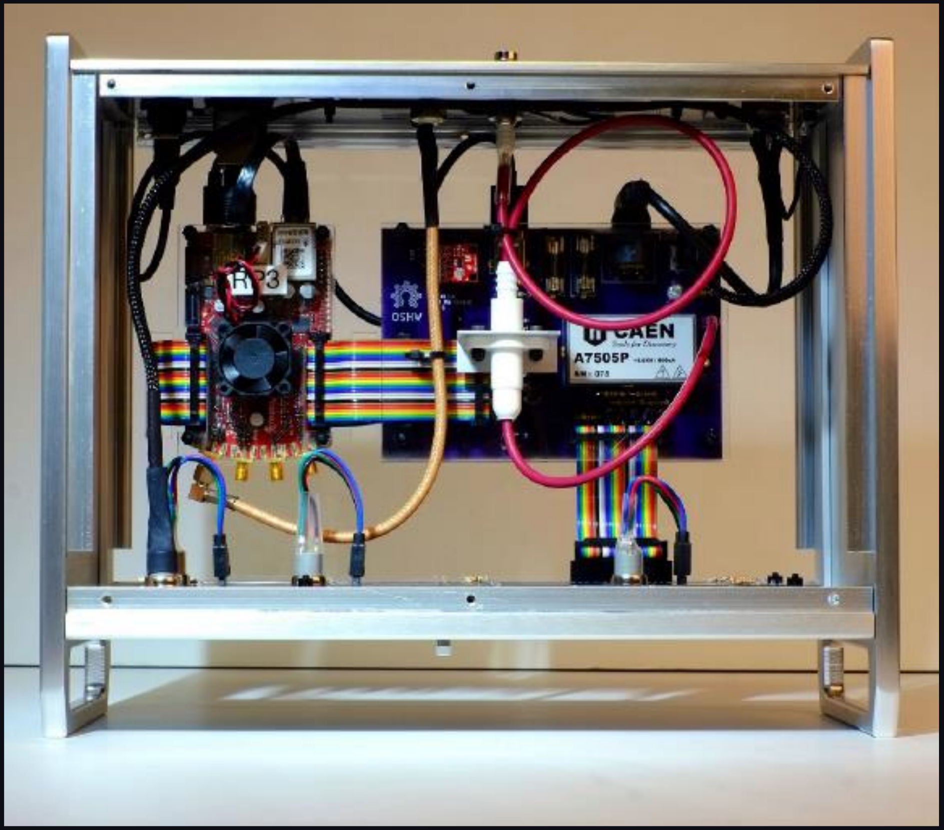
Information Barriers: Gamma Spectrometry

Interpreting gamma spectra as probability density distributions
Hypothesis testing (Kolmogorov Smirnov Test)



Sodium iodide detector
(Based on MCNP simulations)

Cumulative distribution function



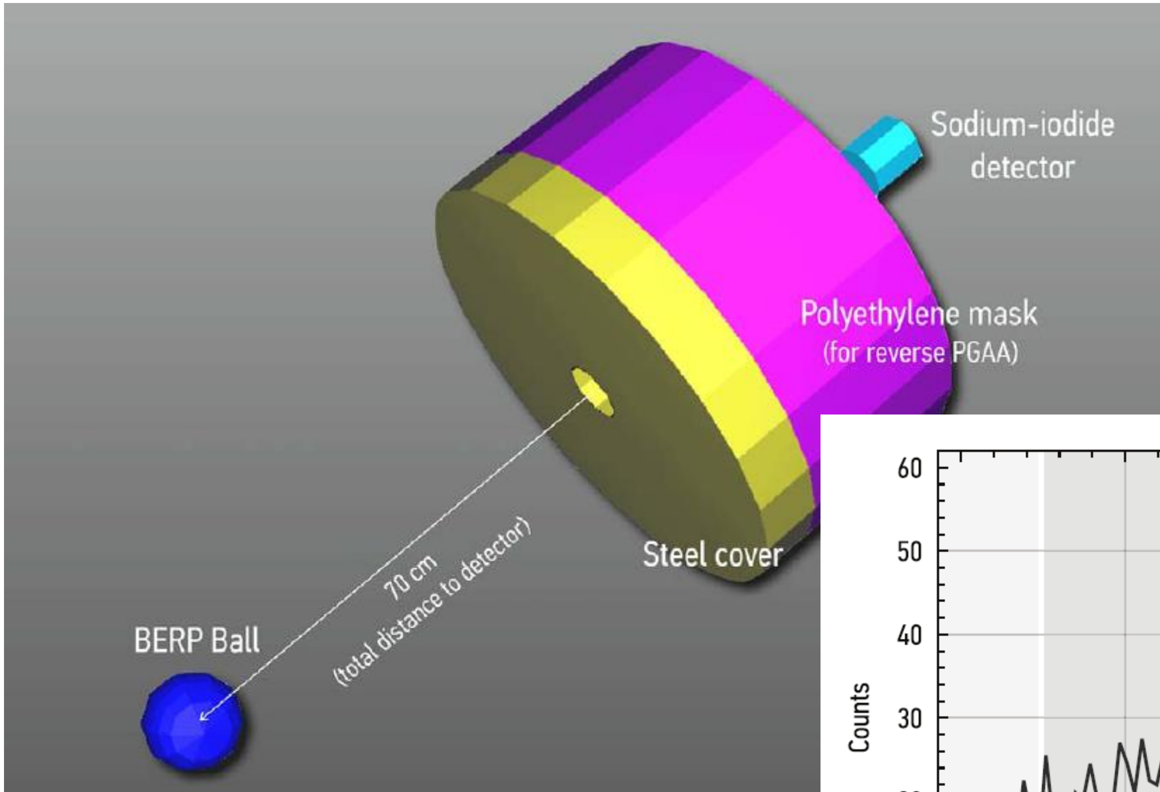
M. Kütt, M. Göttsche, A. Glaser, *Measurement* 114:185-190, 2018

Information Barriers: Neutron counting

How to determine fissile mass?

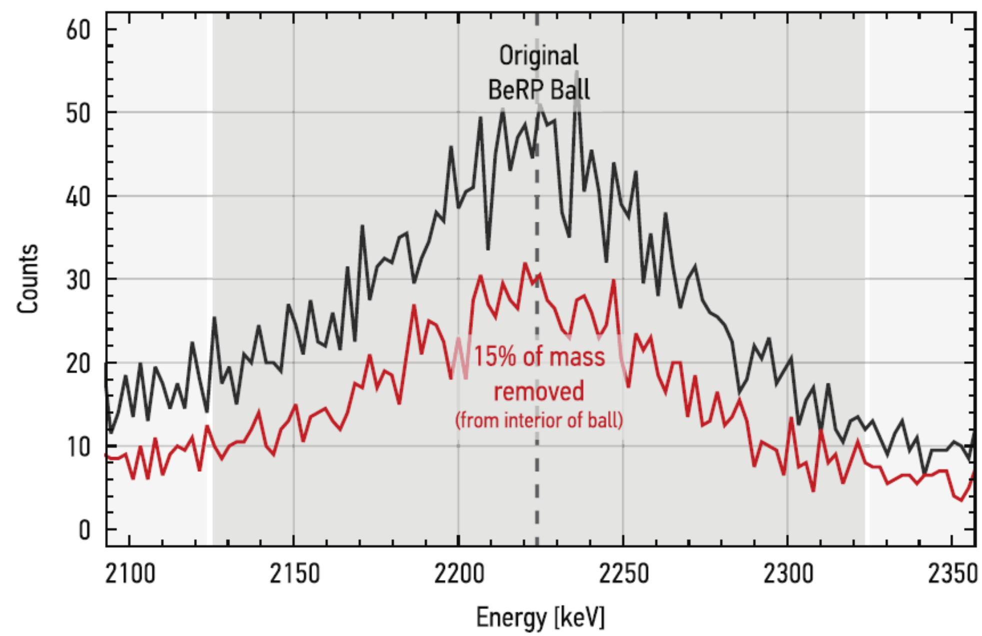
- Due to strong (self-)absorption of gamma rays in high-Z materials, gammas that escape come from close to the surface

Information Barriers: Indirect neutron detection



(n, γ) in hydrogen

Neutron counts for simulated 30 s measurement



M. Göttsche, J. Schirm, A. Glaser, *Nuclear Instruments and Methods A* 840:139-144, 2016

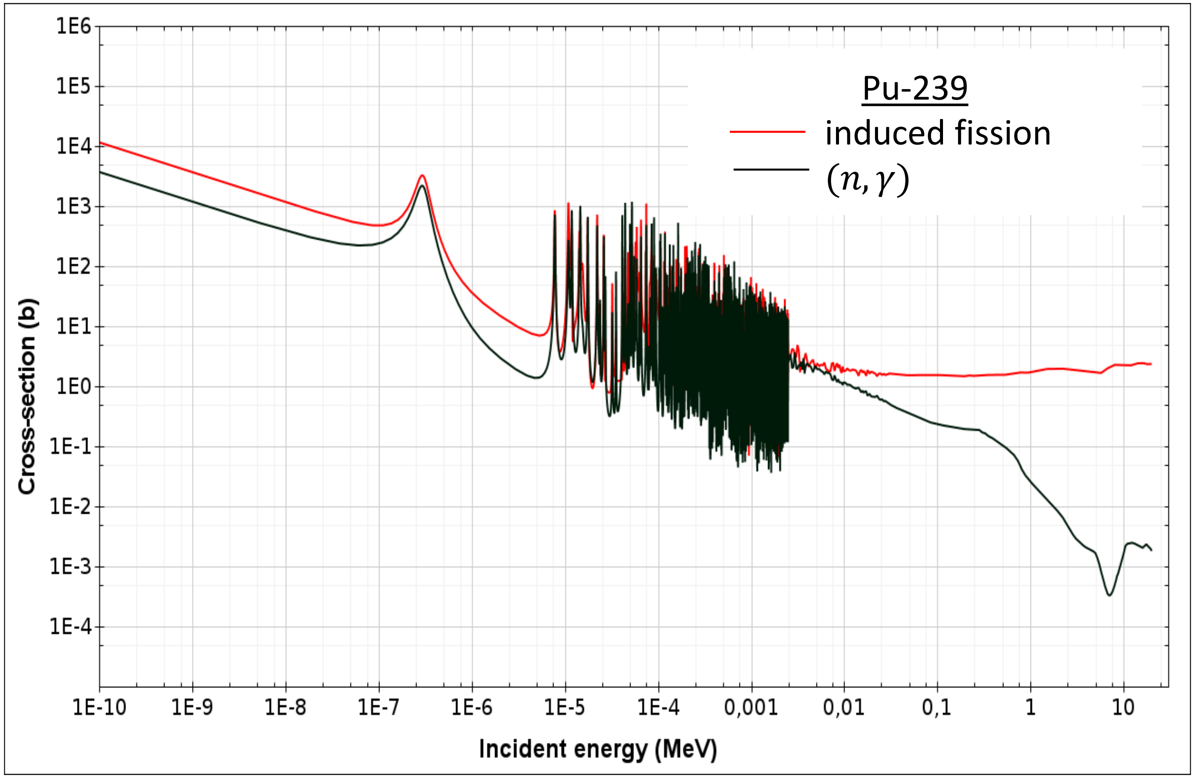
Information Barriers:
Neutron Multiplicity Counting

Primary neutrons (plutonium)

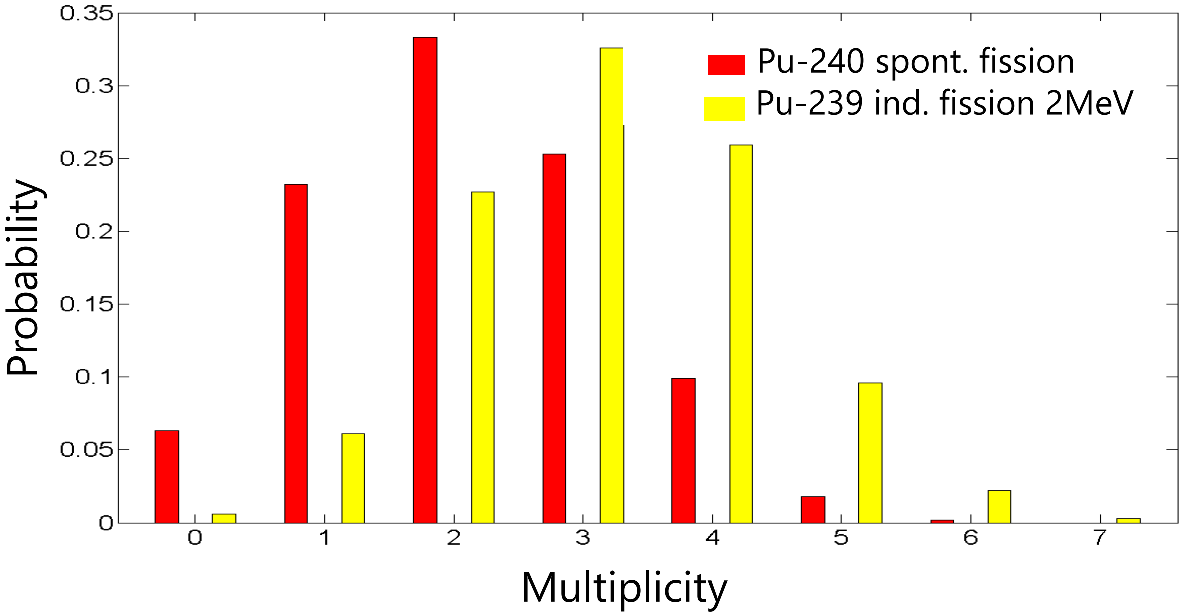
- Pu-240 spontaneous fission — fission rate F $= m_{240} \cdot 479{,}1\ fissions/g$
- (α, n) reactions in oxide — $\alpha = n_\alpha / n_{spont.fission}$

Neutron multiplication

M = Number of neutrons leaking the Pu source in total per primary neutron



Assessing Fissile Mass: Neutron Multiplicity Counting



„Super fission" model

Analytical description of primary neutrons and subsequent neutron multiplications by a single multiplicity distribution

Assessing Fissile Mass: Neutron Multiplicity Counting

Measuring the multiplicity distribution of a „super-fission"

Describing the measured distribution by ist first three moments

$$S = \boldsymbol{F}(1+\boldsymbol{\alpha})\boldsymbol{M} \cdot \epsilon \nu_{sf1}$$

$$D = 1/2 \cdot \boldsymbol{F} \cdot \boldsymbol{M}^{\boldsymbol{2}} \cdot \epsilon^2 f_d [\nu_{sf2} + \frac{\boldsymbol{M}-1}{\nu_{i1}-1} \nu_{sf1}(1+\boldsymbol{\alpha})\nu_{i2}]$$

$$T = 1/6 \cdot \boldsymbol{F} \cdot \boldsymbol{M}^{\boldsymbol{3}} \cdot \epsilon^3 f_t \{\nu_{sf3} + \frac{\boldsymbol{M}-1}{\nu_{i1}-1}[3\nu_{sf2}\nu_{i2} + \nu_{sf1}(1+\boldsymbol{\alpha})\nu_{i3}] + 3\left(\frac{\boldsymbol{M}-1}{\nu_{i1}-1}\right)^2 \nu_{sf1}(1+\boldsymbol{\alpha})\nu_{i2}^2\}$$

Solving the system of equations numerically

$$\boldsymbol{F} = m_{240} \cdot 479{,}1\, fissions/g$$

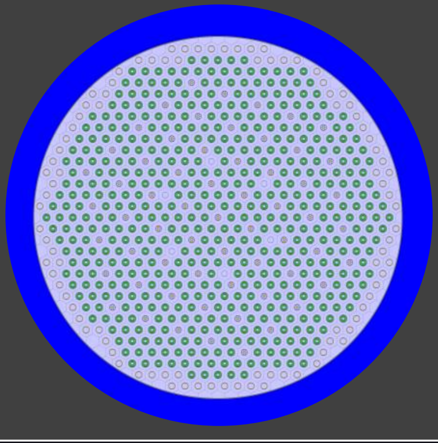
M. Göttsche, G. Kirchner, *Nucl. Instr. Meth. A* 798, 2015
K. Böhnel, *Nuclear Science & Engineering* 90:75-82, 1985

My verification research

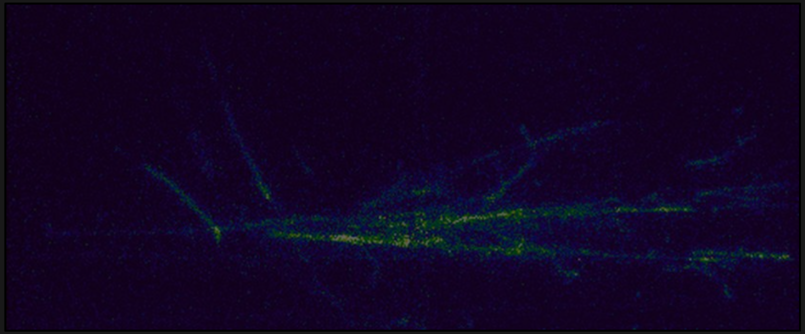
Gamma & neutron detection

A. Glaser

Computational nuclear archaeology



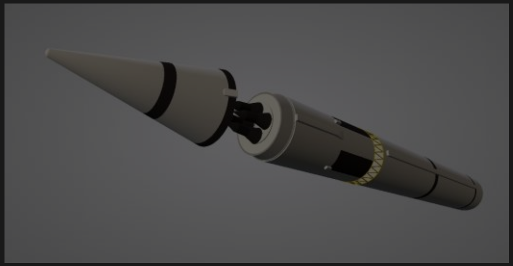
Antineutrino detection



K. Mavrokoridis

Nuclear disarmament verification

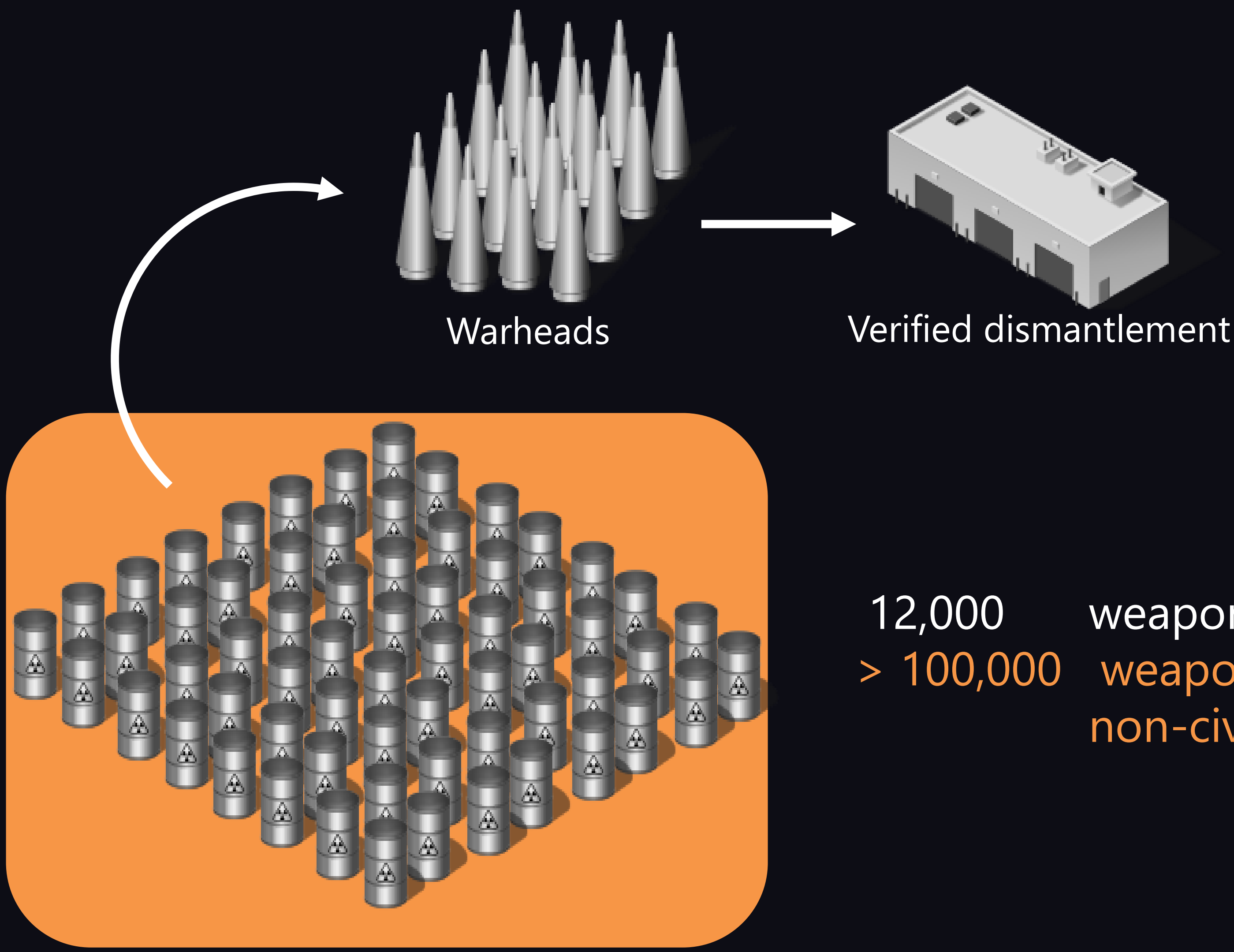
Delivery systems



Warheads

Fissile materials

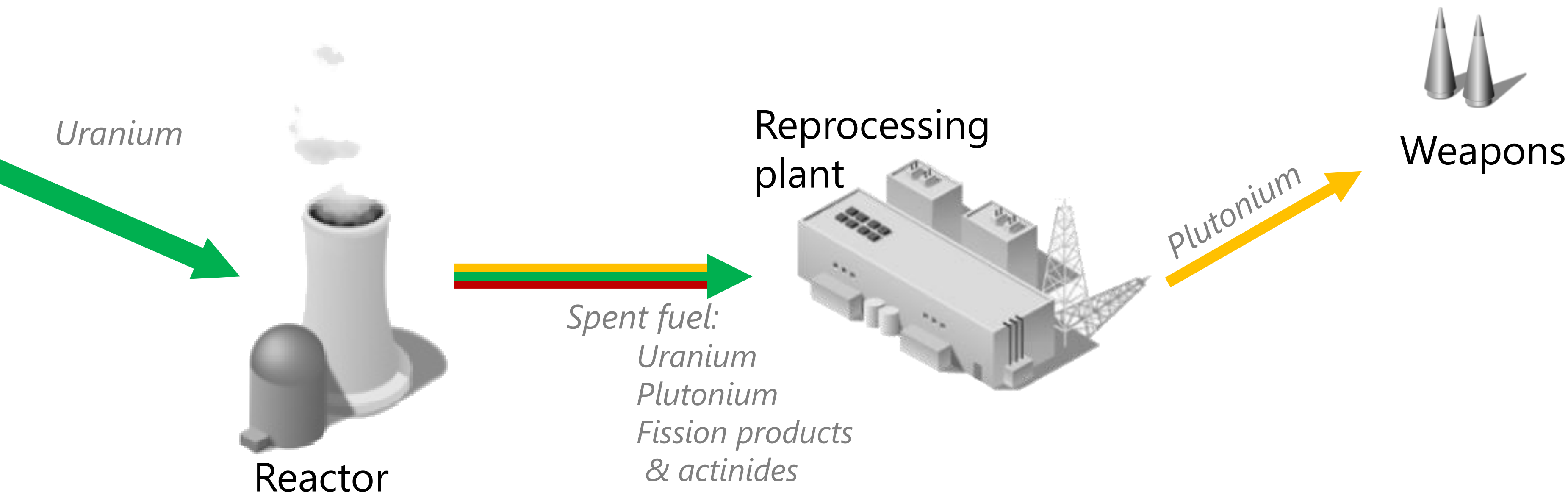
Verifying Fissile Material Inventories

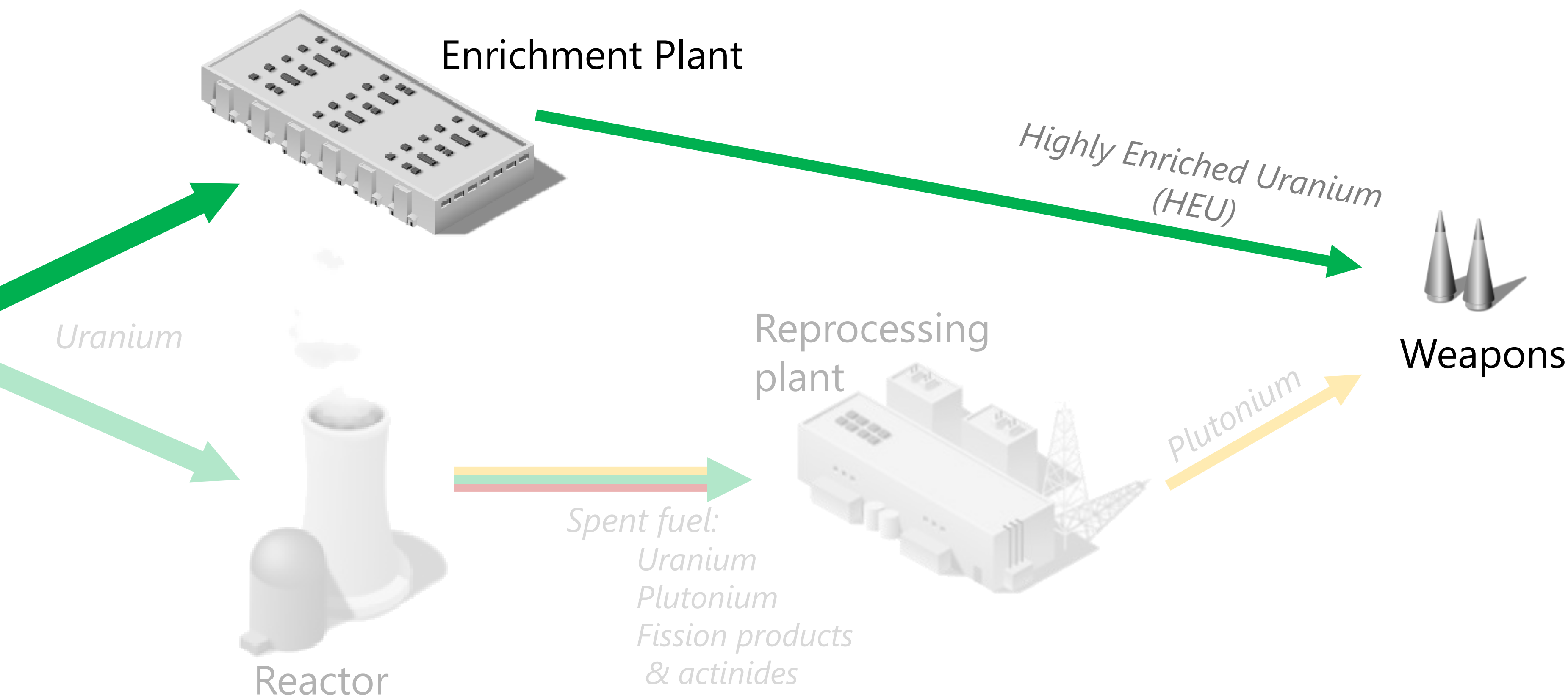


12,000 weapons today

> 100,000 weapon-equivalents of non-civil fissile materials

Independent fissile material estimates – now


Uranium
Reactor
Spent fuel:
Uranium
Plutonium
Fission products
& actinides
Reprocessing plant
Plutonium
Weapons



Enrichment Plant
Highly Enriched Uranium
(HEU)
Weapons
Uranium
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Plutonium
Spent fuel:
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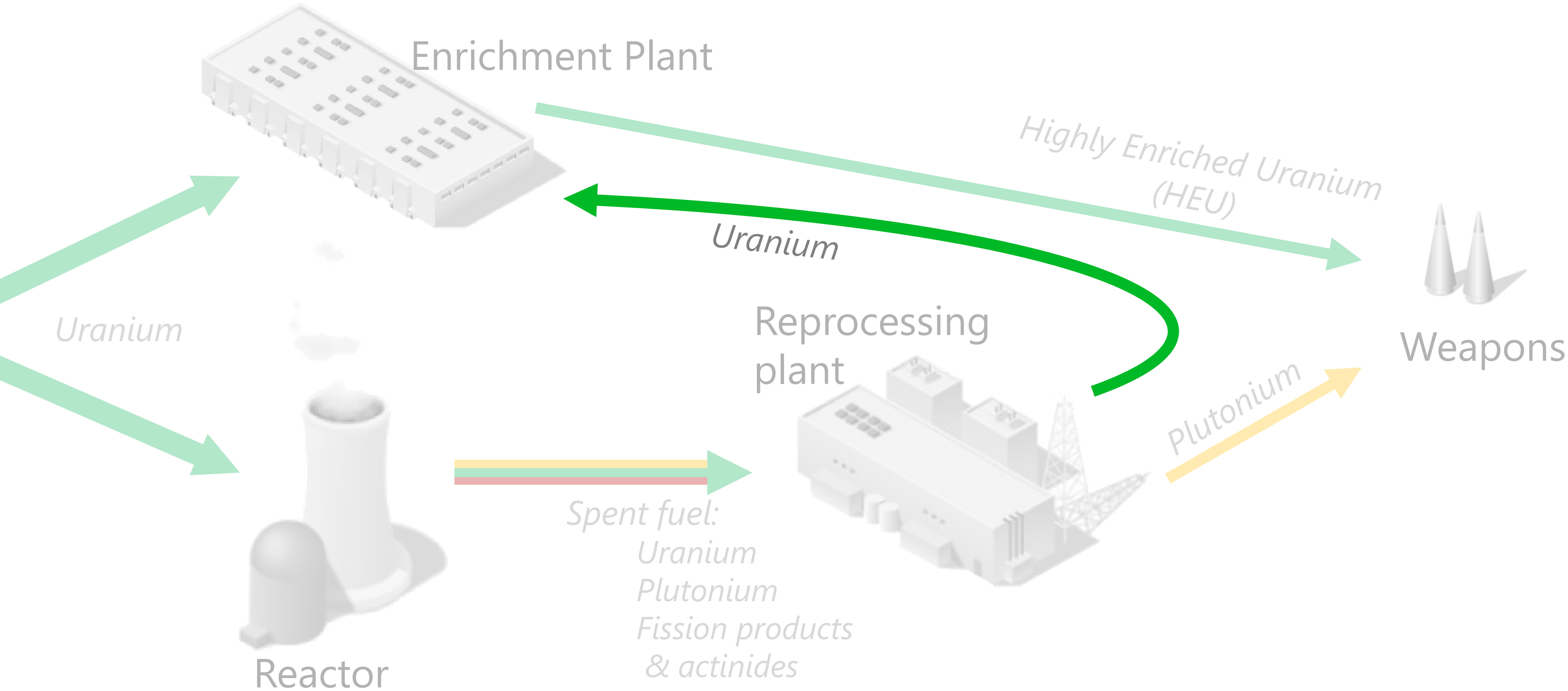
Plutonium
Fission products
& actinides
Reactor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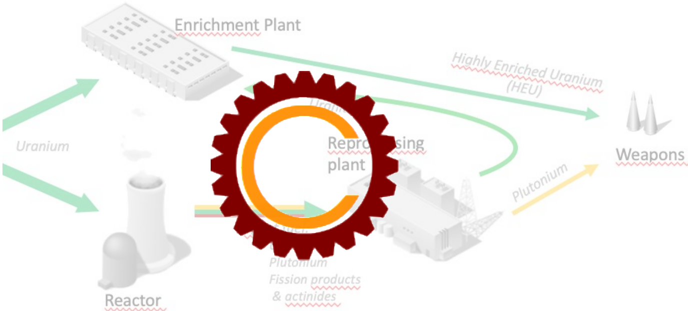


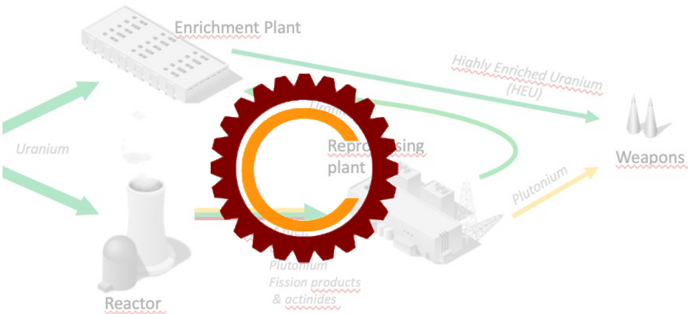
Fuel cycle simulations: CYCLUS

- Physics-based facility agents (specified parameters)
- Optimized material transfers over time

Combining with statistics: BICYCLUS

- e.g. parameter sampling (quasi-random Monte Carlo), uncertainty propagation

M. Schalz, L. Bormann, M. Göttsche, Trans. Am. Nucl. Soc. 126, 2022
K. Huff, Adv. Eng. Softw., 2016



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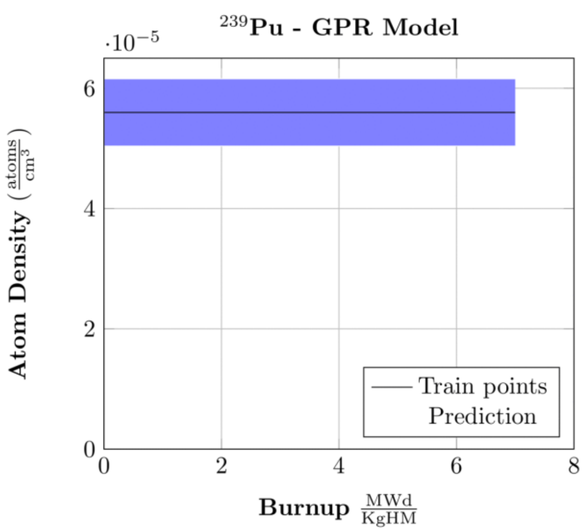
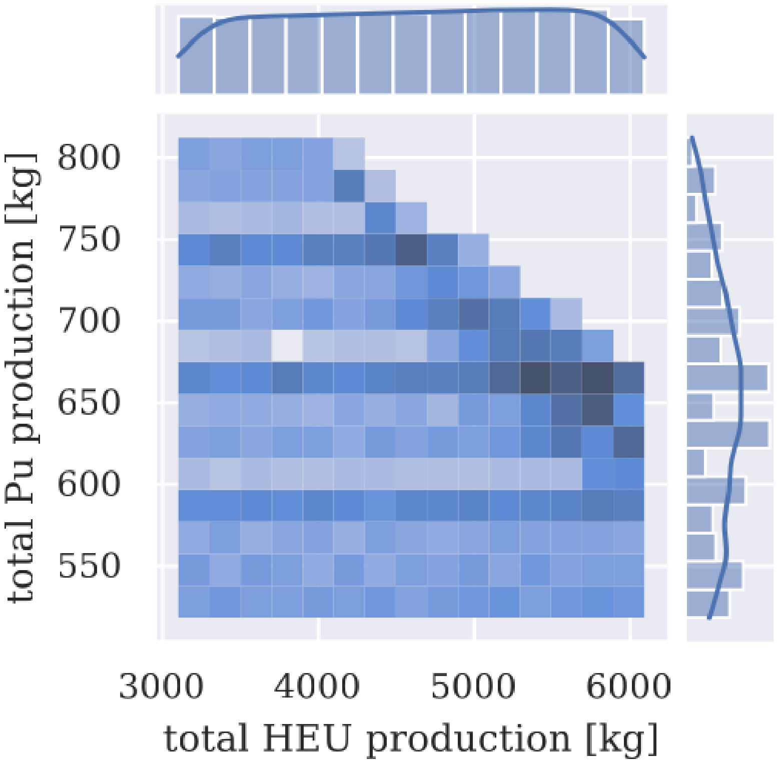


Creating a fast reactor surrogate model

- Reactor model to predict spent fuel composition in a split-second
- Machine learning: Gaussian Process Regression
- Outperforms currently used regressions

A. Figueroa, M. Göttsche, Ann. Nucl. Energy 156, 2021

Independent fissile material estimates: Forward-simulations



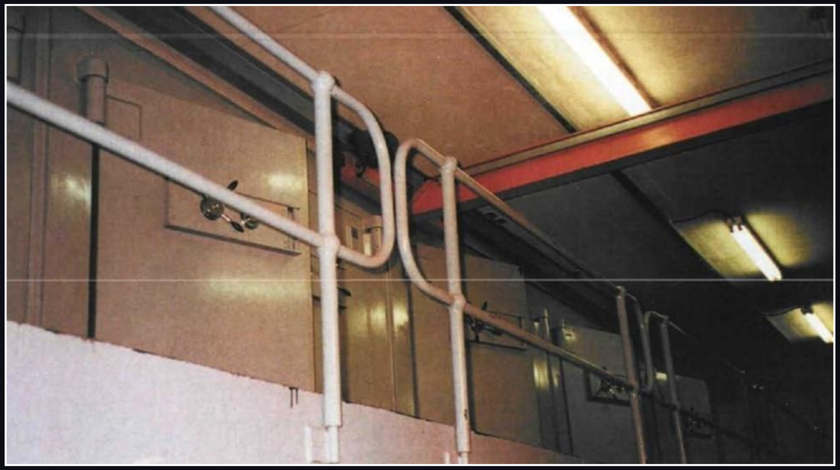
- More robust estimates than previously possible, robust uncertainties

From independent fissile material estimates
to cooperative verification:

Nuclear archaeology

Combining simulations with measurements

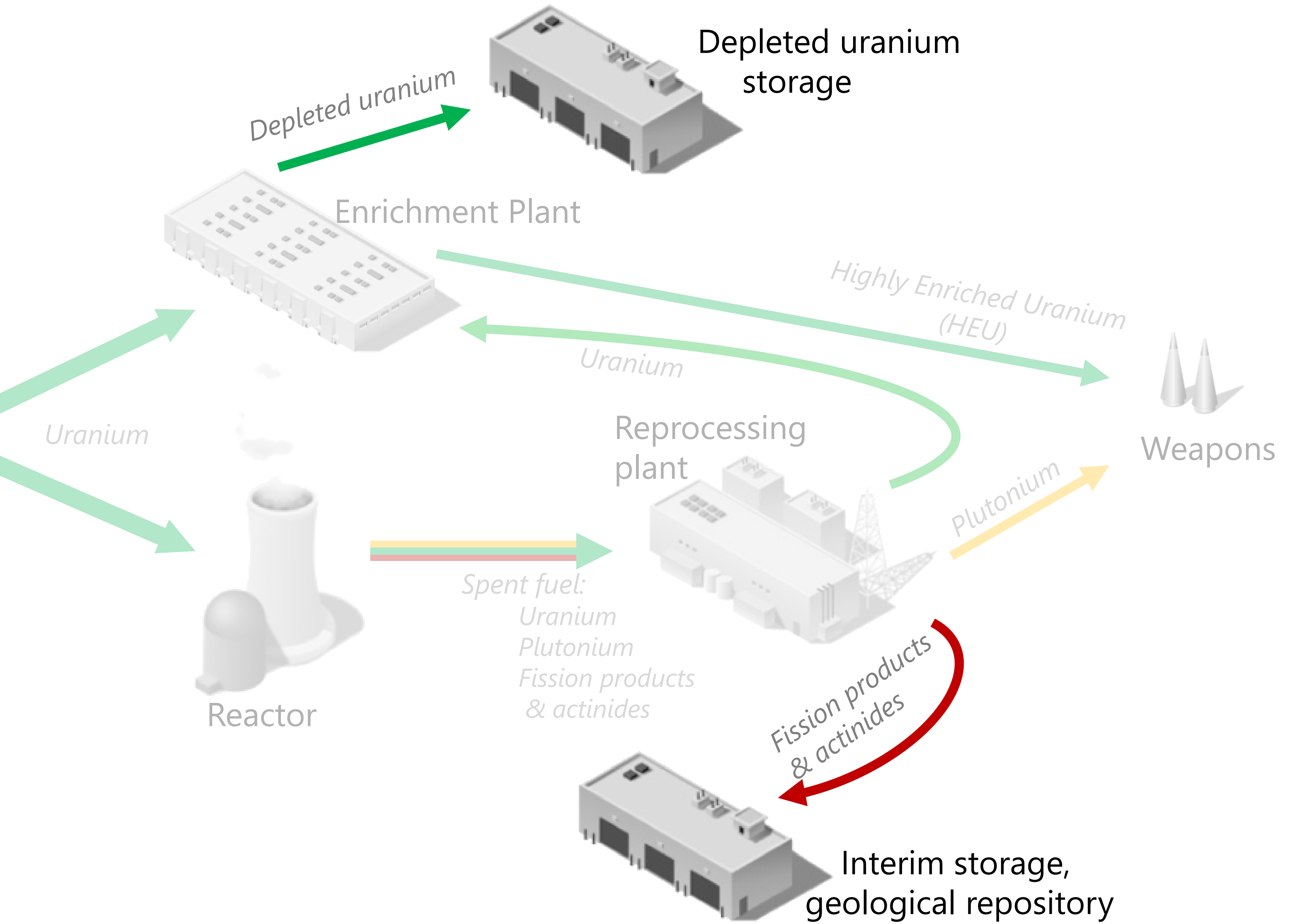
“Nuclear archaeology” precedent



South Africa 1993

South Africa:

- Examining **documentation** from facility operations for consistency (thousands of pages)
- **Re-simulating** operations to independently obtain produced fissile materials
- Taking various **measurements** to clarify inconsistencies (e.g. uranium in enrichment tails)



Depleted uranium storage
Depleted uranium
Enrichment Plant
Highly Enriched Uranium (HEU)
Uranium
Weapons
Uranium
Reprocessing plant
Plutonium
Spent fuel:
Uranium
Plutonium
Fission products
& actinides
Reactor
Fission products
& actinides
Interim storage,
geological repository

Nuclear archaeology as an inverse problem

Bayesian Inference

$$p(x|y) \propto p(y|x) * p(x)$$

Posterior　　Likelihood　　Prior

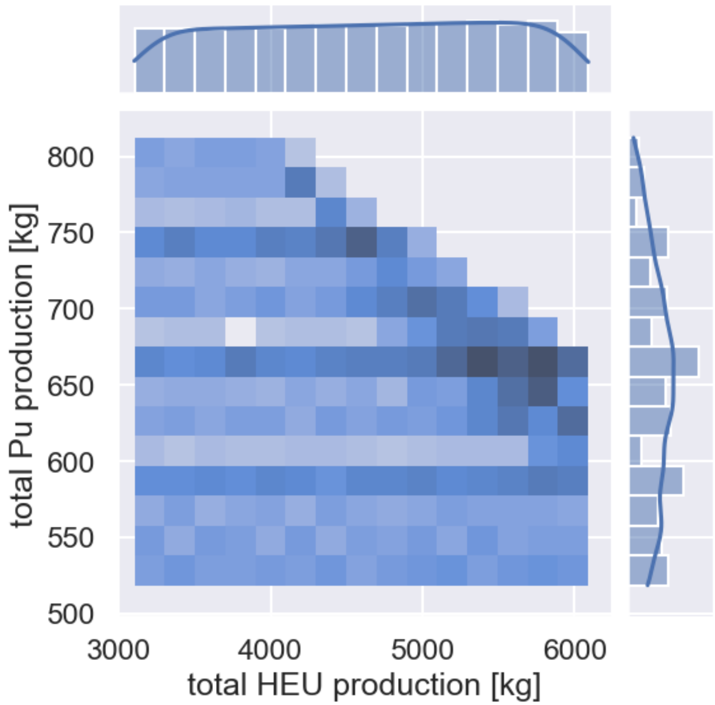
Prior information	$p(x)$
Test a specific set of parameters x	$F(x)$: forward-simulation (GPR)
Compare to measurements y	$p(y\|x) \propto \exp\left(-\left(\frac{y-F(x)}{\sqrt{2}\sigma}\right)^2\right)$

Markov Chain Monte Carlo

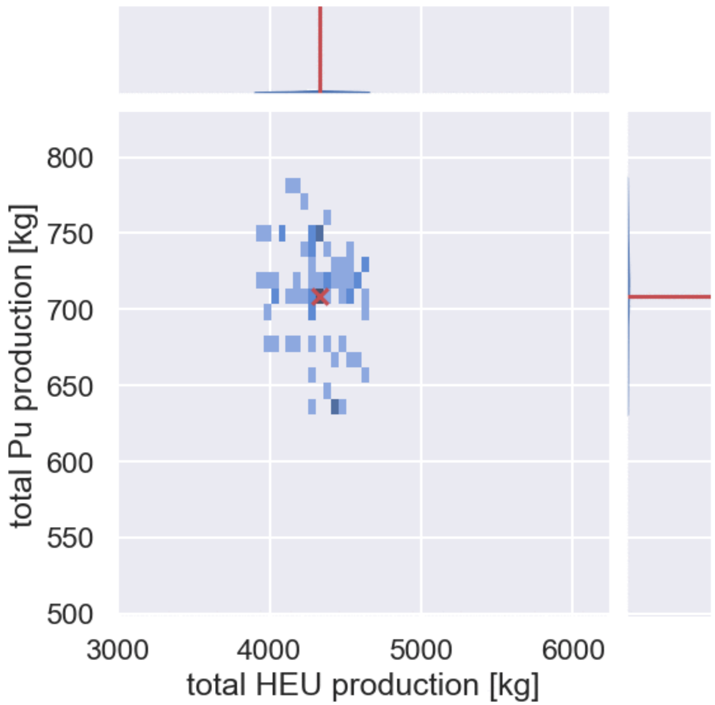
A. Figueroa, M. Göttsche, ESARDA Bulletin 59, 2019

Results

Independent assessment
(forward)



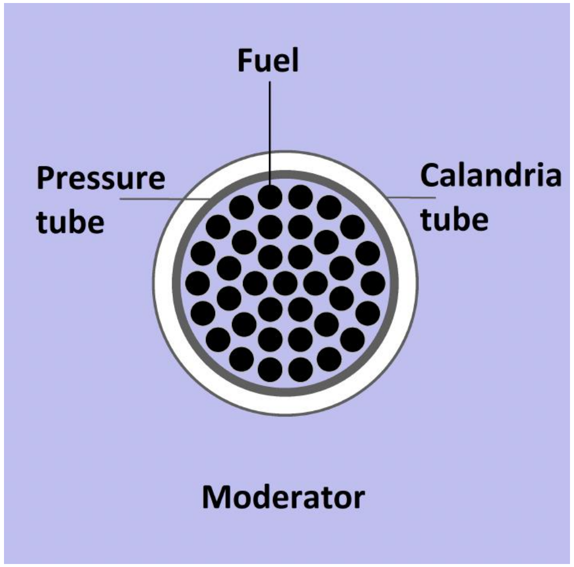
Nuclear archaeology
(inverse)



M. Schalz, L. Bormann, M. Göttsche, Ann. Nucl. Energy. 196, 2024

Archaeology with shut-down reactors

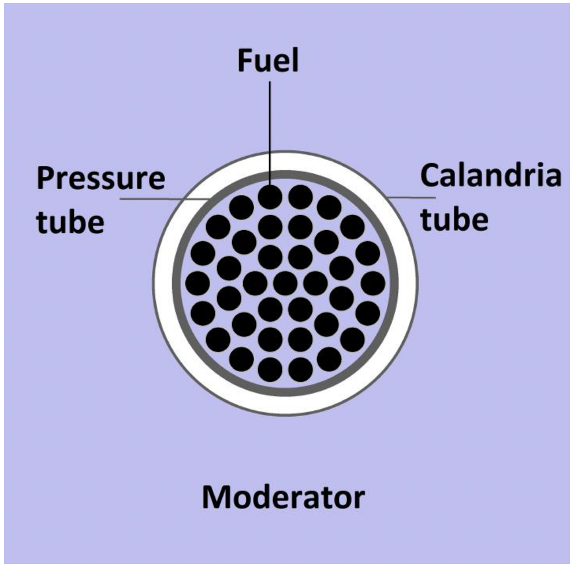
Example: CANDU reactor



- Sampling permanent structures inside core (e.g. pressure tube)
- Trace elements in zircaloy
- Sensitivity analysis to identify isotopic ratios that tell about the history

Archaeology with shut-down reactors

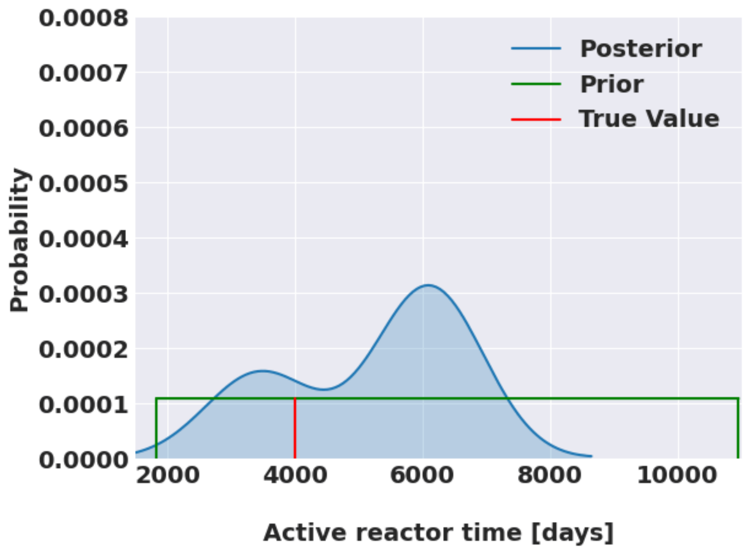
Example: CANDU reactor

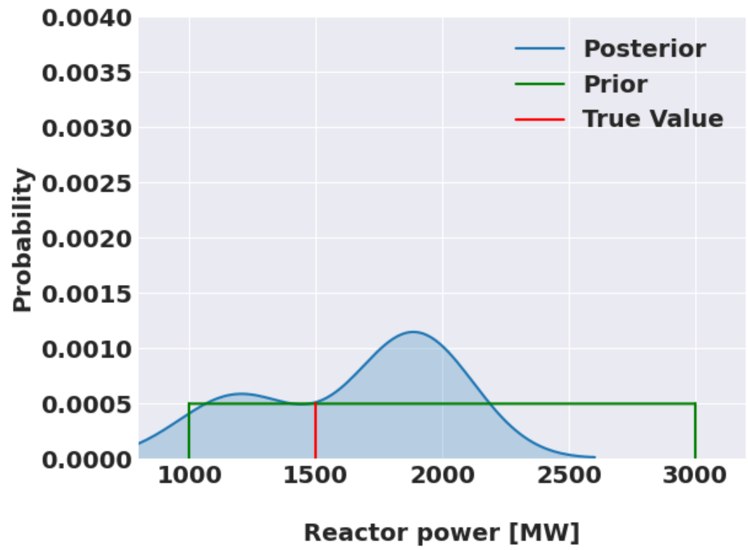


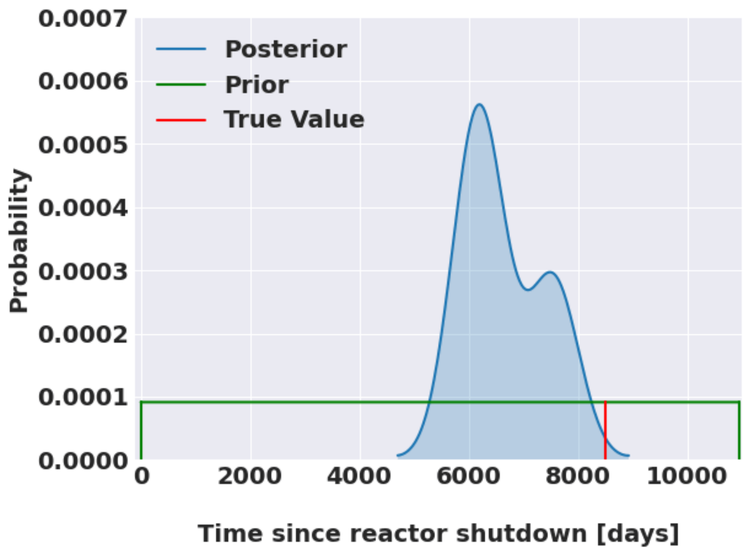
- Sampling permanent structures inside core (e.g. pressure tube)
- Trace elements in zircaloy
- Sensitivity analysis to identify isotopic ratios that tell about the history

Isotopic ratio	Sensitivity	Explanation
O-17/O-18	Active period	Neutron capture, stable isotopes
Hf-180/Hf-182	Thermal power	2x capture via short-lived Hf-181
Sr-86/Sr-90	Shut-down time	Sr-90 decay, Sr-86 stable

Fast surrogate model & Bayesian inference



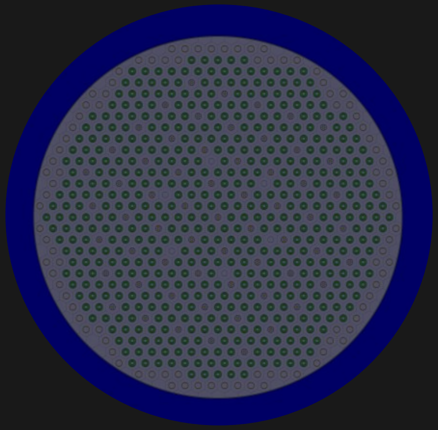




My verification research

Gamma & neutron detection

Computational nuclear archaeology



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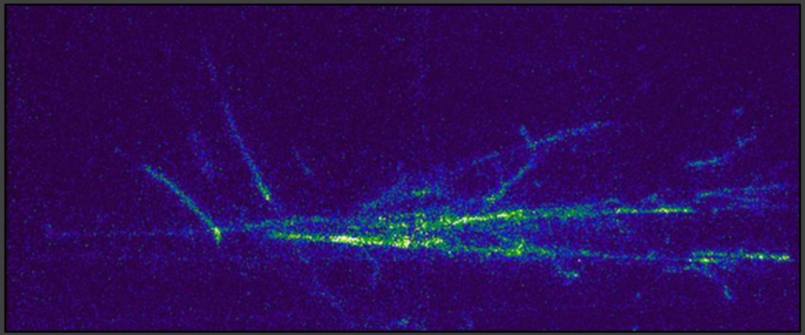
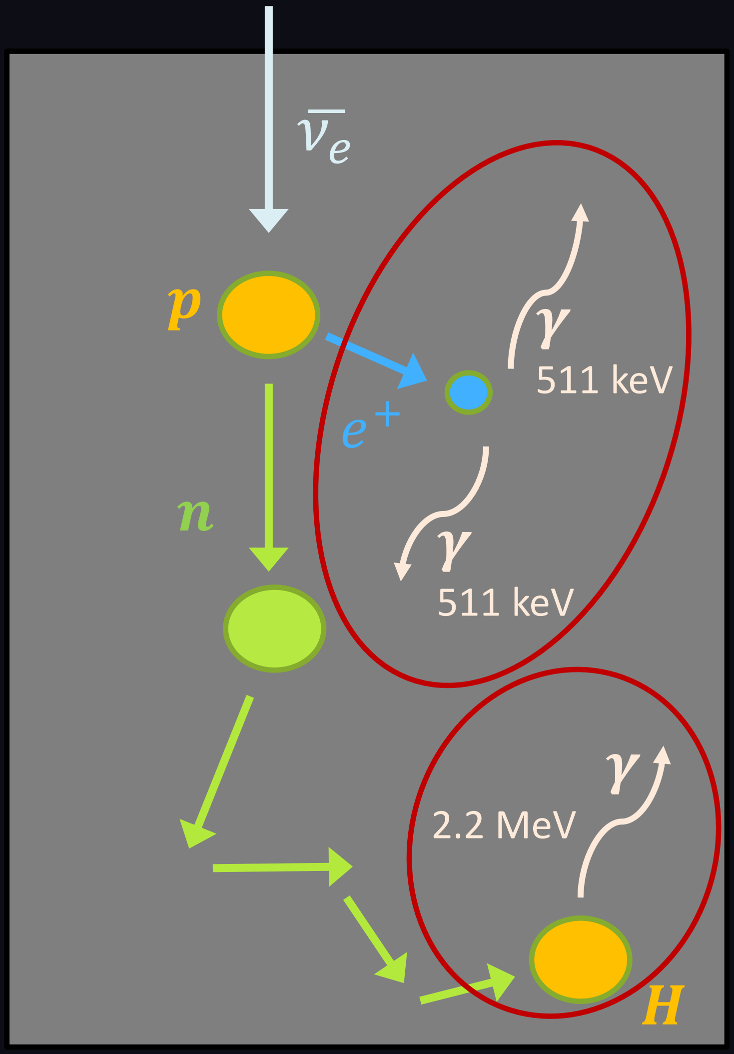
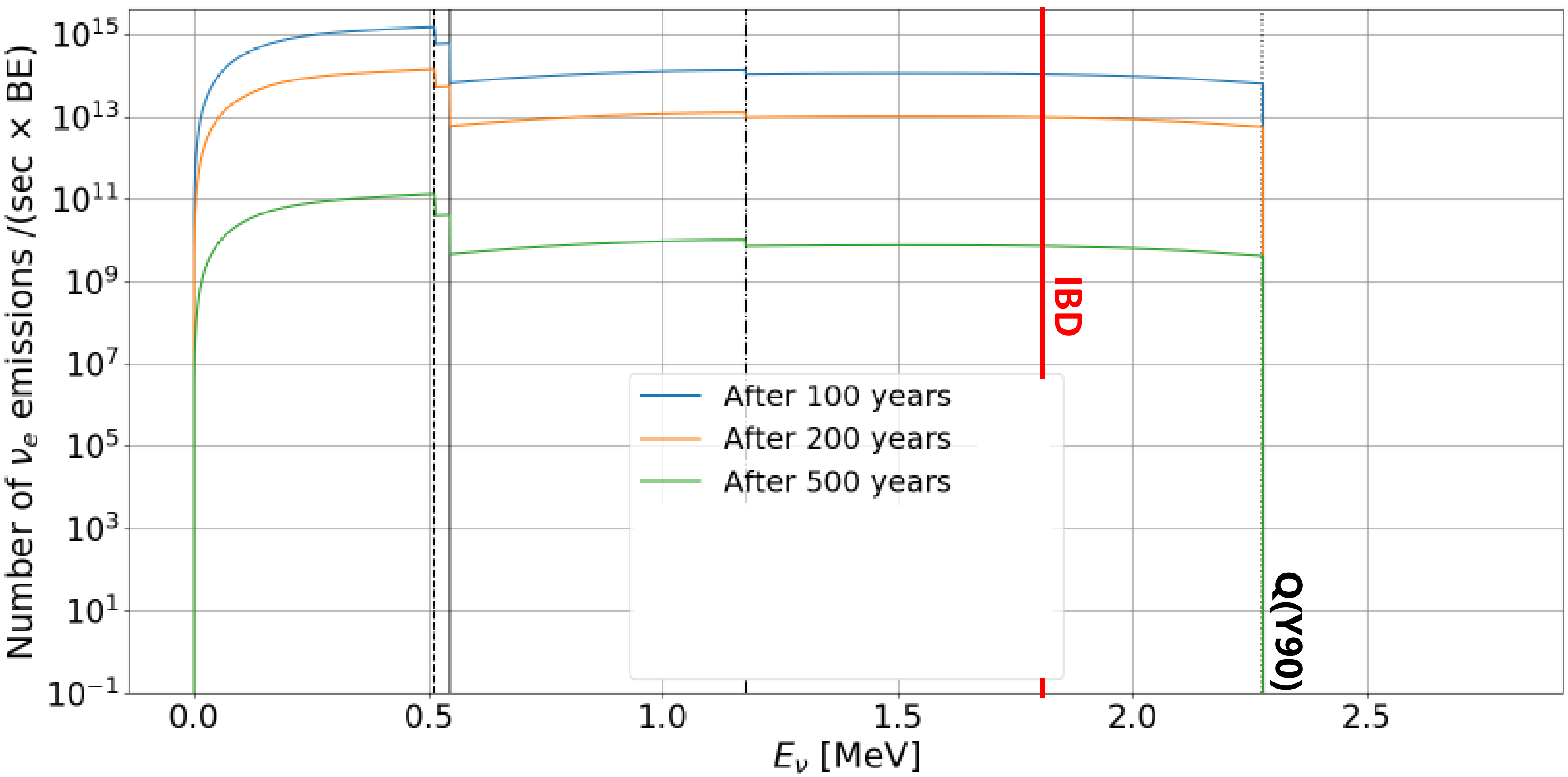


Inverse Beta Decay (IBD)



- Kinetic threshold 1.8 MeV
- Additional energy essentially transferred to positron
- Detection in scintillator via delayed coincidence of two energy depositions
- Background sources mimic signal

Monitoring radioactive waste

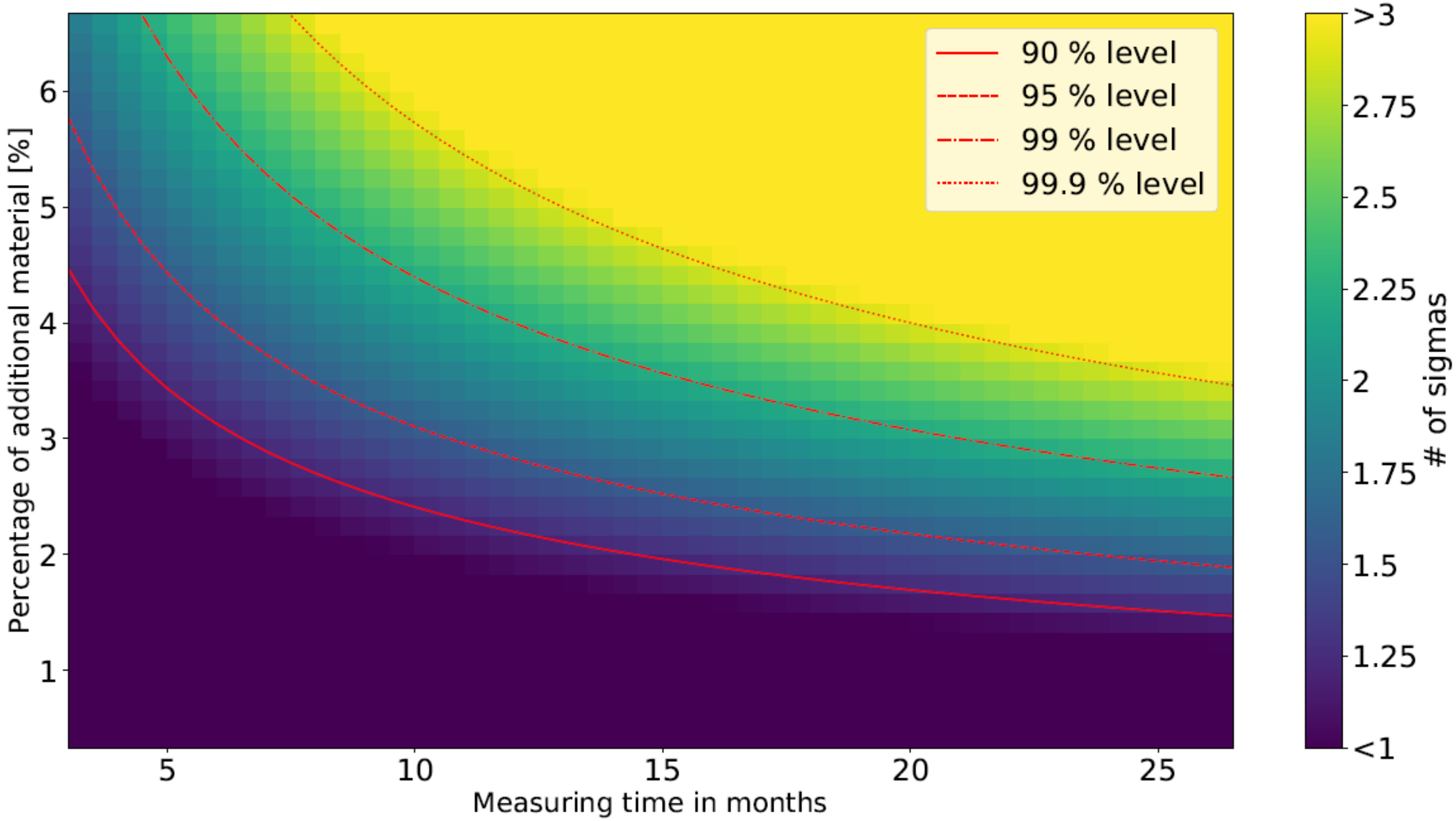


M. Wittel, M. Göttsche, ESARDA Bulletin 60, 2020

Is a radioactive waste site as declared?

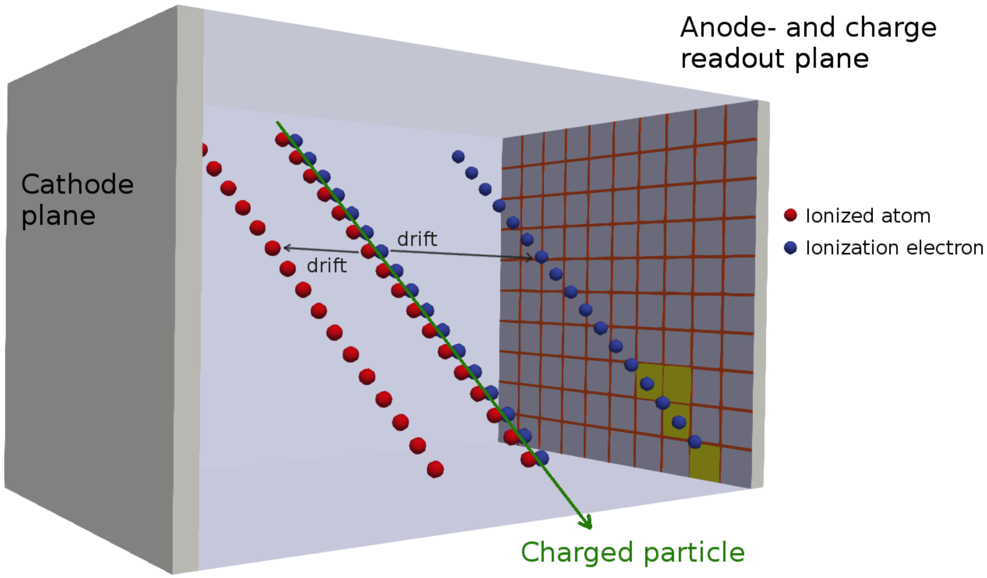
Google Maps, 2020

Is a radioactive waste site as declared?



Organic scintillator, 80 m^3 detection volume, <u>no background considered</u>

Time Projection Chamber



Organic liquid medium

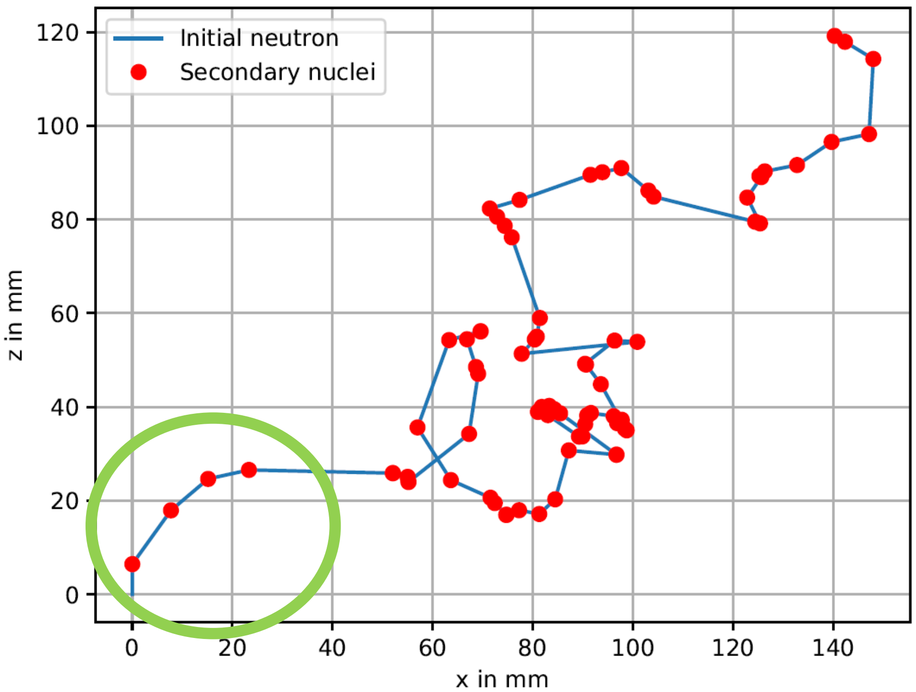
J. Dawsen, D. Kryn, JINST 9, 2014
S. Wu, et al., Nucl. Instr. Meth. A 972, 2020

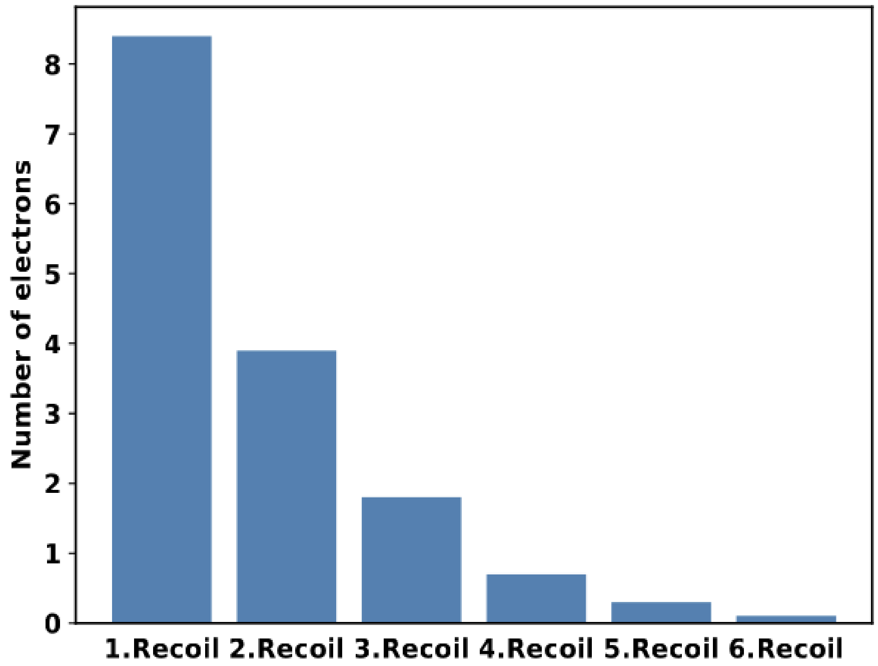
H density comparable to typical scintillators

Measure IBD tracks!

<u>Partner:</u> S. Roth (RWTH Aachen University)
<u>Current status:</u> Simulations, build prototype

Time Projection Chamber: First results





T. Radermacher, J. Bosse, S. Friedrich, M. Göttsche, S. Roth, G. Schwefer, Nucl. Instr. Meth. A 1054, 2023

Thank you for your attention.