Nuclear Disarmament Verification via Resonant Phenomena

(and other adventures in nuclear security)

Areg Danagoulian

Outline

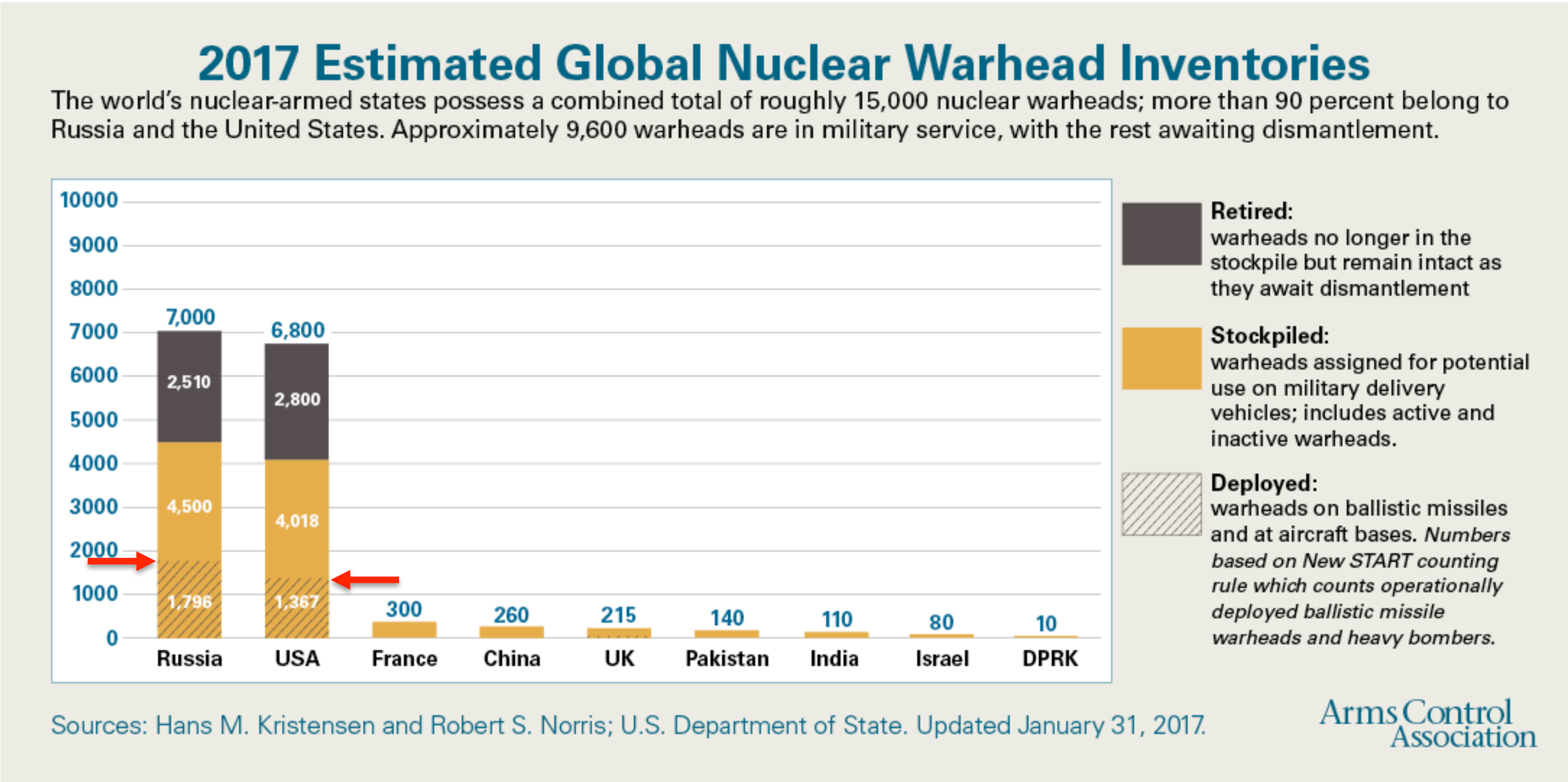
- What’s the big problem? (Nuclear Arms Reduction Treaties)

- Why template verification and how does it work?

- What is Nuclear Resonance Fluorescence (NRF)?
  - → NRF based verification

- Epithermal neutron physics
  - → epithermal neutron verification

Nuclear Arsenals



- Significant Reduction since the Cold War
- ,, Доверяй, но проверяй! '' Но как? How? Ինչպե՞ս:

VERIFICATION

- How do treaty partners verify that the other side is dismantling actual warheads and not fakes? They don't.

- Verification: **delivery vehicles** – eas**ier** to verify.



- Problems: large leftover of non-deployed warheads
  - theft → nuclear terrorism, nuclear proliferation

→ **Authenticate warheads, without revealing secret information**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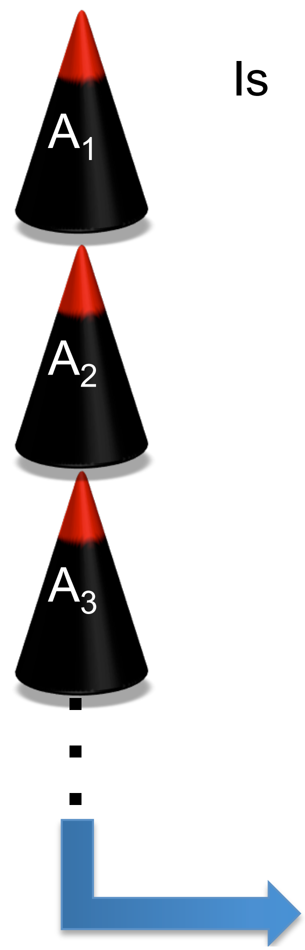
Our Research:
physics-based cryptography, *template* verification

Authenticated template "golden copy" of W88
Picked from a randomly selected ICBM

Candidate copies, W88



Is $A_0 = A_1$? ✓
$A_0 = A_2$? ✓
$A_0 = A_3$? ✓
⋮

To dismantlement

<ins>**Challenge**</ins>: perform checks while

- protecting secrets
- <ins>isotopicaly sensitive</ins>

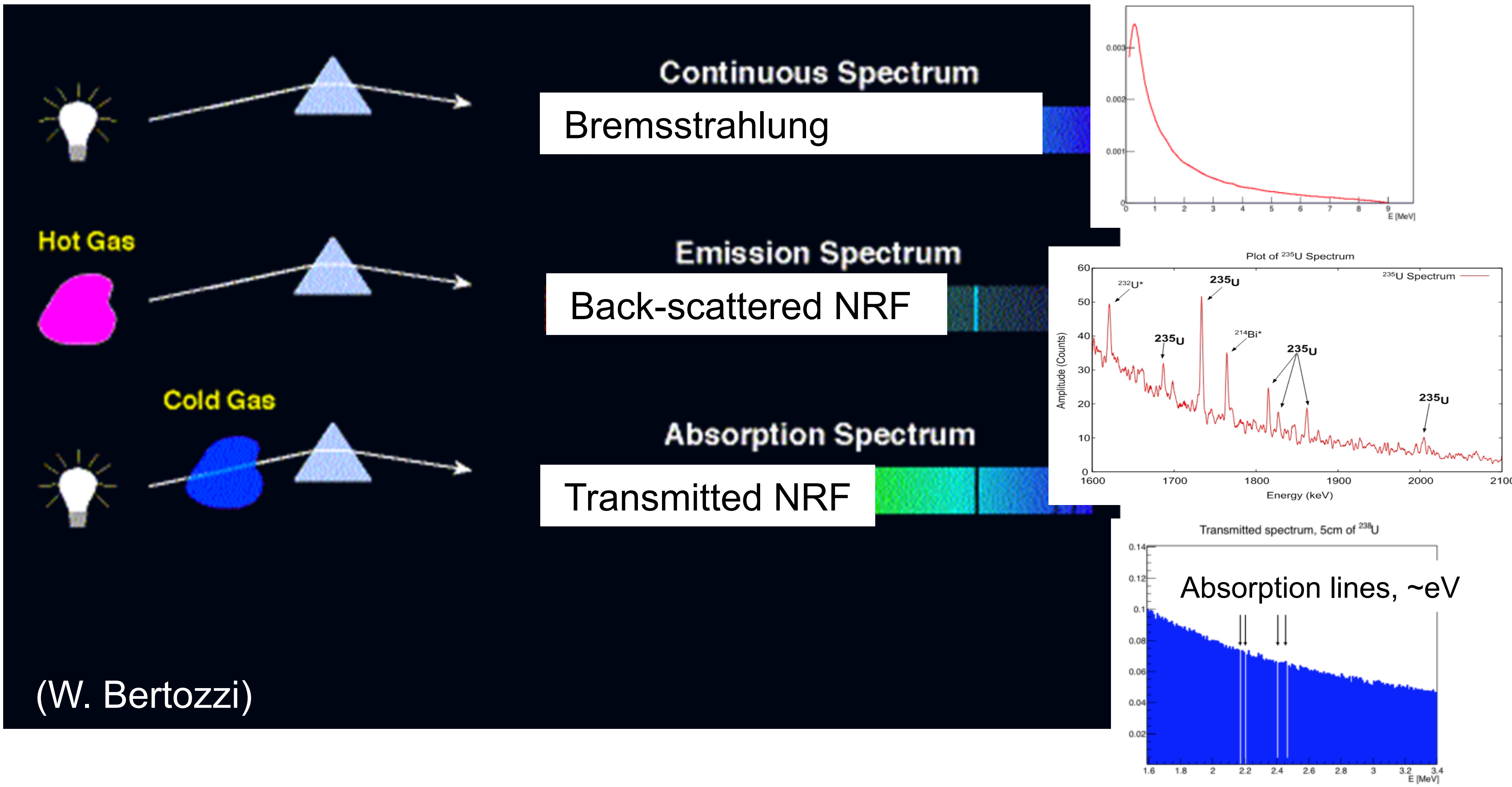
→ need cryptography - **physical** cryptography

→ need **resonances!**

Analogy: NRF to Optical Spectroscopy

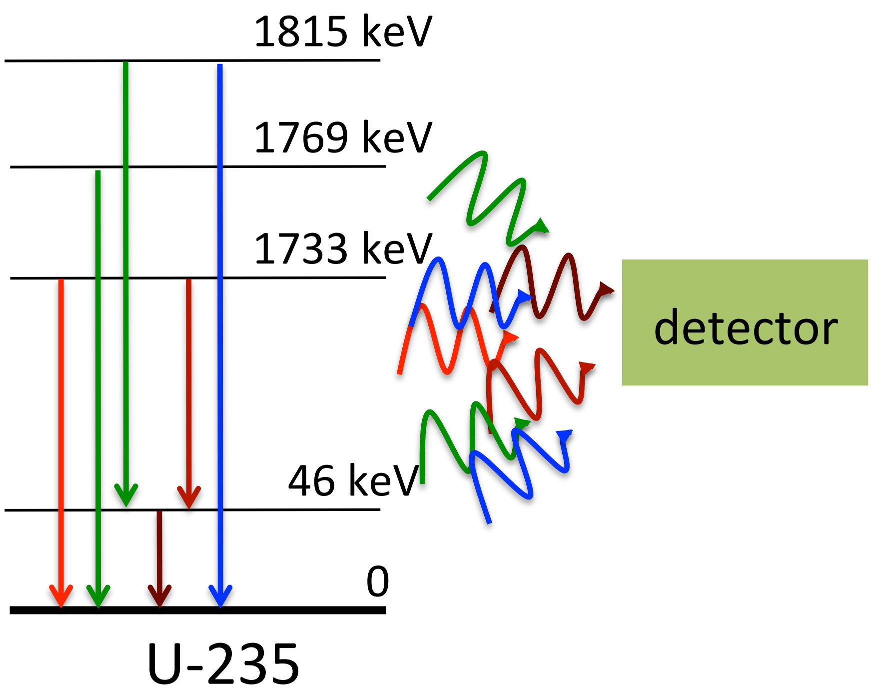
Optical Spectroscopy

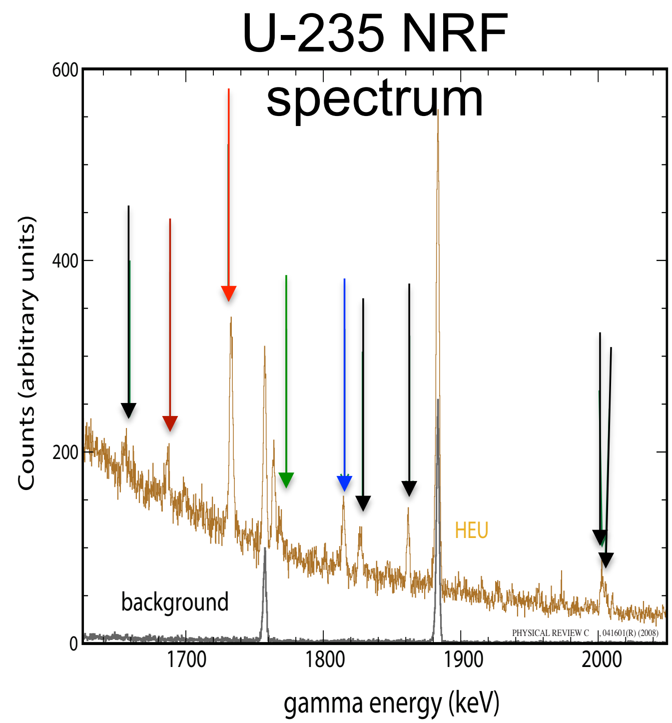
Nuclear Spectroscopy



NRF: unique fingerprint of isotopics

Broad-spectrum source → NRF



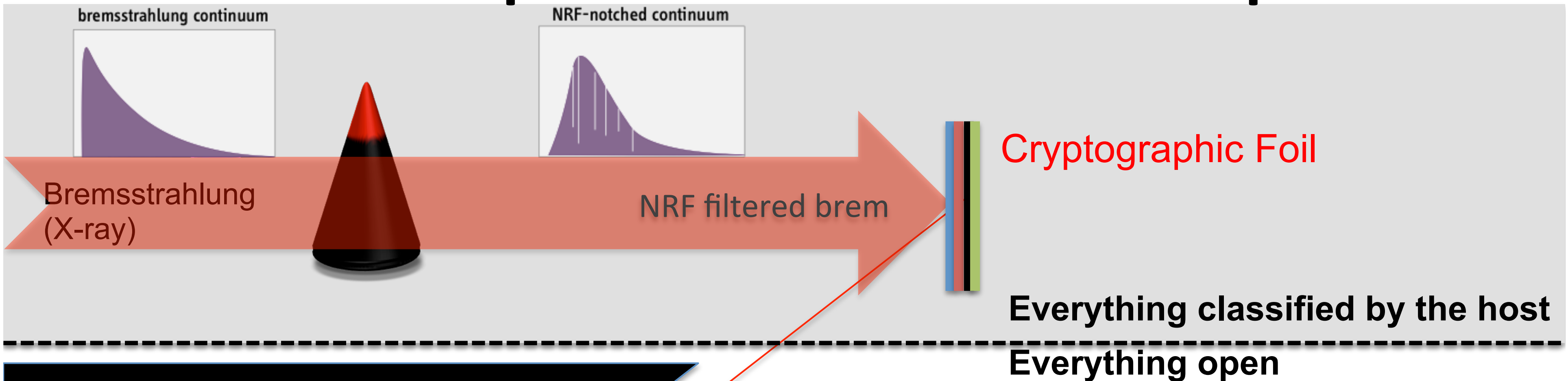


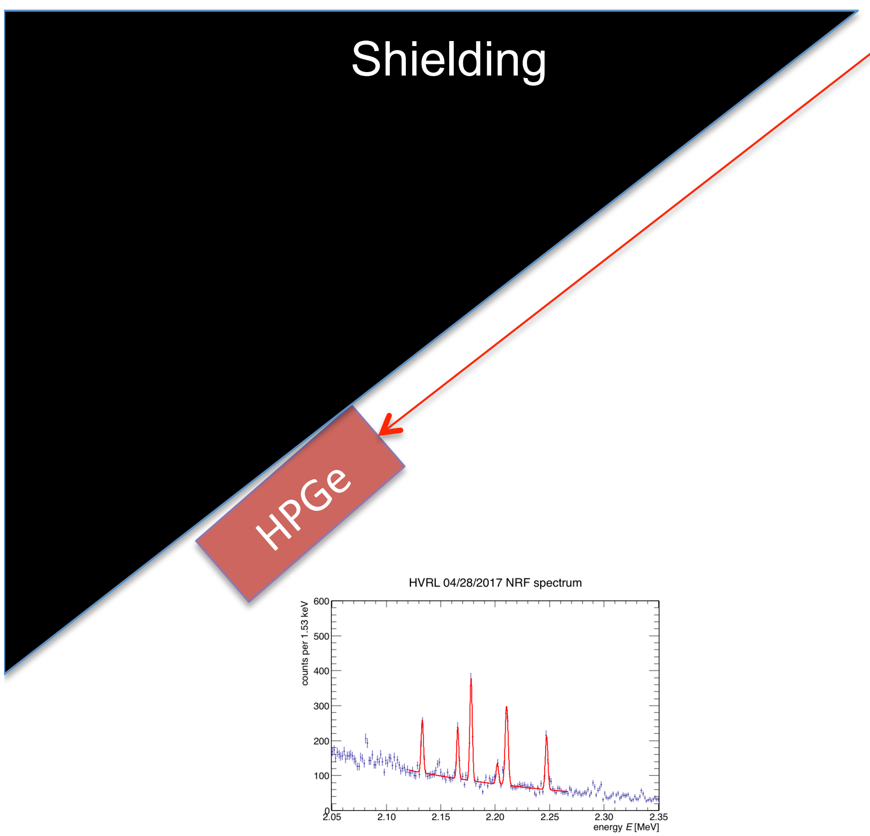
unique line spectra for U-235, U-238, Pu-239, Pu-240…

$$\sigma^{\mathrm{NRF}}_{r,j;\,0\,\mathrm{K}}(E) = \pi g_r \left(\frac{\hbar c}{E}\right)^2 \frac{\Gamma_{r,0}\Gamma_{r,j}}{(E-E_r)^2 + (\Gamma_r/2)^2}.$$

Γ~ meV → thermal motion → eV

NRF Weapon authentication Concept





Hosts:

- provide the candidate warheads (to be authenticated)
- Foil – thickness unknown to the inspectors, but of agreed upon isotopes

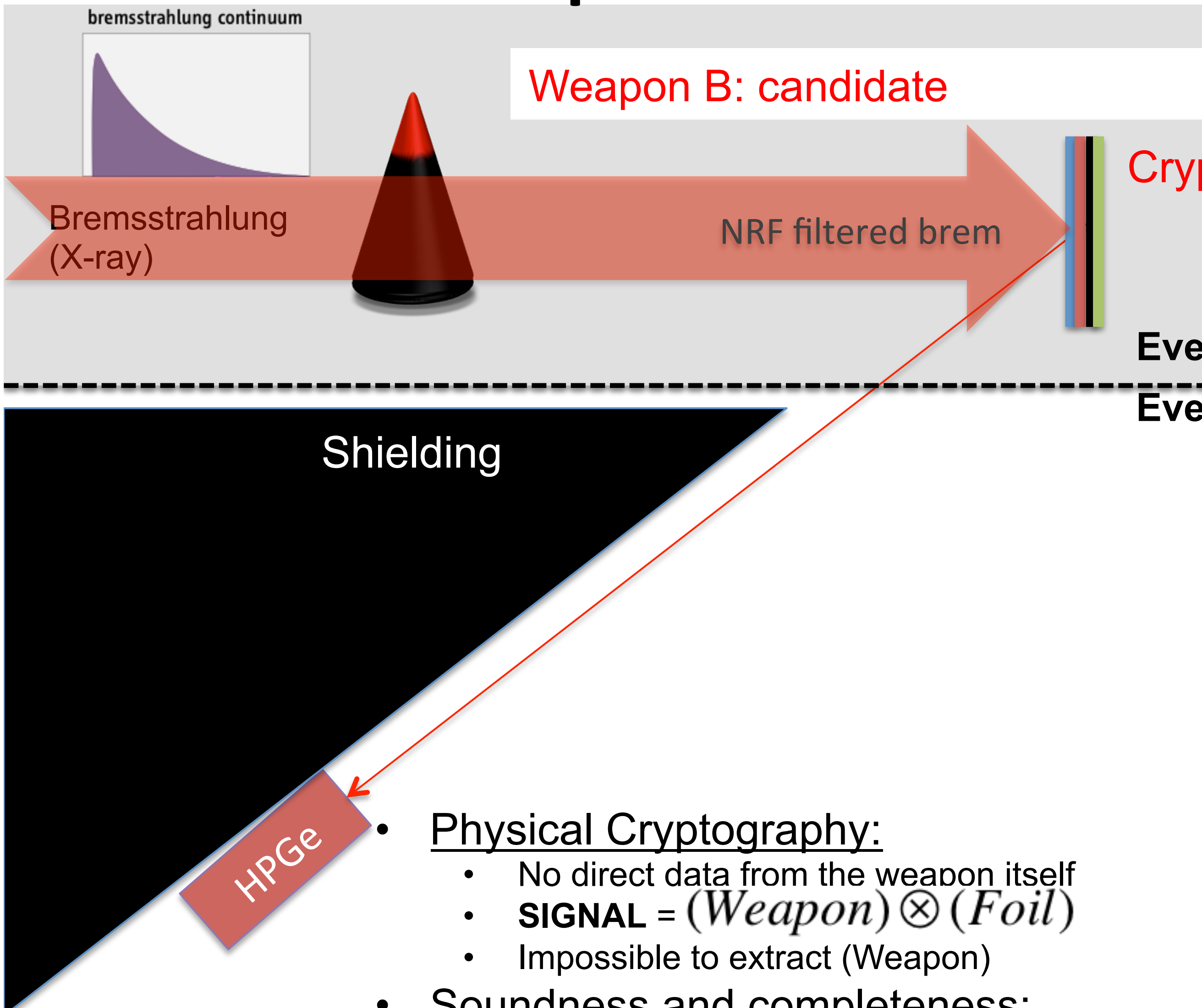
Inspectors:

- Detector, electronics (to be verified by hosts)
- Visual access to the foil

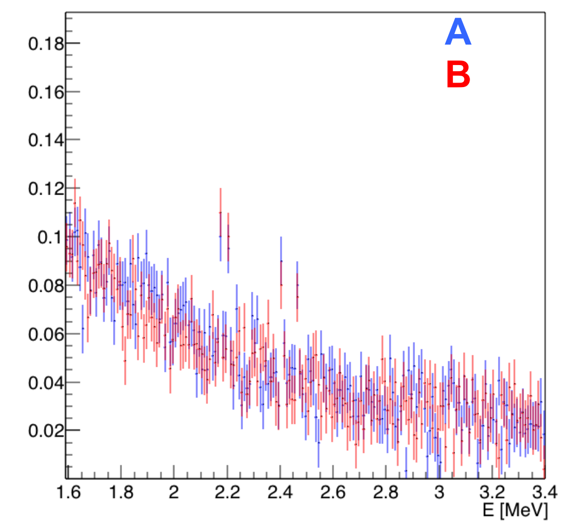
Joint:

- Template ("golden copy")

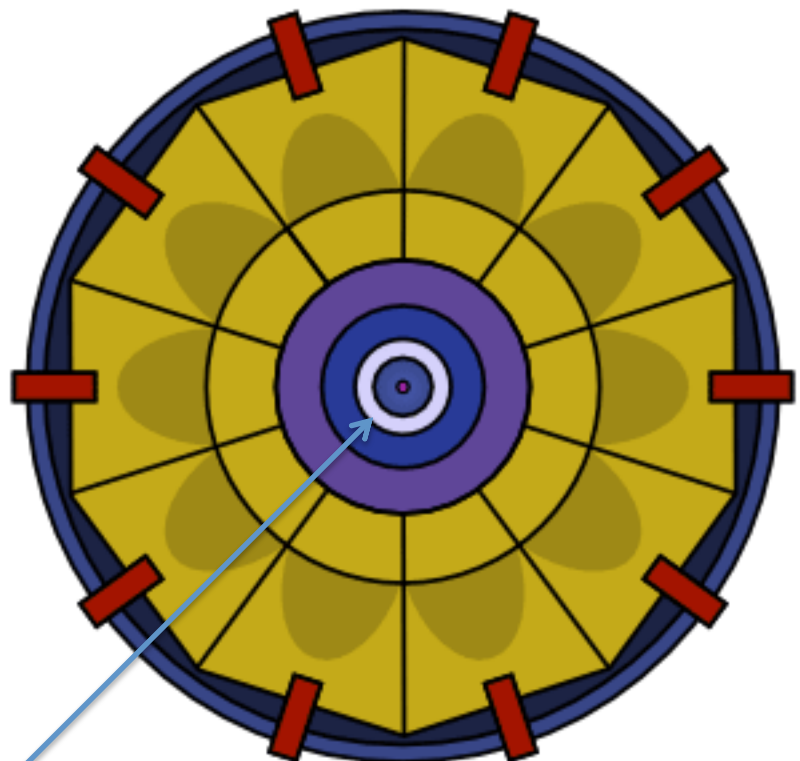
NRF Weapon authentication Concept



- Physical Cryptography:
  - No direct data from the weapon itself
  - **SIGNAL** = $(Weapon) \otimes (Foil)$
  - Impossible to extract (Weapon)
- Soundness and completeness:
  - Authenticated template A -- acquire $S_{NRF}(A)$
  - Candidate weapon B -- acquire $S_{NRF}(B)$ and compare

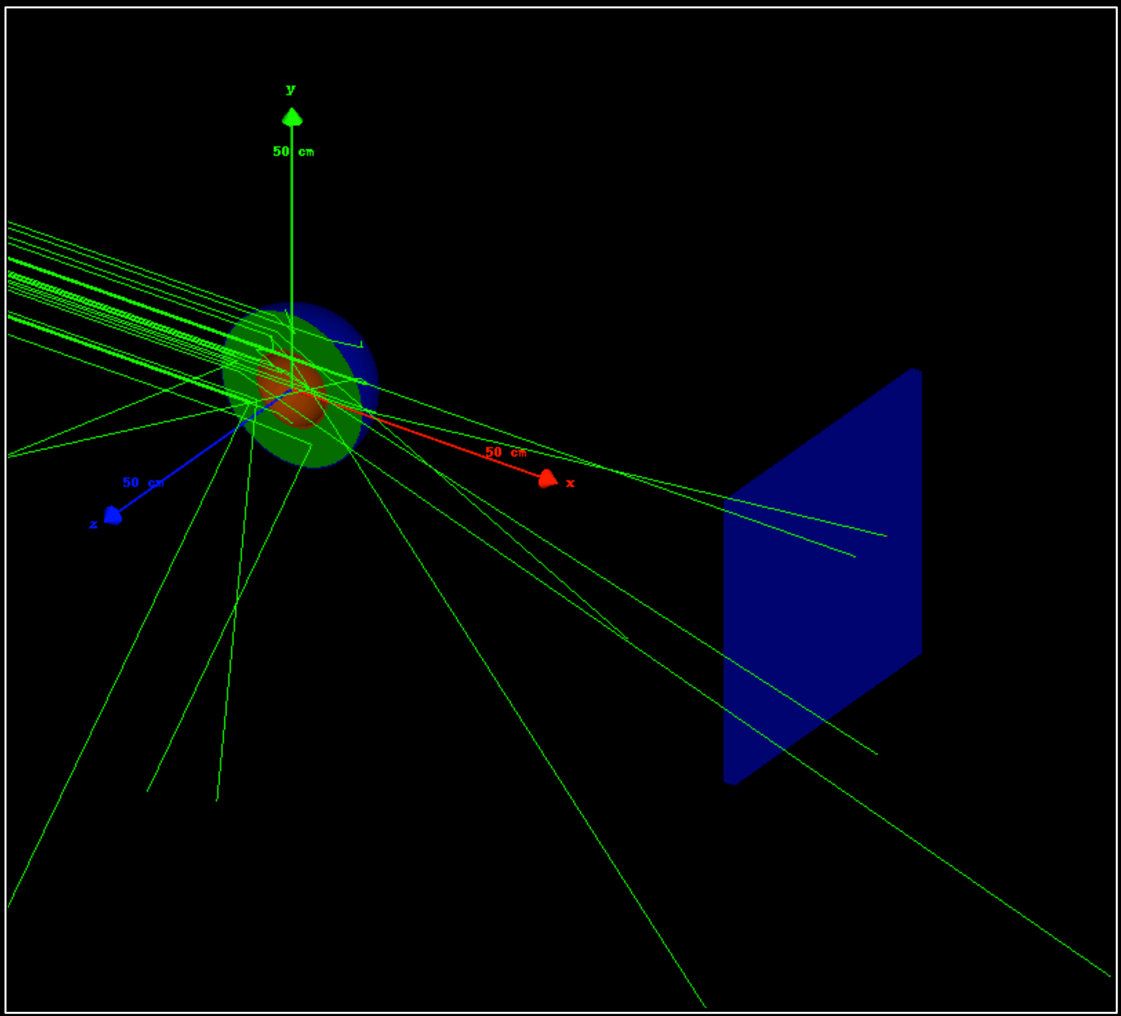


What's a bomb and how does it work?



Plutonium or Uranium

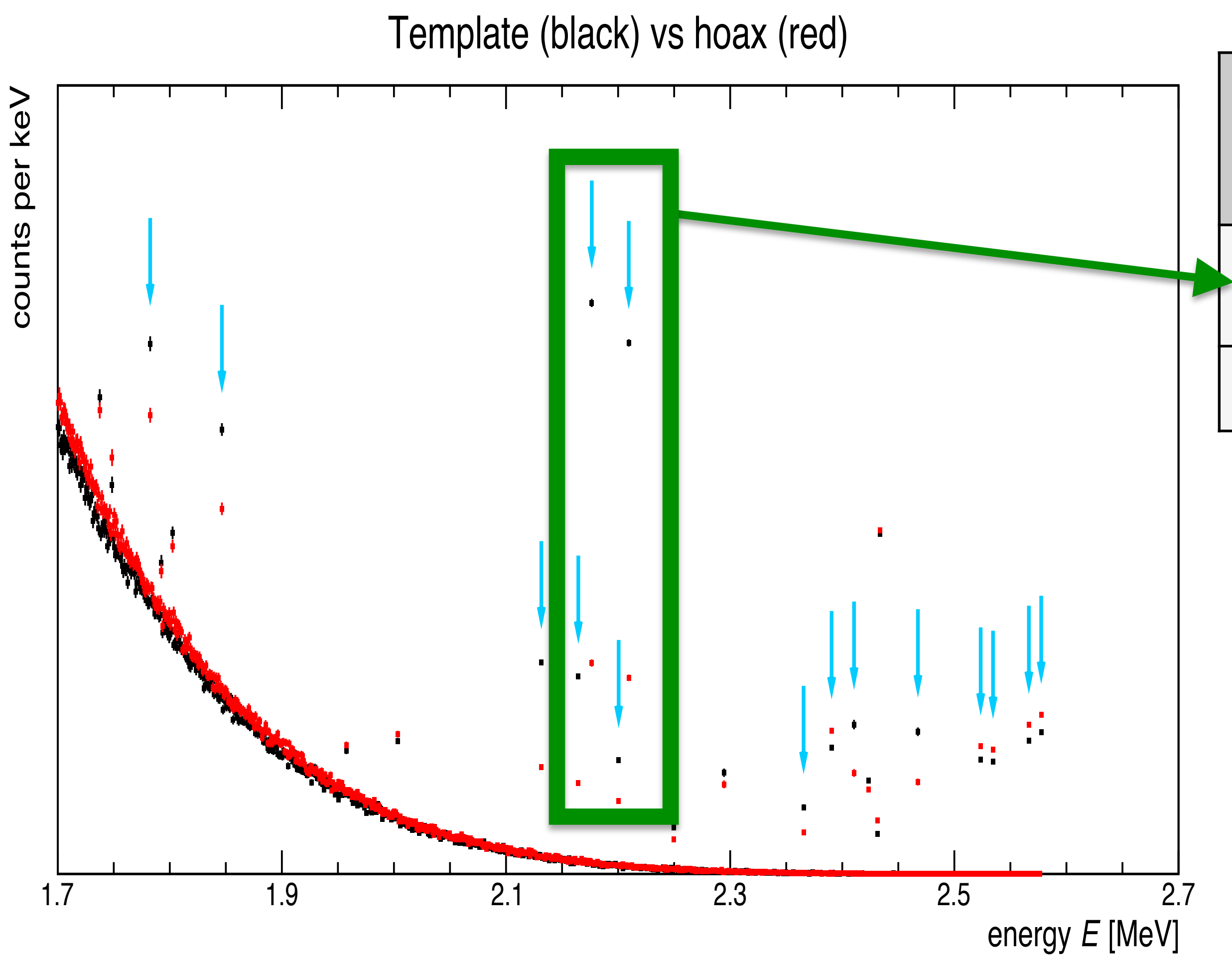
(source: wikipedia)



Simulated 2.1 or 2.5 MeV bremsstrahlung beam

> 1000 core hours for sufficient NRF statistics

Canonical hoax scenarios

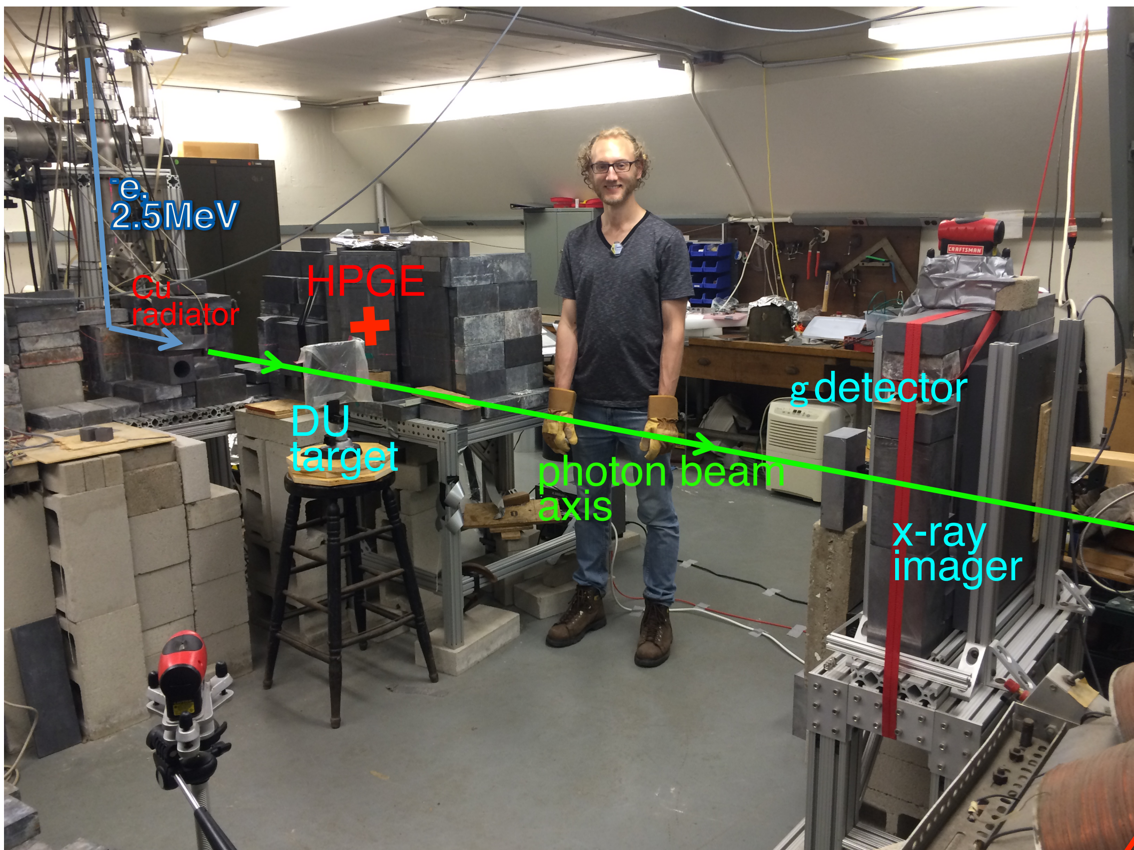


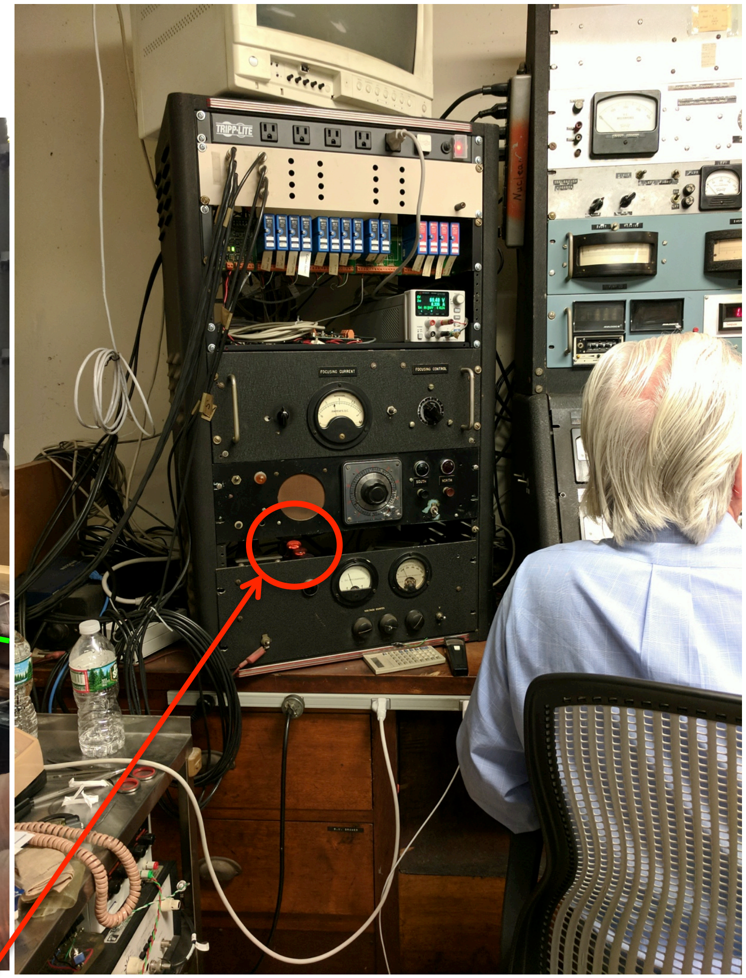
Hoax scenario	Strongest discrepancy (σ)
WGPu → U-238	107
WGPu → FGPu	14.6

R.S. Kemp, A. Danagoulian, R. Macdonald, J.Vavrek, *Physical cryptographic verification of nuclear warheads*, ***PNAS*** 113 (2016) 31.

NRF experimental setup

- Van de Graaff Accelerator
- 2.5 MeV e-, DC beam
- 20 mA



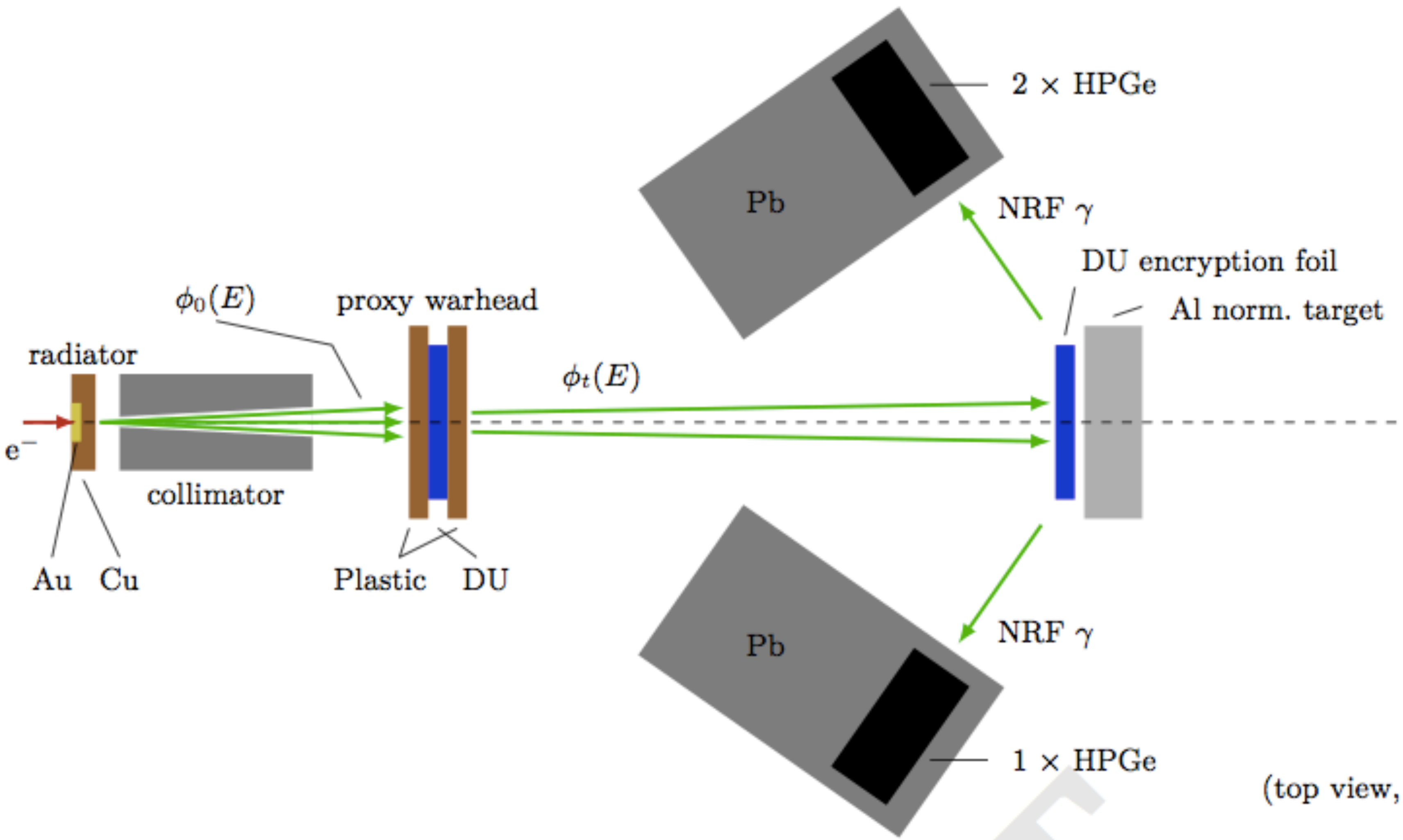


Vacuum Tubes!!!

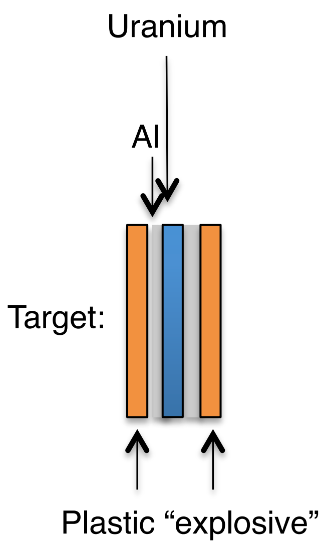
Proxy Warhead

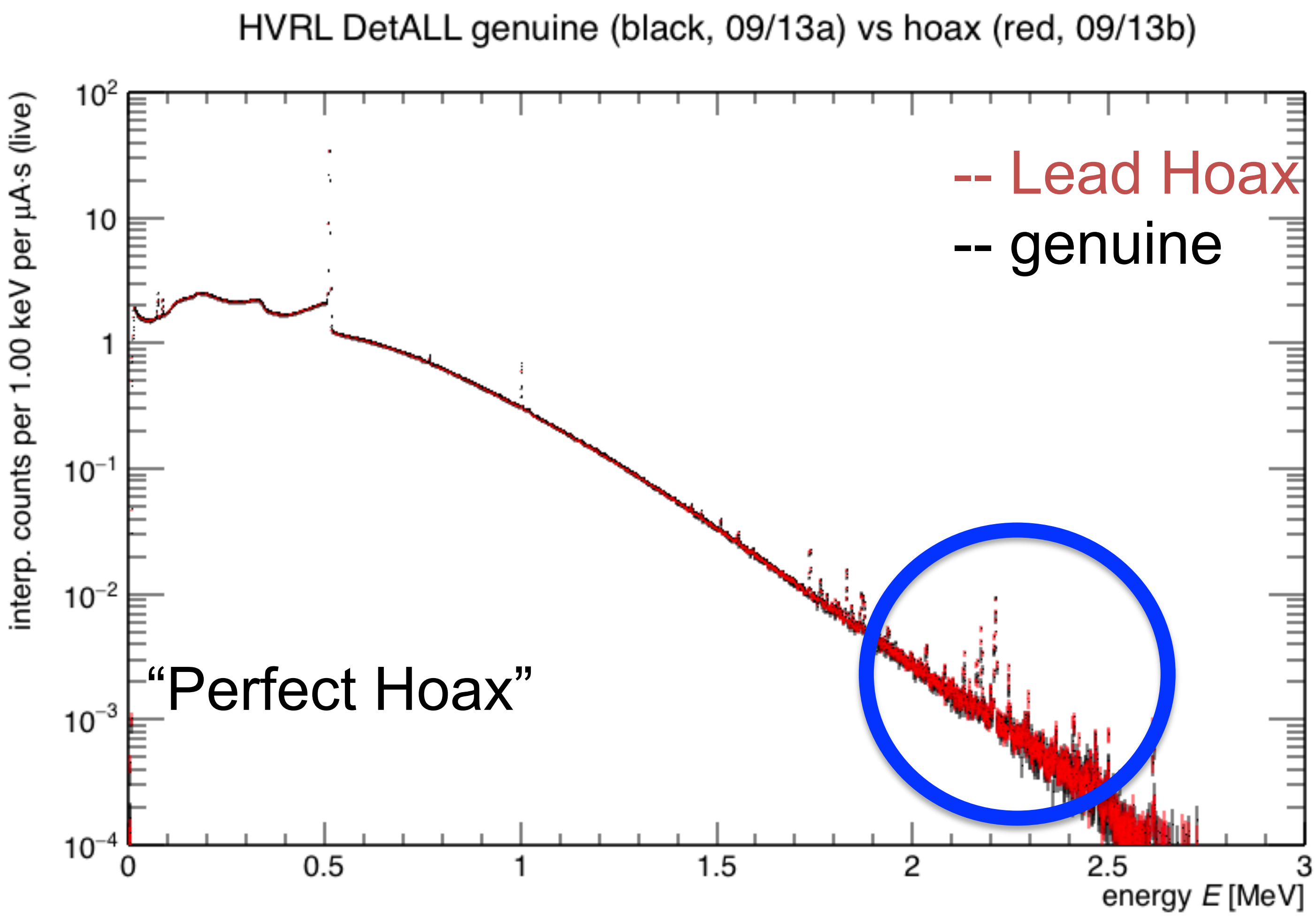
- 3mm of ^{238}U
- 0.5mm of ^{27}Al
- 1.5” of plastic
- “MIT Linear Implosion Design”

Experimental setup

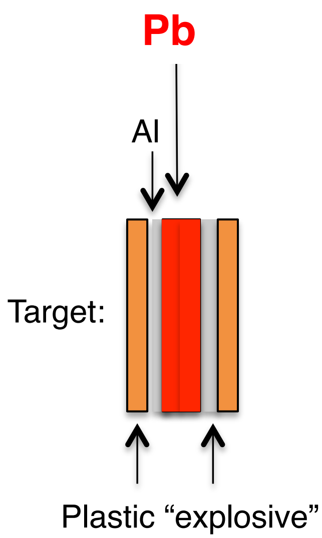


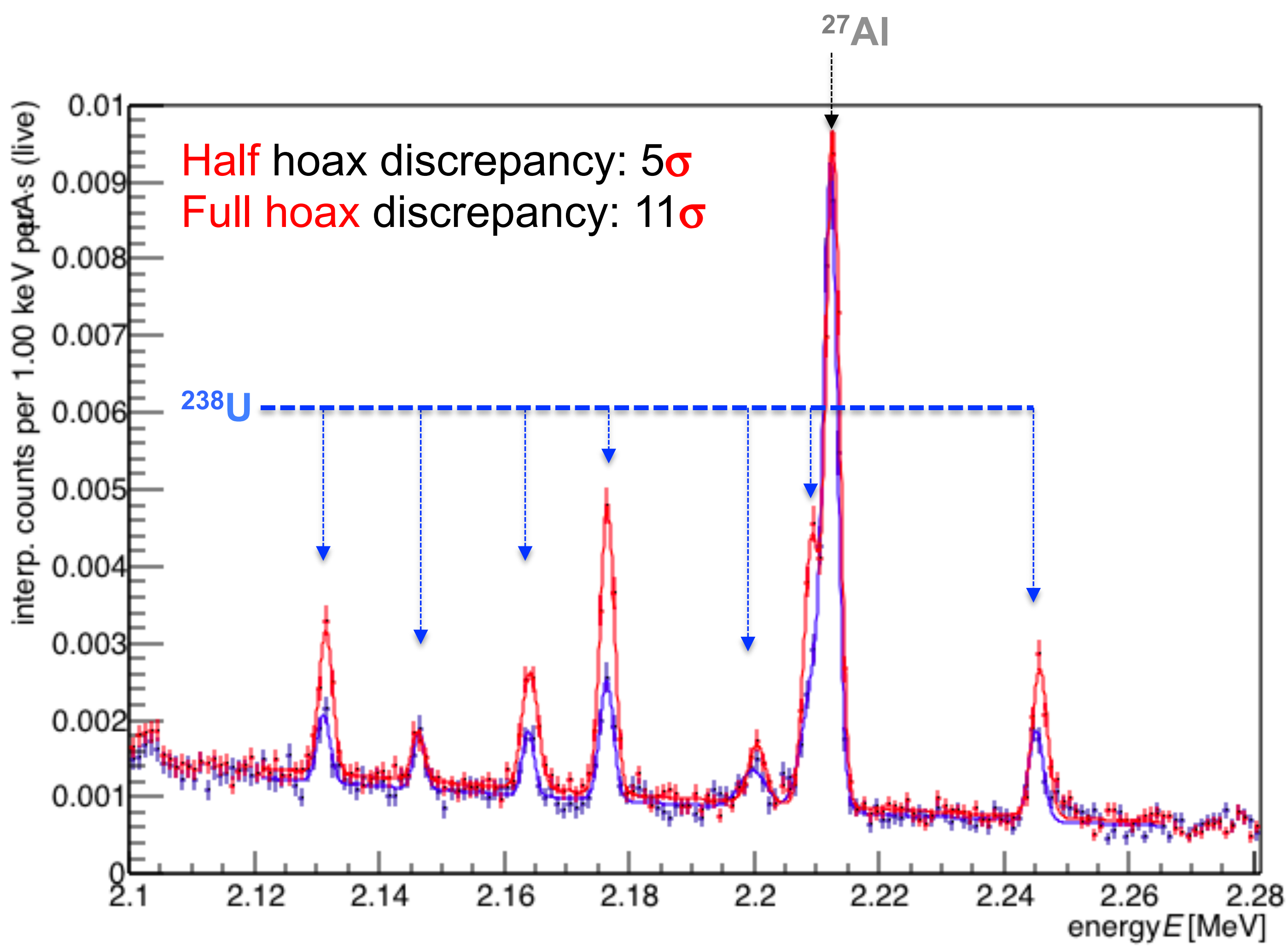
Hoax to Genuine comparisons





Hoax to Genuine comparisons





- **11σ** discrepancy in U lines
- identical counts in Al

Extrapolations: the real bomb

- 5-10 σ in a (1+1)-hour proof-of-concept
- "Black Sea" model:
- 6X rate decrease

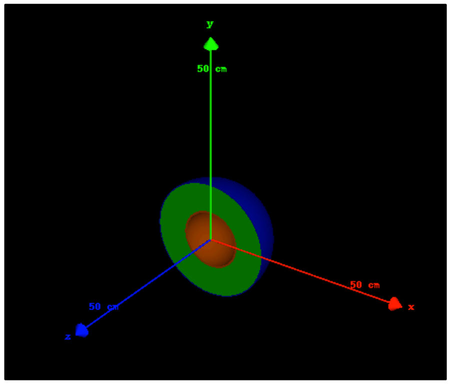
25 uA → 2.5 mA beam current:

- 100x rate increase

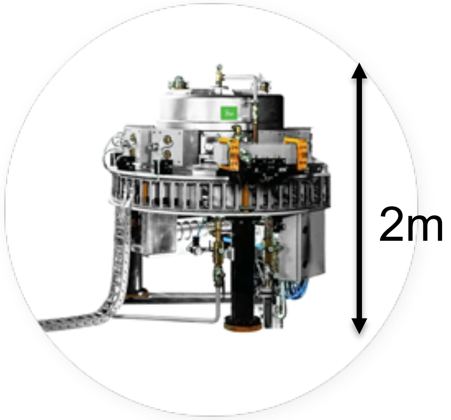
3 → 30 HPGe detectors:

- 10x rate increase

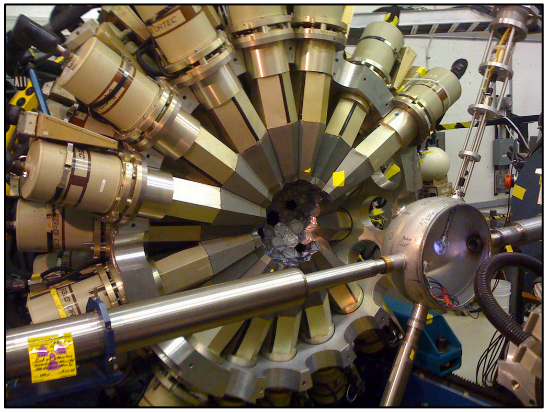
→ measurement times of **~minutes**



Black Sea Model



IBA TT100 Rhodotron



GammaSphere

J. R. Vavrek, B. S. Henderson, A. Danagoulian, "Experimental demonstration of an isotope-sensitive warhead verification technique using nuclear resonance fluorescence," ***PNAS*** (2018), 201721278; DOI: 10.1073/pnas.1721278115

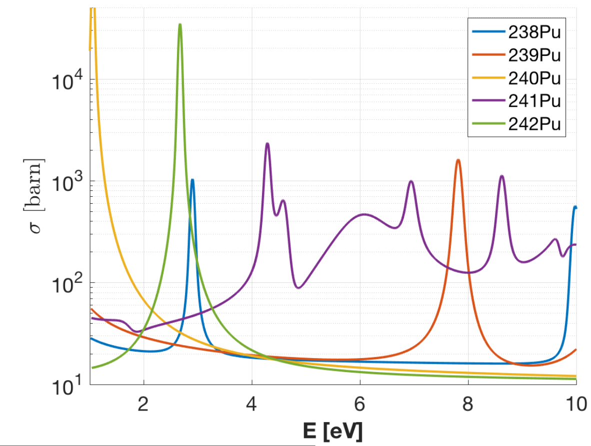
Verification with Epithermal Resonant Assay (VERA)

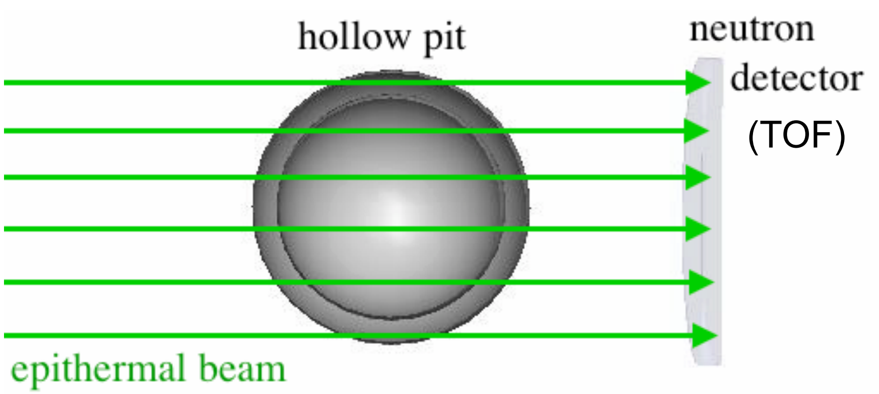
Epithermal Resonant Cryptographic Radiography

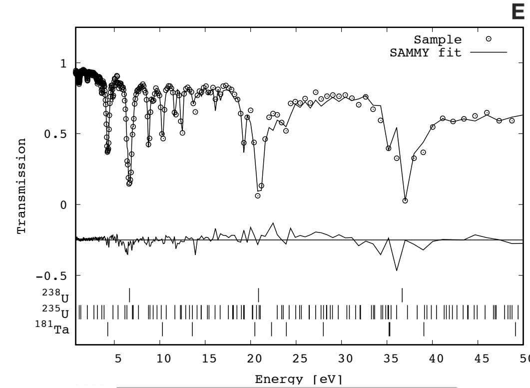
- Epithermal neutron resonances in the 1-10 eV
- Neutron Resonance Transmission Assay (NRTA)

Chichester, D. L. & Sterbentz, J. W. Assessing the Feasibility of Using Neutron Resonance Transmission Analysis (NRTA) for Assaying Plutonium in Spent Fuel Assemblies. JNMM XL, 4 (2012).

- Transmitted spectrum = isotopics $\otimes$ geometry
- cryptographic reciprocal mask







- choose a resonance
- → **isotopic image**

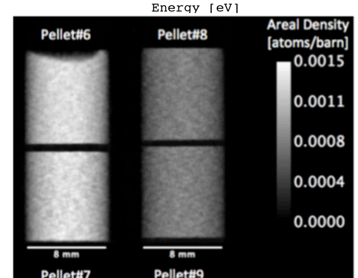
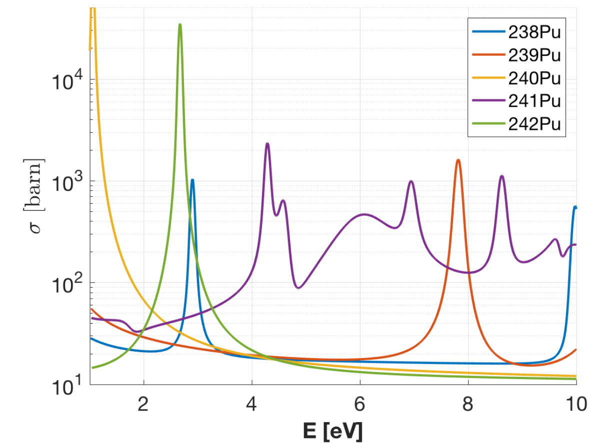
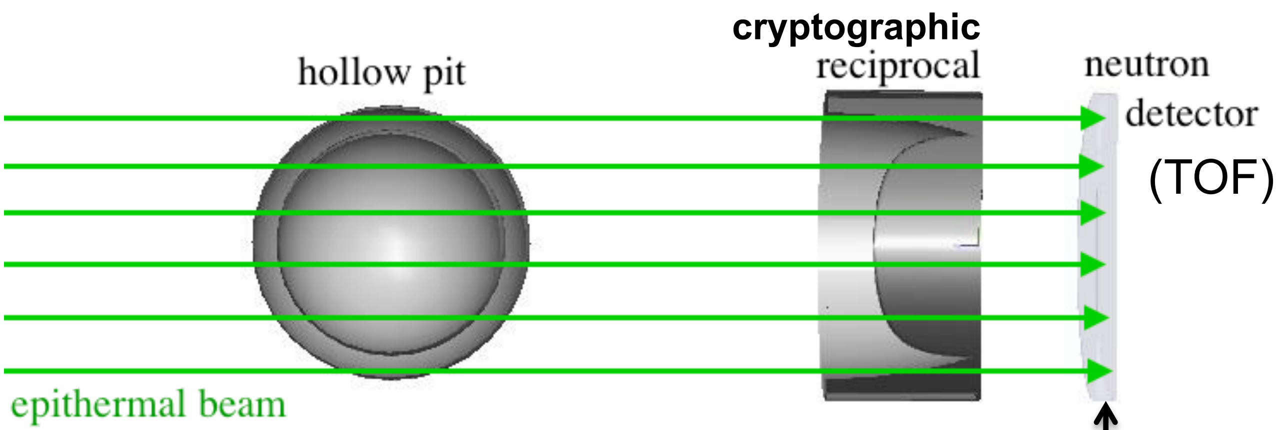


Fig. 6. Reconstructed projection for ^{235}U using the SAMMY code

Epithermal Resonant Cryptographic Radiography

- Epithermal neutron resonances in the 1-10 eV
- Transmitted spectrum = isotopics $\otimes$ geometry.
- cryptographic reciprocal mask

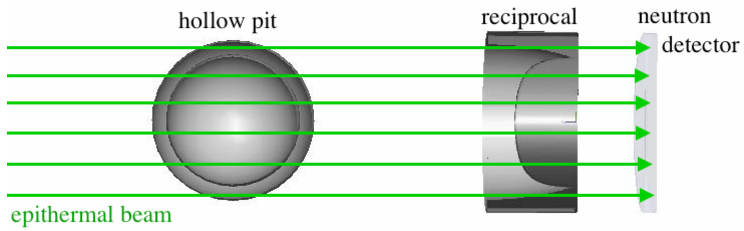




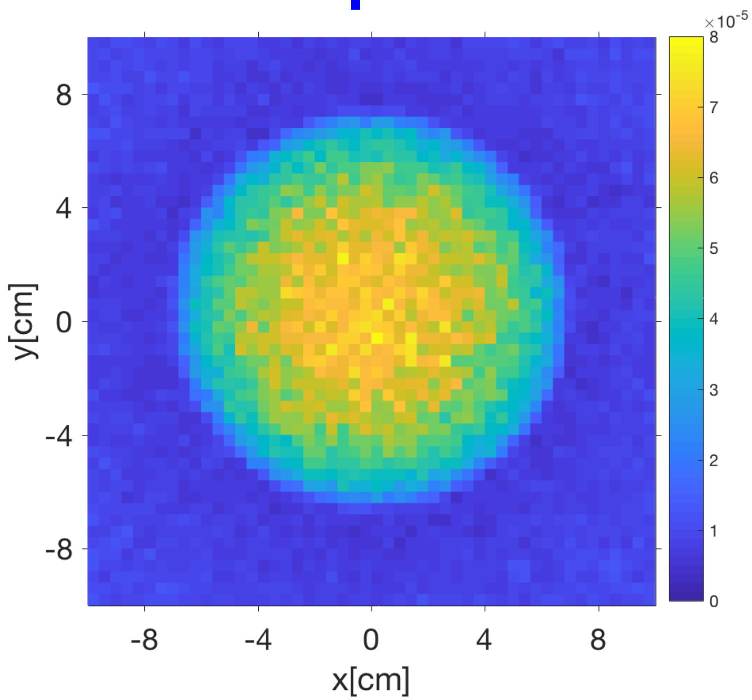
$$A_{recip} = 1/\left(A_{object} \times const.\right)$$

- ~ flat image: no geom. information
- spectrum reveals nothing about the pit

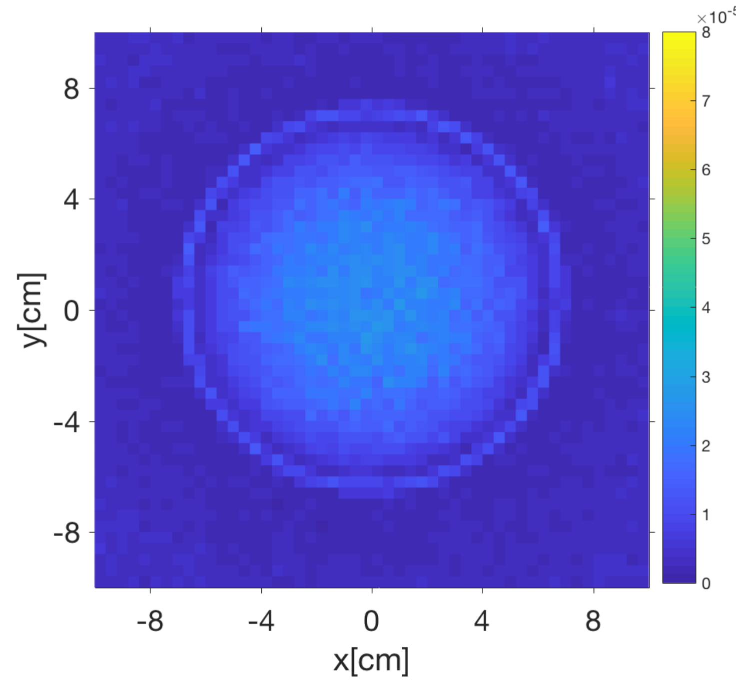
Simulations: Geometric hoax resistance



template



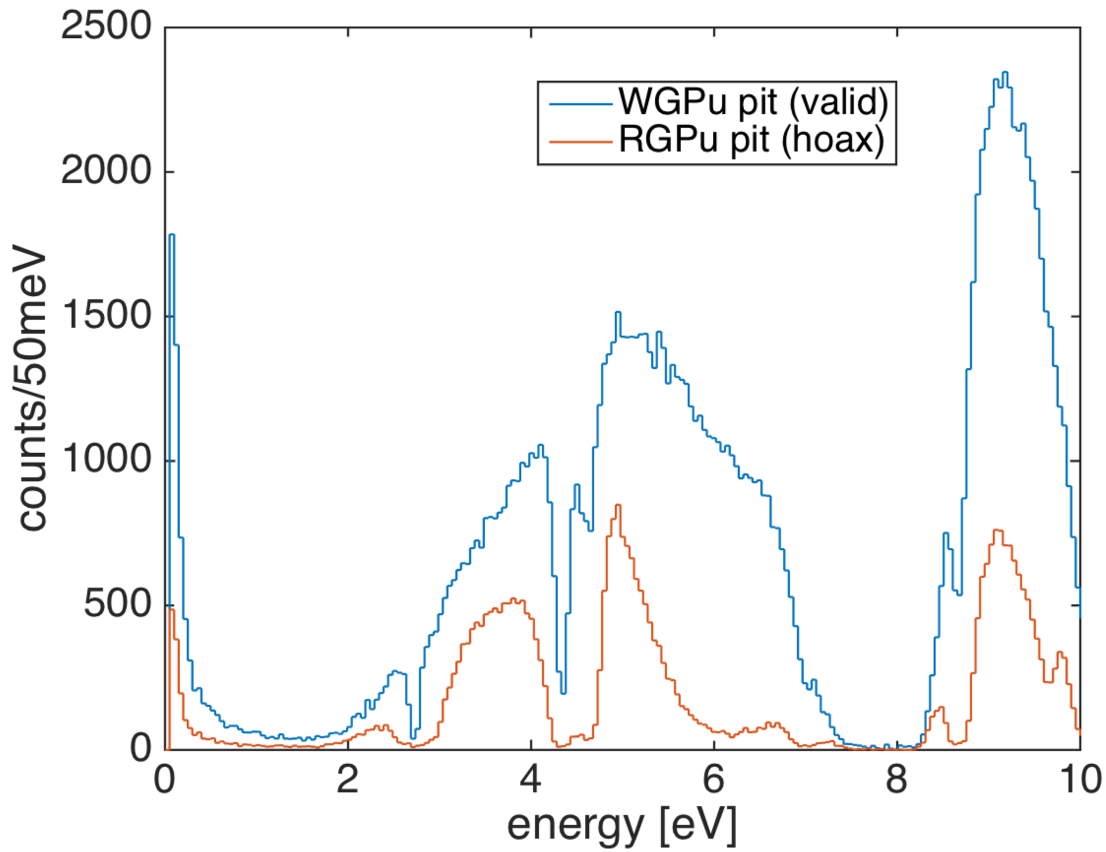
hoax



(J. Hecla)

Simulations: WGPu pit vs. a RGPu hoax

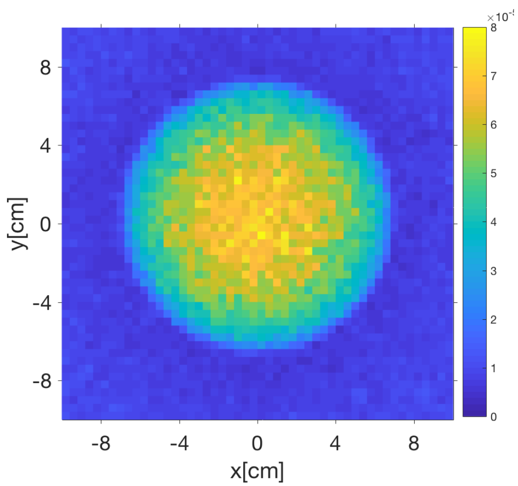
+ Different isotopics result in different transmission spectra
+ Only ~100k incident counts necessary for a 5σ detection



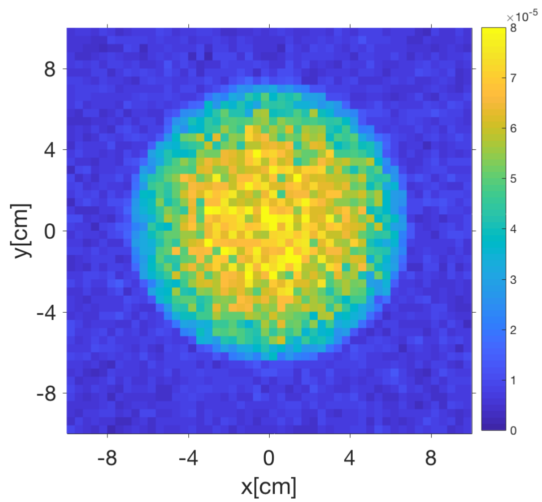
Geometric Information Security

+ Compare the transmission image of the pit+reciprocal to that of a flat plate of the same total thickness
+ Images and spectra are identical – can't differentiate, thus cannot infer any geometric information → geometric **Zero Knowledge**

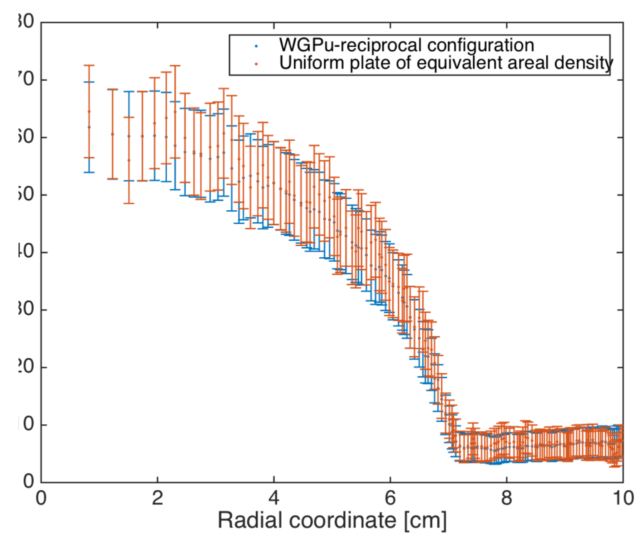
pit+reciprocal



plate



radial comparison



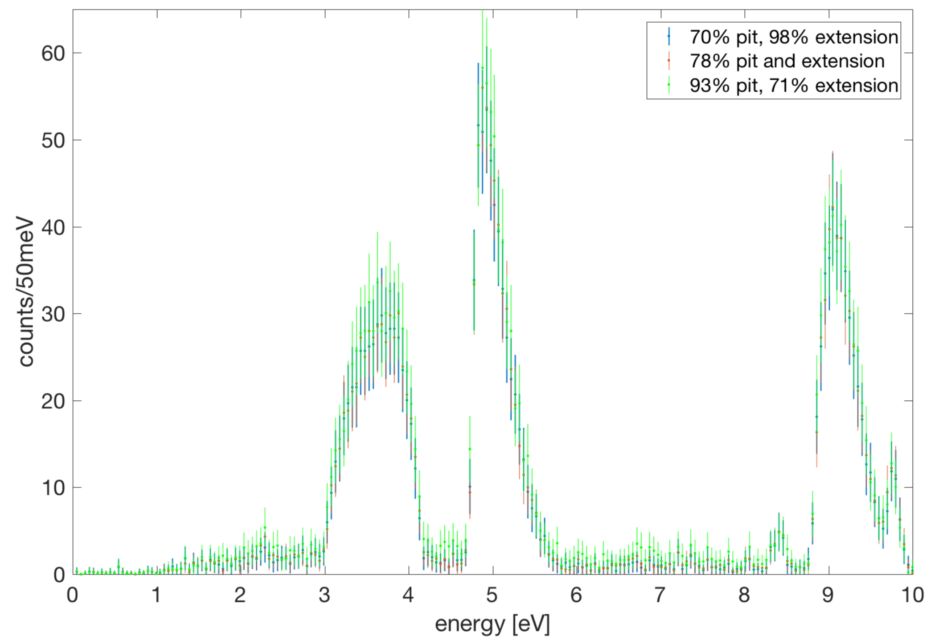
Isotopic Information Security

+ Protect the isotopics of the pit.

+ isotopics(pit+reciprocal) ≠ isotopics (pit)

+ MC simulations of three scenarios:
  - 70% 239Pu enriched pit, 98% enriched extension
  - 78% enriched pit and extension
  - 93% pit, 71% extension
  - the transmitted spectra are **identical**

→ **isotopic Zero Knowledge**

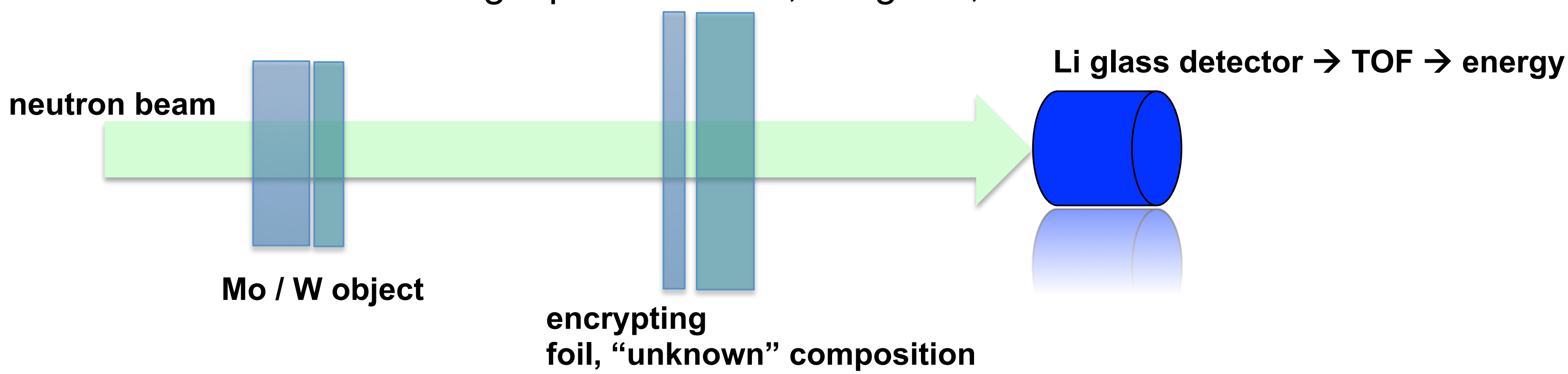


- Jake's MIT undergrad thesis

Jake J. Hecla, Areg Danagoulian, "Nuclear Disarmament Verification via Resonant Phenomena," ***Nature Communications*** 9, 2041-1723 (2018)

POC Experiments: Rensselaer Polytechnic Institute

- Can we avoid simple imaging? Yes – single pixel tomography
  - no need for complicated reciprocals
  - simple detectors
- Experimentally prove the feasibility of the concept
- Proxies for "honest" template pit and "hoax" pit:
  - template: 90% Mo / 10% W (Mo ←→ ^{239}Pu : W ←→ ^{240}Pu)
  - isotopic hoax – different isotopic ratio
  - geometric hoax – perform rotations
- Measurements: single pixel detector, 6Li glass, TOF



- Work with PPPL on using smaller, precisely moderated DT sources for ~eV neutron beams.

The Future

- Perform epithermal experiments at to prove the epithermal concept

- Collaborate
  - national labs
  - other countries
  - Russia

- Need technological solutions for treaty verification → more ambitious, far reaching treaties

- How can we, physicists, help solve major societal problems?

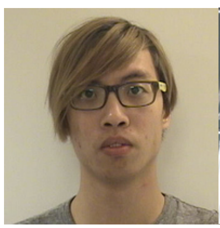
The Team

Postdoc:

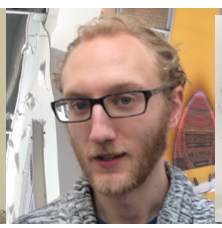
Dr. Brian Henderson

Students:

PhD



Jimmy



Jayson

Julie

Will

Ethan

S.M.

Ezra

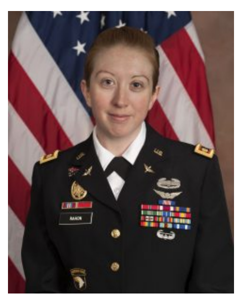
Undergrad

Ben

Alumni:

Jake Hecla

Dr. Buck O'Day



Jill Rahon

Bobby Nelson

Jeremiah Collins