Experimental demonstration of a physical cryptographic warhead verification protocol using nuclear resonance fluorescence

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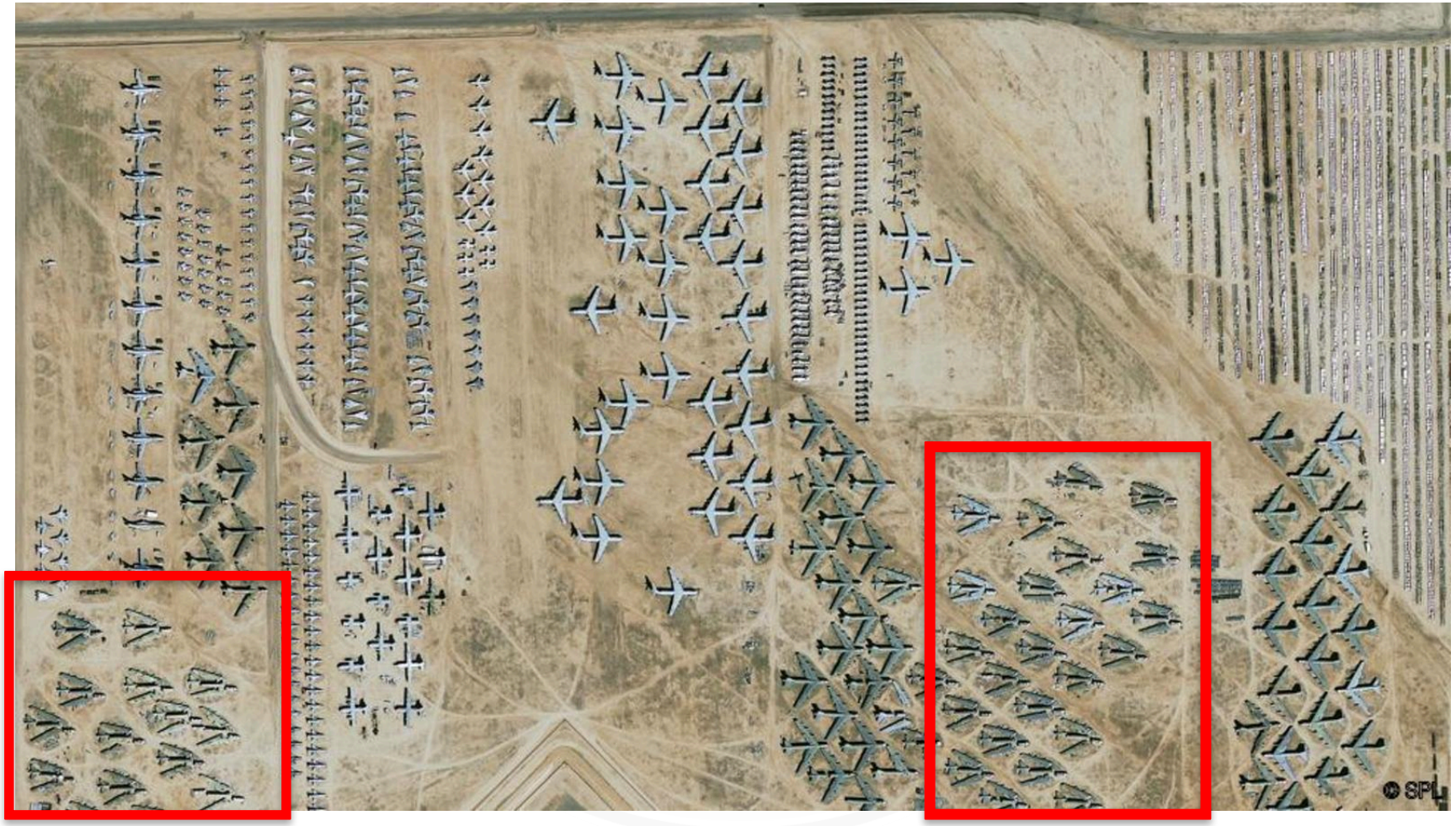
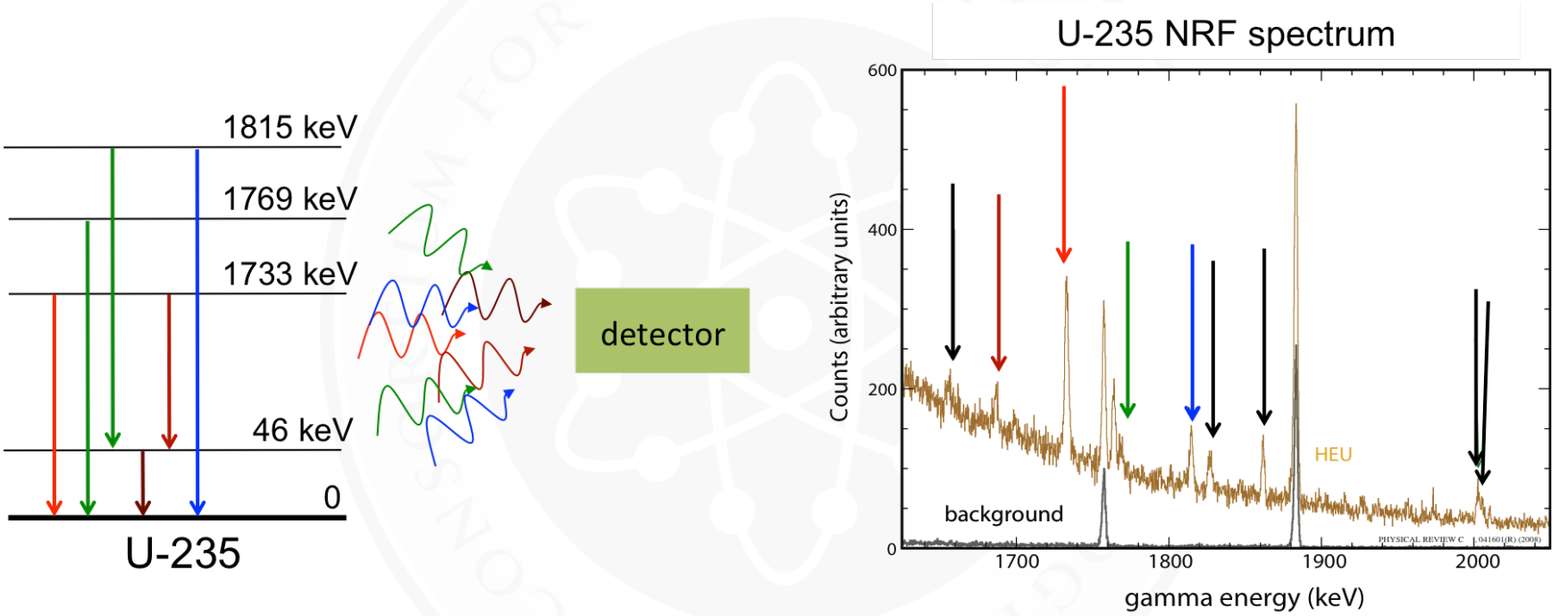
Massachusetts Institute of Technology

How can an inspector verify a warhead is real without revealing classified information?



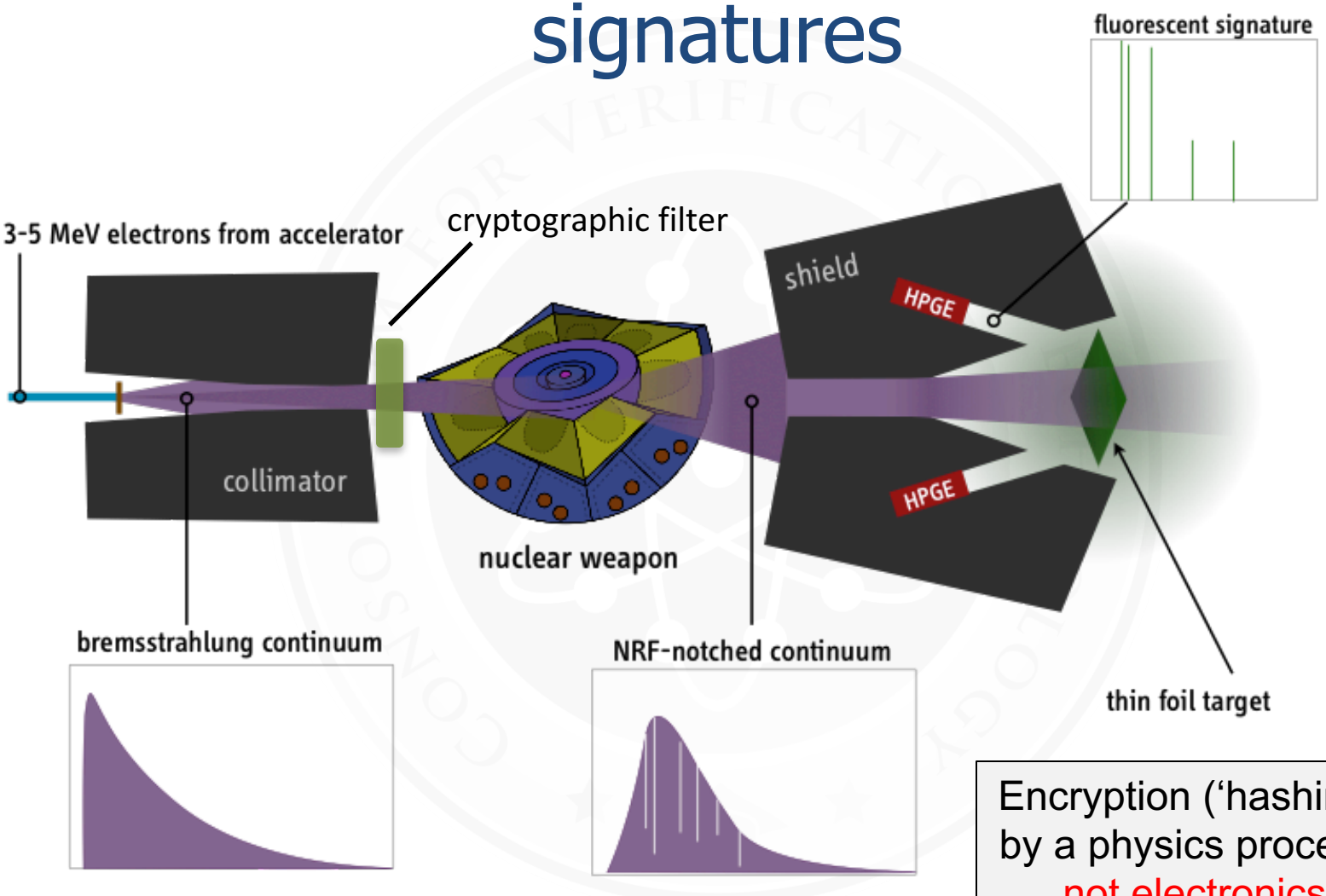
Davis-Monthan Air Force Base | bbc.com

We use nuclear resonance fluorescence (NRF) to make isotope-specific measurements



different line spectra for U-235, U-238, Pu-239, Pu-240…
other resonant processes?...

The inspector can only compare NRF signatures



Encryption ('hashing') by a physics process, not electronics

Multi-line inference, cryptographic filters

- First layer of security: foil thickness *X* and warhead thickness *D* are both unknown and both affect the NRF rate
  - One equation, two unknowns
  - Problem: build a system of equations, use neighboring lines, take ratios to cancel systematics, make some approximations

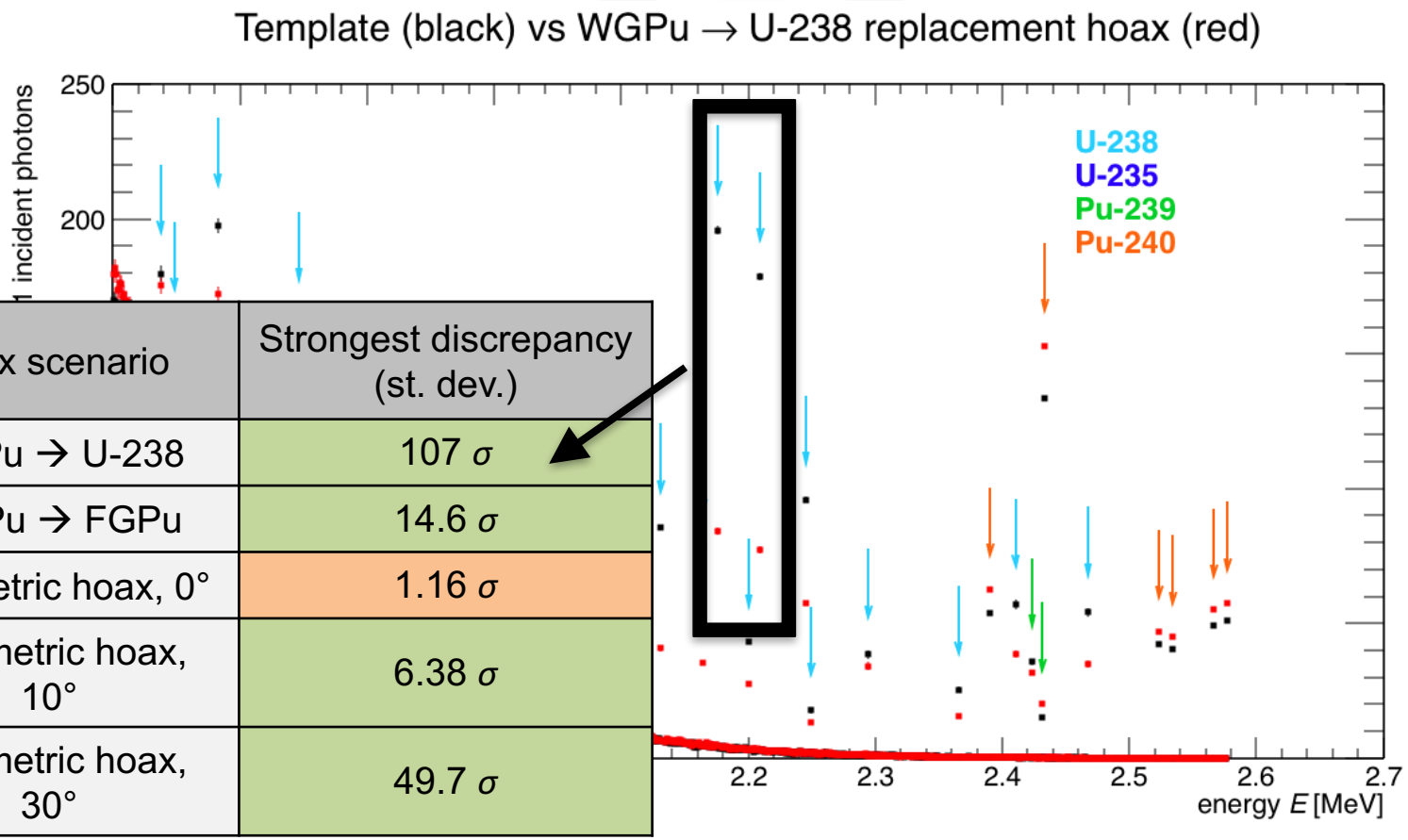
    → infer foil *X* → infer warhead *D*

- Solution: introduce a cryptographic filter of warhead isotopes

  → at most, can infer $D + \Delta D$

  → bonus: inspector can bring the foil, and it can be thick to maximize stats

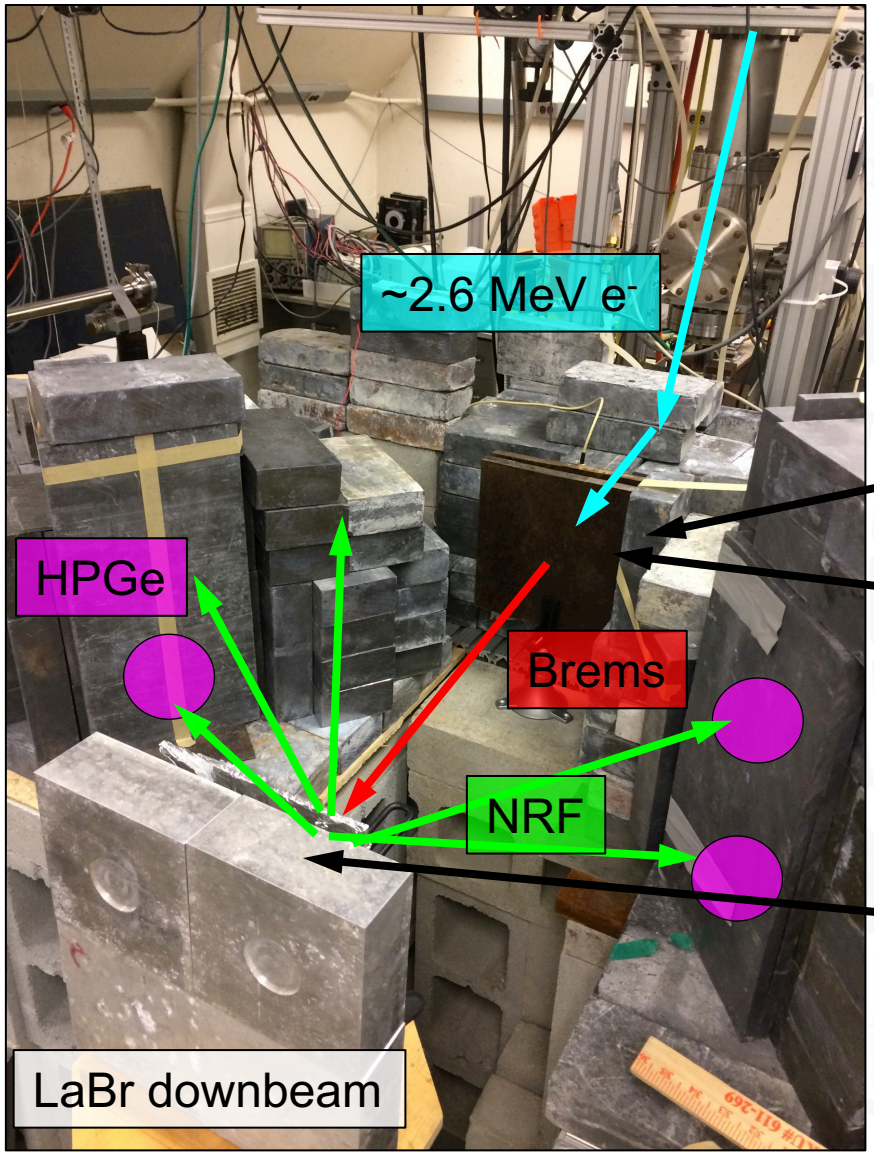
Simulations showed strong hoax resistance



Hoax scenario	Strongest discrepancy (st. dev.)
WGPu → U-238	107 σ
WGPu → FGPu	14.6 σ
Geometric hoax, 0°	1.16 σ
Geometric hoax, 10°	6.38 σ
Geometric hoax, 30°	49.7 σ

R.S. Kemp, A. Danagoulian, R.R. Macdonald, J.R. Vavrek, "Physical Cryptographic Verification of Nuclear Warheads," Proceedings of the National Academy of Sciences, vol. 113 no. 31 (2016)

Fall 2017 experiments at MIT HVRL



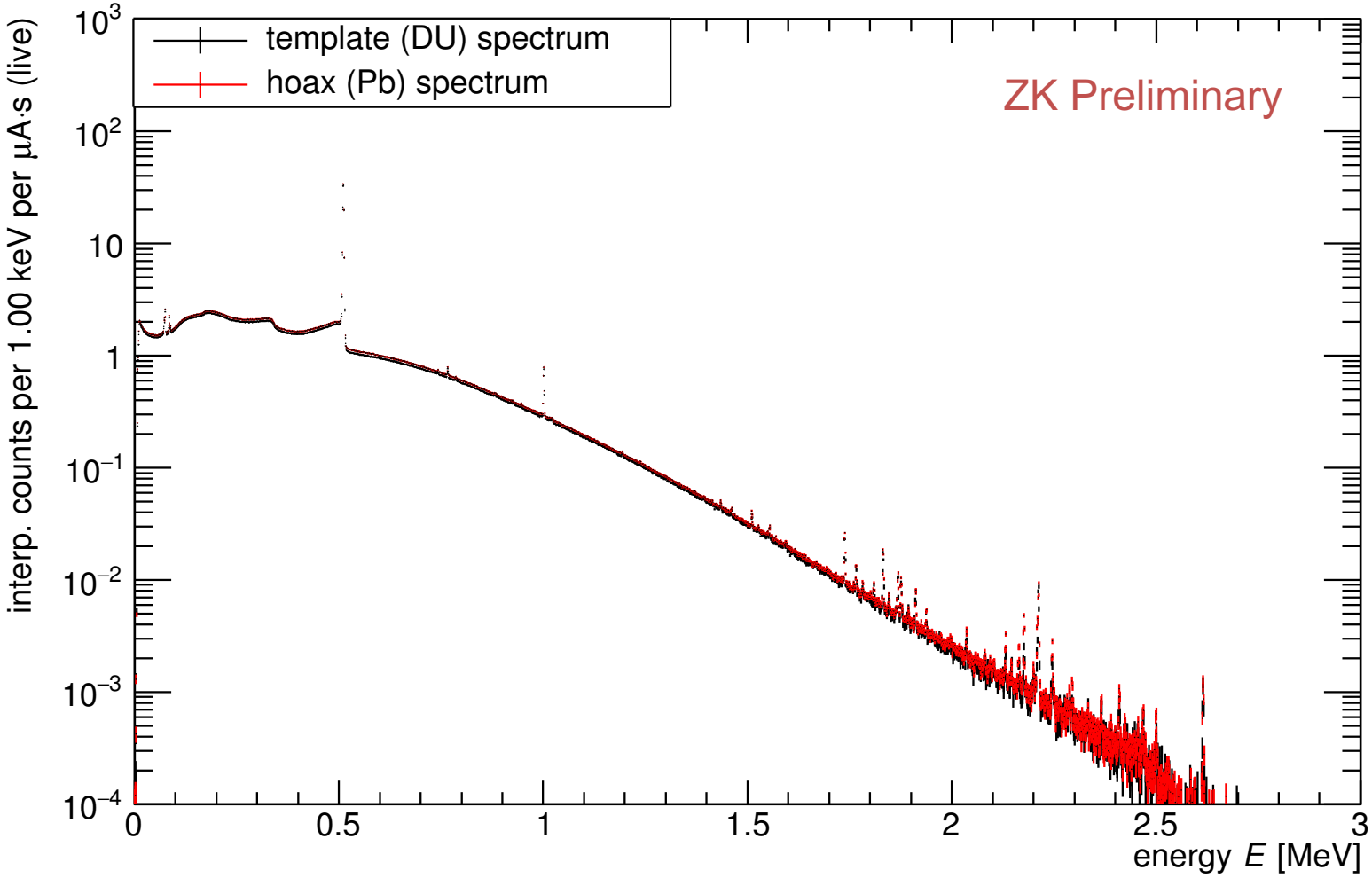
Radiator
(Cu + Au)

Warhead proxy

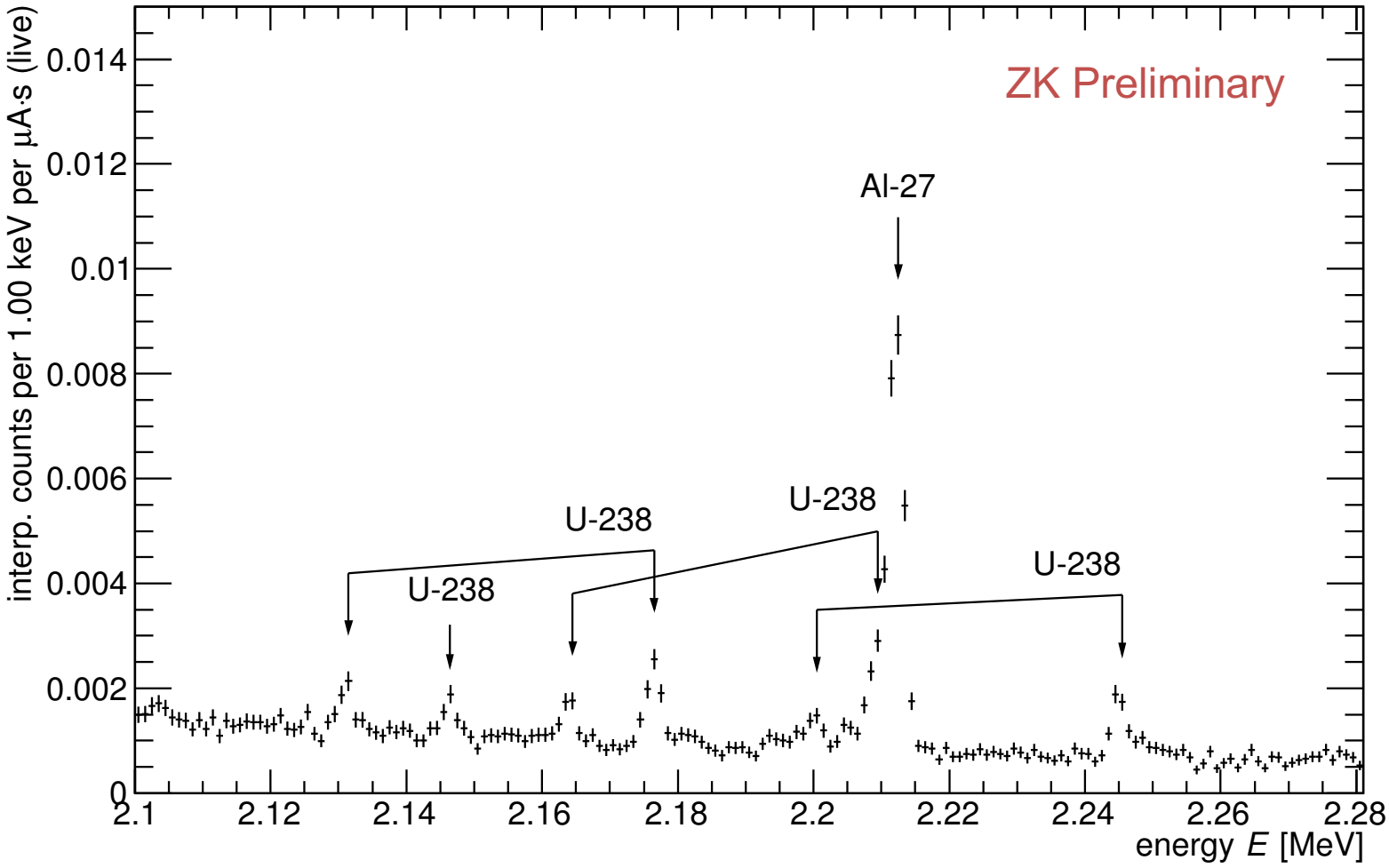
- Genuine: DU + plastic
- Hoax: Pb + plastic

Encrypting foil
(DU + Al)

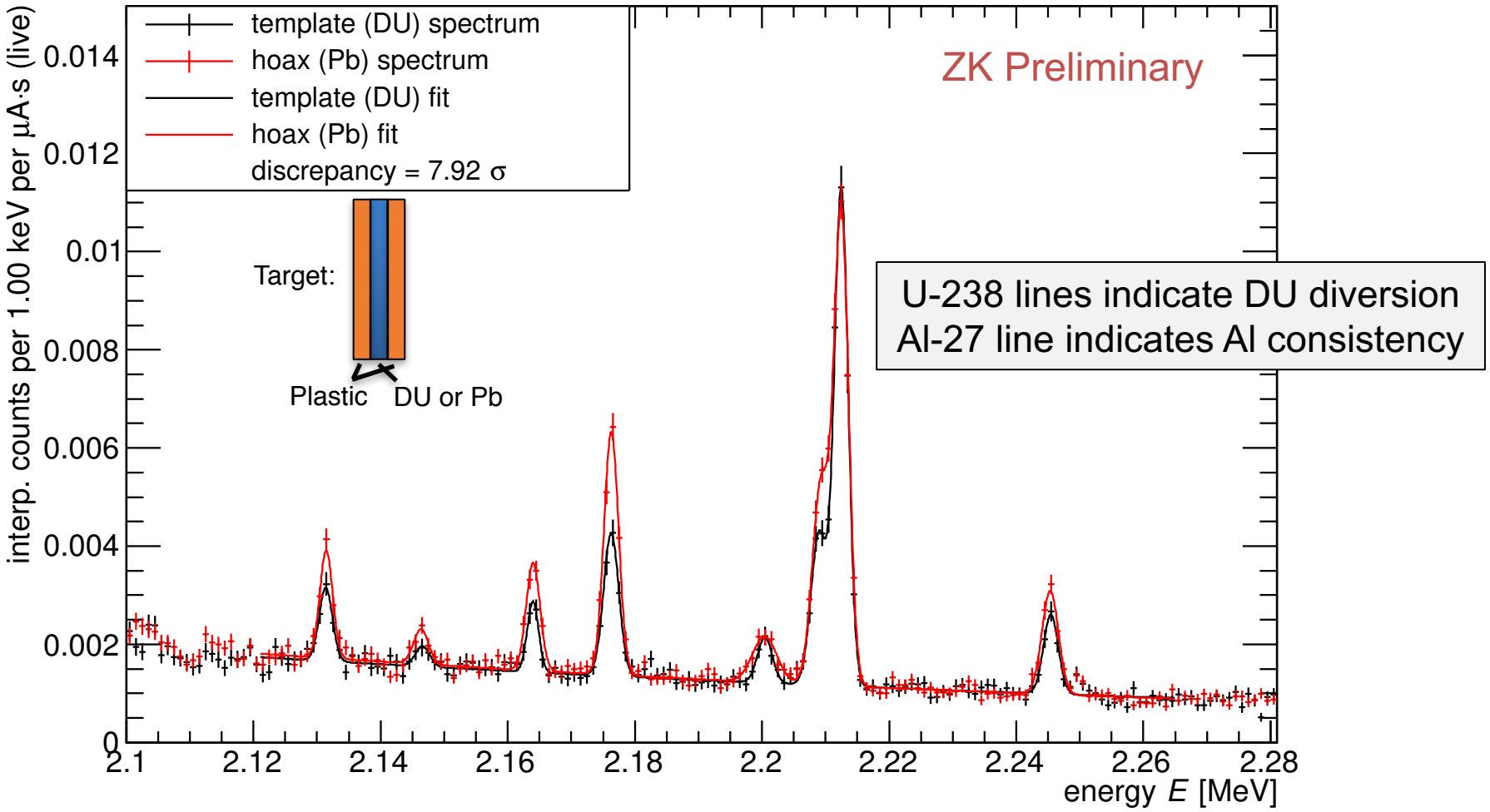
The spectra appear to match remarkably well…



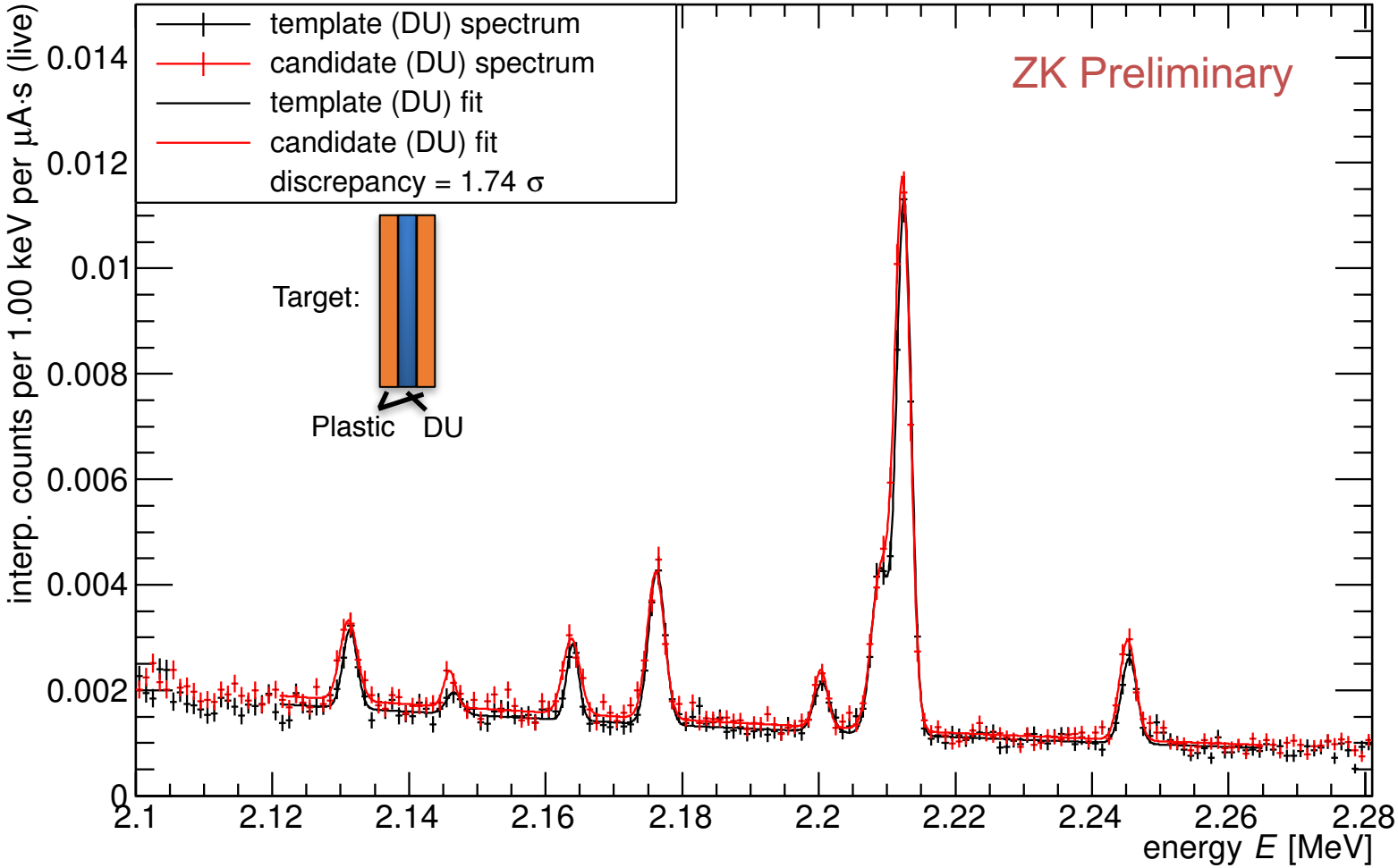
…but let's zoom into the NRF region…



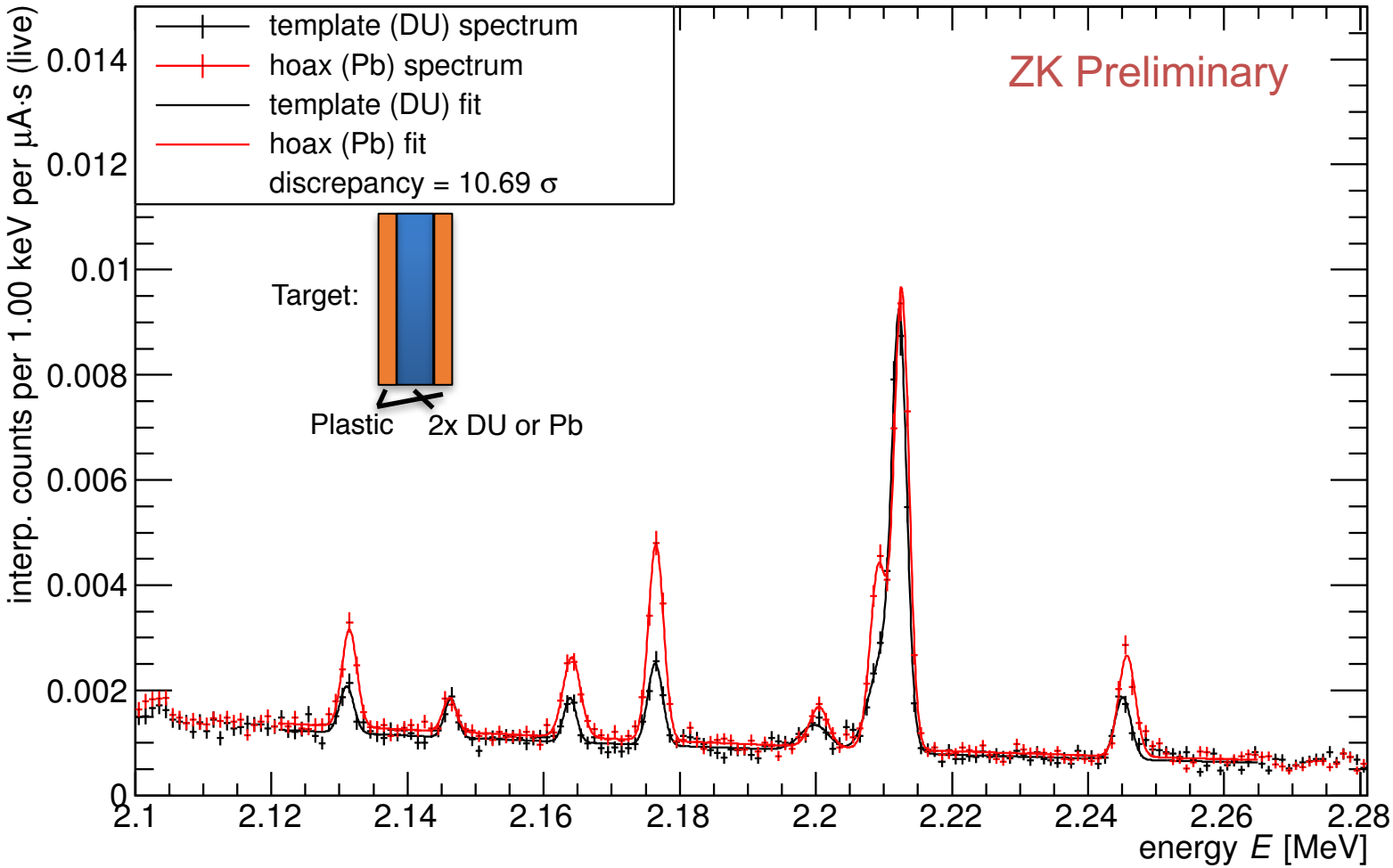
Template (DU) vs hoax (Pb)



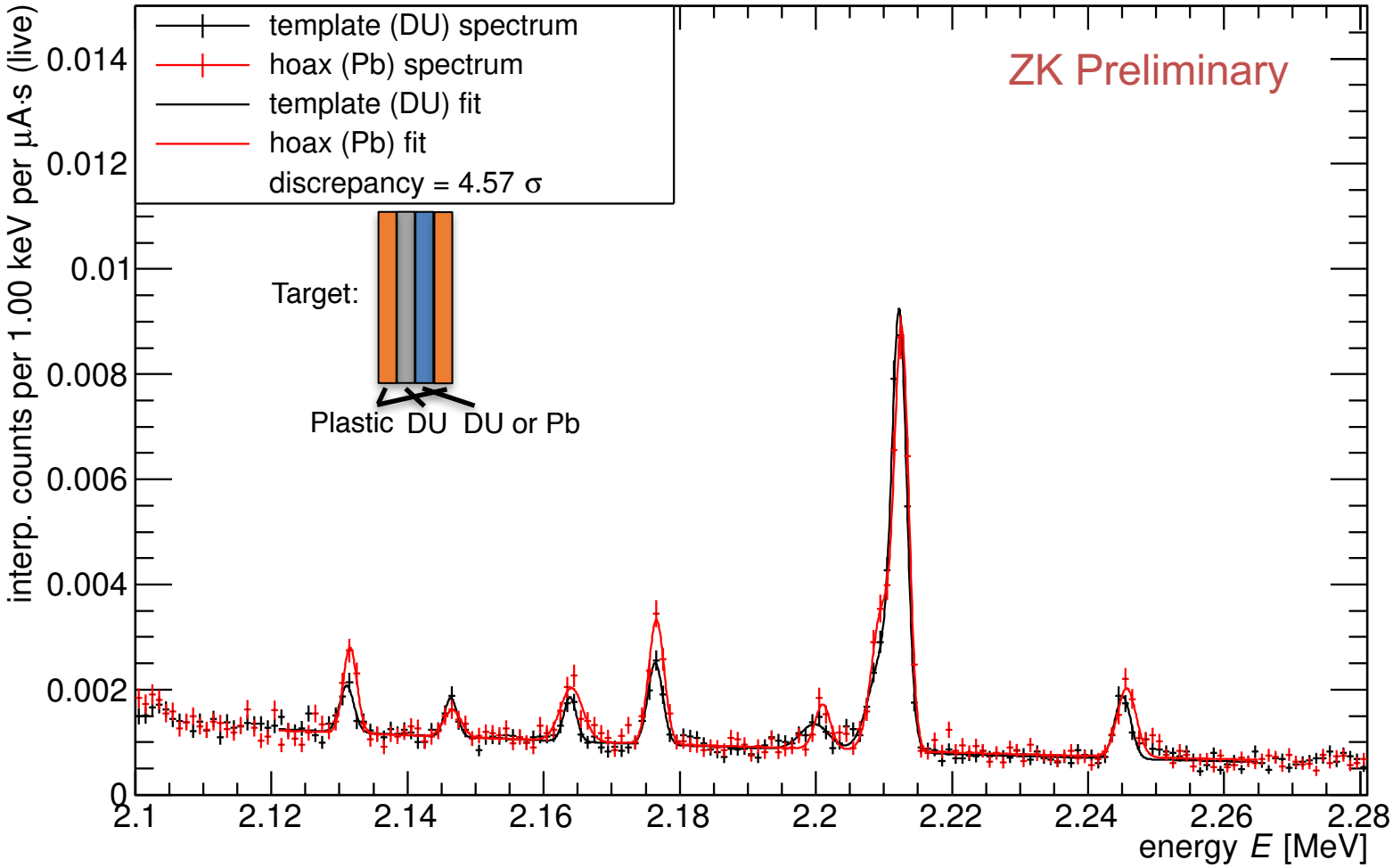
Template (DU) vs genuine candidate (DU)



Template II (DU) vs hoax (Pb)



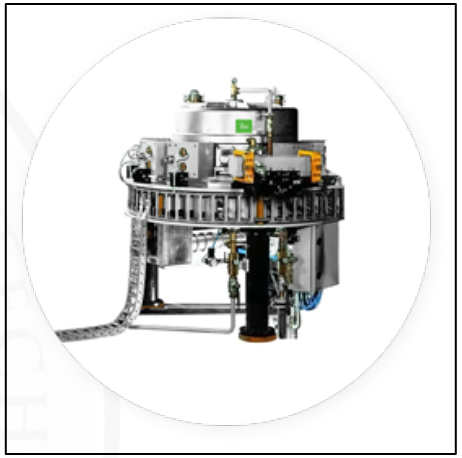
Template II (DU) vs partial hoax (Pb/DU)



What could we achieve with a dedicated verification facility?

5-10 σ in a (1+1)-hour proof-of-concept:

- How long for realistic (thicker) designs?
- Weaker NRF lines of fissile U-235, Pu-239?



IBA Rhodotron

<u>25 uA → 5 mA beam current</u>:

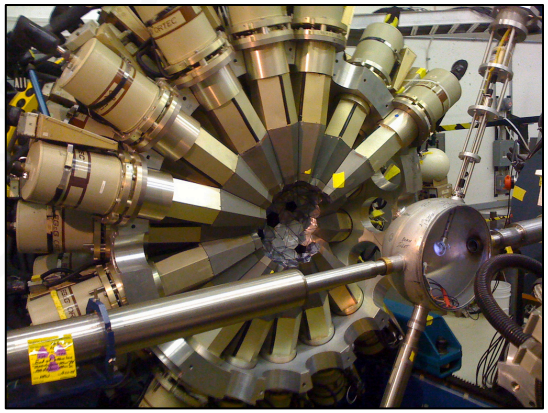
- 200x rate increase

<u>3 → 30 HPGe detectors</u>:

- 10x rate increase

→ Measurement times on the order of 20 minutes

→ *O*($5 M) for full system



GammaSphere

Future work

1. Continue investigations of information security
   - Multi-line inference
   - Continuum background

2. Investigate combined verification measurements
   - Neutrons (Princeton) *and* photons (MIT)
   - Secure ADCs (Umich)

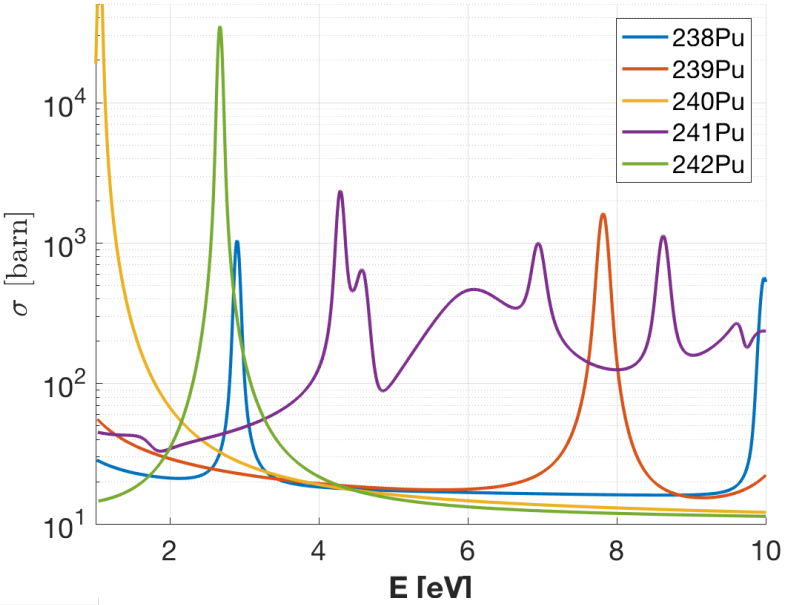
3. Conduct further experiments
   - Reciprocals?
   - Other resonant processes

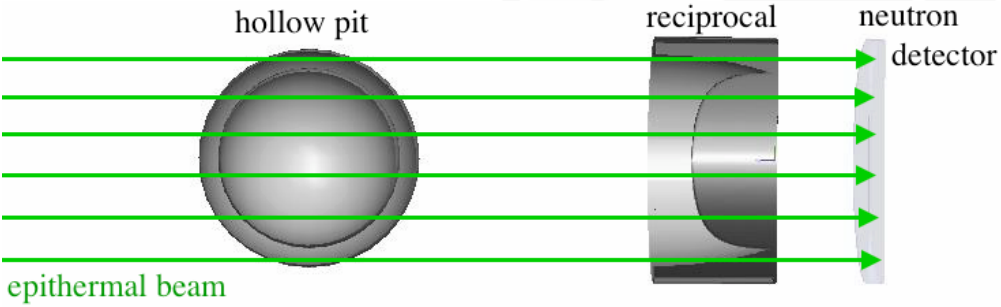
Disarmament verification with epithermal neutron resonances

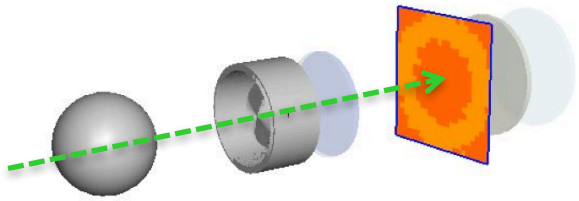
Areg Danagoulian,
Ezra Engel, Jake Hecla

Basic Concept

+ Epithermal neutrons in the 1-10 eV also have resonances.
+ Perform direct transmission, use TOF to reconstruct energy: transmitted spectrum will have both geometric and isotopic sensitivity.
+ Use the “reciprocal” mask to achieve a true Zero Knowledge verification



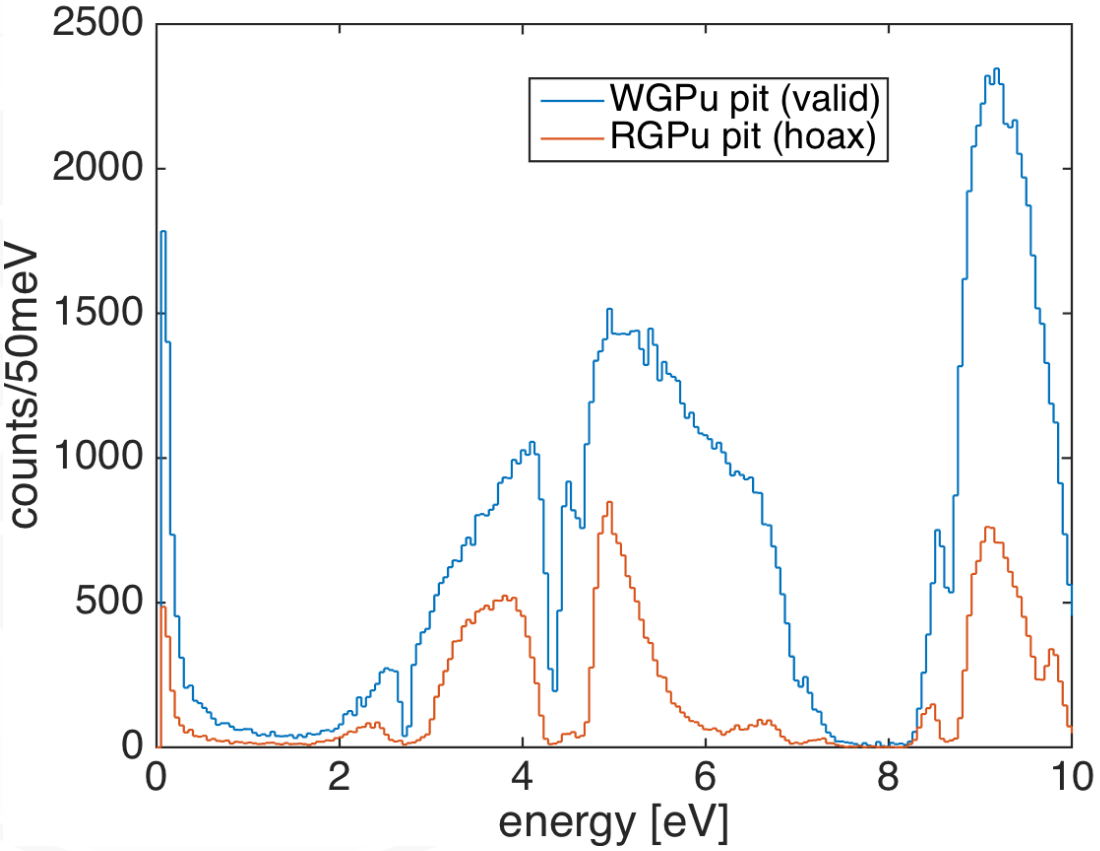




Slide: Areg Danagoulian

WGPu pit vs. a hoax (Reactor Grade) → isotopic hoax resistance

+ Different isotopics result in different transmission spectra
+ Only ~100k incident counts necessary for a 5σ detection
  - Use accelerator, p + 7Li → minutes
  - Use LANL spallation source
  - MIT reactor



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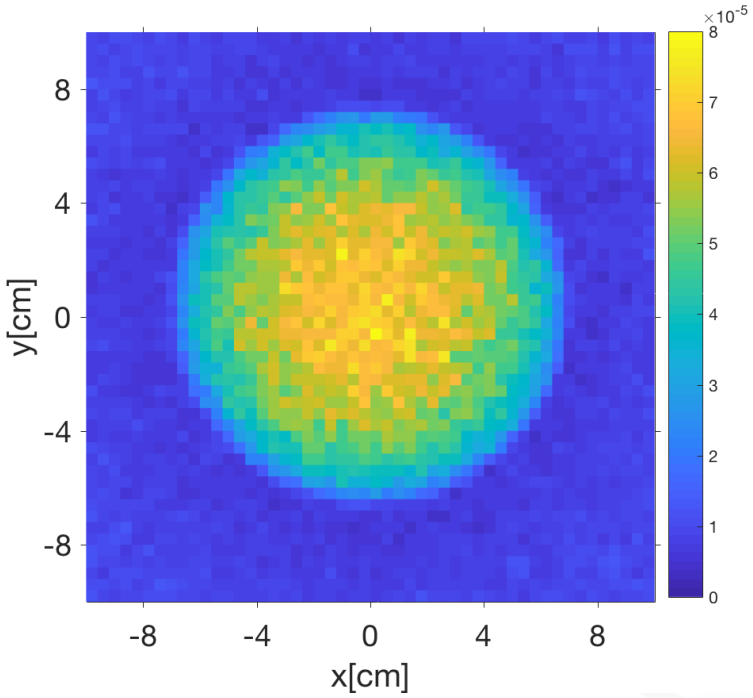
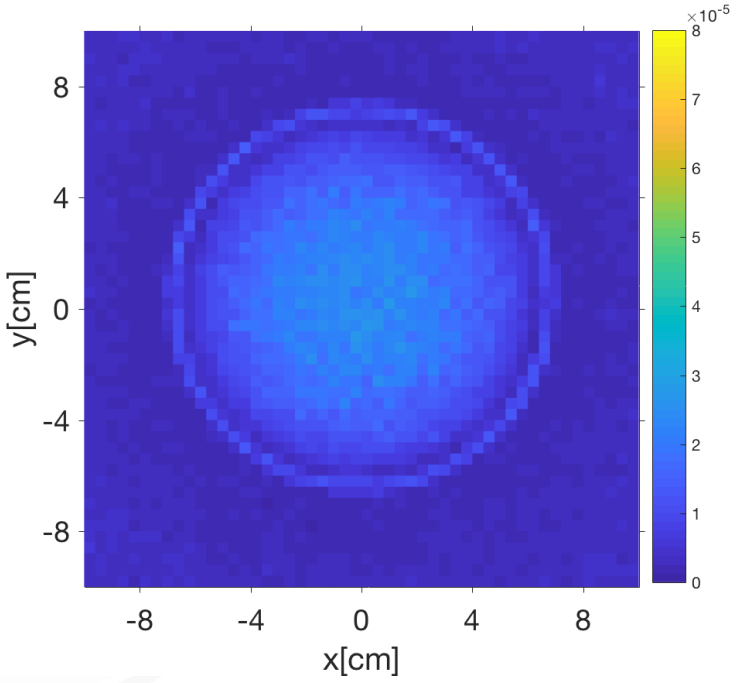
Geometric hoax resistance





Slide: Areg Danagoulian

Status

+ J. Hecla, A. Danagoulian, “Nuclear Disarmament Verification via Resonant Phenomena,” *Nature Communications* (arXiv:1709.09736), in review

→ collaborate with the labs (Lujan Center, LANL?) for a proof-of-concept

- Students: Ezra Engel (MIT), Jake Hecla (now at Berkeley)

+ J. Vavrek, B. Henderson, A. Danagoulian, “Experimental implementation of a warhead verification protocol using nuclear resonance fluorescence,” in preparation

Slide: Areg Danagoulian

Conclusions

We have completed proof-of-concept, isotope-sensitive warhead verification measurements using NRF

We have developed and simulated a new verification measurement using epithermal neutron radiography

Resonant phenomena provide promising warhead verification techniques

Physical cryptography collaboration

Faculty:

Prof. Areg Danagoulian

Prof. Scott Kemp

Dr. Richard Lanza

Stanton post-doctoral fellow:

Brian Henderson

Graduate students:

Jayson Vavrek

Ruaridh Macdonald

S Jeremiah Collins

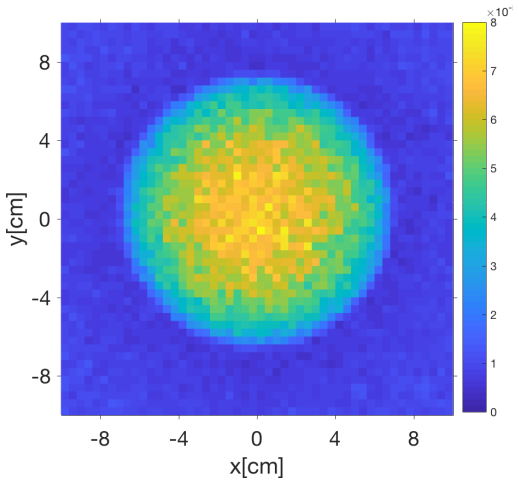
Jake Hecla

BACKUP

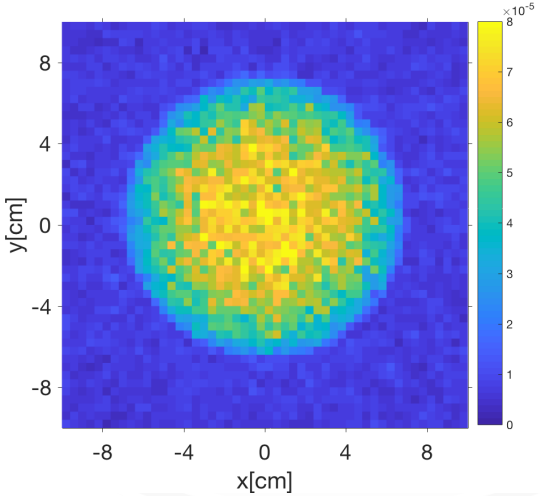
Geometric Information Security

+ 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 ZK!

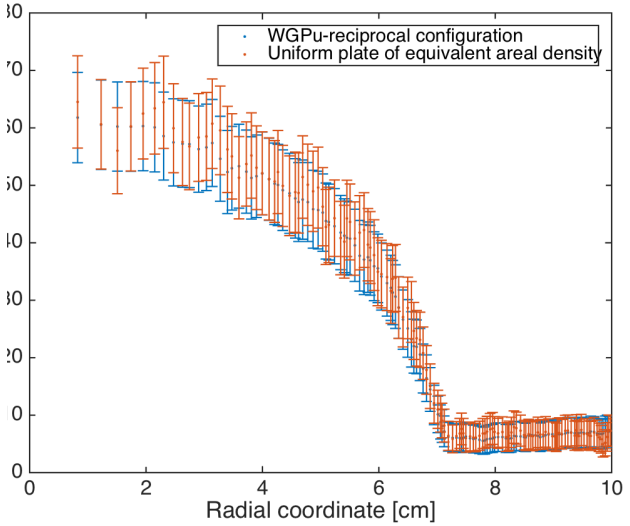
pit+reciprocal



flat plate



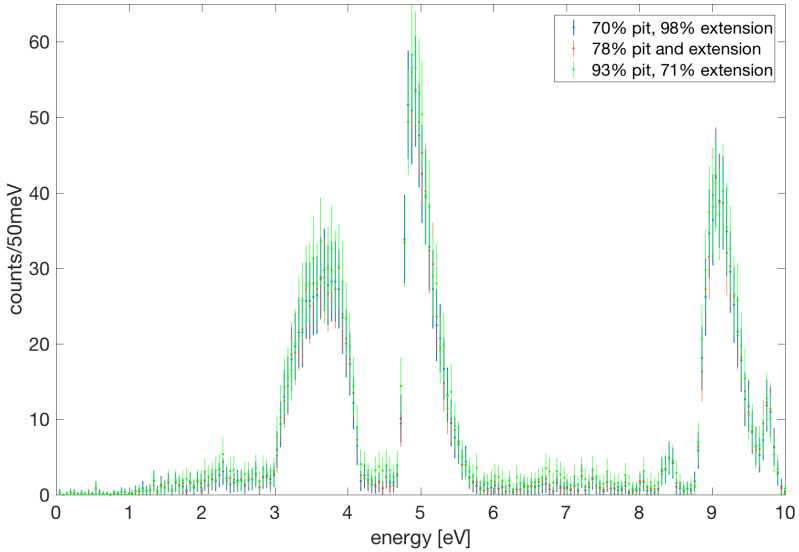
radial comparison



Isotopic Information Security

+ Protect isotopics of their weapons
+ 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 ZK



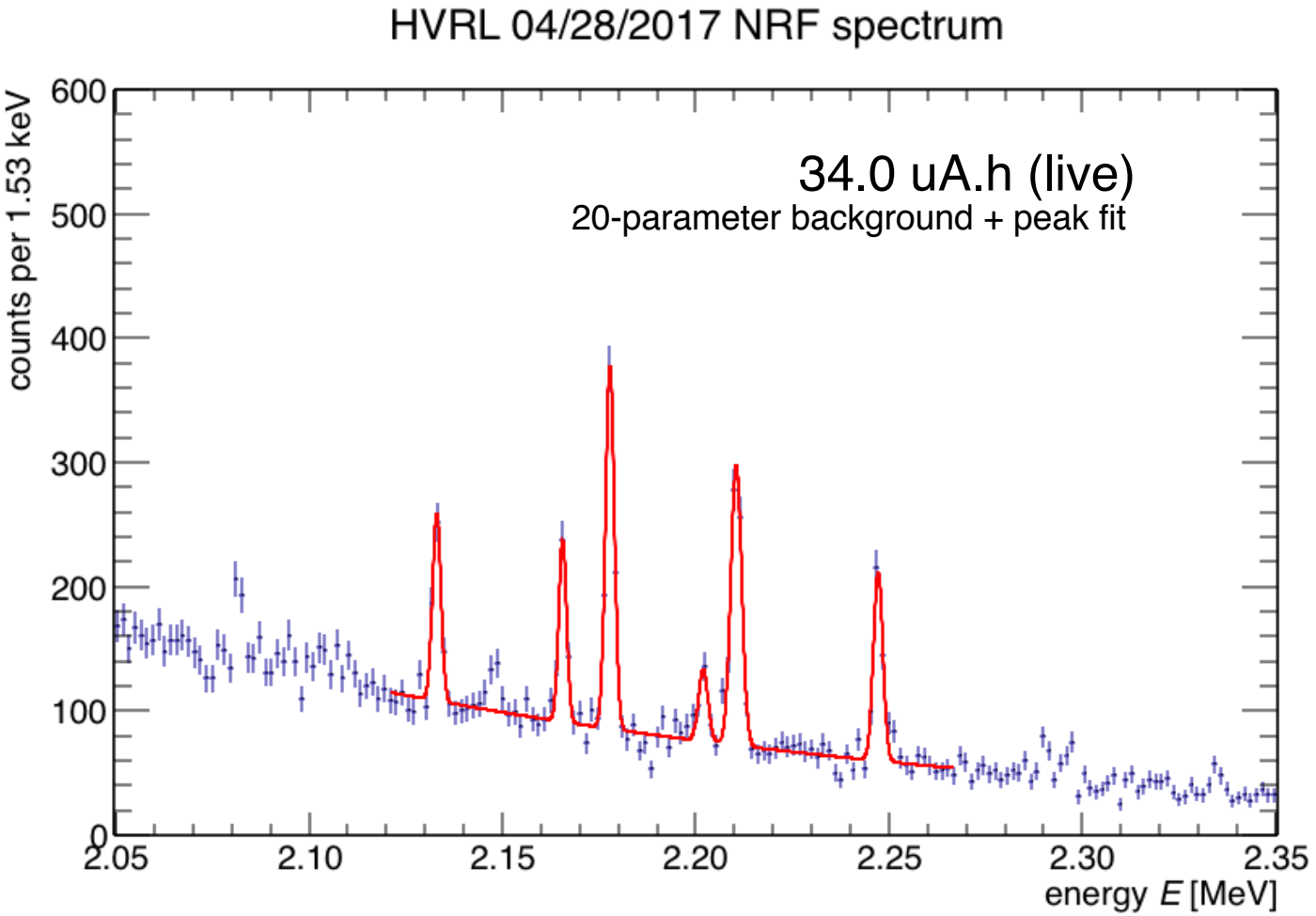
The Goldston filter

- A nefarious host could place a layer of Pb directly upstream of the filter to induce notch refill and lower sensitivity of NRF
- For a 2.6 MeV endpoint beam, the Goldston filter will induce ~3x as much notch refill than expected from standard geometries
  - Modest reduction in sensitivity
  - Could be caught by other spectral changes
  - Can enforce minimum SNRs

The glass equation

Semi*-analytical model for NRF count rates, single isotope:

$$\underbrace{\frac{d^3n}{dE\,d\Omega\,dx}}_{\text{count rate}} = \underbrace{\phi_t(E)}_{\text{transmitted flux}} \underbrace{b\,\mu_{\mathrm{NRF}}(E)}_{\text{production in foil}} \underbrace{\frac{W(\theta)}{4\pi}}_{\text{anisotropy}} \underbrace{\exp\left\{-x\left[\mu_{\mathrm{NRF}}(E)+\mu_{\mathrm{nr}}(E)+\frac{\mu_{\mathrm{nr}}(E')}{\cos\theta}\right]\right\}}_{\text{attenuation in foil}} \underbrace{\epsilon_{\mathrm{int}}(E')P_f(E')}_{\text{detector losses}}$$

* Initial bremsstrahlung flux is often computed via MC

April 2017 direct NRF data