A Very Short Introduction to Princeton's

NUCLEAR FUTURES LAB

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July 2014

Current
Areas of Research

Nuclear Energy and Climate Change

Are there new reactor technologies that could be potential "game changers" for nuclear power?

Nuclear Energy and Nuclear Proliferation

Can one safely expand the use of nuclear power without increasing the risk of nuclear proliferation?

Nuclear Disarmament Verification

Can one dismantle an atomic bomb without learning anything about its design?

How To Dismantle an Atomic Bomb

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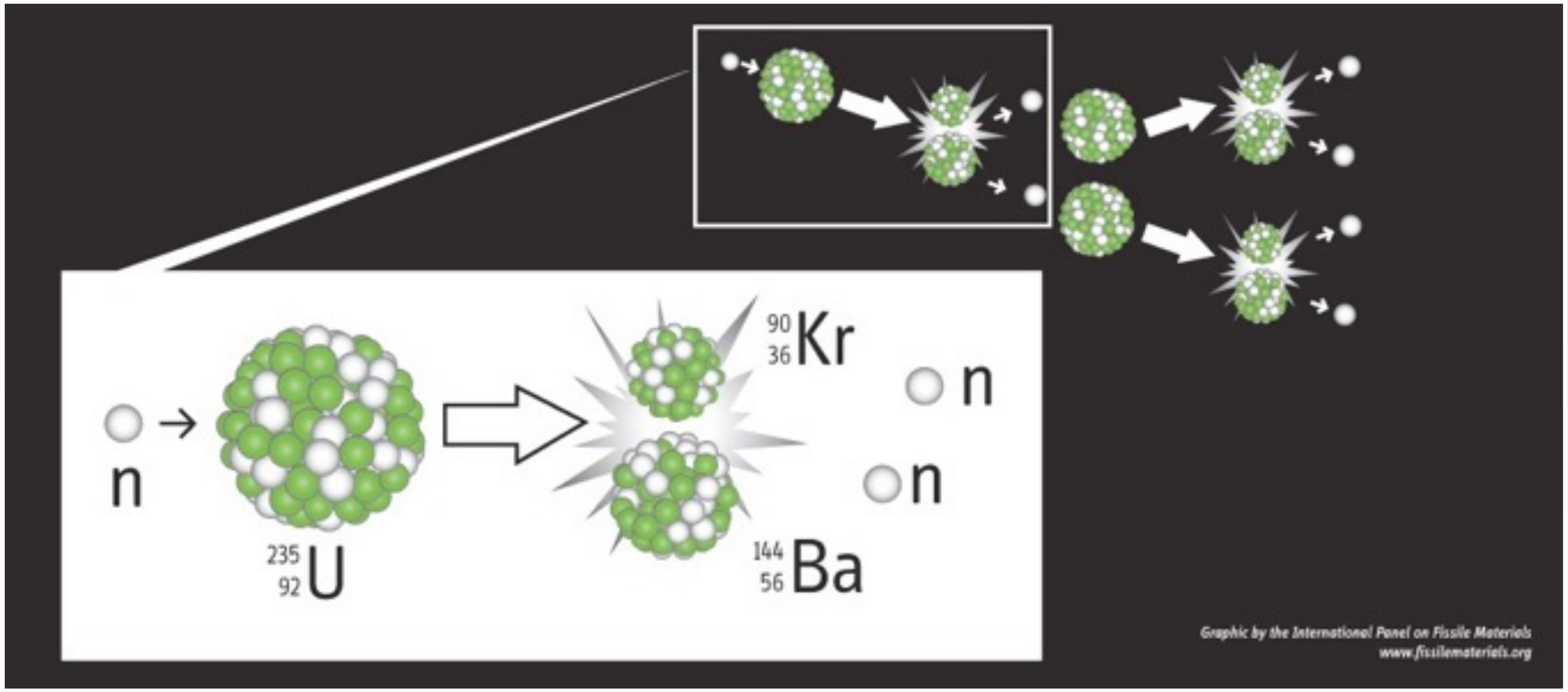
Princeton University

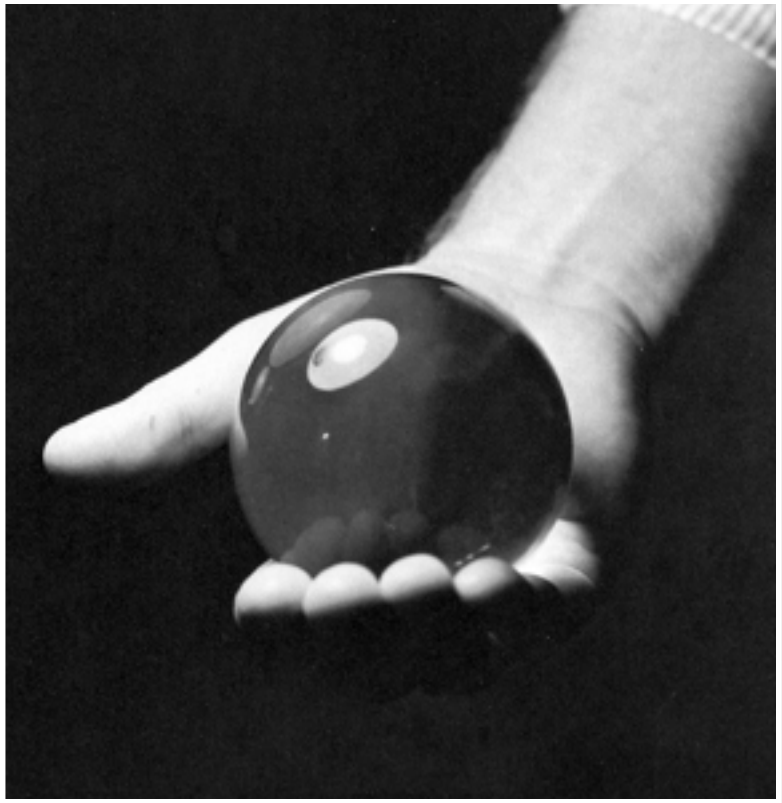
Research Experience for Undergraduates
Princeton University, July 28, 2014

Revision 1x

Background

Fissile Materials and Nuclear Weapons





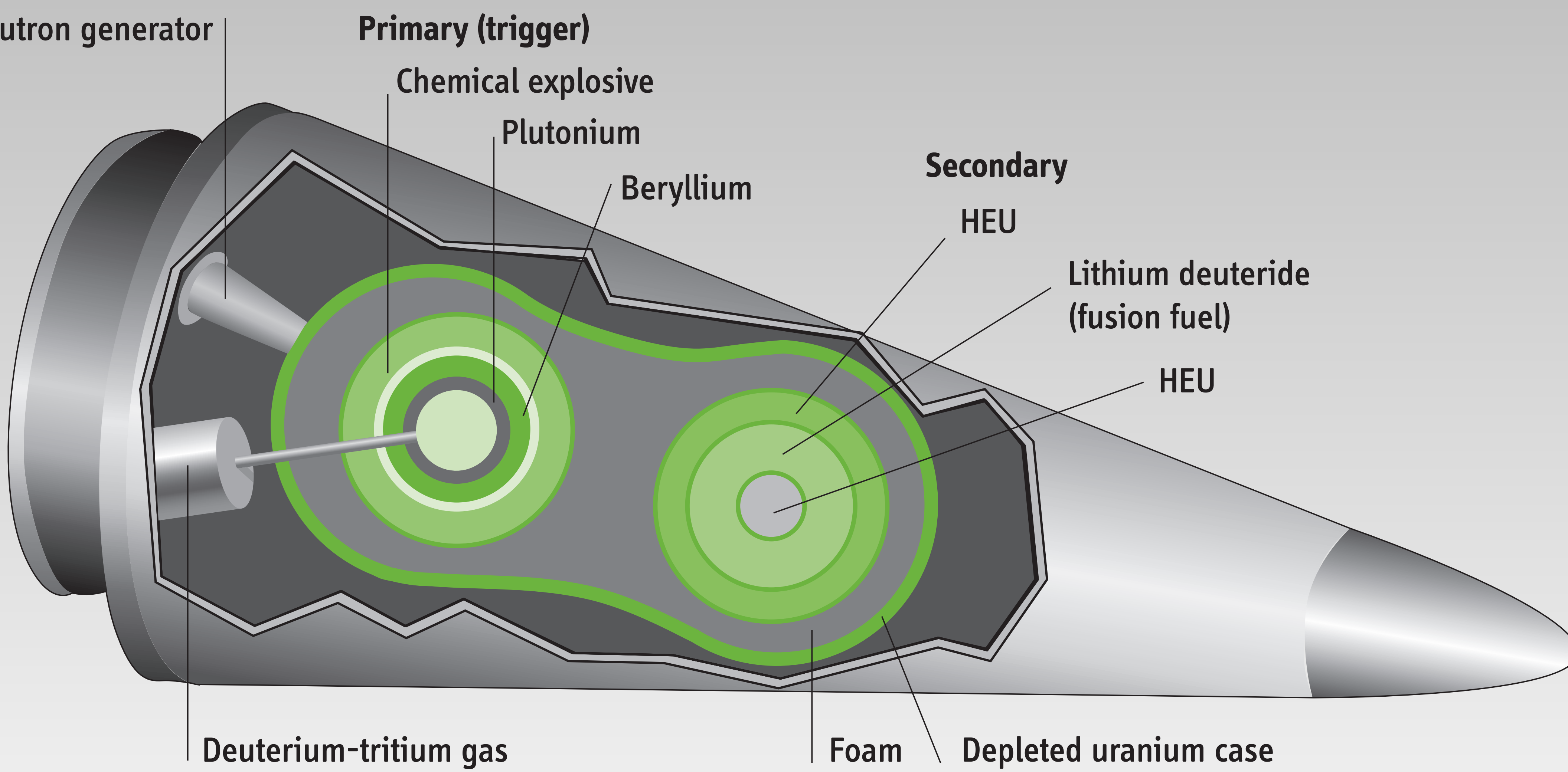
HEU in weapons usually more than 90% enriched in U-235 (0.7% in nature)

The Hiroshima bomb used 60 kg of 80%-enriched HEU

Plutonium (mostly Pu-239) separated from irradiated uranium

The Nagasaki bomb used 6 kg of Plutonium

Fissile Materials and Nuclear Weapons



A modern thermonuclear warhead contains on average 3–4 kg of plutonium and 25 kg highly enriched uranium

Adapted from Final Report of the Select Committee on U.S. National Security and Military/Commercial Concerns with the Peoples Republic of China ("Cox Report"), U.S. House of Representatives, 3 January 1999

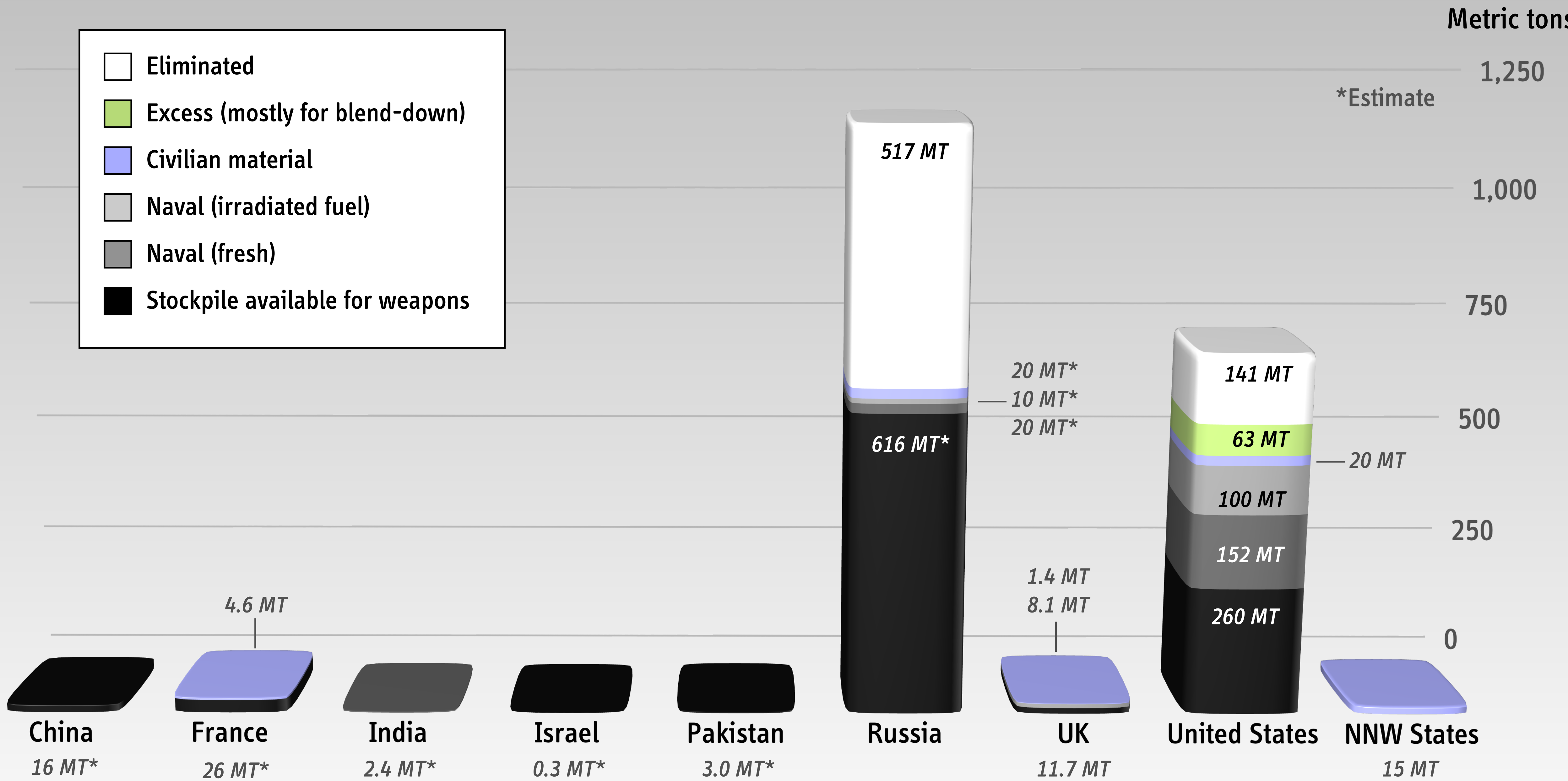
Fissile Material Production for Weapons

Country	HEU production	Plutonium production for weapons
China	stopped 1987 (unofficial)	stopped 1991 (unofficial)
France	stopped 1996	stopped 1992
Russia	stopped 1989	stopped 1994
United Kingdom	stopped 1962 (but imports from United States)	stopped 1995
United States	stopped 1992	stopped 1988

Israel, India, Pakistan, and North Korea are still producing

Highly Enriched Uranium, mid 2013

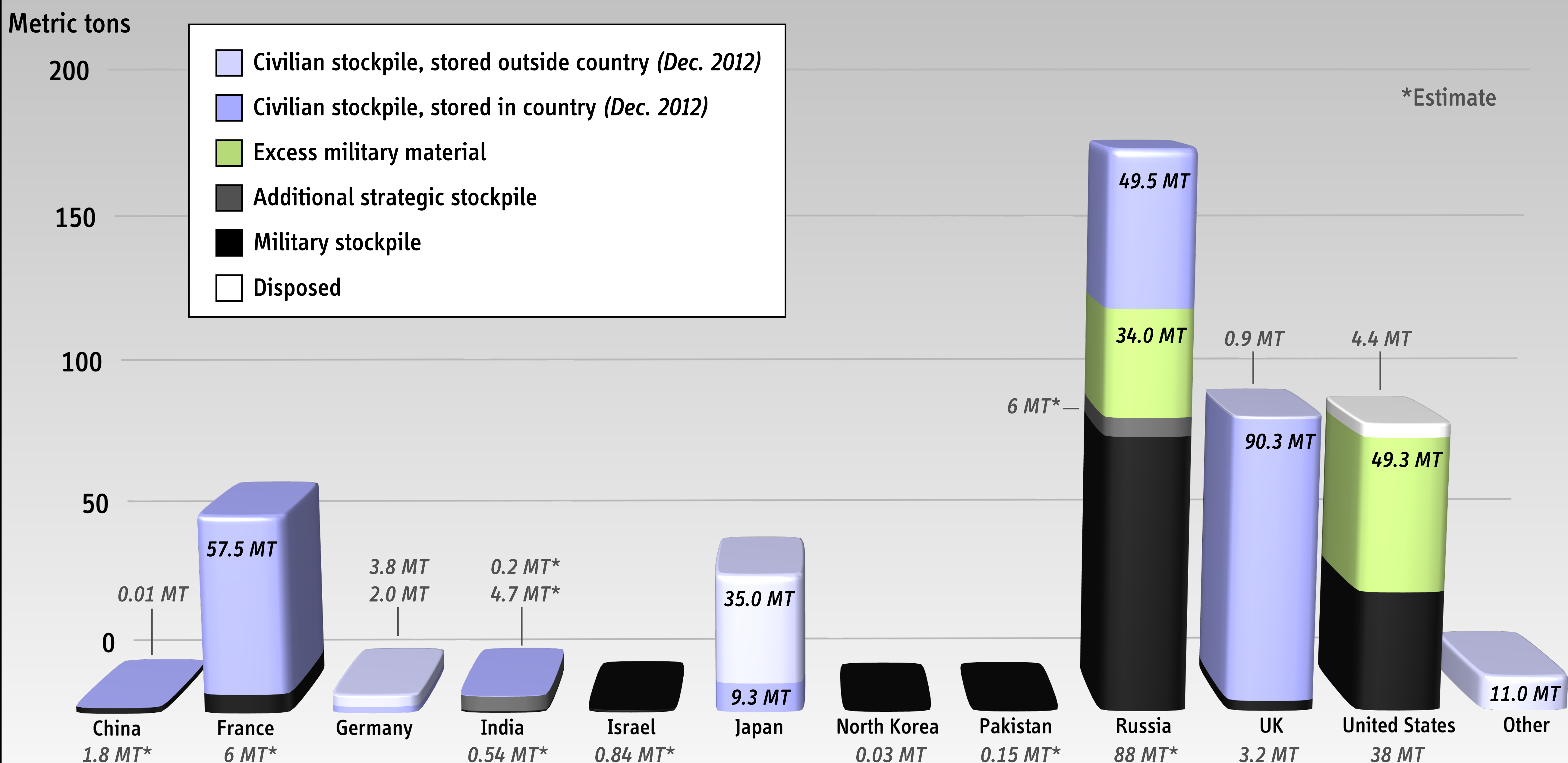
Global stockpile is about 1350 tons, almost 99% is in weapon states



(25 MT of HEU are equivalent to 1,000–2,000 nuclear weapons)

Separated Plutonium, mid 2013

Global stockpile is about 500 tons, more than half is civilian and this stock is growing



(5 MT of plutonium are equivalent to 1,000–1,500 nuclear weapons)

A Fissile Material Approach to Nuclear Disarmament and Nonproliferation

Secure all existing stocks
Whenever possible dispose off (excess) stocks

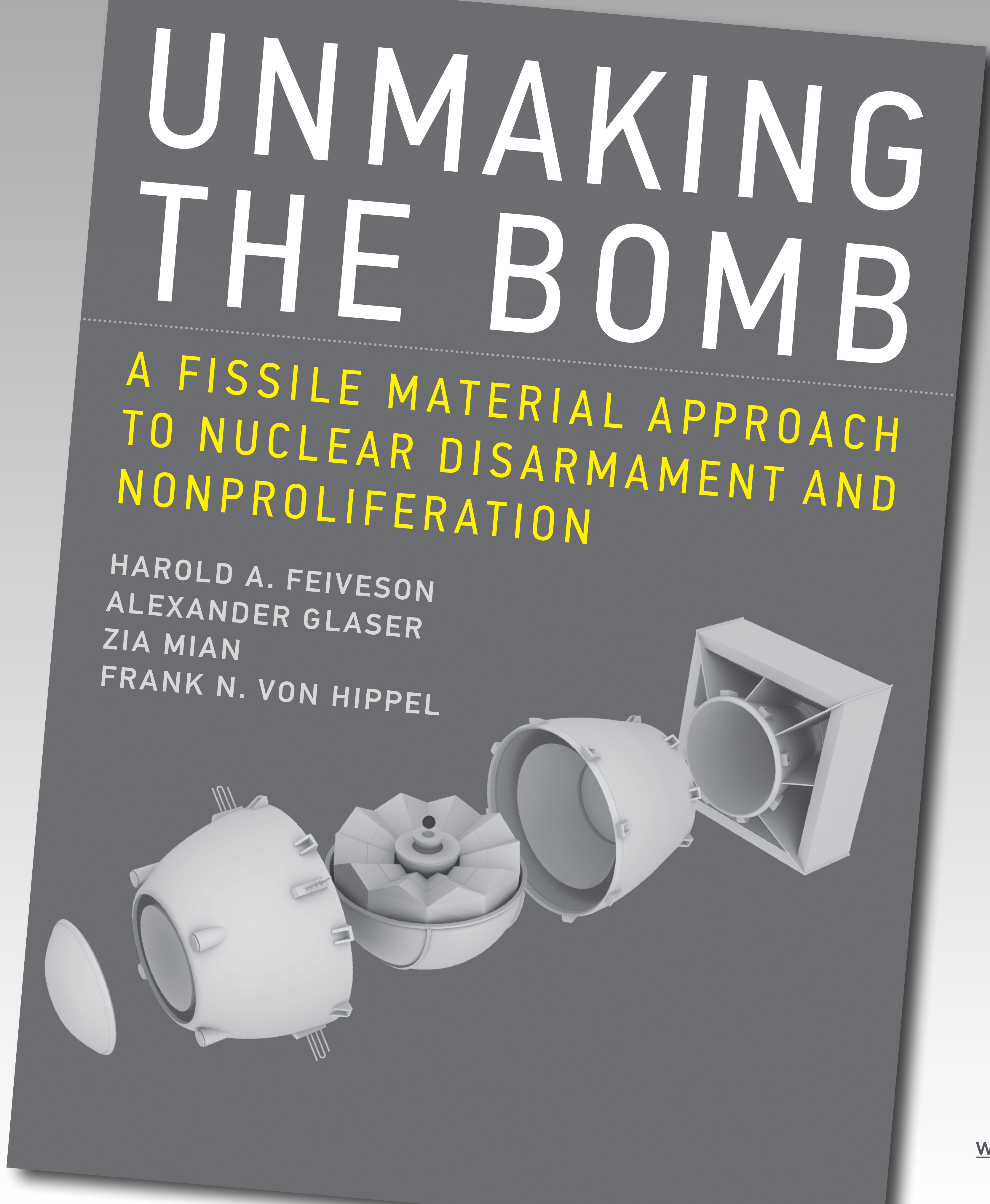
Nuclear energy

Use nuclear energy in ways that do not involve (or easily enable) production and use of fissile materials

Nuclear weapons reductions

Make sure to recover (all) fissile materials from dismantled nuclear weapons and verifiably dispose off these materials

(Understand how much fissile material actually exists today)

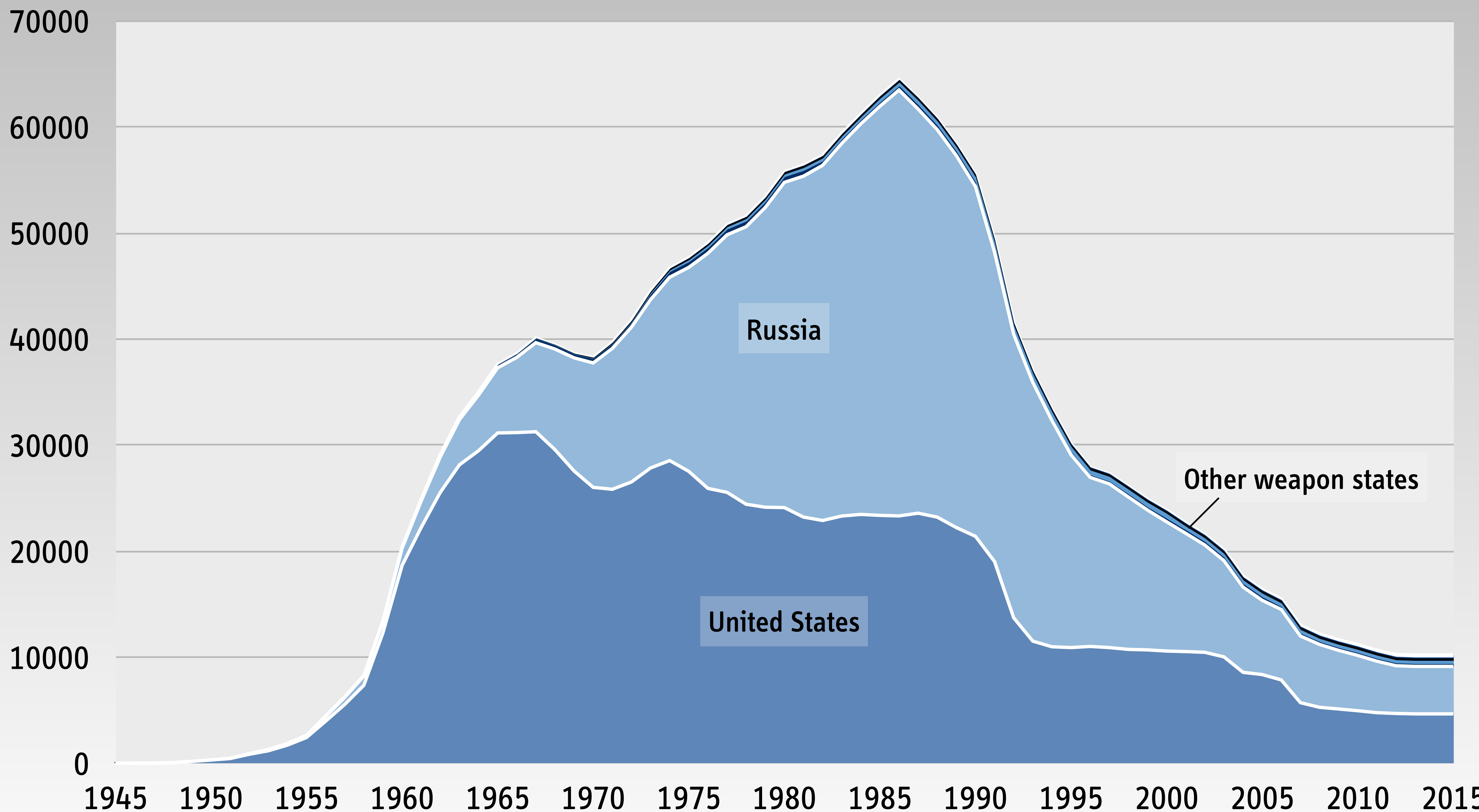


MIT Press
www.unmakingthebomb.com
September 26, 2014

Nuclear Warhead Dismantlement Verification

Global Nuclear Weapons Stockpile

from 1945 to 2013, does not include several thousand warheads in dismantlement queue



H. M. Kristensen and R. S. Norris, "Nuclear Weapons Inventories, 1945–2013," *Bulletin of the Atomic Scientists*, 69, 2013, pp. 75–81

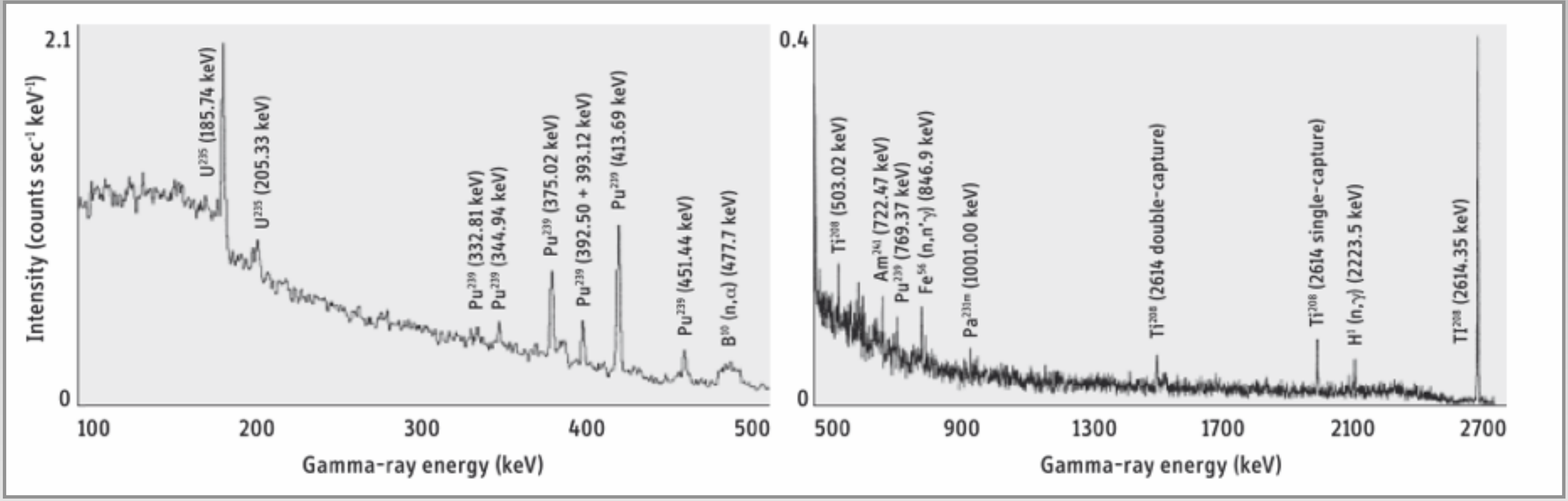
Thousands of Nuclear Weapons Are No Longer Deployed and Currently In Storage

W87/Mk-21 Reentry Vehicles in storage, Warren Air Force Base, Cheyenne, Wyoming

Photo courtesy of Paul Shambroom, www.paulshambroom.com

Nuclear Warheads Have Unique Signatures

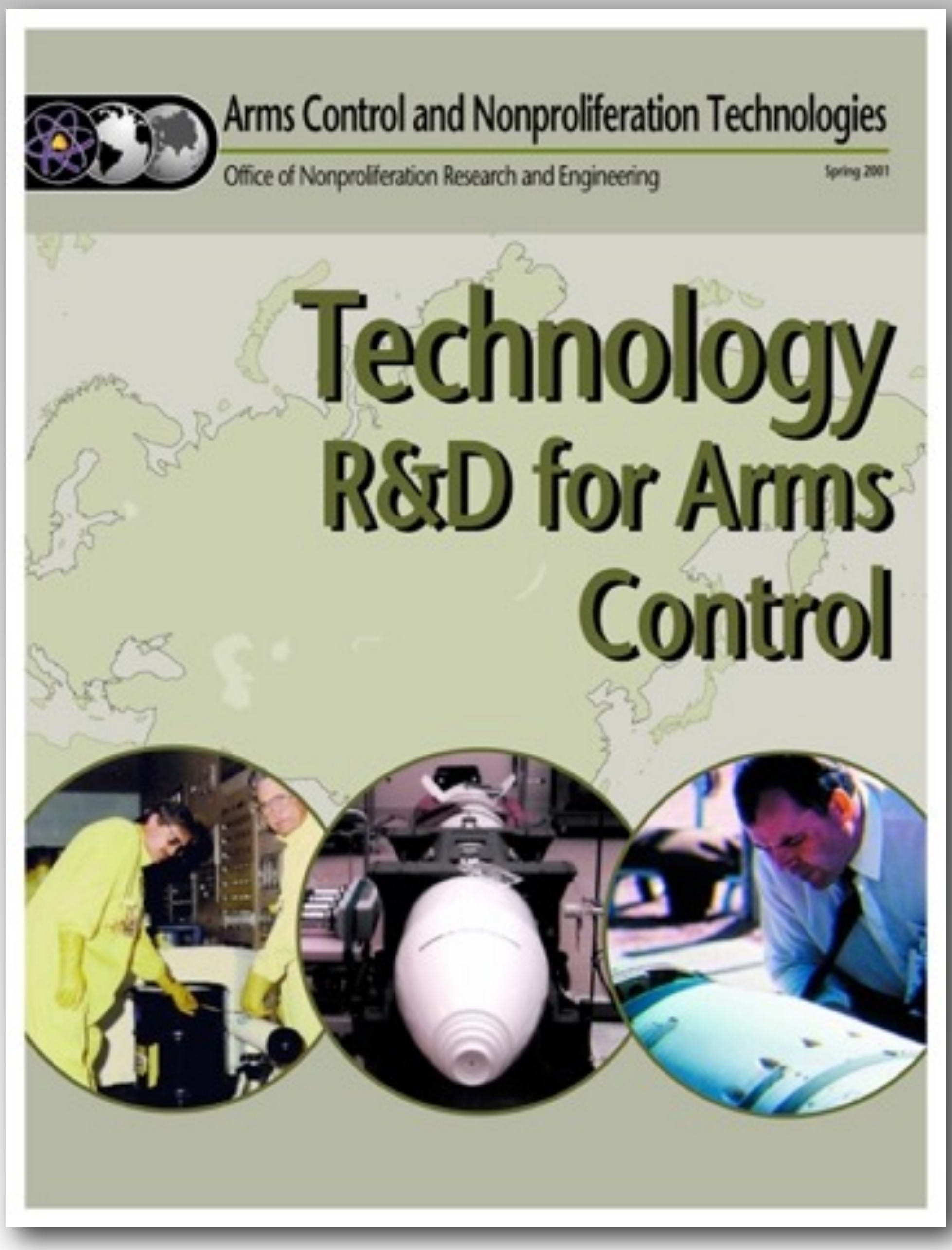
(but most of them are sensitive and cannot be revealed)



Gamma radiation spectrum from a Soviet warhead measured in 1989

Steve Fetter, Thomas B. Cochran, Lee Grodzins, Harvey L. Lynch and Martin S. Zucker
"Measurements of Gamma Rays from a Soviet Cruise Missile," *Science*, Vol. 248, 18 May 1990, pp. 828–834

Inspection Systems for Nuclear Warhead Verification Have Been Under Development Since the 1990s



edited by David Spears, 2001

Attribute Approach

Confirming selected characteristics of an object in classified form (for example, the presence/mass of plutonium)

Template Approach

Comparing the radiation signature from the inspected item with a reference item ("golden warhead") of the same type

Information Barrier

Technologies and procedures that prevent the release of sensitive nuclear information (generally needed for both approaches)

Attribute Measurement System

with Information Barrier

Secure Mode

Sample	Isotopics?	Mass?	No Oxide?	Pu Present?	Symmetry?	Age?
Weapon component	🟢	🟢	🟢	🟢	🟢	🟢
Large oxide sample on its side	🟢	🟢	🔴	🟢	🔴	🟢

Fissile Material Transparency Technology Demonstration (FMTTD), Los Alamos, August 2000

David Spears (ed.), *Technology R&D for Arms Control*, U.S. Department of Energy, Office of Nonproliferation Research and Engineering, Washington, DC, 2001

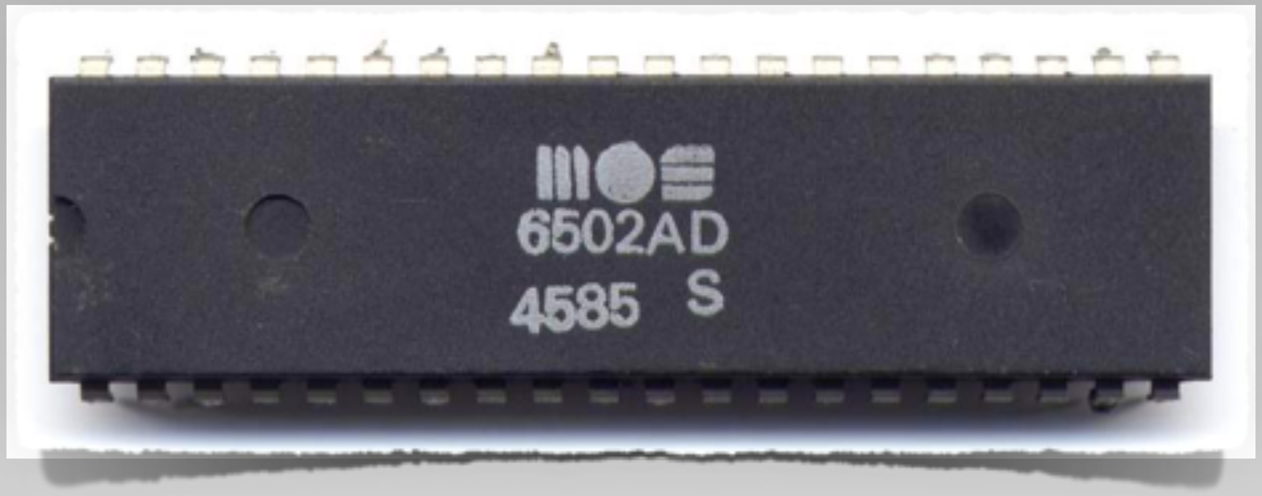
Information Barriers Have Been Critical Elements

for inspection systems measuring classified information

UK-Norway Initiative, 2nd Prototype Information Barrier

David Chambers et al., “UK-Norway Initiative: Research into Information Barriers to Allow Warhead Attribute Verification Without Release of Sensitive or Proliferative Information,” INMM 51st Annual Meeting, Baltimore, MD, USA, July 11–15, 2010

Can You Trust This Chip?



Hardware Trojans

Malicious changes or additions to an integrated circuit
that add or remove functionalities or reduce the reliability of the system

G. Becker, Intentional and Unintentional Side-Channels in Embedded Systems
PhD dissertation University of Massachusetts Amherst, February 2014

Insertion is possible in every stage of the product cycle

For example, during design, manufacturing, assembly, and shipping (supply-chain)

Bubble Detectors May Offer A Way To Implement this Protocol

(and Avoid Electronics on the Detector Side)

Detectors with different neutron-energy thresholds are available
(no cutoff, 500 keV, 1 MeV, 10 MeV)

Princeton Global Zero Verification Project

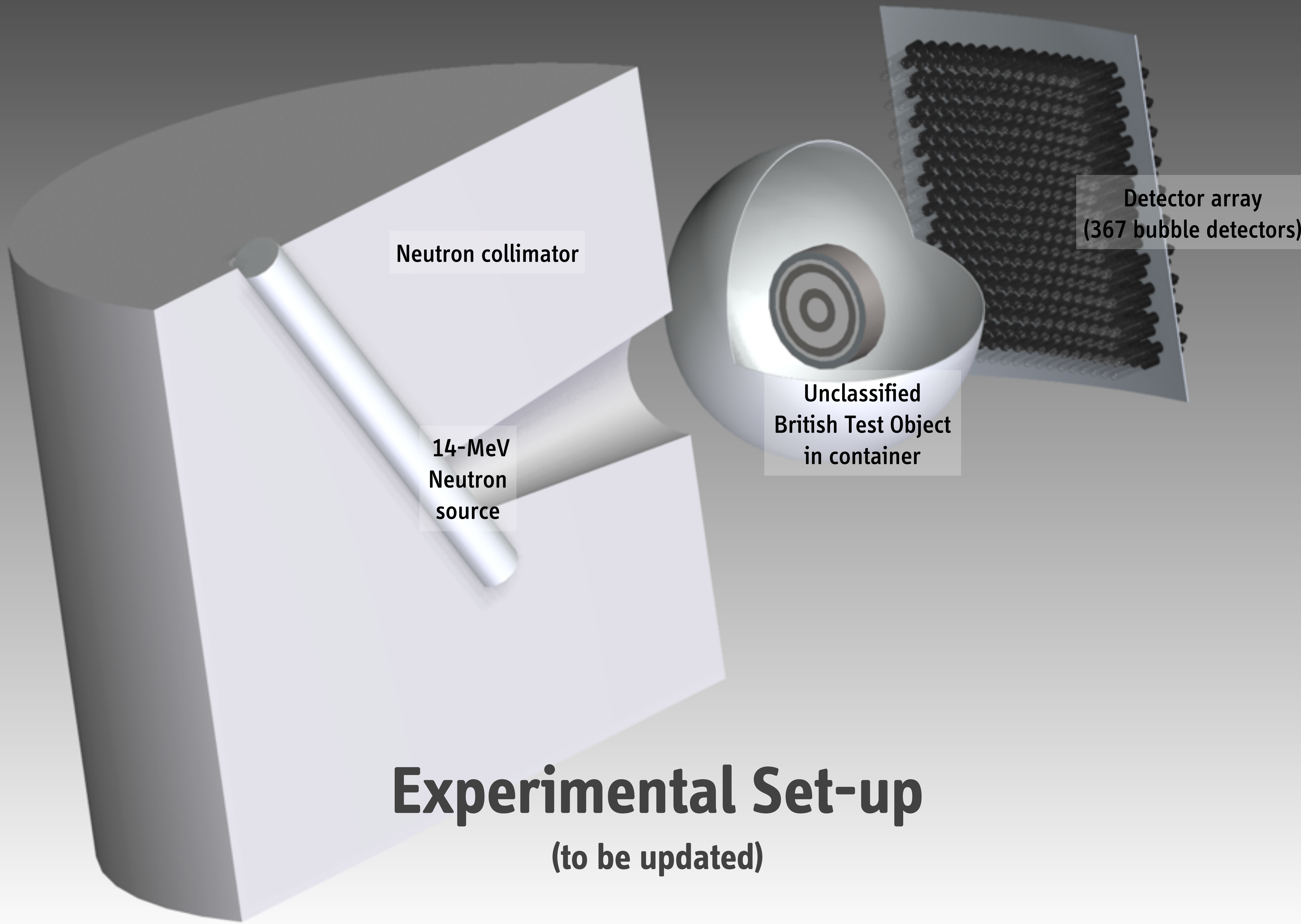
Princeton/Global Zero Verification Project

using Non-electronic Detectors with a Zero-knowledge Protocol

GENERAL APPROACH

- 14.1-MeV neutron source (10^8 n/s) available at PPPL
- Unclassified test objects that do not contain fissile materials (tungsten, lead, depleted uranium, ...)
- Template approach without information barrier
- Non-electronic bubble or activation detectors
- Validate conceptual approach with simulated data

Project funded by Global Zero (www.globalzero.org)
and previously supported by U.S. Department of State and PPPL Proposal Development Funds



Experimental Set-up

(to be updated)

How Do We Prevent Sensitive Information from Being Detected?

(Physical Implementation of a Zero-knowledge Protocol)

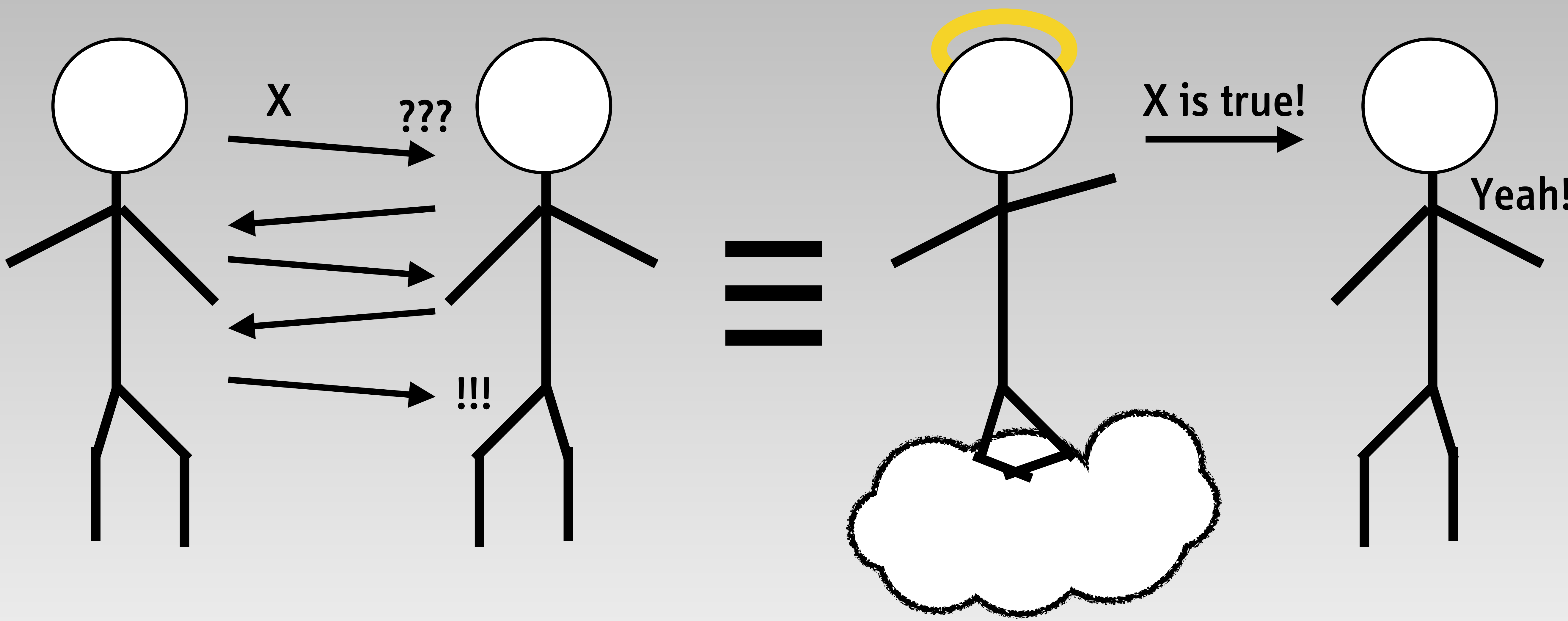
7,779,194,804,244,557

is not a prime number

23,985,737 x 324,325,861 = 7,779,194,804,244,557

Can one prove that a number is not a prime
without revealing its factors?

“Zero-Knowledge Interactive Proofs”

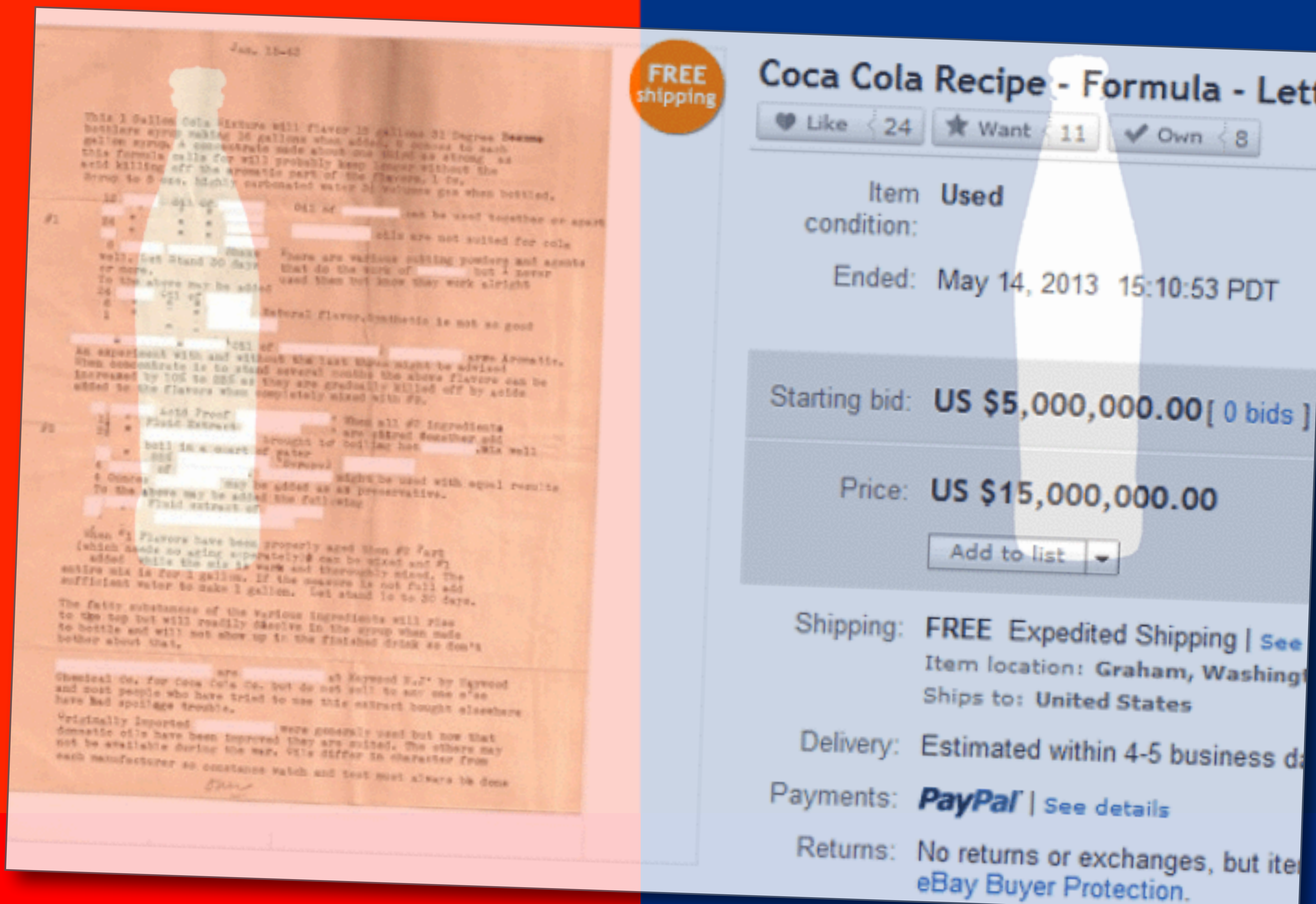


Zero-Knowledge Proofs: Peggy (P) proves to Victor (V) that she knows a secret without giving anything about the secret itself away

O. Goldreich, “Foundations of Cryptography, Volume 1: Basic Techniques,”Cambridge University Press, 2001

Coca-Cola

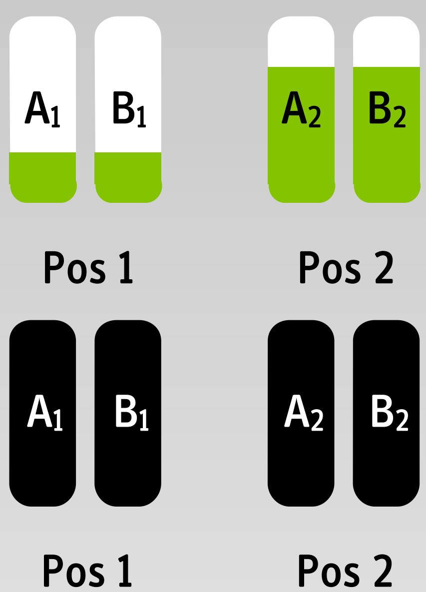
pepsi



Proposed “Hardware Implementation” of a Zero-Knowledge Protocol for Warhead Verification

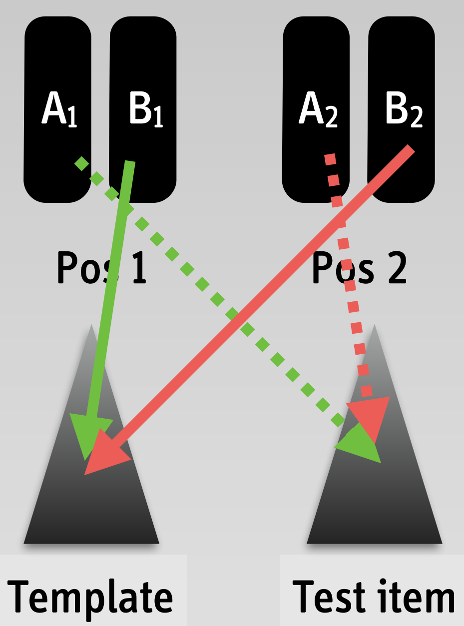
1

Host preloads secretly n pairs of bubble detectors with “negative” radiograph of the template



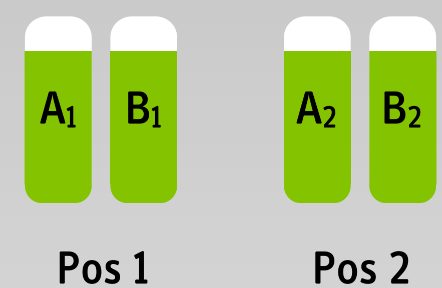
2

For every position, inspector chooses randomly, which detector (A_i, B_i) to use on template or test item



3

After interrogation, inspector verifies all detectors contain the same bubble count

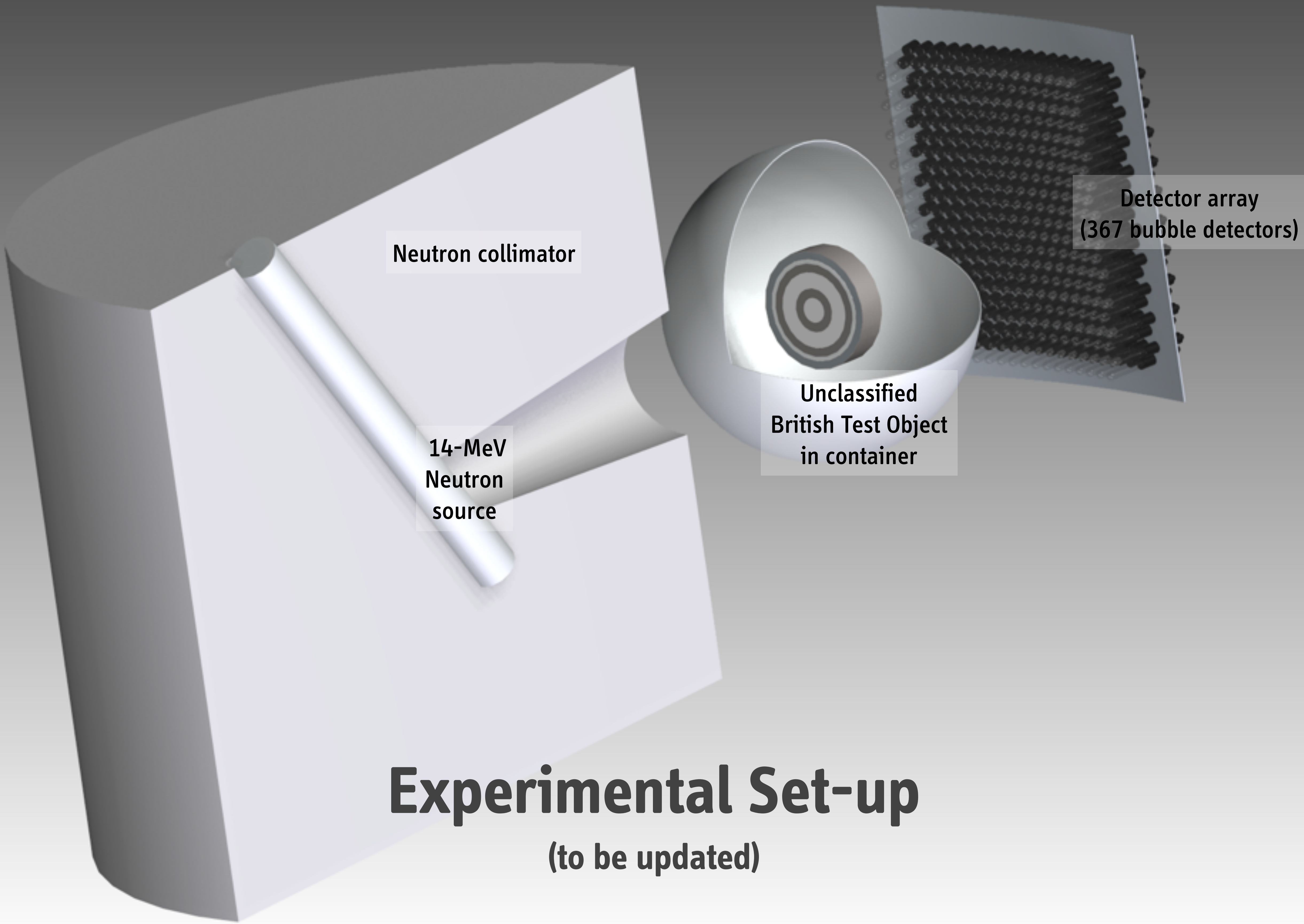


50% confidence after 1st inspection

75% confidence after 2nd inspection

95% confidence after 5th inspection

Results of Monte Carlo Neutron Transport Simulations

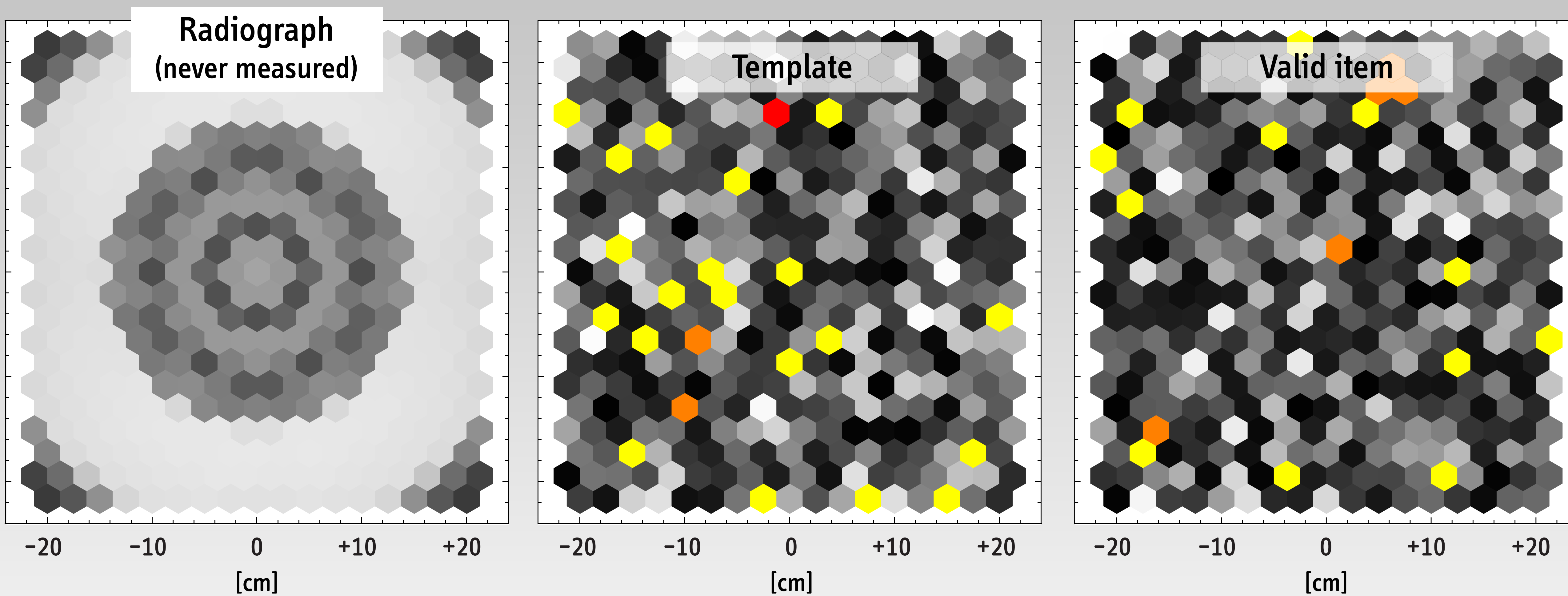


Experimental Set-up

(to be updated)

Zero-knowledge Warhead Verification

(Authenticating warheads without ever measuring classified information)



Small deviations from N_{MAX} Significant deviations from N_{MAX} (2.0, 2.5, 3.0 sigma)

Simulated data from MCNP5 calculations, neutron energies > 10 MeV, N(max) = 5,000

Glaser, Barak, and Goldston, "A Zero-knowledge Protocol for Nuclear Warhead Verification," *Nature*, 510, June 2014, pp. 497–502

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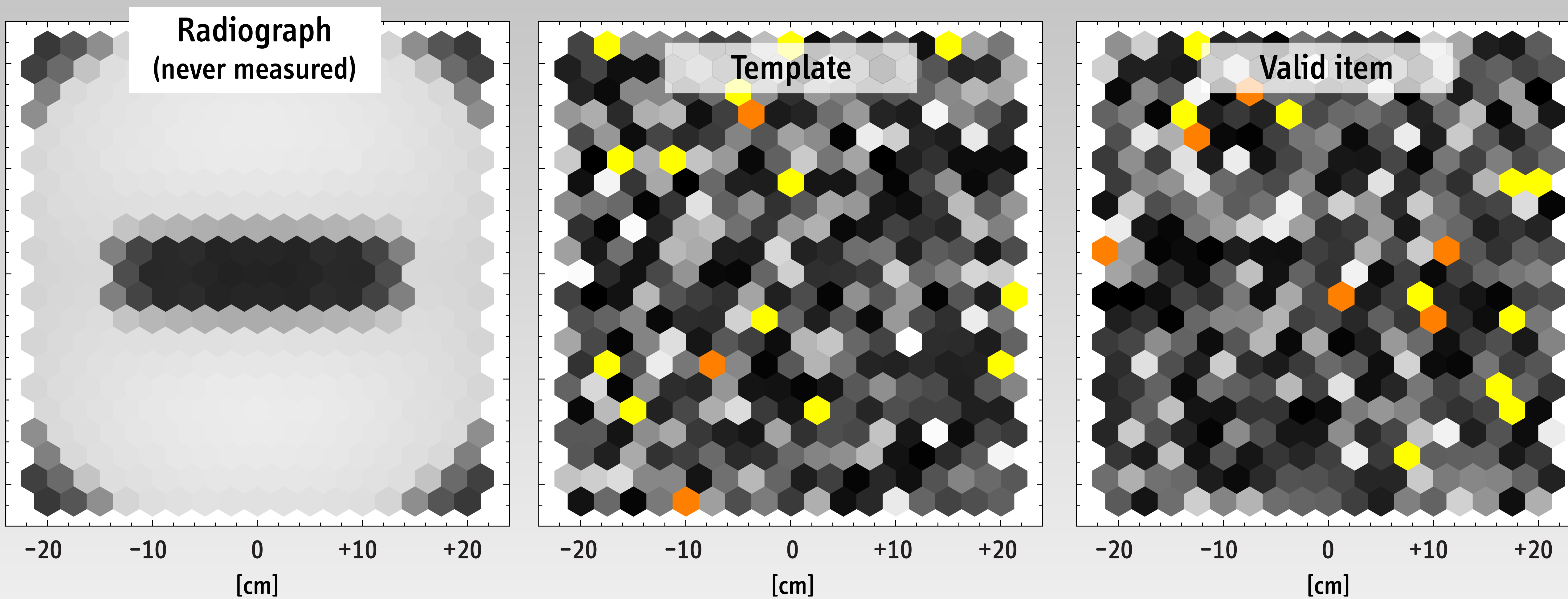

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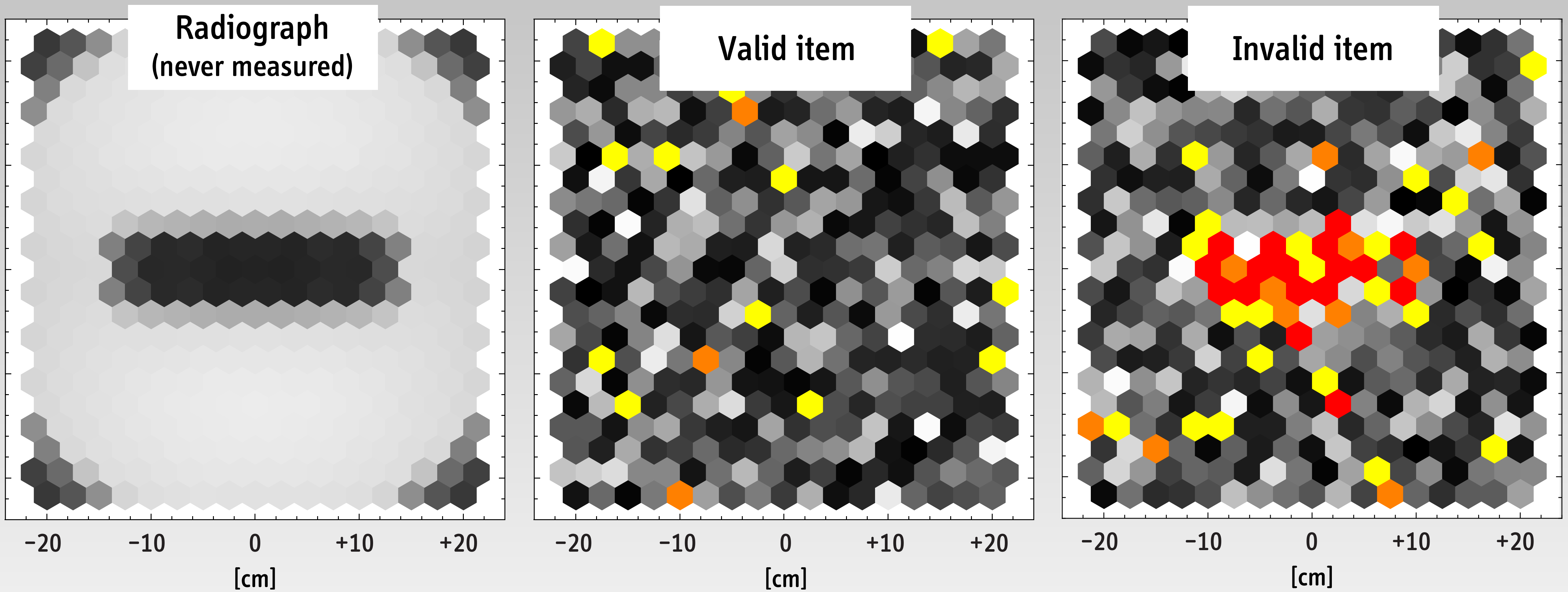
Zero-knowledge Warhead Verification

Information may be released, however, if the host tries to cheat



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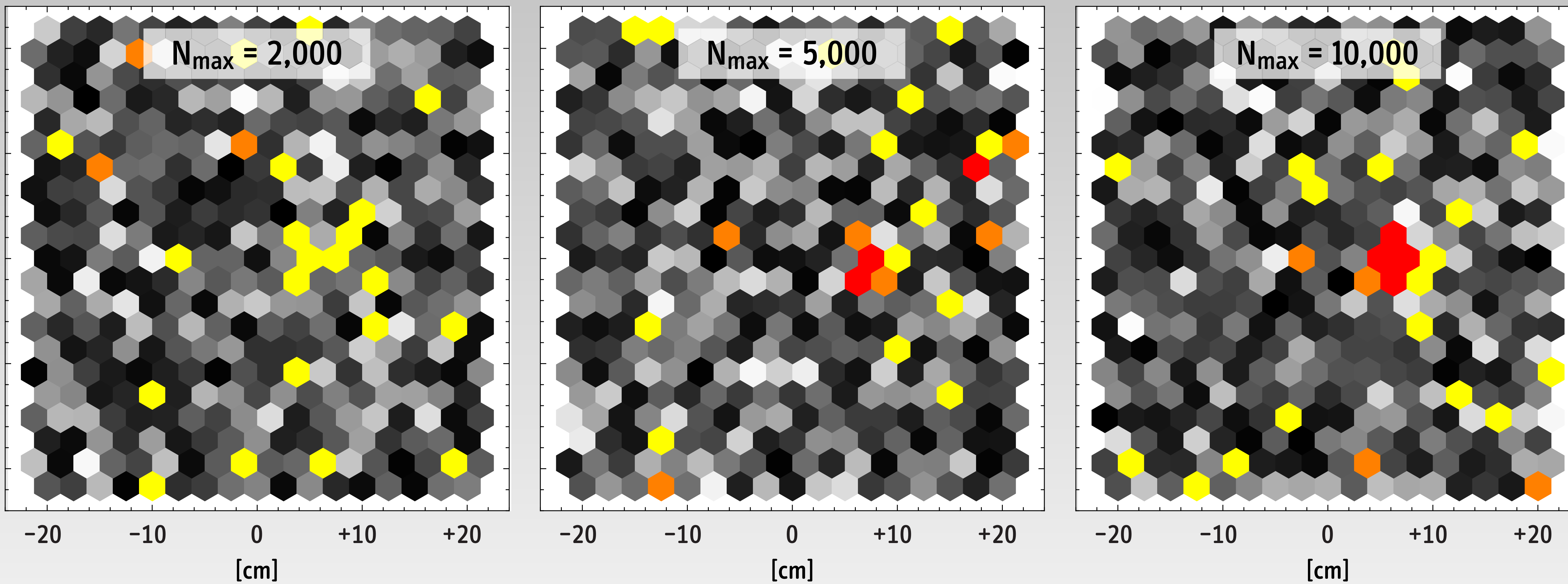
Zero-knowledge Warhead Verification

Detectability of (small) diversions depends on experimental conditions



Small deviations from N_{MAX} Significant deviations from N_{MAX} (2.0, 2.5, 3.0 sigma)

543 grams of tungsten removed from outer ring of BTO; Simulated data from MCNP5 calculations, neutron energies > 10 MeV
Glaser, Barak, and Goldston, “A Zero-knowledge Protocol for Nuclear Warhead Verification,” *Nature*, 510, June 2014, pp. 497–502

Summary

Summary

New Verification Technologies for Arms Control and Disarmament

Requirements for Existing or Next-generation Arms Control Treaties

Technology gaps for verification of some expected treaties (e.g. CTBT/FMCT) are small

BUT: Nuclear disarmament verification requires new approaches and techniques

Important opportunities to initiate new development and demonstration projects

Nuclear Warhead Authentication and Verified Dismantlement

Develop and demonstrate practical inspection systems

Demonstrate viability of cooperation between nuclear and non-nuclear weapon states

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