How To Dismantle an Atomic Bomb

On Overview of the Global Zero Nuclear Warhead Verification Project

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Massachusetts Institute of Technology, November 27, 2013

Revision 3

Background

Nuclear Weapons After the Cold War and the Challenge of Verifying Nuclear Disarmament

Going “Beyond New-START”

“While the new START treaty is an important step forward, it is just one step on a longer journey. As I said last year in Prague, this treaty will set the stage for further cuts. And going forward, we hope to pursue discussions with Russia on reducing both our strategic and tactical weapons, including non-deployed weapons.”

U.S. President Obama, upon signing the New START Treaty, April 2010

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

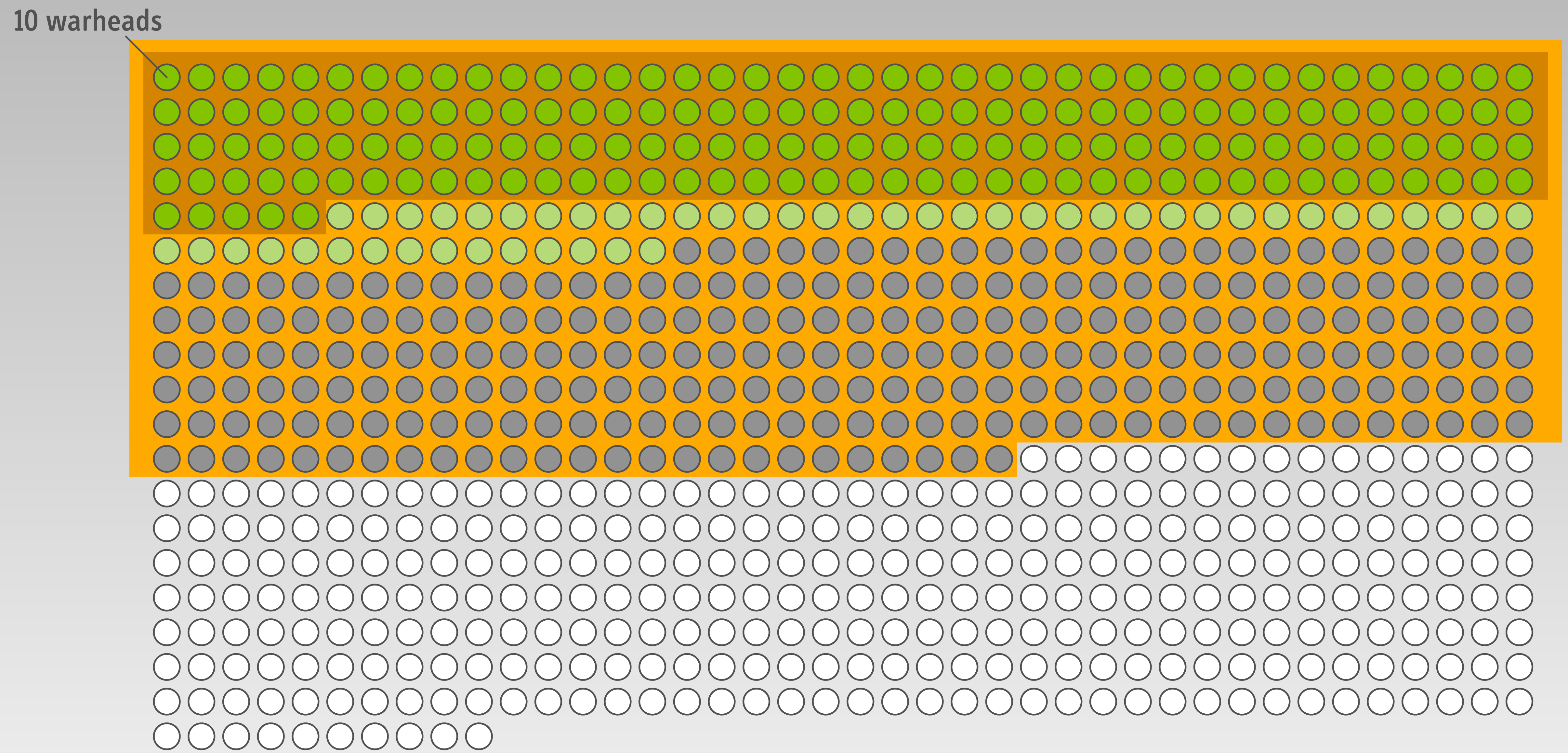
Photo courtesy of Paul Shambroom, www.paulshambroom.com

What Are We Worried About?

(The Challenges of Nuclear Disarmament Verification)

Example

(U.S. Nuclear Arsenal, 2013)



1,650 Deployed strategic warheads (as declared under New Start, March 2013) — declared numbers

2,150 Total deployed warheads (estimated)

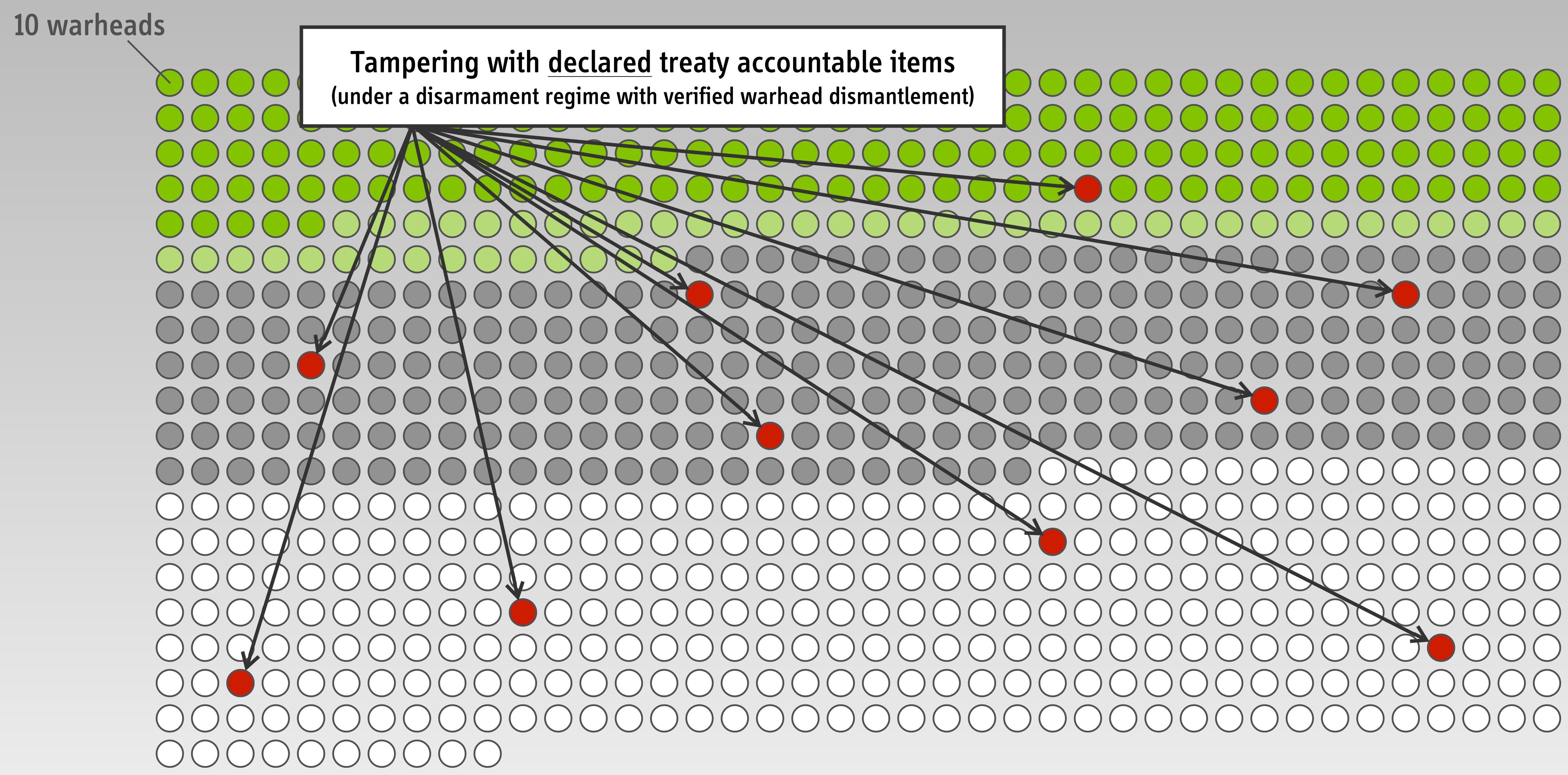
4,650 Total stockpile, including reserve (declared, 5,113 as of September 2009)

7,700 Total stockpile, including reserve and retired (but intact) warheads (estimated)

H. M. Kristensen and R. S. Norris, "Global Nuclear Weapons Inventories, 1945–2013," *Bulletin of the Atomic Scientists*, 69 (5), 2013, pp. 75–81

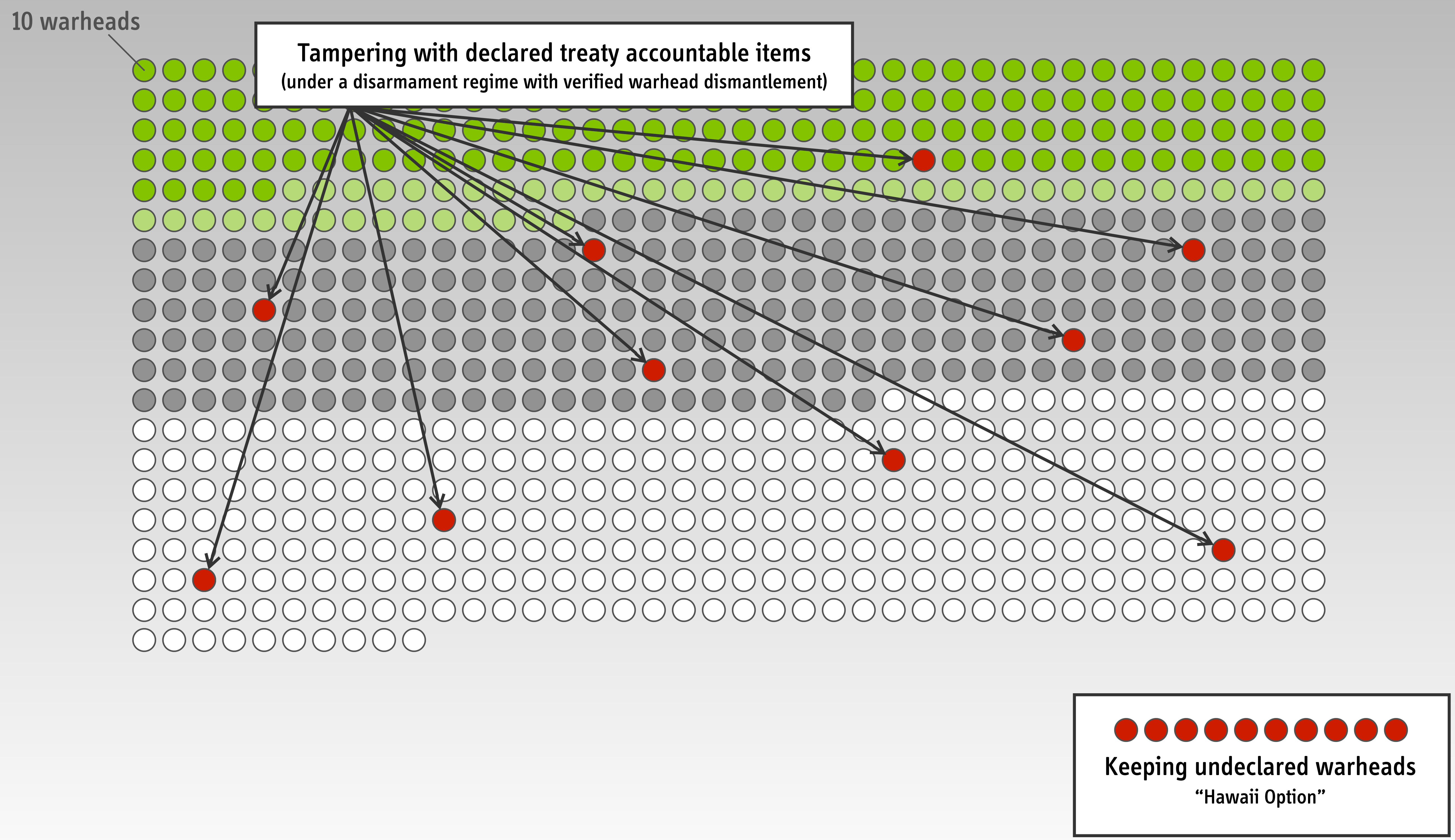
Example

Notional Cheating Scenarios




What About the Secret Nuclear Weapons Stockpile
Stashed Away on that Remote Island?

Notional Cheating Scenarios



Main Cheating Scenarios and Associated Verification Challenges

1

Party offers hoax or tampered devices instead of authentic treaty accountable items (TAI) so that real warheads, warhead components, or fissile material can be "diverted" to a secret stockpile of nuclear weapons

⇝ **Verifying the dismantlement of nuclear warheads**

2

Party provides incomplete baseline declarations so that some treaty accountable items (e.g. warheads) are never part of the verification regime

⇝ **Verifying the completeness of declarations**

3

Party has undeclared fissile material production capacities, which are used to supply material for new weapons, e.g. to replace dismantled TAI

⇝ **Verifying the non-production of new fissile material for weapons**

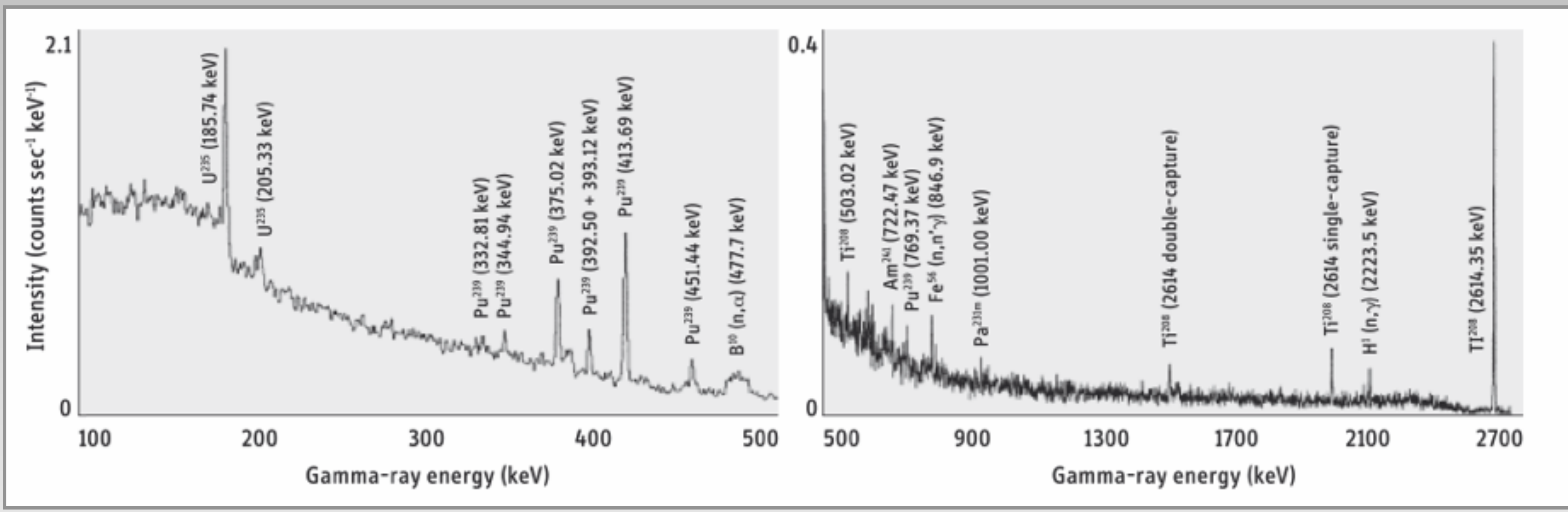
(Same challenge for NPT and FMCT)

Verified Warhead Dismantlement

(Previous Efforts)

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 (needed for both approaches)

Warhead Dismantlement Verification

Some Precedents Exist and Future Work Can Build on Them

Inspection System developed as part of the 1996–2002 Trilateral Initiative during a demonstration at Sarov
Source: Tom Shea

Visual contact with a mockup nuclear weapon during a UK-Norway Initiative Dismantlement Exercise
Source: UK Norway Initiative, David Keir

"After all these years, no one has yet demonstrated either an attribute or template type system using a classified test object in such a way that specialists from the inspecting country can then thoroughly examine and proof the measurement equipment."

James Fuller, October 2012

Global Zero Verification Project

Princeton/PPPL Verification Project

GENERAL APPROACH

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

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

What We Don't Use

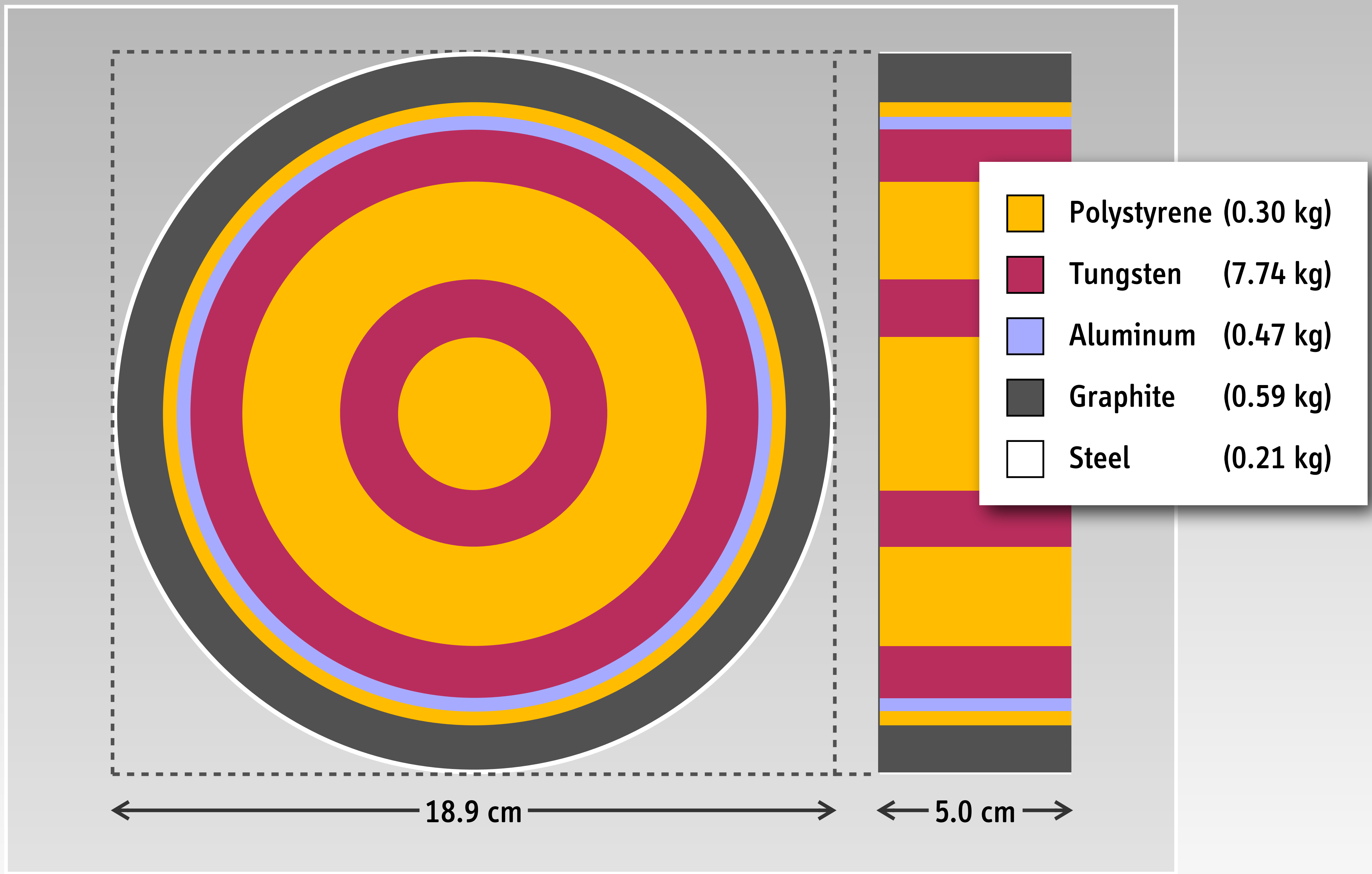
(and Don't Need for Our Proof-of-concept)

Mockup of a MK-12 Reentry Vehicle with a W62 warhead

(Note: the final W62 was dismantled in August 2010, www.energy.gov/articles/dismantling-history-final-w62-warhead)

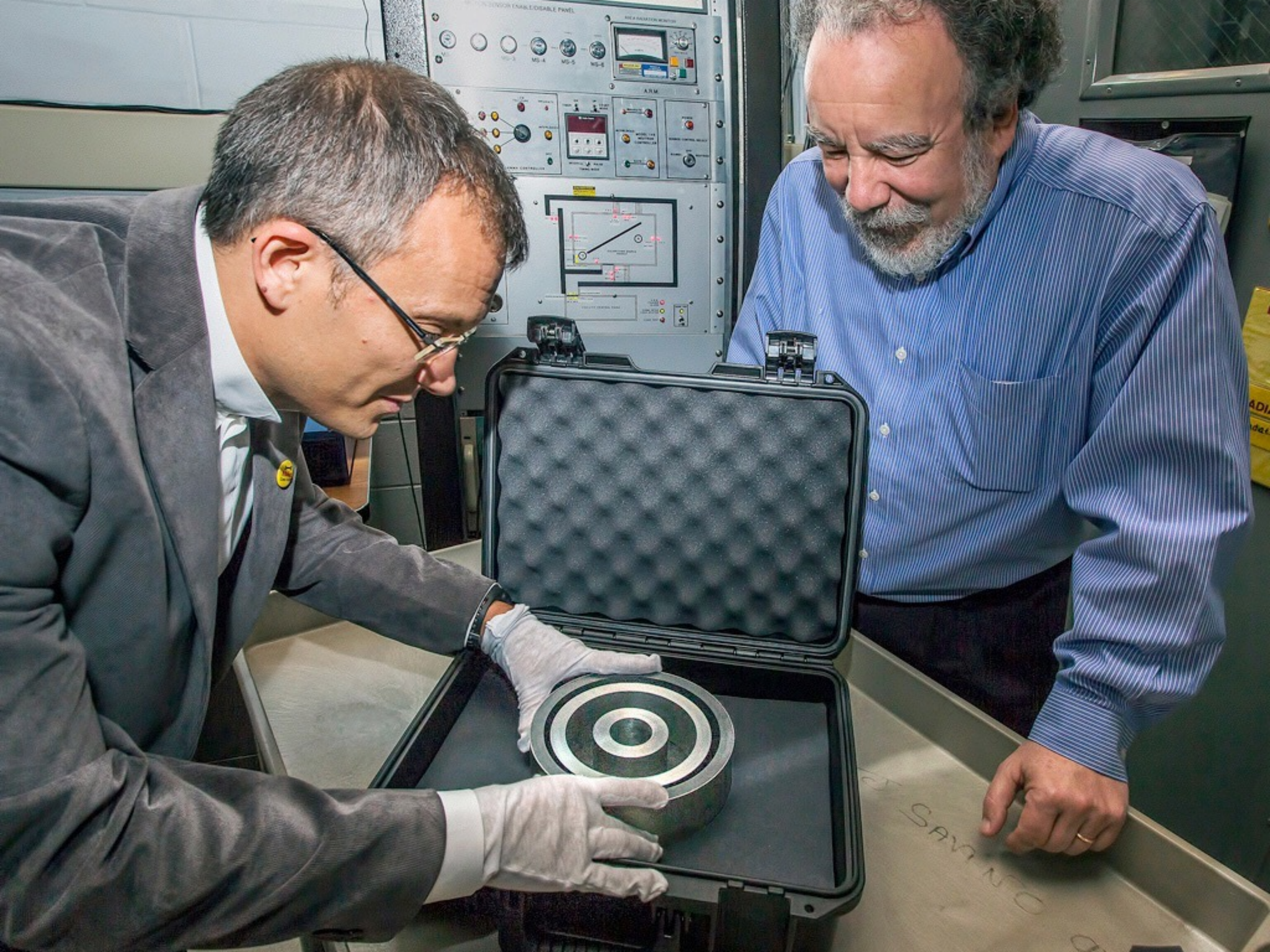
What We Use Instead

"British Test Object"



James Hall, "Uncovering Hidden Defects with Neutrons," *Science & Technology Review*, May 2001, www.llnl.gov/str/May01/Hall.html

7.75 kg of tungsten


MS-4
MS-5
MS-6
A.R.M.

Experimental Setup

Detector array
(367 bubble detectors)

Neutron
source

British Test Object
in container

Neutron collimator
(polyethylene)

Graphics: Sébastien Philippe

How Do We Prevent Sensitive Information from Being Detected?

(Basic Inspection Protocol)

We Use 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?

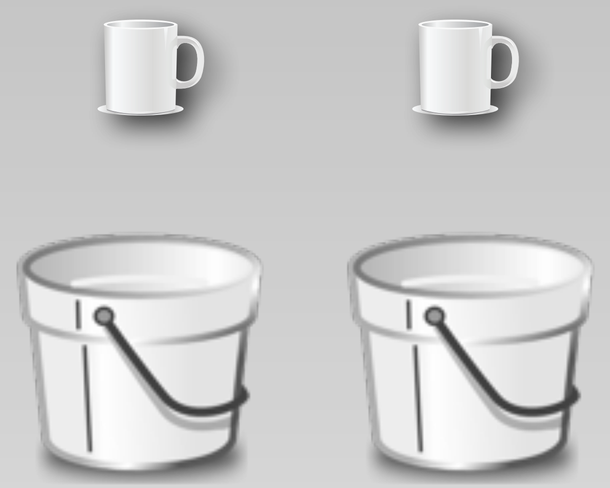
"Number of Marbles in a Cup"

Alice has two small cups each containing the same number of marbles. She wants to prove to Bob that both cups contain the same number of marbles without revealing to him what this number is.

“Number of Marbles in a Cup”

1

Alice claims that the two cups contain the same number of marbles



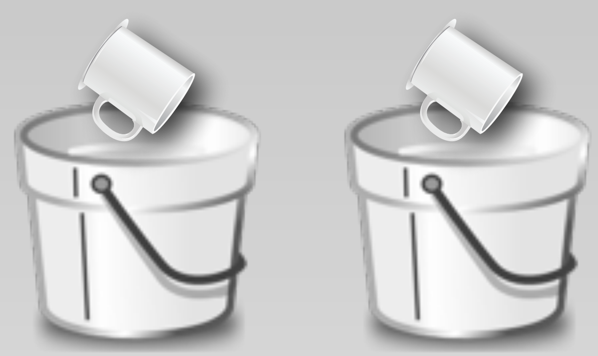
She then also offers two buckets of marbles

Presumably, these buckets also contain an identical number of marbles

2

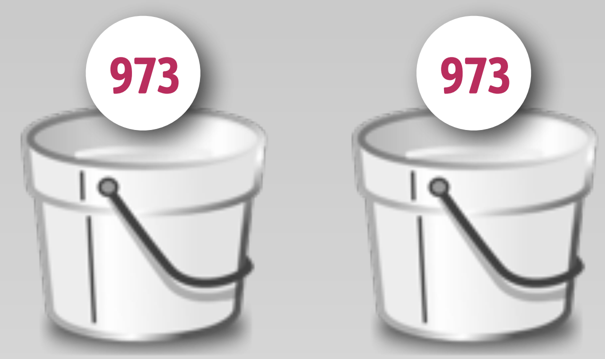
Bob can choose into which bucket which cup is poured

(L,L) and (R,R) or (L,R) and (R,L)



3

Bob is now allowed to count the marbles in each bucket and should find the same number in both



50% confidence after 1st game

75% confidence after 2nd game

99% confidence after 7th game

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)

Inspection Protocol

(simplified)

1

Template
("Golden warhead")
selected at deployment site

Warheads offered for
inspection/dismantlement
(presumably already in storage)

2

Template and test items
are placed in sealed
containers

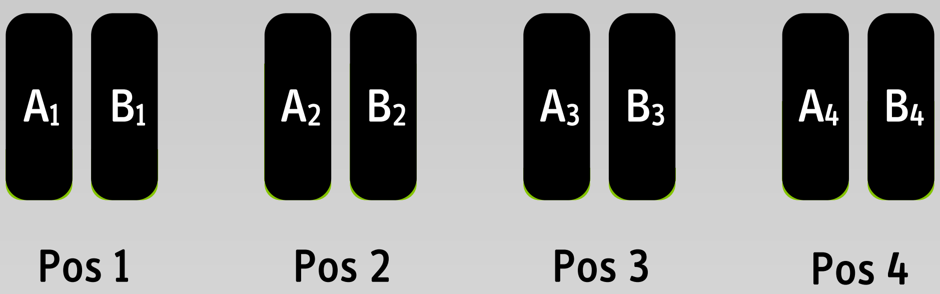
All items are brought to
a dedicated
dismantlement facility

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

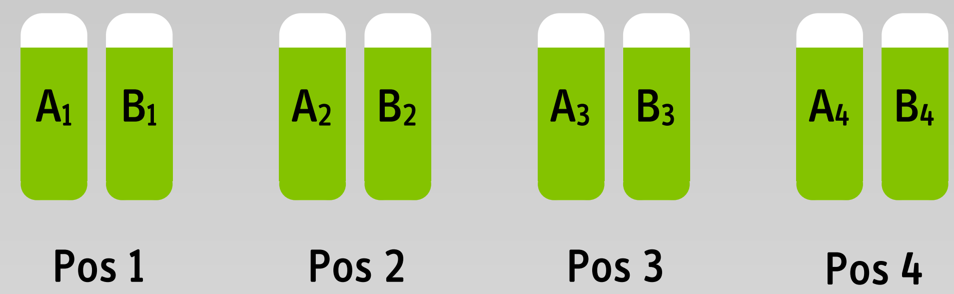
After every measurement, each bubble detector has "exactly" the same number (N_{MAX}) of bubbles

Since the host knows the "secret" (i.e., the design of the warhead), she can individually preload pairs of detectors for every orientation/direction so that they will be "topped up" to N_{MAX} during the measurement

Before measurement



After measurement



Preload is unknown to inspector, i.e., bubble detectors are "wrapped in black tape"

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

(so that it becomes impossible for the host to conceal a spoof by unequally initializing the detectors)

Inspection Protocol

(simplified)

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3

Inspector announces
which detector positions
she wants to measure

Host prepares
pairs of preloaded bubble
detectors

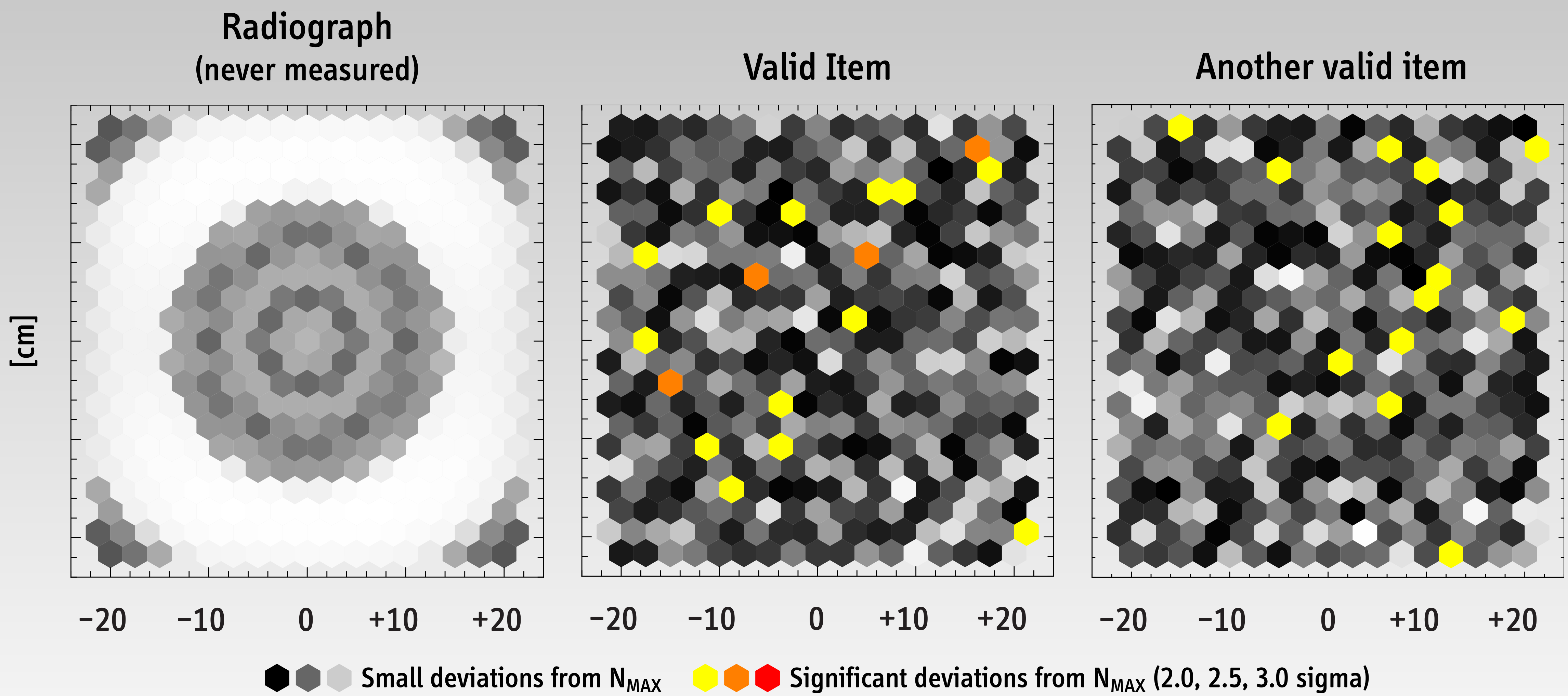
4

Inspection
is carried out
(template vs test item)

Inspector should find
the number N_{max}
in all measurements

Valid versus Suspect/Invalid Item

Simulated data (MCNP5) for N_{MAX} = 1000 bubbles per detector



Valid versus Suspect/Invalid Item

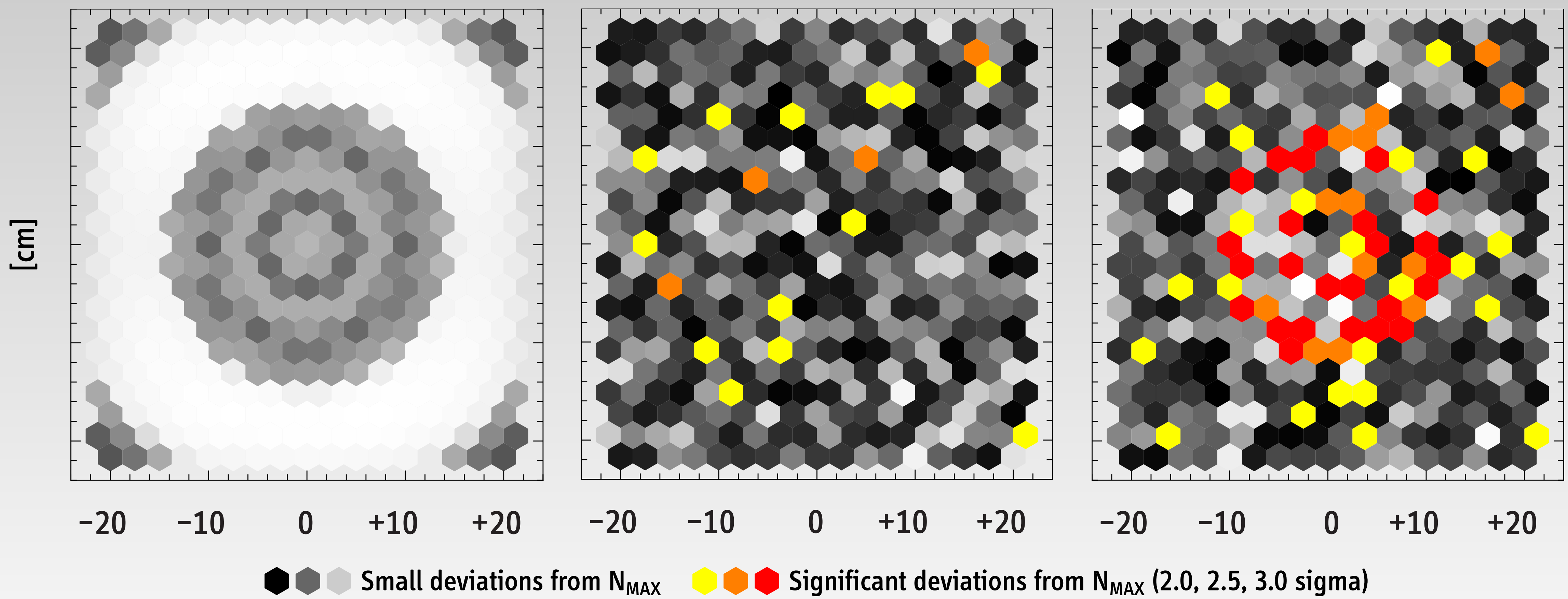
Simulated data (MCNP5) for N_{MAX} = 1000 bubbles per detector

Radiograph
(never measured)

Valid Item

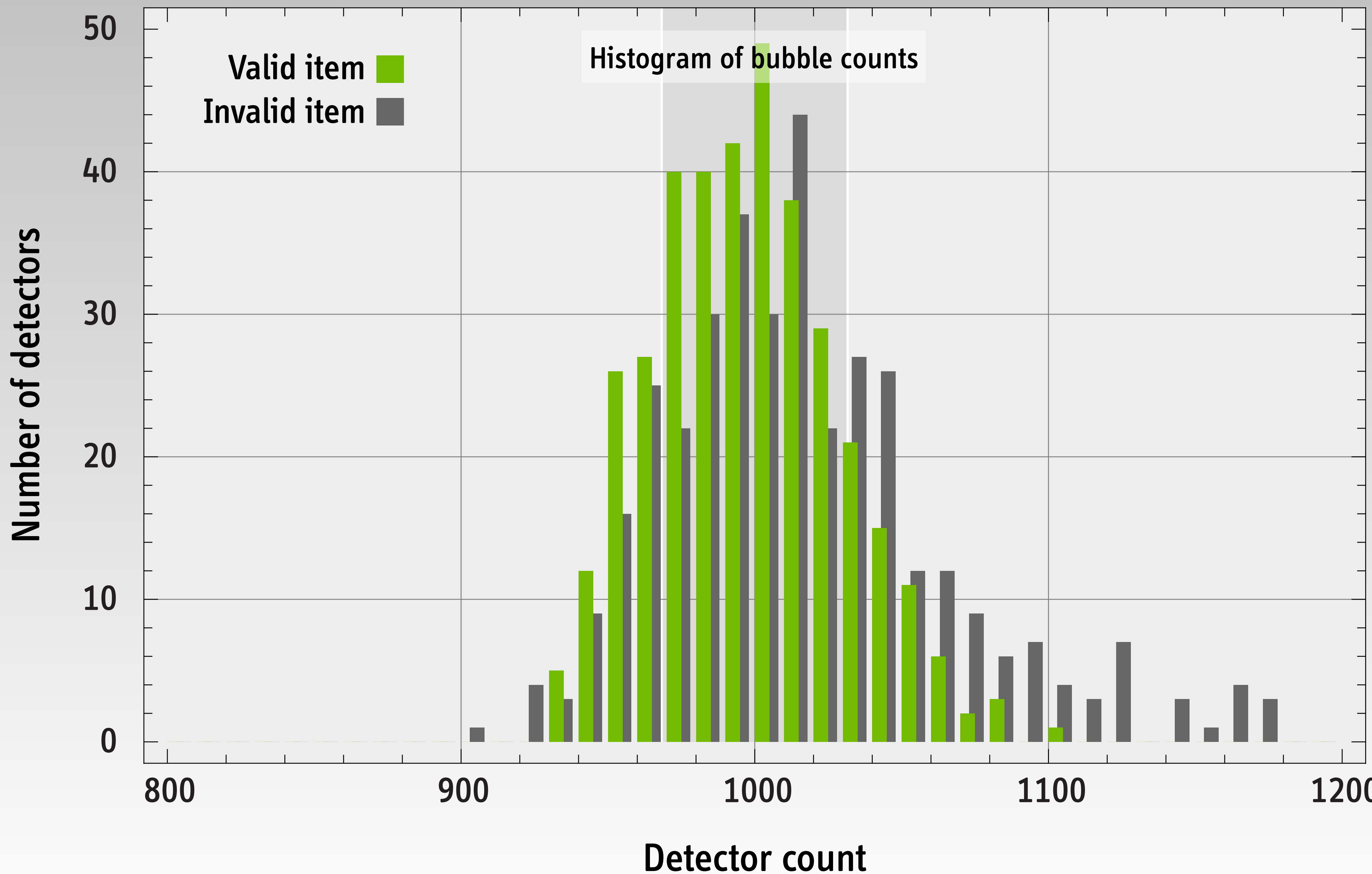
Diversion Scenario A
(tungsten rings replaced by lead rings)

Invalid Item



Statistical Noise of Measurement = $(N_{MAX})^{0.5}$

(No information in signal or its noise)

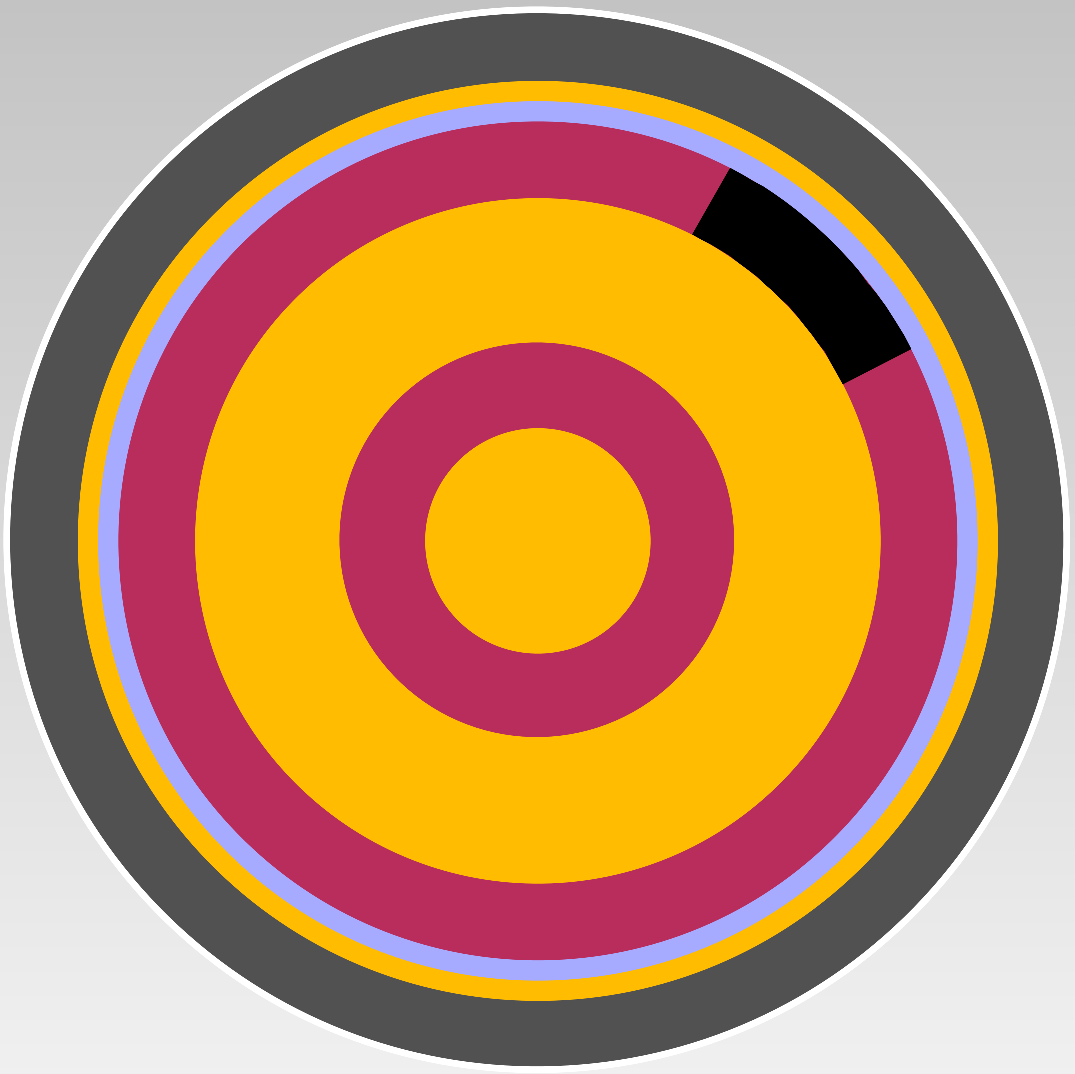


Localized Diversions

and the “Battleship Game Approach”

Localized Tungsten Diversion

36-degree segment of outer tungsten ring (543 grams, 7% of total tungsten)

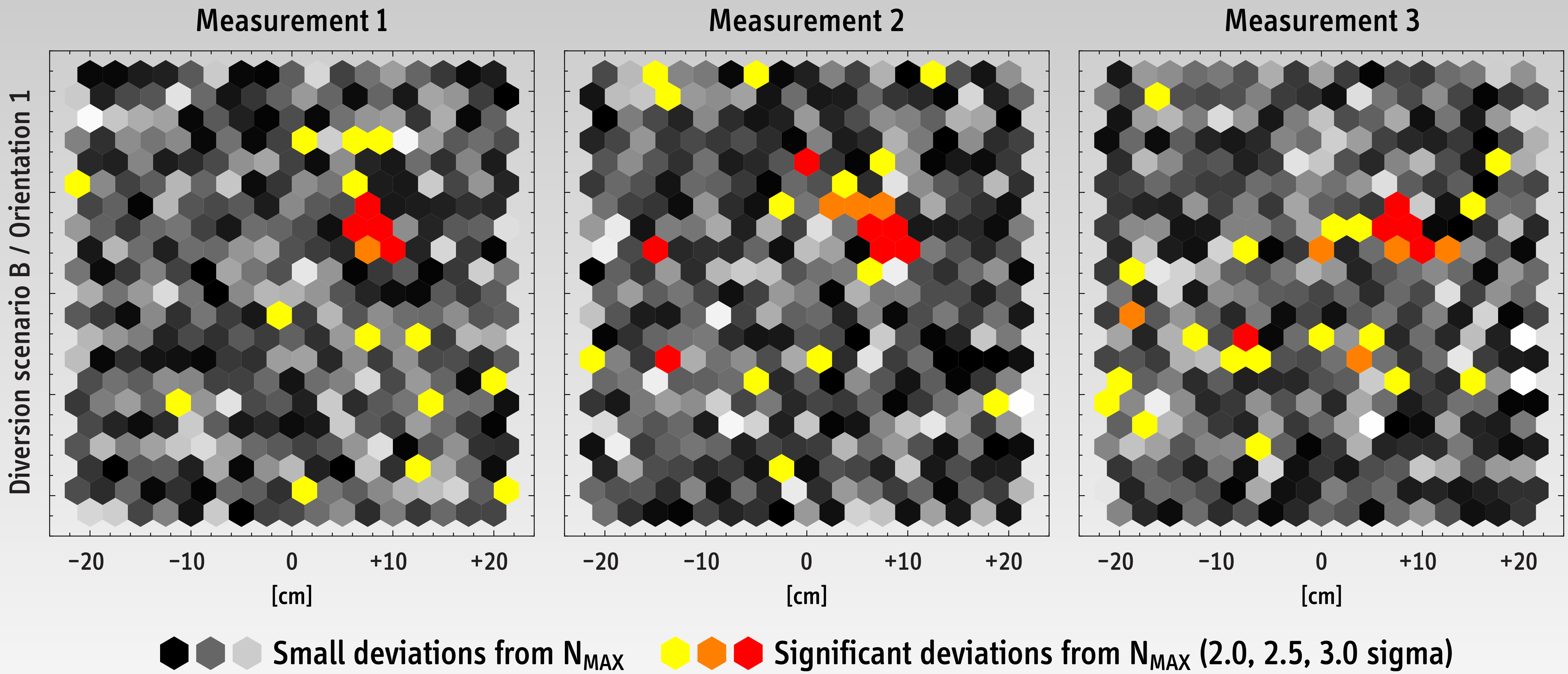


Diversion Scenario B

Simulated data (MCNP5) for N_{MAX} = 1000 bubbles per detector

BTO in Orientation 1 (unknown to inspector)

Bubble detectors are sensitive to neutron energies above 1 MeV

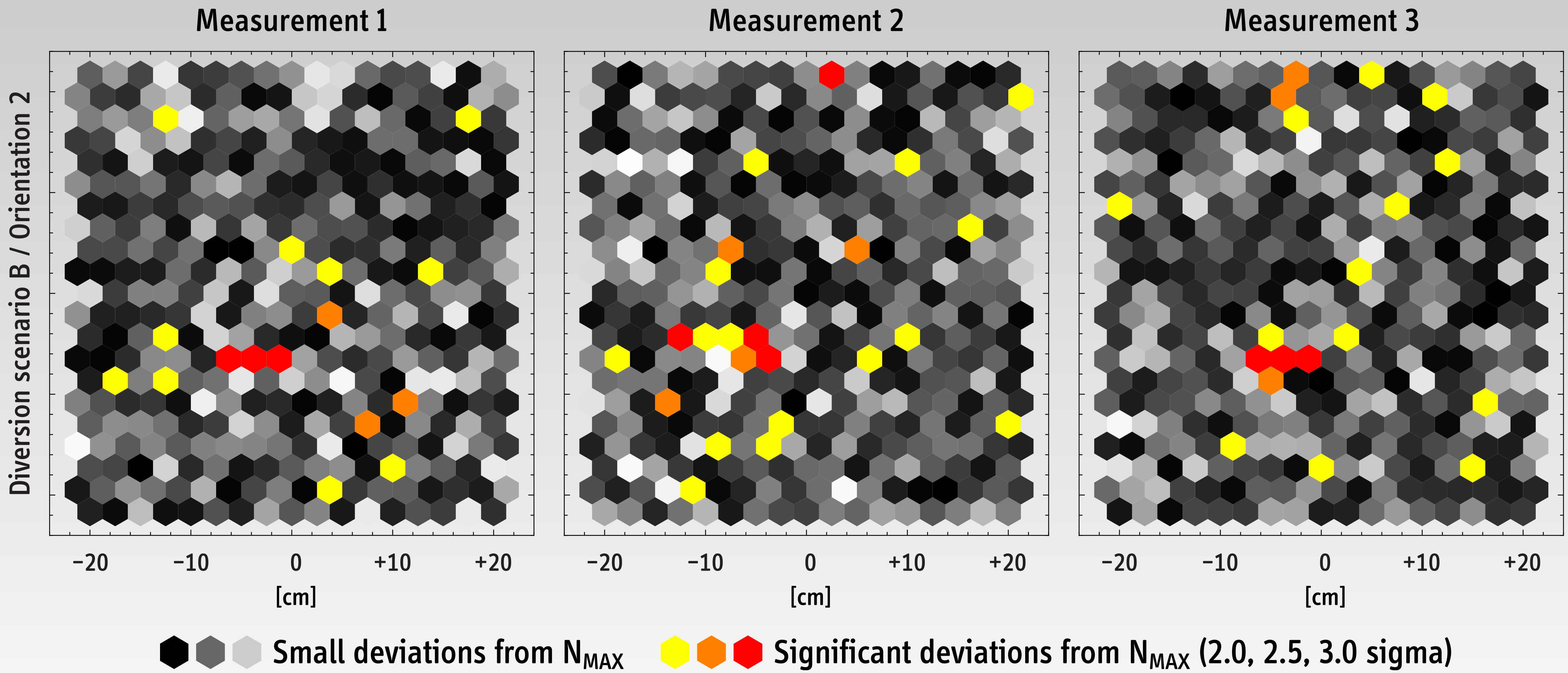


Diversion Scenario B

Simulated data (MCNP5) for N_{MAX} = 1000 bubbles per detector

BTO in Orientation 2 (unknown to inspector)

Bubble detectors are sensitive to neutron energies above 1 MeV

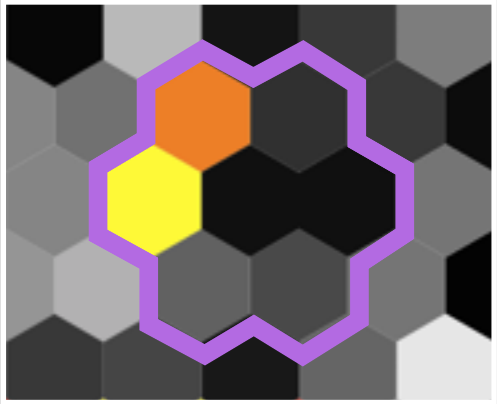


Scoring Function

Detector counts $X_1 \dots X_n$ are independent Poisson variables with expectation N_{max}
(approximated in the following as normal variables)

Define ℓ-pixel "windows" with standard normal variables Y_j

(k windows can be tested across the detector bank)



$$Y_j = \left(\sum_{i=1}^{\ell} (X_i - N_{max}) \right) \Big/ \sqrt{\ell\, N_{max}}$$

$$S = \max_j \left| Y_j \right|$$

Test is positive ("diversion detected") if score S > T

T is computed such that a valid item fails the test with probability $p = 0.05$

T depends on the number of windows; e.g. for $k = 295$, $T = 3.76$

Results

Based on 10,000 simulations using results from MCNP5 calculations
Bubble detectors are sensitive to neutron energies above 1 MeV

		"295-pixel" (1 draw)	"7-pixel" (295 draws)	"1-pixel" (295 draws)
		T = 1.96	T = 3.76	T = 3.76
Match *Orientation 1*	Success Rate *(Score)*	95% *(0.82 ± 0.62)*	95% *(3.03 ± 0.40)*	95% *(3.08 ± 0.36)*
Scenario A *Orientation 1*	Success Rate *(Score)*	> 99.9% *(11.32 ± 1.00)*	> 99.9% *(7.69 ± 0.62)*	> 99.9% *(5.96 ± 0.52)*
Scenario B *Orientation 1*	Success Rate *(Score)*	61.0% *(2.23 ± 0.98)*	> 99.9% *(12.84 ± 1.06)*	> 99.9% *(10.57 ± 1.03)*
Scenario B *Orientation 2*	Success Rate *(Score)*	24.3% *(1.38 ± 0.87)*	99.6% *(6.35 ± 0.96)*	97.1% *(5.28 ± 0.91)*
Scenario B *Orientation 3*	Success Rate *(Score)*	10.5% *(0.98 ± 0.72)*	13.0% *(3.21 ± 0.50)*	7.0% *(3.16 ± 0.40)*

What's Next?

Way Forward

THIS PROJECT

Provide proof-of-concept experimentally

Zero-knowledge protocols appear as an important new approach to nuclear warhead verification

DISARMAMENT VERIFICATION IN GENERAL

Concepts and technologies need to be developed now in order to be available for the next round of arms-control negotiations

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