REMOTE & VIRTUAL INSPECTIONS

AN UPDATE ON PRINCETON'S WORK ON NUCLEAR VERIFICATION

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Program on Science and Global Security
Princeton University

Lawrence Livermore National Laboratory
Livermore, CA, October 14, 2022

Revision 0

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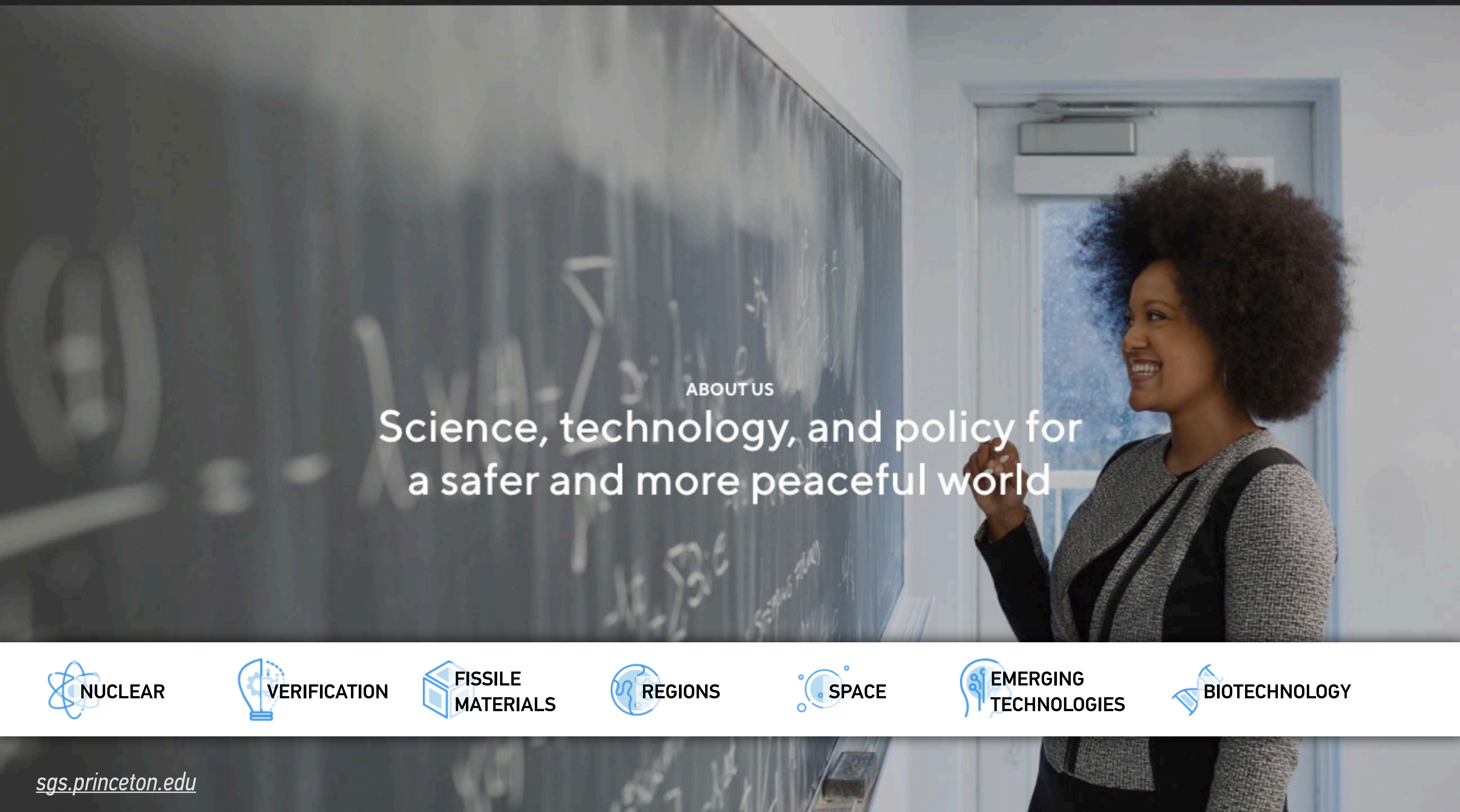
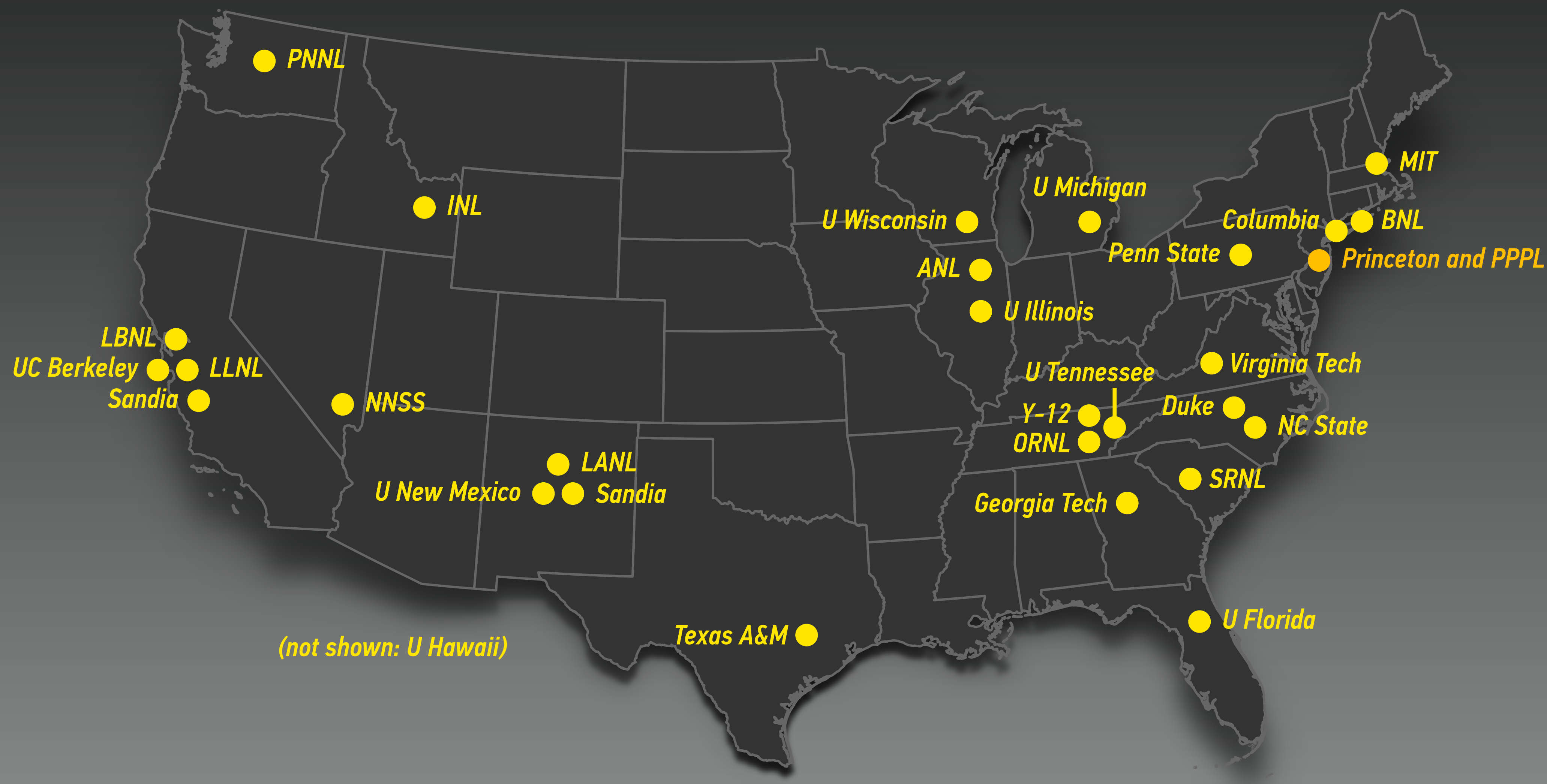


sgs.princeton.edu

CONSORTIUM FOR MONITORING, TECHNOLOGY, AND VERIFICATION (MTV)



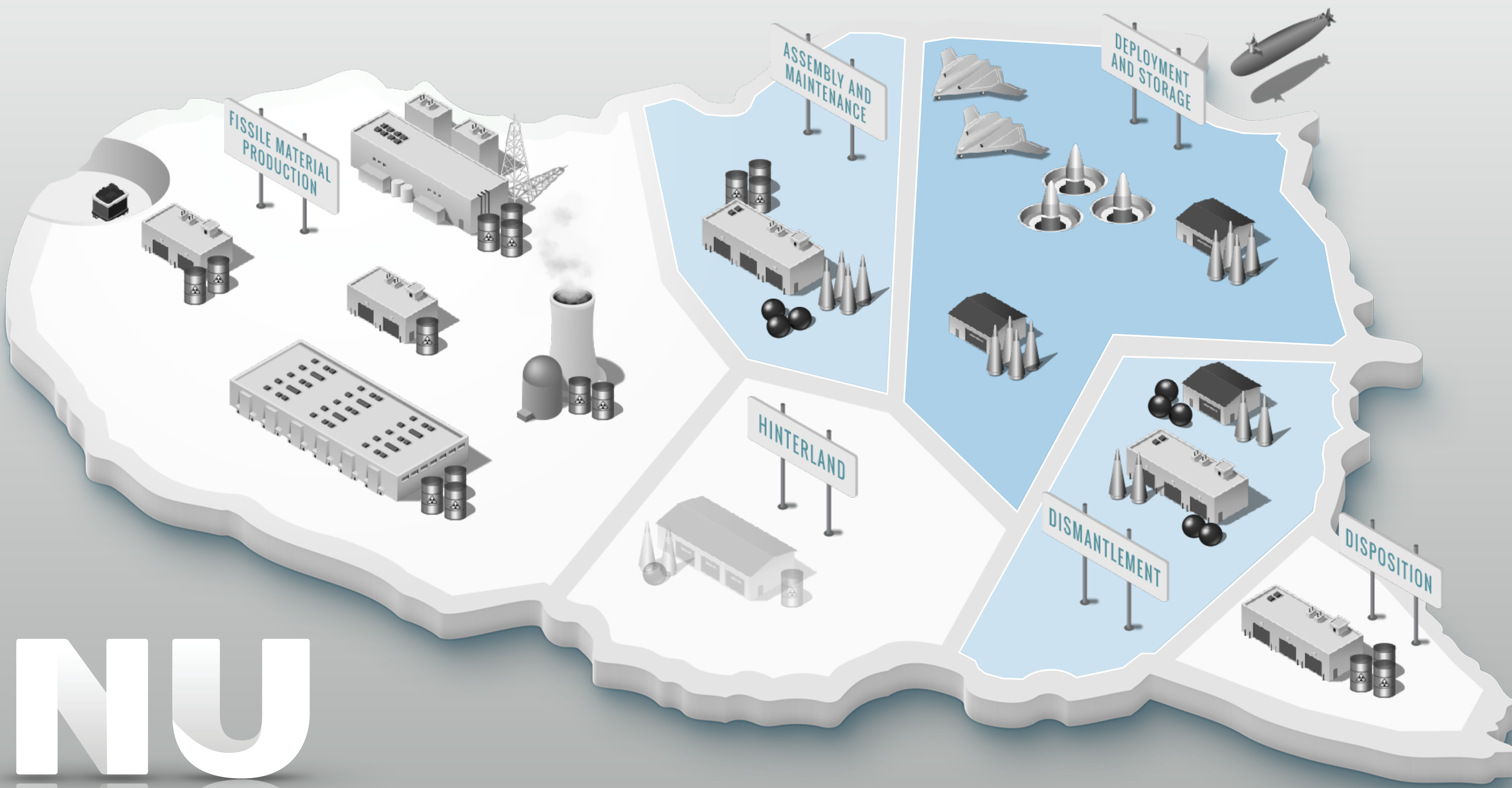
Five-year project, funded by U.S. DOE, 14 U.S. universities and 13 national labs, led by U-MICH

Princeton participates in the research thrust on Signals & Source Terms for Nuclear Nonproliferation

Verification Research at Princeton

(A very brief overview)

GRAND (VERIFICATION) CHALLENGES



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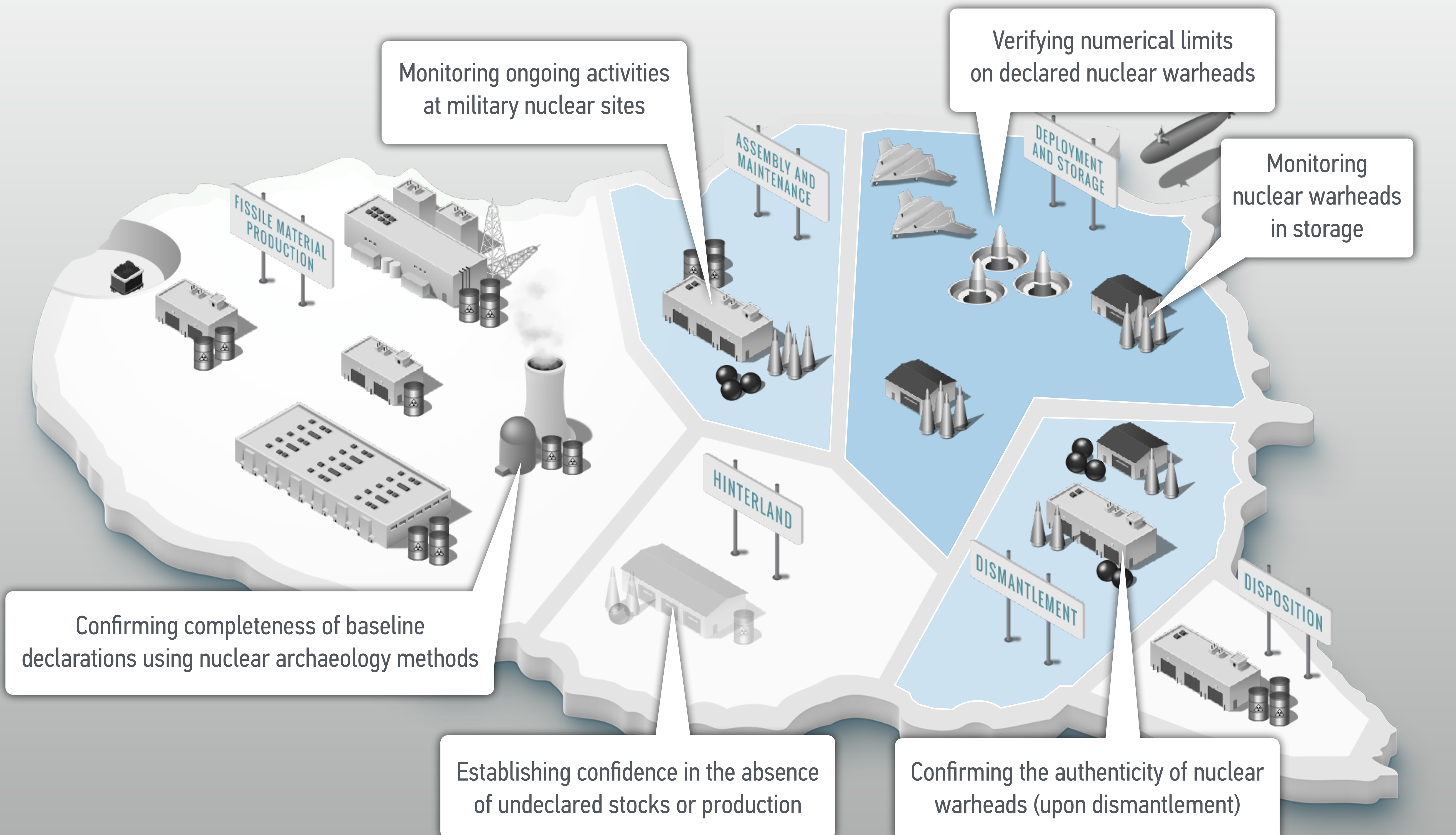
www.verification.nu

GRAND (VERIFICATION) CHALLENGES



HOW NOT TO GIVE AWAY A SECRET

CONTINUE IMPROVING TECHNOLOGIES AND APPROACHES

Work on information barriers with a particular focus on certification and authentication; in particular, identify joint hardware and software development platforms

REINVENT THE PROBLEM: NEVER ACQUIRE SENSITIVE INFORMATION TO BEGIN WITH

Explore fundamentally different verification technologies and approaches; for example, avoid need for trusted hardware or seek alternatives to onsite inspections at certain sensitive facilities

REVEAL THE SECRET

Requirement to protect sensitive information is typically the main reason for complexity of verification approaches; for example, mass of fissile material in a nuclear weapon

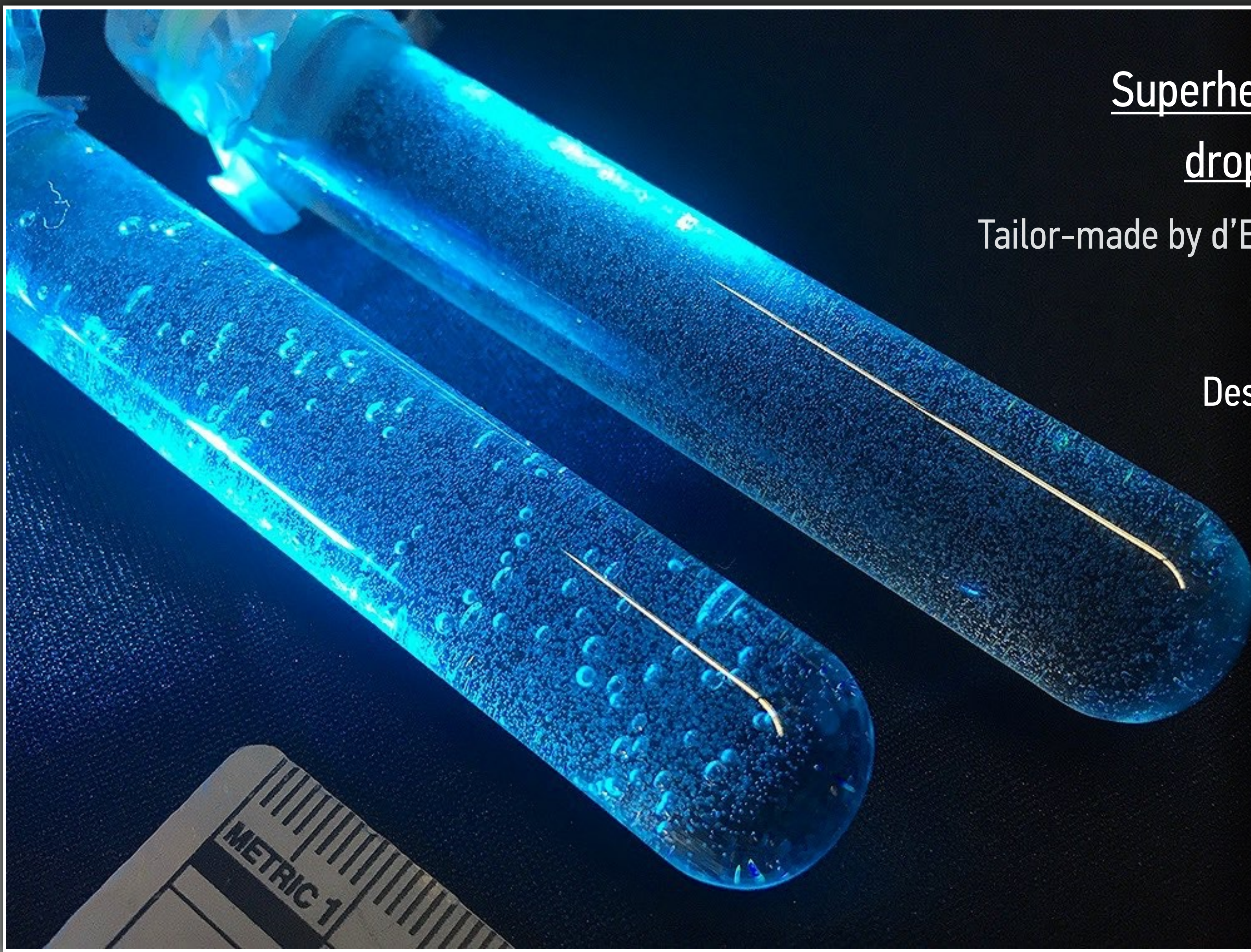
Source: Author (top and bottom) and Johannes Tobisch (middle)

EXAMPLE #1

Zero-knowledge Verification

SUPERHEATED DROPLET DETECTORS MAY OFFER A WAY TO IMPLEMENT SECURE INSPECTIONS

BY AVOIDING DETECTOR-SIDE ELECTRONICS



Superheated C-318 fluorocarbon (C_4F_8) droplets suspended in aqueous gel

Tailor-made by d'Errico Research Group, Yale University

Sensitive to neutrons with $E_n > E_{min}$

Designed to be insensitive to γ-radiation

Active volume .... : 6.0 cm^3

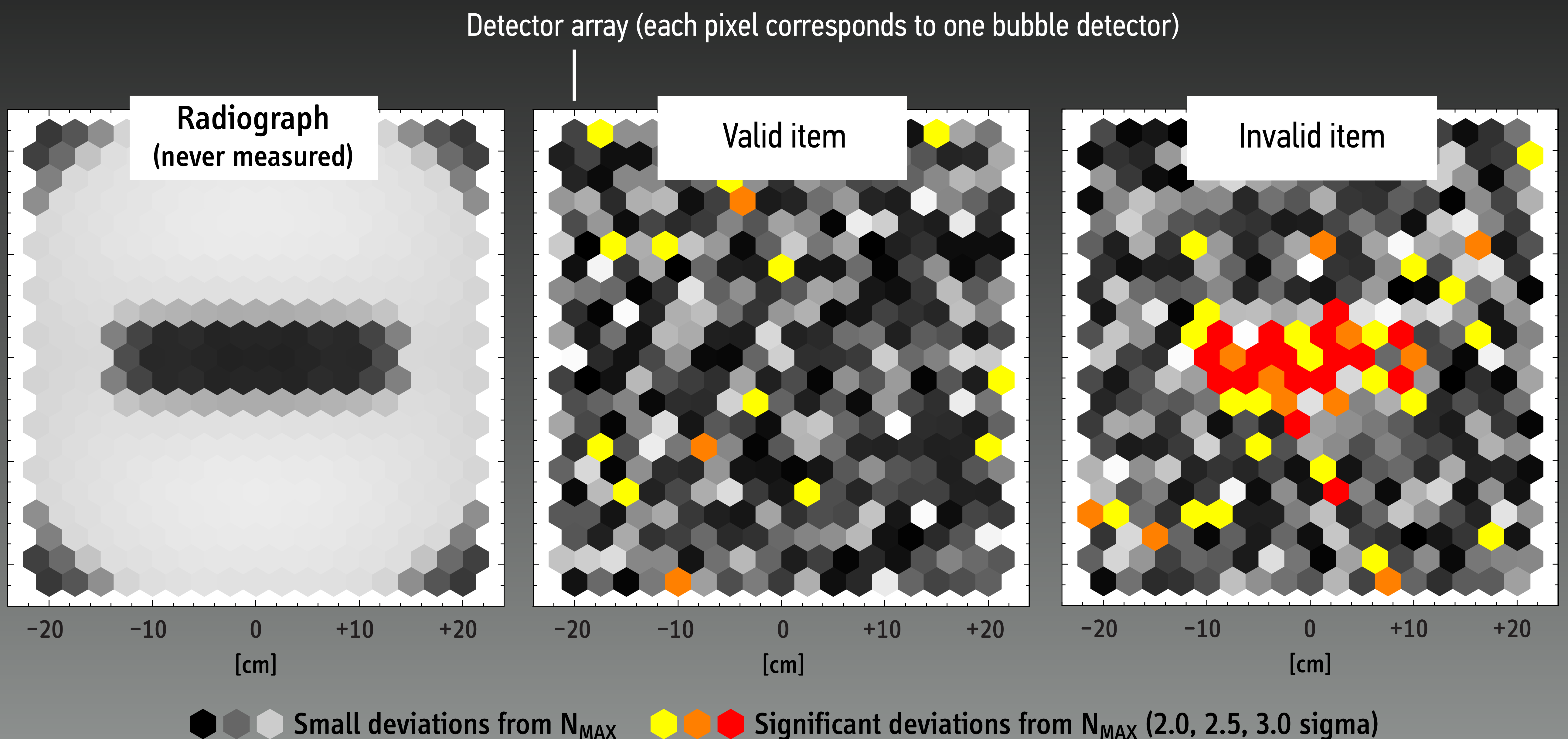
Droplet density .... : 3500 cm^{-3}

Droplet diameter ...... : ~100 μm

Absolute Efficiency ... : 4×10^{-4}

ZERO-KNOWLEDGE NEUTRON RADIOGRAPHY

WITH PRELOADED, NON-ELECTRONIC (BUBBLE) DETECTORS

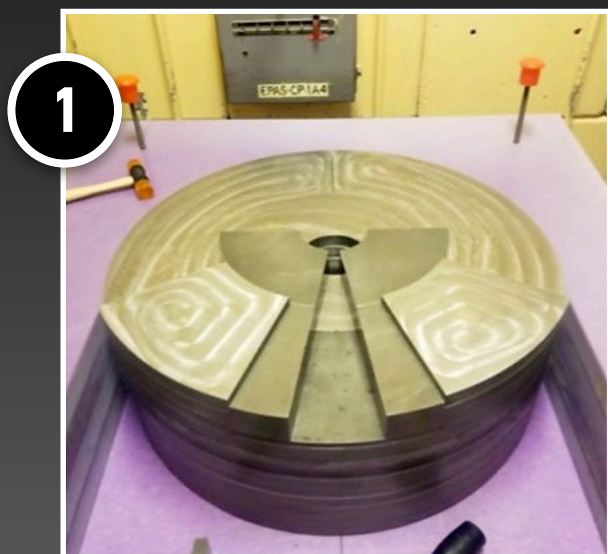


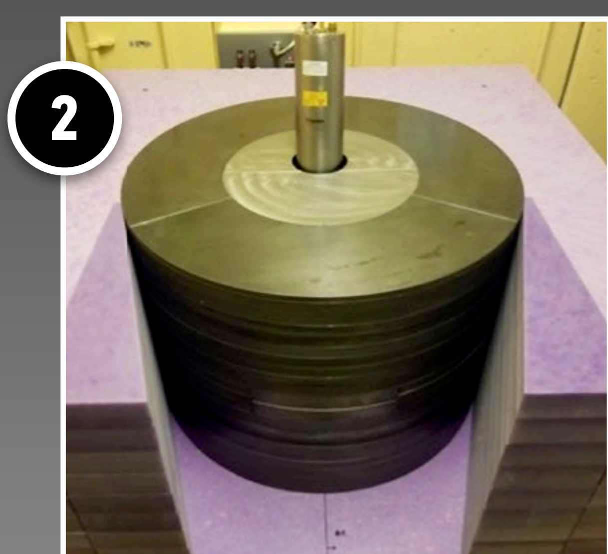
A. Glaser, B. Barak, R. J. Goldston, "A Zero-knowledge Protocol for Nuclear Warhead Verification," *Nature,* 510, 26 June 2014

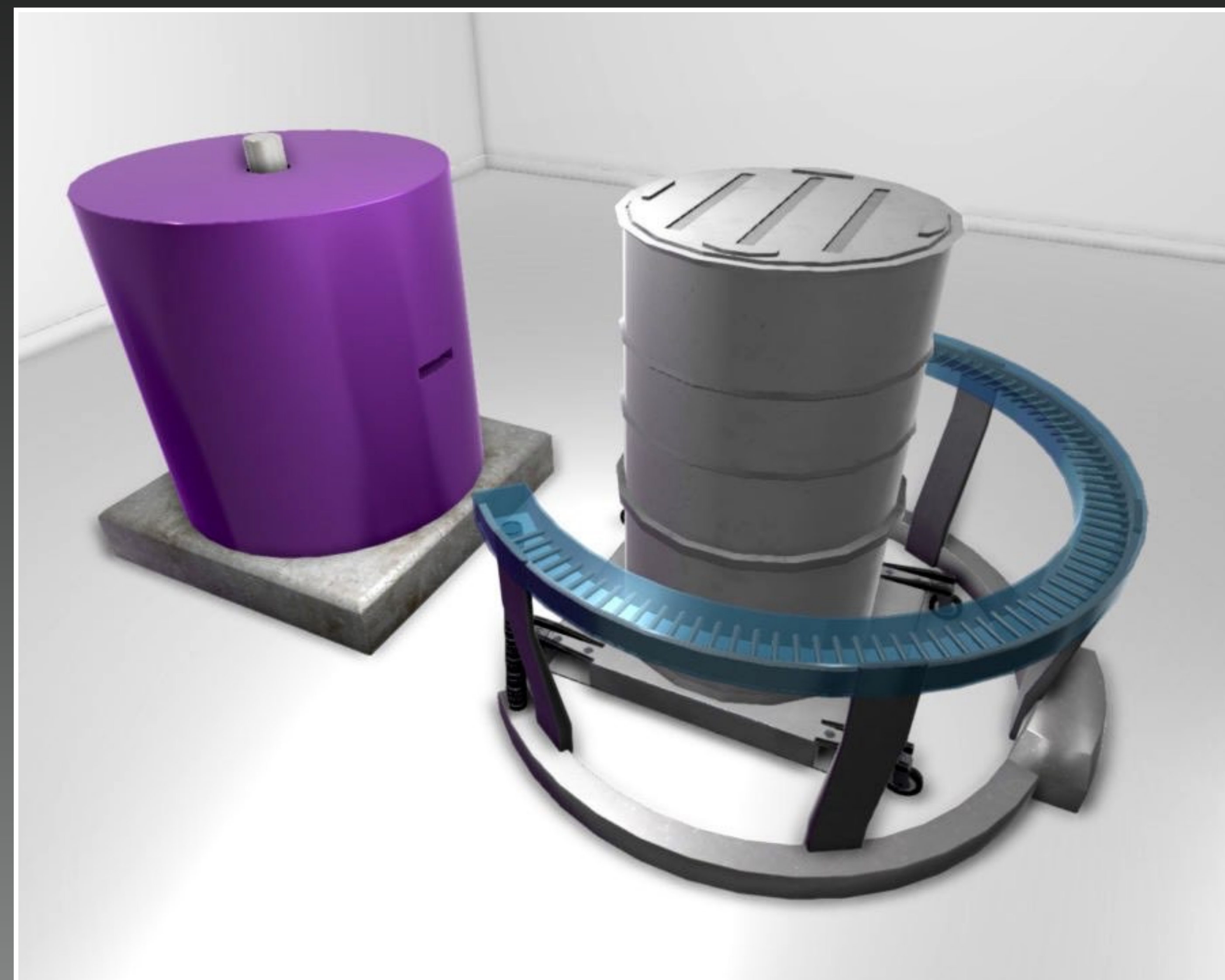
S. Philippe, R. J. Goldston, A. Glaser, F. d'Errico, *Nature Communications,* 7, September 2016

ZERO-KNOWLEDGE NEUTRON RADIOGRAPHY

(EXCALIBUR @ PPPL)





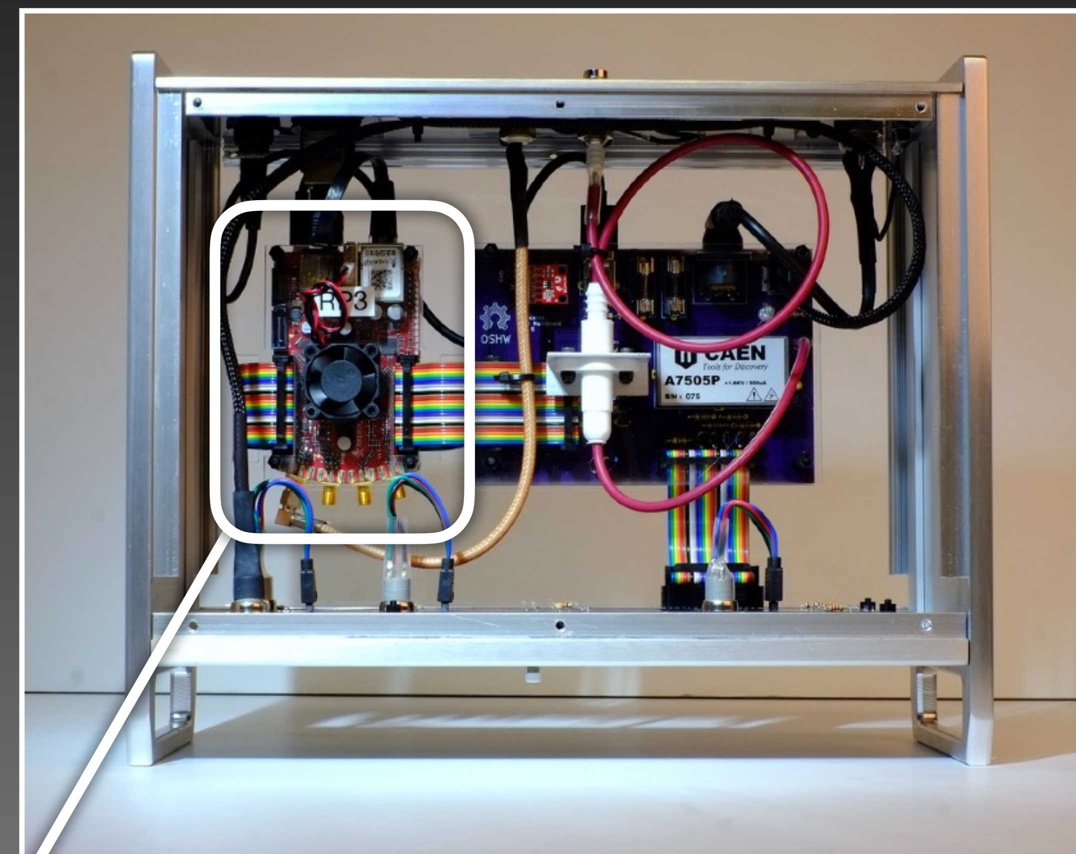


E. Gilson, A. Glaser, R. J. Goldston, and J. Jeon, The EXCALIBUR Neutron Source, 63rd Annual INMM Meeting, July 2022
S. Philippe, R. J. Goldston, A. Glaser, F. d'Errico, Nature Communications, 7, September 2016
A. Glaser, B. Barak, and R. Goldston, A Zero-knowledge Protocol for Nuclear Warhead Verification, Nature, 510, June 2014

EXAMPLE #2

Inspection Systems based on Gamma Signatures

INFORMATION BARRIER EXPERIMENTAL (IBX)



Red Pitaya single-board computer (redpitaya.com)

Xilinx Zynq 7010, SoC with FPGA and ARM A9

14-bit ADC, 125 million samples per second

M. Kütt, M. Göttsche, and A. Glaser, "Information Barrier Experimental: Toward a Trusted and Open-source Computing Platform for Nuclear Warhead Verification," *Measurement,* 114, 2018, doi.org/10.1016/j.measurement.2017.09.014

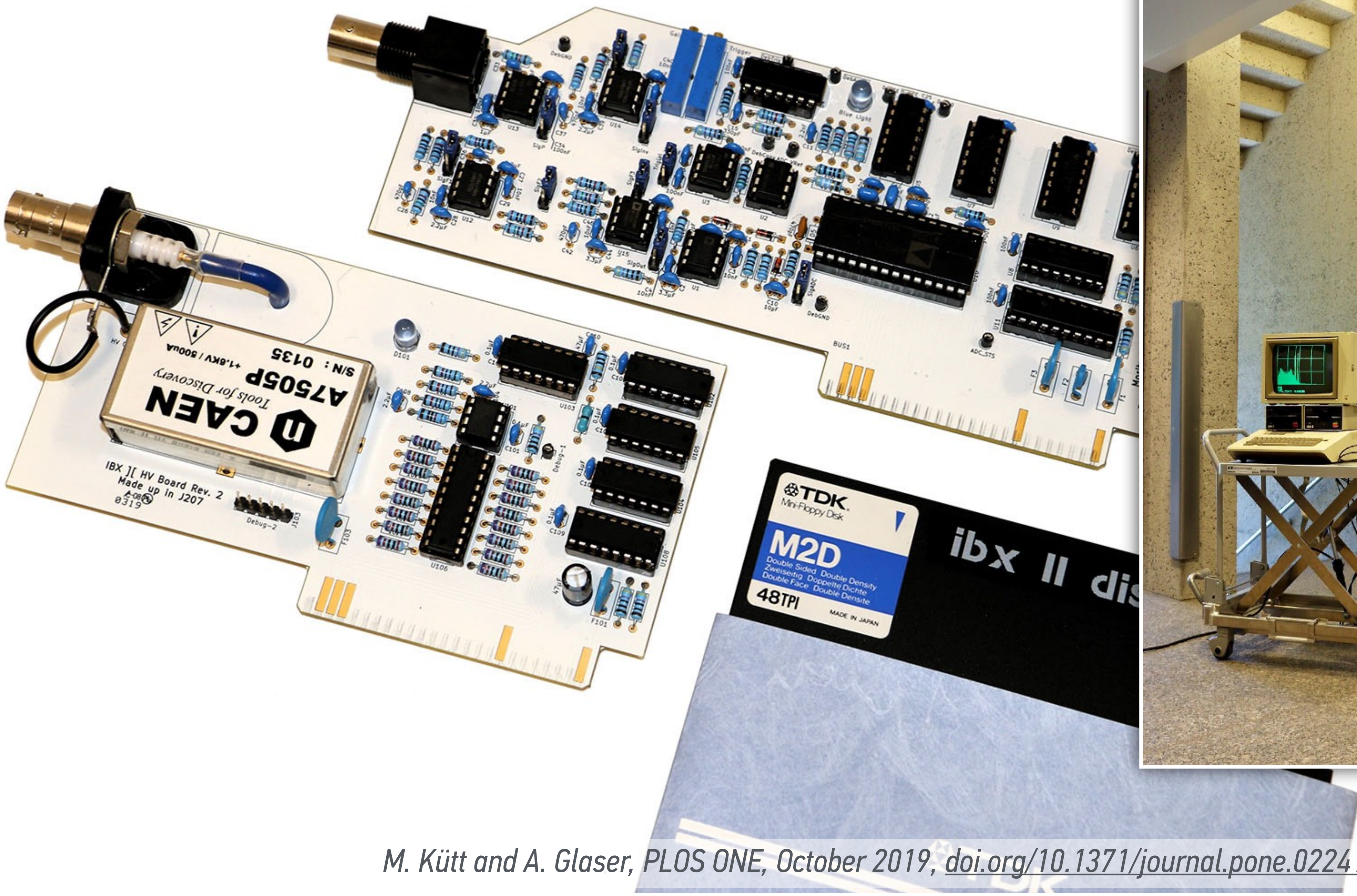
PROTOTYPE OF AN ABSENCE MEASUREMENT SYSTEM

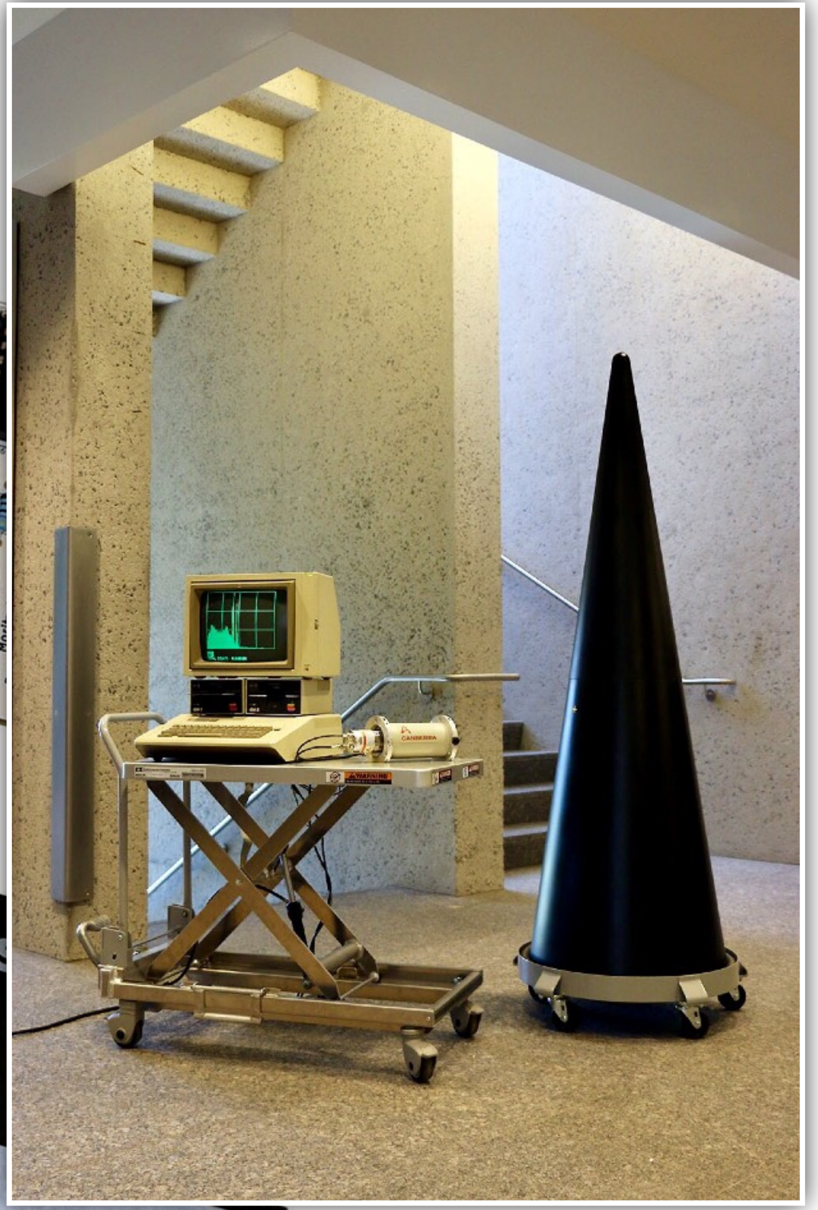
USING PASSIVE GAMMA-RAY DETECTION

E. Lepowsky, J. Jeon, and A. Glaser, Confirming the Absence of Nuclear Warheads via Passive Gamma-Ray Measurements, Nuclear Instruments and Methods in Physics Research A, 990, 2021, doi.org/10.1016/j.nima.2020.164983

"SIMPLICITY THROUGH OBSOLESCENCE"

(STANDARD SODIUM-IODIDE DETECTOR & 12-BIN TEMPLATE)





M. Kütt and A. Glaser, PLOS ONE, October 2019, doi.org/10.1371/journal.pone.0224149

Toward Remote & Virtual Inspections

FROM ONSITE TO REMOTE INSPECTIONS

PROS & CONS OF ONSITE INSPECTIONS

Onsite inspections remain the “gold standard” for IAEA safeguards and nuclear arms-control verification

Inspections tend to be costly and are often considered intrusive, especially in the arms-control context

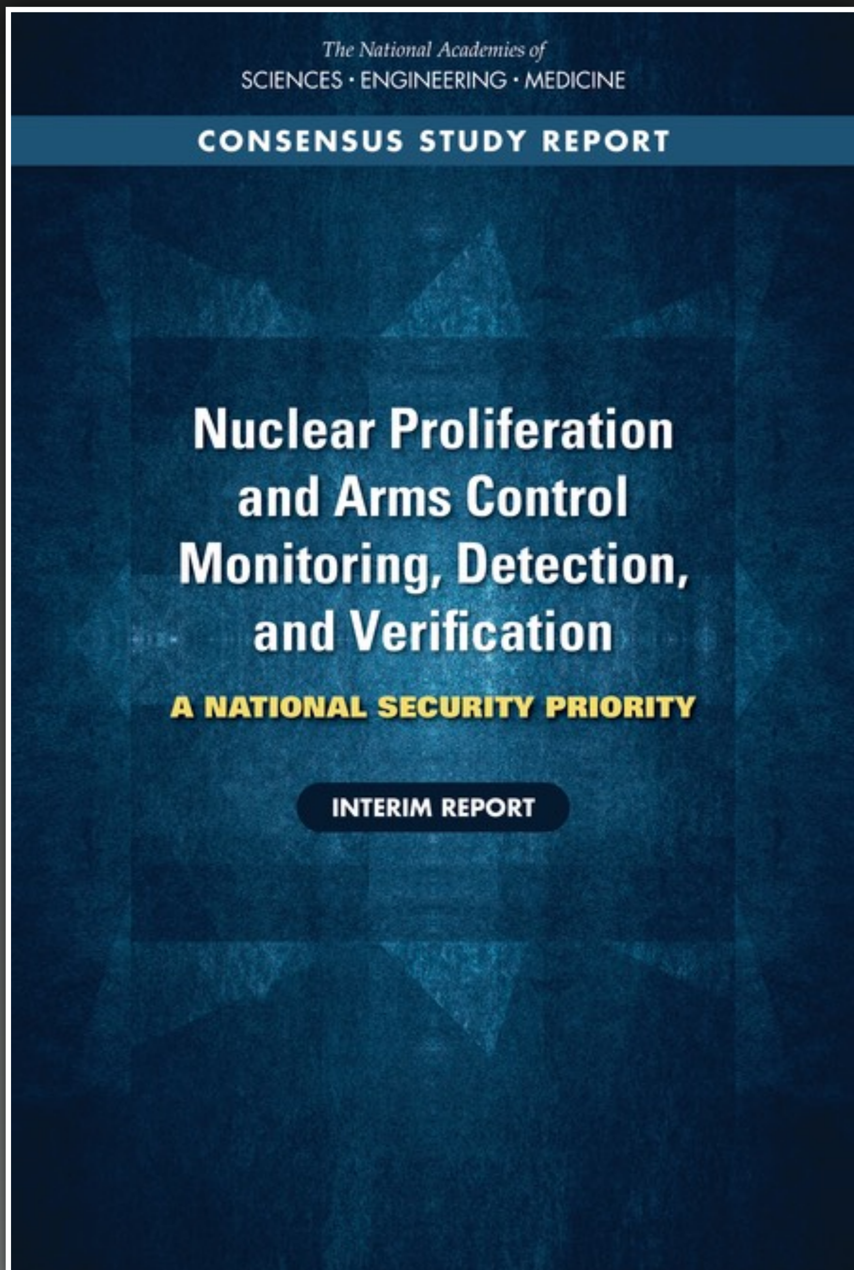
CAN WE (PHYSICALLY) “SEPARATE” HOST & INSPECTOR ?

Many concerns could be addressed and resolved if inspectors were not “physically” present onsite

As part of our MTV efforts, we explore various remote inspections techniques with a particular emphasis on robotic inspections

Source: ukni.info (top) and microsoft.com (bottom)

FINDINGS FROM A 2021 NATIONAL ACADEMIES STUDY



3.4 MDV FOR ARMS CONTROL

3.4.1 Capability Needs

…

Treaties that include weapons in storage or weapons designed for shorter-range delivery systems are anticipated to require new MDV techniques. As a minimum, ***such treaties would likely require access to storage areas either directly or remotely,*** *and confirmation of warhead count (either a baseline confirmation or through routine/challenge inspections).*

Jill Hruby, Corey Hinderstein, et al., Committee on the Review of Capabilities for Detection, Verification, and Monitoring of Nuclear Weapons and Fissile Material, National Academy of Sciences, Washington, DC, 2021, doi.org/10.17226/26088

EXAMPLE #3

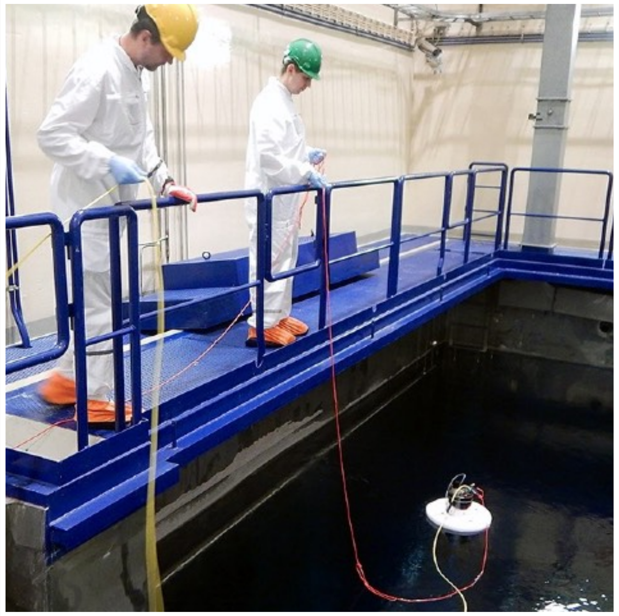
Robotic Inspections

ROBOTIC INSPECTIONS

THE IDEA IS NOT NEW

"The ROBIN provides a potential tool that ... allows the inspector to collect data inside a facility without actually entering that facility ... [and] limits the potential disclosure of sensitive technology."

Frank F. Dean, *ROBIN: A Way to Collect In-Plant Safeguards Data with Minimal Inspector Access*, SAND82-1588C, Sandia National Laboratories, Albuquerque, New Mexico, 1982



IAEA ROBOTICS CHALLENGE

"Some of the most common tasks undertaken by IAEA nuclear safeguards inspectors involve making repetitive measurements in locations that can be difficult to access and/or have elevated radiation levels. This is an area where robotics has the potential to play a useful role."

www.iaea.org/topics/safeguards-in-practice/robotics-challenge-2017

Source: SRI International (Shakey, 1966–1972, top) and IAEA (bottom)

SAFEGUARDS & ARMS CONTROL

POSSIBLE APPLICATIONS IN NUCLEAR SAFEGUARDS

Confirming the absence of undeclared activities in gas-centrifuge enrichment plants

- Detecting hidden feed & withdrawal stations in cascade areas
- Monitoring (declared) feed & withdrawal areas in the plant

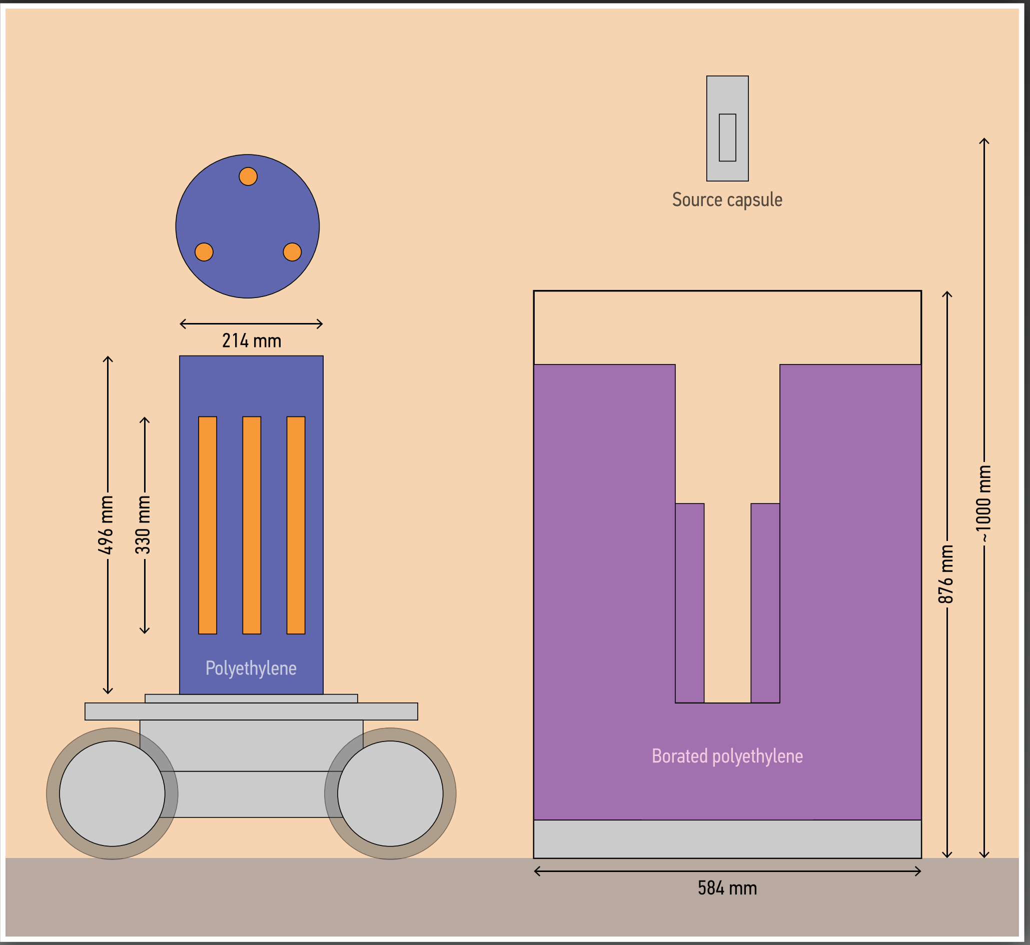
POSSIBLE APPLICATIONS IN ARMS-CONTROL VERIFICATION

Confirming that a neutron field in a storage facility remains unchanged

- Robot should not “learn” or “remember” measurement data
- Use template-matching approach that results in simple non-sensitive output (e.g. 8-bit number) after inspection

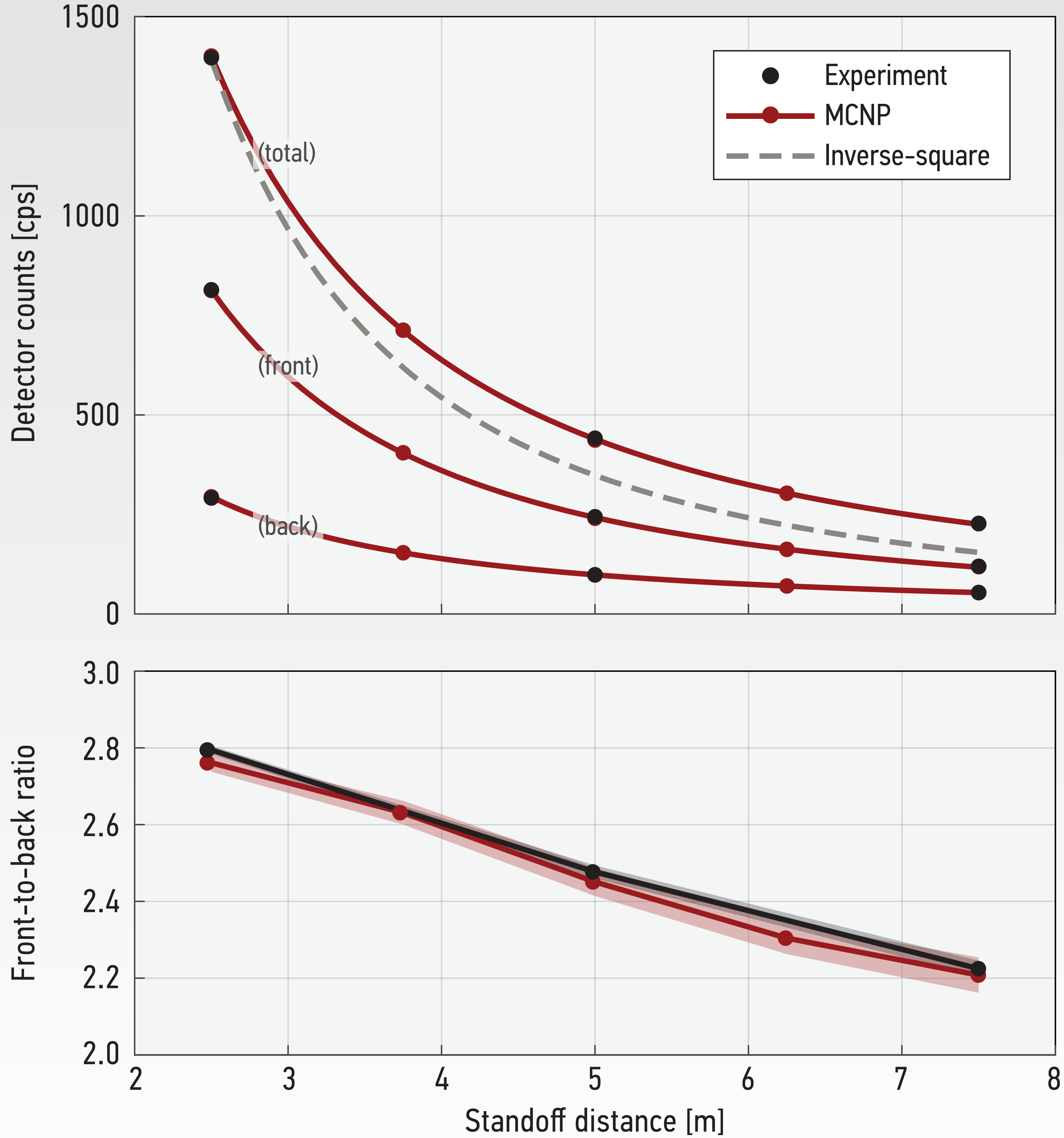
Source: president.ir (top) and commons.wikimedia.org (D5481026, bottom)

N-SpecDir Bot

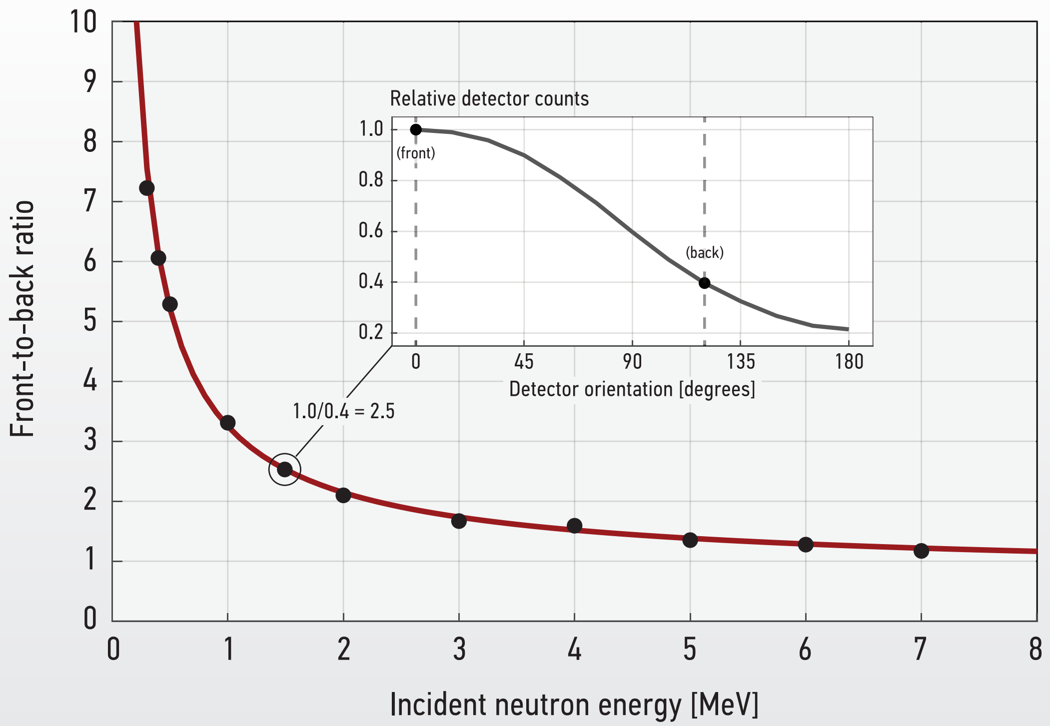


Boron-coated straw (BCS) detectors embedded in a polyethylene cylinder
One 3-detector (pictured) and two 6-detector systems available
Method for “single-shot” directional measurements
Experimentally-benchmarked MCNP model

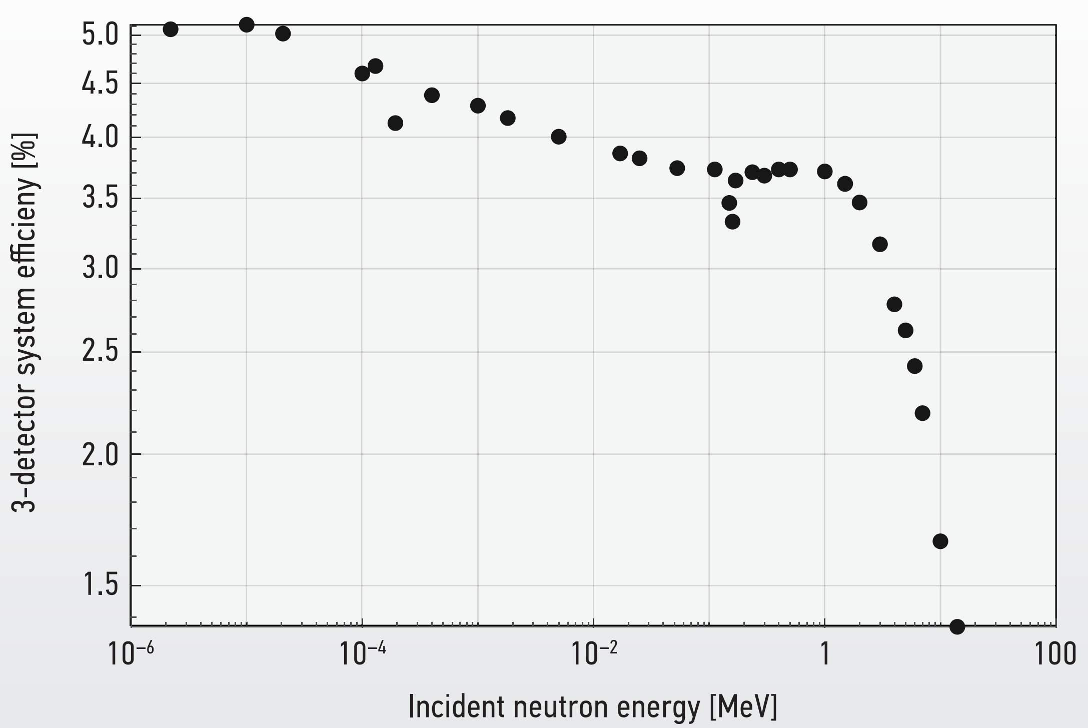
EXPERIMENTAL CALIBRATION



SPECTRAL SENSITIVITY



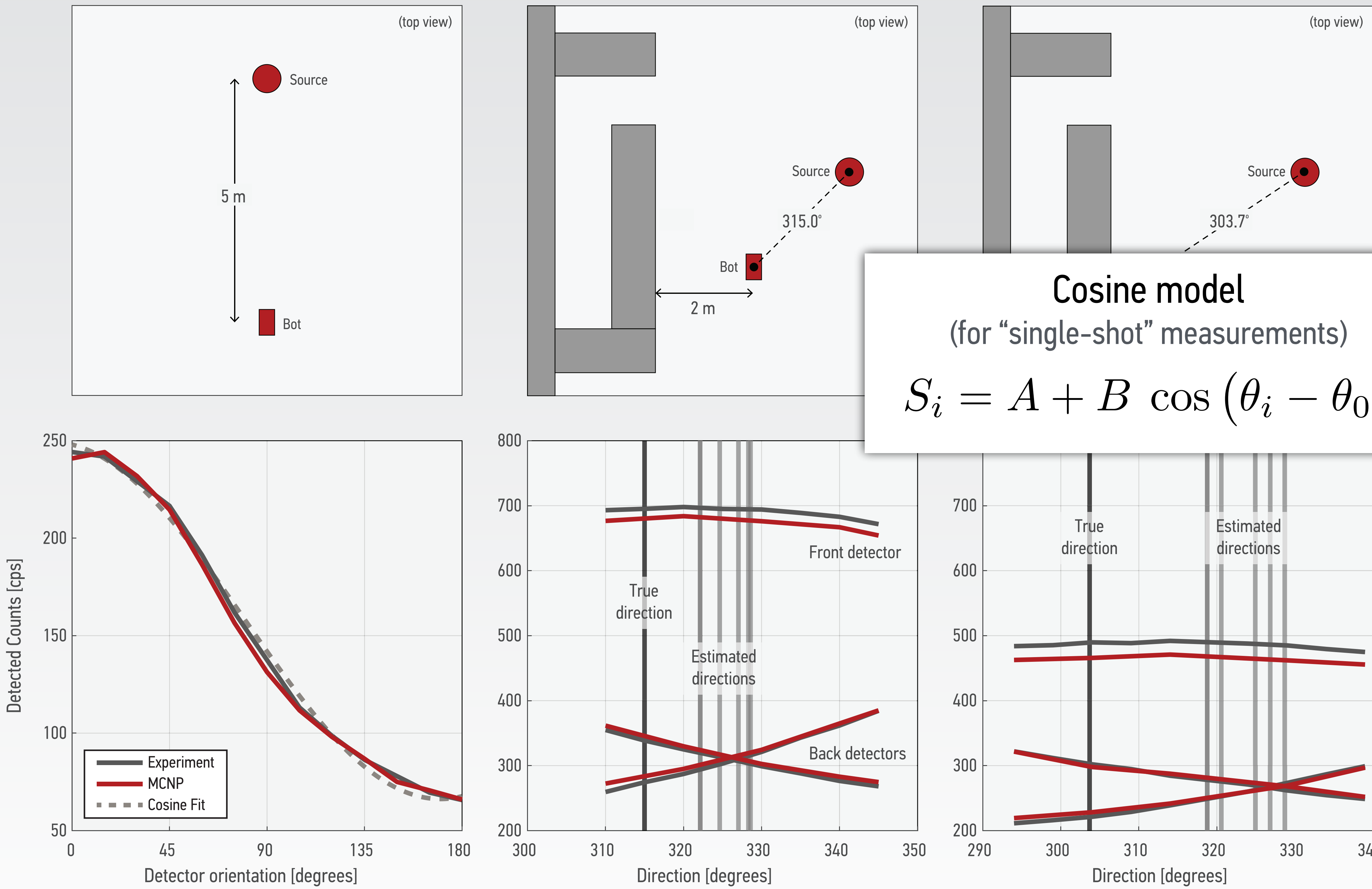
Front-to-back ratio indicative of
the (average) energy of incident neutrons



Response of a distributed energy source
can be predicted by weighting the monoenergetic results
by the detector efficiency

E. Lepowsky, M. Kütt, S. Aslam, H. Fetsch, S. Snell, A. Glaser, and R. J. Goldston, “Experimental Demonstration and Modeling of a Robotic Neutron Detector with Spectral and Directional Sensitivity for Treaty Verification,” *Nuclear Instruments and Methods in Physics Research A,* August 2022

DIRECTIONAL SENSITIVITY

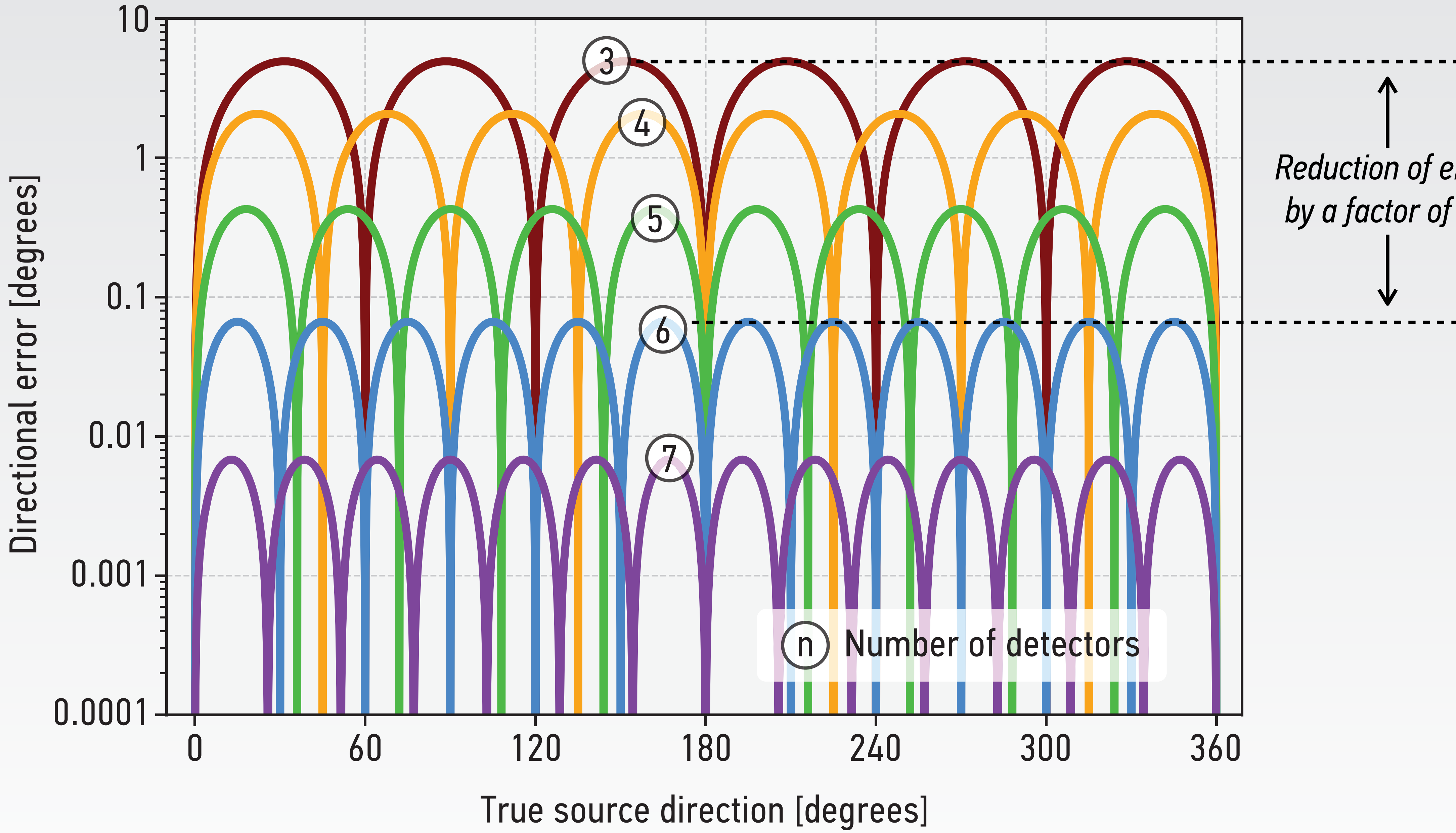


Cosine model

(for "single-shot" measurements)

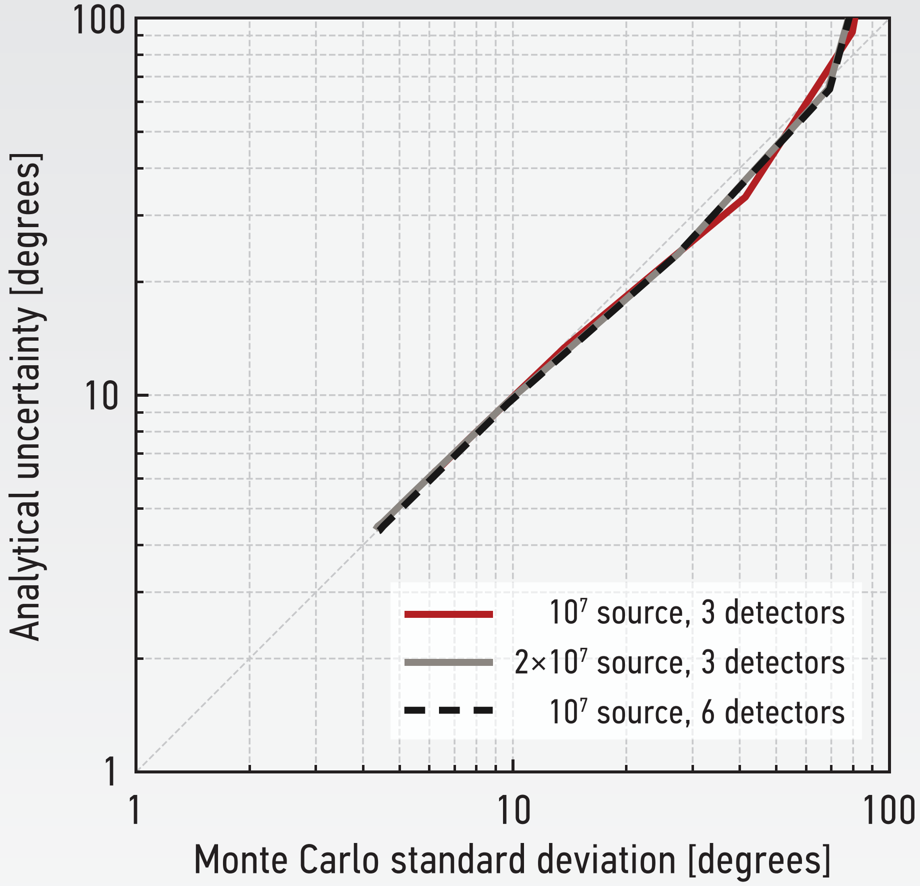
$$S_i = A + B \cos\left(\theta_i - \theta_0\right)$$

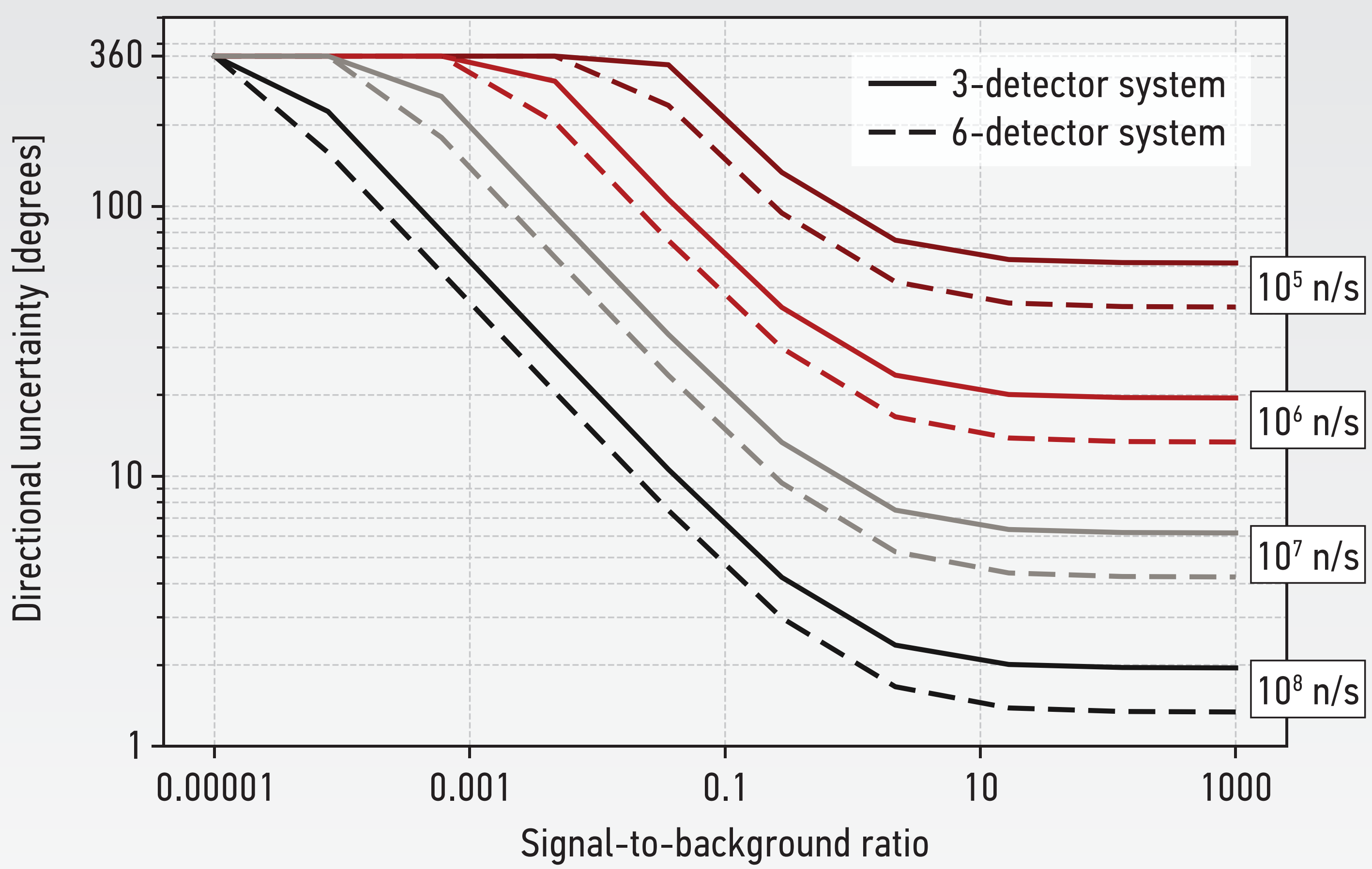
REDUCING SYSTEMATIC ERROR



E. Lepowsky, M. Kütt, S. Aslam, H. Fetsch, S. Snell, A. Glaser, and R. J. Goldston, "Experimental Demonstration and Modeling of a Robotic Neutron Detector with Spectral and Directional Sensitivity for Treaty Verification," *Nuclear Instruments and Methods in Physics Research A,* August 2022

STATISTICAL UNCERTAINTY PROPAGATION





Uncertainty is analytically propagated from the counting statistics to the directional estimate

Doubling the detectors yields the expected √2 improvement

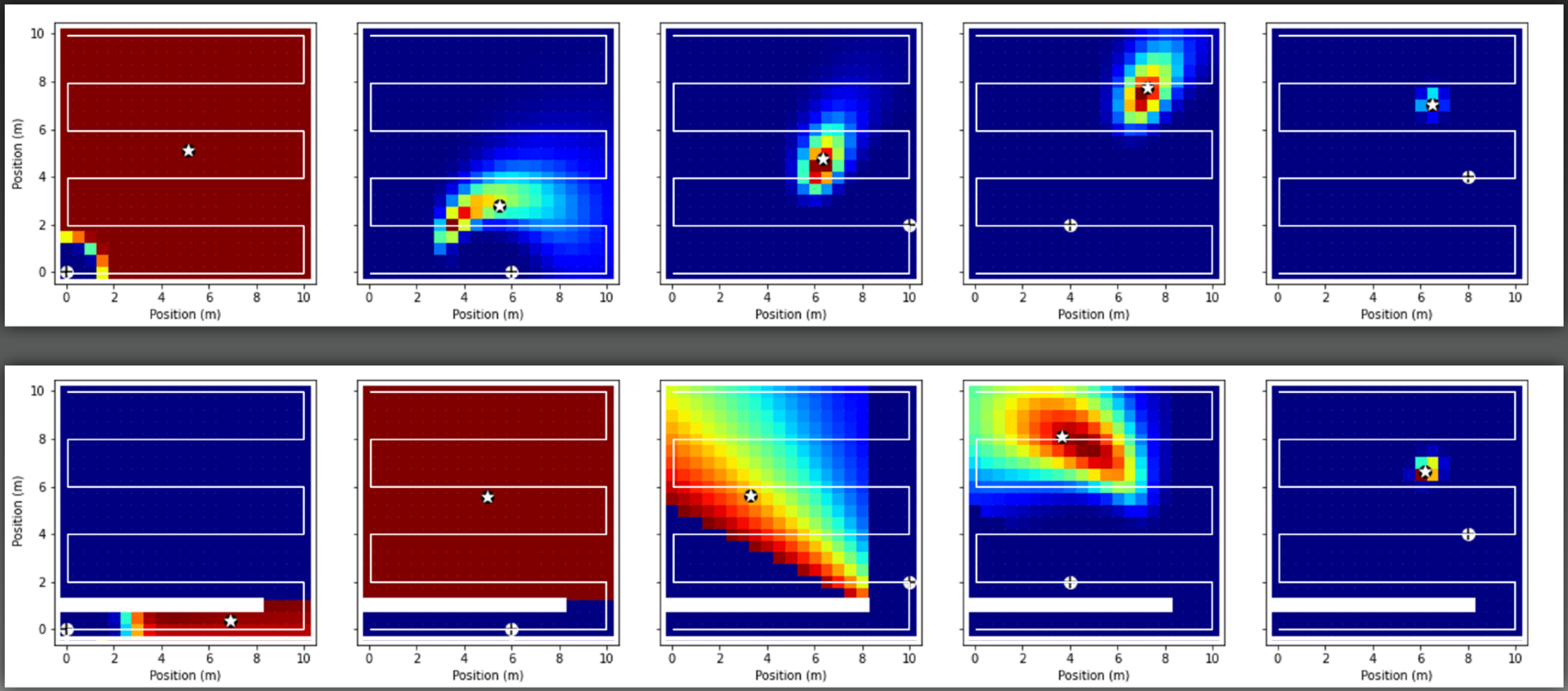
Directional uncertainty of order unity is achievable for high count rates with low background

E. Lepowsky, M. Kütt, S. Aslam, H. Fetsch, S. Snell, A. Glaser, and R. J. Goldston, "Experimental Demonstration and Modeling of a Robotic Neutron Detector with Spectral and Directional Sensitivity for Treaty Verification," *Nuclear Instruments and Methods in Physics Research A,* August 2022

Searching for a Source

(when there is not supposed to be one)

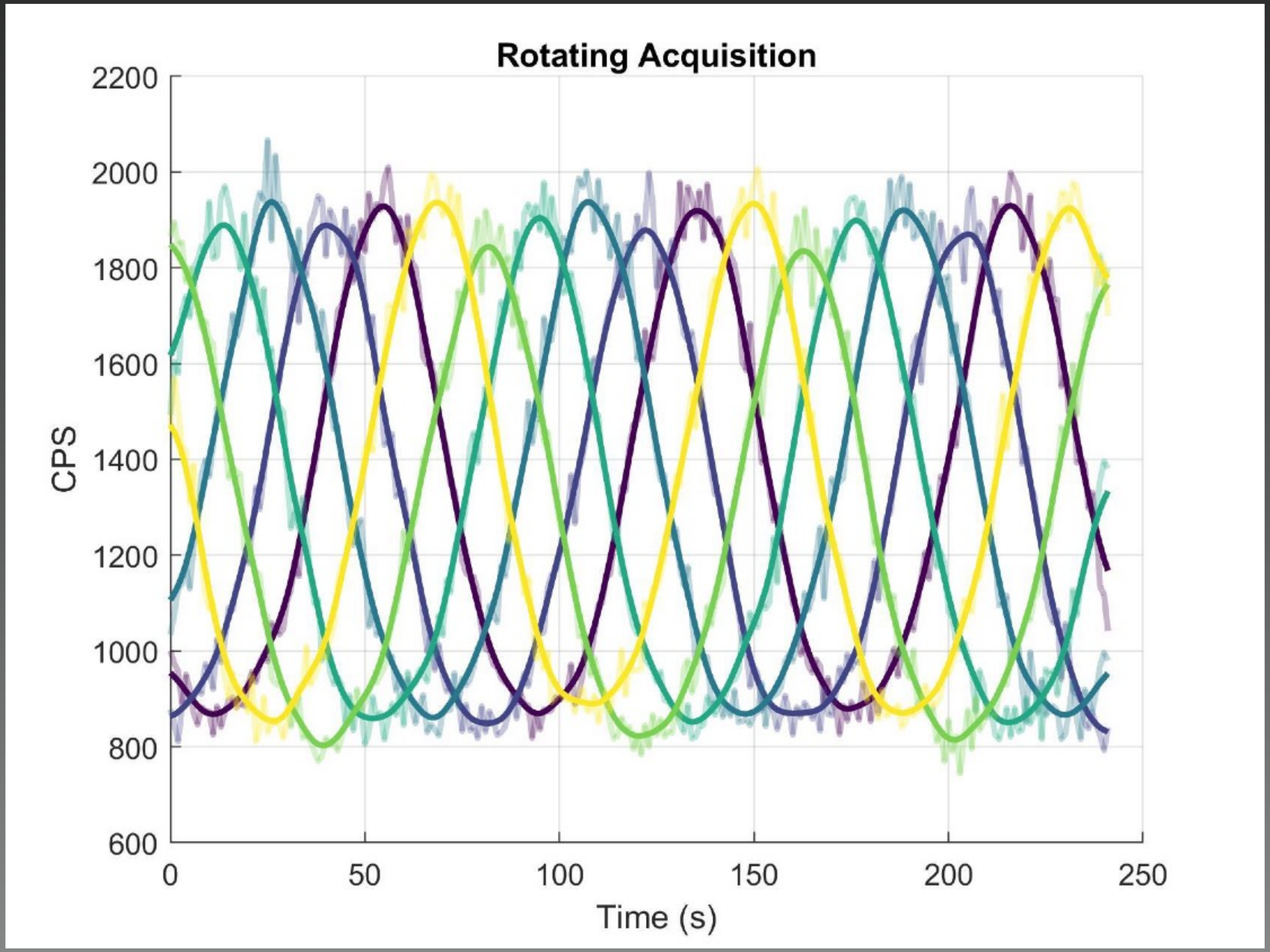
PARTICLE FILTER
FOR SOURCE LOCALIZATION



Robot follows a predefined raster pattern and updates particle weights with each measurement

ONGOING & FUTURE WORK

CHARACTERIZING THE NEW 6-DETECTOR SYSTEMS



Measurements at Princeton Plasma Physics Laboratory, October 2022
using a PuBe source at PPPL's Calibration and Service Laboratory (CASL)

ONGOING & FUTURE WORK

EXPERIMENTAL DEMONSTRATION OF SIX-DETECTOR SYSTEMS

Implement the cosine model for “finding” a source with/without reflection and with/without the particle filter at PPPL; search for a source; measure application-relevant sources

PATH PLANNING, SEARCH STRATEGIES, AND SOURCE LOCALIZATION

Various types of obstacles: transparent, reflective, partially and fully absorbing

Different exploration strategies and localization methods (or absence confirmation)

USE CASE: N-SpecDir BOT FOR SAFEGUARDS & ARMS-CONTROL APPLICATIONS

Find a withdrawal cylinder within a row of centrifuges and/or centrifuge hall

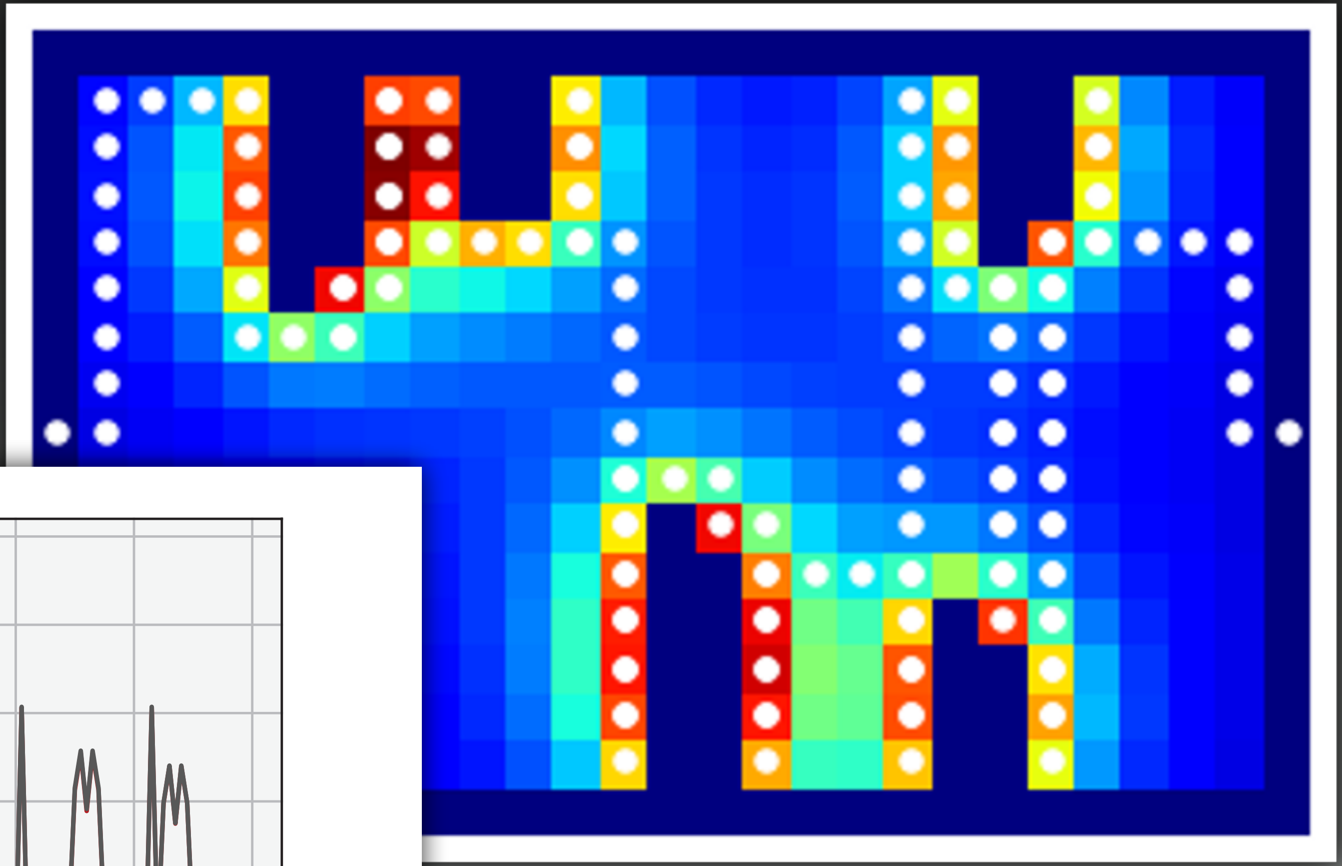
Need for more realistic test beds

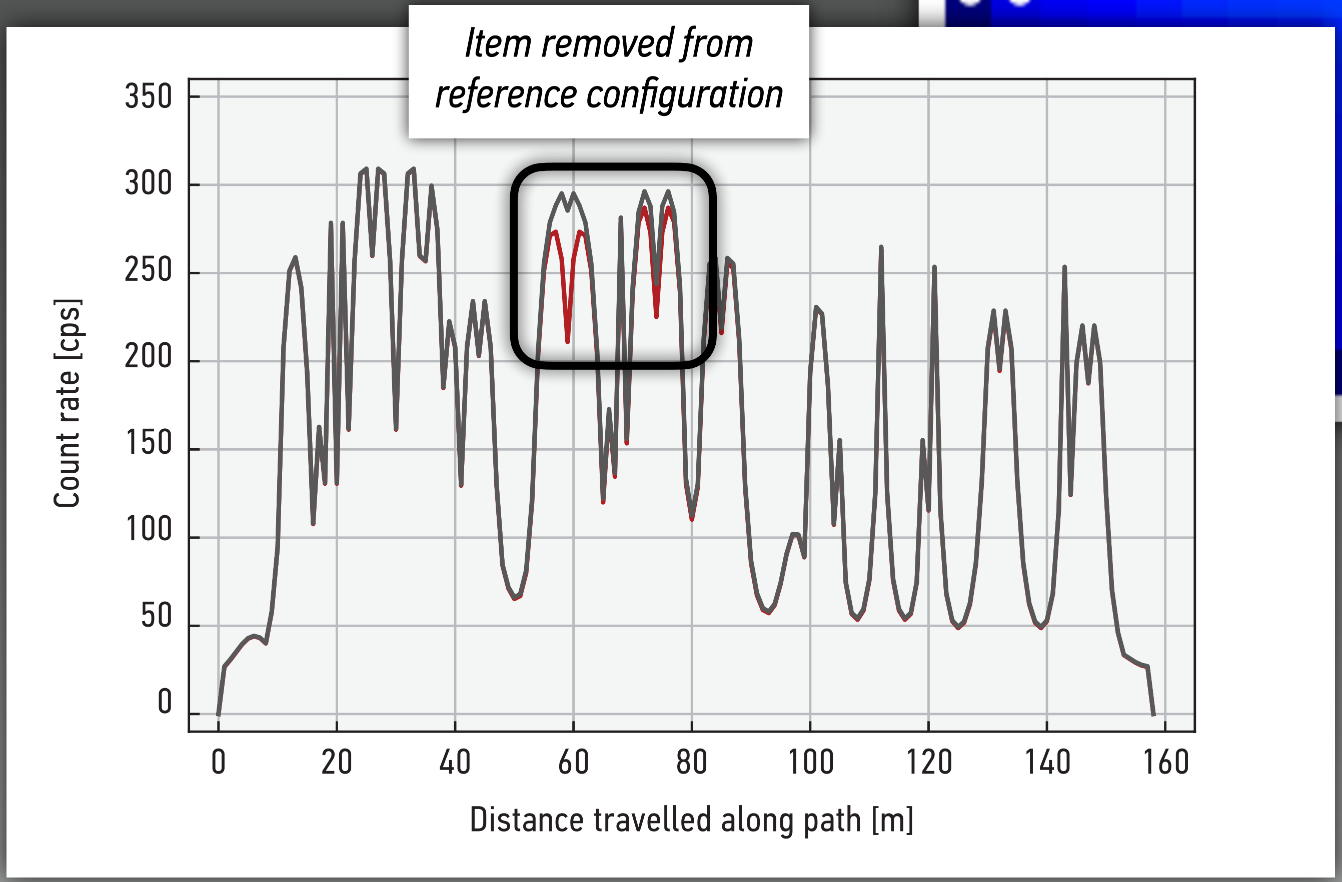
Source: Authors (top), IBRoomba (middle), president.ir (bottom)

NOTIONAL ARMS-CONTROL SCENARIO

TEMPLATE-MATCHING IN A STORAGE FACILITY

Can we confirm that the neutron field in a storage facility has remained unchanged between inspections…





…without revealing any sensitive information about the facility or its contents in the process ?

EXAMPLE #4

Virtual Inspections

Can we remotely follow certain (allowed) activities that the host performs ?

VIDEO BROADCAST

KEY REQUIREMENTS

SECURITY & PRIVACY

How to follow relevant activities without also capturing additional information that is considered sensitive but irrelevant for the task at at hand?

DATA TRANSMISSION & INTEGRITY

How to transmit the footage to an offsite location, especially from the interior of a hardened and highly secured building? (Can it be done in real-time?)

LIVE VERIFY & LOCAL VERIFY (Johnston and Warner, 2010)

How to ensure that the footage is recorded in real-time? (How to preclude replay attacks?)
How to ensure that the data is transmitted from the correct location?

Source: IAEA (top and middle) and author (bottom)

EVENT-BASED VISION

iniVation DAVIS346

FEATURES

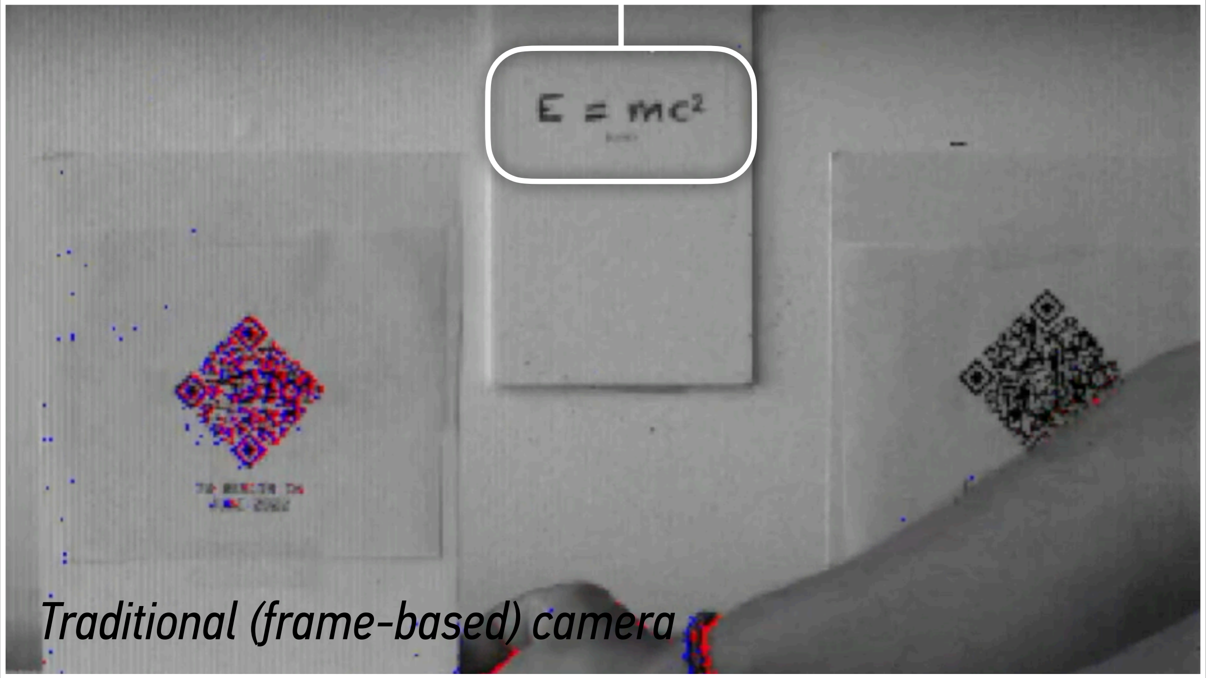
- Extremely low bandwidth, no redundant data
- Very low power consumption (~ 100 mW)
- Asynchronous, fast data acquisition (μs-scale)
- High-dynamic range (> 120 dB)
- Sensitive to relative changes, not absolute values

- Commercially available since early 2010s
- Resolution: originally ~ 320 x 240 pixels
  Currently moving to megapixel designs

"NOTHING TO SEE HERE"

EVENT-BASED VISION FOR INTRINSIC INFORMATION SECURITY

"Secret" information visible at inspected site



Recorded at TU Berlin, June 2022, courtesy of Guillermo Gallego

EXAMPLE #5

Virtual Reality

VIRTUAL REALITY

AS A TOOL FOR THE JOINT DEVELOPMENT OF NEW VERIFICATION APPROACHES

THE ORIGINAL IDEA

Create open and flexible virtual environments to explore new verification concepts and approaches

(... which could also lay a basis for live exercises and new policy initiatives)

CURRENT MAIN FOCUS OF PROJECT

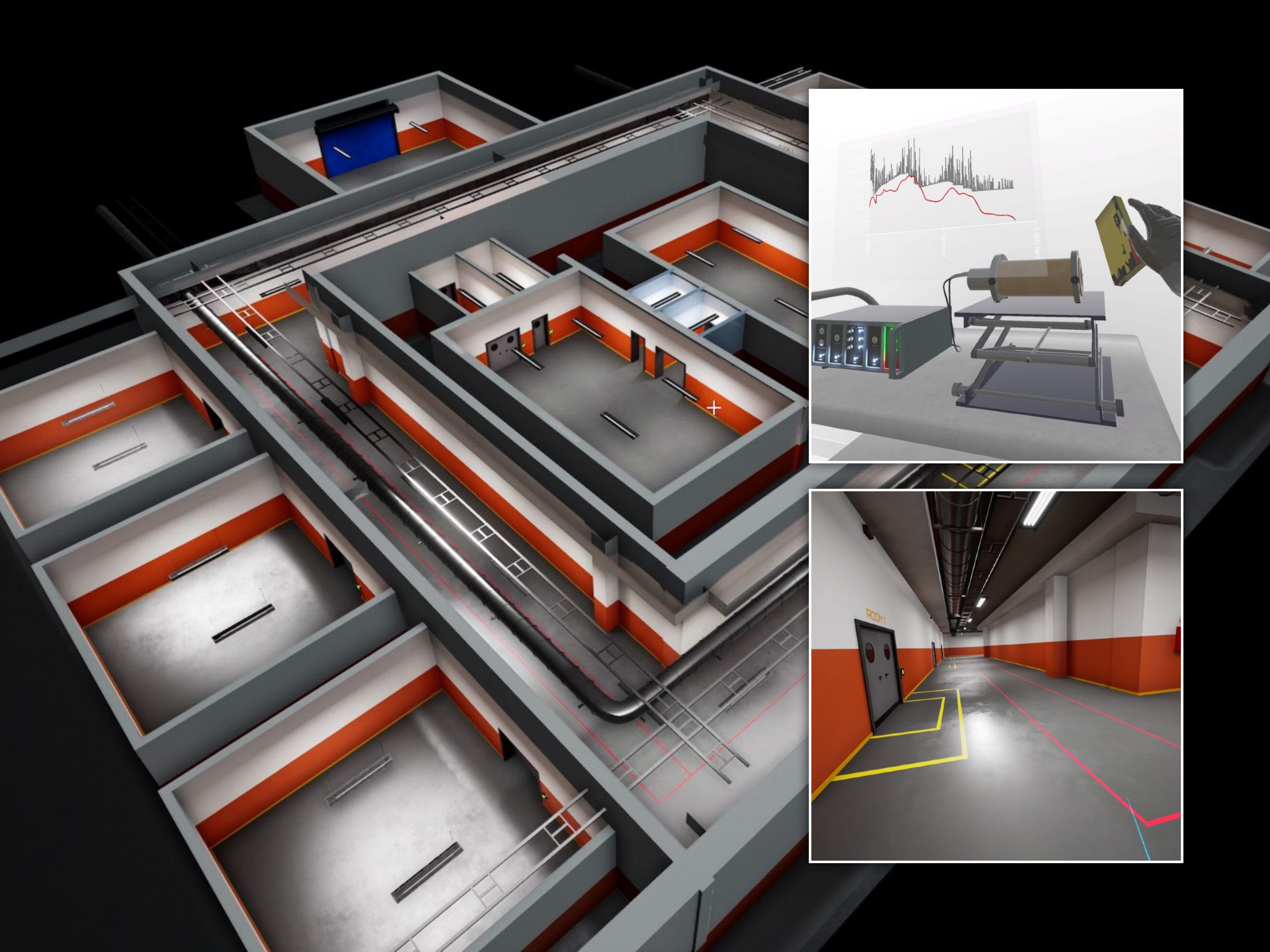
Examine fundamental questions related to interactivity, user experience, and presence in virtual environments; but also explore “cheating scenarios” relevant for assessing the effectiveness of different verification approaches

Source: Authors

Demonstration of earlier project at the UN, Geneva

on the margins of a meeting of the Group of Governmental Experts on nuclear disarmament verification, Palais des Nations, May 2018

Source: Pavel Podvig


500 keV
1.000 keV
ROOM 1

SUMMARY AND OUTLOOK

(IN LIEU OF CONCLUSIONS)

PERSISTENT AND EMERGING VERIFICATION CHALLENGES

25 years of research and development have not (yet) produced the technologies needed to verify future arms-control agreements

Remote and virtual inspection techniques could play an important role in future arms-control verification and safeguards

RE-IMAGINING NUCLEAR DISARMAMENT VERIFICATION

Explore verification approaches that minimize the need of access to sites and treaty accountable items or avoid measurements on those

Consider approaches that offer “on-ramps,” i.e., that start off simple and can accommodate “upgrades” later on

Source: Sandia National Laboratories (top) and IAEA, flickr.com/photos/iaea_imagebank/albums/72157659464420989 (bottom)

ACKNOWLEDGEMENTS

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