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Optimization of a CONFIDANTE System (CONfirmation using a Fast-neutron Imaging Detector with Anti-image Null-positive Time Encoding)

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Arms control context

- **Current & previous treaties counted delivery vehicles as a measure of the number of deployed nuclear weapons**
- **At a small number of weapons and for stockpile dismantlement, individual warheads may need to be verified**
- **In a future arms control treaty, how do we authenticate a warhead?**
- **The monitoring party needs confidence that an item truly is what it is declared to be**
- **The host country needs confidence that sensitive information about the item remains secure**

Arms control context – template verification

- **In a future arms control treaty, how do we authenticate a warhead?**
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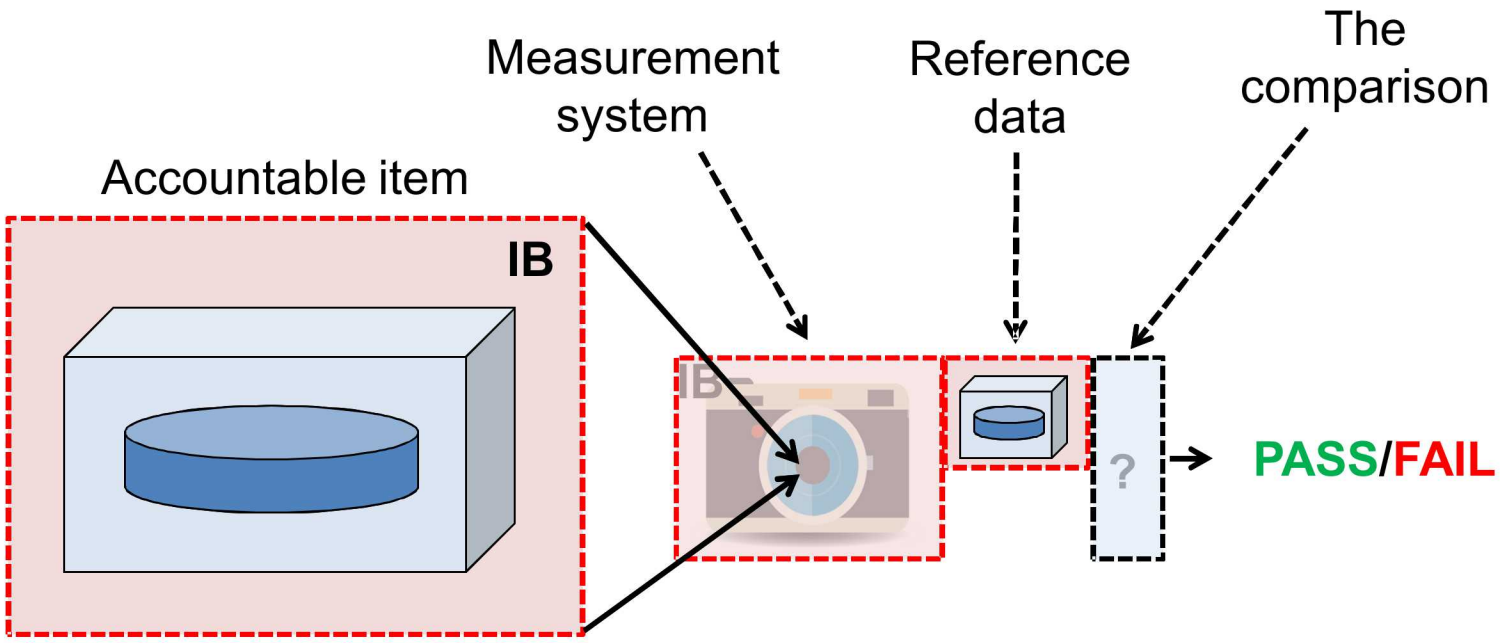
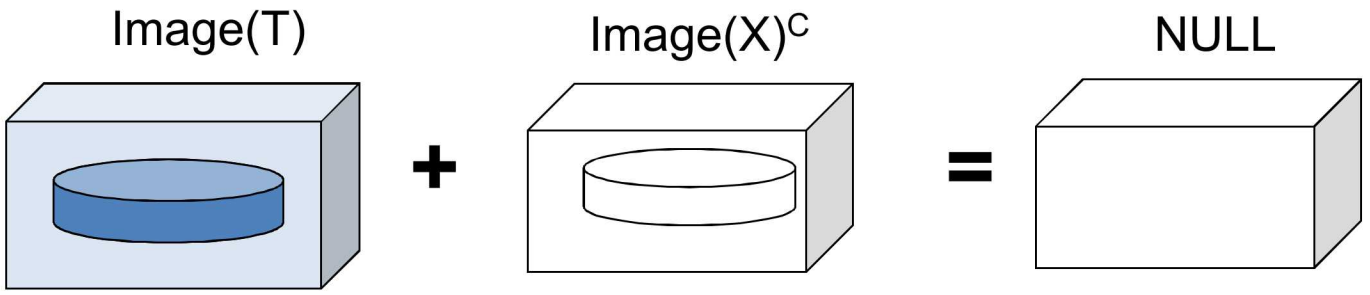


Arms control context

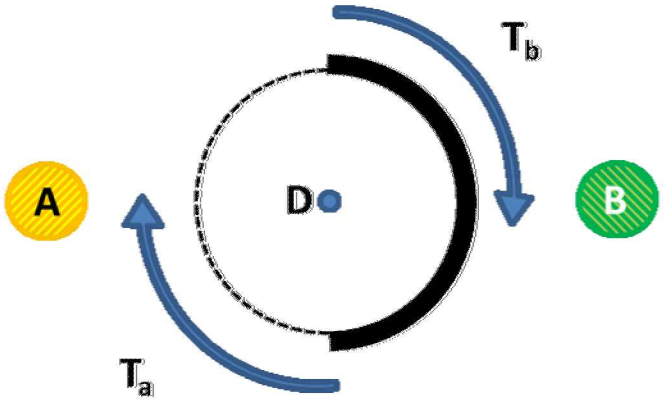
- **In a future arms control treaty, how do we authenticate a warhead?**
- **The monitoring party needs confidence that an item truly is what it is declared to be**
- **The host country needs confidence that sensitive information about the item remains secure**
- **Can we decrease the amount of information behind information barriers while still maintaining confidence?**

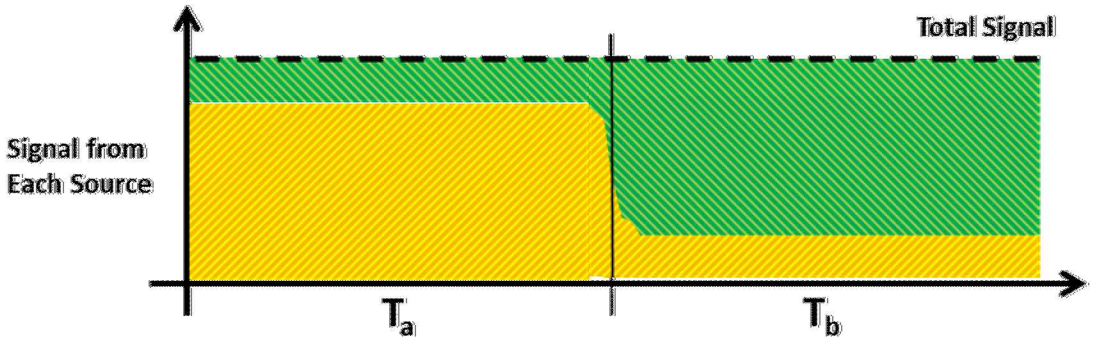
Arms control context

- **In a future arms control treaty, how do we authenticate a warhead?**
- **The monitoring party needs confidence that an item truly is what it is declared to be**
- **The host country needs confidence that sensitive information about the item remains secure**
- **Proposed solution: complementary comparison (turn one image into its complement) at all times**



A simple example

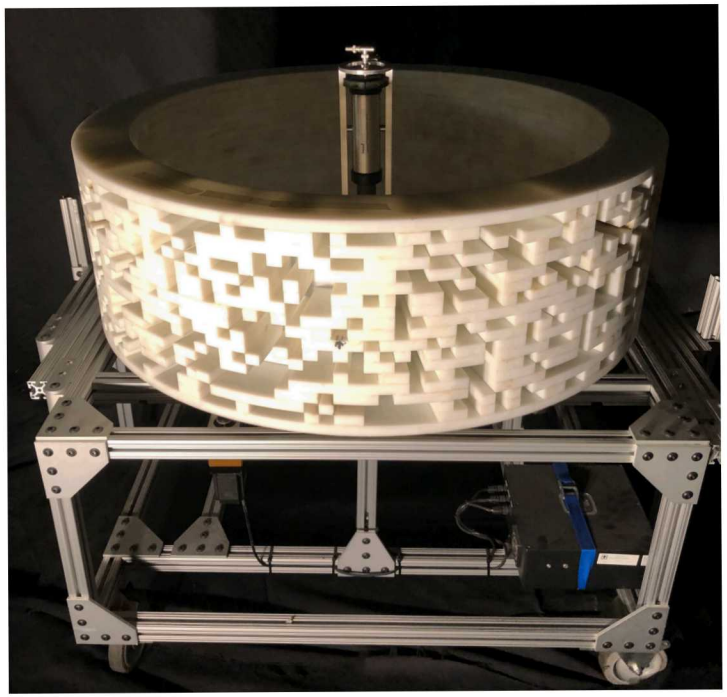


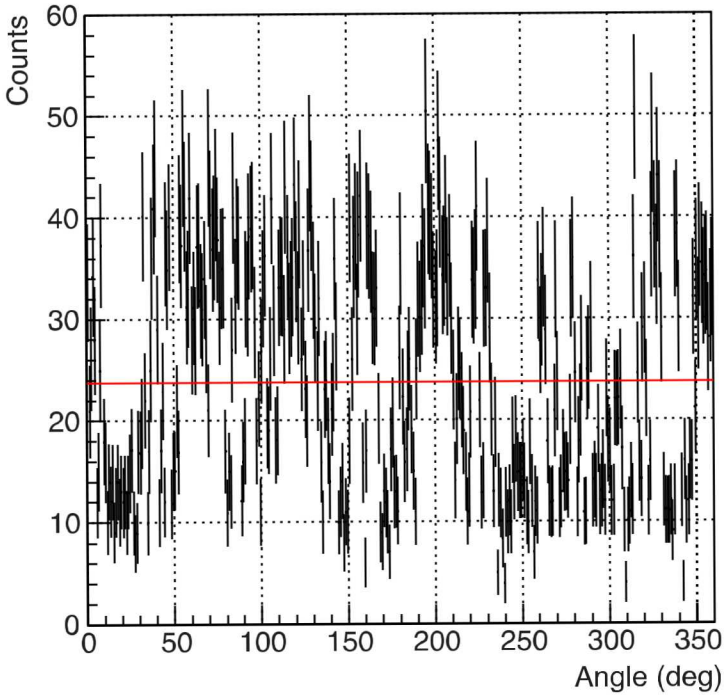


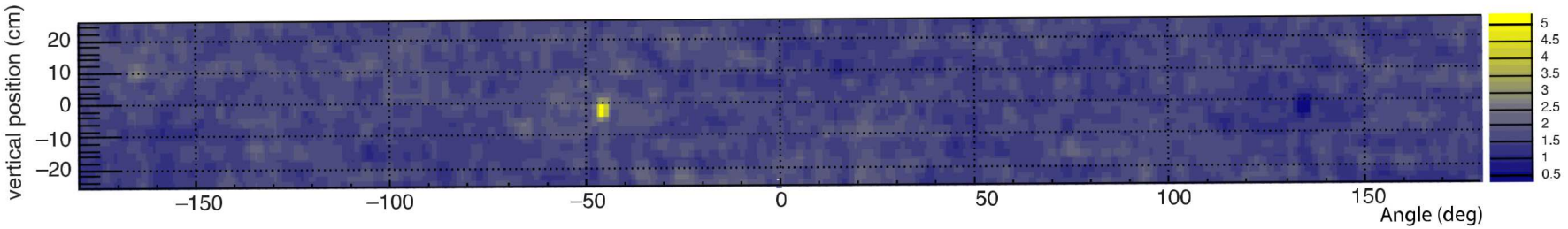
- The simplest possible imaging system with this property: half mask, half aperture.
- The fraction of total count rate coming from A and B is unknown at any given angle.
- In this example, the location (and shape) of the boundary between regions is not revealed.

Time-Encoded Imaging

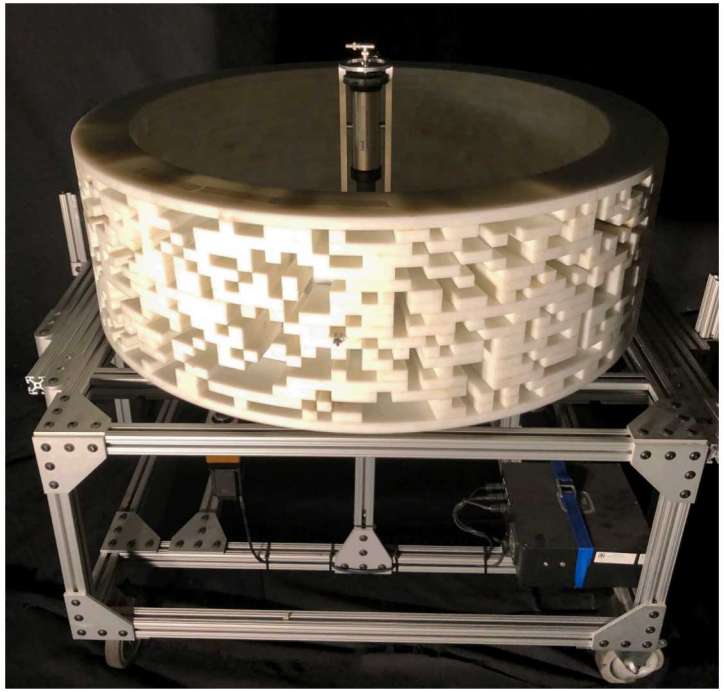
2-D coded mask modulates the source as the mask rotates; the modulation pattern can be unfolded to a 2-D image



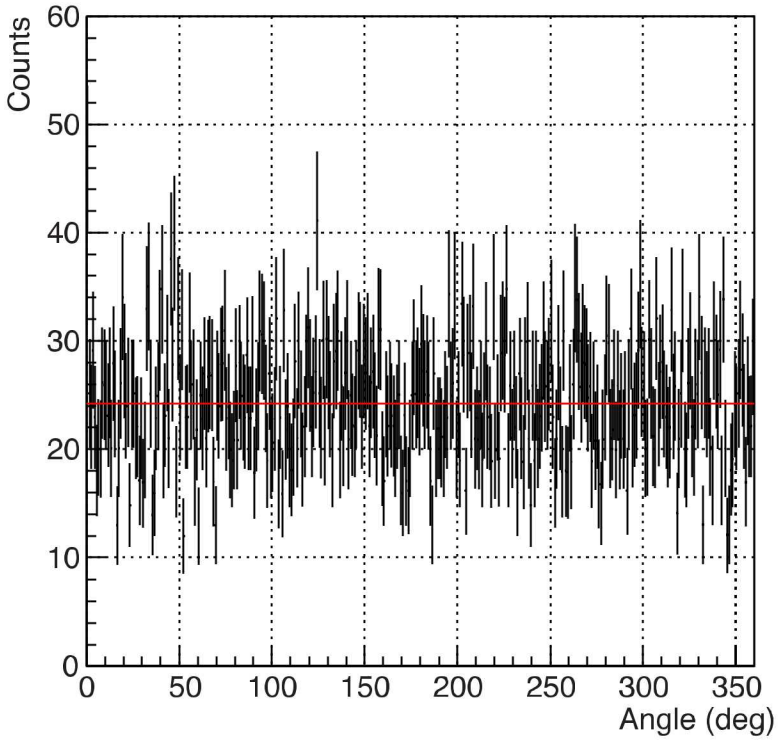




CONFIDANTE proof-of-concept system



- An anti-symmetric mask with sources on opposite sides of the mask has a constant event rate if the sources match
- Results below are from two Cf-252 sources
- Quantify results by comparing to mean counts/bin and calculating χ^2 value



R. K.-W. P. S. P. Marleau, "Proof of concept demonstration of CONFIDANTE (CONfirmation using a Fast-neutron Imaging Detector with Anti-image Null-positive Time Encoding)," in *INMM Annual Meeting Proceedings*, 2018.

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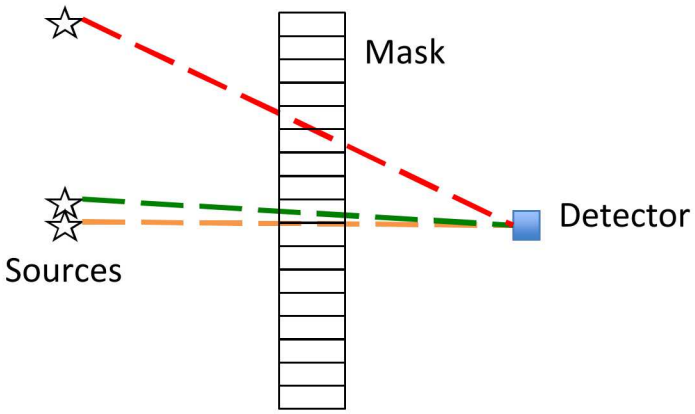
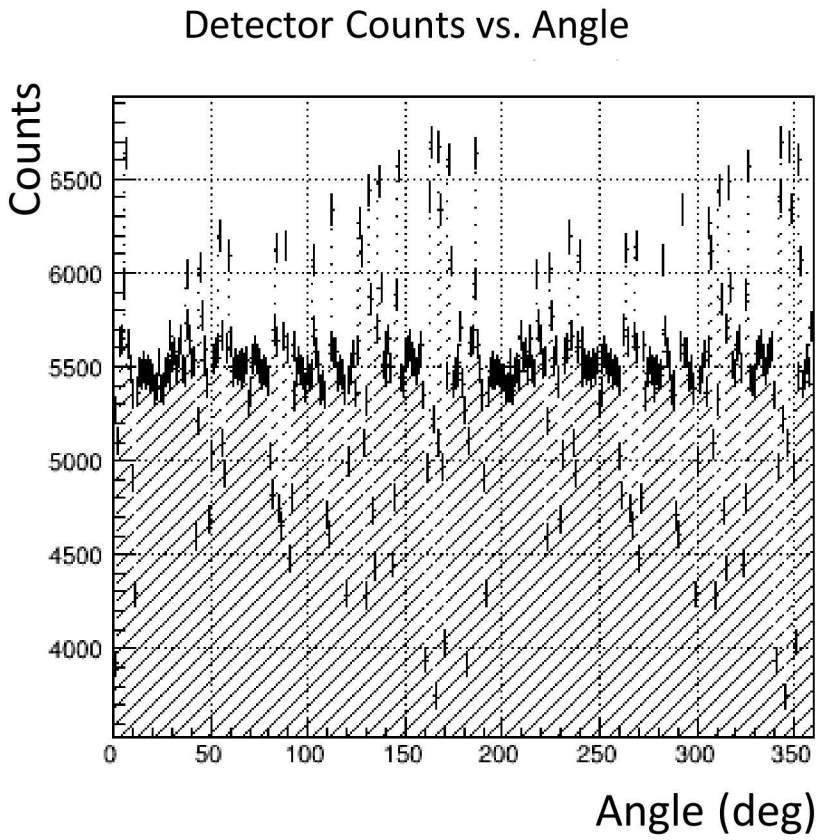
Mask Improvement Goals

- **Removing imaging artifacts caused by shape of system**
- **Decreasing the overall system size**
- **Understand tradeoffs in system size, efficiency, and imaging performance**

Artifacts from cylindrical mask

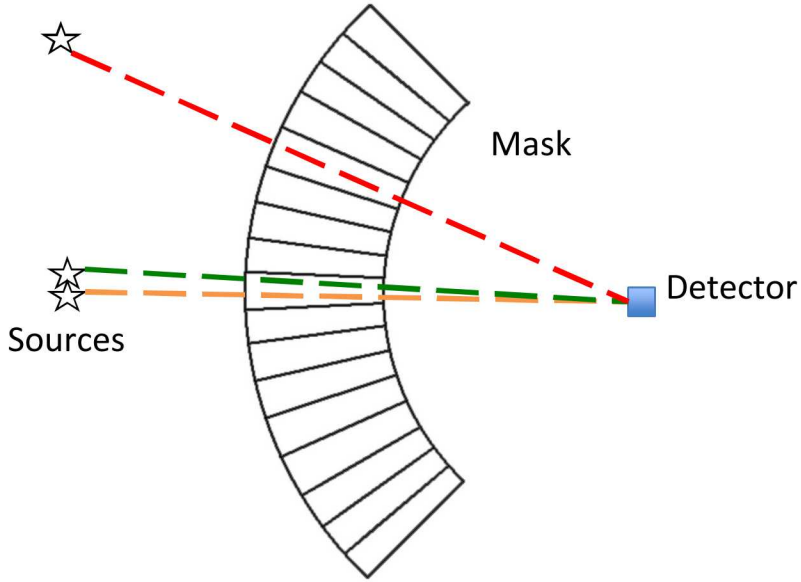
- Improve imaging performance by changing the shape of the mask and detector
- Concern: edge effects in a cylindrical mask cause partial attenuation instead of the desired open/closed effect

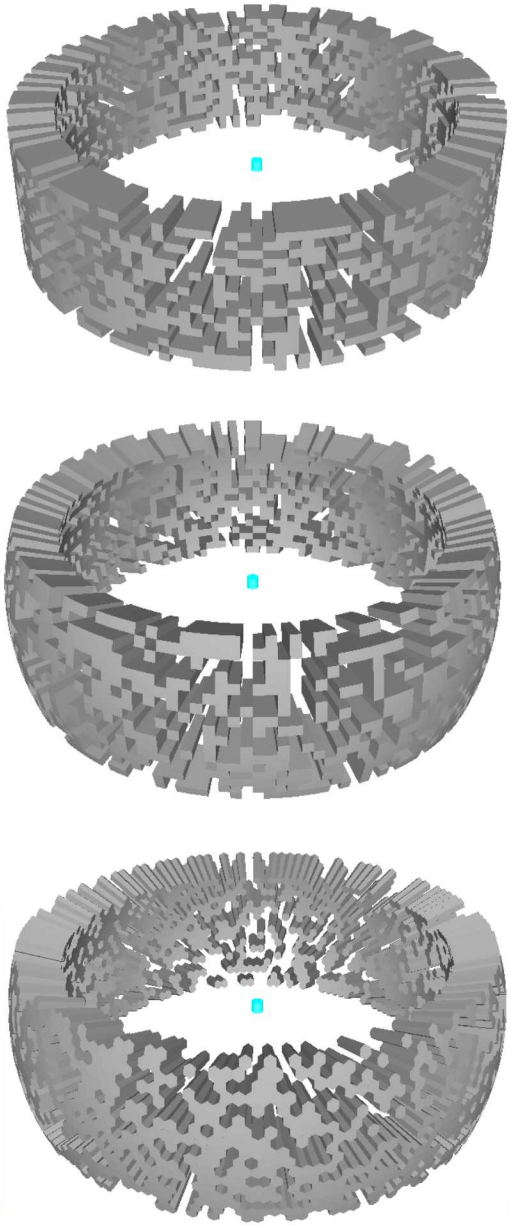




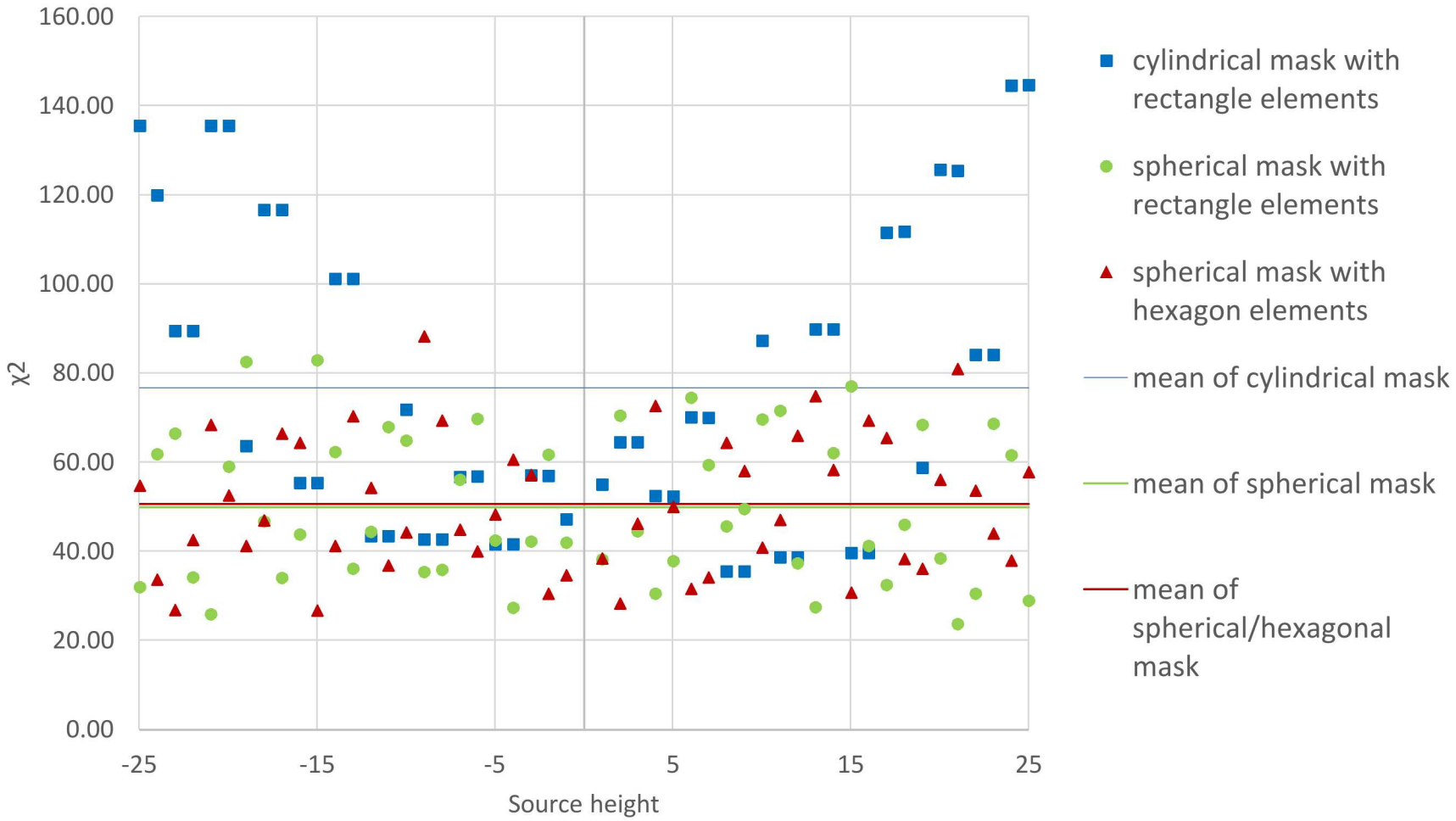
Removing artifacts caused by mask

- Concern: edge effects
- Potential solutions: spherical mask, spherical detector, hexagonal mask elements
- Modeled mask and detector combinations in ROOT/C++ with matching point sources at different heights and calculated the χ^2 value



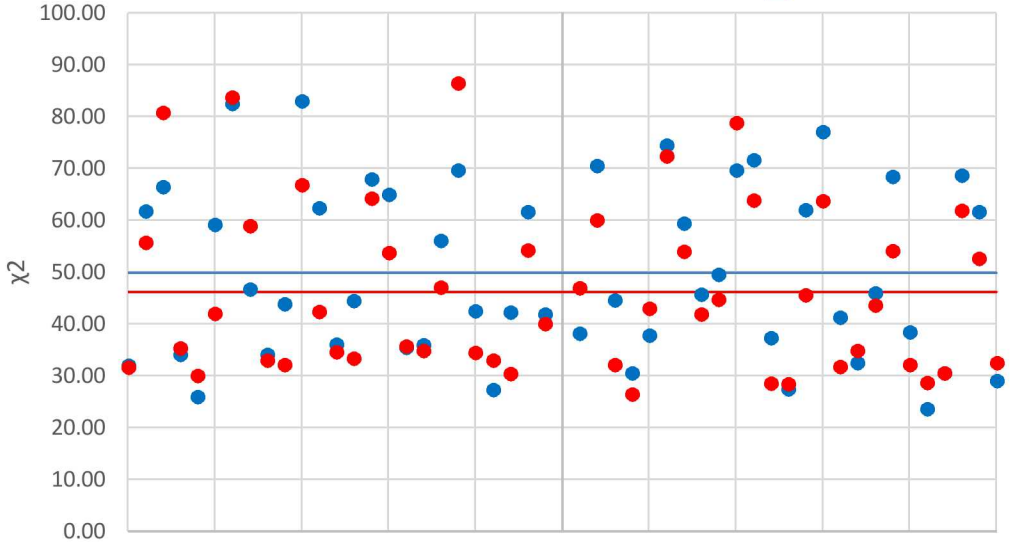


Comparison of mask and mask element shapes

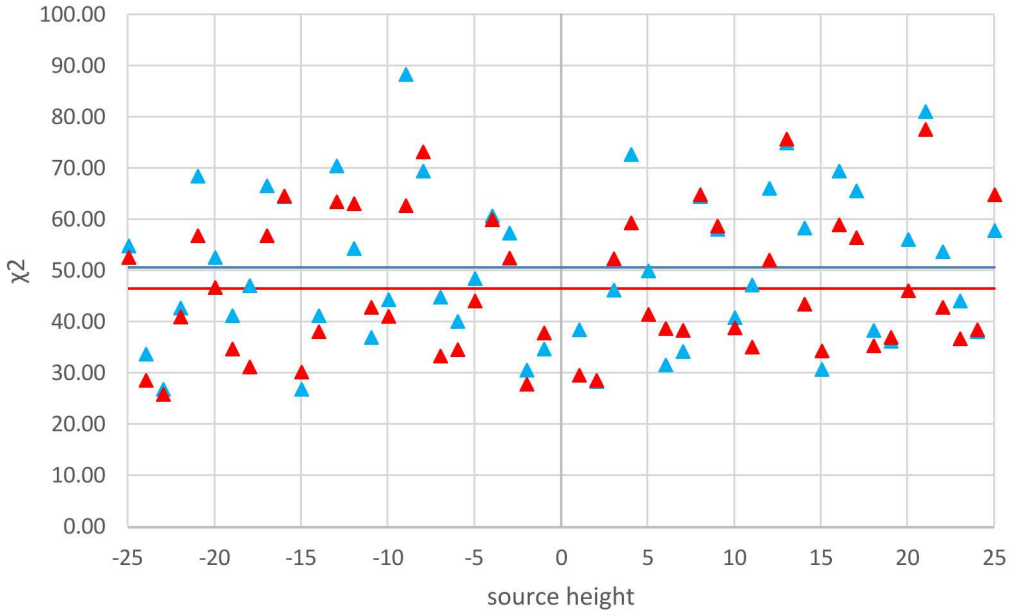


Comparison of detector shapes

Spherical mask with rectangular elements



Spherical mask with hexagonal elements

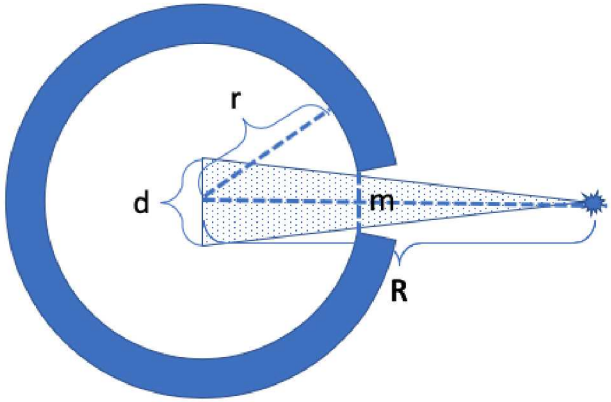


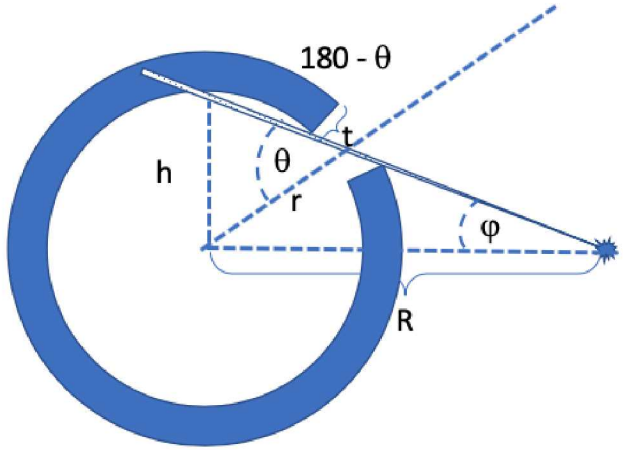
Decreasing the system size

- **What effect does making the system smaller have?**
- **Need to balance tradeoffs in**
  - Size
    - Smaller system is easier to work with
    - Smaller size worsens efficiency and time to detection, or the system angular resolution
  - Measurement time
    - Shorter measurement time is preferred
    - Shorter measurement times require a larger detector; this either worsens the system angular resolution and performance or drives the entire system to a larger size
  - Performance
    - Need sufficient angular resolution for imaging
    - Better angular resolution either drives the system size up or the detector size down, decreasing efficiency and increasing measurement times

Metrics for imaging performance

For good imaging, the mask projection onto the detector, *d*, should be large and the sweeping distance *2h* should be small.





$d = mR/(R-r)$

$\tan(\theta) = m/t$

$\sin(\varphi) = r/R \sin(180-\theta)$

$h = R \tan(\varphi)$

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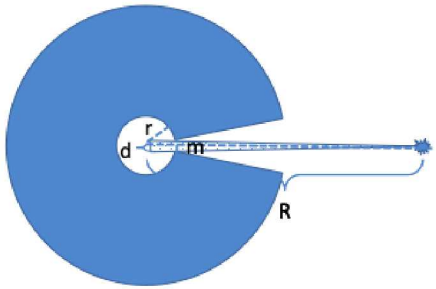

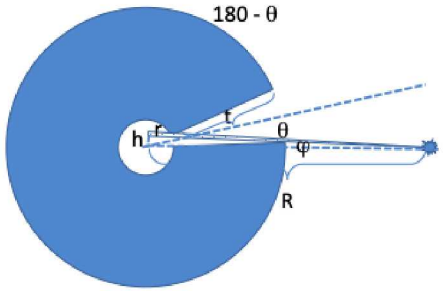

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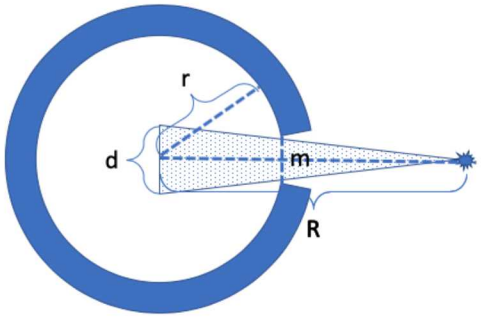
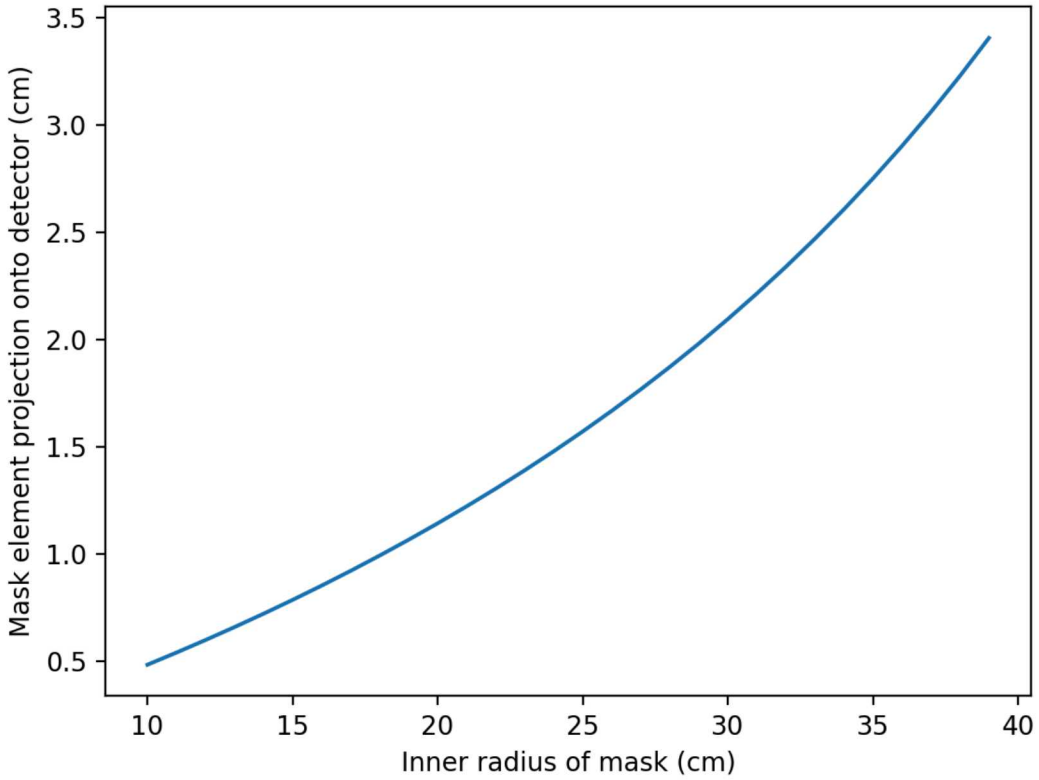
Calculated mask projection on detector

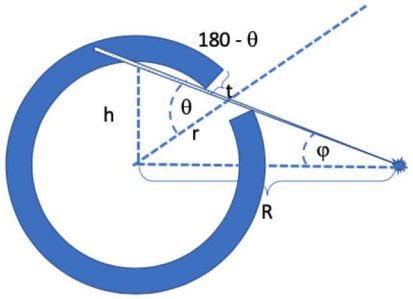


d = mR/(R-r)

- Better if larger

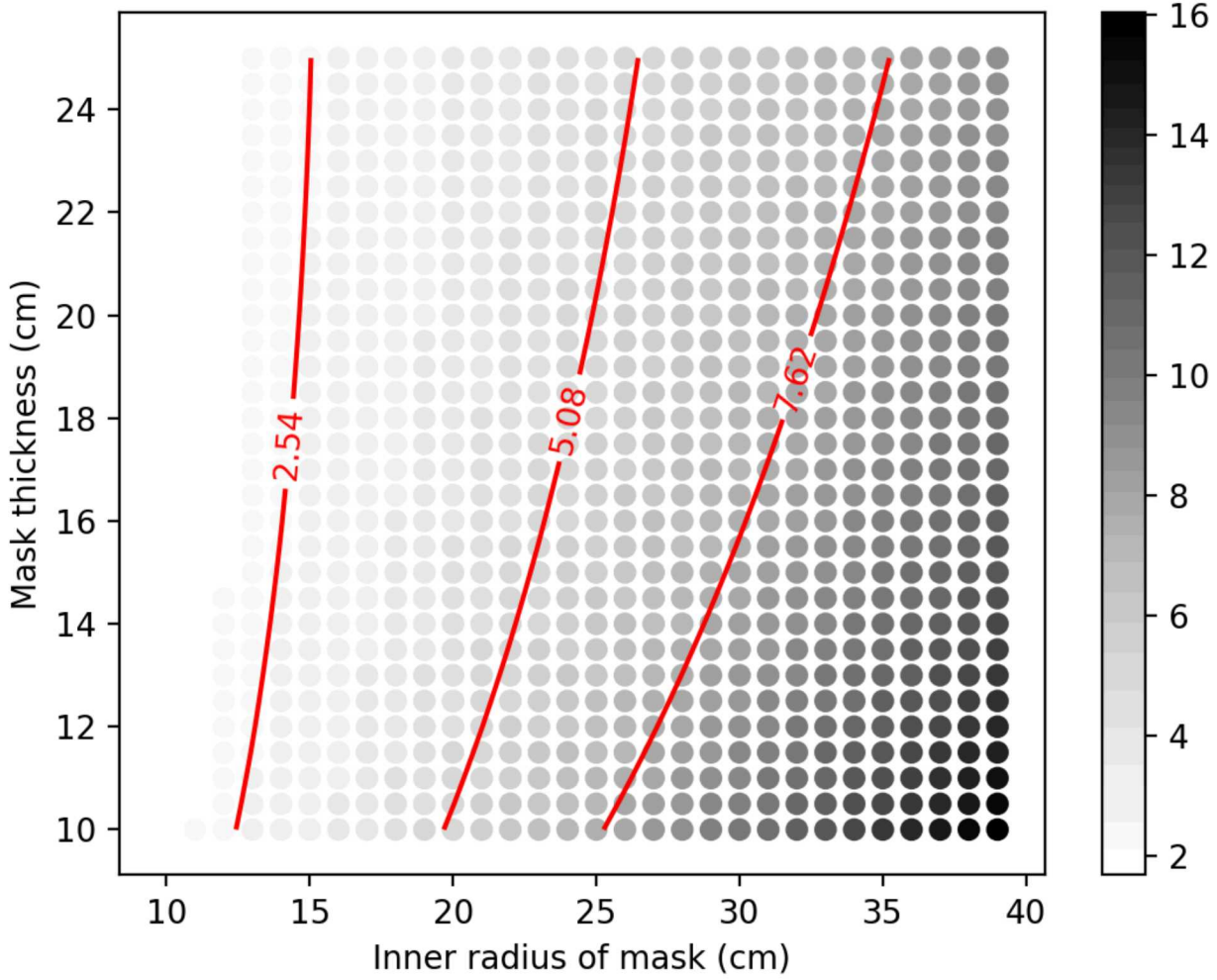


Calculated sweeping distances



$\tan(\theta) = m/t$
$\sin(\varphi) = r/R \sin(180-\theta)$
$h = R \tan(\varphi)$

- Better imaging if smaller
- Contour lines where 2*h* equals 1”, 2”, or 3”



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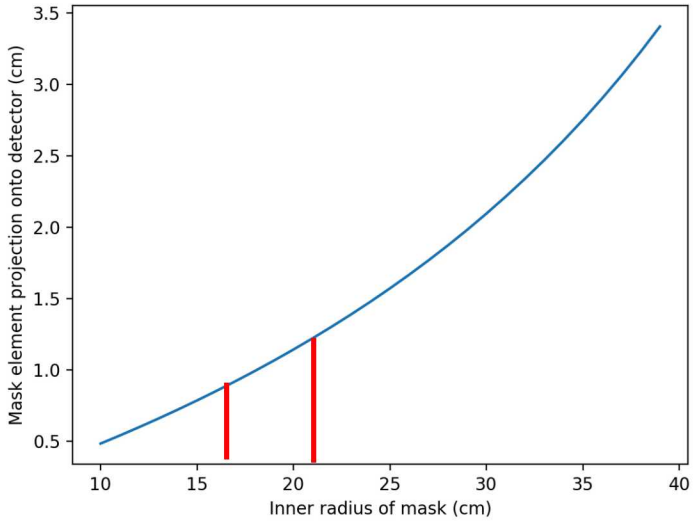
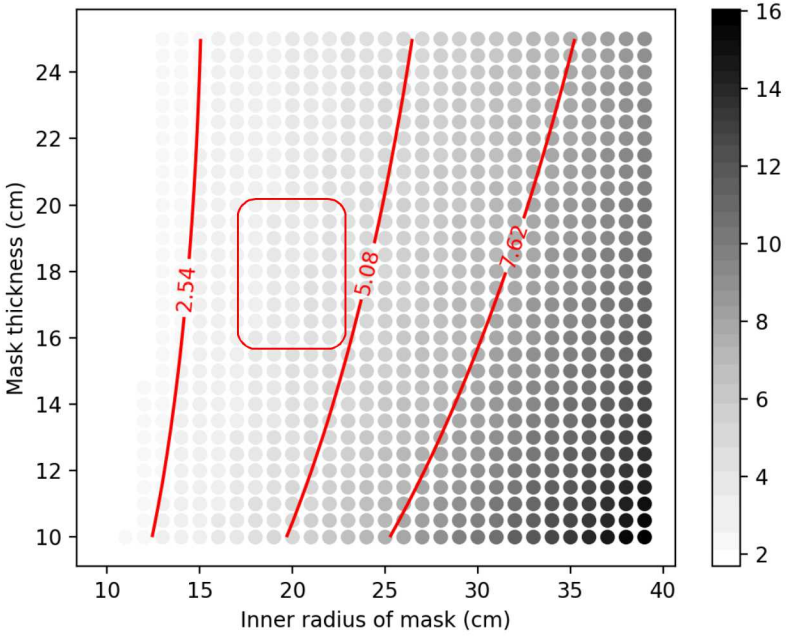
Best radius and thickness

- No perfect combination of values for
  - large mask projection
  - small sweeping angle
  - small system
- Compromise in middle ranges
- Needs more testing with more complex model including scatter





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Summary and Future Work

- **Based on modeling and calculations, an improved system will have:**
  - Spherical mask
  - Rectangular mask elements
  - Cylindrical detector
  - Inner radius of between 16-22 cm
  - Total mask thickness of 16-20 cm
- **Future work**
  - Add scatter to the models with smaller radii
  - Calculate efficiency and measurement times for different angular resolution masks
  - Mask pattern optimization

Acknowledgements

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Kai Vetter

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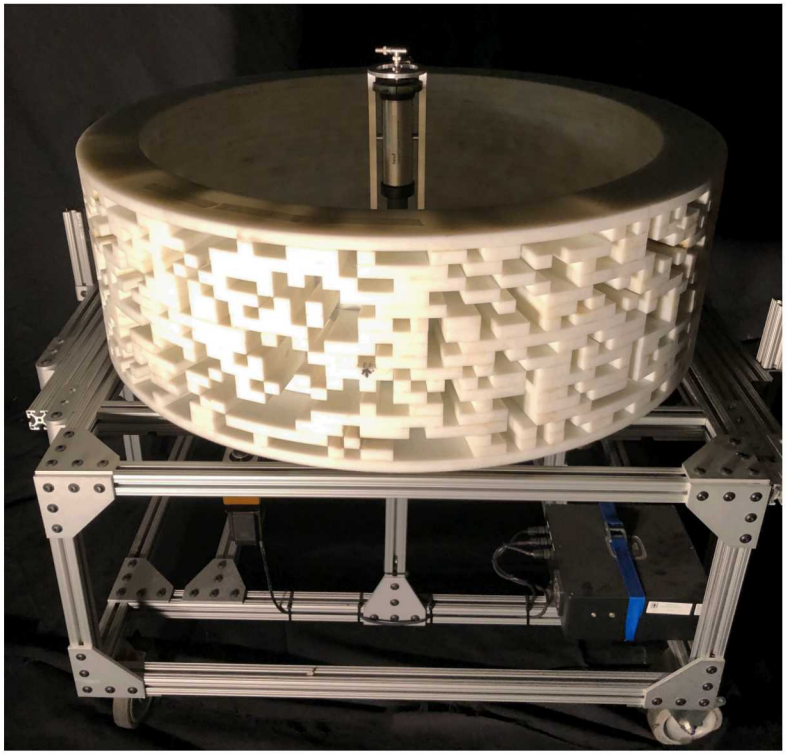
CONFIDANTE proof-of-concept system



- HDPE mask
  - 1.9 cm x 1.9 cm x 10.16 cm elements
  - 150 elements/layer
  - 17 layers
  - 1 m diameter
- 2.54 cm x 2.54 cm stilbene detector
- 2 sets of measurements
  - Small Cf-252 source
  - PuO_2 hemispherical shells

Arms control context – attribute verification

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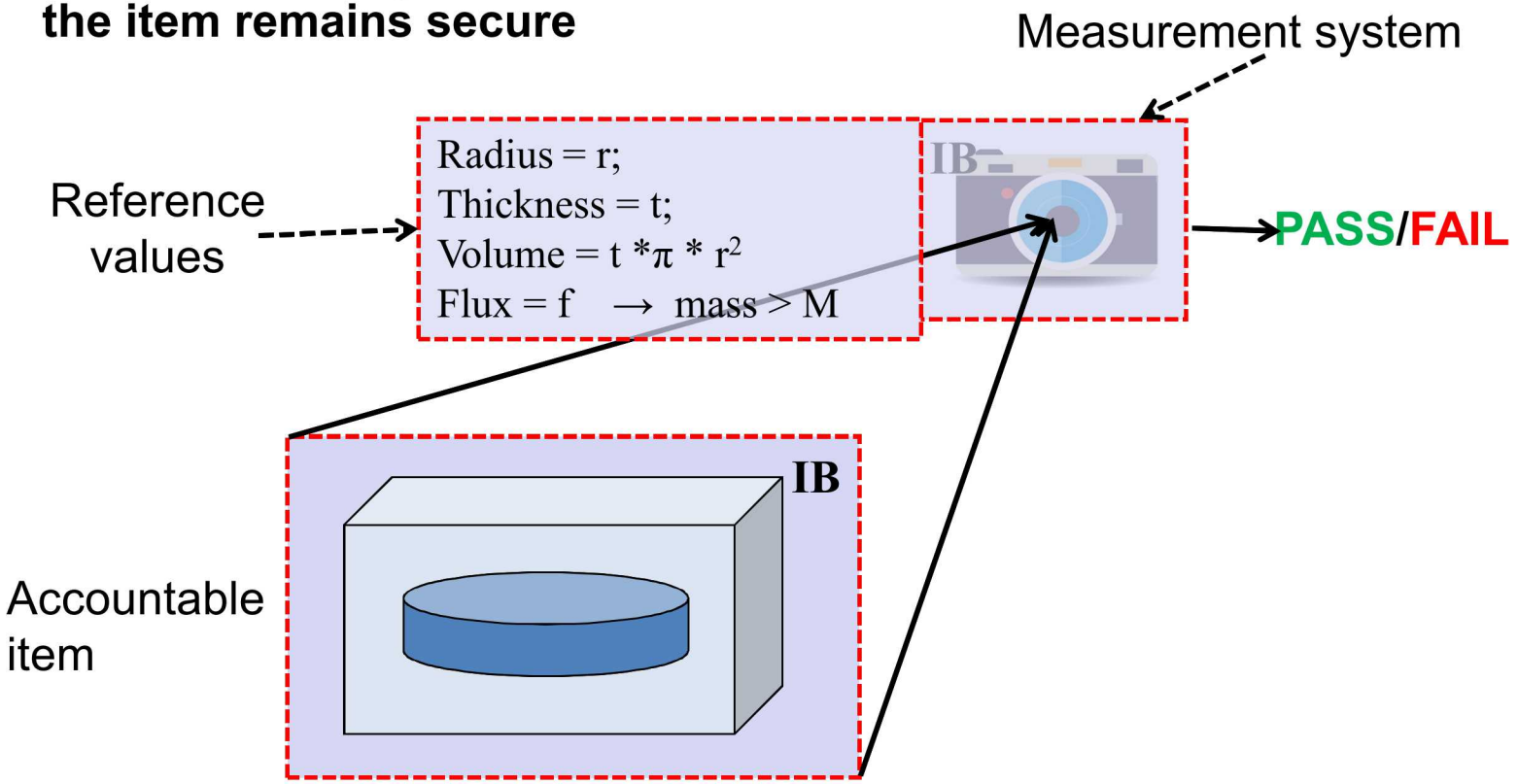
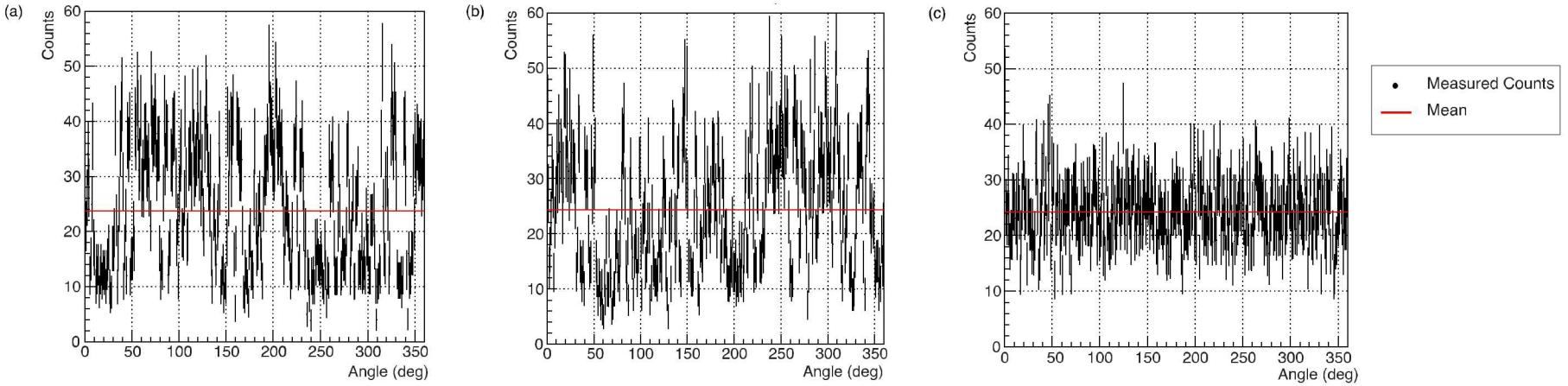


Neutron system with a small Cf-252 source

Counts in the detector as a function of mask rotation angle



Distribution of counts per unit angle