SAND2016-10179PE

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CONfirmation using a Fast-neutron Imaging Detector with Anti-image NULL-positive Time Encoding (CONFIDANTE)

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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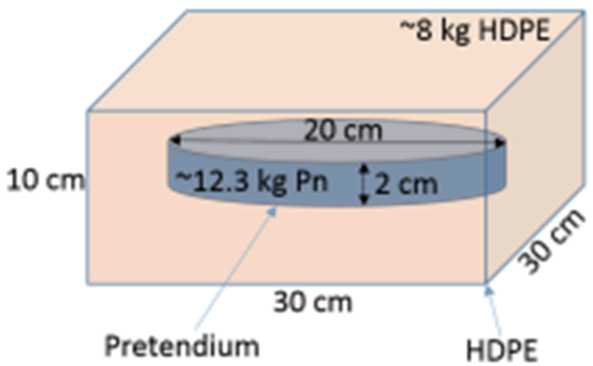
Outline

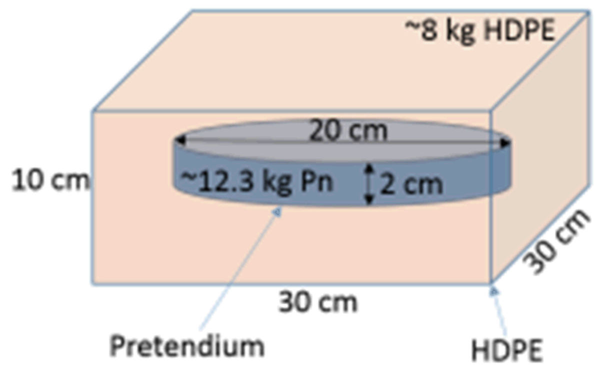
- Basics of arms control
- Challenge problem
- Template-based CONOPS
- Zero Knowledge – what does it buy you?
- Comparison Measurements – a new CONOPS?
- Two-dimensional time-encoded imaging
- CONfirmation using a Fast-neutron Imaging Detector with Anti-image NULL-positive Time Encoding (CONFIDANTE)
- Preliminary results

Challenge problem

- The inspecting party has or had access to measure item T, which is known to be a valid type 1 treaty accountable TAI through some other mechanism.
- In the course of an inspection, the host presents item X and declares it as a type 1 TAI
- Item X should pass the verification measurement if it is a type 1 TAI, and fail if it is significantly different.



Object T = valid type 1 TAI

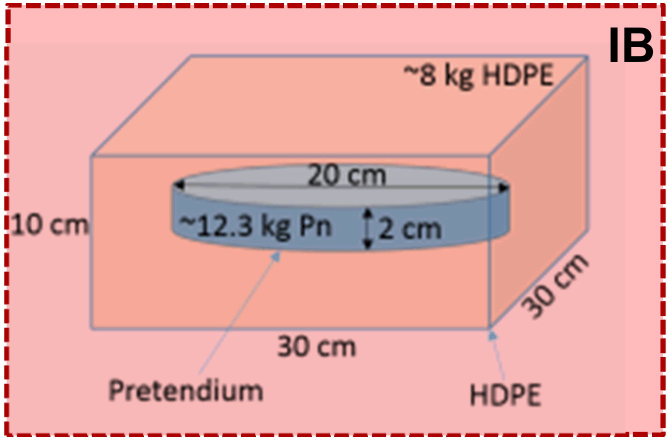


Object X = ?

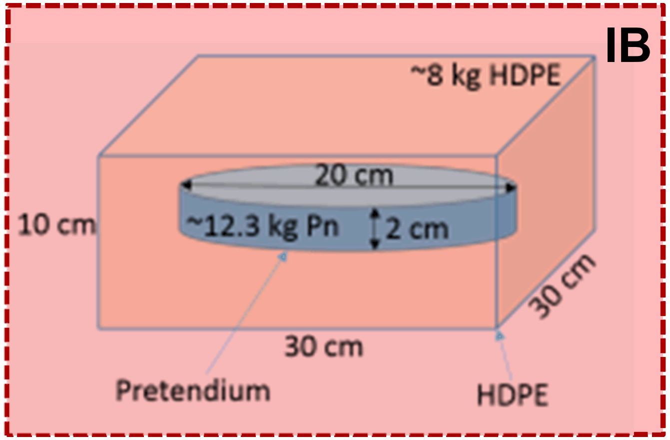
E. Brubaker, "Workshop on Techniques for Protection of Imaging Information: Challenge Problem", SAND2016-4047 O

Challenge problem

- The host must be confident that the inspector has not learned the diameter *d* of the pretendium in item X, or any type 1 TAI



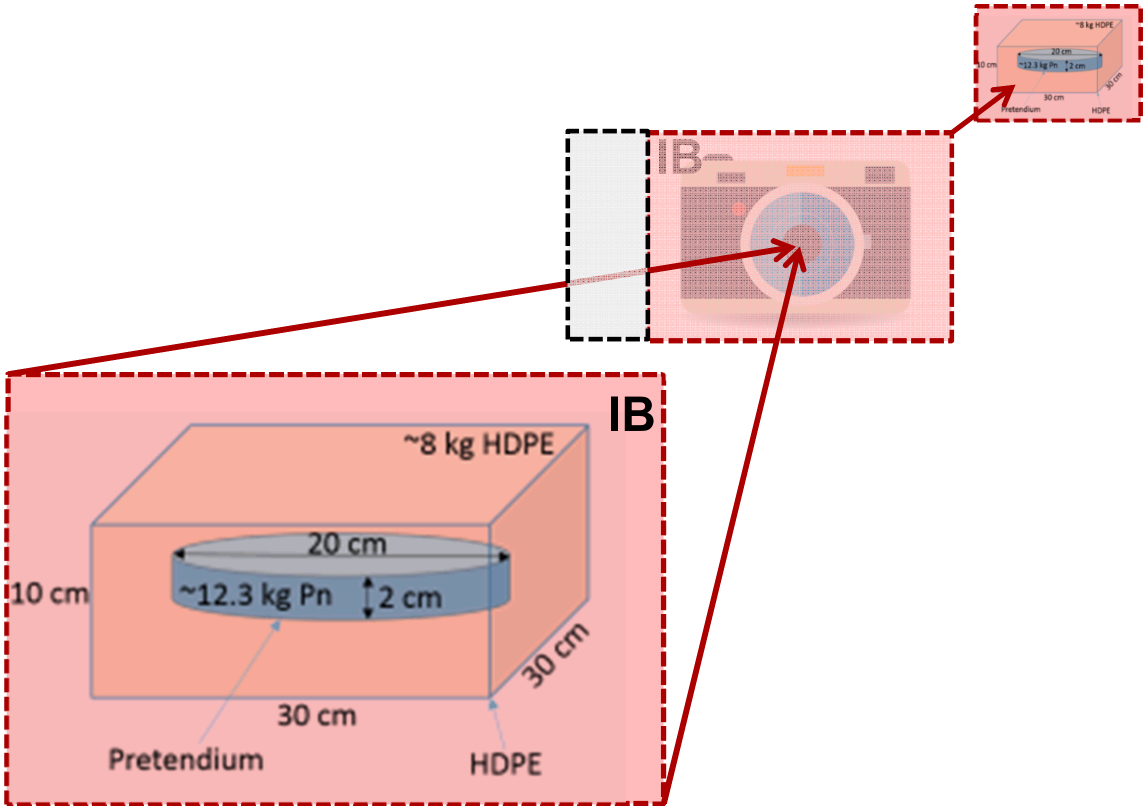
Object T = valid type 1 TAI



Object X = ?

Templates - generation

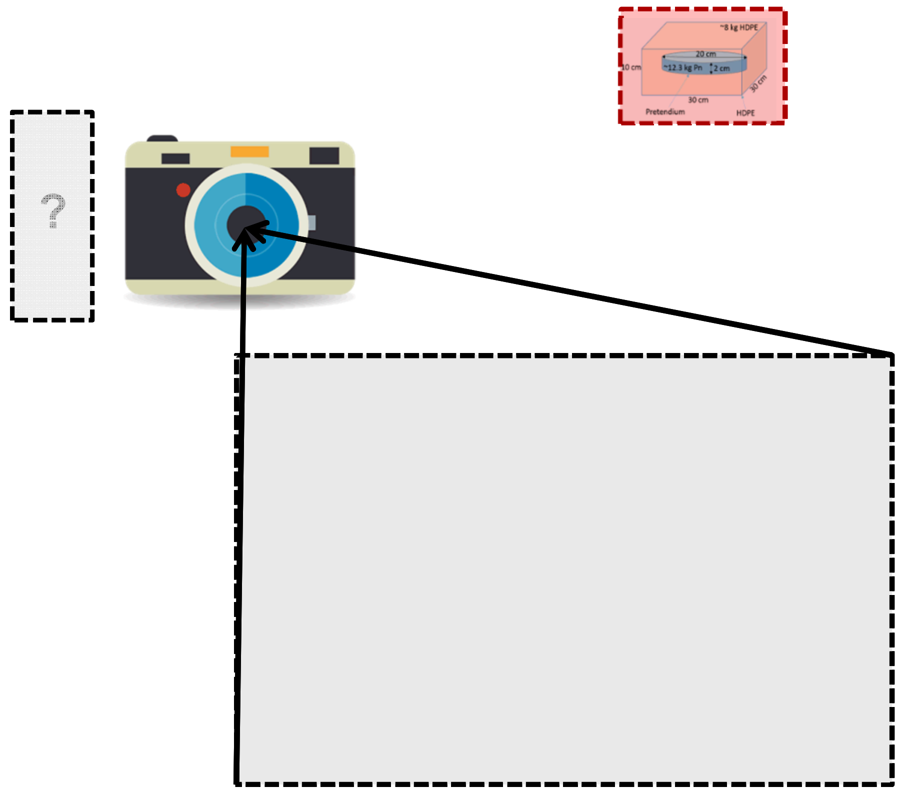
- We could generate a template behind an information barrier (IB) …



Object T = valid type 1 TAI

Templates - authentication

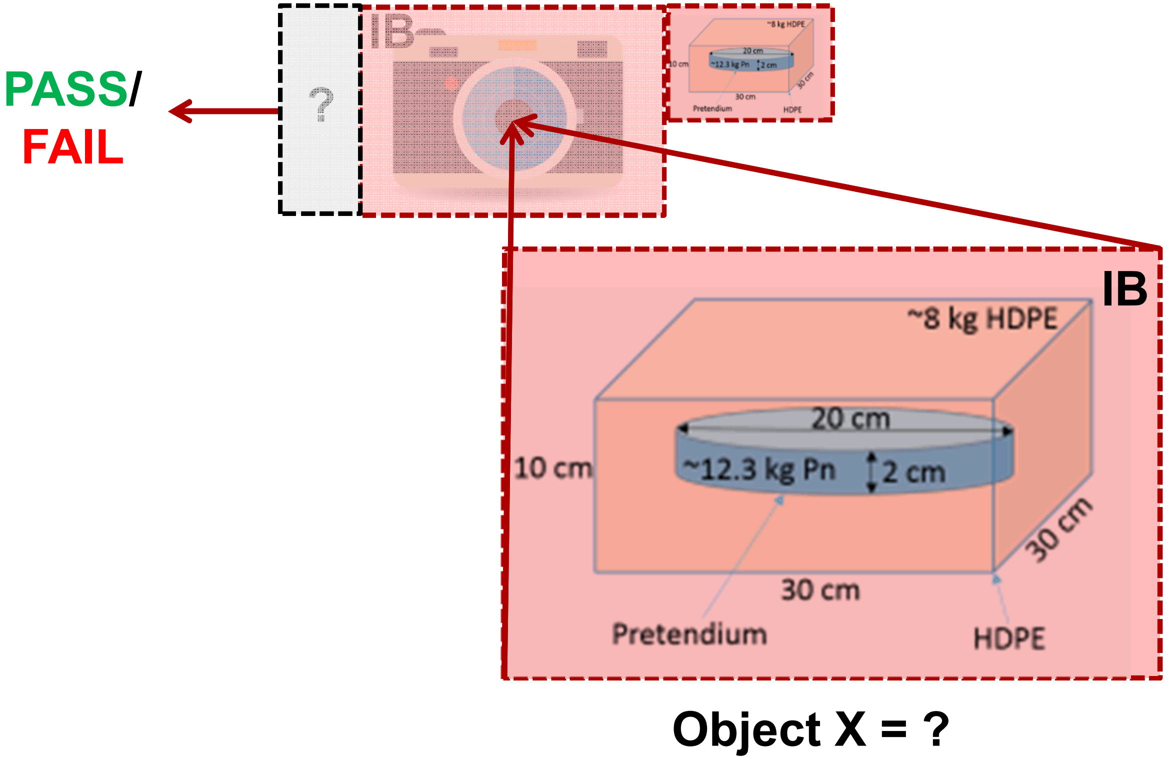
- Sequester sensitive information
- Authenticate equipment …



Object Z = ?

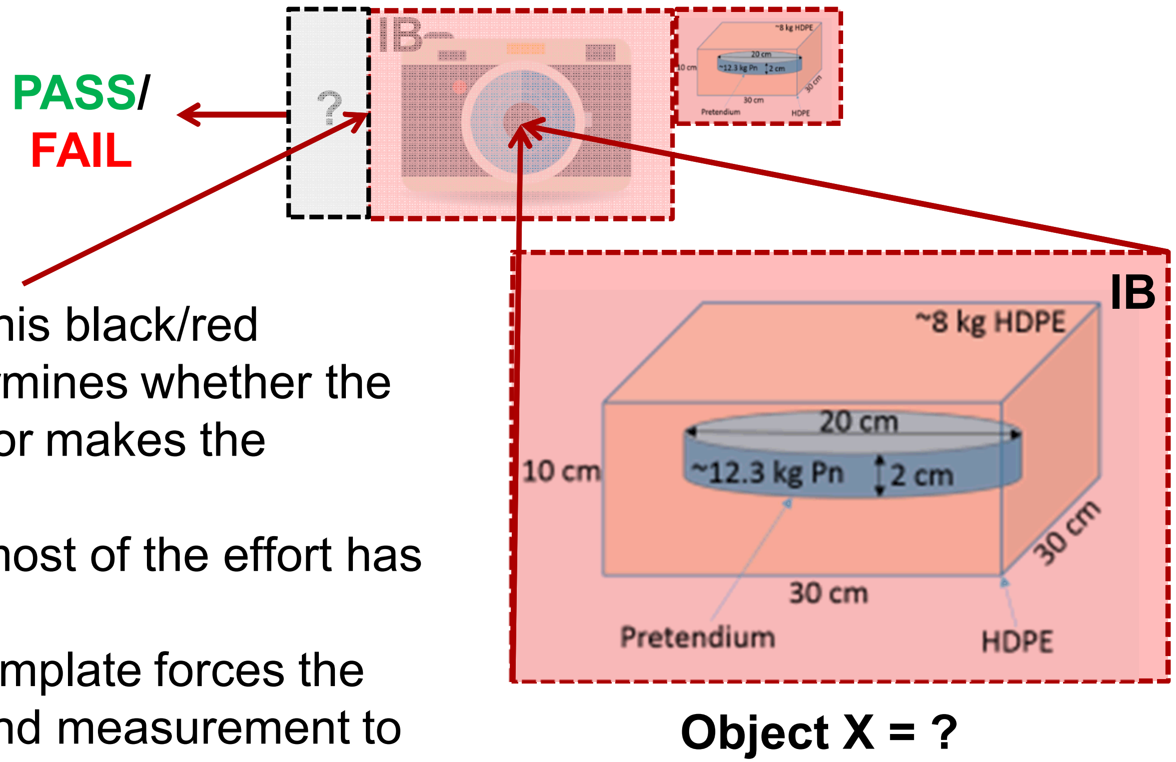
Templates - comparison

- Make comparison measurement…



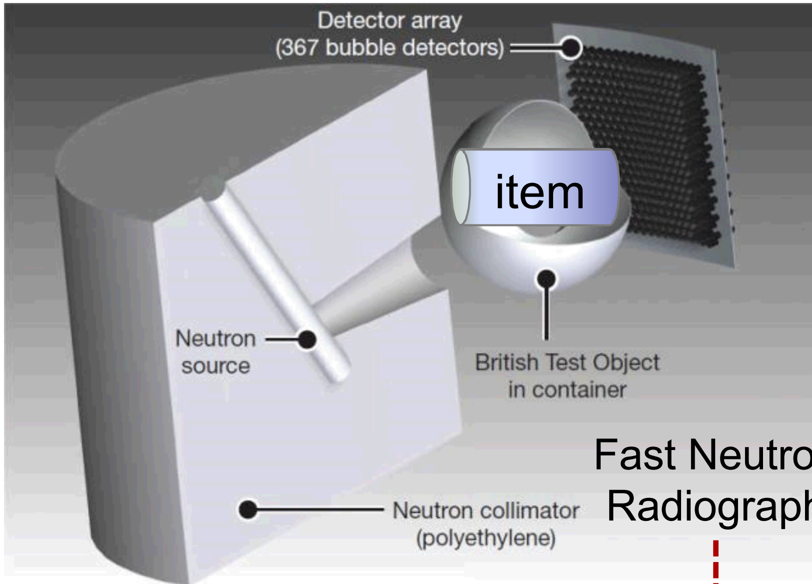
Templates – who measures?

- Who makes the measurement? Is the measurement itself authenticatable?

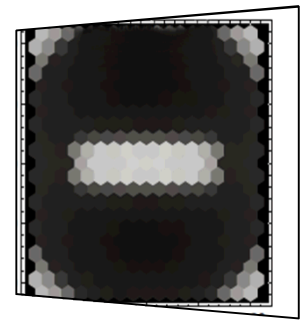


- The nature of this black/red boundary determines whether the host or inspector makes the measurement.
- This is where most of the effort has gone.
- At worst, the template forces the entire device and measurement to be behind an IB.

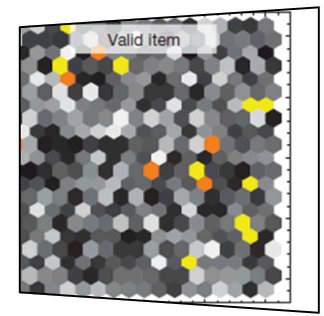
ZKP – Princeton edition



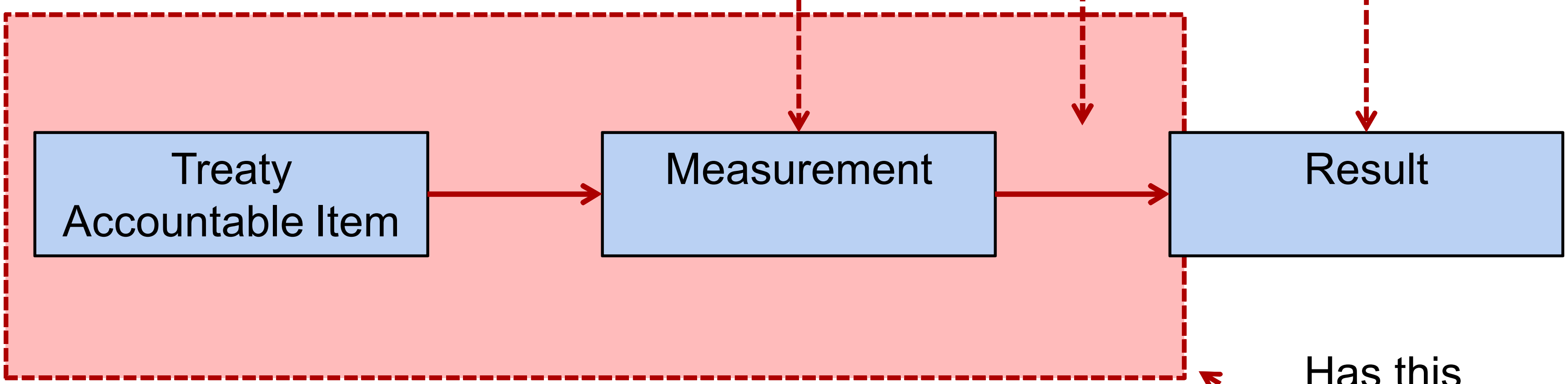
Fast Neutron Radiograph



Analog bubble detectors with preloaded complement “template”



Flat featured image (NULL) is a true positive.



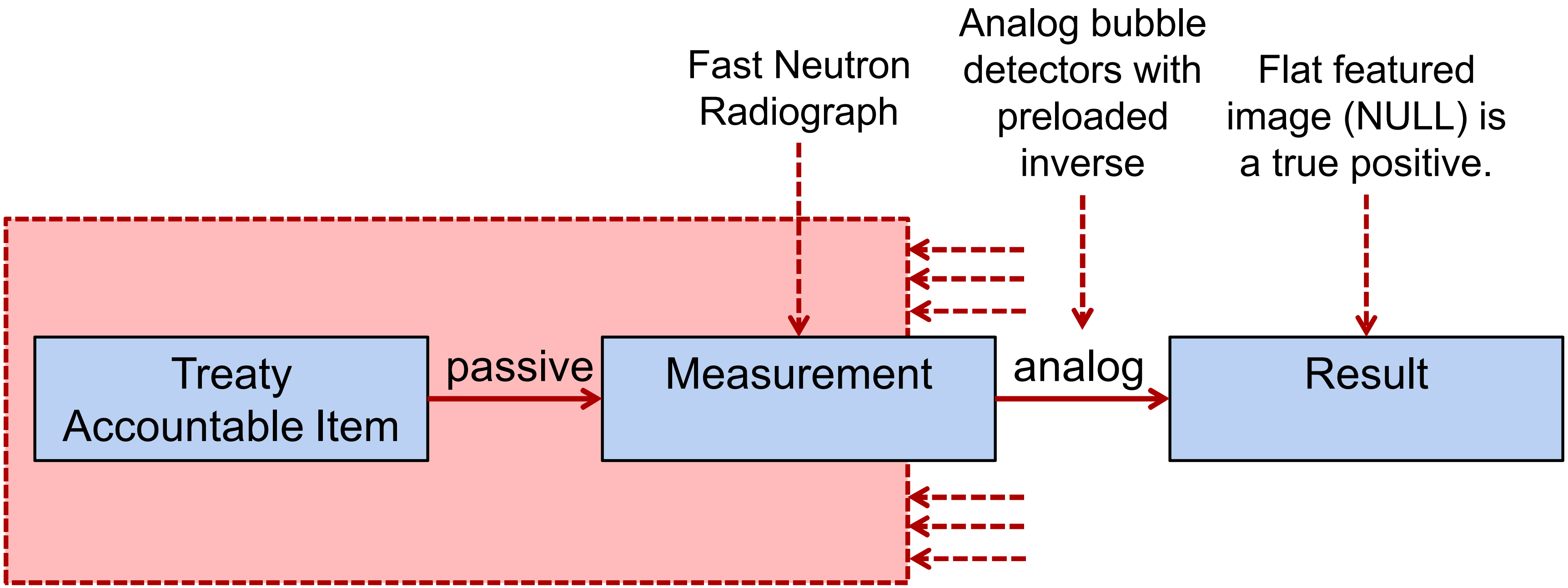
Has this boundary moved?

Images borrowed from: Glaser, Barak, and Goldston, “A zero-knowledge protocol for nuclear warhead verification”, doi:10.1038/nature 134557

ZKP – authentication measures

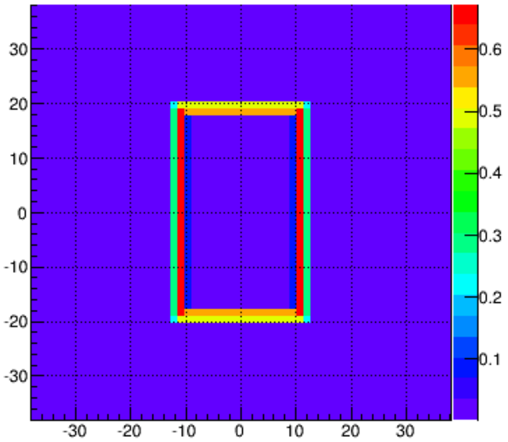
Research Questions

- Can we share the rates in a subset (up to all) of the detector pixel counts with spatial information removed before/during/after the measurement?
- **What sensitive information is at risk?**

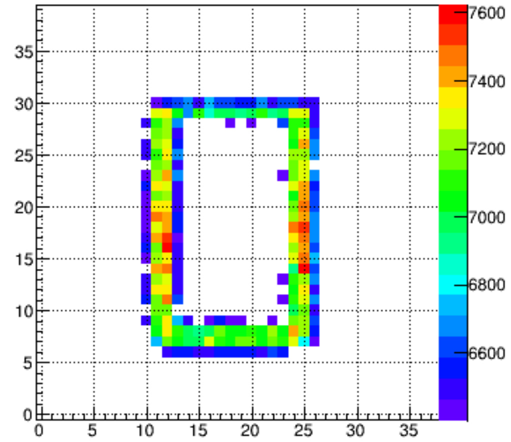


Test case - Simulated Rectangular Source (1e7 counts)

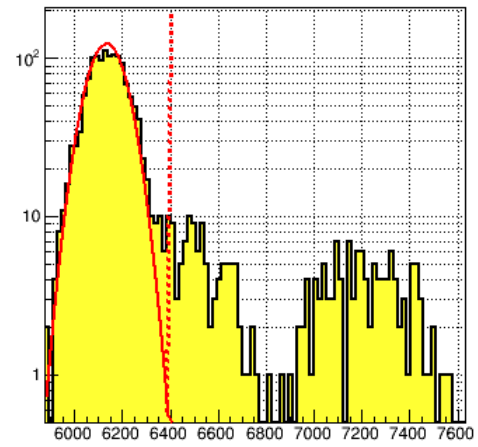
Input distribution



Projected Image



Pixel Count Distribution



- A passive pinhole imager test case was simulated.
- A Gaussian with sigma equal to its mean is shown - the background counts seem to match statistical fluctuations in the pixel count distribution.
- It can be seen that all counts to the right of 6400 (~3.4 sigma) originate from a pixel within the rectangular source.
- 8.57e6 counts represented in Gaussian. 1.43e6 counts in source.

Rectangular Source Counts

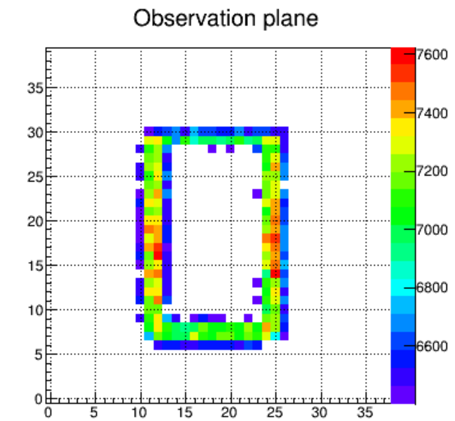
- 8.57e6 counts represented in Gaussian.
- 1.43e6 counts in source.

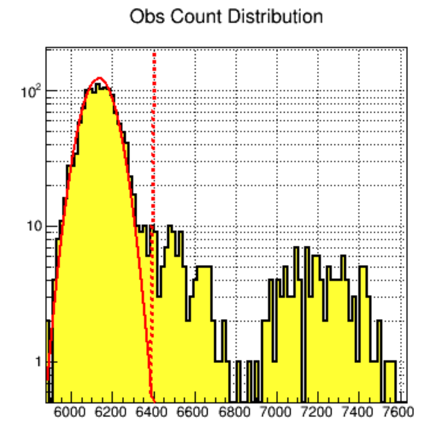
- The mask is not opaque, so the source is also the primary contribution to the “background” counts.
- Knowledge of mask opacity and mean counts therefore provides **source activity.**

- There are 230 pixels to the right of the threshold. Therefore these excess source counts are distributed across an object of this **total angular size**.

- What else can we learn? What can the shape of the distribution tell us? Have we gone far enough?

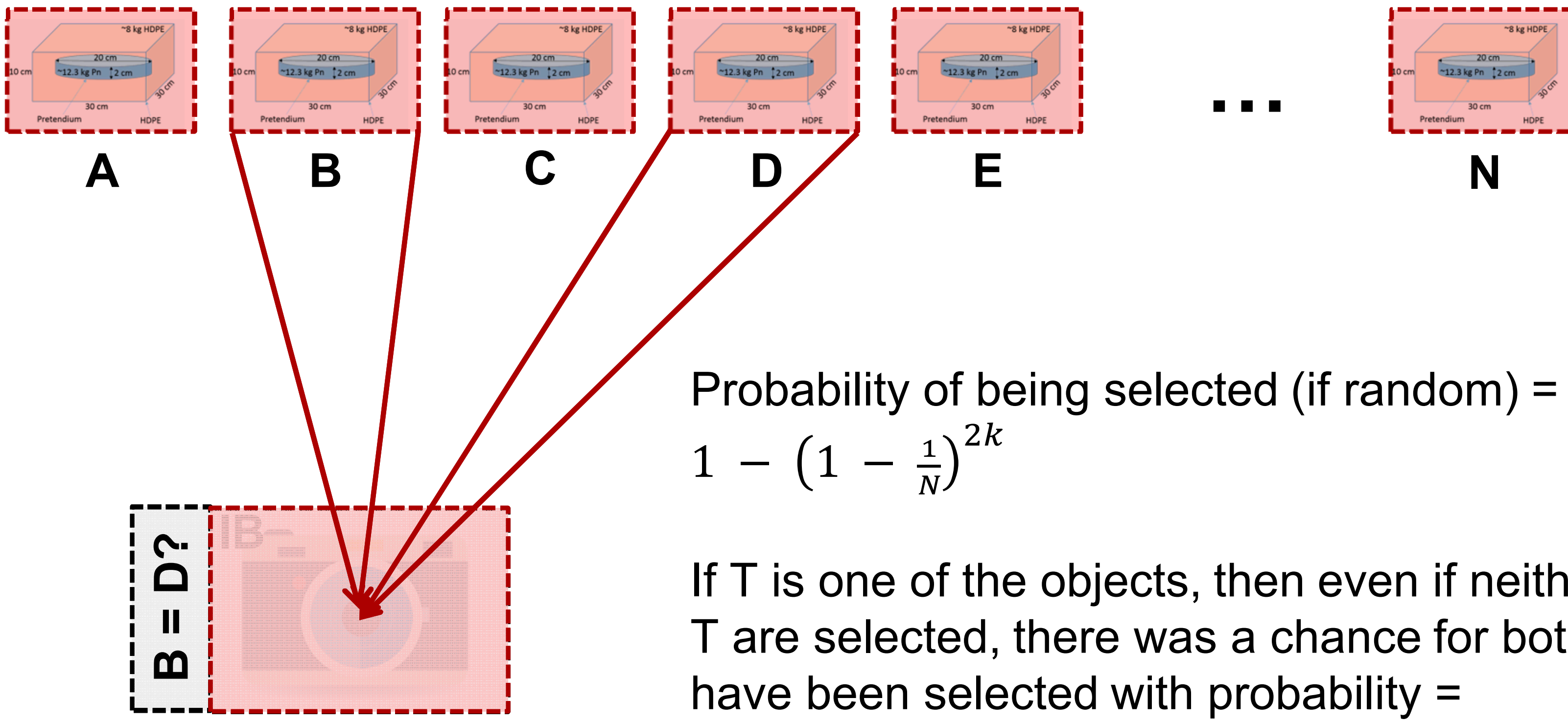
$\rightarrow \textit{Classified Study}$





ZKP – CONOPS and Inspector choice

- Presented with N objects and k comparison measurements will be made.



Probability of being selected (if random) =

$$1 - \left(1 - \frac{1}{N}\right)^{2k}$$

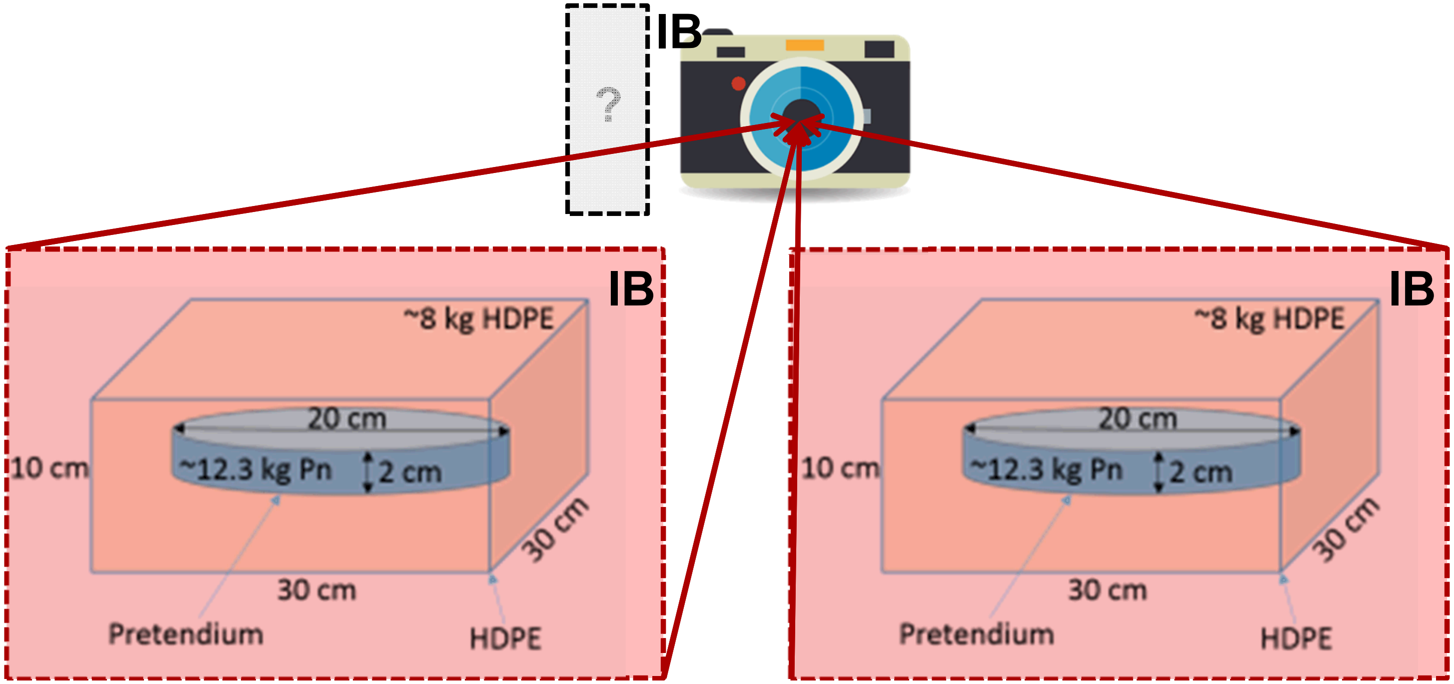
If T is one of the objects, then even if neither X nor T are selected, there was a chance for both to have been selected with probability =

$$\left(1 - \left(1 - \frac{1}{N}\right)^{2k}\right)^{2}$$

providing some degree of confidence

Zero Knowledge comparison measurement?

- Is there a physical implementation of the confirmation measurement that the inspector can watch and authenticate?
- **It would be great if we could get a physical NULL as an indication of positive confirmation at all times, even during the measurement.**

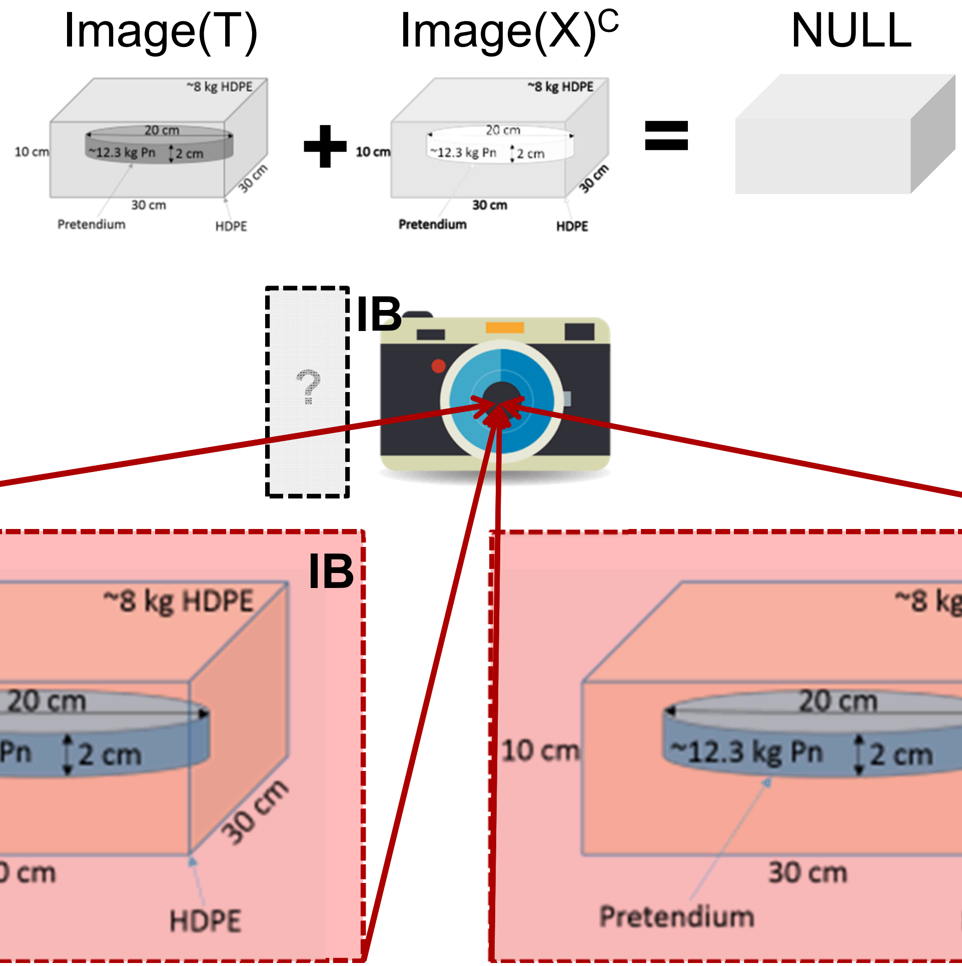


Object T = valid type 1 TAI

Object X = ?

Proposal – complementary comparison

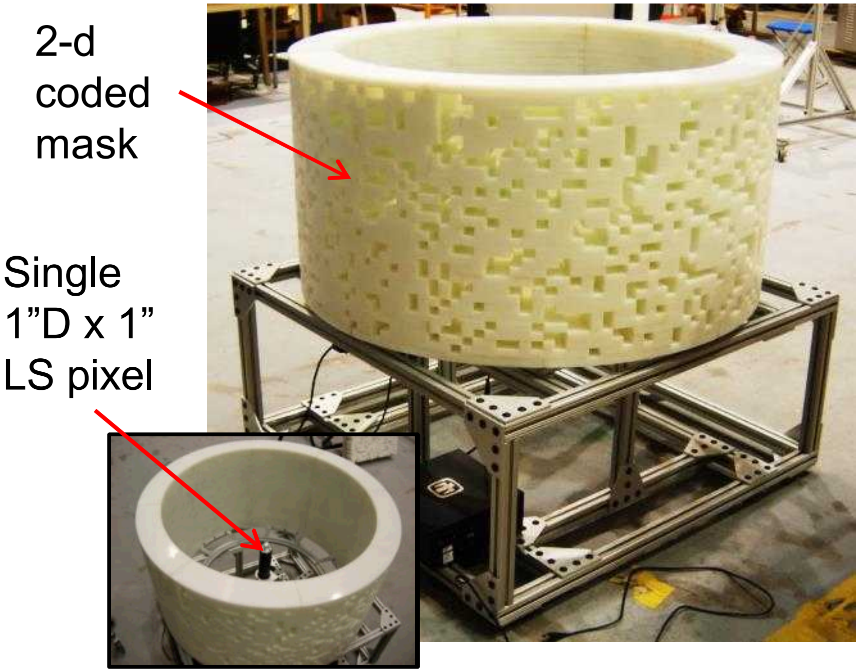
- What we need is to turn one image into its complement ***at all times***.

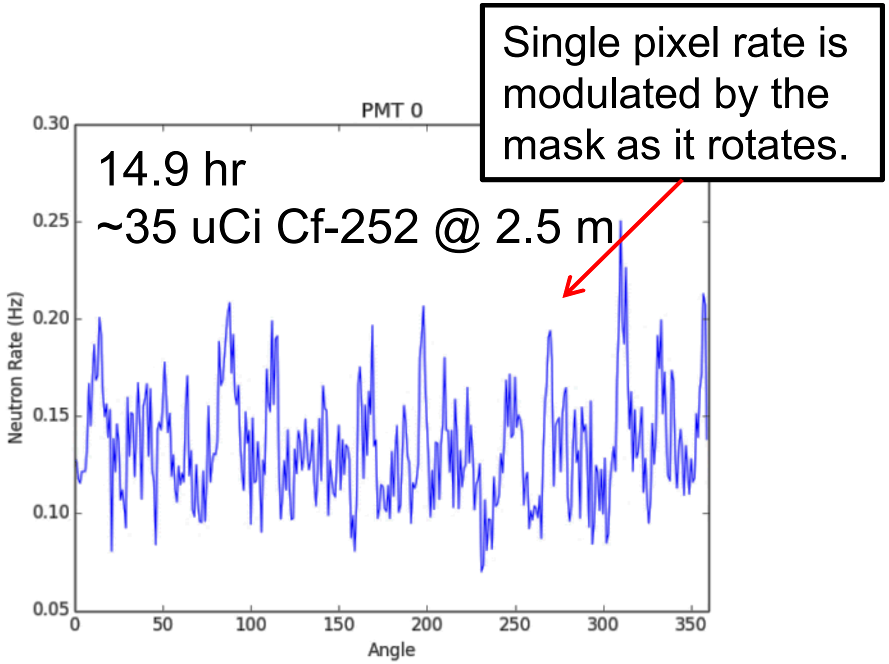


Object T = valid type 1 TAI

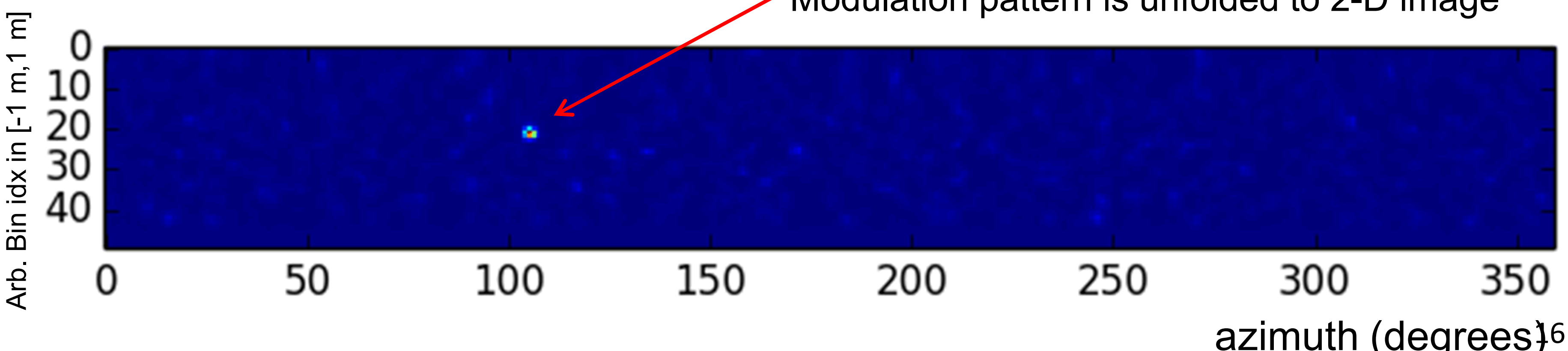
Object X = ?

2D Time-encoded Imaging (TEI)





Modulation pattern is unfolded to 2-D image

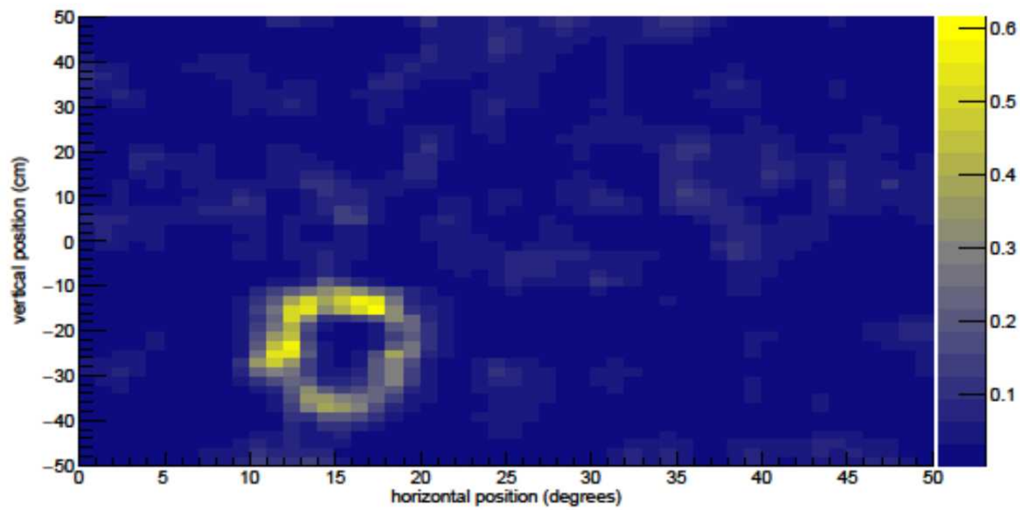


J. Brennan, E. Brubaker, M. Gerling, P. Marleau, K. McMillan, A. Nowack, N. LeGalloudec, M. Sweany, "Demonstration of Two-dimensional Time-encoded Imaging of Fast Neutrons", Nuclear Instruments and Methods A, 2015

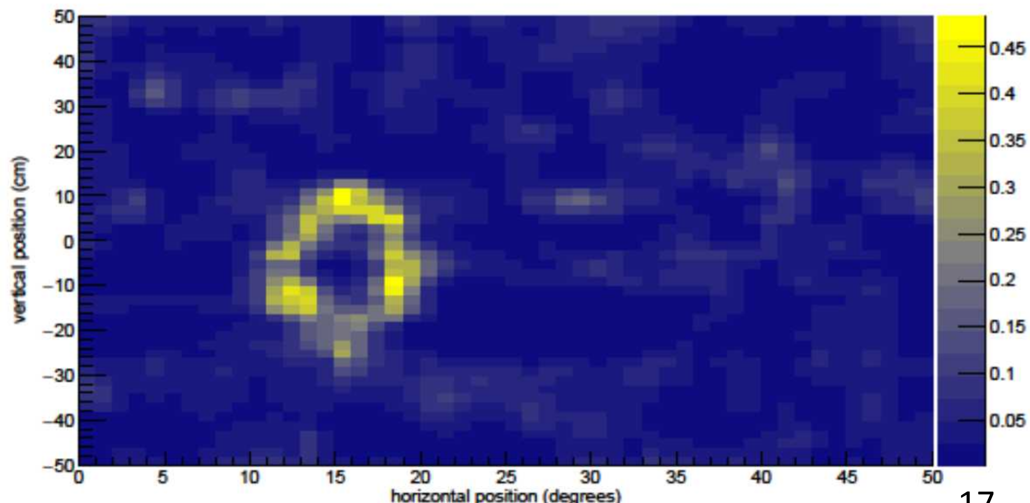
TEI-2D imaging – extended sources

A single 1.4e5 n/s ^{252}Cf source move through an extended pattern at 2 m.

72 hours
(100 mlem iterations)



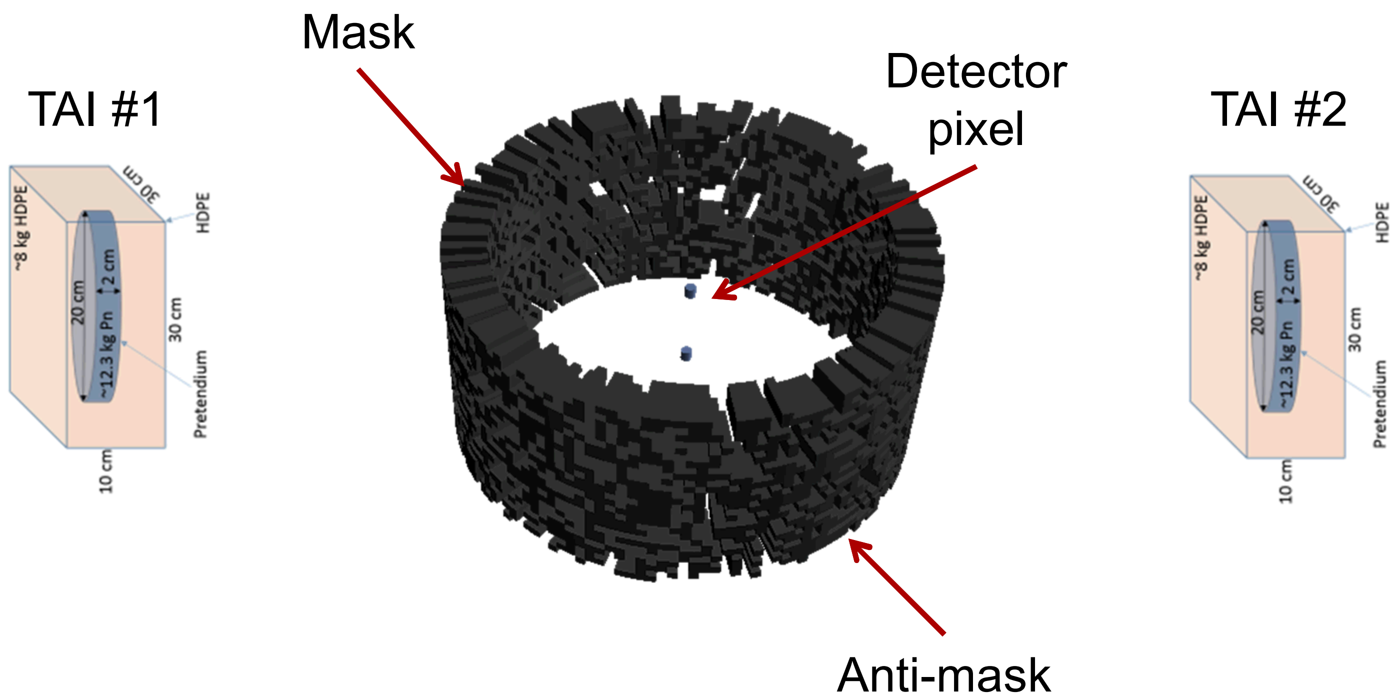
94 hours
(100 mlem iterations)



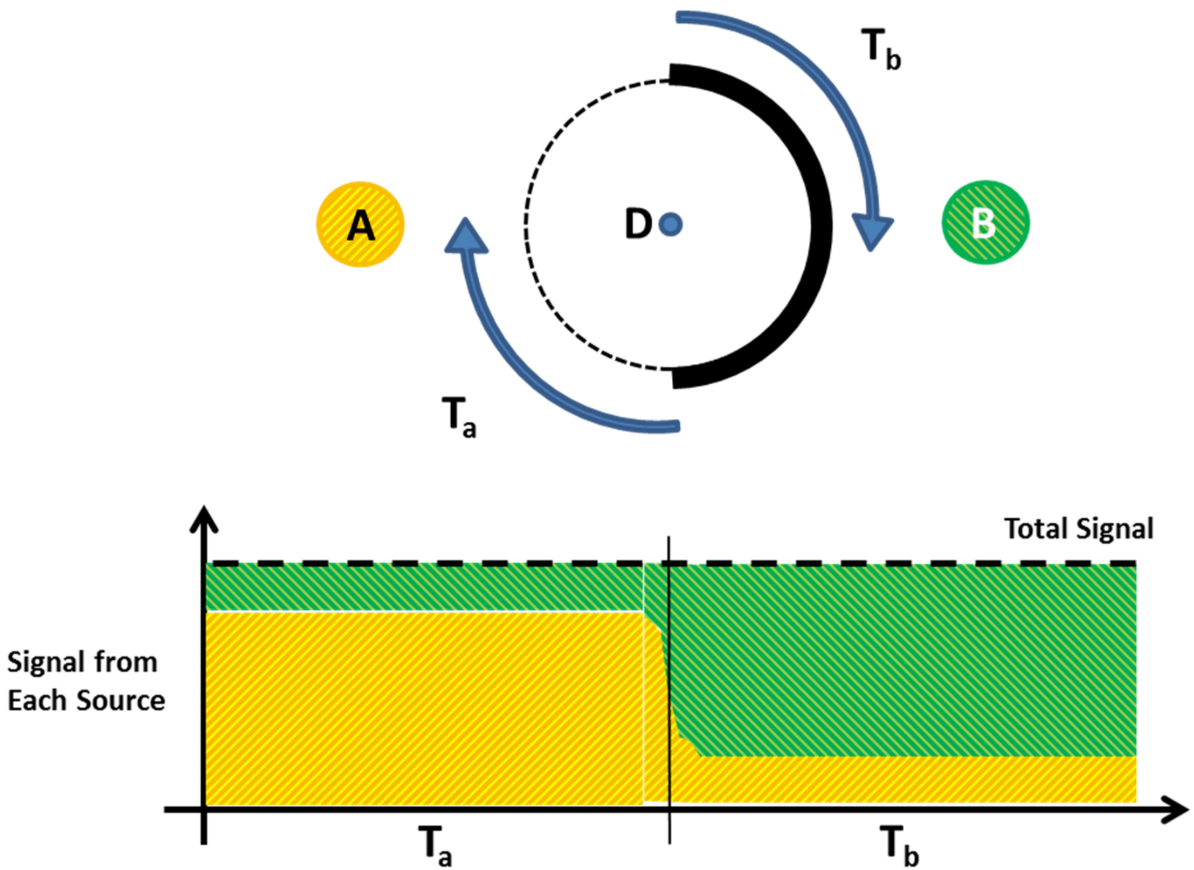
J. Brennan, E. Brubaker, M. Gerling, P. Marleau, K. McMillan, A. Nowack, N. LeGalloudec, M. Sweany, "Demonstration of Two-dimensional Time-encoded Imaging of Fast Neutrons", Nuclear Instruments and Methods A, 2015

Here's where the magic happens …

If the mask is designed such that one side is the anti-mask of the other, then **TAI #2 projects the anti-image of TAI #1 at all times**
if and only if they are identical!

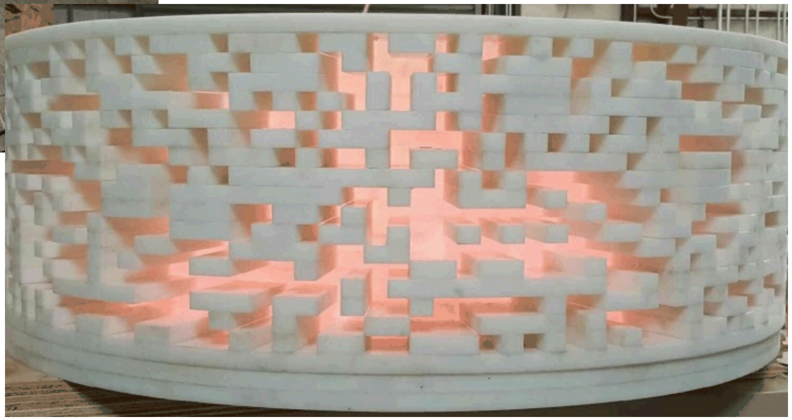


A very simple example



- For example, take a very simple mask: 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.

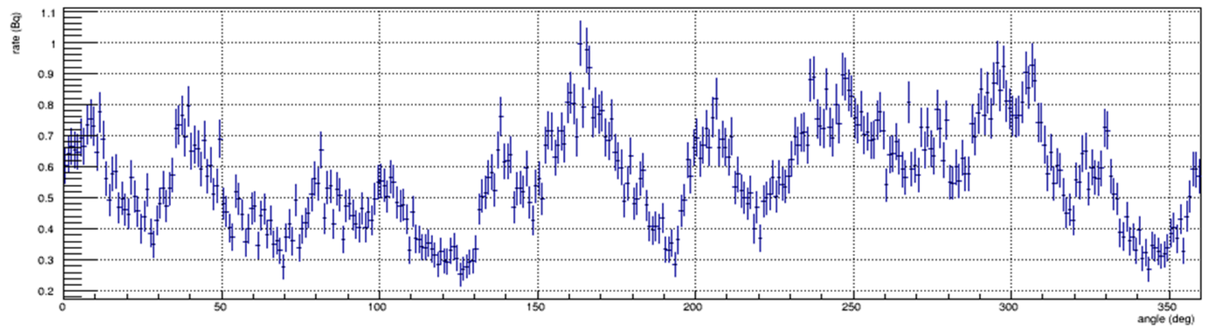
We’ve made one!



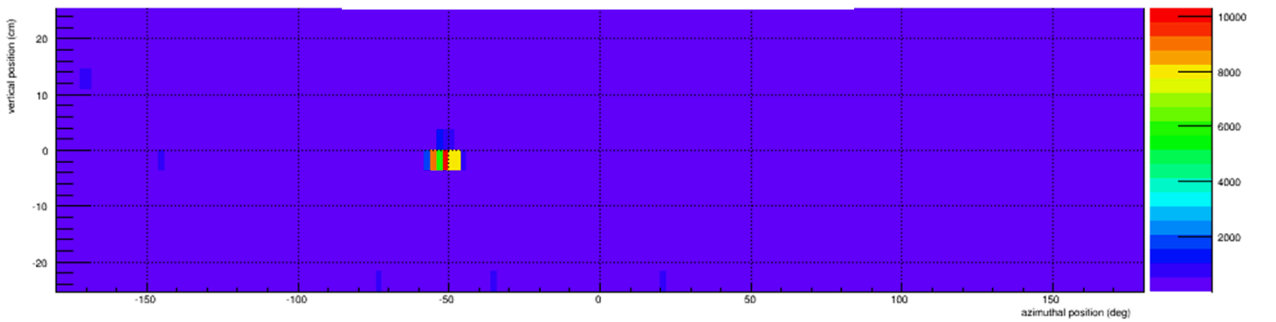
Preliminary results – Single point source

Measurement of a single point source

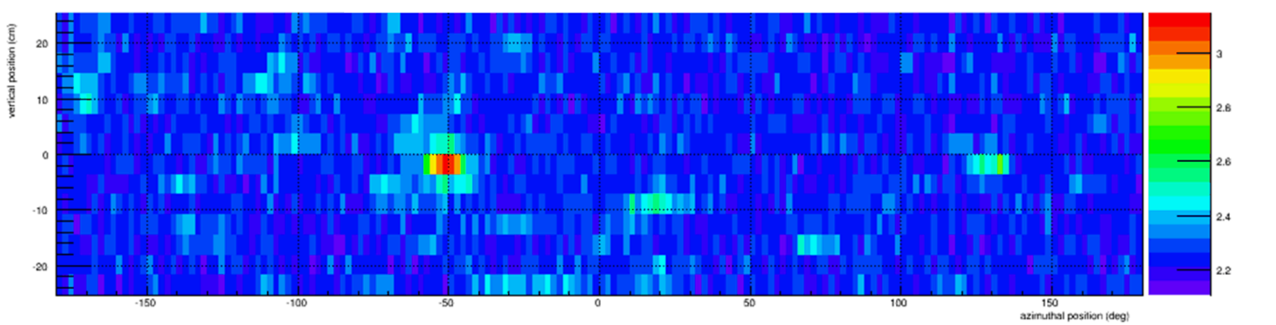
Neutron Rate



MLEM Reconstruction



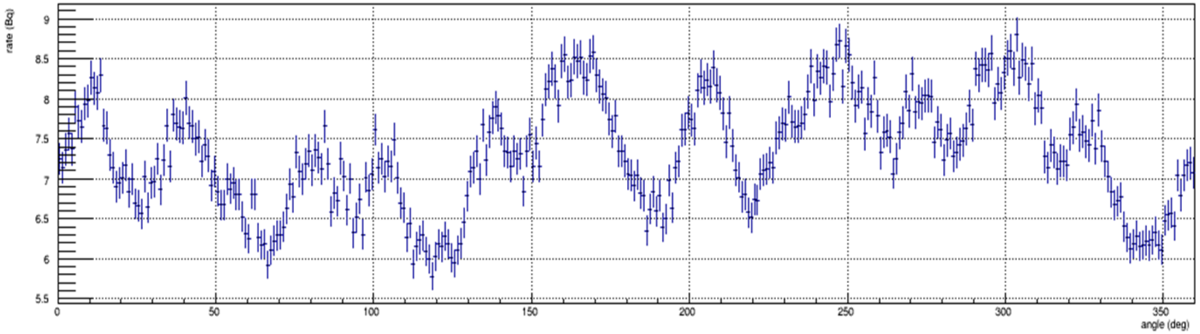
Relative Variance



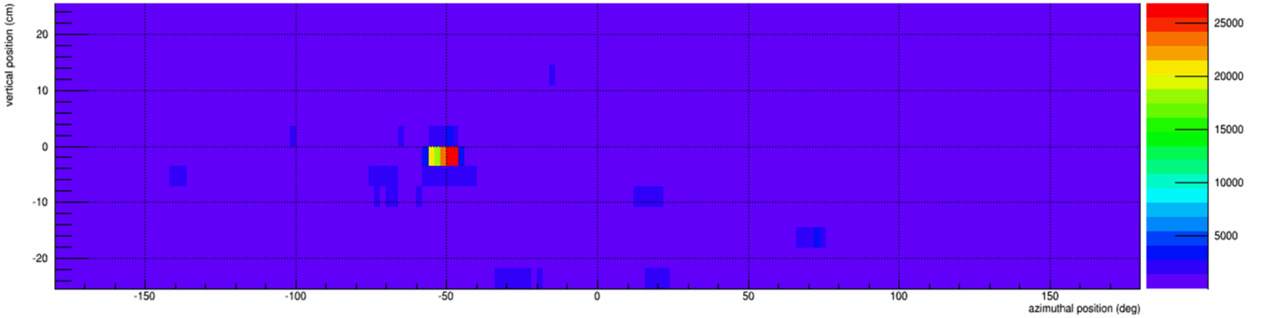
Preliminary results – Single point source

Measurement of a single point source

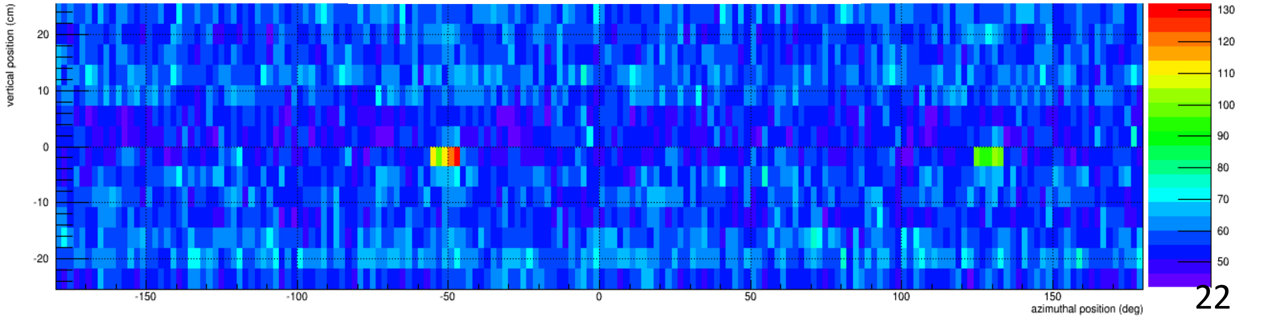
Gamma Rate



MLEM Reconstruction



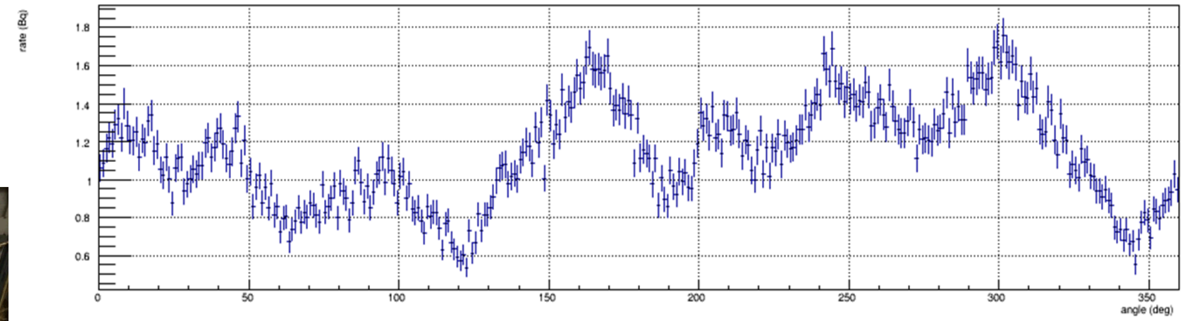
Relative Variance



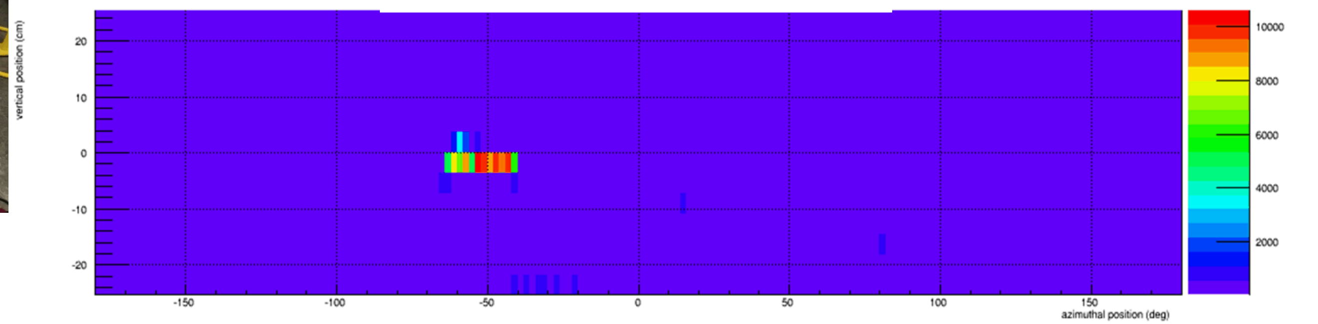
Preliminary results – Point source pair

Measurement of a two point sources separated by 19 cm

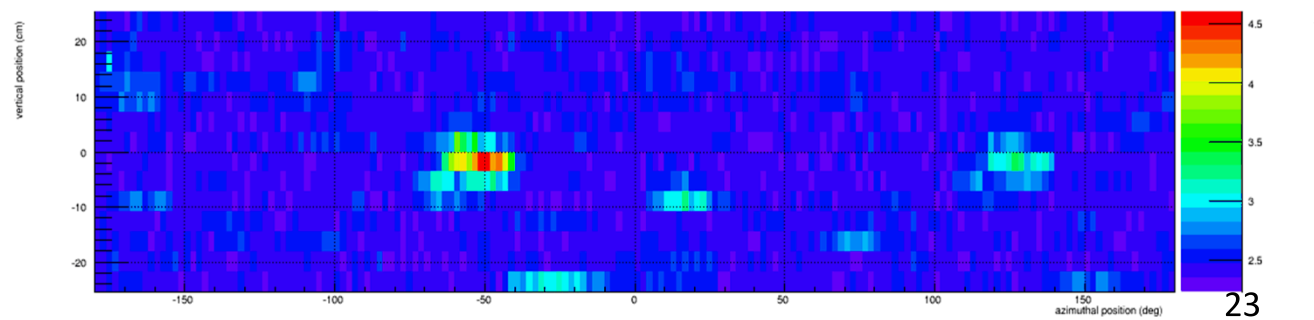
Neutron Rate



MLEM Reconstruction



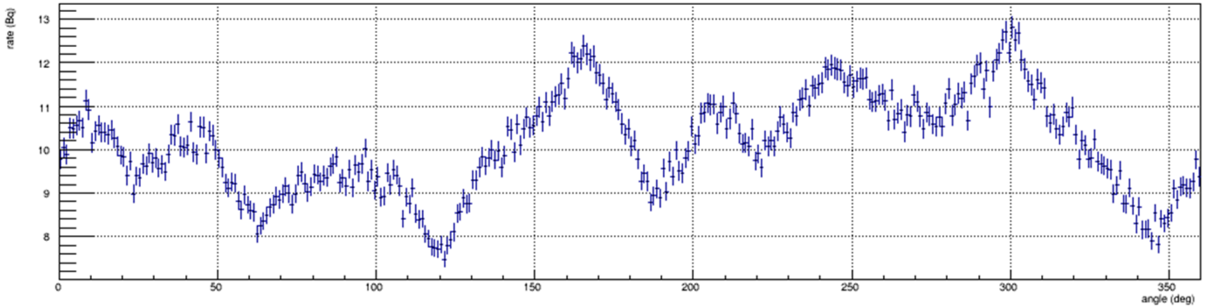
Relative Variance



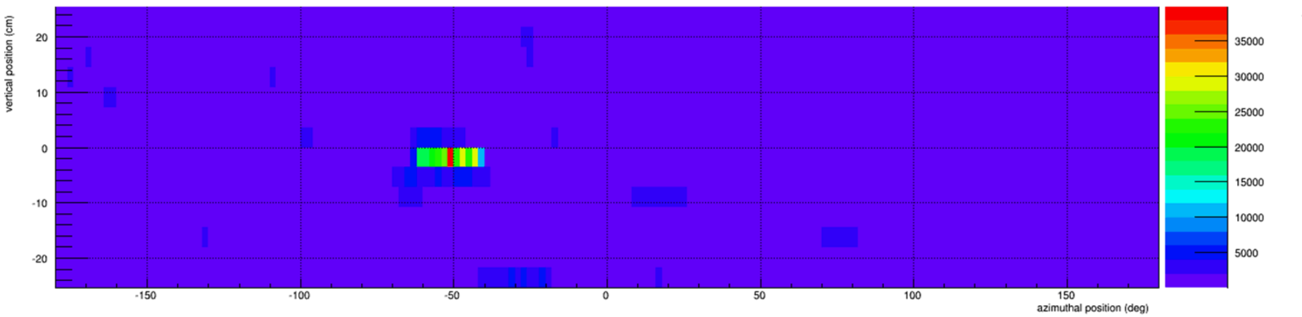
Preliminary results – Point source pair

Measurement of a two point sources separated by 19 cm

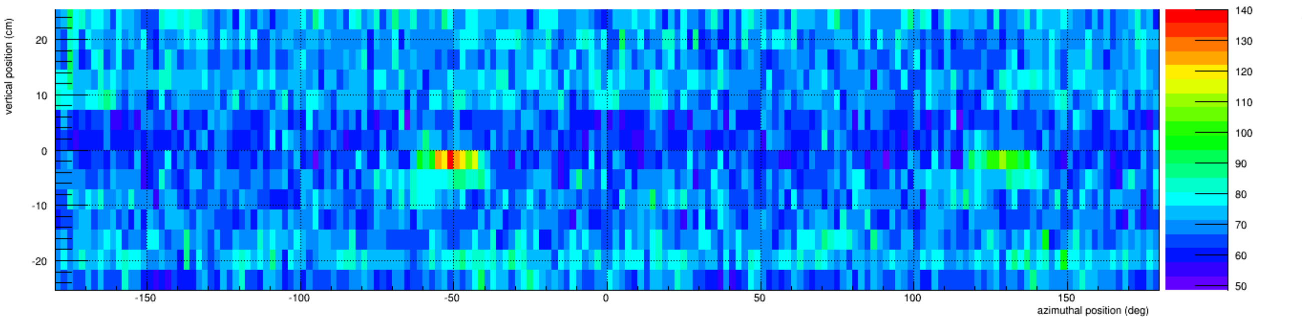
Gamma Rate



MLEM Reconstruction



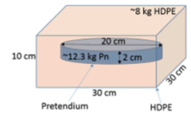
Relative Variance

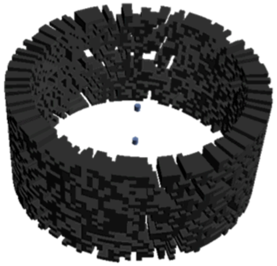


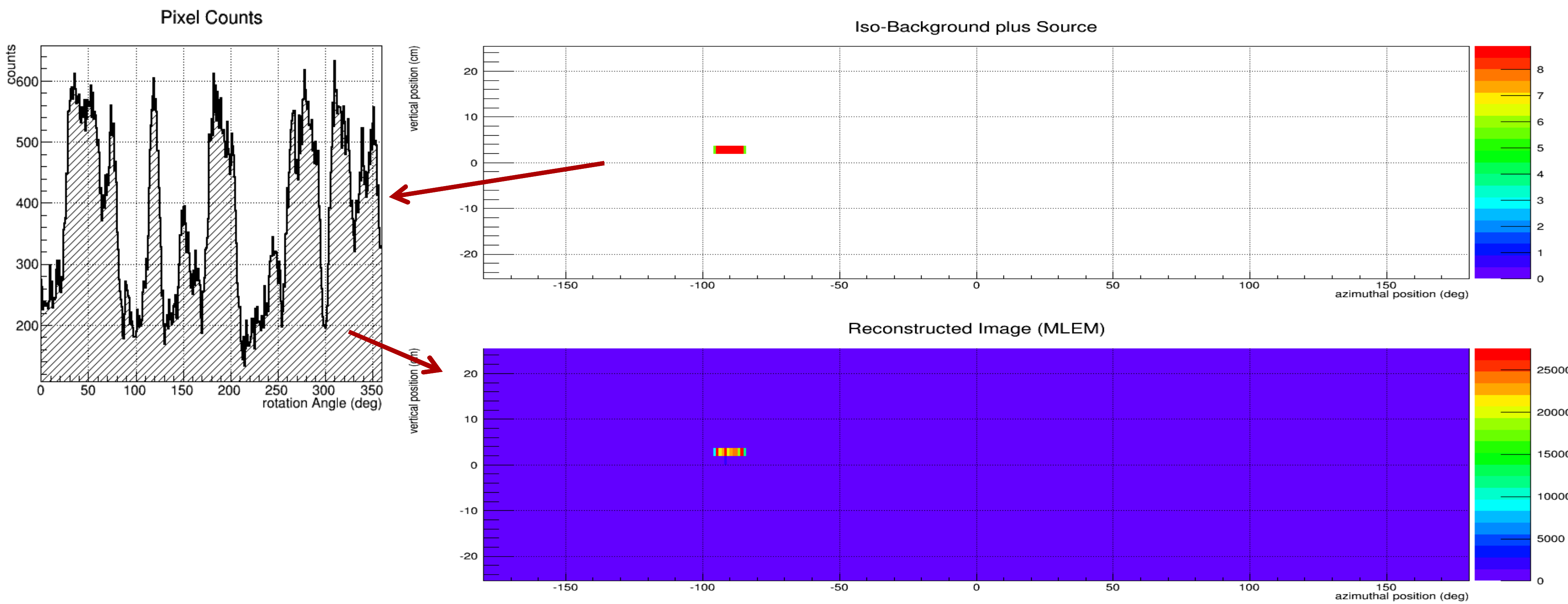
Modeling results - Single type 1 TAI (2.5e5 counts)

Measurement of single TAI demonstrates that the instrument is sensitive to the 2D distribution of material.

TAI T

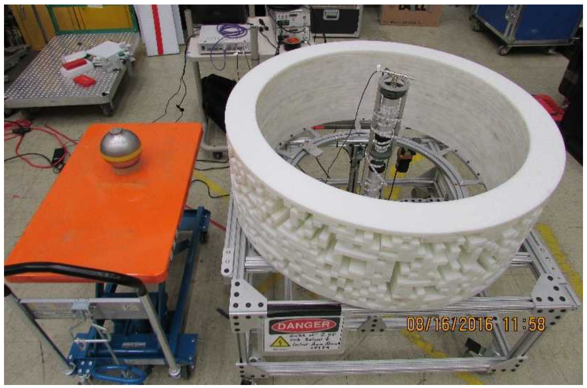




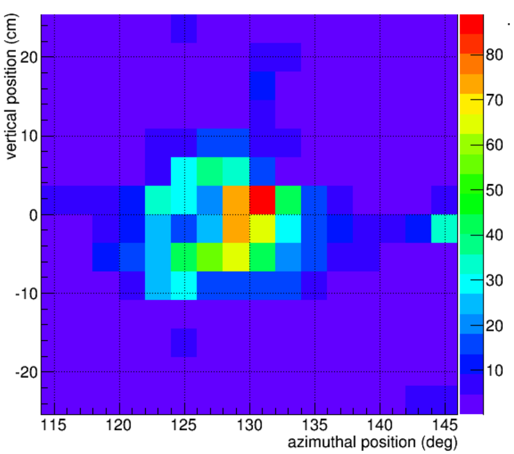


Preliminary results – Pu sphere

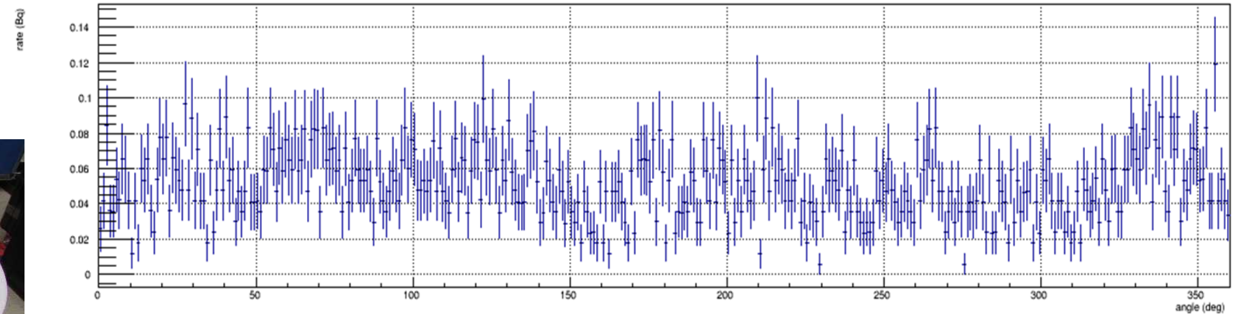
Measurement of a single sphere



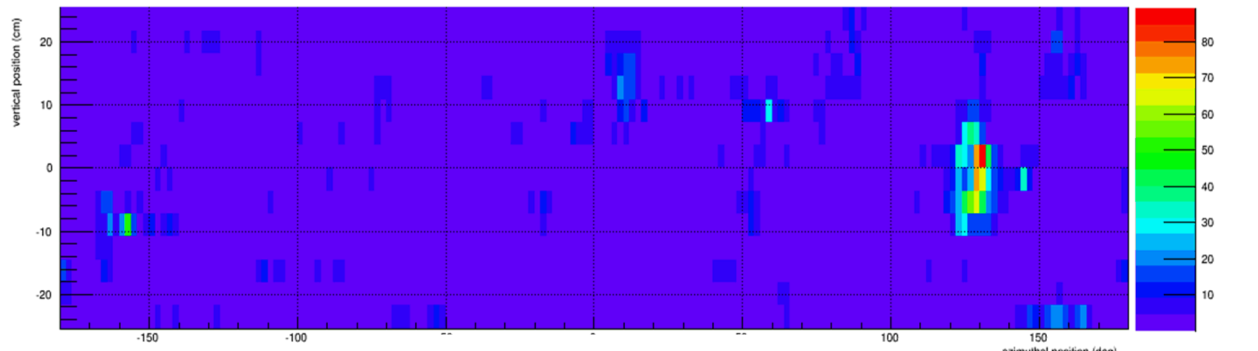
Reconstructed Image (MLEM)



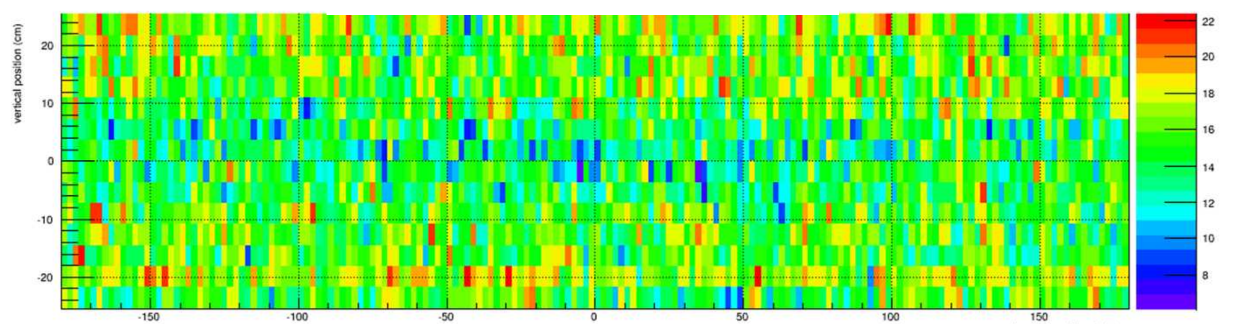
Neutron Rate



MLEM Reconstruction

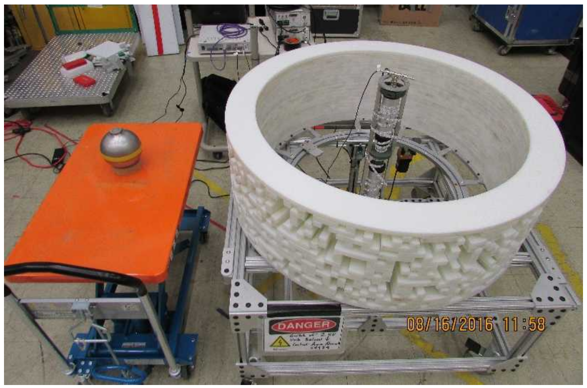


Relative Variance

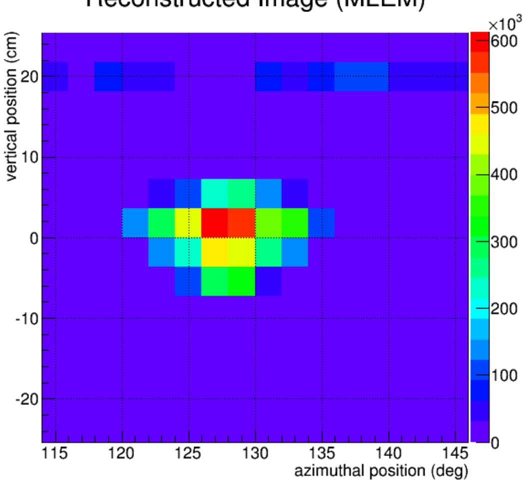


Preliminary results – Pu sphere

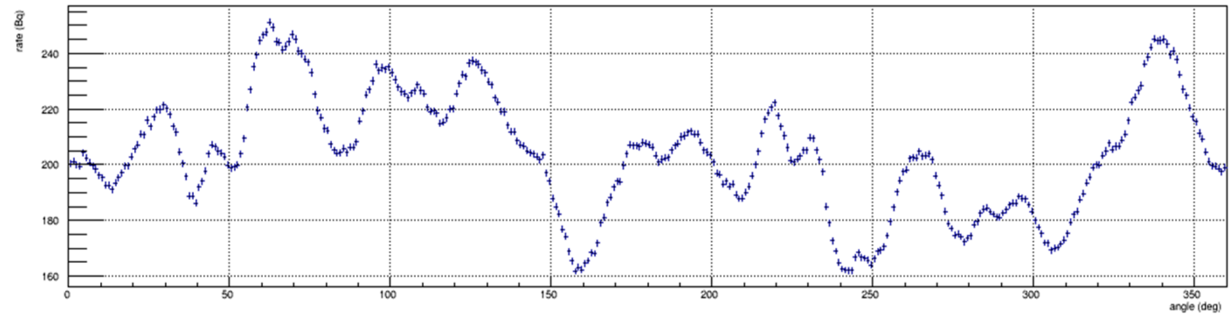
Measurement of a single sphere



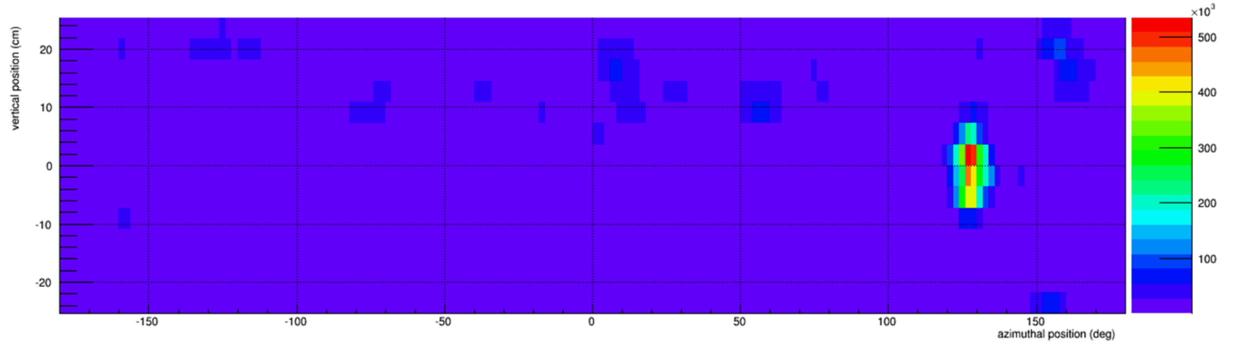
Reconstructed Image (MLEM)



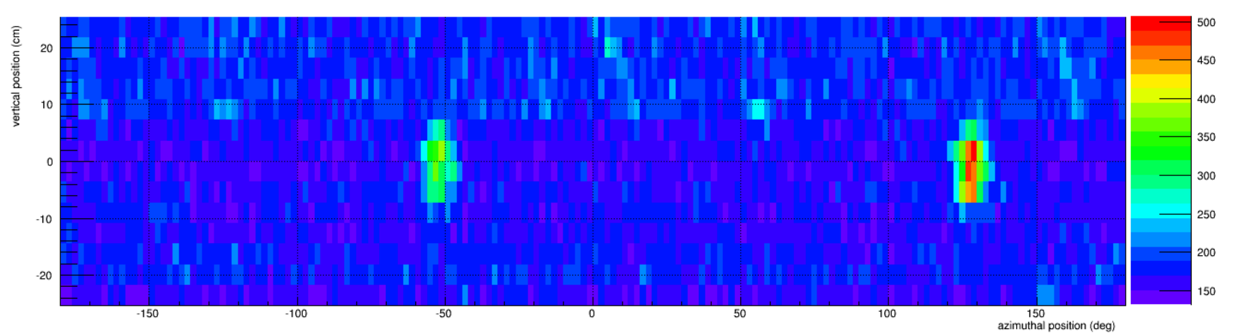
Gamma Rate



MLEM Reconstruction

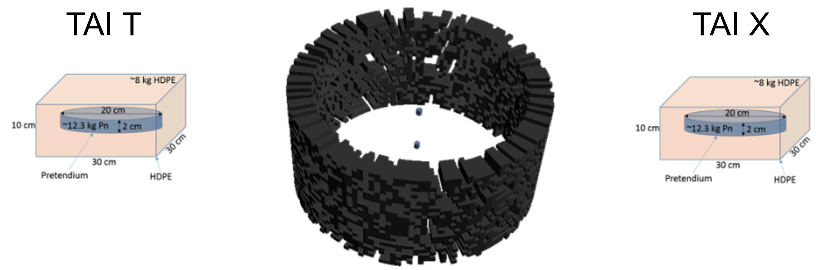


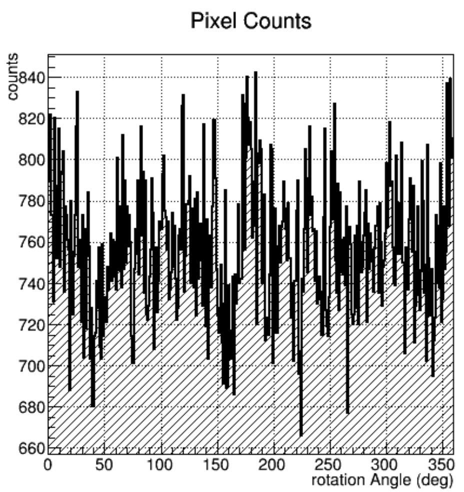
Relative Variance

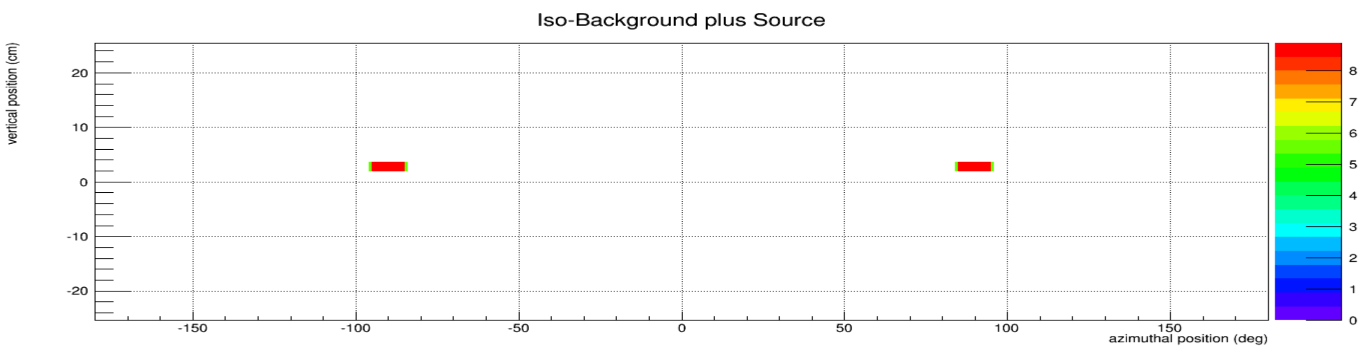


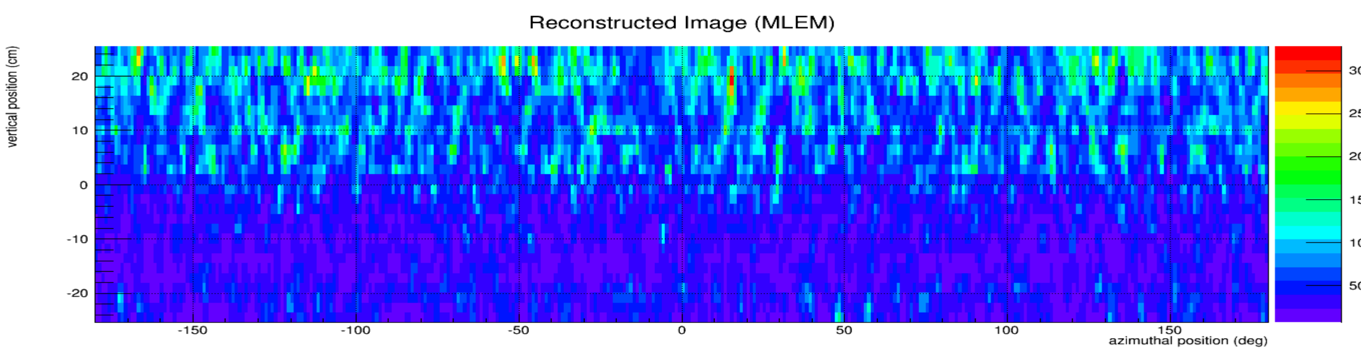
Modeling results – T vs. X (5e5 counts)

True "null"-positive confirmation comparison measurement between two type 1 TAIs.



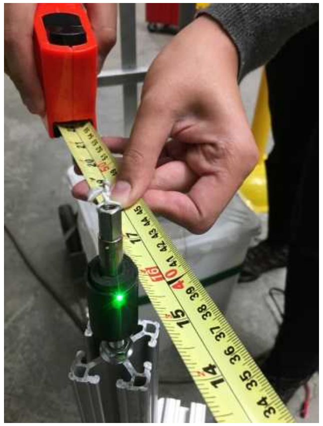




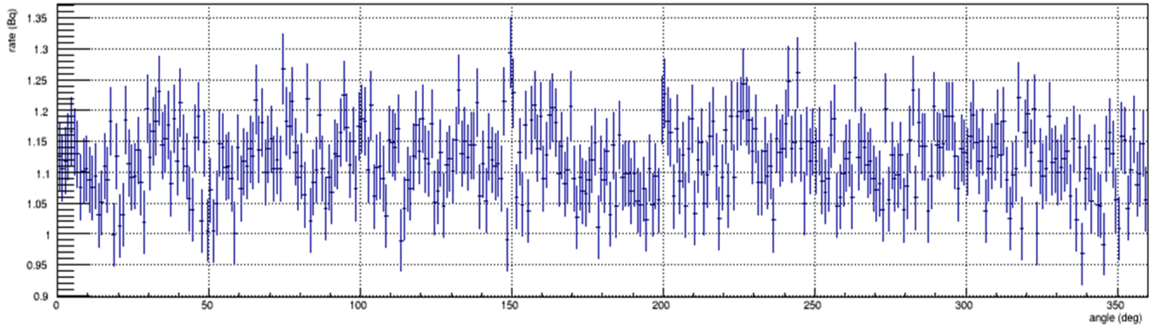


Preliminary results – Two point source pairs

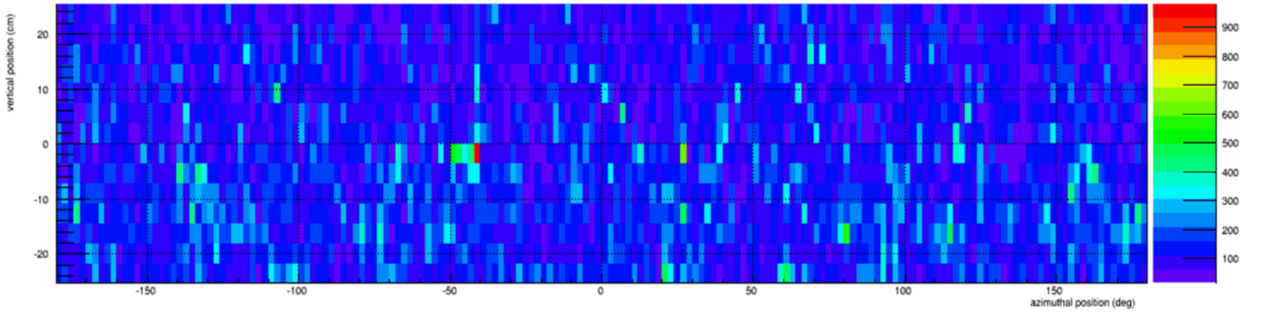
Measurement of two point source pairs separated by 19 cm 180 degrees apart



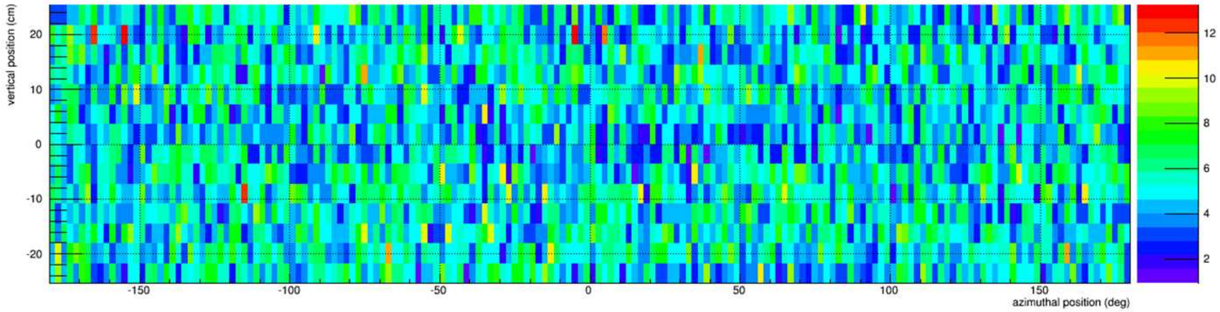
Neutron Rate



MLEM Reconstruction



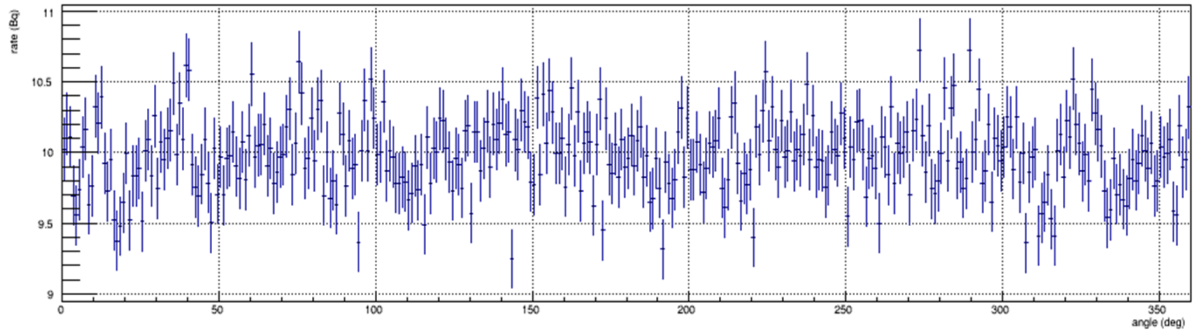
Relative Variance



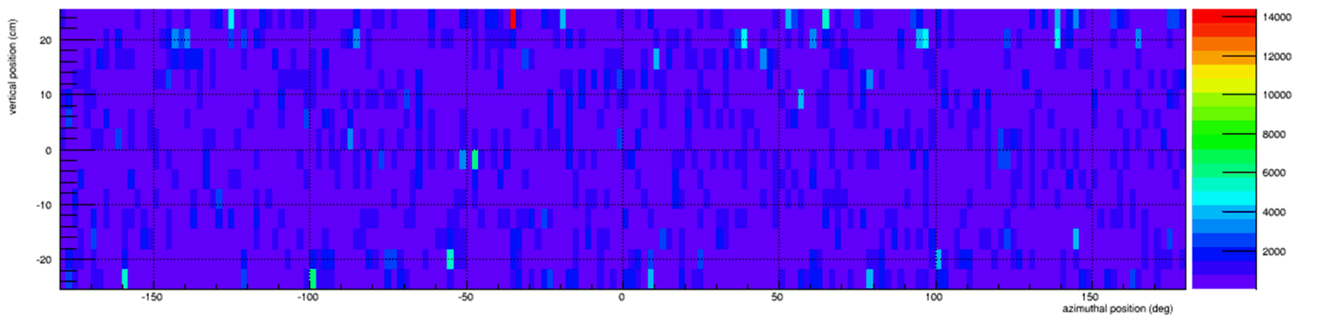
Preliminary results – Two point sources

Measurement of two point sources 180 degrees apart

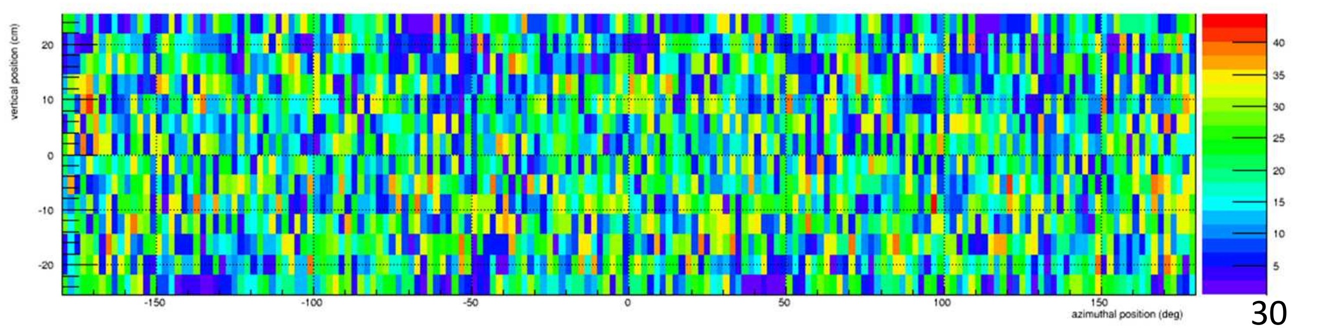
Gamma Rate



MLEM Reconstruction



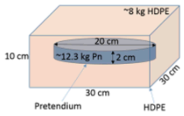
Relative Variance

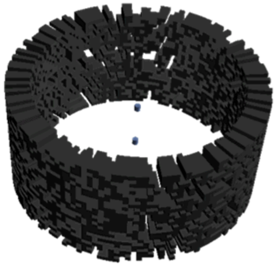


Modeling results – T vs. F (5e5 counts)

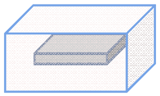
True non-null-negative confirmation comparison measurement between objects T and F.

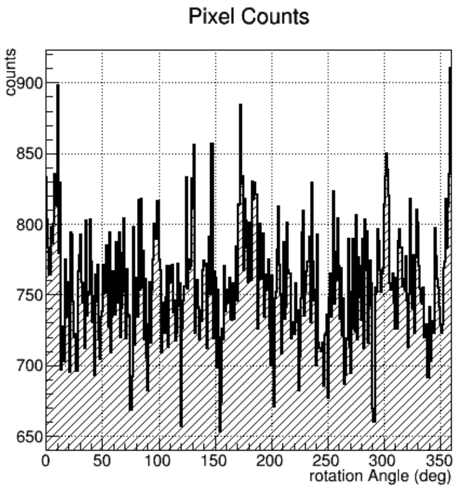
TAI T

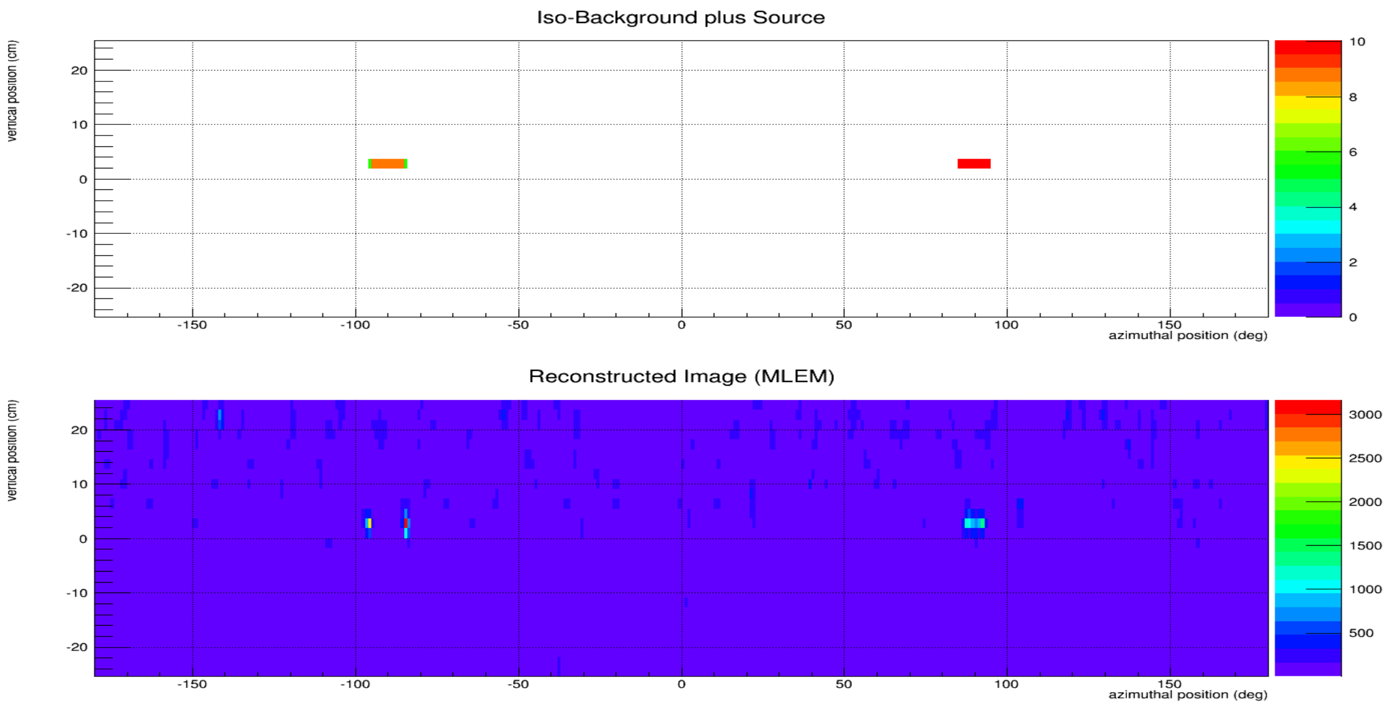




TAI F



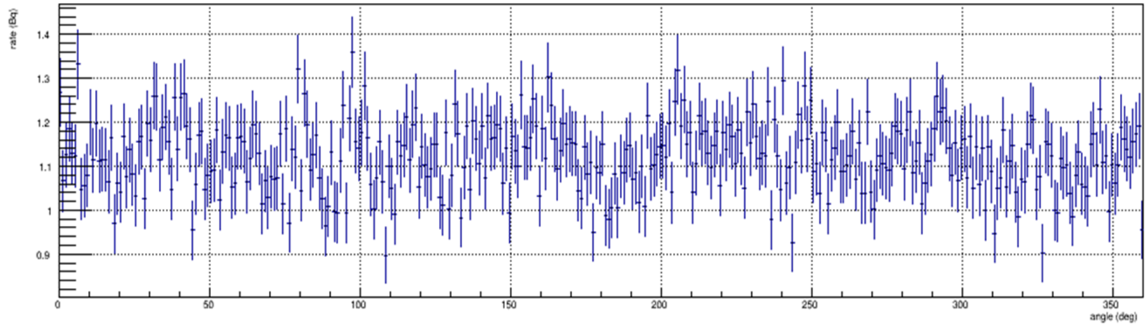




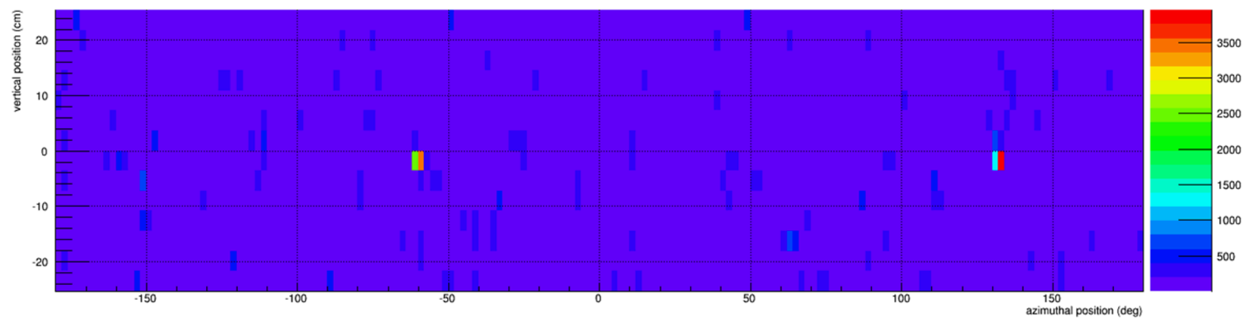
Preliminary results – Two point sources (2.5 degrees apart)

Measurement of two point sources 182.5 degrees apart

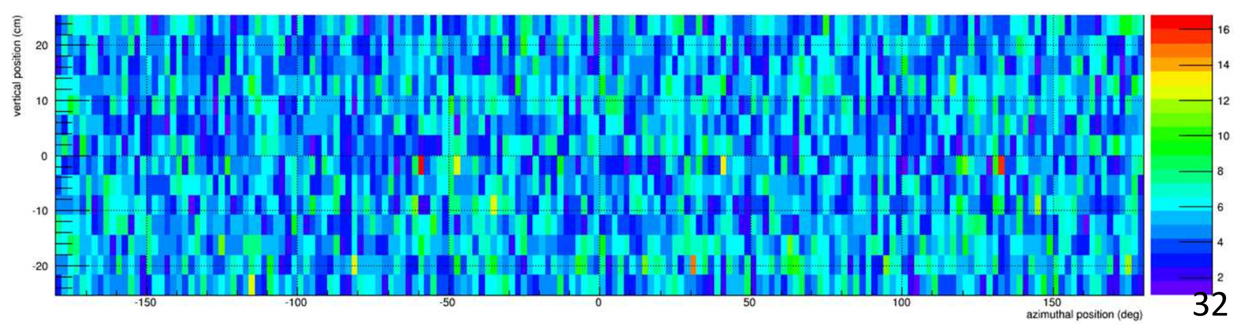
Neutron Rate



MLEM Reconstruction



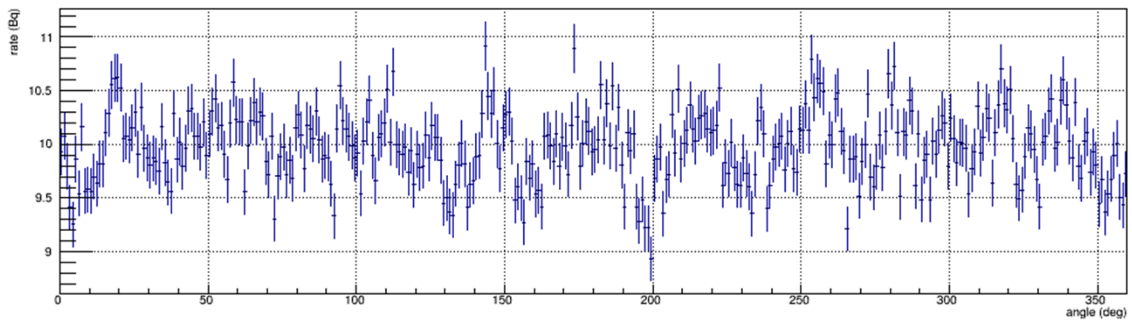
Relative Variance



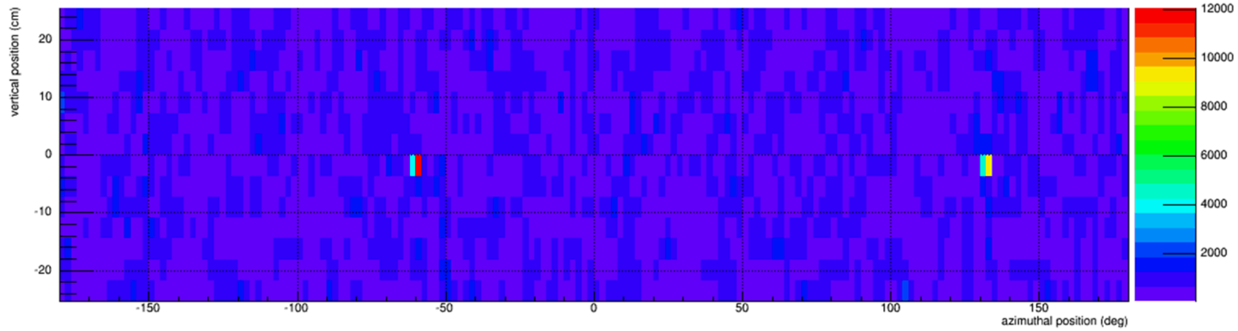
Preliminary results – Two point sources (2.5 degrees apart)

Measurement of two point sources 182.5 degrees apart

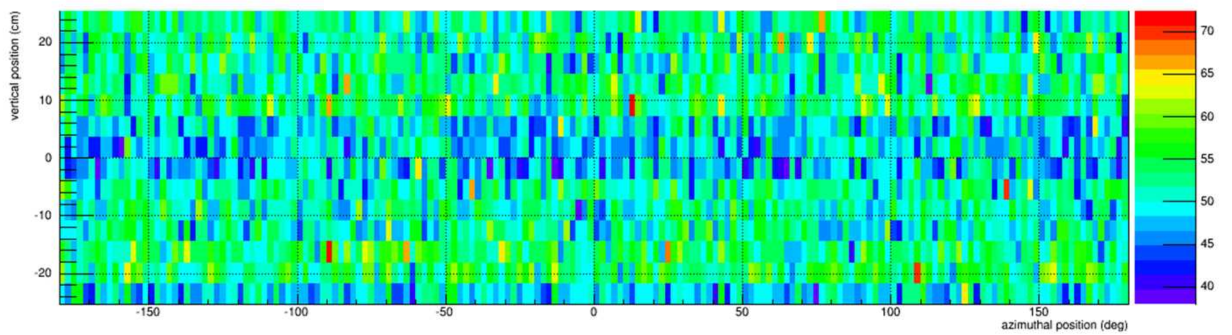
Gamma Rate



MLEM Reconstruction

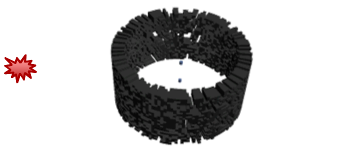


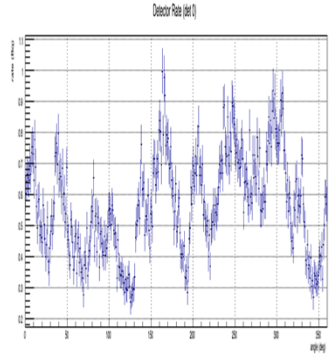
Relative Variance

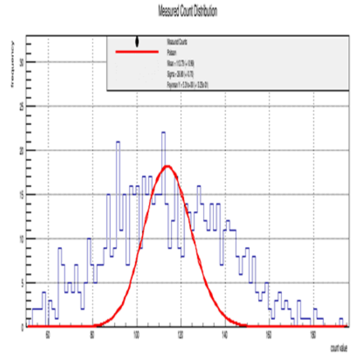


Single Test Statistic – Feynman Y (preliminary)

Single Point Source







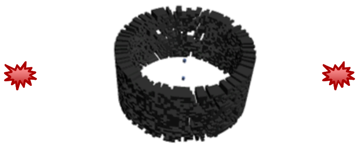
Feynman Y

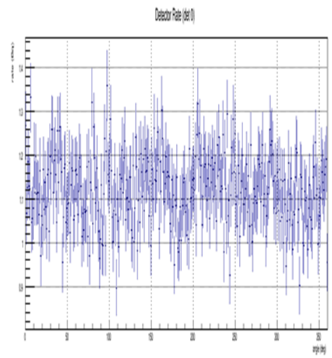
$= \left(\frac{variance}{mean} - 1\right)$

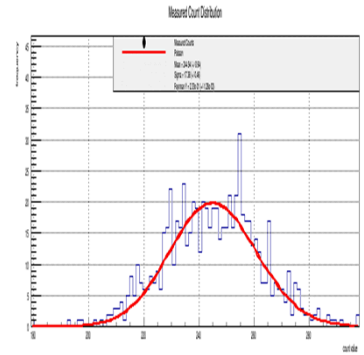
= 5.3 (+/-0.3)

→ Far from Poisson

Two Point Sources (aligned)







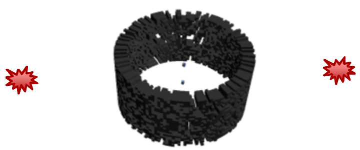
Feynman Y

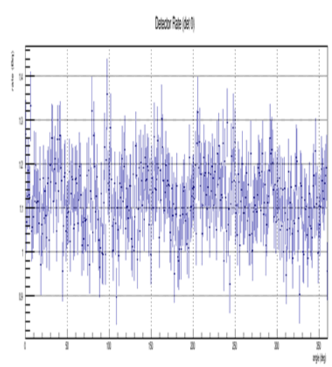
$= \left(\frac{variance}{mean} - 1\right)$

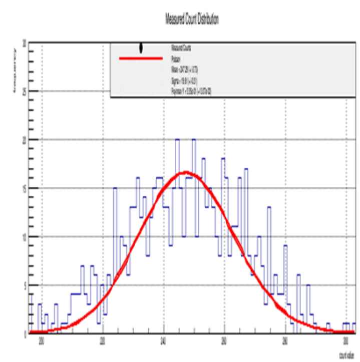
= 0.23 (+/-0.01)

→ Fairly Poisson

Two Point Sources (misaligned)







Feynman Y

$= \left(\frac{variance}{mean} - 1\right)$

= 0.56 (+/-0.03)

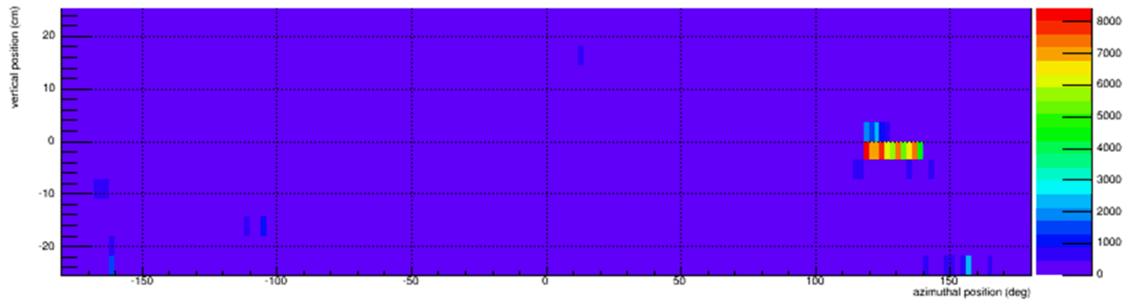
→ Less Poisson

Preliminary results – Two point source pairs

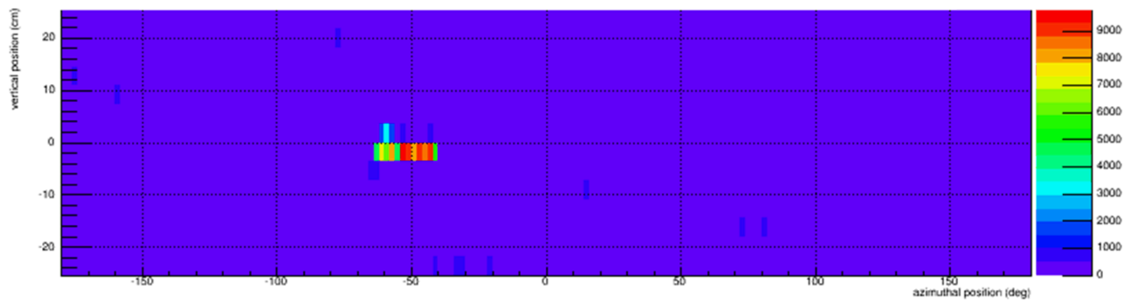
Measurement of two point source pairs separated by 19 cm 180 degrees apart

Each pair was measured separately and the results added together digitally

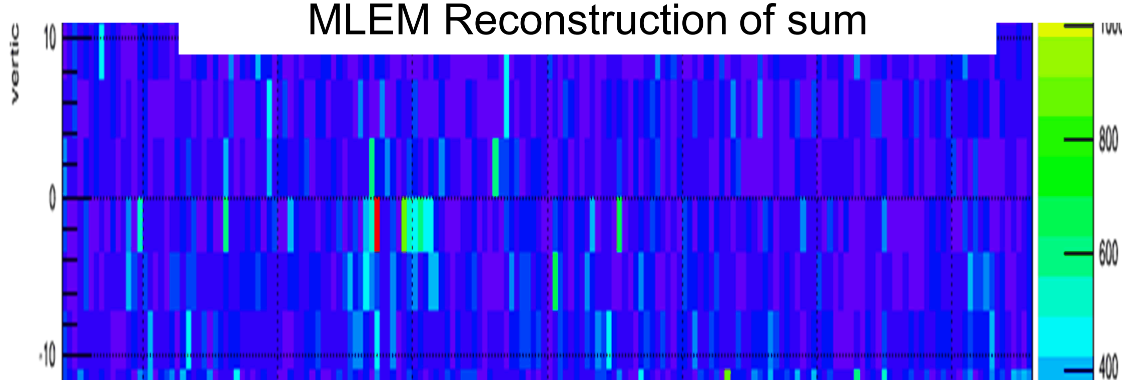
MLEM Reconstruction of sources at 90



MLEM Reconstruction of sources at 270



MLEM Reconstruction of sum

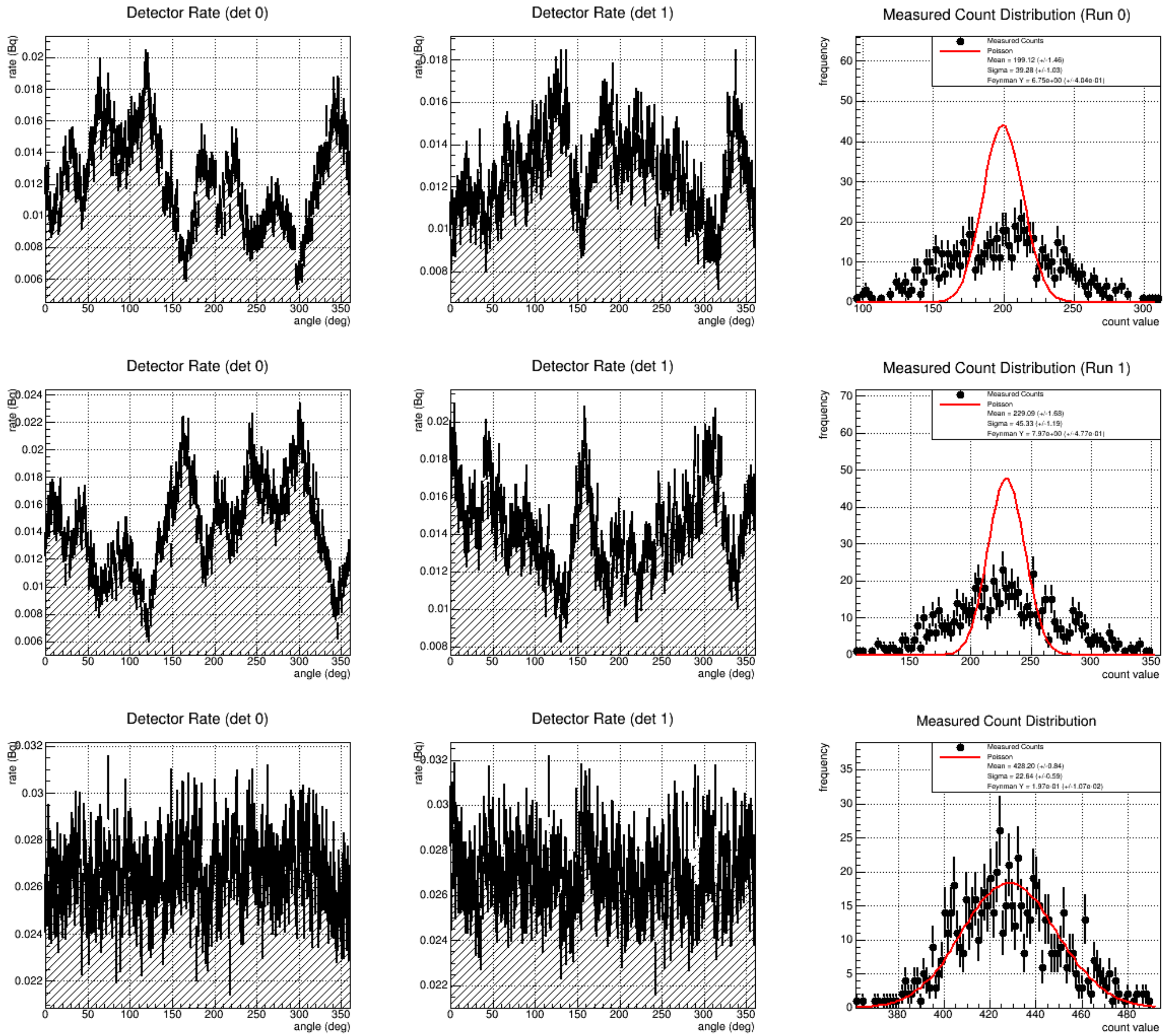


Preliminary results – Two point source pairs

Measurement of two point source pairs separated by 19 cm 180 degrees apart

Each pair was measured separately and the results added together digitally

Feynman-Y:
0: 6.75 (+/-0.40)
1: 7.97 (+/-0.48)
Sum: 0.197 (+/-0.01)

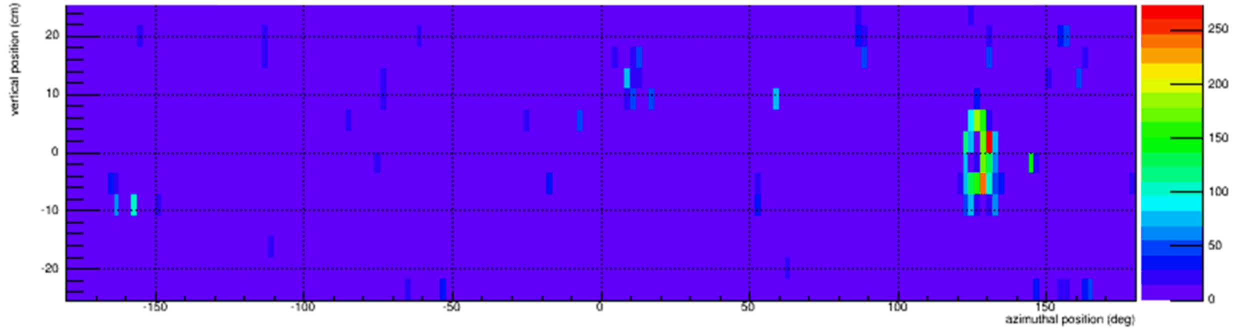


Preliminary results – Two Pu spheres

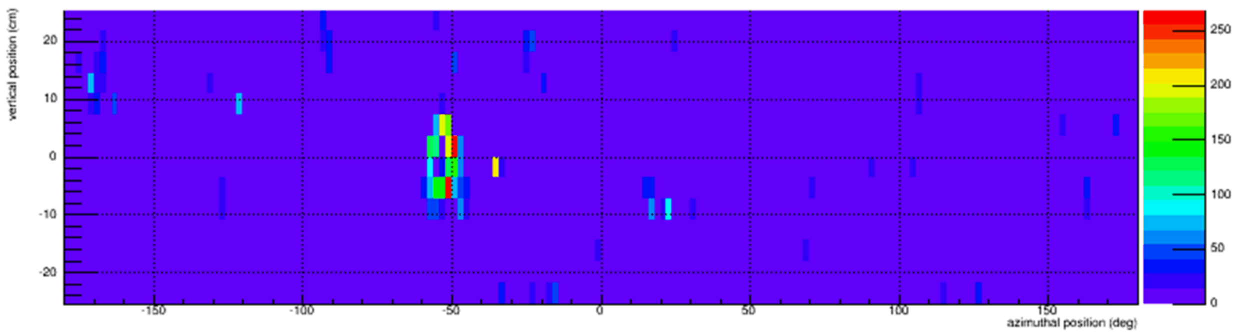
Individual Pu sphere measured

Digitally shifted data by 180° and added to itself

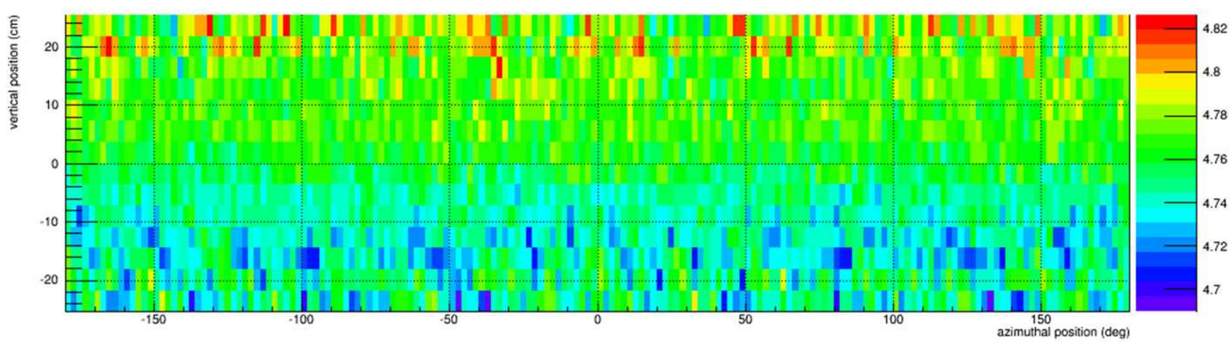
MLEM Reconstruction of sphere at 90



MLEM Reconstruction of sphere at 270



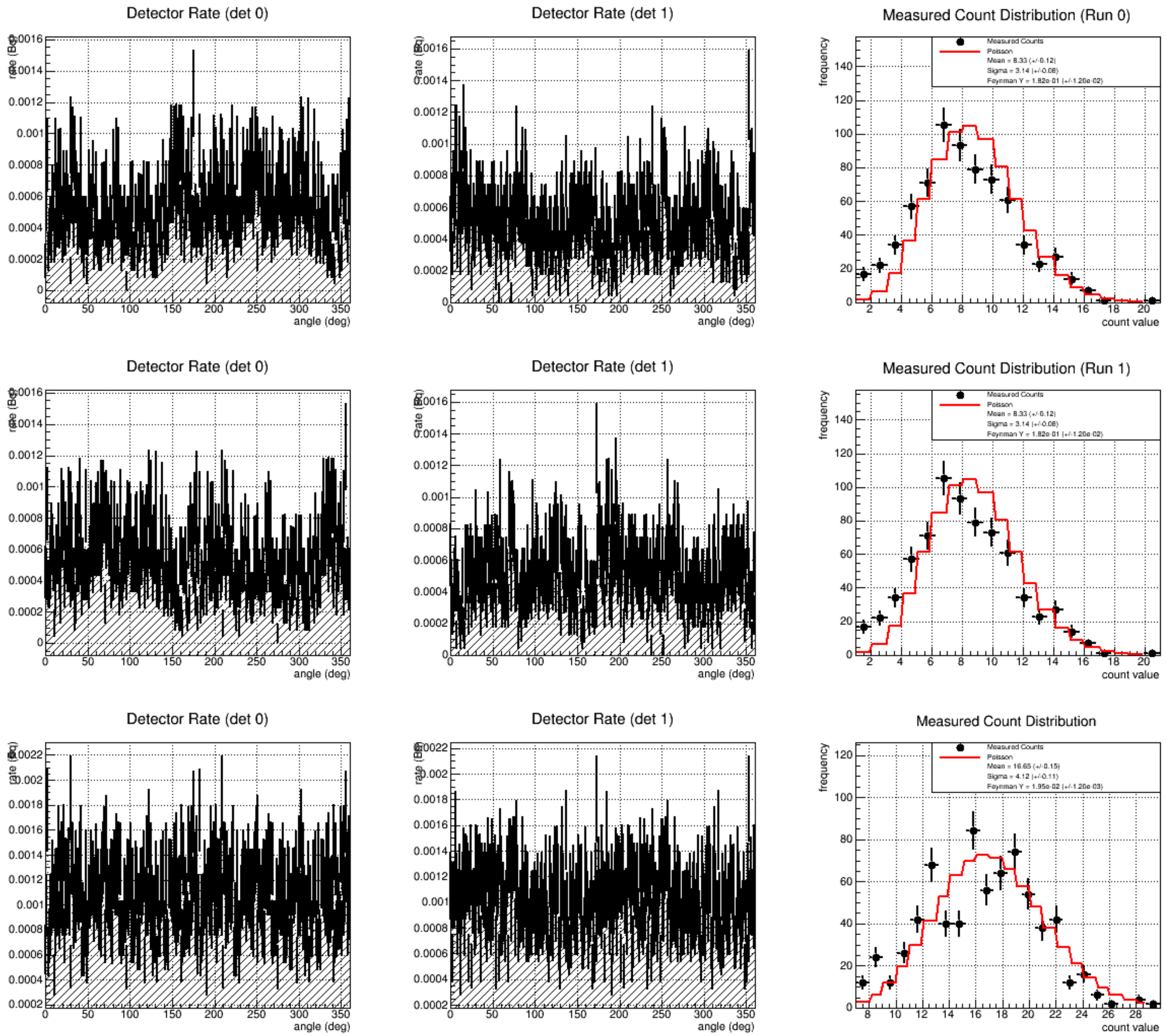
MLEM Reconstruction of sum



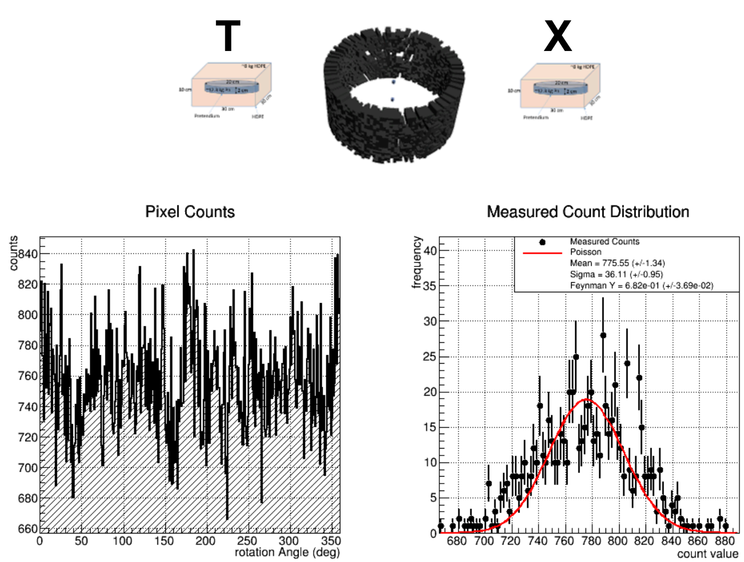
Preliminary results – Two Pu spheres

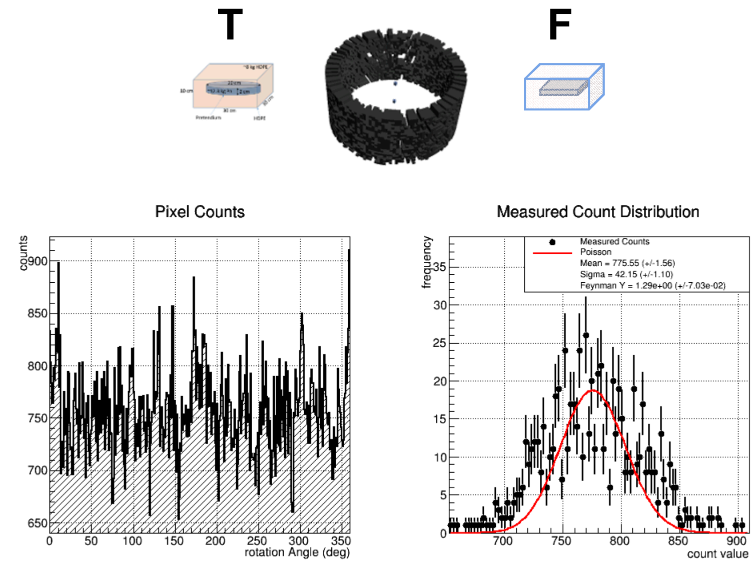
Individual Pu sphere measured

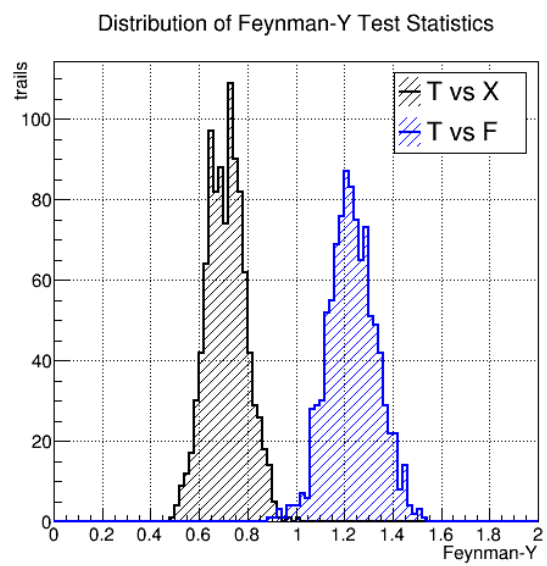
Digitally shifted data by 180◦ and added to itself



Feynman Y Test Statistic – 1000 trials of 5e5 counts

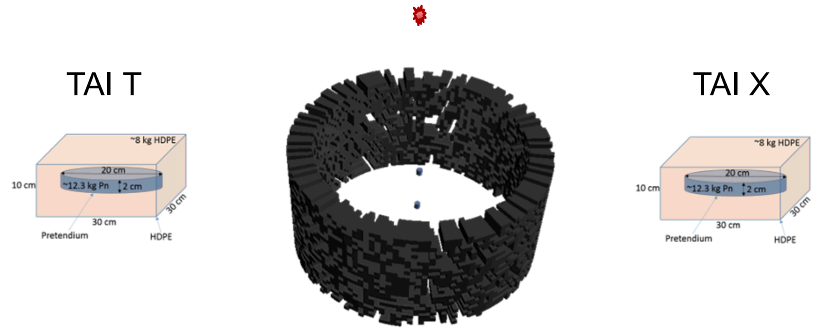


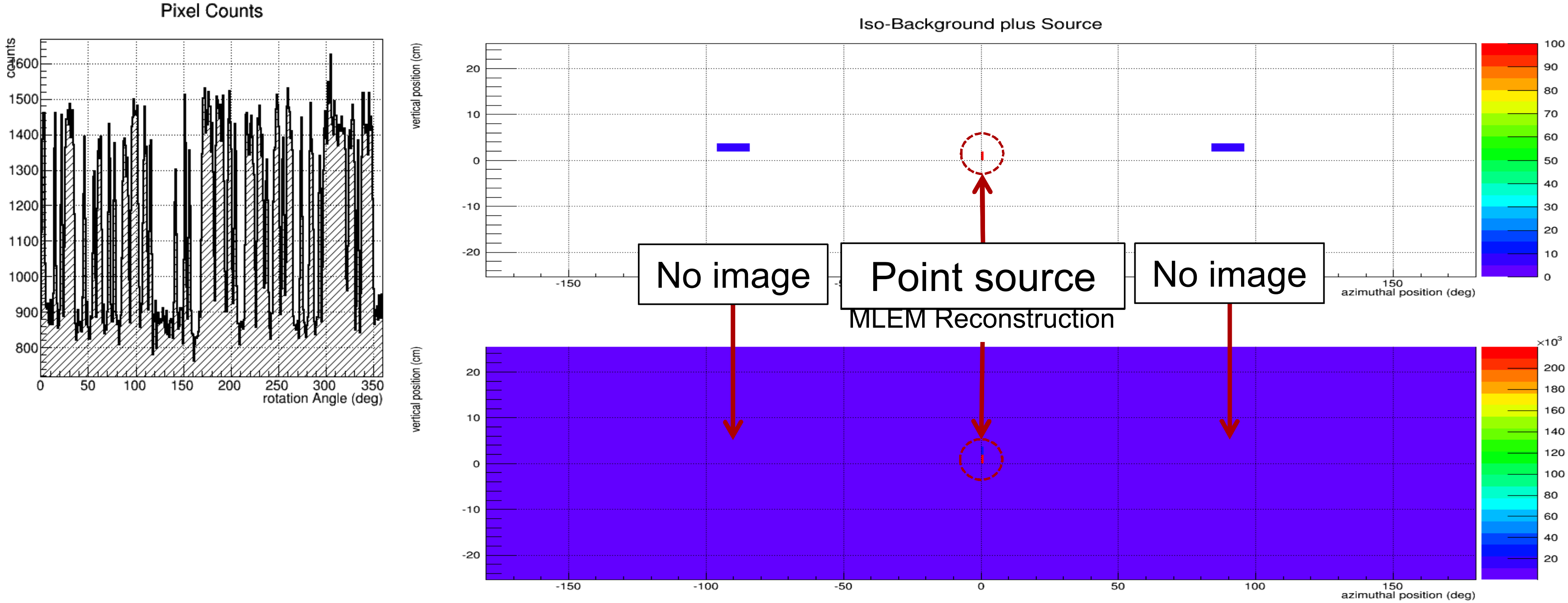




Modeling results – T vs. X plus point source (8e5 counts)

If (and only if) the TAIs are identical, only the third source is visible!





Conclusions & Future Work

A properly designed two-dimensional time-encoded imager can:

- Confirm that two objects are identical in a single measurement with NULL (constant rate) indicating a positive result.
- Because a NULL (constant rate) is present at all times, the inspecting party might be allowed full access to the measurement and data.
- The Feynman-Y test statistic can be updated to further protect against sensitive information loss.
- Can image any third inspector provided object during the confirmation measurement without revealing the first two objects as an authentication measure.

Future Work

- Better characterize alignment
- Find minimum run time to see difference
- Measurements with third object/digitally adding third object

Extra Slides

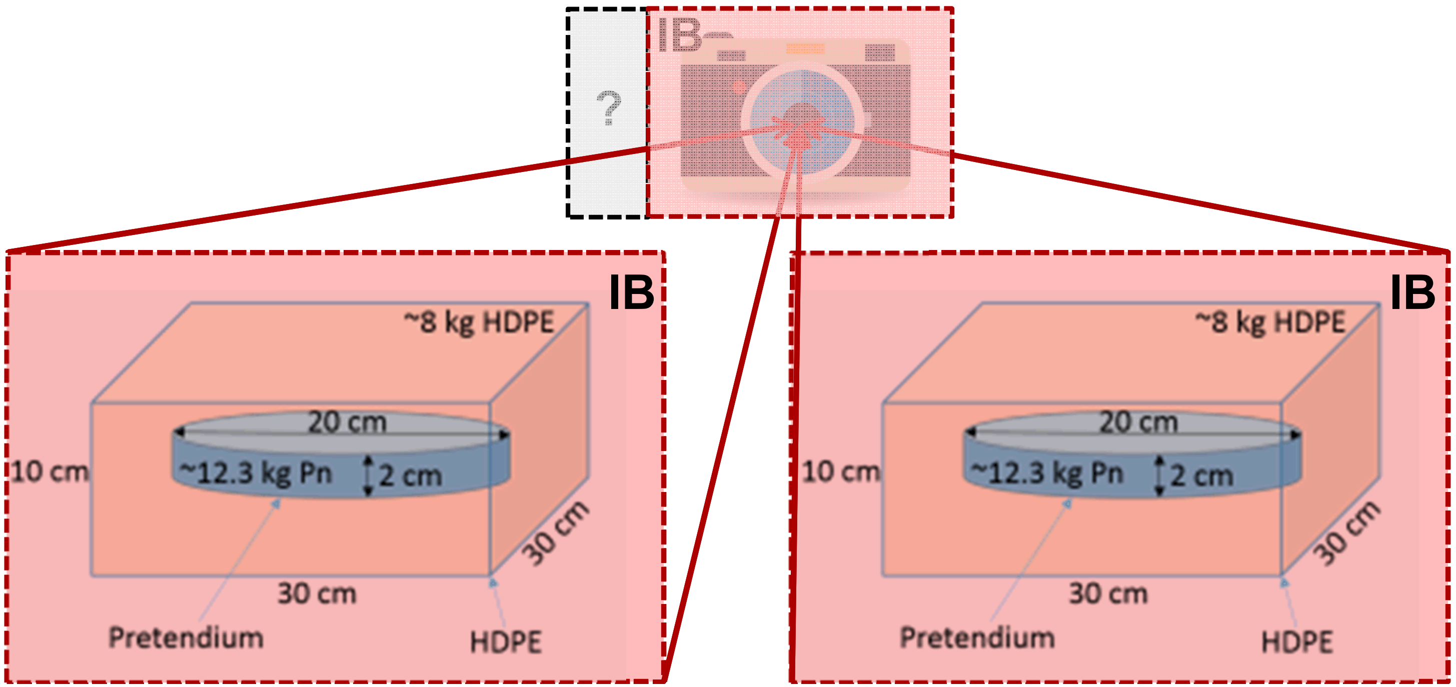
Certification vs. Authentication: It's not just for hardware

Certification – the process by which a host party gains confidence that sensitive information regarding an entity or facility remains secure.

Authentication - the process by which a monitoring party gains confidence that reported characteristics of an entity reflect the true state of that entity

Proposal – comparison measurements

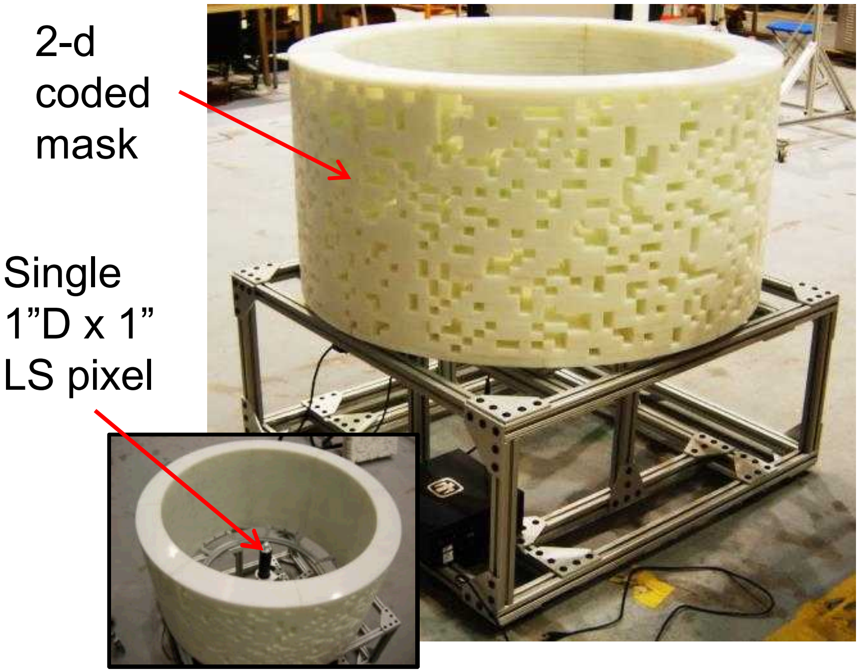
- Can we compare two objects directly without generating a template?
- If one object is T, then X is confirmed as a type 1 TAI.
- If neither object is T, then they are confirmed to be identical, but not T.
- If multiple object comparisons are confirmed and even one is T, then all objects are confirmed as type 1 TAIs.



Object T = valid type 1 TAI

Object X = ?

2D TEI – confirmation measurements?

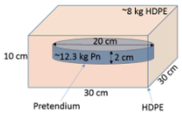


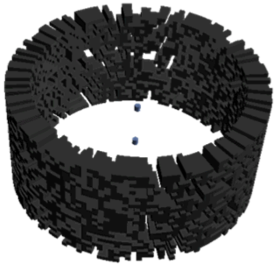
- **TEI is simple**
  1. Only one instrumented channel.
  2. Minimal calibration issues
     a) Information encoded in the relative rate of a single detector.
     b) Absolute gain doesn't matter.
     c) Gain can drift over time.
  3. Potential real-time analysis
     a) Single data stream.
     b) Events can be processed one at a time and update a test statistic.
- **Can we design a TEI confirmation system such that the detection rates can be monitored by an inspector without putting sensitive information at risk?**

Modeling results – T vs. X (1000 trials of 5e5 counts)

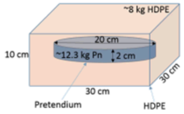
Even after summing 1000 trials worth of data, there isn't much evidence that sensitive information is present. This must be made more rigorous.

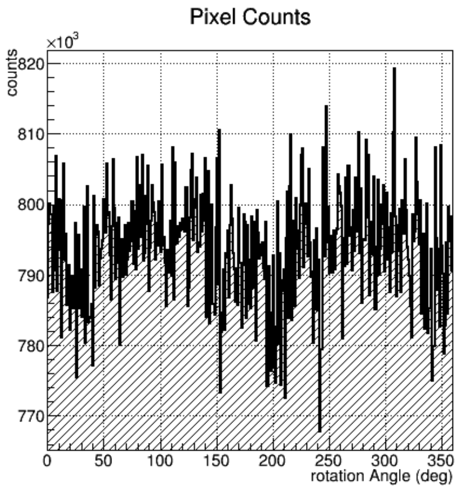
TAI T

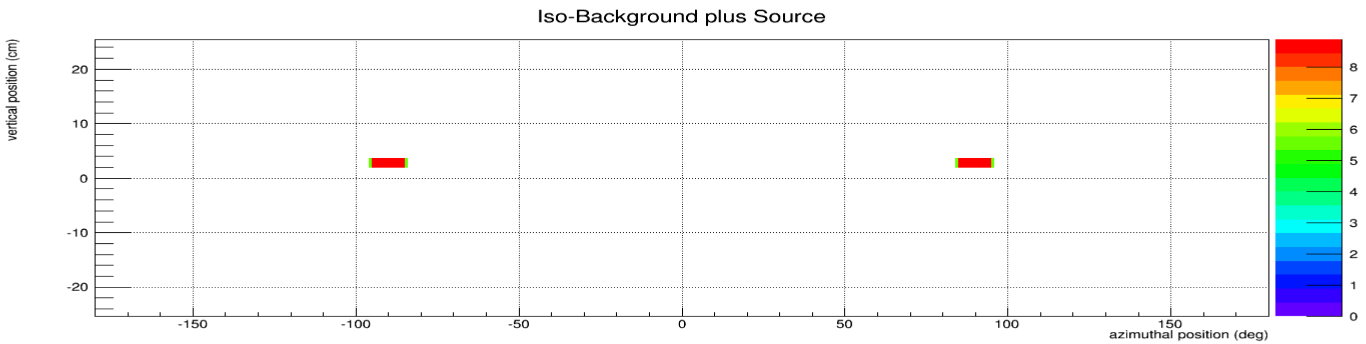


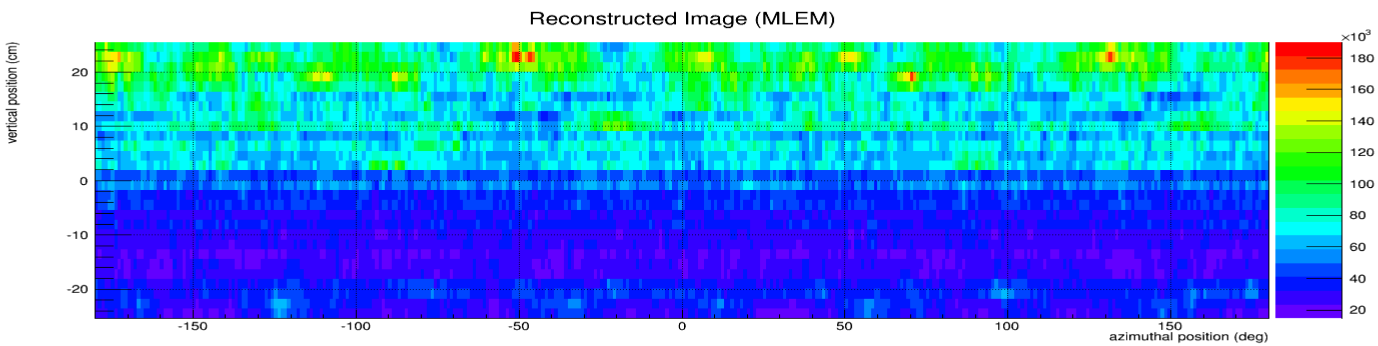


TAI X

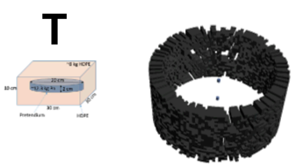


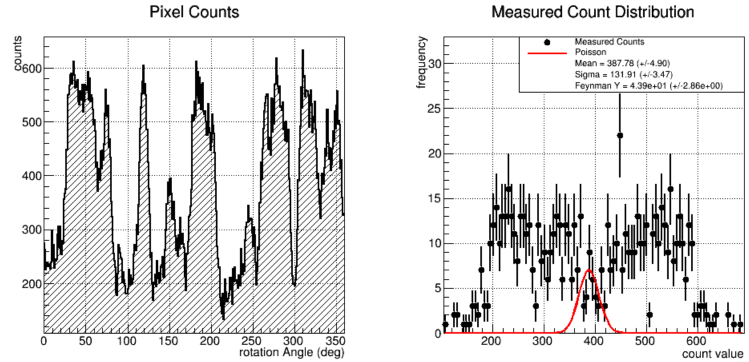






Single Test Statistic – Feynman Y (modeling)



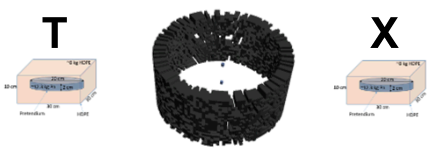


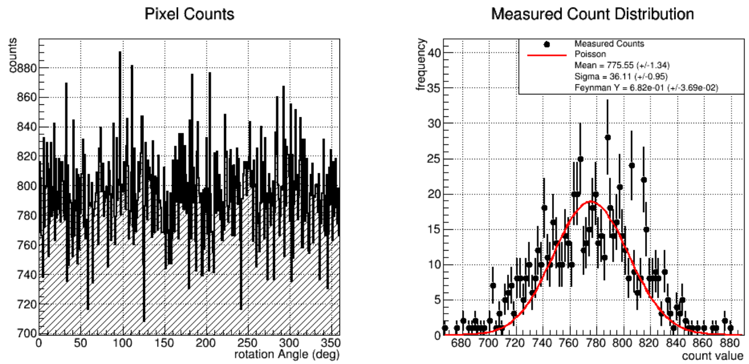
Feynman Y

$$= \left(\frac{variance}{mean} - 1\right)$$

= 86.8 (+/-5.7)

→ Far from Poisson



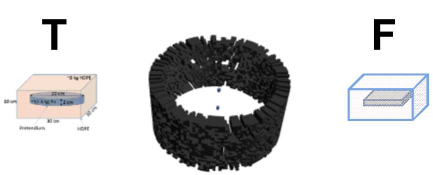


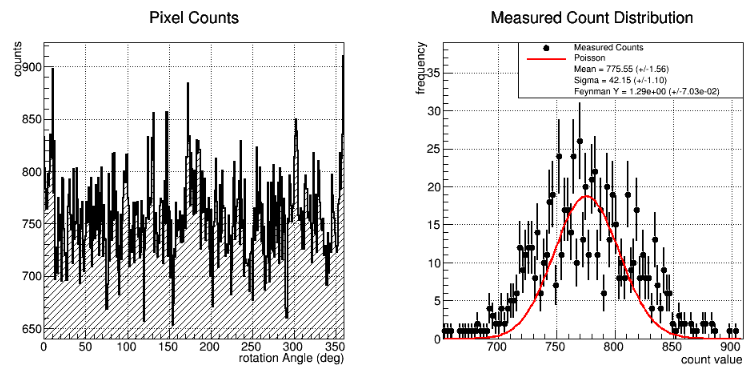
Feynman Y

$$= \left(\frac{variance}{mean} - 1\right)$$

= 0.68 (+/-0.04)

→ Fairly Poisson





Feynman Y

$$= \left(\frac{variance}{mean} - 1\right)$$

= 1.3 (+/-0.07)

→ Less Poisson