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Aperture-based radiation imaging techniques

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Sandia National Laboratories

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MTV Nuclear Engineering Summer School

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Outline

- Introduction
- Aperture imaging theory
- Image reconstruction
- Systems/results
  - Neutron coded aperture imager
  - Gamma coded aperture imager
  - Time-encoded imager (2D)
  - Time-encoded imager (1D)
  - Single-volume scatter camera with optical coded aperture

Focus on detector systems and results from my research (neutrons!)

SNM detection/imaging

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- Applications
- Tasks
- Techniques
- Instruments

We develop systems for eventual application in a range of scenarios:

Standoff detection

Cargo screening

SNM detection applications

- Low signal rate
  - Need large area detectors!
- Low signal to background
  - Need background discrimination!

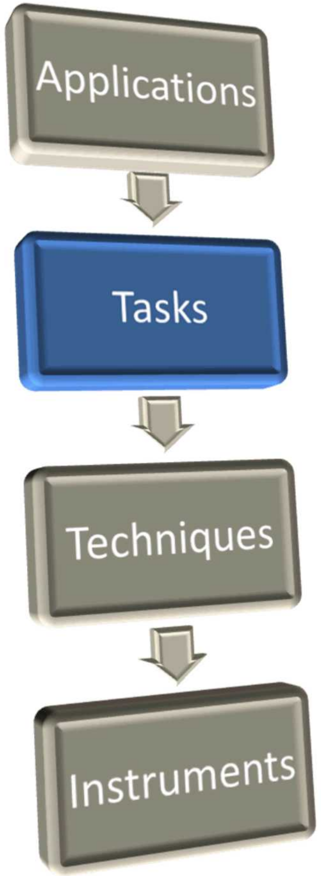
Arms control treaty verification

Emergency response

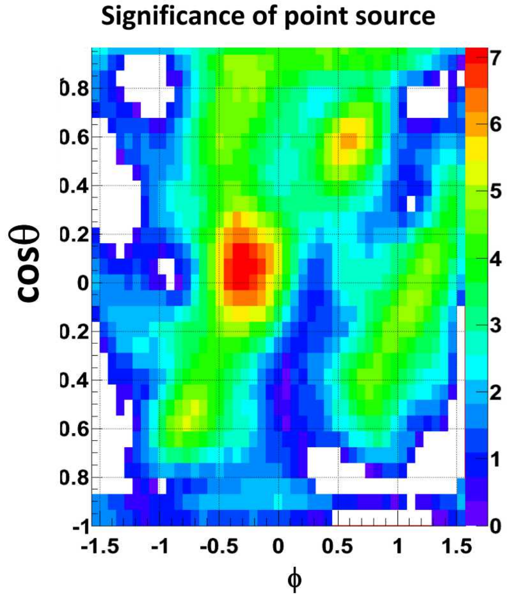
SNM imaging applications

- High resolution required
  - Fine detector segmentation
- Multiple or extended sources

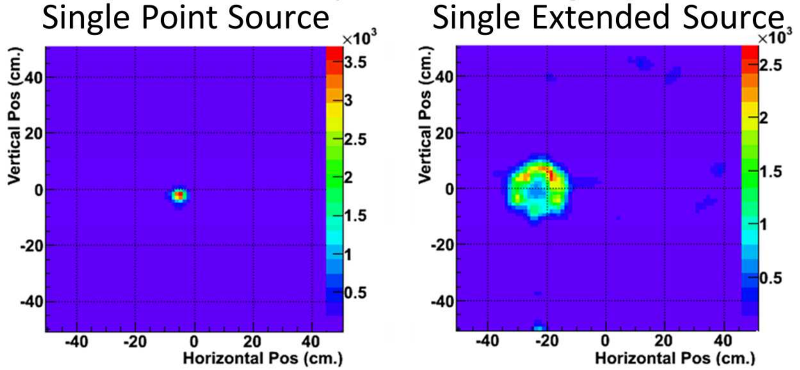
Directional radiation detector “tasks”



- Detection
  - Is there a localized source present w.r.t. diffuse background?
  - Directional information can help, but in the limit no “image reconstruction” is needed
- Localization
  - What is the direction to a localized source?
  - Can assume a single source on top of background
  - Can perform image reconstruction (w/ constraints?) or query raw data directly
- Imaging
  - Most general case, includes possibility of multiple or extended sources
  - Need full image reconstruction methods
  - May want to include constraints (e.g. smoothness or sharp edges) in reconstruction
  - May want to query image after the fact for e.g. dimensions or locations



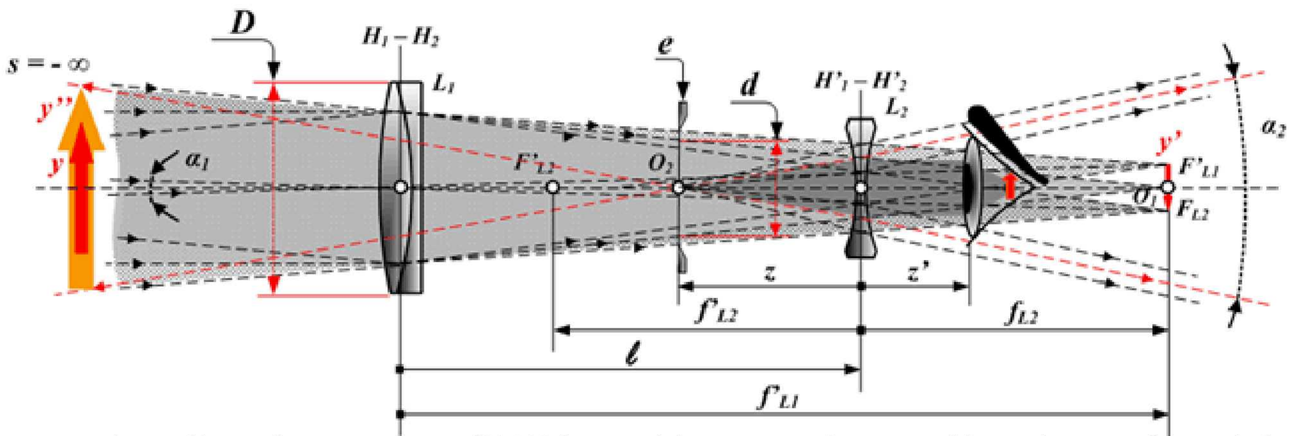
Coded aperture images



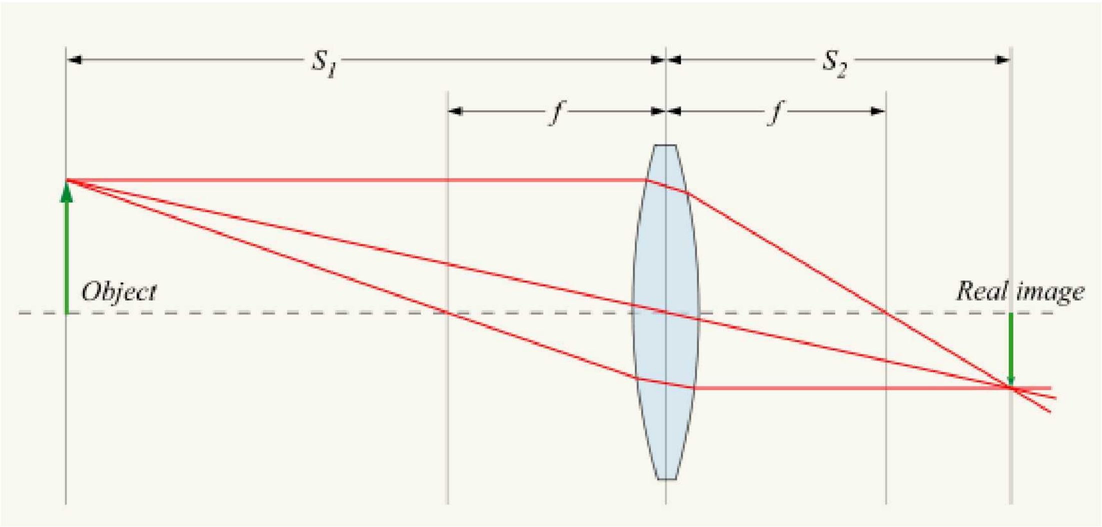
Aperture imaging

Optical cameras

- Lens converts position in the real world to position on a small position-sensitive detector
- Conveniently, 1-to-1 mapping of detected location to real-world location
- But we can't lens neutrons (or energetic photons, i.e. gammas)



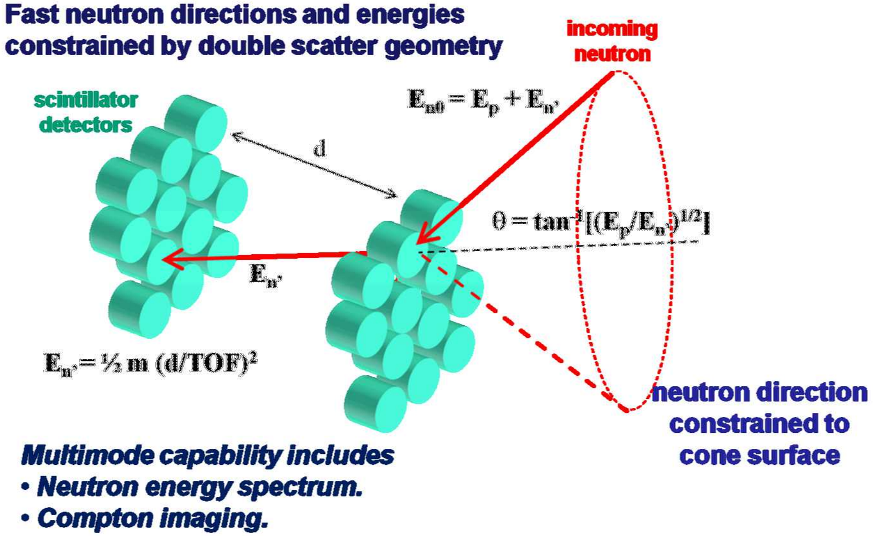
https://www.howtogeek.com/63409/htg-explains-cameras-lenses-and-how-photography-works/

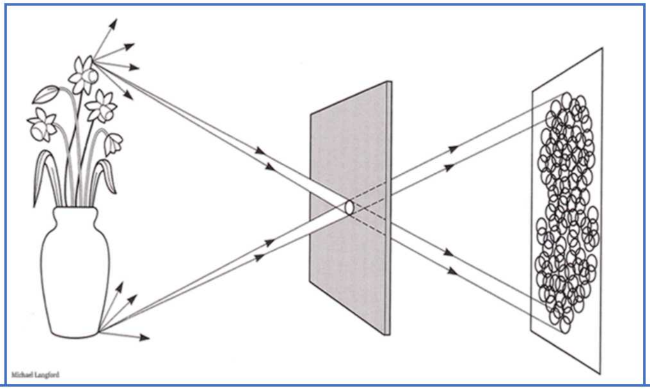


https://aijaz.net/2010/01/23/how-camera-lenses-work/index.html

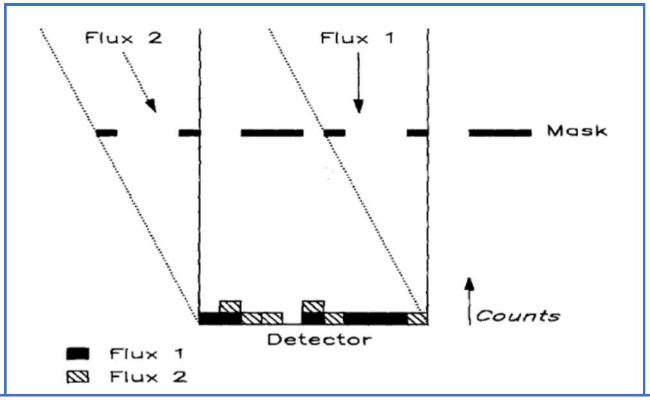
Radiation emission imaging methods

Kinematic imaging



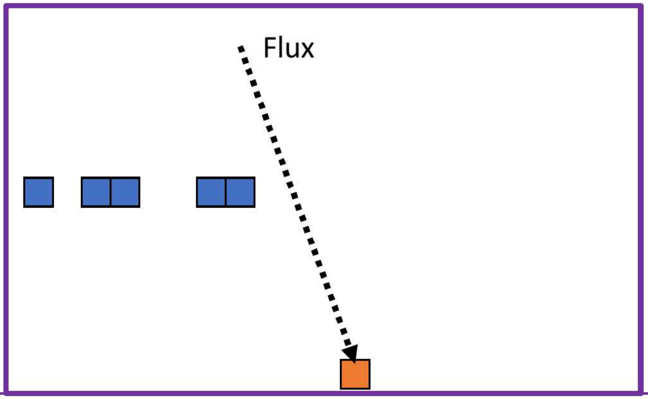


Pinhole: High Resolution, Low Throughput



Coded aperture: High Resolution, High Throughput

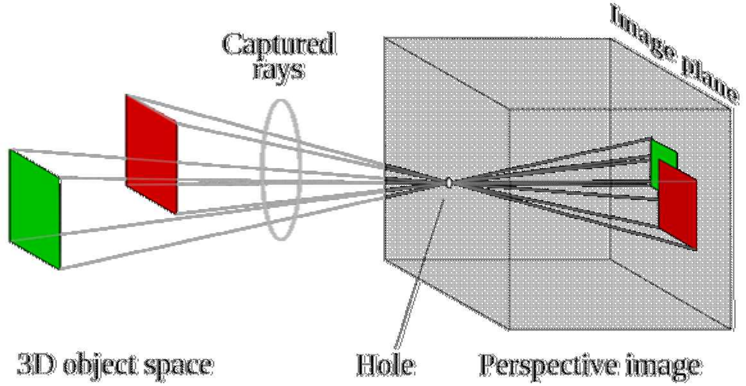
Aperture imaging



Time-encoded imaging: Low Sensitivity, Low complexity

Pinhole imaging

- Photons/particles stream through a small hole in an otherwise opaque mask
- Notice parameters of interest:
  - Pinhole size: resolution/sensitivity tradeoff
  - Mask-detector distance: magnification
  - Image plane size: field of view
- For energetic radiation, two more:
  - Image plane resolution (incl detector thickness): limits angular resolution
  - Mask thickness: vignetting (FOV)



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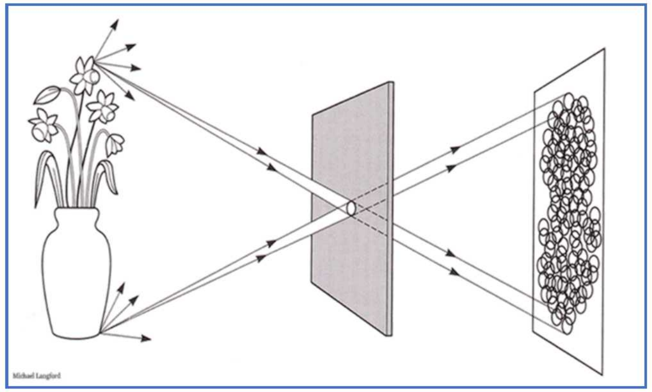
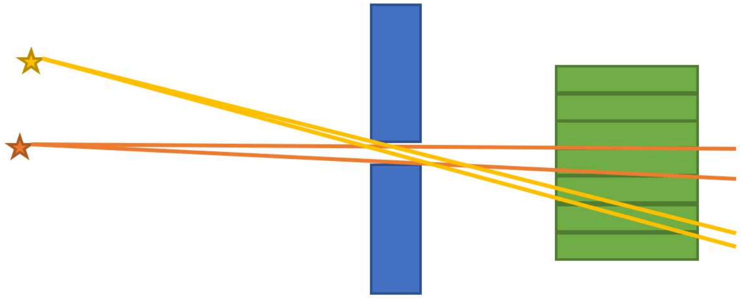
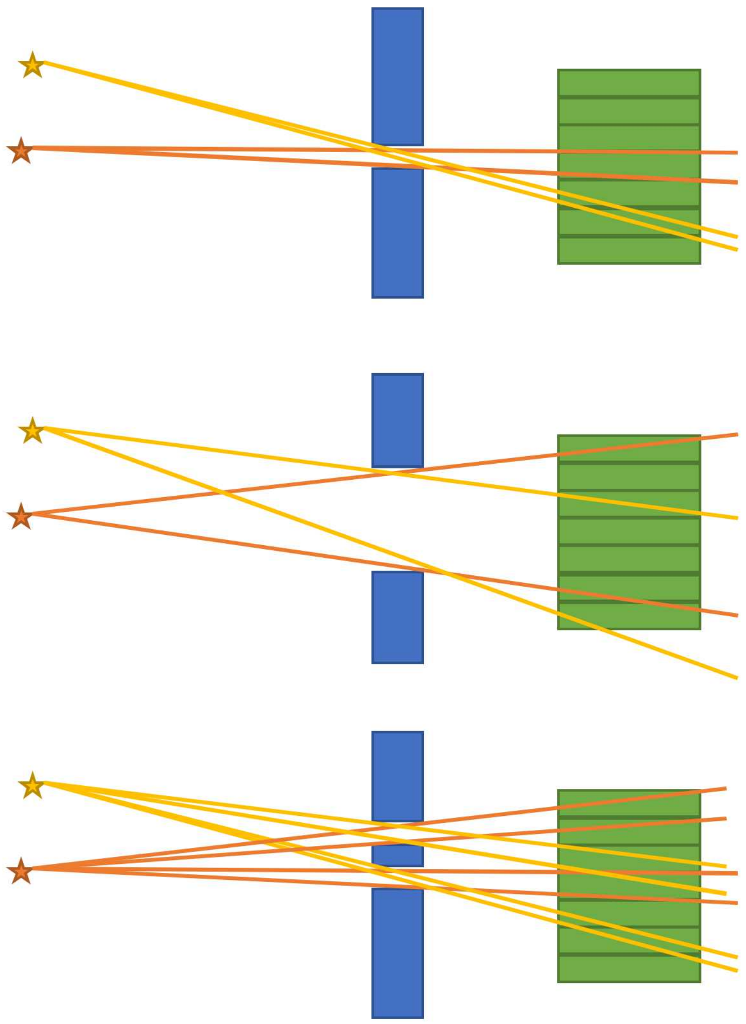




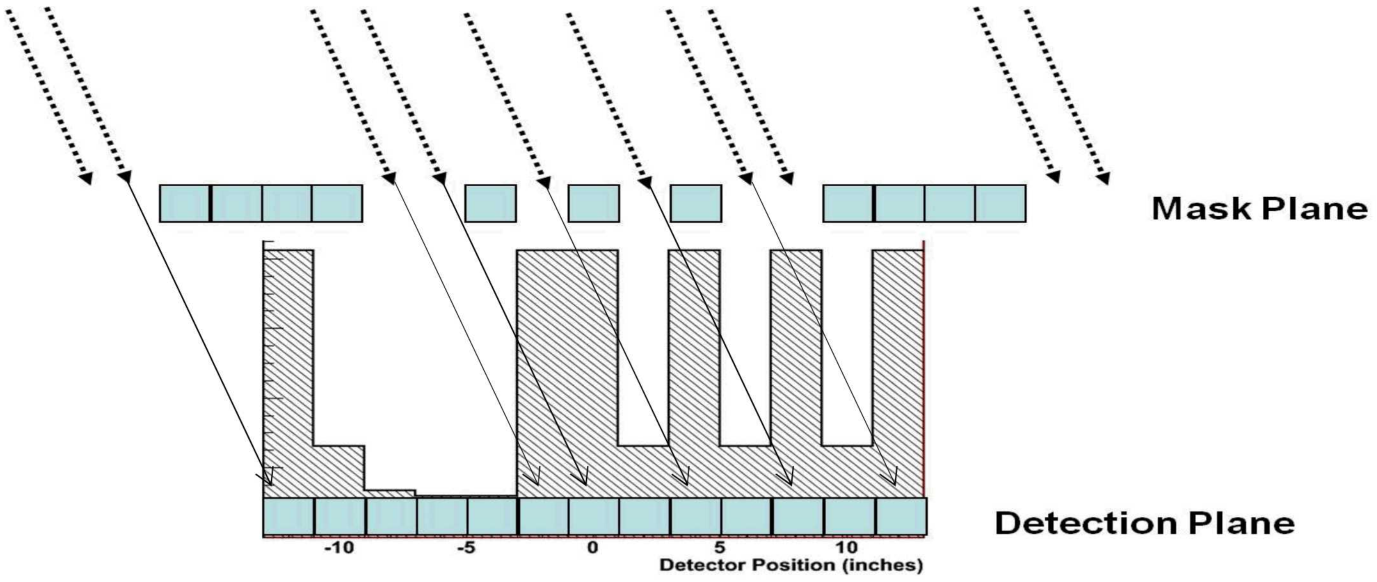
Pinhole -> coded aperture

- What if we need more sensitivity but also good resolution?
- Diminishing returns on making pinhole larger
- Instead make many smaller holes
- Now have high sensitivity, high resolution, BUT also high complexity reconstruction



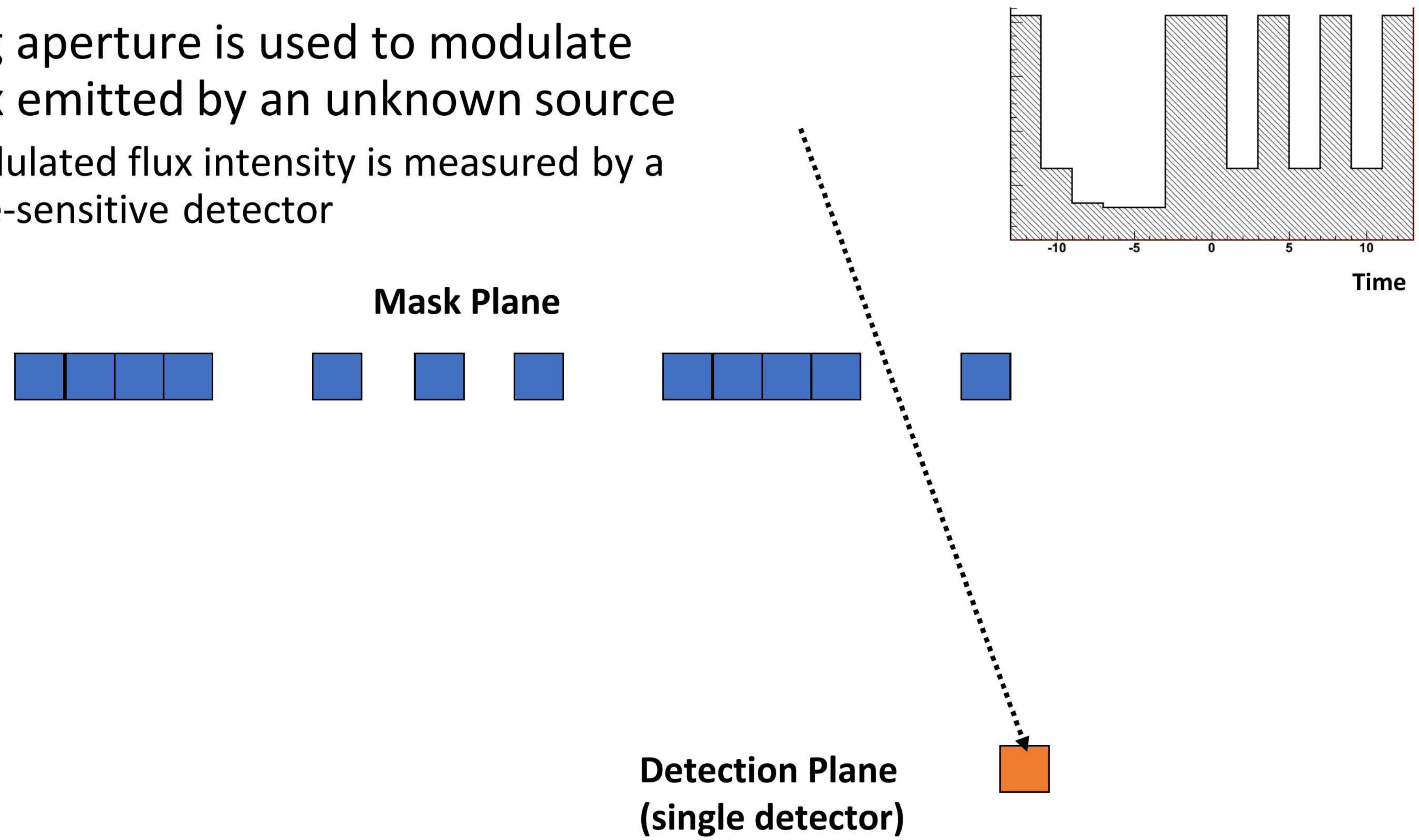
Coded Aperture Imaging

- Static aperture is used to modulate the flux emitted by an unknown source
  - Modulated flux intensity is measured at the detector plane by a position sensitive detector
- High-sensitivity extension of pinhole imaging
- Mask pattern is essential



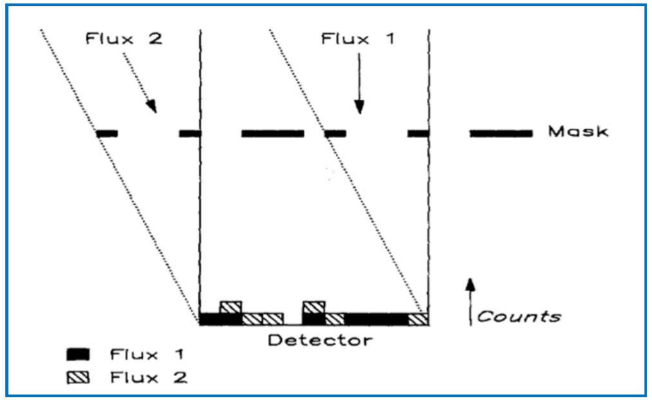
Time-Encoded Imaging

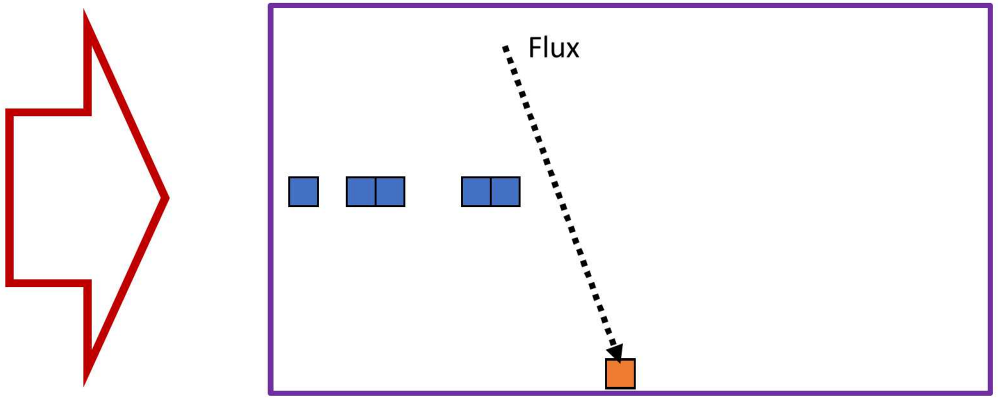
- Moving aperture is used to modulate the flux emitted by an unknown source
  - Modulated flux intensity is measured by a time-sensitive detector



Why TEI?

- Time-encoded imaging (TEI) is analogous to coded aperture imaging:
  - The *spatial* modulation of a particle flux induced by a fixed mask on a *position-sensitive image plane* is replaced by the *time* modulation of a particle flux induced by a moving mask on one or a few *time-sensitive detectors*.



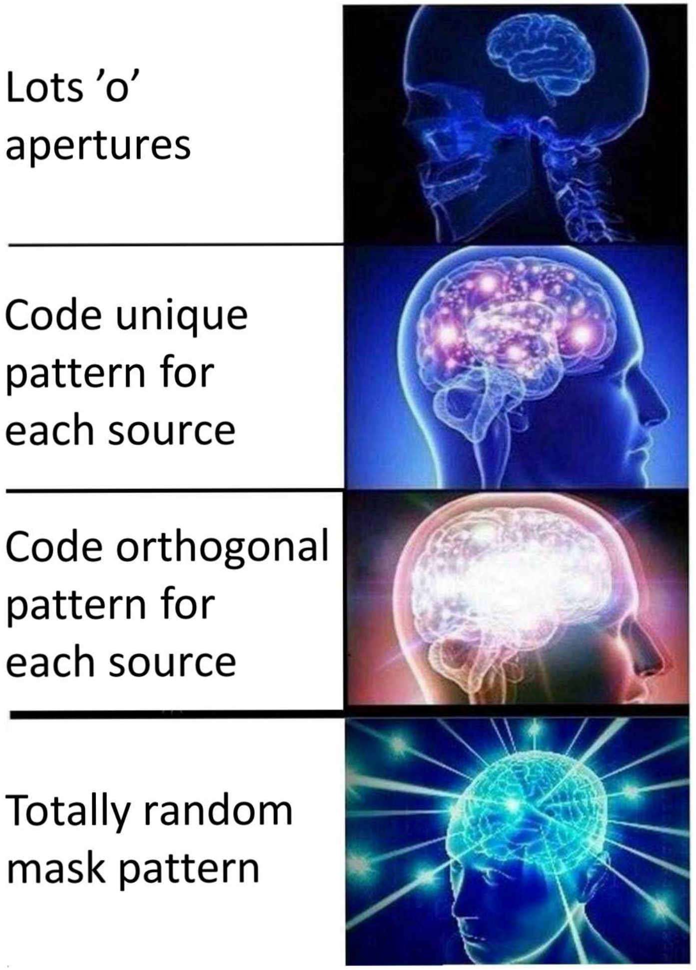


- Spatial resolution in detectors is expensive. Time resolution in detectors is ~free!
- Accurately resolving spatial patterns requires precise inter-calibration of detector channels or regions. In TEI, a single detector can be used; or if multiple, they are independent.
- Simple and robust, low-channel-count systems.
- Scalable to large effective area.
- Tradeoffs are low sensitivity and/or low resolution.

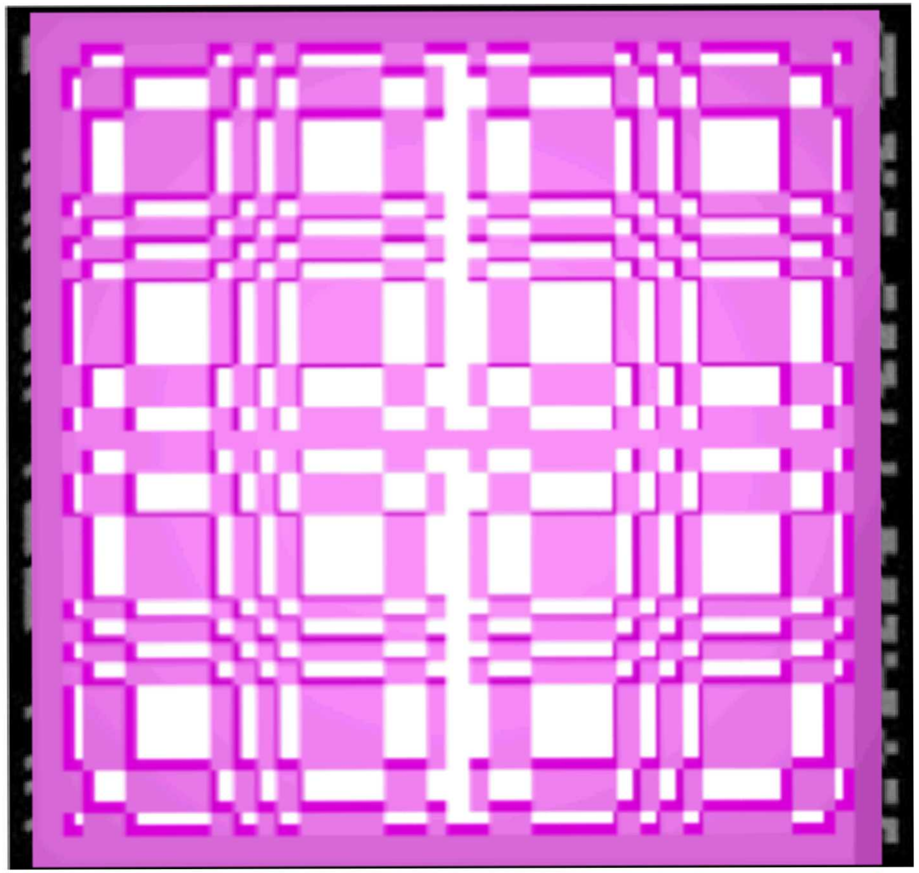
Image reconstruction

Mask patterns

- Mask pattern is key to coded aperture image reconstruction



Rank 19 modified uniformly redundant array (MURA)



DOI: 10.1007/s11214-017-0454-5

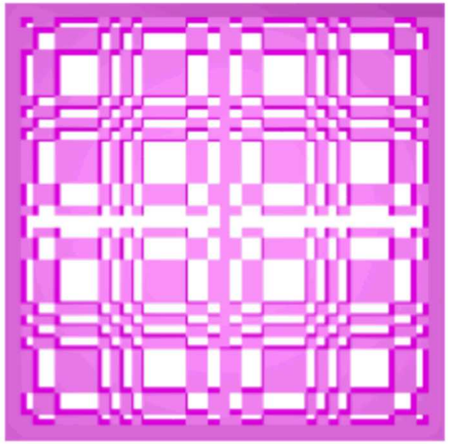
Coded aperture image reconstruction

- Reconstruction procedure:
  - with known mask pattern (*A*)
  - measure the projected pattern (*D*) with a pixelated detector: includes an un-modulated background term (*B*) in addition to modulated term (*A*S*)
  - reconstruct the source distribution ($\hat{S}$) by decoding with suitable matrix ($G*A = \delta$):

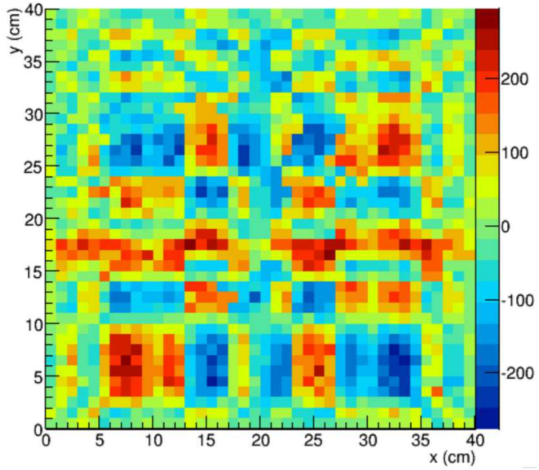
$$\hat{S} = G*D = S + G*B$$

- Modified Uniformly Redundant Array (MURA):
  - optimizes signal to noise ratio for point source
  - approximate delta-function point spread response, so there will be some artifacts
  - Tile MURA to get anti-mask (*A'*) via rotation—adds second pattern ($D' = A'*S + B$), and subtracted pattern ($D'' = D - D' = A*S - A'*S = 2A*S$)

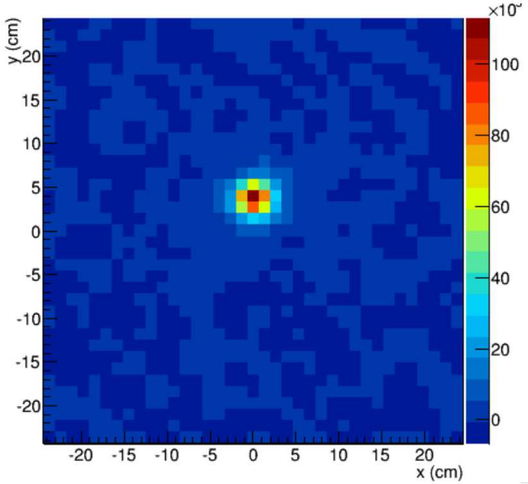
A:



$D = A*S + B$:



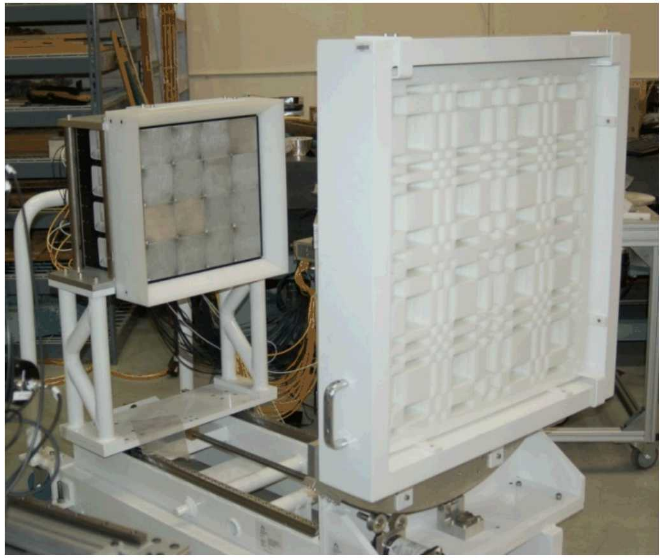
$\hat{S} = S + G*B$

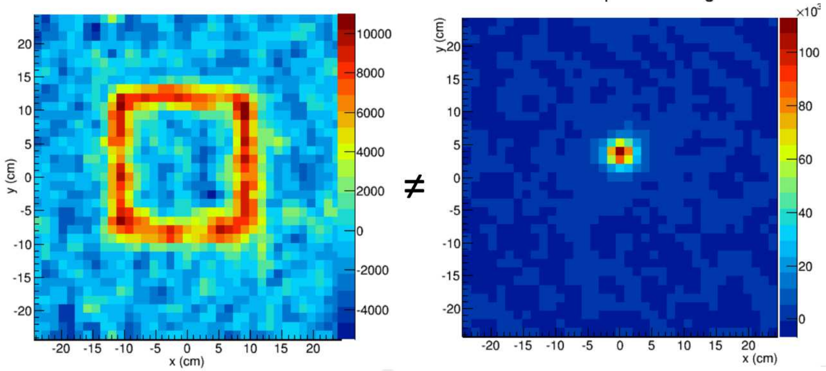


Neutron coded aperture

ORNL/SNL neutron coded-aperture imager

- Fast neutrons, and to a lesser degree gammas, modulated by rank-19 MURA made of HDPE
- Mask rotates to acquire mask/anti-mask data
- Mask thickness, detector-mask separation are adjustable to trade off field of view, contrast, and imaging resolution
- PSD capable plastic scintillator (EJ-299-34) based fast neutron detector
  - 16 pixelated block detectors with 100 pixels each: 1600 one cm pixels total
  - Each block detector read out by four PMTs, with pixel determined by Anger logic
- Enables characterization of SNM based on geometrical layout

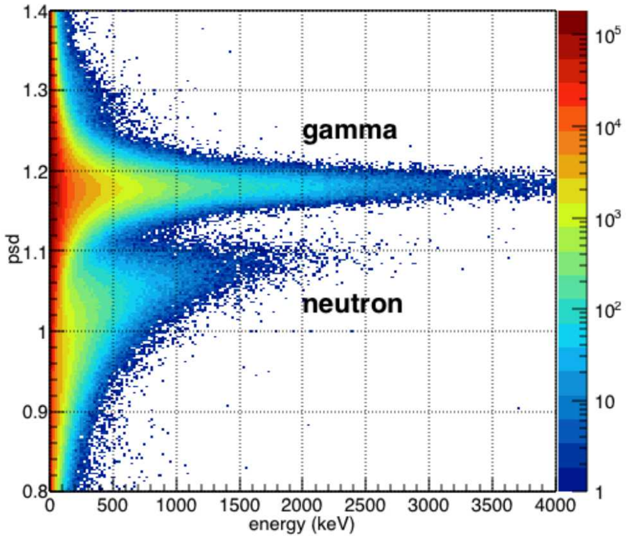


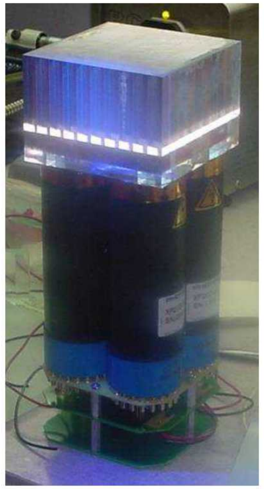


Slides based on presentation by Melinda Sweany (SNL)

ORNL collaborators on NCAI:
Paul Hausladen
Jason Newby
Matthew Blackston

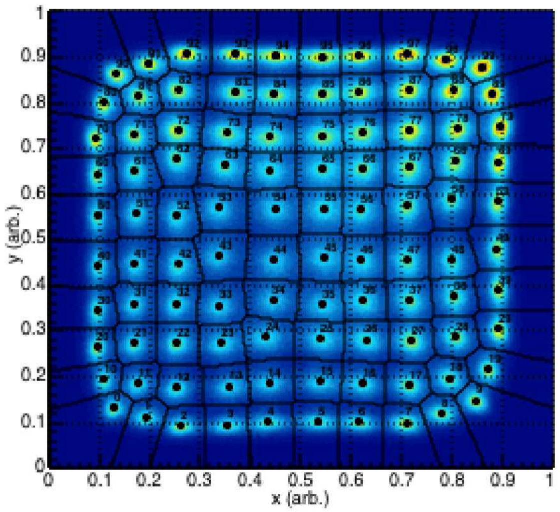
Pixelated fast neutron/gamma detection

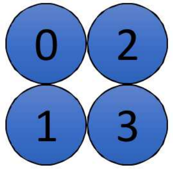




- Gamma/neutron discrimination with EJ-299-34
- Scintillation from optically separated 1x1 cm pixels propagate through light guide to PMTs
- Normalized sum of two orthogonal PMTs yield pixel responses in x and y:

$$x = (2+3)/(0+1+2+3)$$
$$y = (0+2)/(0+1+2+3)$$





- Algorithm creates a Look Up Table (LUT) that maps x and y centroids to pixel numbers

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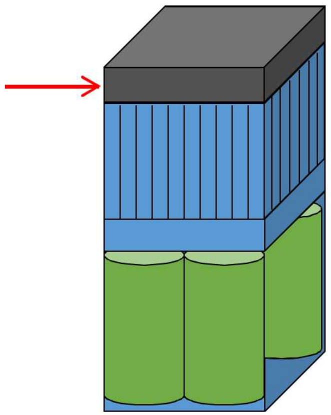
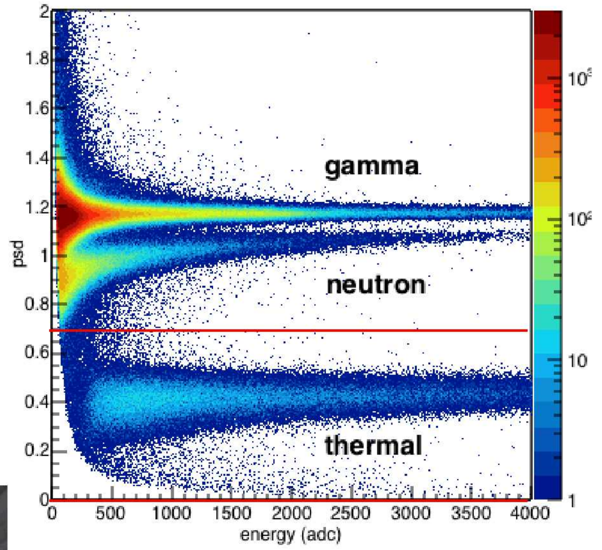
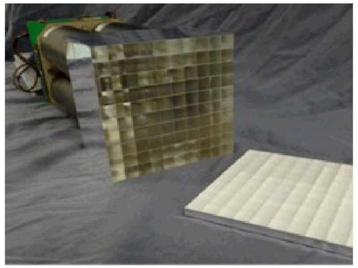
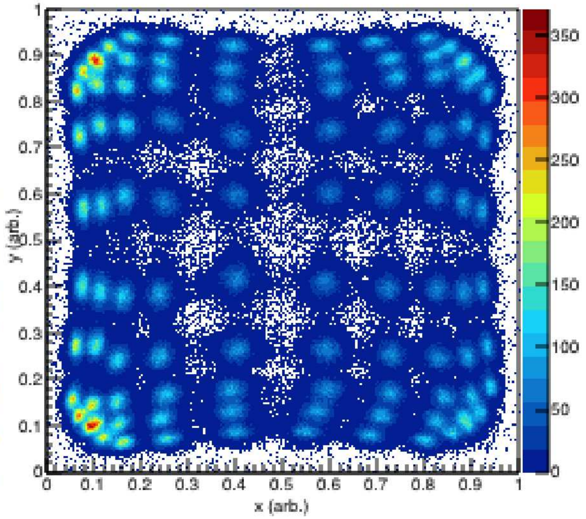
Thermal Neutron detection/modulation

- Thermal neutrons add information on nearby moderating material—image the surface of last scatter
  - High explosives
  - Shielding materials
- Thermal detection from added layer of EJ-426HD ($^{6}Li/ZnS:Ag$):
  - $n + {}^{6}Li \rightarrow \alpha + t$
  - Pulse shape easily separable from gamma & fast neutron
- Thermal neutrons are modulated with borated polyethylene mask, situated between HDPE (fast neutron mask) and detector array

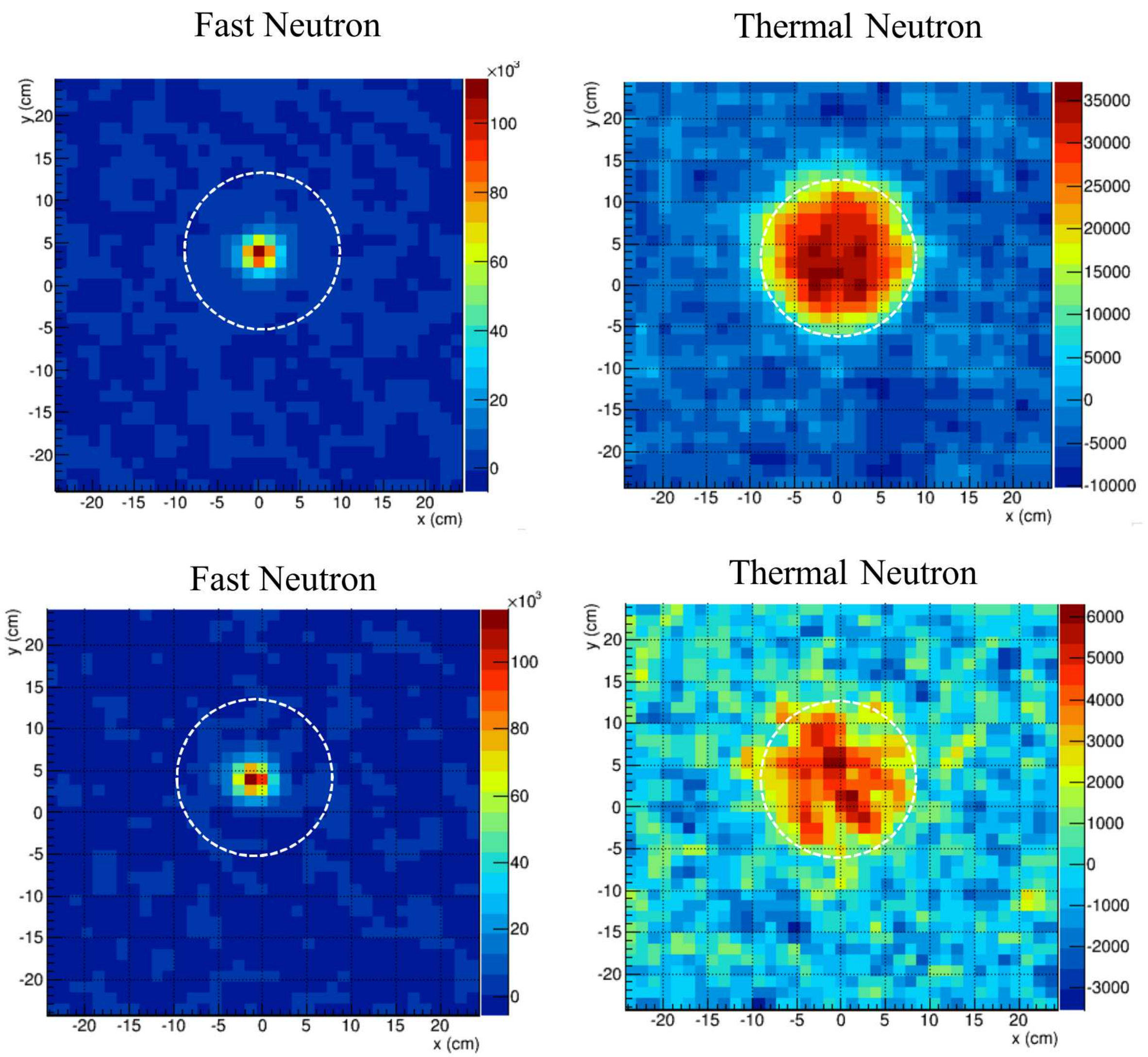








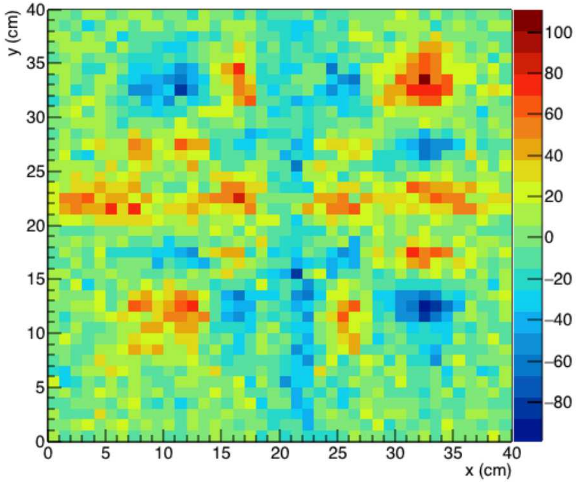
^{252}Cf inside 7” polyethylene vs. 7” borated polyethylene sphere



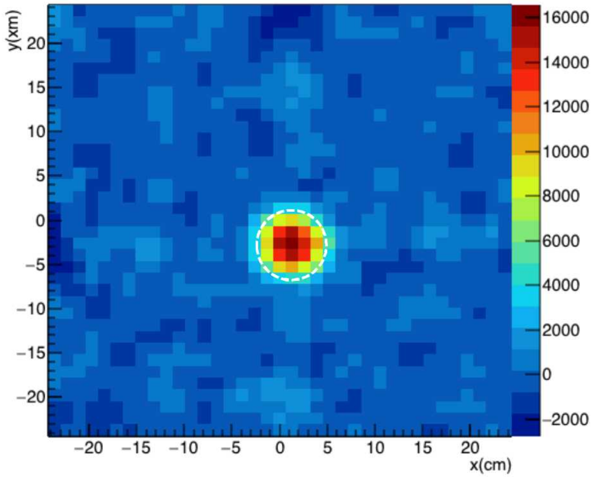
- Fast neutron image shows point source from ^{252}Cf
- Thermal image shows polyethylene moderator edge
- Borated polyethylene sphere shows some leakage, but thermal source strength is cut by ~6x

Bare BeRP Ball – 12 mins total

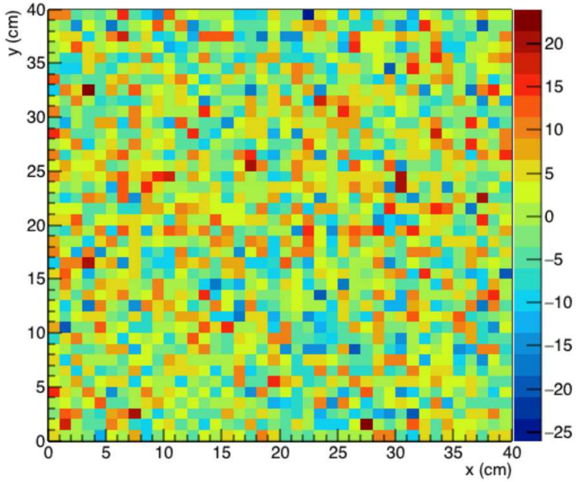
Raw Fast Neutron Data



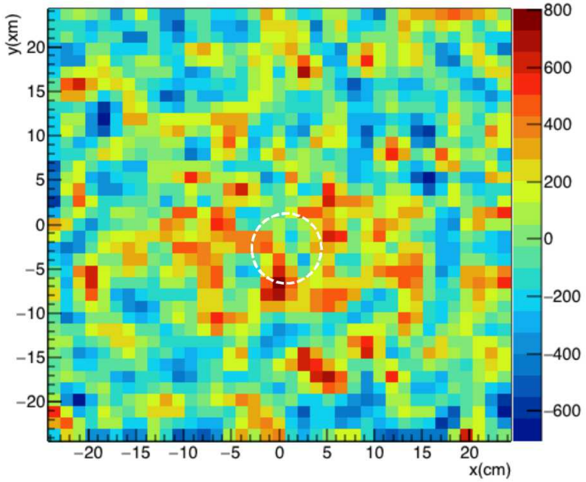
Fast Neutron



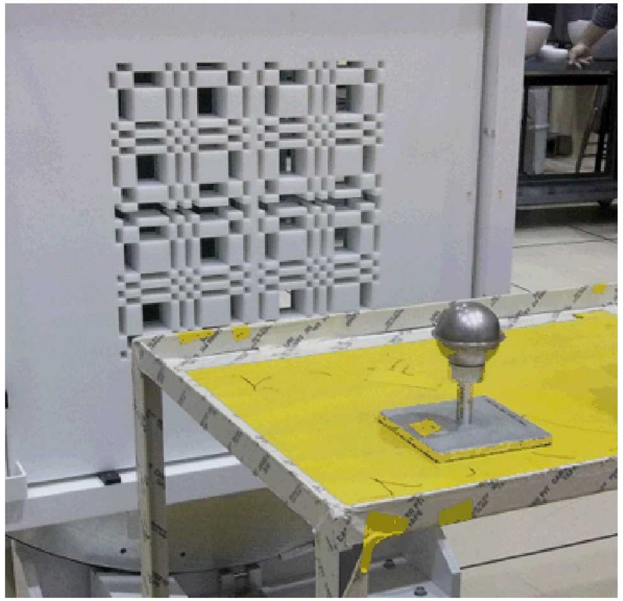
Raw Thermal Data



Thermal Neutron



- BeRP Ball:
  - 3.8 cm radius sphere
  - 4.5 kg WGPu



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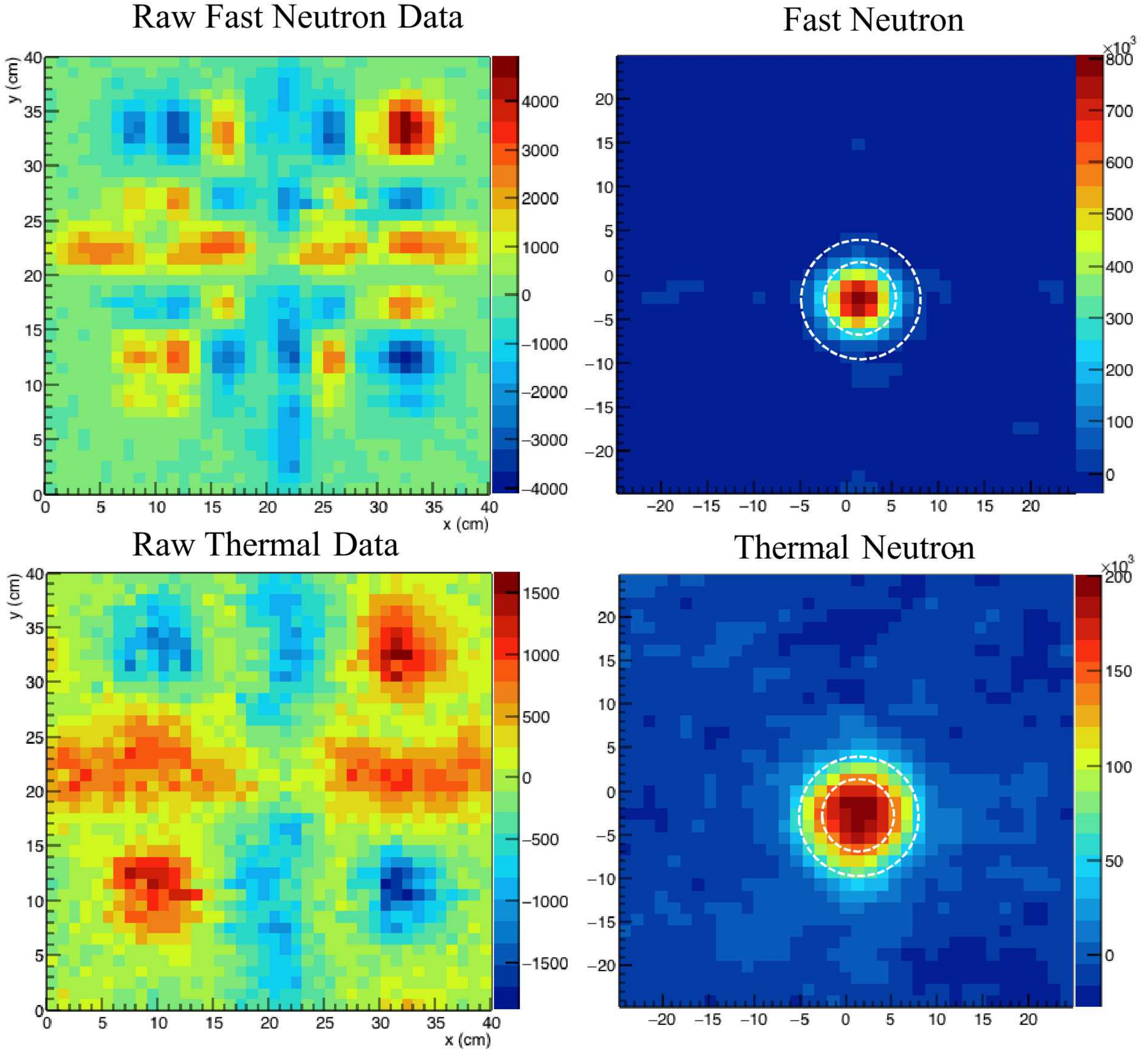
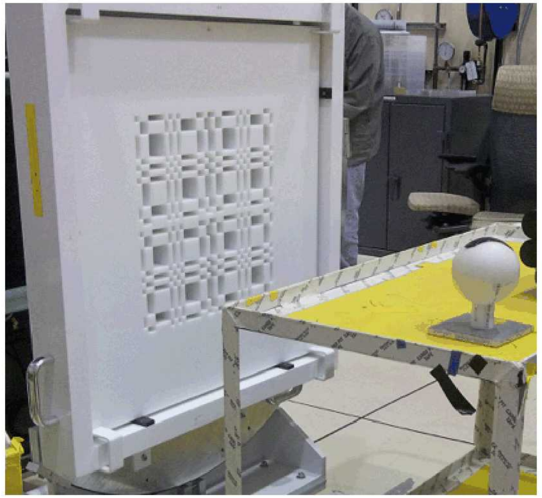
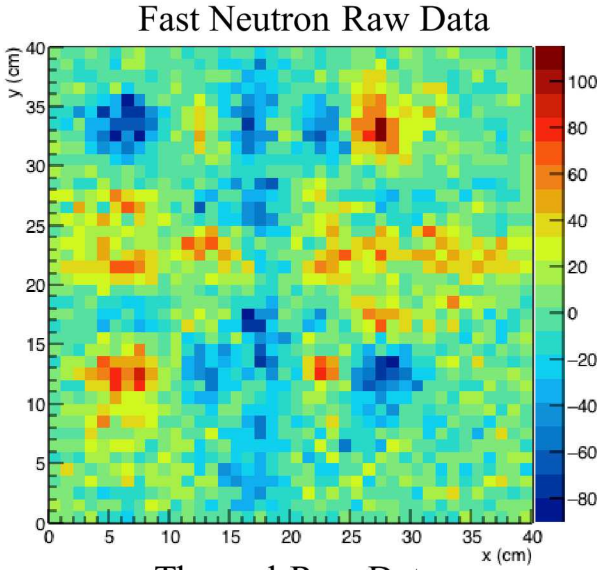
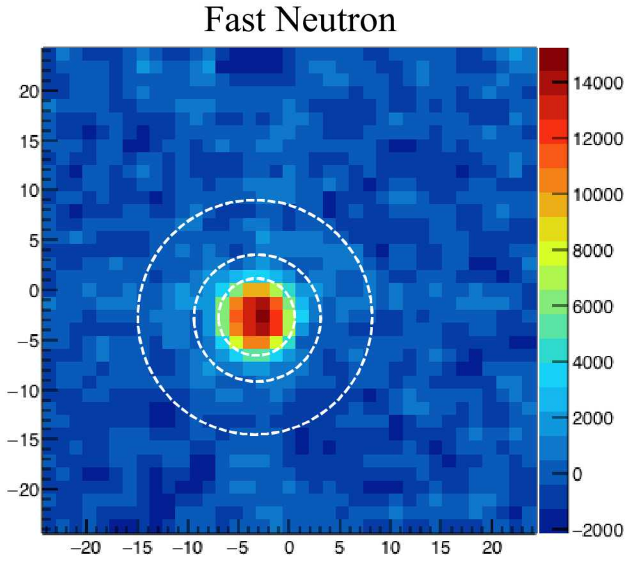
BeRP Ball with 1” Poly – 15 hours total

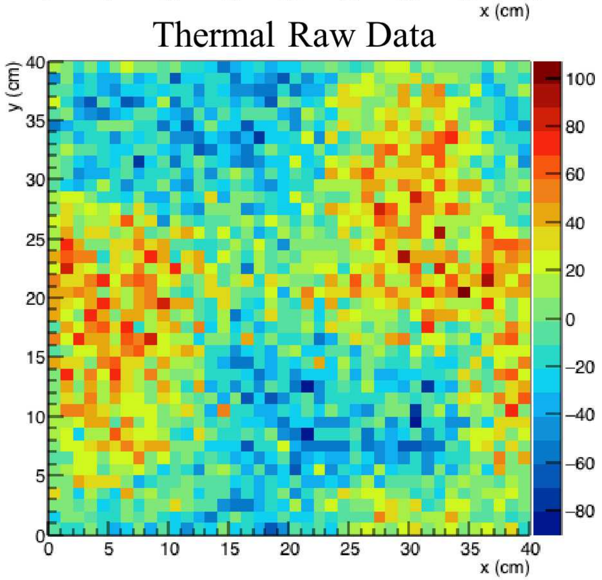


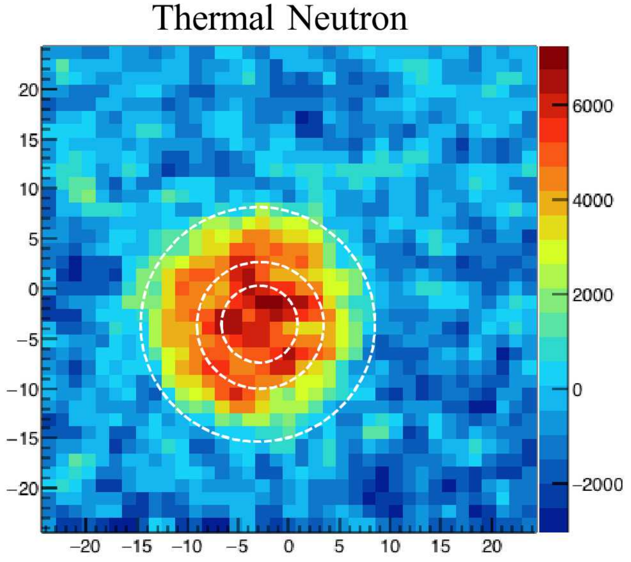


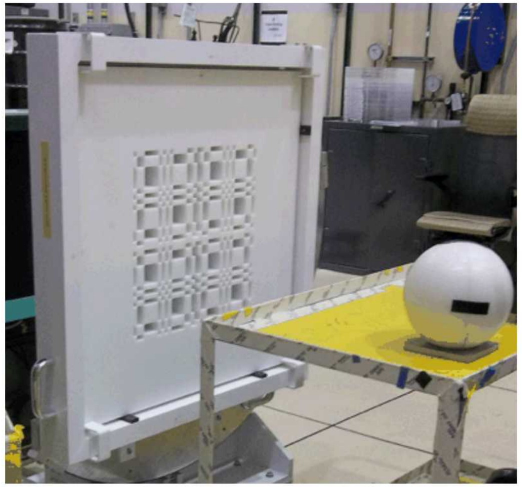
BeRP Ball with 1” void, 2” Poly – 28 mins total



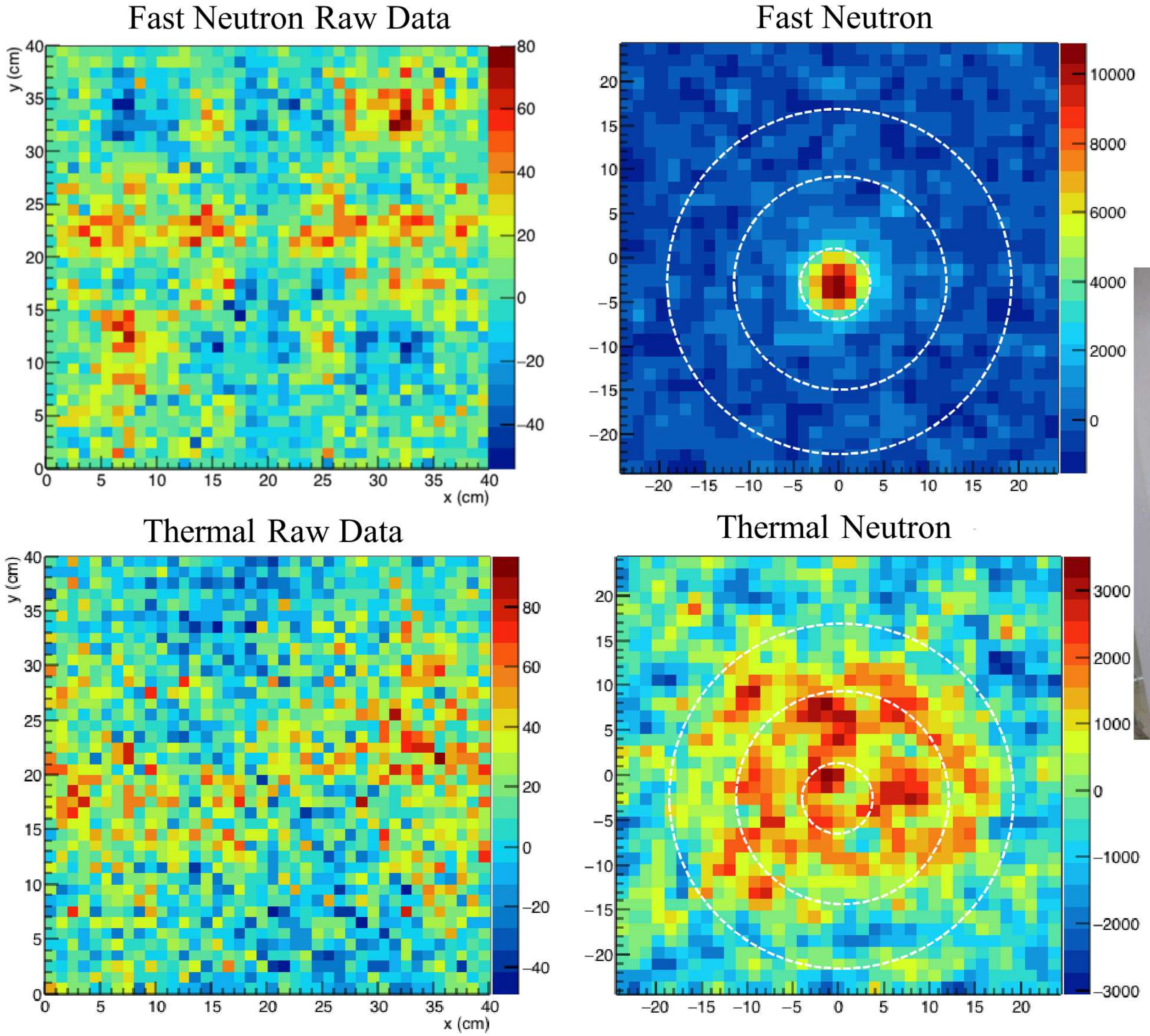


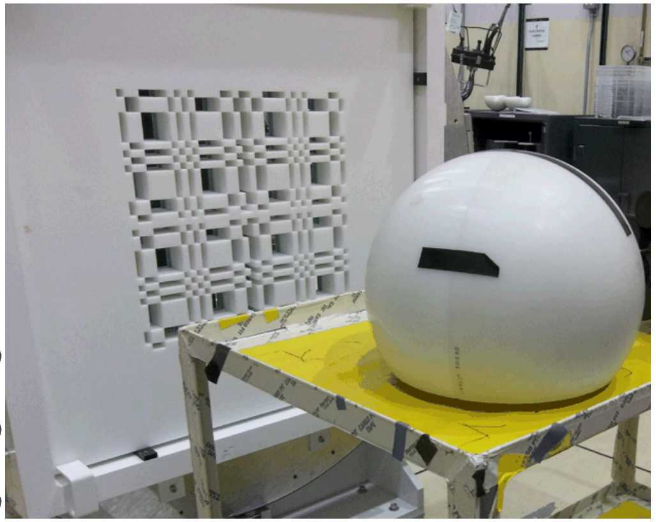




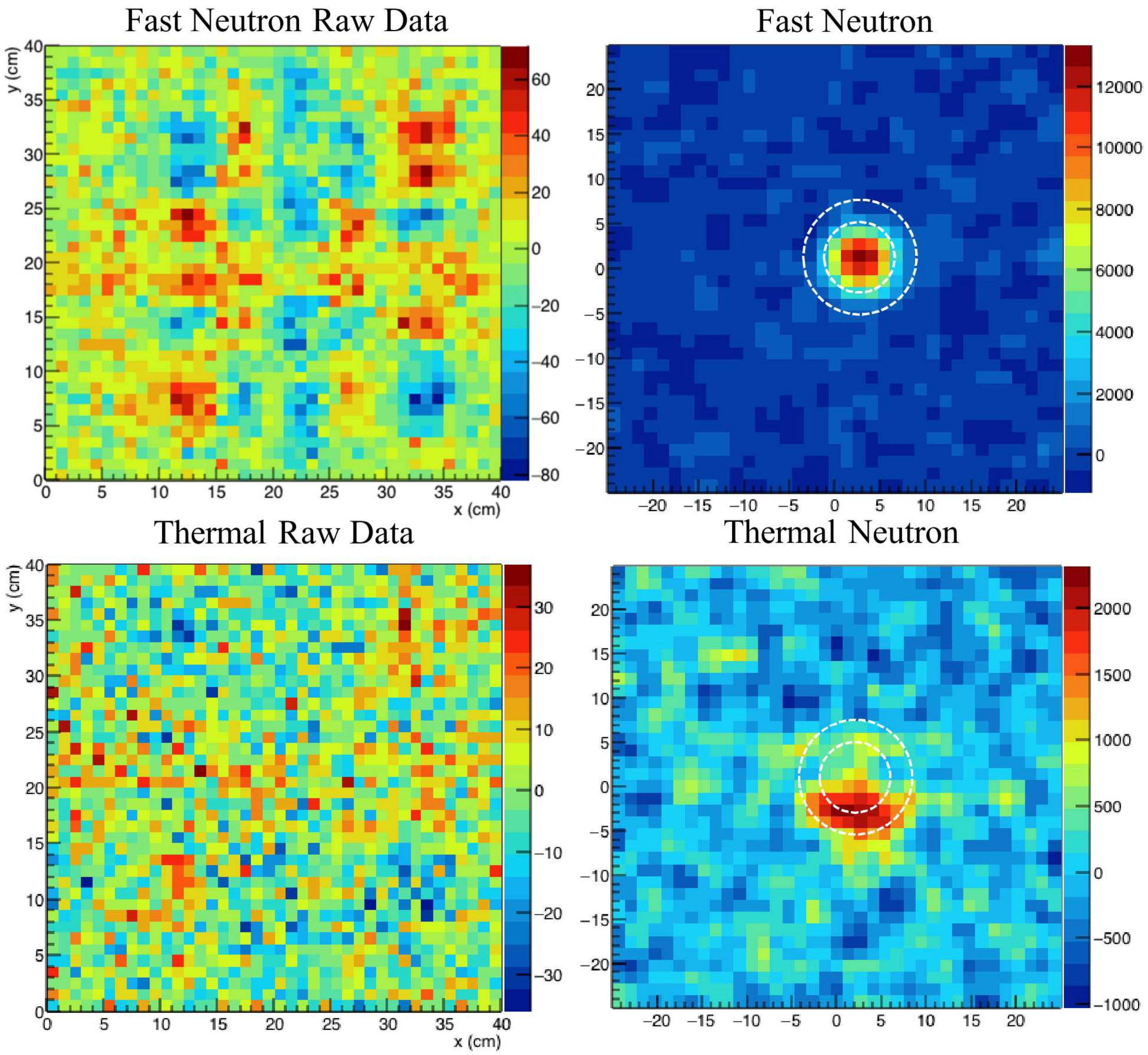


BeRP Ball with 3 inch void, 3 inch Poly – 48 mins total





BeRP Ball with 1.25" Poly Hemi – 16 mins total



Gamma coded aperture

What is different for gammas?

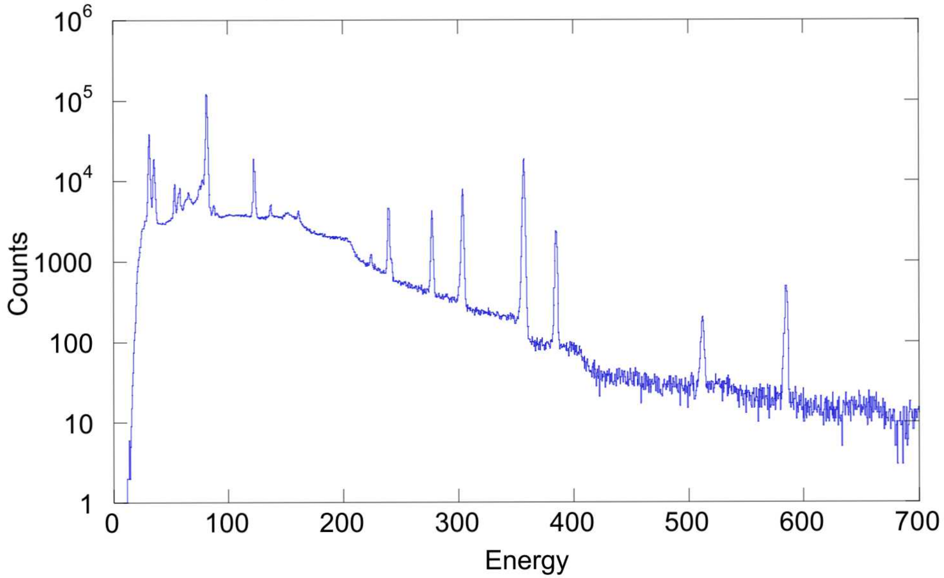
- Physics of gamma production (well-defined decay lines)
- Physics of gamma interactions
- Typically higher rates

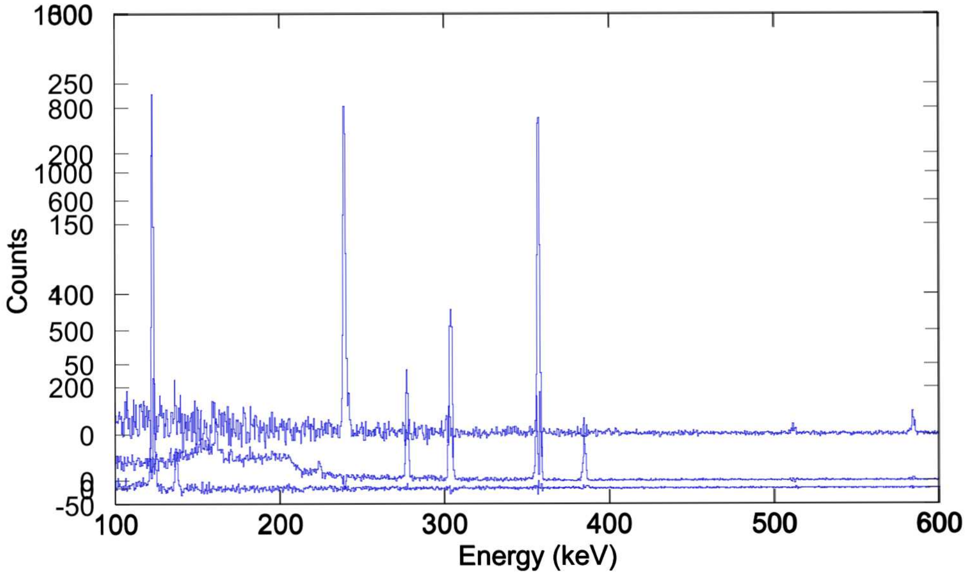
↓

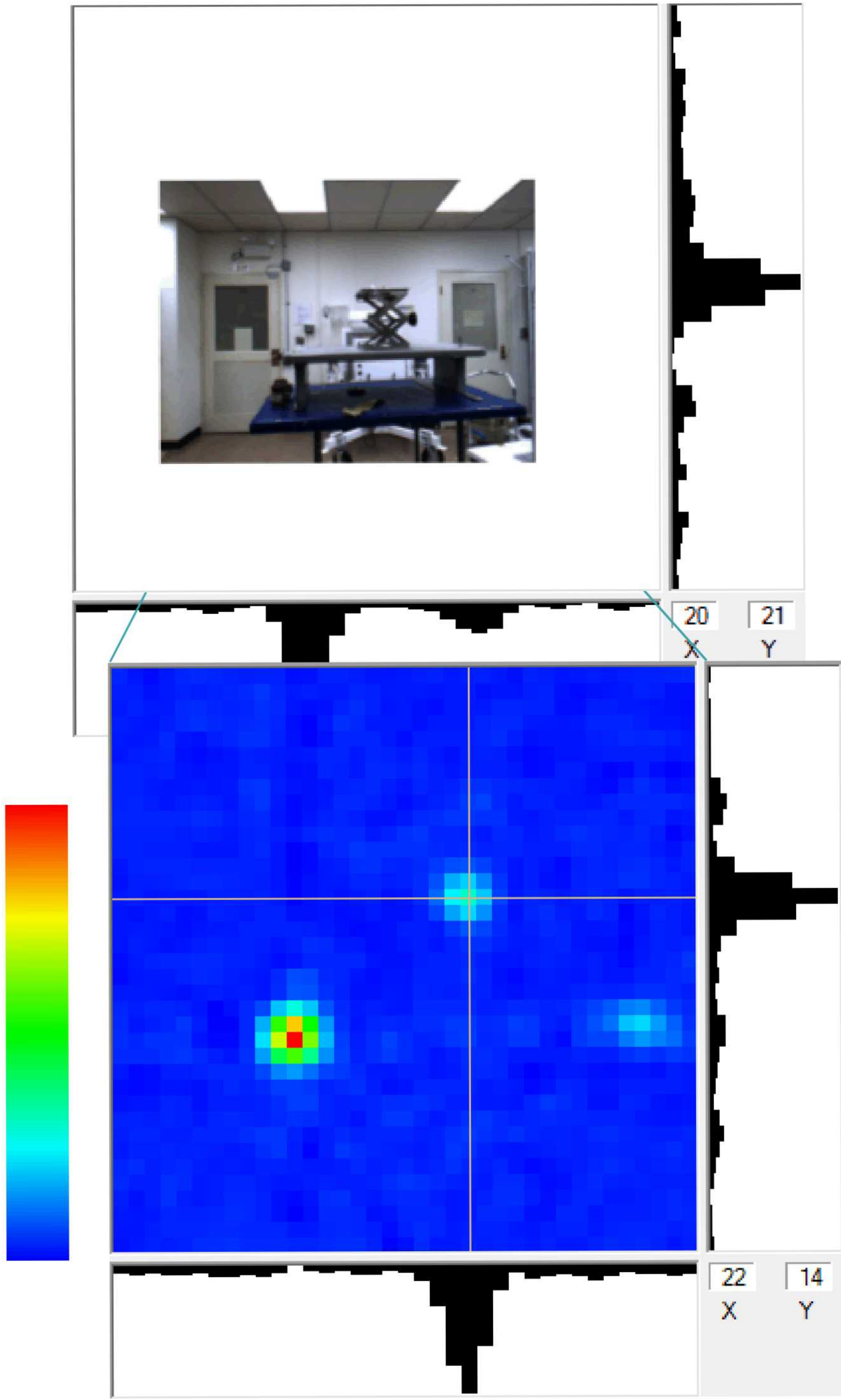
- Detector material: NaI, HPGe, CZT
- Mask material: high-Z (lead, tungsten, etc.)
- Detector/mask thickness
- Spectroscopy

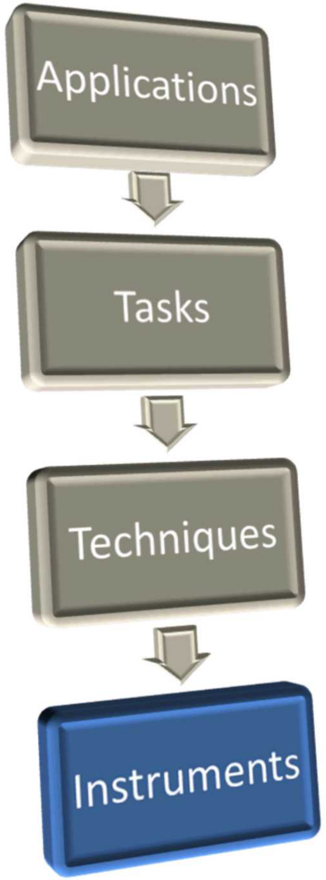
ORNL HPGe Coded-Aperture Imager

Thanks to
Klaus Ziock (ORNL)









TEI-2D

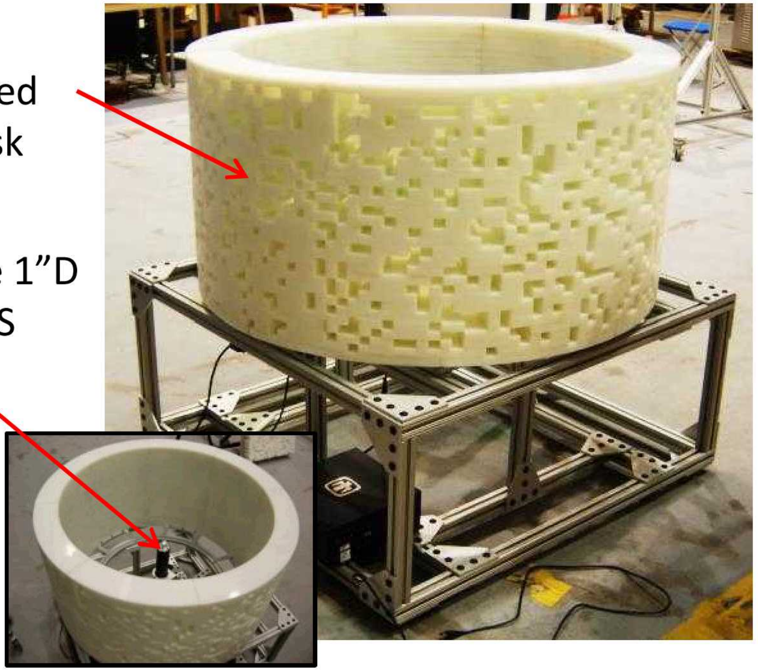
Many SNL contributors:

Peter Marleau
Melinda Sweany
Nathalie Le Galloudec
Mark Gerling
Aaron Nowack
Jim Brennan
Etc.

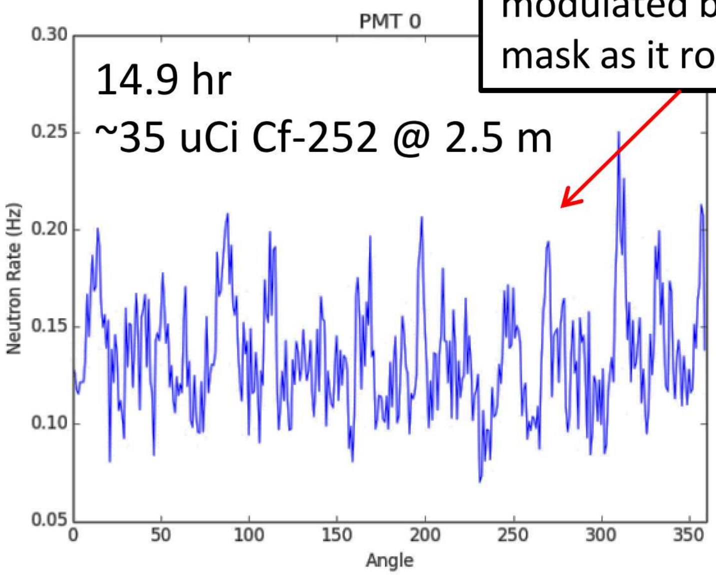
TEI-2D demonstration system

2-d coded mask

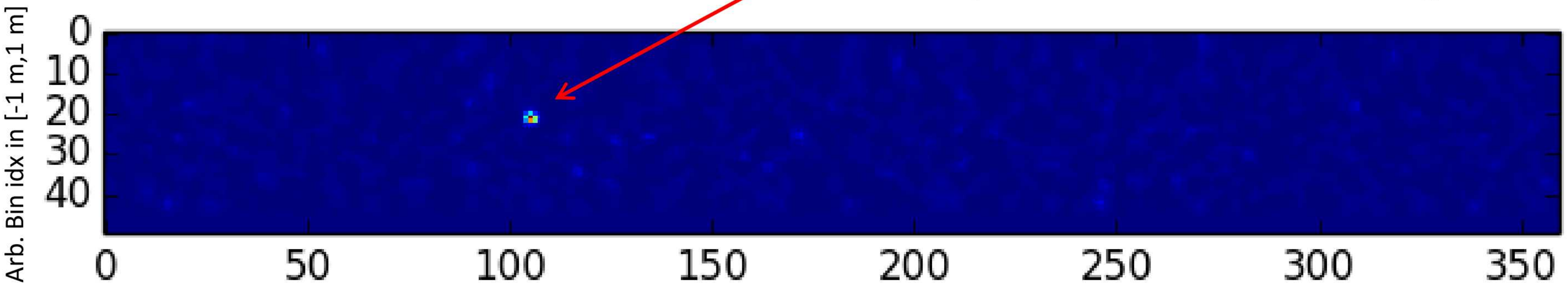
Single 1"D x 1" LS pixel



Single pixel rate is modulated by the mask as it rotates.



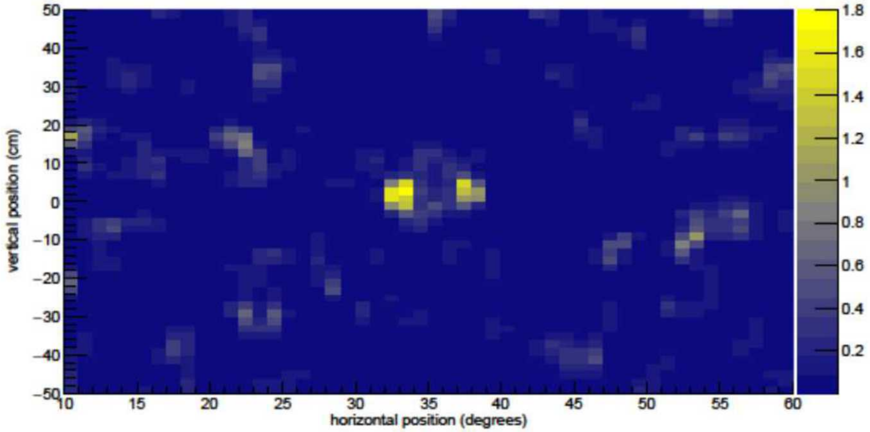
Modulation pattern is unfolded to 2-D image



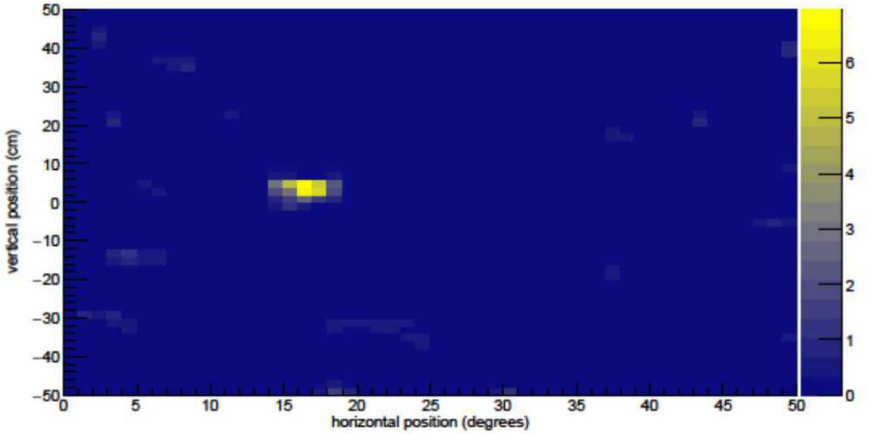
TEI-2D results (1)

Two 1.4e5 n/s ^{252}Cf point sources at 2 m distance from center of detector.

5 degree separation in 1 hour
(50 mlem iterations)



2 degree separation in 24 hours
(250 mlem iterations)

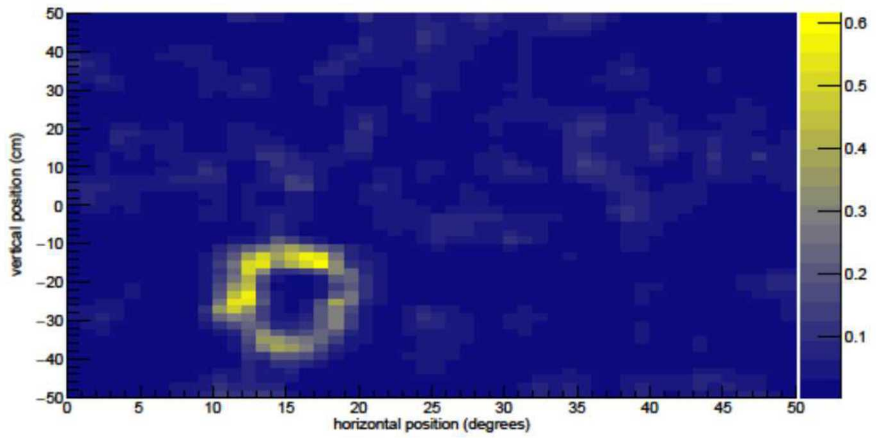


NIM A, **802** (2015) p. 76

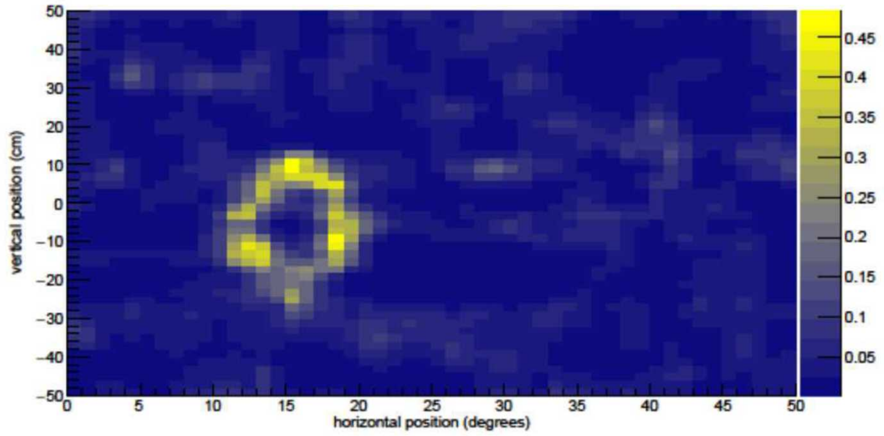
TEI-2D results (2)

Single 1.4e5 n/s ^{252}Cf point source moved through a ring pattern at 2 m distance.

Location 1: 72 hr
(100 MLEM iterations)



Location 2: 94 hr
(100 MLEM iterations)



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What is it good for?

- TEI-2D provides cm-scale neutron emission image resolution with a single detector channel
- Requires long measurement times
  - Reduce somewhat by adding cells (more detectors)
  - Or by worsening resolution (larger detector)
- Potentially applicable when simple, robust detector is attractive, long dwell time acceptable
  - Arms control treaty verification (CONFIDANTE)
  - Material holdup measurements
  - Monitored material storage

Sandia National Laboratories

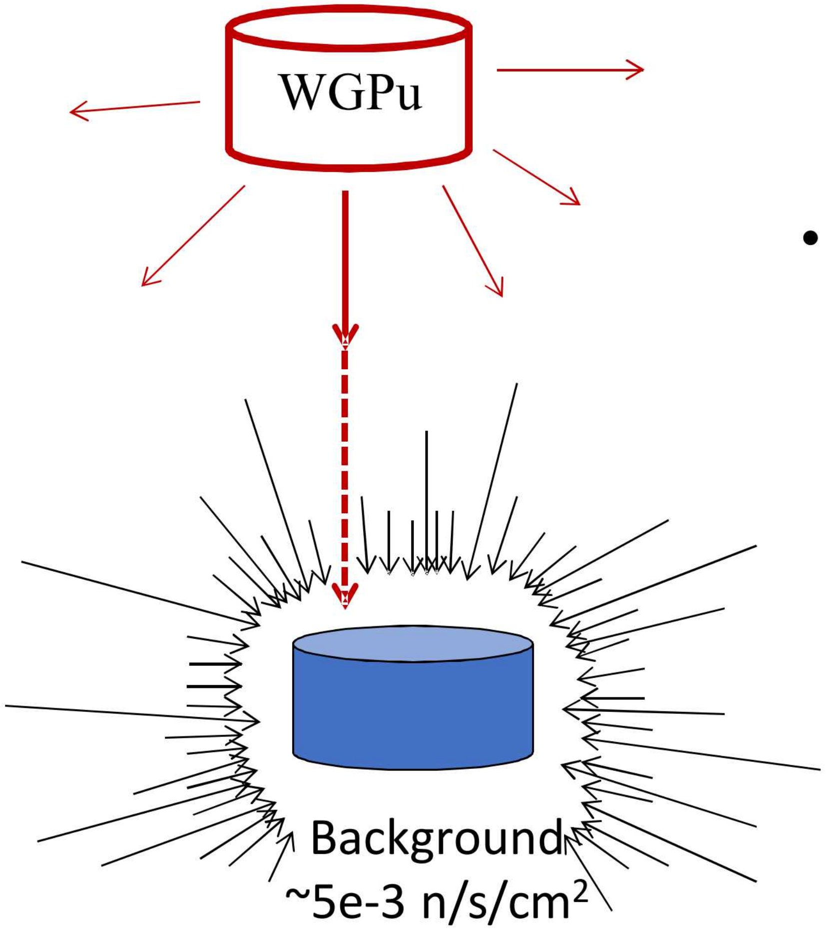
TEI-1D

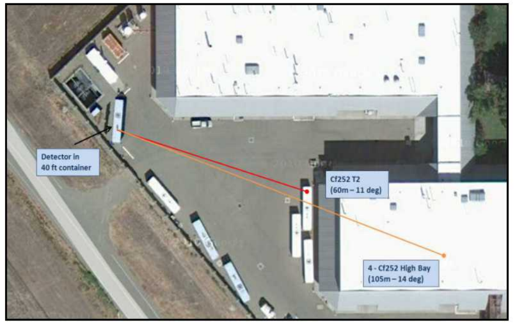
Many SNL contributors:

Peter Marleau
Melinda Sweany
Patricia Schuster
Aaron Nowack
Mateusz Monterial
Jim Brennan
Dan Throckmorton
Etc.

Standoff detection

~5.5e4 n/s/kg
IAEA sig = 8 kg





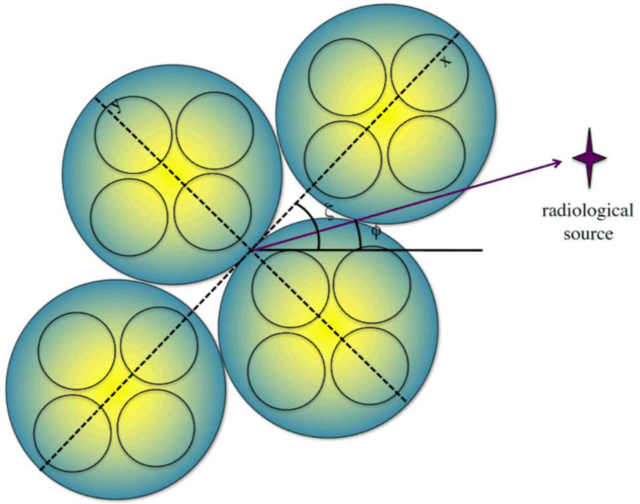
- Example: Large stand-off application (100 m)
  - 8 kg WGPu = ~4.4e5 n/s →
    4.4e5 *exp(-R/100)/4πR^2 $\approx$**1.3 n/s/m^2**
  - Background = ~**50 n/s/m^2** (at sea level)
  - 100% efficient, 1 m^2 detector →
    5σ detection in **~13 minutes**
  - 10% efficient, 1 m^2 detector →
    5σ detection in **~2 hours**
  - 10% efficient, 1 m^2 detector,
    3% bg rate systematic →
    5σ detection in **never**

Directional information, however, allows to simultaneously measure signal and background, change **never** to **< never**.

TEI-1D demonstration system

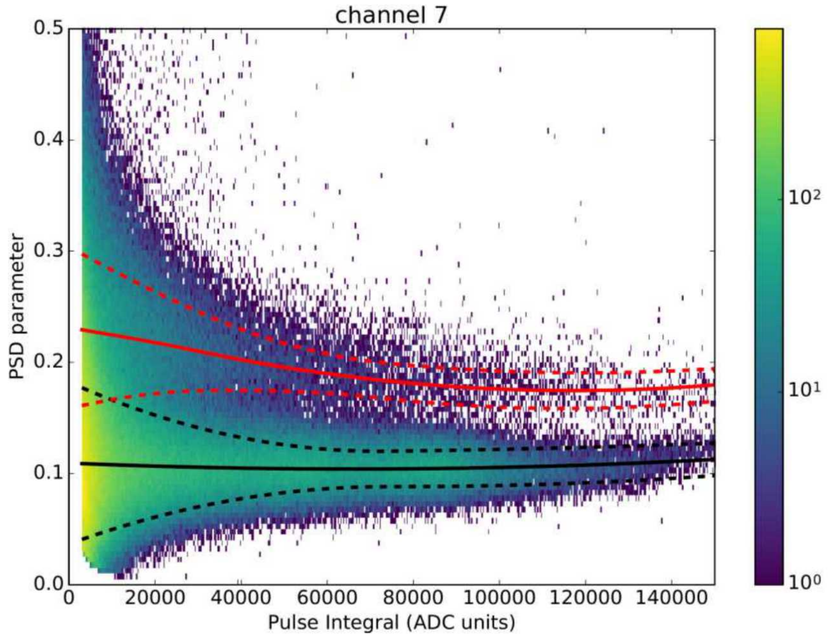
- Detector effective area is key.
  - 27 L of scintillator x 4 cells
- Use self-modulation to add some directional information—discriminate localized threat source from diffuse background

- Four large cells: 12”D x 15” LS
- Read out with 4x 5” PMTs each
- Configured in diamond pattern
- Placed on rotating turntable
- Each cell is analyzed independently

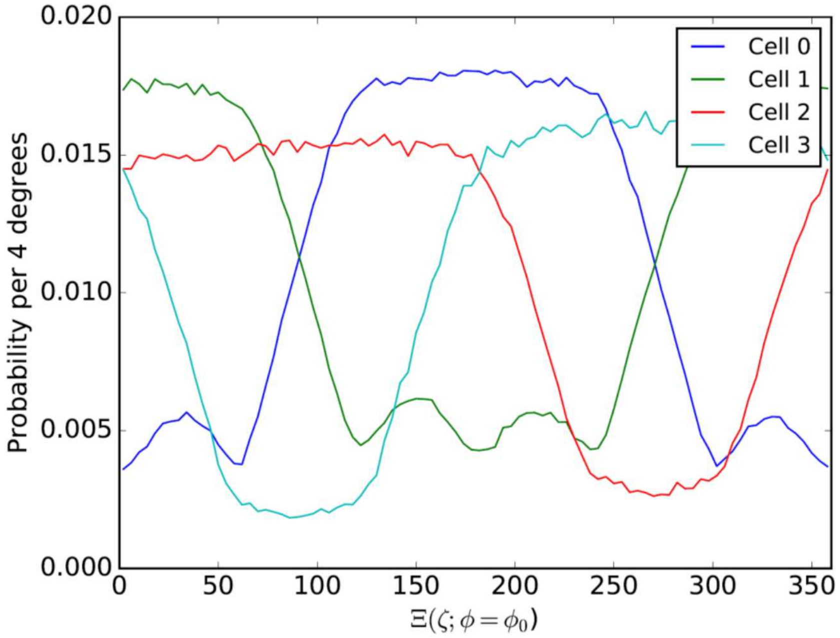


Detector calibration

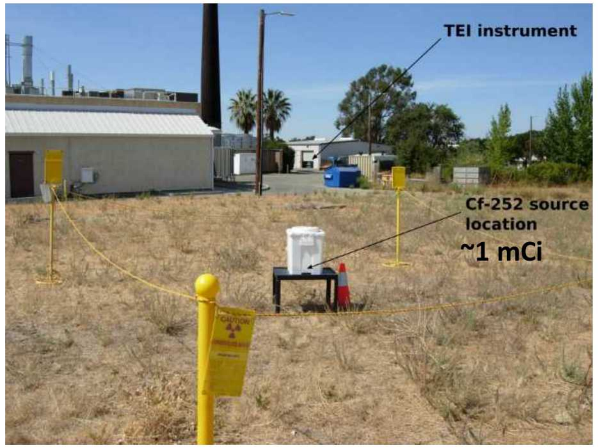
Pulse shape discrimination: biggest challenge in large-volume cells



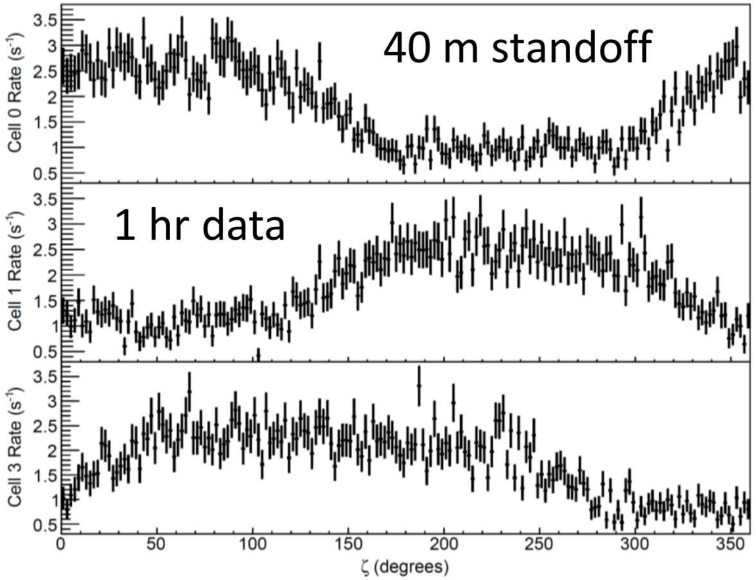
Modulation function: broad features, goal is detection, not resolution

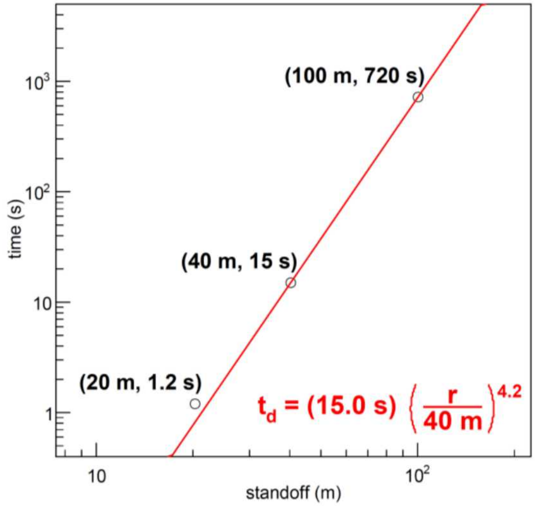


Standoff detection results

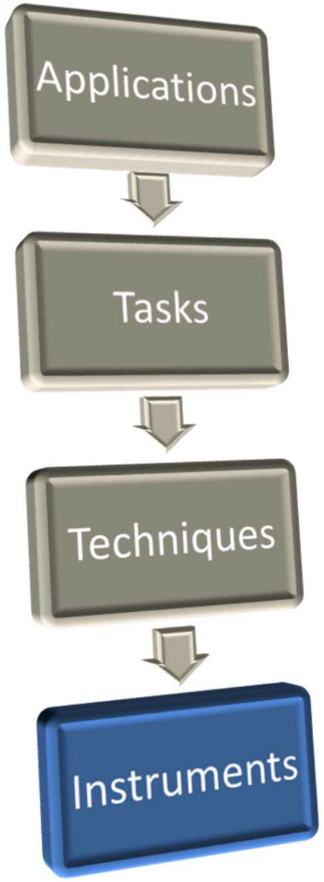


- ~1 mCi Cf-252 source at 20 m, 40 m, 100 m standoff
- Only 3 working detectors
- Detection (90% TP, 10% FP) at 100 m in 720 s





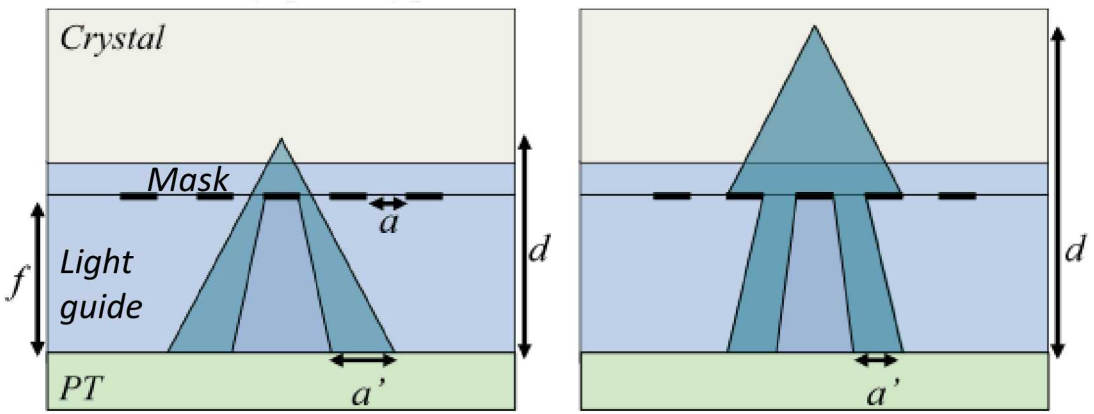
NIM A, doi:10.1016/j.nima.2017.09.052



SVSC/OCA

Interaction resolution via optical coded aperture

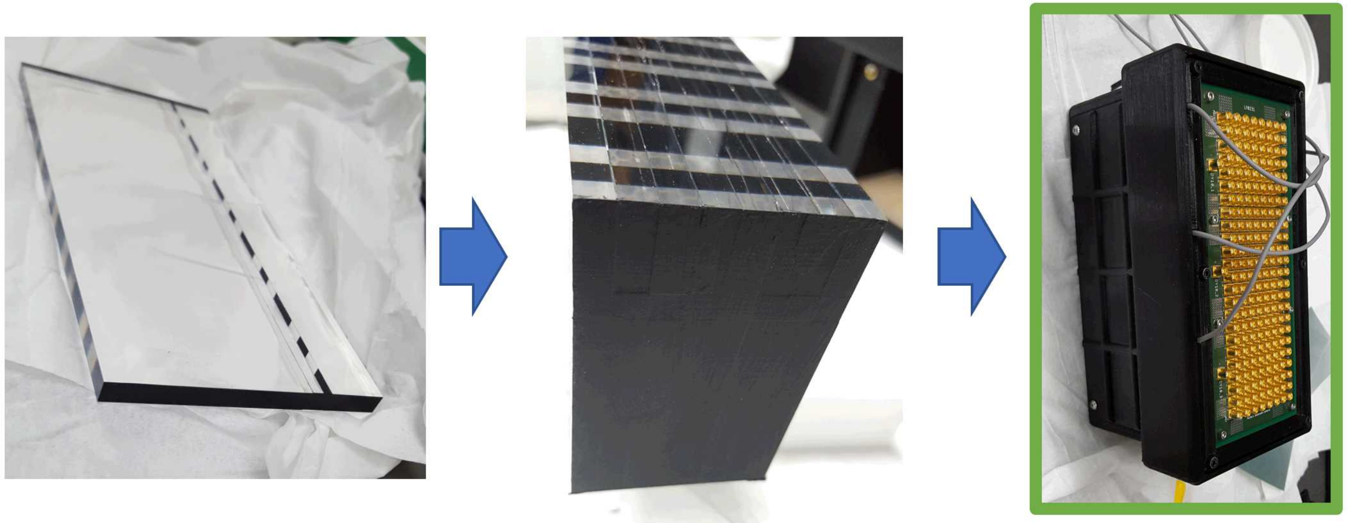
- So far, coded aperture was for the energetic radiation (n,γ)
- But can use optical coded aperture (OCA) for scintillation light itself -> resolve interaction position in a bulk scintillator
- Supports various imaging modalities

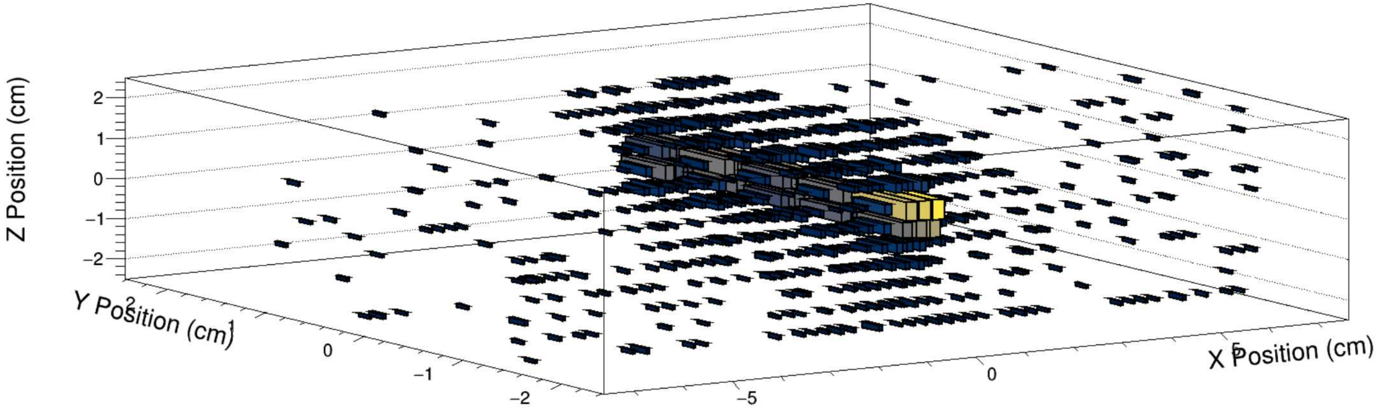


Klaus Ziock / Micah Folsom (ORNL/UTK)

Neutron scatter camera using OCA

- Micah Folsom (UTK/ORNL) built a detector comprising a stack of organic scintillator slabs, each with a 1-D OCA
- Position resolution in x via coded pattern shifts, y via slab ID, z via coded pattern magnification
- Calibrated position results using gamma beam from collimated Ba-133 source



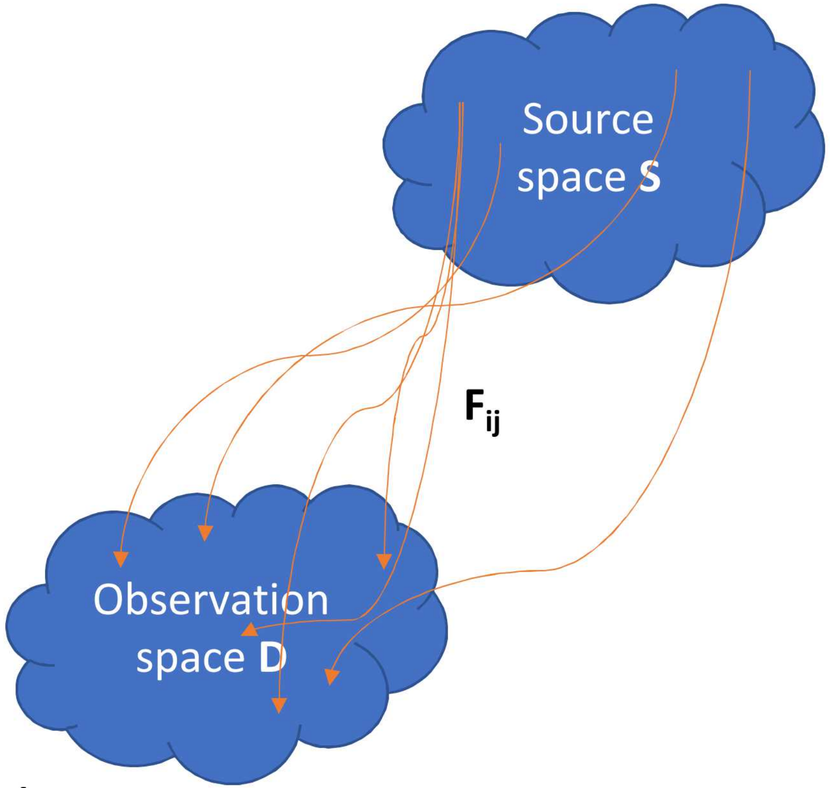


Conclusions

- System parameters (esp. physical dimensions) drive tradeoffs:
  - Sensitivity vs resolution
  - Field of view vs zoom
  - Capability vs complexity
  - Etc.
- Wide range of aperture-based radiation imaging systems:
  - High-resolution coded aperture imaging
  - Single-detector time-encoded imaging
  - Large, high-sensitivity time-encoded imaging
- Together with double-scatter imaging (Will’s presentation) and transmission imaging (x-ray, neutron radiography), elements of toolkit for imaging with energetic radiation

Other topics

General image reco problem



- Consider a scenario defined by:
  - Consider binned spaces for simplicity
  - A source space **S** (s_j)
    - e.g. 1 m x 1 m plane at 3 m from the detector
    - e.g. spherical coordinates (theta,phi) in the far field
  - An observation space **D** (d_i)
    - e.g. detector pixel ID in a coded aperture system
    - e.g. (d**x**,dt,E_1) for a SVSC (5 dimensional space!)
  - A set **F** (F_{ij}) of probability density functions connecting them.
    - $\text{Sum}_i(F_{ij}) = 1$ (or $= \varepsilon_j$): For each source location j, the probability to observe the event in the various detector bins is a p.d.f. (normalized or unnormalized)
- Then for a given source distribution **s**, we expect to observe **d**=**Fs**
- How to solve the inverse? Given **d**, what is **s**?

Iterative methods

- Then for a given source distribution **s**, we expect to observe **d**=**Fs**
- How to solve the inverse? Given **d**, what is **s**?
- Simple! **s**=**F**$^{-1}$**d**, right?
  - Oops, **F**$^{-1}$ may be difficult to compute
  - Even more oops, in many cases **F** is only approximate, and inverse is ill-conditioned, so **F**$^{-1}$ is not reliable
- Need a solution that takes into account response **F**, and also measurement noise—in our case mostly Poisson stats
  - **d**=**Fs** is just the expected value; really $d_i \sim \text{Pois}((\mathbf{Fs})_i)$
  - Likelihood $L = \Pi_i(\text{Poisson}(d_i,(\mathbf{Fs})_i)$
  - Just need to maximize L over **s**: $\hat{\boldsymbol{s}} = (\arg\max)_{\boldsymbol{s}} L$
  - Pushes us toward iterative methods

Maximum likelihood expectation maximization (MLEM)

- ML vs MLEM
- Shepp and Vardi (1982):

the likelihood function is given by

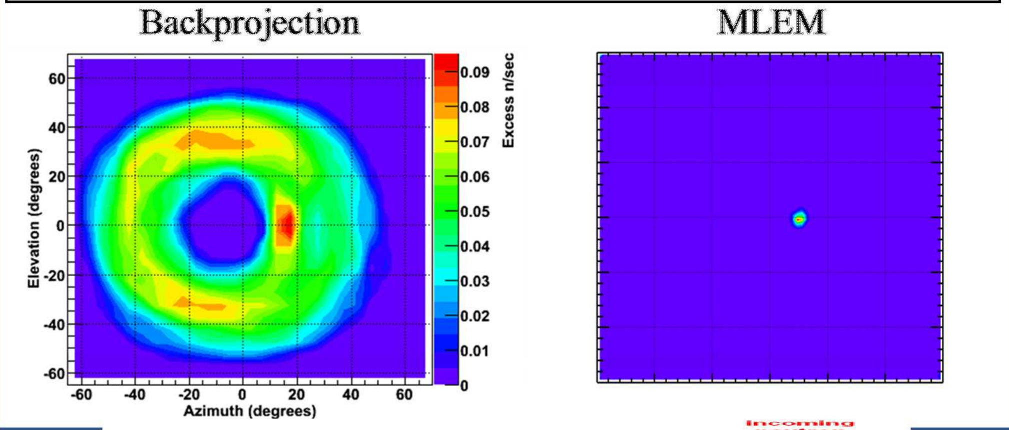
$$L(\boldsymbol{\lambda}) = P(\boldsymbol{n}^* | \boldsymbol{\lambda}) = \sum_{A} \prod_{\substack{b=1,\cdots,B \\ d=1,\cdots,D}} e^{-\lambda(b,d)} \frac{\lambda(b,d)^{n(b,d)}}{n(b,d)!}$$

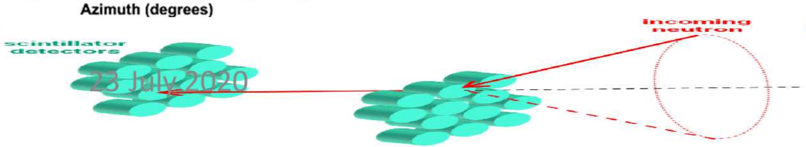
Tedious, extremely obvious math that I won't bore you with

Under fairly general conditions, this iterative update equation converges to mathematically (!) optimal solution:

$$\hat{\lambda}^{\text{new}}(b) = \hat{\lambda}^{\text{old}}(b) \sum_{d=1}^{D} \frac{n^*(d)\, p(b,d)}{\sum_{b'=1}^{B} \hat{\lambda}^{\text{old}}(b')\, p(b',d)}, \qquad b = 1, \cdots, B.$$

Neutron scatter camera with planes pulled apart





System response function

- All more complex image reconstruction methods (iterative techniques) require a system response function to be defined.
- First question, what are the source and observation spaces **s**,**d**?
- How to estimate the response **F**?
  - Data (best fidelity, tedious, depends on environment)
  - Monte Carlo (lots of CPU, large uncertainties in low-probability regions)
  - Pseudo-MC (equal uncertainties across regions, not necessarily faster)
- This is the hardest part! Once you have **F**, there are lots of options for the reconstruction method itself!

More MLEM

- Standard MLEM issue: what is the stopping condition?
  - More iterations converge to mathematically optimal answer, but that may not be real-world optimal!
  - Can stop after a certain number of iterations, but no generally accepted way to choose that
- Can add regularization terms to the likelihood.
  - E.g. a term that penalizes high-frequency changes
  - Or, edge-preserving prior
  - But, for generic terms added to the likelihood, Shepp & Vardi iterative update equation no longer applies; need more complicated minimization methods e.g. surrogate functions
  - Alenius, Sakari, and Ulla Ruotsalainen. "Generalization of median root prior reconstruction." *IEEE Transactions on Medical Imaging* 21.11 (2002): 1413-1420.
- What is list-mode likelihood?

Stochastic Origin Ensembles (SOE)

- Based on Markov Chain MC methods (Metropolis-Hastings)
- Source density **s** as the thing to be estimated
- Each event came from one particular location on its cone
- Use the density itself to "walk through" the posterior distribution of the density
  - First set of iterations converges on the right neighborhood
  - Further iterations map out posterior distribution

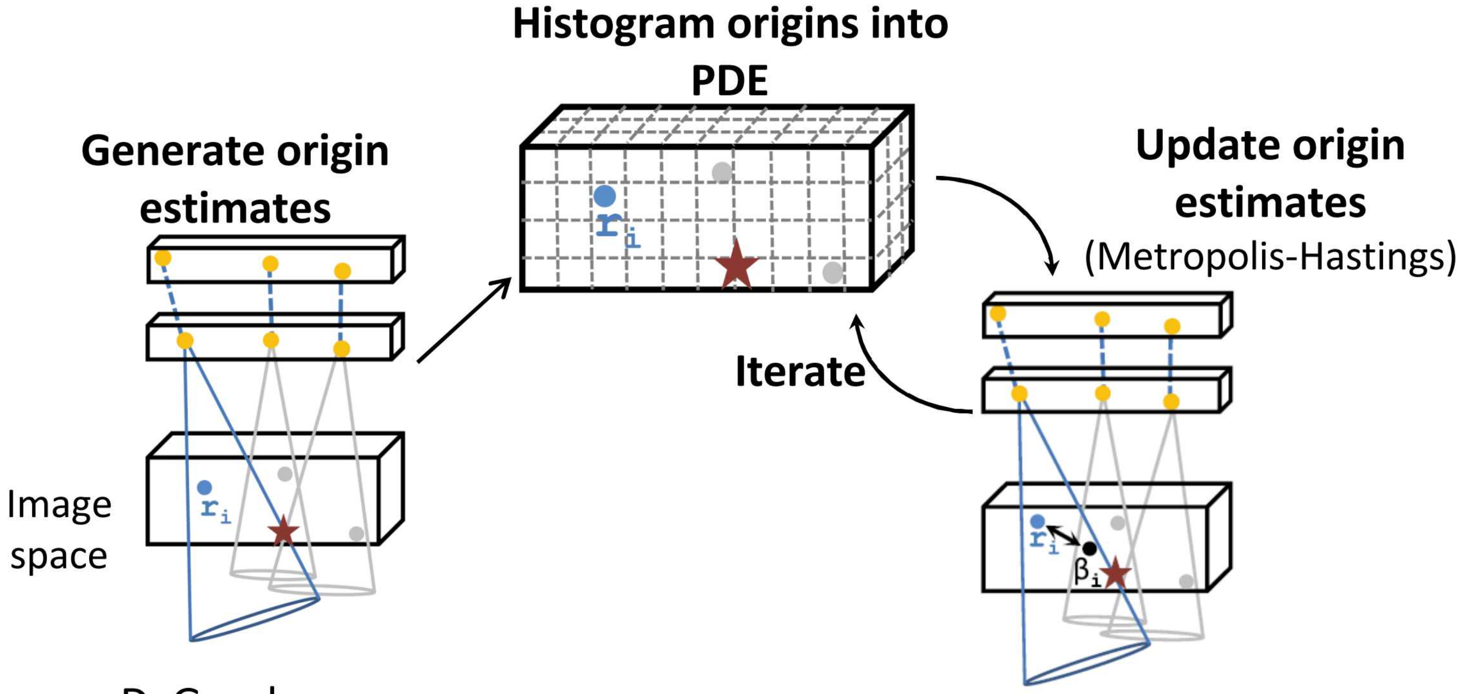


Image: D. Goodman

[1] D. Mackin *et al.* 2012

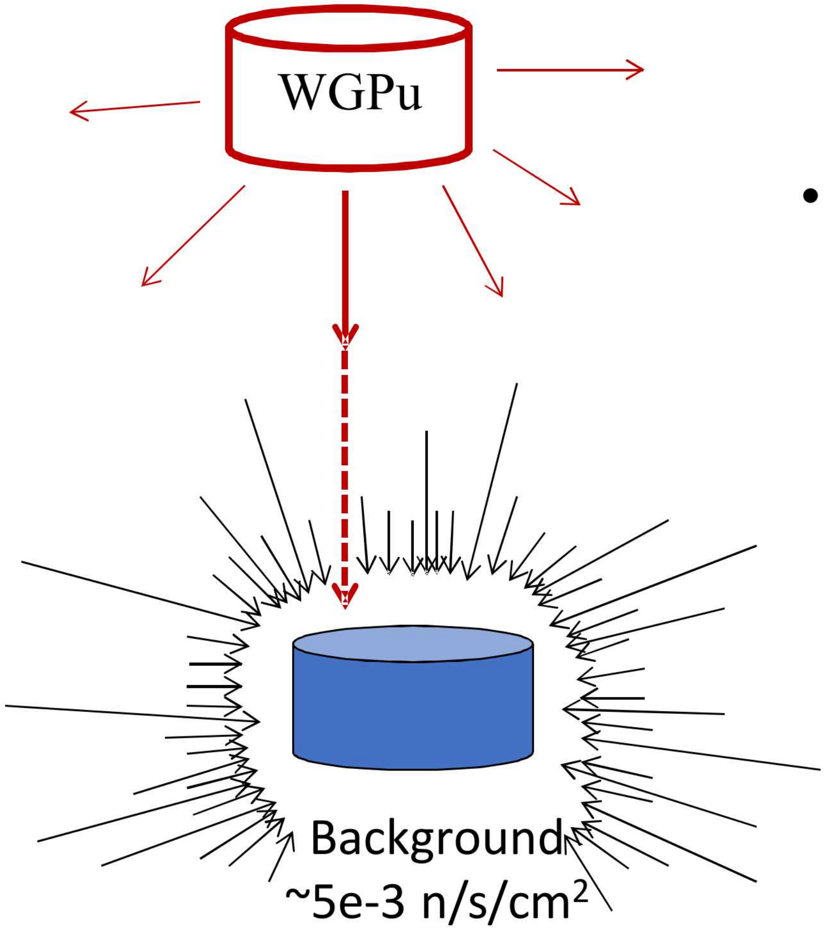
Additional image reconstruction methods

- SOE: stochastic origin ensemble
- MLE: maximum likelihood estimation (for point source reconstruction)
- Sparsity condition (compressive sensing)

- Machine learning—e.g. (de)convolutional neural network
  - Only one that _may_ not require high-quality system response function

Standoff detection

~5.5e4 n/s/kg
IAEA sig = 8 kg



Case: background unknown

- Example: Large stand-off application (100 m)
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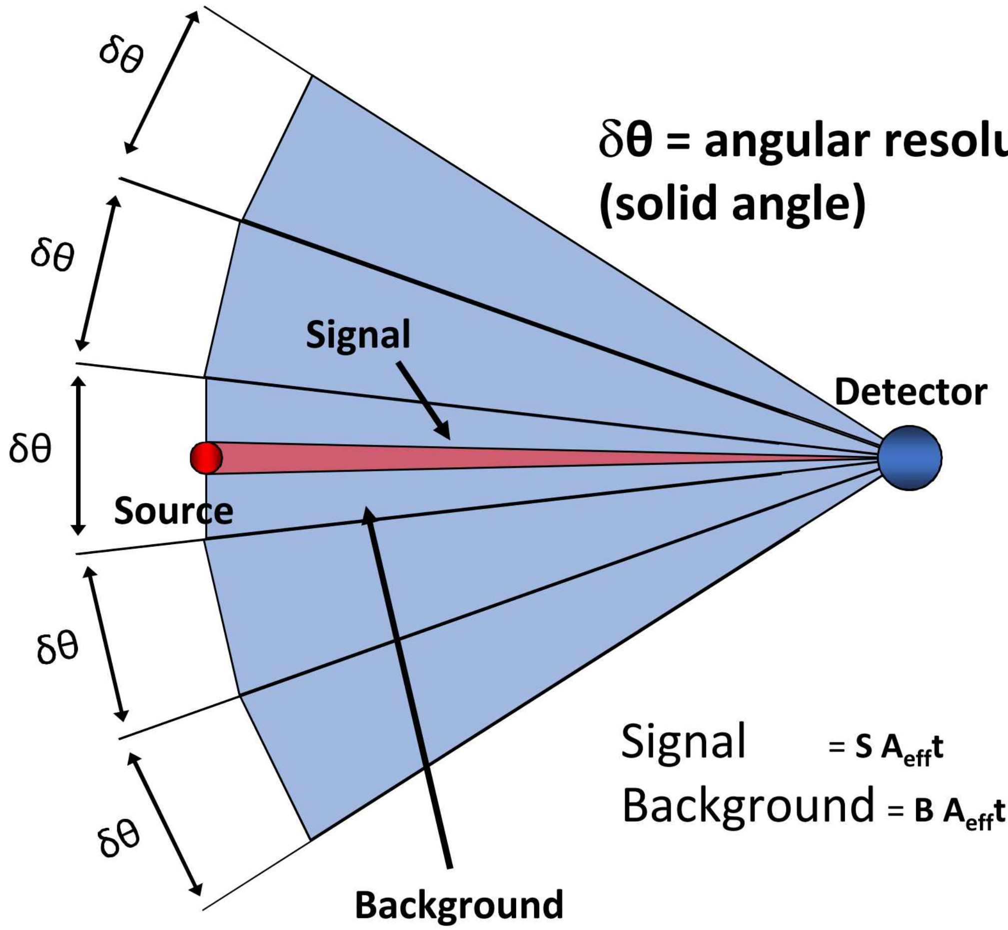
Directional information, however, allows to simultaneously measure signal and background, change **never** to **< never**.

Detection again

Case: background known

- What about when the background is independently known?
  - Example: portal monitor. Effectively have repeated background measurements in between occupancies.
  - Example: building monitoring. Looking for changes in the rad field due to an approaching source.
- Now is there an advantage from imaging?
  - Cartoon at right due to Peter Marleau.
  - But real imagers do not have simple angular resolution like cartoon.
  - Also generally take a hit on efficiency.

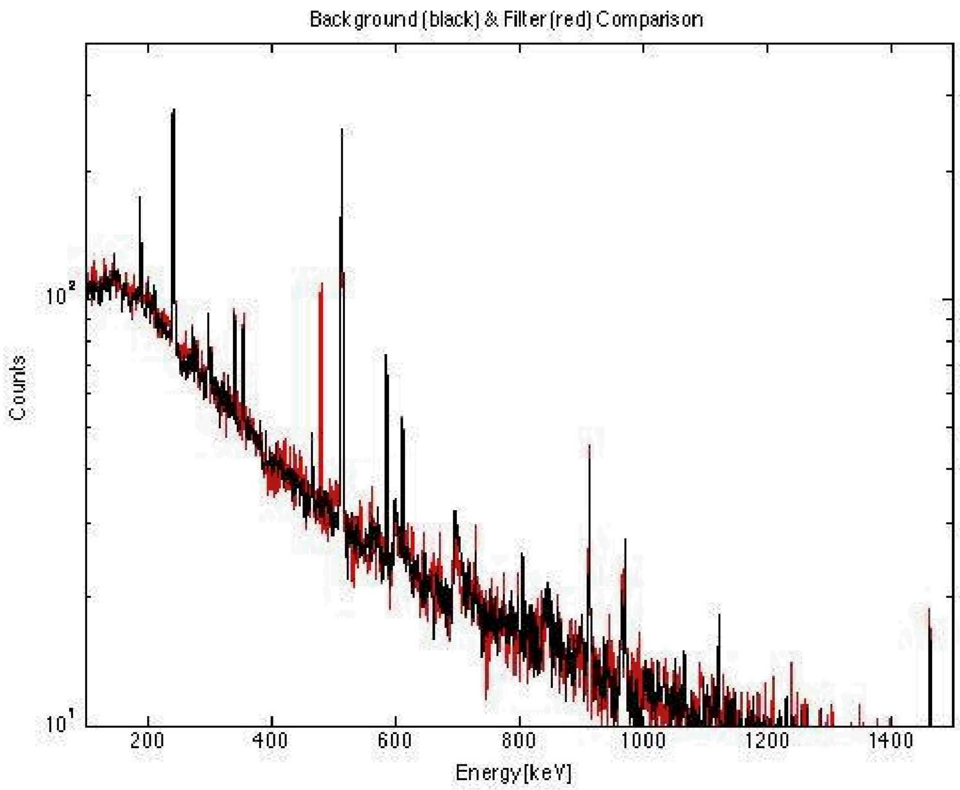


$\delta\theta$ = angular resolution (solid angle)

Signal = $S\, A_{eff} t$

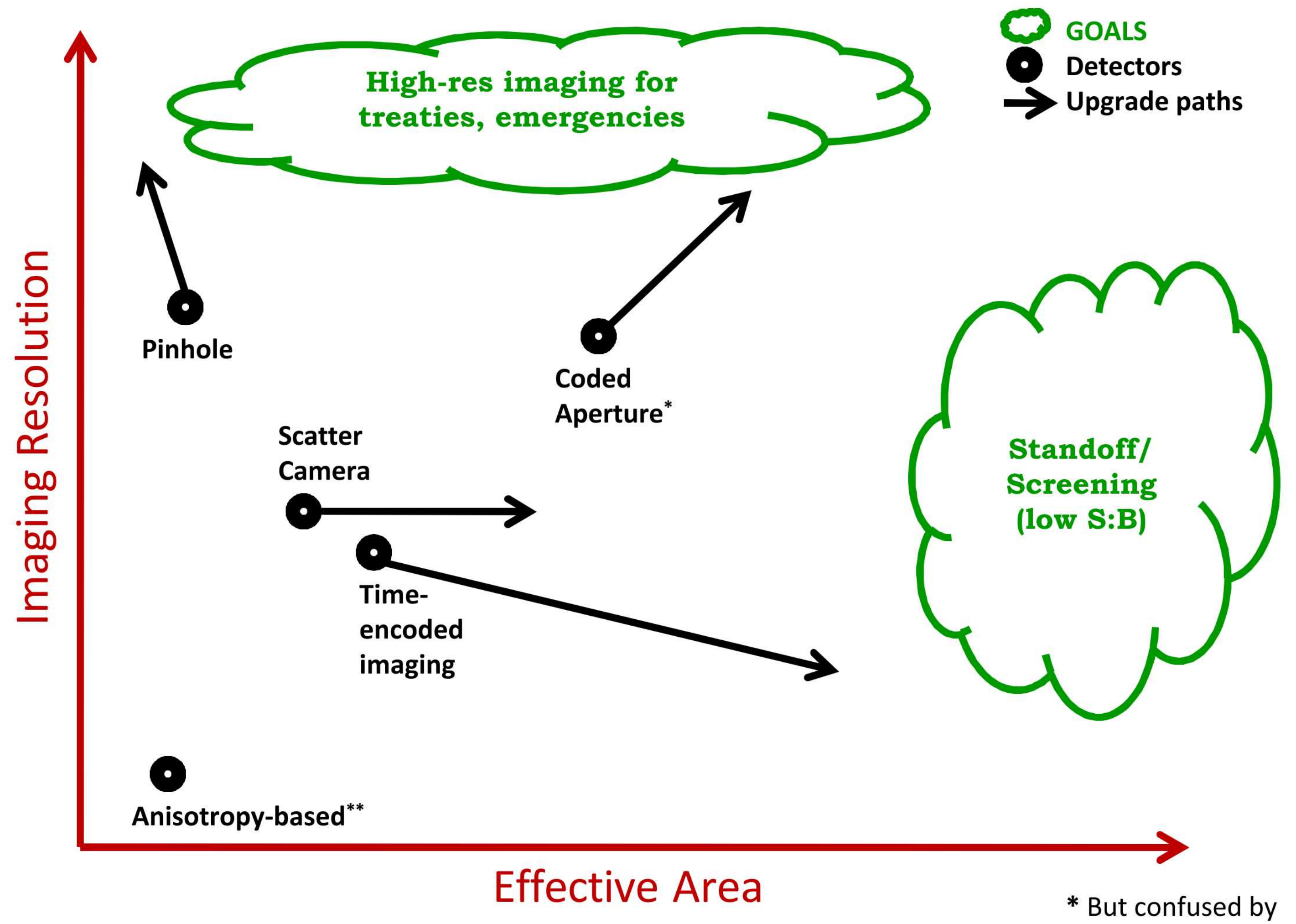
Background = $B\, A_{eff} t\, (1-\cos(\delta\theta))/2$

Gamma spectral analogy



- Analogy to information from gamma spectrum.
  - Estimate background (systematic).
  - Ignore most background (statistical).

The neutron imager zoo



* But confused by multiple/extended sources
** But compact