Fast neutron detection and imaging for nuclear security applications

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Sandia National Laboratories, Livermore, CA

30 November 2011

LBL Instrumentation Seminar

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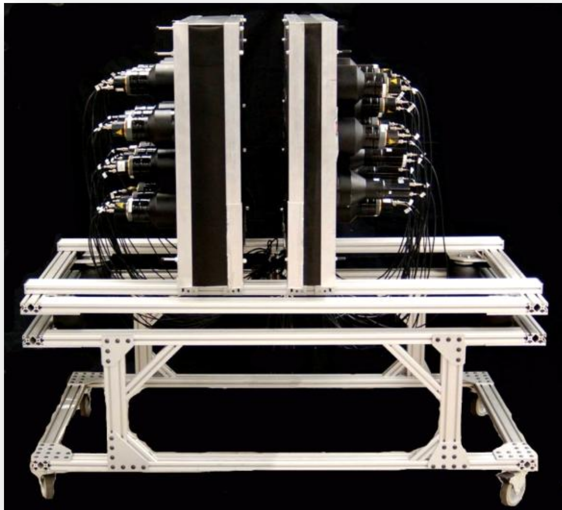
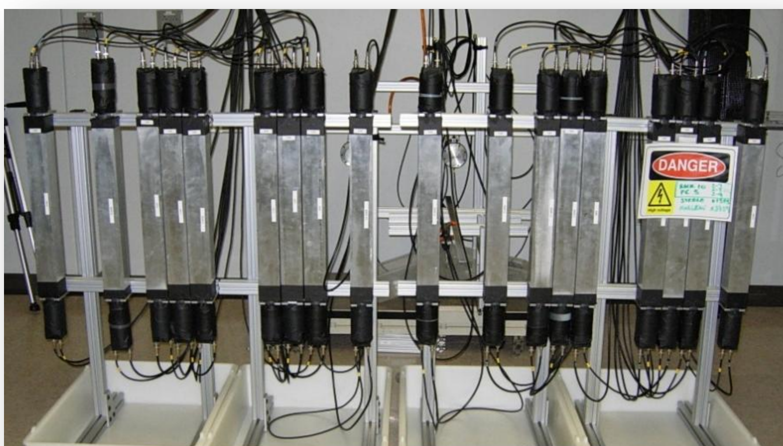
Fast neutron imagers @ SNL/CA





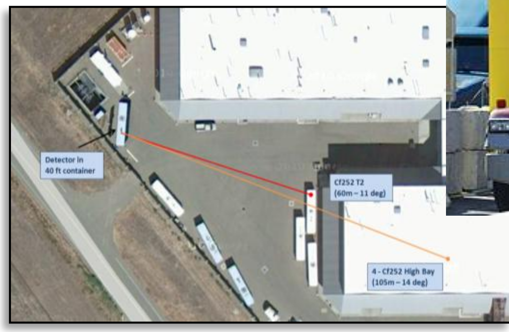
Cast:
P. Marleau
N. Mascarenhas
J. Lund
J. Goldsmith
J. Steele
S. Mrowka
J. Brennan
M. Gerling
A. Nowack
P. Schuster
K. McMillan

Outline

- Motivation
  - SNM detection/imaging.
  - Why fast neutrons?
  - Why imaging?
- Detector design
  - Physics
  - Design considerations
- Detector zoo
- Miscellaneous topics

SNM detection/imaging

Standoff detection



Cargo screening

Arms control treaty verification

Emergency response

SNM detection applications

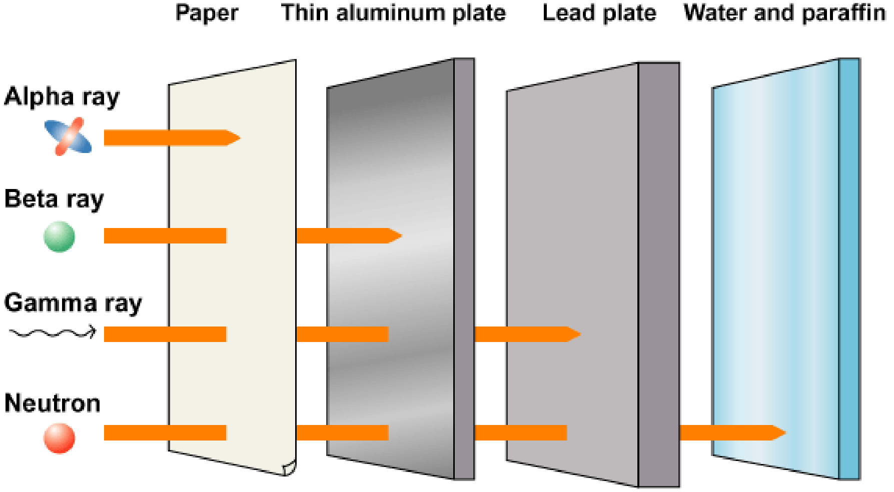
- Low signal rate
  - Need large area detectors!
- Low signal to background
  - Need background discrimination!

SNM imaging applications

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

Why neutrons?

- Special nuclear material emits ionizing radiation.
  - Sensitive and specific signature
- Only neutral particles penetrate shielding.
- Neutrons are more specific:
  - Lower natural backgrounds
  - Fewer benign neutron emitters



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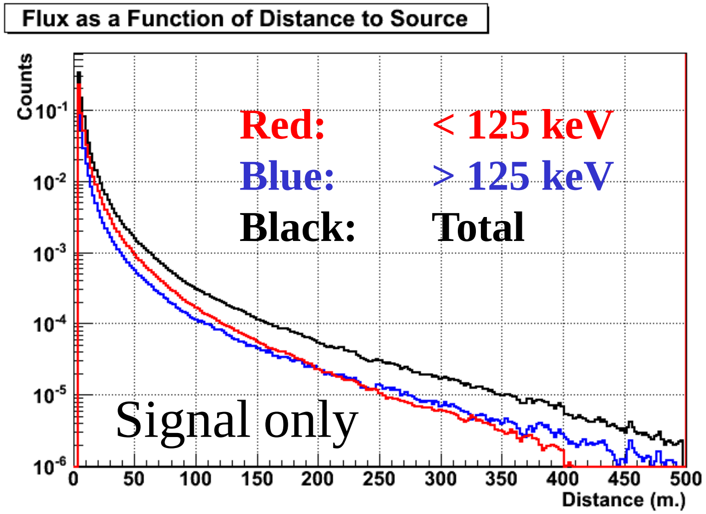
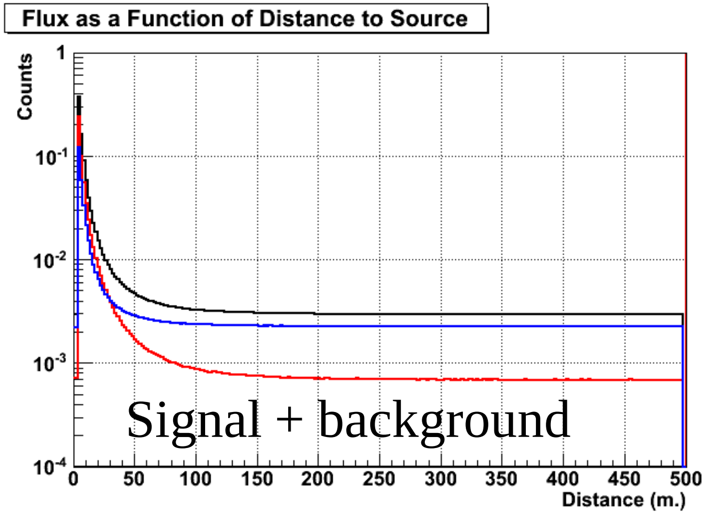
Why fast neutrons?

- Fast neutrons likely have not scattered—retain directional history.
- Shielding turns fast neutrons into thermal neutrons—but also absorbs thermal neutrons.

- Directional information helps
  - Distinguish signal from background—isolate a point source.
  - Produce image of multiple or extended radiation sources.

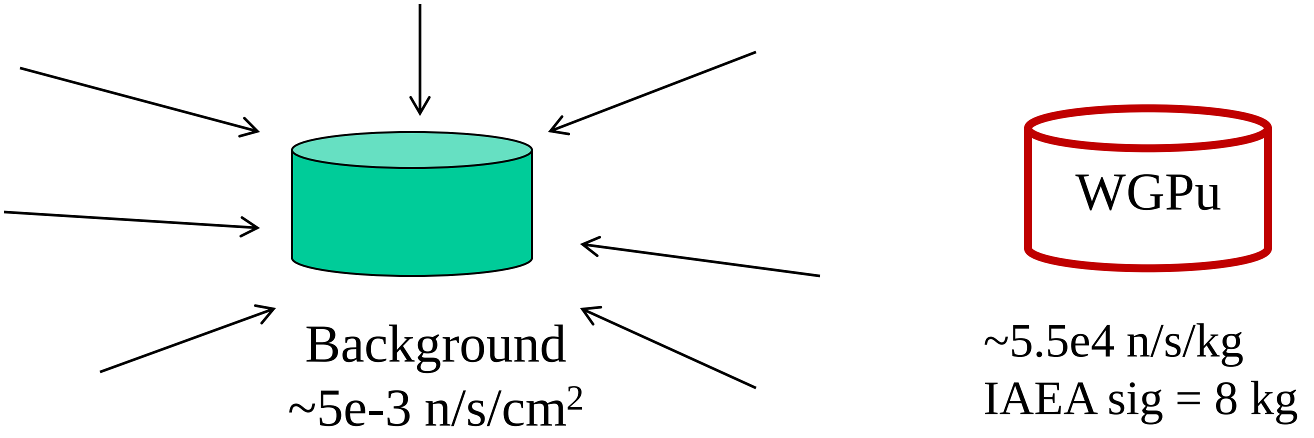




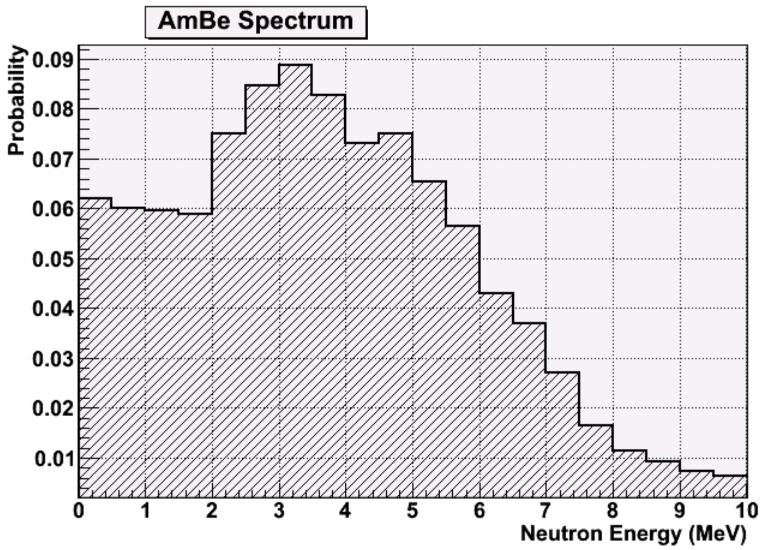
Low S:B: what does it mean?

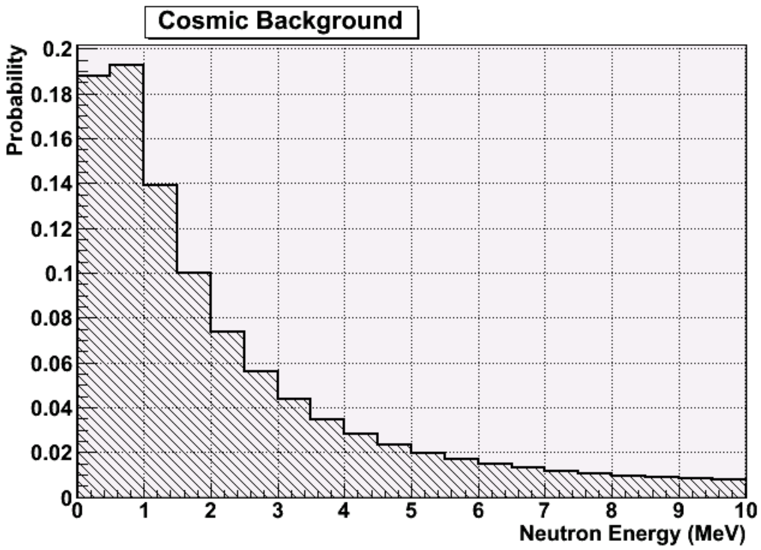
- Example: Large stand-off application (100 meters)
  - 8 kg WGPu = ~4.4e5 n/s → 4.4e5 *exp(-R/100)/4πR^2 ~1.3 n/s/m^2
  - Background = ~50 n/s/m^2 (at sea level)

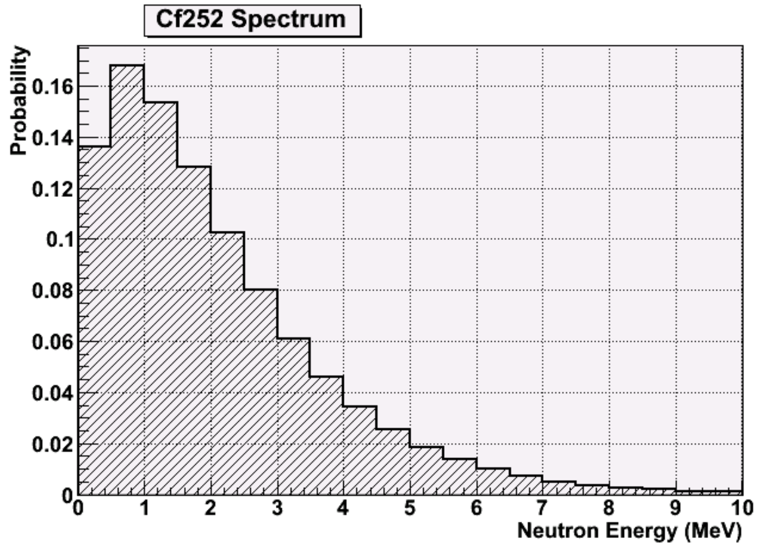
  - 100% efficient, 1 m^2 detector → 5σ det in ~13 minutes
  - 10% efficient, 1 m^2 detector → 5σ det in ~2 hours



Signal/noise: Spectrometry







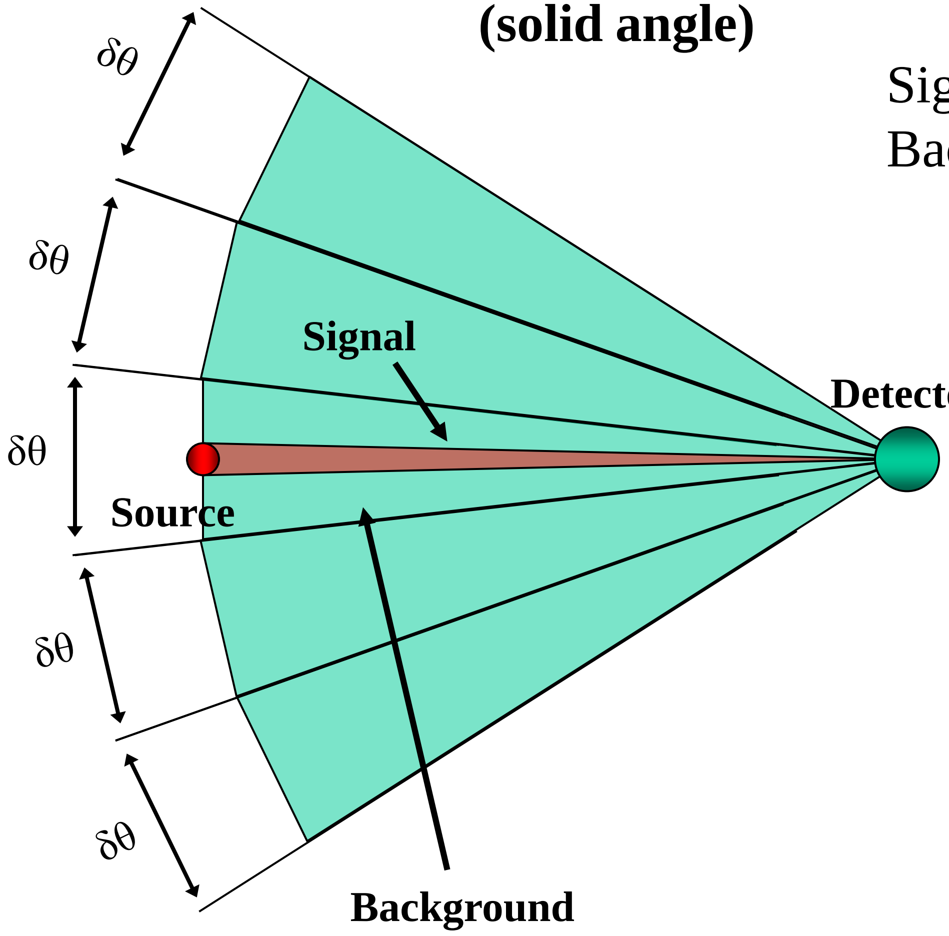
Energy resolution doesn't enhance fast neutron S/N much.

Signal/noise: Imaging

δθ = angular resolution (solid angle)

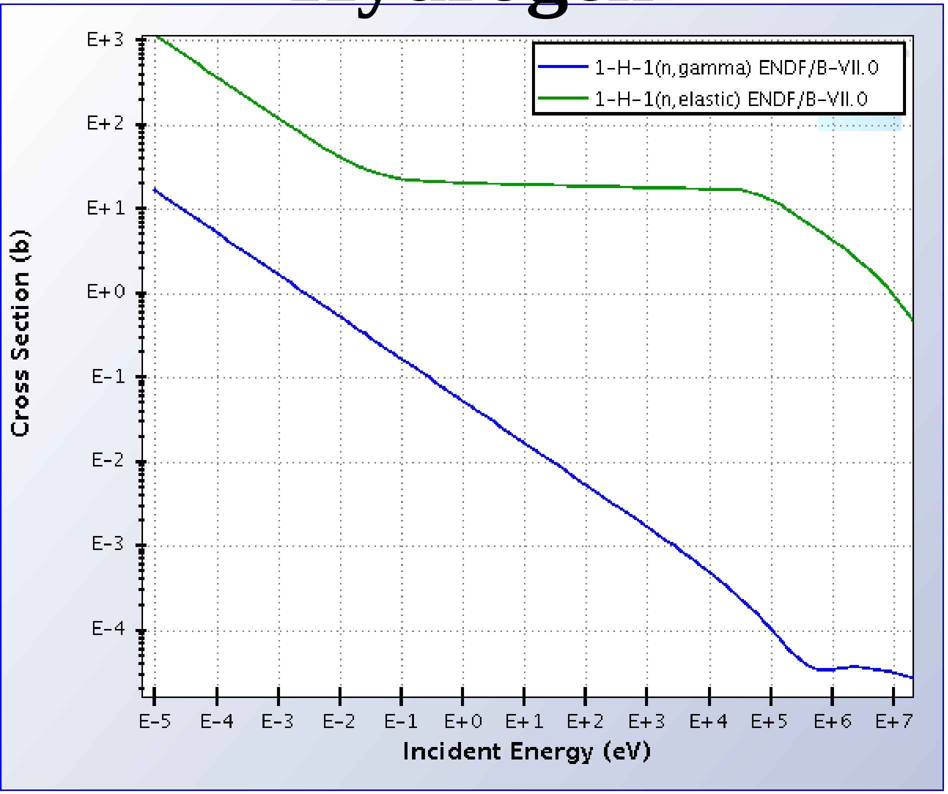
Signal = **$S\,A_{eff}t$**

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

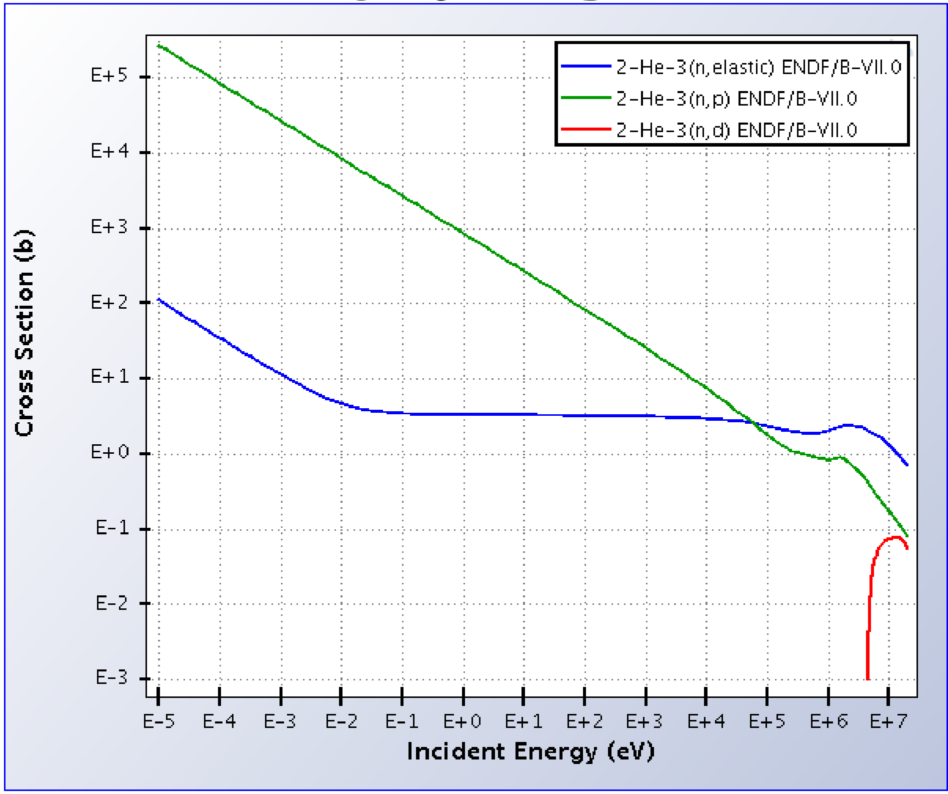


Neutron Detection

Hydrogen



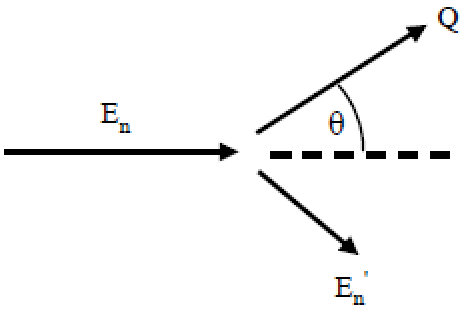
Helium-3



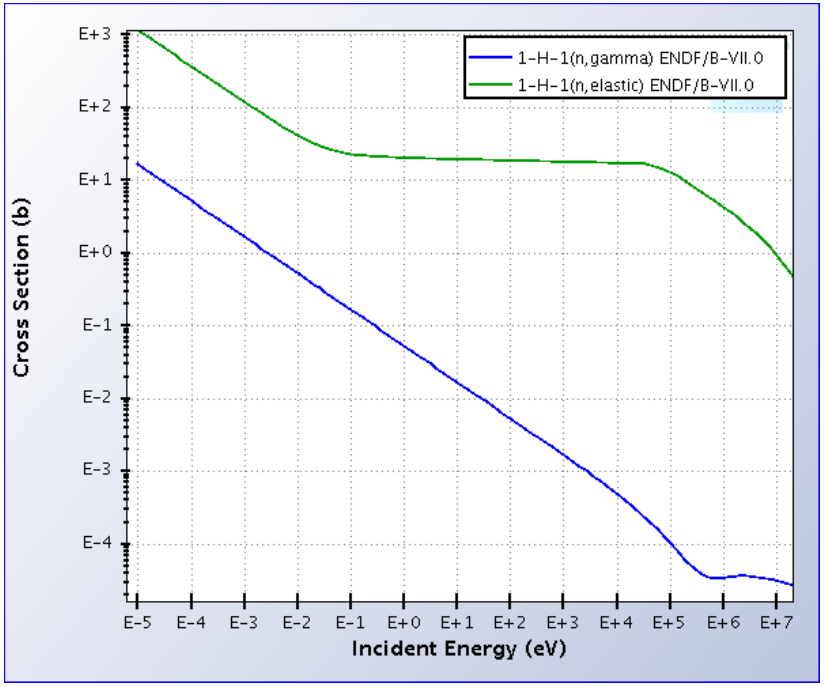
Taken from ENDF database

Neutron Detection - Elastic

$$Q_{max} = \frac{4mME_n}{(M+m)^2}$$



Nucleus	Q_{max}/E_n
$^{1}_{1}H$	1.000
$^{2}_{1}H$	0.889
$^{4}_{2}He$	0.640
$^{9}_{4}Be$	0.360
$^{12}_{6}C$	0.284
$^{16}_{8}O$	0.221
$^{56}_{26}Fe$	0.069
$^{118}_{50}Sn$	0.033
$^{238}_{92}U$	0.017



Detector design considerations

- Scalability/size
  - For interesting problems, must scale to O(1 m^2).
- Interaction length/cross-sections
  - Reasonable efficiency dictates thickness of active medium and shielding > 2".
- Robustness/fieldability
  - Temperature sensitivity
  - Calibration issues

How to build a neutron imager

- N-P elastic scattering
- Sensitivity to direction
  - Event by event (kinematics)
  - Statistical (many events form a pattern)
- Liquid scintillator based.
  - Gamma discrimination
- Shielding is hydrogenous material.

Two primary attributes:

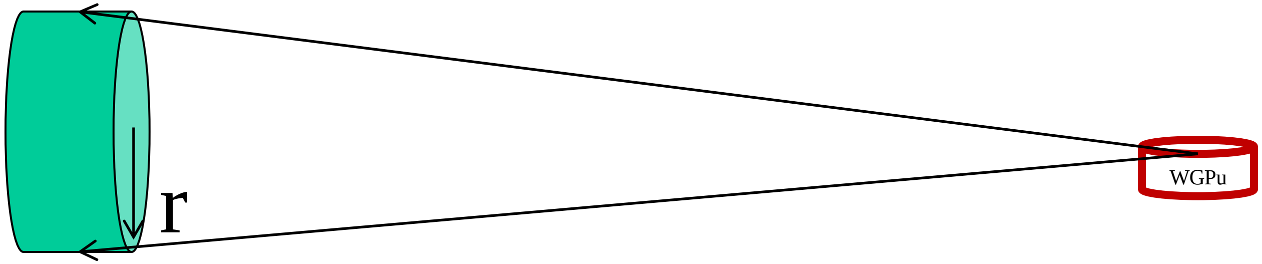
Effective Area

Imaging Resolution

Effective Area

- Effective area over which the detector would be 100% efficient.
- Physical cross-sectional area times the detection efficiency.

$$A_{eff} = A_{phys} * \varepsilon$$

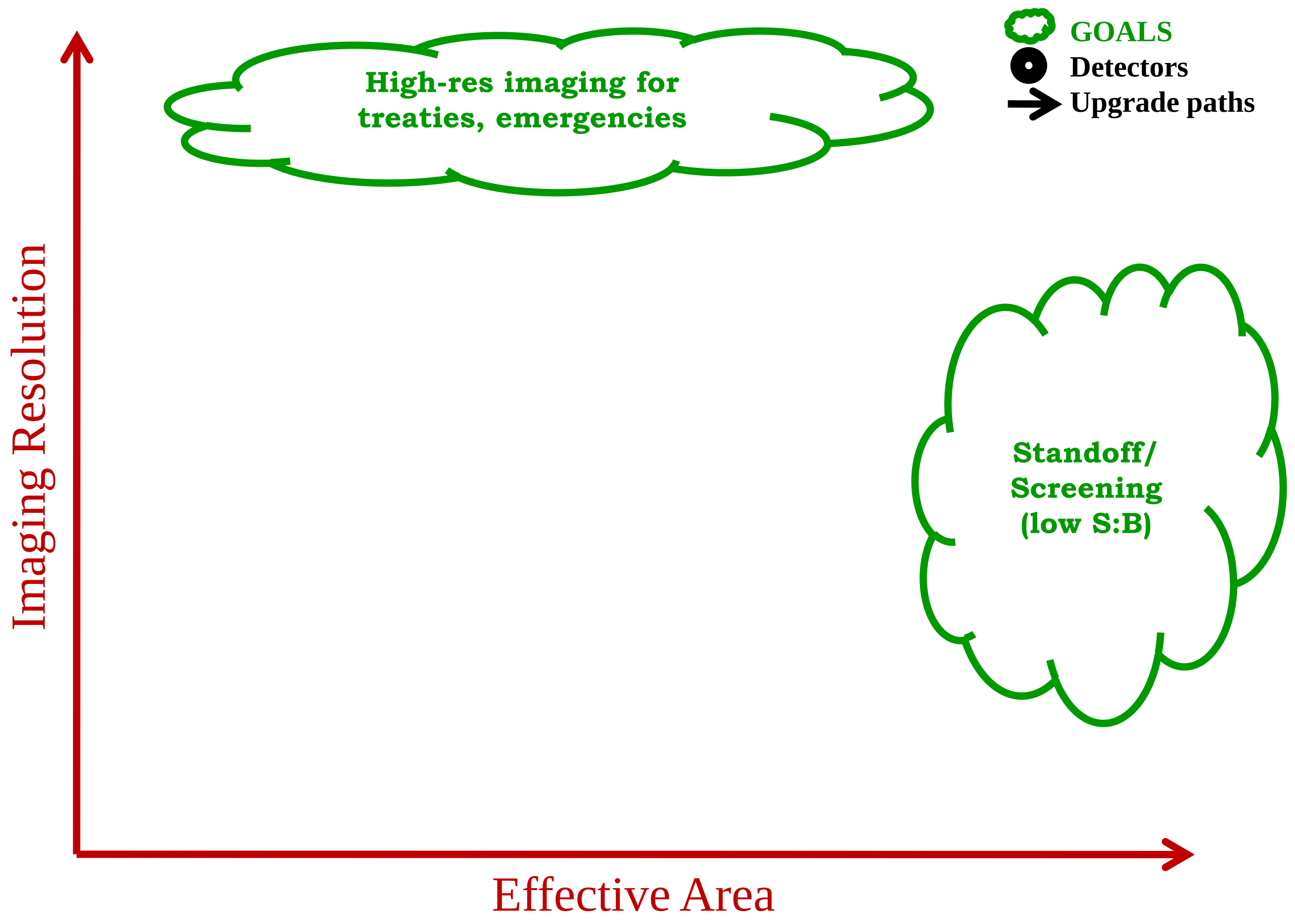


$A_{phys} = \pi r^2$

Not in this talk

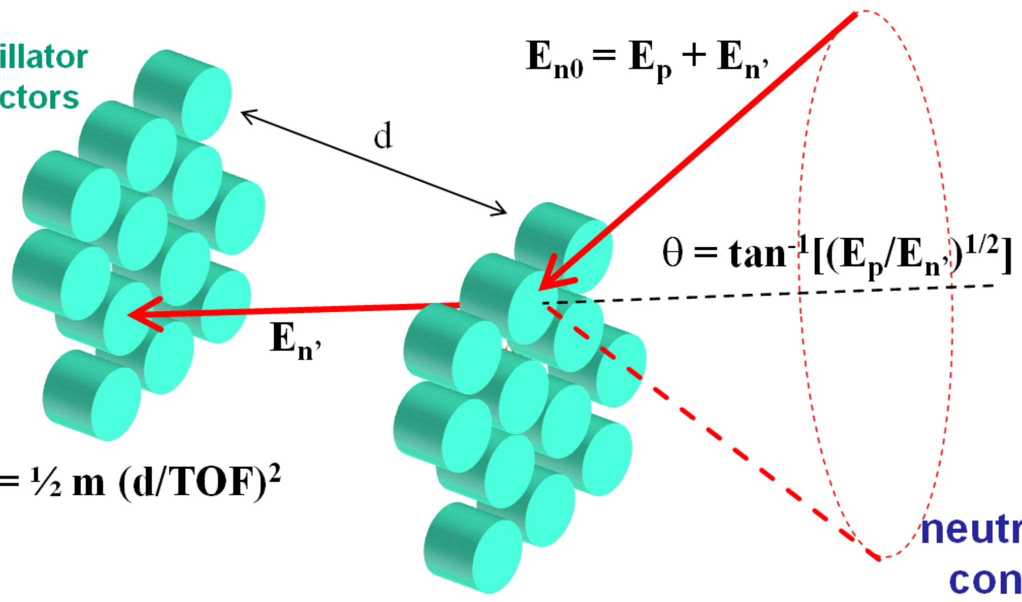
- Other neutron imagers for security applications:
  - Thermal neutron imagers
  - Neutron TPCs
  - Bubble chambers
  - ^{4}He-based detectors
- Other application spaces
  - Dark matter detection
  - DM background characterization
  - Fusion diagnostics
    - Tokamaks
    - ICF
  - Neutron radiography
    - Thermal
    - Fast

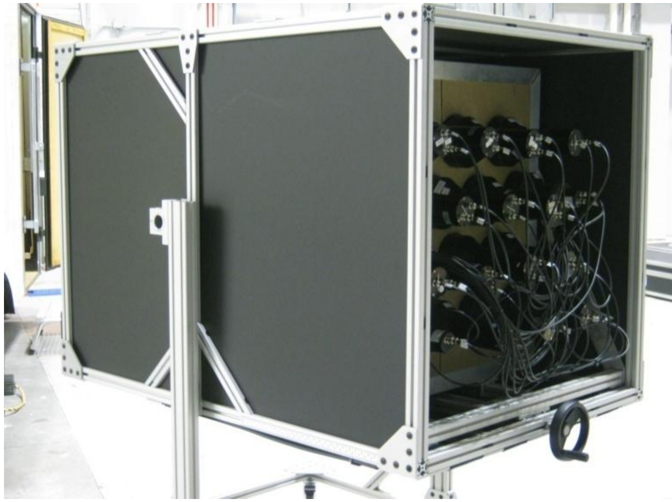
The detector zoo

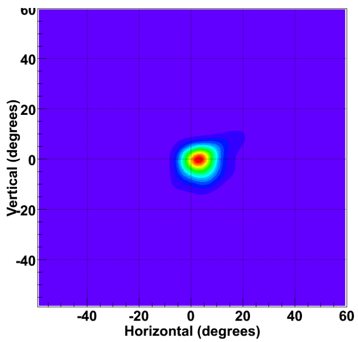


Neutron scatter camera

Fast neutron directions and energies constrained by double scatter geometry



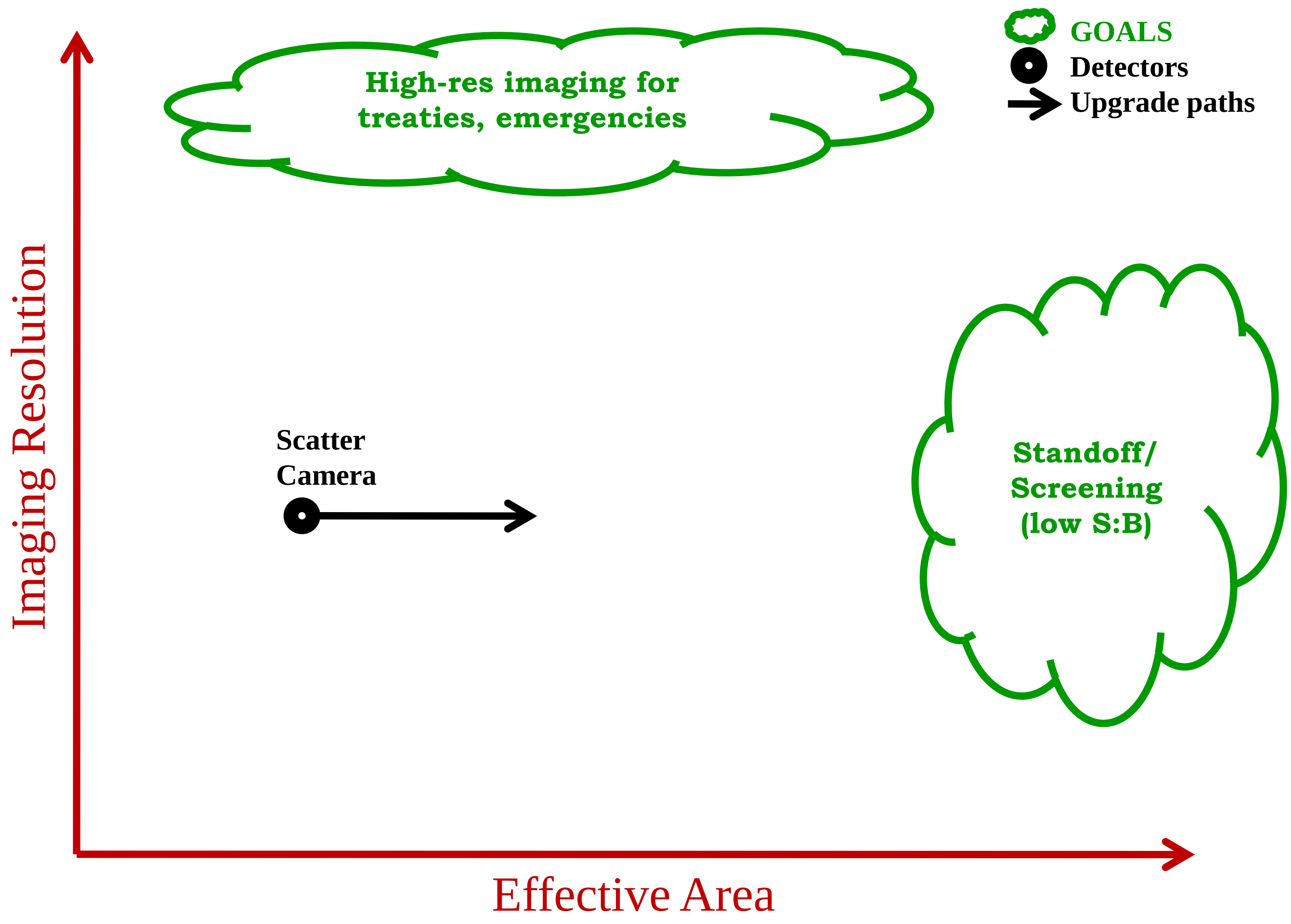




An MLEM-reconstructed neutron point source image.

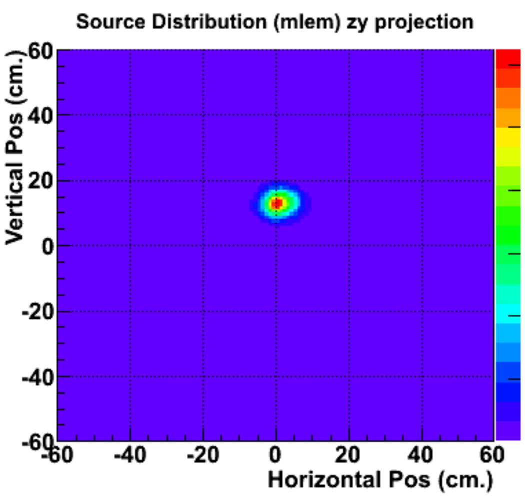
Multimode capability includes
- ***Neutron energy spectrum.***
- ***Compton imaging.***

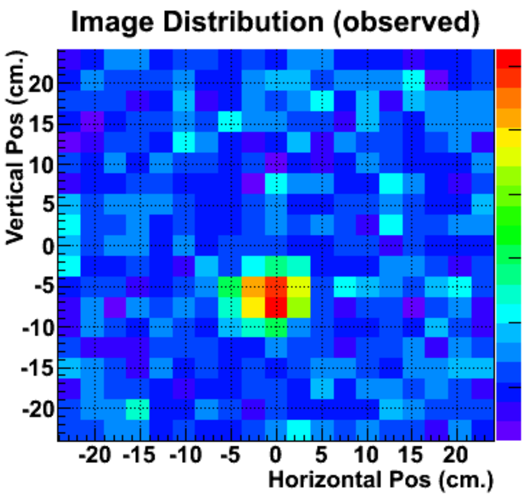
The detector zoo

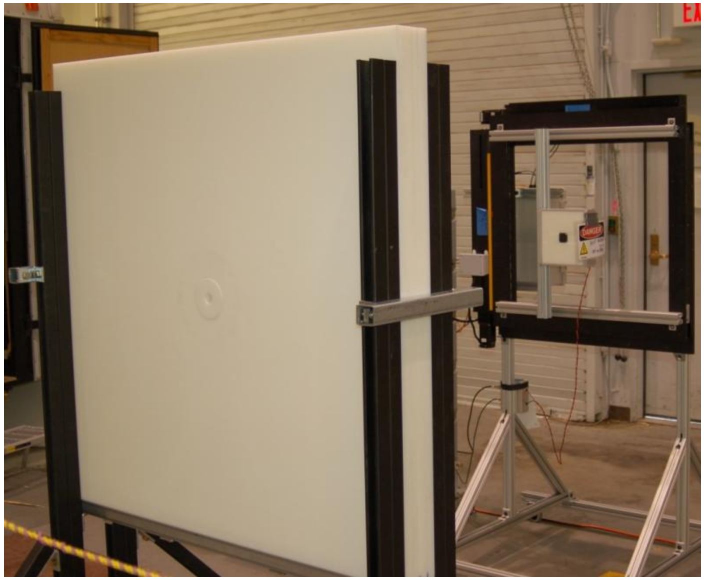


Pinhole imager

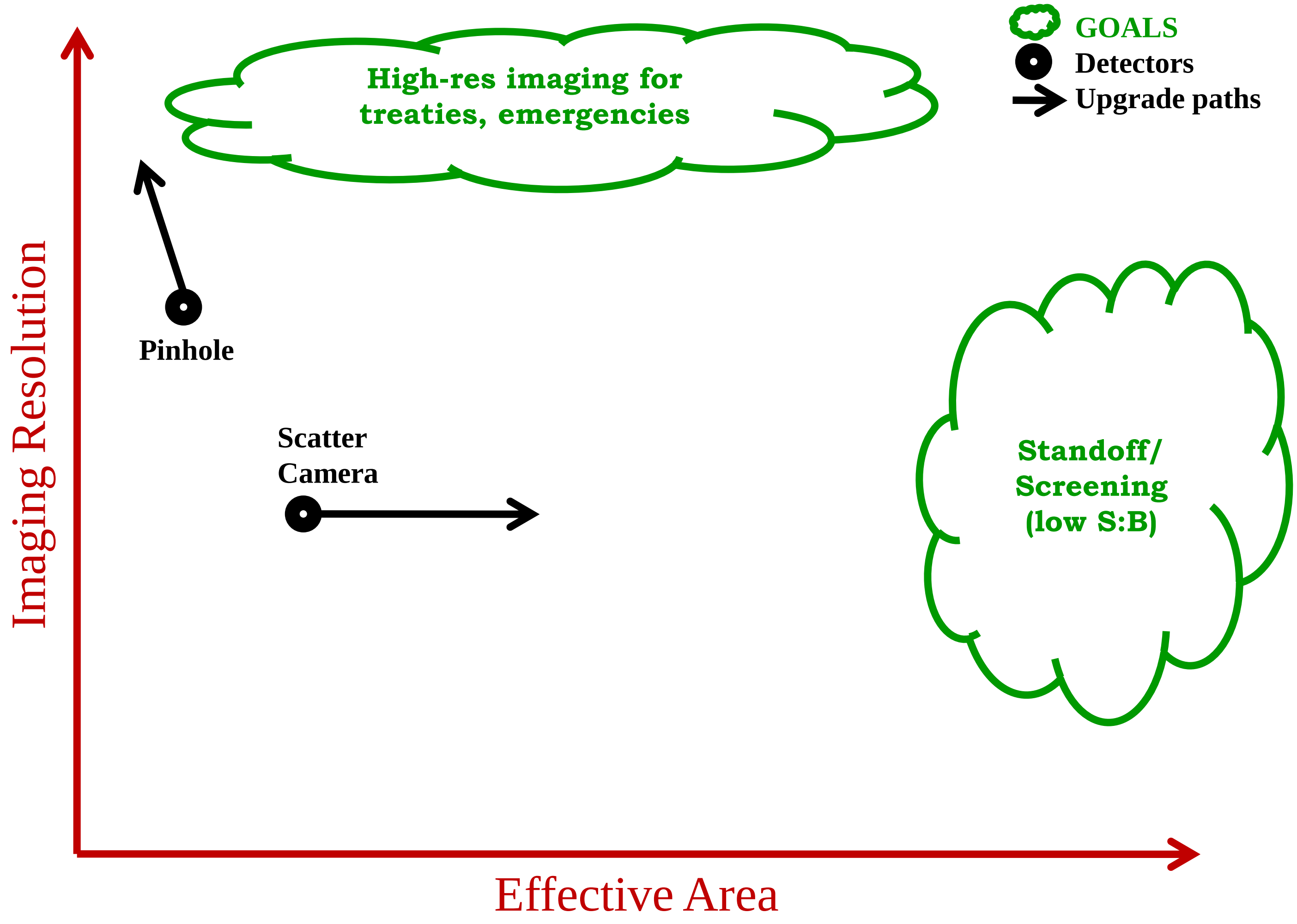
- Just like a pinhole camera—detect neutrons streaming through a single hole in a thick mask.
- Simplest possible directional detector.
- But low effective area.







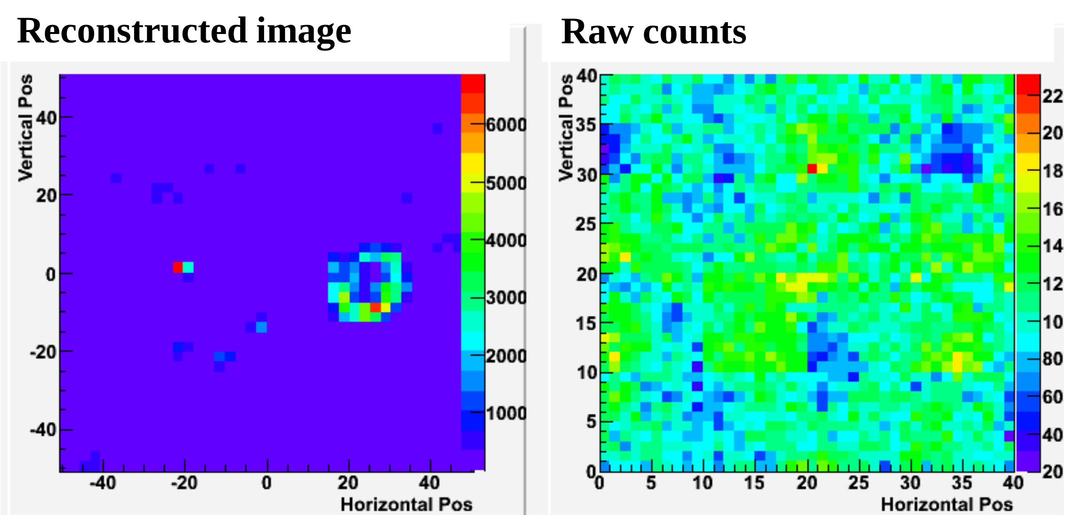
The detector zoo

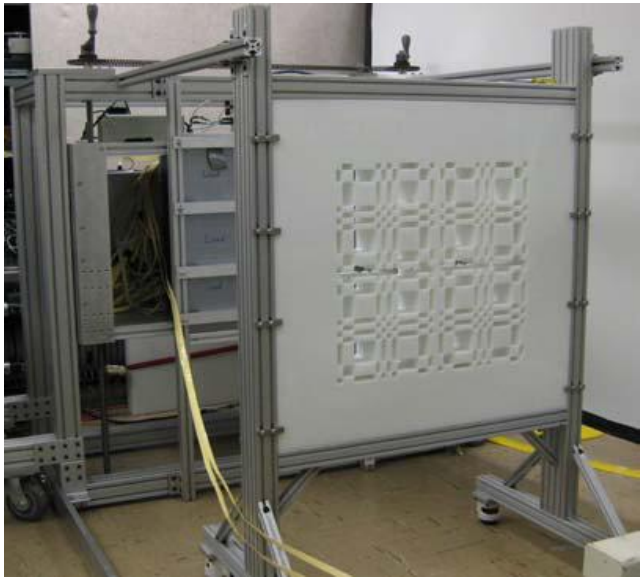


Coded aperture imagers

- Extension of pinhole with much higher effective area: signal modulated in unique patterns.
- Excellent imaging resolution.
- Potential problems with multiple/extended sources.

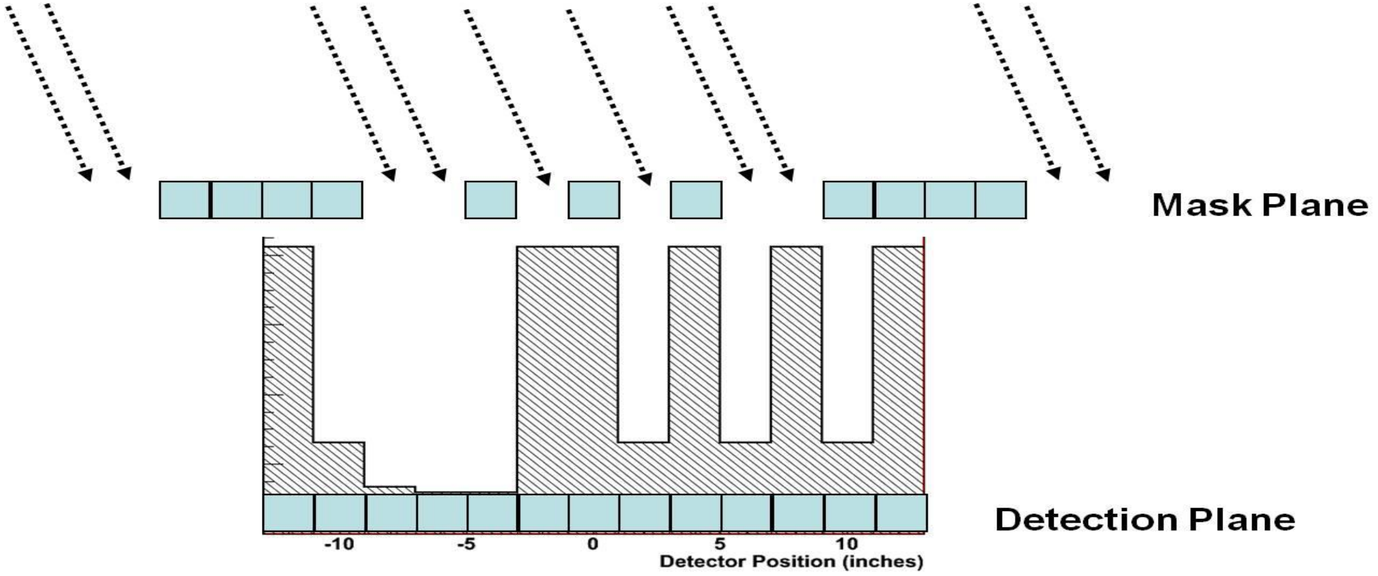
Collaboration with ORNL:
P. Hausladen
J. Newby
M. Blackston





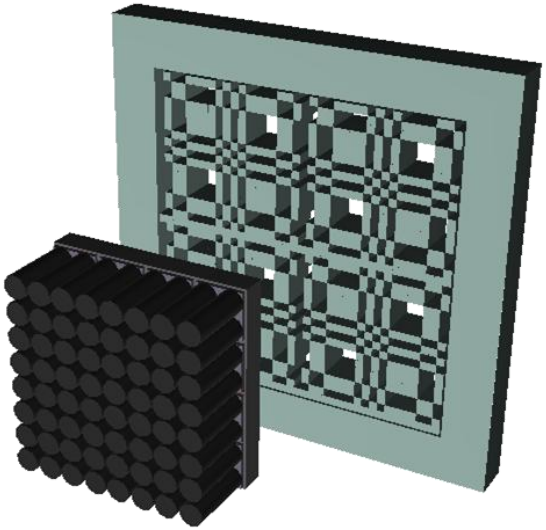
Coded aperture imaging

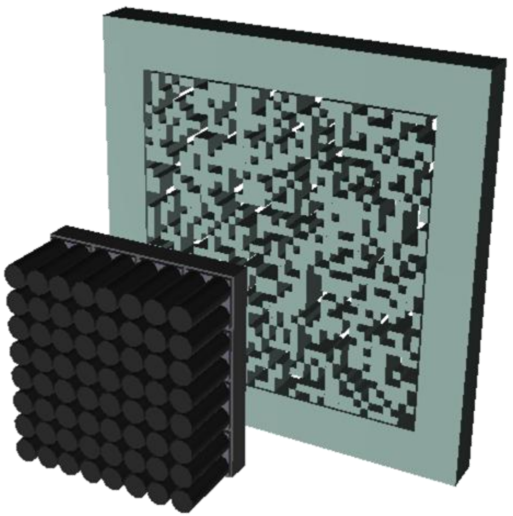
- Aperture is used to modulate the flux emitted by an unknown source distribution
  - Modulated flux intensity is measured at the detector plane by a position sensitive detector
- Ideal theory vs fast neutron reality?



Aperture types

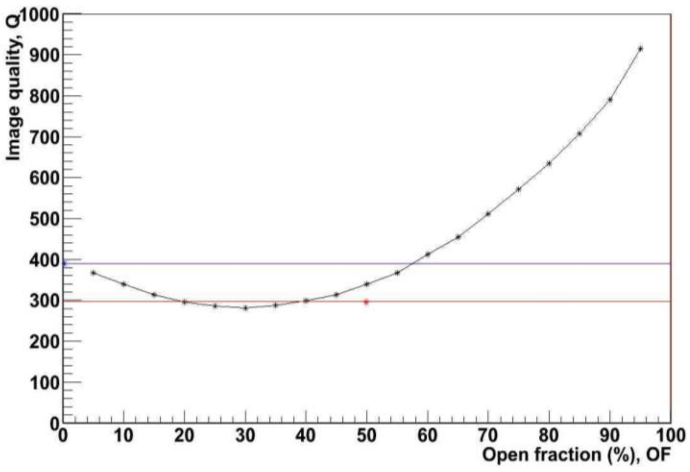
- Uniformly redundant array (URA)
  - Arrays with constant sidelobes of their periodic autocorrelation function
  - URAs can be generated in any length L that is prime and of the form $L = 4m + 3$, $m = 1,2,3,\ldots$
  - Throughput equal to $(L – 1)/2L$ ~= 50%
- Random
  - Not limited by a mathematical formula
  - Can be built for any mask size or open fraction

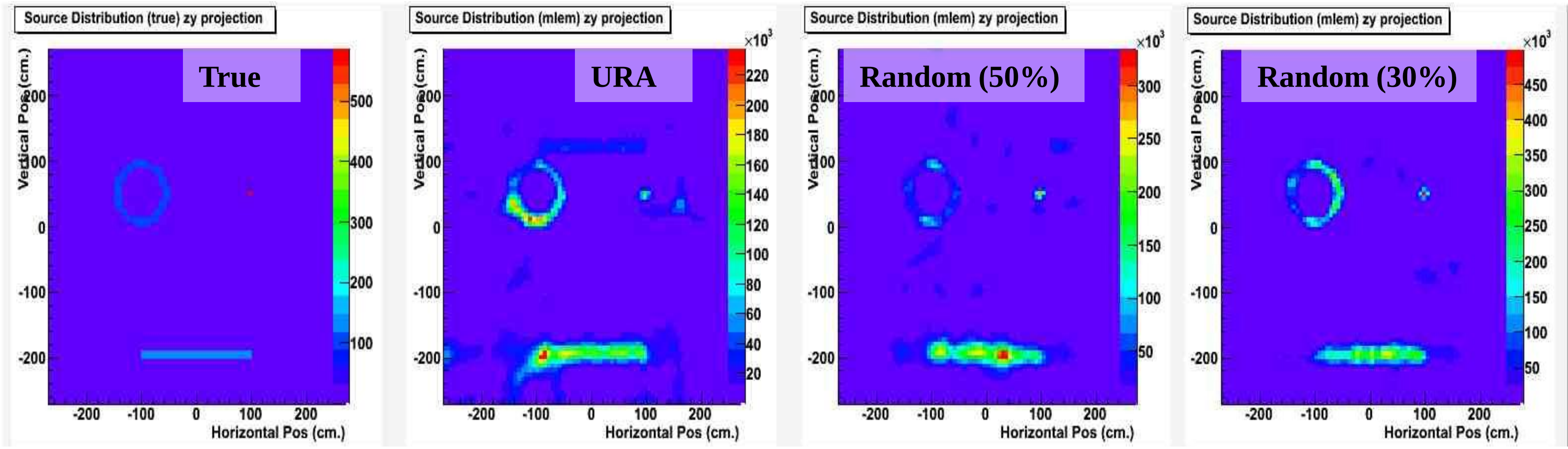




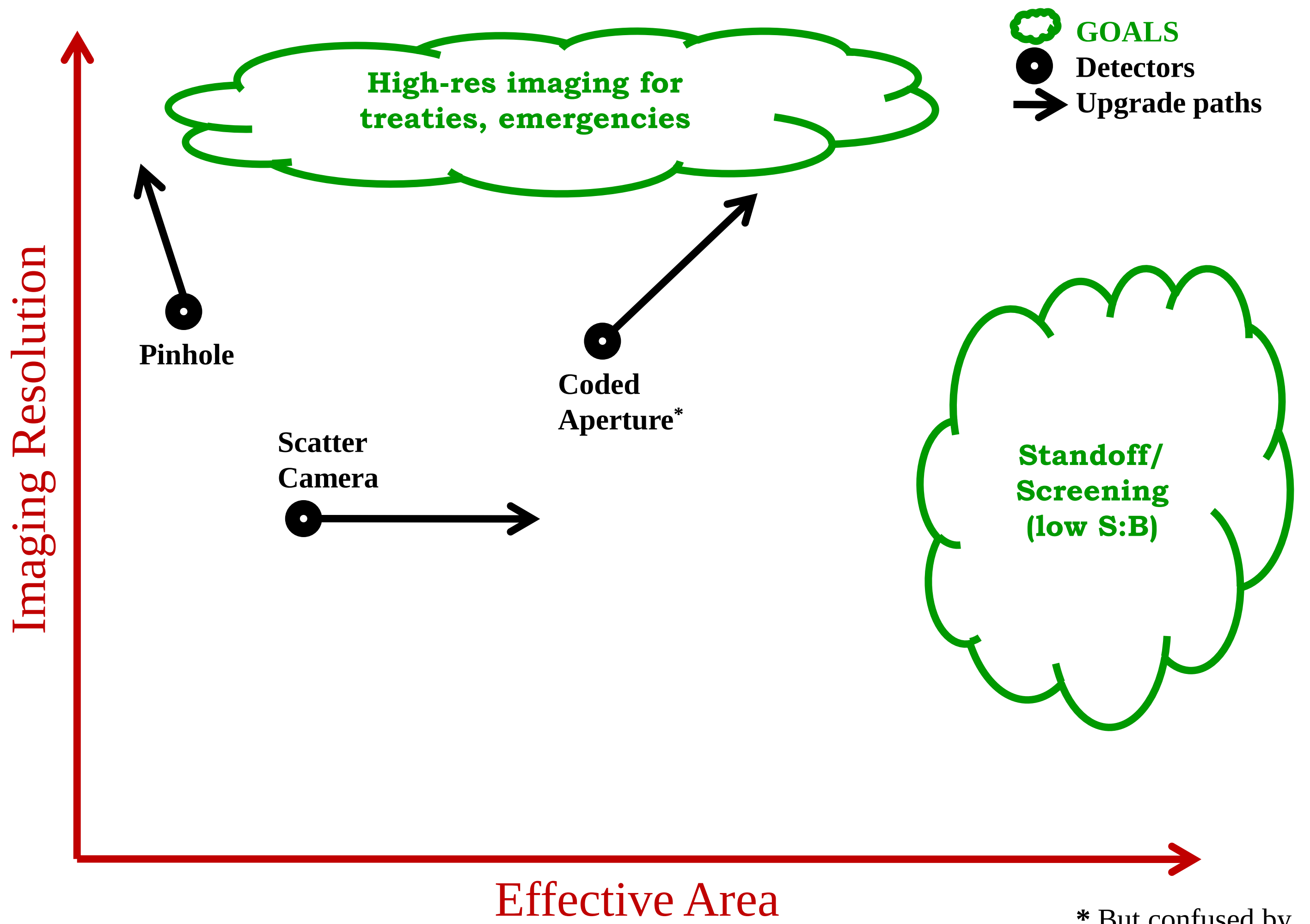
Extended source optimization

- Ring, block, point source arrangement
- Define image quality as ~χ^2 between image, true source.
- Optimize open fraction
  - Red line represents URA performance
  - Blue line represents pinhole performance





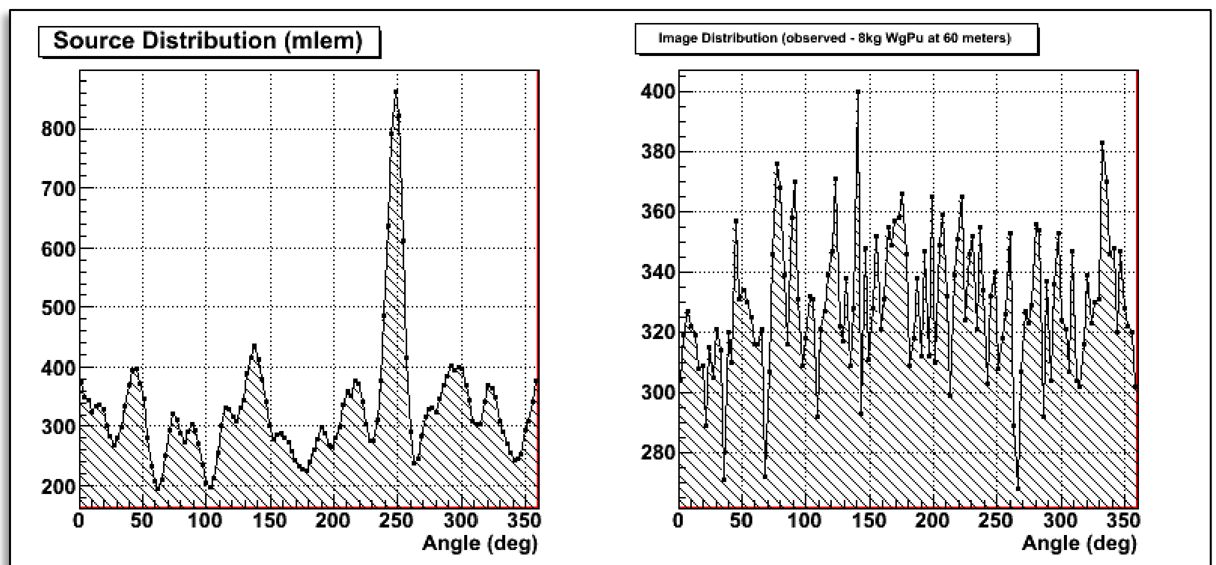
The detector zoo

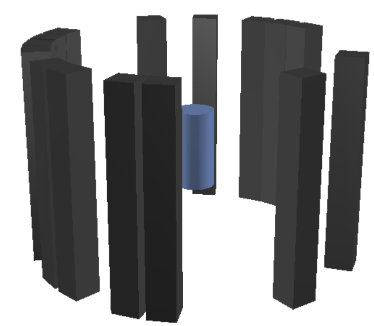


* But confused by multiple/extended sources

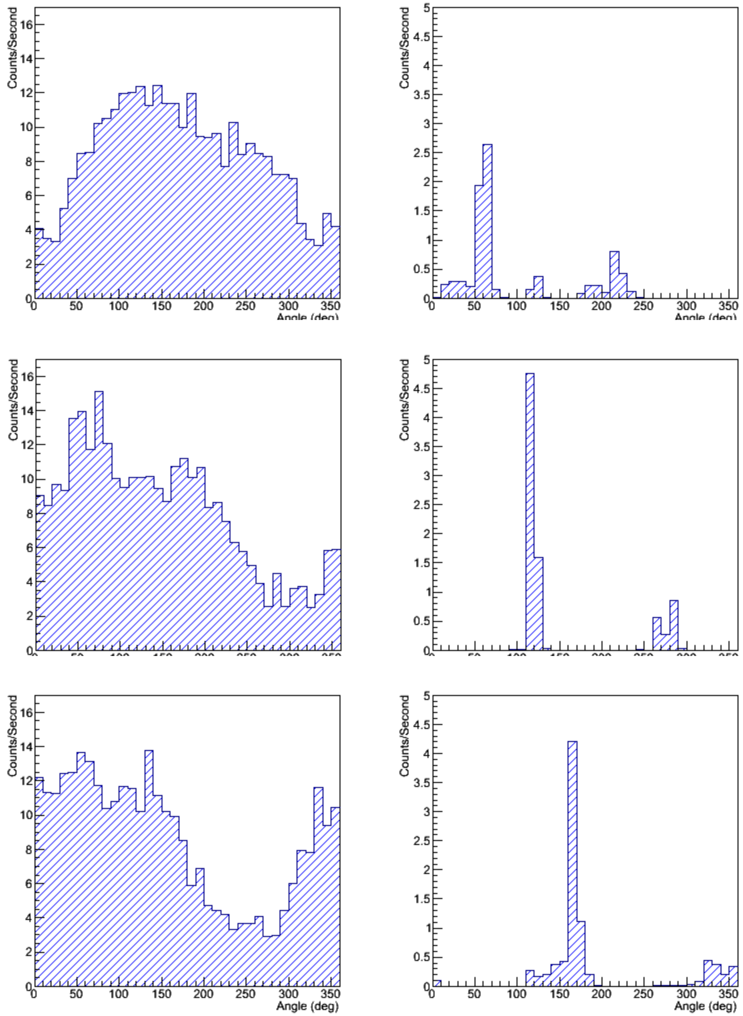
Time-encoded imaging

- Switch spatial modulation for time modulation.
- Simple and robust, low-channel-count detectors.
- Can scale to large effective area.



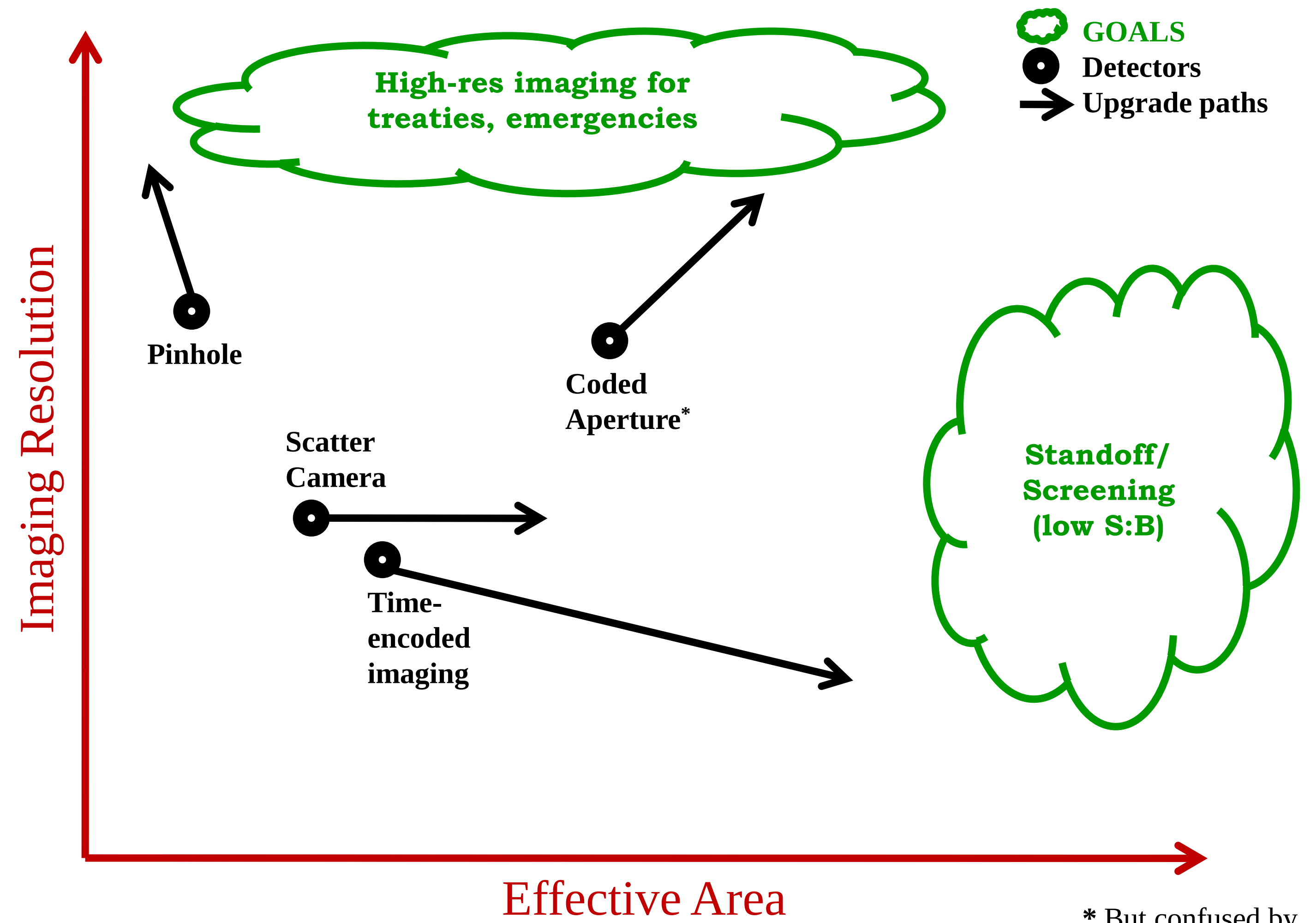


Rotational Self Modulation



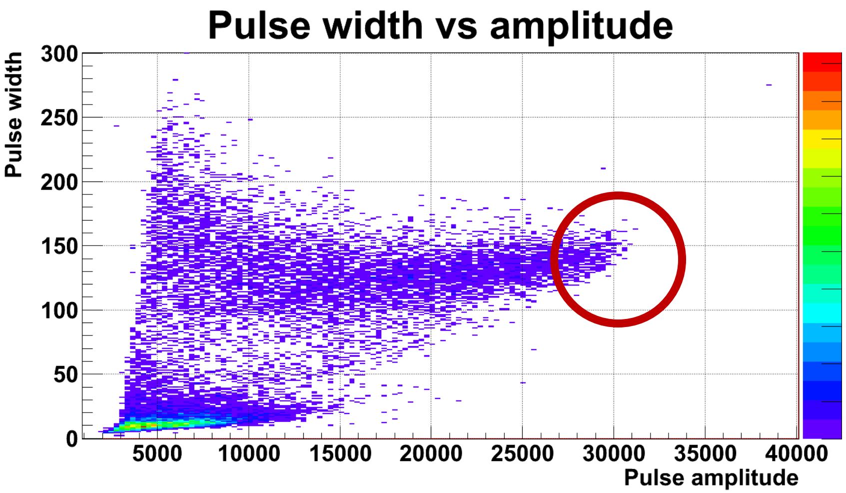
- More compact and more easily scalable at the cost of lower S/N

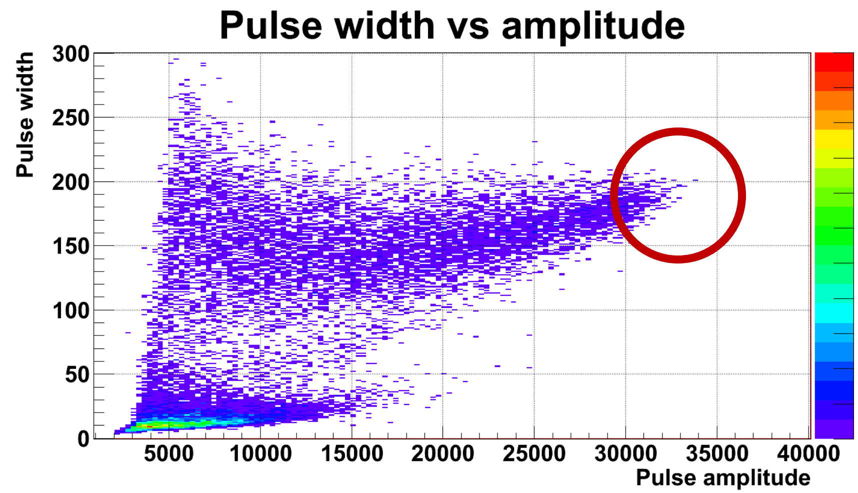
The detector zoo



* But confused by multiple/extended sources

Imaging via anisotropies



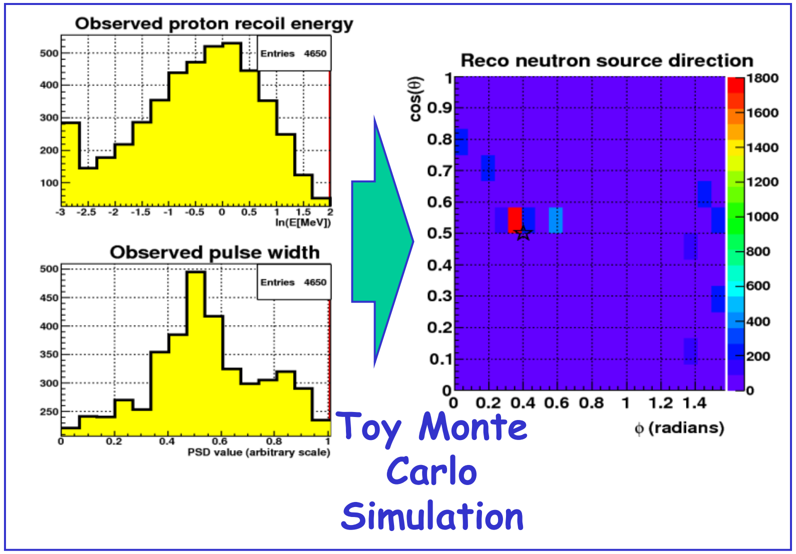


– DPA crystal

– 14 MeV neutron generator

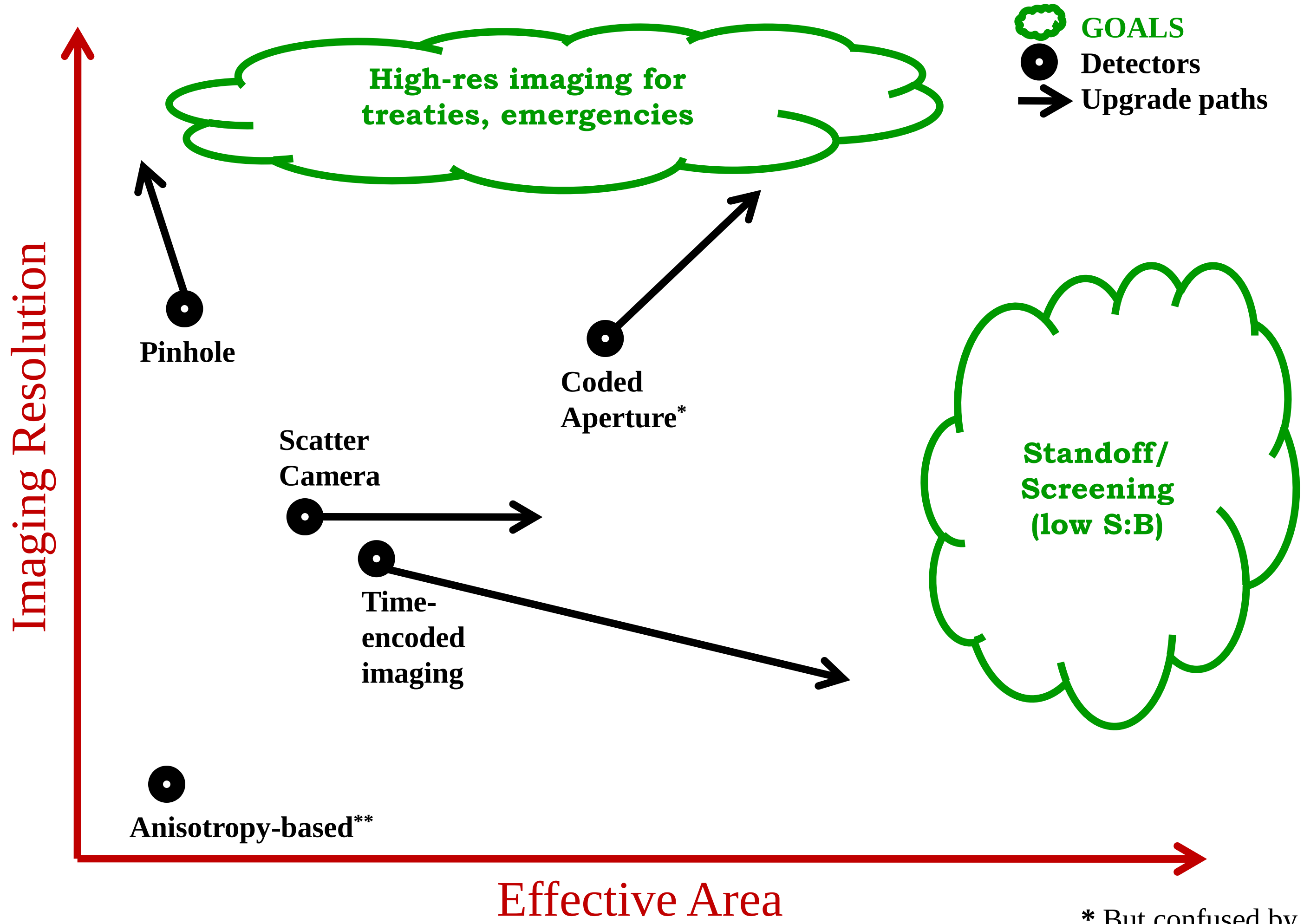
– Crystal was rotated by 90º

– Neutron pulse height and width increased!



Can we invert the effect to *measure* neutron direction?

The detector zoo



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

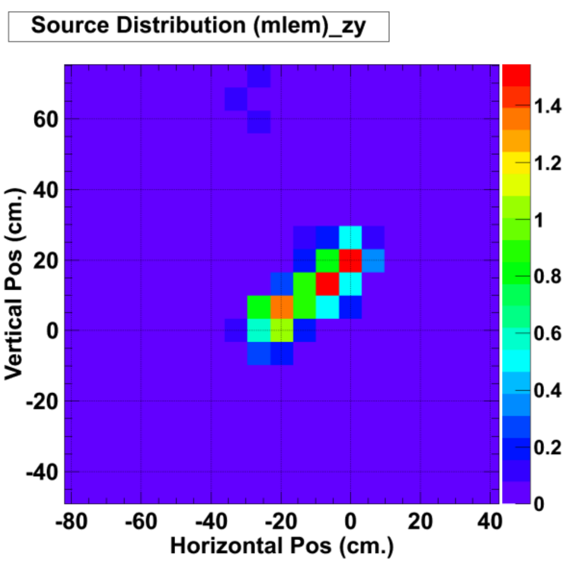
Recurring themes

- Optimize the detector for the application!
- Importance of reconstruction algorithms.
- Simulation as a tool for detector design.
- Need to understand the background.
- Need quantitative tests and characterization.

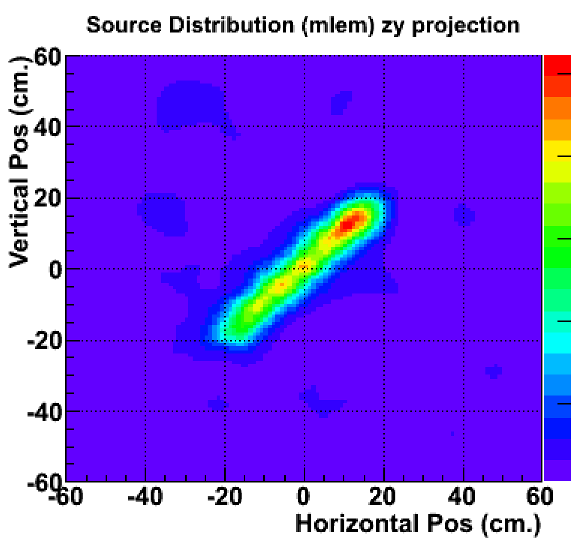
Use the right detector!

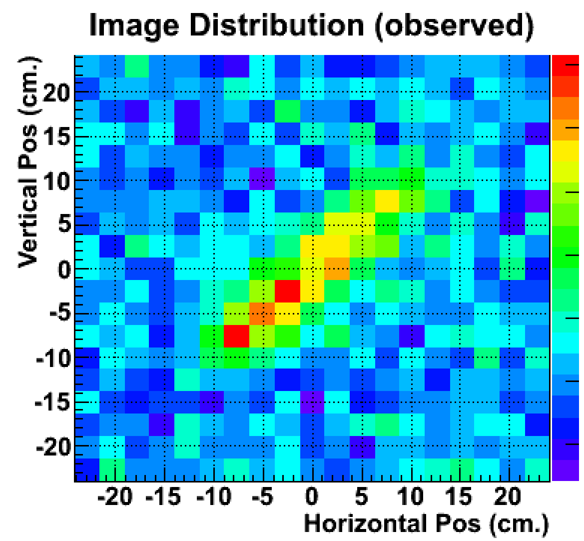
- Extended source imaging: 20” line source.
- Sizeable source at 3 m – S:B not an issue.
- Pinhole camera outperforms the scatter camera.

Neutron scatter camera



Pinhole imaging system

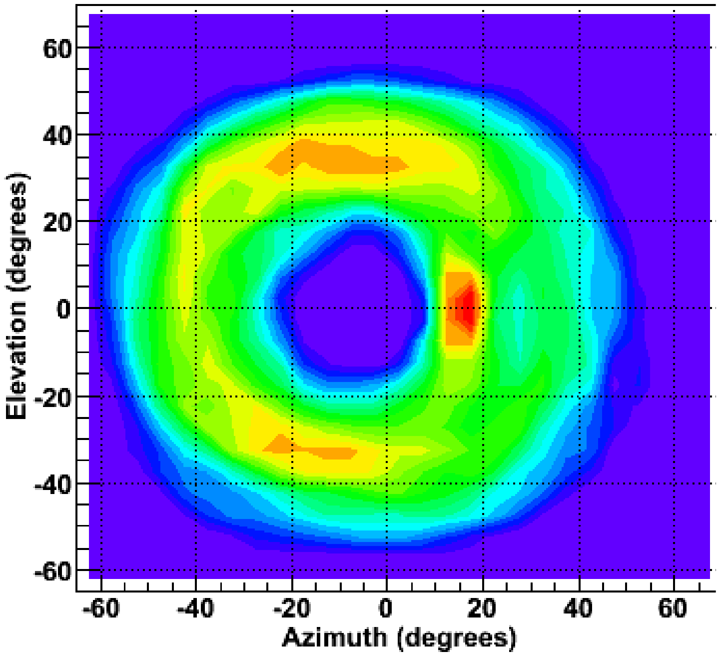




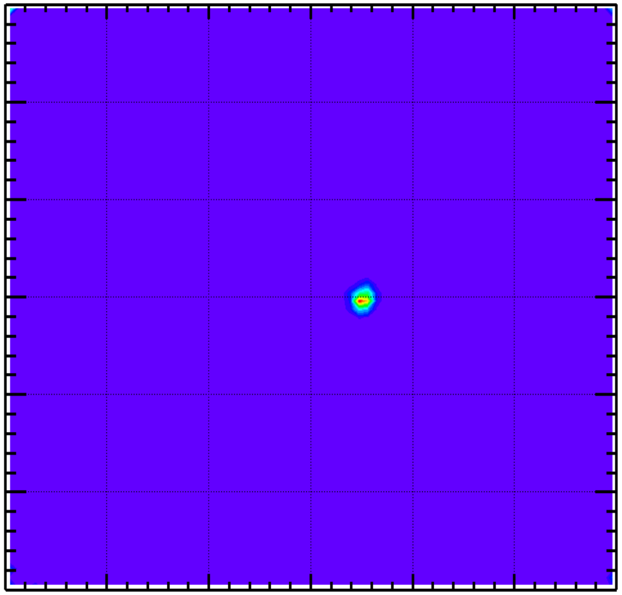
Algorithms matter

Single neutron scatter camera dataset:

Backprojection

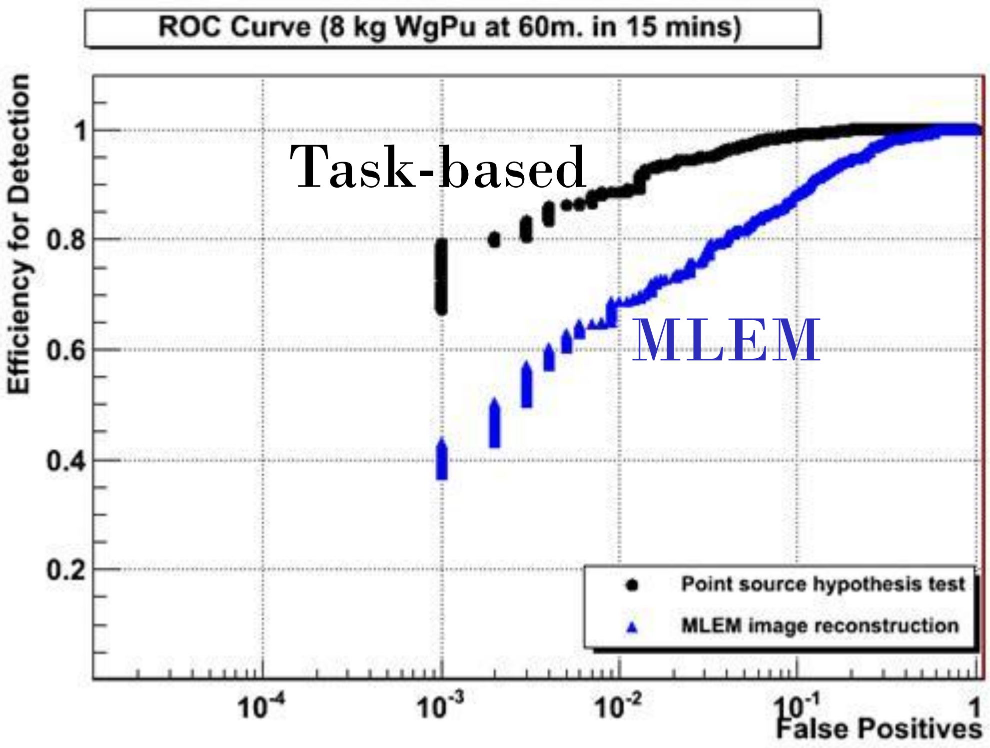


MLEM



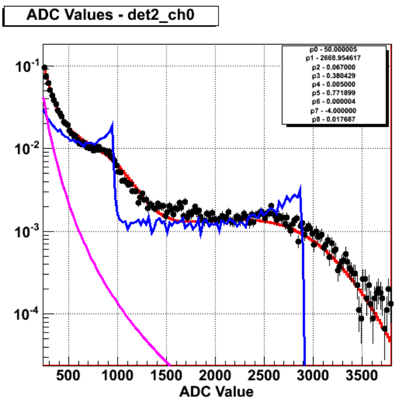
Algorithms matter

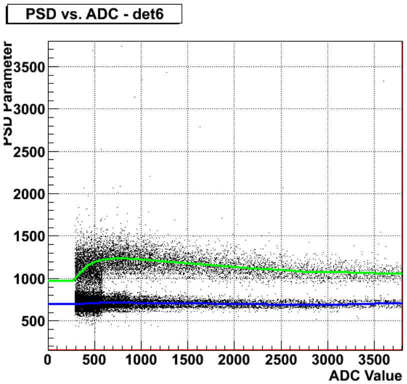
- 1-D Coded aperture LDRD detector.
- Image reconstruction is ideal for obtaining images, not finding sources.
- Use "task-based" algorithms.

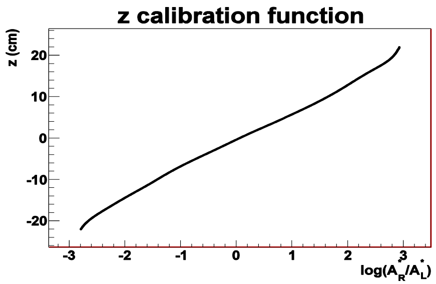


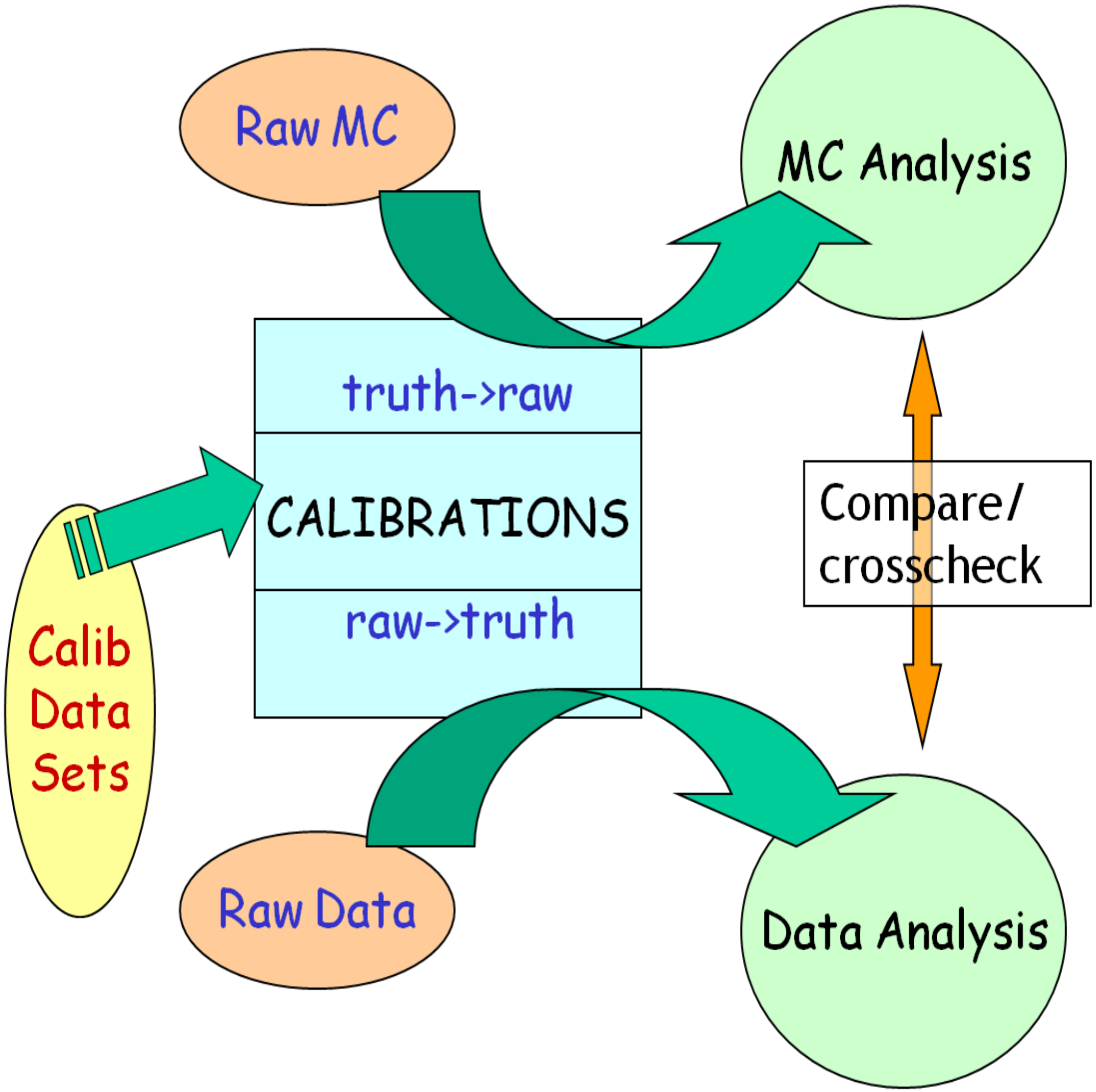
$$LLR = \ln \frac{L(\text{data} \mid s+b)}{L(\text{data} \mid b)}$$

Calibration and simulation







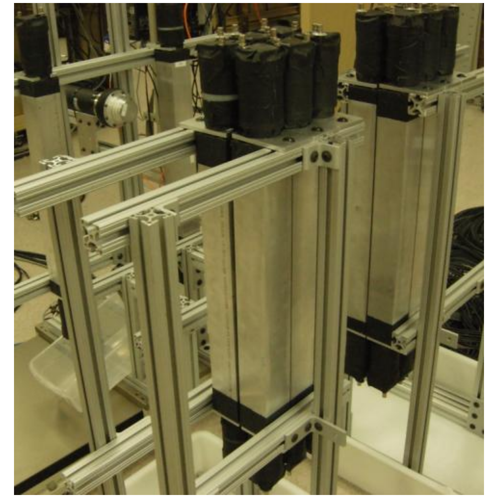


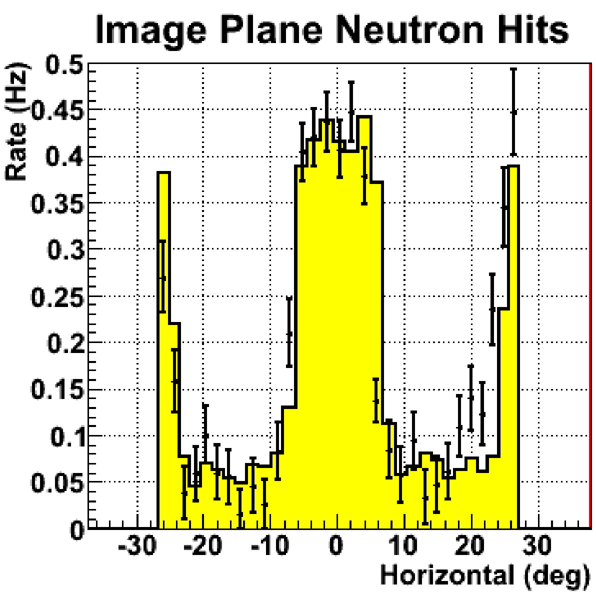
- Test hypotheses
- Inform future direction
- Understand physics

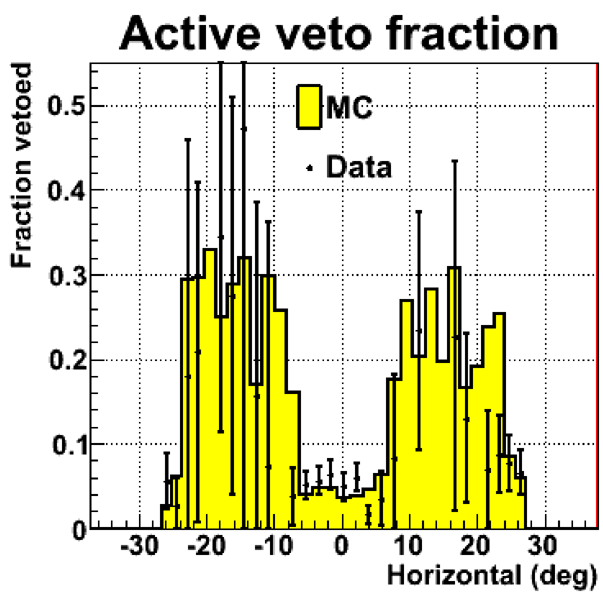
- Proof of principle
- Describe current capabilities
- Refine procedures

Simulation cross-check

- Single-slit experiment.
- AmBe source.
- No full image plane → scan 2”D x 2” liquid cells (highest quality PSD).
- Data has background subtracted.
- Total MC rate normalized to data.







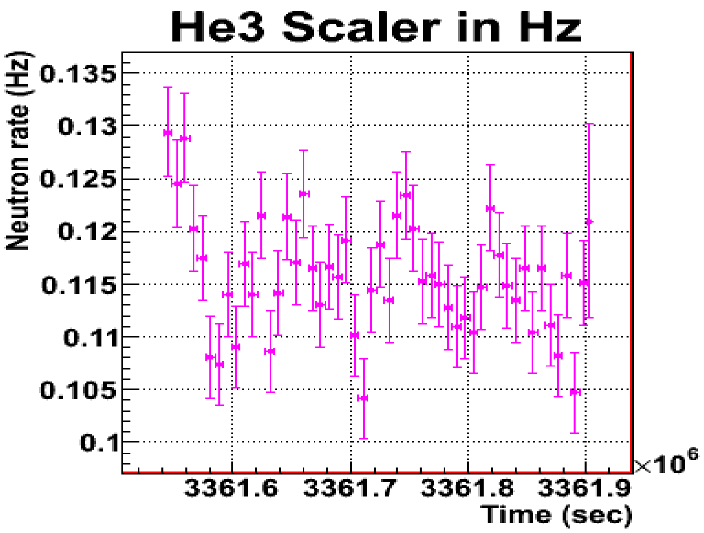
Monte Carlo simulation models data fairly well:

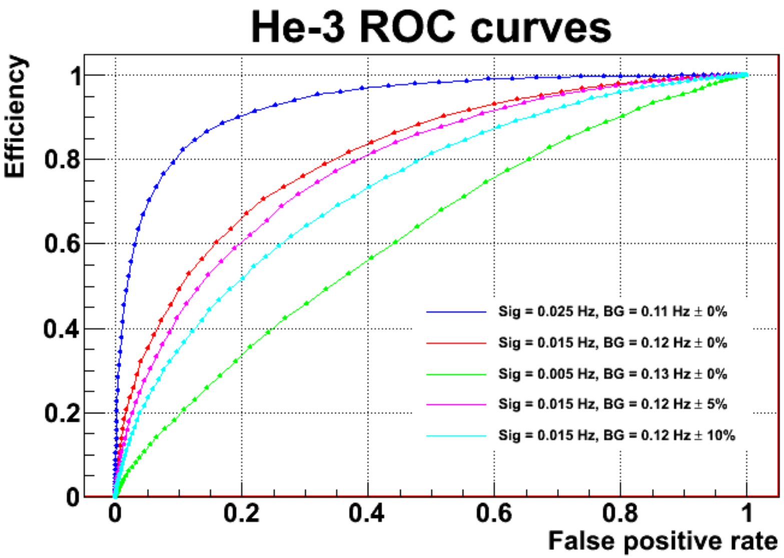
* Overall opacity

* Effect of active veto

Understanding background

- Systematic uncertainties in background are dominant performance limitation in low-S:B scenarios.
- Imaging can help!





Recurring themes

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- Importance of reconstruction algorithms.
- Simulation as a tool for detector design.
- Need to understand the background.
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Conclusions

- Fast neutron imaging improves on the state of the art and addresses pressing problems in nuclear security.
- We have designed, built, and tested several fast neutron imagers based on different detection concepts.
- We are pursuing quantitative evaluation of different systems in different scenarios; and learning how to optimize detectors for particular scenarios.