SAND2013-8664P

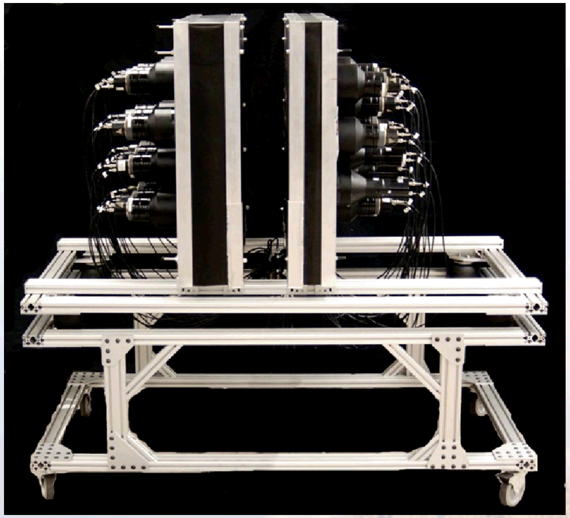
Keeping things that go BOOM out of the wrong hands –

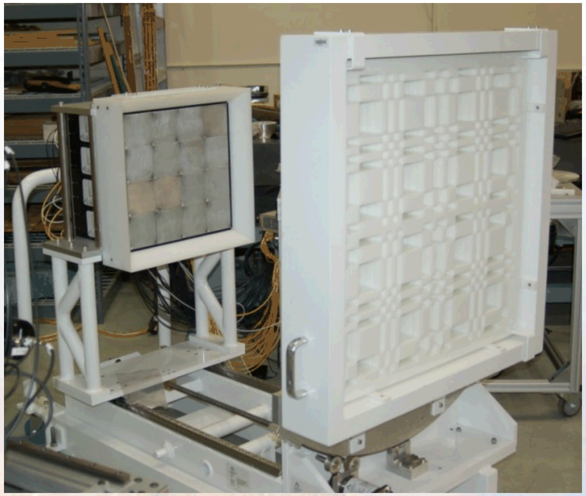
Nuclear non-proliferation and explosives detection

Peter Marleau

Sandia National Labs

UC Davis, Oct 2013





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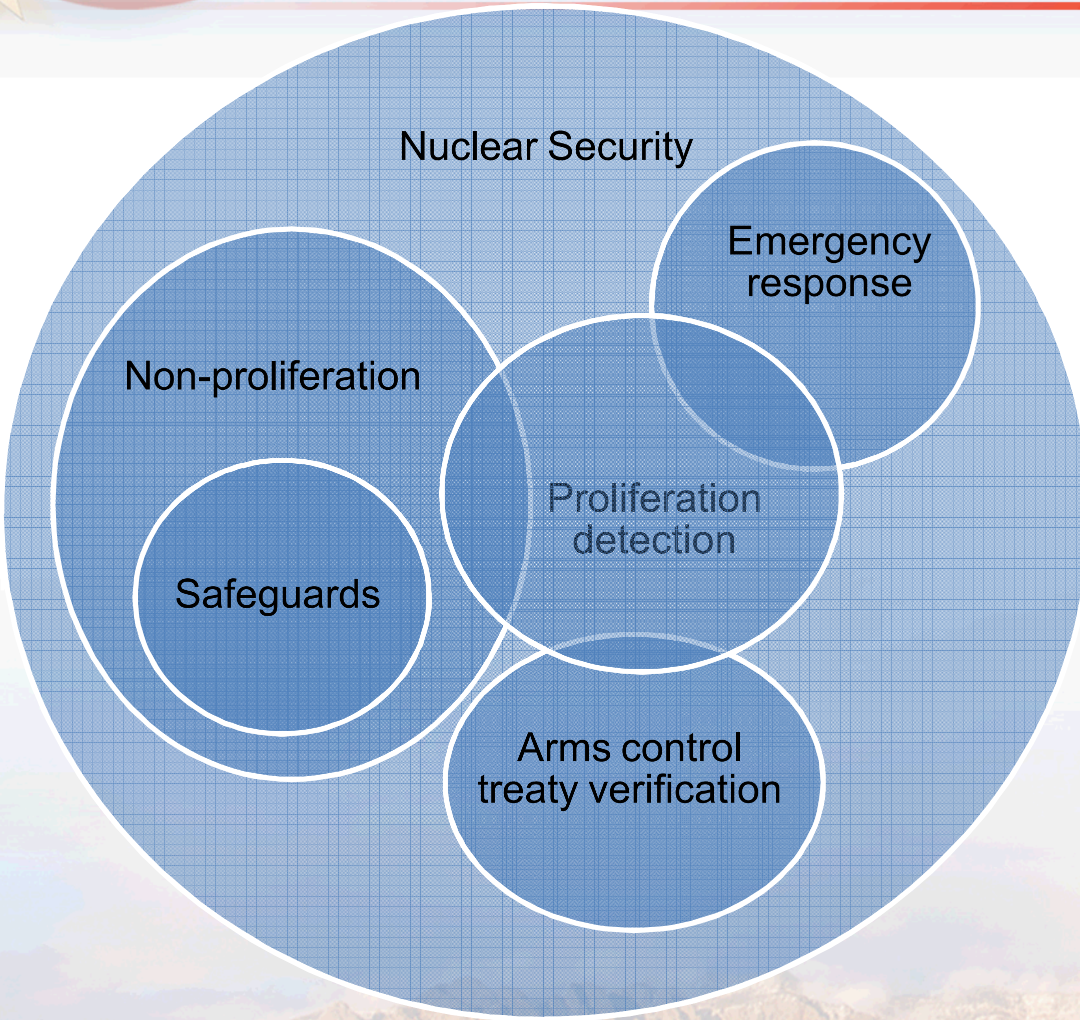
Outline

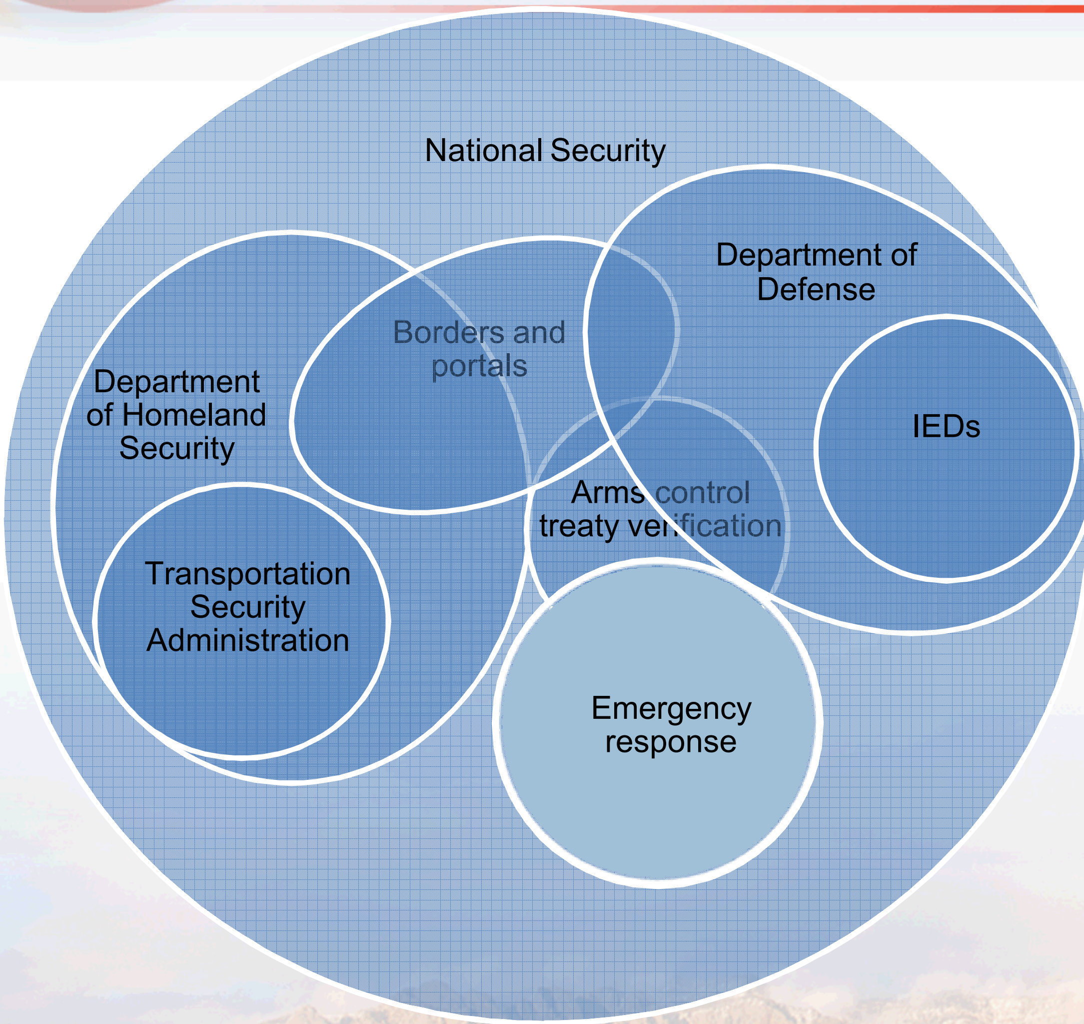
- **Nuclear security and radiation detection**
  - What is SNM?
  - SNM detection
  - SNM detection/characterization challenges
- **Motivation for fission-energy neutron detection/imaging**
- **Detector concepts and prototypes**
  - Gammas
  - Multiplicity counters
  - Fast neutron imagers
- **Explosives detection (Sweany)**
  - Materials identification by Resonant Attenuation.
  - Future research and points of collaboration.

Nuclear security Venn diagram



- Special nuclear material (SNM) is the common element.
  - Detect
  - Locate
  - Characterize
- Radiation detection can help!

National security Venn diagram



- Explosive material is the common element.
  - Detect
  - Locate
  - Characterize
- Where there is SNM likely there are explosives.
  - Confirm presence or absence.

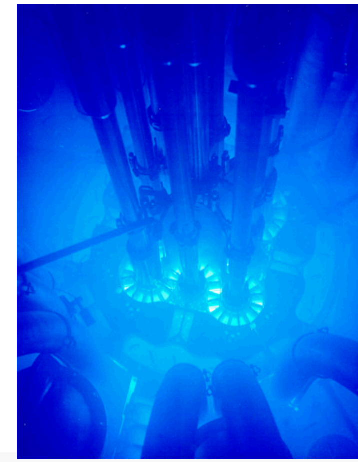
Special Nuclear Material - detection/characterization

Standoff detection

Cargo screening

Arms control treaty verification

safeguards



emergency response

SNM detection

- **Presence/absence of SNM**
- **Low signal rate**
  - Need large area detectors!
- **Low signal to background**
  - Need background discrimination!

SNM characterization

- **Imaging, mass, isotopics, multiplication**
- **Presence/absence of explosives**

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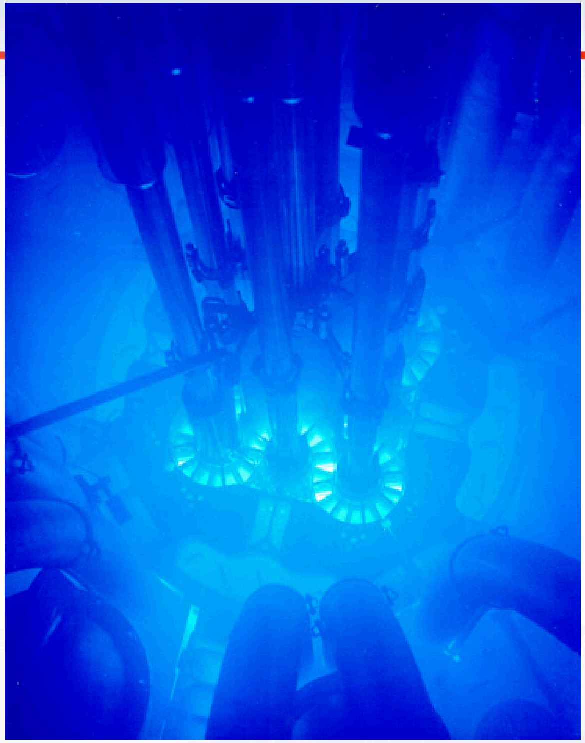
Cargo screening

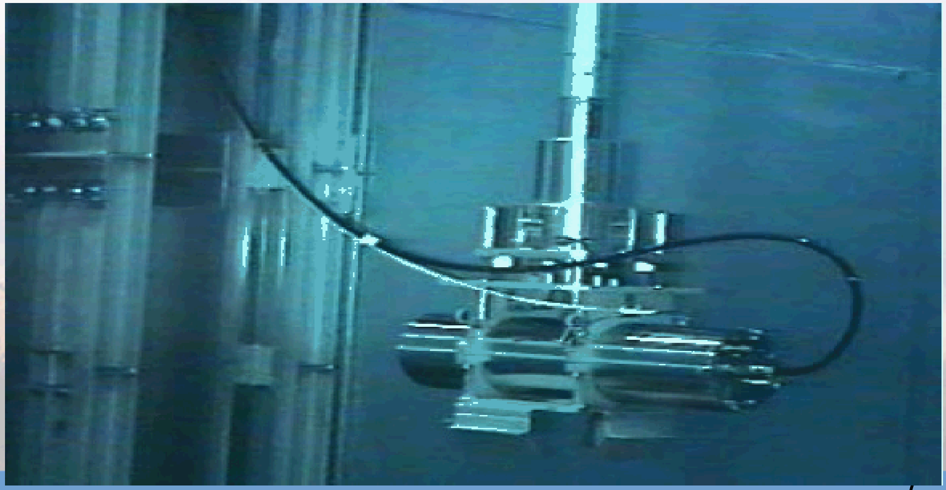
- **Extremely challenging problem!**
  - Needle in a haystack
  - Flow of commerce
  - Potential for heavy shielding
  - Background variations
- **Primary screening, secondary, etc.**

- **Neutrons for weak source detection:**
  - Low background, very few benign neutron emitters.
  - Fewer nuisance neutron alarms expected.

Safeguards

- IAEA and state driven.
- Heavy reliance on inspections, visual surveillance, satellite imagery.
- Cherenkov imaging, densitometry, calorimetry, gamma spectrometry, multiplicity counters.
- Challenging environments – very high radiation through shielding.





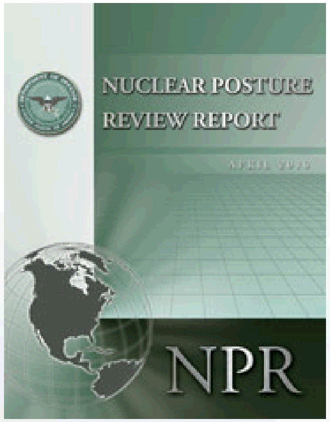
Emergency response

- **Learn as much as possible, as quickly as possible, about a package containing SNM.**
- **All information is potentially useful.**

National Policy Foundation

"…negotiate a new Strategic Arms Reduction Treaty with the Russians this year. … And this will set the stage for further cuts, and we will seek to include all nuclear weapons states in this endeavor."

President Obama, Remarks in Prague
April 2009



"Non-strategic nuclear weapons, together with the non-deployed weapons of both sides, should be included in any future reduction arrangements between the United States and Russia."

Nuclear Posture Review
April 6, 2010

"… the United States will seek to initiate, …, negotiations with the Russian Federation on an agreement to address the disparity between the non-strategic (tactical) nuclear weapons stockpiles of the Russian Federation and of the United States and to secure and reduce tactical nuclear weapons in a verifiable manner; …"

Senate Resolution of Ratification, New START Treaty
December 2010

Arms control treaty verification

- **Trust but verify**
- **Canonical example: warhead counting**
- **Warhead authentication**
- **Technical solutions that are just good enough, but no better**

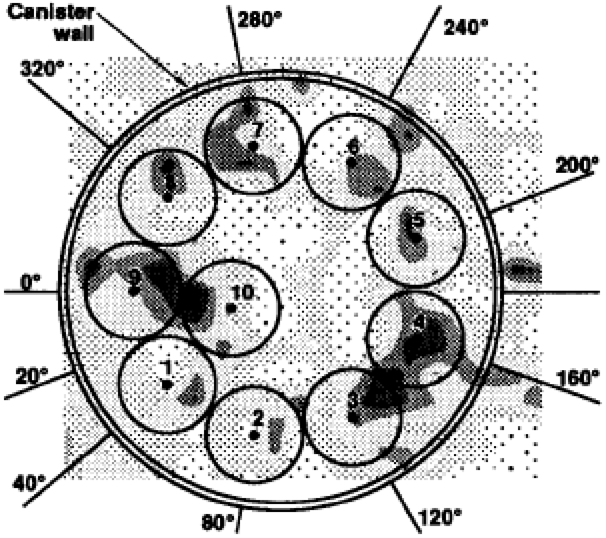


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Fig. 5. Loadout of a Peacekeeper missile obtained during the F. E. Warren field trial. The open circles represent warhead locations.

Ziock et al., 1991 NSS/MIC conf rec.

Nuclear Material?

As defined by the IAEA:

Nuclear Material – metals uranium, plutonium, and thorium in any form.

Special Nuclear (fissile) Material – U-233, U-235, Pu-239

Source Material – everything that is not special

Special Nuclear Material?

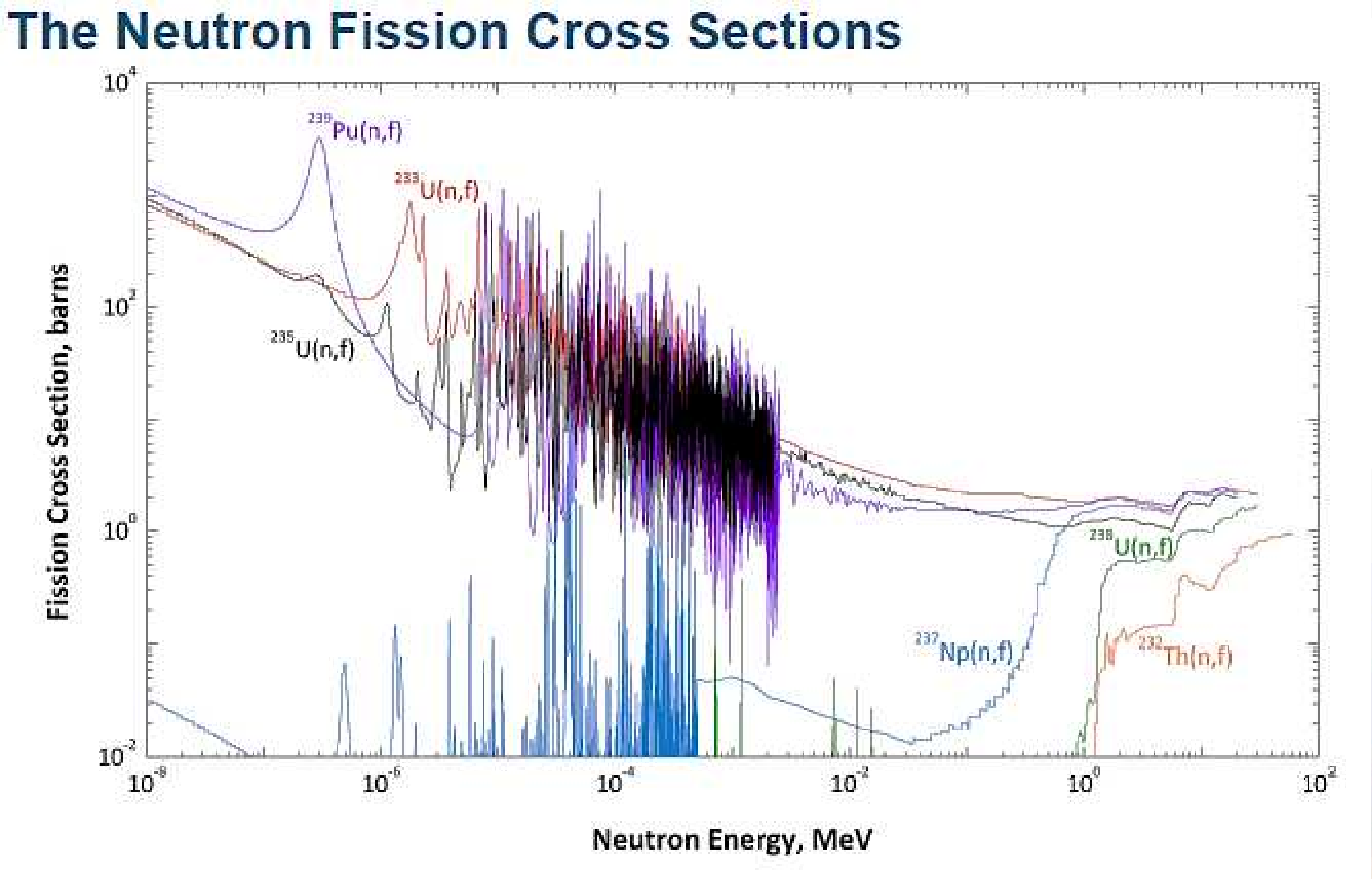
The Passive Neutron Signatures

Isotope	Half Life	Spontaneous Fission Yield (n/s-kg)	Spontaneous Fission Multiplicity ν	Induced Thermal Fission Multiplicity ν
^{232}U	71.7 yr	1,300	1.71	3.13
^{233}U	1.59×10^5 yr	0.86	1.76	2.4
^{234}U	2.45×10^5 yr	5.02	1.81	2.4
^{235}U	7.04×10^8 yr	0.299	1.86	2.41
^{236}U	2.34×10^6 yr	5.49	1.91	2.2
^{238}U	4.47×10^9 yr	13.6	2.01	2.3
^{237}Np	2.14×10^6 yr	0.114	2.05	2.70
^{238}Pu	87.7 yr	2.59×10^6	2.21	2.9
^{239}Pu	2.41×10^4 yr	21.8	2.16	2.88
^{240}Pu	6.56×10^3 yr	1.02×10^6	2.16	2.8
^{241}Pu	14.35 yr	50 ±	2.25	2.8
^{242}Pu	3.76×10^5 yr	1.72×10^6	2.15	2.81
^{244}Cm	18.1 yr	1.08×10^{10}	2.72	3.46
^{252}Cf	2.65 yr	2.34×10^{15}	3.757	4.06

Ref: "Panda Book", values with ± have significant uncertainty

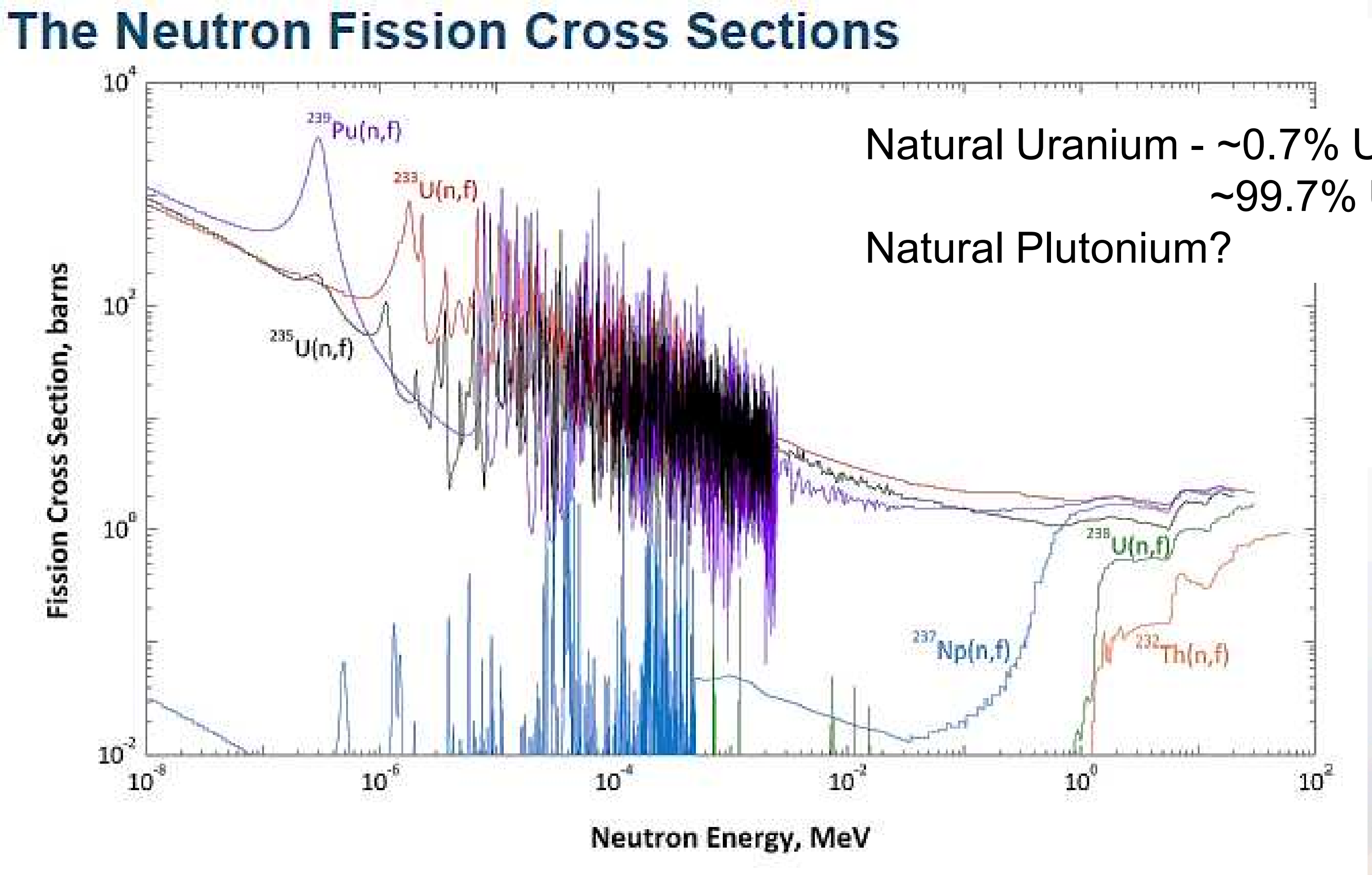
Slide courtesy of David Chichester, INL

Special Nuclear Material …



Slide courtesy of David Chichester, INL

Nuclear Material …



Natural Uranium - ~0.7% U-235
~99.7% U-238

Natural Plutonium?

Slide courtesy of David Chichester, INL

Special Nuclear Material?

The Passive Neutron Signatures

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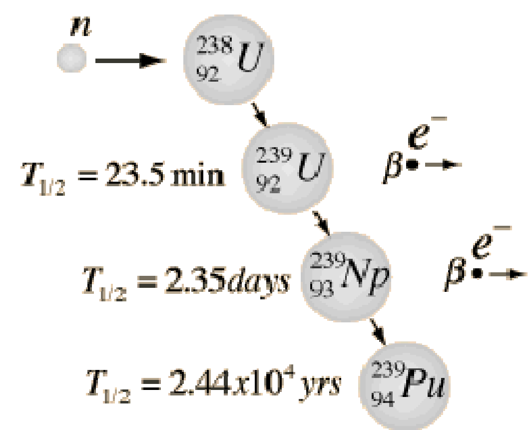
^{237}Np	2.14 x 10^6 yr	0.114		
^{238}Pu	87.7 yr	2.59 x 10^6		
^{239}Pu	2.41 x 10^4 yr	21.8		
^{240}Pu	6.56 x 10^3 yr	1.02 x 10^6		
^{241}Pu	14.35 yr	50 ±		
^{242}Pu	3.76 x 10^5 yr	1.72 x 10^6		
^{244}Cm	18.1 yr	1.08 x 10^{10}		
^{252}Cf	2.65 yr	2.34 x 10^{15}		

There isn't natural Plutonium to be found, but …

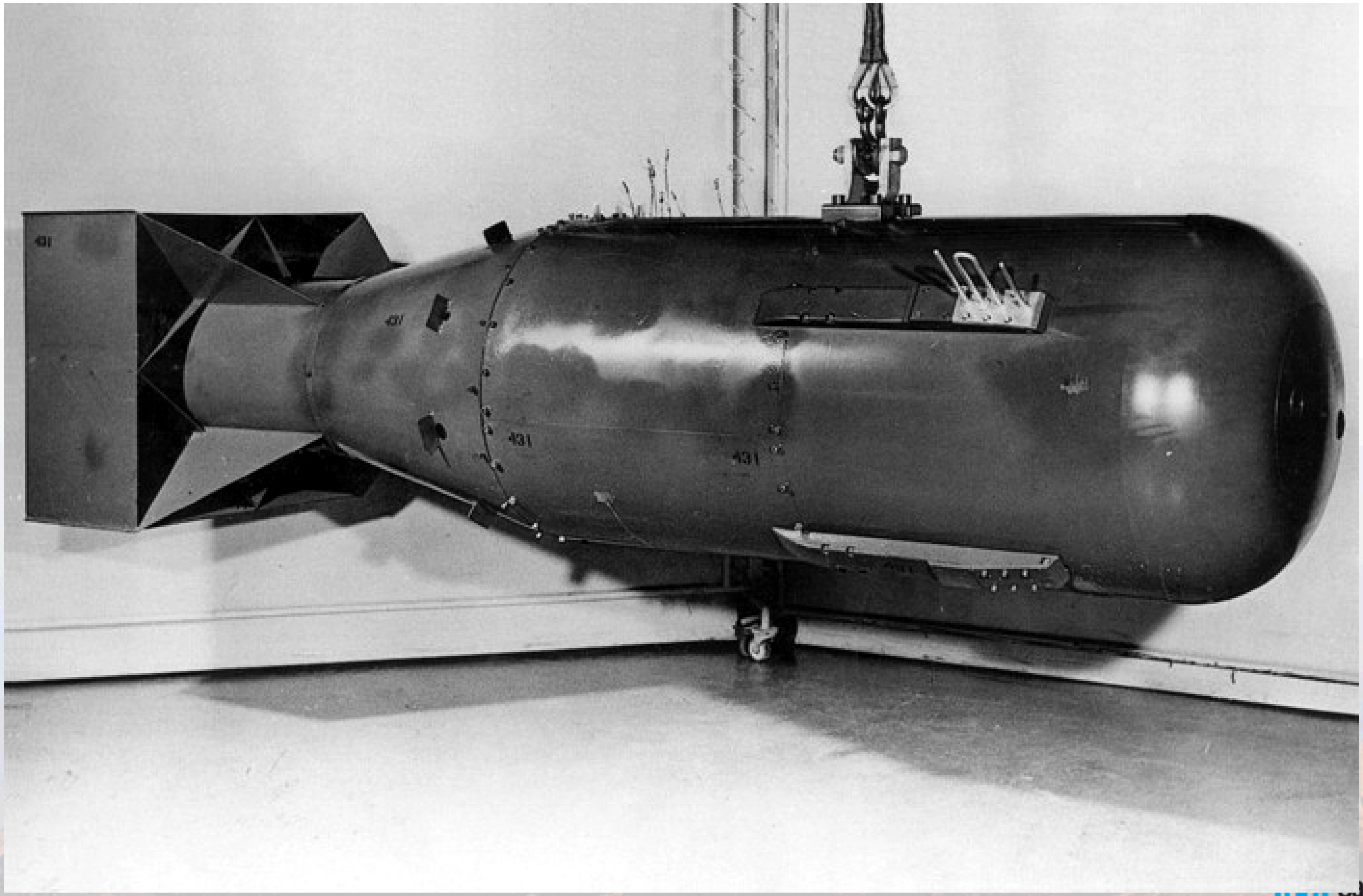


Ref: "Panda Book", values with ± have significant uncertainty

Special Nuclear Material?

Highly Enriched Uranium (HEU) - >20% U-235

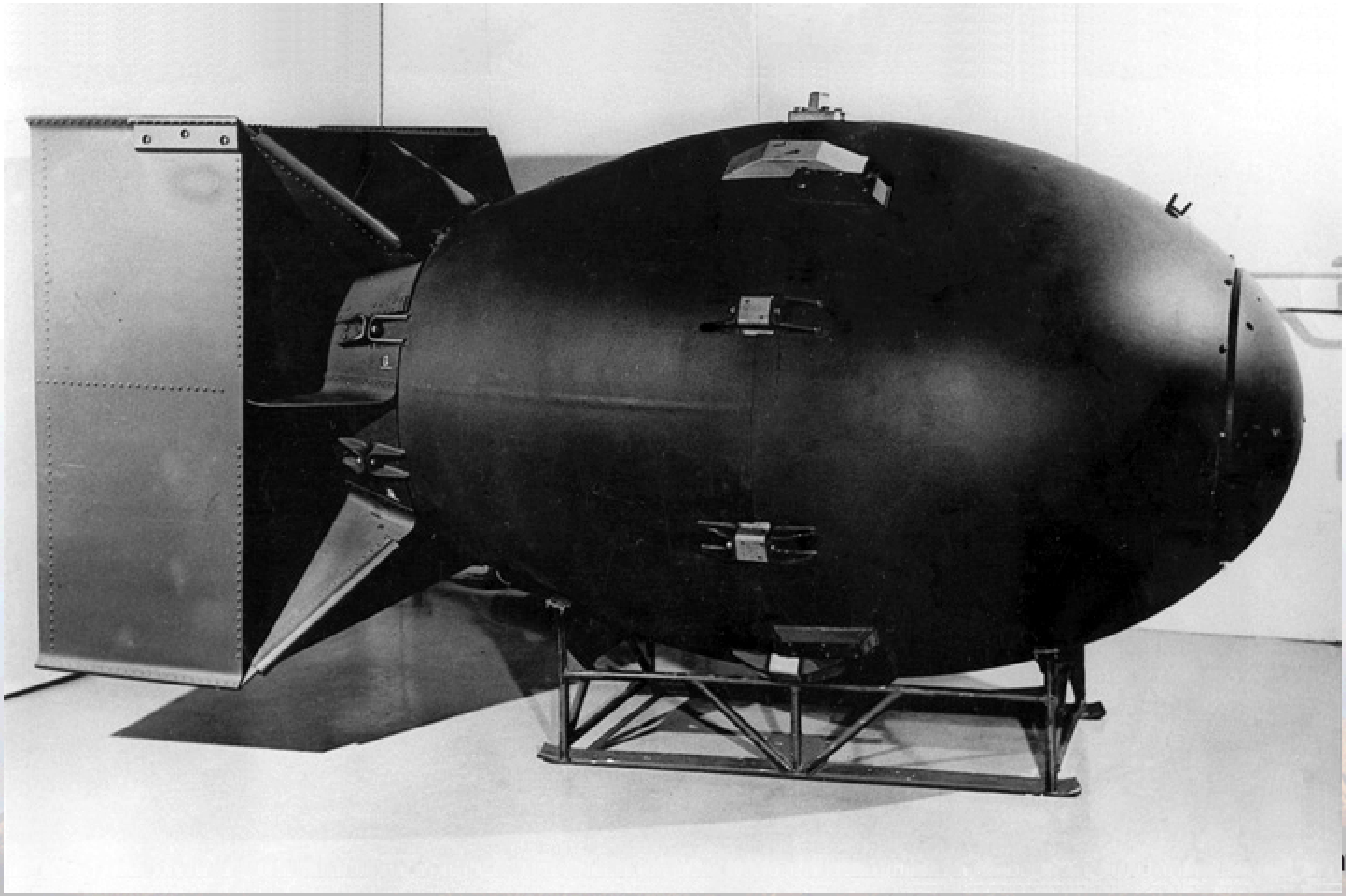
Little Boy



Special Nuclear Material?

Weapons Grade Plutonium (WGPu) - >93% Pu-239

Fat Man



Special Nuclear Material Detection

Gamma-rays

Isotope	Energy (keV)	Activity (γ/g-s)
^{234}U	120.9	9.35×10^4
^{235}U	143.8	8.40×10^3
	185.7	4.32×10^4
^{238}U	766.4	2.57×10^1
	1001.0	7.34×10^1
^{238}Pu	152.7	5.90×10^6
	766.4	1.387×10^5
^{239}Pu	129.3	1.436×10^5
	413.7	3.416×10^4
^{240}Pu	45.2	3.80×10^6
	160.3	3.37×10^4
	642.5	1.044×10^3
^{241}Pu	148.6	7.15×10^6
	208.0	2.041×10^7
^{241}Am	59.5	4.54×10^{10}
	125.3	5.16×10^6

Neutrons

Isotope	Half Life	Spontaneous Fission Yield (n/s-kg)
^{232}U	71.7 yr	1,300
^{233}U	1.59×10^5 yr	0.86
^{234}U	2.45×10^5 yr	5.02
^{235}U	7.04×10^8 yr	0.299
^{236}U	2.34×10^6 yr	5.49
^{238}U	4.47×10^9 yr	13.6
^{237}Np	2.14×10^6 yr	0.114
^{238}Pu	87.7 yr	2.59×10^6
^{239}Pu	2.41×10^4 yr	21.8
^{240}Pu	6.56×10^3 yr	1.02×10^6

Slide courtesy of David Chichester, INL

Special Nuclear Material Detection – why neutrons?

The Passive Gamma-Ray Signatures

Isotope	Energy (keV)	Activity (γ/g-s)	Mean Free Path (mm) (High-Z, ρ)	(Low-Z, ρ)
^{234}U	120.9	9.35×10^{4}	0.23	69
^{235}U	143.8	8.40×10^{3}	0.36	73
	185.7	4.32×10^{4}	0.69	80
^{238}U	766.4	2.57×10^{1}	10.0	139
	1001.0	7.34×10^{1}	13.3	159
^{238}Pu	152.7	5.90×10^{6}	0.40	75
	766.4	1.387×10^{5}	9.5	139
^{239}Pu	129.3	1.436×10^{5}	0.27	71
	413.7	3.416×10^{4}	3.7	106
^{240}Pu	45.2	3.80×10^{6}	0.07	25
	160.3	3.37×10^{4}	0.45	76
	642.5	1.044×10^{3}	7.4	127
^{241}Pu	148.6	7.15×10^{6}	0.37	74
	208.0	2.041×10^{7}	0.86	83
^{241}Am	59.5	4.54×10^{10}	0.14	38
	125.3	5.16×10^{6}	0.26	70

These materials are dense; self-shielding is not negligible

Ref: "Panda Book"

Slide courtesy of David Chichester, INL

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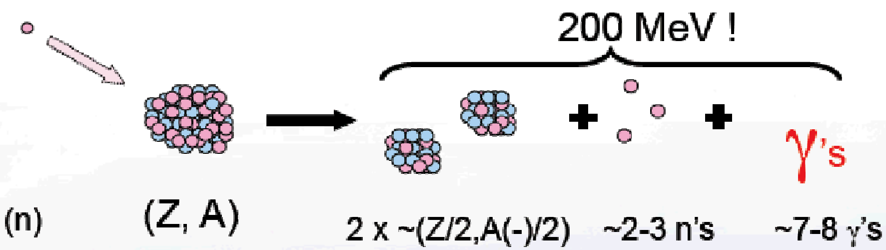
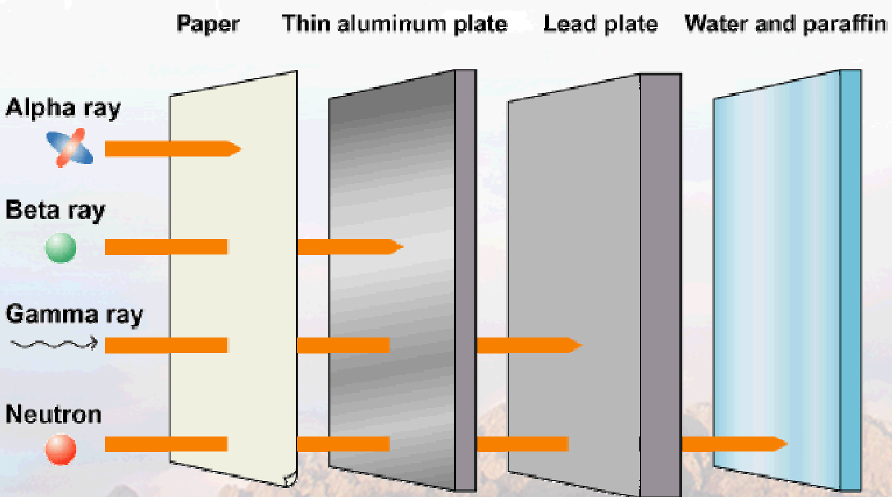
SNM Detection?

- **Special nuclear material emits ionizing radiation.**
  - Sensitive and specific signature
- **Only neutral particles penetrate shielding.**

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

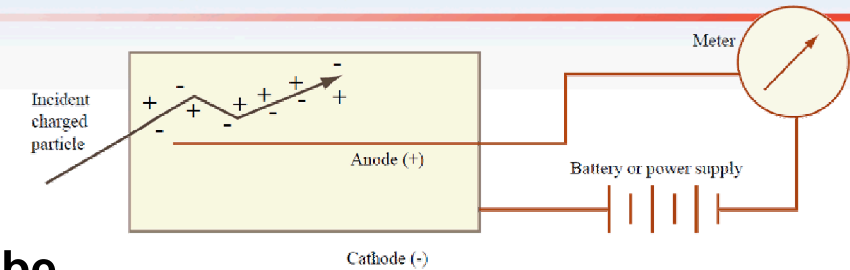
~1.5 n/s/kg
IAEA sig = 20 kg





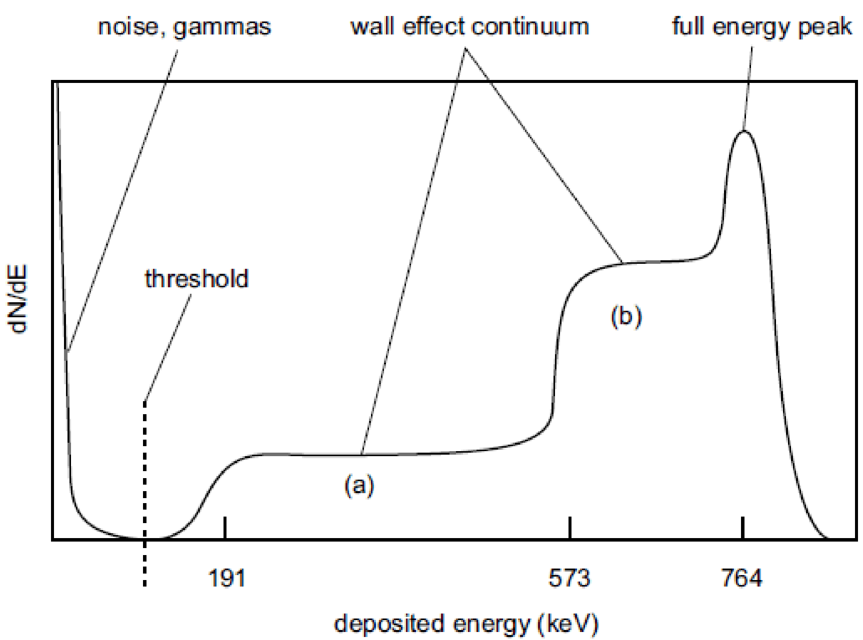
www.remnet.jp

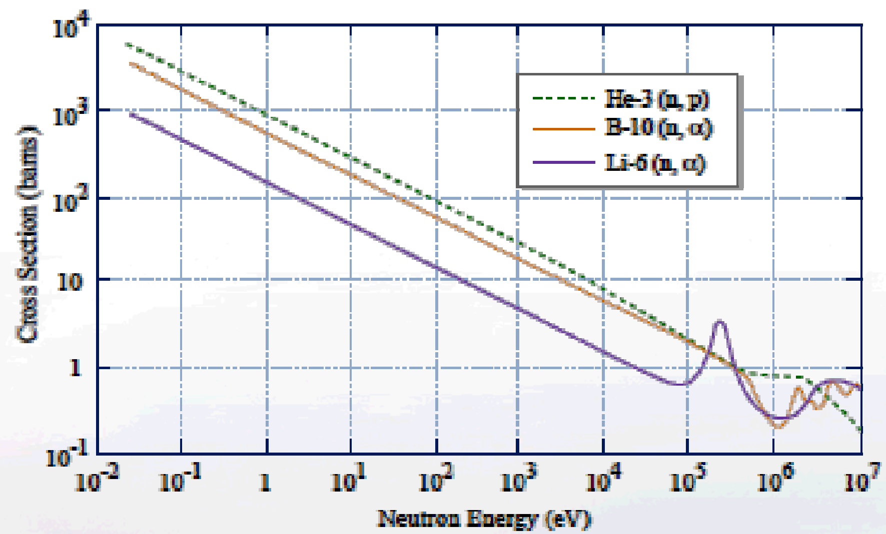
Gas Filled Neutron Counters



He3 Tube

$$n + {}^{3}He \rightarrow {}^{3}H + {}^{1}H + 0.764\ MeV$$

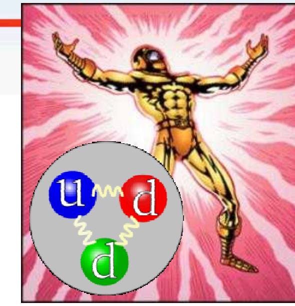


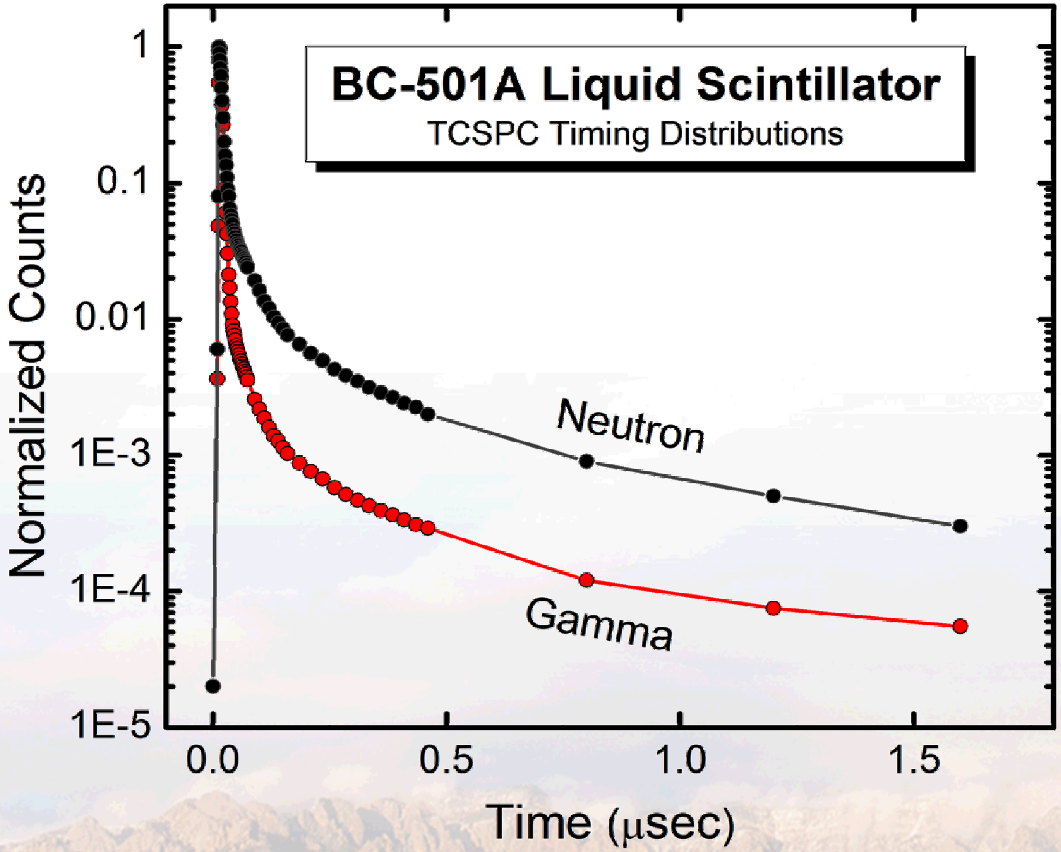


Neutron/gamma Detection – Scintillator

- Luminescence - When a material is excited and it subsequently gives off light.
- How it is excited determines the type of luminescence.
- Scintillation – luminescence produced by ionizing radiation excitation.
- Fluorescence – photoluminescence or scintillation that has a fast decay time (ns to μs).
- Phosphorescence – same as fluorescence, but with much slower decay time (ms to seconds)

Pulse Shape Discrimination





*Szczesniak, T. et al *IEEE Trans. Nucl. Sci.* **2010**, 57, 3846.

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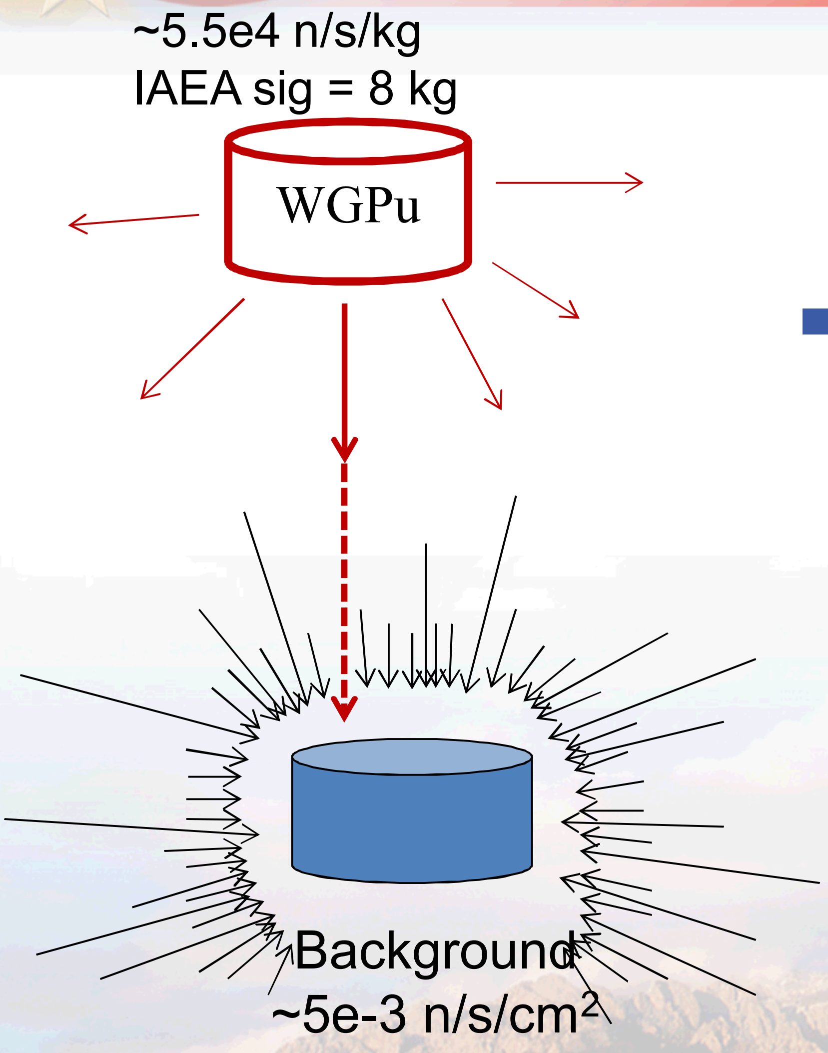
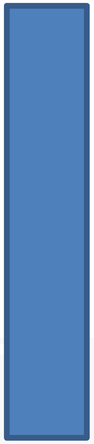
Standoff detection



- **Example: Large stand-off application (100 meters)**
  - 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**

4 π Counter



Signal = $\Sigma n\ ((A/n)\ \varepsilon\ S\ t)$
Background = $\Sigma n\ ((A/n)\ \varepsilon\ f\ B\ t)$

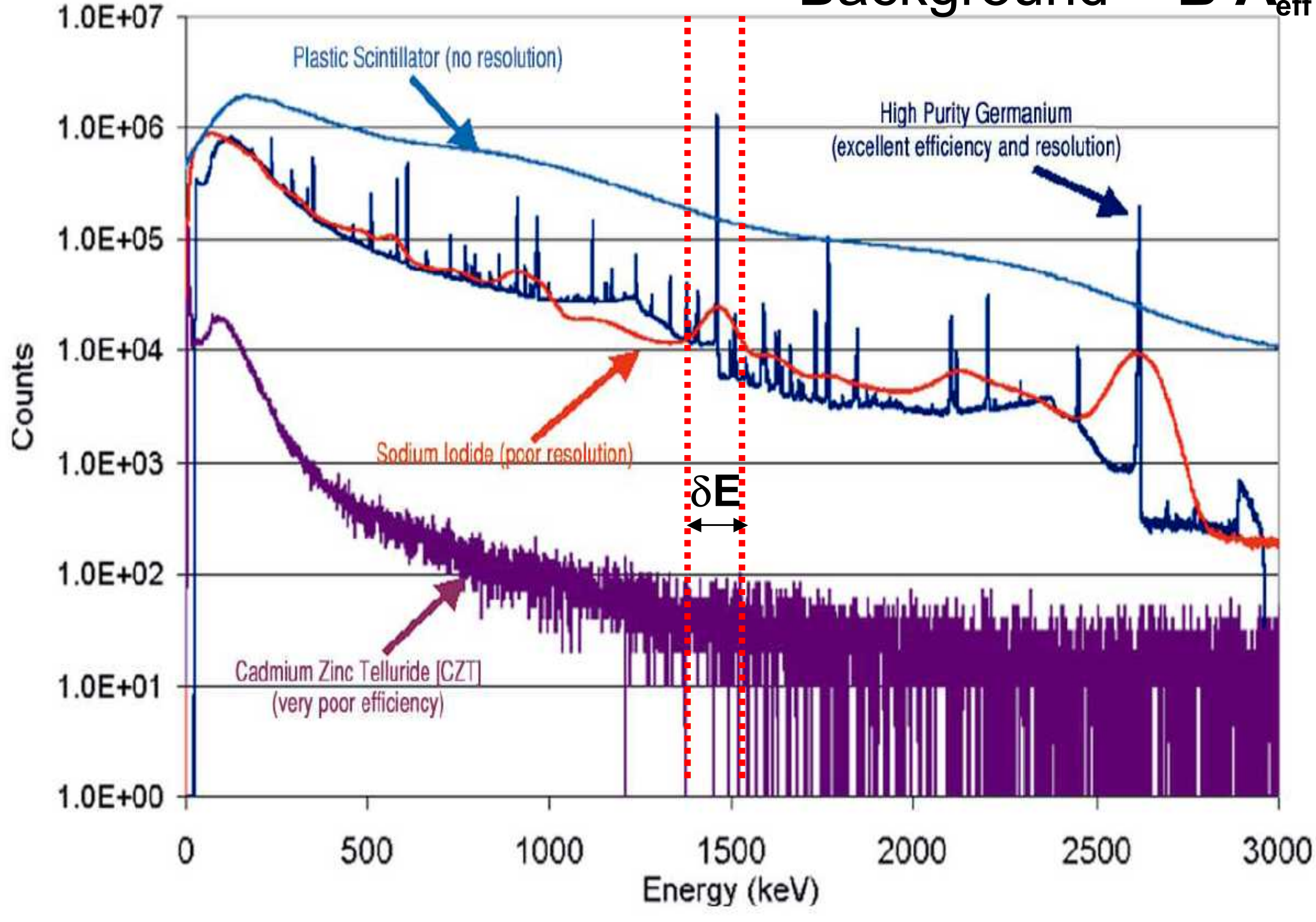
σ_{det} = Signal/$\sqrt{\text{Background}}$
= $S\ \sqrt{(A\ \varepsilon\ t/(f\ B))}$
= $S\ \sqrt{(A\ \varepsilon\ t/(B))}$

A = physical area
ε = efficiency
S = signal flux
B = background flux (4π)
t = time
n = number of pixels
f = FOV fraction per pixel = 1

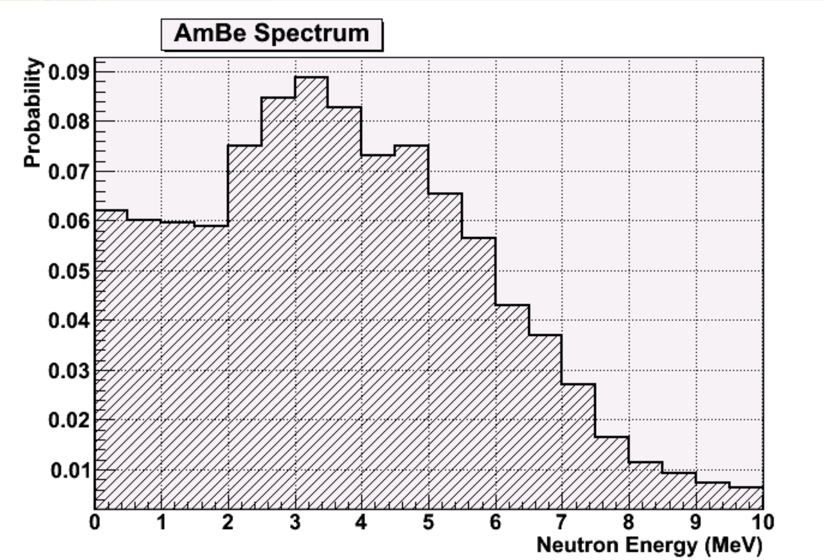
Spectroscopy

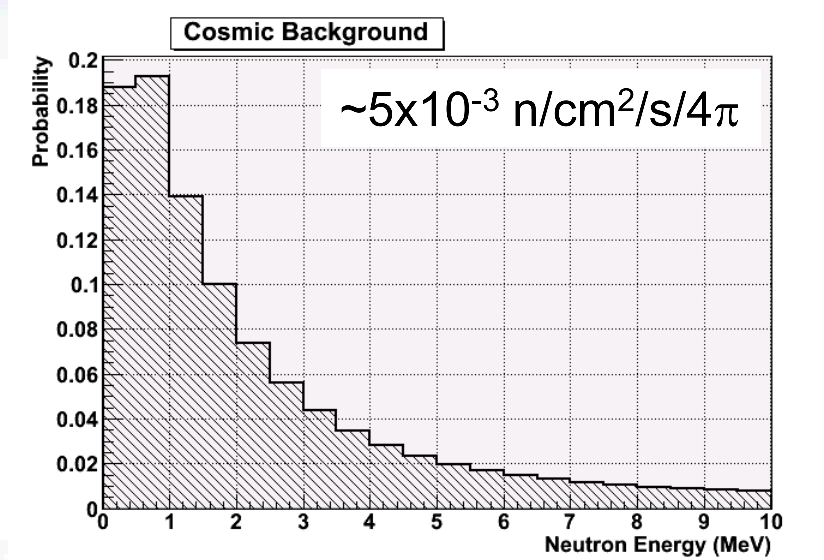
Signal = $\mathbf{S\ A_{eff}t}$

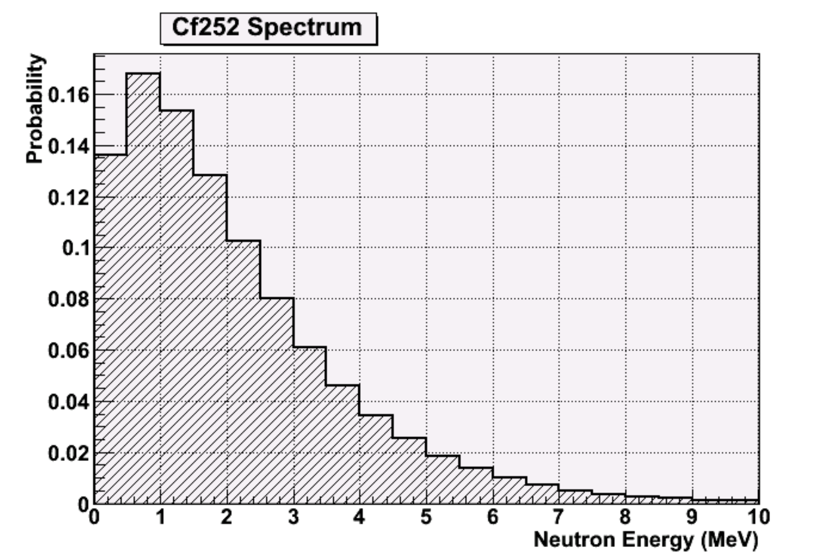
Background = $\mathbf{B\ A_{eff}t\ (\delta E)}$



Neutron Spectroscopy?



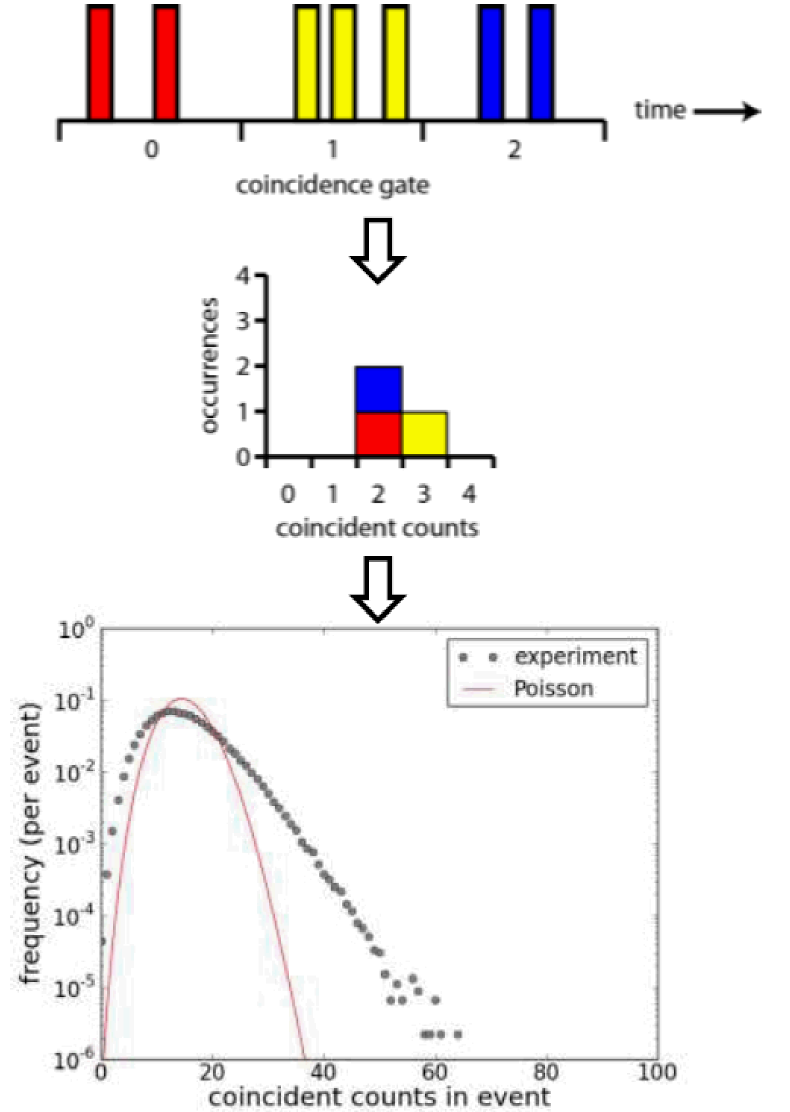




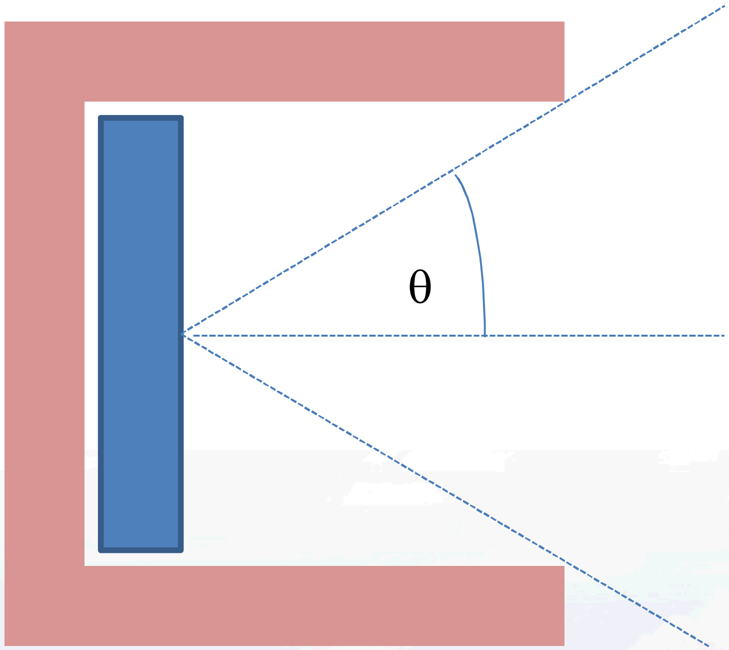
Probably not …

Neutron Multiplicity

Isotope	Induced Thermal Fission Multiplicity ν
^{232}U	3.13
^{233}U	2.4
^{234}U	2.4
^{235}U	2.41
^{236}U	2.2
^{238}U	2.3
^{237}Np	2.70
^{238}Pu	2.9
^{239}Pu	2.88
^{240}Pu	2.8
^{241}Pu	2.8
^{242}Pu	2.81
^{244}Cm	3.46
^{252}Cf	4.06



Collimated Counter



Signal $= \Sigma n\, ((A/n)\, \varepsilon\, S\, t)$

Background $= \Sigma n\, ((A/n)\, \varepsilon\, f\, B\, t)$

σ_{det} $= \text{Signal}/\sqrt{\text{Background}}$

$= S\, \sqrt{(A\, \varepsilon\, t/(f\, B))}$

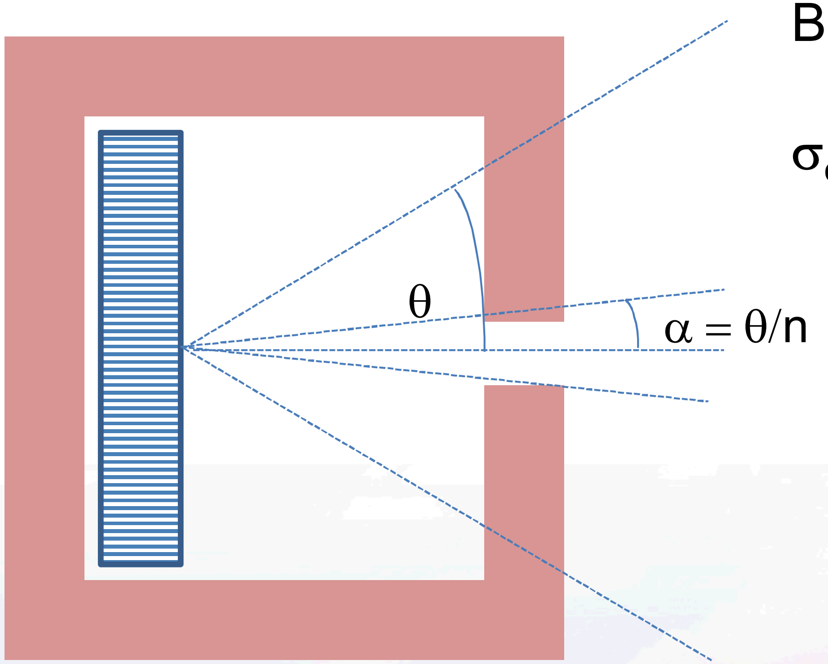
$= S\, \sqrt{(A\, \varepsilon\, t/(B\, (1-\cos(\theta))/2\,))}$

$=$ **Counter** $/ \sqrt{\, (1-\cos(\theta))/2\, }$

> Counter

A = physical area
ε = efficiency
S = signal flux
B = background flux (4π)
t = time
n = number of pixels
f = FOV fraction per pixel
= (1-cos(θ))/2

Pinhole Imager



Signal = $(A/n)\,\varepsilon\,S\,t$ *(1 pixel)*

Background = $(A/n)\,\varepsilon\,f\,B\,t$ *(1 pixel)*

σ_{det} = Signal/√Background

= $S\sqrt{(A\,\varepsilon\,t/(n\,f\,B))}$

= $S\sqrt{(A\,\varepsilon\,t/(n\,B\,(1-\cos(\theta/n))/2\,))}$

= **Counter** / $\sqrt{(n/2\,(1-\cos(\theta/n)))}$

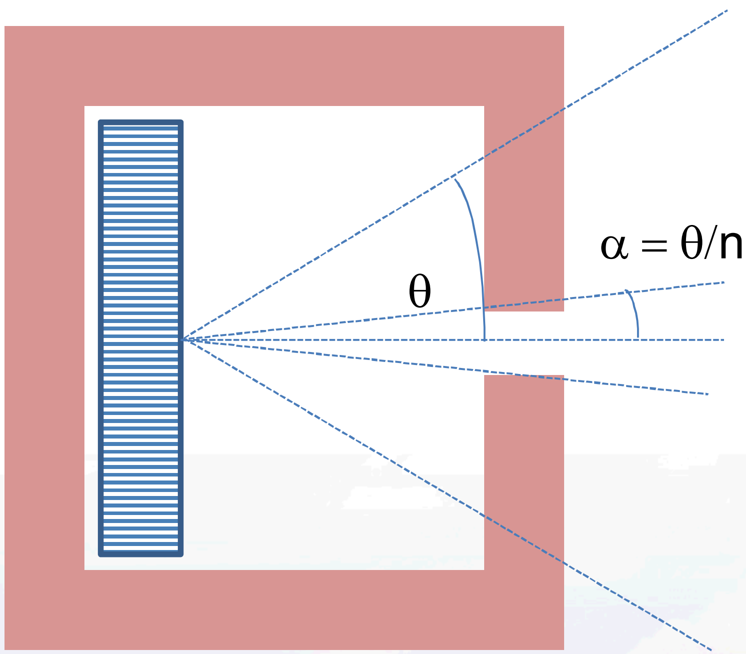
< Counter (n > 1)

= Collimator (n = 1)

A = physical area
ε = efficiency
S = signal flux
B = background flux (4π)
t = time
n = number of pixels
f = FOV fraction per pixel
= $(1-\cos(\theta/n))/2$

$\alpha = \theta/\sqrt{(n)}$ (for 2-D)

Pinhole Imager
(Unknown Background)



Signal = $(A/n)\,\varepsilon\, S\, t$ *(only 1 pixel)*

Background = $(A/n)\,\varepsilon\, f\, B\, t$ *(only 1 pixel)*

Background uncertainty estimate

= $\sqrt{((A/n)\,\varepsilon\, f\, B\, t)/(n-1)}$ *(others)*

σ_{det} = Signal/$\sqrt{(\text{Background}+\text{uncertainty}^2)}$

= $S\,\sqrt{(A\,\varepsilon\, t/(f\, B\, n^2/(n-1)))}$

= $S\,\sqrt{(A\,\varepsilon\, t/(n^2/(2(n-1))\, B\, (1-\cos(\theta/n))))}$

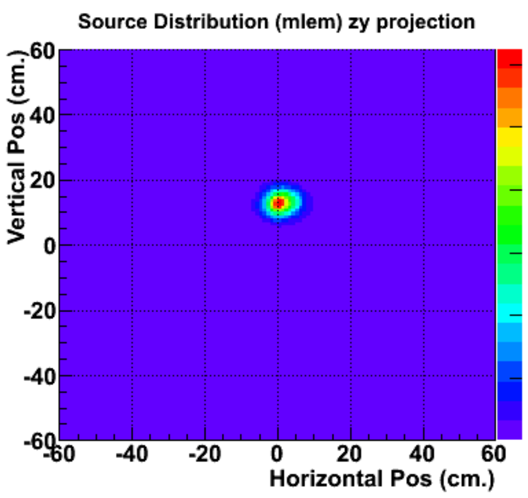
Counter - cannot estimate uncertainty without conditions allowing a "no source" data set to be taken.

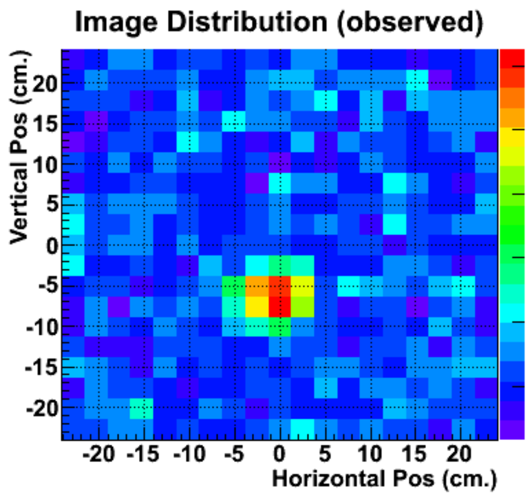
Collimator - cannot estimate uncertainty unless its FOV can change (ie rotation).

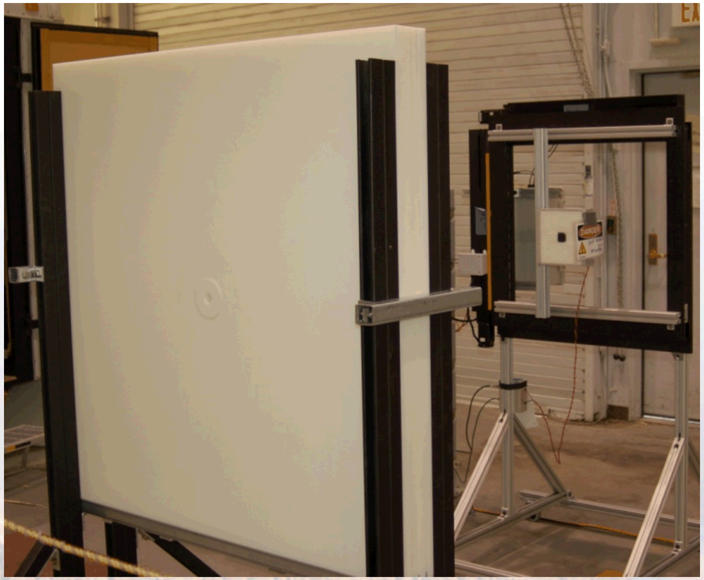
$\alpha = \theta/\sqrt{(n)}$ (for 2-D)

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.

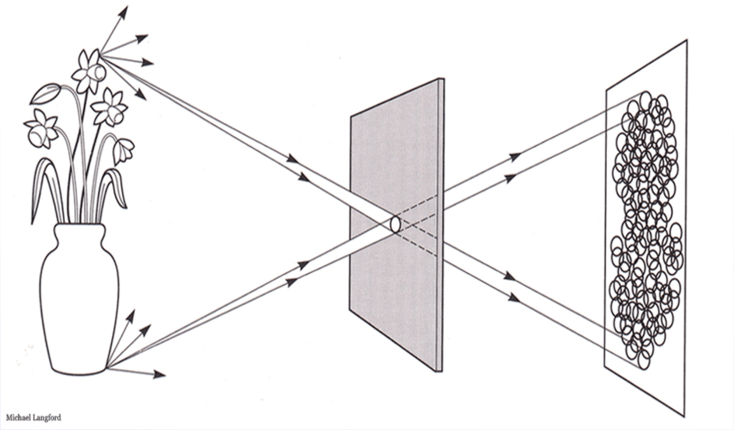




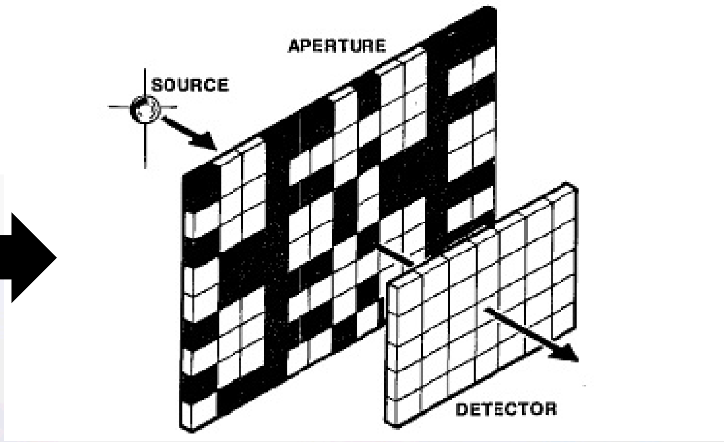


Coded aperture imaging

- **Extension of pinhole imaging with higher mask open fraction to improve the throughput of neutrons**



Pinhole
High Resolution, Low Throughput

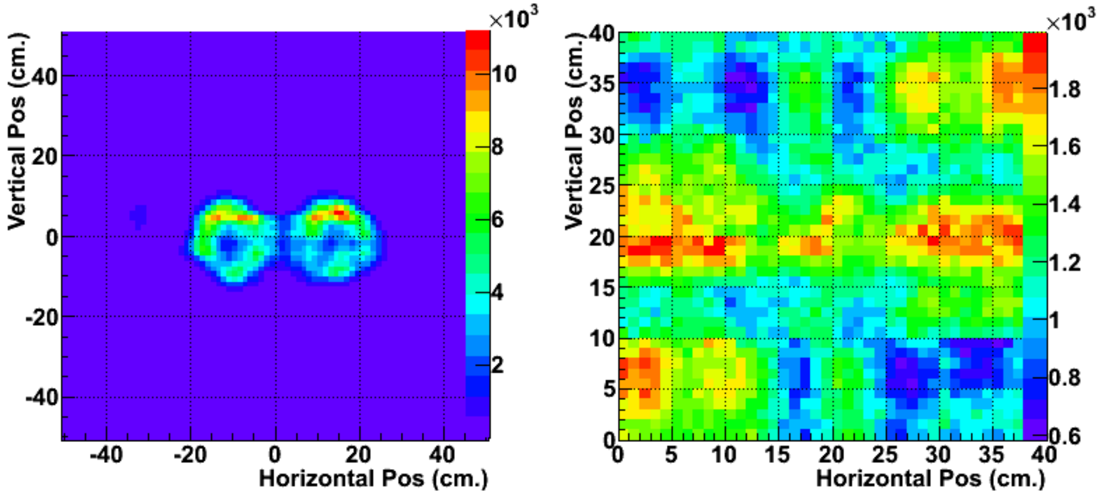


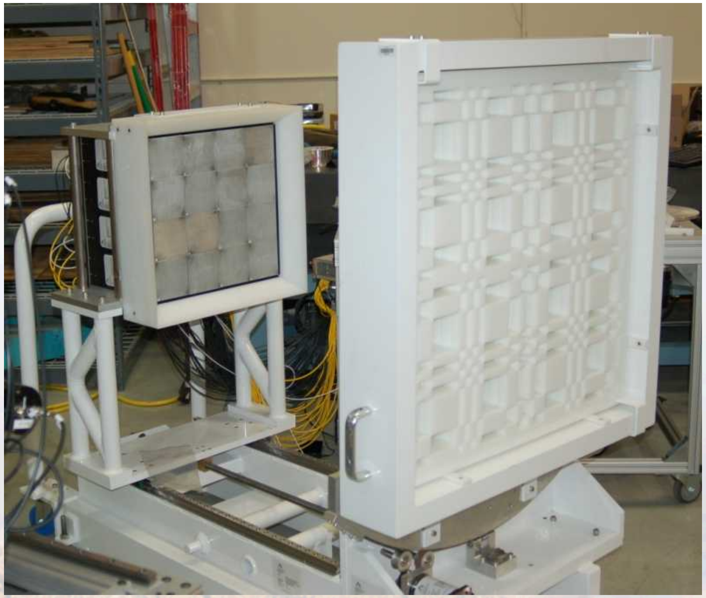
Coded aperture
High Resolution, High Throughput

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.

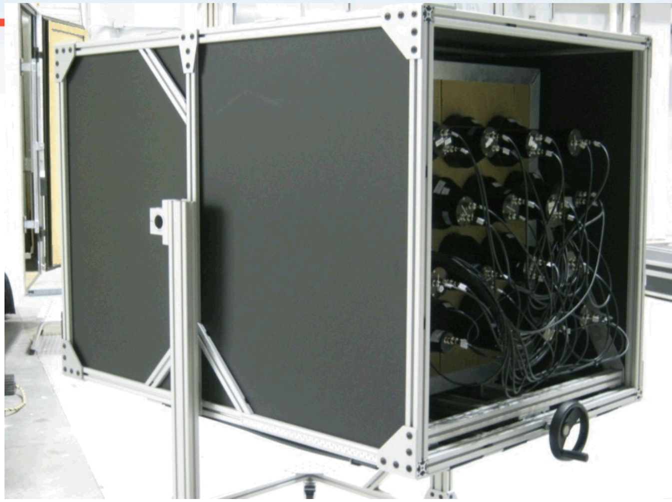
Each source equivalent to IAEA significant quantity (1 hour dwell)



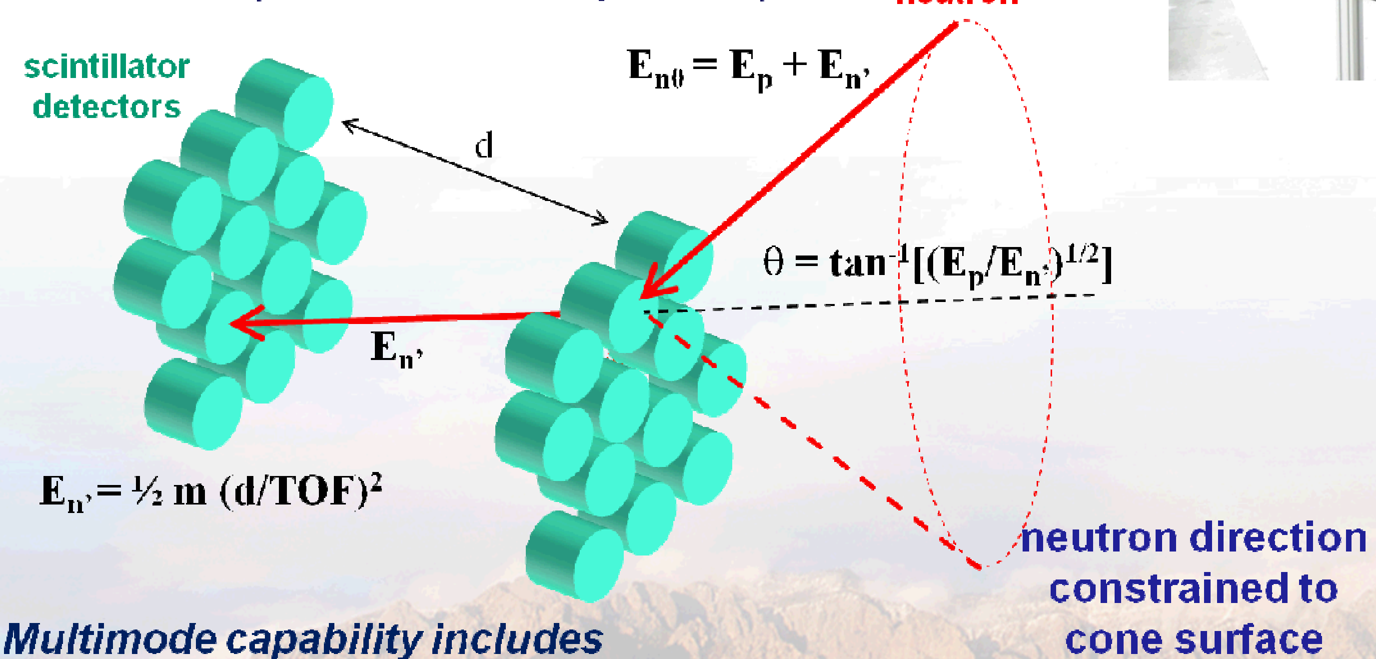


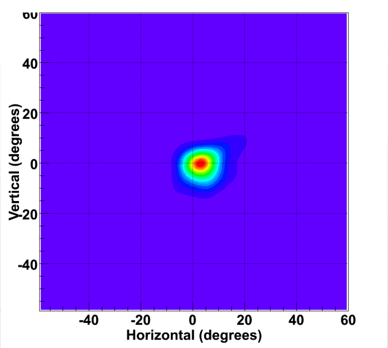
Neutron scatter camera

- Fast neutron imaging spectrometer
- Variable plane separation allows tradeoff of effective area, image resolution



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.*

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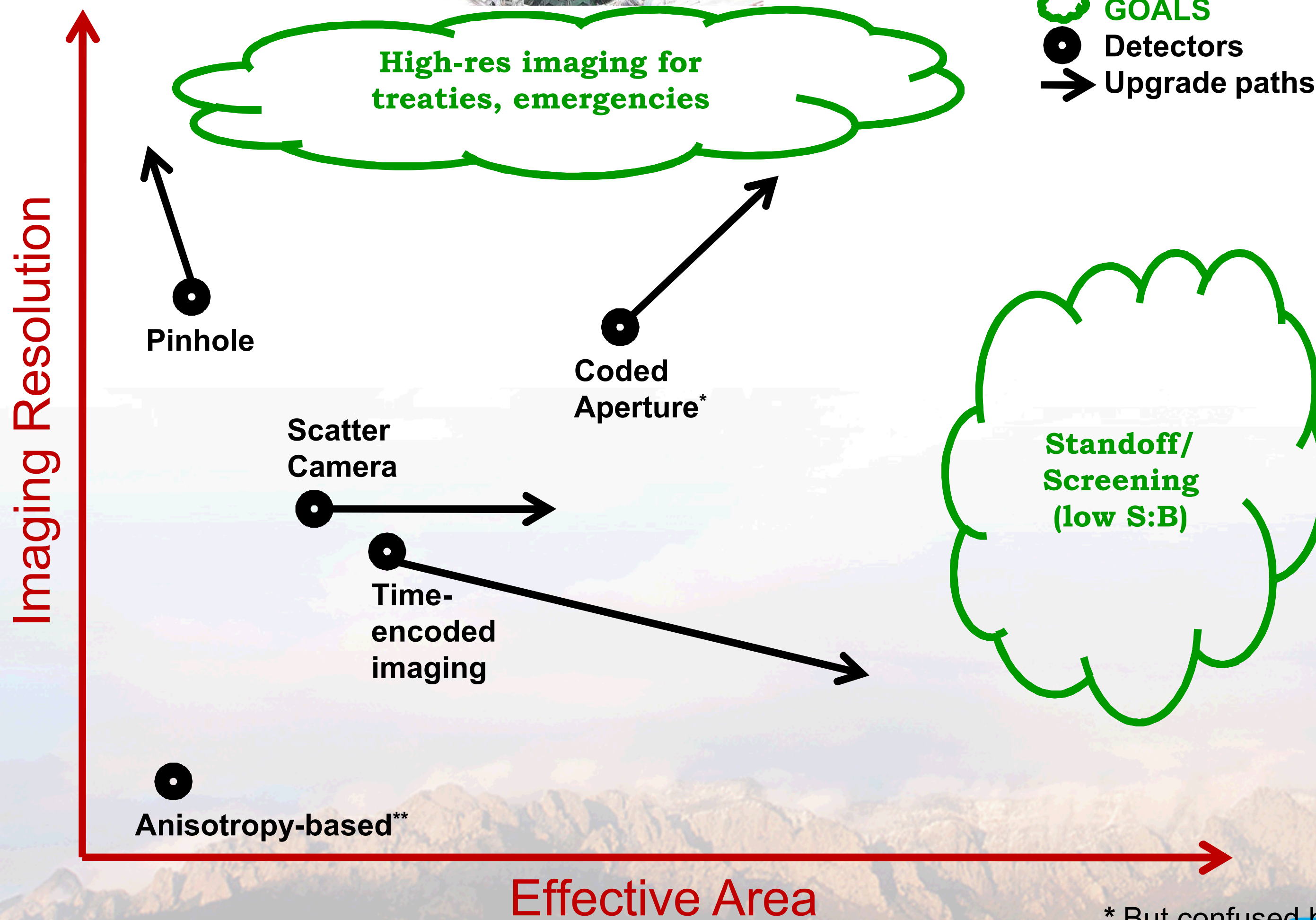
The detector zoo



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

Conclusions

- **Nuclear security is a multifaceted and complicated issue.**
- **Radiation detection/characterization can help.**
- **Because of their penetrating nature and low, well behaved, relatively well understood background, fast neutron detection is well motivated in the search and characterization of SNM.**
- **Low signals and backgrounds motivate large imaging detectors.**
- **Detection and imaging have different motivations.**
- **Pick the right detector for your application.**

Extra Slides

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How spectroscopy is used with other imagers?

- Example of a 2D HPGe Coded-Aperture system from Ziock et al.
- Use spectroscopic information to discriminate between sources, even if they superpose on same pixel

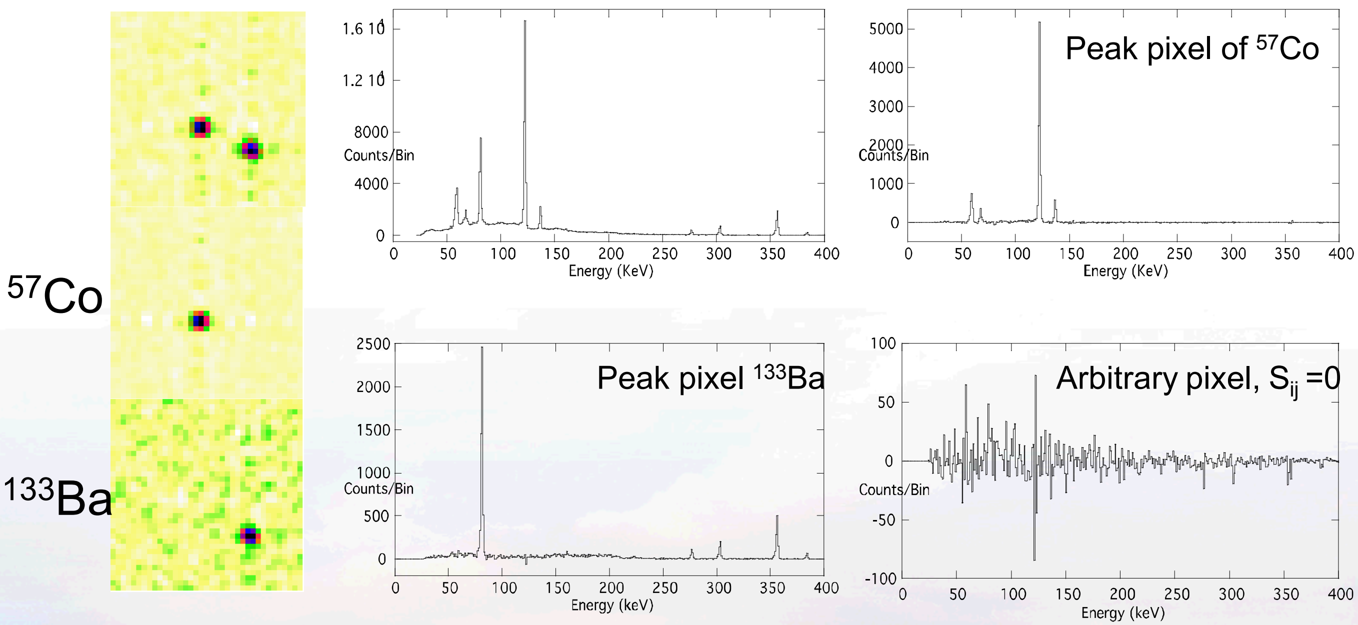
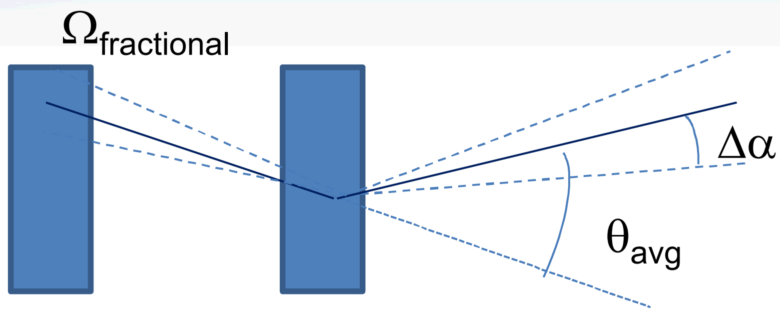


Fig. 10. Energy spectra associated with the top left image of Fig. 8. Top left is the straight spectrum from the detector. Top right is the spectrum from the peak pixel of the left source in the image. Bottom left is the spectrum from the peak pixel of the right source. In addition to providing the ability to identify the type of source, the spectra from the images are inherently background subtracted as shown by the spectrum on the bottom right which is from an arbitrary pixel in the image.

Double Scatter Imager



Signal = A/n ε_{pair} S m t = A/4 ε^2 Ω S n t

Background = A/n ε_{pair} f B m t = A/4 ε^2 Ω f B n t

σ_{det} = Signal/$\sqrt{}$Background

= S $\sqrt{}$(A ε^2 Ω n t/(4 f B))

= **Counter** * $\sqrt{}$ (ε Ω n /(4 f))

≈ **Counter** * $\sqrt{}$ (ε $\Omega_{rear\ plane}$ /(4 f))

A = physical area

ε_{pair} = efficiency for a pair = ε^{2}* $\Omega_{fractional}$

S = signal flux

B = background flux (4π)

t = time

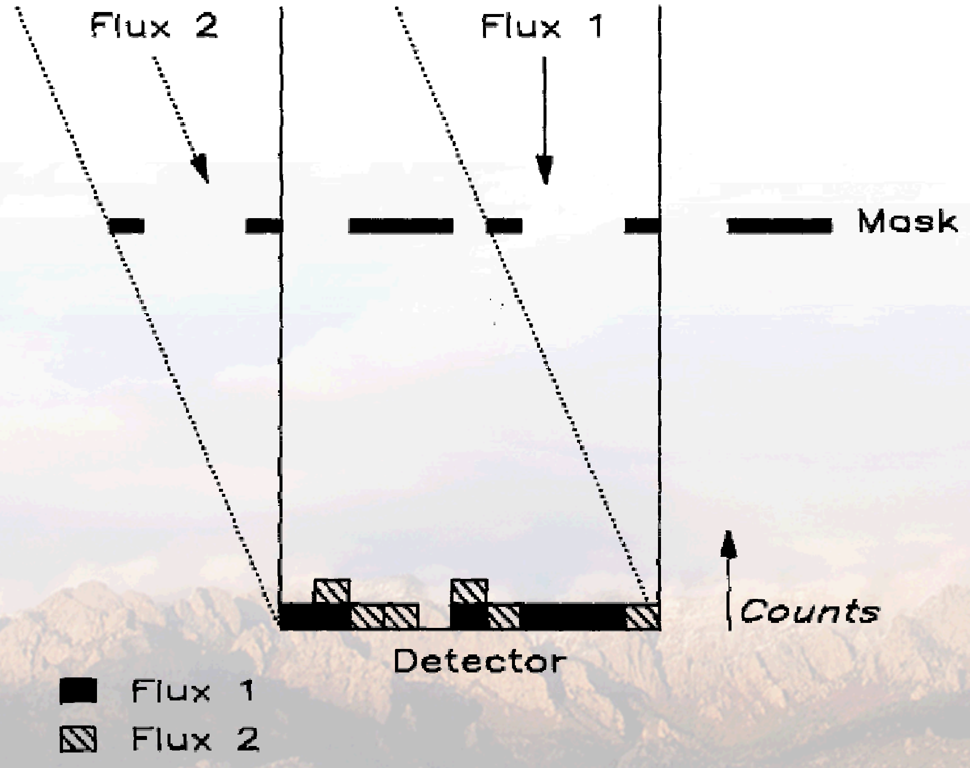
n = number of pixels

m = number of pairs = $(n/2)^2$

f = FOV fraction per pair ≈ $(\sin^2(\theta_{avg}+\Delta\alpha) - \sin^2(\theta_{avg}-\Delta\alpha))/2$

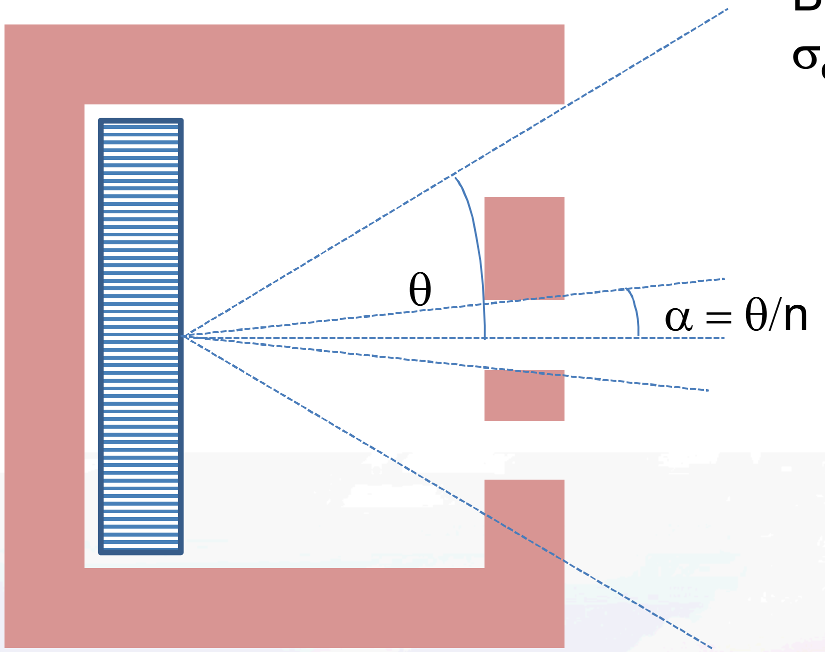
Coded aperture imaging

- **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



Carolli et al, Space Science Reviews 45 (1987), 349-403

Coded Aperture Imager



Signal = $(A/2)\,\varepsilon\, S\, t$ *(1/2 the pixels)*

Background = $(A/2)\,\varepsilon\, f\, B\, t$ *(1/2 the pixels)*

σ_{det} = Signal/√Background

= $S\,\sqrt{(A\,\varepsilon\, t/(2\, f\, B))}$

= $S\,\sqrt{(A\,\varepsilon\, t/(2\, B\,(1-\cos(\theta/2))/2\,))}$

= **Counter** / $\sqrt{(1-\cos(\theta/2))}$

= **Pinhole** * $\sqrt{(n/2)}$

* $\sqrt{((1-\cos(\theta/n))\,/\,(1-\cos(\theta/2)))}$

< Counter,

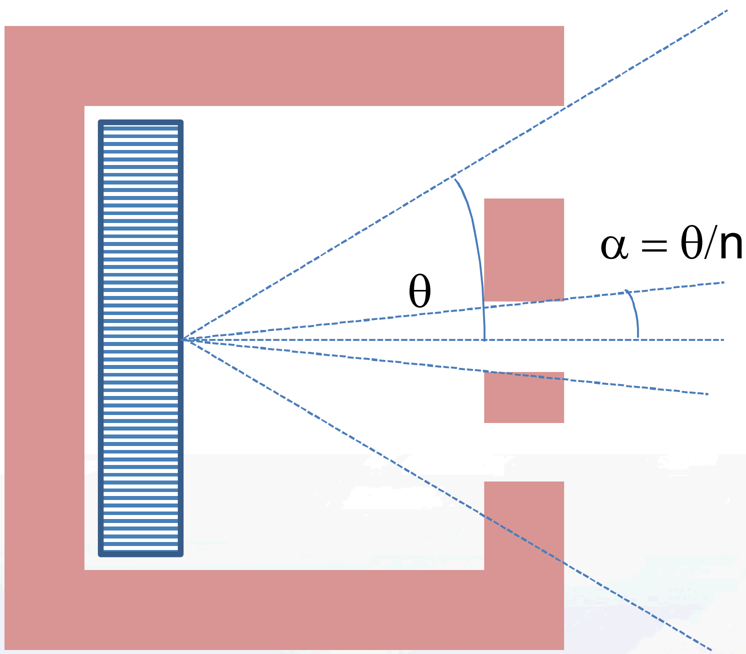
> Pinhole (n > 2)

$\alpha = \theta/\sqrt{(n)}$ (for 2-D)

A = physical area
ε = efficiency
S = signal flux
B = background flux (4π)
t = time
n = number of pixels
f = FOV fraction per pixel
= (1-cos(θ/2))/2

Coded Aperture Imager

(Unknown Background)



Signal = $(A/2)\,\varepsilon\,S\,t$ *(1/2 the pixels)*

Background = $(A/2)\,\varepsilon\,f\,B\,t$ *(1/2 the pixels)*

Background uncertainty estimate

= $\sqrt{(A/2)\,\varepsilon\,f\,B\,t}$ *(other 1/2)*

σ_{det} = Signal/$\sqrt{\text{Background}+\text{uncertainty}^2}$

= $S\sqrt{A\,\varepsilon\,t/(4\,f\,B)}$

= $S\sqrt{A\,\varepsilon\,t/(2\,B\,(1-\cos(\theta/2)))}$

= **Pinhole** * $\sqrt{n^2/(n-1)}$

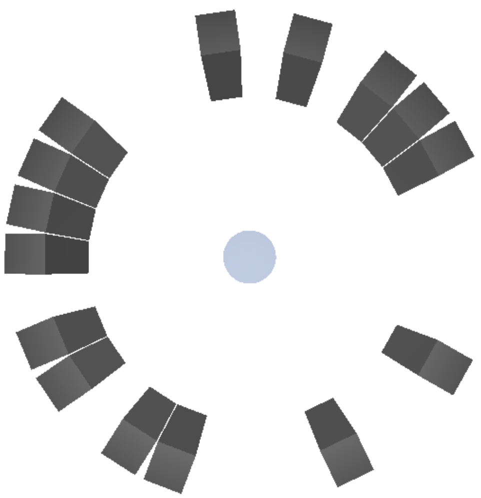
* $\sqrt{(1-\cos(\theta/n))\,/\,(1-\cos(\theta/2))}$

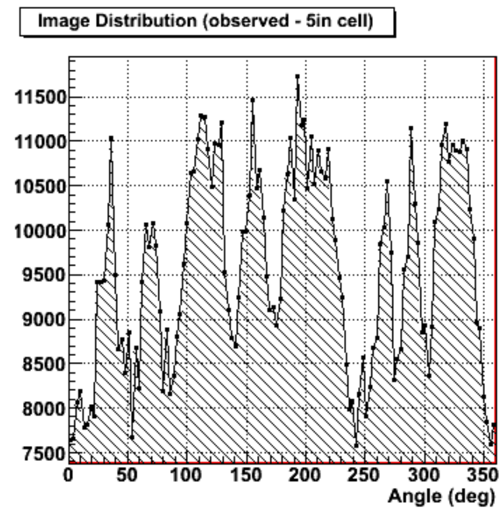
> Pinhole ($n > 2$)

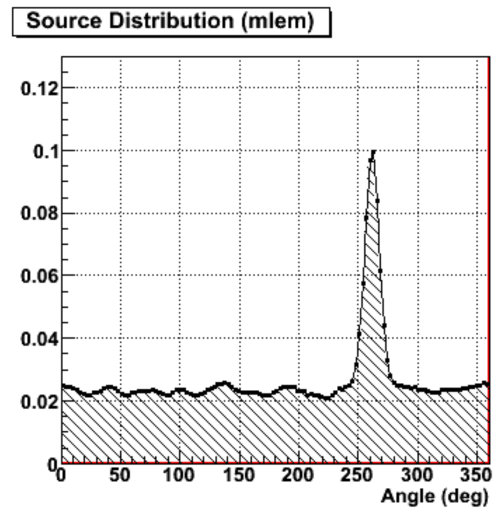
$\alpha = \theta/\sqrt{n}$ (for 2-D)

- A = physical area
- ε = efficiency
- S = signal flux
- B = background flux (4π)
- t = time
- n = number of pixels
- f = FOV fraction per pixel = $(1-\cos(\theta/2))/2$

Time Encoded Concept

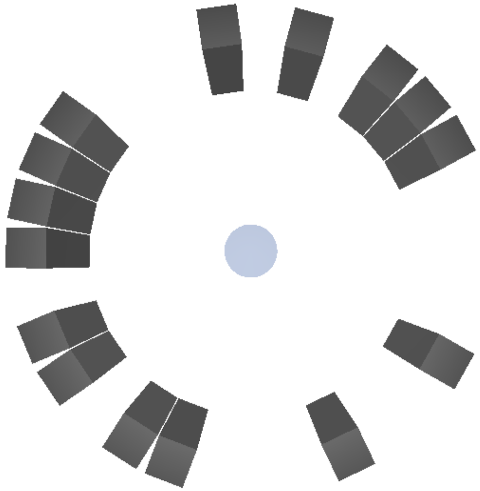


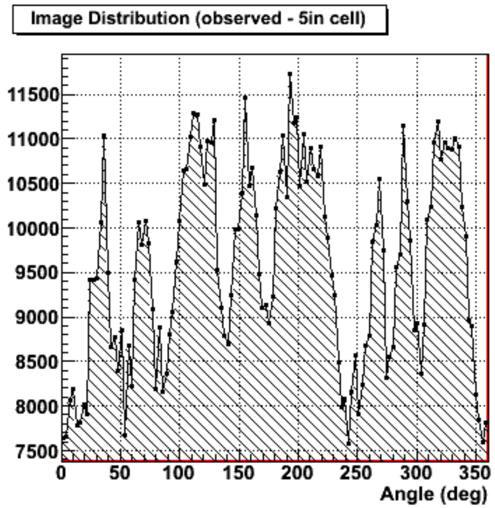


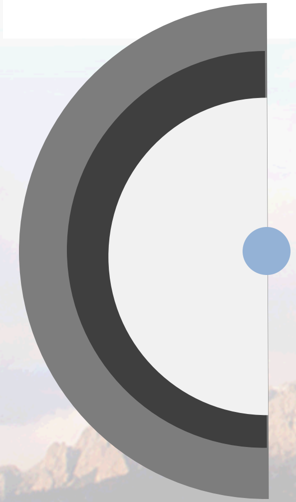


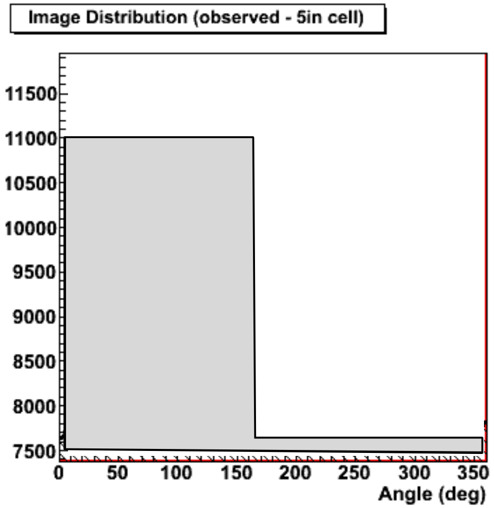
- Switch spatial modulation for time modulation.
- Simple and robust, low-channel-count detectors.
- Can scale to large effective area.

S/N vs. Angular Resolution

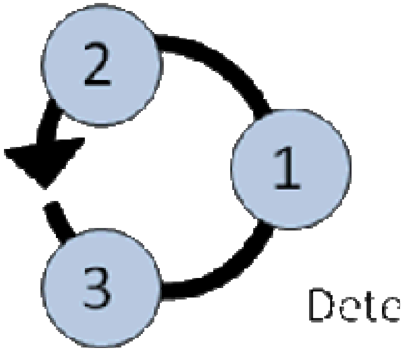


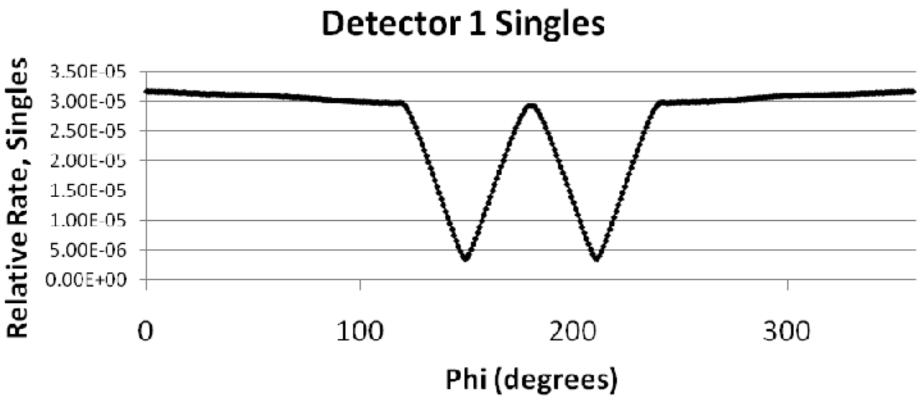






Rotational Self Modulation Concept

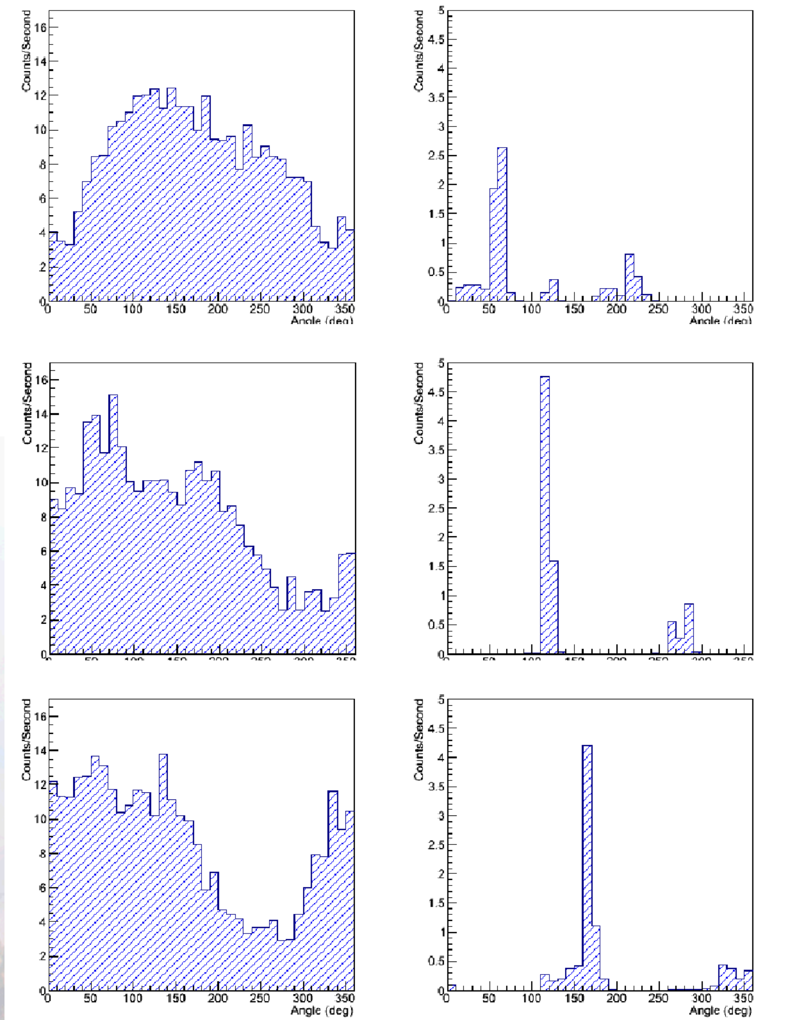




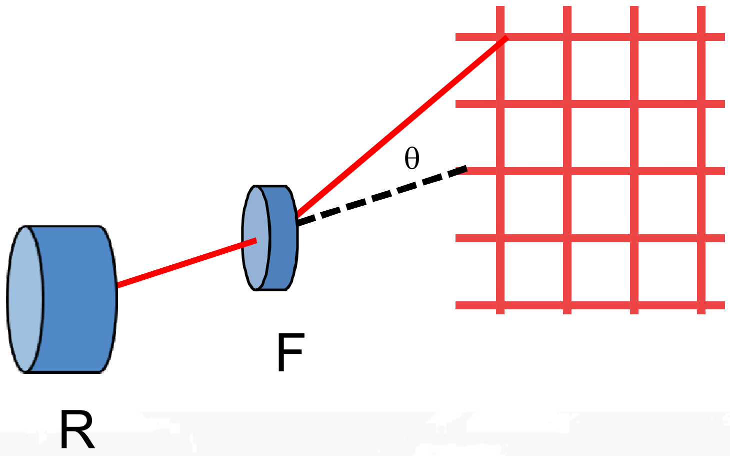
- **Portable Rotating Imager using Self Modulation (PRISM).**
- **Rotating Collimator minus passive shielding material.**
- **More compact and easily scalable at the cost of intrinsic angular resolution.**

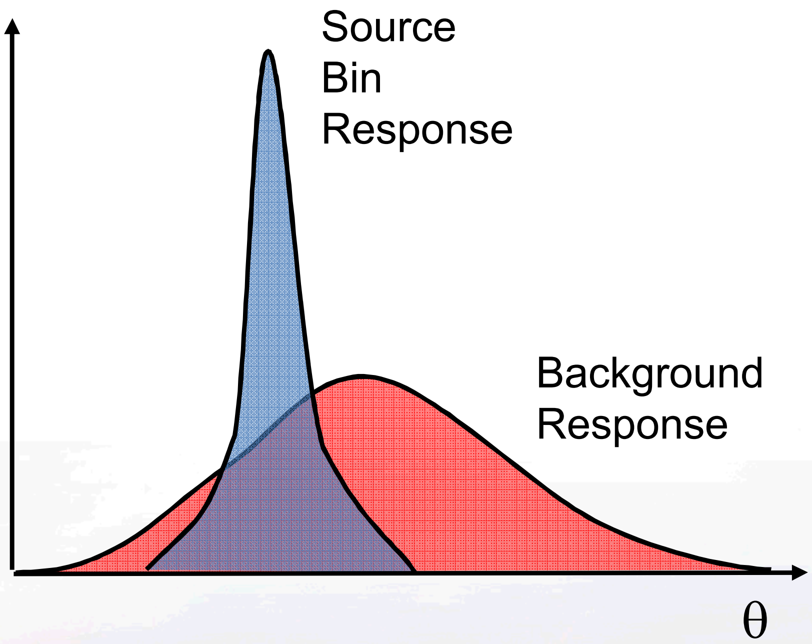
Rotational Self Modulation

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



Maximum Likelihood Imaging



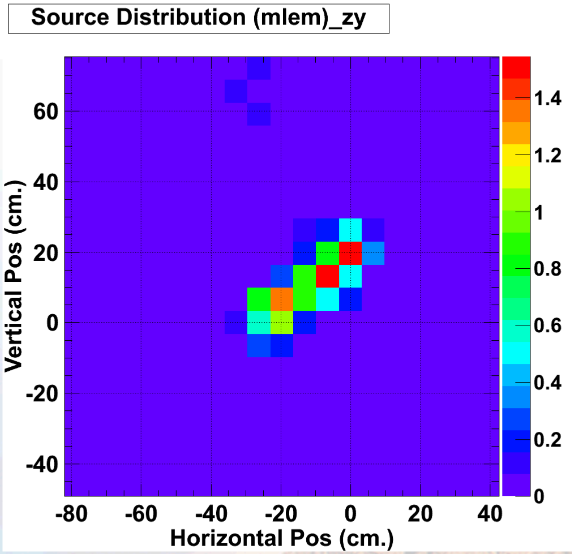


- Generate observation probability distribution for all possible source positions.
- Use detector response to generate an observation assuming a source distribution and calculate the likelihood that this represents the data.
- Maximum Likelihood Expectation Maximization iteratively adjusts the source distribution to increase the likelihood.

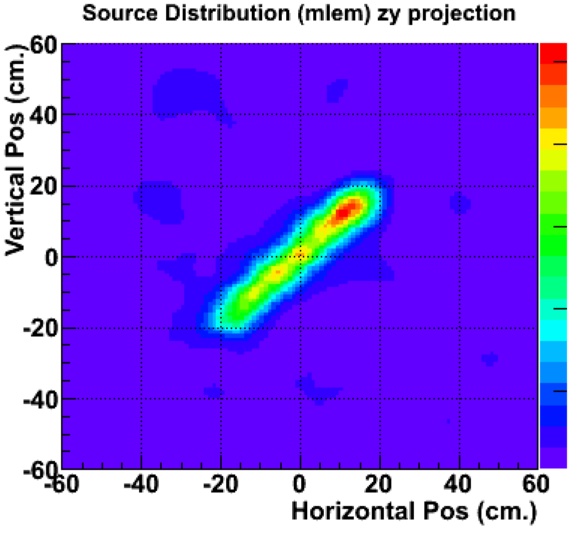
Use the right detector!

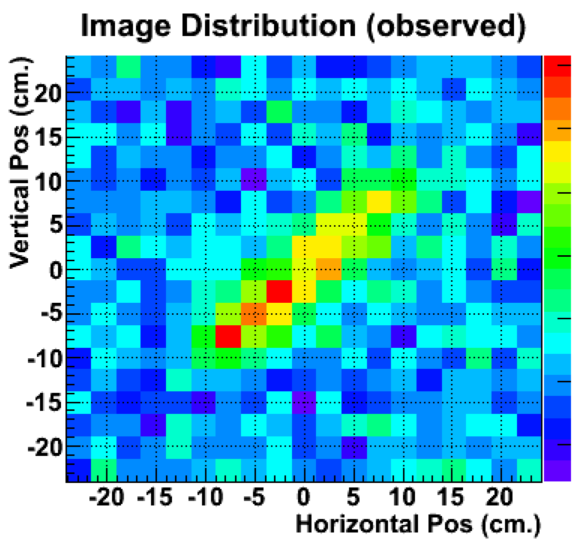
- Extended source imaging: 20” line source.
- Sizeable source at 3 m – S:B not an issue.
- Pinhole camera outperforms the scatter camera.

Neutron scatter camera



Pinhole imaging system





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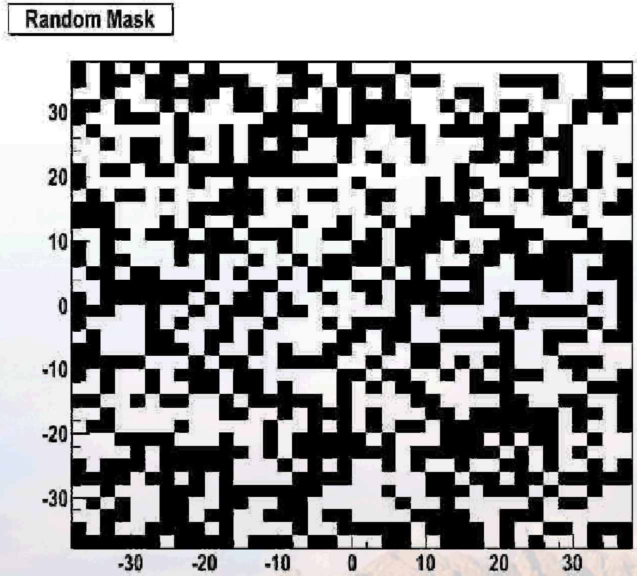
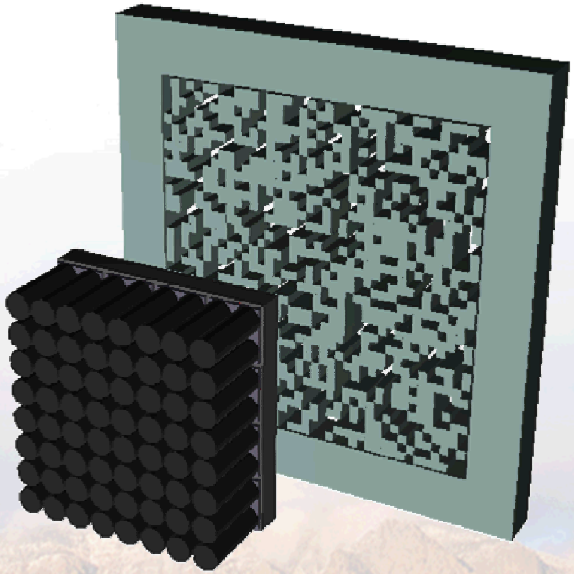
Aperture types

- **Random**
  - Not limited by a mathematical formula
  - Can be built for any mask size or open fraction





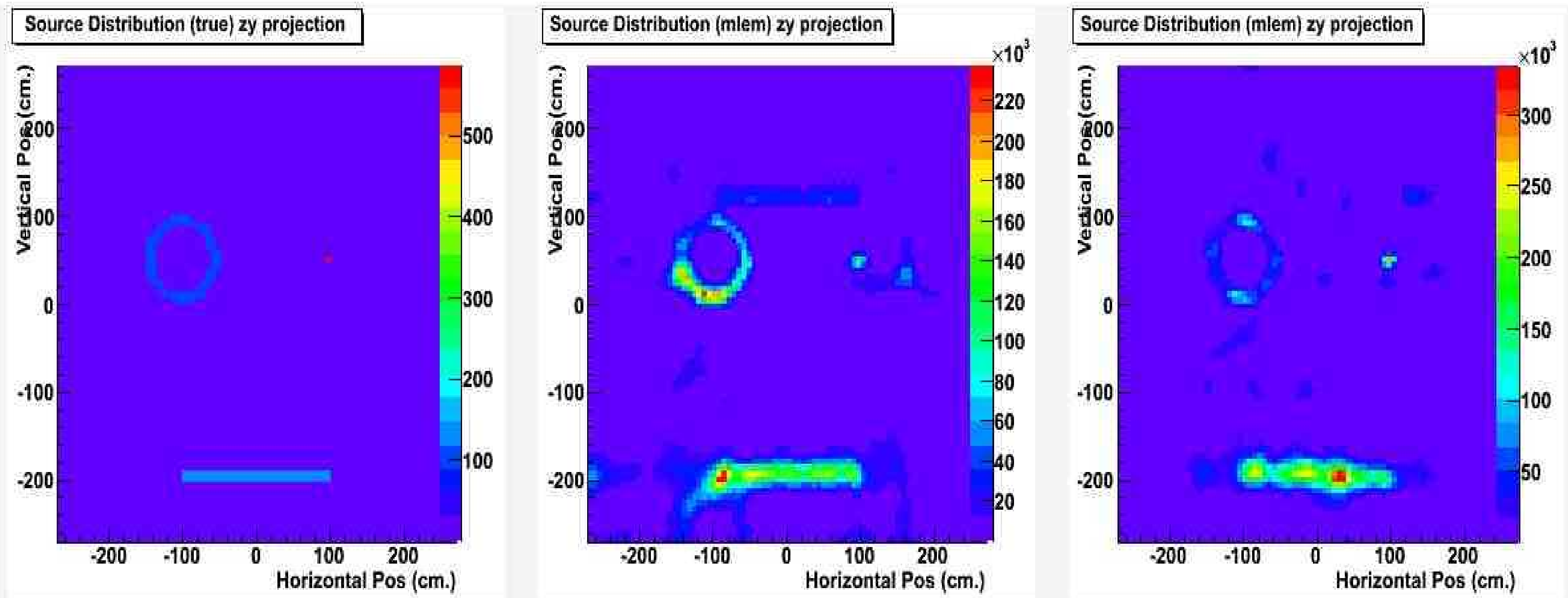
Motivation for using random masks

- **URAs only exist for a limited number of aperture sizes and open fractions**
  - Aperture size may be constrained by the available detector size and resolution and cannot always be chosen arbitrarily
- **Under non-ideal conditions (which typically exist), tiling the URA pattern to increase the field of view (FOV) of the imager introduces ambiguities in the reconstructed image**

Extended source optimization

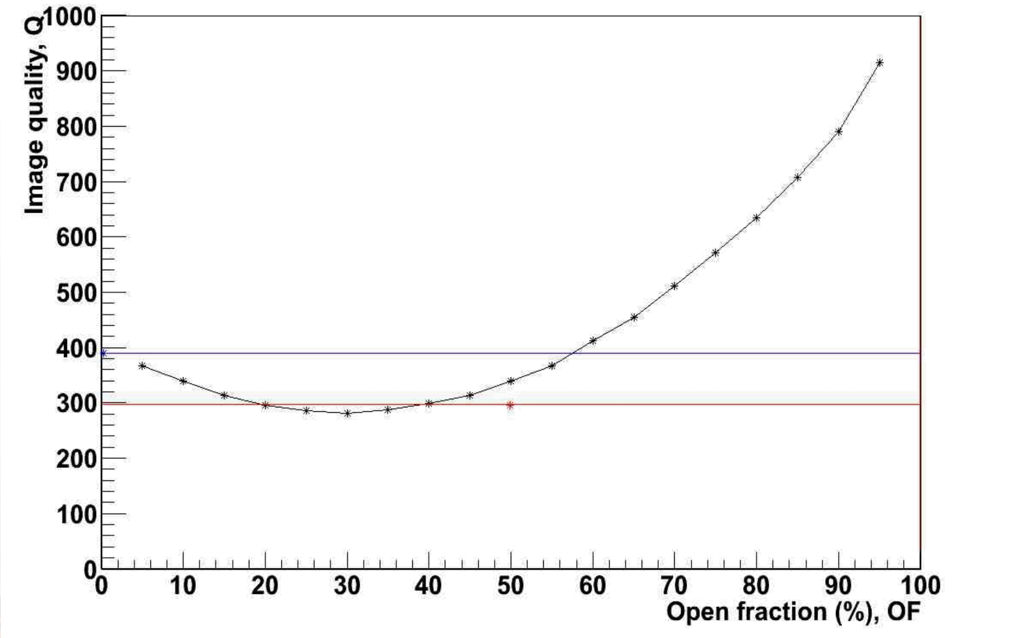
- **Ring, block, point source arrangement**

True | **URA** | **Random (50% open fraction)**



Extended source optimization

- **Optimal open fraction**
  - Red line represents URA performance
  - Blue line represents pinhole performance



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Extended source optimization

- Ring, block, point source arrangement

True | URA | Random (30% open fraction)