SAND2018-10909PE

SVSC: A Compact, High Efficiency Neutron Imager Using Picosecond Timing

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Outline

- Radiation detection for nuclear non-proliferation
  - Application space
  - Why imaging?
  - Neutron imaging solutions
    - ORCA, TEI-1D, NSC
- Single-volume neutron scatter camera
- Selected challenges/results
  - Single-bar characterization results
  - Single-photon timing results
  - Scintillator characterization
  - Current status / hardware teasers
- Trend: photon-focused detection for scintillators?

Radiation detection for nuclear non-proliferation

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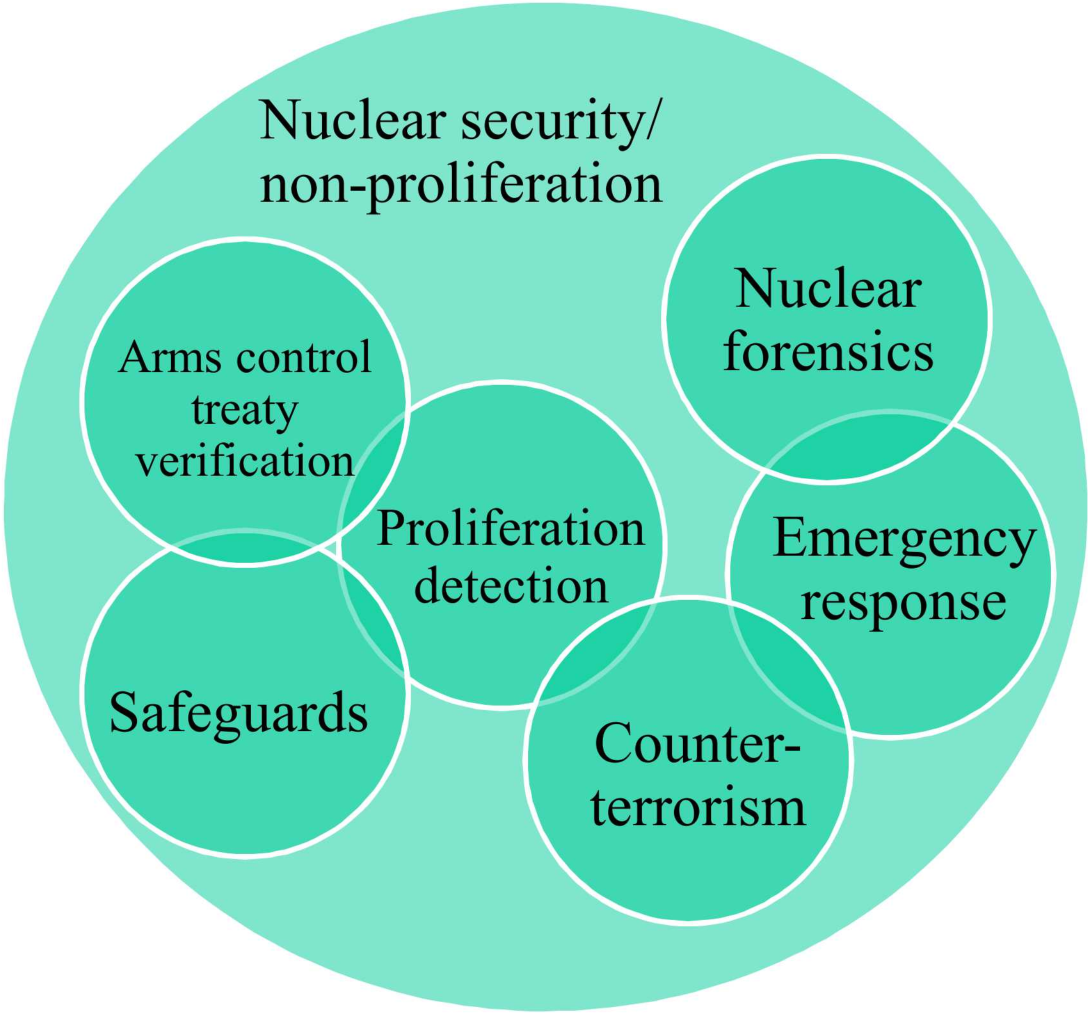
Some terminology


Nuclear security/ non-proliferation

Arms control treaty verification

Proliferation detection

Safeguards

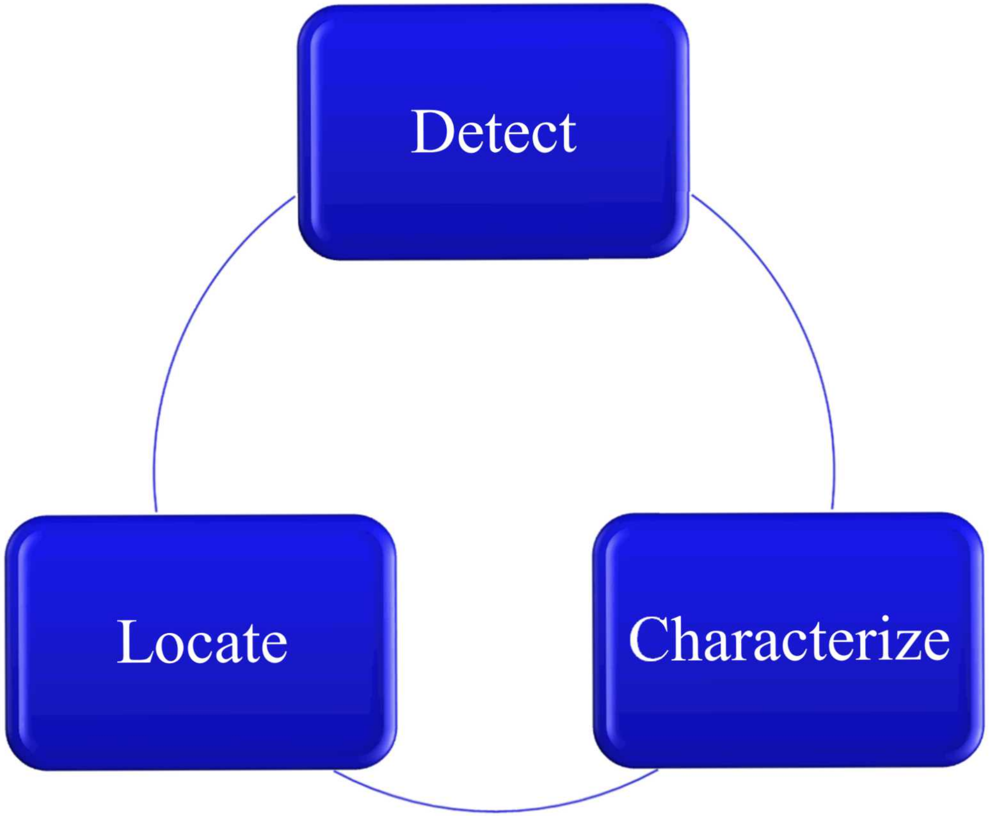
Nuclear forensics

Emergency response

Counter-terrorism

- Horizontal proliferation: new actors acquiring nuclear capabilities
- Vertical proliferation: existing NWS increasing nuclear capabilities
- Special nuclear material (SNM) is the common element.
  - o Detect
  - o Locate
  - o Characterize
- Radiation detection can help!

SNM tasks for rad detection



Detect

Characterize

Locate

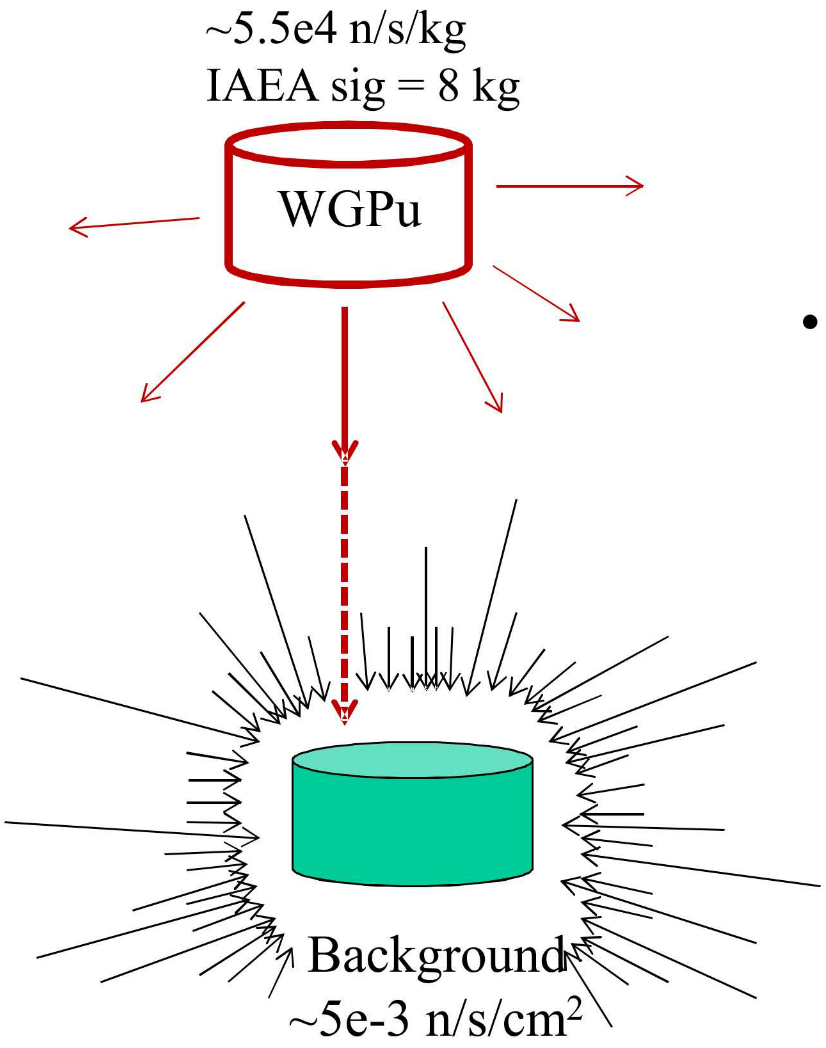
Rad detection for detecting SNM

Notional scenarios:

- Sources indicate that a significant quantity of nuclear material is present in X neighborhood. Find it or provide all clear.
- Radiographic/active interrogation of rail cargo: scan rates of 8 to 24 km/h, scan lengths over one kilometer, and a penetration depth of 90 cm of steel

- By definition, interesting/difficult cases have low S:B.
- Active interrogation can increase signal at cost of more/different background
- Radiation detection needs:
  - High efficiency
  - Scalability
  - S:B discrimination

Standoff detection



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

Background
~5e-3 n/s/cm^2

- Example: Large stand-off application (100 meters)
  - 8 kg WGPu = ~4.4e5 n/s → 4.4e5 $*\exp(-R/100)/4\pi R^2$ ≈**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**

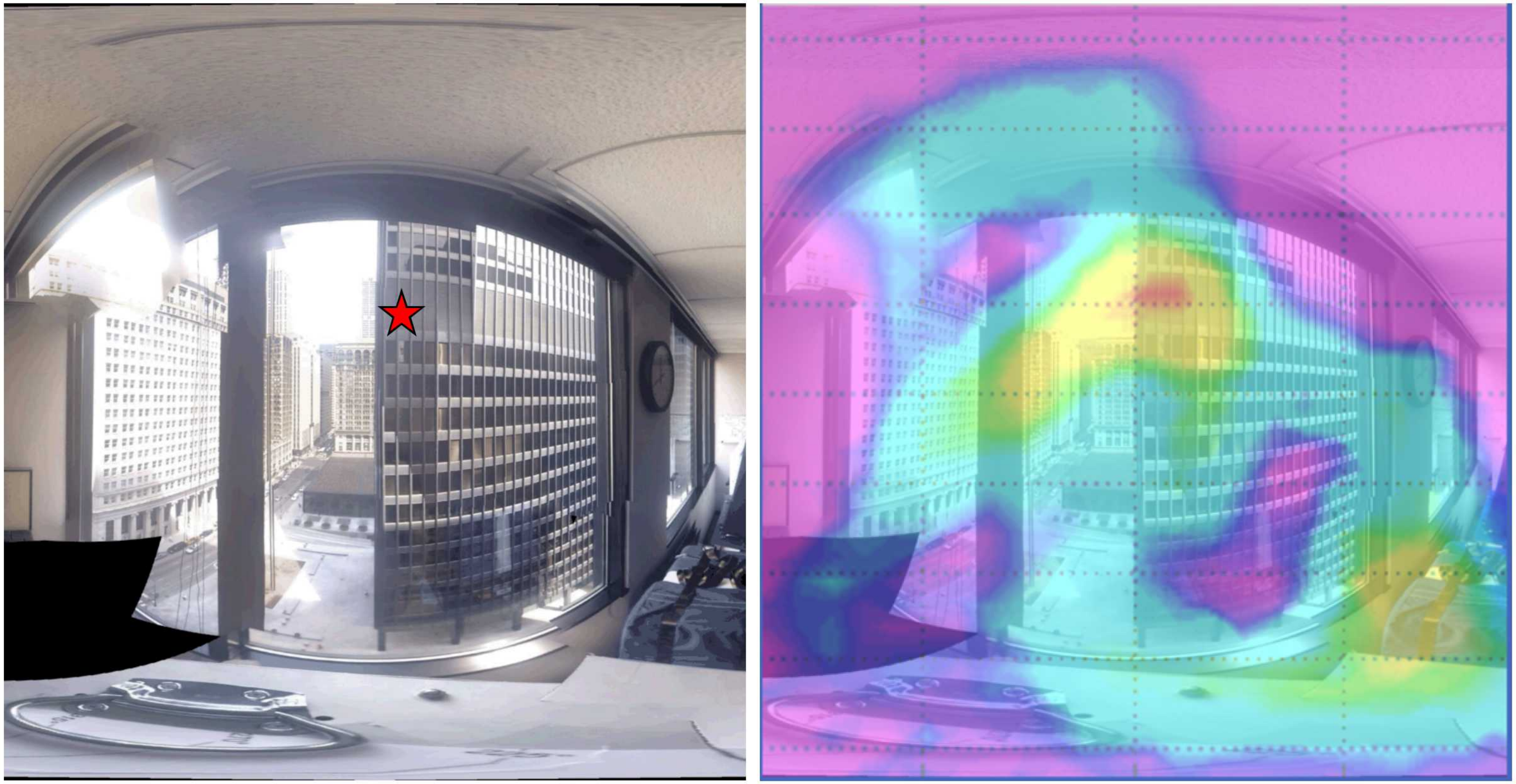
Rad detection for locating SNM

Notional scenarios:

- Nuclear material is present in building X. Determine which floor/apartment.
- Count number of nuclear warheads on an ICBM without visual access.

- Radiation detection needs:
  - Directional information
  - Field of view depends on specific application

MINER: Building to Building Imaging



Left: source location (red star) in adjacent high-rise (28 m distance).

Right: neutron image overlaid on photograph

Detect, Locate

Rad detection: characterizing SNM

Notional scenarios:

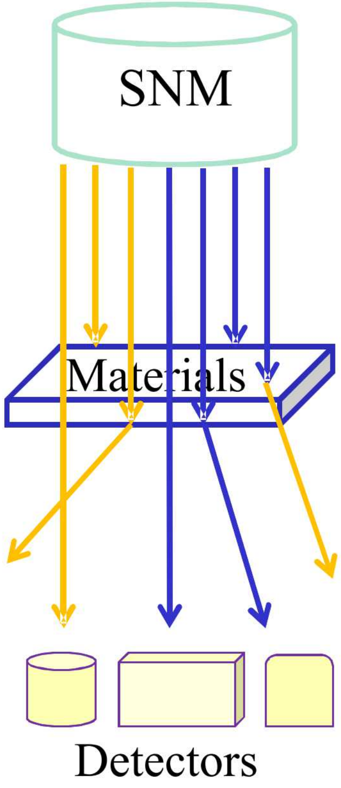
- Determine U-235 content of UF_6 cylinder leaving enrichment facility.
- Box with SNM signatures found in train station. Quickly gather information for neutralization &/or consequence management.

- Complex interdependent signatures
- Leverage multiple sensors and information streams where possible
- Radiation detection needs:
  - Spectroscopy
  - Imaging
  - Gamma and neutron
  - (Everything)

Rad detection for characterizing SNM

Signatures (physics)

- **SNM emits** γ, n radiation
  - {Spectrum, rate, vector field, correlations} determined by {SNM mass, isotopics, configuration}
- **Surrounding material** attenuates, scatters, modifies signature
- **Interactions** between SNM, surroundings



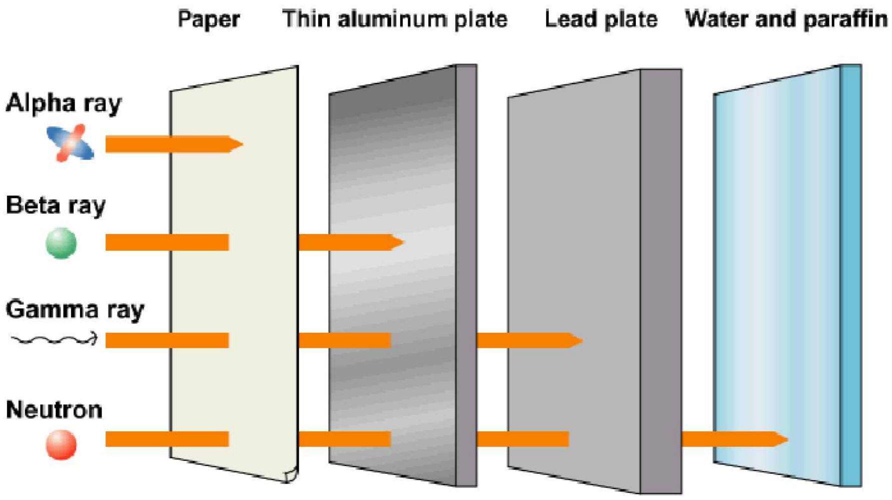
Detectors (technology)

- Typically optimized for measuring one aspect of the radiation signature, e.g.
  - Gamma spectrum → good energy resolution
  - Neutron timing correlations → Large effective area for n detection
  - SNM configuration → position, direction resolution
  - Low-rate processes → active stimulation

Why (neutron) imaging?

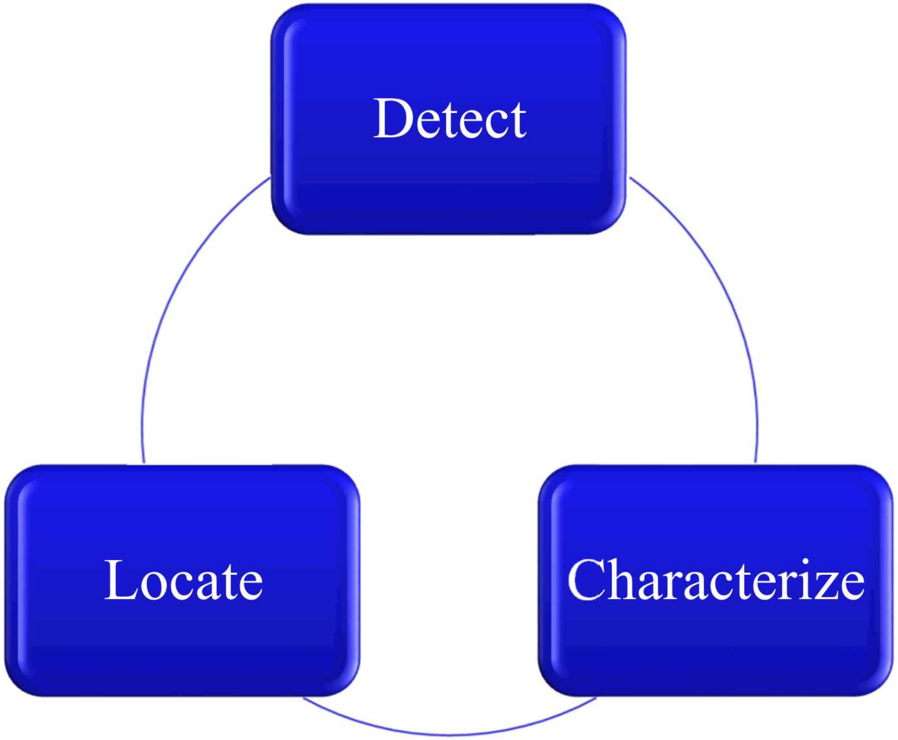
Why neutrons?

- 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



www.remnet.jp

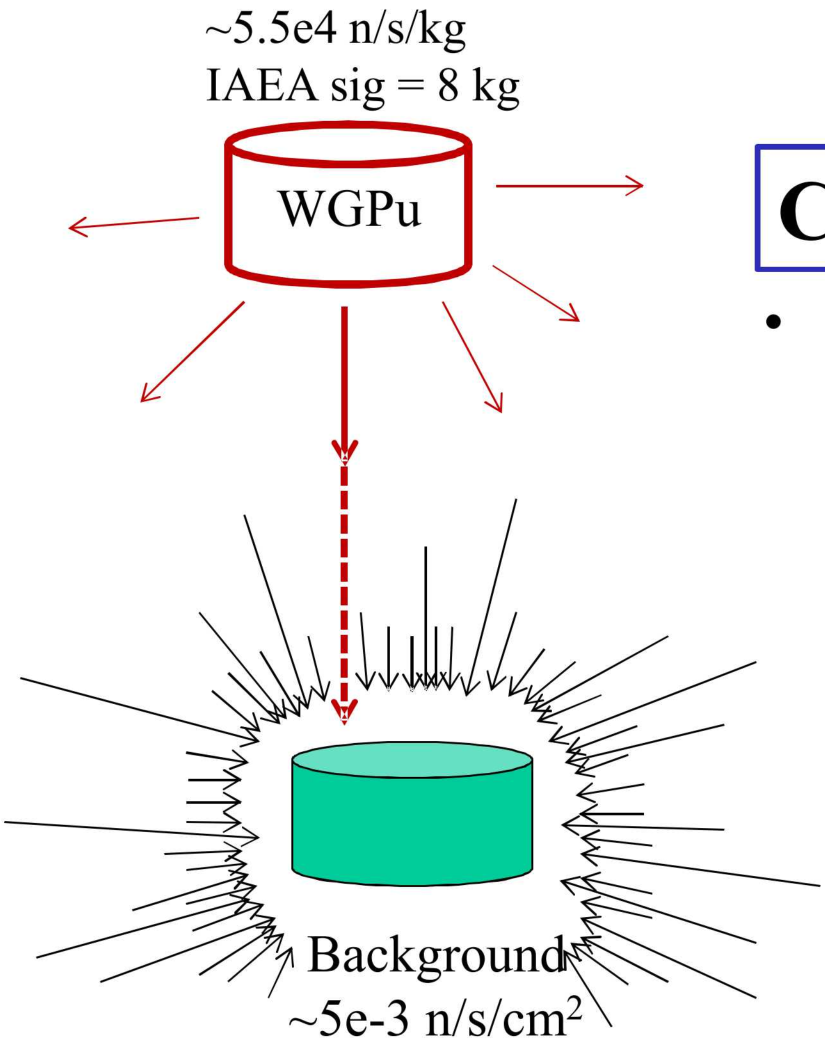
Why (neutron) imaging?



[Imaging vs directional information]

- Need imaging?
  - Imaging applications: **Yes**
    - ER diagnostics, AC
  - Localization: **Yes**
    - Direction to detected source
  - Detection: **???**
- For detection, consider neutron signature; two sub-cases:
  - Background unknown
  - Background known

Standoff detection



Case: background unknown

- Example: Large stand-off application (100 meters)
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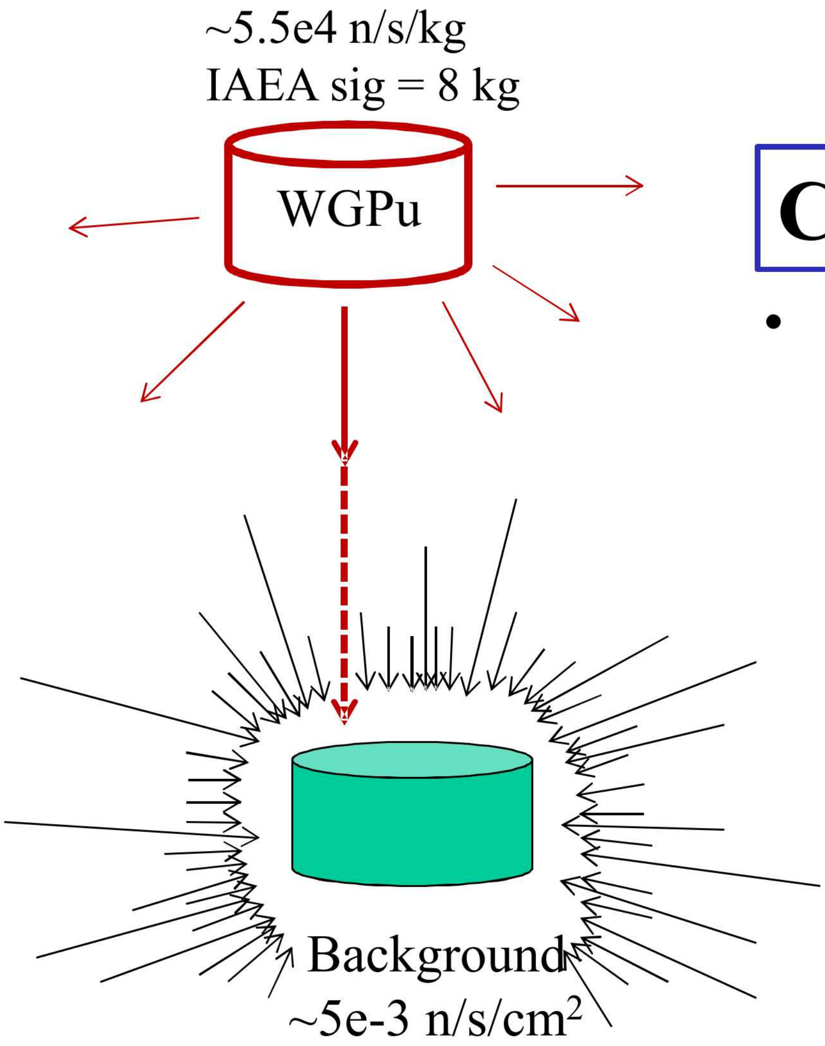
Standoff detection



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

WGPu

Background
~5e-3 n/s/cm^2

Case: background unknown

- Example: Large stand-off application (100 meters)
  - 100% efficient, 1 m^2 detector → 5σ detection in **~13 minutes**
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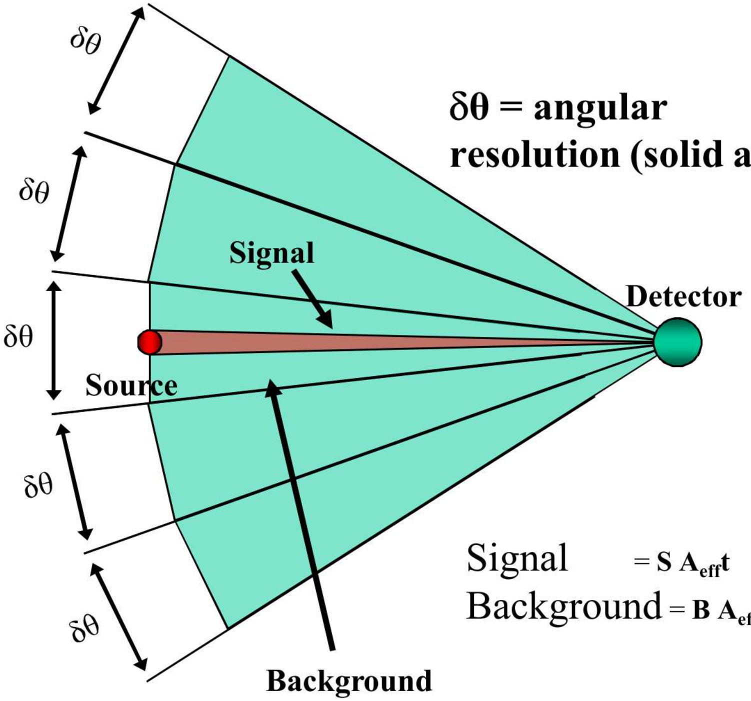
  - 10% efficient, 1 m^2 detector, *3% bg rate systematic* → 5σ detection in **never**
  - Directional information, however, allows to *simultaneously measure* signal and background, change **never** to **< never**.

Detection again

- 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 implies yes!
  - But real imagers do not have simple angular resolution like cartoon.
  - Also, always take a hit on efficiency.
  - So no easy answer; balance improved background rejection vs reduced efficiency.

Case: background known



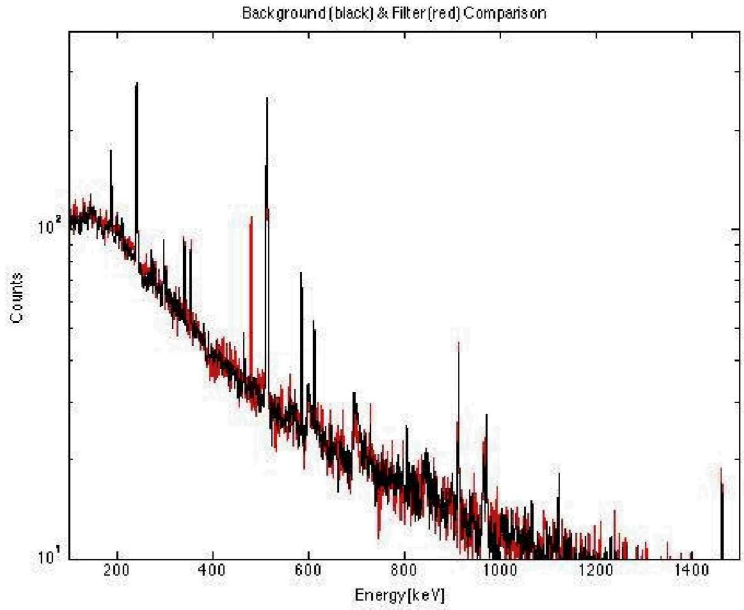
$\delta\theta$ = angular resolution (solid angle)

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

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

Why (neutron) imaging?

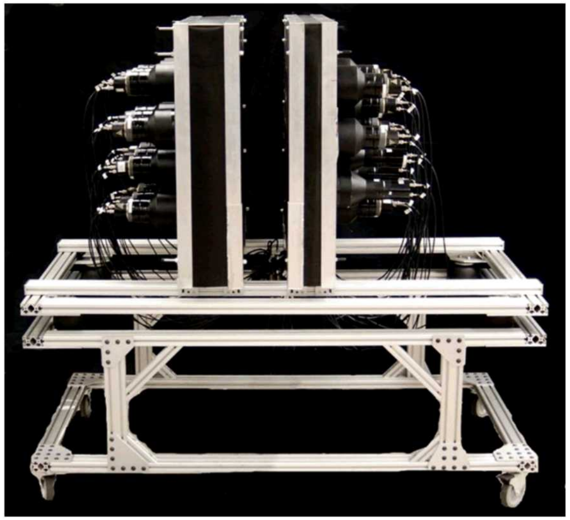
- Analogy to information from gamma spectrum.
  - Estimate background (systematic).
  - Ignore most background (statistical).

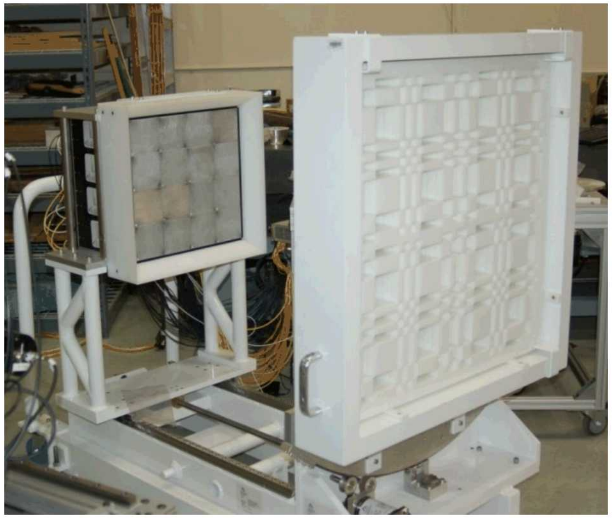


- Need imaging?
  - Imaging applications: **Yes**
    - ER diagnostics, AC
  - Localization: **Yes**
    - Direction to detected source
  - Detection, background unknown: **Probably**
    - Long-dwell standoff detection
  - Detection, background known: **Need very high quality imager**
    - Portal monitor, building monitoring

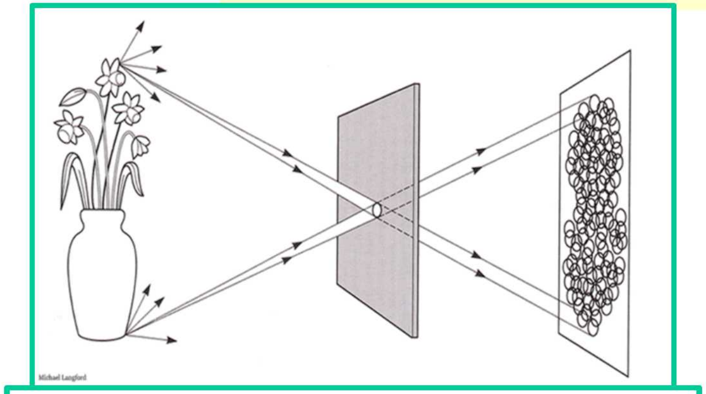
Some neutron imagers

Fast neutron imagers @ SNL/CA

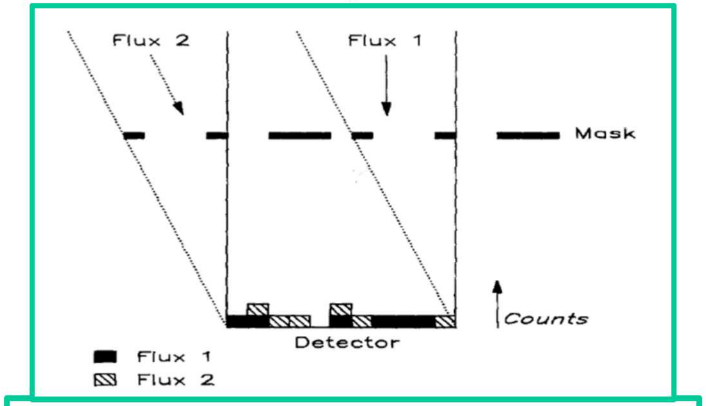




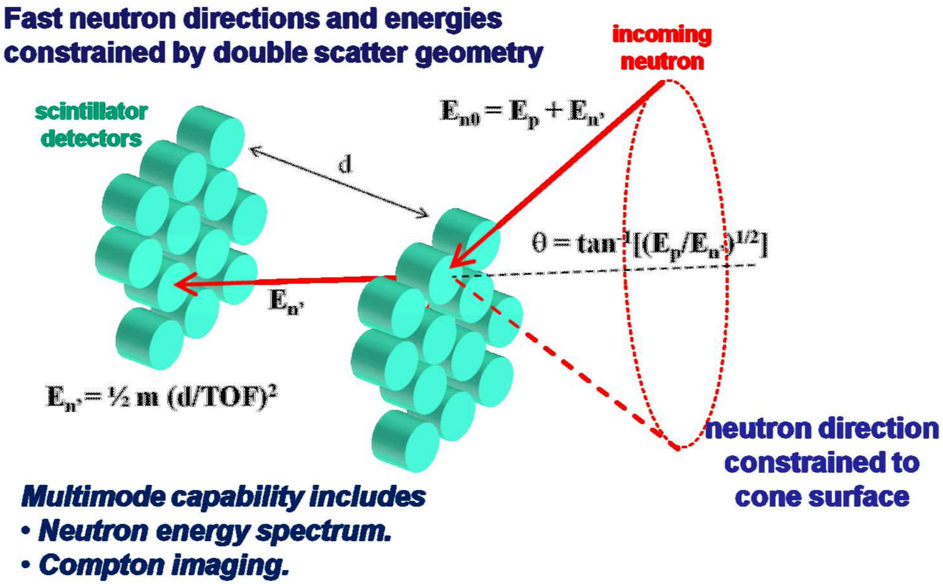
Neutron camera approaches



Pinhole: High Resolution, Low Throughput



Coded aperture: High Resolution, High Throughput



Fast neutron directions and energies constrained by double scatter geometry

$E_{n0} = E_p + E_{n'}$

$\theta = \tan^{-1}[(E_p/E_{n'})^{1/2}]$

$E_{n'} = \frac{1}{2} m (d/TOF)^2$

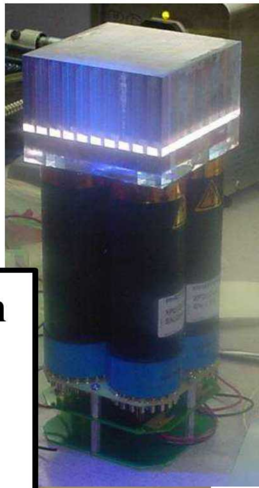
neutron direction constrained to cone surface

Multimode capability includes

- ***Neutron energy spectrum.***
- ***Compton imaging.***

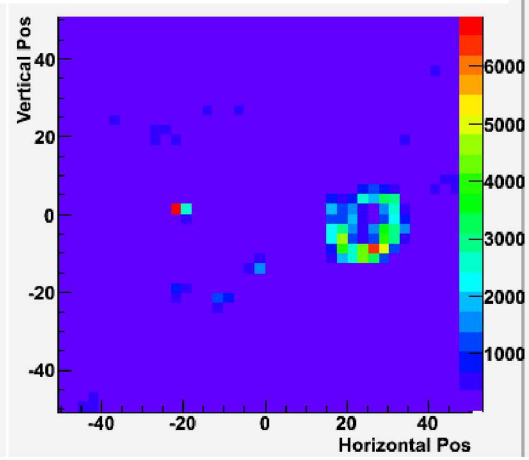
Neutron coded aperture imager

- Extension of pinhole with much higher effective area: signal modulated in unique 2-d patterns.
- ORNL/SNL fast neutron coded aperture imager was developed for arms control treaty verification.
- Image plane consists of 16 liquid organic scintillator pixilated block detectors
  - Each block consists of a 10x10 array of 1 cm. pixels.
  - PSD and pixel id accomplished by 4 photomultiplier tubes.
- Mask plane consists of 2.5 to 10 centimeters of HDPE.

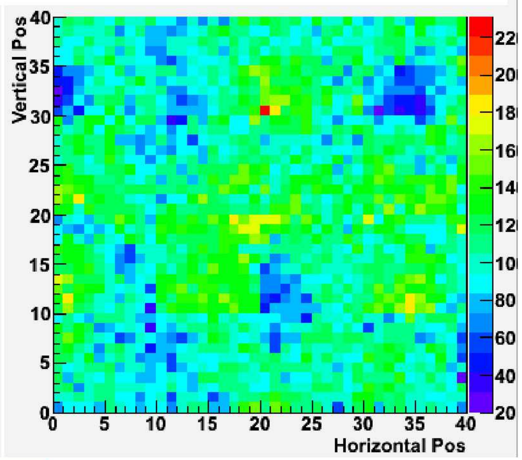


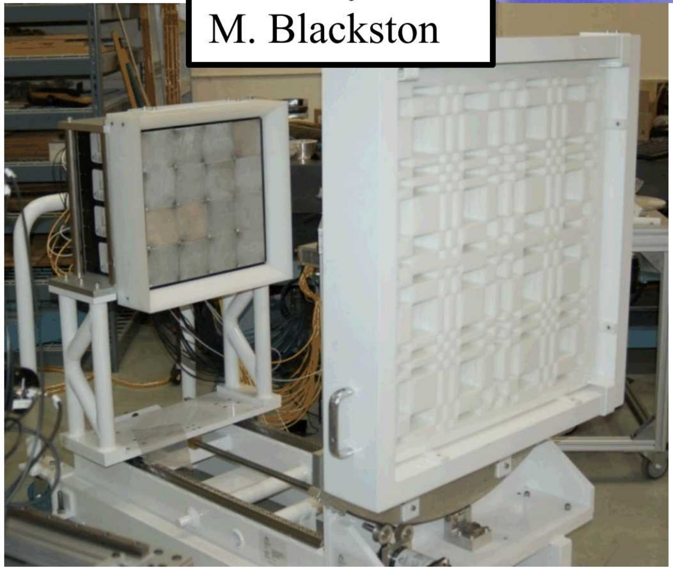
Collaboration with ORNL:
P. Hausladen
J. Newby
M. Blackston

Reconstructed image



Raw counts





Locate, Characterize

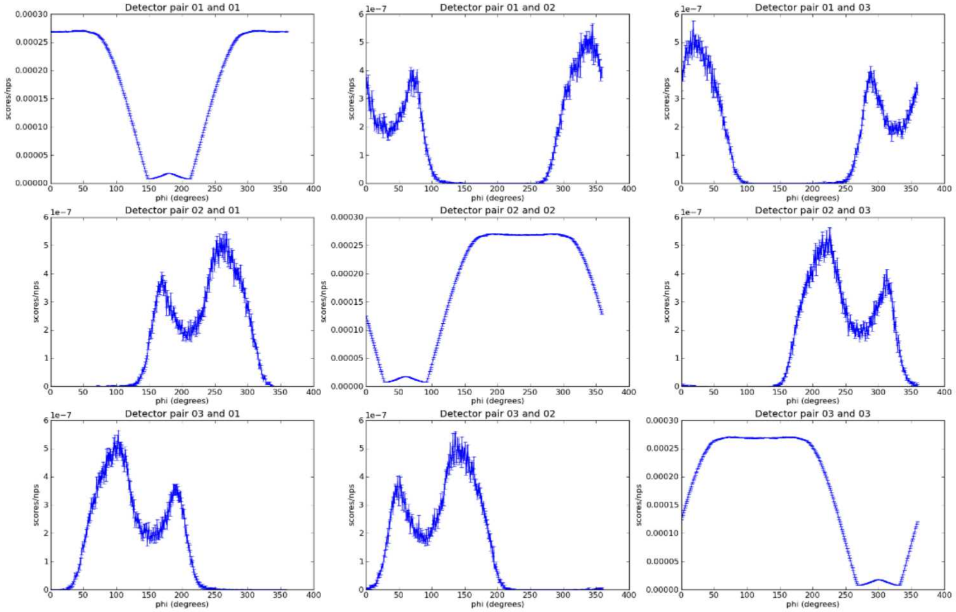
Neutron coded aperture imager

- Advantages:
  - Excellent system angular resolution.
  - Good detection efficiency.
- Disadvantages:
  - Poor event angular resolution.
  - Complex detectors.
  - Performance degrades with multiple/extended sources.
- Potential use:
  - High-resolution, good S:B applications: arms control treaty verification, emergency response.

TEI-1D

Considerations for detect:
- High efficiency
- Scalability
- S:B discrimination

- Time-encoded imaging: self-modulation



Response map vs rotation angle for a fixed source location

Detect, Locate

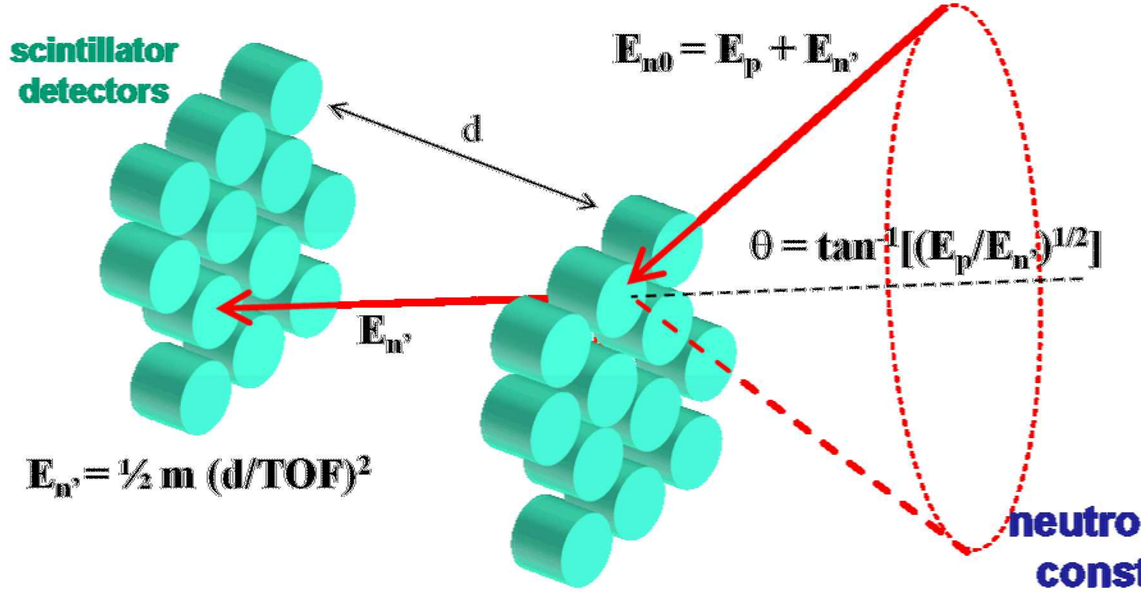
TEI-1D

- Advantages:
  - Scalable to large effective area at low cost.
  - Simple detector system.
- Disadvantages:
  - Low event and system angular resolution.
  - Poor energy resolution.
- Potential use:
  - Weak source detection with low S:B.
  - Source detection at 100 meter standoff with a time-encoded imaging system (doi:j.nima.2017.09.052)

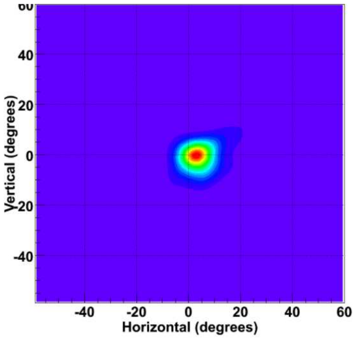
Neutron scatter camera

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

Fast neutron directions and energies constrained by double scatter geometry



neutron direction constrained to cone surface



An MLEM-reconstructed neutron point source image.

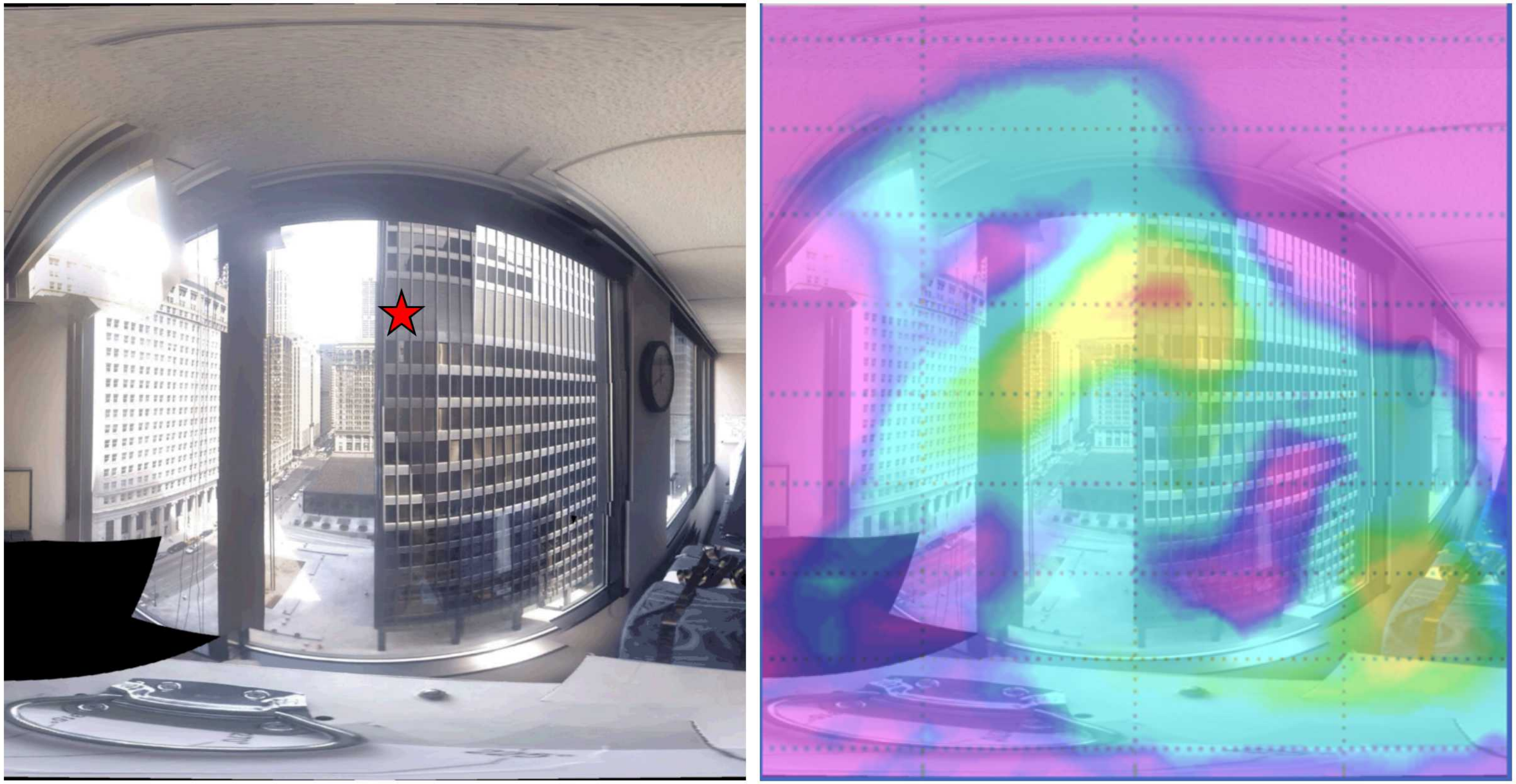
Multimode capability includes
- ***Neutron energy spectrum.***
- ***Compton imaging.***

Detect, Locate, Characterize

Neutron scatter camera

- Advantages:
  - Mature, proven detector system.
  - Excellent energy resolution.
  - Good event angular resolution.
  - Large LS volume for singles.
- Disadvantages:
  - Average system angular resolution.
  - Very low efficiency (double scatters).
- Potential use:
  - Neutron spectroscopy.
  - High background, low S:B environment.

MINER: Building to Building Imaging

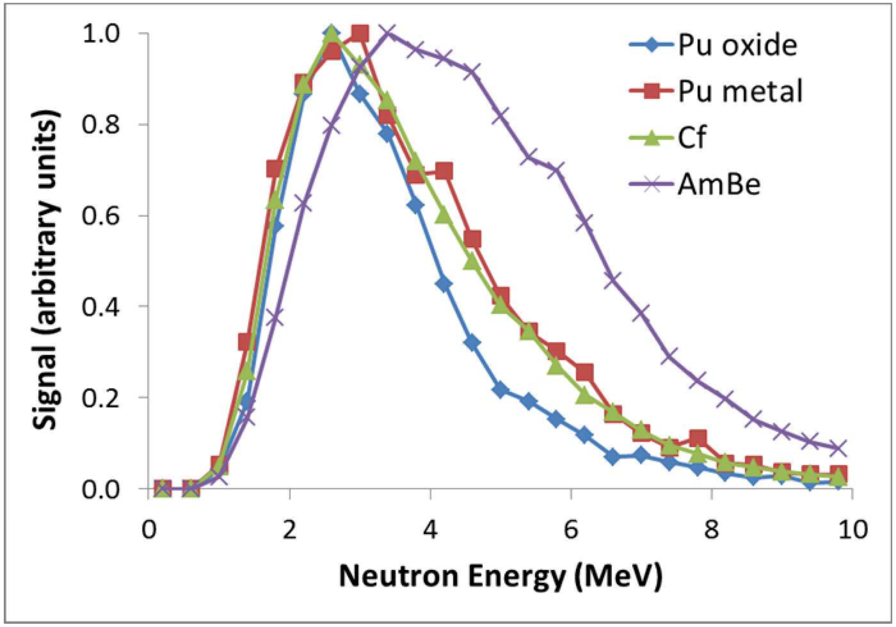


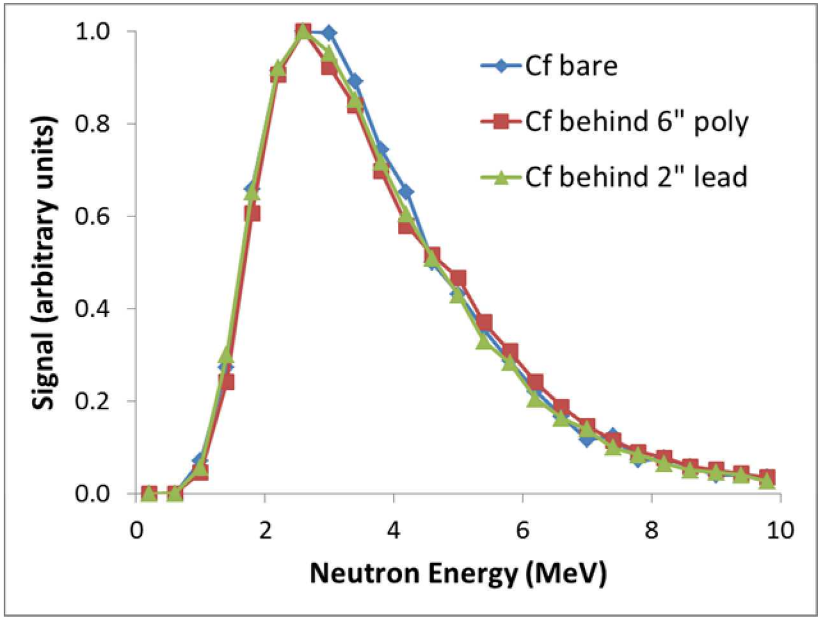
Left: source location (red star) in adjacent high-rise (28 m distance).

Right: neutron image overlaid on photograph

Detect, Locate

MINER: Neutron Spectroscopy



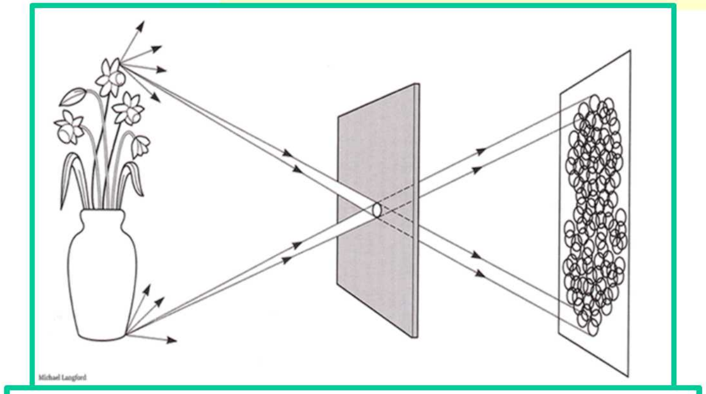


Left – peak-normalized spectra as measured using MINER. Right – insensitivity of Cf spectrum to intervening material as measured by MINER.

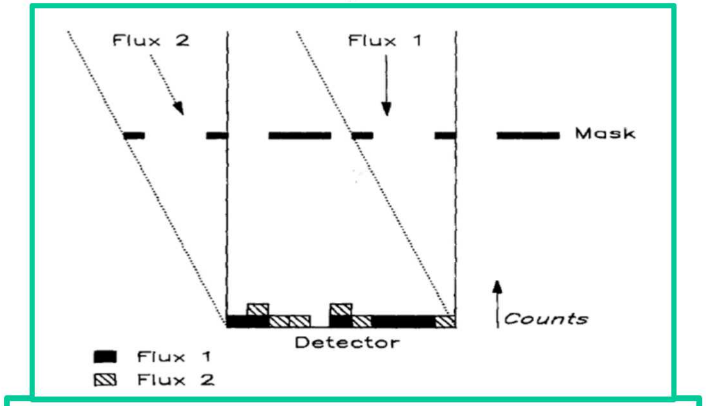
Characterize

Single-volume neutron scatter camera

Neutron camera approaches

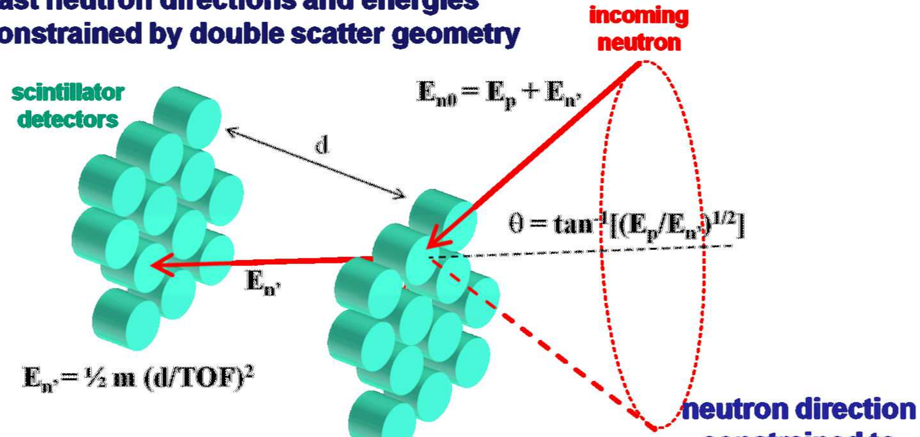


Pinhole: High Resolution, Low Throughput



Coded aperture: High Resolution, High Throughput

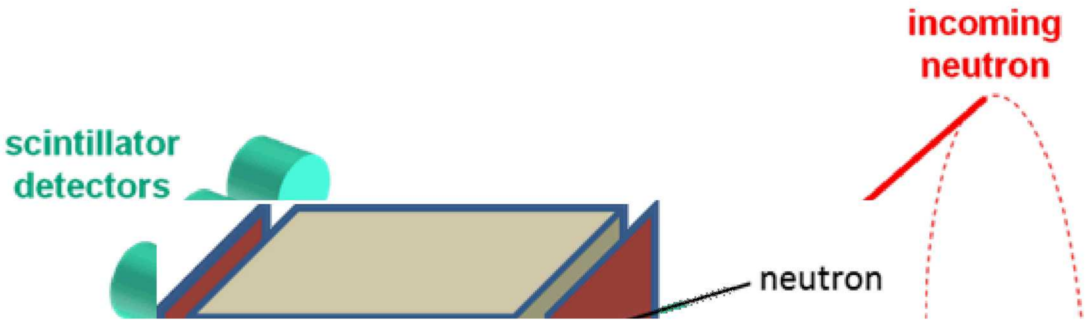
Fast neutron directions and energies constrained by double scatter geometry

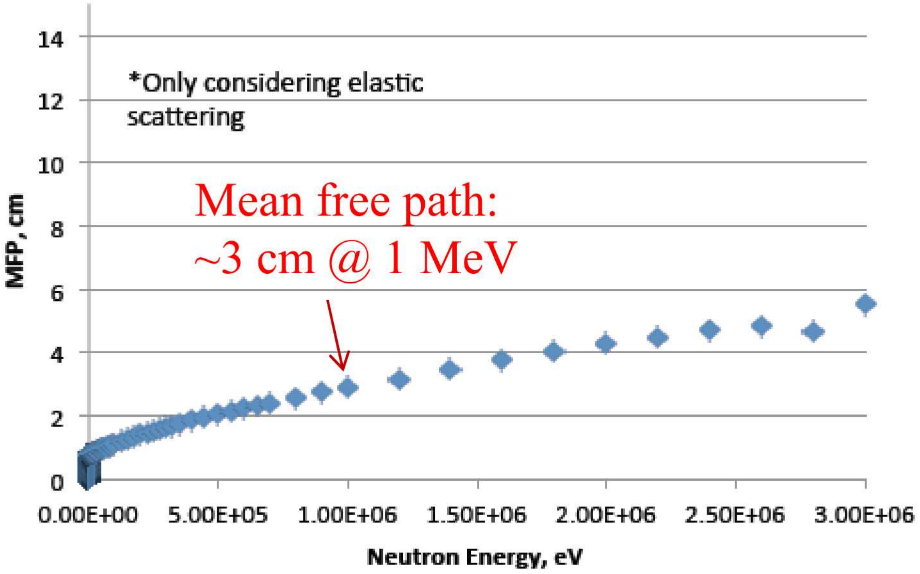


neutron direction constrained to cone surface

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

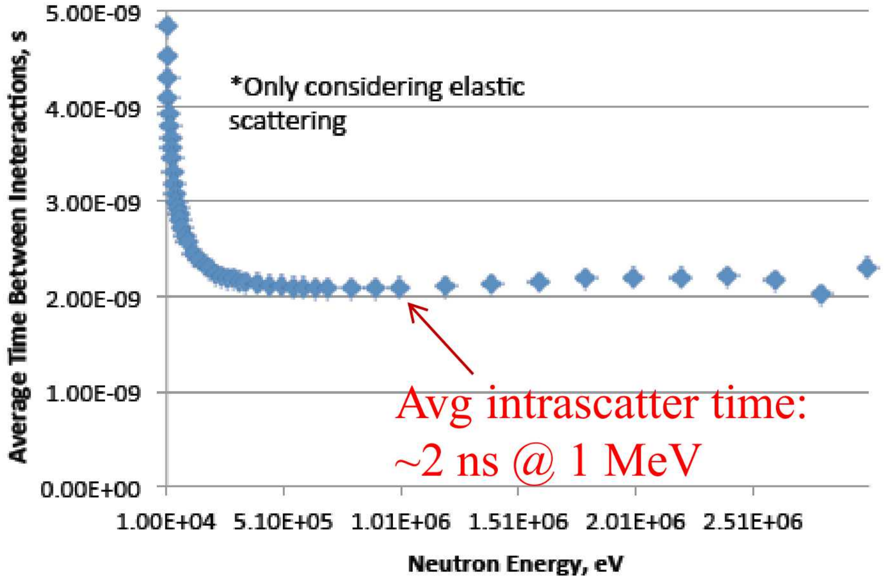
Single-Volume Neutron Scatter Camera





*Only considering elastic scattering

Mean free path: ~3 cm @ 1 MeV

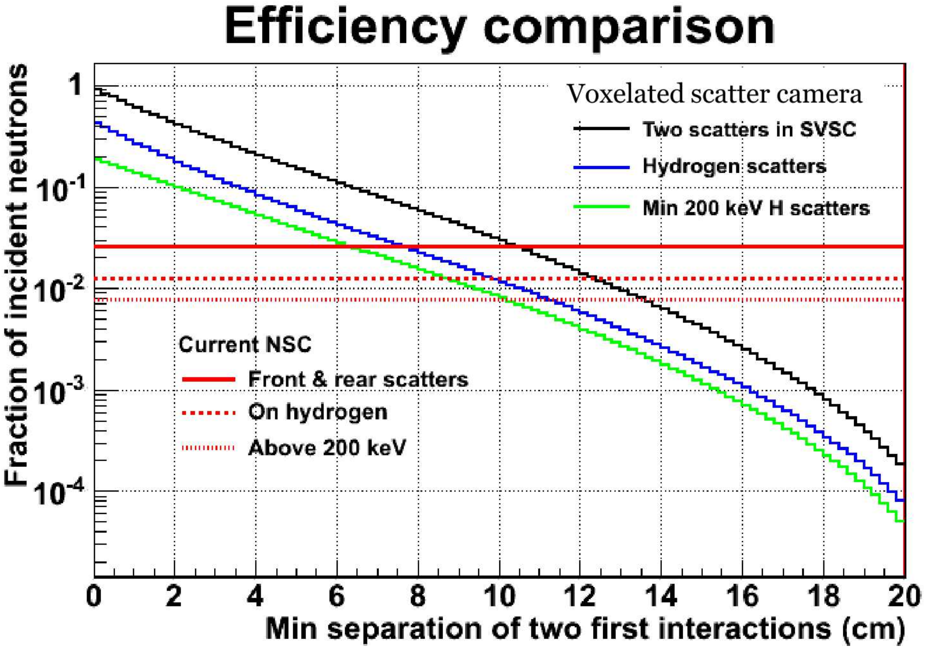


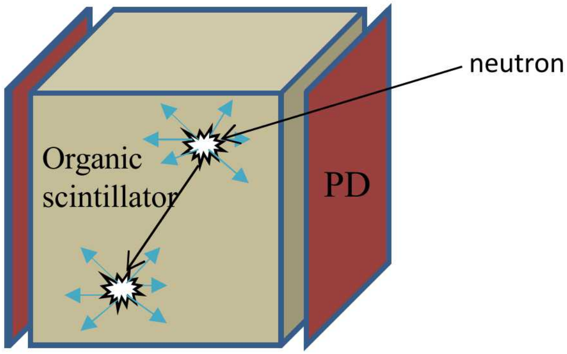
*Only considering elastic scattering

Avg intrascatter time: ~2 ns @ 1 MeV

Single-Volume Neutron Scatter Camera

- A scatter camera built from a highly voxelated volume can recover more than an order of magnitude of efficiency if nearby interactions can be resolved.
- Resolving multiple interactions of a neutron separated by O(cm) and O(ns) is difficult!
- Excellent spatial and temporal resolution of photodetectors based on microchannel plates is the key enabling technology.



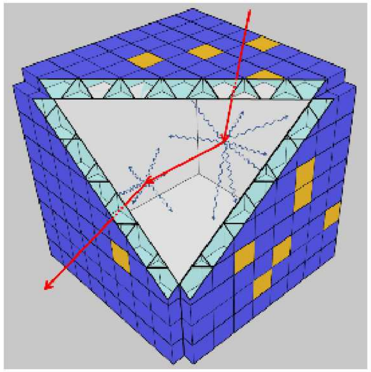


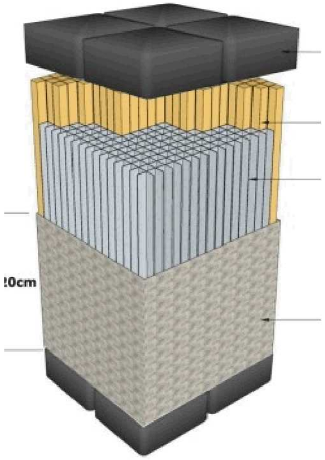
If successful:

- Spectroscopic capability
- Good per-event angular resolution
- High efficiency
- Compact form factor

Event localization

Concept requires a method of determining ***two*** (or more) event locations within a compact scintillator to sub-cm precision.
$\vec{X} = (x, y, z, t)$





1. **Monolithic**: Arrival positions and times of isotropically emitted photons at surfaces of the volume determine most likely $\vec{X}$.
2. **Optically segmented**: Constrain photon propagation within bulk to associate specific PD channels with $\vec{X}$.

SVSC collaboration

SNL/CA: E. Brubaker, M. Sweany, J. Brown, J. Steele, B. Cabrera-Palmer, P. Marleau, J. Carlson

ORNL: P. Hausladen, M. Febbraro, K. Ziock, M. Folsom

U of Hawaii: J. Learned, K. Nishimura, A. Druetzler, A. Galindo Tellez, Ryan Dorrill, Nathaniel Kaneshige, Kevin Keefe, Bae Wonseok

UC Berkeley: B. L. Goldblum, T. Laplace, J. Manfredi

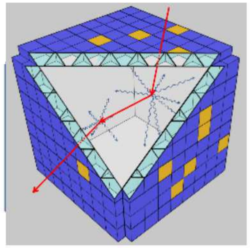
NCSU: J. Mattingly, K. Weinfurther, M. Mishra

ANL: J. Elam, A. Mane, M. Gebhard

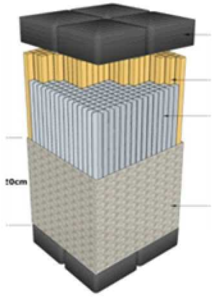
SVSC project

Prototyping

Monolithic

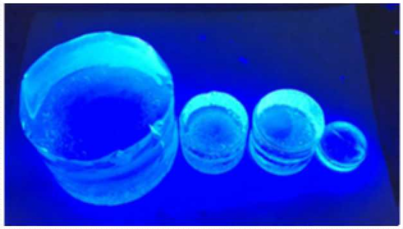


Opt. Segmented



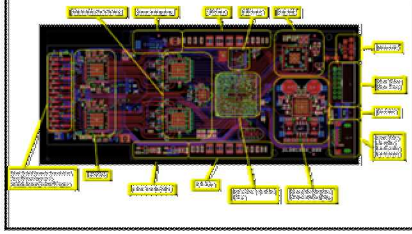
Components

Scintillators

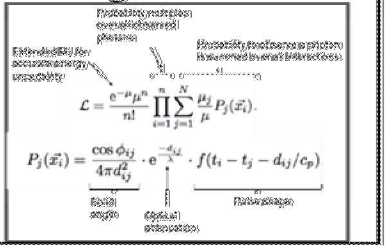


Photodetectors

Electronics



Algorithms



$$\mathcal{L} = \frac{e^{-\mu}\mu^{n}}{n!}\prod_{i=1}^{n}\sum_{j=1}^{N}\frac{\mu_j}{\mu}P_j(\vec{x_i})$$

$$P_j(\vec{x_i}) = \frac{\cos\phi_{ij}}{4\pi d_{ij}^2}\cdot e^{\frac{-d_{ij}}{\lambda}}\cdot f(t_i - t_j - d_{ij}/c_p)$$

Why is fast timing important?

- Distinguish interactions 2 ns & 3 cm apart
- Determine TOF to ~10% → 200 ps
- Correlated with position resolution: c/n = 20 cm/ns → 3 mm ~ 15 ps

System components:

1. Organic scintillator—fast plastic, O(1 ns) decay time
2. Fast photodetectors—MCP-PMTs, SiPMs, etc. Low tts ~100 ps if possible
3. Fast electronics—sufficient to take advantage of PDs. Must be scalable
4. Algorithms—use all information available

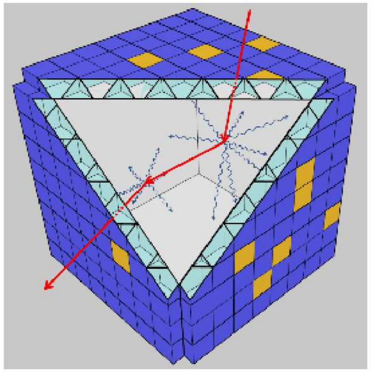
Single-volume scatter camera concepts

Sandia National Laboratories

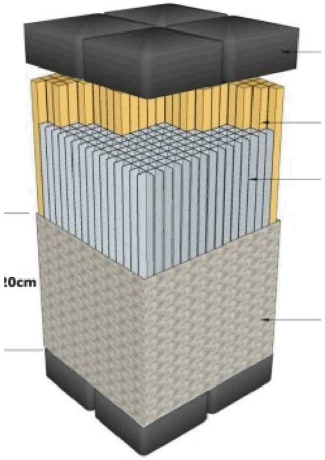
Event localization

Concept requires a method of determining ***two*** (or more) event locations within a compact scintillator to sub-cm precision.

$\vec{X} = (x, y, z, t)$

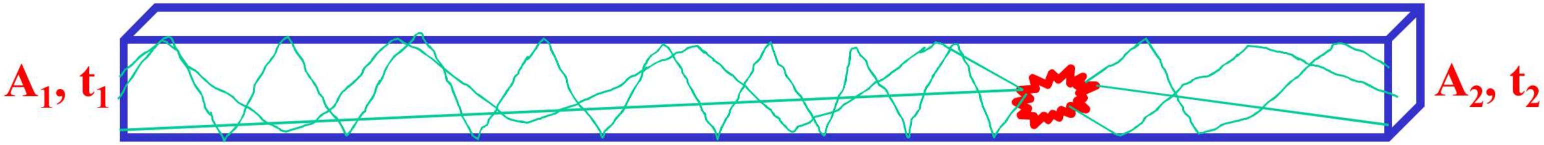


1. **Monolithic**: Arrival positions and times of isotropically emitted photons at surfaces of the volume determine most likely $\vec{X}$.
2. **Optically segmented**: Constrain photon propagation within bulk to associate specific PD channels with $\vec{X}$.



OS technical challenge

- Recall: double-scatter reconstruction requires 1) position, 2) time, 3) energy deposited for two neutron-proton scatters.
- Key questions for OS approach are resolutions of interaction position along bar and interaction timing

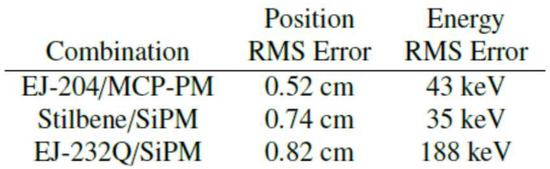


Position: $z \sim (t_1 - t_2)$ AND $z \sim \log(A_2/A_1)$
Time: $t \sim (t_1 + t_2)/2$
Energy: $E \sim \mathrm{sqrt}(A_1 A_2)$

OS simulation studies

Kyle Weinfurther (NCSU) paper

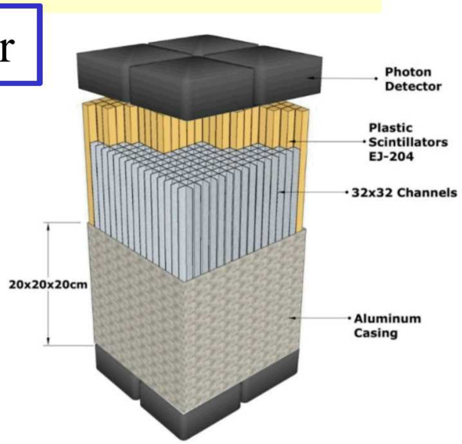
- Answer the question “Can it work?”
- Simulation uses a 2D array of scintillator pillars
- Each pillar is surrounded by a 1 mm air gap to allow for total internal reflection (TIR) and reflective film
- Investigated single-pillar performance for multiple scintillators, photodetectors, and pillar geometries



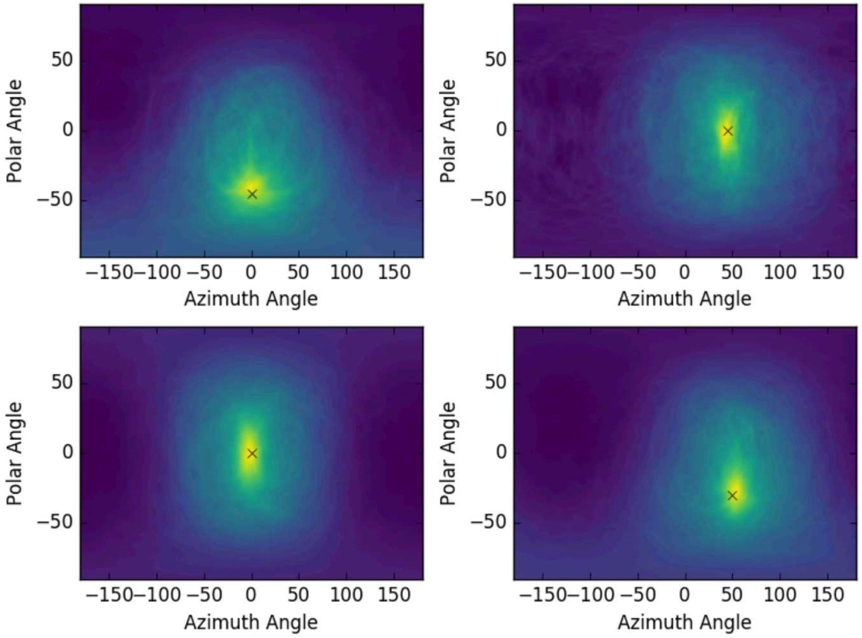
Combination	Position RMS Error	Energy RMS Error
EJ-204/MCP-PM	0.52 cm	43 keV
Stilbene/SiPM	0.74 cm	35 keV
EJ-232Q/SiPM	0.82 cm	188 keV

- Reconstruction via backprojection accurately determines simulated source location

(NIM A doi:10.1016/j.nima.2017.11.025)



Back-projected images

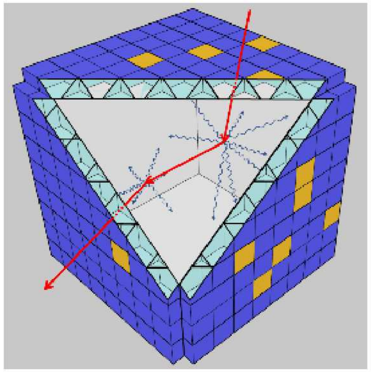


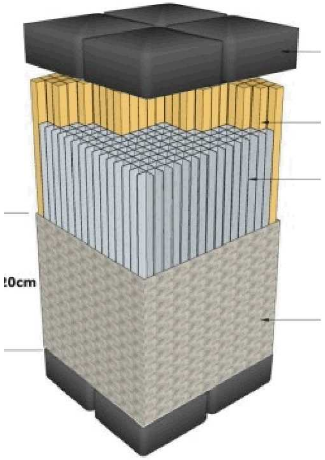
Event localization

Concept requires a method of determining ***two*** (or more) event locations within a compact scintillator to sub-cm precision.

$\vec{X} = (x, y, z, t)$

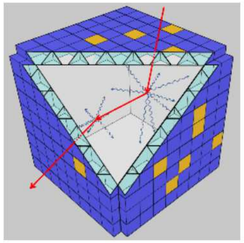
1. **Monolithic**: Arrival positions and times of isotropically emitted photons at surfaces of the volume determine most likely $\vec{X}$.
2. **Optically segmented**: Constrain photon propagation within bulk to associate specific PD channels with $\vec{X}$.





Direct reconstruction

1. **Direct reconstruction**: Arrival positions and times of isotropically emitted photons at surfaces of the volume determine most likely $\vec{X}$.

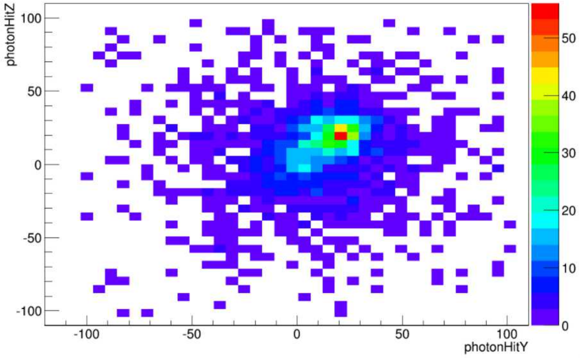


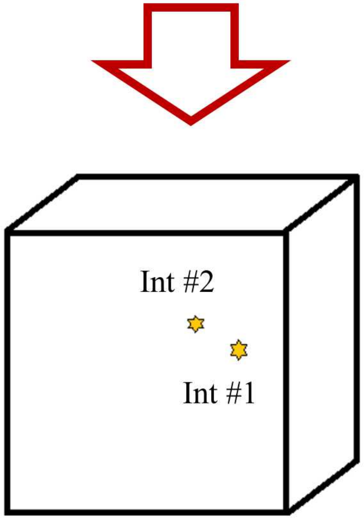
Extended ML for accurate energy uncertainty

$$\mathcal{L} = \frac{e^{-\mu}\mu^n}{n!}\overbrace{\prod_{i=1}^{n}}^{\text{Probability multiples over all observed photons}}\overbrace{\sum_{j=1}^{N}\frac{\mu_j}{\mu}P_j(\vec{x_i})}^{\text{Probability to observe a photon is summed over all interactions}}$$

$$P_j(\vec{x_i}) = \underbrace{\frac{\cos\phi_{ij}}{4\pi d_{ij}^2}}_{\text{Solid angle}} \cdot \underset{\uparrow\ \text{Optical attenuation}}{e^{\frac{-d_{ij}}{\lambda}}} \cdot \underbrace{f(t_i - t_j - d_{ij}/c_p)}_{\text{Pulse shape}}$$

list of photon arrival positions and times





(x,y,z,t,μ) for each int

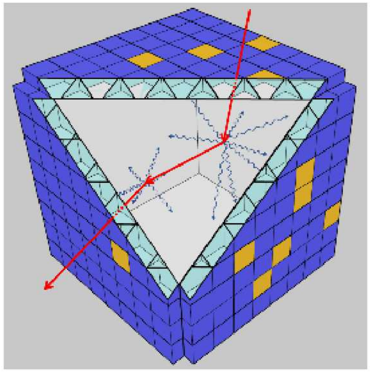
Can it work? (DR)

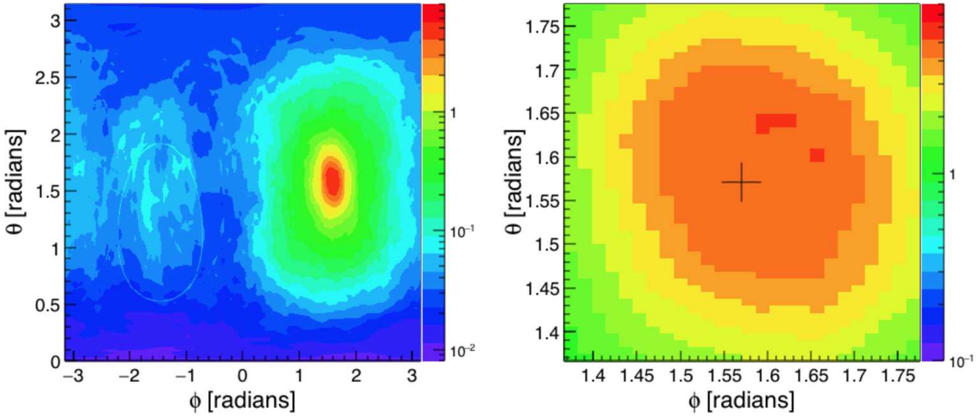
Belkis Cabrera-Palmer (SNL)

- Before we invest in building something, we need to convince ourselves the available information is sufficient to reconstruct events, and thence images.
- Key questions for DR approach are:
  - Is the information contained in the scintillation photons sufficient for reconstruction?
    - Yes!
  - Reconstruction performance over the complete set of neutron trajectories
  - Limitations of simulation, especially optical transport

	σ
Δx_0	3.02 mm
Δy_0	3.05 mm
Δz_0	3.02 mm
Δt_0	0.08 ns
Δn_0	45 photons

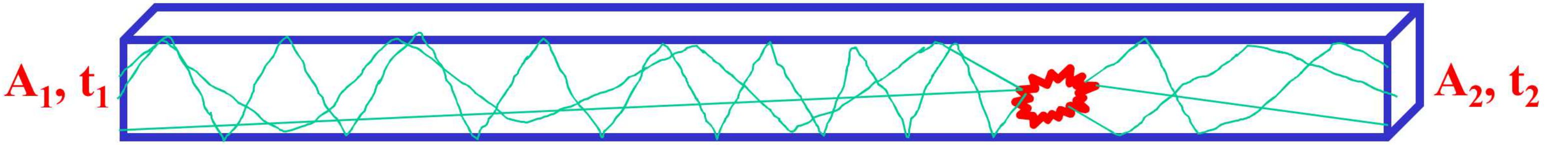
	σ
Δx_1	4.94 mm
Δy_1	5.08 mm
Δz_1	4.95 mm
Δt_1	0.14 ns
Δn_1	30 photons





For a simulated 2.7 uCi Cf252 neutron source located at 1 m, this image is equivalent to 29 minutes of measurement time, without background.

Selected challenges/results: Single-bar characterization (OS)



Position: $z \sim (t_1 - t_2)$ AND $z \sim \log(A_2/A_1)$
Time: $t \sim (t_1 + t_2)/2$
Energy: $E \sim \mathrm{sqrt}(A_1 A_2)$

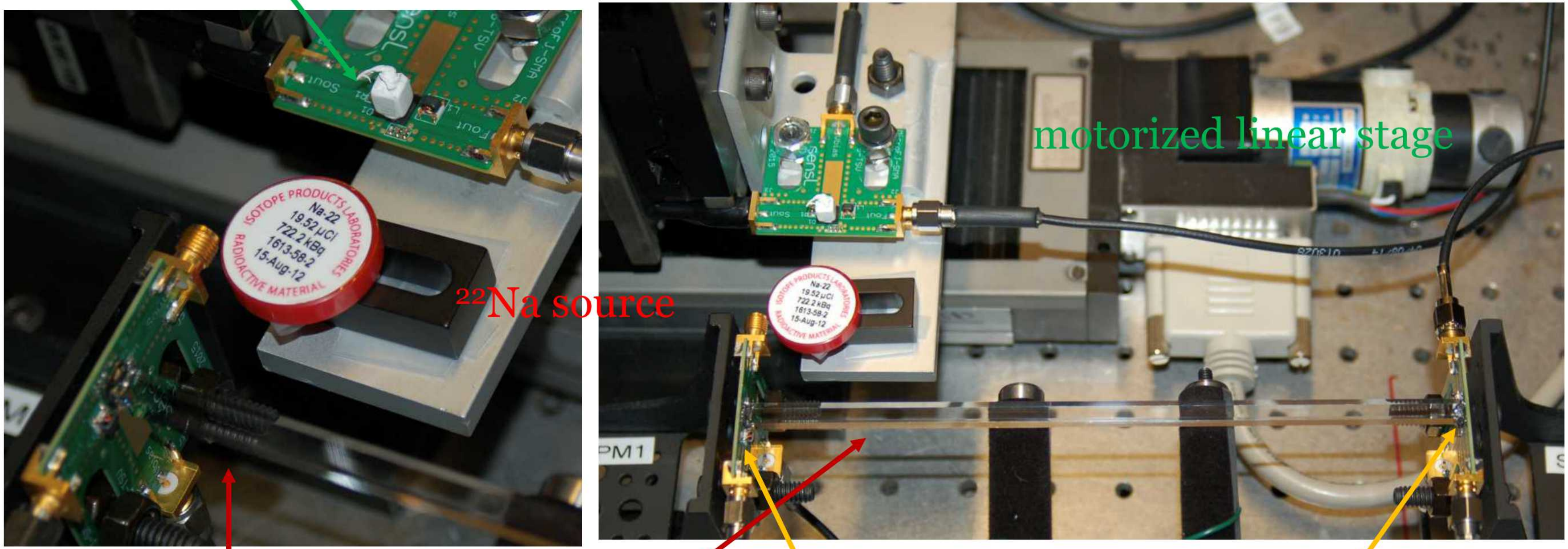
Sandia
National
Laboratories

Na-22 measurements

SNL Experimental Setup

Melinda Sweany (SNL)

tag scintillator: 5x5x5 mm stilbene crystal coupled to J-series SiPM



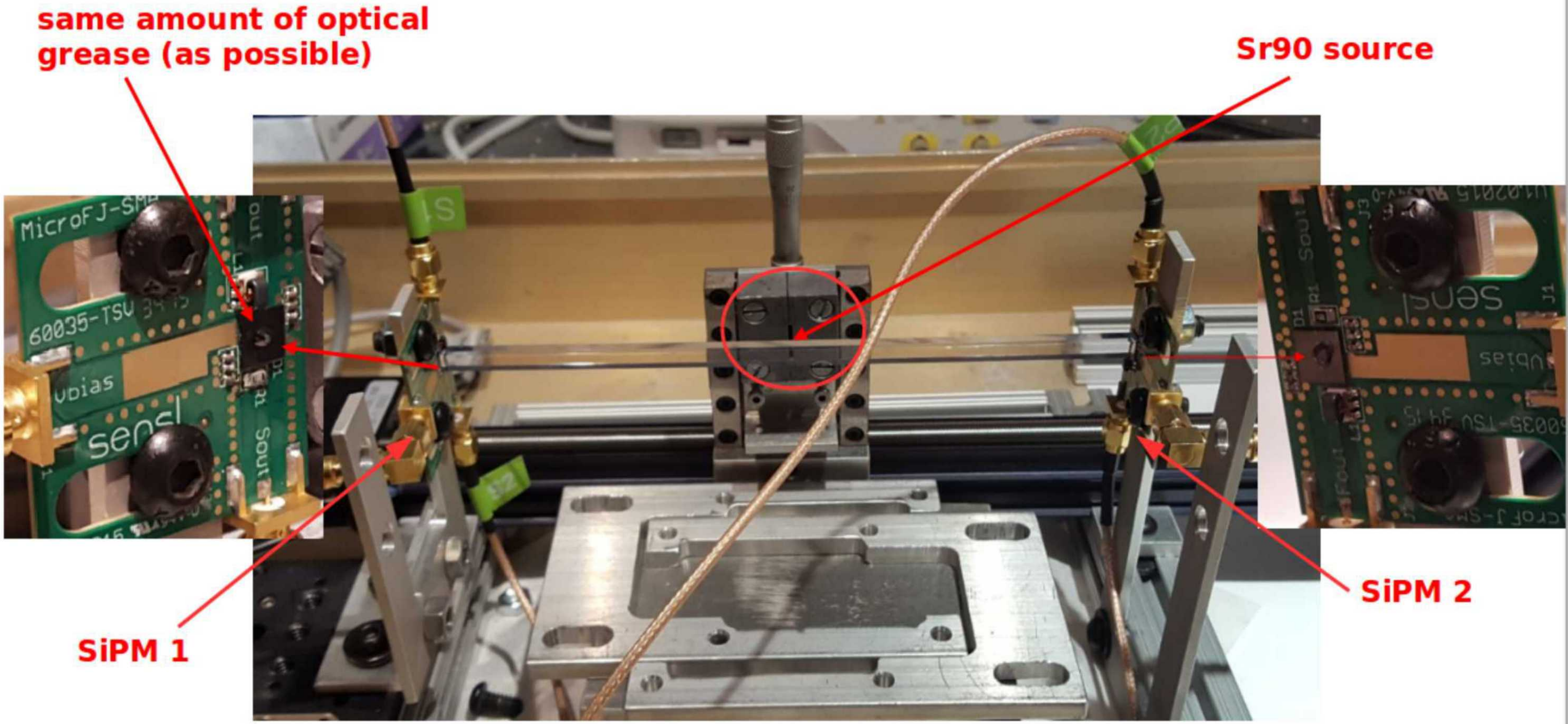
test scintillator bar

Scintillator bar readout:
SensL J-series SiPM

Sr-90 measurements

A. Galindo Tellez et al. (Hawaii)

U Hawaii Experimental Setup

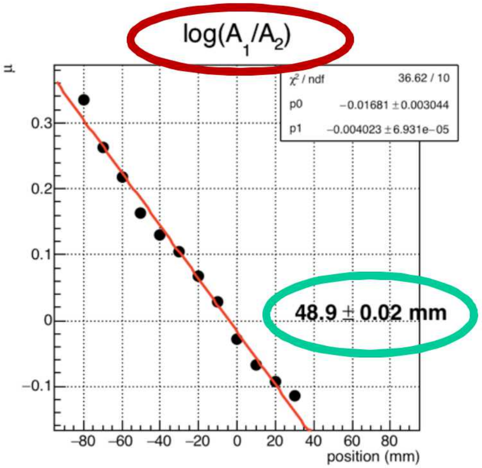


Results

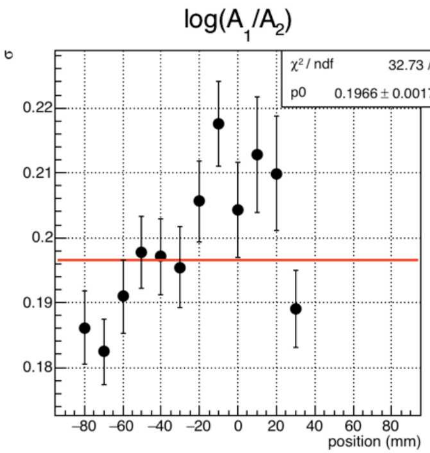
Melinda Sweany (SNL)

Example Results – EJ200 bare

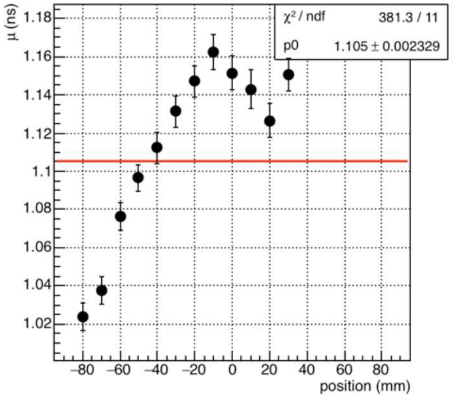
Preliminary



48.9 ± 0.02 mm

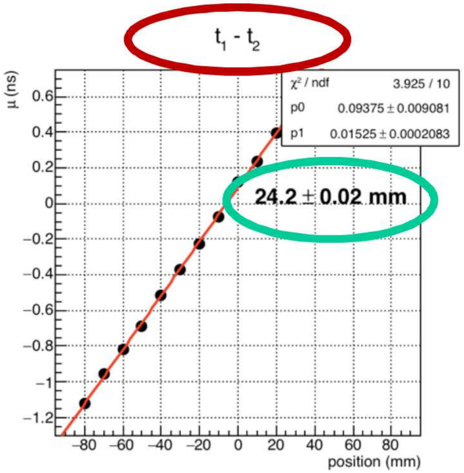


All resolutions given as σ



Interaction position resolution

Interaction time resolution

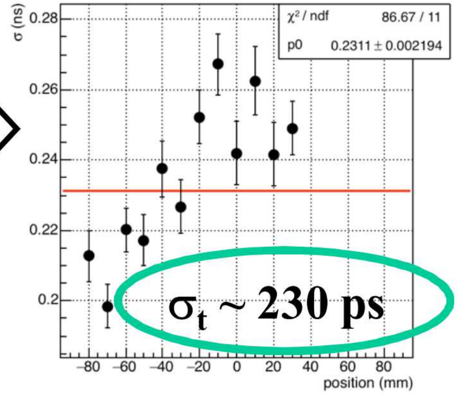


24.2 ± 0.02 mm

Na-22 source:
- threshold – 340 keV

Unwrapped bar:
- light losses
- good timing

Best position resolution:
- combine amplitude, timing info

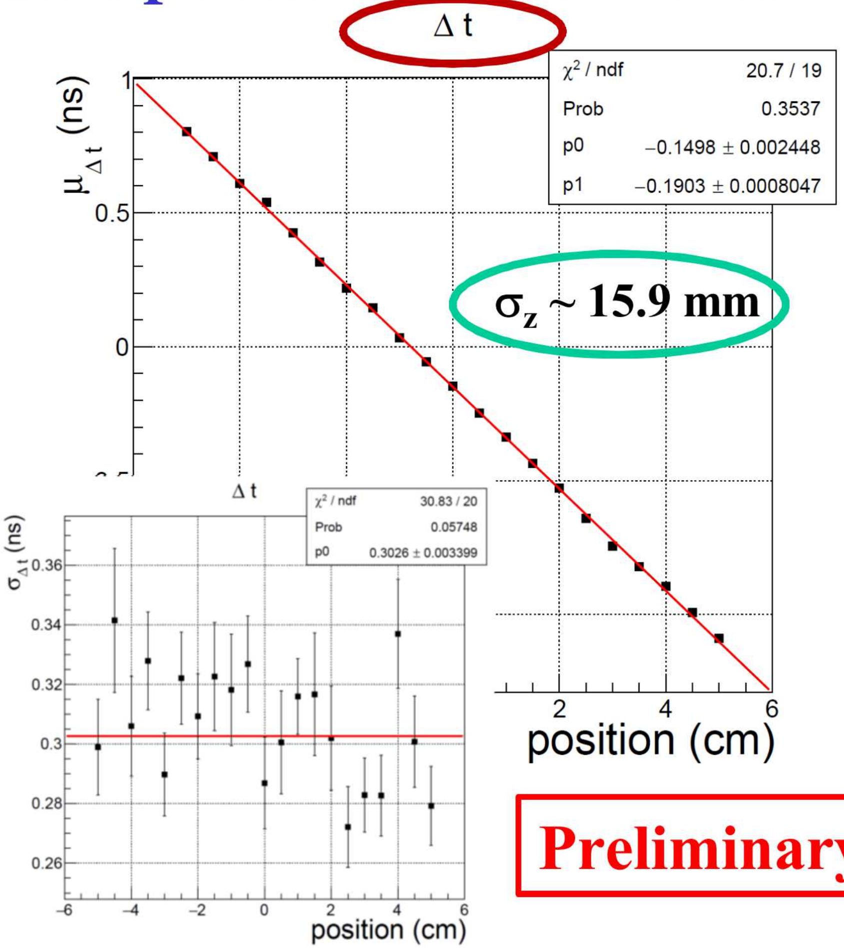


$\sigma_t \sim 230$ ps

Results (UH)

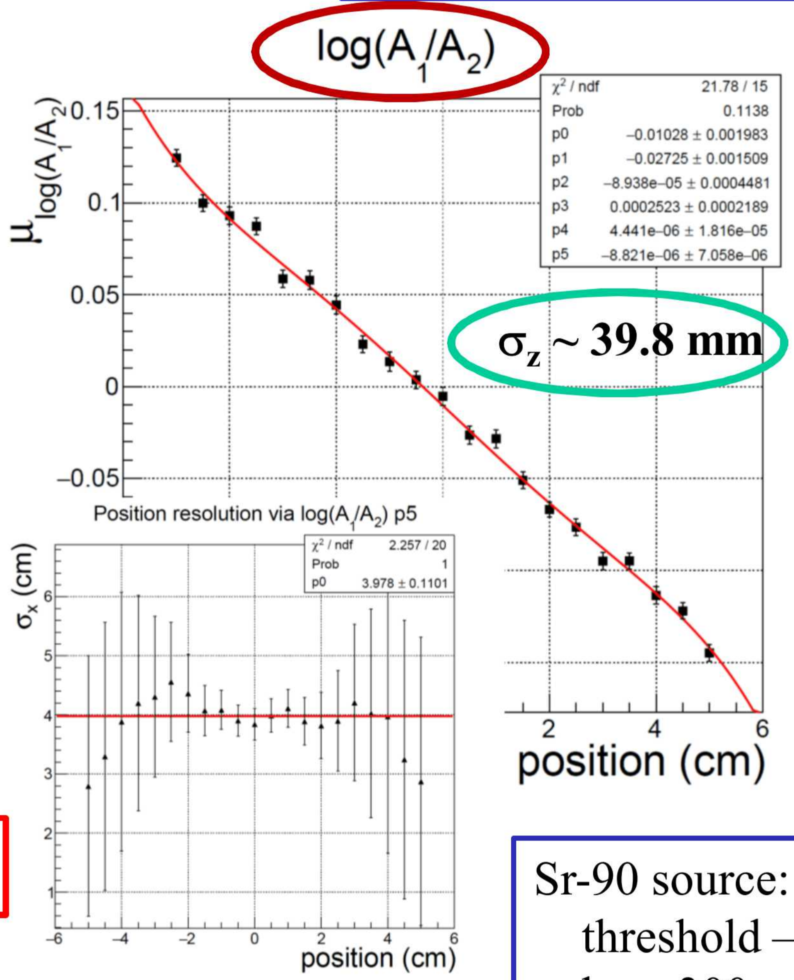
A. Galindo Tellez et al. (Hawaii)

Example Results – EJ200 bare



$\sigma_z \sim 15.9$ mm

Preliminary



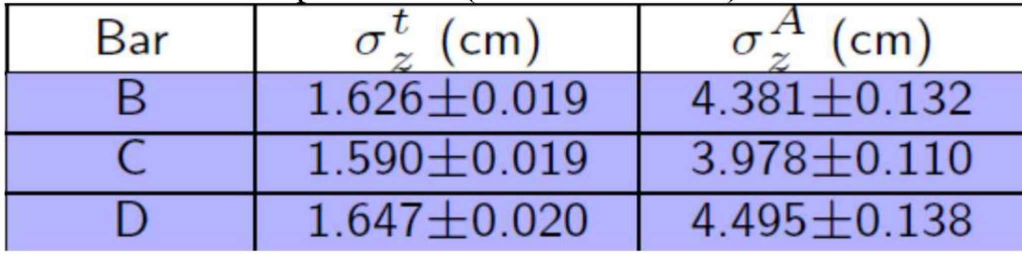
$\sigma_z \sim 39.8$ mm

Sr-90 source:
threshold – 2.3 MeV
here 300 – 400 keV

Single-bar conclusions

- Can evaluate position resolution, time resolution, energy resolution
- Good cross-checks and confidence from using two measurement setups

Estimate systematics via tests of multiple bars, and/or same bar multiple times (table from UH).

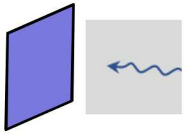


Bar	σ_z^t (cm)	σ_z^A (cm)
B	1.626±0.019	4.381±0.132
C	1.590±0.019	3.978±0.110
D	1.647±0.020	4.495±0.138

- Very significant differences among scintillators (EJ-200, EJ-204, EJ-230, EJ-276)
- Wrapped bars (Teflon, ESR) tend to outperform bare bars
- What is good enough?

  Recall 3 cm, 2 ns typ. separation
  Transverse bar size = 0.5 cm
  Simulation: < 1 cm poss.

Selected challenges/results: Single-photon timing (monolithic)

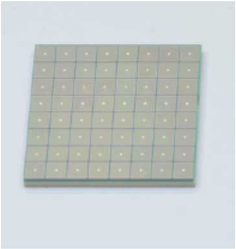


Photodetectors

Photek PMT210

- 1 cm MCP-PMT
- Gold standard for timing
- Not scalable

Hamamatsu MPPC S13360

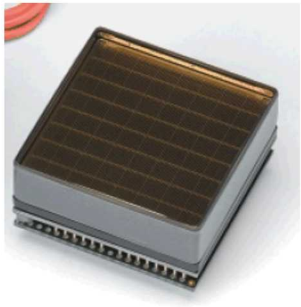


- 6 mm SiPM
- Arrays available
- 50 μm microcell

Photonis Planacon XP85012

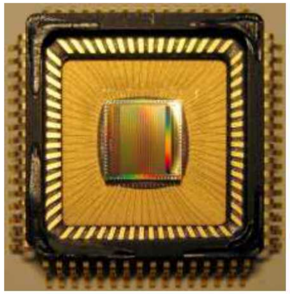
- 25 μm pore MCP-PMT
- 8x8 anode (6 mm)

Hamamatsu H8500 MAPMT



- Metal channel multi-anode PMT
- 8x8 anode (6 mm)

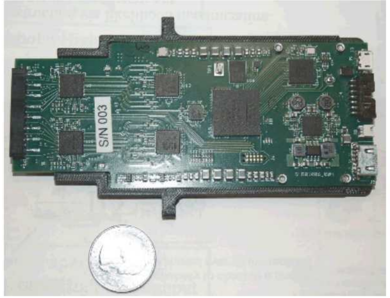
DRS4 waveform capture



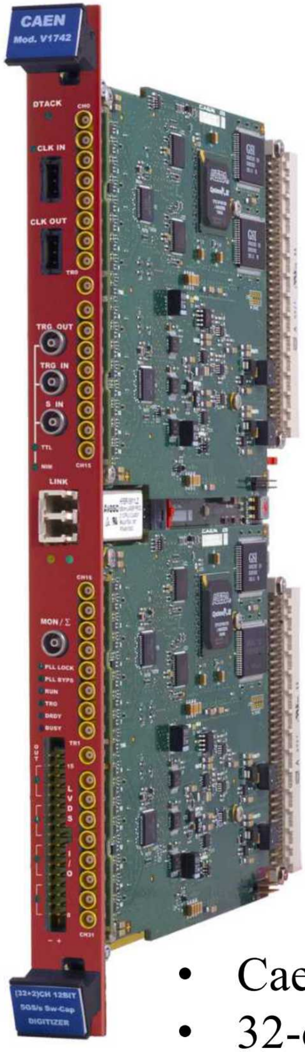
PSI

- DRS4: 9-ch switched capacitor array ASIC
- **5 GS/s**, **950 MHz**, 11.5 enob, **1024 samples**
- Long readout time

- 4-channel DRS4 eval board (PSI)
- Not scalable



- SNL 16-channel DRS4-based board
- 14 cm x 6 cm footprint
- Plugs directly into Planacon

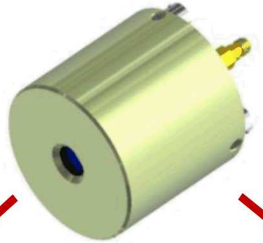


- Caen V1742
- 32-channel
- DRS4-based

Best case (not scalable)

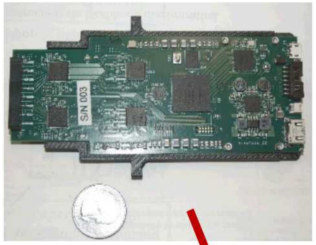
J. Brown (SNL)

Photek LPG-405
- pulse ~ 40 ps FWHM

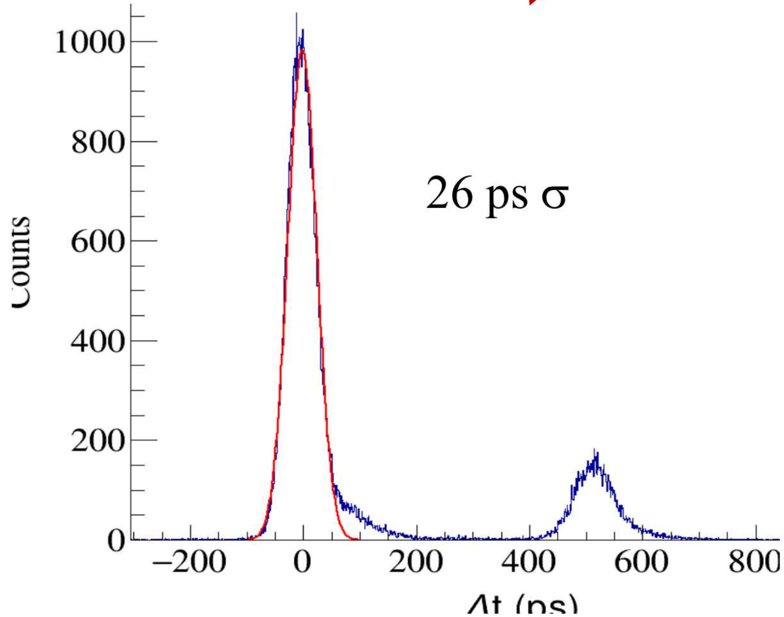


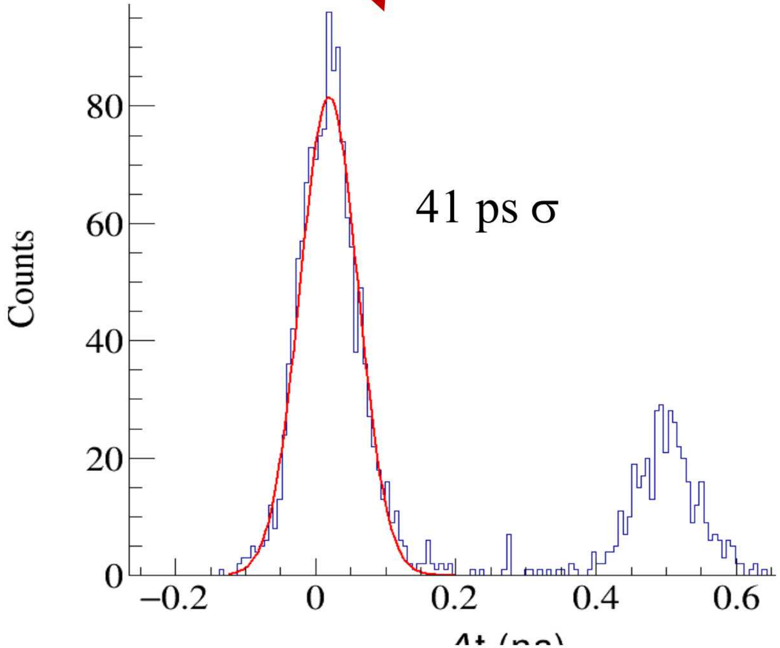
Photek PMT210
- tts ~ 30 ps
- single ph width ~ 150 ps

LeCroy WR 640Zi
- 4 GHz
- 20 GS/s

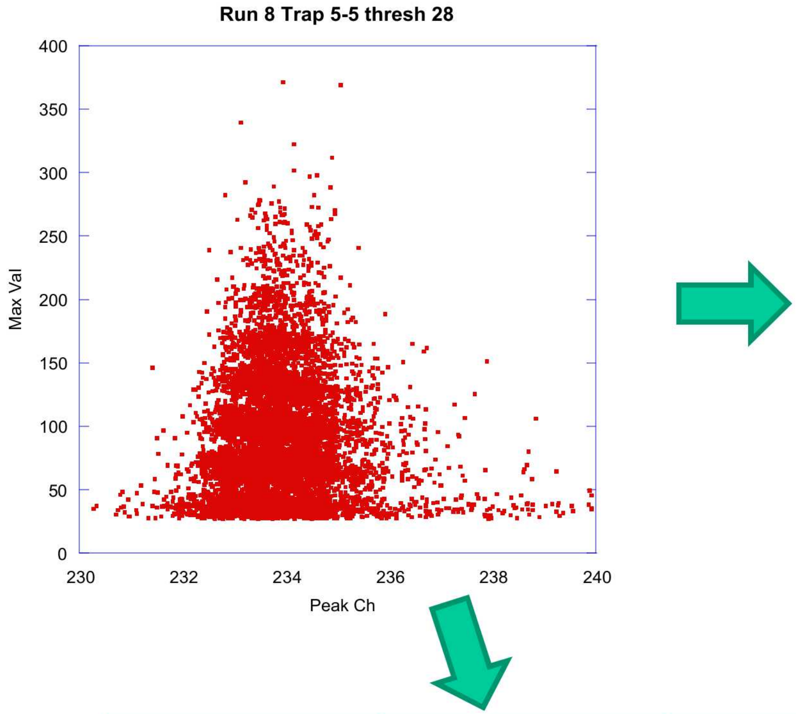


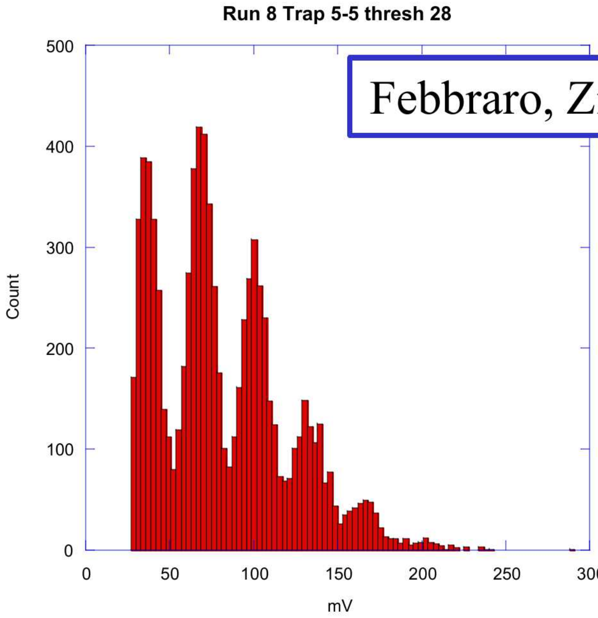
SLAcq (DRS4)
- 5 GS/s





Hamamatsu S13360-6050CS



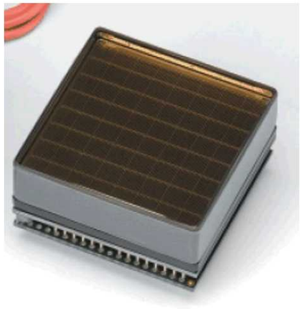


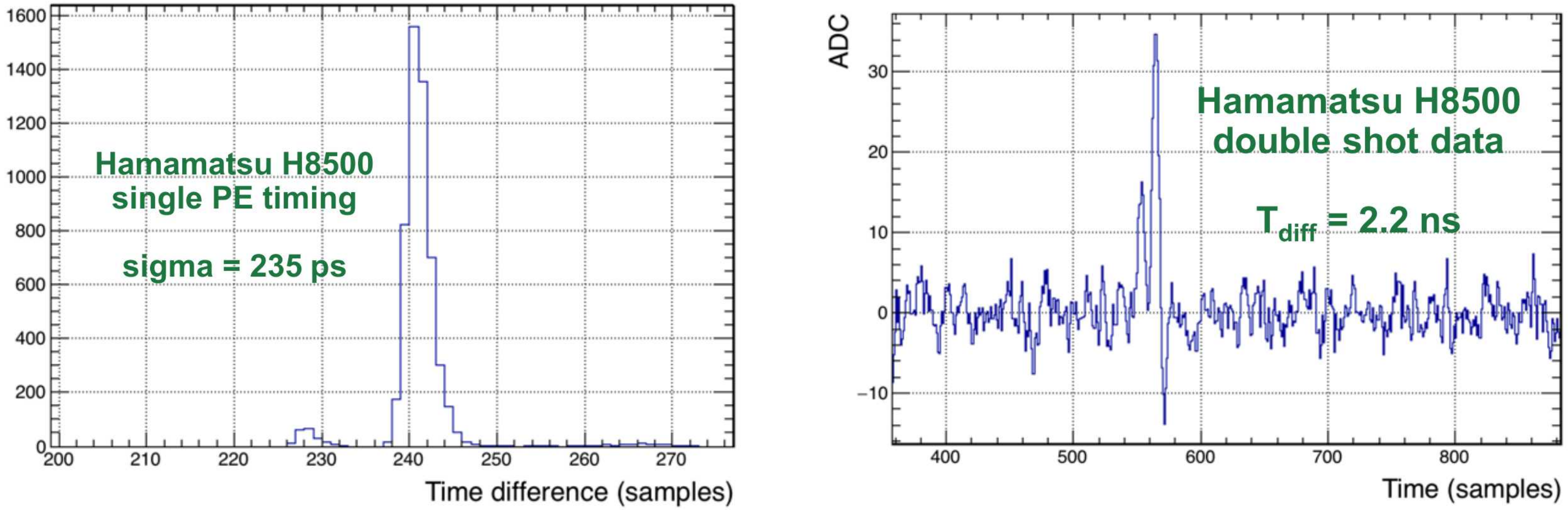
Febbraro, Ziock (ORNL)

# PE	1 sigma (chan)	counts	1 Sigma width	FWHM (ps)
1	0.855	2162	**171**	402
2	0.709	2735	142	333
3	0.668	1983	134	314
4	0.638	1032	128	300
5	0.549	361	110	258
6	0.60	87	120	282

H8500 multi-anode PMT

Febbraro, Ziock (ORNL)

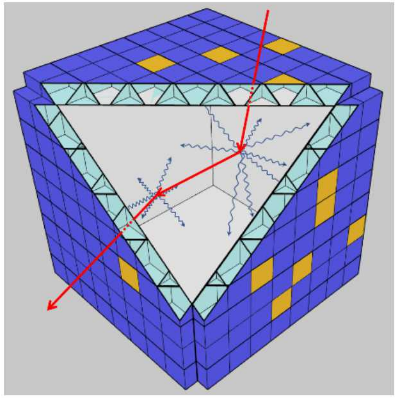




- Single-photon time resolution worse
- But, fast pulses ease analysis of multi-photon traces
- Low dark rate, no add'l amplification needed

Results summary

Photodetector	Photek PMT210	Photonis Planacon	Hamamatsu SiPM 50 μm	H8500 MAPMT	Comments
4 GHz scope	26 ps				Not scalable
DRS4 eval board		107 ps $(\sigma/\mu)_1$=0.53			Not scalable
Caen V1742			171 ps $(\sigma/\mu)_1$=0.10	235 ps	Cables, SWaP
SLAcq board	41 ps	82 ps $(\sigma/\mu)_1$=0.83			Low S:N
Comments	Not scalable	Crosstalk Non-uniform	High dark rate Need 100x amp Afterpulsing	Non-uniform	



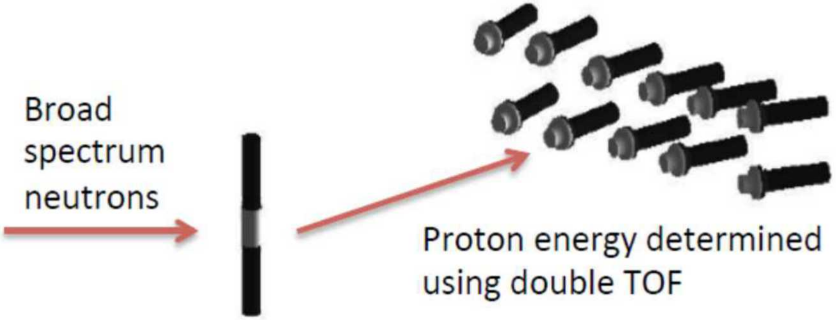
What do we conclude for SVSC monolithic neutron imager?

- No clear winner
- Evaluate tradeoffs in simulation
- Could proceed with any of these options and learn a great deal from a full prototype!

Selected challenges/results: Scintillator characterization

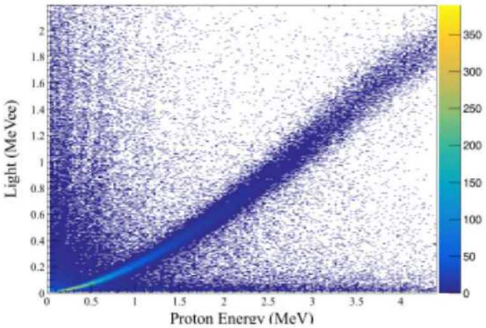
Light Yield Measurements – LBNL/UCB Approach

New dTOF method developed at LBNL extends the indirect technique using a high-flux tunable broad spectrum d-breakup neutron source



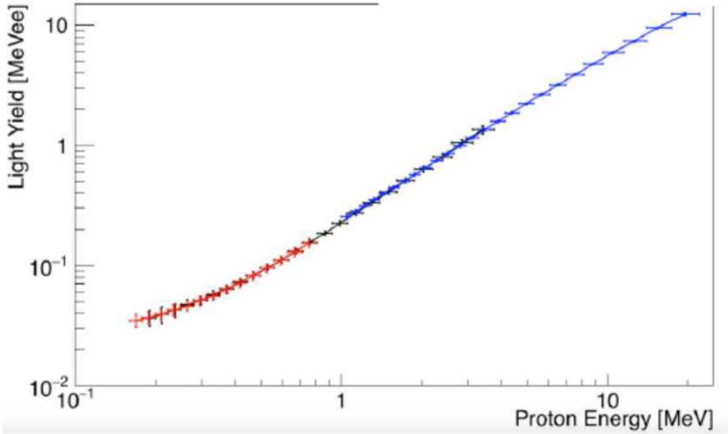
Broad spectrum neutrons

Proton energy determined using double TOF



Each detector pair results in a continuous light yield measurement over a broad energy range

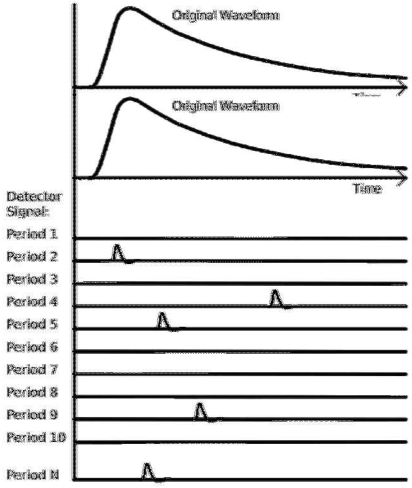
- ***Higher flux = Shorter measurement times***
  - DT generator (commercial): <10^7 n/s/sr
  - ***88-Inch Cyclotron: >10^{11} n/s/sr at 0°***
- ***Higher flux = More accurate measurements***
  - Smaller detectors and larger flight times while maintaining reasonable event rates
- ***Multiple secondary detectors***
  - Increased statistics
  - Same result from independent detectors as systematic check

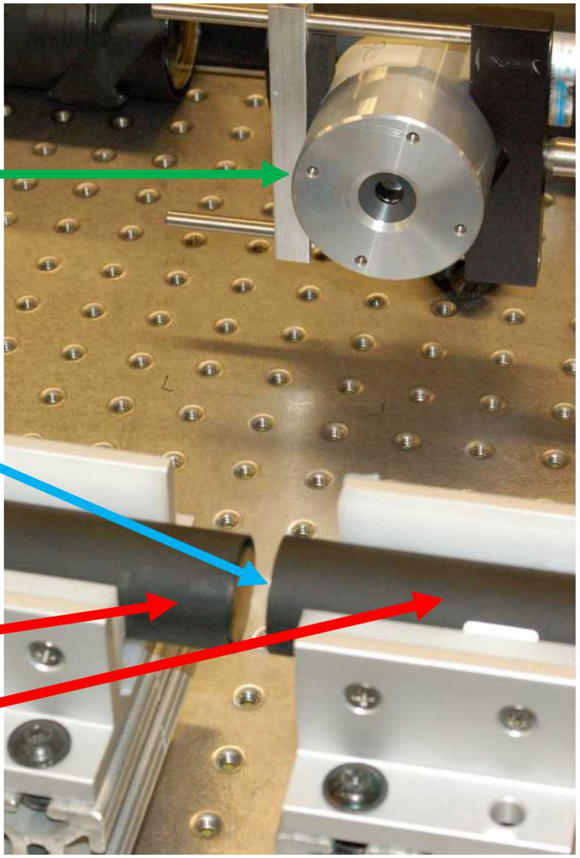


Outcome: Enables accurate simulation of advanced neutron detection systems, neutron image reconstruction, and next-gen detector materials prospecting

TCSPC (50 ps res?)

Time Correlated Single Photon Counting



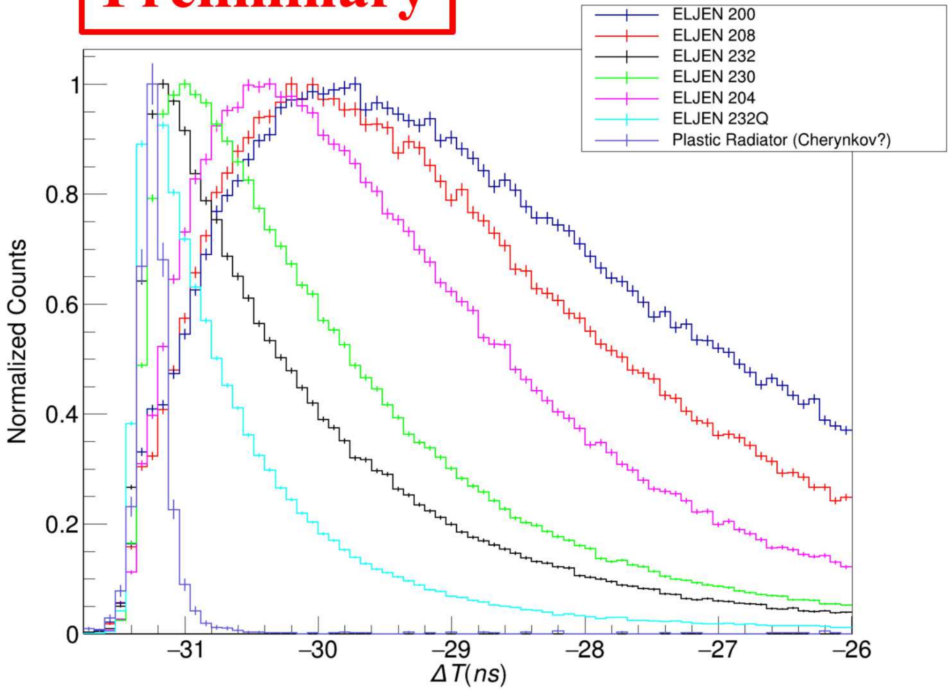


PHOTEK PMT-210
~30ps std dev SPTR

Fast Plastic
Scintillator

H1949-50
~220ps std dev
SPTR

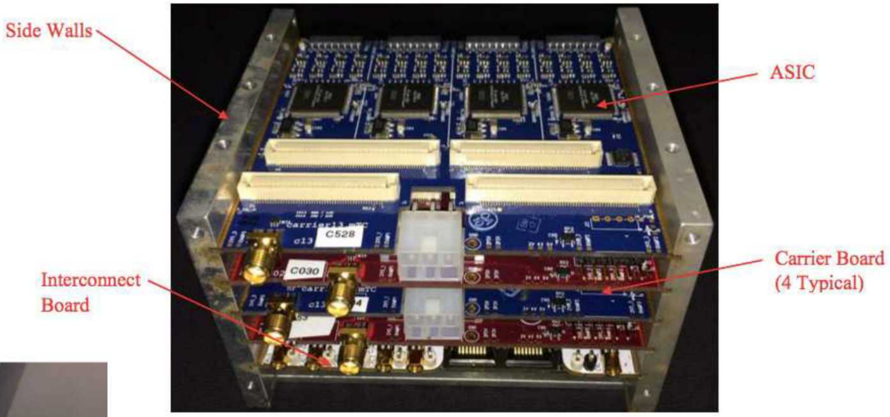
Preliminary



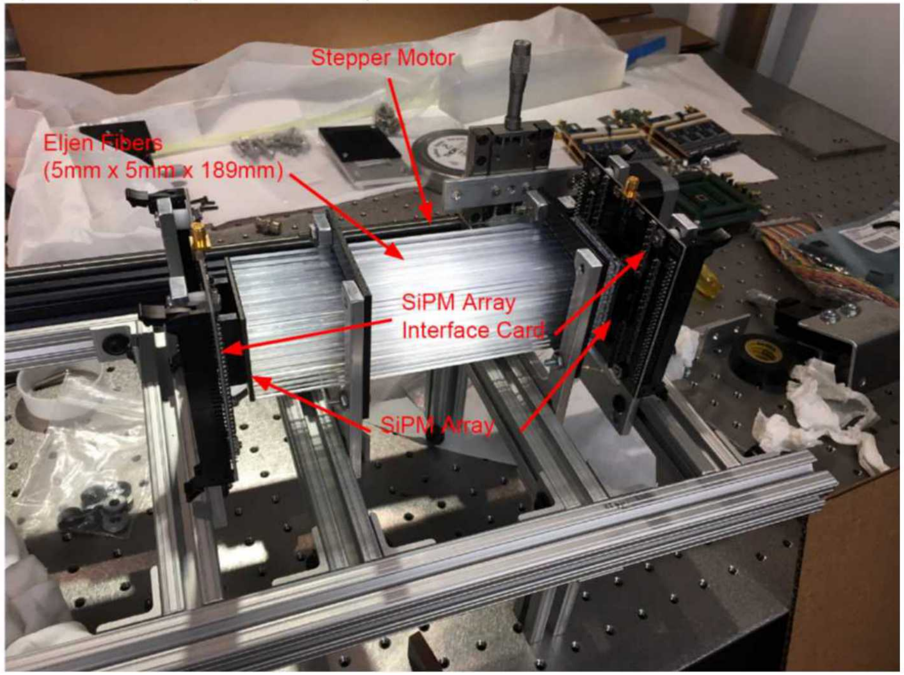
Current status

OS integrated prototype @ UH

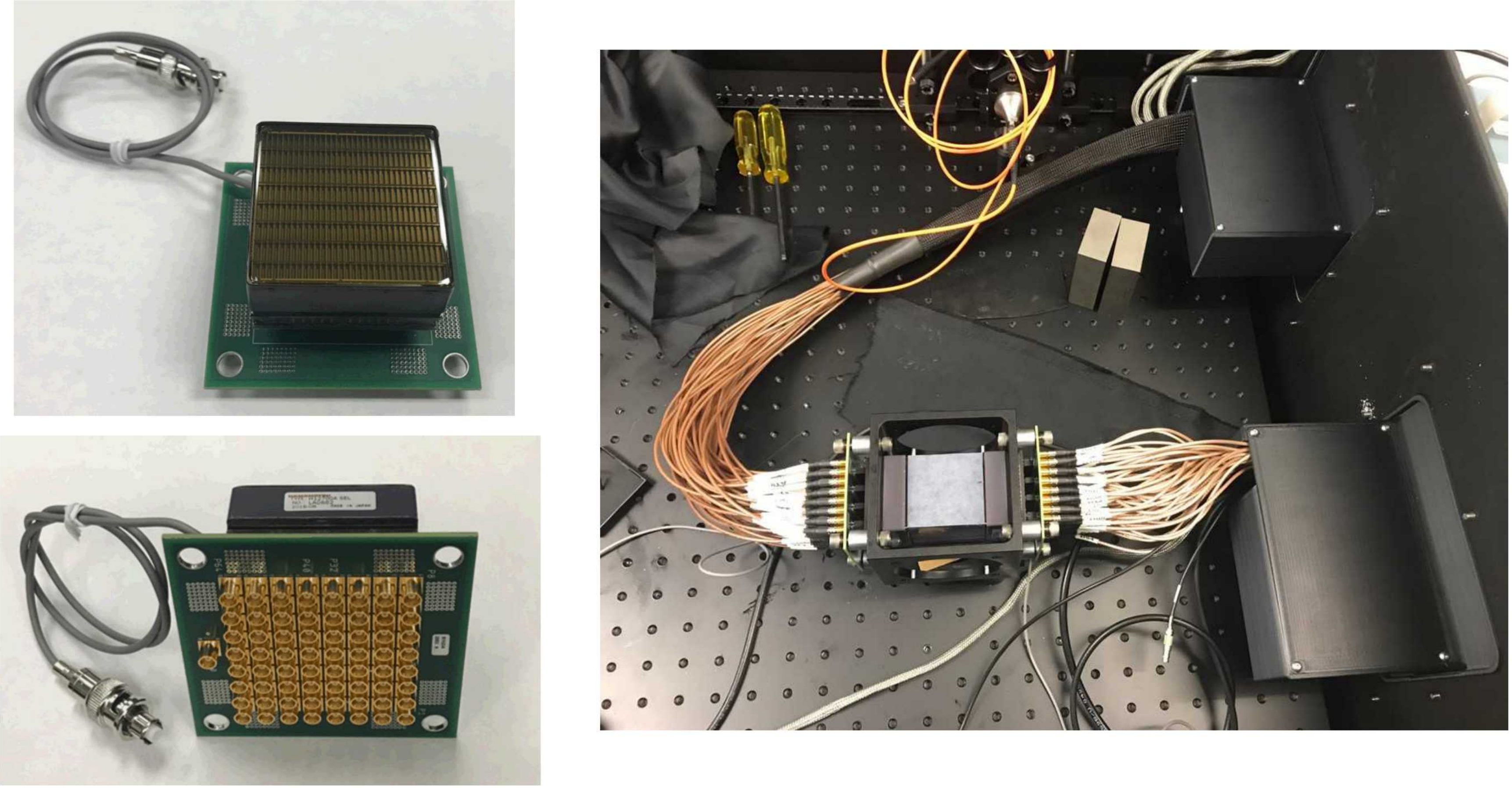
- U of Hawaii:
  - Array of scintillator bars
  - Electronics stack



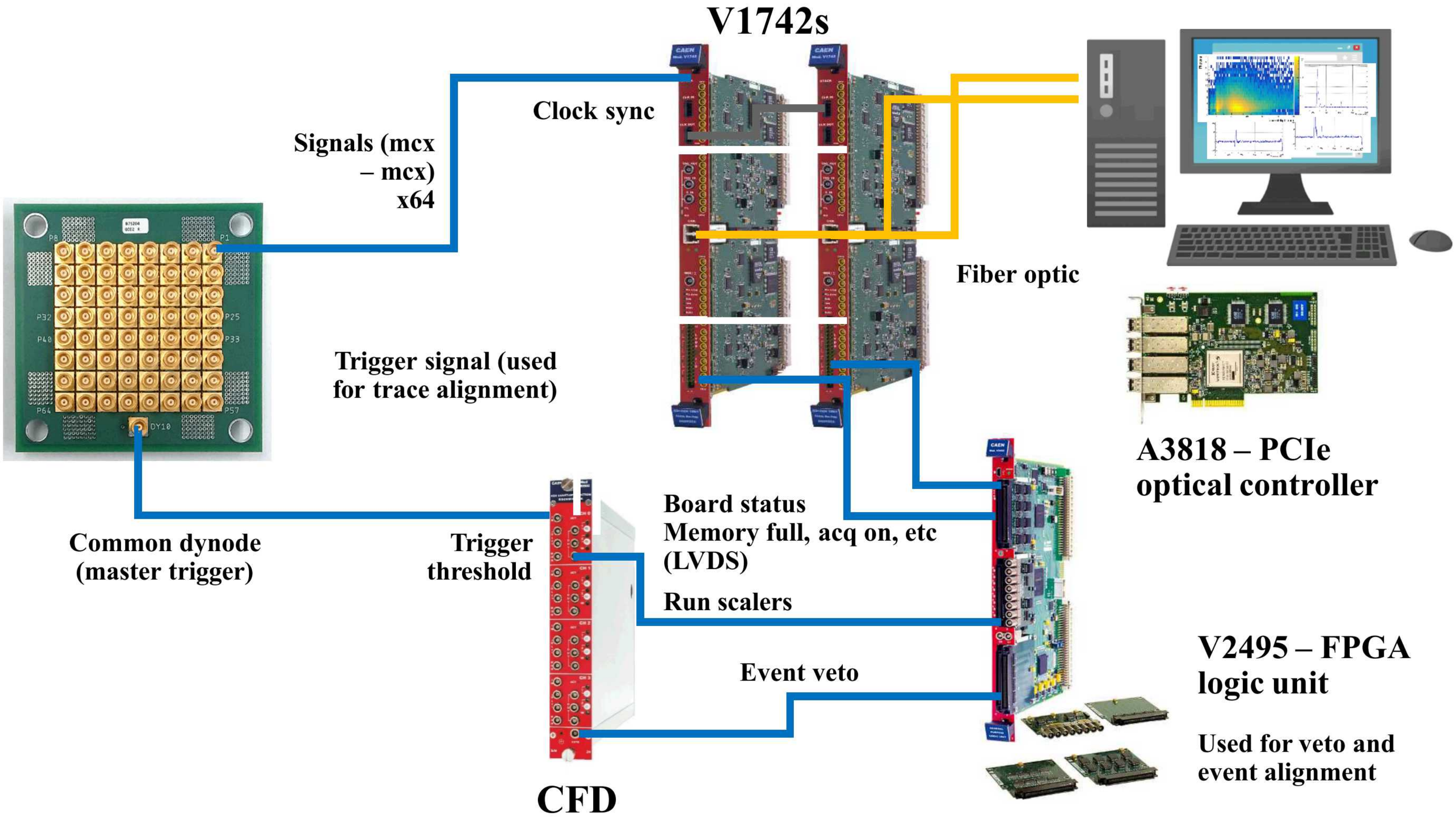
Full (8x8) Fiber Array Test Setup:



Monolithic integration @ ORNL



ORNL readout details



V1742s

Clock sync

Signals (mcx
– mcx)
x64

Fiber optic

A3818 – PCIe optical controller

Trigger signal (used
for trace alignment)

Common dynode
(master trigger)

Trigger
threshold

Board status
Memory full, acq on, etc
(LVDS)

Run scalers

Event veto

V2495 – FPGA logic unit

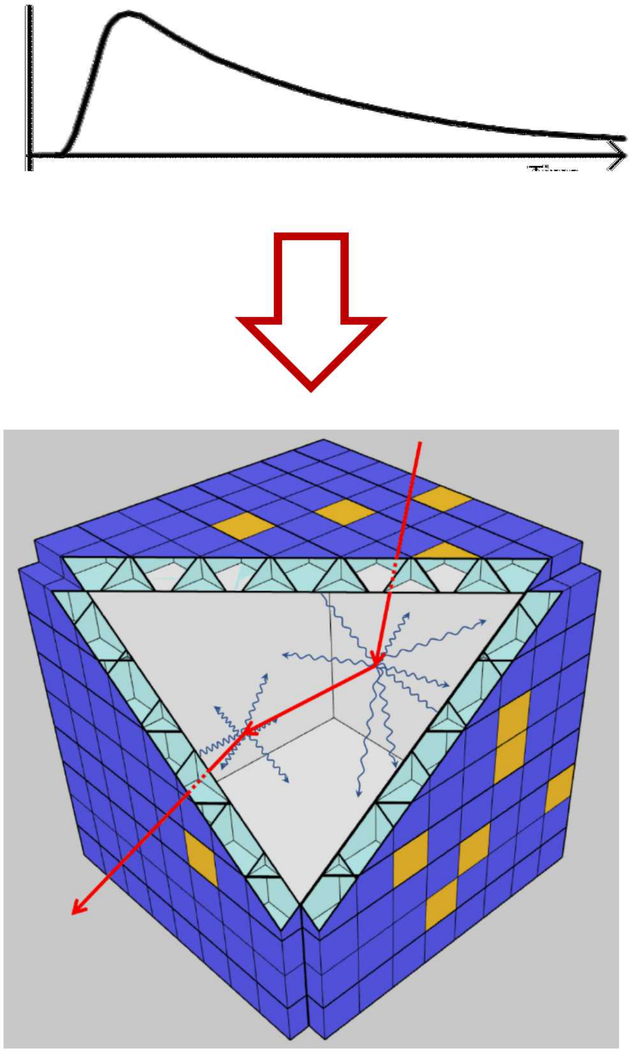
Used for veto and
event alignment

CFD

Final thoughts

Photon-focused detection

- Are we seeing a trend toward measuring *every photon* in a scintillation event, rather than every pulse?
  - Driven by need to extract maximal information
  - Enabled by capable photodetectors, electronics
  - Enabled by increases in computing power
- Other examples:
  - DIRC/RICH detectors
  - Neutrino detectors
  - TOF-PET
  - Optical coded aperture for Compton imaging



Summary

- **Neutron imaging** has a role in nuclear security/non-proliferation applications
  - Detect (BG unknown), Locate, Characterize
- **Diversity of neutron imagers** driven by optimization for different needs
- **Single-volume scatter camera** can increase efficiency *and* reduce size vis-à-vis predecessors
  - Simulation studies demonstrate feasibility
  - Prototype integration underway
- Are we seeing a trend toward **photon-focused scintillation detection**?

Thanks to NNSA DNN R&D for support and funding!

Additional slides

SNM detection/imaging

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

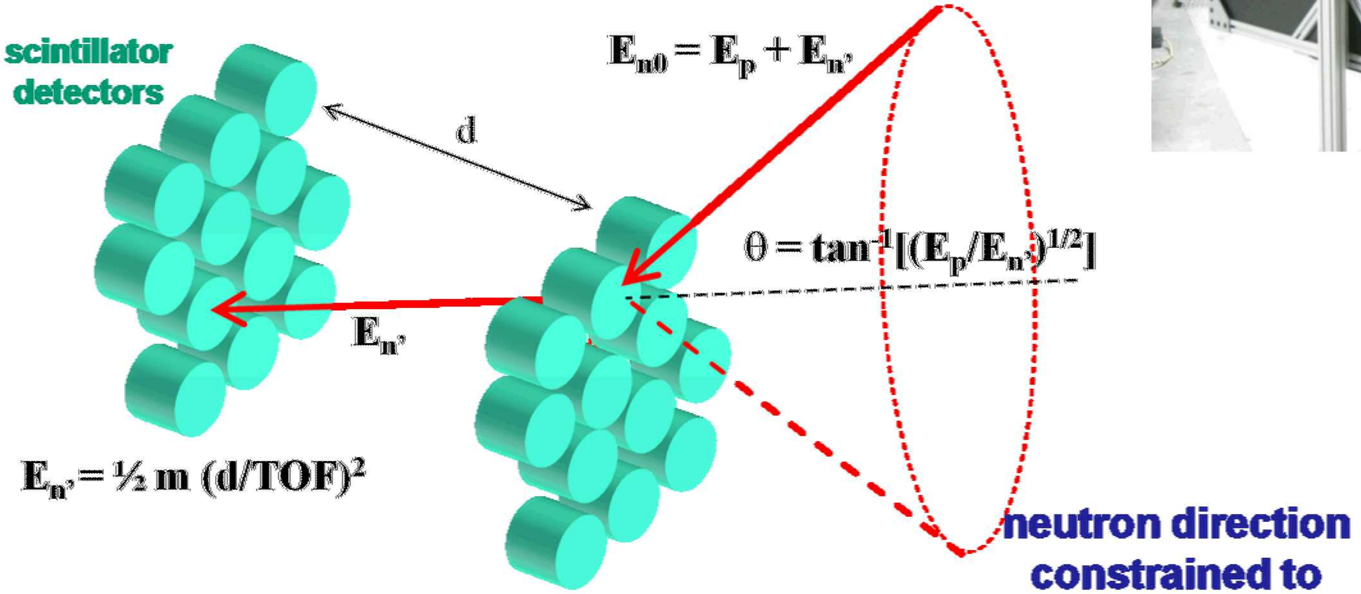
SNM imaging applications

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

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



incoming neutron

scintillator detectors

d

$E_{n0} = E_p + E_{n'}$

$\theta = \tan^{-1}[(E_p/E_{n'})^{1/2}]$

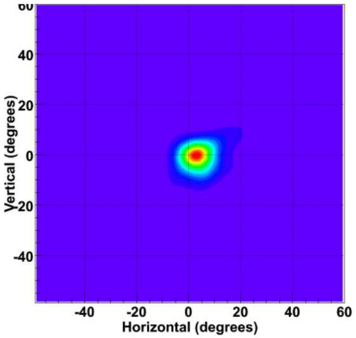
$E_{n'}$

$E_{n'} = \frac{1}{2} m (d/TOF)^2$

neutron direction constrained to cone surface

Multimode capability includes

- ***Neutron energy spectrum.***
- ***Compton imaging.***

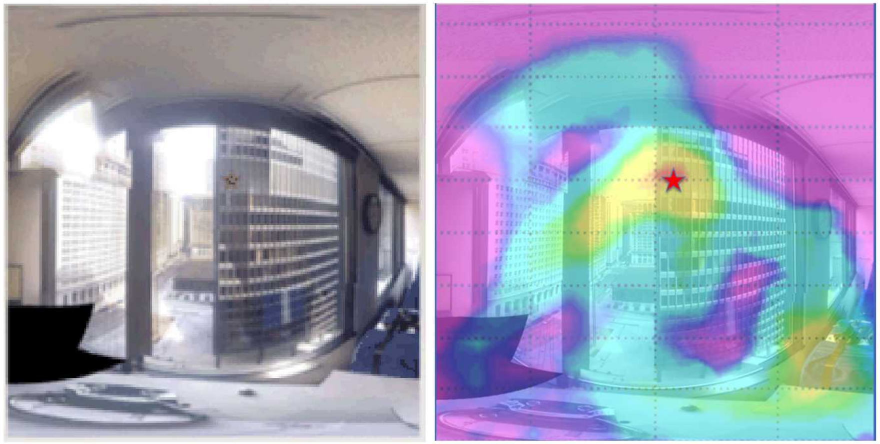


An MLEM-reconstructed neutron point source image.

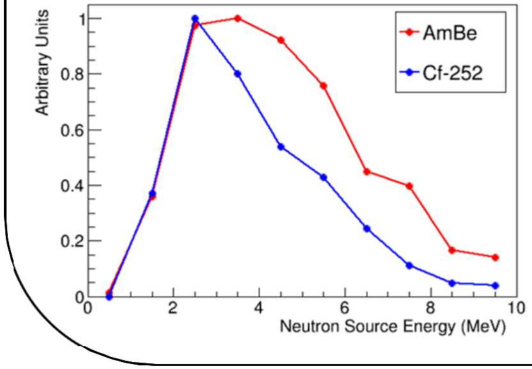
MINER Demonstrations
Emergency Response Scenarios

High Rise to High Rise

28 m to sources to detectors



Cf-252, 30 minutes

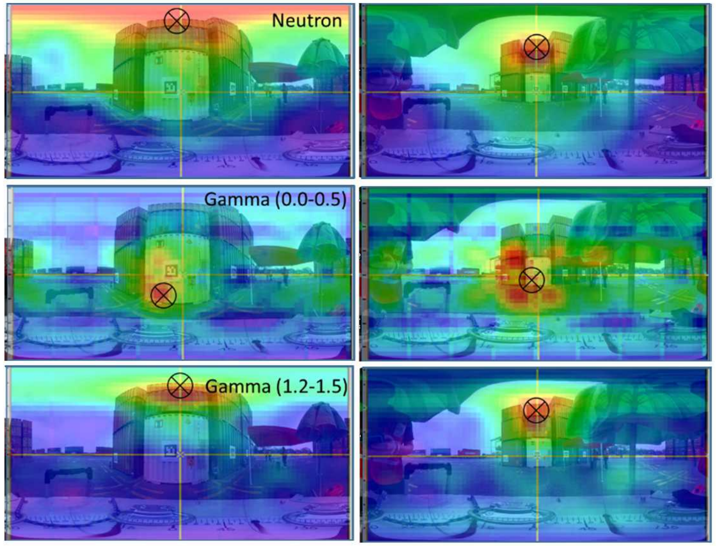


Reconstructed neutron spectra used to distinguish Cf-252 from AmBe at a standoff

Port of Savannah

Container Stack

Successfully located mixed neutron and gamma sources within container stacks

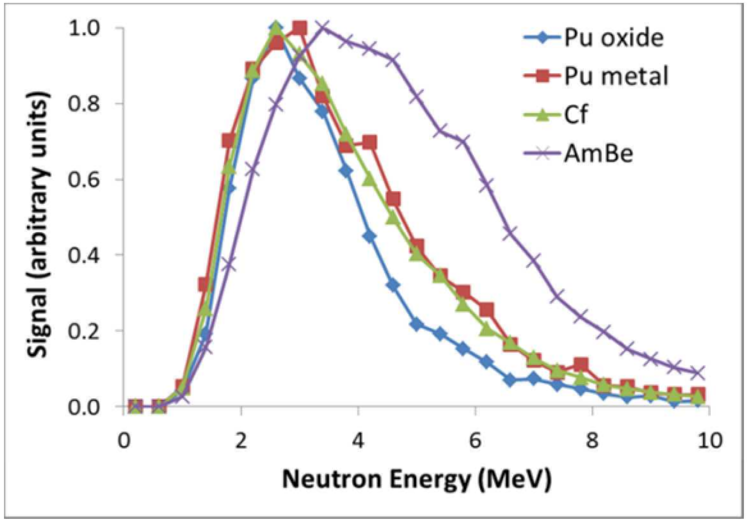


MINER Demonstrations

Energy Spectroscopy

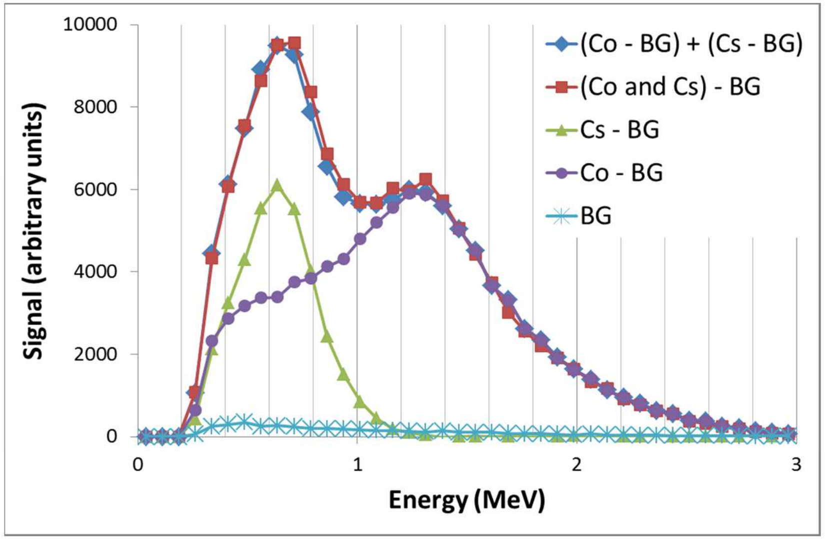
Neutrons

- Possible to distinguish between
  - Fission spectra
  - (α,n) spectra
  - Mixed spectra



Gammas

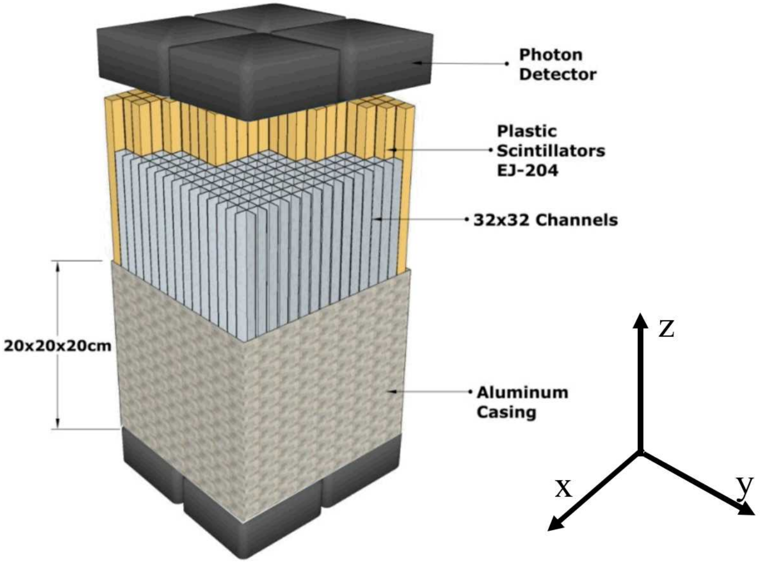
- Low-resolution gamma spectroscopy possible by approximating the energy of the scattered gamma

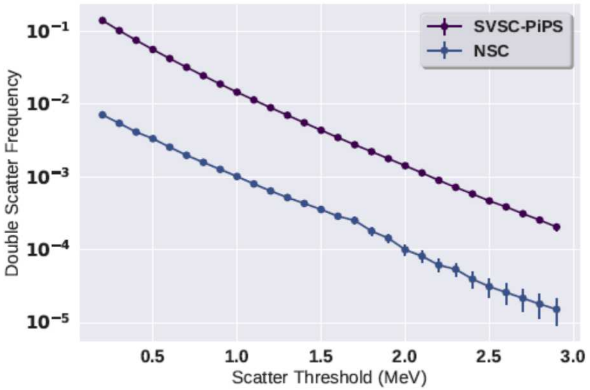


OS simulation studies

- Uses a 2D array of scintillator pillars
- Each pillar is surrounded by a 1 mm air gap to allow for total internal reflection (TIR)
- Pillars are optically isolated from neighboring pillars by a reflective film/paint
- Explore computational design of OS SVSC
  - Photodetectors modeled
    - Microchannel plate photomultiplier (MCP-PM)
    - Silicon photomultiplier (SiPM)
  - Scintillators modeled
    - EJ-204, EJ-232Q, stilbene
  - Pillar geometry
    - 10 cm and 20 cm lengths
    - 0.5 cm and 1.0 cm side widths

Kyle Weinfurther (NCSU) paper

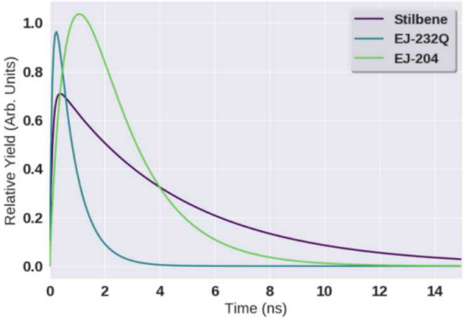




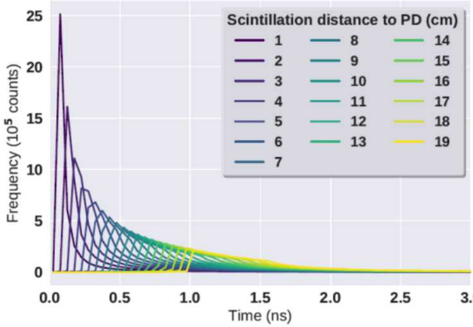
Simulated Responses

Kyle Weinfurther (NCSU) paper

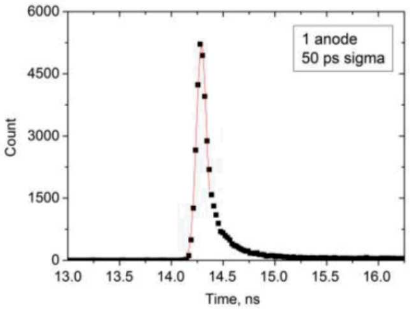
$R_{scint}(t)$



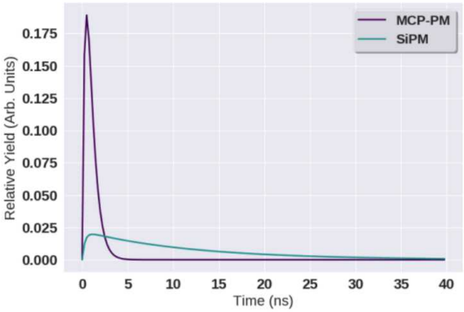
$*$ $R_{pil}(t)$

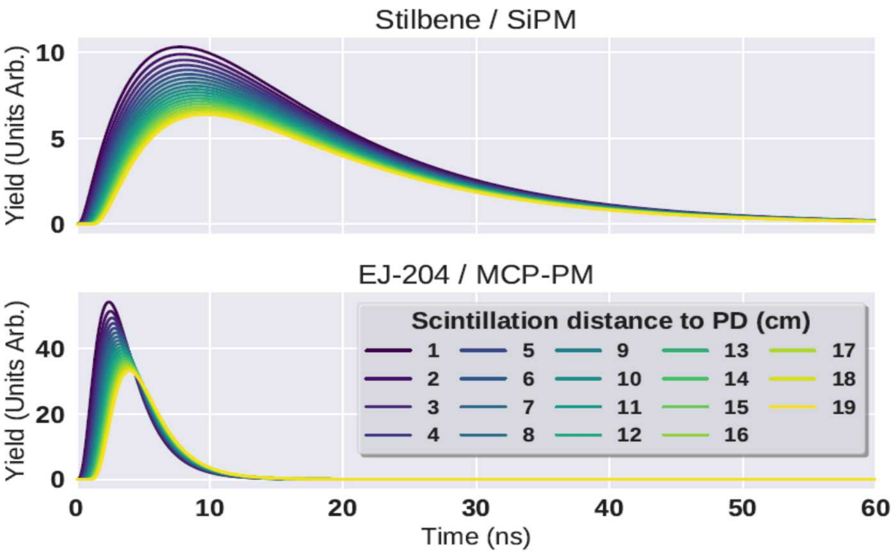


$*$ $R_{TTS}(t)$



$*$ $R_{imp}(t)$



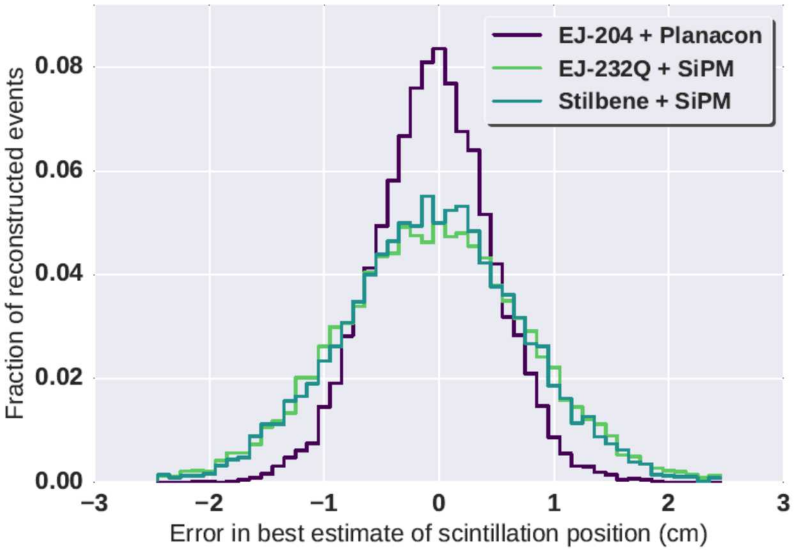


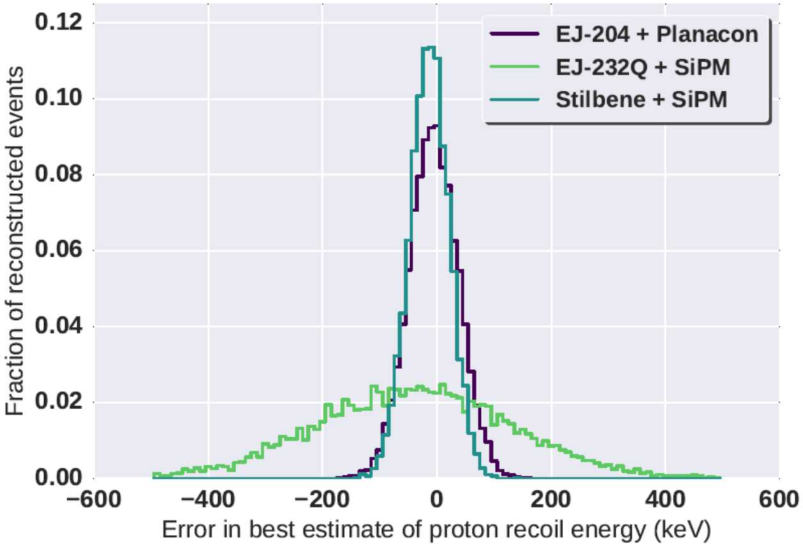
$$\boxed{R_{nom}(t)} = R_{scint}(t) * R_{pil}(t) * R_{TTS}(t) * R_{imp}(t)$$

Estimation of Scintillation Position and Proton Recoil Energy

- Simulated 10,000 events uniformly distributed along pillar
- Computed root mean squared (RMS) error
- 2 MeV proton recoil
  - 1 cm x 1 cm x 20 cm pillar with a 1 mm air gap and ESR lining the housing walls
- Reconstructed position precision
  - Mainly based on speed of scintillation and photodetector impulse response
- Reconstructed proton recoil energy precision
  - Mainly based on photon counting statistics

Combination	Position RMS Error	Energy RMS Error
EJ-204/MCP-PM	0.52 cm	43 keV
Stilbene/SiPM	0.74 cm	35 keV
EJ-232Q/SiPM	0.82 cm	188 keV



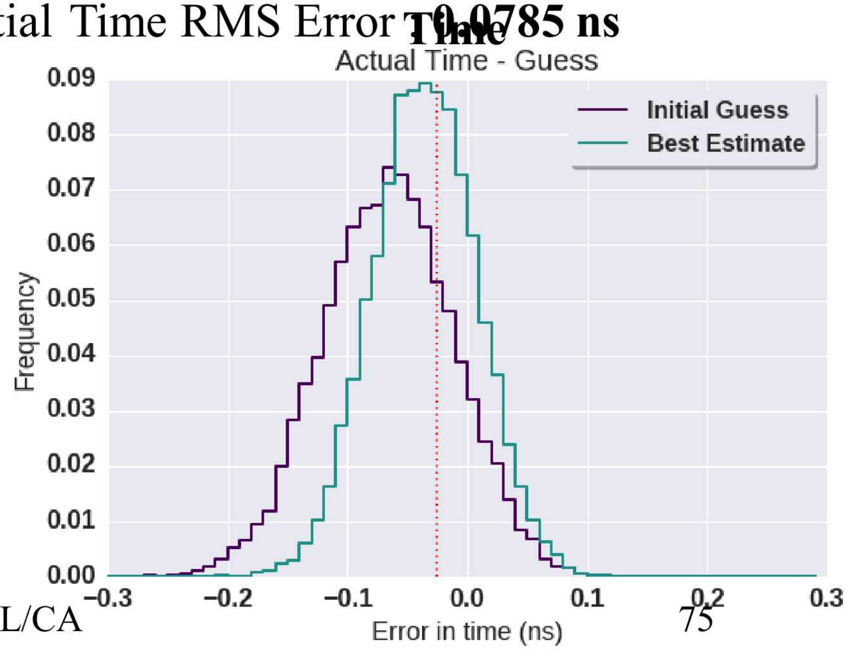


Estimation of Scintillation Time

- Thus far, we have assumed we know the precise start time of scintillation
  - Waveforms started at true scintillation time
  - Results in more precise estimates
- Real world applications will use a lower level discriminator
- Recalculated errors while estimating simulation position and scintillation time simultaneously
- Scintillation time varied randomly between 5 ns and 20 ns
- 2 MeV proton recoil
  - 50 ps RMS error
  - < 0.3 mm increase in position RMS error
- 1 MeV proton recoil
  - 100 ps RMS error
  - 1 mm increase in position RMS error
- Currently, 30 ps bias observed

Results (2 MeV proton recoil):
Position RMS Error w/o fitting time: **0.515 cm**
Position RMS Error fitting time : **0.542 cm**

Best Time RMS Error : **0.0501 ns**
Initial Time RMS Error **0.0785 ns**

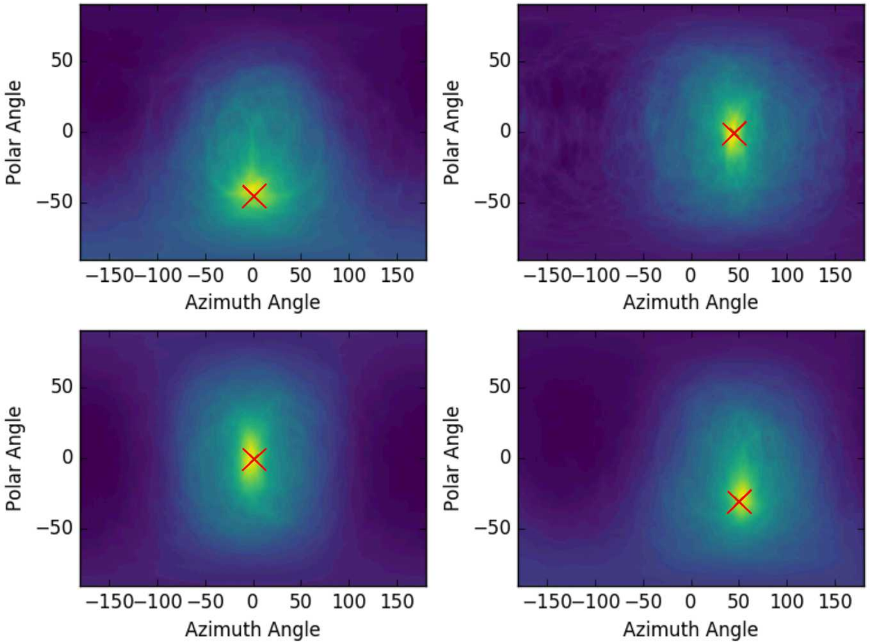


Simulated Source Localization

Kyle Weinfurther (NCSU) paper

- Estimate image resolution using EJ-204/MCP-PM using Monte Carlo
- Simulated Cf-252 neutrons at 1 m distance away from the center of an OS SVSC device (20 cm x 20 cm x 20 cm)
  - Pillar dimensions fixed at 1 cm x 1 cm x 20 cm
  - Source locations (θ, ϕ): ($-45°$, $0°$), ($0°$, $-45°$), ($0°$, $0°$), ($-30°$, $-50°$)
- Uncertainty in parameters produces cone with apparent "thickness"
- Rejected scatters in same pillar
- Threshold of 500 keV
- Not able to discriminate on incorrect pointing vectors

Back-projected images



Sandia National Laboratories

It's always easier in simulation land…

Belkis Cabrera-Palmer (SNL)

Simulation assumptions	**Realistic detector**
perfectly polished optical interfaces and nearly matching indexes of refraction	imperfect optical coupling and rougher surfaces
complete photocathode coverage	e.g., scintillator edges and corners not covered
no background; only neutron emission from ^{252}Cf	real data will have background and gammas

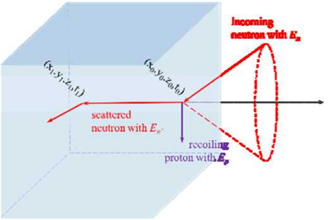
Reconstruction assumptions	**Realistic detector**
each photon positions and time individually resolved	overlapping single photo-electron waveforms
Include the effect of the MCP-PMT finite timing and spatial resolution: • Gaussian smear the photon arrival time with $\sigma_t = 0.1$ ns • Gaussian smear the photon arrival coordinates with $\sigma_X =$.	resolutions not strictly Gaussian and not constant with position; photo-e$^-$ scattering from MCP can occur in ~10% of detections
Constrain N >= 2 (number of neutron scatters depositing > 300 keV) and assume N is known. *But use all emitted photons.*	guess N from photons' arrival time and spatial profile
In minimization algorithm, set initial guess close to the known simulation interaction location, time and number of emitted photons	…as above…

Event Reconstruction: scatters

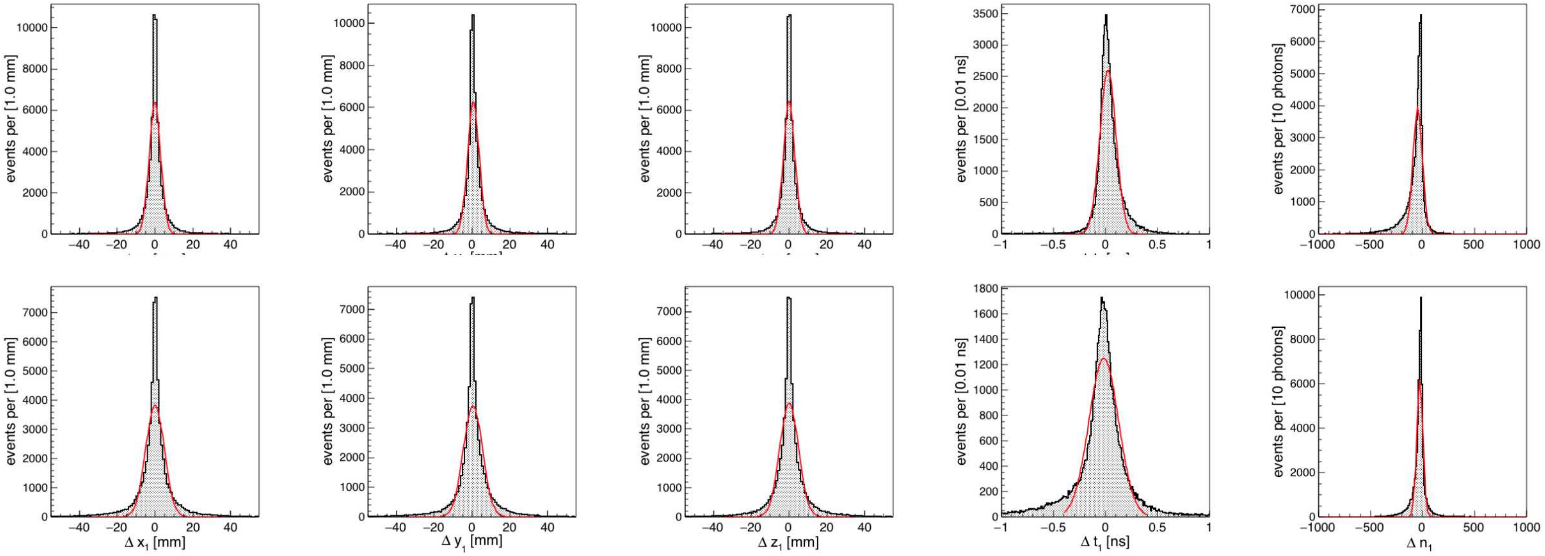
Belkis Cabrera-Palmer (SNL)

To evaluate the Event Reconstruction algorithm: let's plot the histograms of the difference between the reconstructed quantities and their simulation "true" values: $\Delta A = A_{recon} - A_{true}$

Δ-histograms for the **directly reconstructed quantities**: the locations, times and detected number of photons of the first and the second above-threshold proton recoils, $(\Delta x_0, \Delta y_0, \Delta z_0, \Delta t_0, \Delta n_0)$ and $(\Delta x_1, \Delta y_1, \Delta z_1, \Delta t_1, \Delta n_1)$



	σ
Δx_0	3.02 mm
Δy_0	3.05 mm
Δz_0	3.02 mm
Δt_0	0.08 ns
Δn_0	45 photons



	σ
Δx_1	4.94 mm
Δy_1	5.08 mm
Δz_1	4.95 mm
Δt_1	0.14 ns
Δn_1	30 photons

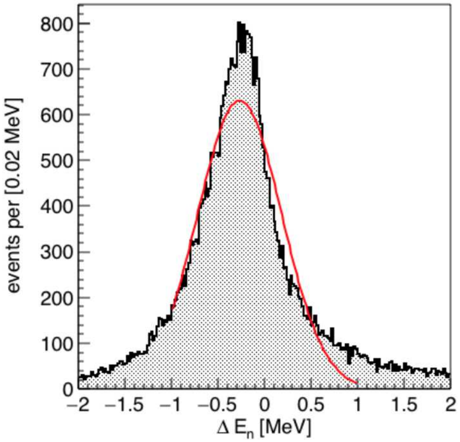
The reconstruction of the second interaction is generally less accurate.

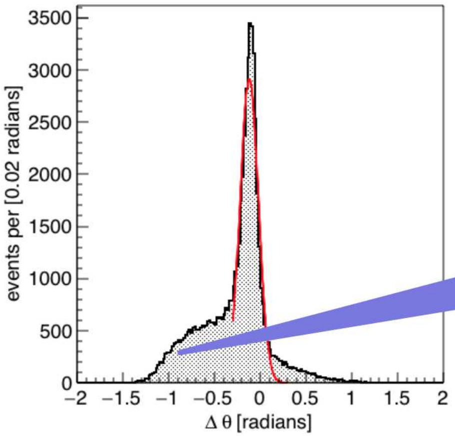
Event Reconstruction: high-level

Belkis Cabrera-Palmer (SNL)

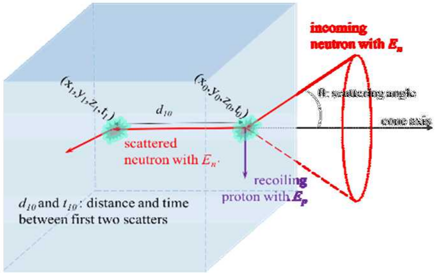
Δ-histograms of **source quantities**:
incident neutron energy E_n,
scattering cone angle θ

	σ
ΔE_n	0.45 MeV
$\Delta\theta$	0.1 rad



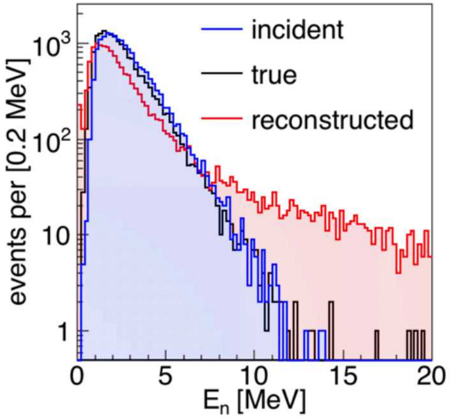


Hump for negative $\Delta\theta$, representing reconstructed scattering angles smaller than the simulated angles



Spectrum and Image reconstruction

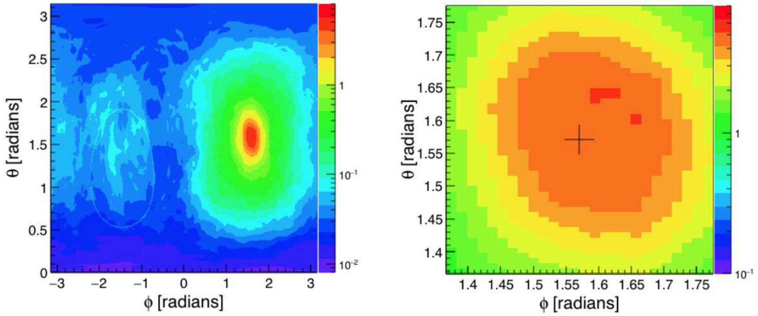
Belkis Cabrera-Palmer (SNL)



The energy spectrum obtained using the reconstructed interactions smears out around the maximum producing a tail at larger energies: the SVSC response is dominated by the uncertainties in time, distance and number of photons introduced by the reconstruction algorithm and the measurement process.

For a simulated 2.7 uCi Cf252 neutron source located at 1 meter, this image is equivalent to 29 minutes of measurement time, without background.

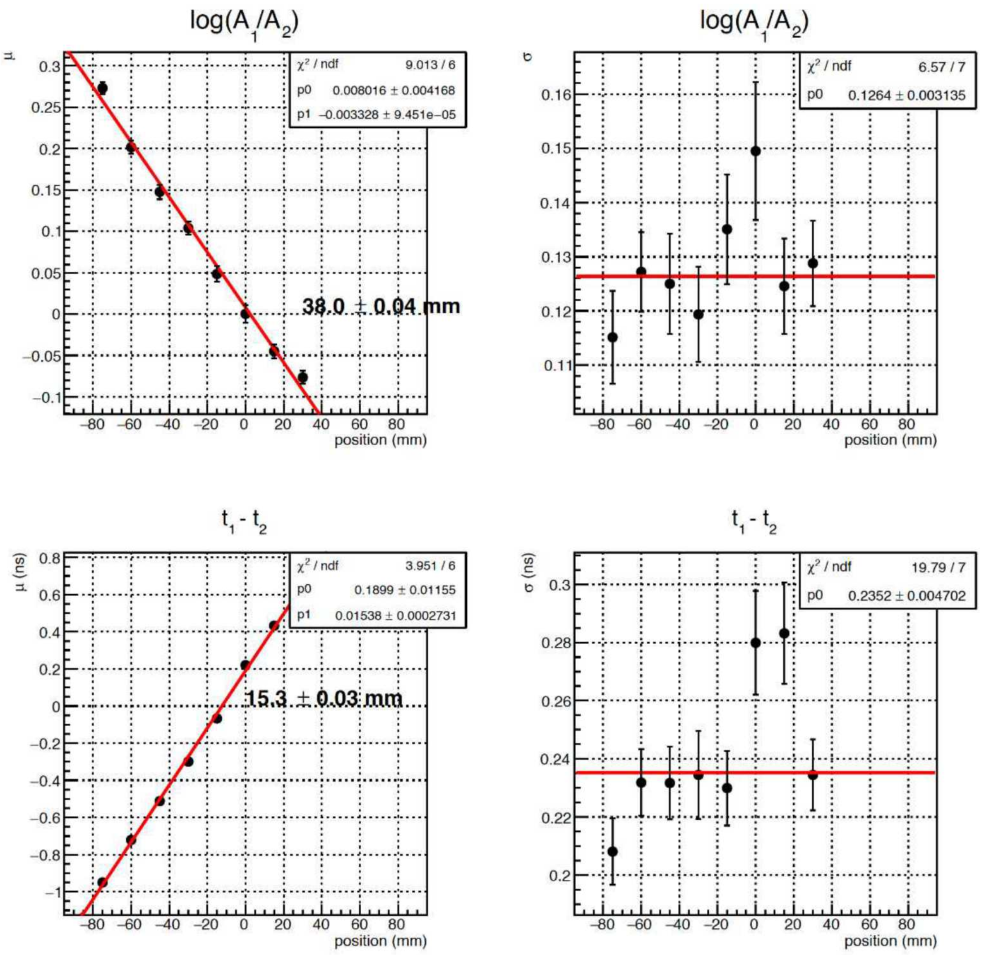
<u>Image generated with list-mode MLEM</u>: response map constructed on the flight by back-projecting the cone of each coincident event and assigning a 2D probability distribution (in terms of source θ and ϕ) around the cone projection according to the variances of θ and Δα.



Results

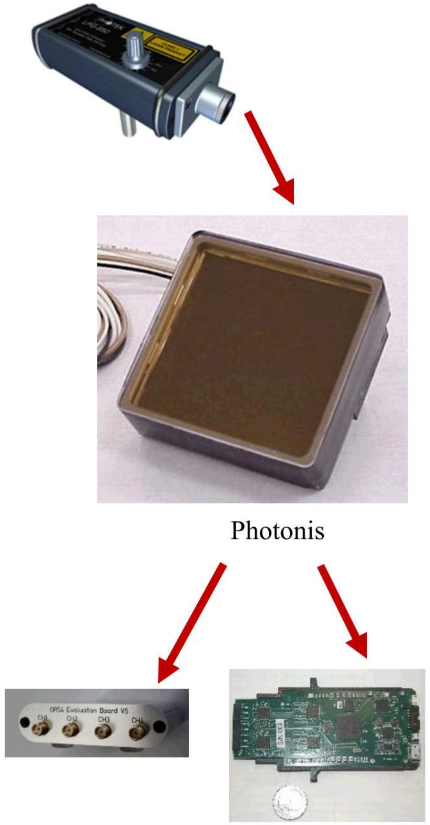
Example Results – EJ200 bare

Melinda Sweany (SNL)

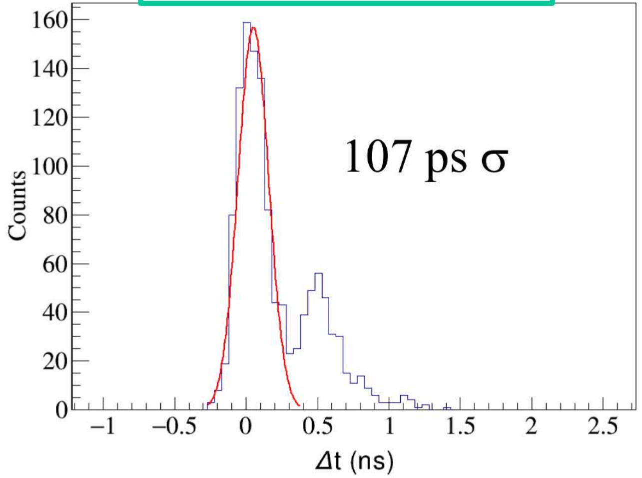


Planacon

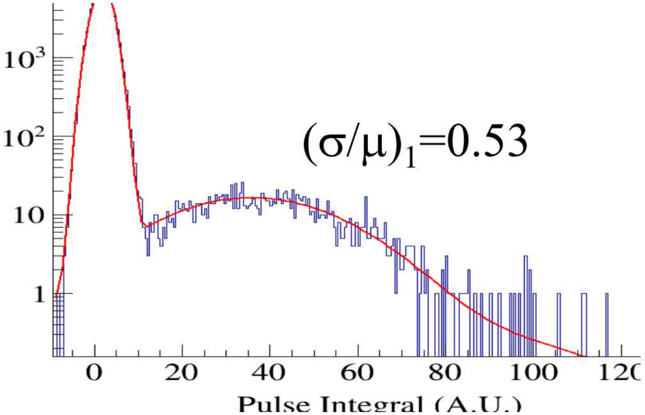
J. Brown (SNL)



+ DRS4 eval board

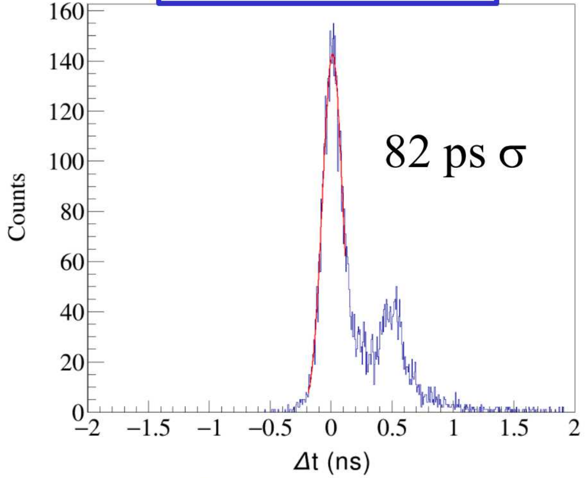


107 ps σ

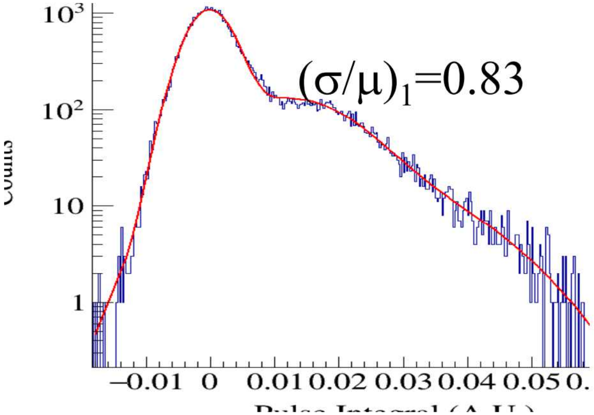


$(\sigma/\mu)_1$=0.53

+ SLAcq board



82 ps σ

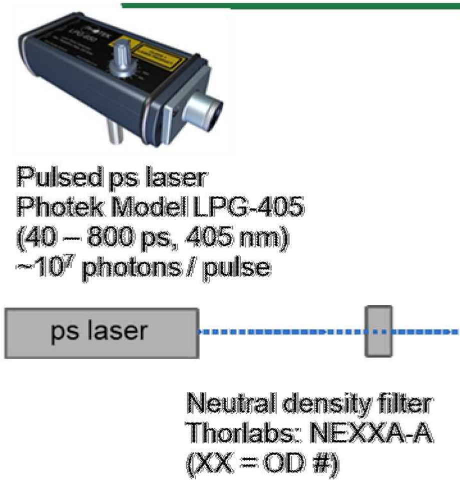


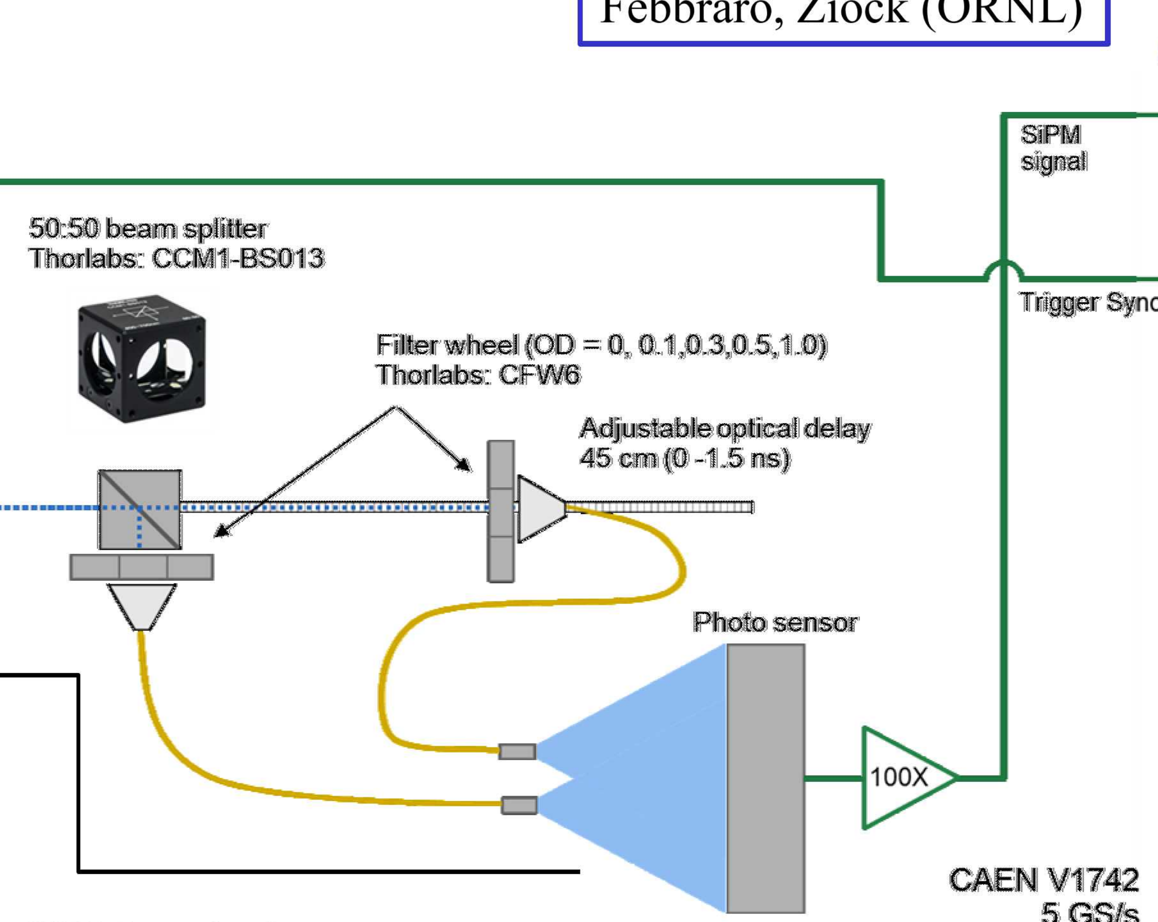
$(\sigma/\mu)_1$=0.83

Good timing performance;
Significant S:N degradation

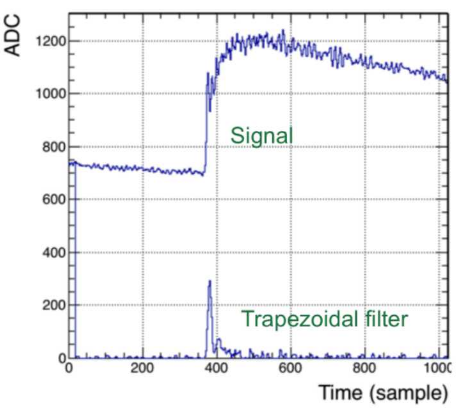
Experimental setup 2

Febbraro, Ziock (ORNL)





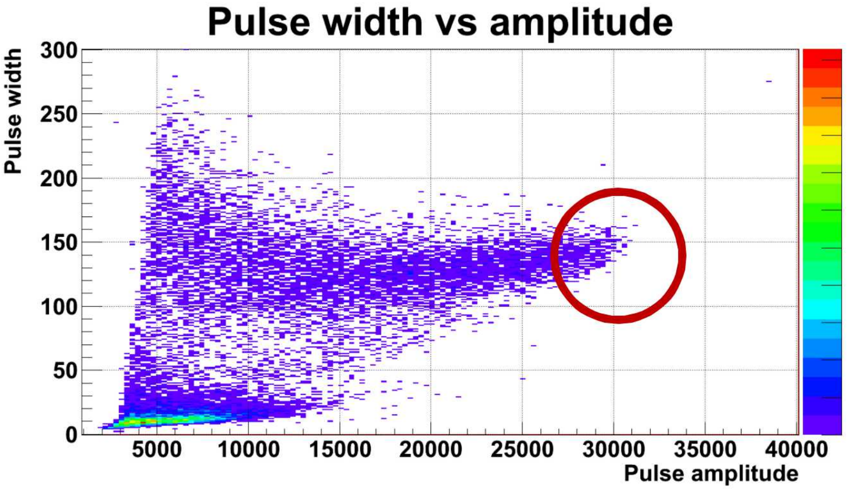
CAEN V1742
5 GS/s
12-bit

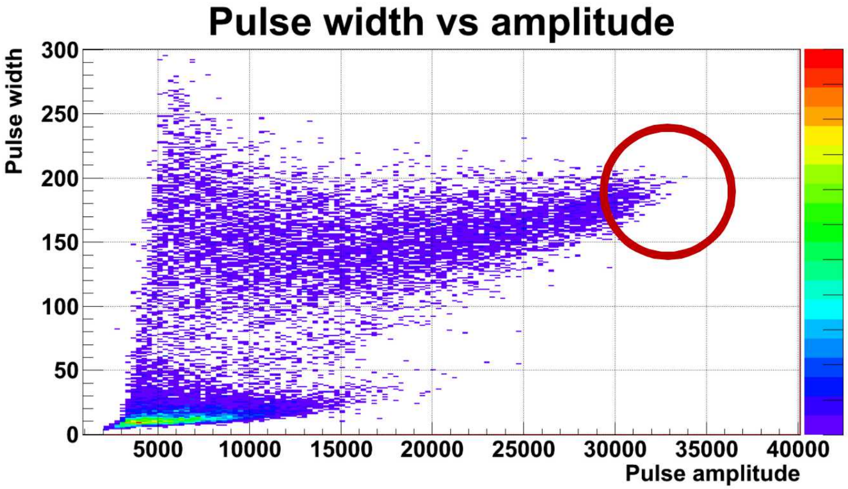


SiPM analysis:

- 100x amplifier necessary for S:N
- Trapezoidal filter → amplitude & timing

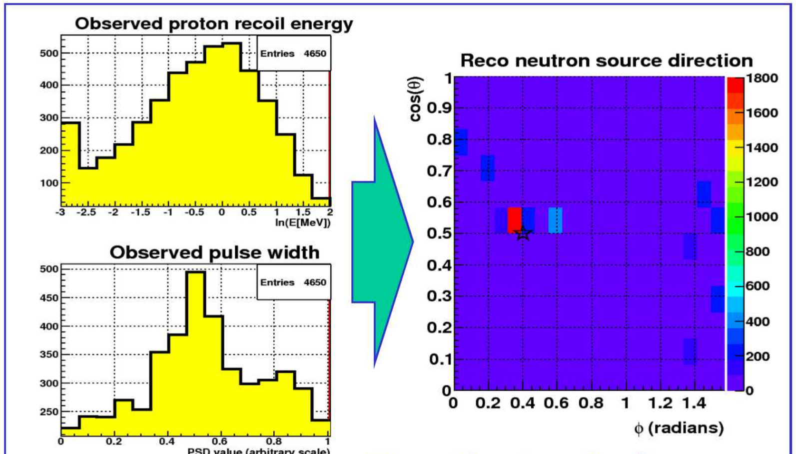
Imaging via anisotropies





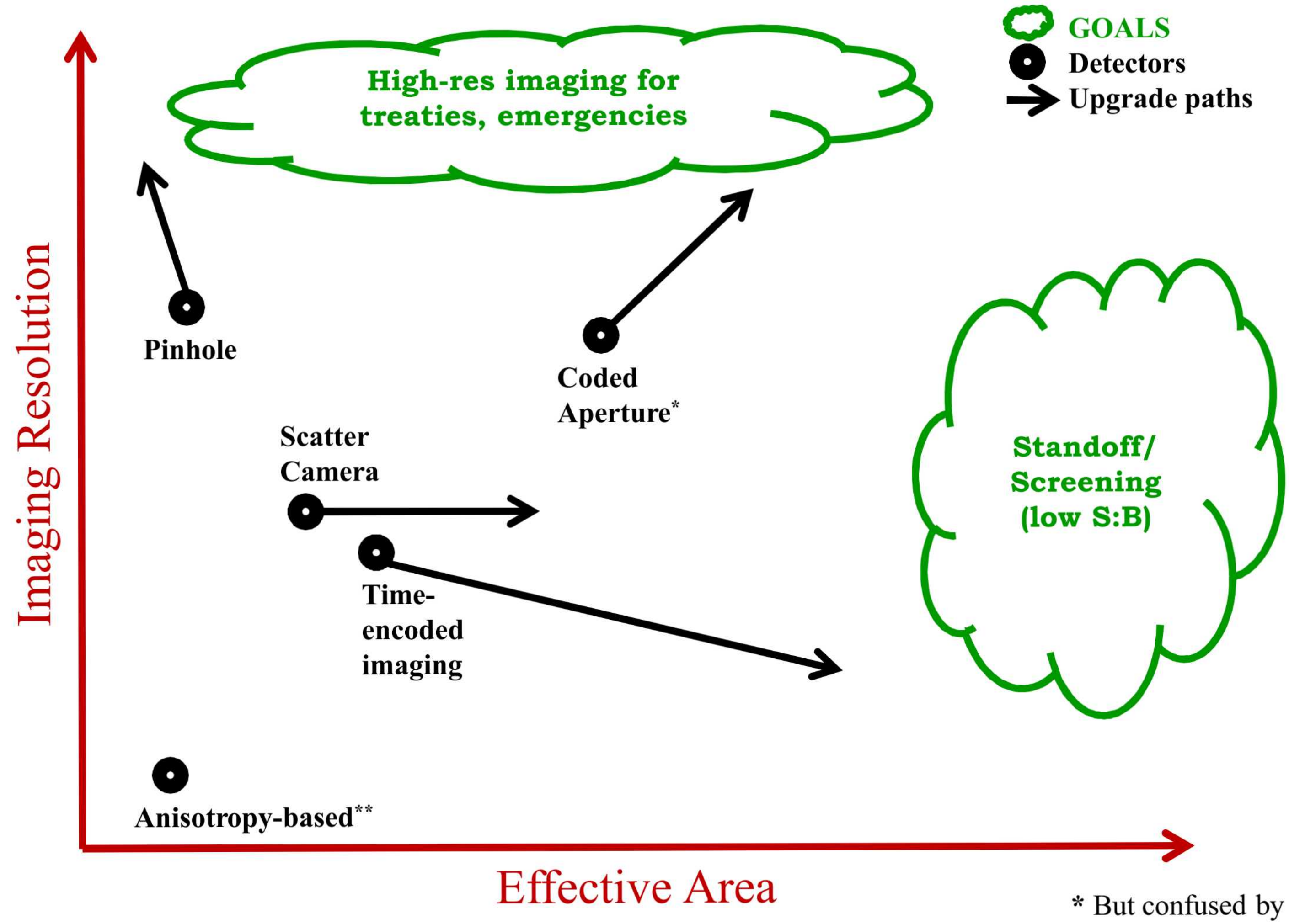
- DPA crystal
- 14 MeV neutron generator
- Crystal was rotated by 90°
- Neutron pulse height and width increased!

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



Toy Monte Carlo Simulation

The neutron detector zoo



🟩 **GOALS**
● **Detectors**
→ **Upgrade paths**

High-res imaging for treaties, emergencies

Standoff/ Screening (low S:B)

Pinhole

Coded Aperture*

Scatter Camera

Time-encoded imaging

Anisotropy-based**

Imaging Resolution

Effective Area

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