SAND2019-7244PE

Single-Volume Neutron Scatter Camera Development Independent Review Project Overview

Erik Brubaker

Sandia National Laboratories

June 25, 2019

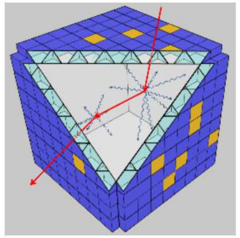
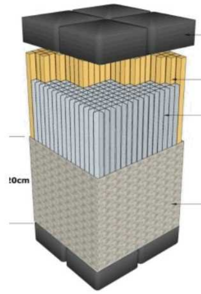
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

What are we trying to do?

- **Why neutron emission imaging?**
  - **1) Improves detection of weak SNM sources, enables localization.**
  - **2) Characterizes the spatial distribution of plutonium or other neutron emitters.**
- **A compact imager is easy to transport and deploy, has high efficiency, and can be placed near an item to increase sensitivity & spatial resolution.**
- **For passive neutron imaging to be useful for nuclear security, we need to improve on existing systems by making them smaller *and* more efficient.**
  - **Size goal: ~2 m^3 (NSC) → ~0.2 m^3 (MINER) → ~0.05 m^3 (SVSC)**
  - **Efficiency goal: Order of magnitude improvement over NSC/MINER**
- **How? Detect and resolve 2+ neutron scatters in a single active region.**
  - **Monolithic approach: Detect each individual photon propagating isotropically.**
  - **Optically segmented approach: Guide light to ends of bars.**
- **Outcomes/deliverables: Prototypes, performance studies; Improved photodetectors, electronics, scintillators; Papers, theses, human capital**





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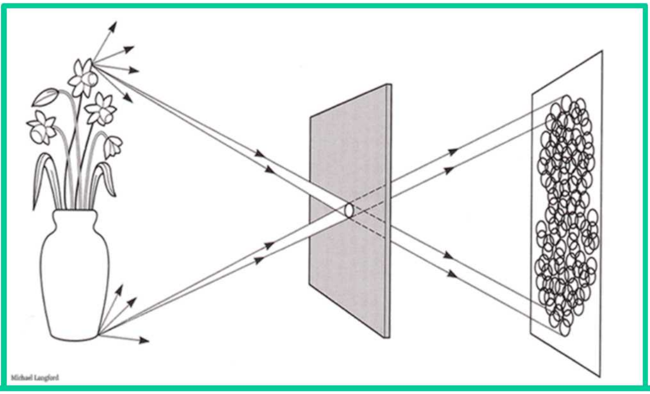
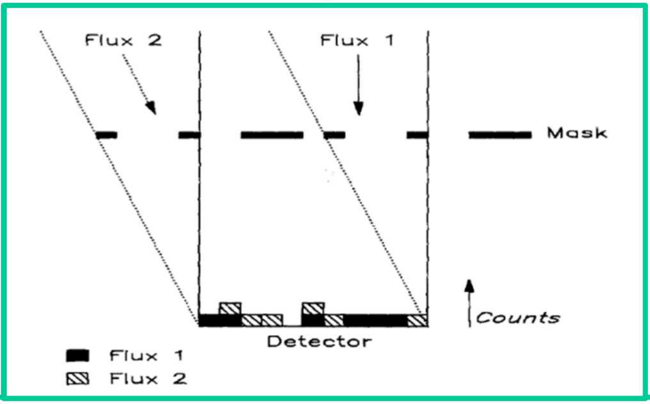
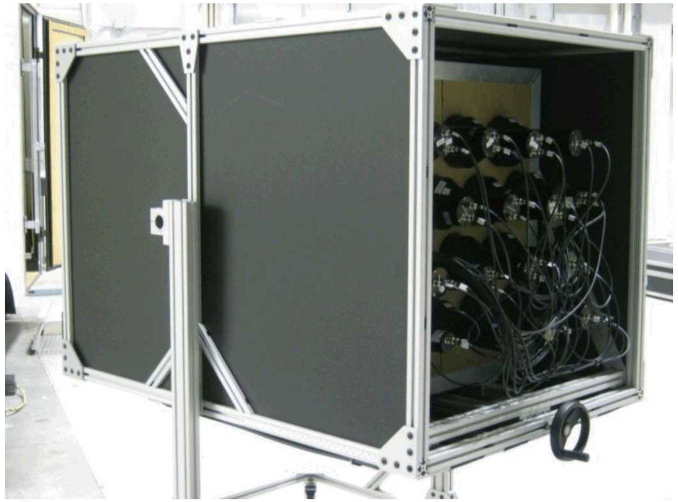
How is n emission imaging done today?

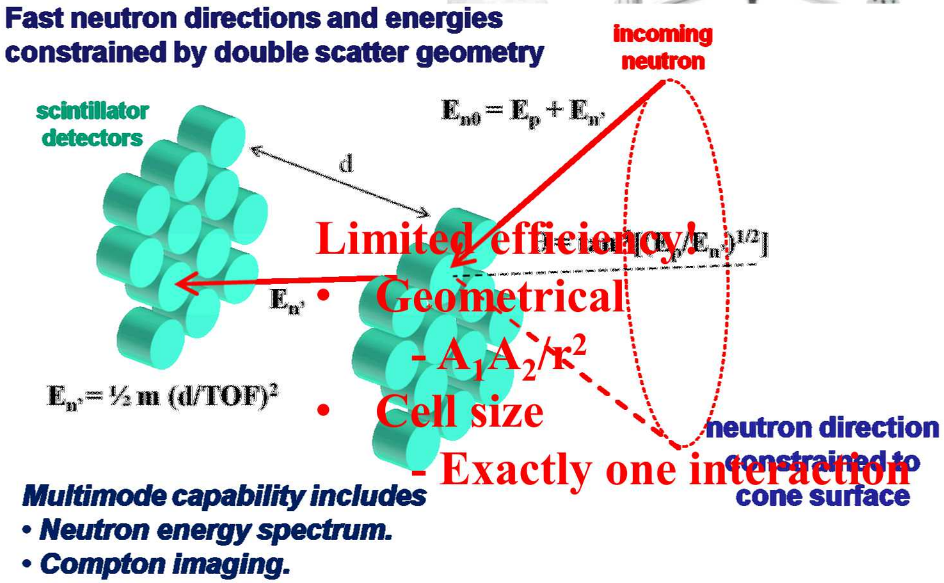


Pinhole: High Resolution, Low Throughput



Coded aperture: High Resolution, High Throughput





Limited efficiency!

- Geometrical
  - A_1A_2/r^2
- Cell size
  - Exactly one interaction

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What is our new approach?

- Cell-based → single volume
- Two configurations:
  - Monolithic scintillator
  - Optically segmented scintillator
- Both rely on excellent time resolution:
  - Distinguish interactions 2 ns & 3 cm apart
  - Determine TOF to ~10% → 200 ps
  - Contributes to position resolution: c/n=20 cm/ns → 3 mm ~ 15 ps
  - Discriminate n/γ?

Prototyping

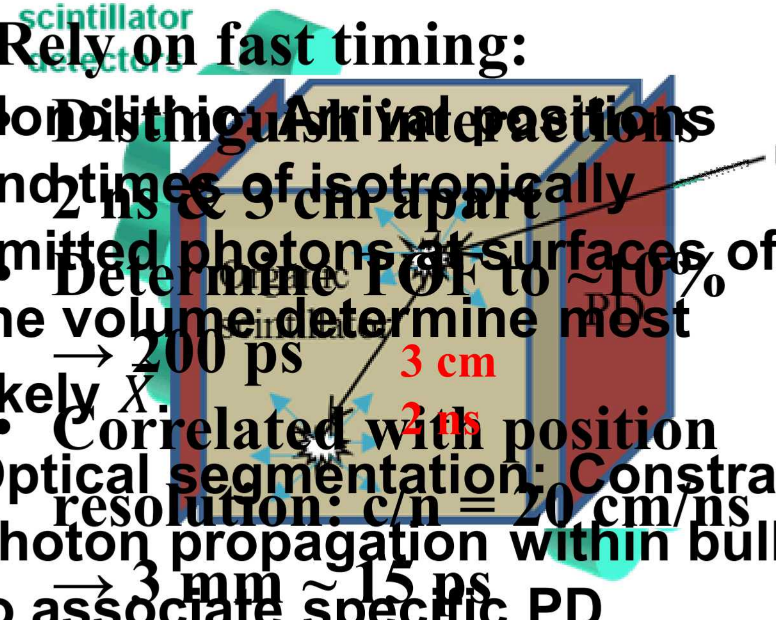
Monolithic | Opt. Segmented

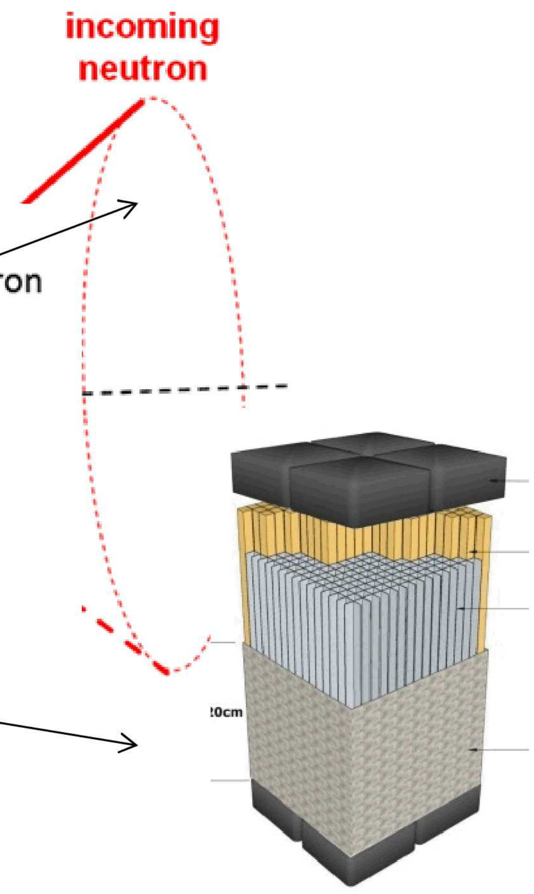
Concept requires a method of determining *two* (or more) event locations within a bulk scintillator to sub-cm precision. $\vec{X} = (x, y, z, t)$

Rely on fast timing:

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

- 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
- Discriminate n/γ?

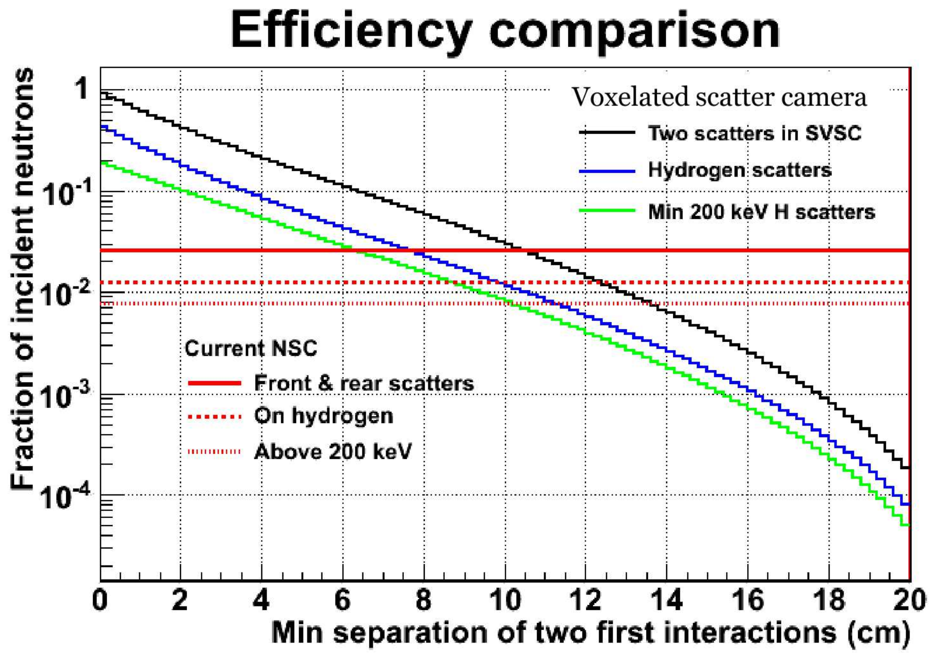




Who cares? What difference will it make?

Compact high-efficiency neutron imager:

- **High efficiency reduces measurement time to acquire given information.**
- **Compact form factor allows easy transport, deployment in tight spaces, close approach to threat sources.**
- **Application spaces:**
  - **SNM search/standoff detection**
  - **Cargo screening**
  - **Arms control**
  - **Emergency response**



Technology development:

- **Fast pixelated photodetector/readout enables other improved systems: coded aperture, transmission neutron imaging, etc.**
- **Advances in scintillators & characterization methods, photodetectors, electronics feed other fields: medical imaging, basic science (neutrinos!), etc.**

If successful:

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

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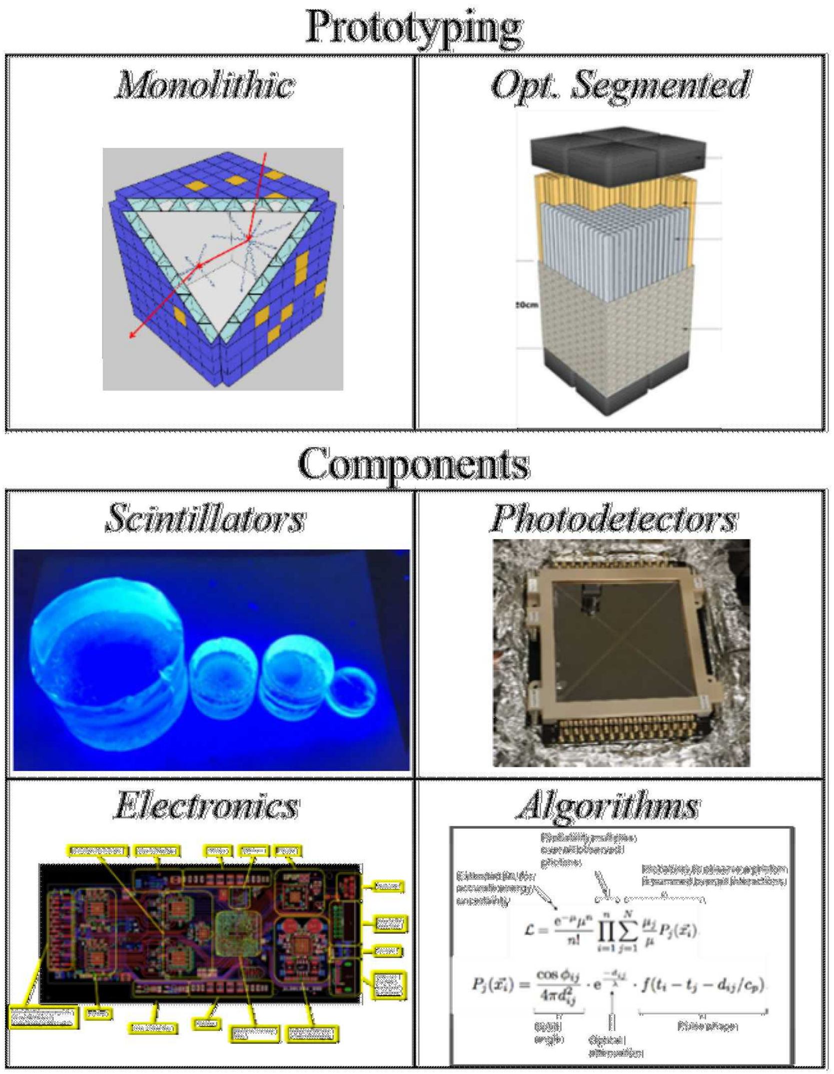
Project organization

Project team

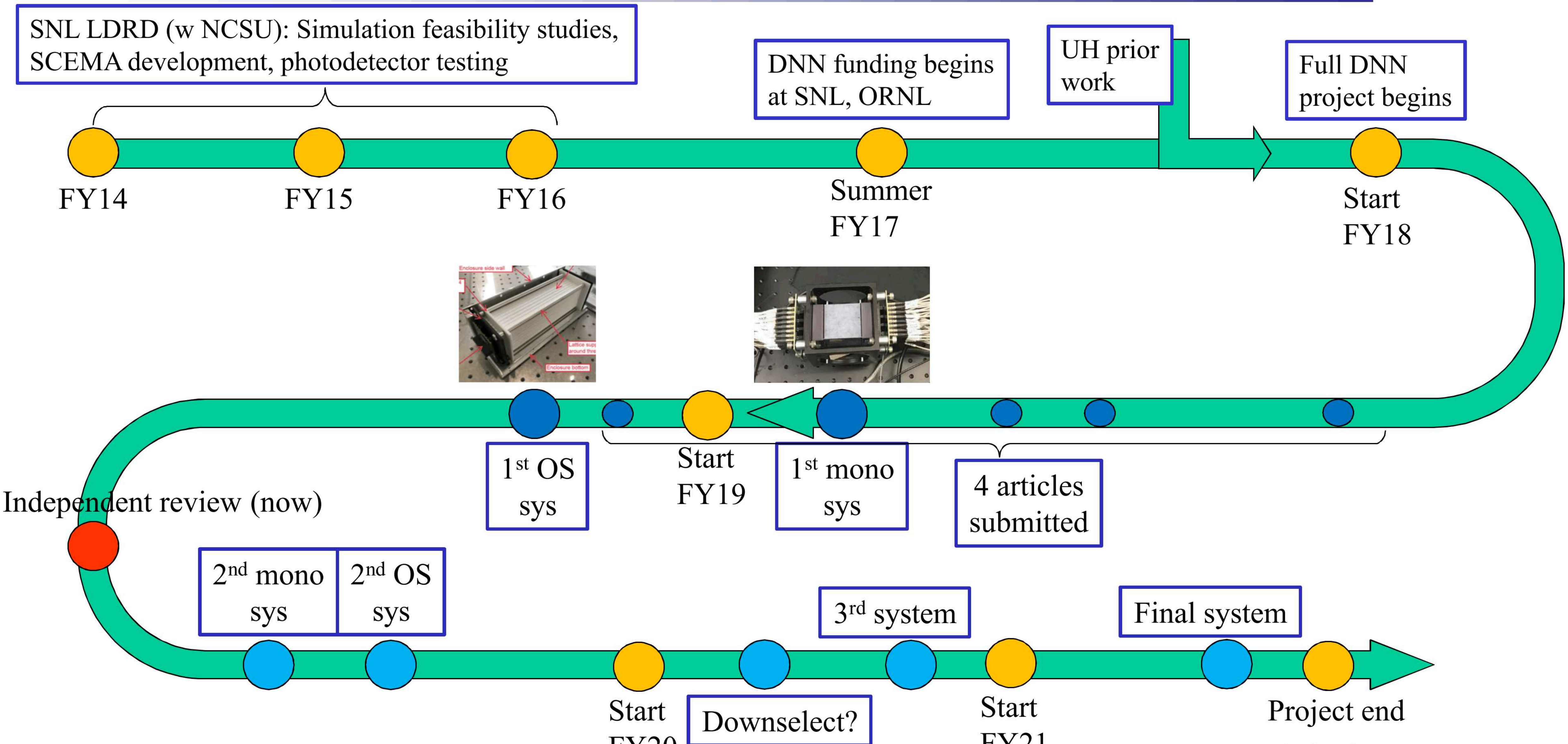
- Project title: "**Single-Volume Scatter Camera Development**"
- Participants: Six institutions
  - **SNL/CA (lead)**: E. Brubaker, M. Sweany, J. Brown, J. Steele, B. Cabrera-Palmer, et al.
  - **ORNL**: P. Hausladen, K. Ziock, M. Febbraro, M. Folsom, J. Nattress, et al.
  - **ANL**: J. Elam, A. Mane, M. Gebhard, A. Letorneau
  - **U Hawaii**: K. Nishimura, J. Learned, A. Druetzler, A. Galindo Tellez, R. Dorrill, K. Keefe, N. Kaneshige, et al.
  - **UC Berkeley/LBNL**: B. Goldblum, T. Laplace, J. Manfredi, et al.
  - **NCSU**: J. Mattingly, K. Weinfurther, M. Mishra, A. Moustafa

Project structure

- ~50% effort: system-level rapid development
  - Goal is 1 prototype/yr of monolithic, OS
  - Build best system we can *at the time*
  - Learn from integrating the system—lessons expected and unexpected
    - Focus efforts on what matters for overall system
    - Inform next prototype
  - If appropriate, downselect and focus efforts after next round of prototypes
- ~50% effort: component work
  - Characterization: Inputs to prototypes
  - Development: Advances that could apply in 1-3 yrs
    - Roll into prototypes when demonstrated
  - Can have value beyond SVSC
- This is a well-resourced project



Timeline

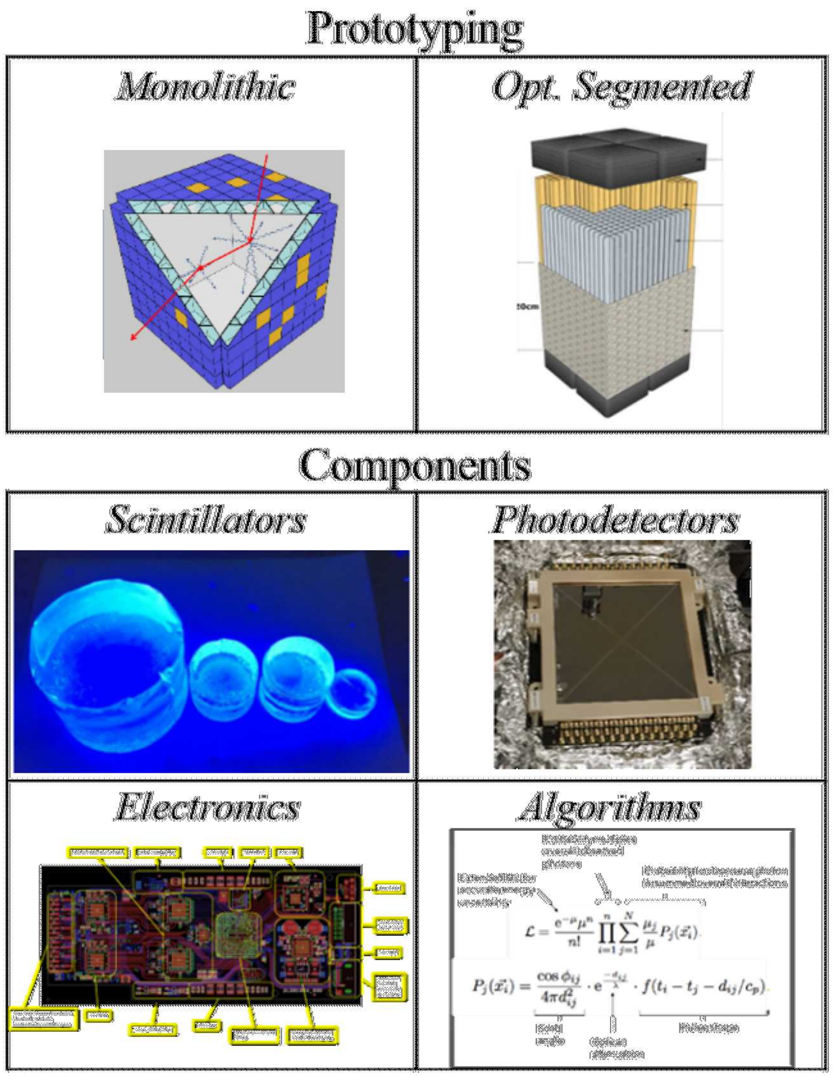

SNL LDRD (w NCSU): Simulation feasibility studies, SCEMA development, photodetector testing
DNN funding begins at SNL, ORNL
UH prior work
Full DNN project begins
FY14
FY15
FY16
Summer FY17
Start FY18
1st OS sys
Start FY19
1st mono sys
4 articles submitted
Independent review (now)
2nd mono sys
2nd OS sys
3rd system
Final system
Start FY20
Downselect?
Start FY21
Project end

Project efforts

▢ = Separate presentation today

Monolithic prototype development (SNL, ORNL)

OS prototype development (SNL, UH, UCB, NCSU)



Fast/bright scintillator (SNL)

GRIN scintillator (ORNL)

Tranloc eval (SNL, UH)

Scintillator properties (UCB, SNL)

SCEMA electronics (SNL)

Freq. domain multiplexing (NCSU)

ALD for MCPs (ANL)

LAPPD eval (SNL, UH)

Optical coded aperture (ORNL)

Code development (all)

SNR study (ORNL)

Why neutron imaging?

Why neutron imaging?

Neutrons are a sensitive and specific signature of special nuclear material (SNM)

Standoff detection

Cargo screening

SNM detection/localization

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

Arms control treaty verification

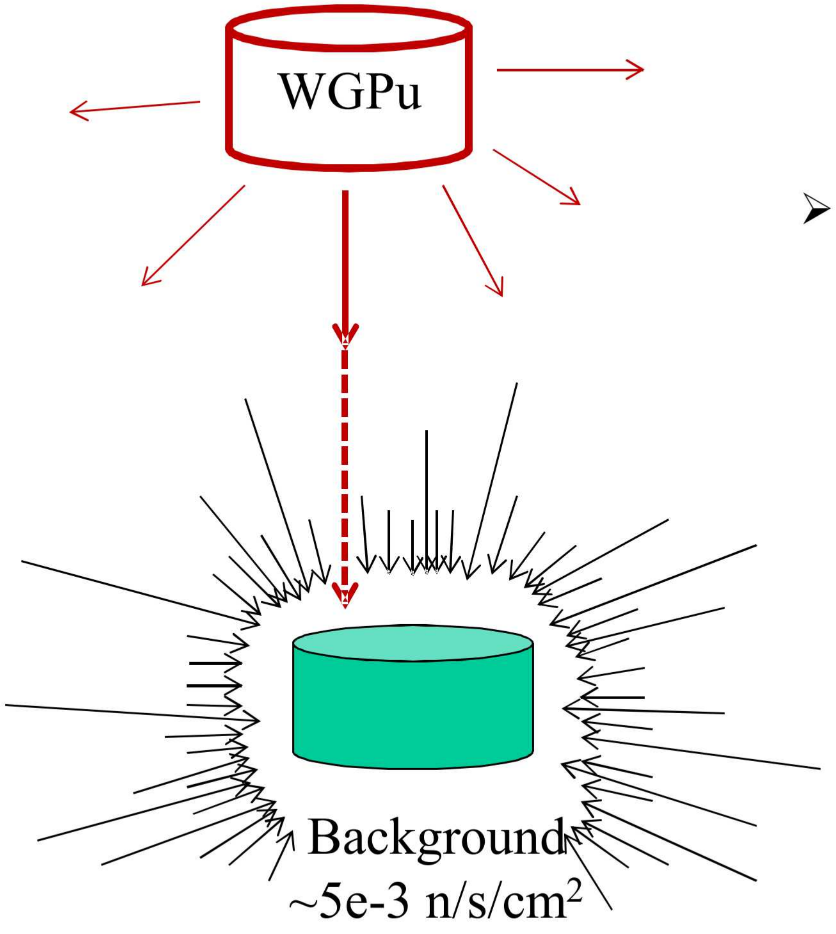
Emergency response

SNM imaging

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

Standoff detection

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



Case: background unknown

- **Example: Large stand-off application (100 m)**
  - **8 kg WGPu = ~4.4e5 n/s →**
    4.4e5 *exp(-R/100)/4πR² ≈1.3 n/s/m² ($4.4e5 \cdot \exp(-R/100)/4\pi R^2 \approx 1.3$ n/s/m^2)
  - **Background = ~50 n/s/m² (at sea level)**
  - **100% efficient, 1 m² detector →**
    5σ detection in ~13 minutes
  - **10% efficient, 1 m² detector →**
    5σ detection in ~2 hours
  - **10% efficient, 1 m² detector,**
    ***3% bg rate systematic* →**
    5σ detection in never

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

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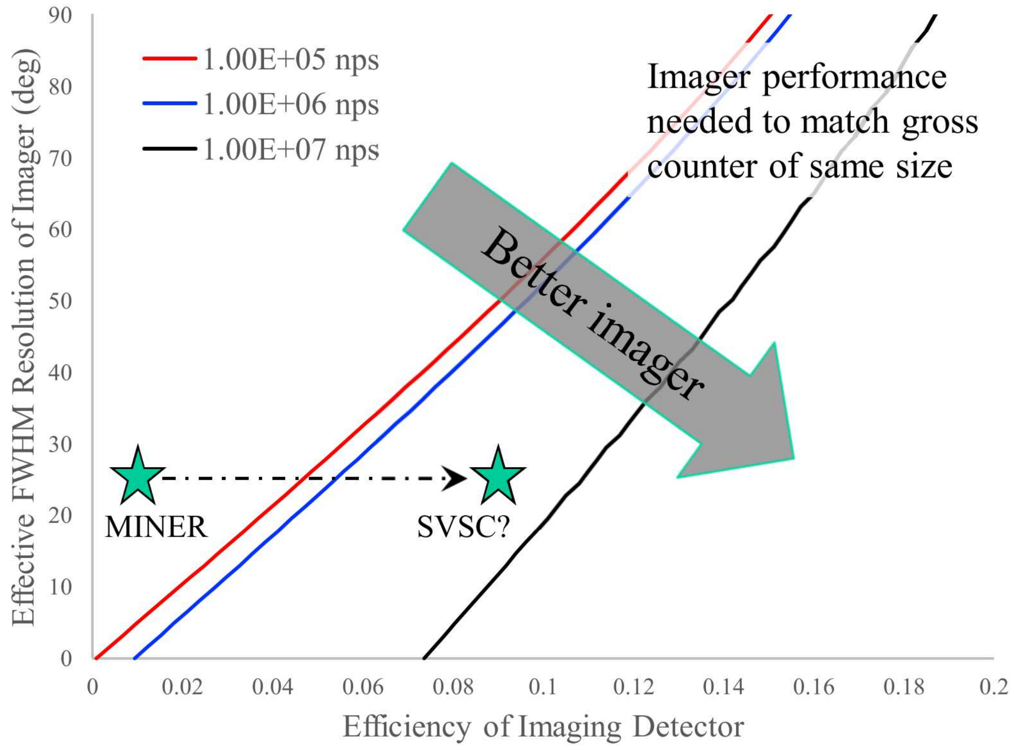
Case: background known

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?**
  - **In principle, yes, because background is reduced by directional info.**
  - **But real imagers have complex directional info (angular resolution).**
  - **Also generally take a hit on efficiency.**

- Study by Paul H (ORNL)
- Equal area detectors, background known
- Specific plot below uses one particular set of assumptions (bg rate, exposure time, etc.)
- *Punchline: Difficult to achieve performance to beat gross counter.*



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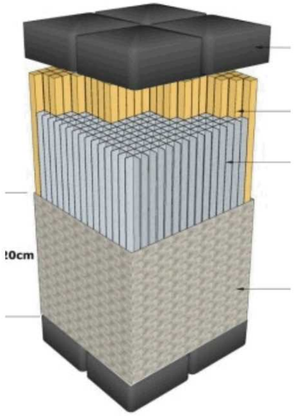
Why (neutron) imaging?

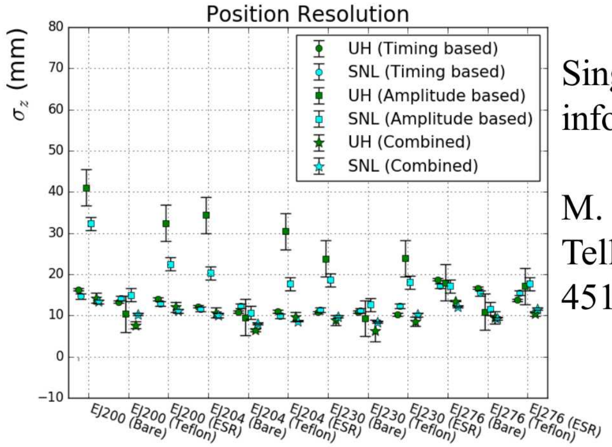
- **Summary: need imaging?**
  - **Imaging applications: Yes**
    - **Emergency response diagnostics, Arms control treaty verification**
  - **Localization: Yes**
    - **Direction to detected source**
  - **Detection, *background unknown*: Probably**
    - **Long-dwell standoff detection**
  - **Detection, *background known*: Need very high quality imager**
    - **Portal monitor, building monitoring**

Progress to date

Optically segmented prototype development

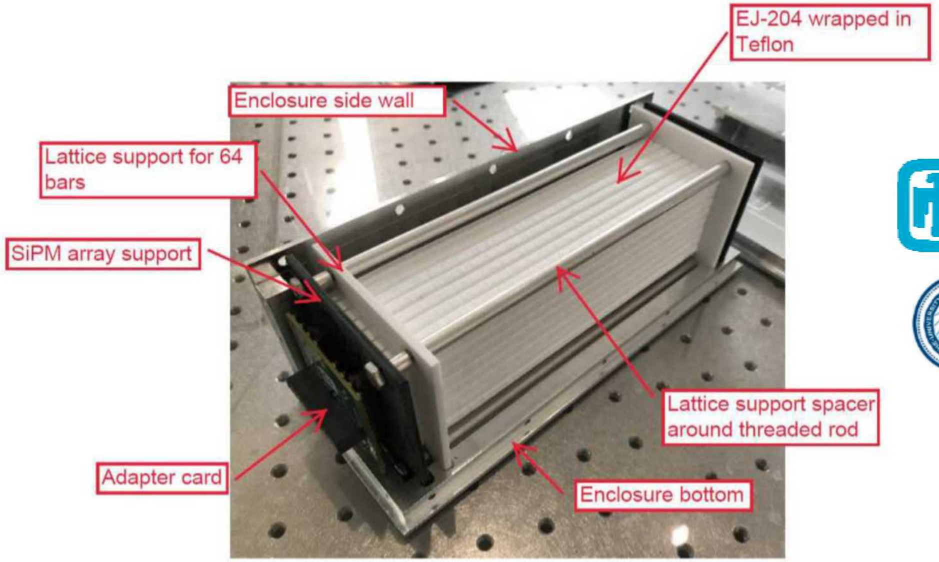
- First prototype constructed at U of Hawaii:
  - 64x 5 mm x 5 mm x 20 cm EJ-204
  - 2x SensL J-series 6 mm SiPM arrays
  - UH IRS3D-based digitization
- Currently performing calibrations, testing for crosstalk (optical & electronic)
- Simulation studies generating comparison points for data; investigating particle ID via TOF in absence of PSD
- **See next talk**





Single-bar testing results informed prototype:

M. Sweany, A. Galindo-Tellez, et al., NIM A927, 451-462 (2019)



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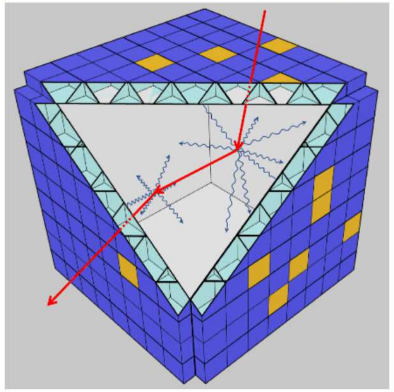
Monolithic prototype development

- First prototype constructed at ORNL:
  - 5 cm x 5 cm x 5 cm EJ-204
  - 2x H12700 multi-anode PMTs
  - DRS4-based Caen V1742 digitizers
- Observed unexpected crosstalk in H12700 PMTs
- Likelihood reconstruction method updated for variable pixel size, variable QE, and non-hermetic photodetector coverage
- **See third talk**



Probability multiples over all observed photons

Extended ML for accurate energy uncertainty

Probability to observe a photon is summed over all interactions

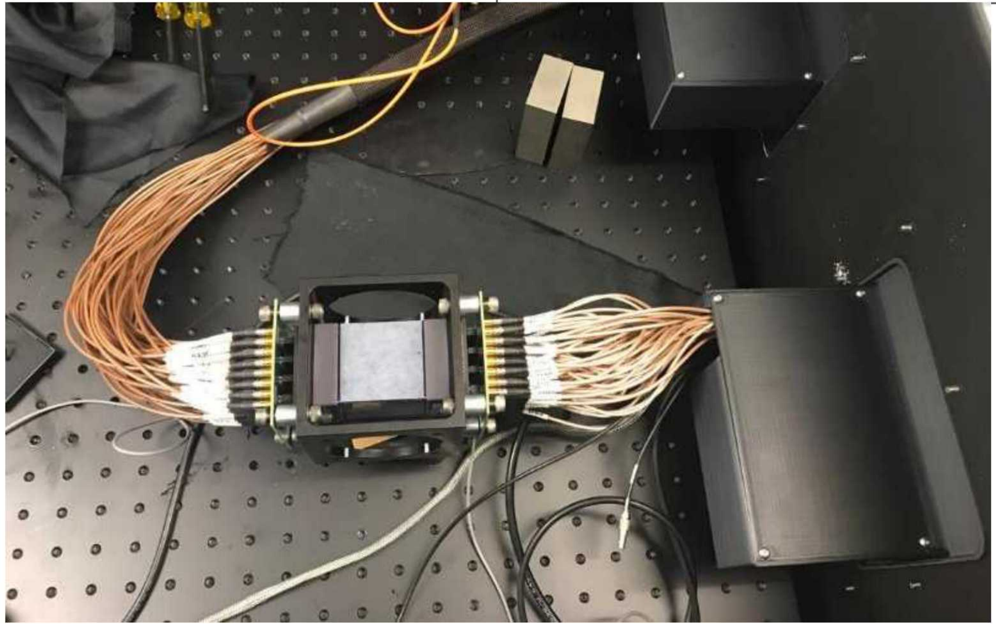
$$\mathcal{L} = \frac{e^{-\mu}\mu^{n}}{n!}\prod_{i=1}^{n}\sum_{j=1}^{N}\frac{\mu_j}{\mu}P_j(\vec{x}_i)$$

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

Solid angle

Optical attenuation

Pulse shape



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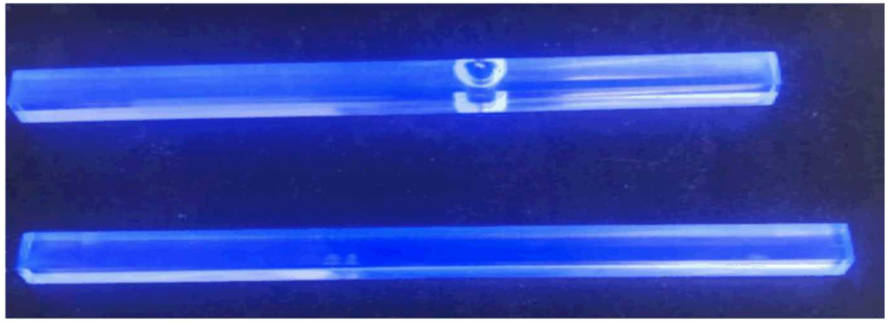
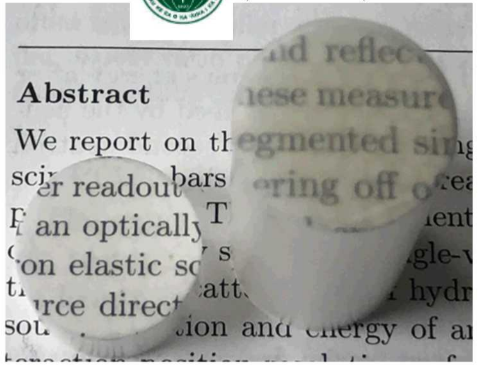
Materials development/evaluation

- **Organic glass (Feng, Carlson)**
  - **SNL formulations being considered for OS detector**
- **Gradient Refractive Index (GRIN) scintillator (Febbraro)**
  - **GRIN polymers used in other applications. Can we make GRIN scintillator?**
  - **Provides natural guiding and improved time resolution (equalizes photon path lengths)**
  - **Need to polymerize in centrifuge**
- **Tranloc**
  - **Concept based on transverse Anderson localization. Scintillating Tranloc under development at Paradigm/Incom.**



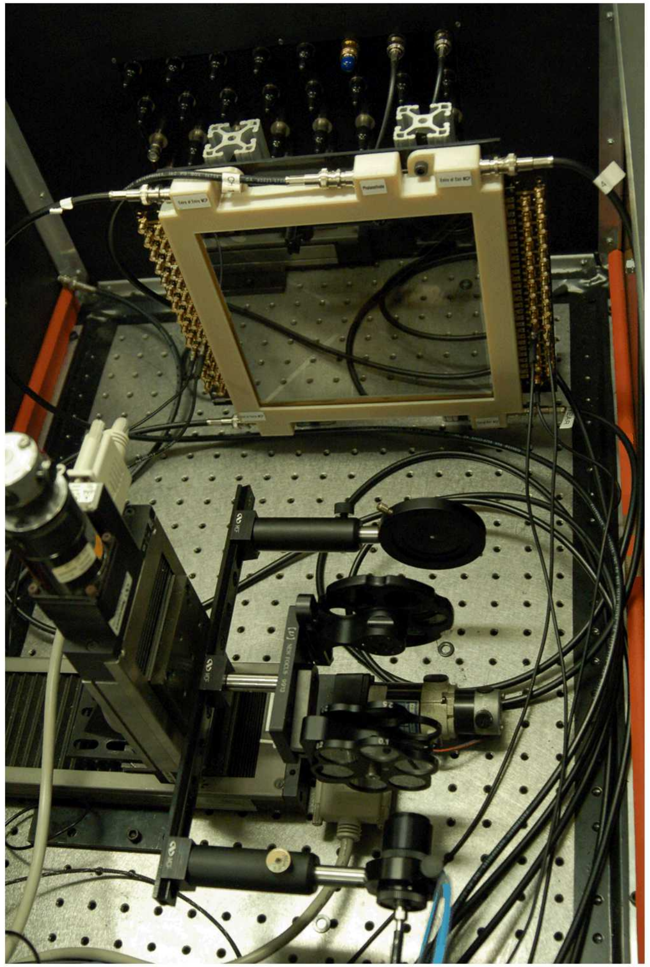
(Keefe)



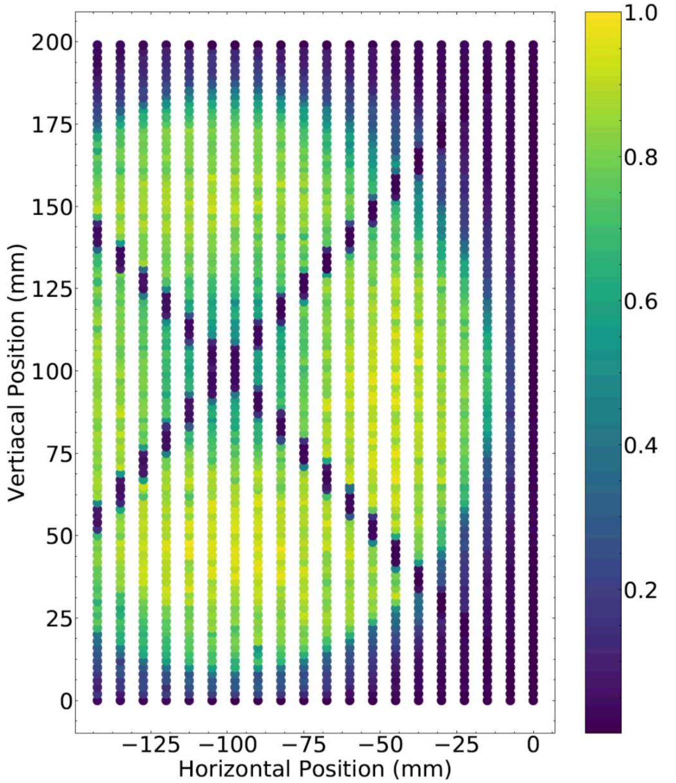
LAPPD characterization

Josh Brown (SNL), Ben Land (UCB/LBNL)

- Large Area Picosecond Photodetector (LAPPD) is a 20 cm x 20 cm MCP-PMT with sub-100 ps single-photon time resolution, few mm spatial resolution
- Second commercial unit acquired by this project for characterization
- Characterized single-photon efficiency variations, gain, gain width, timing resolution, position resolution
- Current version has strip anodes, future versions may have capacitively coupled pixelated anodes



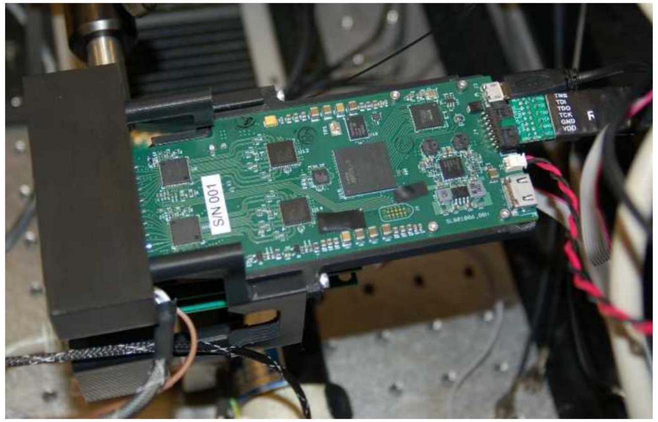
Sample result: relative single-photon detection efficiency vs position



Electronics development -> mono, OS

- Need high performance, high channel count, compact electronics
- Sandia Compact Electronics for Modular Acquisition (SCEMA)
  - 16+2 channels
  - 5 GS/s (DRS4)
  - 14 cm x 6 cm
  - Revision in progress
- UH SCROD
  - Full stack, 128 channels
  - 2.7 GS/s (IRS3D)
  - Self-triggering

SCEMA



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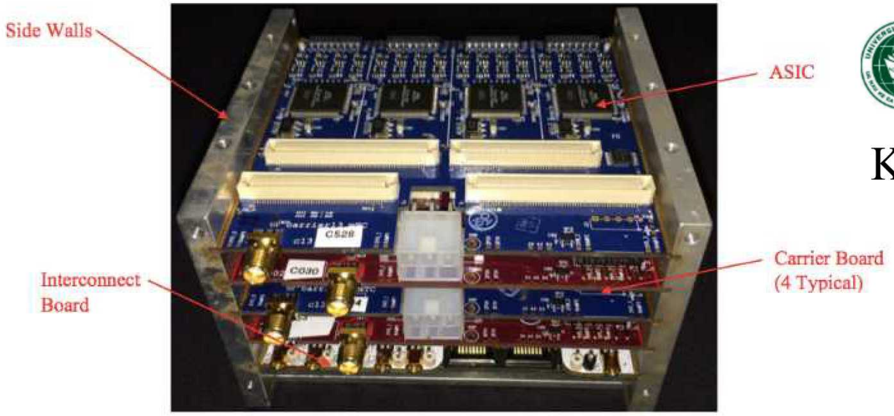
J. Steele, J. Brown, et al.
2019 *JINST* **14** P0203
doi:10.1088/1748-0221/14/02/P02031

UH electronics



UNIVERSITY of HAWAI'I MĀNOA

Kurtis Nishimura, et al.

Graphical agenda

☐ = Separate presentation today

2 Monolithic prototype development (SNL, ORNL)

3 Lab tour

Fast/bright scintillator (SNL)

GRIN scintillator (ORNL)

Tranloc eval (SNL, UH)

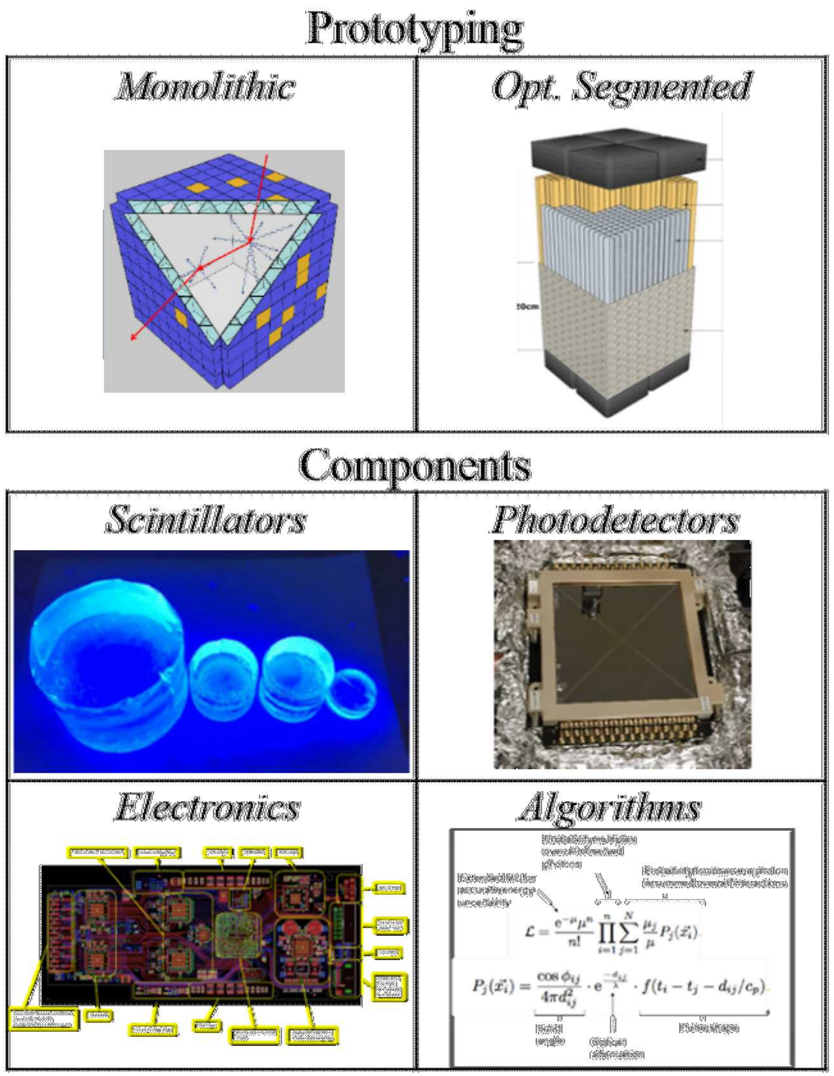
Scintillator properties (UCB, SNL)

4

SCEMA electronics (SNL)

Freq. domain multiplexing (NCSU)

6



1 OS prototype development (SNL, UH, UCB, NCSU)

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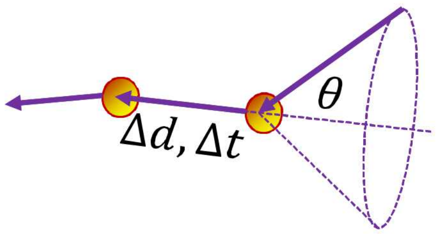
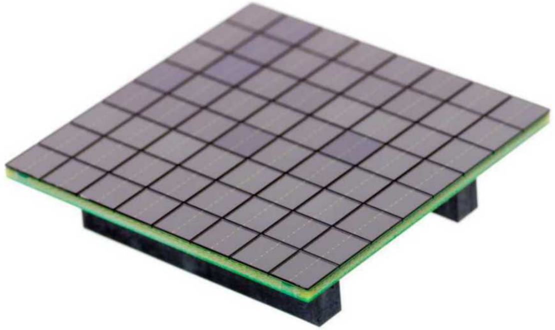




Optically Segmented Single-Volume Scatter Camera

Melinda Sweany

June 25th, 2019

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

The OS team

@North Carolina State University
- John Mattingly
- Mudit Mishra (grad)
- Ahmed Moustafa (grad)
- Kyle Weinfurther (grad)

@Sandia National Laboratories
- Erik Brubaker
- Melinda Sweany

Prior effort

@University of California at Berkeley/LBL
- Bethany Goldblum
- Juan Manfredi (post-doc)

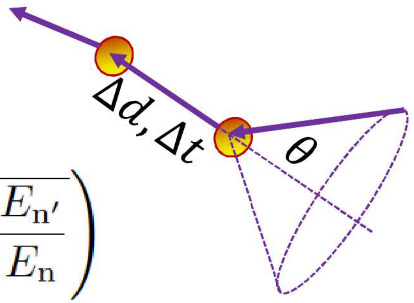
@University of Hawai'i at Mānoa
- Ryan Dorrill (grad)
- Andrew Druetzler
- Aline Galindo-Tellez (post-doc)
- Nate Kaneshige (undergrad)
- Kevin Keefe (grad)
- John Learned
- Kurtis Nishimura
- Devin Schoen (undergrad)
- Benjamim Pinto Souza (undergrad)
- Chauncy Whitworth (grad, non-active)
- Bae Wonseok (undergrad, non-active)

Prior effort

What is the OS-SVSC?

Quick reminder:

- For neutron imaging, we need E_p, Δd, and Δt for θ:

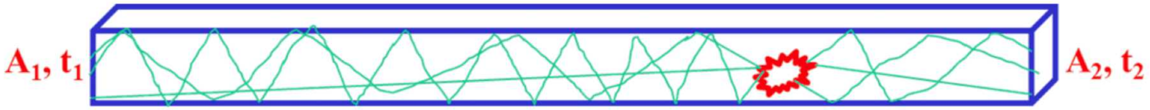


$$E_\mathrm{n} = E_{\mathrm{n}'} + E_\mathrm{p}$$

$$E_{n'} = \frac{1}{2} m_n \left(\frac{\Delta d}{\Delta t}\right)^2$$

$$\longrightarrow \quad \theta = \arccos\left(\sqrt{\frac{E_{\mathrm{n}'}}{E_\mathrm{n}}}\right)$$

Segment the volume into bars of scintillator, read out on ends:



- Position reconstruction in (z):
  - log ratio of total charge at both ends of the bar:
  - Difference in time-of-arrival/pulse shape:
- Position reconstruction in (x,y) is by pixilation
- Event time is average at each end
- Energy is geometric mean of charge

$$\ln\frac{A_1}{A_2} = \ln\frac{e^{-z/\lambda}}{e^{-(L-z)/\lambda}} = \frac{L}{\lambda} - \frac{2z}{\lambda},$$

$$t_1 - t_2 = \frac{z}{v} - \frac{L-z}{v} = \frac{2z}{v} - \frac{L}{v}.$$

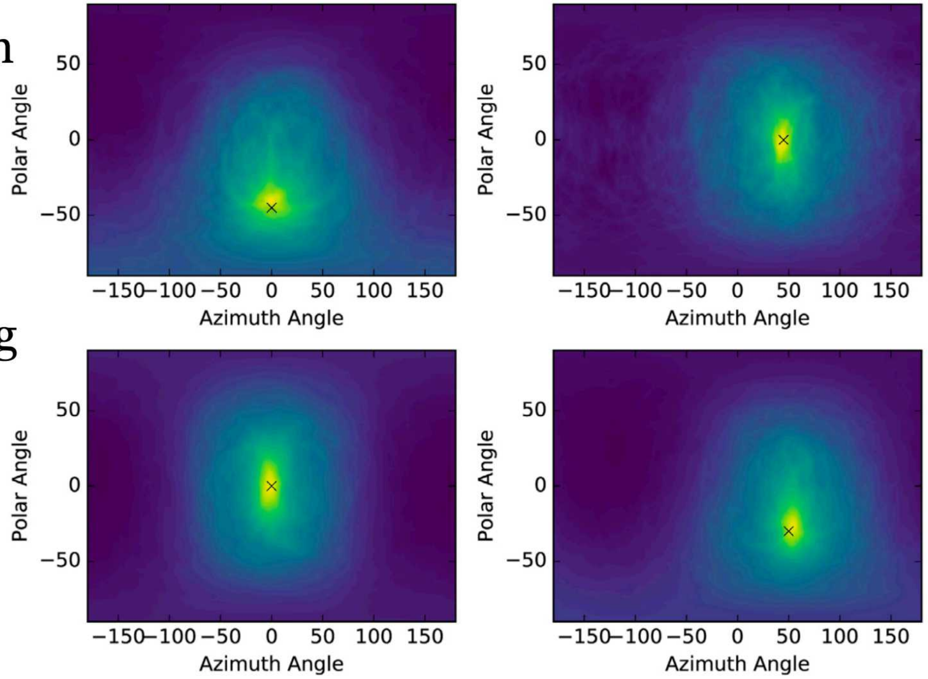
$$E \sim \sqrt{A_1 A_2}$$

$$t_0 = \frac{t_1 + t_2}{2}$$

Will it work?

Given current capabilities is imaging even possible?

- Geant4 optical transport for several different combinations of photo-detector, scintillator, and reflector materials
  - air gap gives best results
  - best case position resolution~5 mm
- Particle transport in MCNPX/ Polimi with smearing of timing, position
  - ^{252}Cf, 1 meter away
  - 20x20x20 cm with 1x1 cm pixels
- Conclusion: with 1x1 cm pixels imaging is doable in a simulated world

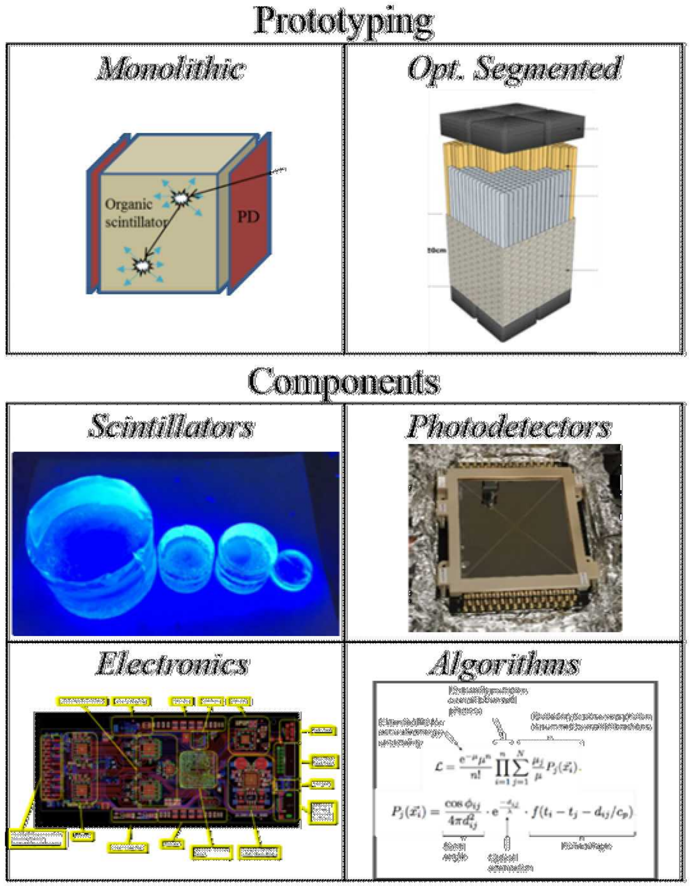


Just defended his Ph.D.thesis!

See: K. Weinfurther, J. Mattingly, E. Brubaker, and J. Steele. "Model-based design evaluation of a compact, high-efficiency neutron scatter camera" *Nucl. Instr. And Meth. A* 883 (2018) 115-135

Design Constraints

- 8x8 array of scintillator bars coupled to photo-detector on the ends
  - Fast photo-detector options are 8x8
  - Readout solutions are x16
- Scintillator bars are ~5x5x200 mm
  - ~5x5 mm couples to fast photo-detector options, leaving room for reflector material and supports
  - 200 mm length is jumping off point to scaling up, approximate volume to monolithic case



Components chosen to realize geometrical acceptance improvements:

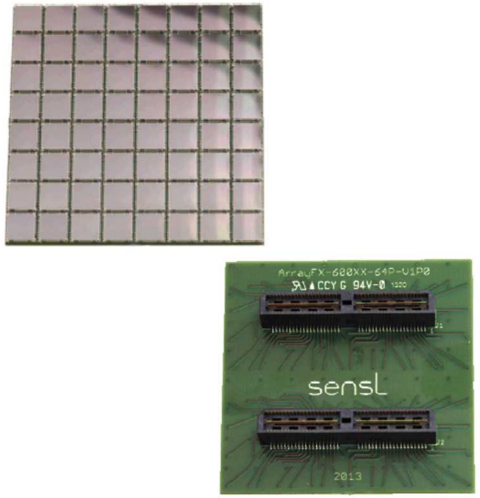
- Overall position resolution should be <1 cm
- Timing resolution should be <1 ns
- Threshold as low as possible for fission neutrons
- No clear metric on energy resolution
- Necessity of PSD is open question

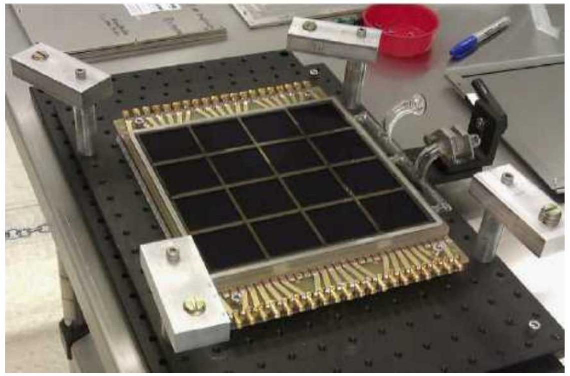
Design Considerations - Photodetectors

We want segmented, fast, linear and robust:

Technology	Manufacturer/Part	Rise Time	Pulse Width	Peak PDE
MCP-PMT	Photonis Planacon XP85012	0.6 ns	1.8 ns	<25%
MCP-PMT	Incom LAPPD	-	1 ns	~14%
SiPM	SensL C/J-series 8x8 array	0.3-1 ns	0.6-3 ns	35/50%

Cross talk issues

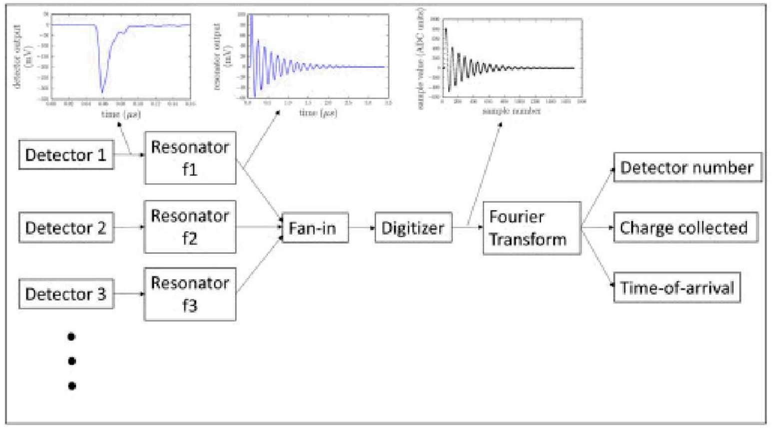




Design Considerations - Electronics

We want high sampling rate or fast analog, low threshold, 128-channel solution:

- Preliminary scans with 5 GS/s, 12-bit DRS4-eval board
- Current UH electronics: 2.7 GS/s, 12-bit IRS3D
- Commercial analog solutions from PET
    - Not for first prototype: we want waveforms to learn about event topology
- Frequency Domain Multiplexing
    - R&D underway @NCSU

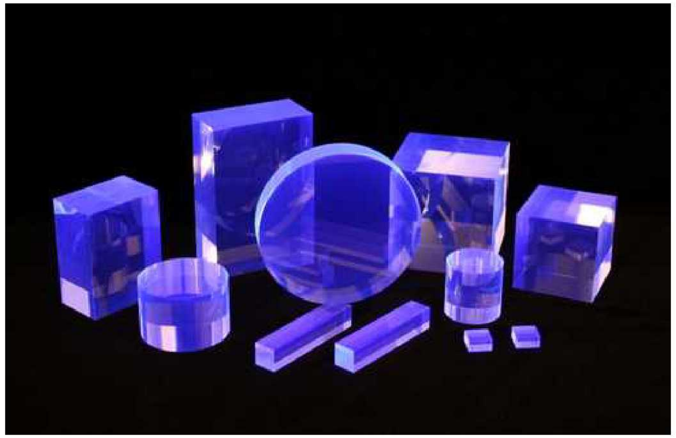


See: M. Mishra, J. Mattingly, J. M. Mueller, and R. M. Kolbas "Frequency domain multiplexing of pulse mode radiation detectors" *Nucl. Instr. And Meth. A* 902 (2018) 117-122

Design Considerations - Scintillator

We want bright, fast, robust:

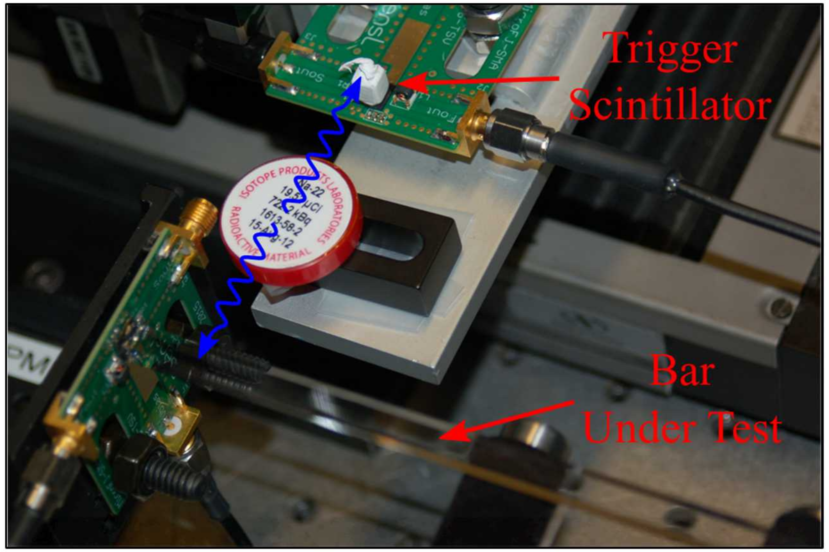
- More light is better for energy reconstruction and position/timing reconstruction
  - output spectrum vs. quantum efficiency of SiPM, as well as yield
- Many properties not well known
  - High-fidelity measurements on-going @UCB/LBNL
- Single bar measurements to inform best option in terms of position, timing

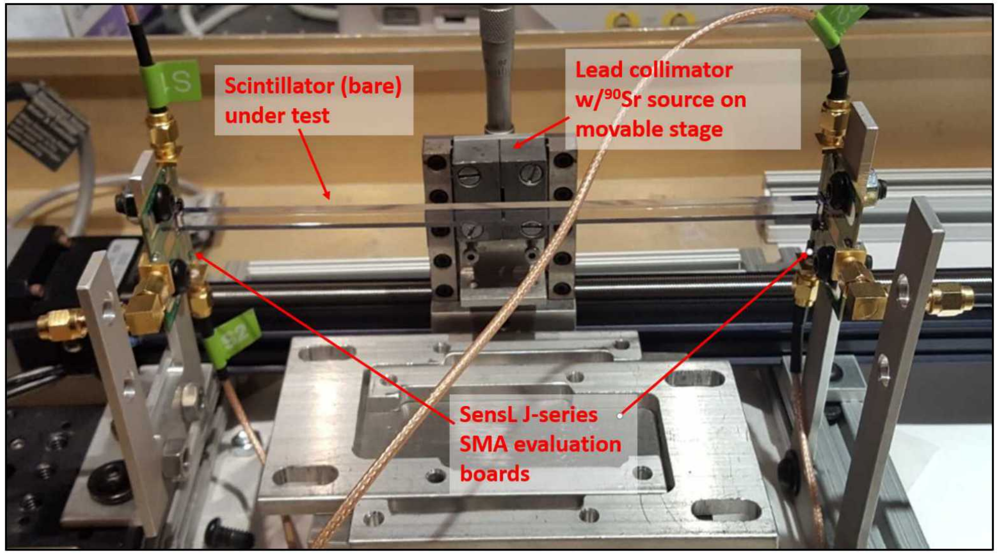


Scintillator	t_R (ns)	λ (cm^{-1})	N_e (MeV^{-1})	N_D (MeV^{-1})
EJ-200	0.9	380	10,000	4,905
EJ-204	0.7	160	10,400	5,084
EJ-208	1.0	400	9,200	4,378
EJ-230	0.5	120	9,700	4,557
EJ-232	0.35	-	8,400	3,679
EJ-260	-	350	9,200	3,470
EJ-262	-	250	8,700	3,548
EJ-276	-	-	8,600	4,203
EJ-276G	-	-	8,000	2,991

See: T.A. Laplace, B.L. Goldblum, J.A. Brown, D.L. Bleuel, C.A. Brand, G. Gabella, T. Jordan, C. Moore, N. Munshi, Z.W. Sweger, A. Sweet, E. Brubaker. "Low energy light yield of fast plastic scintillators" Accepted in *NIM A:* https://doi.org/10.1016/j.nima.2018.10.122

Single Bar Measurements





@SNL

- Tagged Na-22 scan (low eff.)
- Trigger is on 5x5x5 mm Stilbene crystal (no threshold effects on test bar)
- Provides timing, z-position, and energy resolution measurements

@UH

- Collimated Sr-90 scan (high eff.)
- Trigger is on one end of test bar
- Provides z-position and energy resolution measurements
- Double bar measurements provides limited timing measurements

Combination provides cross check and critical systematic errors

Single Bar Results - Summary

Scintillator	σ_t (ps)	σ_z (mm)		σ_E/E (%)	
		^{22}Na	^{90}Sr	^{22}Na	^{137}Cs
EJ-200, bare	155±2	13.35	14.27	16.7	14.1
Teflon	154±3	10.29	7.65	14.5	15.8
ESR	145±3	11.14	12.09	16.6	12.2
EJ-204, bare	136±3	10.08	10.67	15.7	14.7
Teflon	**142±2**	**8.06**	**6.54**	**13.1**	**14.3**
ESR	125±3	8.59	9.64	17.6	12.2
EJ-230, bare	141±3	9.61	8.86	17.8	15.0
Teflon	142±2	8.39	6.32	22.6	13.9
ESR	156±3	10.17	8.52	23.4	13.0
EJ-276, bare	183±5	12.13	13.51	17.8	14.1
Teflon	171±2	9.29	9.54	16.5	14.1
ESR	177±4	11.65	10.45	15.0	11.3
Syst. error	±7	±0.73	±0.42	±3.5	-

We've met our goal of *O*(1cm/1ns) reconstruction!

← **Also, highest light output**

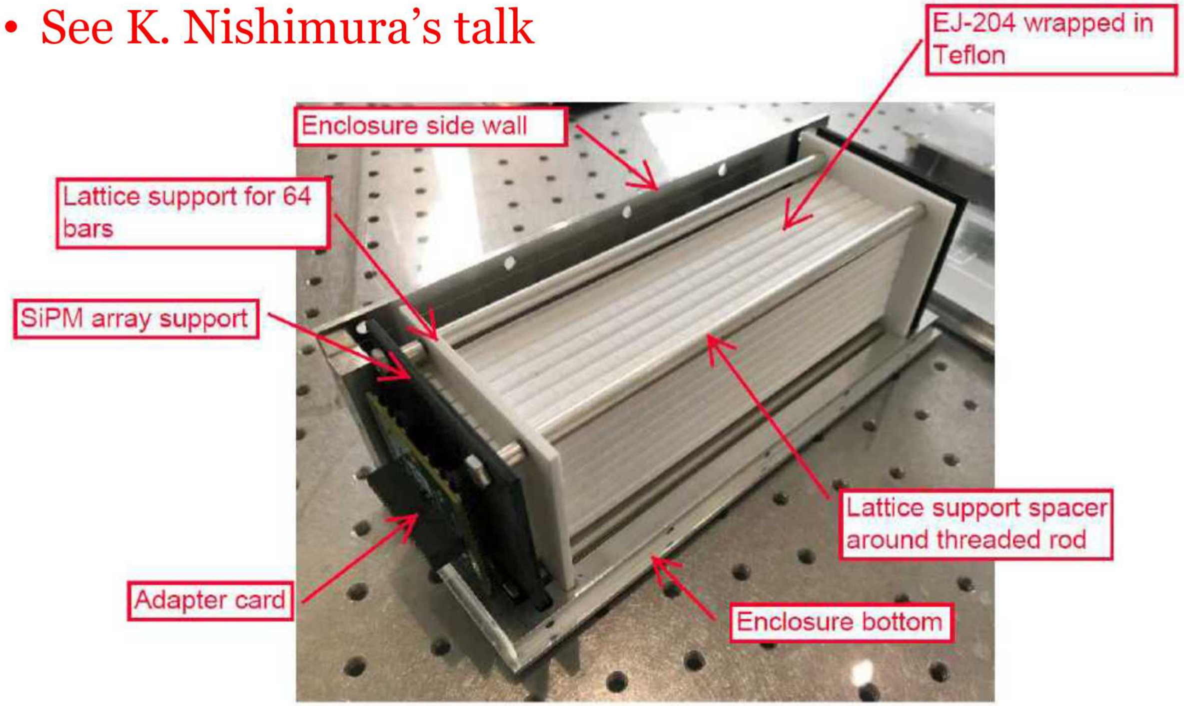
- Lowest possible threshold to optimize detection of fission energy neutrons
- Estimate 30 keVee with 7 mV electronics threshold

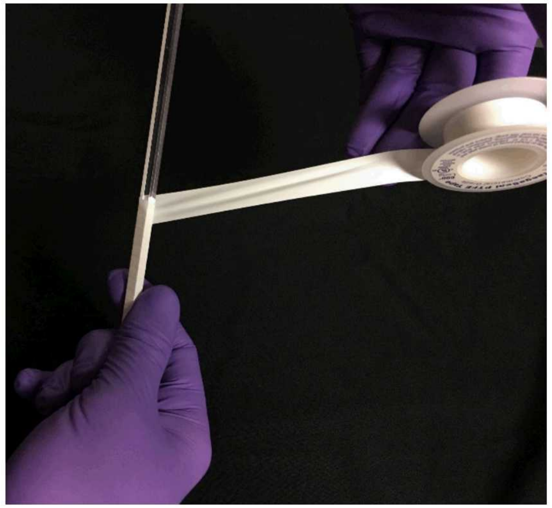
See: M. Sweany, A. Galindo-Tellez, J. Brown, E. Brubaker, R. Dorrill, A. Druetzler, N. Kaneshige, J. Learned, K. Nishimura, and W. Bae. "Interaction position, time, and energy resolution in organic scintillator bars with dual-ended readout" *Nucl. Instr. And Meth. A* *927 (2019) 451-462*

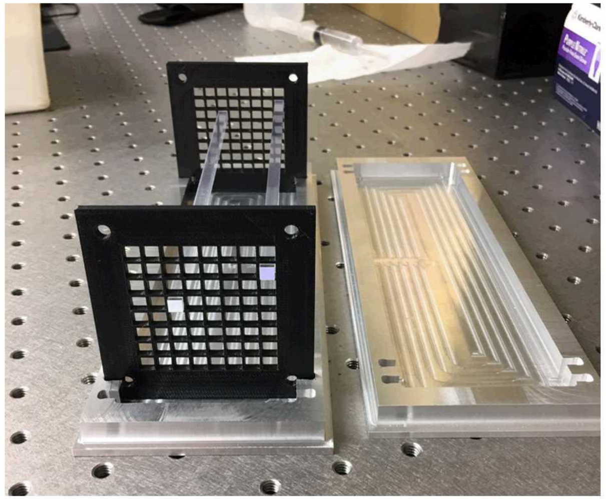
First OS Prototype @UH:

Summary:
- Photodetector: SensL J-series 6x6mm with FOUT
- Readout electronics and trigger: 2.7 GS/s, 12-bit IRS3D
- Scintillator: 5x5x200 mm EJ-204 bars, Teflon-wrapped

Status:
- See K. Nishimura's talk



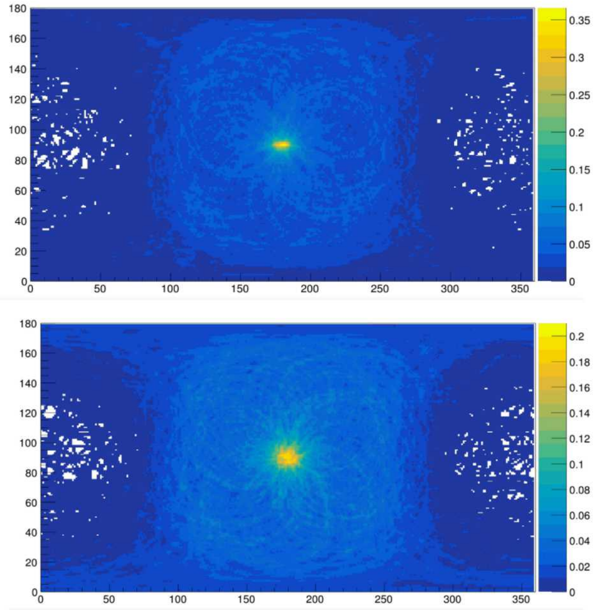




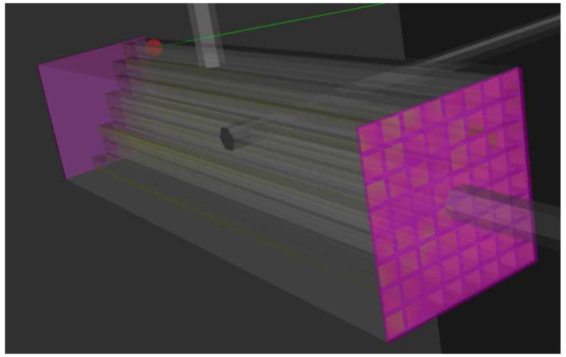
Looking ahead

Next prototype is coming up in December!

- Optimizing performance of components
  - Scintillator:
    - SNL's glass-based scintillator?
    - PSD? Informed by first prototype
    - Advanced optical reflectors?
    - Nanoguide?
  - Photo-detector:
    - Hamamatsu's S13361-6050 MPPC, with improved single photon resolution, timing, and dark count rate?
  - Readout electronics and trigger
    - PETSys electronics' TOFPET2 ASIC
- Modeling study in Geant4 @UCB/SNL to determine the best path forward for imaging:
  - How do timing, position, PSD, energy resolution, PLY, and threshold map to imaging metrics such as resolution, contrast, artifacts, etc. for a given source and acquisition time?
  - How do imaging metrics change with source position?



J. Manfredi, UCB



Optically Segmented Prototype at UH

Kurtis Nishimura
University of Hawaii
June 25, 2019

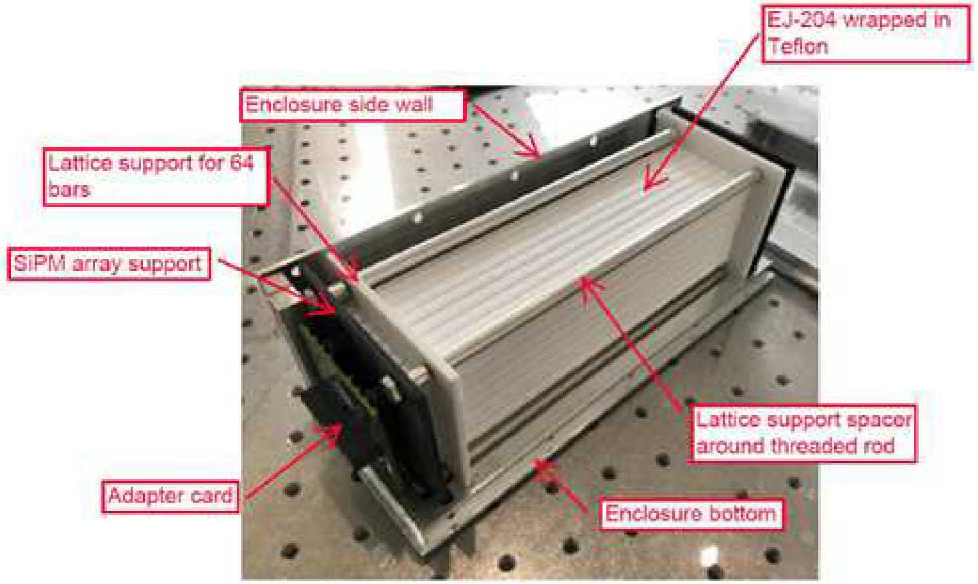
First OS Prototype at UH

Summary:

- Scintillator: **64x** 5x5x200 mm EJ-204 bars, Teflon-wrapped.
- Photodetector: SensL J-series **Array** 6x6mm with FOUT.
- Added interfaces and cabling.
- Readout electronics and trigger: IRS3D from UH
    - 128 channels of 2.7 GSPS waveform digitizer.

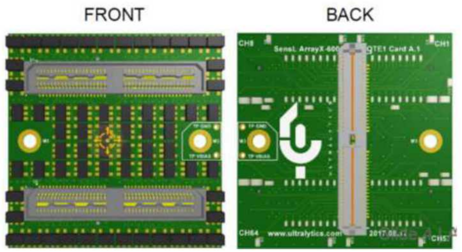
Status:

- All components are assembled.
- Electronics testing underway.
- Crosstalk issues now being studied in detail.
- Combined analysis framework for simulation and data under development.

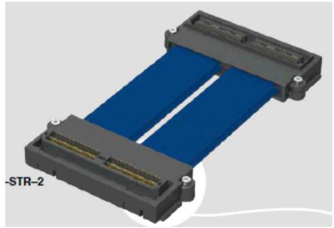


New components (relative to single bar tests) highlighted in green.

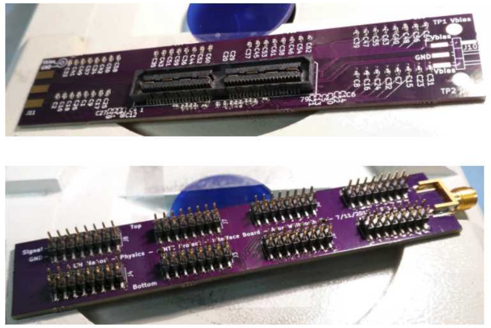
Data Flow of Prototype System



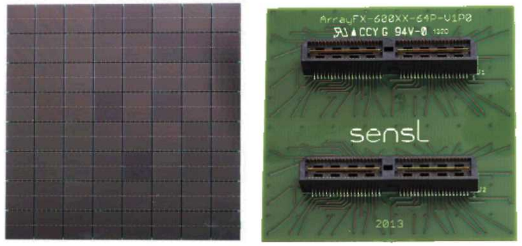
Fast Output (FOUT) Breakout [Ultralytics LLC]
Standard Output card also available



Samtec EQCD Cable



Custom adapter



SensL J-series array (6 mm)

Upgraded commercial components:
- Custom adapter to perform breakout.
- High quality coax cable.

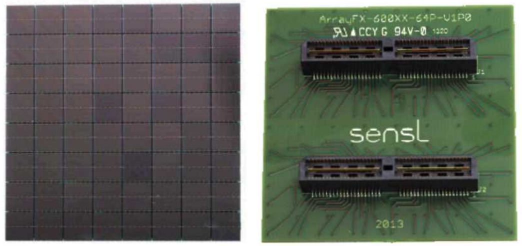
Custom breakout:
- New adapter for new breakout and cabling.
- One module @ 128 channels or two modules @ 64 channels [preferred mode].
  - Waveform sampling at 2.7 GSPS.

Full 64/128 channel electronics module (Custom IRS3D ASICs)

"Single Bar" Scans on Full Prototype

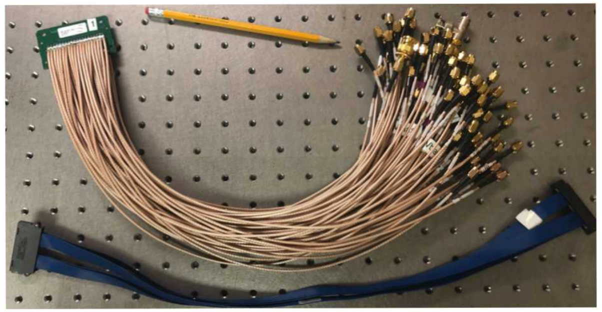
- With full prototype, how is our single bar performance?
- Keep DRS4 electronics chain to make comparisons more straightforward.

Sr-90 Source w/ Collimator
Scanned Along Array



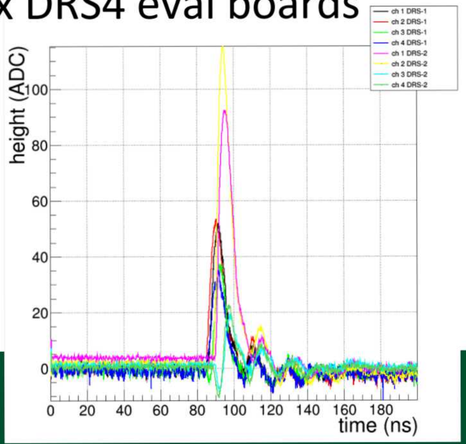
SensL ArrayJ

Ultralytics ArrayX breakout



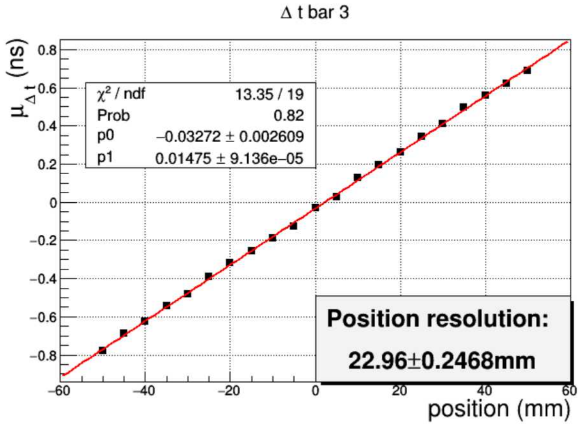
Samtec SMA breakout
to make coupling to DRS4
evaluation boards

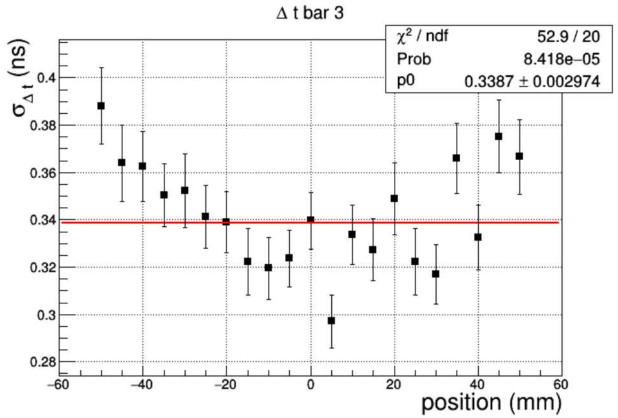
2x DRS4 eval boards



"Single Bar" Scans on Full Prototype

- With full prototype, how is our single bar performance?
- Keep DRS4 electronics chain to make comparisons easier.





Amplitude-based	σ_z^t(mm)
EJ-204 w/ Teflon (single-bar)	10.66 ± 0.22
EJ-204 w/ Teflon (full array)	22.97

Timing-based (shown at left)	σ_z^A(mm)
EJ-204 w/ Teflon (single-bar)	12.33 ± 0.26
EJ-204 w/ Teflon (full array)	22.96

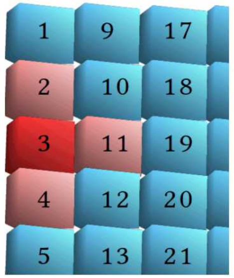
- Roughly 10 mm degradation relative to single bar results, much of it now attributed to optical and electrical crosstalk…

Crosstalk

- Degradation has been largely attributed to optical and electronic crosstalk.
  - It is essential to quantify the optical crosstalk, but very difficult in the presence of large electronic crosstalk.
  - Are we observing significant electronic crosstalk?
    - ➔ **Yes, up to 10% level, generally scales with amplitude.**
  - **We have observed this with photons (next slides) and with injection of electrical pulses (lower right).**

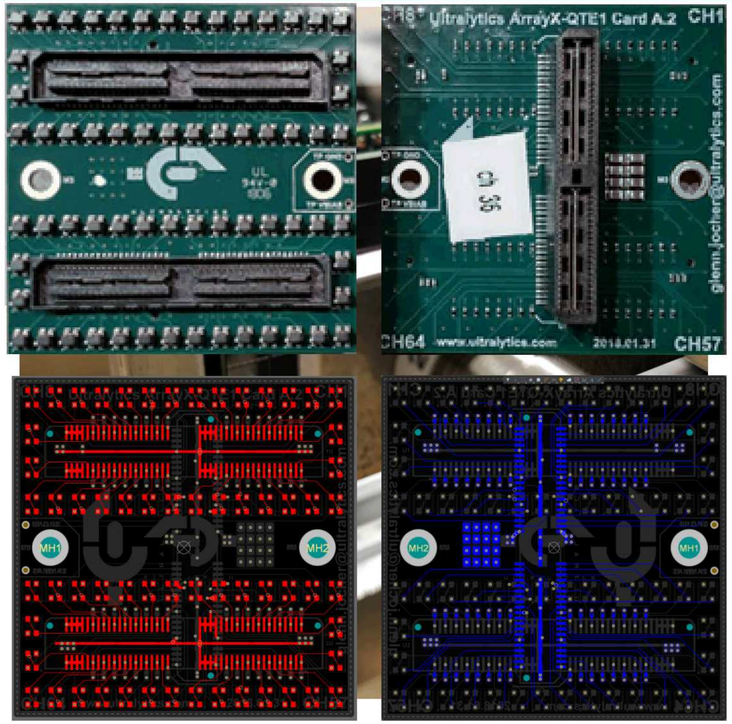
Optical crosstalk in neighbor pixels
can cause electronic crosstalk to primary pixel, resulting
in degraded timing and amplitude measurements.

Example: a hit in bar 3 channels light by optical crosstalk into 2,4,11. These in turn crosstalk electrically at up to 10% level back to channel 3, significantly degrading the amplitude and time measurements on channel 3.



➔ **This situation is far worse if there are actual second scatters in 2,4,11. From simulation the majority of events have second double scatters in adjacent bars!**

Crosstalk Scanning



- Laser spot scanned across pixels, all channels recorded for all incident spots.
- Signal passes through full array, FOUT (or SOUT) breakout card, SMA breakout cable, DRS4…
- Crosstalk generally localized to quadrants on the Samtec connectors.
- 3x pairs of connectors in the full system!

Crosstalk Mitigation

Electrical Mitigations:

- Shorter connectors?
- Interspersed ground pins on connectors?

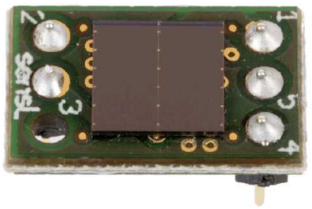
Optical Mitigations:

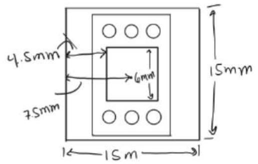
- Custom arrays that can spread pixels out further?
- These also may improve some other aspects of construction & optical coupling (at some cost of compactness).

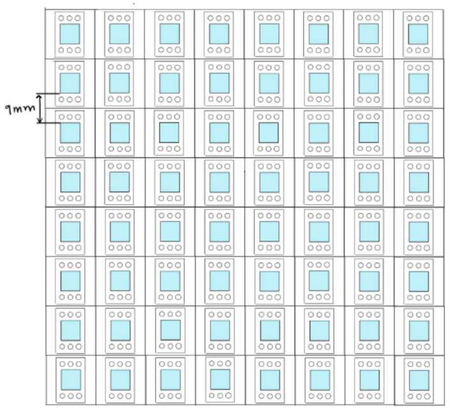
Samtec Conn Heights	
Connector	Height
QTE-040-01	4.27 mm
QTE-040-02	7.26 mm
QTE-040-03*	10.27 mm

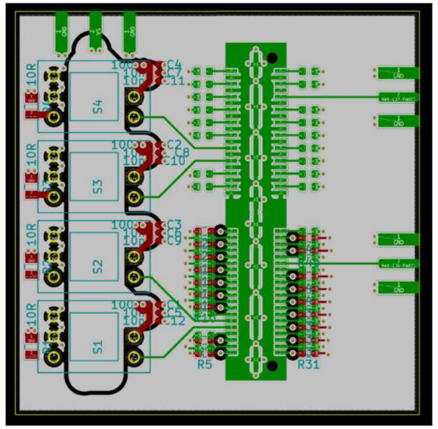
* = the one we are using.

A number of concepts are being explored with fast turnaround PCB prototypes.





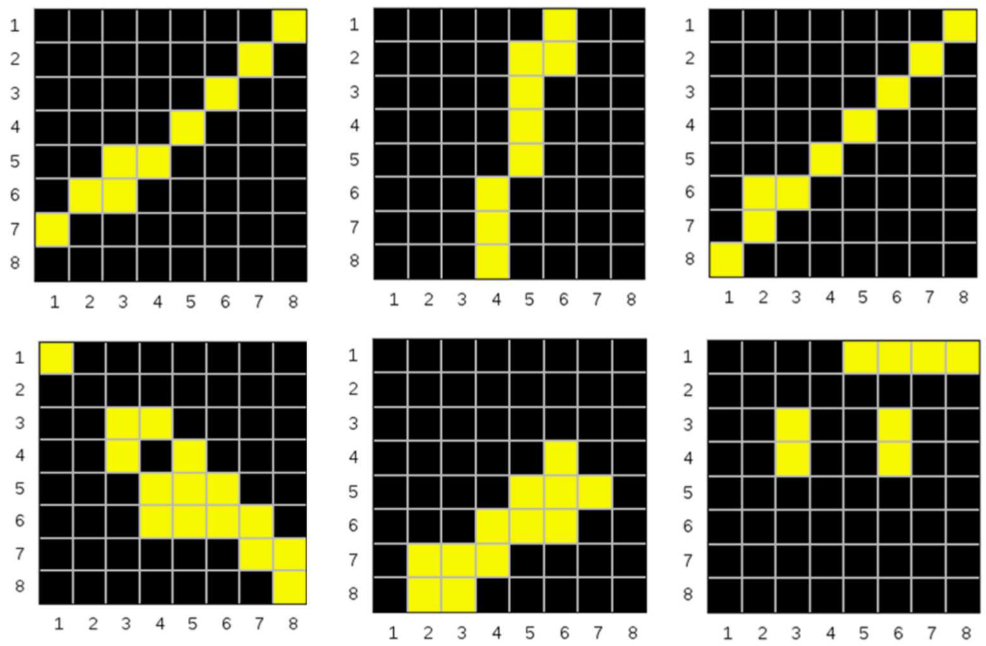


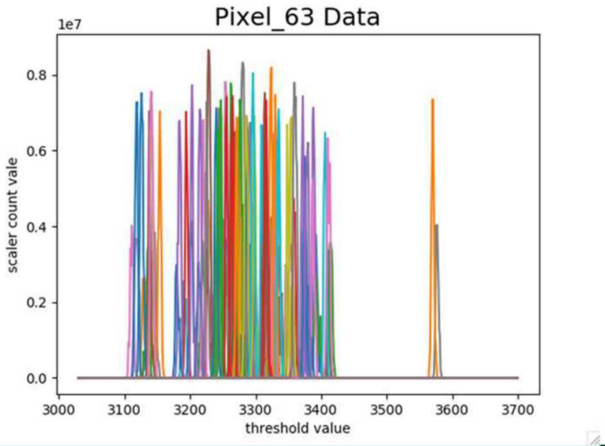


Parallel Work on Full Readout

- In the meantime, still moving forward with full system.
- Various thresholds and ASIC parameters are being tuned up on the full array.
- Trigger is being modified based on first observations from array…

<u>Example of events with a muon trigger</u>:

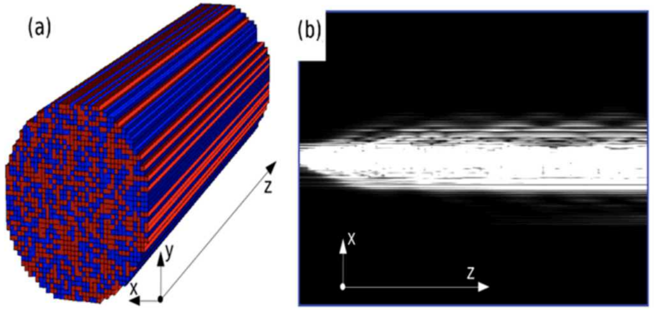




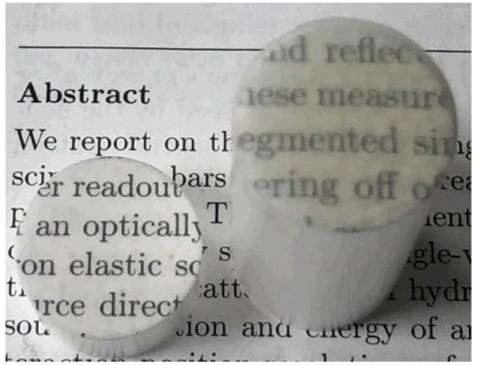
Now tuning trigger conditions based on observations.

Another Kind of OS?

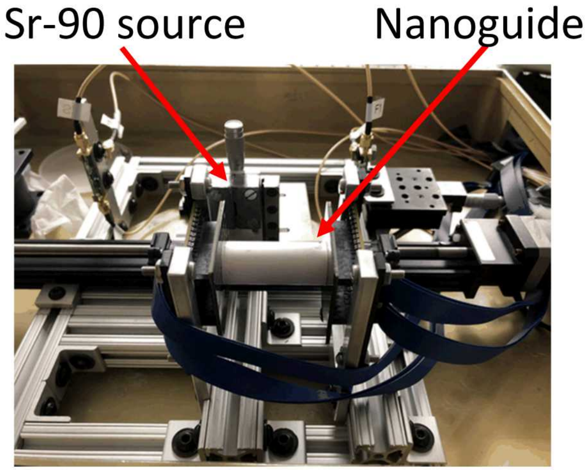
- Anderson Transverse Localization uses an array of randomly oriented (in x-y) fibers, uniform in z. For proper sizes/indices of refraction of fibers, this can cause interference such that light is “localized” in x-y direction as it propagates.
  - Paradigm Optics / Incom Inc. is making such material (Nanoguide/Tranloc), and can use scintillating elements!
  - This could work as an optically segmented detector made from a single piece, vastly simplifying mechanics, optics.



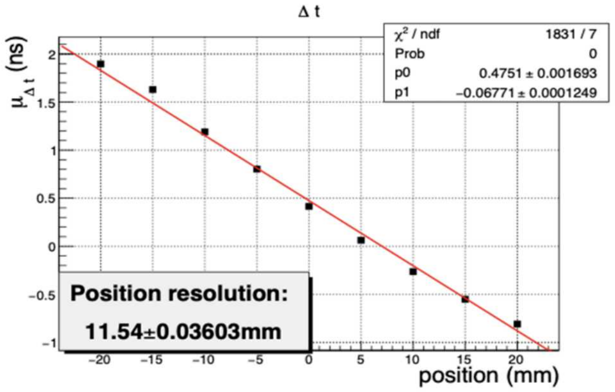
A. Mafi, arXiv:1505.01109

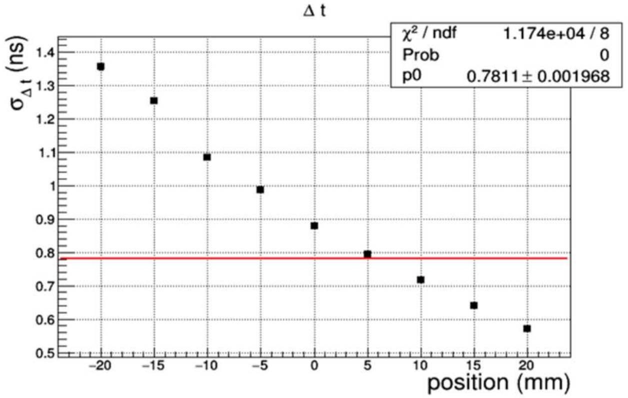


First Nanoguide Tests at UH



- An early sample of Nanoguide was tested at UH using same procedures as the single bar testing.
- Low light output and/or transmission length made analysis and calibration difficult.
- Some systematic effects attributed to this specific sample and issues with its orientation and alignment of fibers relative to longitudinal axis.
- …but generally our single bar procedures worked to localize in *z*, and light was contained to ~1 pixel in *x,y*.





Nanoguide Tests at UH/SNL

UH:

- New larger sample (~5 x 5 x 19.5 cm^3) received at UH shows much better transparency than older samples.
- Exactly matched to SensL array size, so can be tested easily with rest of prototype chain!

SNL:

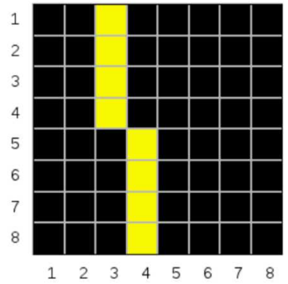
- Smaller single-bar sized samples received by SNL and tested with and without Teflon.
- Low light yield and/or transmission required use of x10 amps.
- Timing resolution badly degraded.

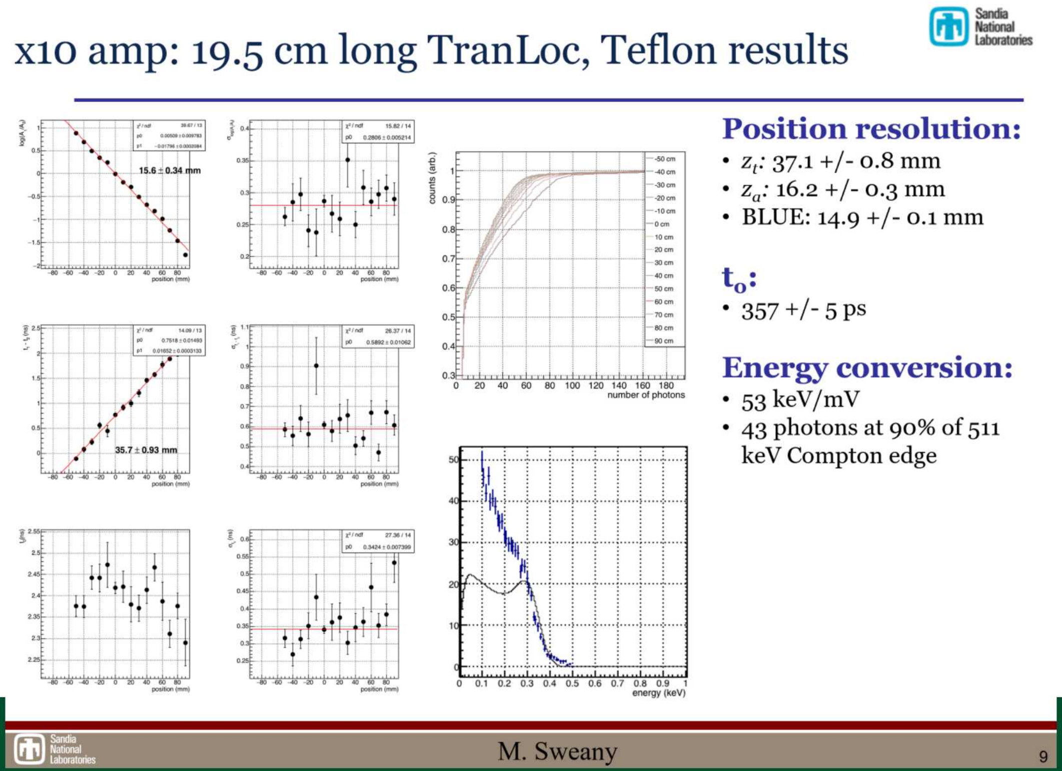
Still, interesting material for longer range studies (past second prototype).

New sample:

Old sample:

A first muon w/ new sample:

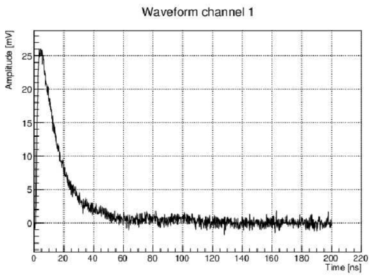


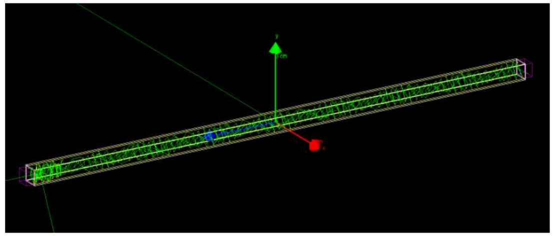
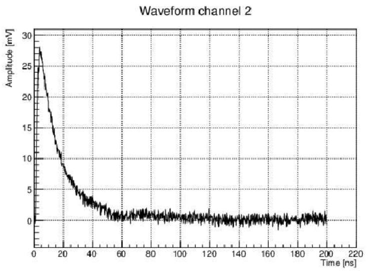


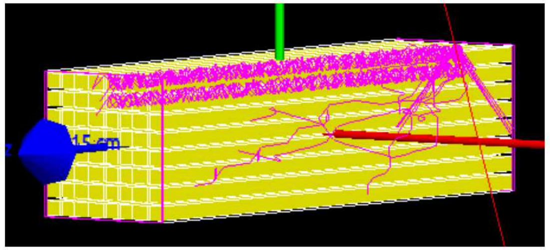
SNL sample (5 mm x 5 mm x 19.5 cm):

Next Steps with Prototype

- Focus on testing that can improve second prototype! For example…
  - Strong focus on electrical crosstalk.
    - To improve performance, but also so that we can better quantify optical crosstalk.
    - Develop/test mitigations for optical crosstalk, depending on results.
  - Measure ability to do velocity measurements for particle ID.
    - This can feed into simulation to guide urgency of PSD requirements.
  - Working toward full imaging, even if not ideal with first prototype.
    - Feed back experience to simulation and analysis frameworks.
    - A framework for analysis of both simulated and experimental data is under development with contributions by UH, NCSU, UCB/LBNL.





- In parallel, some longer term development:
  - E.g., can Nanoguide/Tranloc be a conventional scintillator replacement?

Single-Volume Scatter Camera, Monolithic Prototype

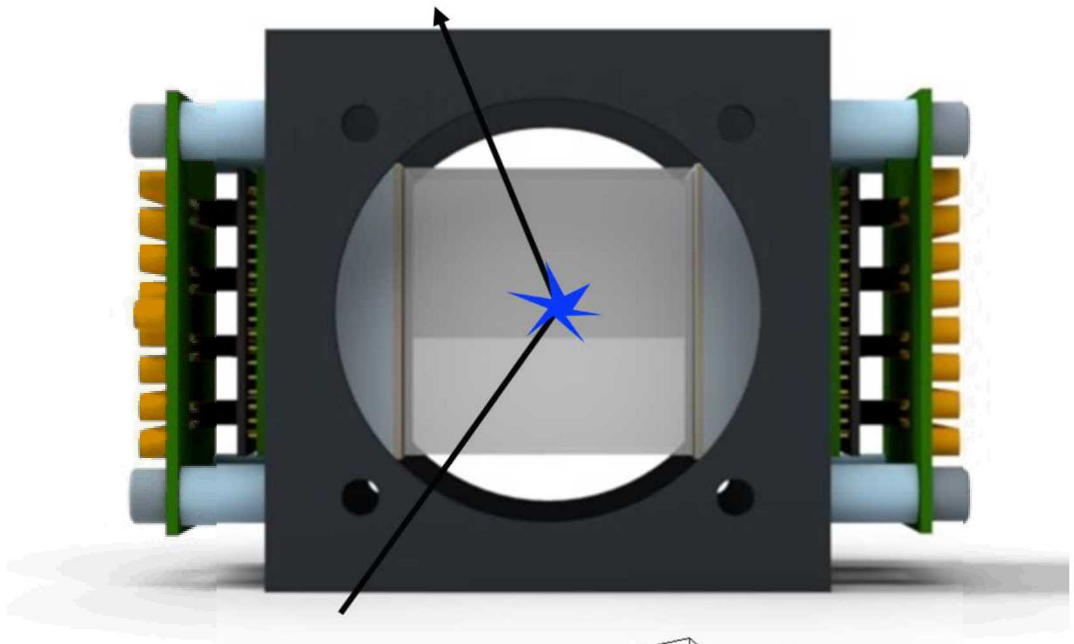
NA-22 Independent Review

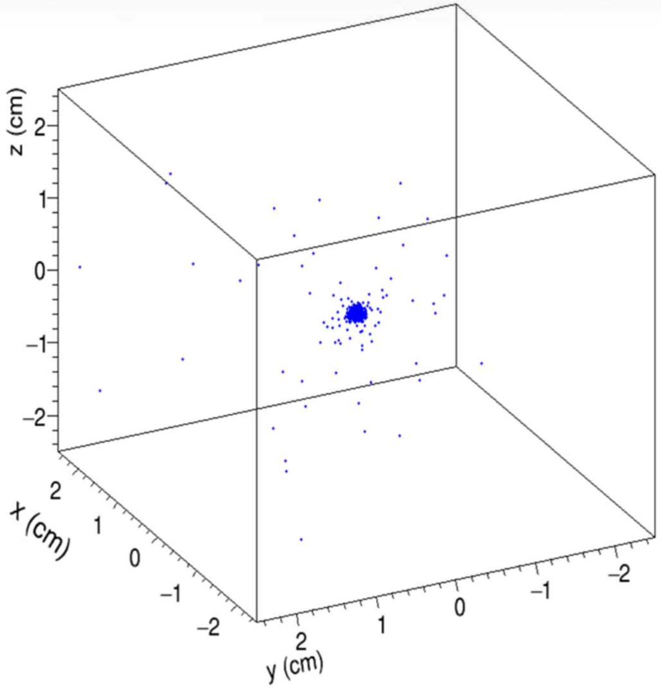
25 June 2019

ORNL is managed by UT-Battelle, LLC for the US Department of Energy

Outline

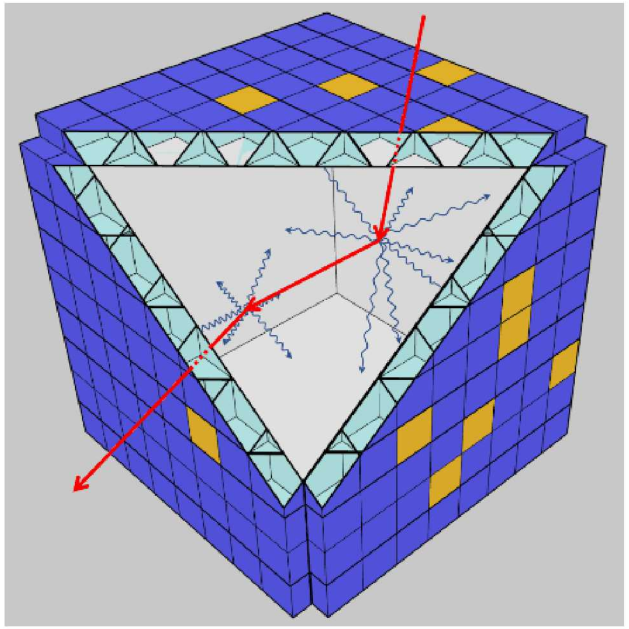
- Overview of the approach
- Prototype
- Essential constituents
  - Photo sensors
  - DAQ
  - Event reconstruction
- Testing
  - Crosstalk compensation
- Future plans





Oak Ridge National Laboratory
Sandia National Laboratories

Monolithic Concept



Probability multiples over all observed photons

Extended ML for accurate energy uncertainty

Probability to observe a photon is summed over all interactions

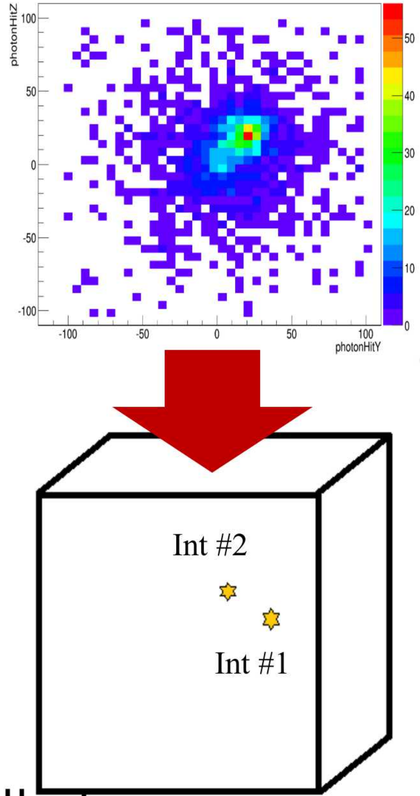
$$\mathcal{L} = \frac{e^{-\mu}\mu^n}{n!}\prod_{i=1}^{n}\sum_{j=1}^{N}\frac{\mu_j}{\mu}P_j(\vec{x_i}),$$

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

Solid angle

Optical attenuation

Pulse shape

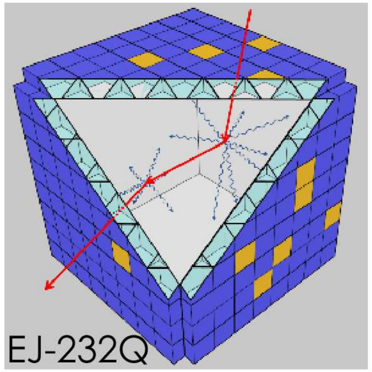


- Neutrons scatter from protons in a monolithic volume of scintillator
- Scintillation photons emitted (isotropically) from the recoil proton tracks are recorded at the surfaces of the volume
- The resulting list of photon arrival positions and times is used to directly reconstruct the most likely (x,y,z,t,μ) for each interaction

Feasibility Study Results

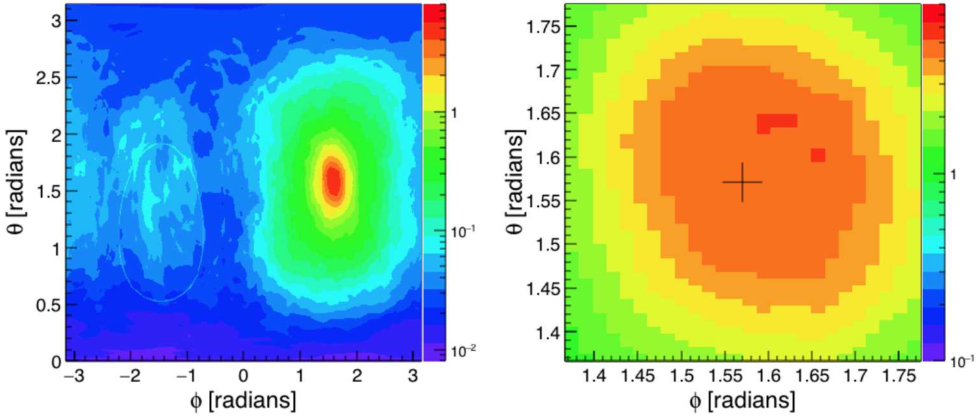
- Available information sufficient to reconstruct events, perform imaging
- However, simulations often overlook experimental complications…
  - Difficult to reproduce optical surfaces (and their nonuniformities)
  - Difficult to extract photoelectron arrival times
- ***So… need to build a prototype***

Belkis Cabrera-Palmer (SNL)



	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

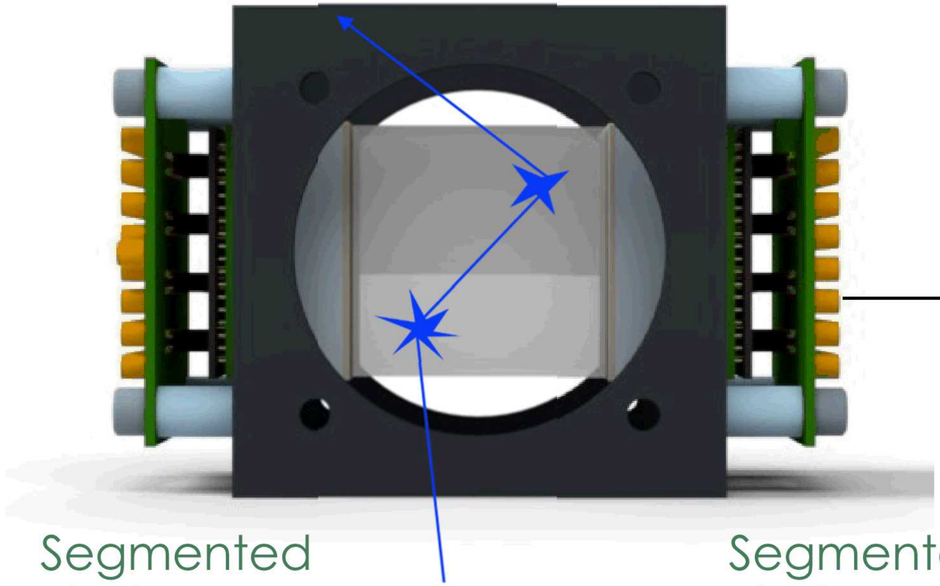
	σ
Δx_1	4.94 mm
Δy_1	5.08 mm
Δz_1	4.95 mm
Δt_1	0.14 ns
Δn_1	30 photons



For a simulated 2.7 uCi Cf-252 neutron source located at 1 m, this image is equivalent to 29 minutes of measurement time, without background.

Prototype Approach

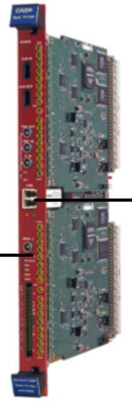
Monolithic scintillator volume



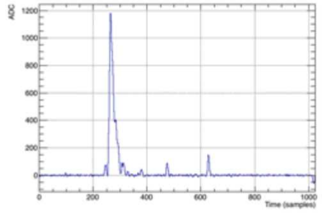
Segmented photosensor

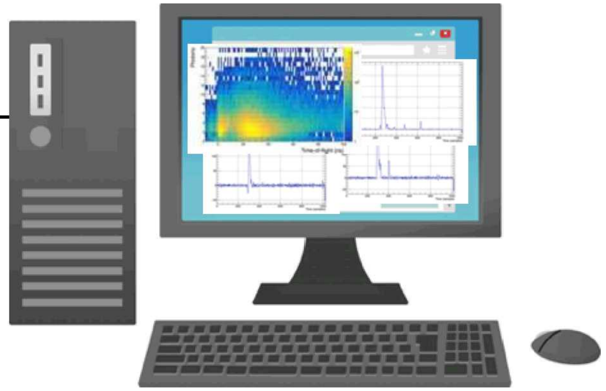
Segmented photosensor

One segment



Digitize





Store/Analyze

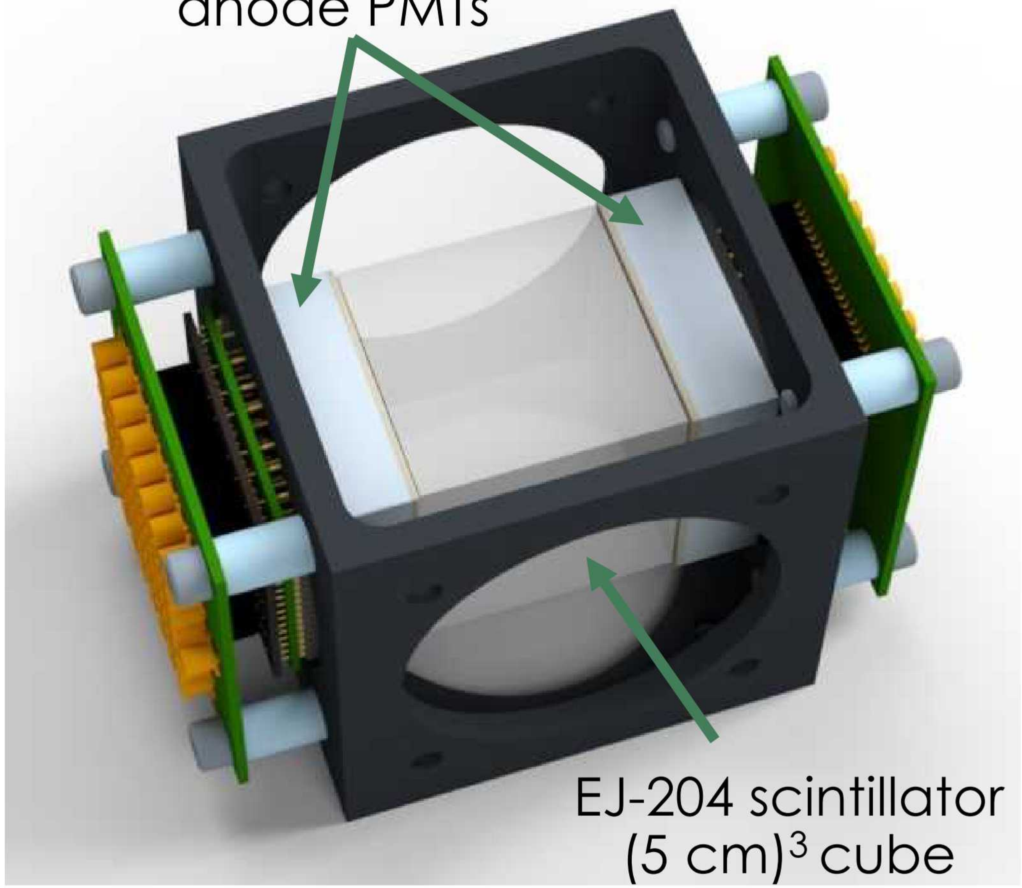
1 **Photosensors:**
- Position sensitive (multi anode)
- Fast timing
- Count single photoelectrons

2 **Data acquisition**:
- Use fast digitizers to record photosensor waveforms

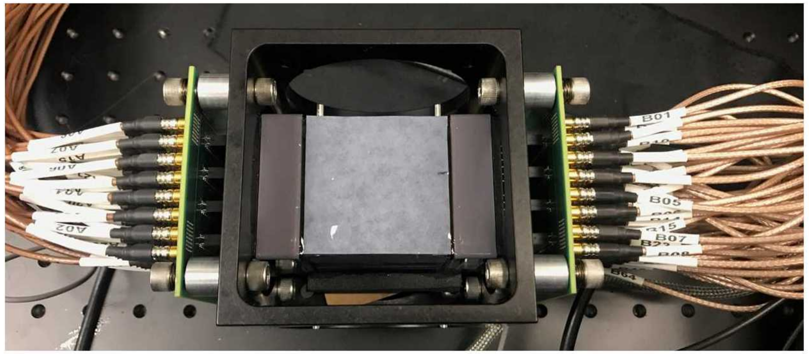
3 **Analysis**
- Extract PE number, locations, times
- Output to event reconstruction

4 **Event reconstruction**
- Maximize likelihood to identify interaction positions, times
- Image double scatters

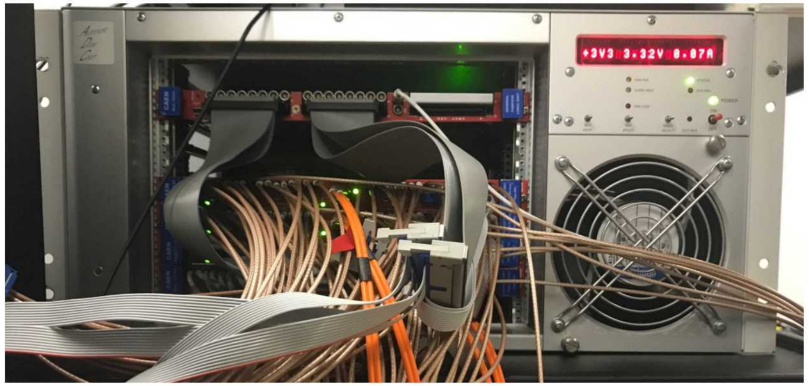
Prototype Monolithic Imager



Scintillator and PMTs

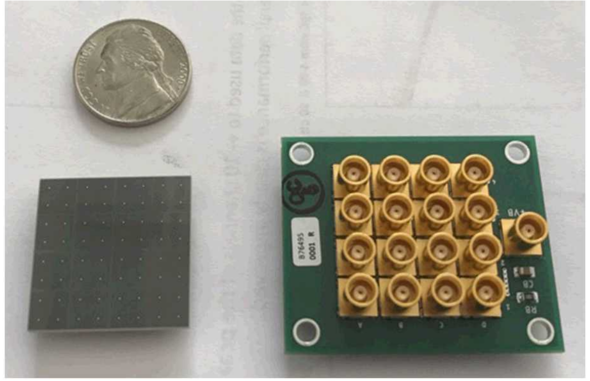


4 CAEN V1742 32-channel, 5 GSs^{-1}, 12 bit digitizers (DRS-4 chip)



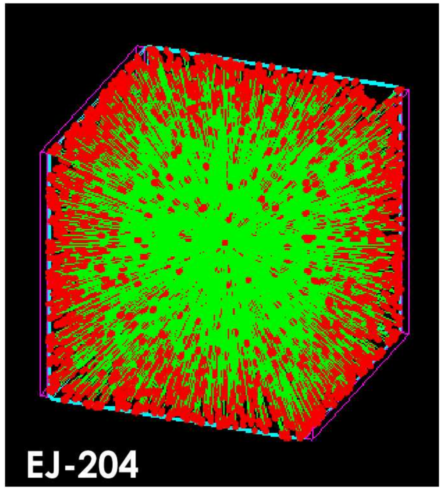
Dell 7920 16-core workstation + CAEN A3818 optical interface

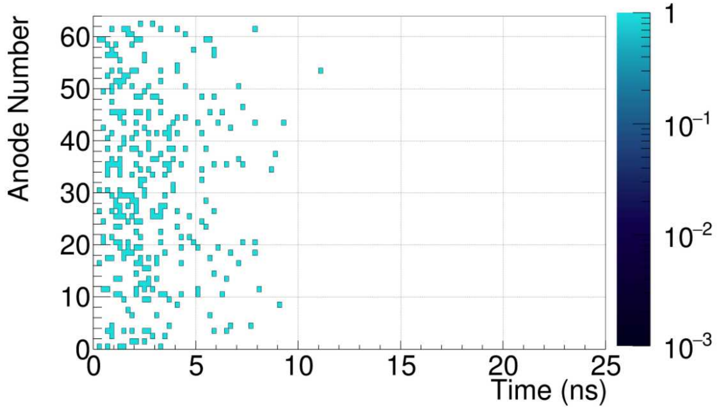
Off-the-Shelf Segmented Photosensor Options



<table>
<tr><th>Category</th><th>SiPMs</th><th>MA-PMTs</th><th>MCP-PMTs</th></tr>
<tr><td>Amplification</td><td>Want ×100 for superior single PE resolution, timing</td><td colspan="2">No additional amplification necessary</td></tr>
<tr><td>Power</td><td>18 W for 64 channels</td><td colspan="2">0.6 W for 64 channels</td></tr>
<tr><td>Dark current</td><td>89k / mm^2 at a gain of 1.7e6</td><td colspan="2">negligible</td></tr>
<tr><td>PE amplitude variation</td><td>~10%</td><td colspan="2">~50%</td></tr>
<tr><td>Timing for 1 pe</td><td>~300 ps FWHM</td><td>~500 ps FWHM</td><td>~150 ps FWHM</td></tr>
<tr><td>Pulse pair resolution</td><td>Difficult to distinguish from afterpulsing</td><td colspan="2">Nanosecond</td></tr>
<tr><td>Cross talk</td><td>Expected small</td><td>OK for segmented</td><td>Known issue</td></tr>
</table>

Resolving Multiple Photoelectrons



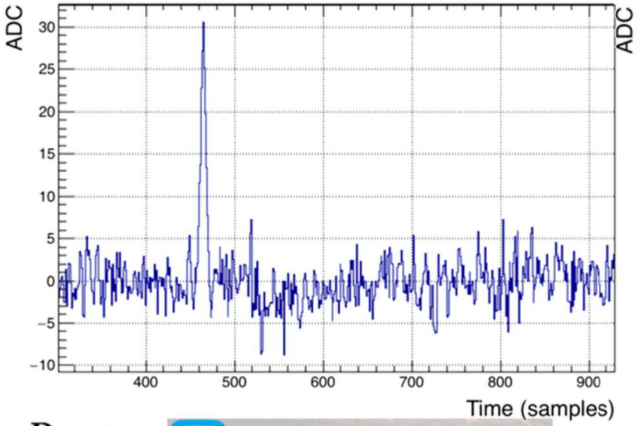


Ideal PE hits by anode in one PMT

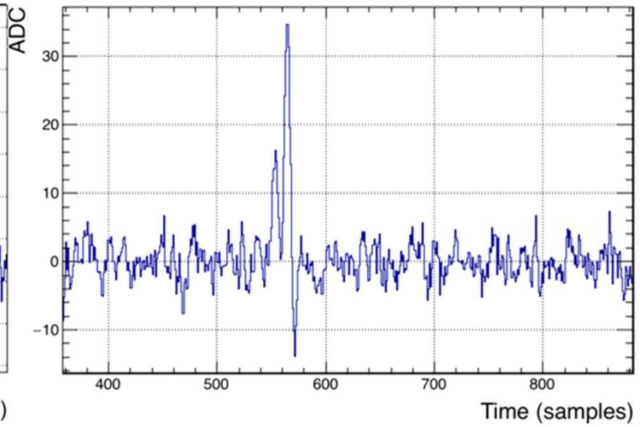
- Simulation of 2 MeV proton recoil gives ~ 5 pe per anode over <10 ns
- For SiPMs, true PEs difficult to distinguish from dark counts, after-pulsing

MA-PMT (Hamamatsu H-12700)

Single pulse
FWHM = 1.23 ns

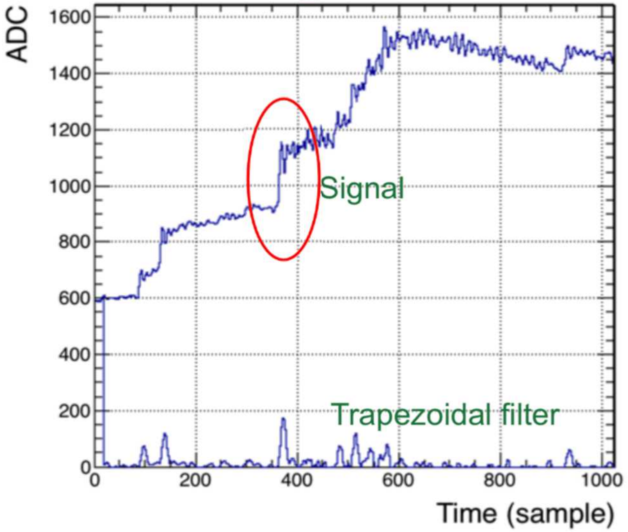


Double pulse
T_{diff} = 2.2 ns

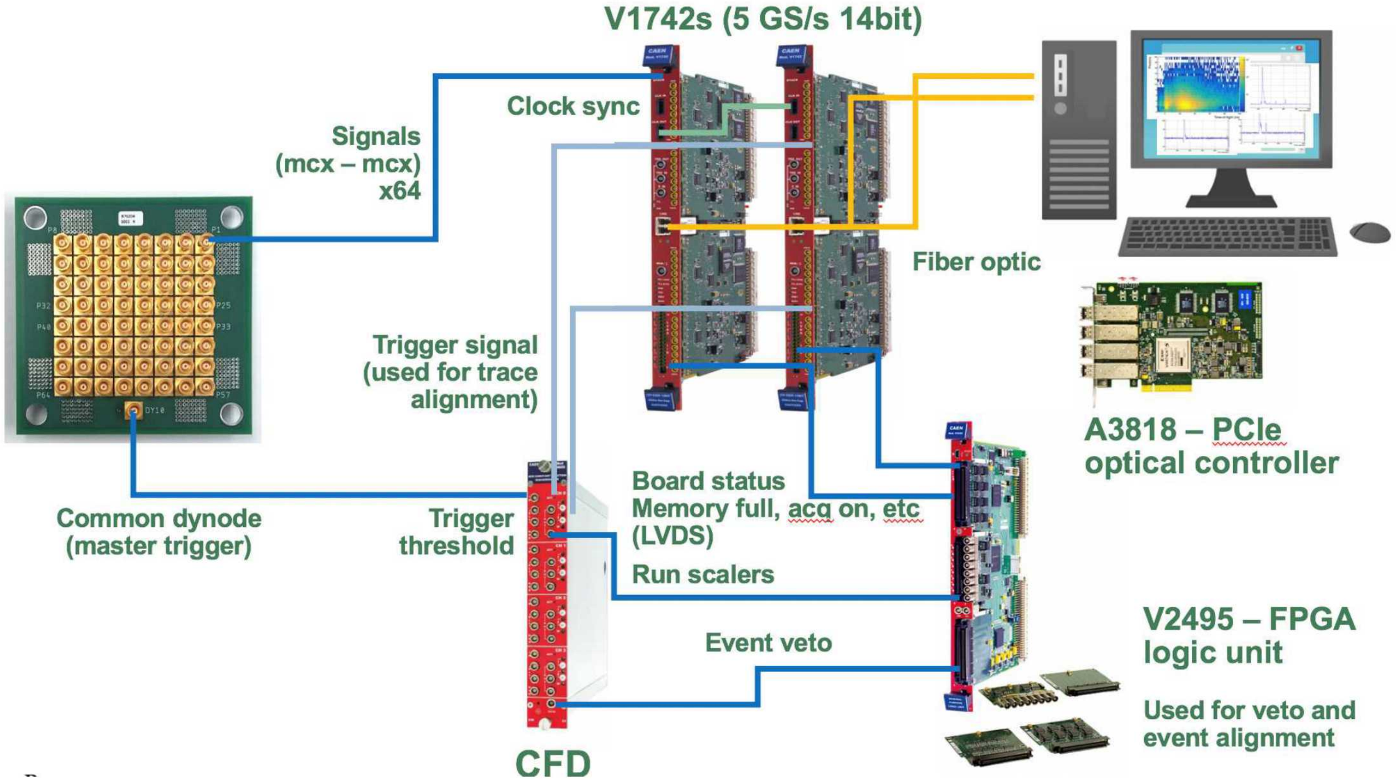


SiPM (Hamamatsu MPPC S13360-6075CS)

"single shot"



SVSC DAQ Hardware



- To preserve photoelectron times in recorded waveforms, prototype uses off-the-shelf CAEN V1742 digitizer package (DRS-4 chip: 5 GS/s, 12 bit)
- Each recorded event consists of 128 digitized channels with a trace length of 1024 samples (this could be reduced ~ 4× to record 50 ns)
- Data rate is ~100 kB per event per PMT; 6 PMTs and 1000 events/s gives ~600 MB/s.

SVSC DAQ Software

- CAEN software supports single-board acquisition; ORNL-developed (via CADRE5) multiple-board acquisition that supports up to 12 - V1742 digitizers
- Software handles board synchronization, event alignment, DRS4 correction factors, first level data processing.
- Sustained trigger rate – 4 boards
  - 128+8 channels, 1024 samples / trace
  - 1500 Hz (Individual optical controller ports)
  - 210 MB/s data rate

```
Run Time (s):      8    | Curr Out Dir: ./rawData/Desired_Run_Title/N1023498

| Dig |    DRS4 Chip     |  Digi  | To Comp | Events |  Raw   |  Comp  | To File |  File  | Current
| Num |   Temperatures   | Status |   Lag   |  Comp  |  Size  |  Size  |   Lag   |  Size  | File
==================================================================================================
|   0 | 42, 42, 42, 42 | Normal |       0 |    735 |   41MB |   34MB |       0 |   33MB | Digitizer_00.dat.0000
|   1 | 42, 42, 42, 42 | Normal |       0 |    735 |   41MB |   34MB |       0 |   33MB | Digitizer_01.dat.0000
|   2 | 42, 42, 42, 42 | Normal |       0 |    735 |   41MB |   34MB |       0 |   33MB | Digitizer_02.dat.0000
|   3 | 42, 42, 42, 42 | Normal |       0 |    735 |   41MB |   34MB |       0 |   33MB | Digitizer_03.dat.0000
|   4 | 42, 42, 42, 42 | Normal |       0 |    735 |   41MB |   34MB |       0 |   33MB | Digitizer_04.dat.0000
|   5 | 42, 42, 42, 42 | Normal |       0 |    735 |   41MB |   34MB |       0 |   33MB | Digitizer_05.dat.0000
|   6 | 42, 42, 42, 42 | Normal |       0 |    735 |   41MB |   34MB |       0 |   33MB | Digitizer_06.dat.0000
|   7 | 42, 42, 42, 42 | Normal |       0 |    735 |   41MB |   34MB |       0 |   33MB | Digitizer_07.dat.0000
|   8 | 42, 42, 42, 42 | Normal |       0 |    735 |   41MB |   34MB |       0 |   33MB | Digitizer_08.dat.0000
|   9 | 42, 42, 42, 42 | Normal |       0 |    735 |   41MB |   34MB |       0 |   33MB | Digitizer_09.dat.0000
|  10 | 42, 42, 42, 42 | Normal |       0 |    735 |   41MB |   34MB |       0 |   33MB | Digitizer_10.dat.0000
|  11 | 42, 42, 42, 42 | Normal |       0 |    735 |   41MB |   34MB |       0 |   33MB | Digitizer_11.dat.0000
==================================================================================================

Available Commands
    Stop  - Stops the run
    Quit  - Stops the run and exits the DAQ

?>
```

Text-based user interface

Output

Ancillary Files

For a system taking data from N digitizers, there are 2*(n+1) files generated in addition to the compressed data files

- `index.json` - The file that is passed to the reader object/library at analysis time. It contains paths to the other (2*n + 1) files relative to itself. It is written at the start of the run.
- `cfg.json` - All of the configuration information for the complete system stored in a single file. It contains all overall parameters and all digitizer parameters. It can be read back in by the main `daq` program as well as be queried from the reader object. This is written out at run start
- `Digitizer_XY_CorrData.csv` - The correction data for the DRS4 chips that are read from digitizer number `XY` and written out in csv format for each run. This is written at run start.
- `Digitizer_XY_Metadata.json` - The metadata for all the raw data files for digitizer `XY`. This file is written every time a raw data file for that digitizer is closed. (So in the event of a crash, only, at most, one file per digitizer is made unreadable.)

Raw Data Files

In addition to the ancillary files, a number of files containing compressed raw data from the digitizers are produced. Each digitizer has a number of these, all listed in the `Digitizer_XY_Metadata.json` files. These files consist of a set of variable length blocks which have an 8 byte header and some number of bytes after it (specified in the header) which can be decompressed in using either the `ZSTD_decompressDCtx` function (faster for buld decompression since you allocate the context externally rather than it repeatedly regenerating a context) or the `ZSTD_decompress` function which does not require an externally allocated context but is slower because of that.

Data Block Format

- Two byte block separator value 0xbfff (little endian format)
- Two byte number of events (little endian format)
- Four byte number of bytes in the compressed data block (does not count the header) (little endian format).
- N bytes of compressed data (N specified in the 4 bytes immediately preceding the block) containing the number of events given in the header.
  - The decompressed data is in a format identical to the format extracted from the digitizer.

External Library List

- 0) Intel Threading Building Blocks (https://www.threadingbuildingblocks.org/)
  - License: Apache 2.0 License (permissive)
- 1) Boost C++ Libraries (https://www.boost.org/)
  - License: Boost License (permissive)
- 2) ncurses - Terminal UI library (https://www.gnu.org/software/ncurses/)
  - X11/MIT License (permissive)
- 3) JSON for Modern C++ (https://github.com/nlohmann/json)
  - MIT License (permissive)
  - Header only and already pulled into the `SvScDaq` git repository
- 4) Zstd - Fast real-time lossless compression library (http://www.zstd.net)
  - BSD License (permissive)
- 6) CAEN Optical Link Driver (http://www.caen.it/csite/CaenProd.jsp?idmod=627&parent=36)
  - Propietary CAEN License
- 6) CAEN VME Library (http://www.caen.it/csite/CaenProd.jsp?idmod=689&parent=38)
  - Propietary CAEN License
- 7) CAEN COMM Library (http://www.caen.it/csite/CaenProd.jsp?parent=38&idmod=684)
  - Propietary CAEN License

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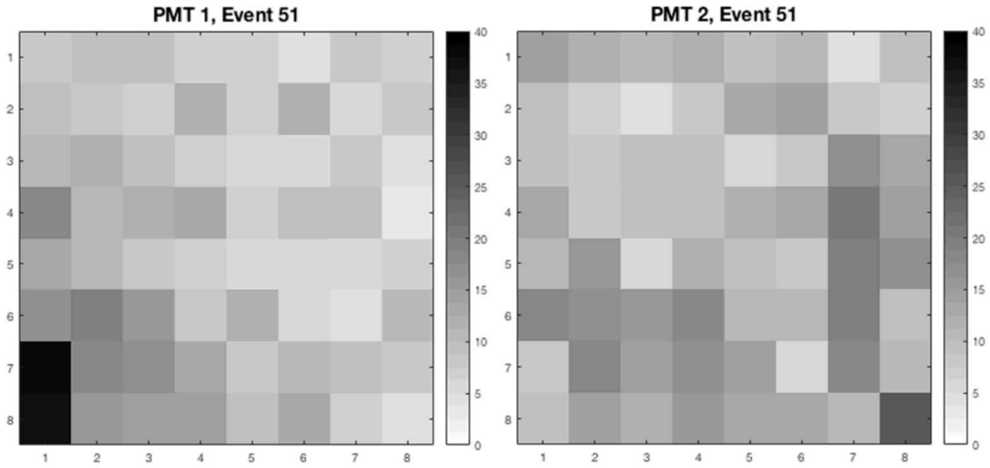
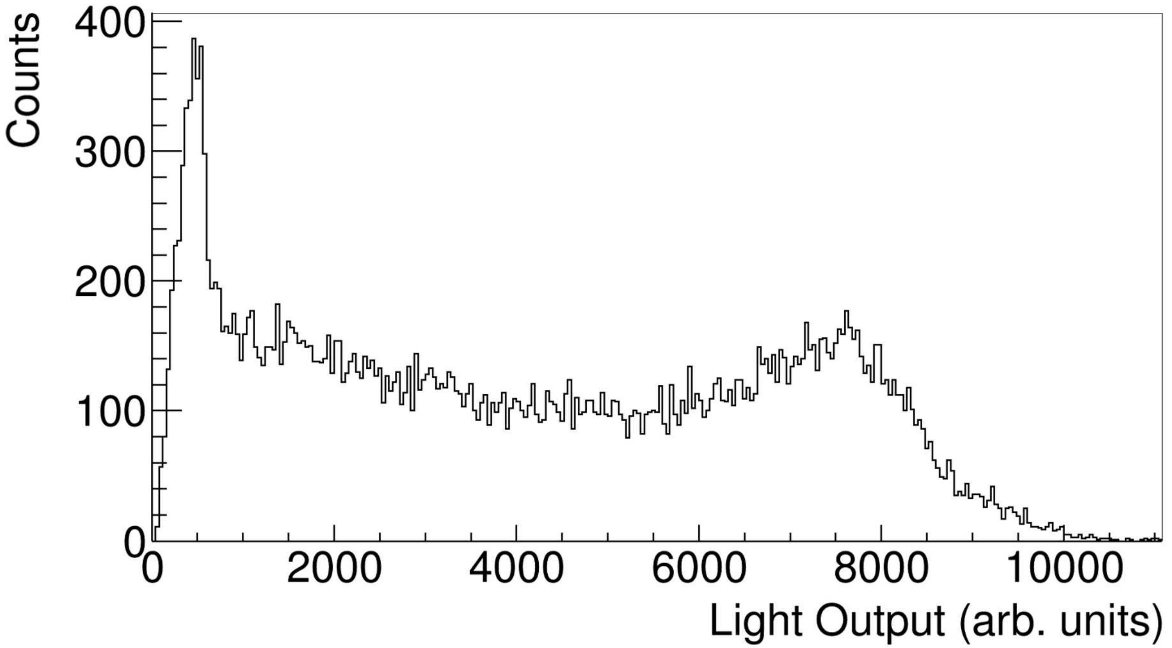
Initial Testing: Cs-137 Spectrum

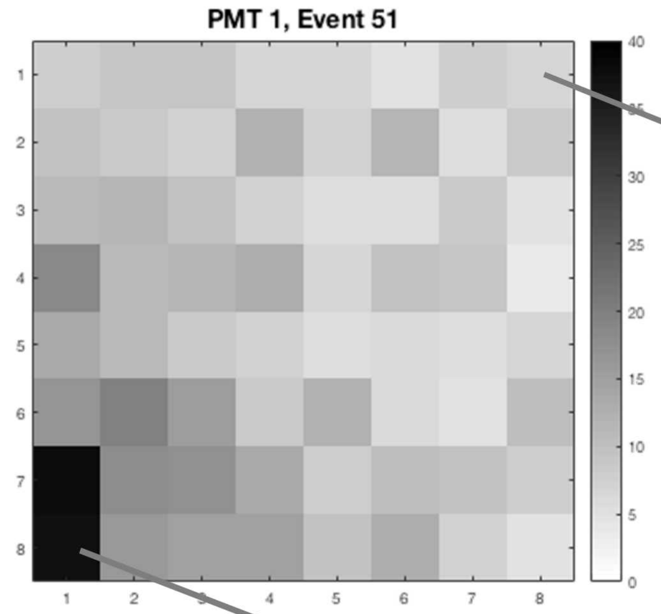
Example hit map in approximate PE #

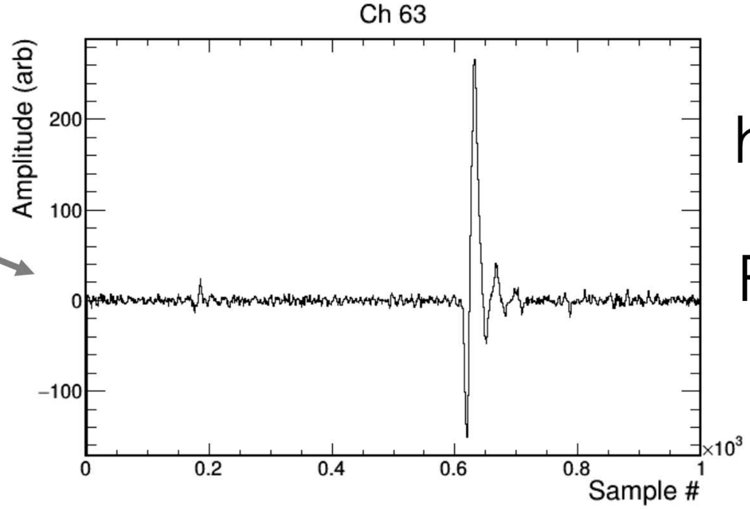




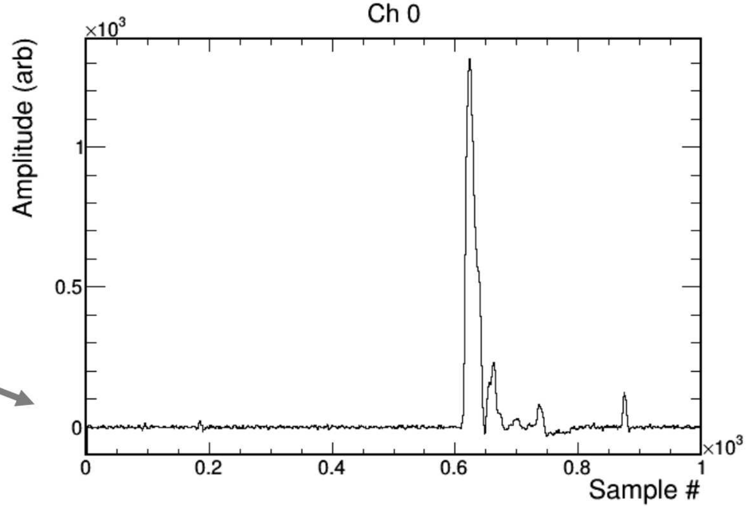
- Cs-137 data used to to build spectrum from individual anodes (exercises gain matching, time alignment of 128 PMT anodes)
- Waveforms used to extract photoelectron hit times…

Example PMT Hit Map





Most pixels have a small fraction of PMT charge; these look bad. Why? Cross talk.



A few pixels may have a large fraction of the PMT charge; these look ok

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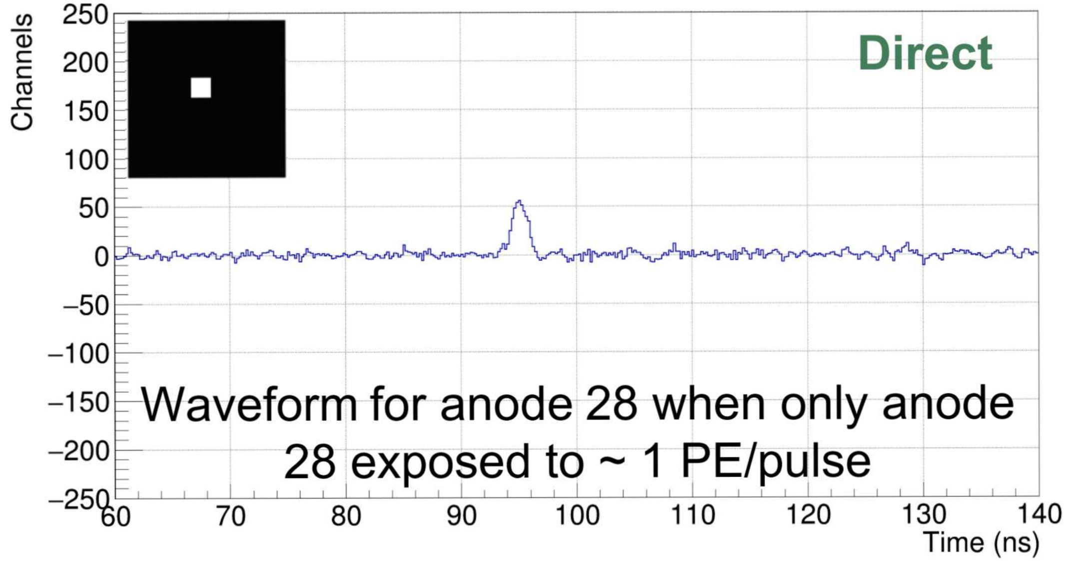
Example Cross Talk with Uniform Illumination



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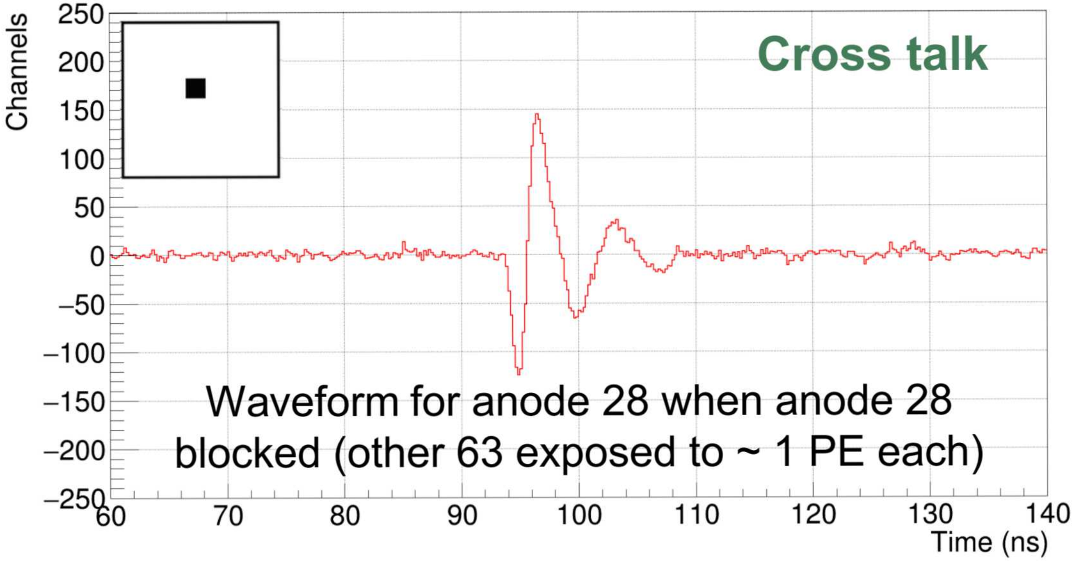

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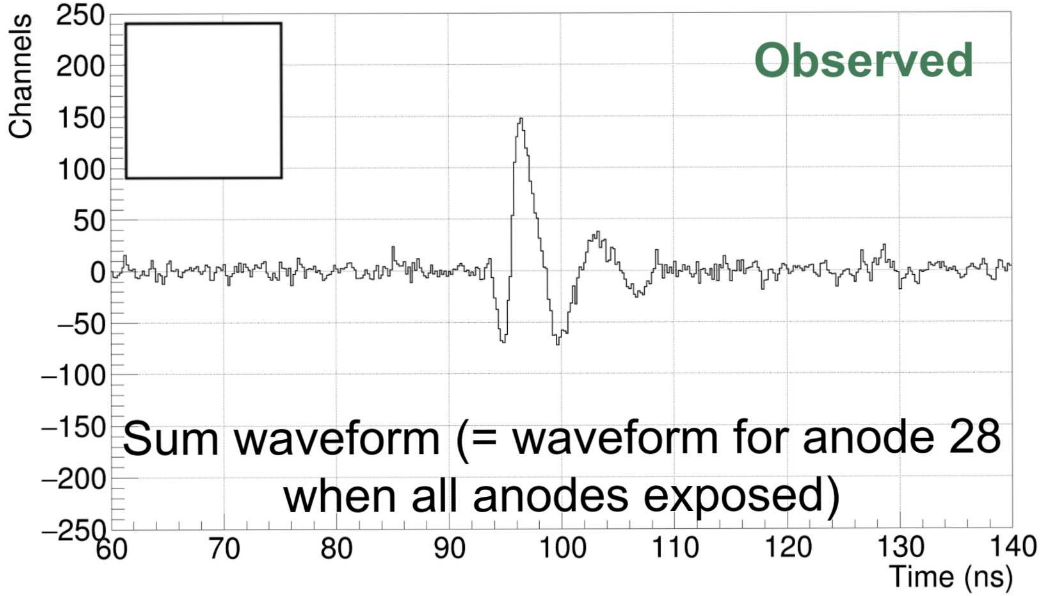

Uniformly exposed PMT to ~ 1pe/anode using laser and diffuser. Each anode gets ~1/64th of total.

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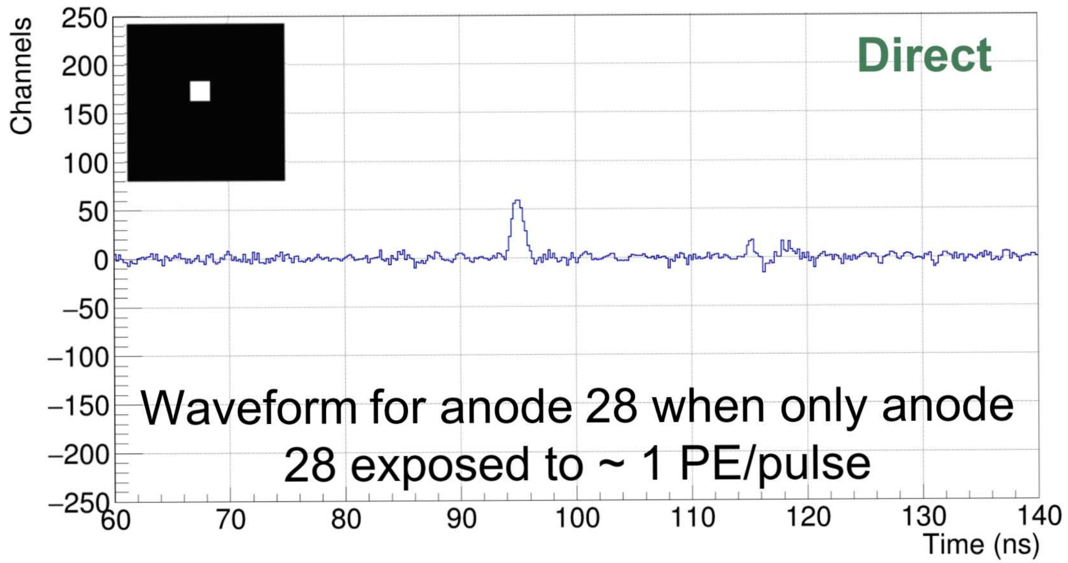
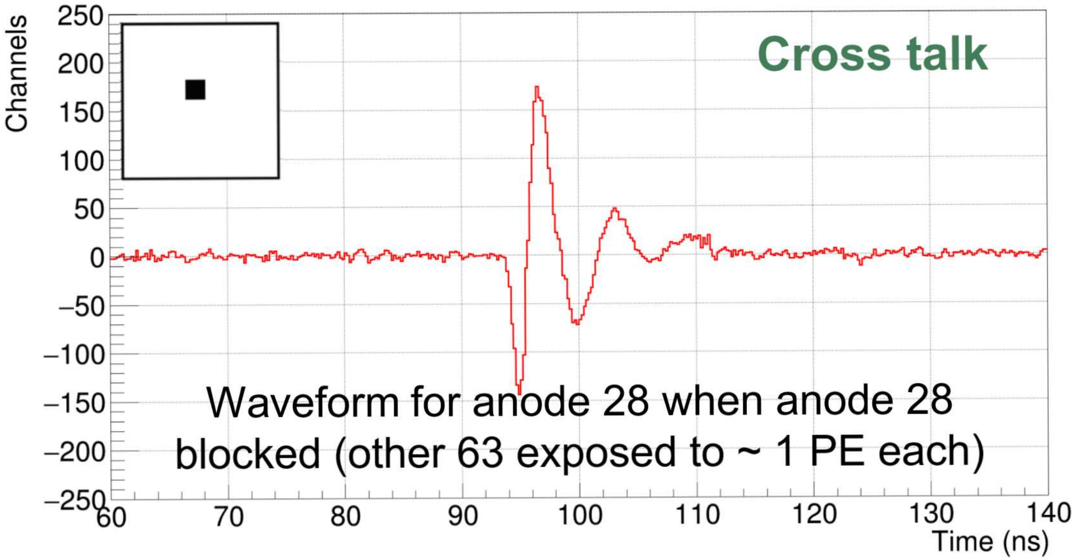
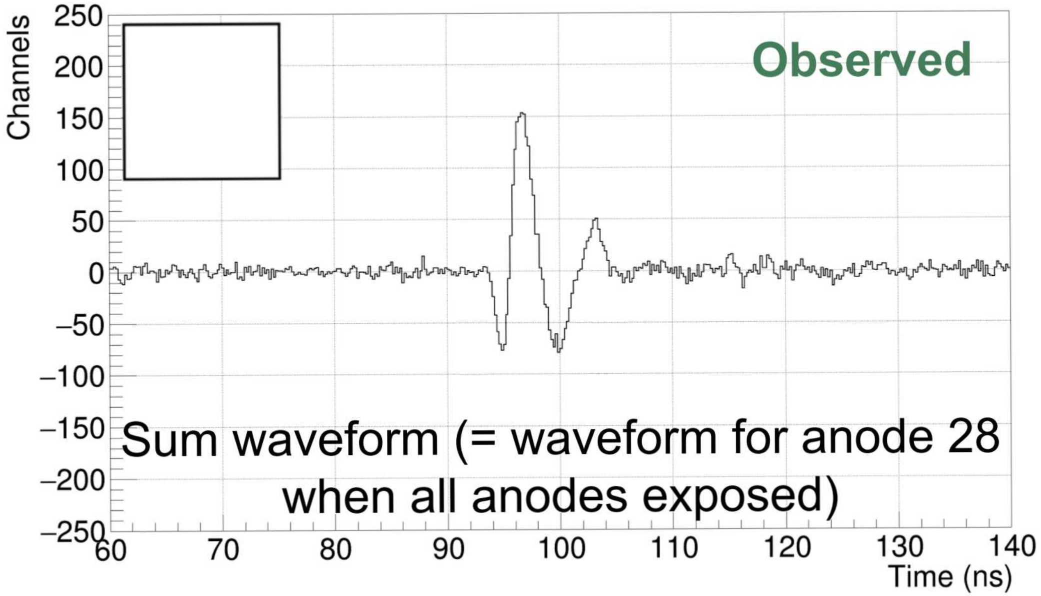
Example Cross Talk with Uniform Illumination



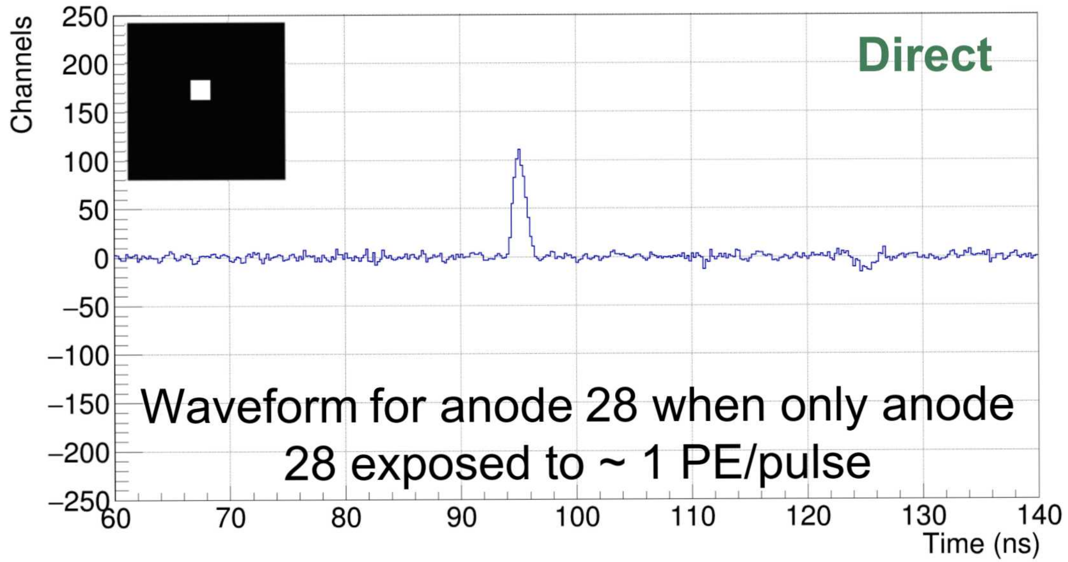
+



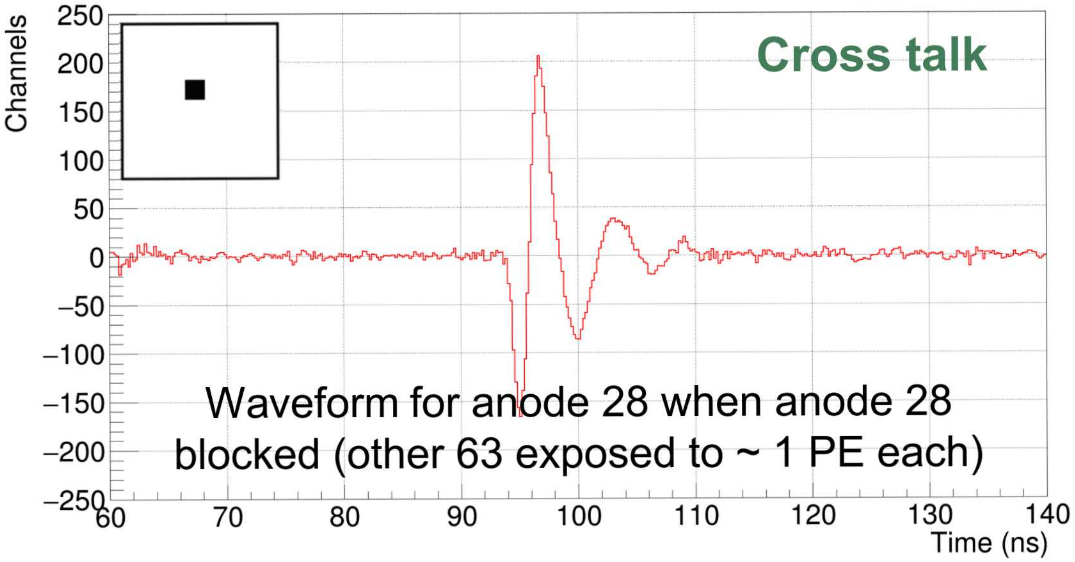
=



Example Cross Talk with Uniform Illumination



+



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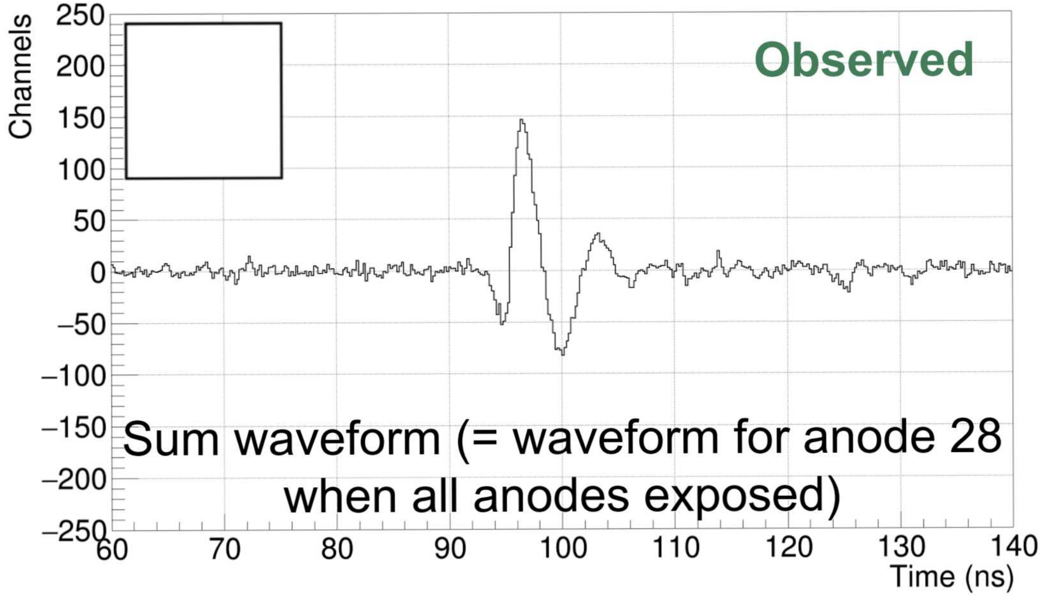
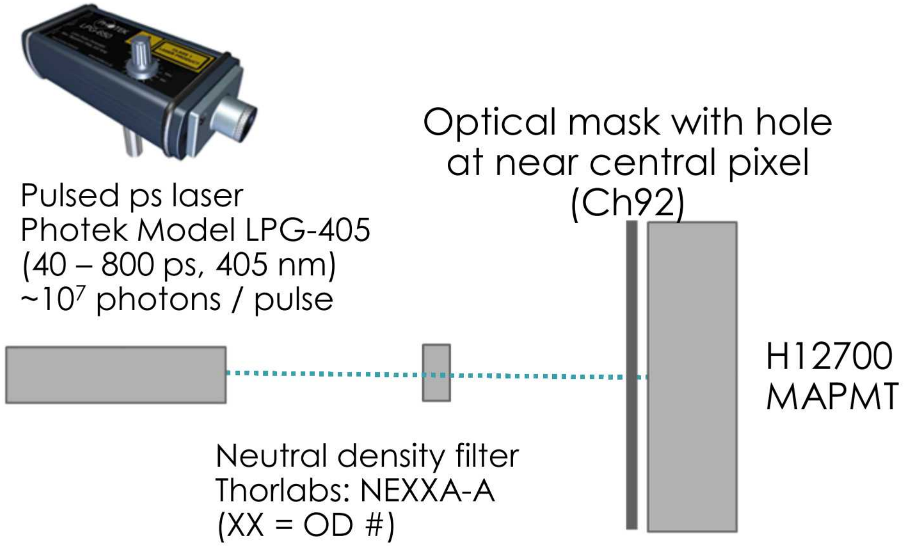
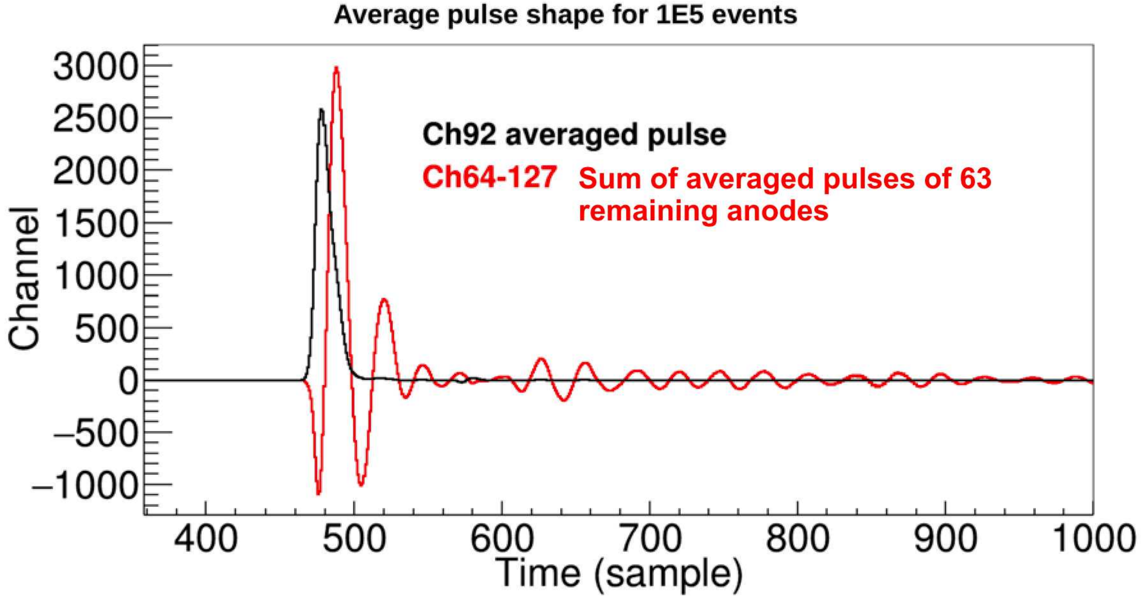
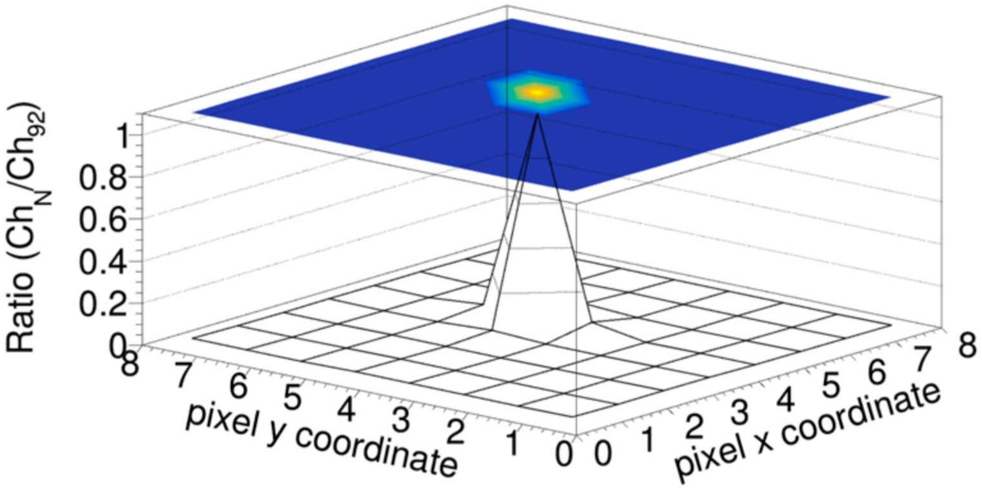


Average Magnitude of Cross Talk





- Signal in one anode induces a few percent cross talk in every other anode due to coupling of anode pixel through common dynode
- Not fixable in hardware



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Compensating for Cross Talk

- Initial tests suggest cross talk from each anode sums, so

Response matrix ↓

Waveforms → $y = Ax$ ← Photoelectron hit pattern (anode, time)

- Can infer x from y, A via

$$x^{j+1} = x^j + CA^T R(y - Ax^j)$$

(C and R contain the inverse of the columns and rows of A)

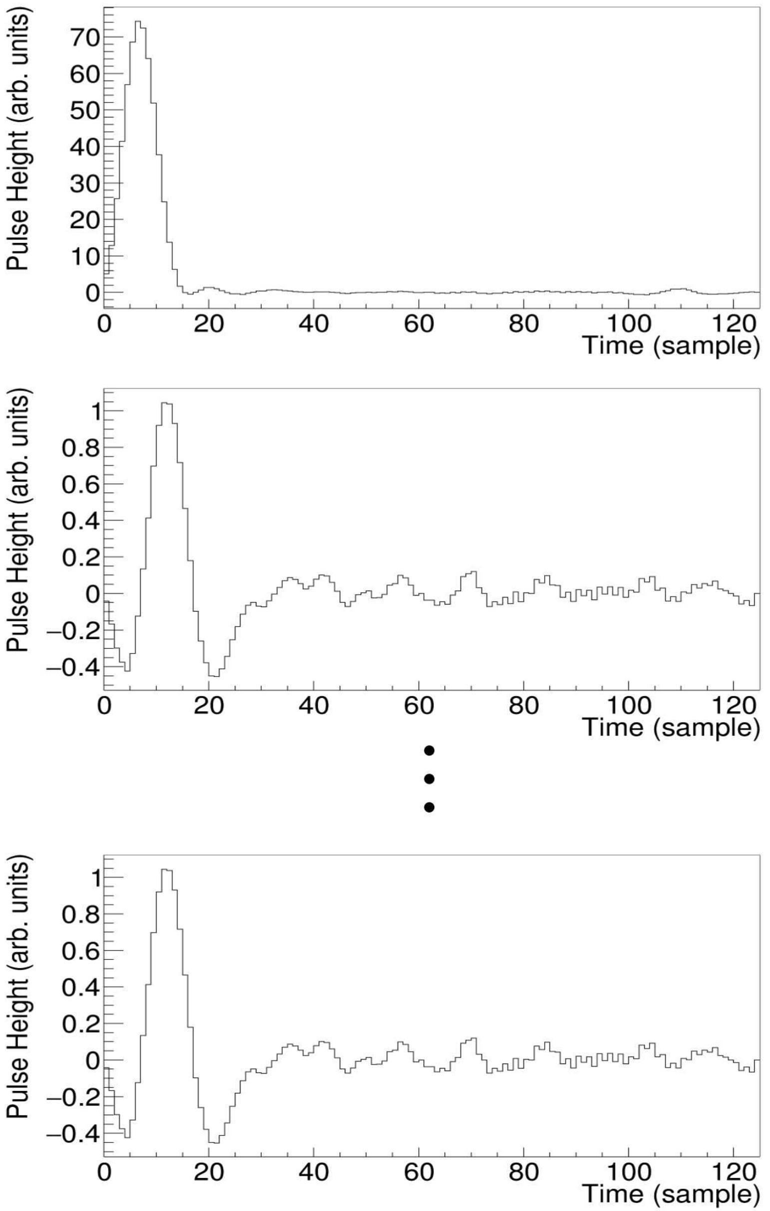
Response to one photoelectron

Anode 1

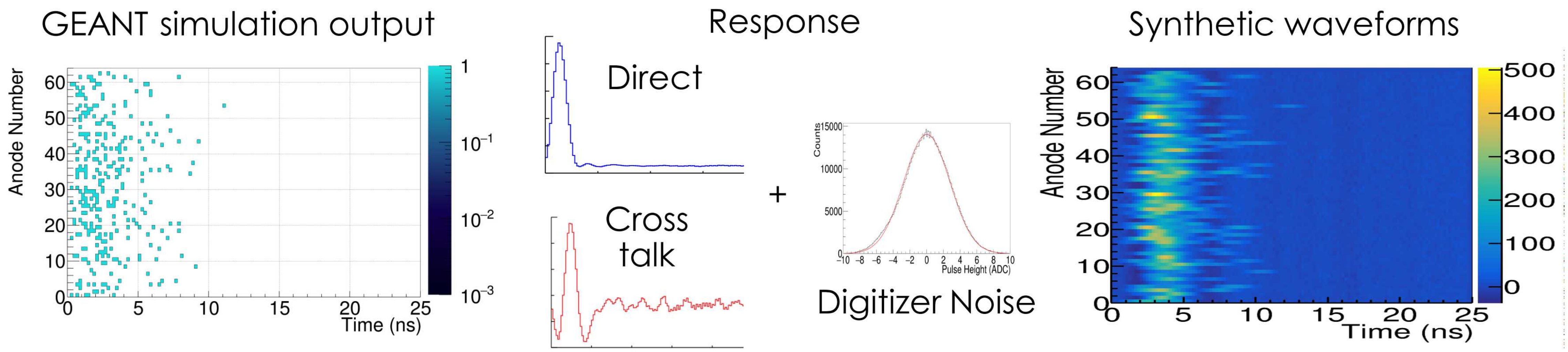
Anode 2

⋮

Anode 64

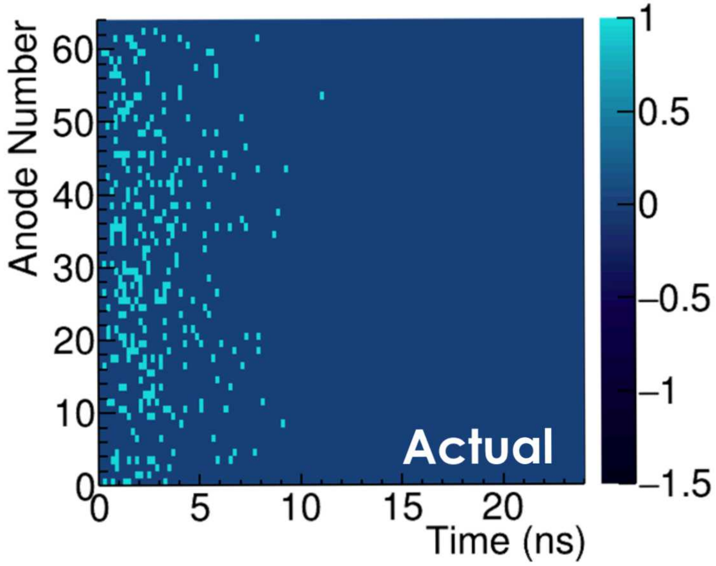


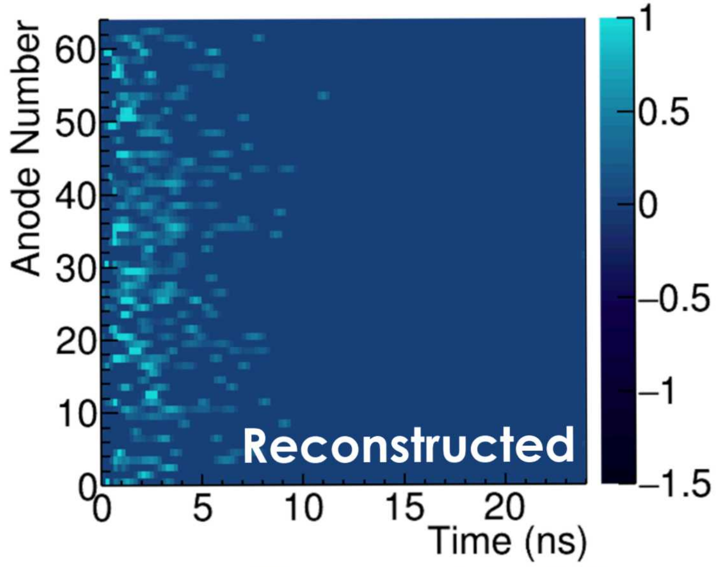
Synthetic Data

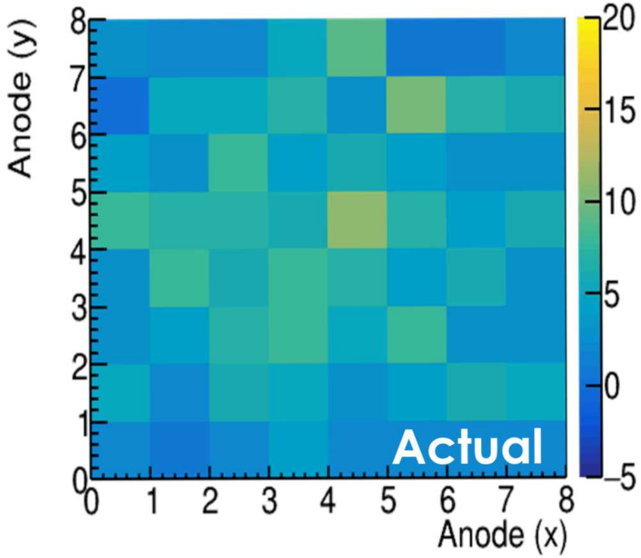


- Does PE reconstruction work for synthetic data?
- Use GEANT-simulated photoelectron arrival times by anode to generate synthetic waveforms using response matrix A + added noise
- Then, reconstruct original hit pattern using iterative method

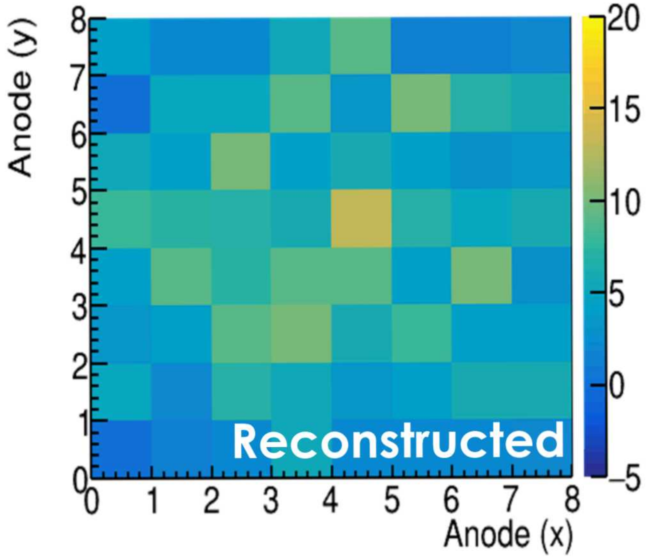
Actual and Reconstructed Hit Patterns

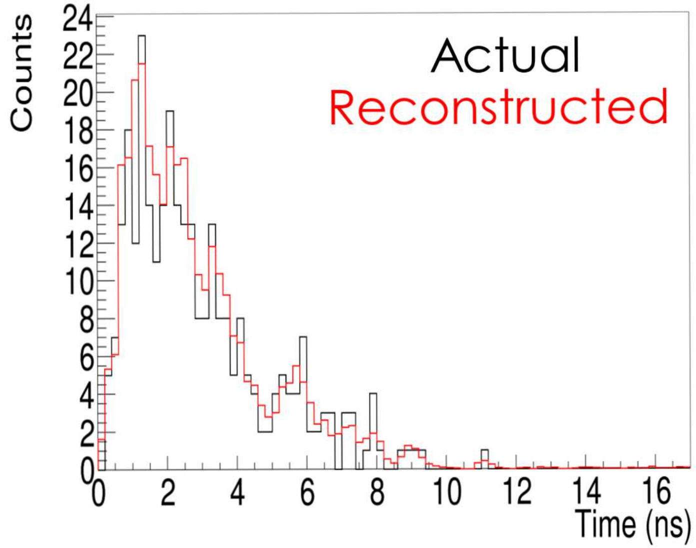






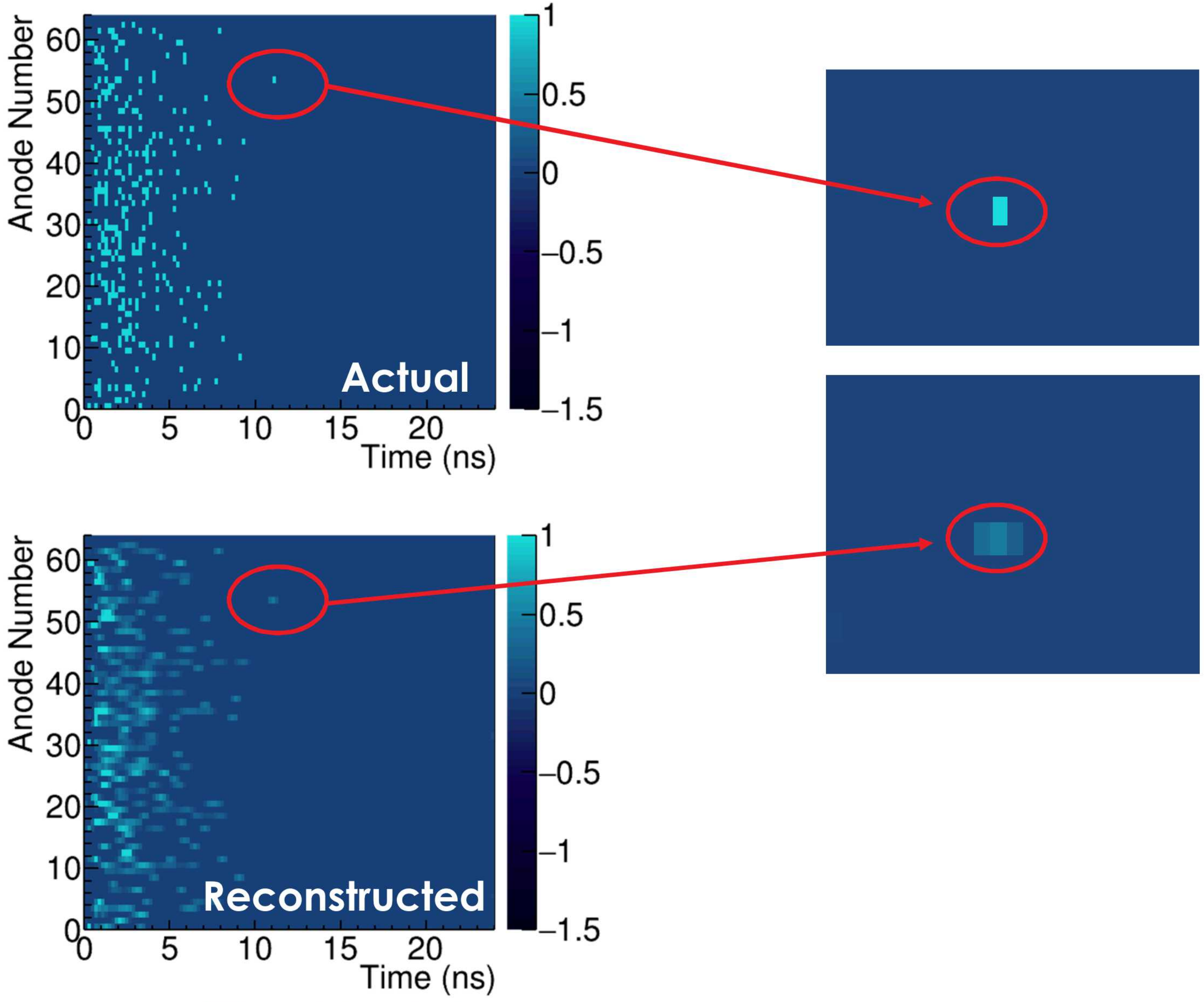
Projection on anodes

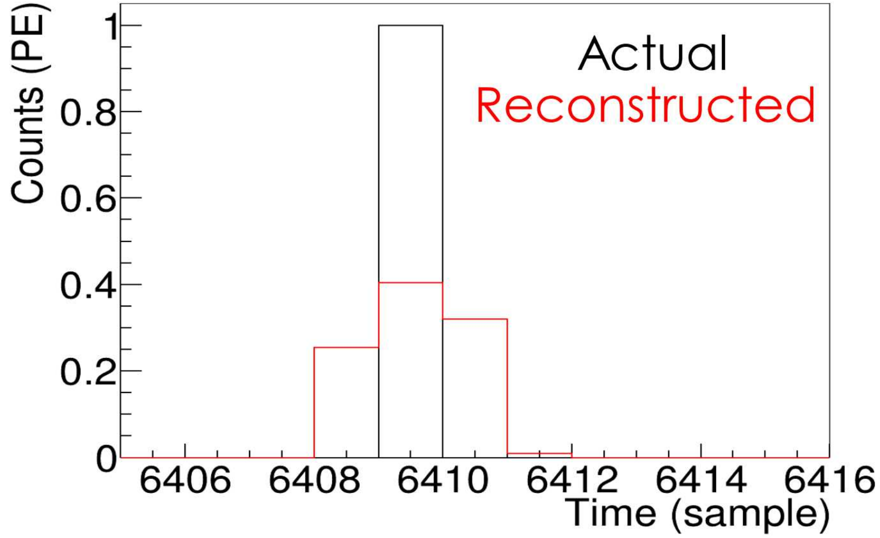




Projection on time

Actual and Reconstructed Hit Patterns





- Area preserved
- Centroid preserved (at level of tens of ps)
- Width is increased to ~500 ps

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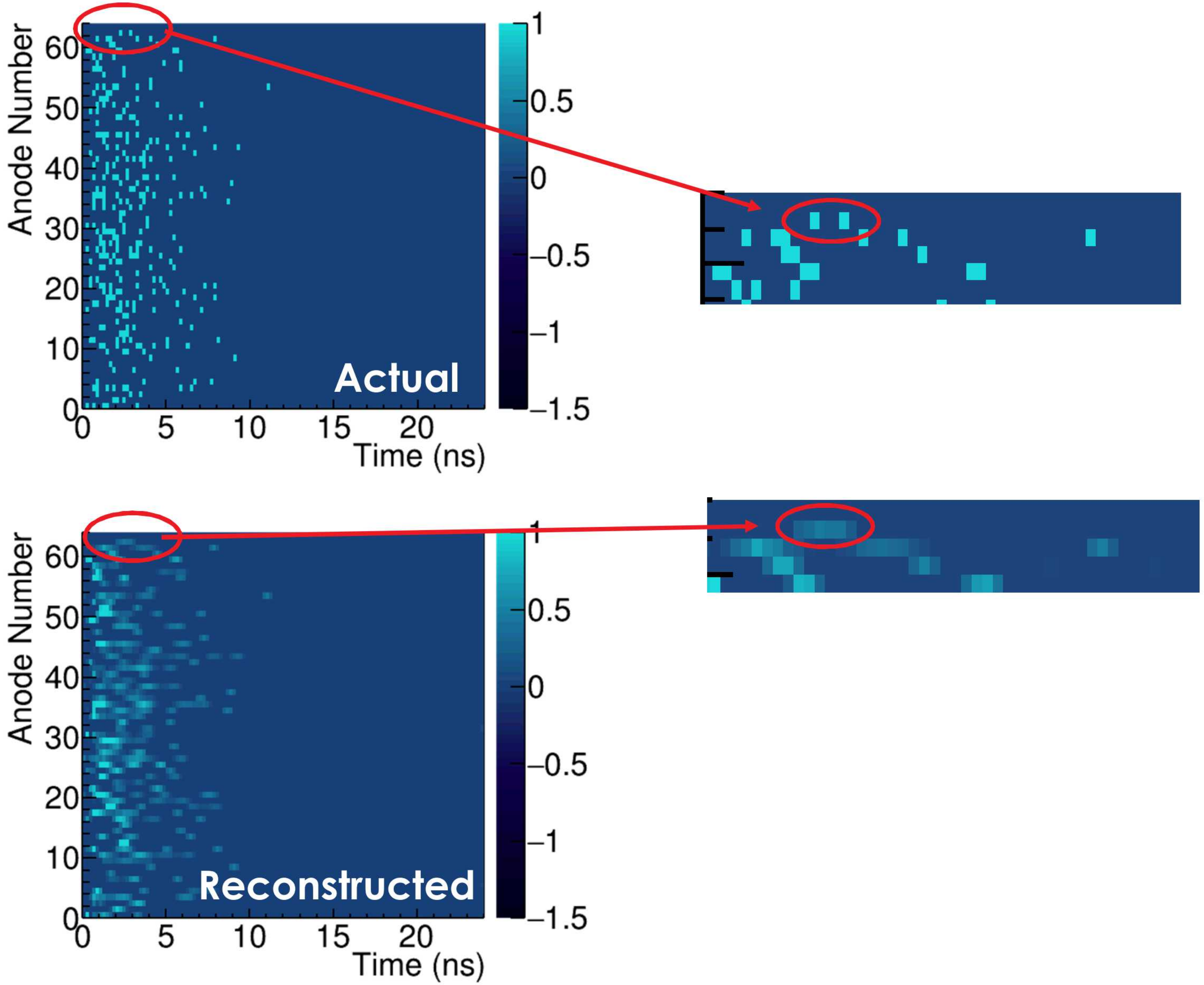
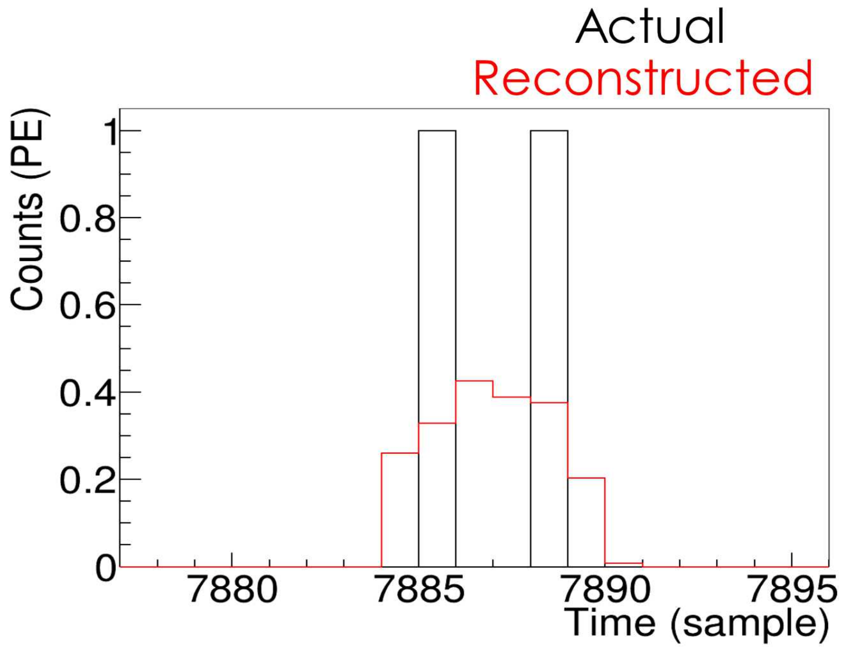
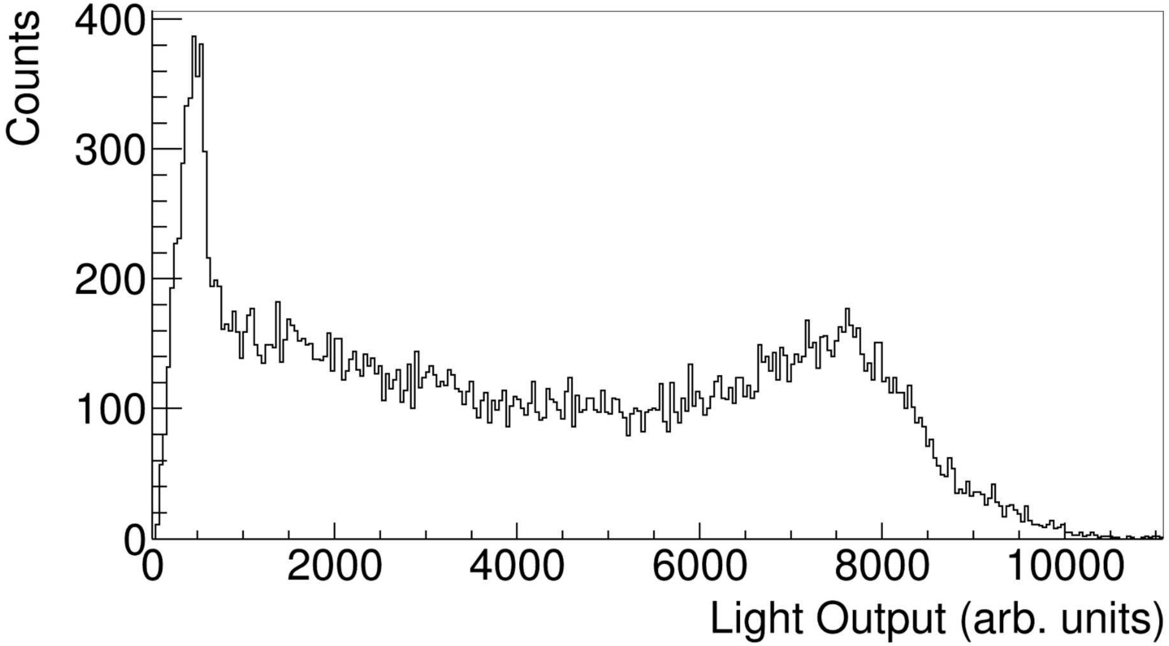
Actual and Reconstructed Hit Patterns

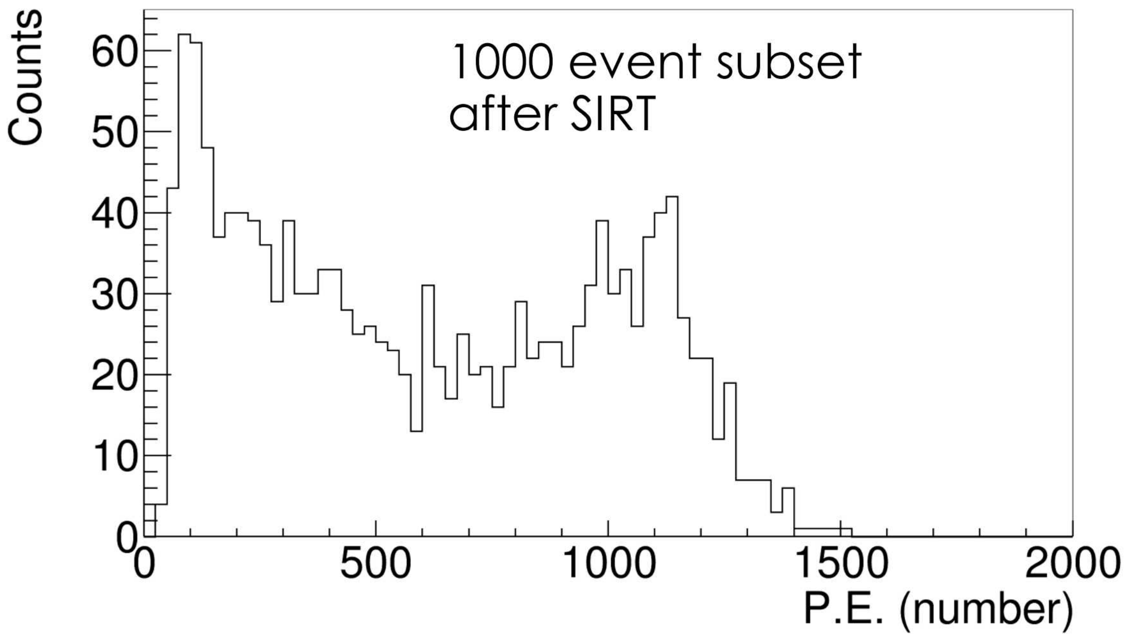




- Area preserved
- Centroid preserved (at level of tens of ps)
- Width is increased to ~500 ps

Cs-137 Spectrum Revisited



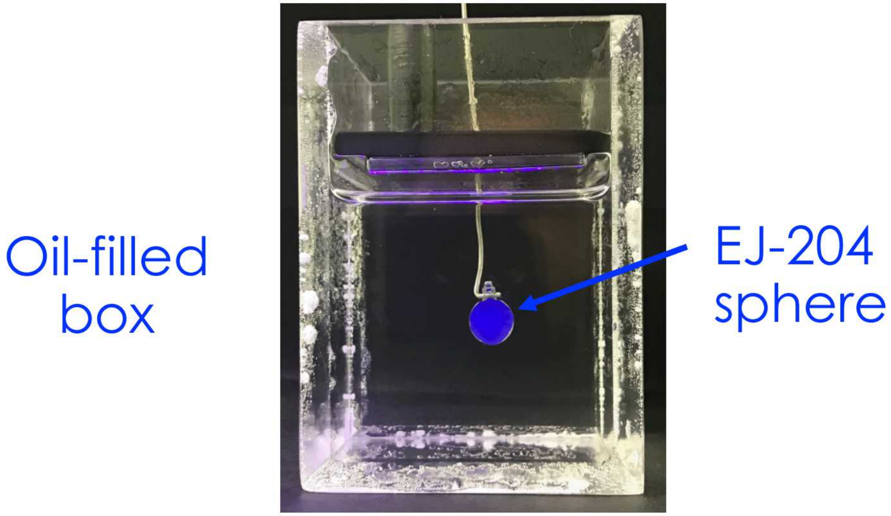


- Number of photoelectrons in Compton edge appears correct given expectations for scintillator light output, QE, CE.

Monolithic Status

- Instrumented monolithic prototype
  - EJ-204 scintillator cube, two 64-anode H12700 PMTs, and DAQ that uses 4 CAEN V1742 digitizer boards and can sustain 1500 events/sec
- Calibration of PMTs (gain, QE, timing)
  - Performed using Photek LPG-405 laser and opaque masks to select anode
- Cross talk
  - PMTs exhibit significant cross talk when they are uniformly illuminated; cross talk appears to sum linearly
  - Developed iterative code to reconstruct PEs from waveforms in presence of cross talk (need to speed up)
  - Presently testing reconstructions of measured data

Future Work



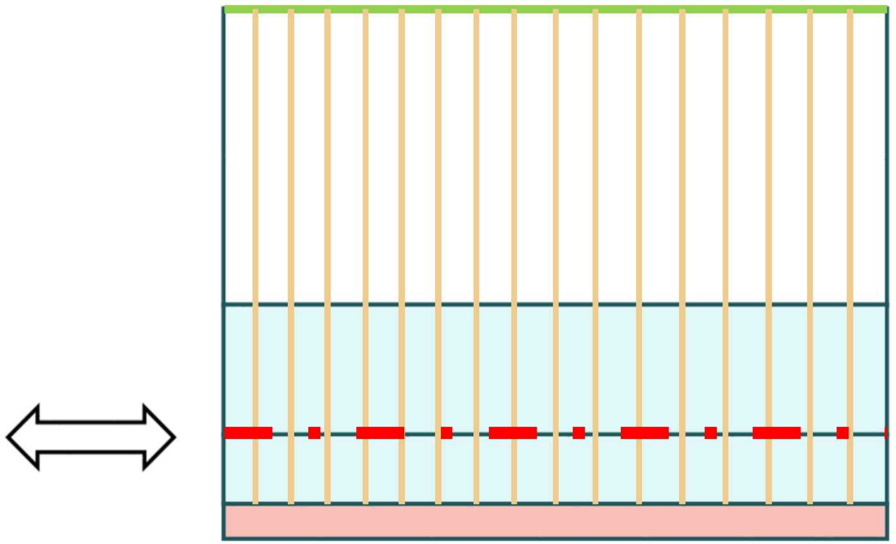
Experiment

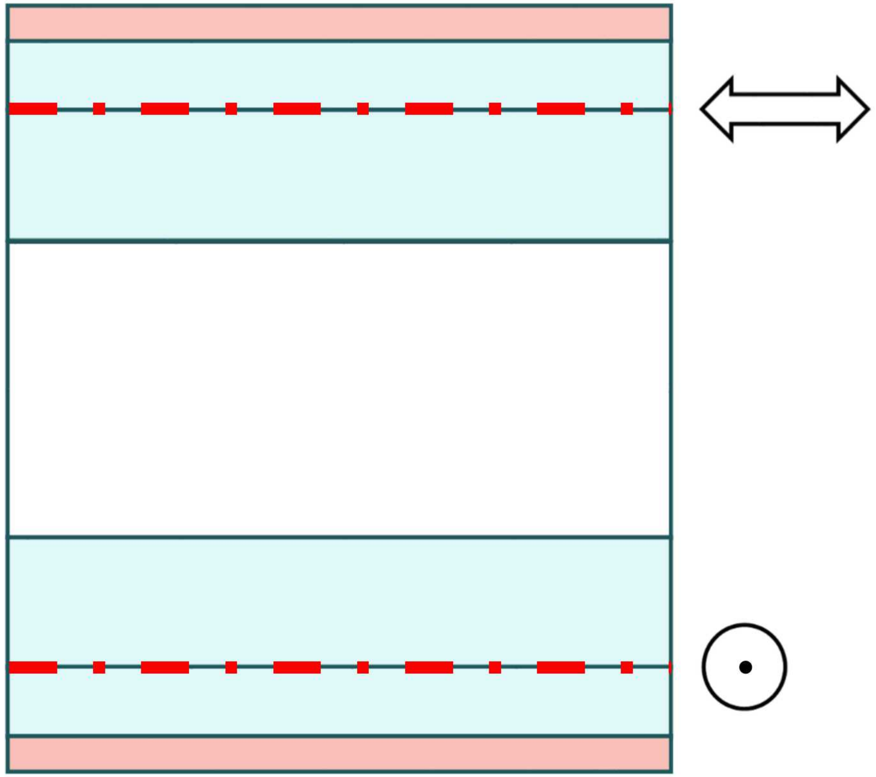
- Single & multisite localization with scintillating spheres at known locations
- Neutron imaging with partial readout (2-sides), tagged Cf neutron source

Simulation

- Event reconstruction
  - Understand limitations on position and time resolution due to: variation in photoelectron amplitude, dark current and/or misattributed photoelectrons, increased time uncertainty, and reduced photosensors (1-5 rather than 6)
  - Understand effect of reconstructing for incorrect number of interactions
- Imaging
  - Identify limiting factors for imaging resolution in prototype imager

Optical Coded-Aperture Readout

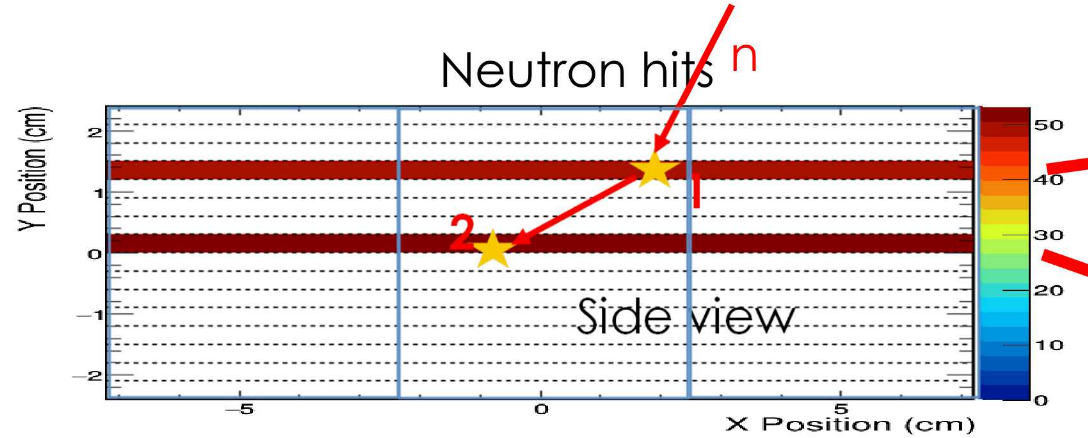




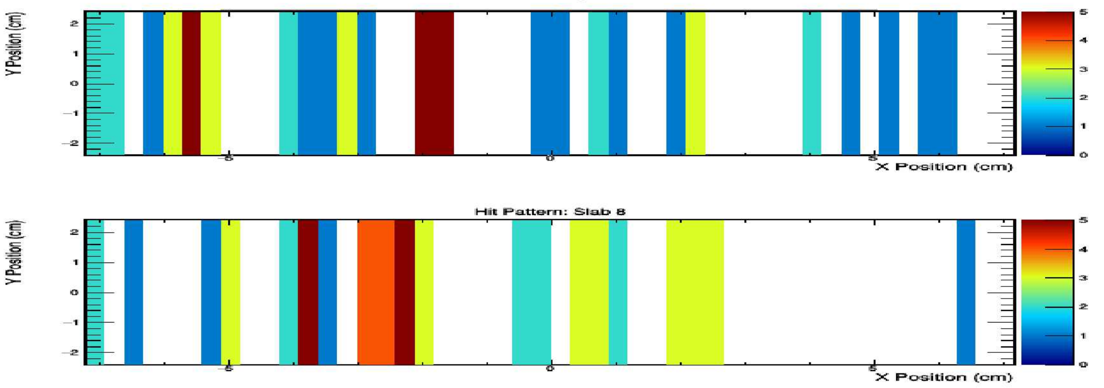
- Start with monolithic design
- Add optical features (CA mask) between scintillator and sensor
- Does this help?
- Two designs: one with optical segmentation, one without

OCA Event Reconstruction: Sample Event

Neutron hits



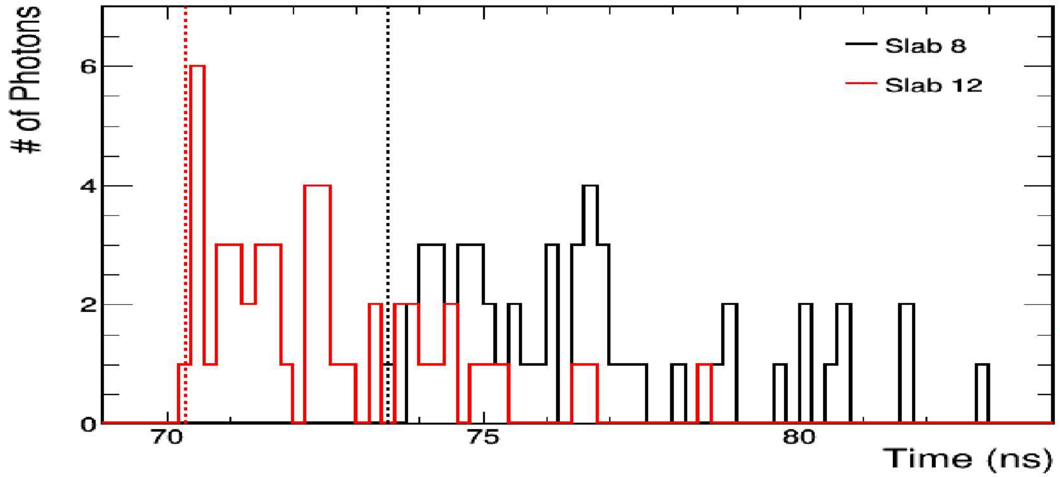
PMT-PE hit patterns



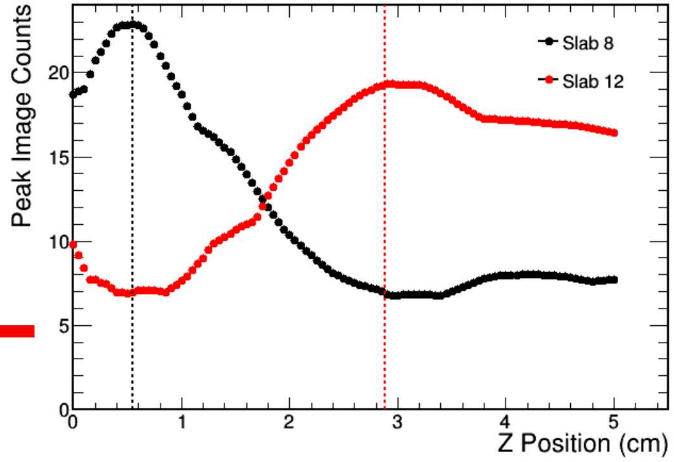
- Recoil 1: 675 keV deposited, 49 photons detected in slab 12
- Recoil 2: 544 keV deposited, 53 photons detected in slab 8

Reconstruct positions

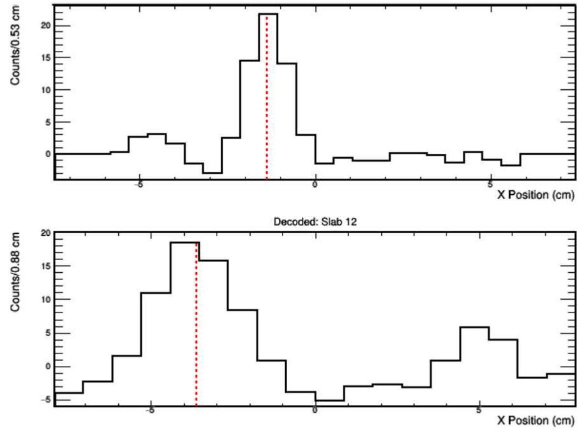
PMT hit times give position-corrected time



Reconstructed Z position



Reconstructed X position



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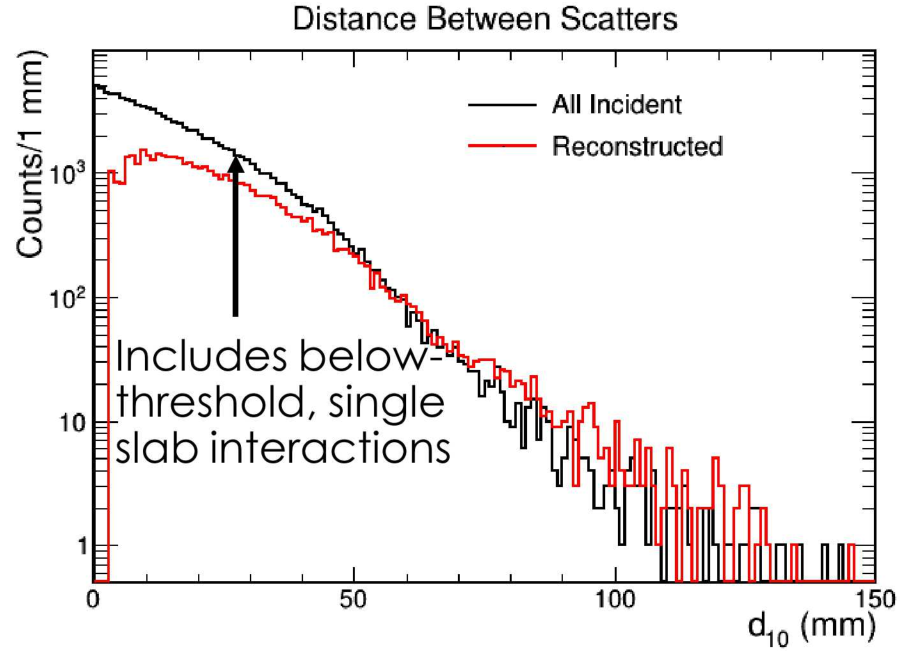
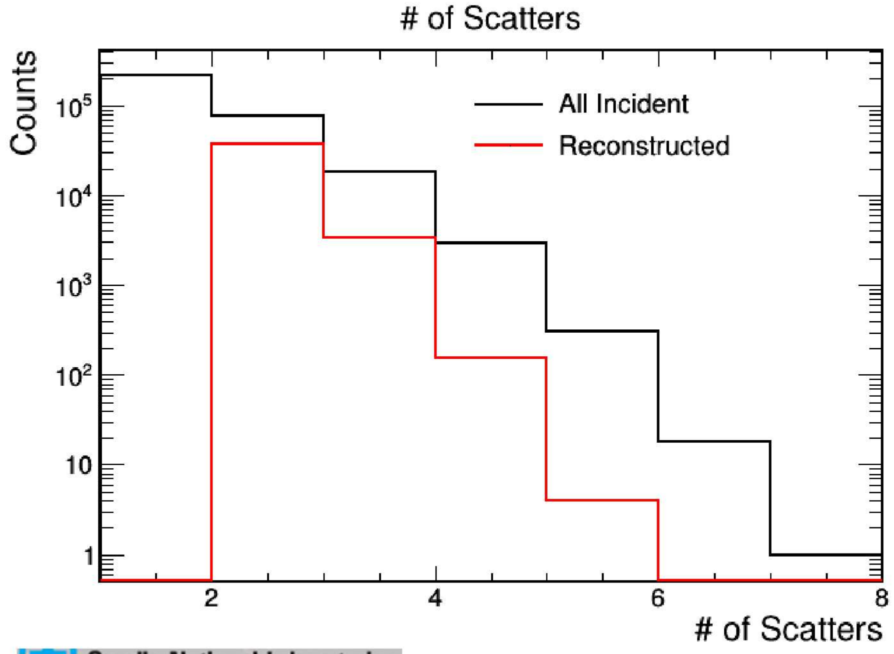
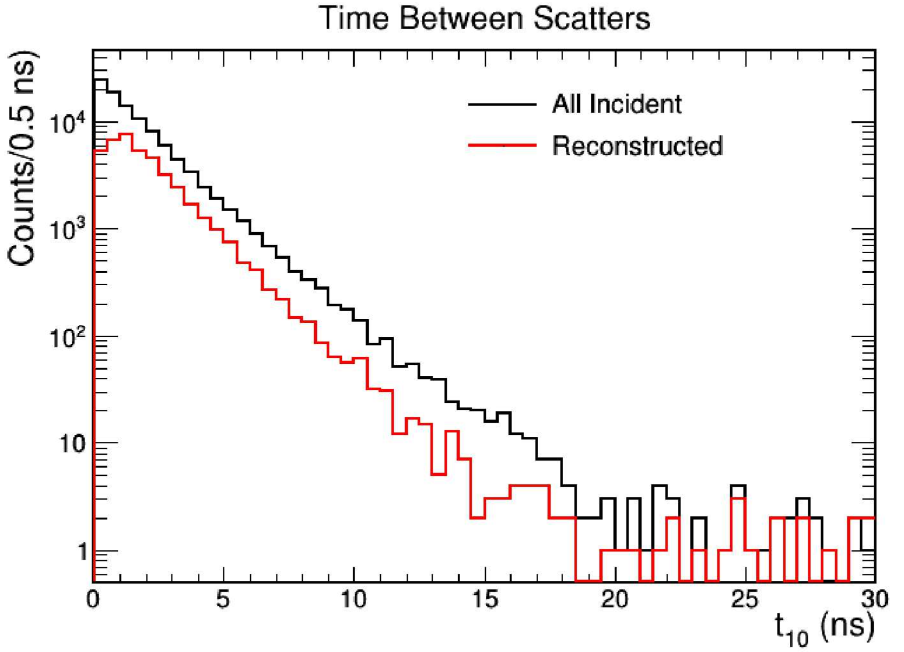
Results

- ^{252}Cf point source 1 m away (+z)
- 320k recoils in detector
- Select events in which 2+ slabs trigger with > 10 photons each
- 41796 reconstructed



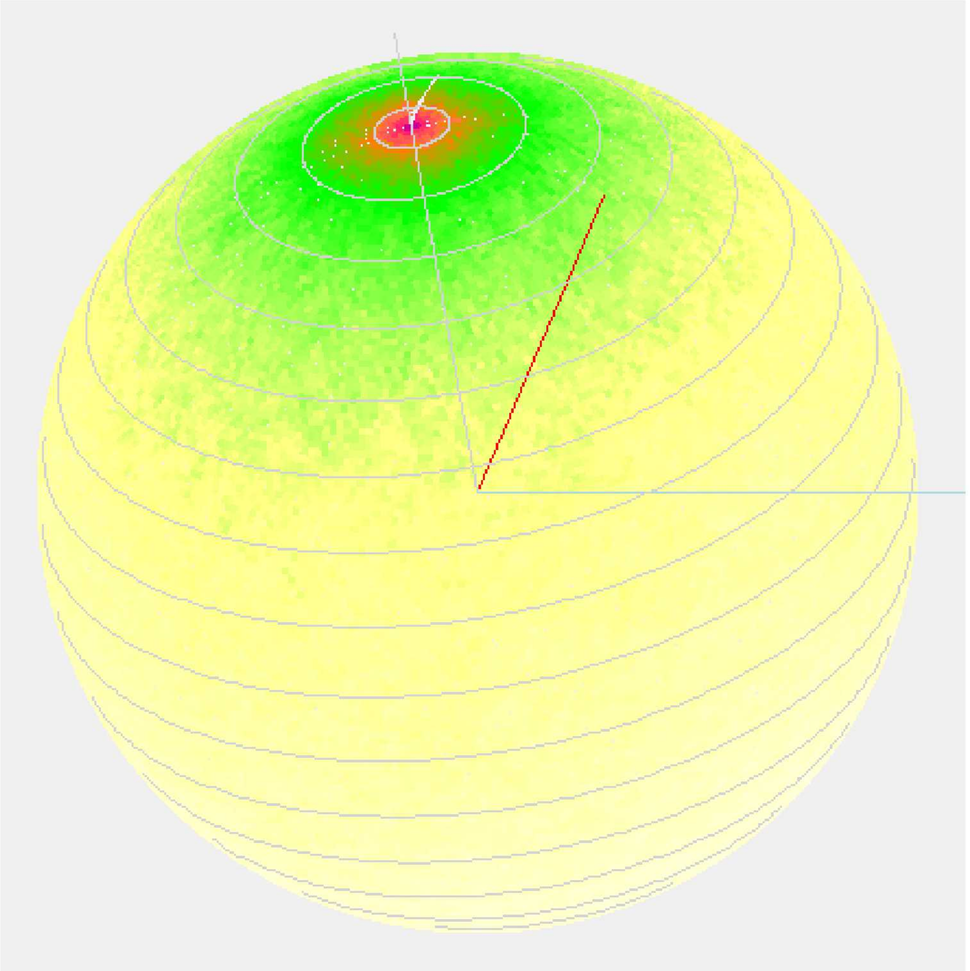




Results Summary

- Image created using simple back-projection
- 41.7k events
- ~25° FWHM

Simulations and upcoming experimental measurements performed by Micah Folsom, UTK graduate student (defending this fall)



	ΔX (mm)	ΔZ (mm)	E_p (keV)	Δt (ps)	E_n (keV)	Δd_{10} (mm)	Δt_{10} (ps)	Δθ (rad)
σ	2.67	3.87	72.8	259	412	4.34	425	0.197
FWHM	3.77	5.83	145	595	479	6.86	846	0.220

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