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An Optically Segmented Single-Volume Scatter Camera for Compact, High-efficiency Neutron Imaging

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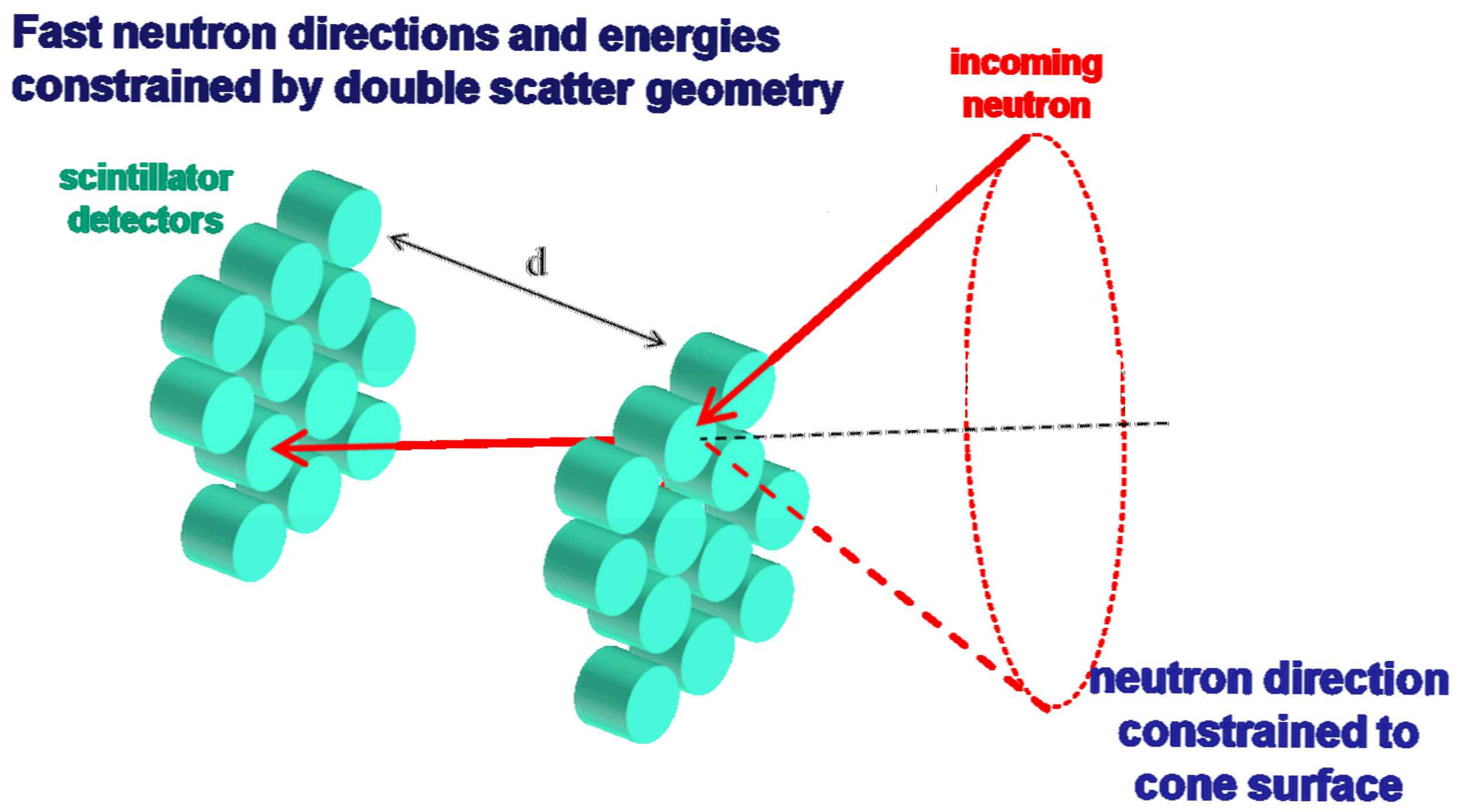
SVSC Project Team

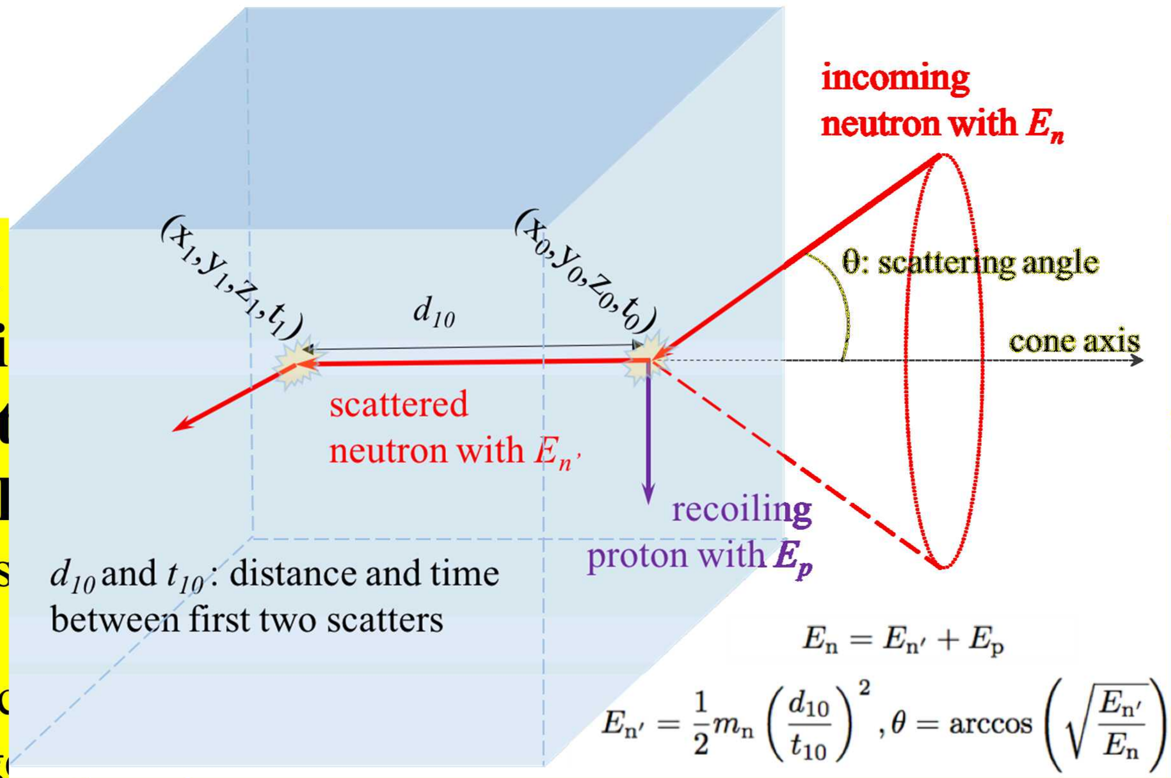
- Participants: Six institutions
  - SNL/CA (lead): E. Brubaker, M. Sweany, J. Brown, J. Steele, B. Cabrera-Palmer, et al.
  - ORNL: P. Hausladen, K. Ziock, M. Febbraro, M. Folsom, J. Nattress, et al.
  - ANL: J. Elam, A. Mane, M. Gebhard, A. Letorneau
  - U Hawaii: K. Nishimura, J. Learned, A. Druetzler, 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

Classic approach to neutron imaging



Single-volume approach

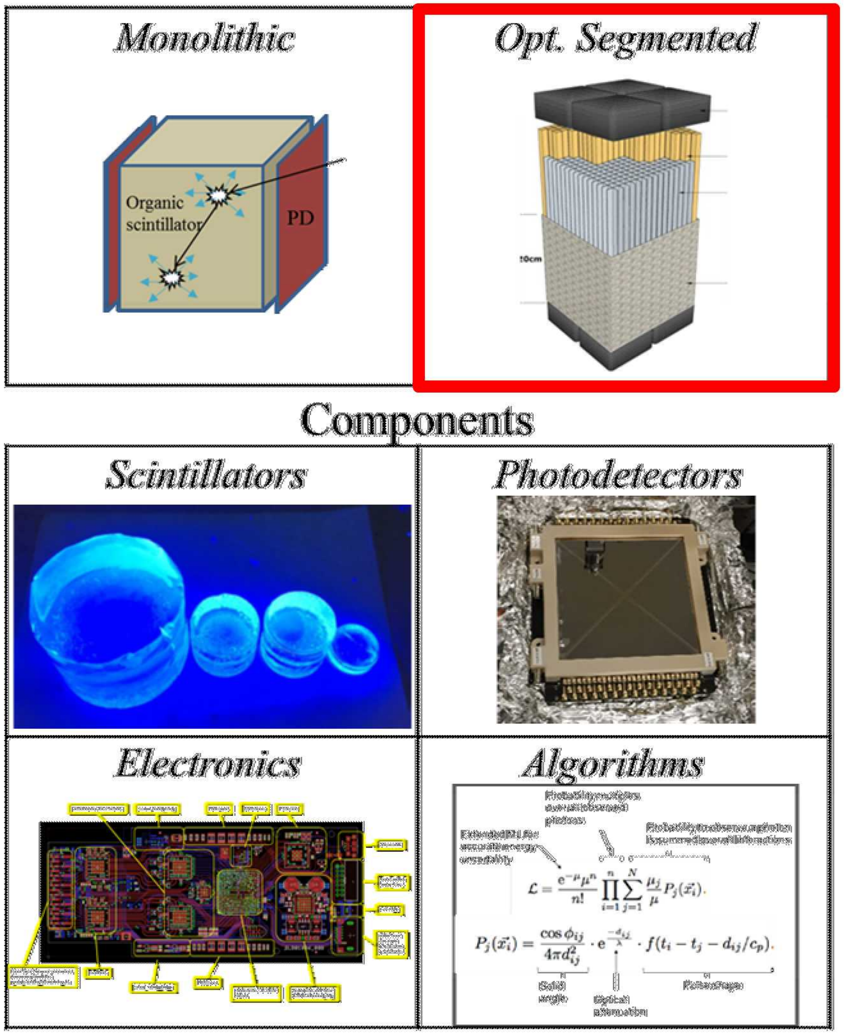
- **Two planes → single volume**



Real-world
- **High effi**
- **Compact** ch
- **Potential**
  - SNM s
  - Cargo
  - Arms c
  - Emerg

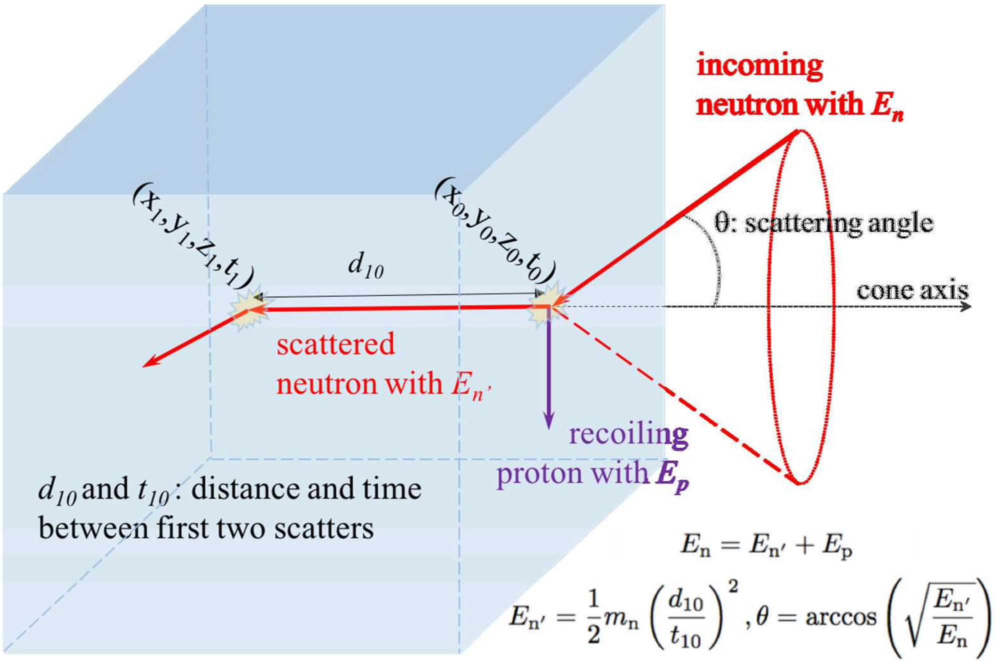
Single-Volume Scatter Camera (SVSC)

- **Two configurations:**
  - Monolithic scintillator (reconstruct positions and times from isotropically emitted photons)
  - Optically segmented scintillator (photon propagation constrained within specific channel)
- **Prototyping underway in concert with component development**



Proton light yield

- To calculate incoming neutron angle we must know the mapping between measured light and proton recoil energy (E_p), called the **relative proton light yield relation (PLY)**
- Previously measured PLY for the OS-SVSC candidate scintillators EJ-200, EJ-204, EJ-208: see Laplace, et al. NIM A (2018)
- **Presented here: PLY for EJ-230, EJ-232, and EJ232Q**

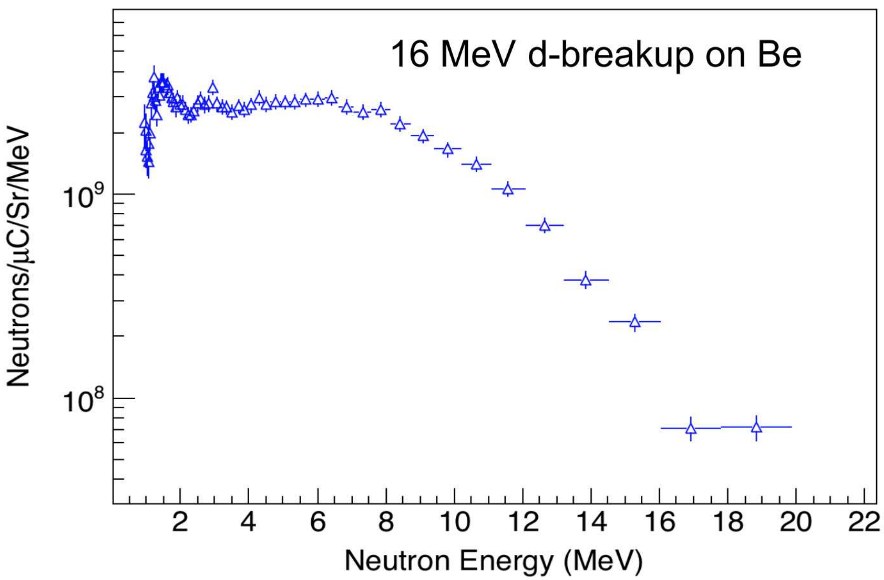


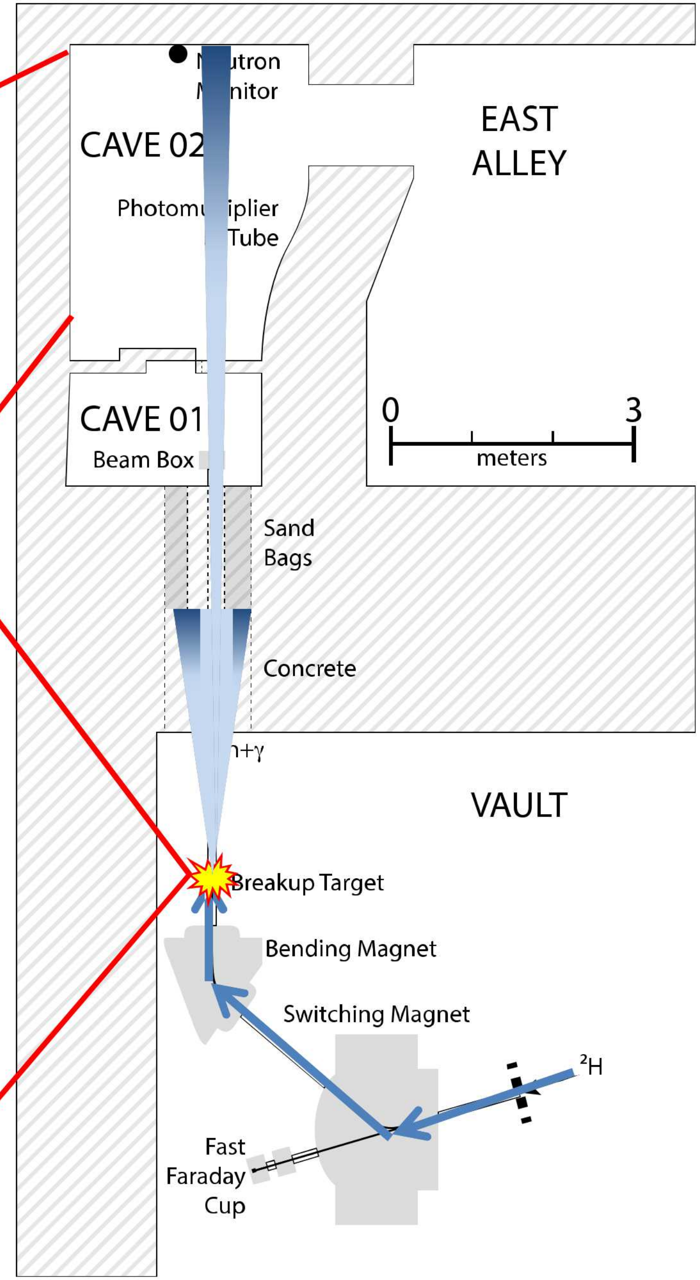
Material	Scintillation Efficiency (photons/MeVee)	Rise Time (ps)	Decay Time (ns)	Commercial Equivalents
EJ-230	9700	500	1.5	BC-420
EJ-232	8400	350	1.6	BC-422, NE-111A
EJ-232Q*	2900	110	0.7	BC-422Q

* 0.5% Benzophenone.

Sweany, et al. NIM A 927 (2019).

D-Breakup neutron source

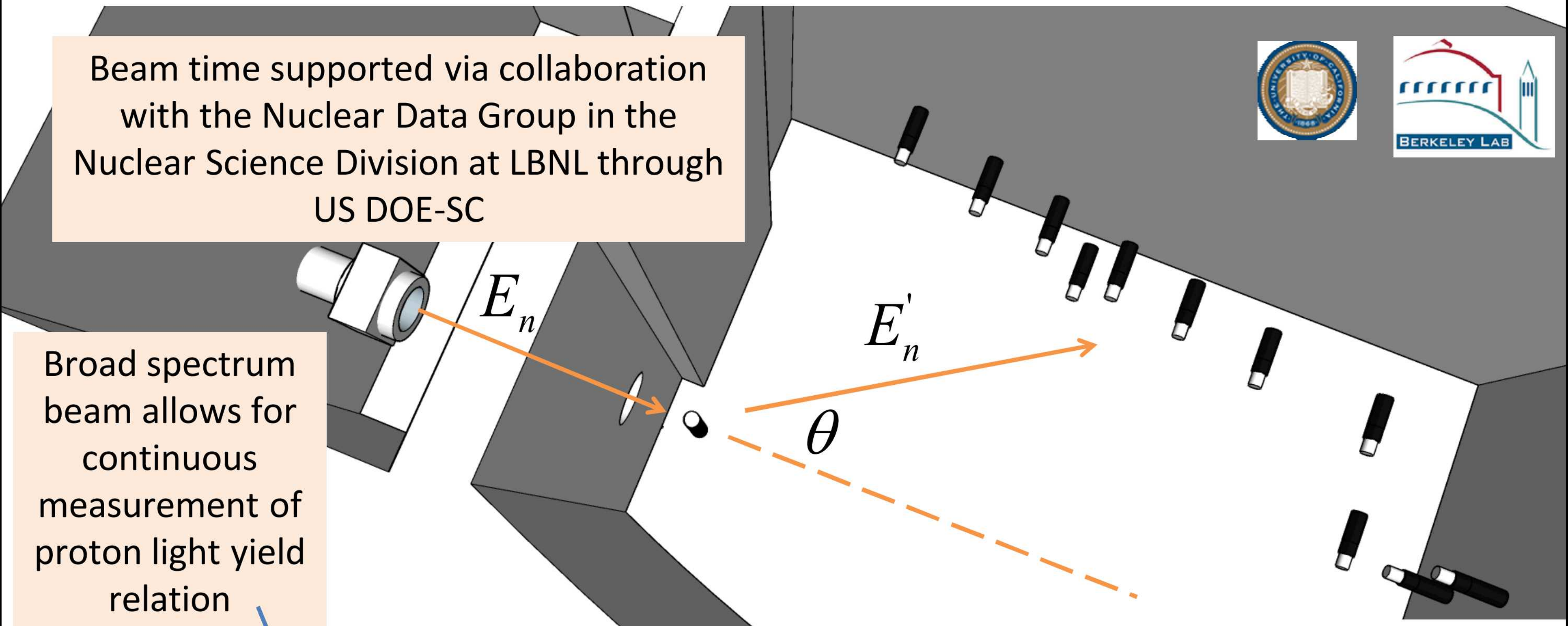




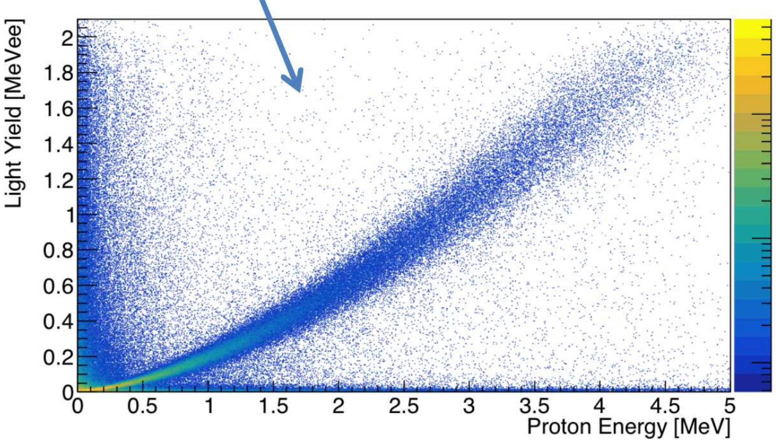
K.P. Harrig , B.L. Goldblum, et al., Nucl. Instrum. Meth. (2017).

PLY measurements at UCB/LBNL

Beam time supported via collaboration with the Nuclear Data Group in the Nuclear Science Division at LBNL through US DOE-SC



Broad spectrum beam allows for continuous measurement of proton light yield relation



Kinematically over-constrained system provides systematic check

$$E_p = E_n^{'} \tan^2 \theta$$

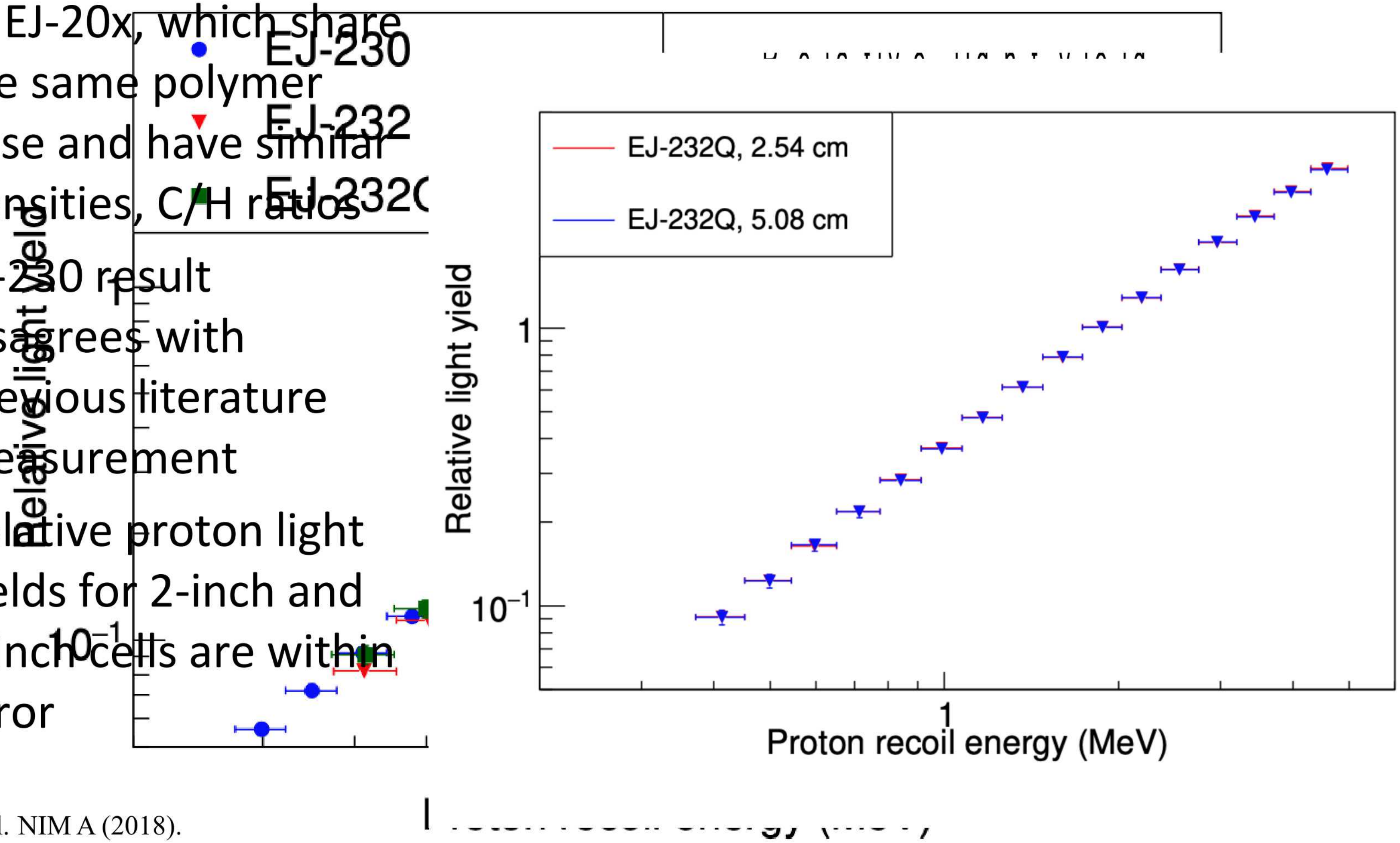
$$E_p = E_n \sin^2 \theta$$

$$E_p = E_n - E_n^{'}$$

J.A. Brown, PhD Thesis, UC Berkeley 2017.
J.A. Brown, et al. Journal of Applied Physics 124, 045101 (2018).

PLY results

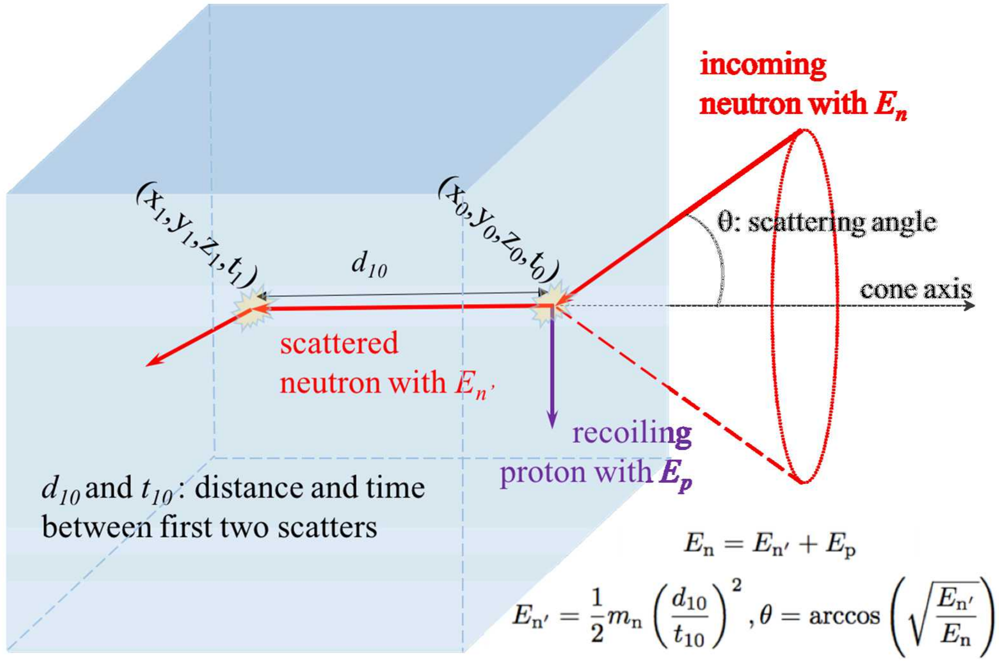
- EJ-23x results consistent with those of EJ-20x, which share the same polymer base and have similar densities, C/H ratios
- EJ-230 result disagrees with previous literature measurement
- Relative proton light yields for 2-inch and 1-inch cells are within error



Laplace, et al. NIM A (2018).
Pozzi, et al. NIM A 524 (2004).
Enqvist, et al. NIM A 715 (2013).

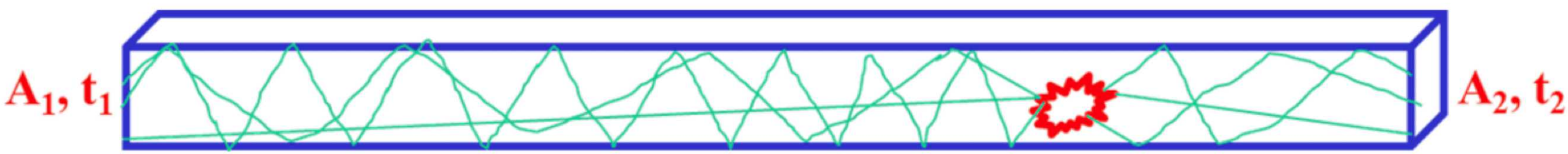
Single bar characterization

- To resolve two separate interactions (and to calculate θ), we need excellent position/time resolutions
- X, Y positions determined by pixilation from array geometry
- Z position reconstructed via one of two methods:
  - **Difference in time-of-arrival**
  - **Log ratio of total charge**



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

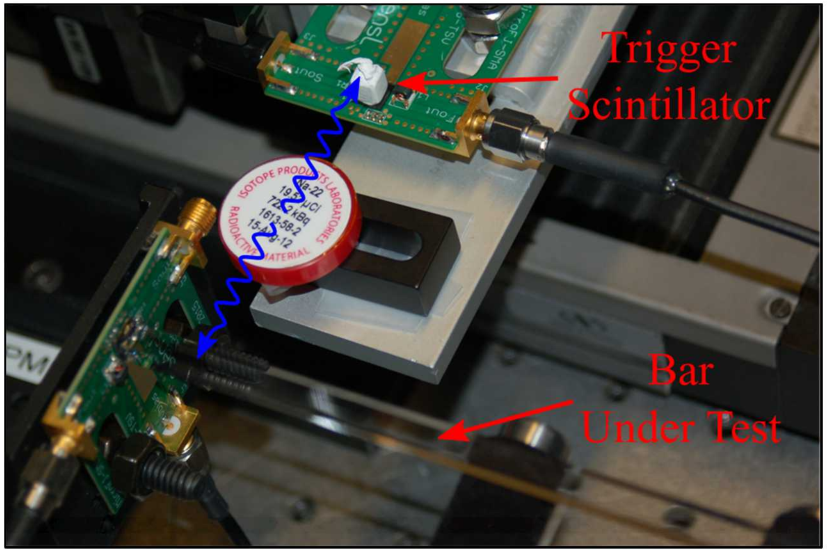
$$E_{\mathrm{n'}} = \frac{1}{2} m_{\mathrm{n}} \left(\frac{d_{10}}{t_{10}}\right)^2, \theta = \arccos\left(\sqrt{\frac{E_{\mathrm{n'}}}{E_{\mathrm{n}}}}\right)$$

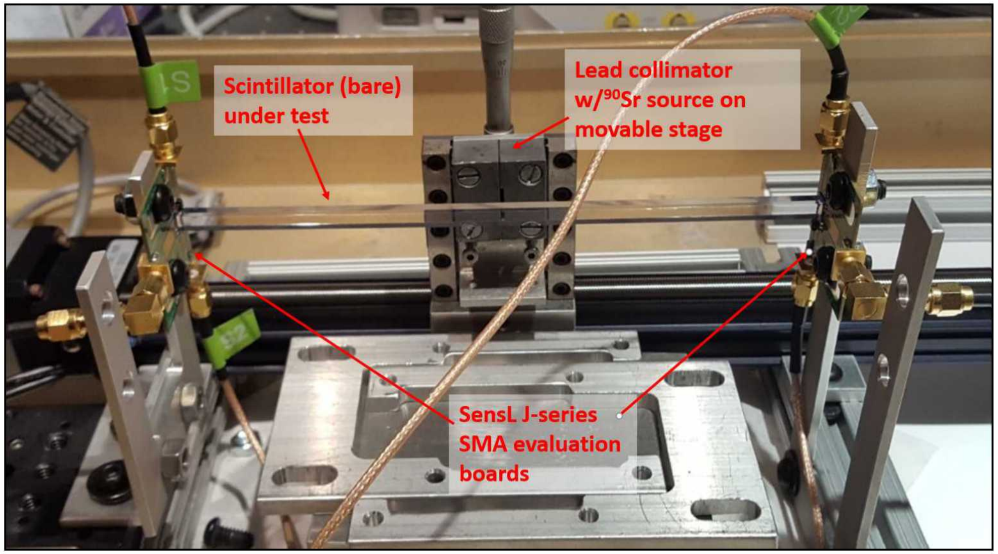


$$\begin{aligned} t_1 - t_2 &= \frac{z}{v} - \frac{L-z}{v} \\ &= \frac{2z}{v} - \frac{L}{v}. \end{aligned}$$

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

Single bar measurements





@SNL

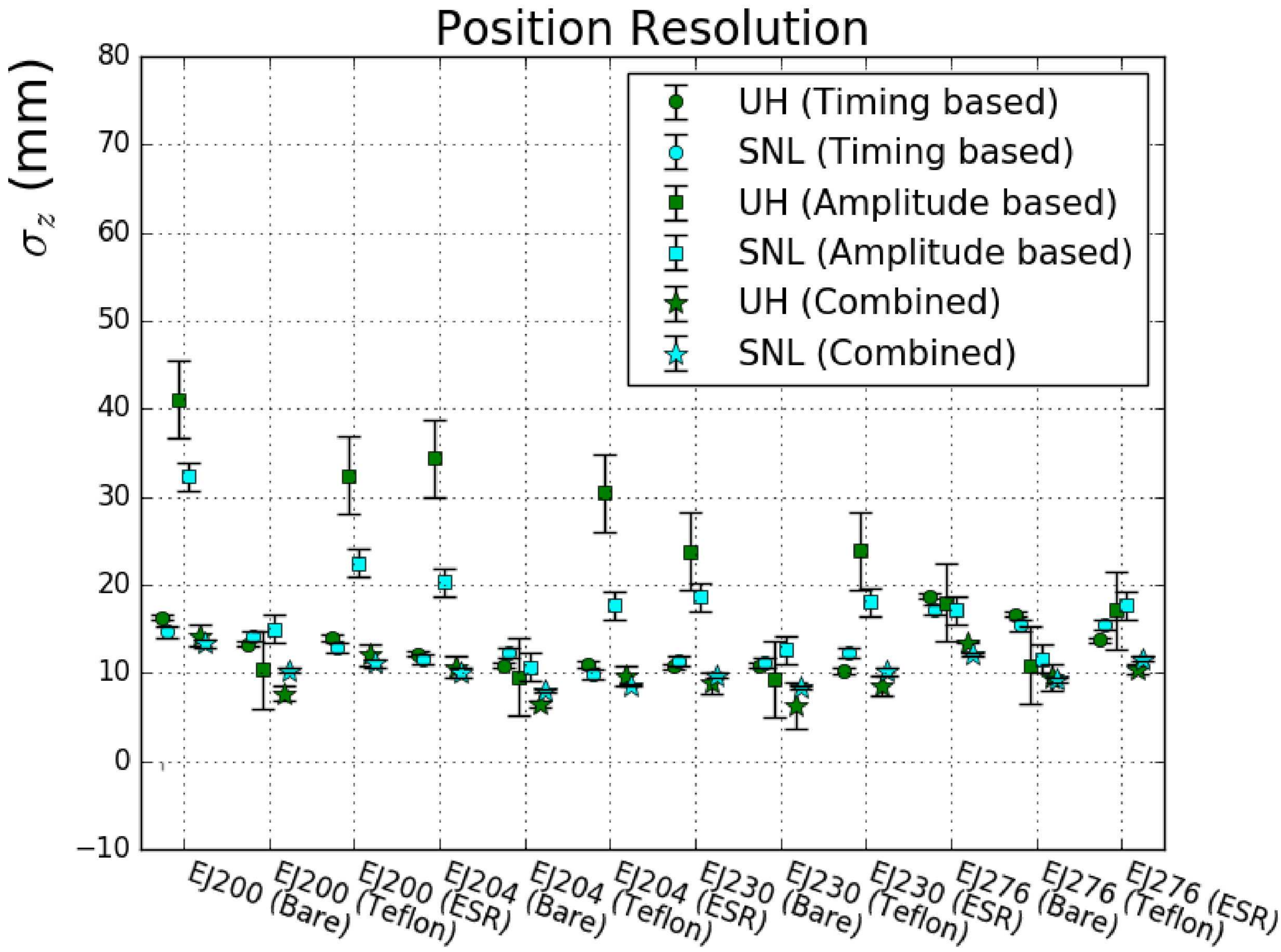
- Tagged Na-22 scan
- Trigger is on 5x5x5 mm Stilbene crystal (no threshold effects on test bar)
- Provides timing, z-position, and energy resolution measurements

@UH

- Collimated Sr-90 scan
- 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

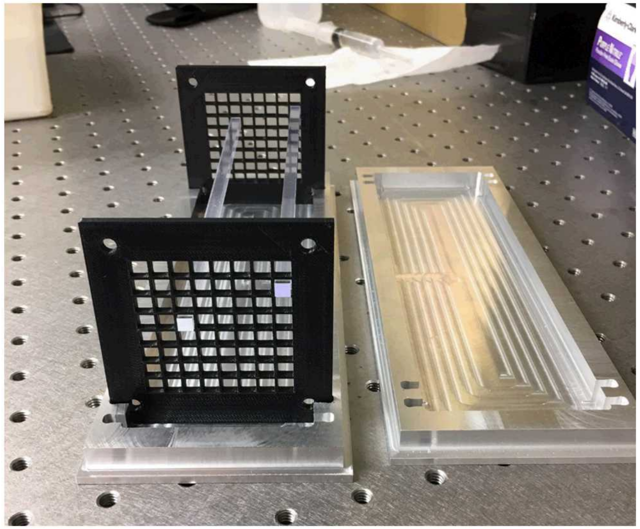
Single bar measurements



First OS prototype at UH-Manoa

Summary:

- Photodetector: SensL J-series 6x6mm with FOUT
- Readout electronics and trigger: drs4-based from UH
- Scintillator: 5x5x200 mm EJ-204 bars, Teflon-wrapped



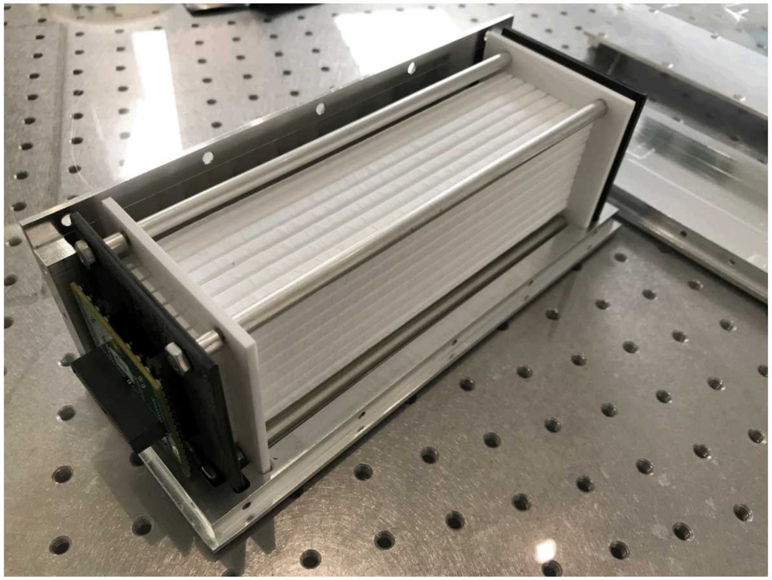


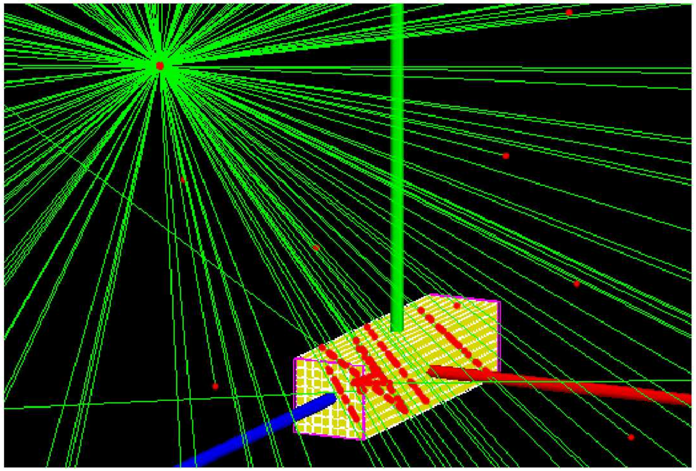
Photo credit: Nathan Kaneshige

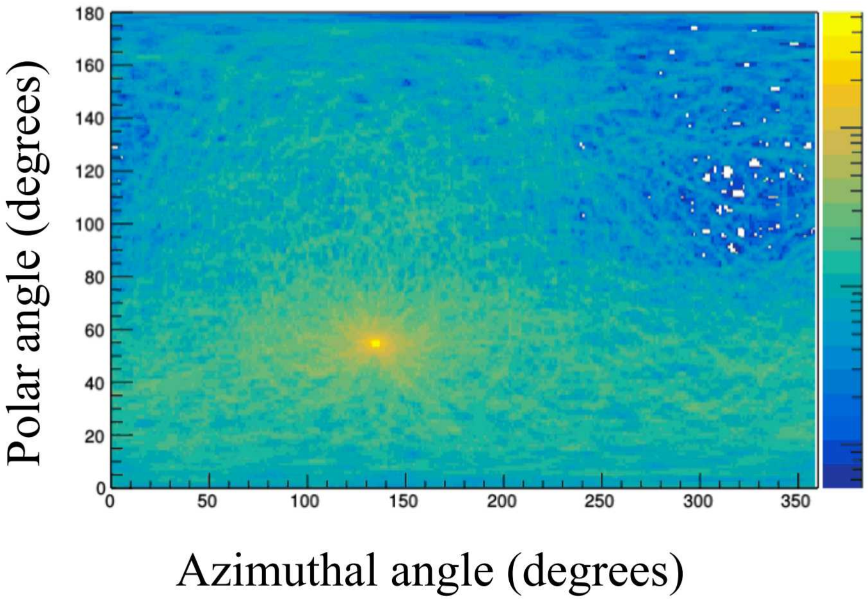
Status:

- All components are assembled
- Electronics testing underway
- Next up is first light (!) and calibrations

OS-SVSC simulation development

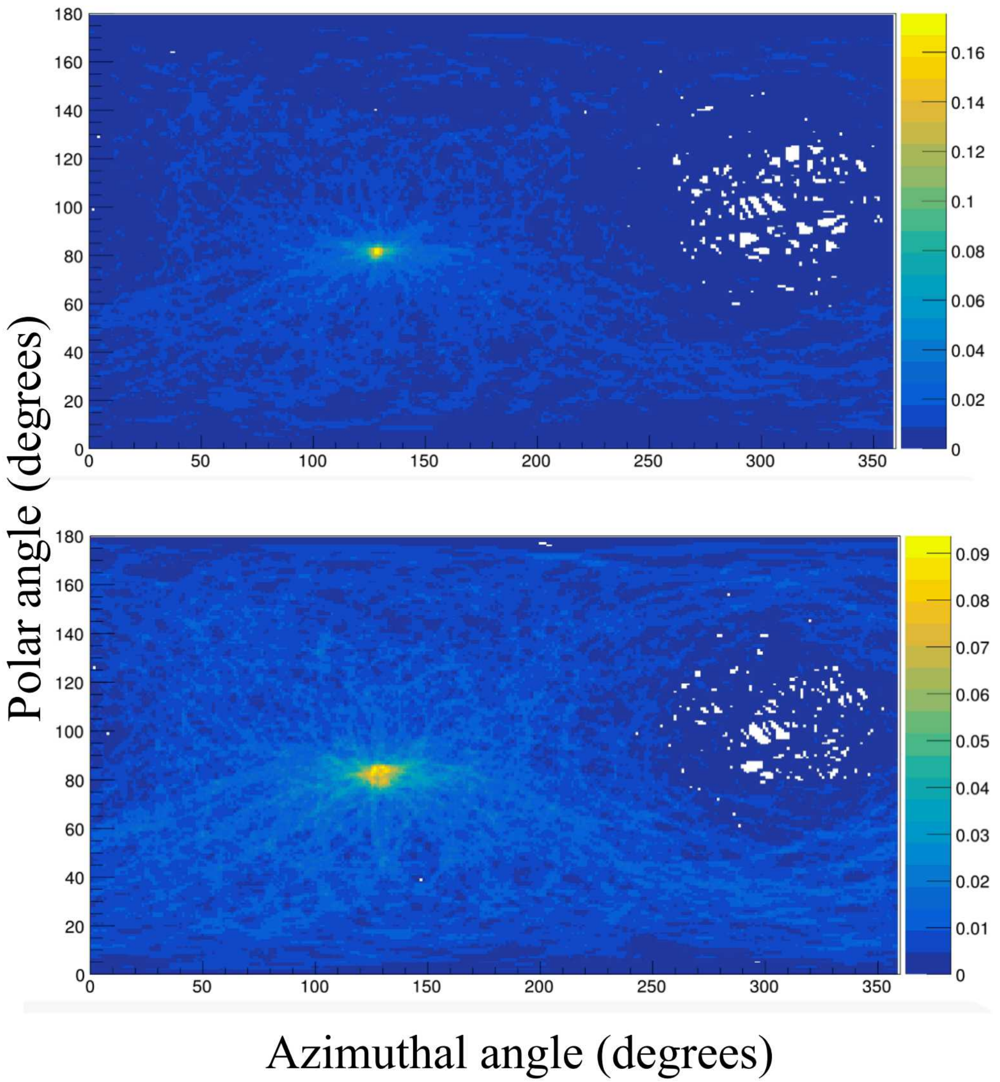
- Component characteristics like PLY affect OS-SVSC performance
- **Goal: in simulation space, understand sensitivity of OS-SVSC imaging capabilities to device characteristics (scintillator material properties, electronics, device dimensions, etc.)**
- Lessons from simulation → future prototype development
- **Goal: create ROOT/C++ framework that can analyze both simulation data and experimental data from the OS prototype**



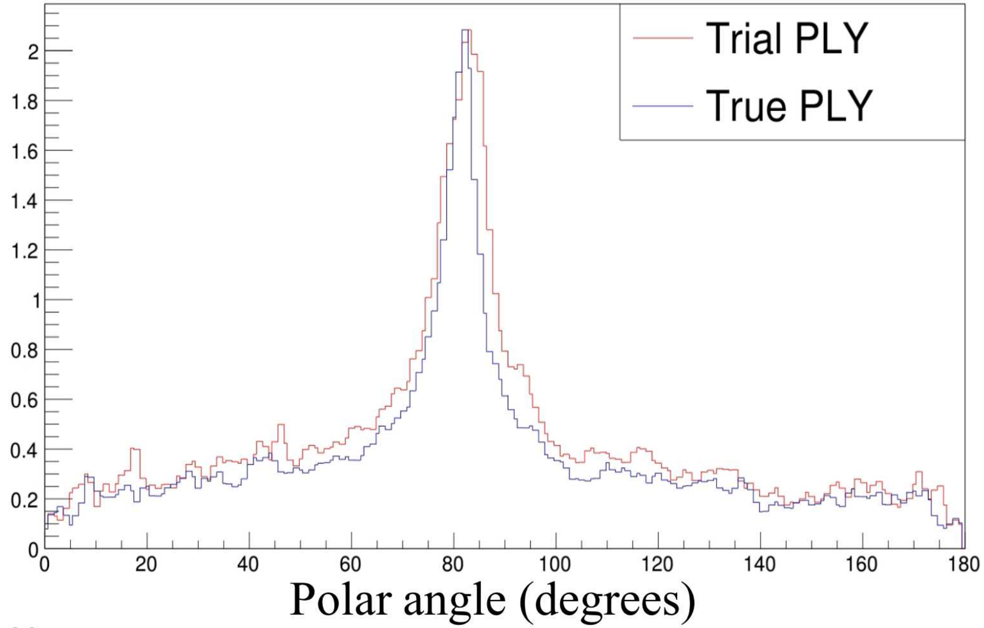


Example: does PLY matter?

- In simulation, we assume a "true" PLY to generate light from proton recoils
- Then, analyze data using either the "true" PLY or a "trial" PLY from the literature to calculate the recoil energy
  - "True": Laplace, NIM 2018.
  - "Trial": Pozzi, NIM 2004.
- The final backprojected images show a clear impact

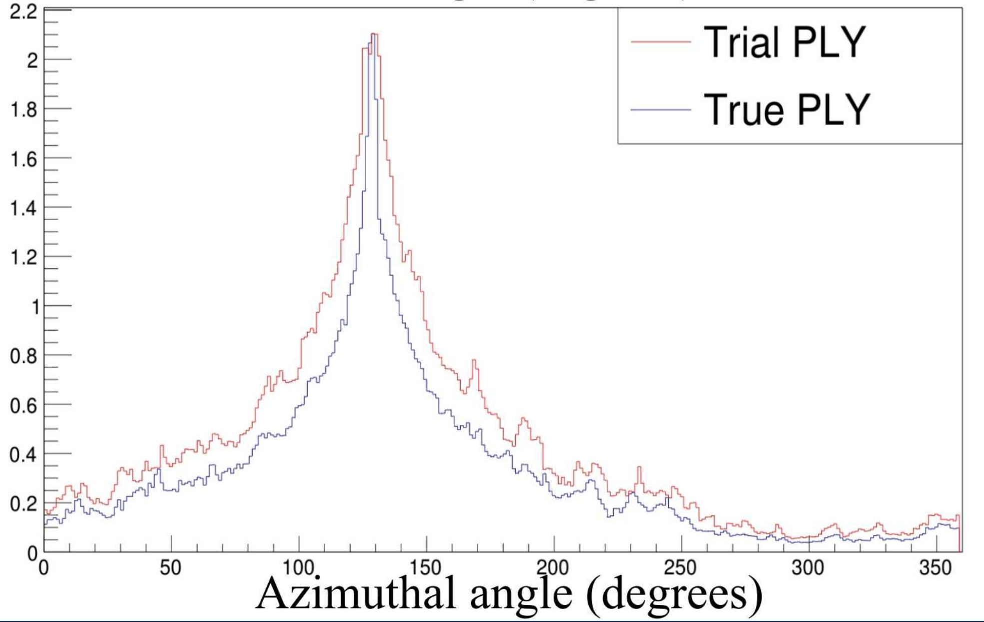


Example: does PLY matter? **Yes!**



Polar projection

- FWHM
  - "Trial" = 14.4°
  - "True" = 9°
- Using the wrong PLY results in a **60%** increase in width and a centroid shift 1°



Azimuthal projection:

- FWHM
  - "Trial" = 41.6°
  - "True" = 20.1°
- Using the wrong PLY results in a **107%** increase in width

Future work

- Big picture: develop → prototype → evaluate → develop …
- Modeling study @UCB/SNL to determine the best path forward for imaging:
  - How do timing, position, PSD, energy resolution, and threshold map to imaging metrics such as resolution, contrast, artifacts, etc. for a given source and acquisition time?
  - For OS specifically: how do imaging metrics change with source position?
- Absolute LY measurements of candidate scintillators
- Next OS Prototype coming in FY 2020

Acknowledgments

- SVSC Collaboration, especially:
  - Bethany Goldblum, Thibault Laplace (PD), Gino Gabella (UGrad), Joey Gordon (Grad), Allison O'Brien (UGrad), Shamin Chowdhury (UGrad)
  - Erik Brubaker, Melinda Sweany, Josh Brown (PD)
  - Aline Tellez (PD), Kurtis Nishimura, Ryan Dorrill (Grad), Andrew Druetzler, Nate Kaneshige (UGrad), John Learned

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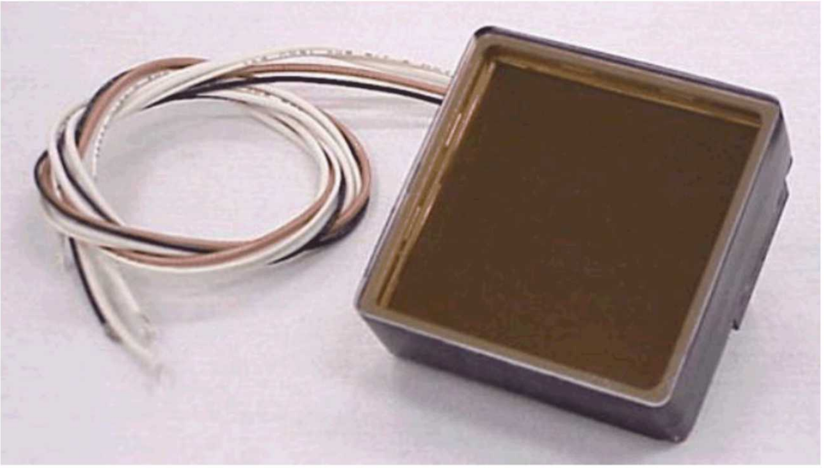
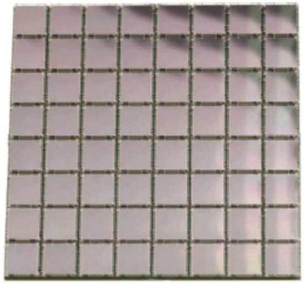
Backup slides

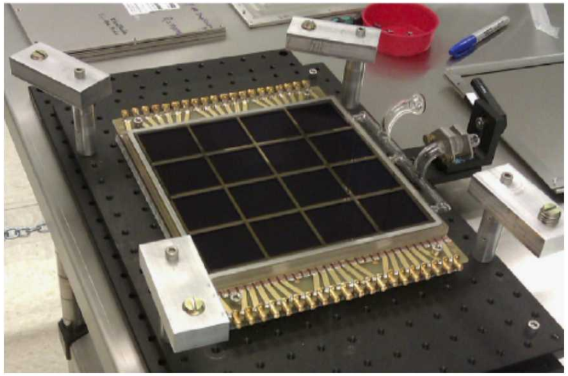
Design Considerations - Photodetectors

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 (see poster)	-	1 ns	~14%
SiPM	SensL C/J-series 8x8 array	0.3-1 ns	0.6-3 ns	35/50%



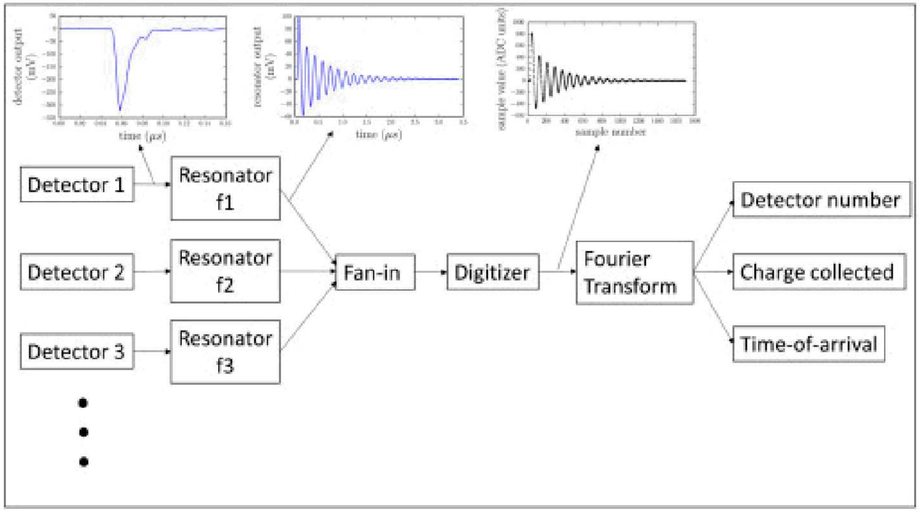




Design Considerations - Electronics

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

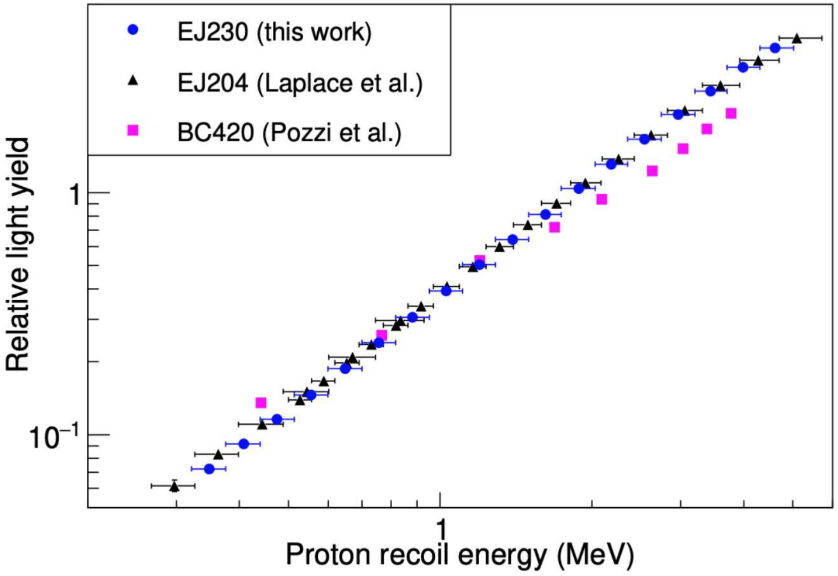
- Current UH electronics: drs4-based
- Commercial analog solutions from PET
  - Not for first prototype: we want waveforms to learn about event topology
- Frequency Domain Multiplexing
  - R&D underway @NCSU

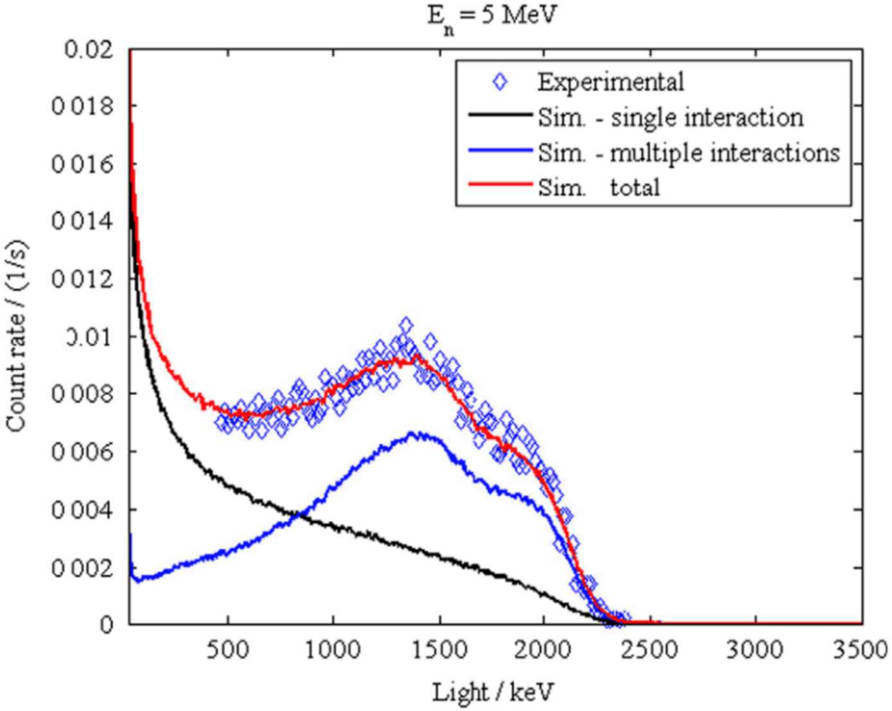


See: M. Mishra, J. Mattingly, J. M. Mueller, and R. M. Kolbas "Frequency domain multiplexing of pulse mode radiation detectors" *Nucl. Instr. And Meth. A* 902 (2018) 117-122

Comparison to literature

- EJ-230 results disagree with previous measurement of commercial equivalent
- Potential issue with Pozzi results: multiple scattering





Pozzi, et al. NIM A 524 (2004).
Tomanin, et al. NIM A 756 (2014).

Single Bar Results - Summary

Scintillator	σ_t (ps)	σ_z (mm) ^{22}Na	σ_z (mm) ^{90}Sr	σ_E/E (%) ^{22}Na	σ_E/E (%) ^{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	-

← **Also, highest light output**

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

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

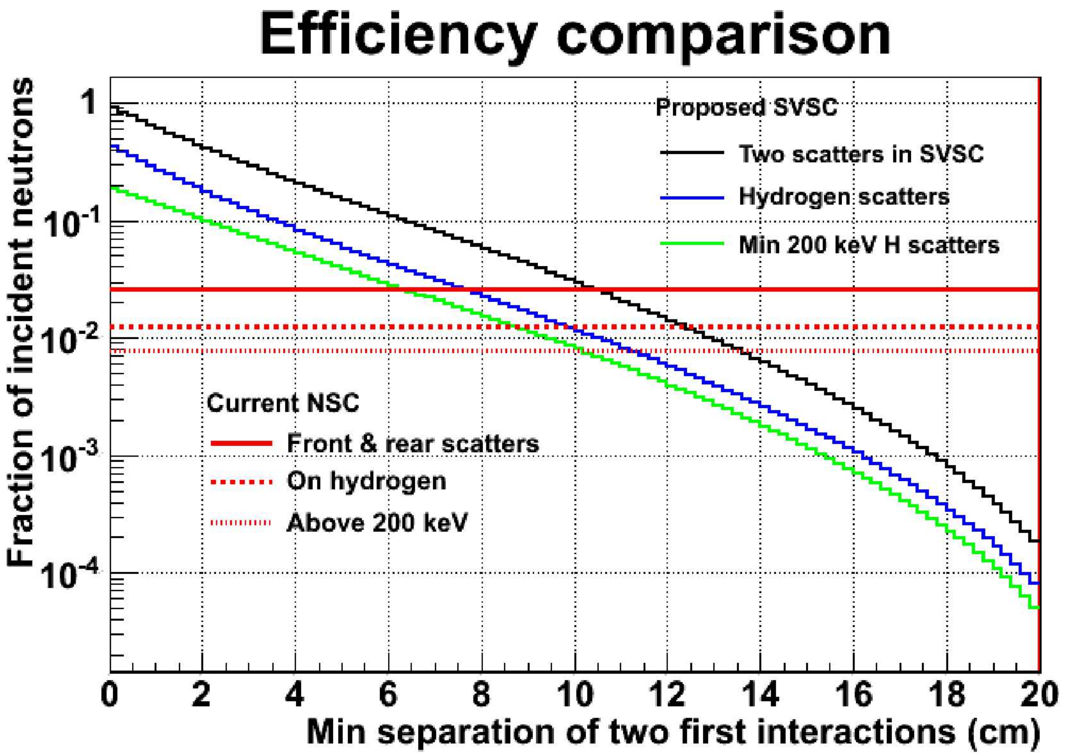
$$E_{\text{n}} = E_{\text{n}'} + E_{\text{p}}$$

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***

Efficiency calculations

Compact high-efficiency neutron imager:

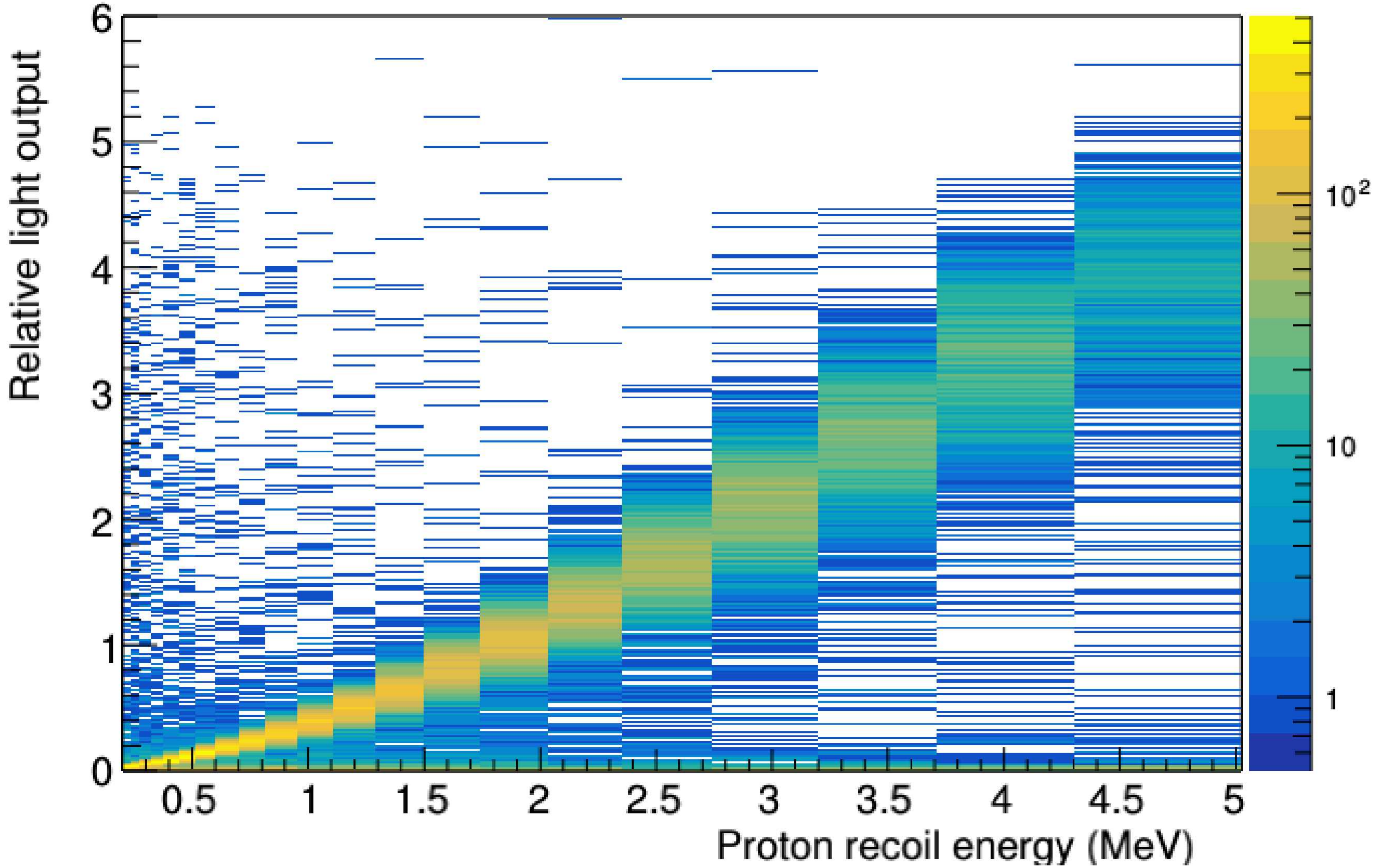
- High efficiency reduces measurement time
- Compact form factor allows easy transport, deployment in tight spaces, close approach to threat sources.
- Application spaces:
  - SNM search/standoff detection
  - Cargo screening
  - Arms control
  - Emergency response



If successful:

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

Proton recoil energy vs. light yield (EJ-230)



Light-yield fitting (EJ-230)