First experimental demonstration of Gamma-ray LiDAR with a quasi-monoenergetic photon beam

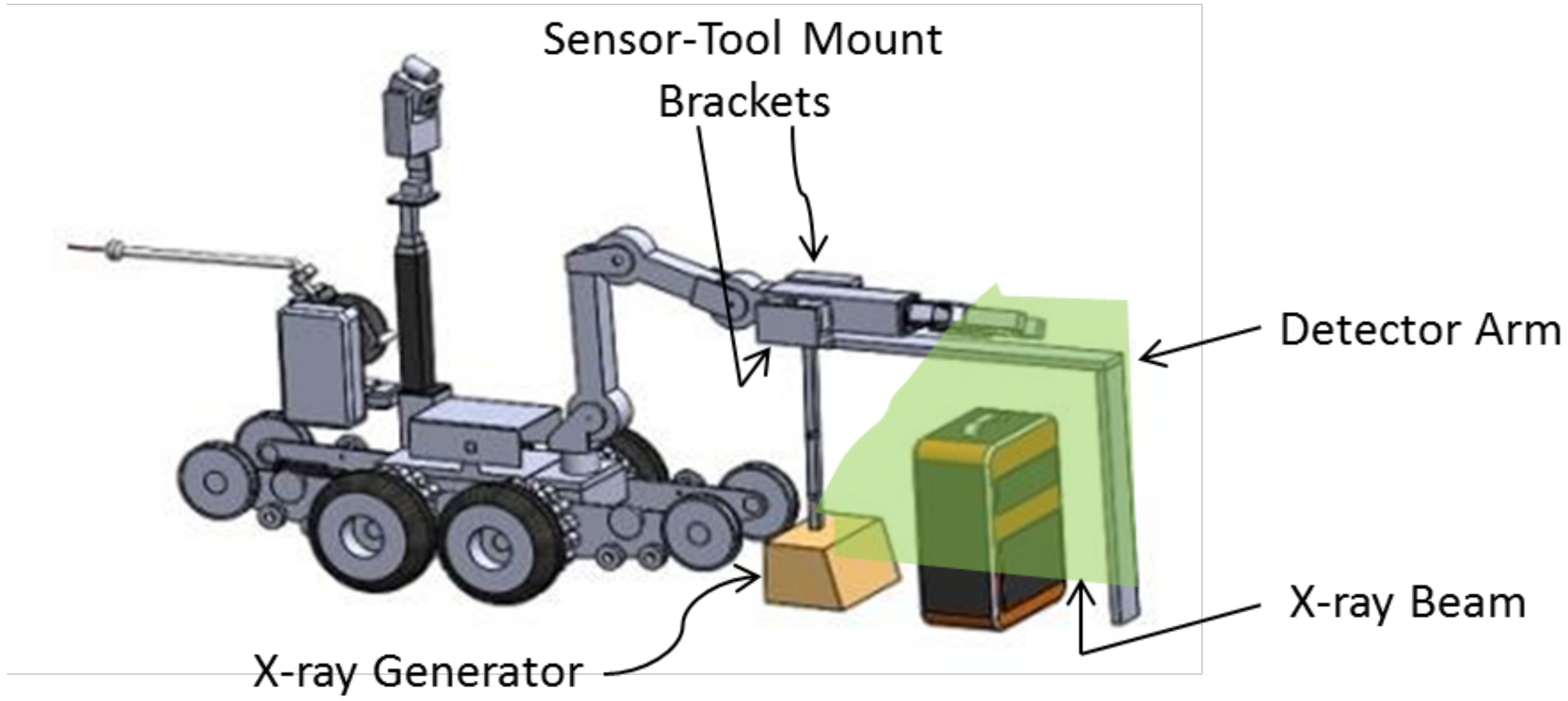
Ryan Heller, LBNL, rheller@lbl.gov

for the Gamma LIDAR collaboration

AccelApp 2024, Norfolk, Virginia

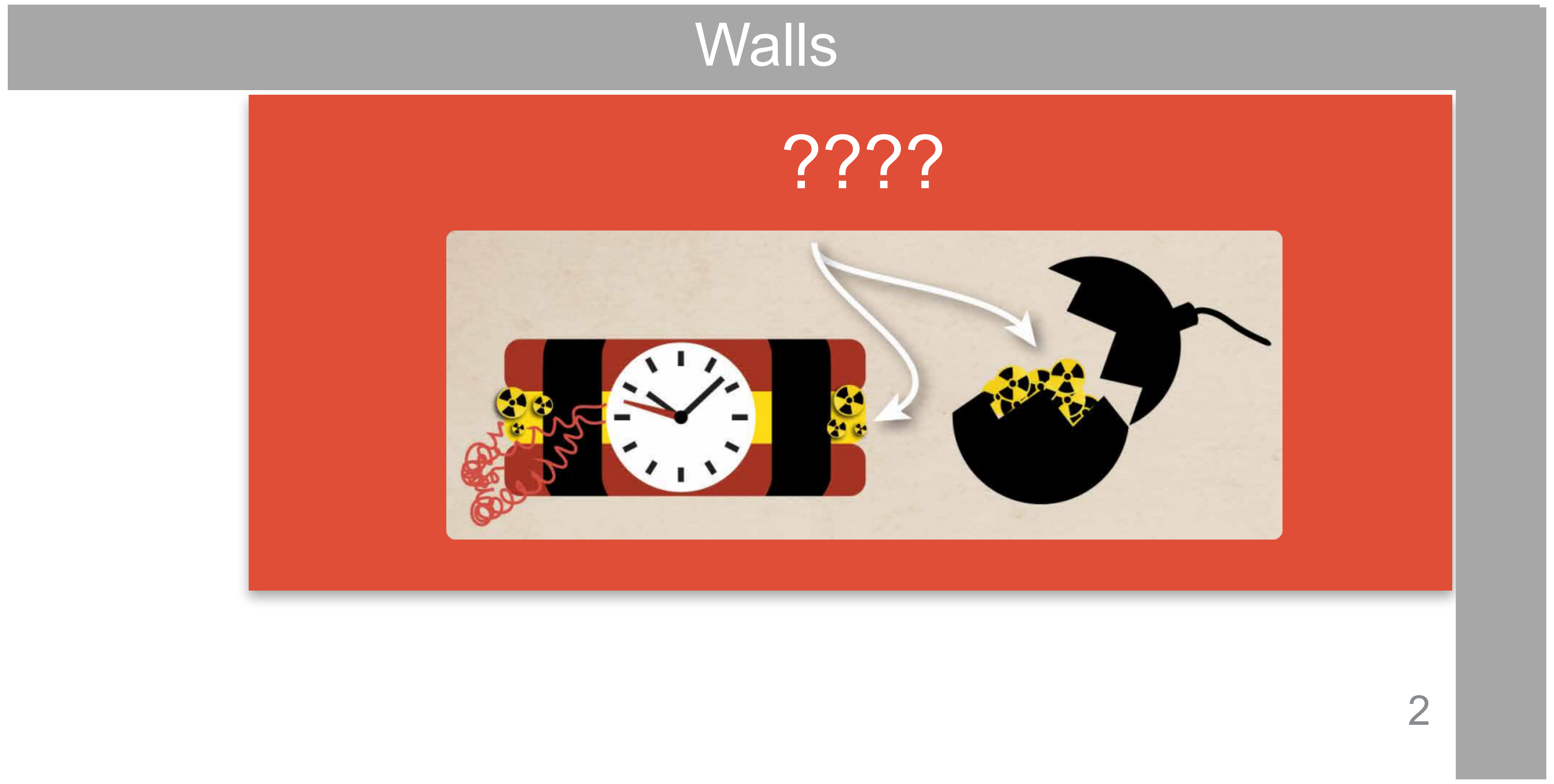
Emergency response imaging

- Find a "suspicious" object—what do you do?
  Scan with X-rays!



Scansilc-2520, idealblasting.com

- But, what if…
  - Object too thick, too shielded, too big
  - Not accessible from multiple sides
  - 3D image needed
  - Material ID desired (nuclear materials, explosives, etc)

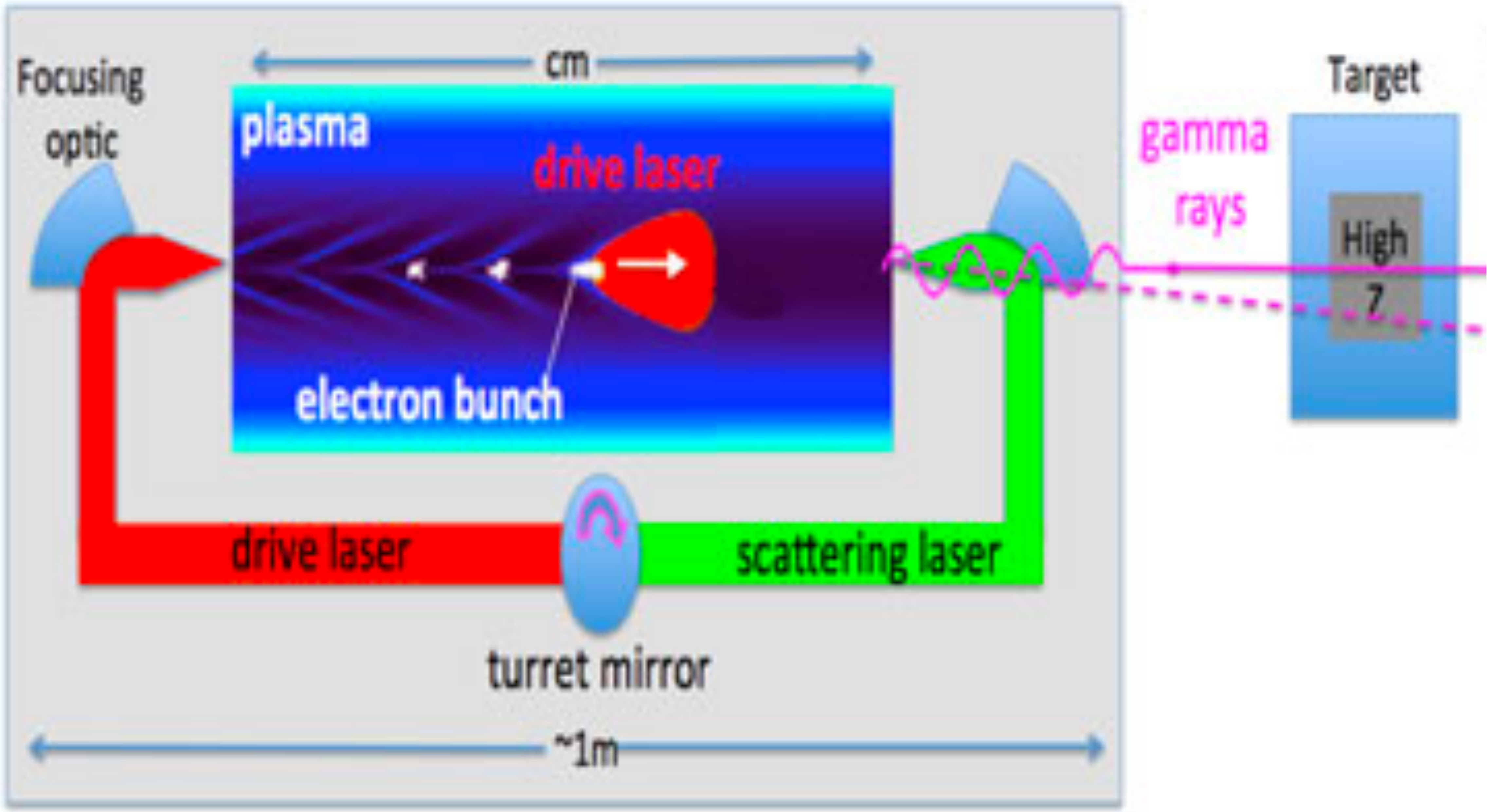


Gamma-ray LIDAR

- Gamma-ray LIDAR: 3D image from one side
  - Fire gamma beam at unknown object.
  - Backscatter ToF gives material vs depth, penetrating into object
  - Scan pencil beam to map X,Y
  - Vary energy to probe material composition, exotic signatures
- Key enabling technologies
  - Femtosecond, monoenergetic tunable photon source
  - Picosecond gamma detectors
- Previous efforts with Brems sources (INL, UTK)

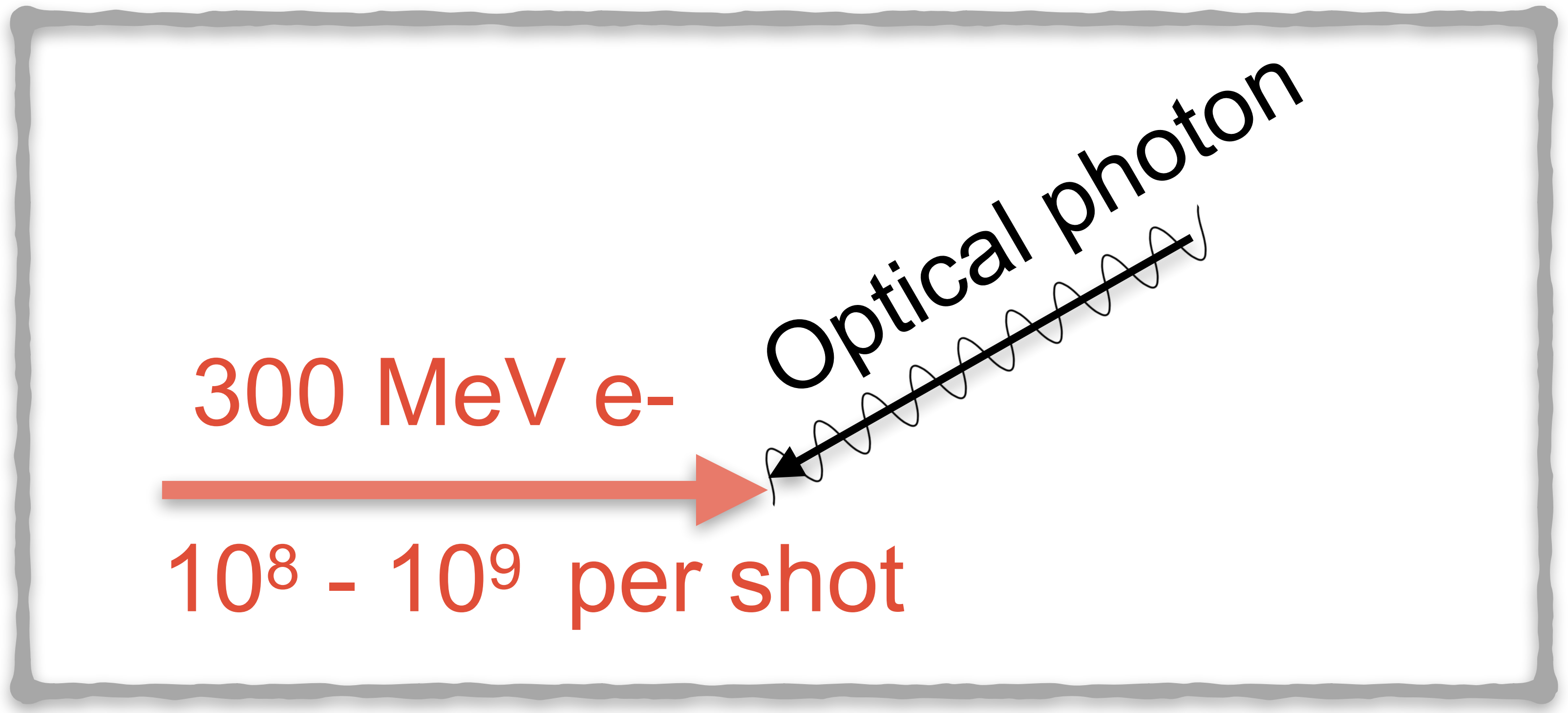
Photon source

- BErkeley Lab Laser Accelerator facility (BELLA)
  - Dedicated talk yesterday by Jeroen van Tilborg
- Produce 200-300 MeV e- beam using laser driver
- Thomson scatter laser photons against electrons
- Produce quasi-monoenergetic gamma beam
- In future, will be compact & portable

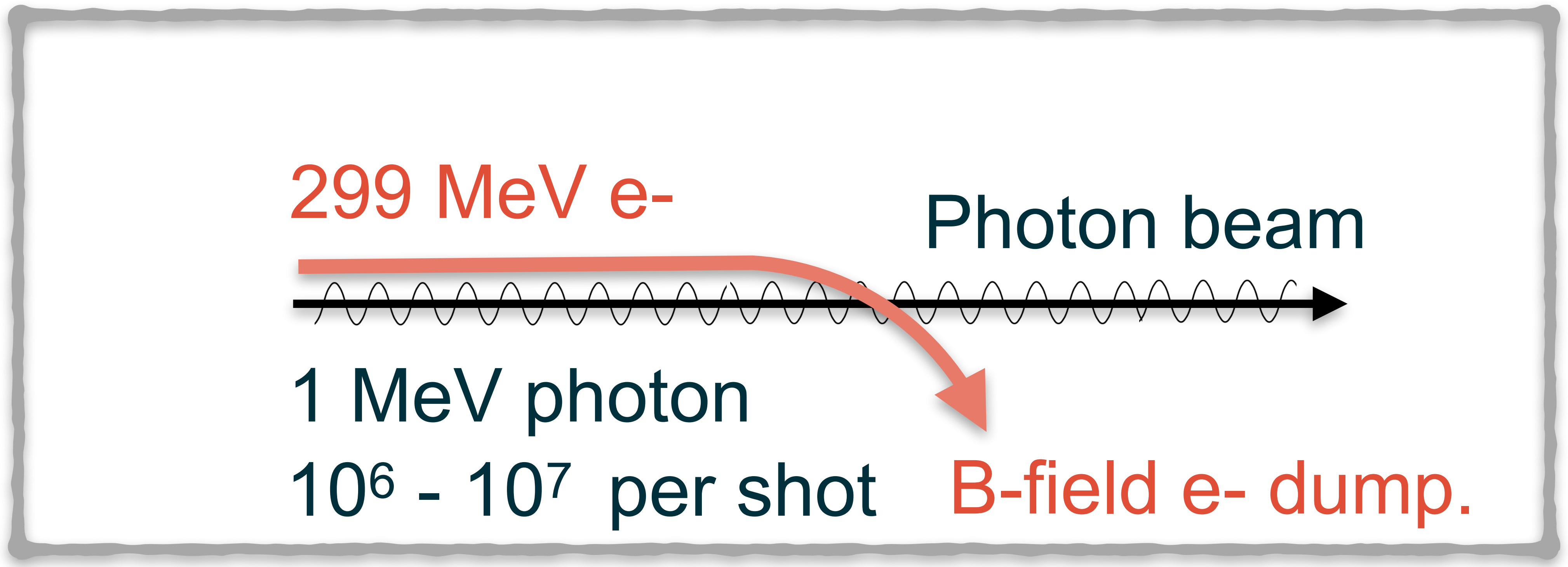


Simplified scattering kinematics:

Initial state



Final state



- Essential feature for gamma LIDAR: femtosecond pulse duration

Detection challenges for Gamma LIDAR

- What are the essential detector requirements?
  - Time resolution: 1 cm depth ~ 67 ps time of flight, round-trip.
  - Photon-resolving, NOT integrating, in contrast to typical radiography

Integrating detector (e.g. radiography): weigh rain after the storm.

"Pileup" of signals: no problem

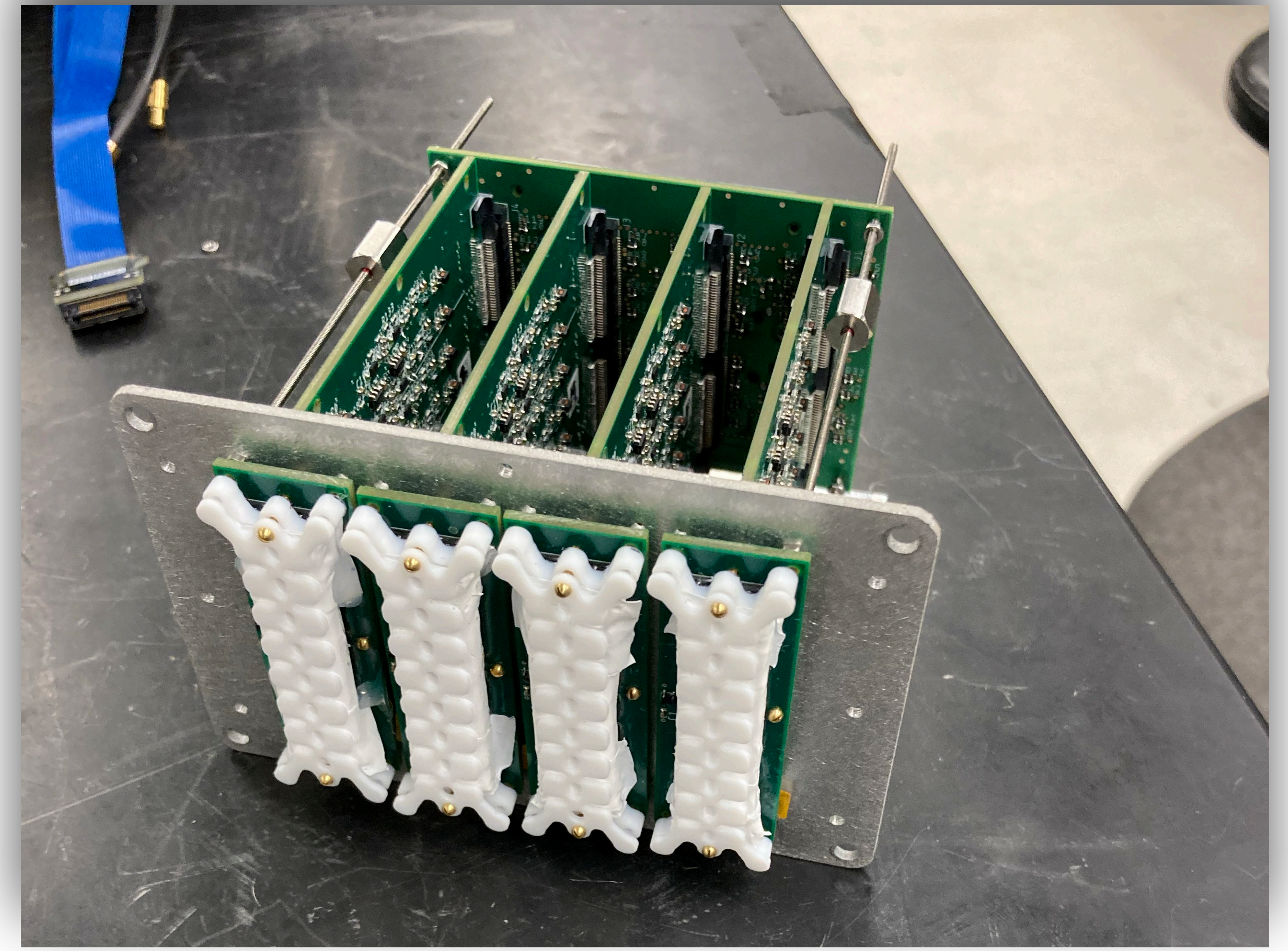
Photon resolving: record each impact.

Pileup destroys information

(BUT, each photon carries more information)

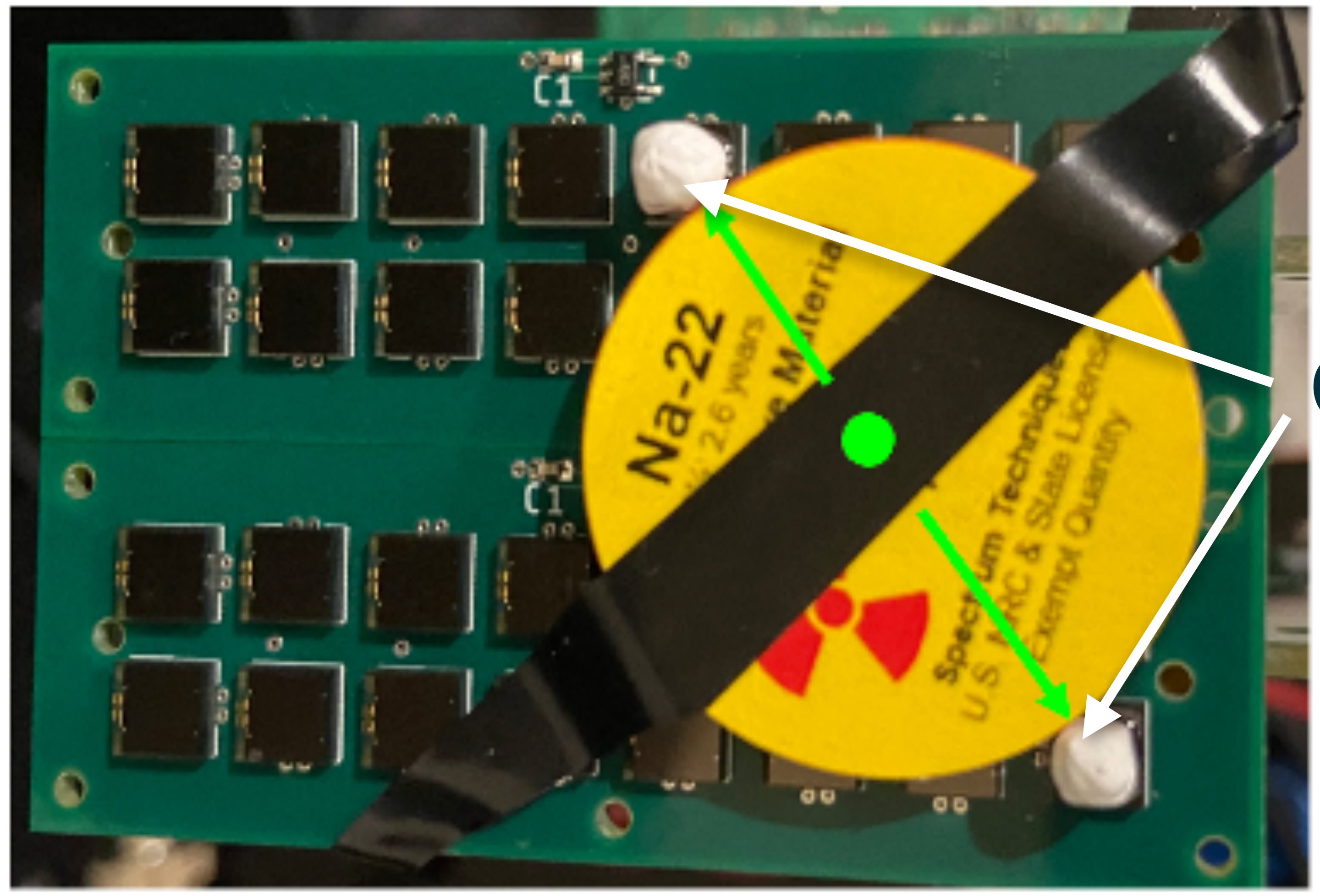
Detectors for gamma LIDAR

- Scintillator + SiPM readout
  - Use cutting edge ToF-PET electronics for excellent timing
  - Tiny crystals for photon-counting (and improved timing)

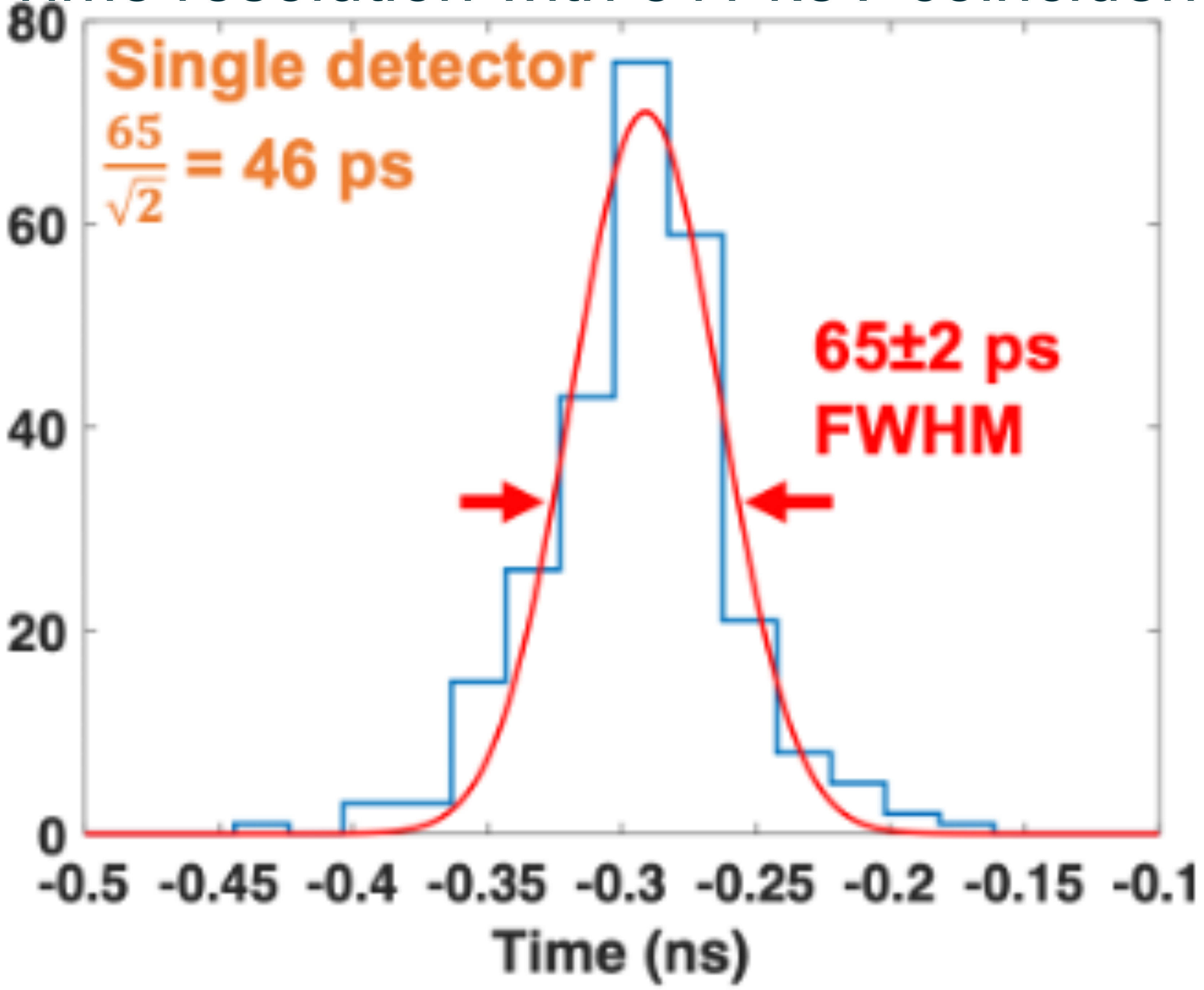


32x LYSO and 32x fast plastic scintillators
Each 2x2x3 mm^3

SiPM arrays w/ positron source



Time resolution with 511 keV coincidence



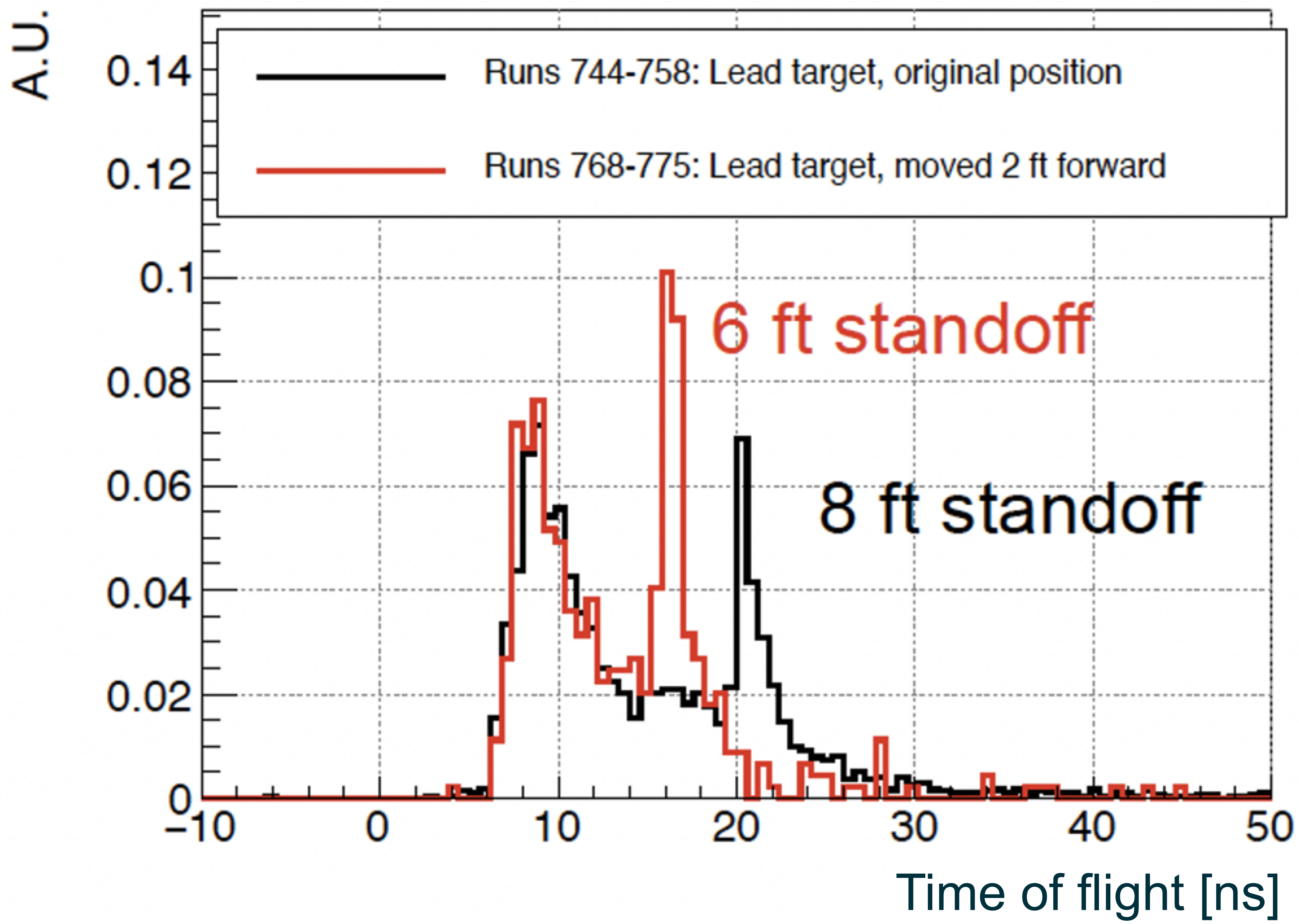
Tiny LYSO crystals: 46 ps resolution at 511 keV
~70 ps for 200 keV backscatters

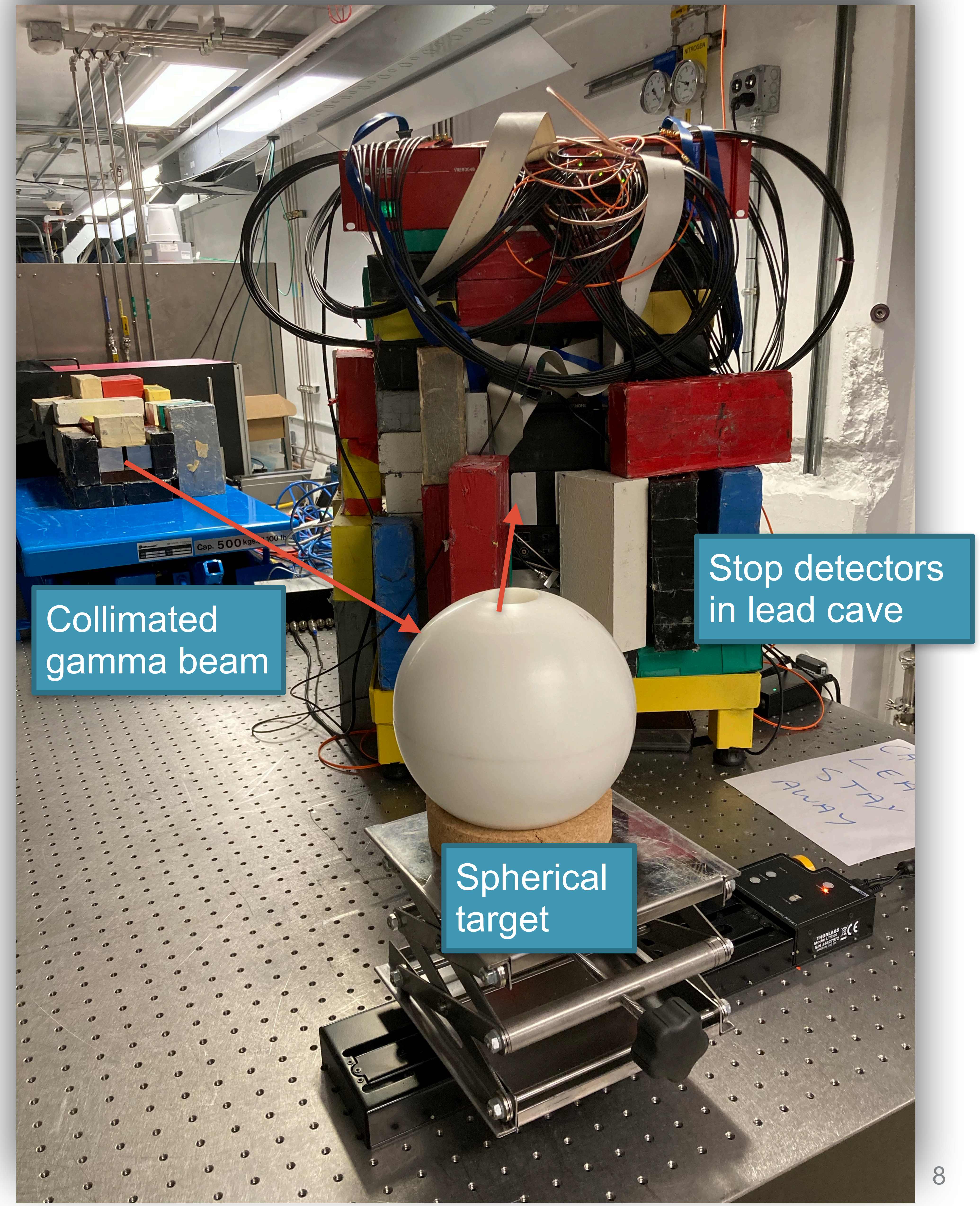
Backgrounds

- Significant backgrounds from bremsstrahlung photons produced by
  - Electrons in beam dump
  - Beam halo striking beampipe
- Minimizing background is critical for success!

Gamma LIDAR experiment

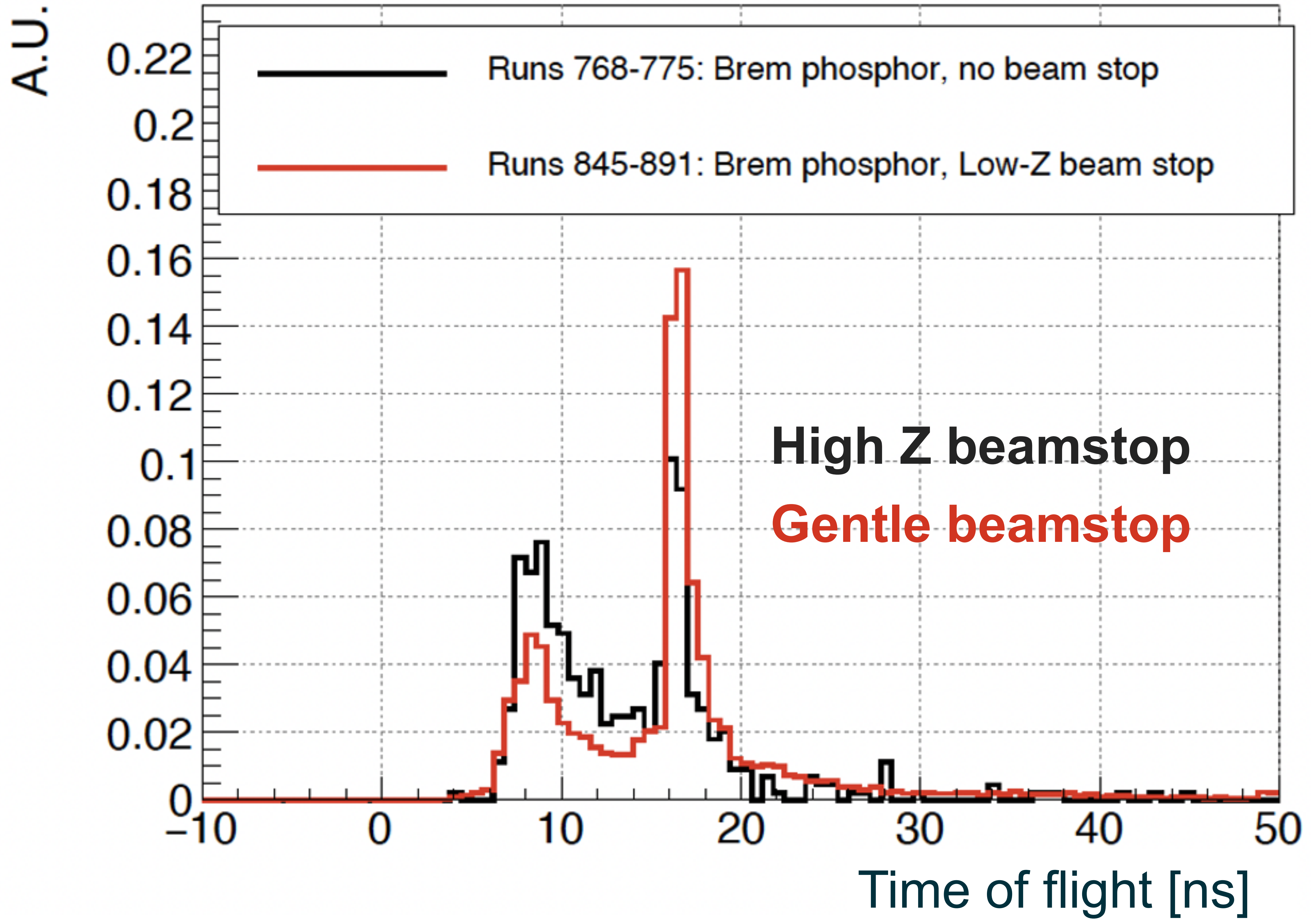
- First steps, fight backgrounds
- Early convincing signal: detect motion of lead brick.



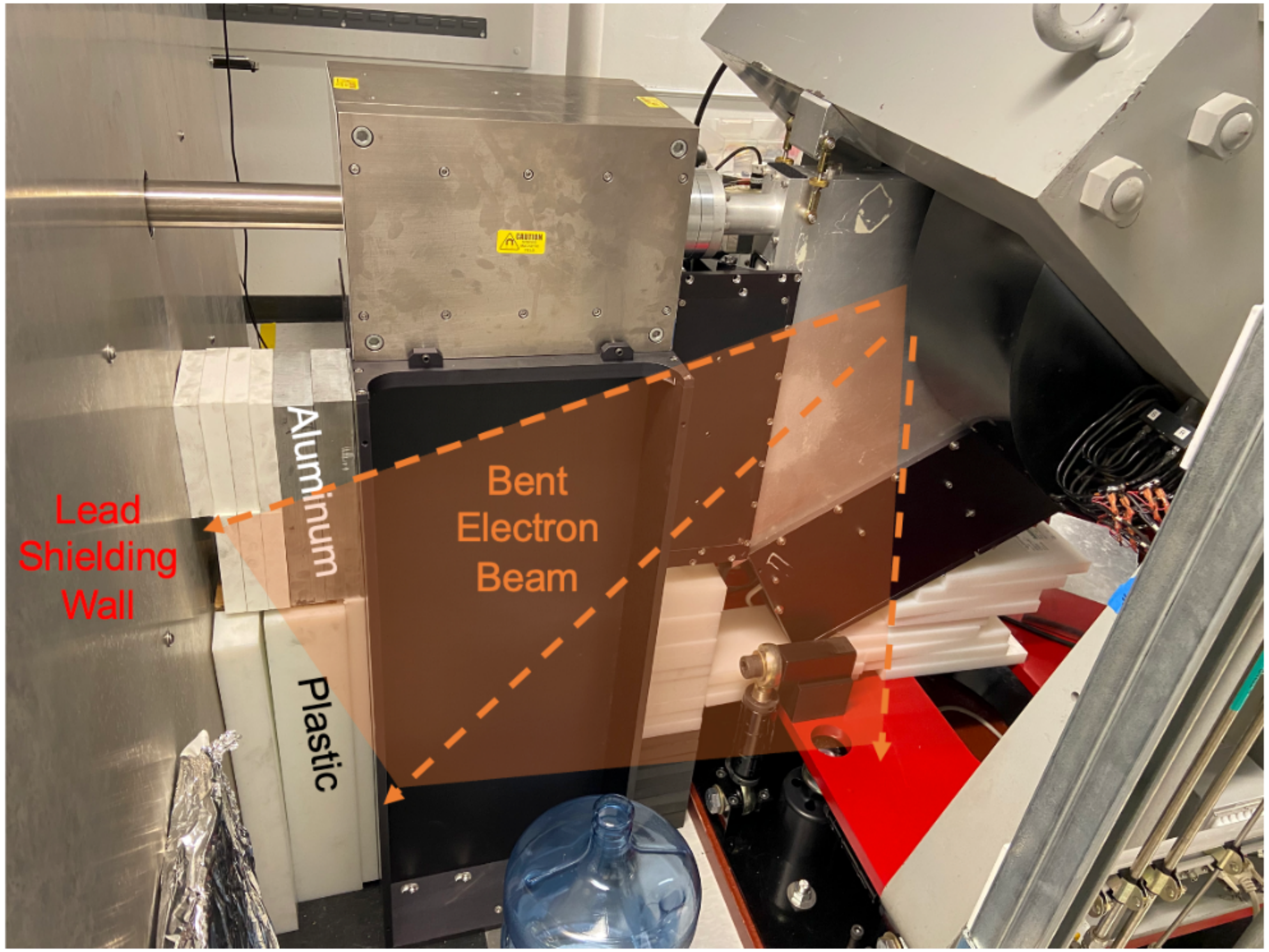


Gamma LIDAR experiment

- Further reduce background with low-Z beam stop, minimizing bremsstrahlung from electron dump.



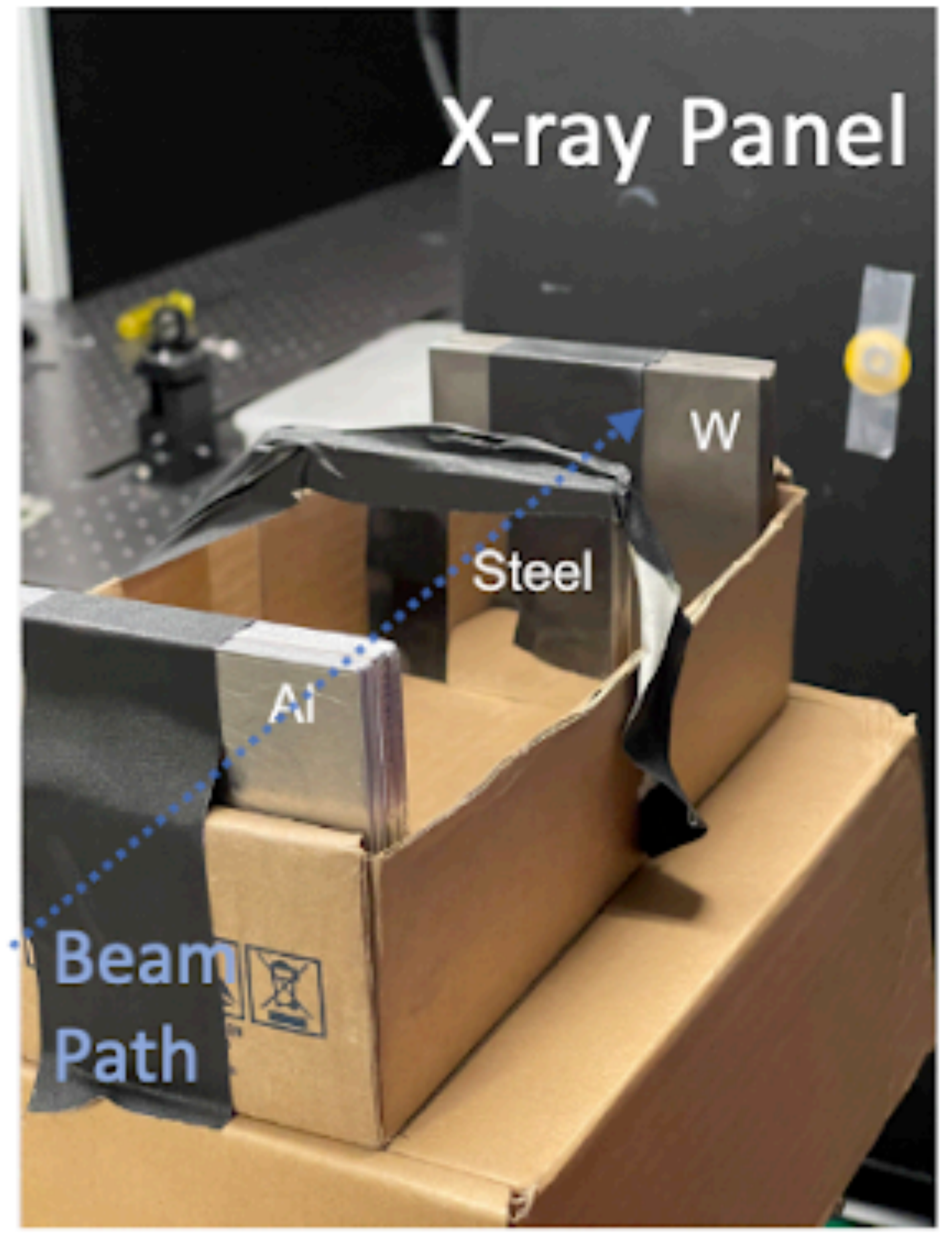
Install gentle beamstop: graphite, HDPE, aluminium

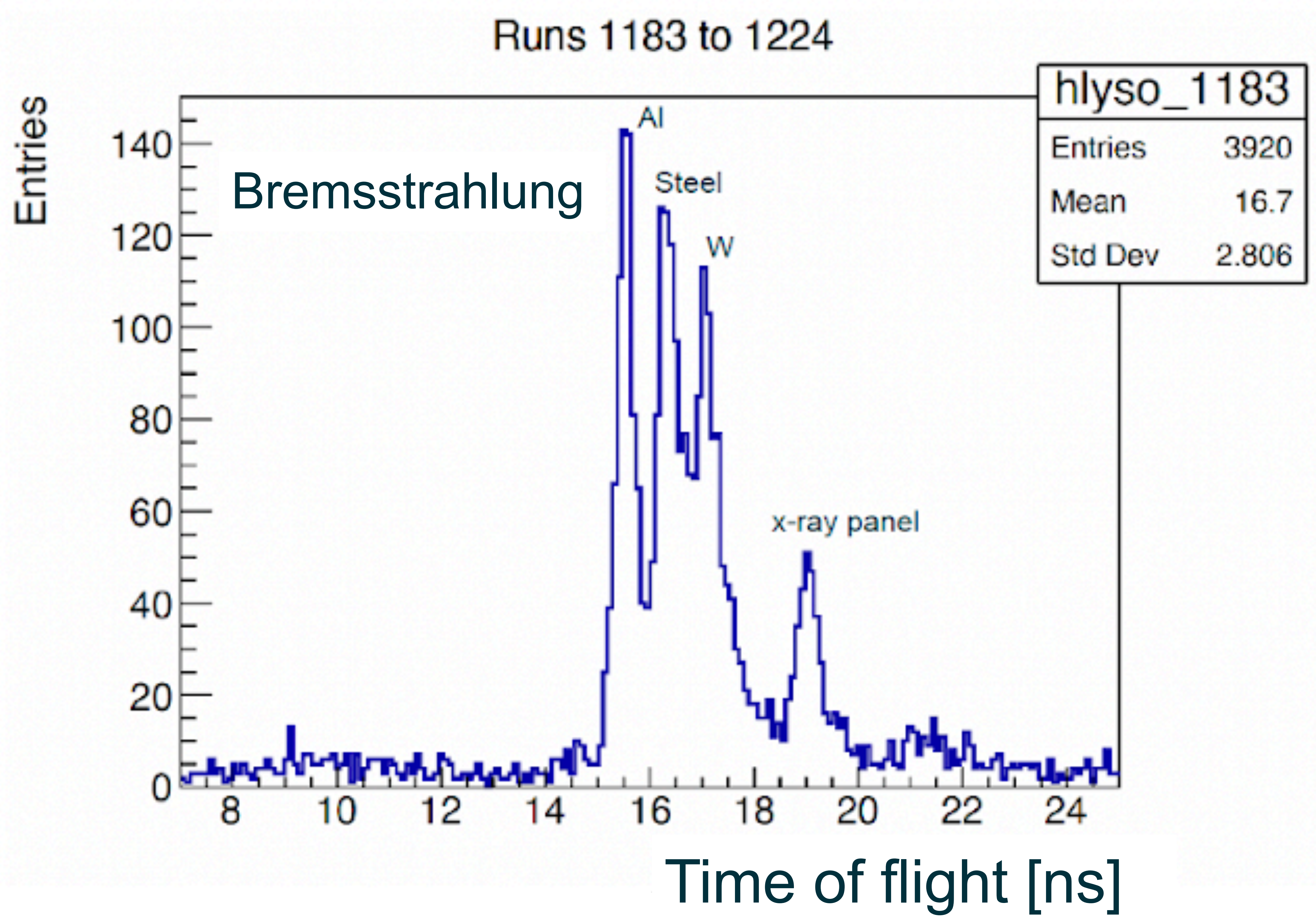


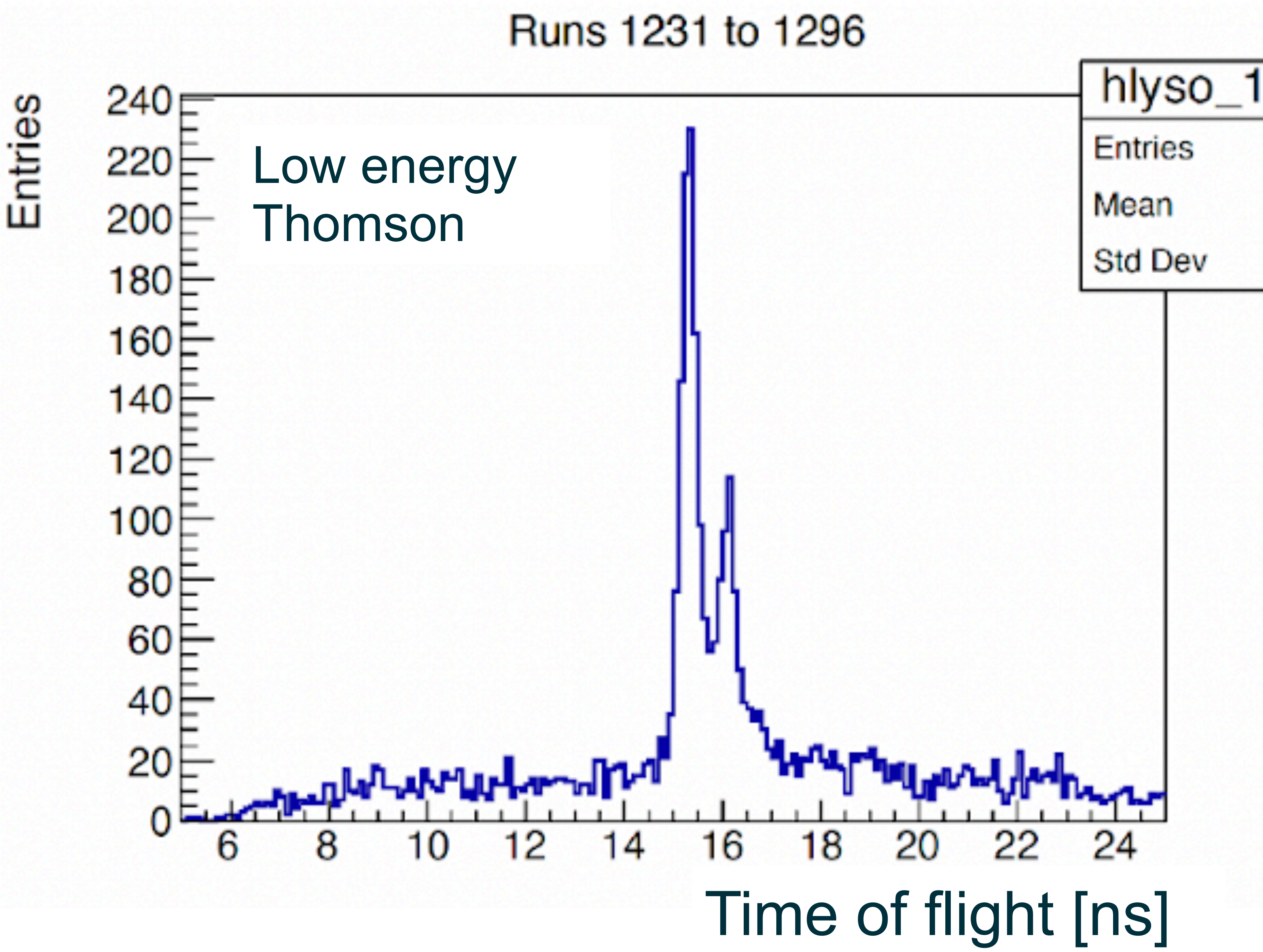
- NB: future photon source will use laser plasma deceleration to eliminate this component

Resolving discrete layers

- More advanced study: resolve discrete layers
  - Aluminum, steel, tungsten layers of 1-2 cm thickness



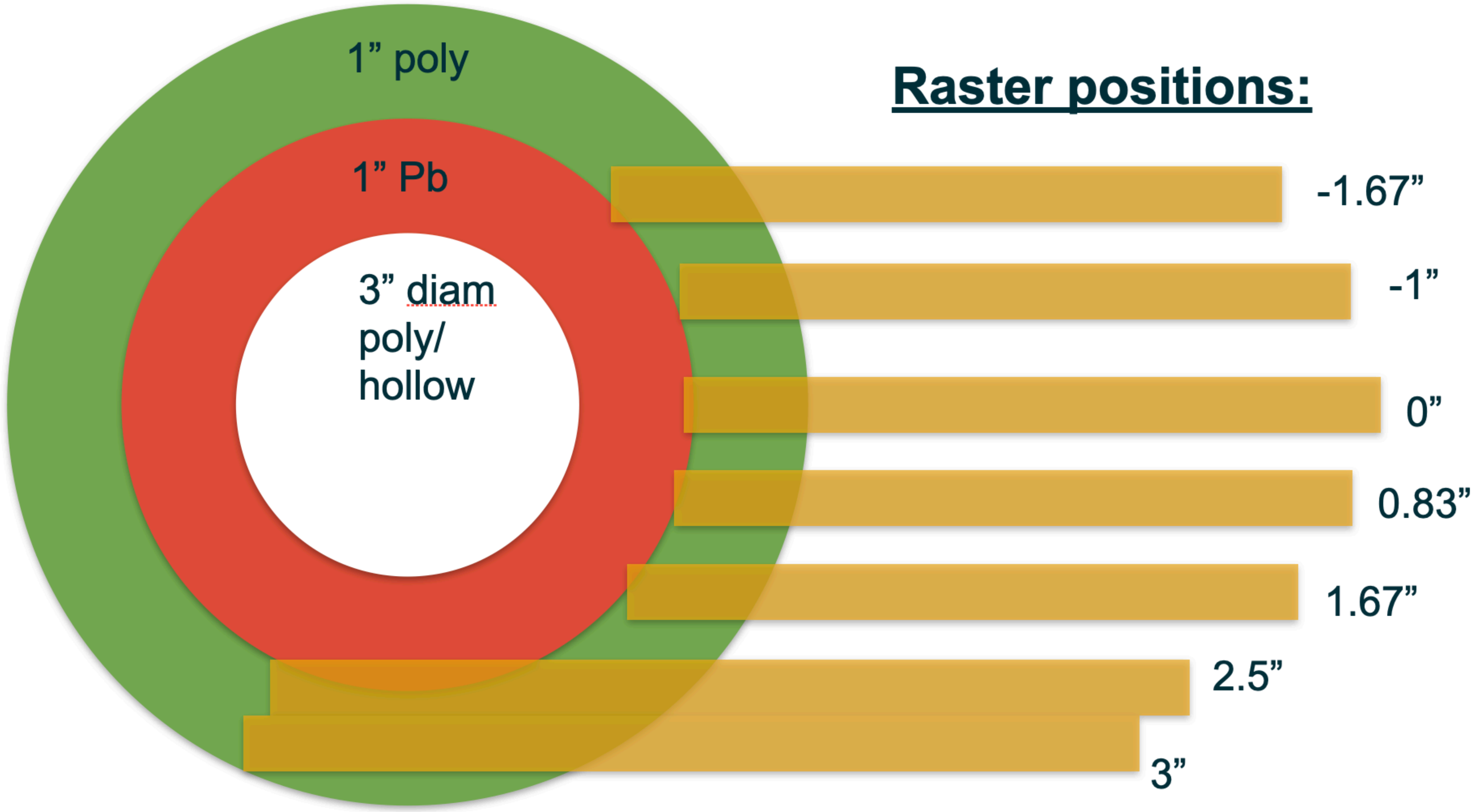




- Probing with different energies reveals information about composition.

Scanning a spherical target

- Study 3D imaging capability using spherical targets
- Concentric layers of HDPE and Lead
- Raster collimated beam across sphere



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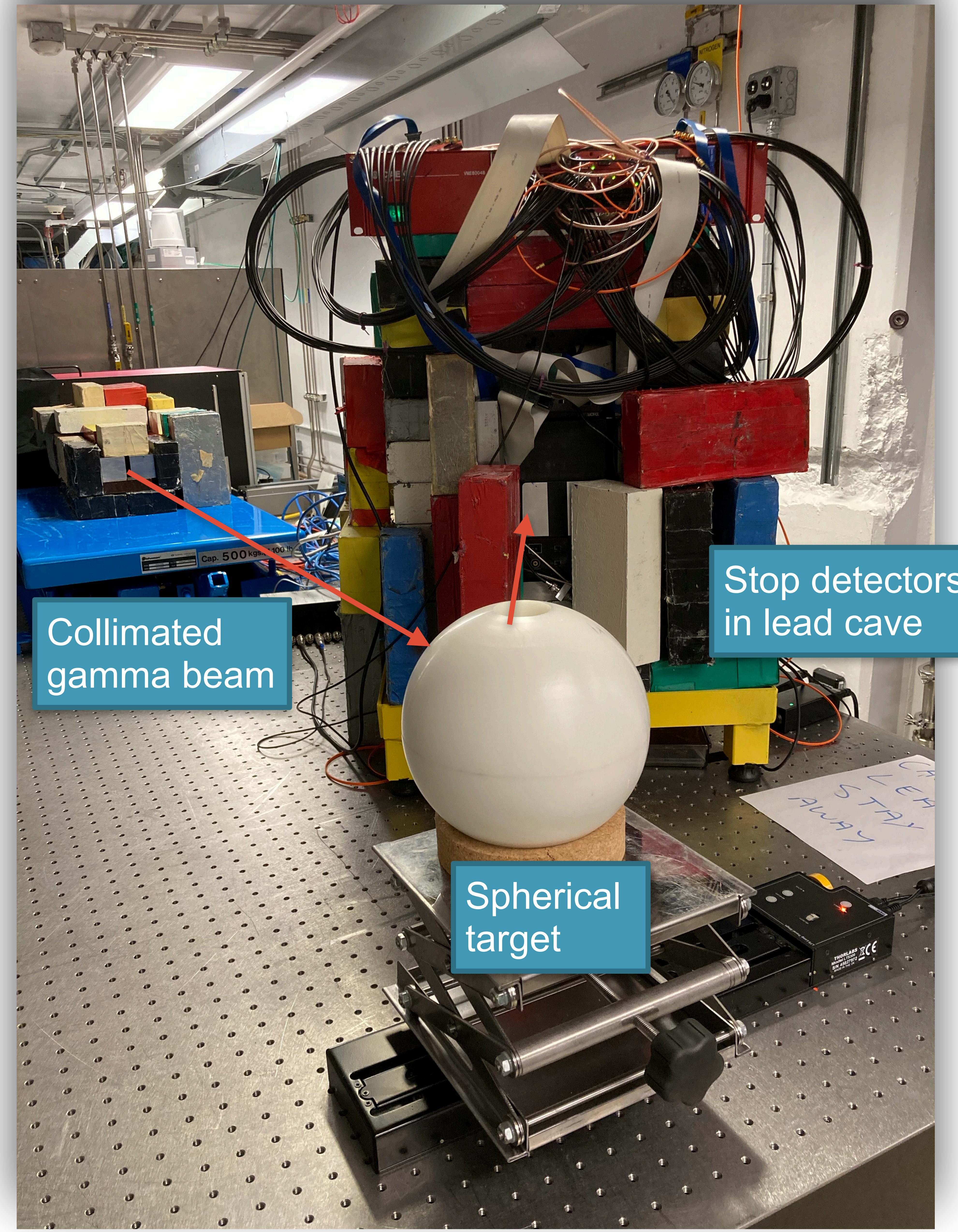
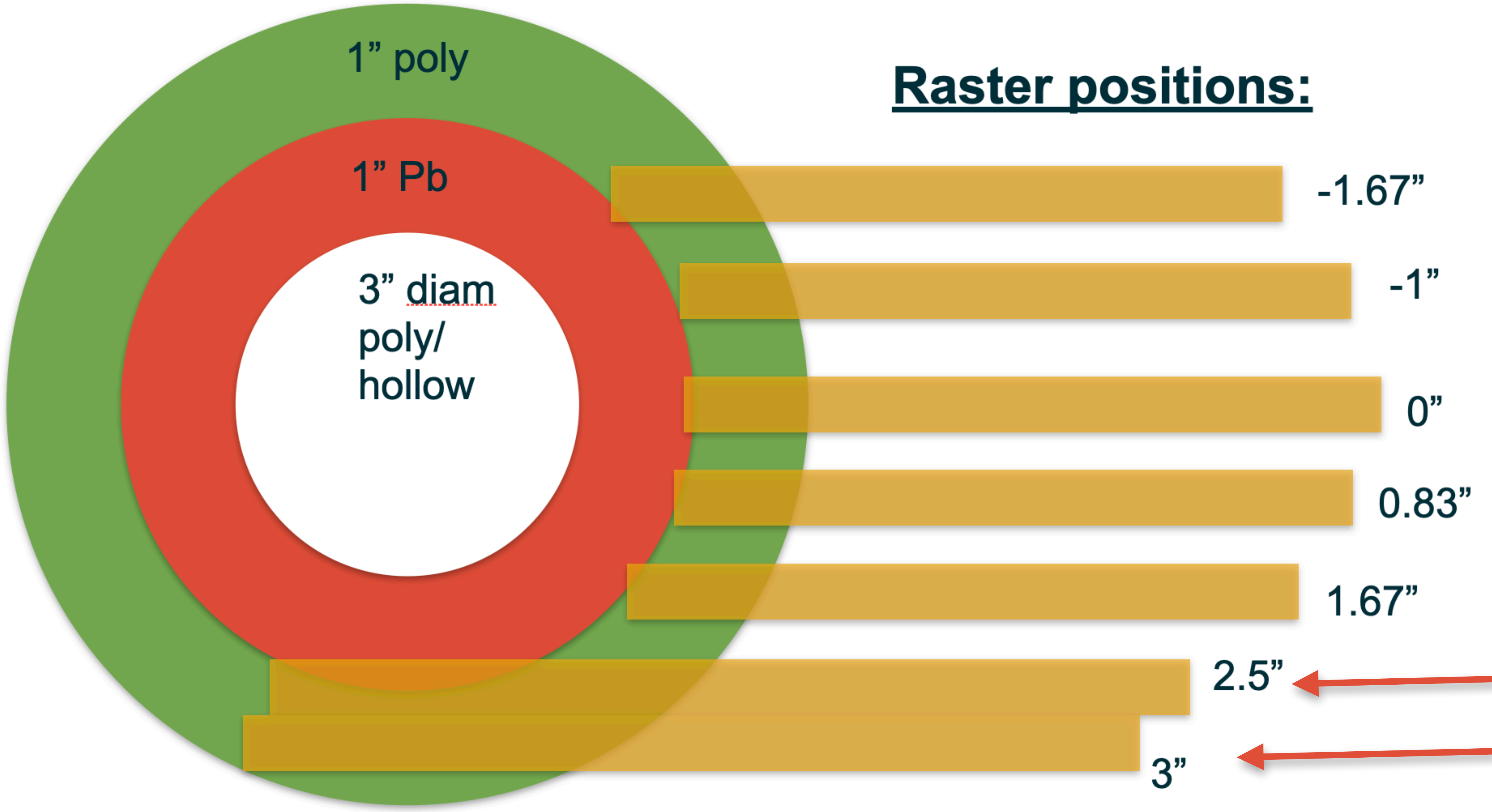
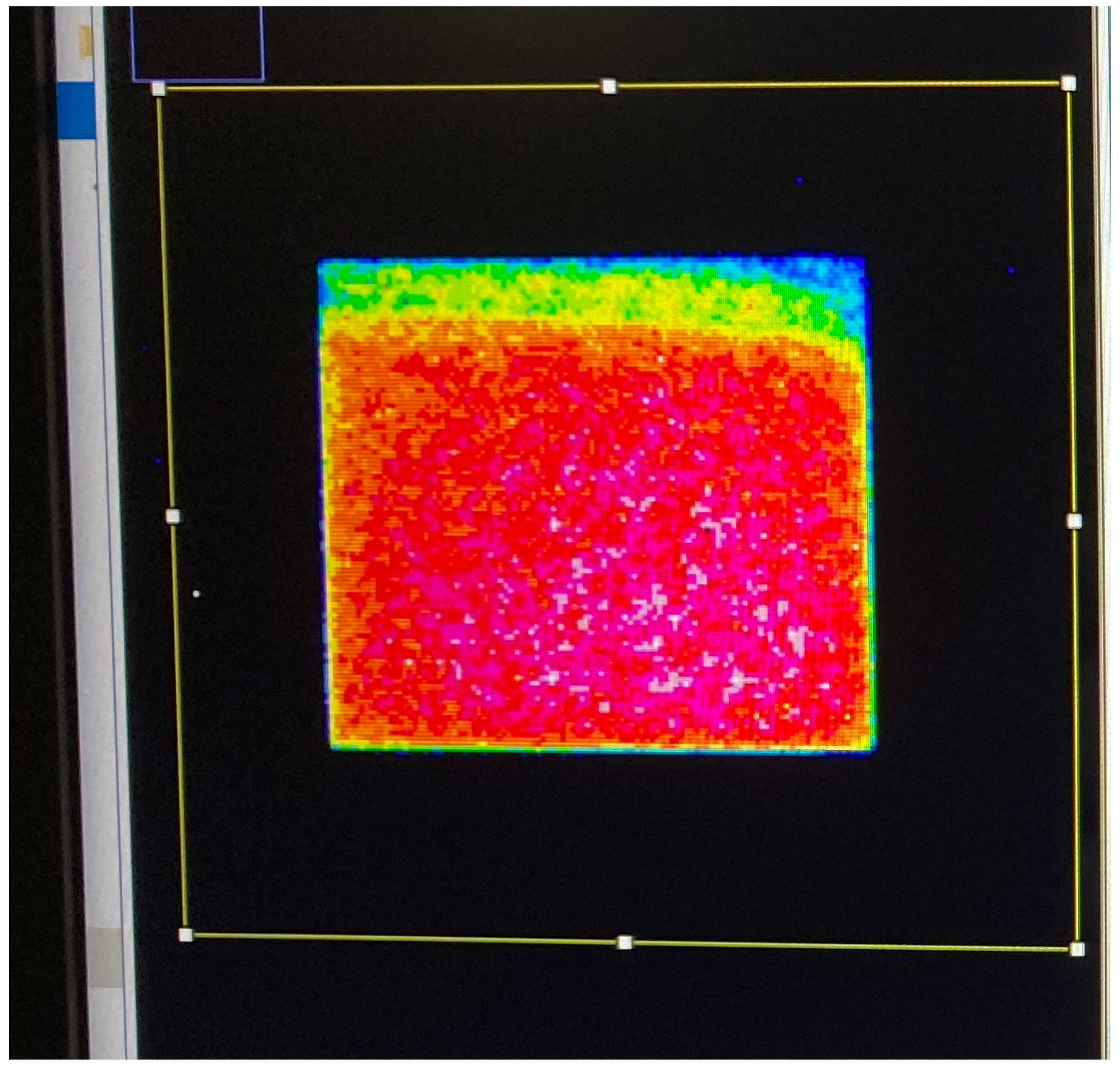


Scanning a spherical target

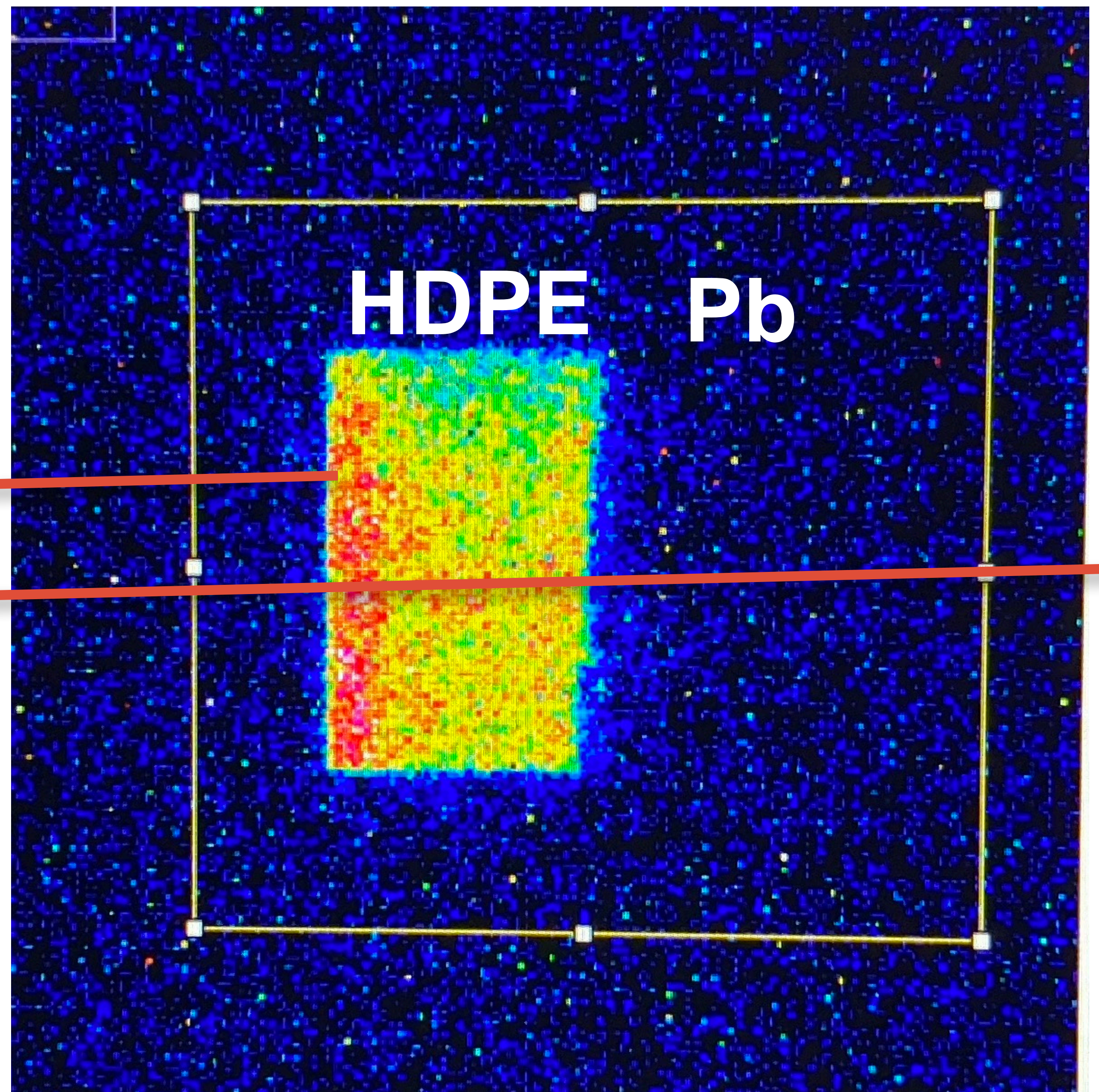
- Use radiography panel to verify alignment with key features in sphere



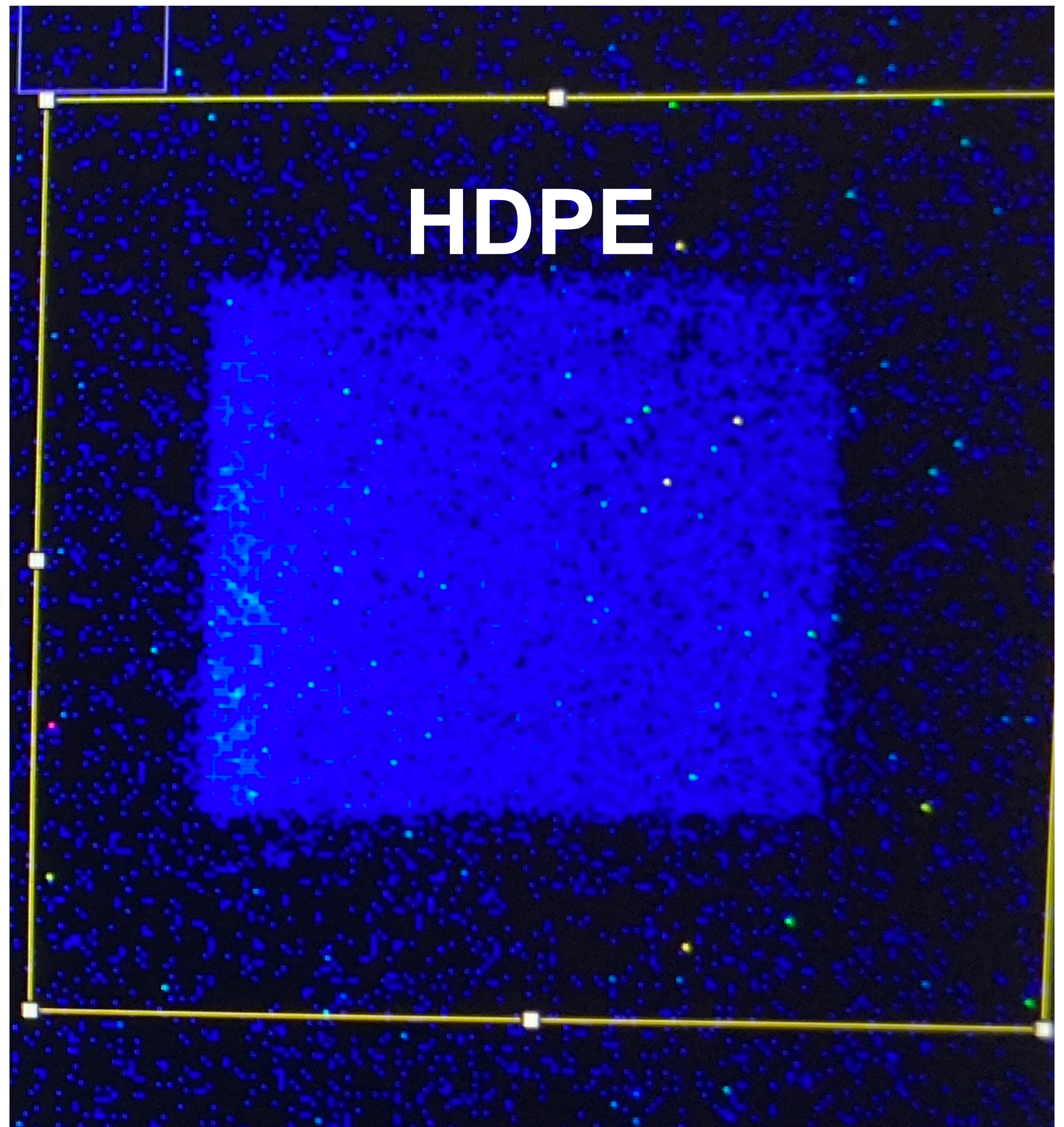
Full beam profile, 1/2" square (no target)



Edge of HDPE / Pb interface

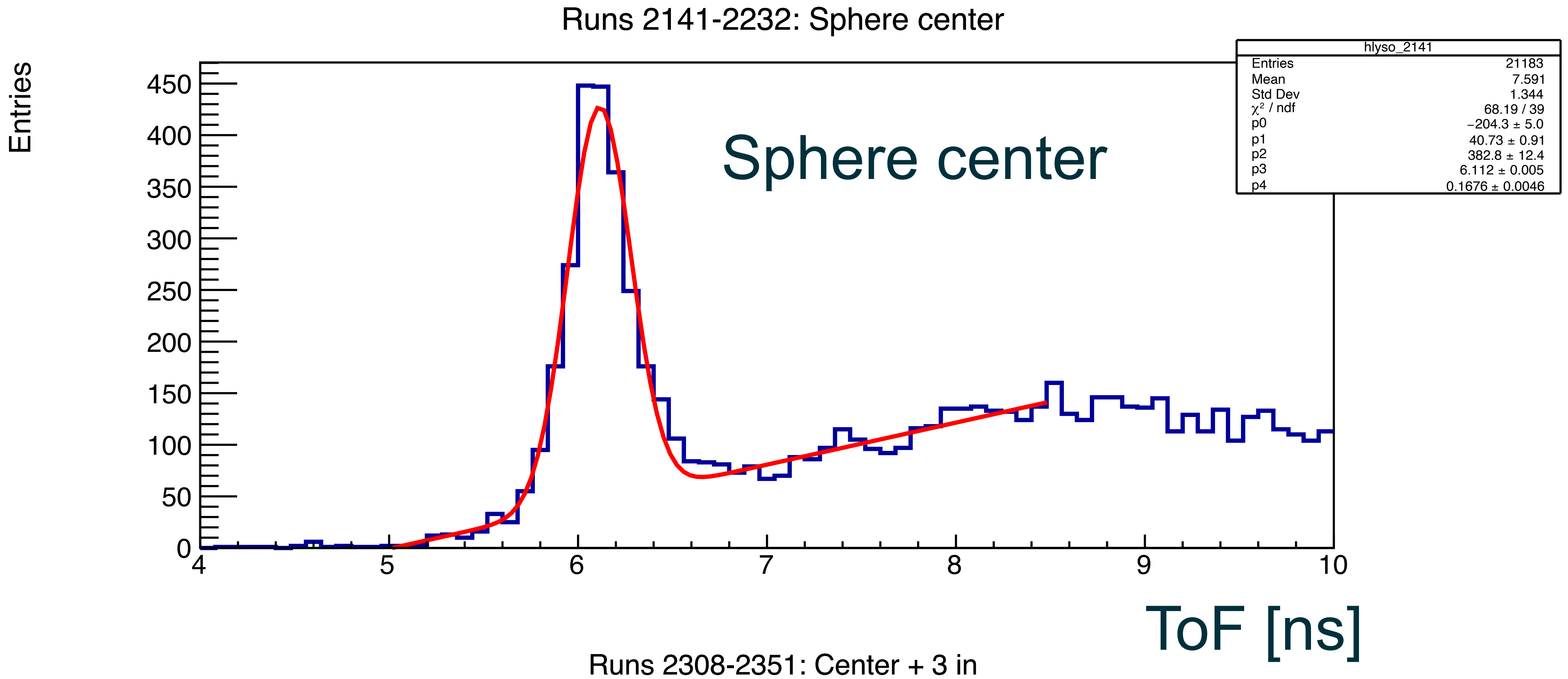


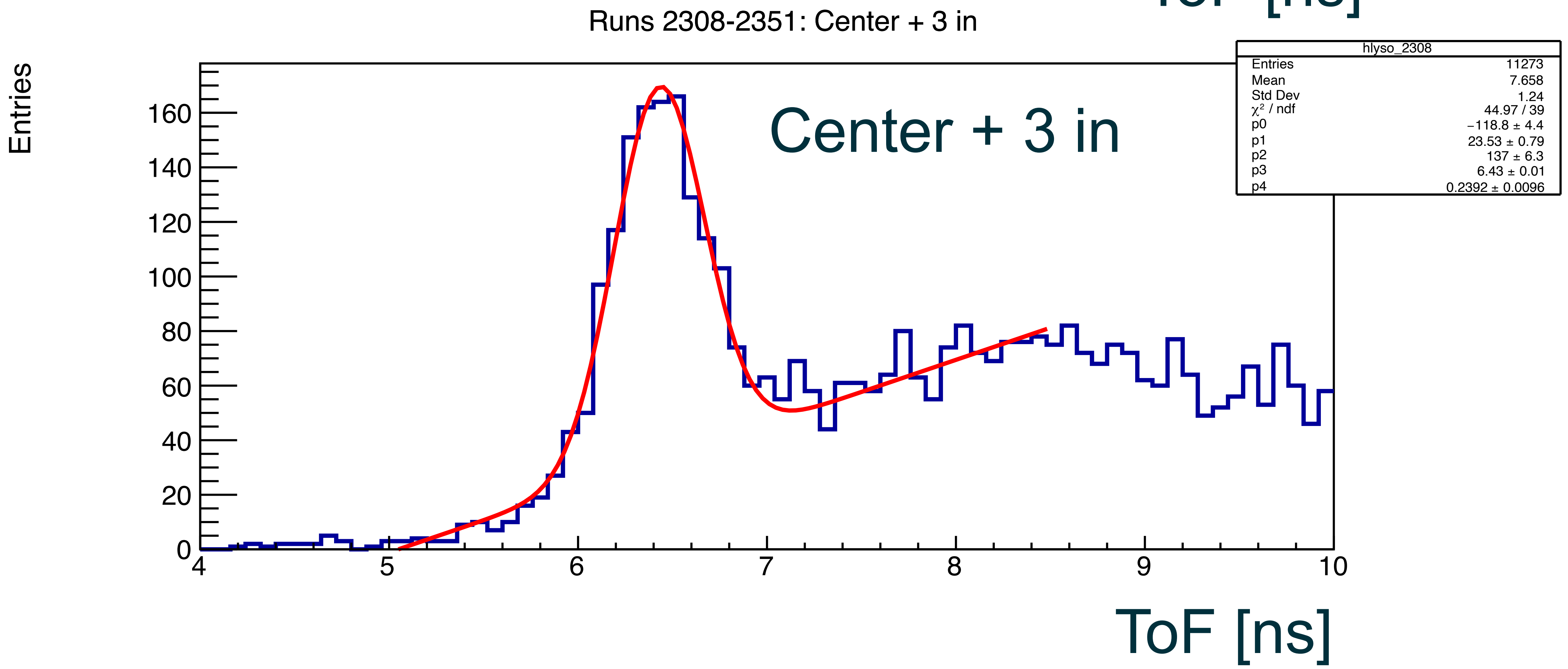
HDPE only



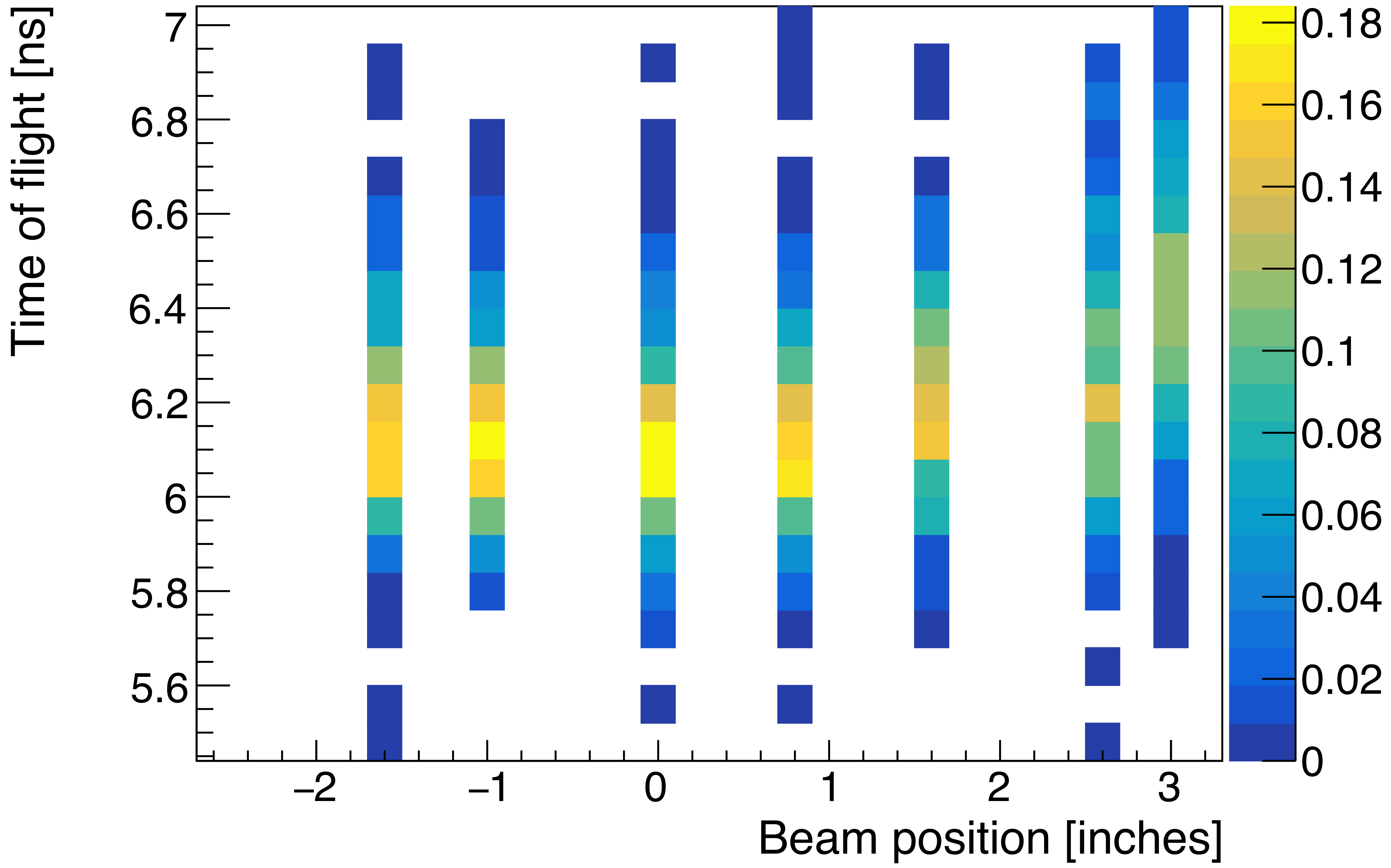
Scanning a spherical target

- Variation in reflection ToF reveals spherical shape





BG-subtracted “image”



Scanning a spherical target

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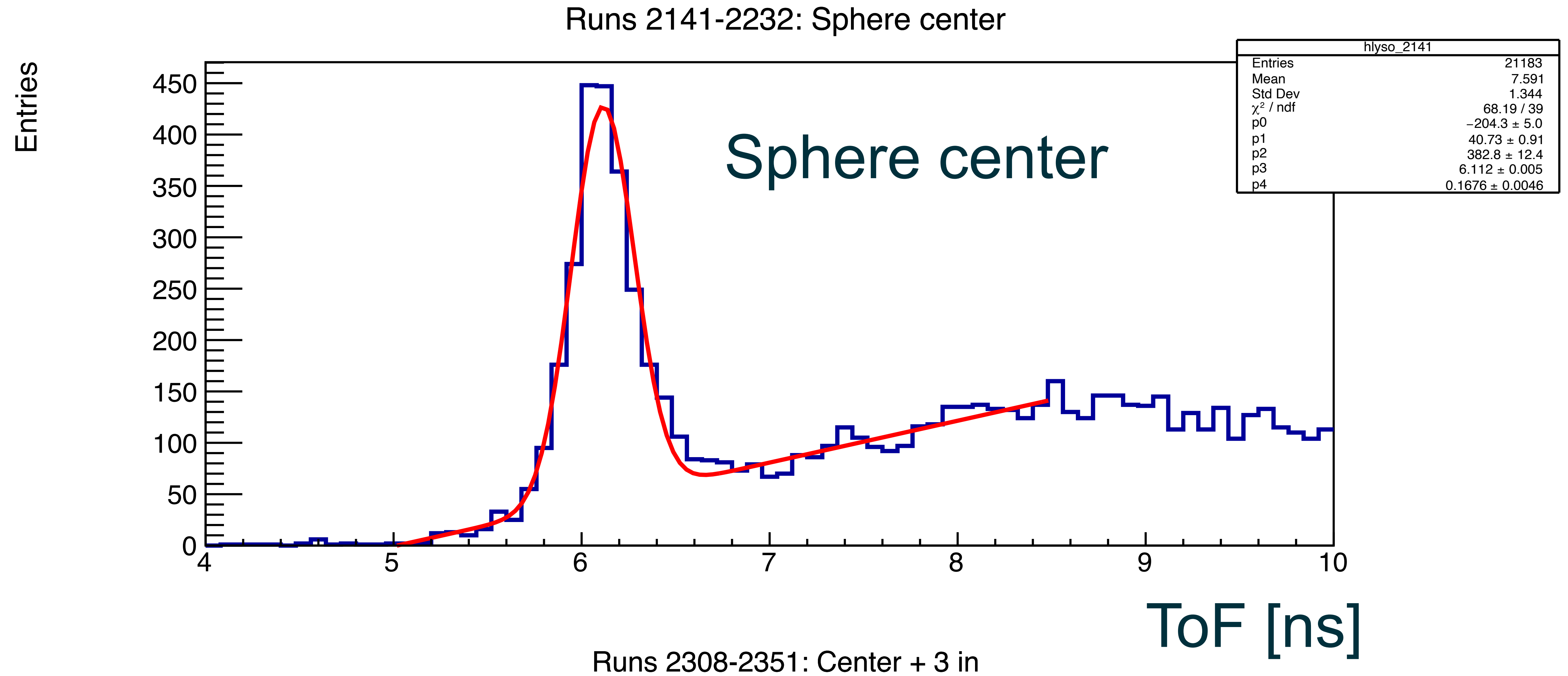

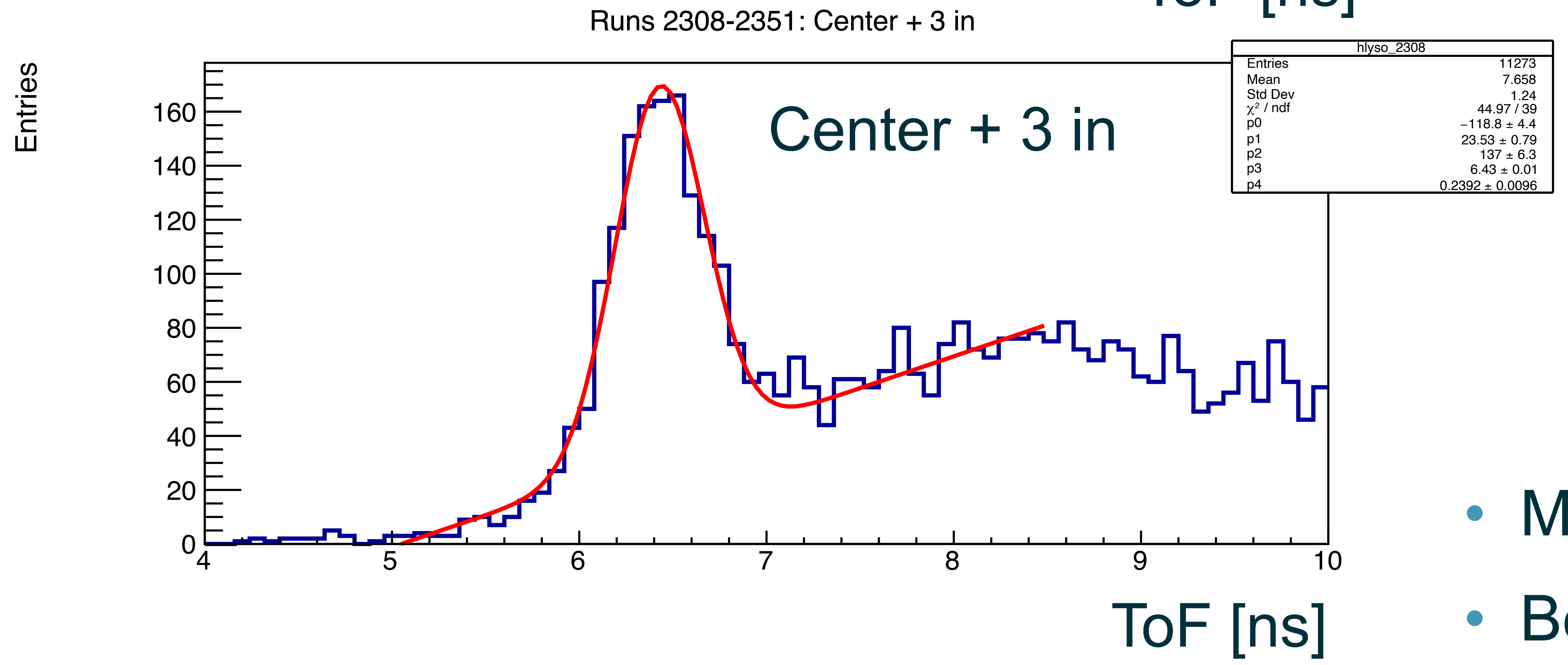

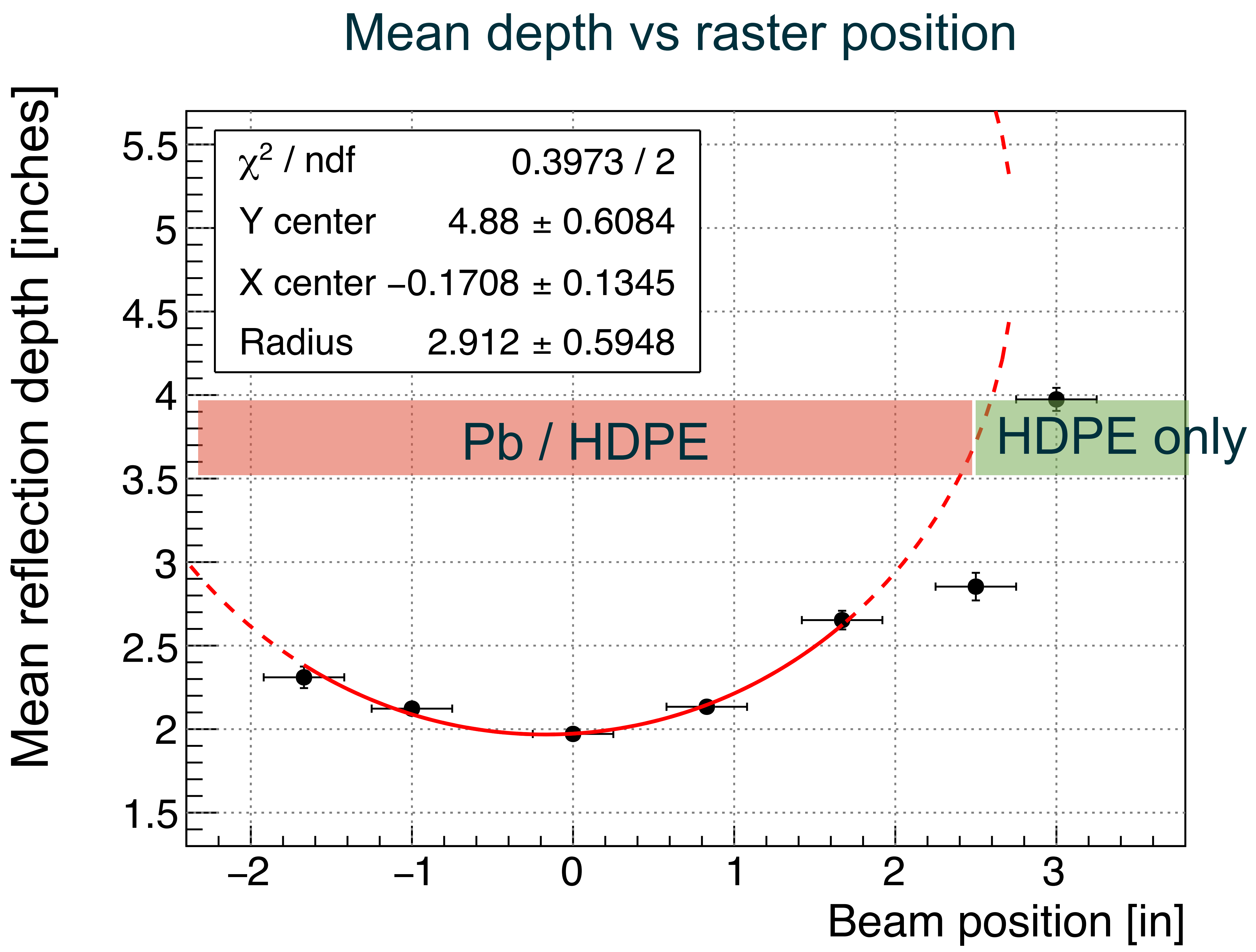

- Mean reflection consistent with expectation: 2.9” radius
- Behavior at outer radius not fully understood

Limitations & future signatures

- This demonstration relied on Compton backscatters from ~ 1 MeV beam.
  - Very low energy; barely grows with beam energy. 200 keV at 1 MeV, only 250 keV at 10 MeV.
  - Severely limits penetration, as backscatters have to escape target!
- Future signals: want higher energy return photons
  - Positron production → 511 keV photons. Positronium lifetime spectroscopy can reveal material information
  - Nuclear Resonance Fluorescence (NRF) → excellent specificity, requires extremely narrow-band photon source.
  - Photofission, requires higher energy.
- High energy photons enable use of Cherenkov based detectors, w/ better time resolution, pileup tolerance, and background rejection

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- Statistics:
  - This experiment operated at 1 Hz with 10^6-10^7 photons / shot.
  - Photon counting mode: only finite information per shot. Huge benefit to higher repetition rate, no benefit to increased intensity per shot.

Summary

- Achieved first demonstration of gamma-ray LIDAR with a monoenergetic photon source, using at the Berkeley Lab Laser Accelerator Center
- Demonstrate capability to resolve multiple discrete layers and reconstruct geometric curvature in spherical target
- Many future opportunities to exploit in gamma LIDAR!

Gamma LIDAR collaboration

LBNL photon source: Cameron Geddes (PI, cgrgeddes@lbl.gov), Qiang Chen, Rob Jacob (NSSC), Ben Greenwood, Hai-En Tsai, Tony Gonsalves, J.-L Vay, Carl Schroeder, Jeroen van Tilborg, E. Esarey

LBNL detector: Brian Quiter, Joshua Cates, Ryan Heller, Victor Negut, Nicholas Parilla

INL: Scott Thompson, James Johnson, Jay Hix, David Chichester

UTK: Jason Hayward

Supported by NNSA Defense Nuclear Nonproliferation R&D

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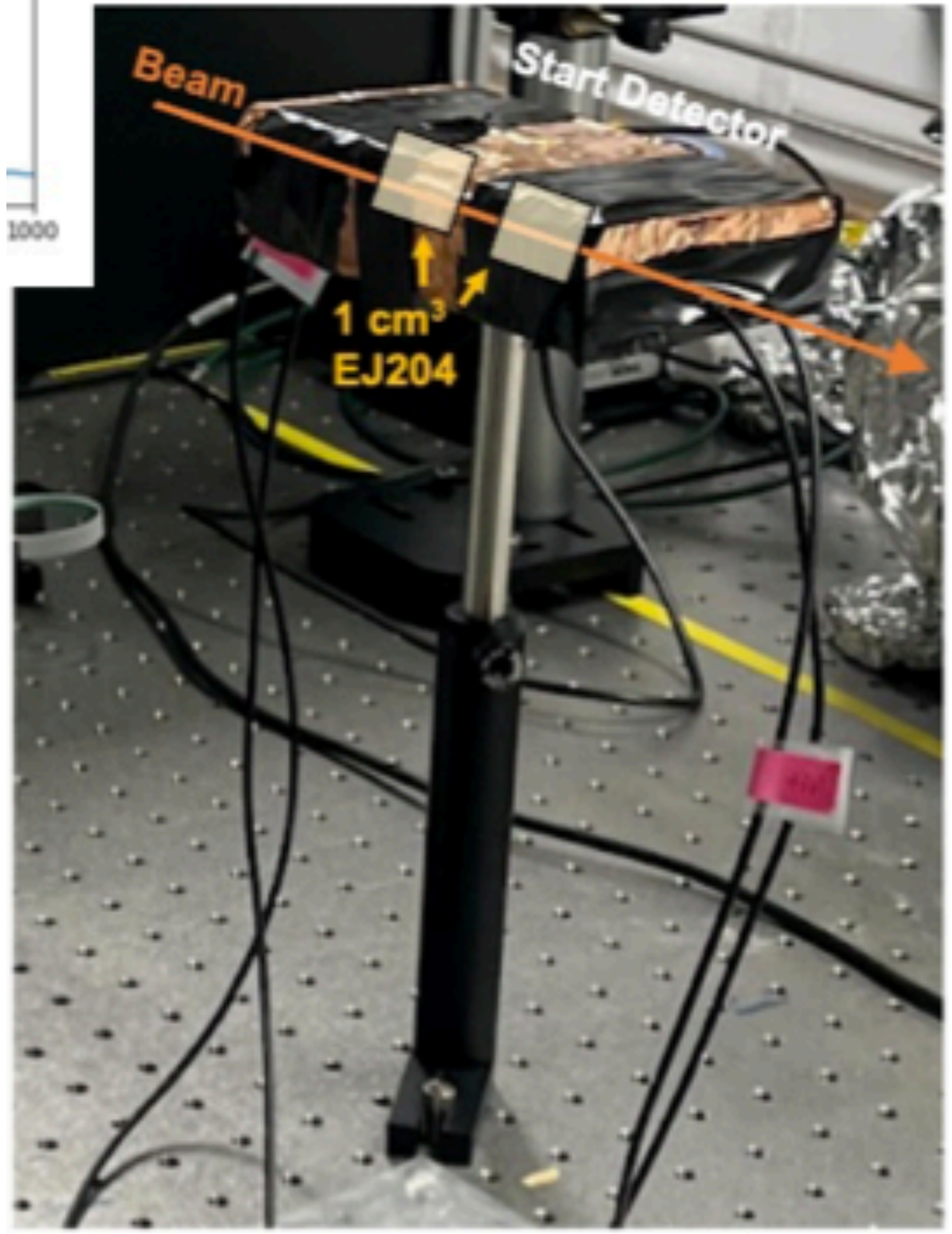
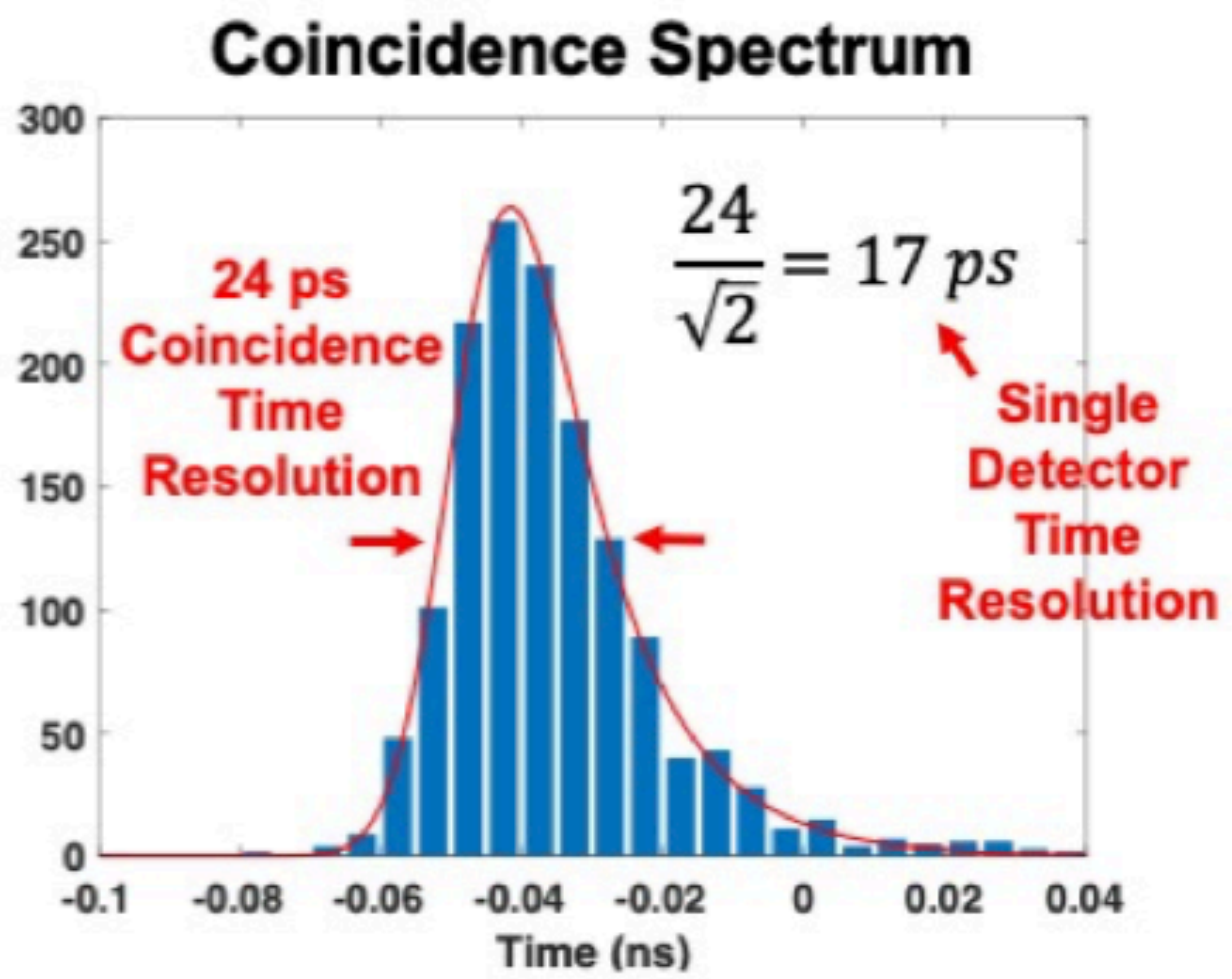
Start detectors

Plastic scintillator detector in path of gamma beam to tag start time.
Two copies were placed in beamline, to enable measuring the time resolution.



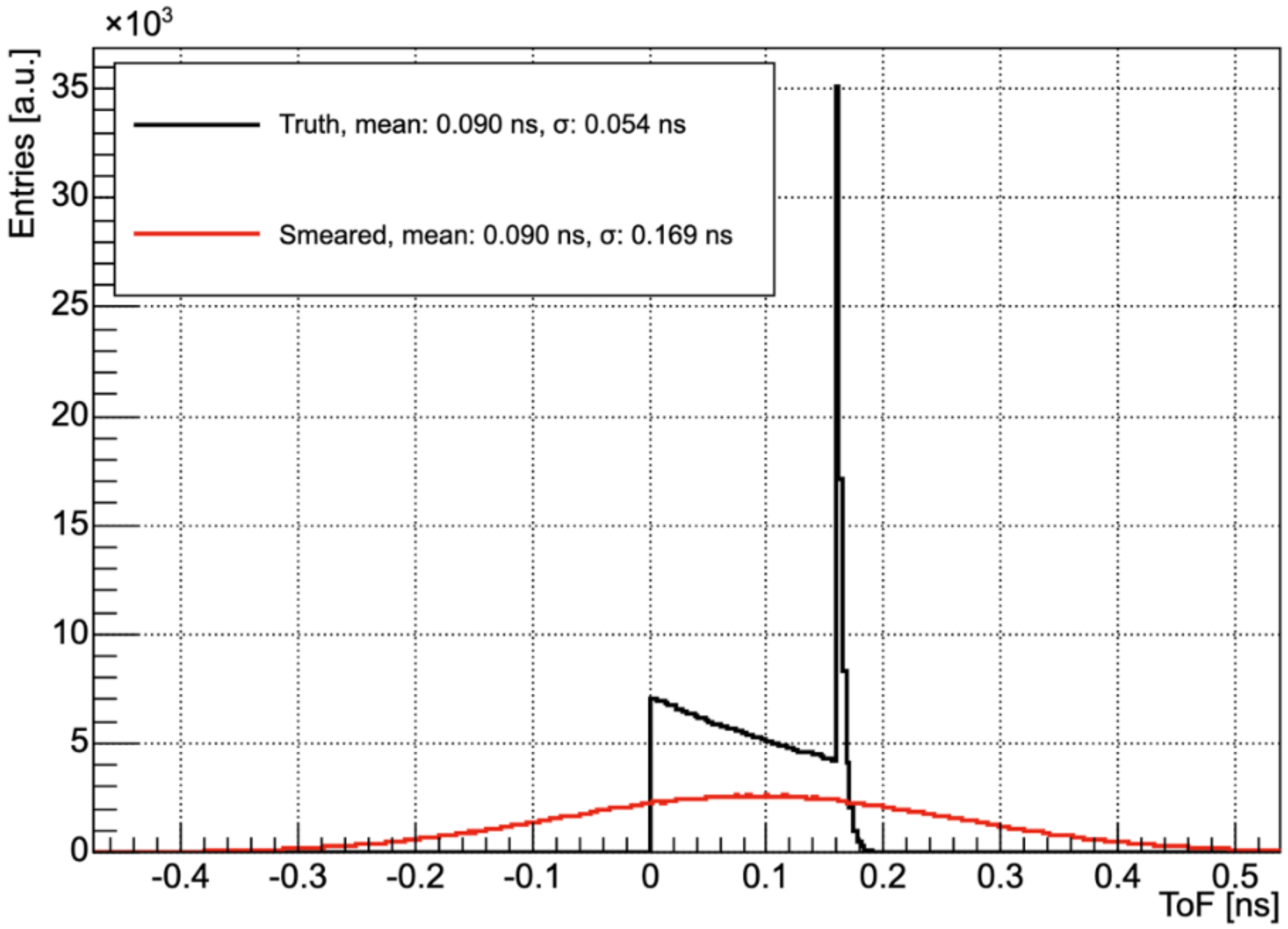


Detectors for gamma LIDAR

Expectations for sphere dataset

- Toy model considering attenuation of primary & reflected beam in HDPE and Pb.

Sphere center



Center + 3” (poly only)