Neutron Dosimetry and Time of Flight Beam Characterization with Hybrid Pixel Detectors

Stuart P. George

Structure of Talk

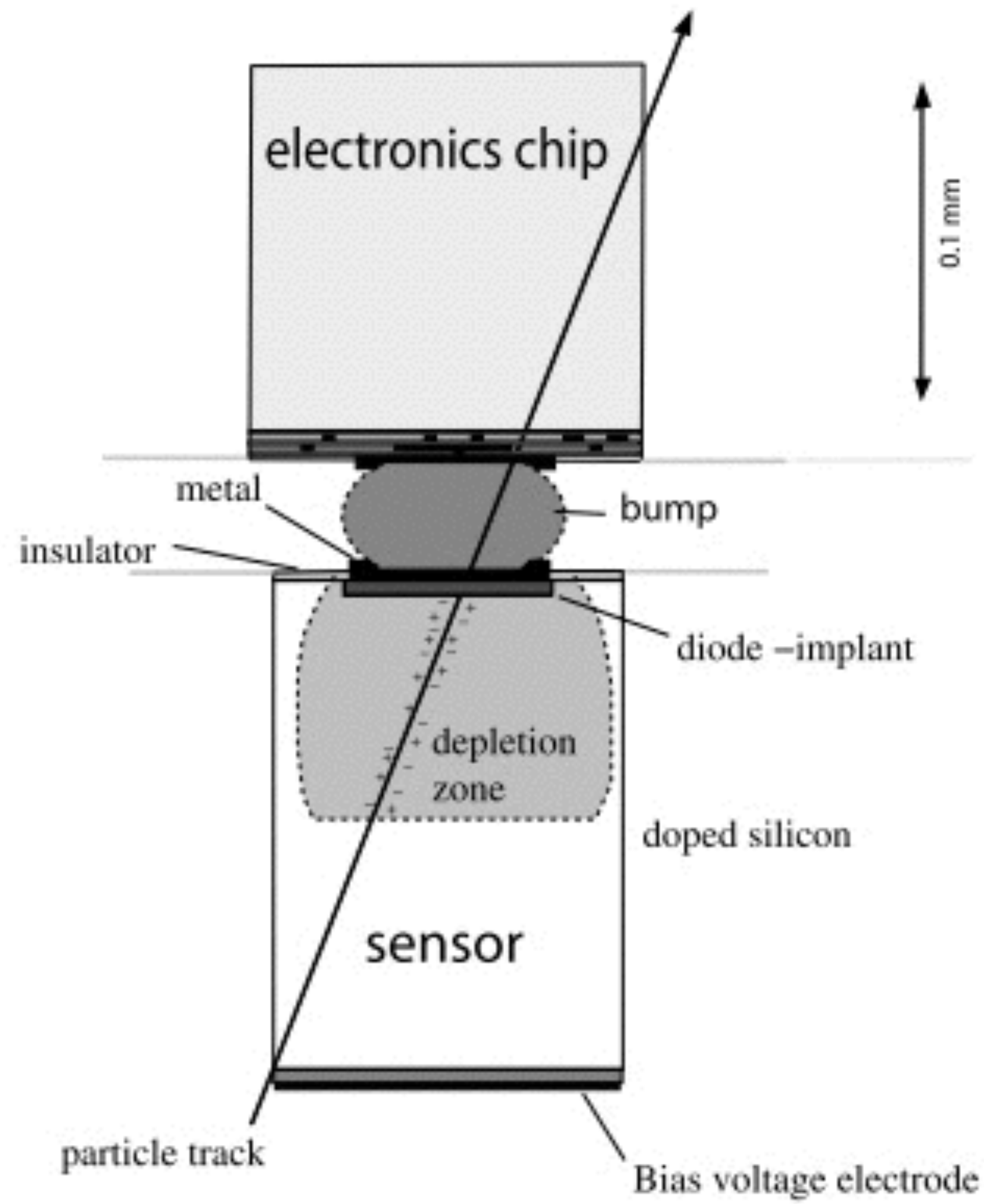
- Introduction to the Timepix hybrid pixel detectors, stacked polyethylene neutron dosimeter concept
- Geant4 development of dosimeter
- Experimental measurements at NTOF facility

What is a Hybrid Pixel Detector

- Hybrid pixel detectors mean that the semiconductor sensor and the readout chip are made separately and joined together later

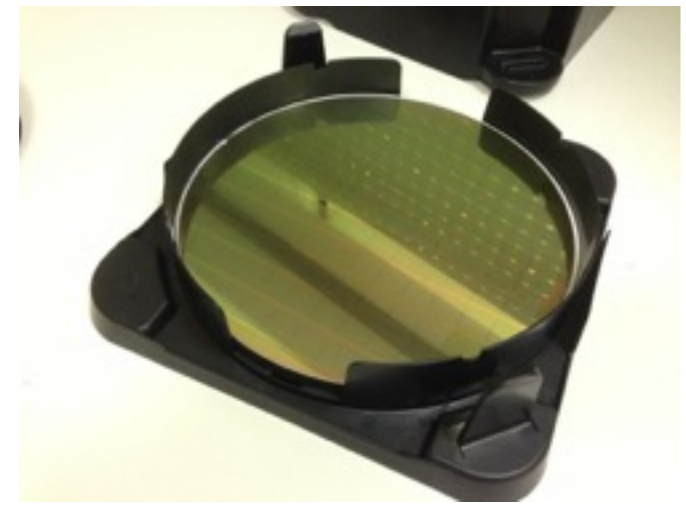
- Allows use of different sensor materials for different applications (Si, CdZnTe, GaAs, Gas)

- Necessitated out of desire to use different Si processes for sensor and readout

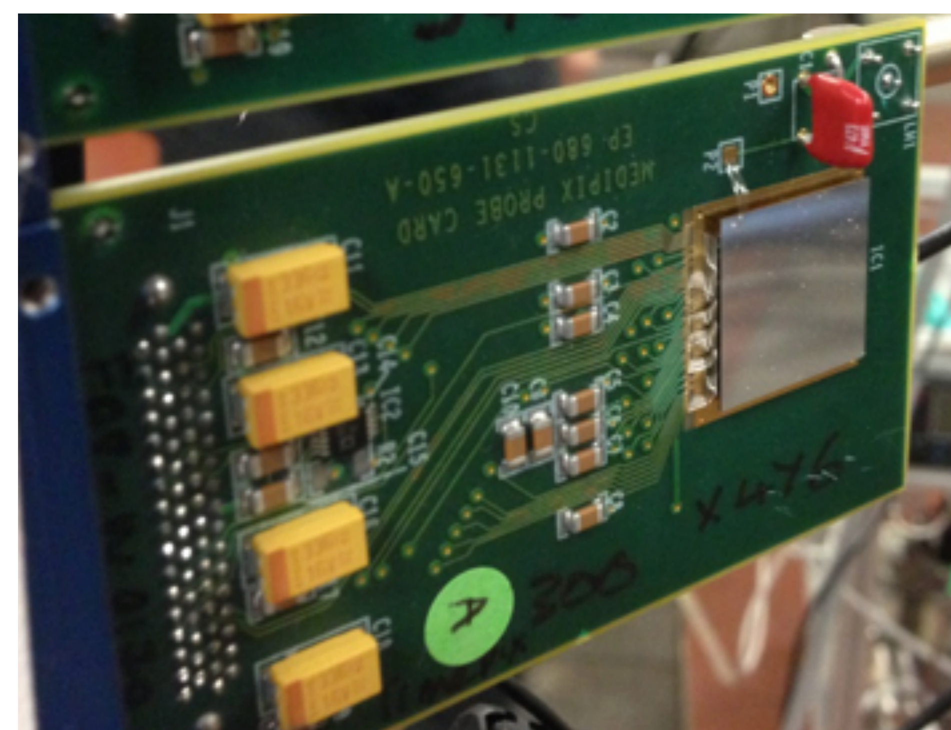


The Timepix - a quick intro

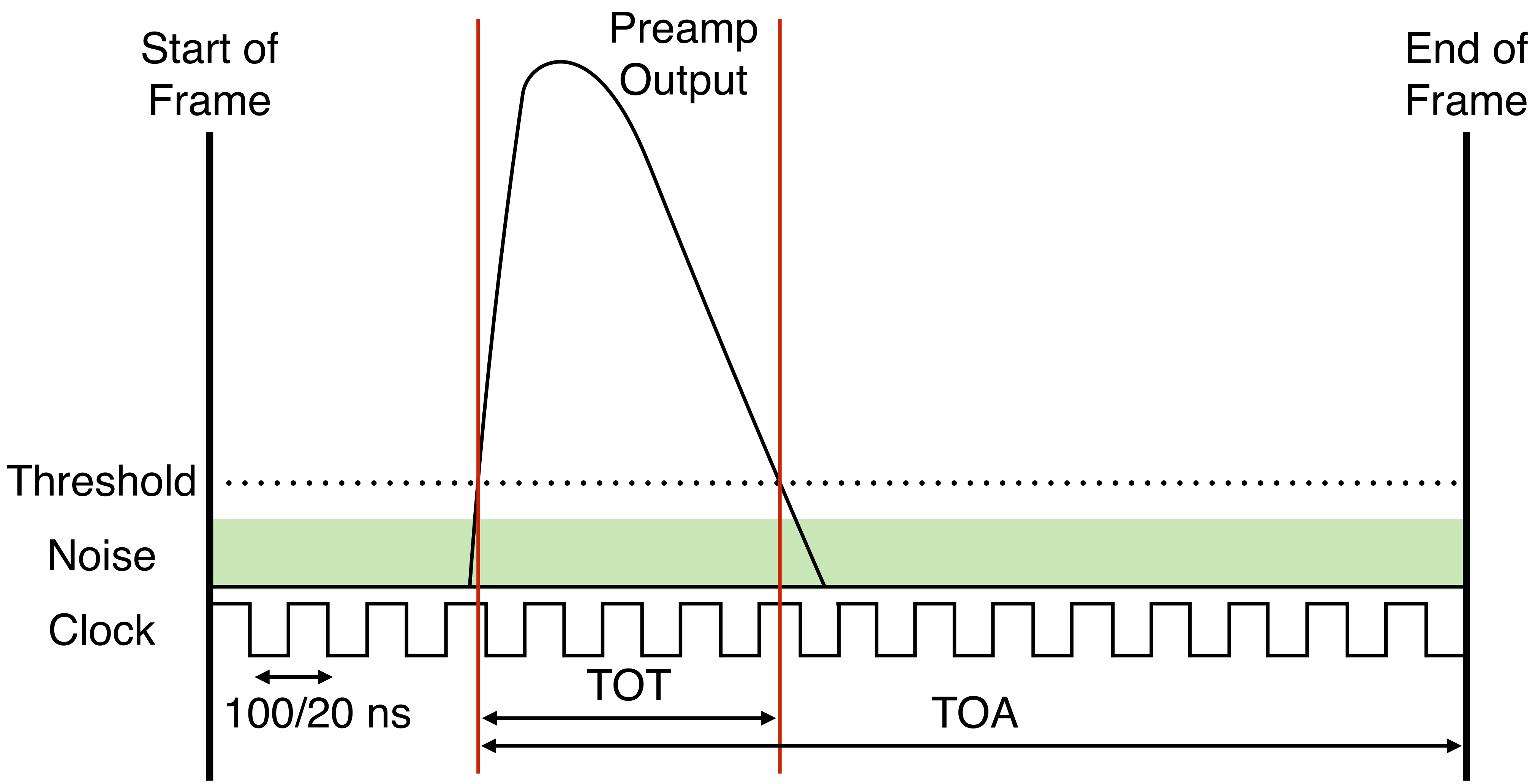
- The timepix consists of 256 x 256 CMOS pixels each measuring 55 x 55 um.
- Each pixel can either measure charge deposited or time of arrival
- The detection threshold is about 1000 electrons
- ASIC connected to 300 um silicon sensor



Timepix ASIC Wafer

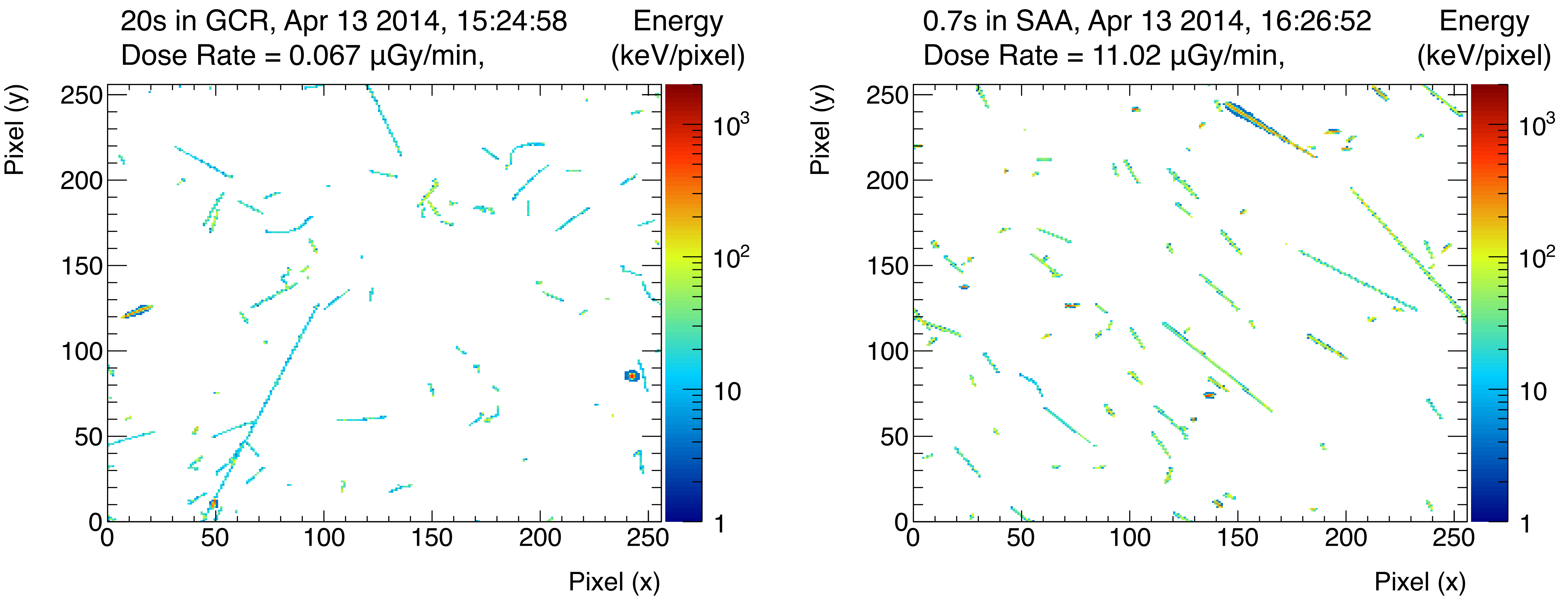


Timepix mounted on CERN probe card



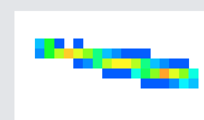
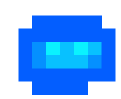
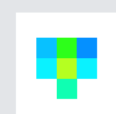
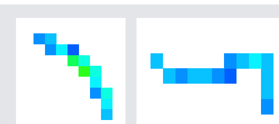
- Medipix (pulse counting)
- TOA (Time of arrival)
- TOT (Charge surrogate measurement as a Wilkinson ADC)
- TOA/TOT achieved with an on chip clock synchronised to all pixels (up to 100 Mhz, but 50 stable)

What do you measure with a Timepix

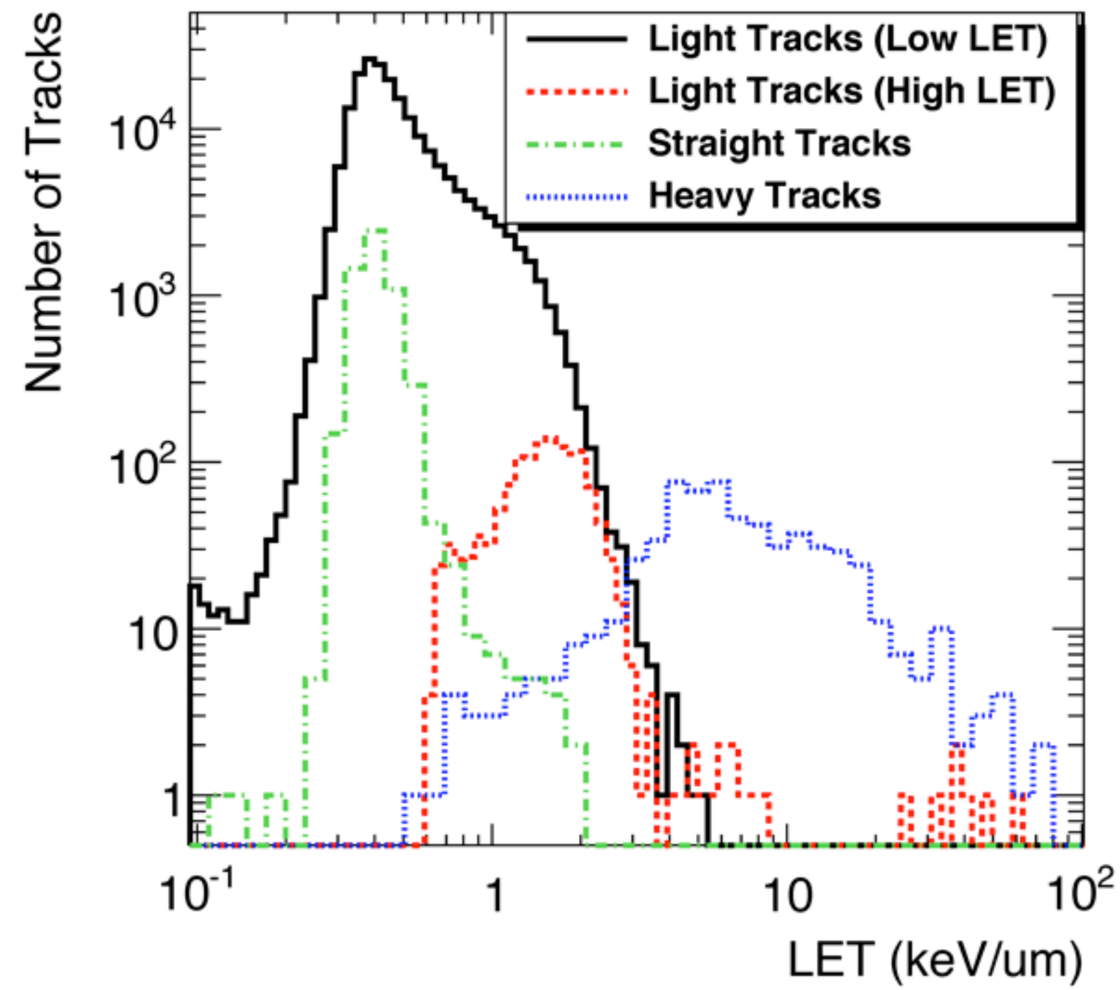


- Each track is left by a single charged particle, the morphology is representative of the physics of the particle

Morphological Clustering

Type	Inner Pixels	Length/ Width Ratio	Other Criteria	
Small Blob	0	-	1 or 2 Pixels 3 if L shape 4 is square	
Heavy Track	> 4	> 1.25	Not S.Blob Density > 0.3	
Heavy Blob	> 4	< 1.25	Not H.Track Density > 0.5	
Medium Blob	> 1	< 1.25	Not H.Blob Density > 0.5	
Straight Track	0	> 8	Not M.Blob Minor axis < 3 pixels	
Light Track	-	-	Not S.Track	

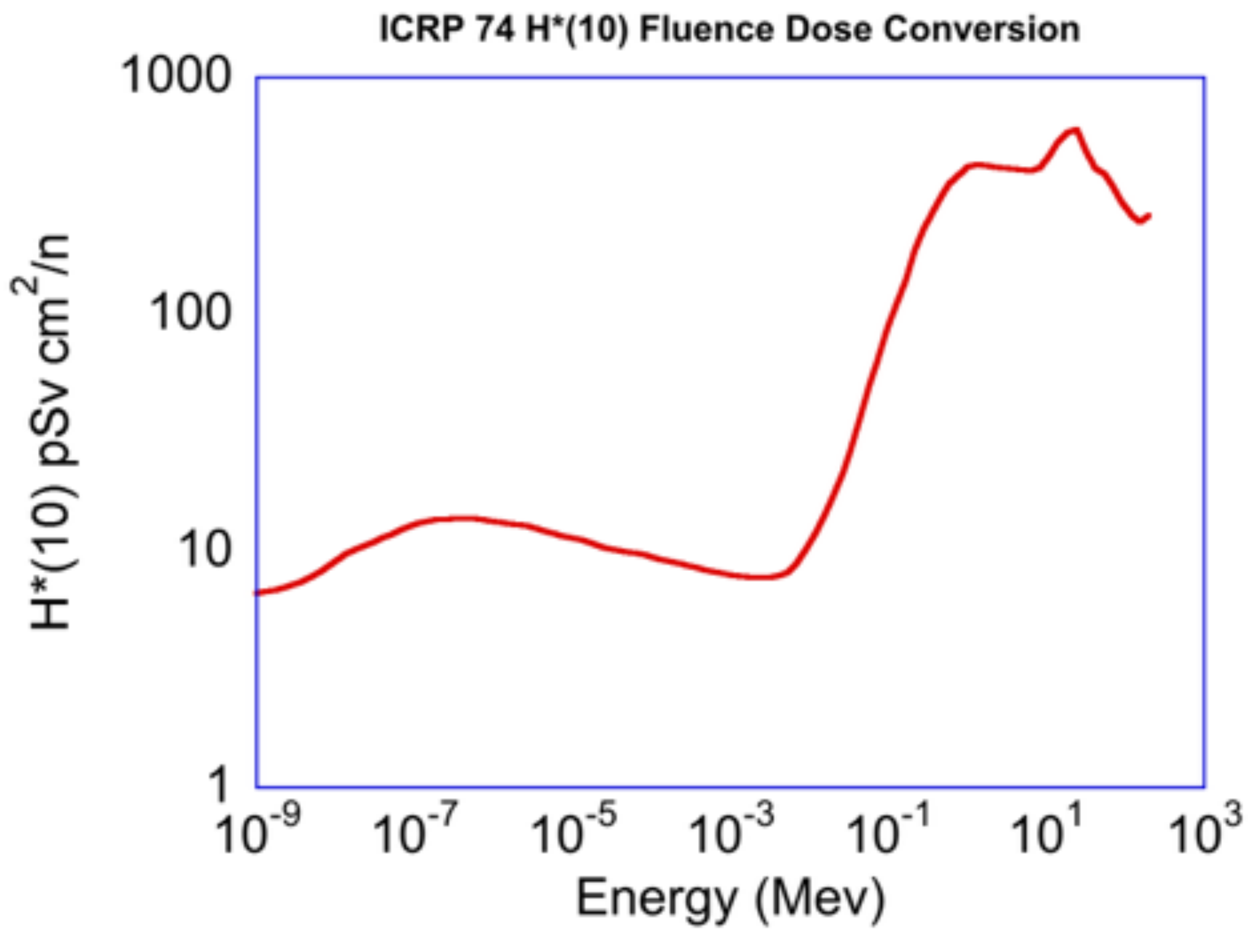
LET spectra in an aviation field (CERF)



- Morphology is broadly representative of LET, but can be uniquely identifying -> straight tracks are secondary muons from accelerator

Neutron Dosimetry and H*(10)

- Neutrons do not directly interact (like photons), but unlike photons produce a wide range of secondary particles in their interactions



- H*(10) is an operational quantity defined as the dose 10 mm inside the ICRP sphere (30 cm diameter TE sphere - approximation for a human)

How to Measure H*(10)

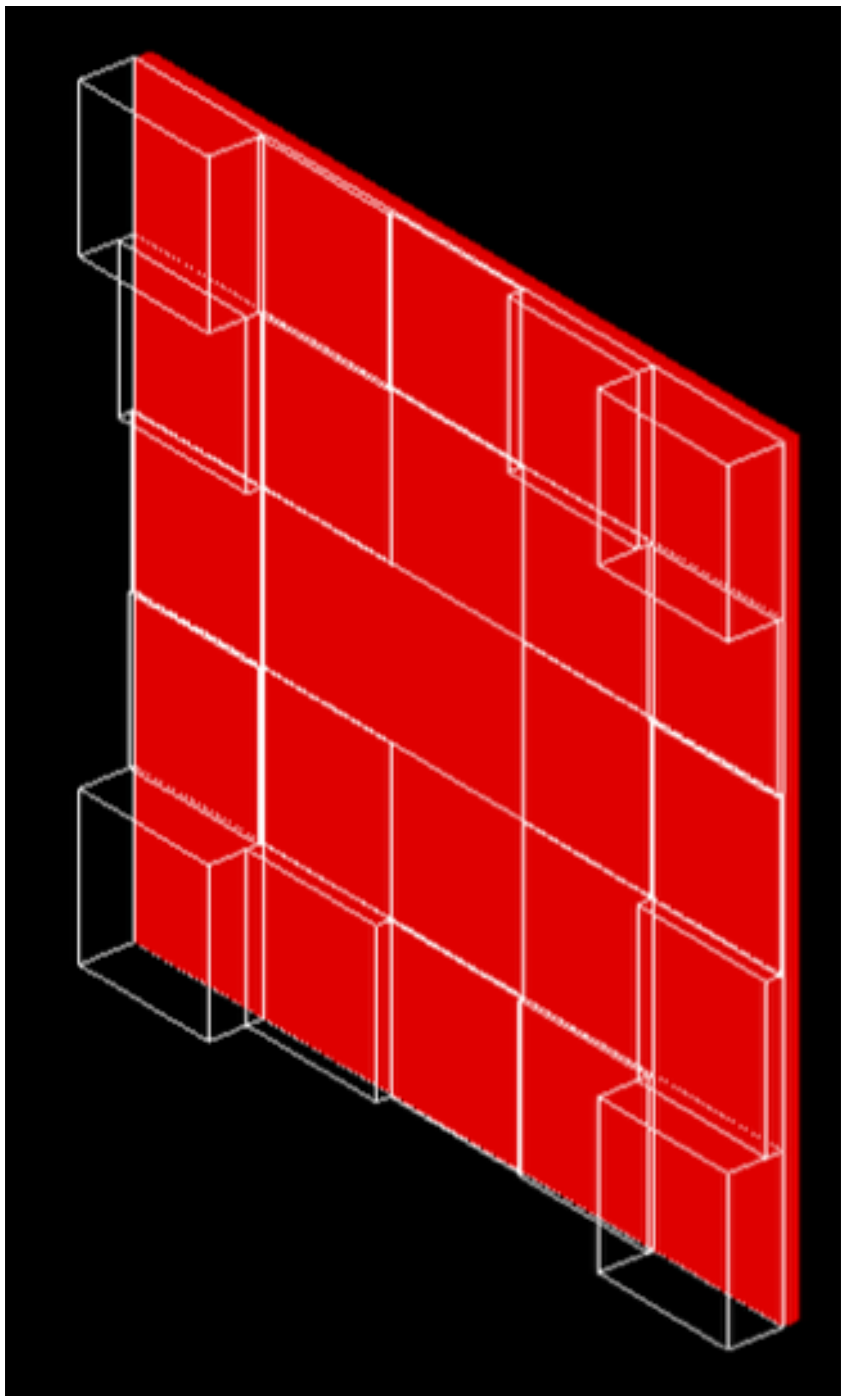
- For fast neutrons use the elastic scattering of neutrons off hydrogen -> use a sheet of hydrogenous plastic

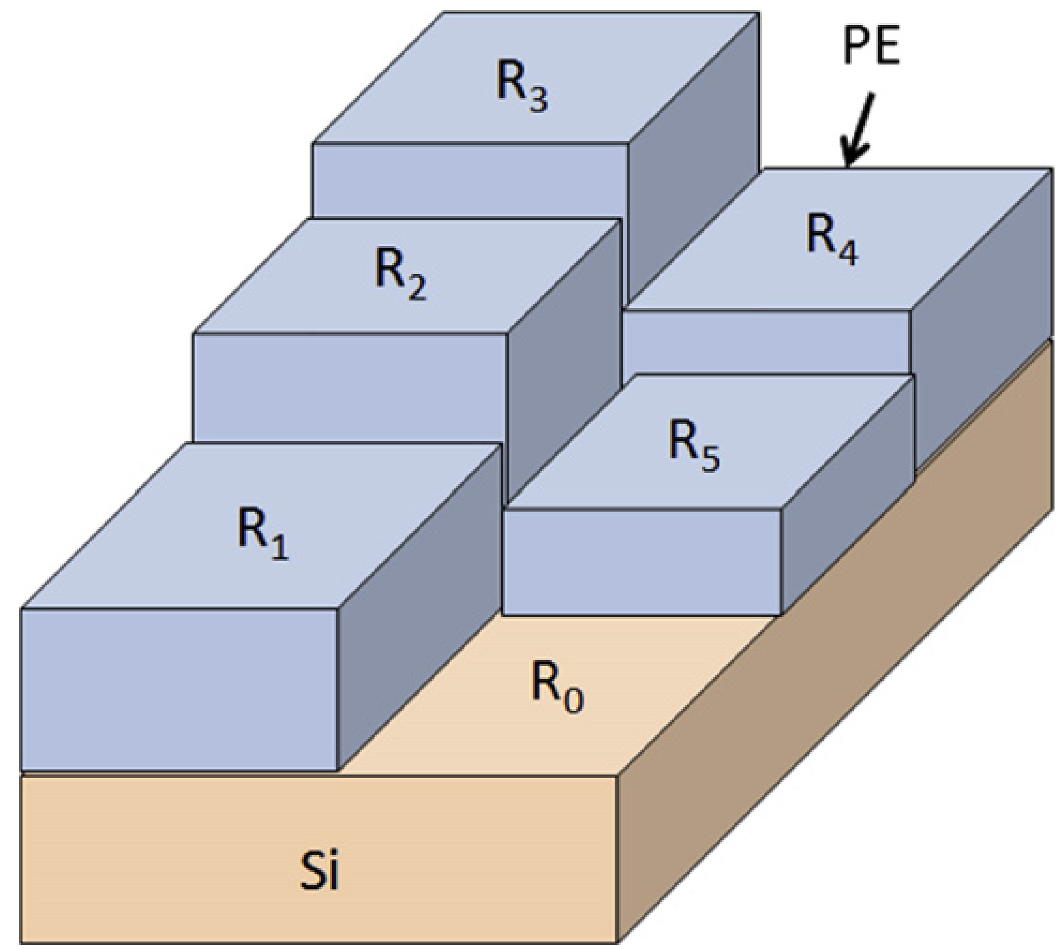
- Measure protons with Timepix

- One sheet of polyethylene does not reproduce H*(10)(E) as a function of neutron fluence -> what about lots of sheets?

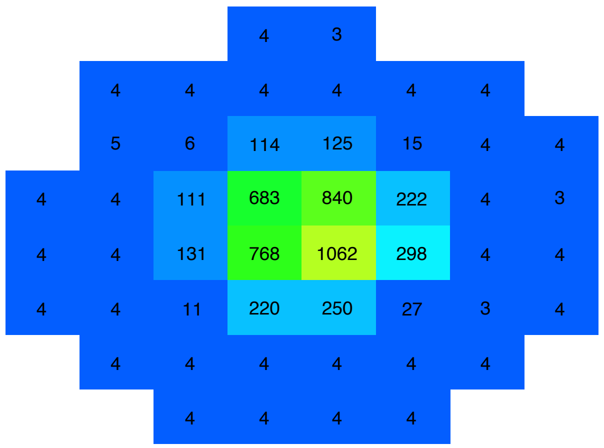
- Stacked geometry concept

Prototype Dosimeter Concept

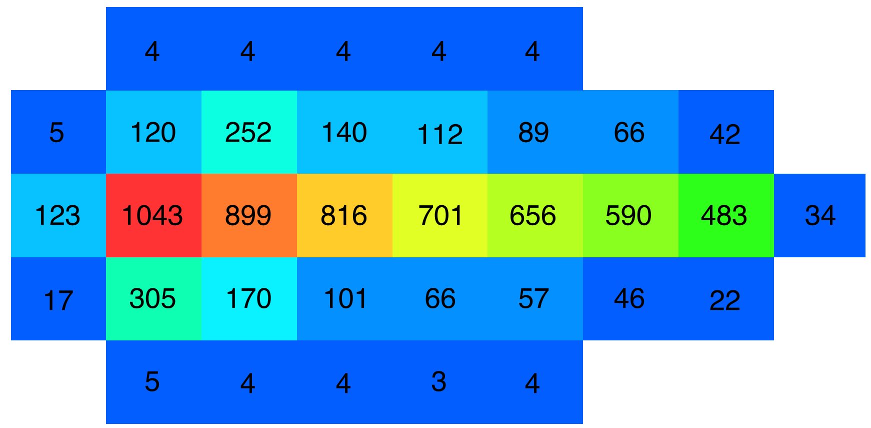




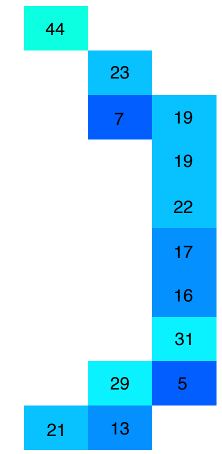
Timepix Discrimination



Alpha (Am241)



Proton (7 MeV)



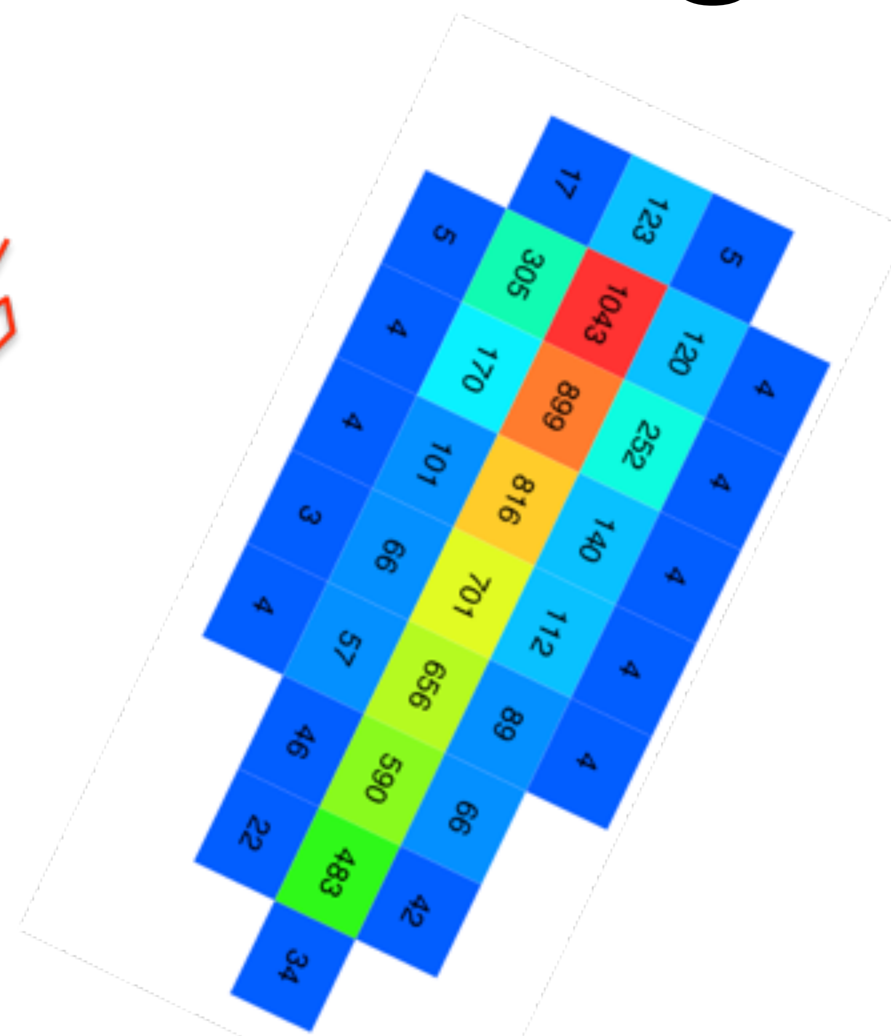
Compton (Co60)

Assumptions

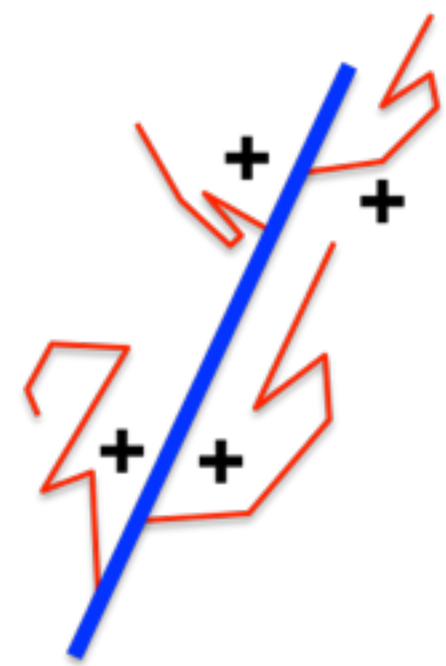
1. We can discriminate all electrons from hadrons
2. We can accurately measure the interaction point/centroid of a hadronic cluster
3. We can accurately measure the energy of a hadronic cluster
4. For now (…) we cannot separate one hadron from another (i.e. protons from alpha particles)

Event Summing Concept

[1]



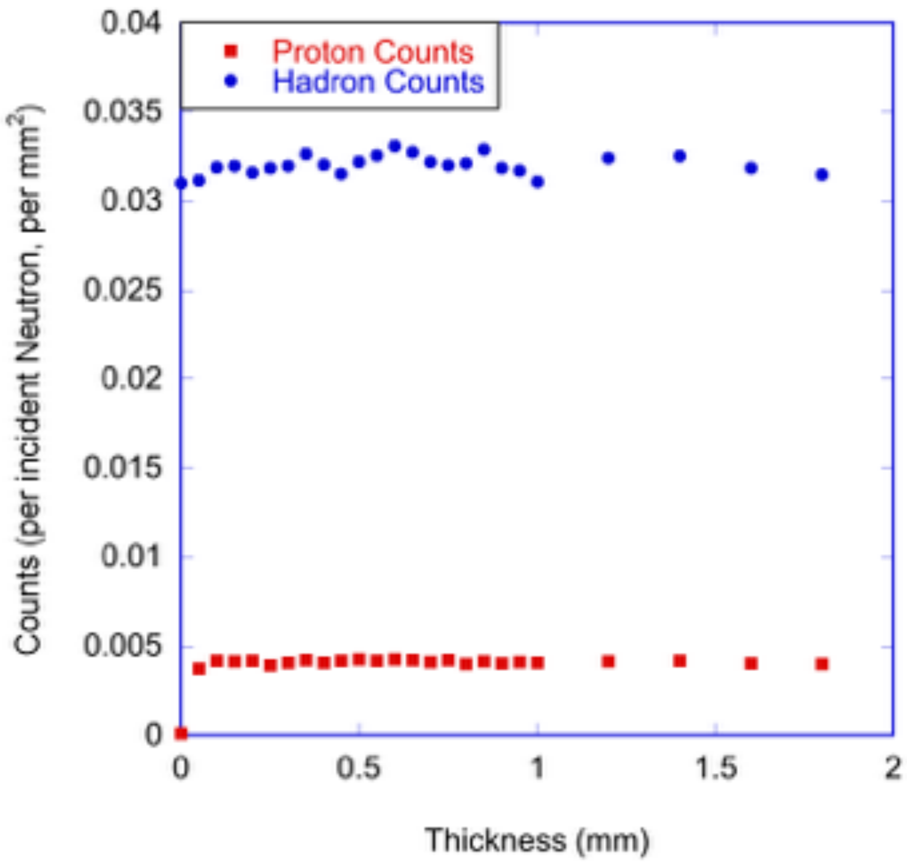
[2]



[3]

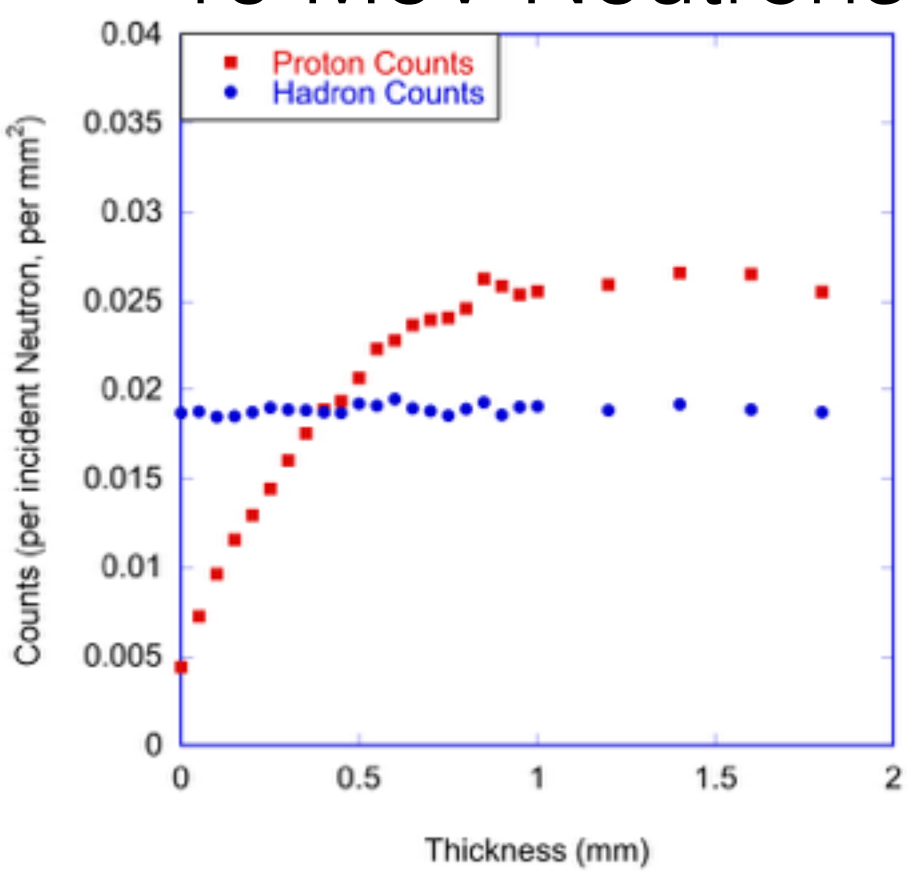
Goal - reproduce the quantities that a physical Timepix measures that we need -> cluster centroid and total energy

2 MeV Neutrons

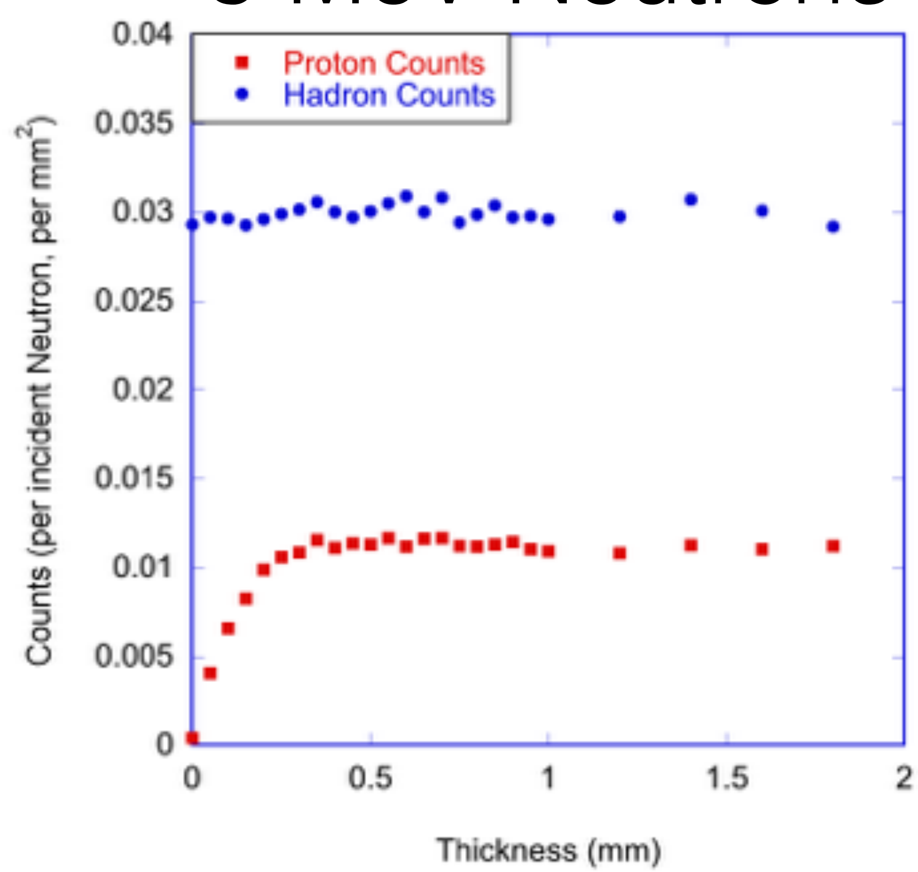


- Protons are mostly produced in the converter
- "Hadrons" are anything that is hadronic but not a proton -> (n,Si) inelastic reactions
- For 2 and 5 MeV neutrons the background dominates the signal -> this is a big problem

10 MeV Neutrons

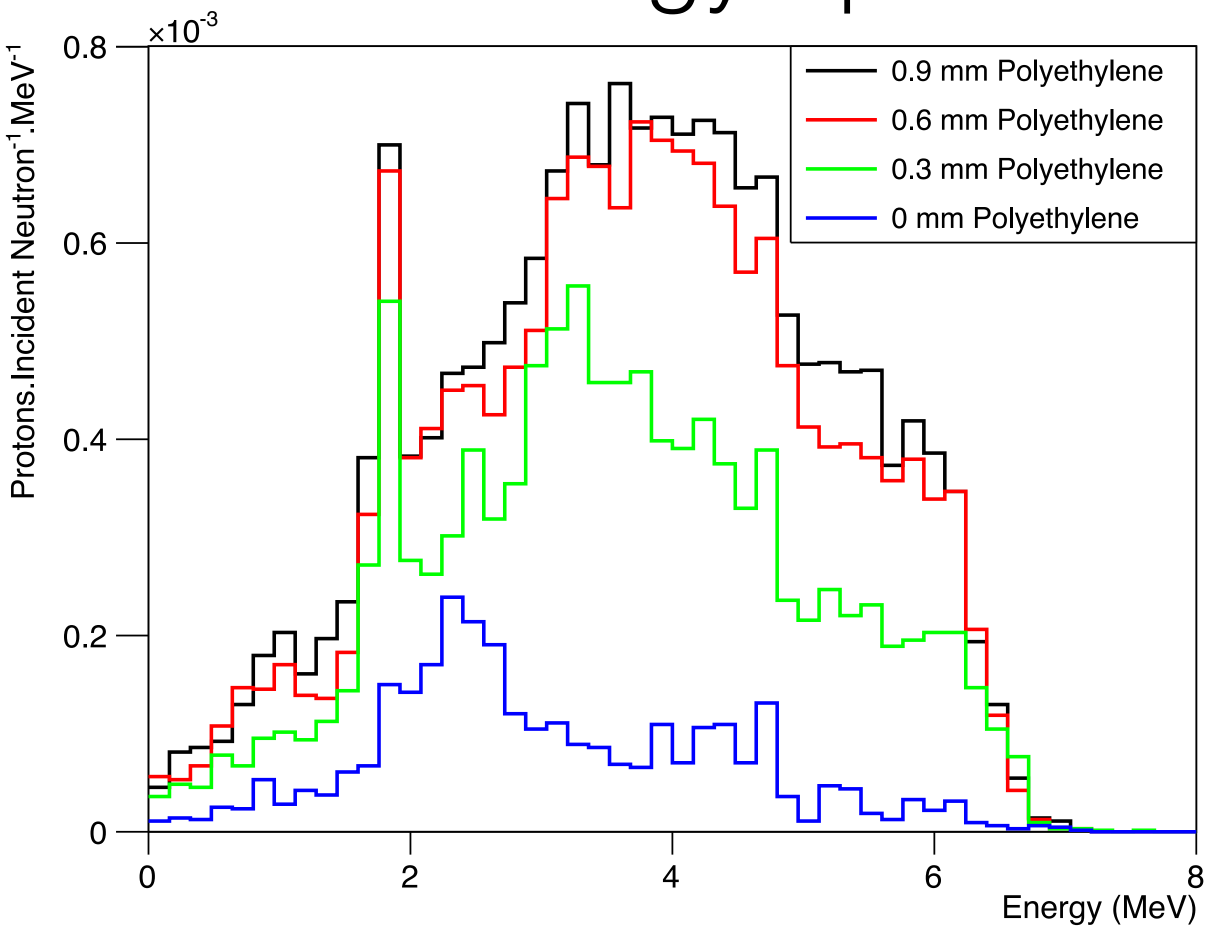


5 MeV Neutrons



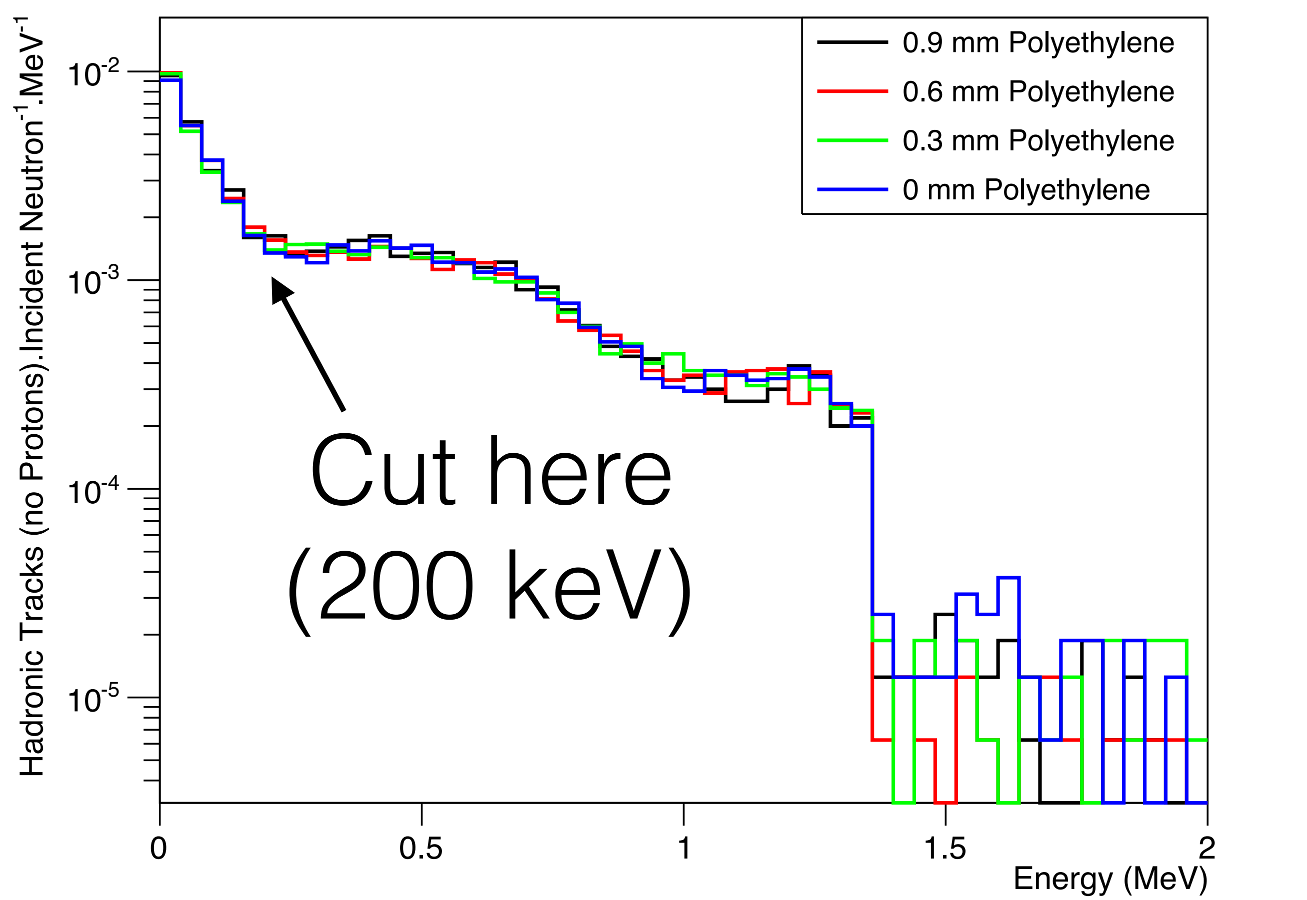
Reducing (n,Si) background - 10 MeV Neutrons

Proton Energy Spectrum



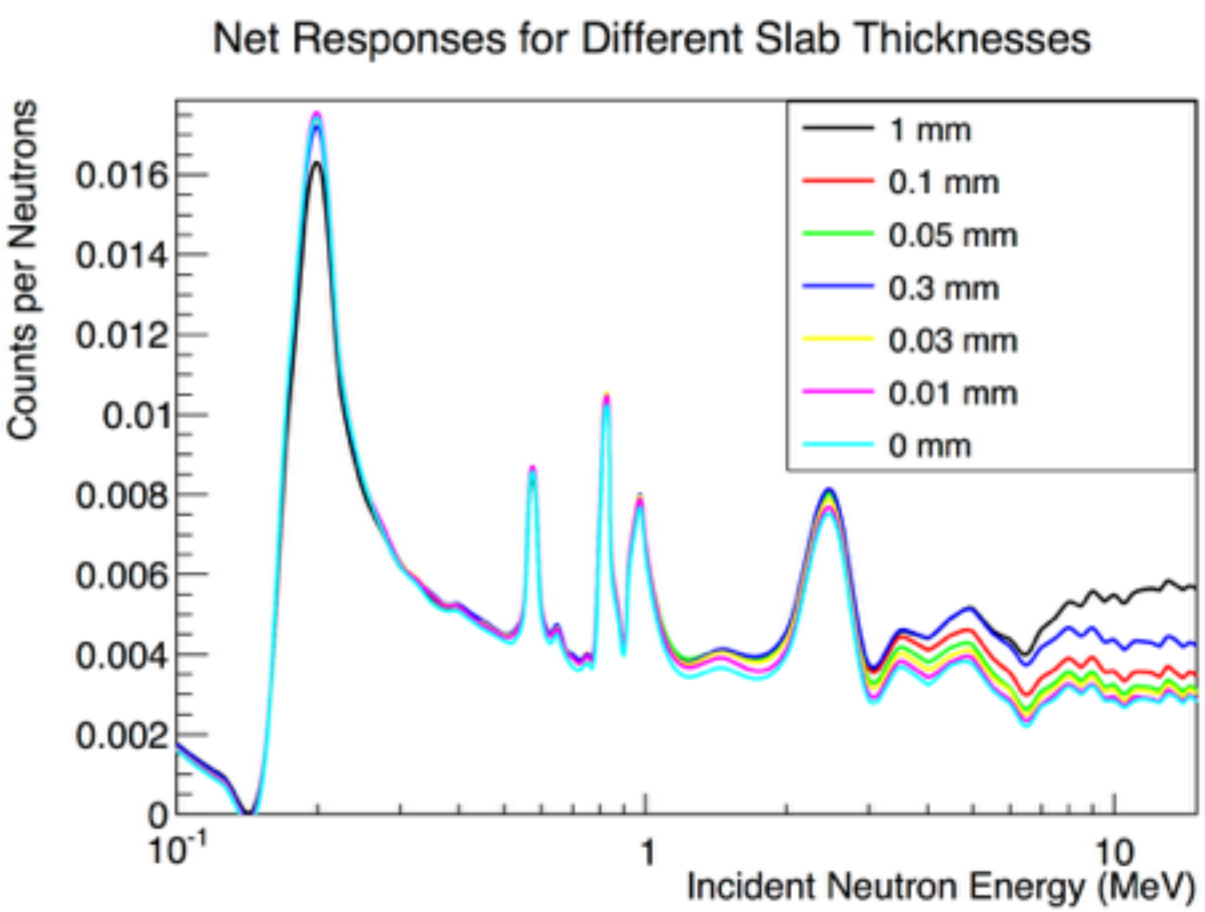
~ 7 MeV - maximum absorbed energy from recoil off hydrogen due to geometrical constraints

Si Interactions Energy Spectrum

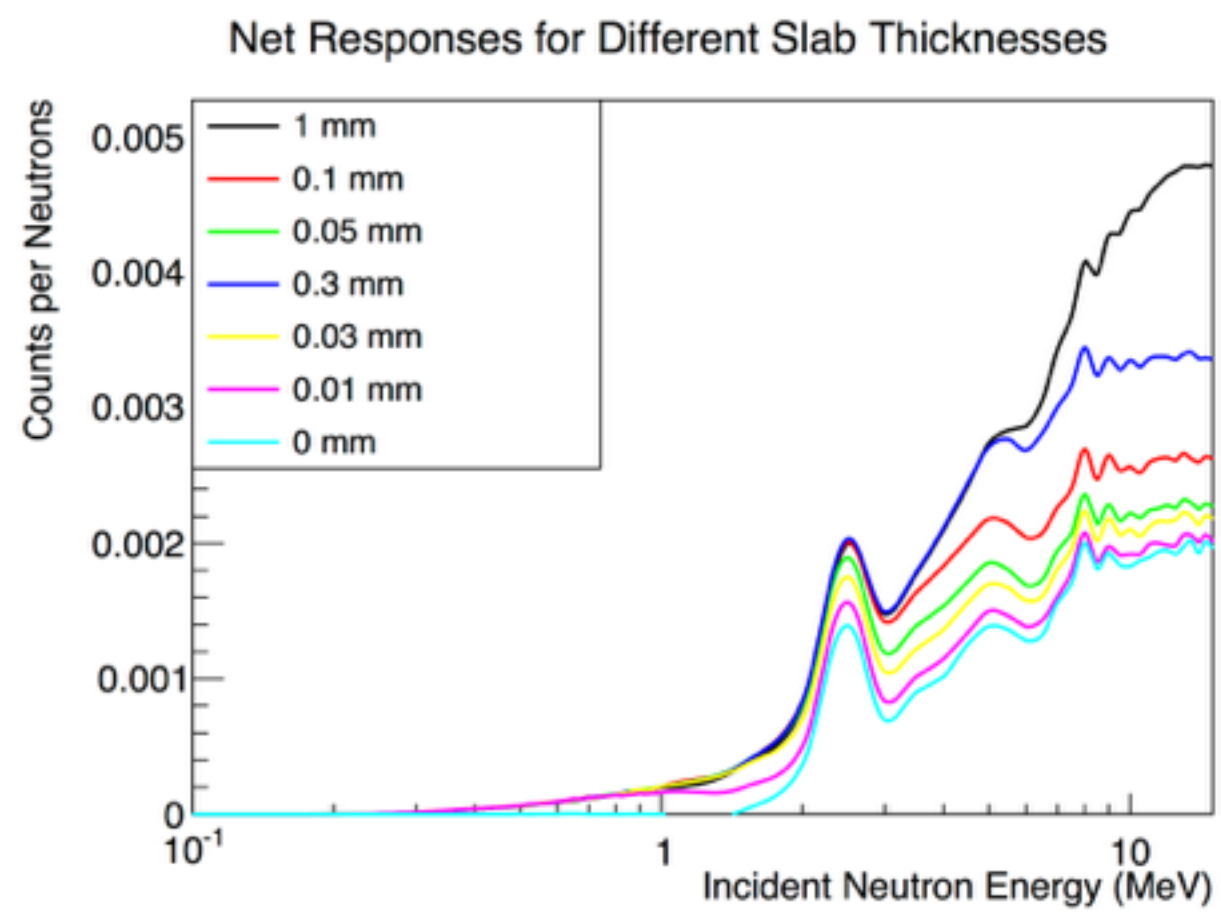


1.33 MeV = Maximum energy transferrable to an Si nucleus by a neutron

Response Functions



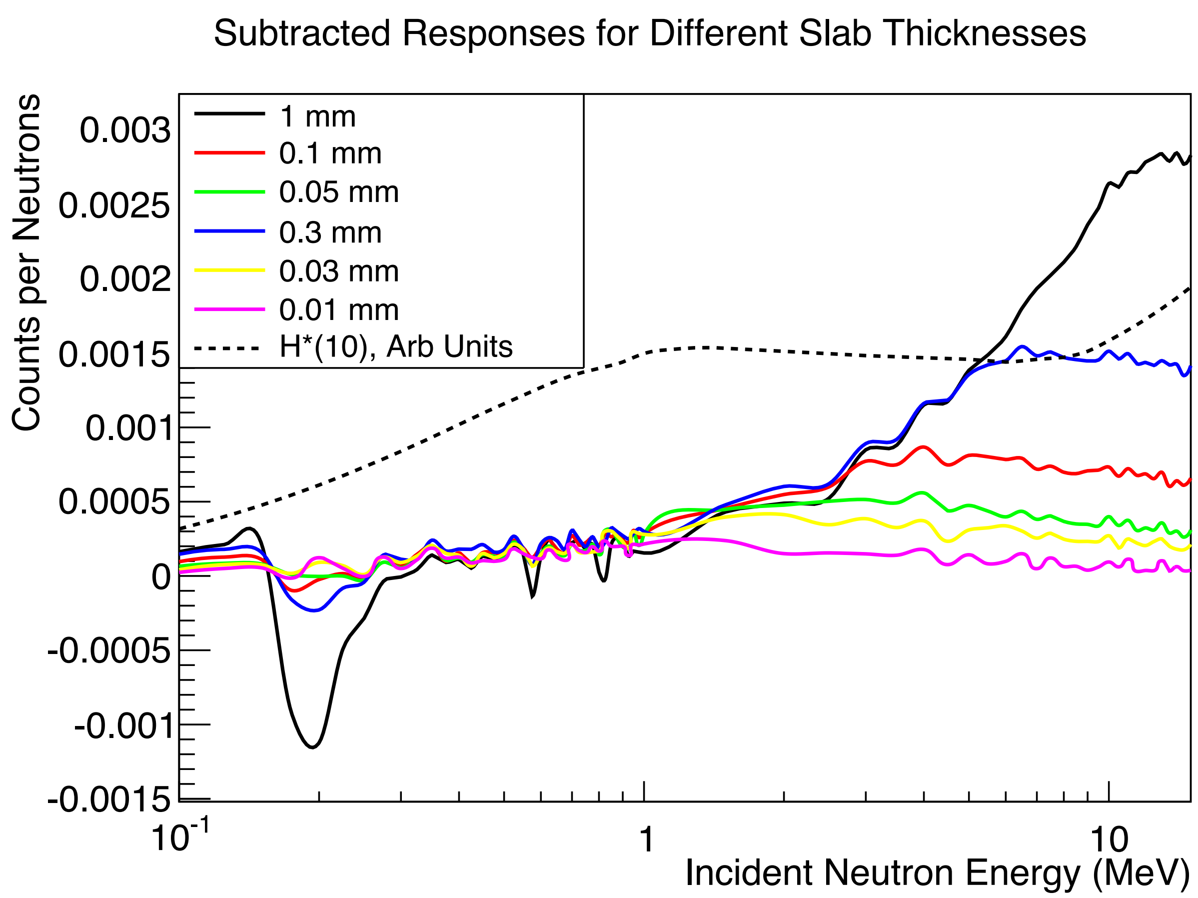
No Cut



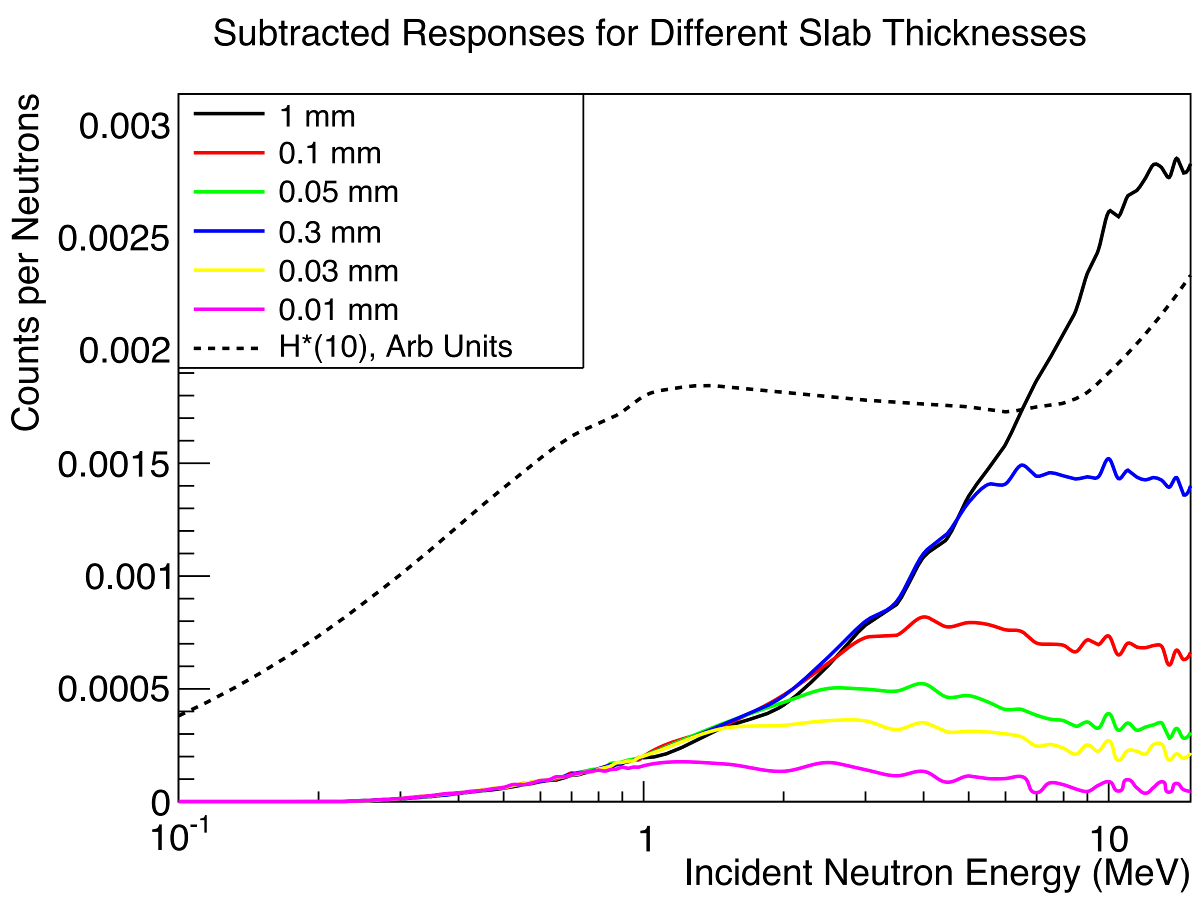
200 keV Cut

Cut removes silicon signal, clearly separates regions

Subtracted Response Functions



No Cut



200 keV Cut

Optimise Response to H*(10)

Linearly scale each response curve R(E) by a constant coefficient

$$H^*(10)(E) = \sum_i \beta_i R_i(E)$$

Minimise this equation in some way (cost function)

$$F = \sum_{E_{\min}}^{E_{\max}} \left| \left[\left(\sum_i \beta_i \int_{E_n}^{E_{n+k}} R_i(E) dE \right) - \int_{E_n}^{E_{n+k}} \mathrm{H}^*(10)(E) dE \right] \right|$$

(Looks horrendous, but its just the sums of the curves over a small energy interval subtract the H*(10) curve)

Optimise Response to H*(10)

Linearly scale each response curve R(E) by a constant coefficient

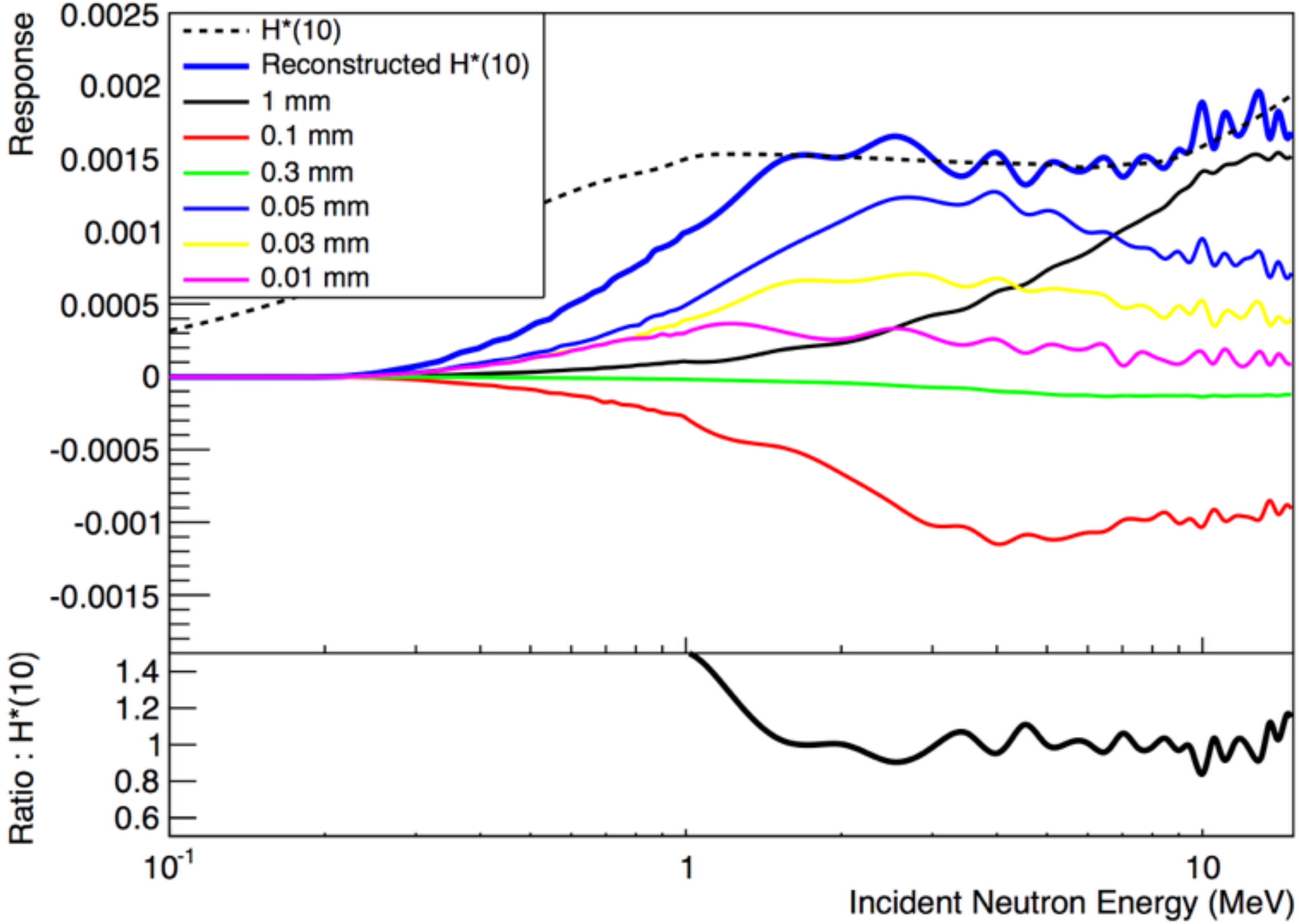
$$H^*(10)(E) = \sum_i \beta_i R_i(E)$$

Minimise this equation in some way (cost function)

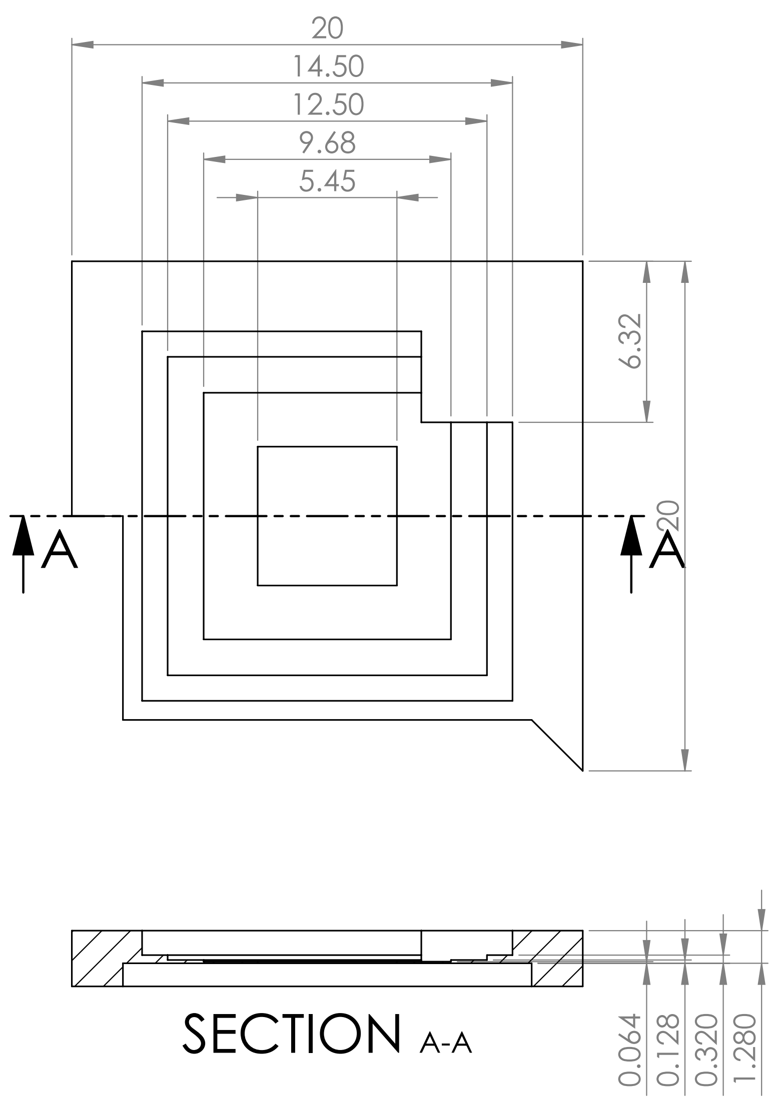
$$F = \sum_{E_{\min}}^{E_{\max}} \left| \left[\left(\sum_i \beta_i \int_{E_n}^{E_{n+k}} R_i(E) dE \right) - \int_{E_n}^{E_{n+k}} \mathrm{H}^*(10)(E) dE \right] \right|$$

(Looks horrendous, but its just the sums of the curves over a small energy interval subtract the H*(10) curve)

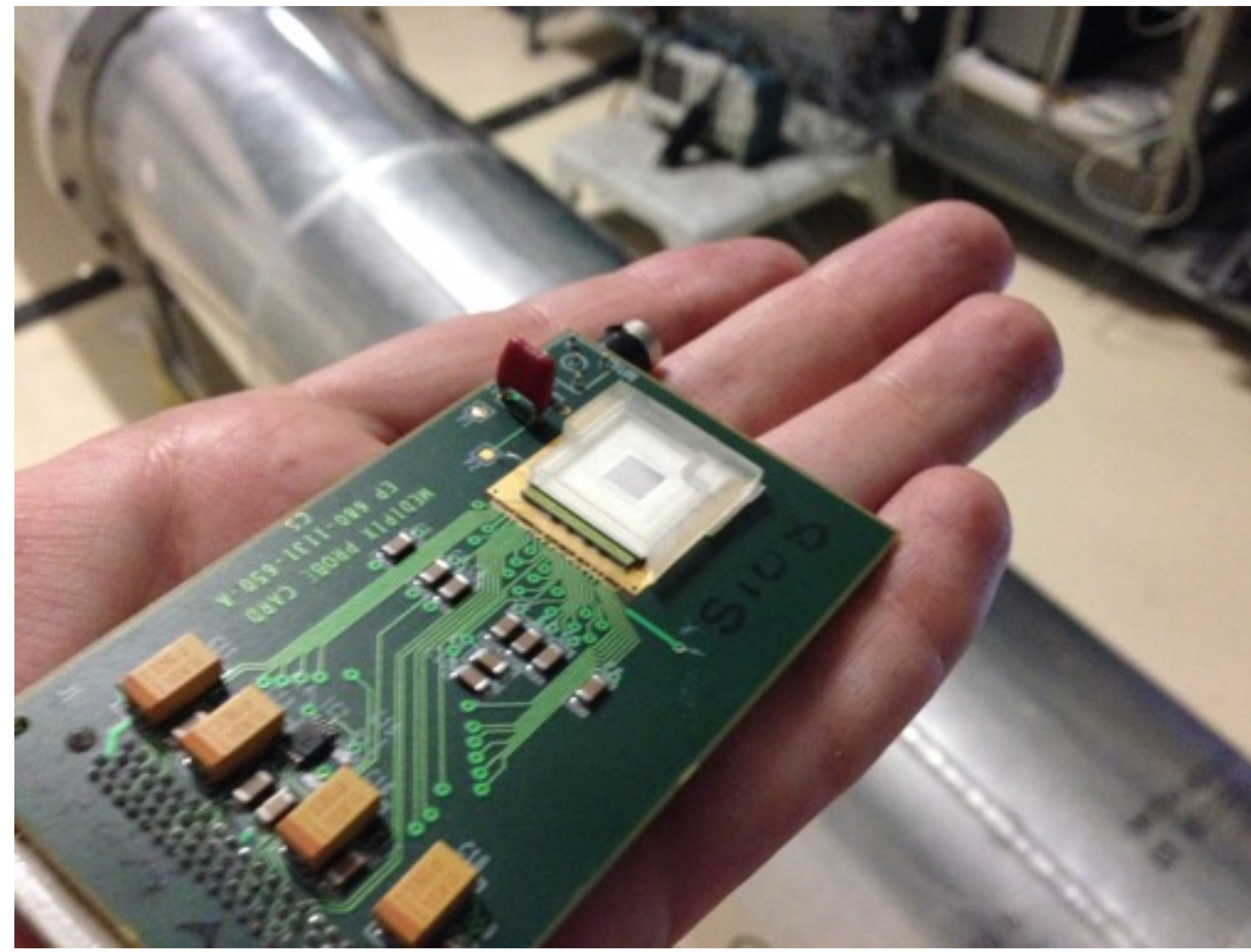
Optimised Response



Real Converters

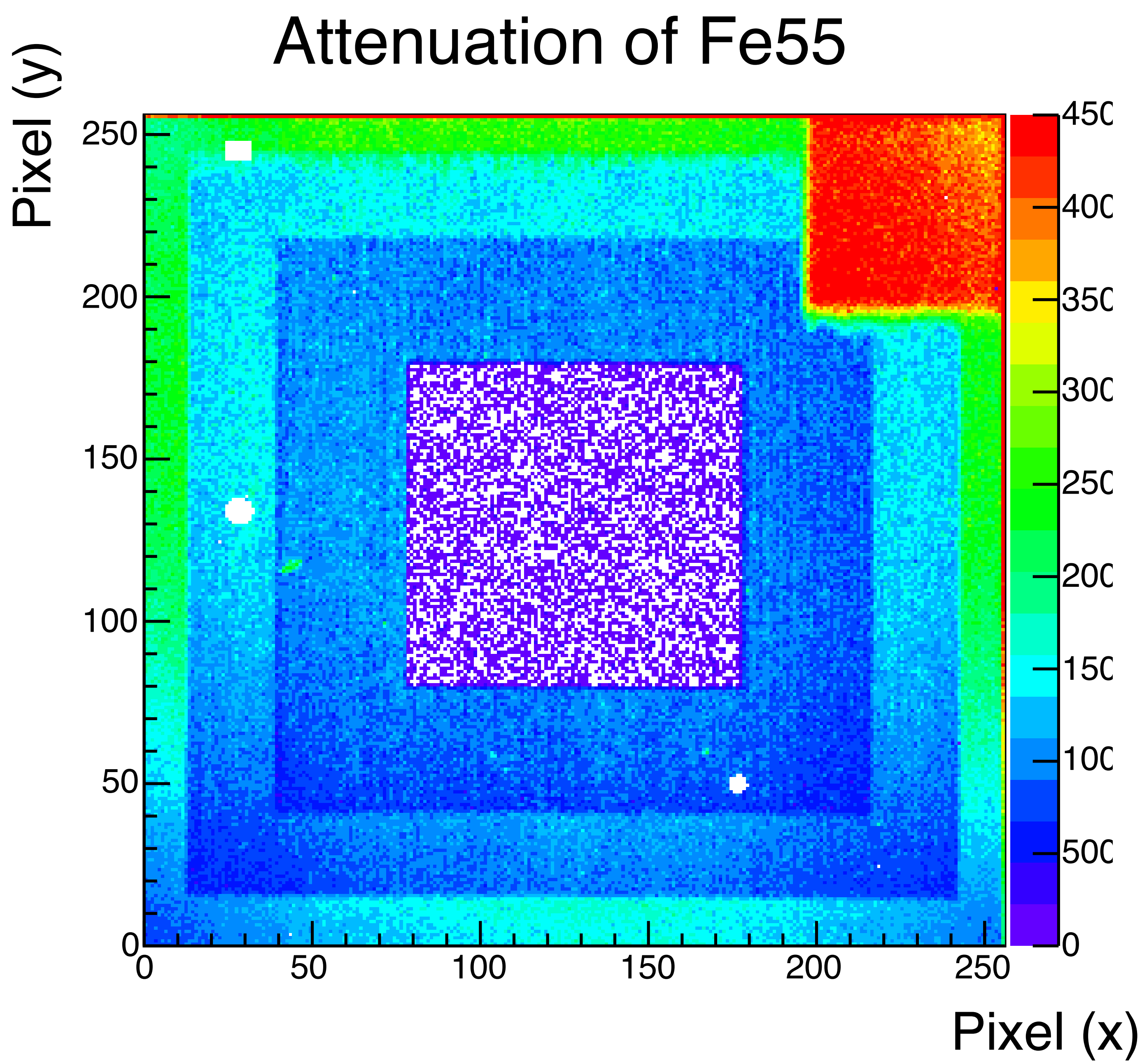


Slab (mm)	Area (mm^2)
Uncovered	29.70
0.064	62.65
0.128	57.29
0.320	37.31
1.280	11.29



Real Converter (thanks to M. Weaver for solidworks expertise)

Real Converters



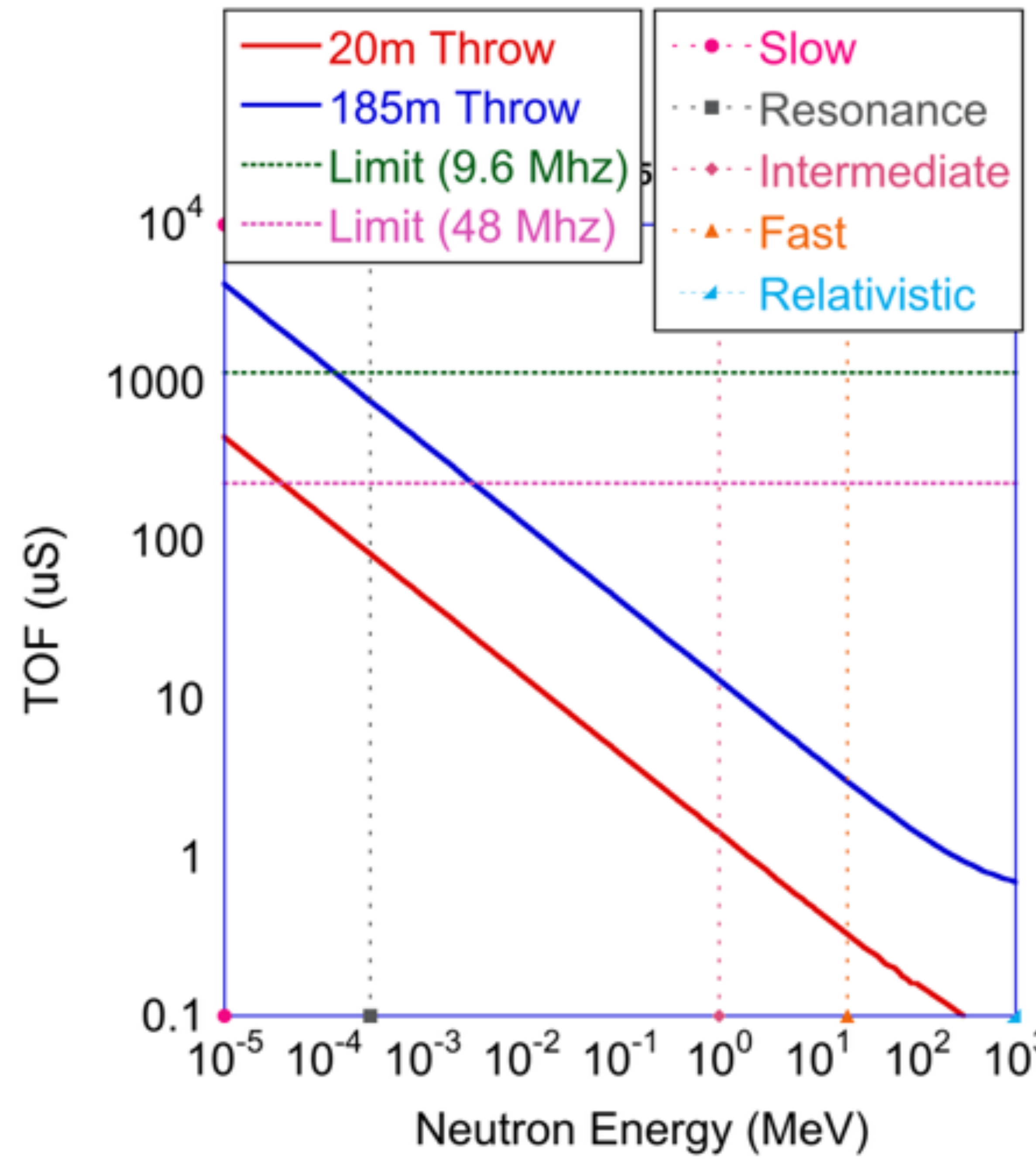
Real Converter (thanks to M. Weaver for solidworks expertise)

The Timepix - Timing Information

- Clock can run at 1, 10 or 50 Mhz (100 as well, but is unstable) -> 1us, 100ns, 20ns time resolution

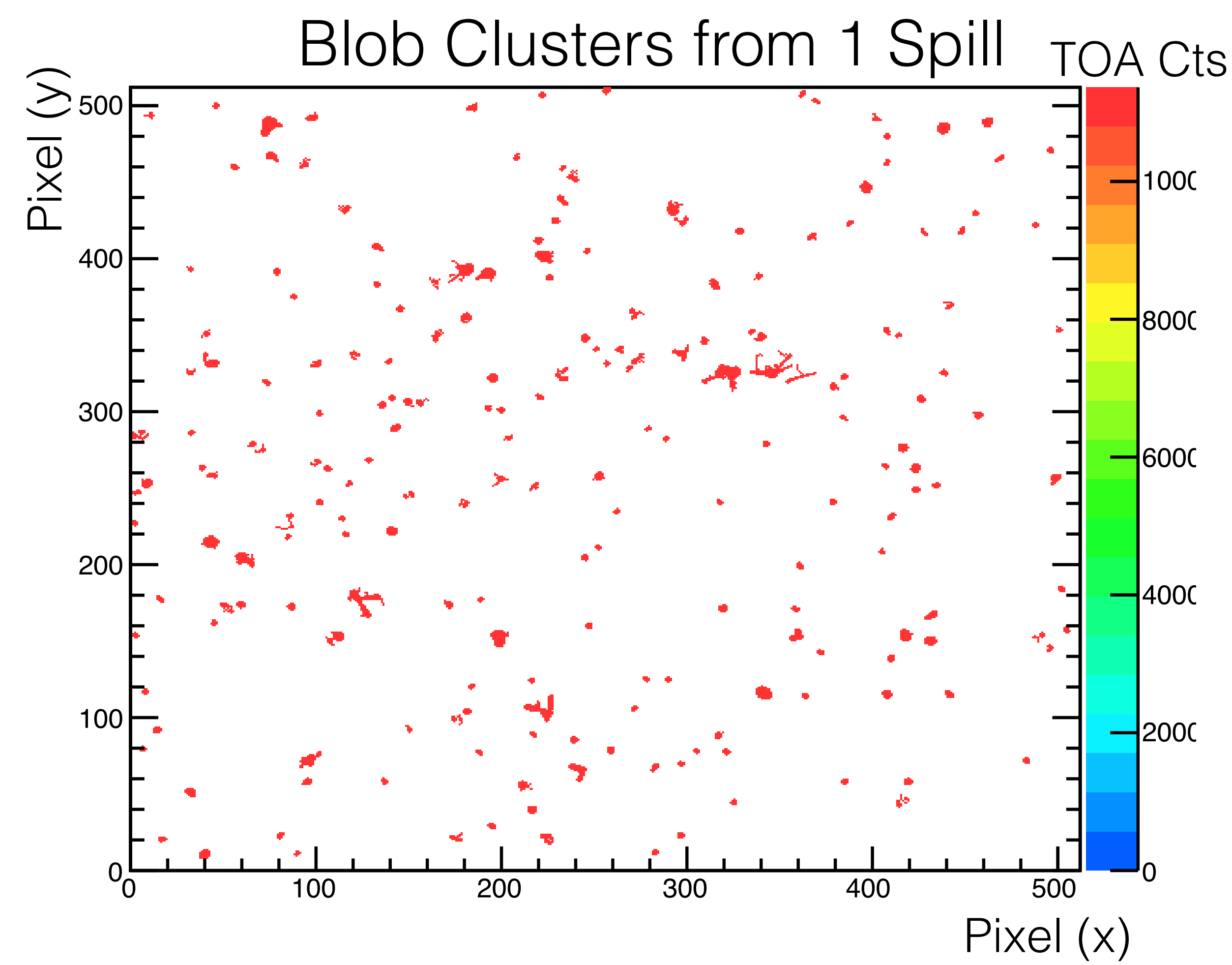
- Counter depth is 11810 - places limits on total acq time.

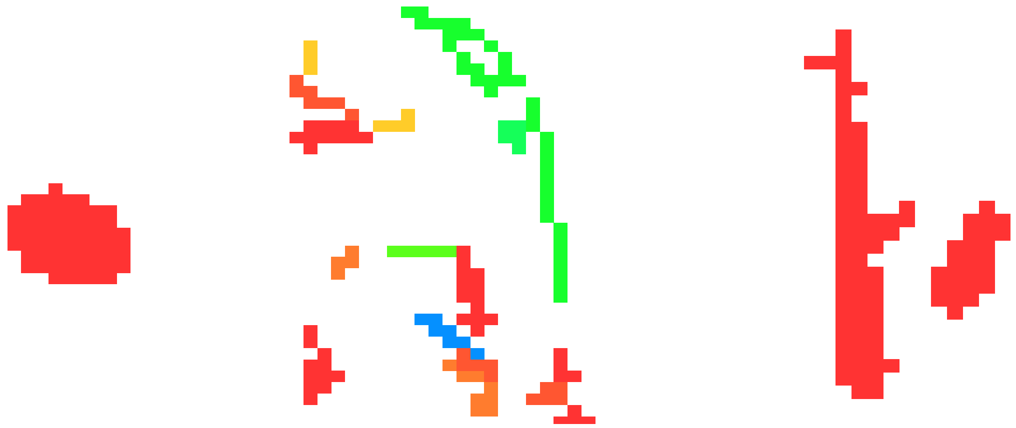
- Readout ~10 mS (**slow**)



Particle Signals - Clusters

- When particle travels through the sensor it activates a cluster of contiguous pixels
- Signal is convolution of physical track and sensor charge transport
- Clustering done by search for particle contiguous in x,y,TOA





Clusters Sorted By Morphology

What is a TOF Neutron Beam?

- A bit like a greyhound track
- Neutrons are generated in a fast pulse and sent down a long tube
- They separate in time based on their kinetic energy (i.e. the faster ones arrive first)
- The photon flash can be used as the gunshot

$$\beta = \frac{D}{Tc}$$

$$E_n = m_n \left(\sqrt{\frac{1}{1-\beta^2}} - 1 \right)$$

$$E_n = \textbf{Neutron Energy}$$

$$m_n = \textbf{Neutron mass} = 939.565\,\mathrm{GeV}$$

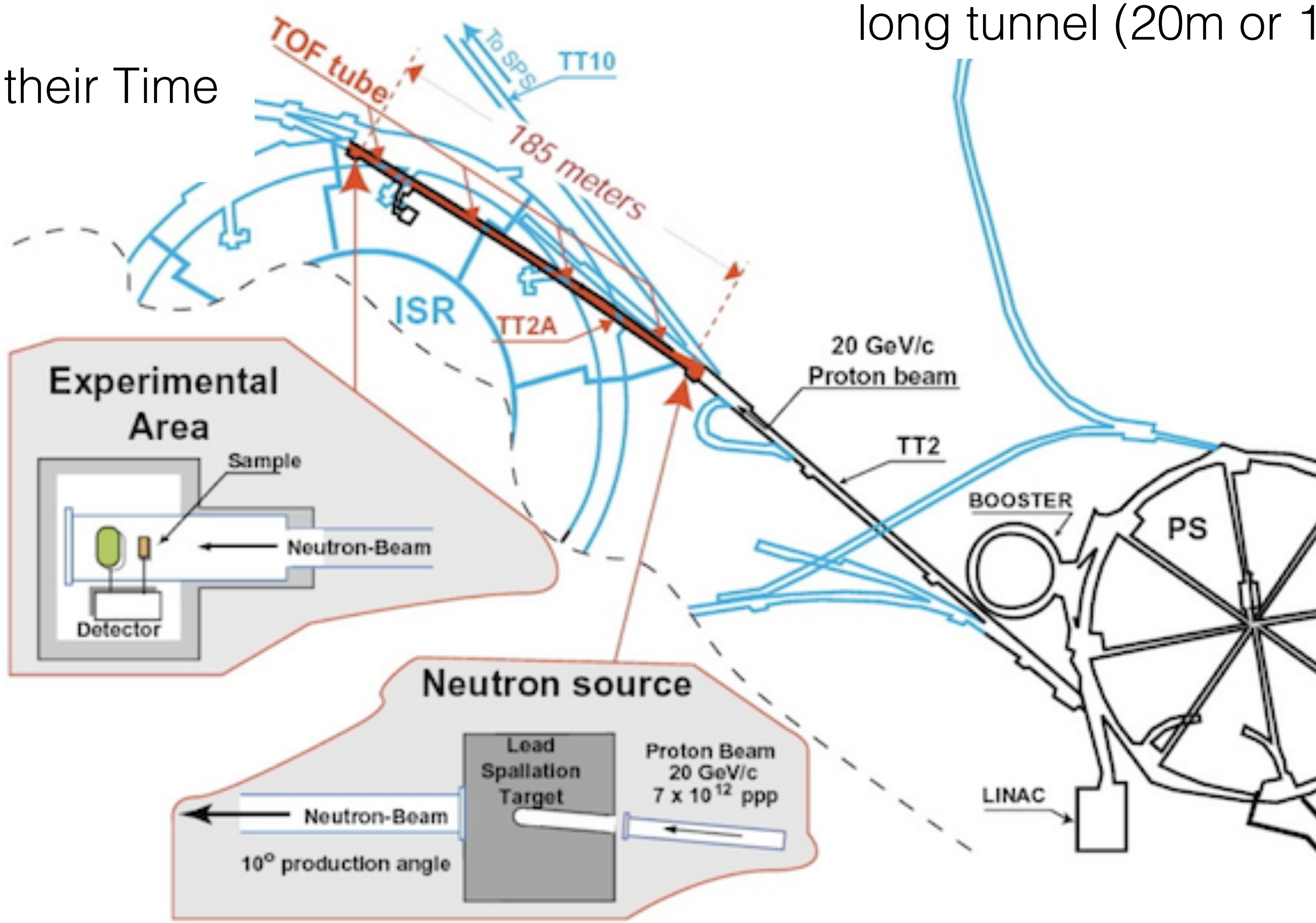
$$D = \textbf{Throw Distance}$$

$$T = \textbf{Time of Flight}$$

The NTOF Facility (CERN)

(3) The energy of the neutrons can be determined from their Time of Flight

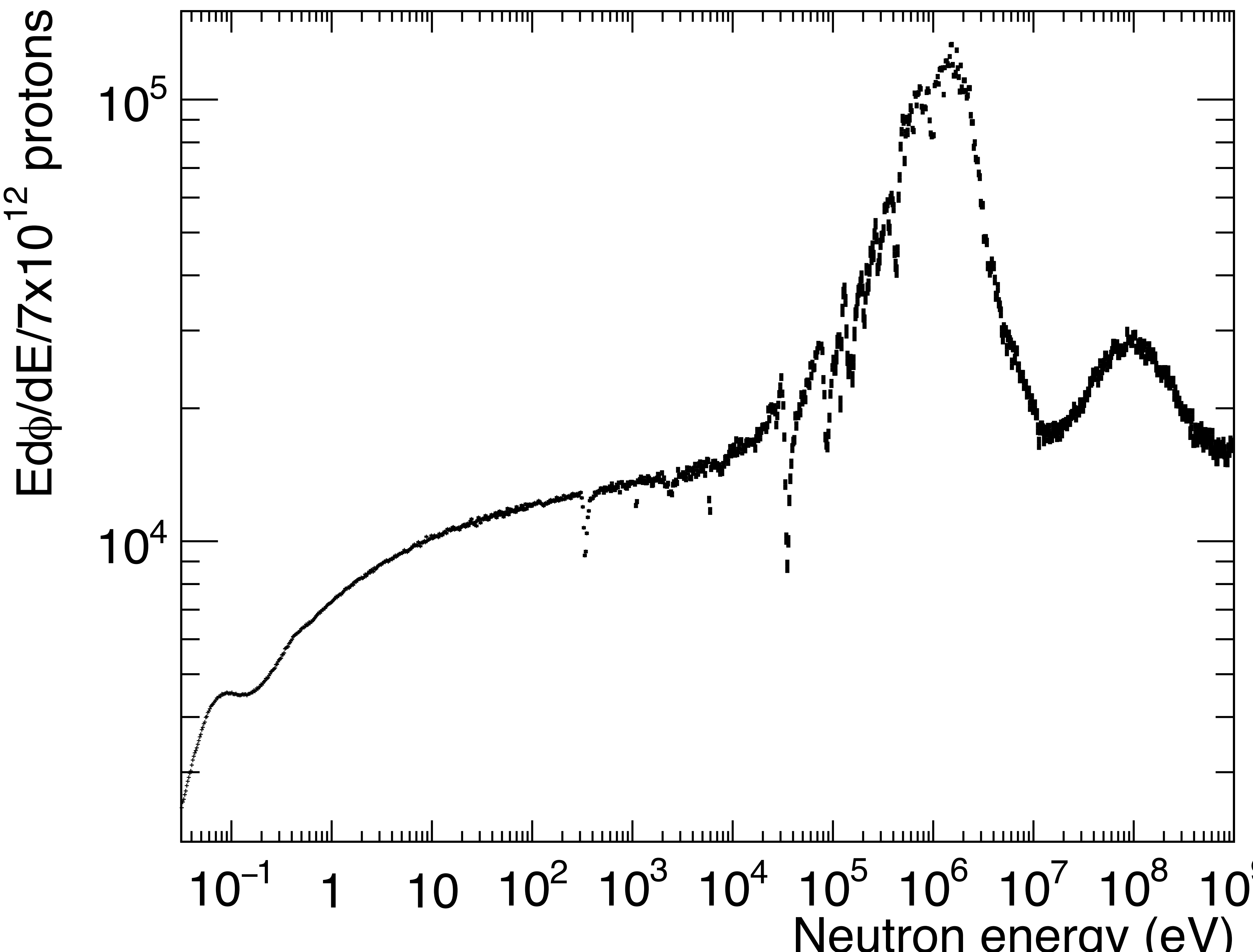
(2) These neutrons travel down a long tunnel (20m or 185m)



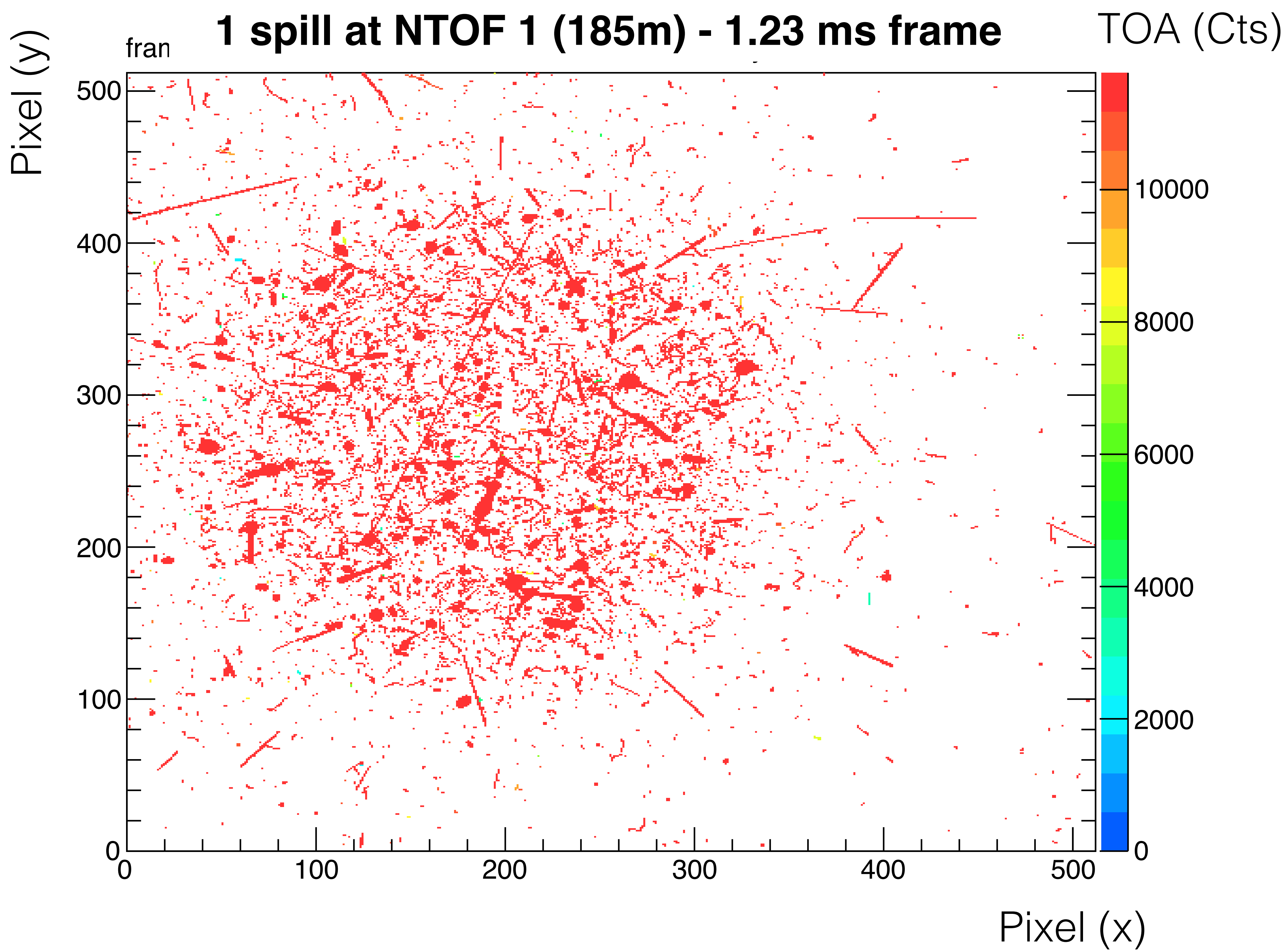
(1) PS Protons collide with a lead target producing neutrons

Interest in characterising the beam position for installing a new laser alignment system. Measurements using a 300 um silicon sensor with a PE converter.

NTOF Energy Spectrum



Measurements NTOF 1



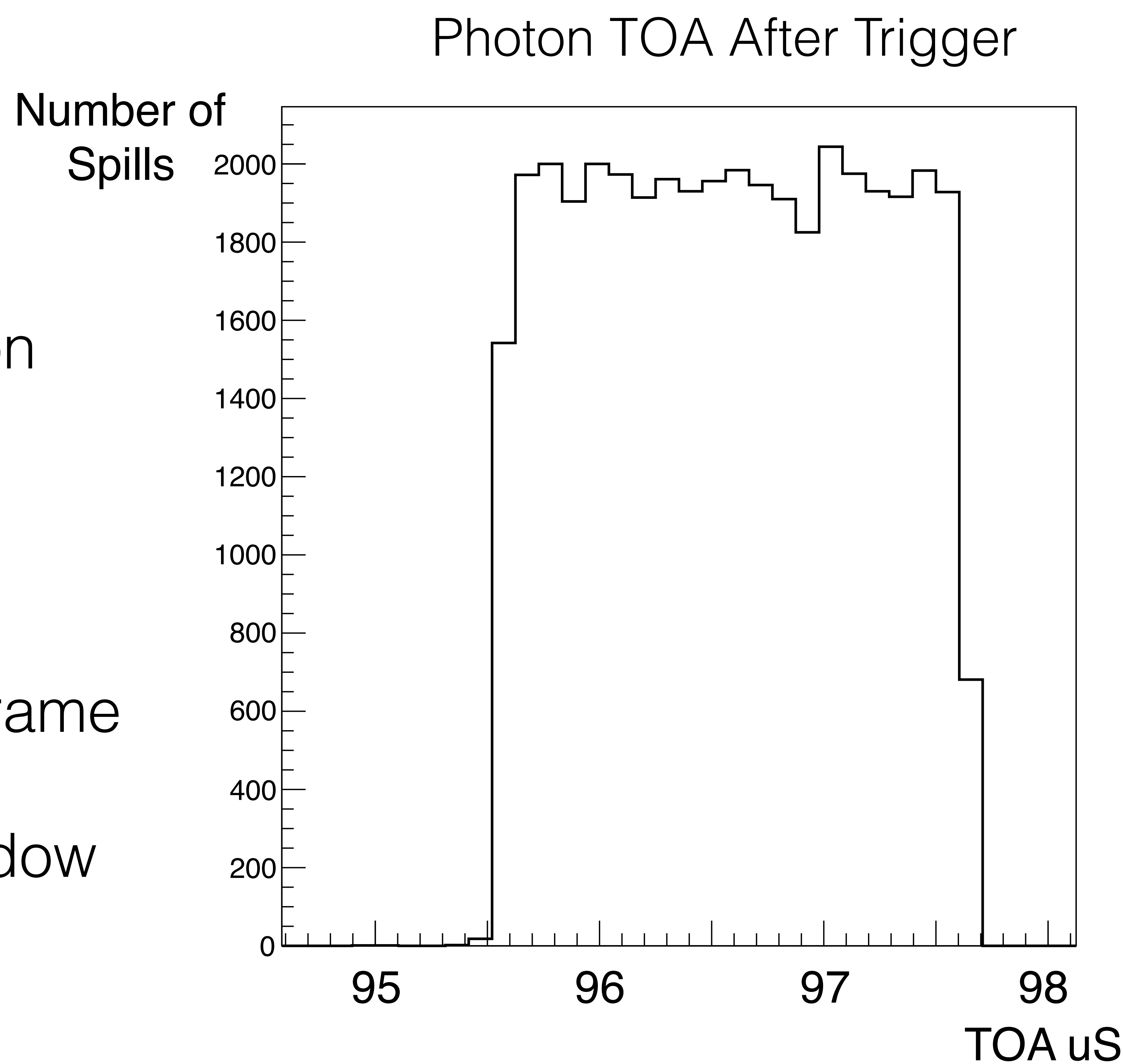
- Detector running in TOA (Time of arrival mode at 9.6 Mhz - time resolution = 50 nS)

Timepix Data

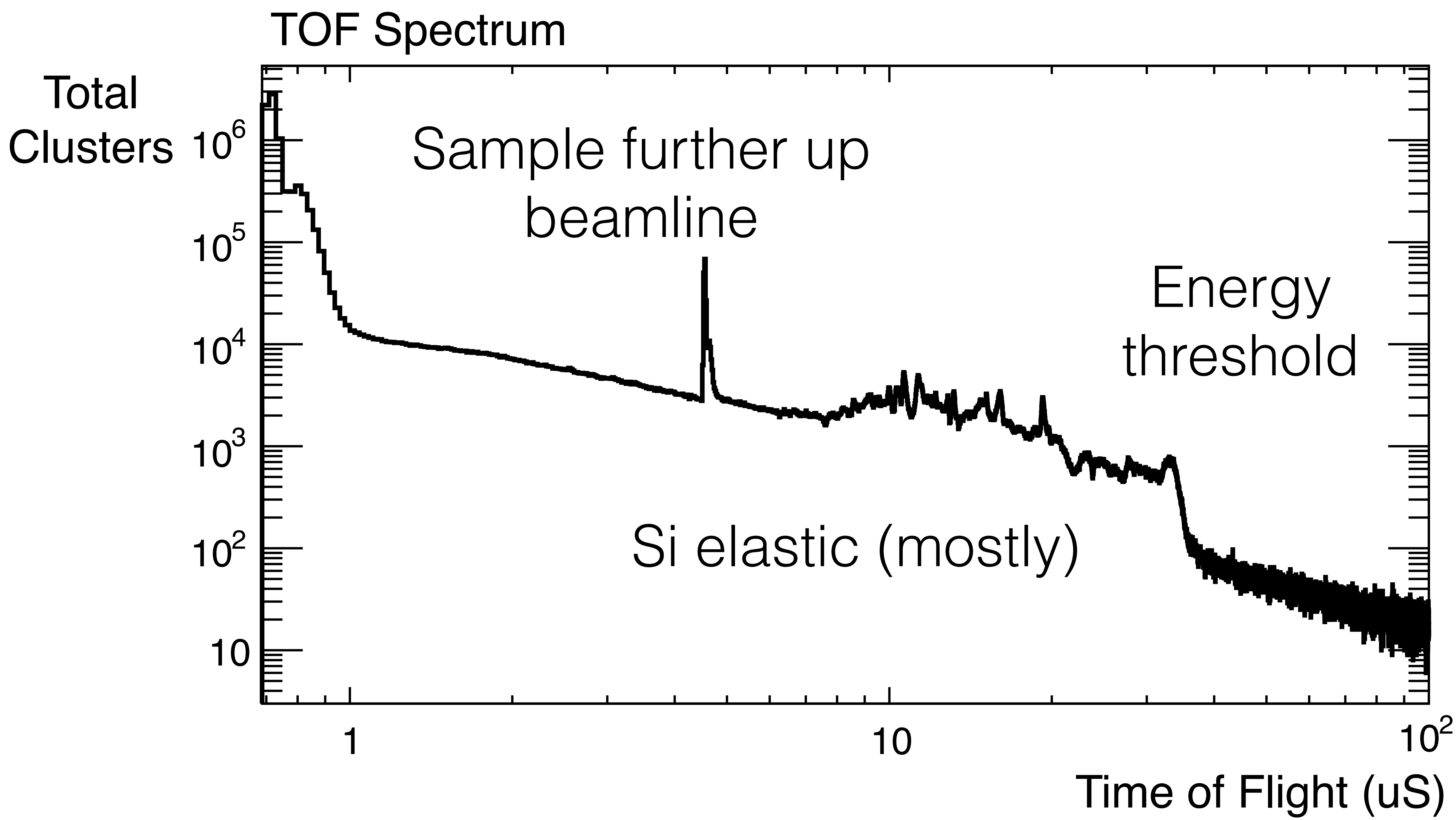
- Each track is left by the interaction of a single particle
- The tracks can be separated based on their measured time of arrival (colour scale)
- The tracks can then be separated by position, energy and type

Measuring Trigger Jitter

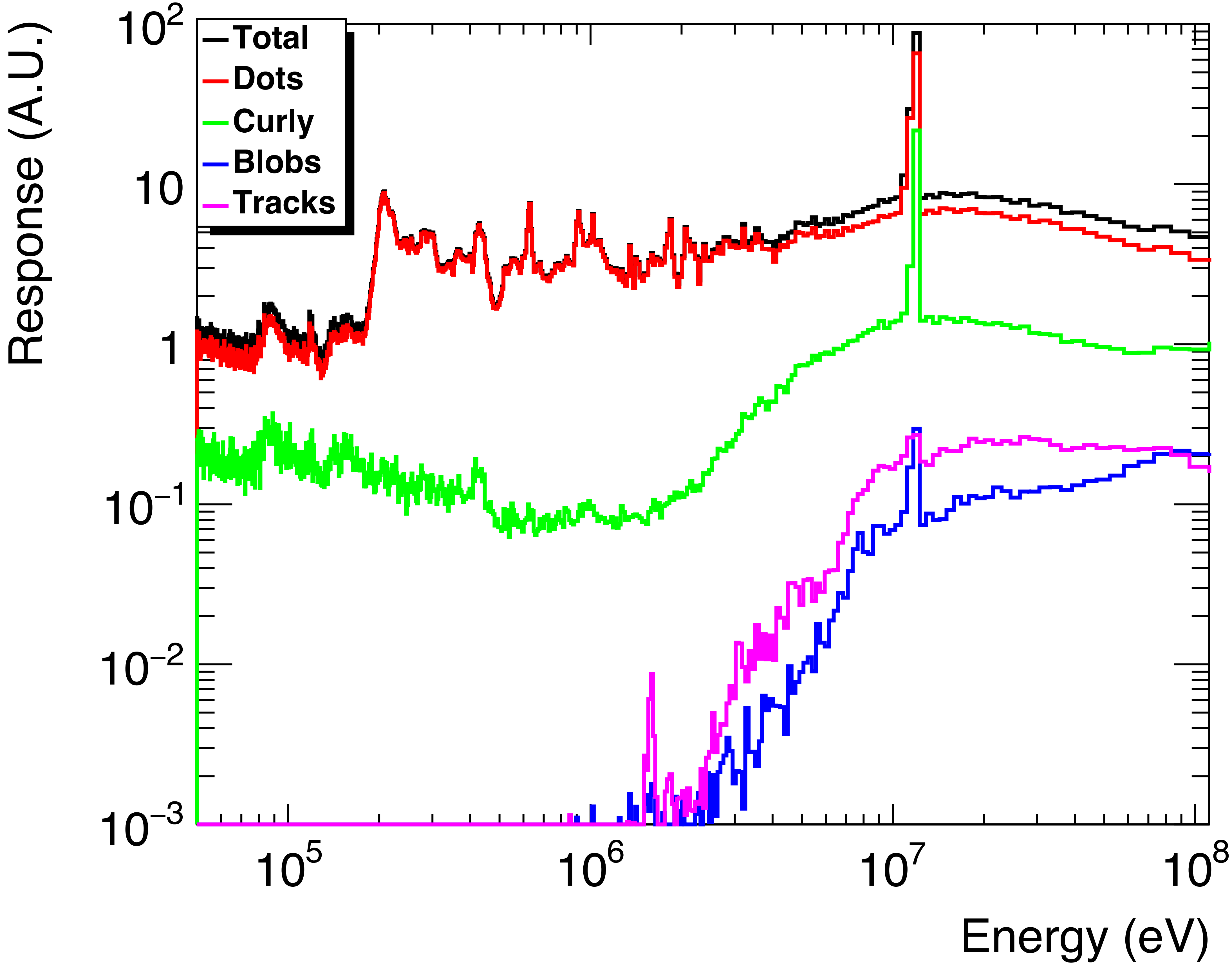
- Measurement is triggered off proton pulse, but only accurate to ~1μs
- Search for first photons in each frame
- ~100 nS time window



NTOF Raw TOF Spectrum

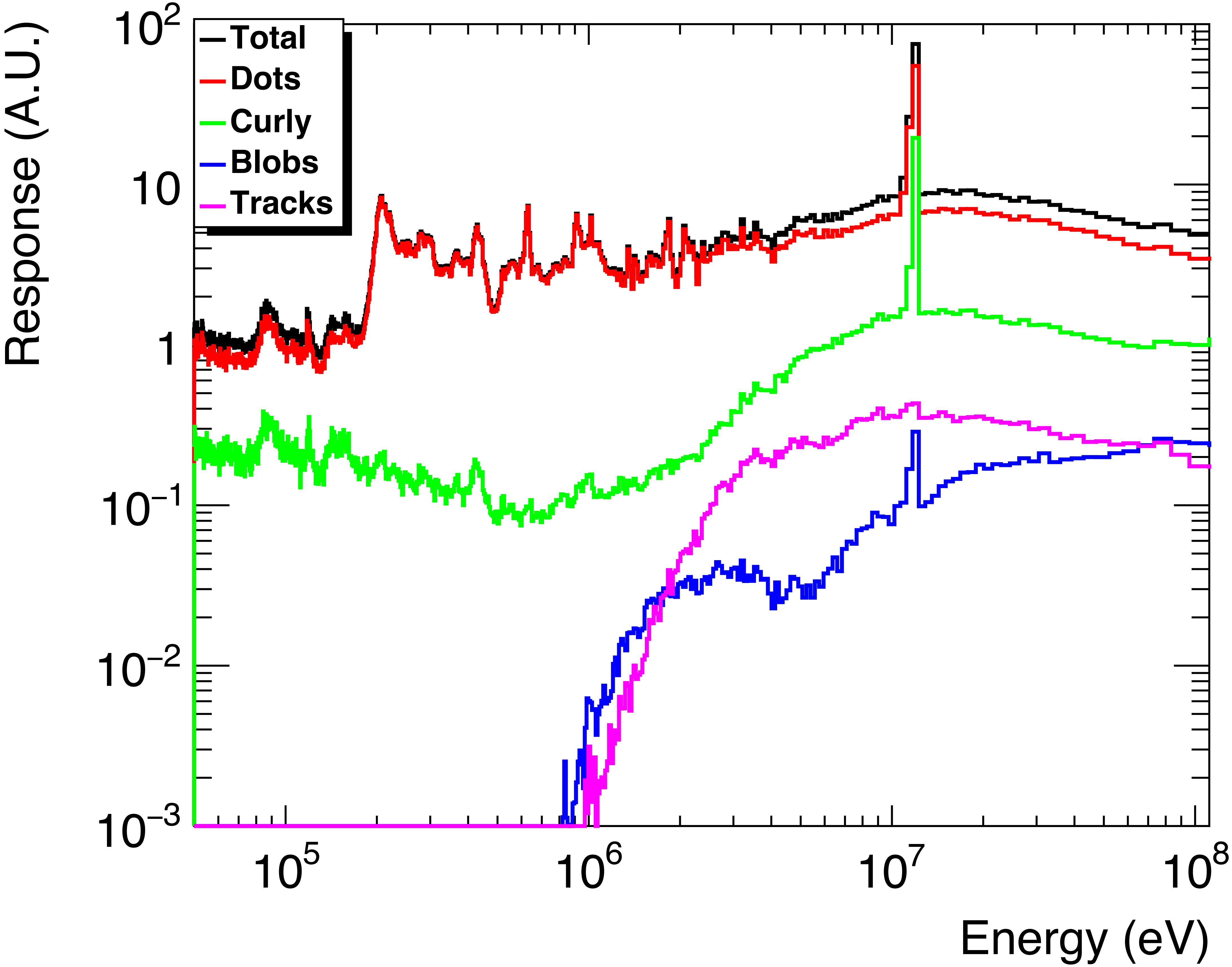


No Converter



TOF spectrum normalised to energy spectrum and clustered

Converter



TOF spectrum normalised to energy spectrum and clustered

Experimental response functions

- Difference in response is largely from blobs and tracks (i.e. high energy transfer particles) - as expected

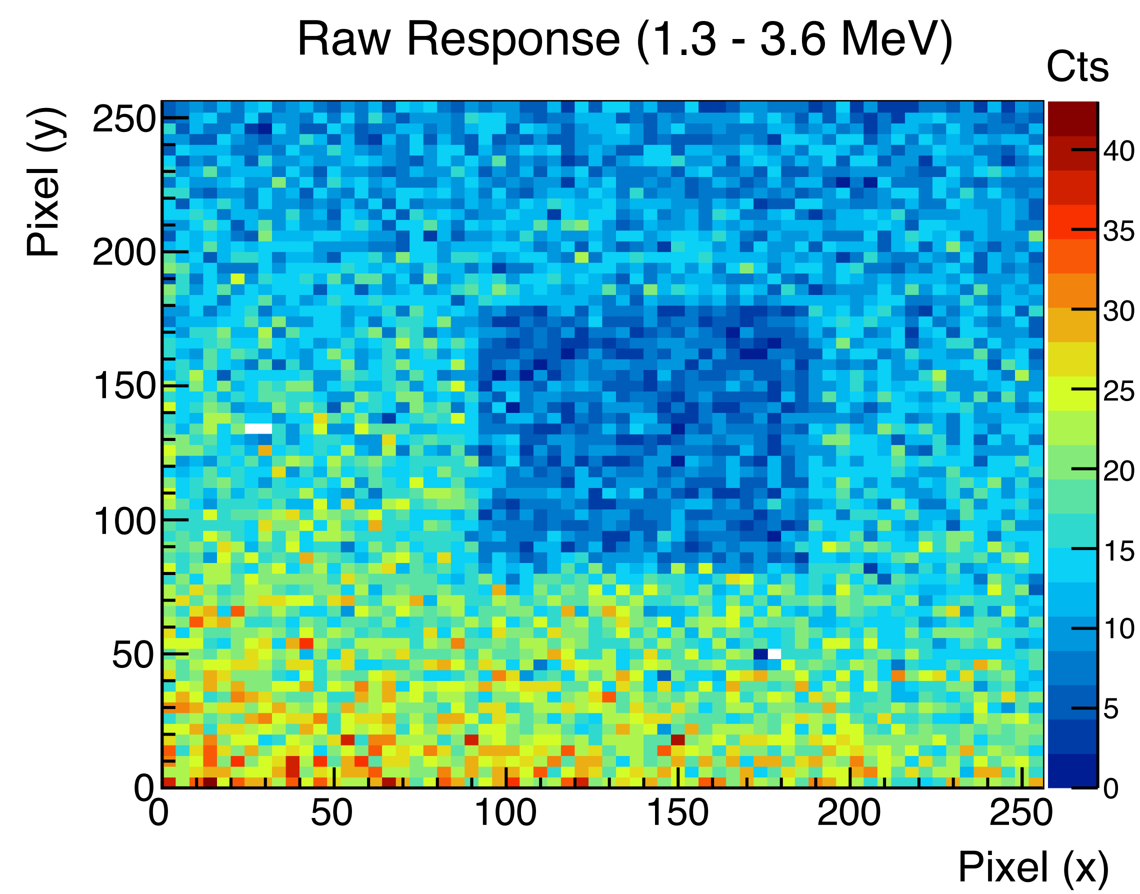
- Not quite the same as simulated response (200 keV cut) - BUT…

- Because we directly measure response functions we can simply use the experimental clustering algorithm with other measurements.

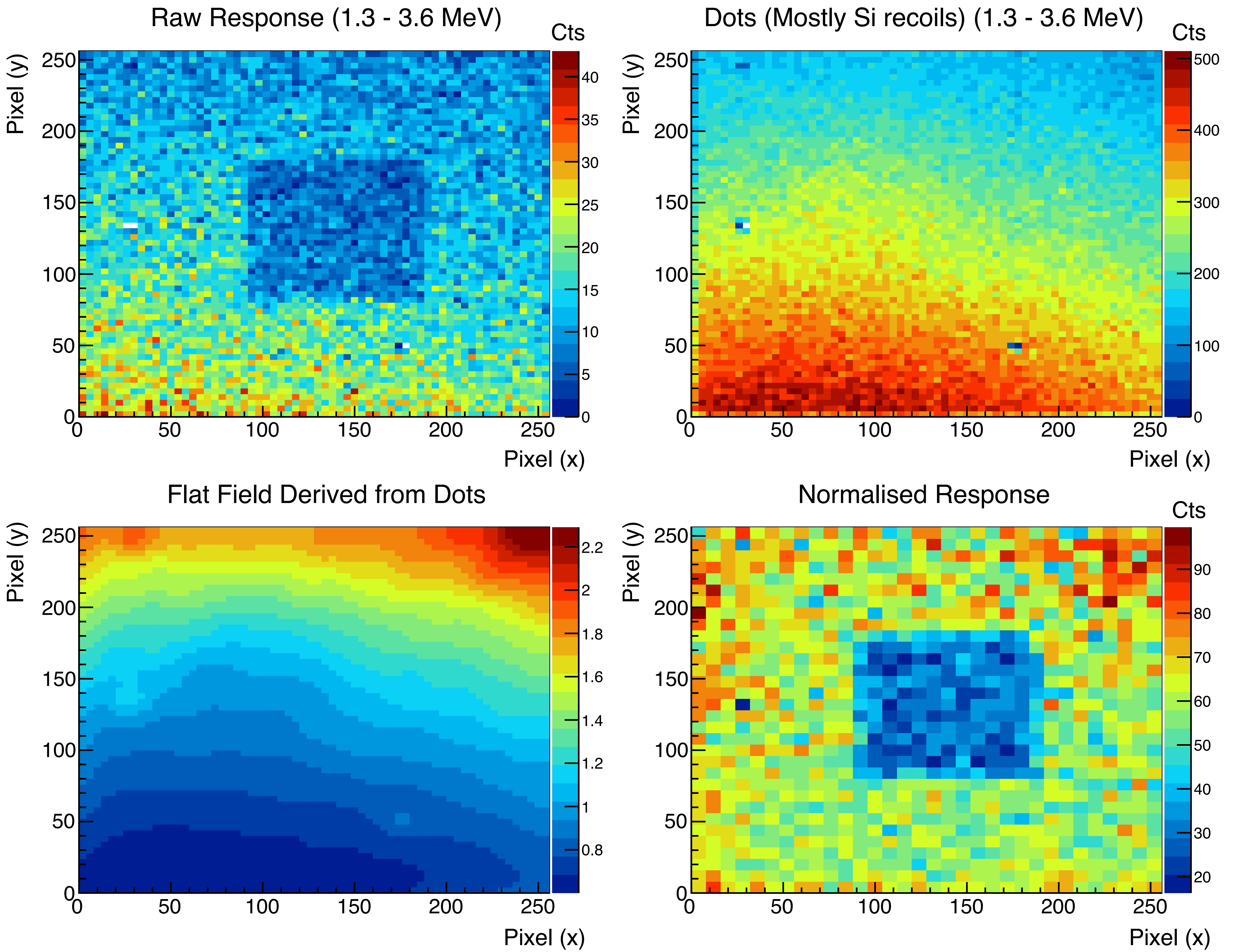
- An additional complication is that the NTOF beam is not homogenous

Experimental response functions

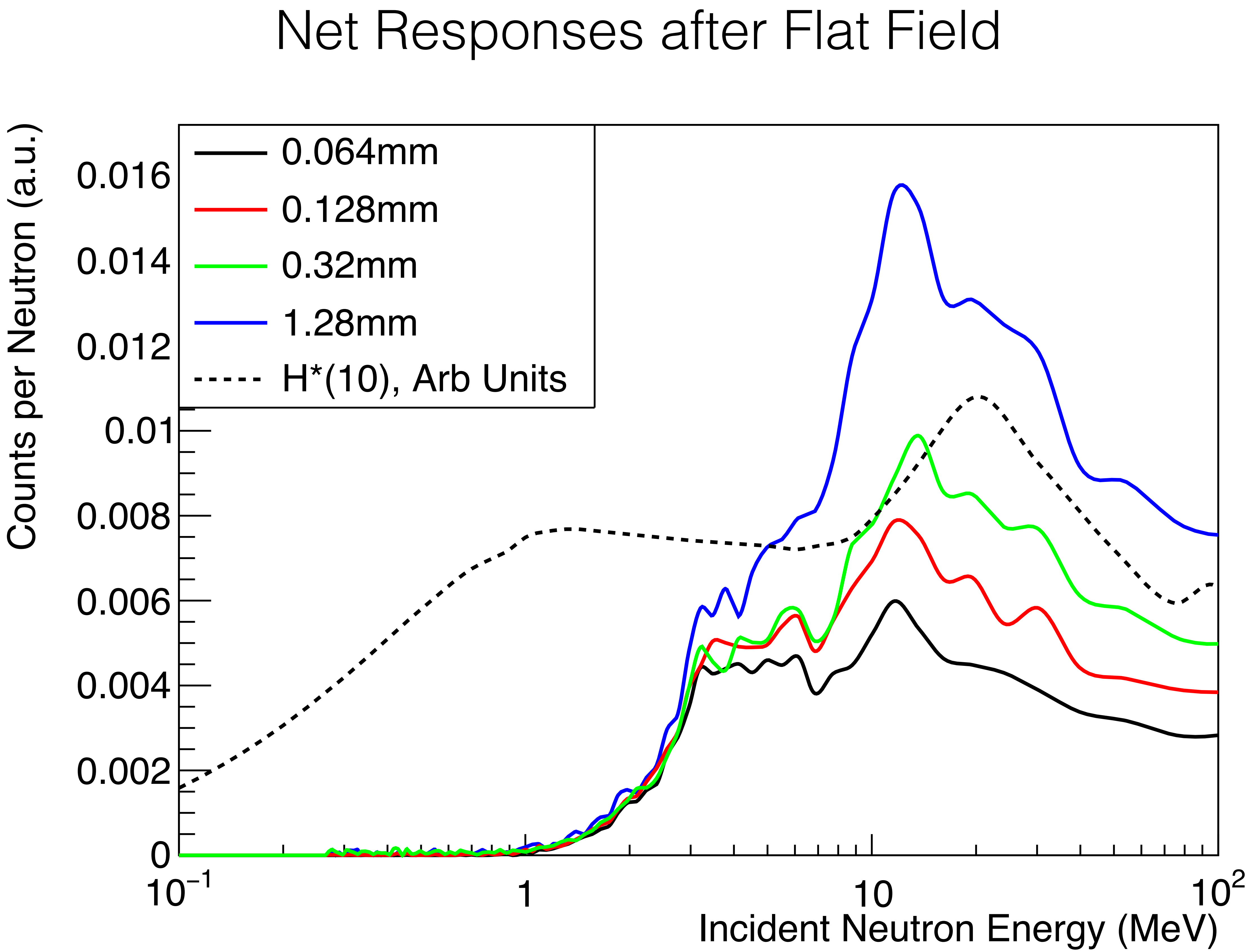
- We flatten the beam by using the elastic scattering interactions
- Most dots are elastic scatters (cut off)
- Elastic scatter rate independent of converter (spectra of dots the same with/without)
- Elastic scatter rate proportional to neutron flux in a given energy window



Inhomogeneity visible across converter

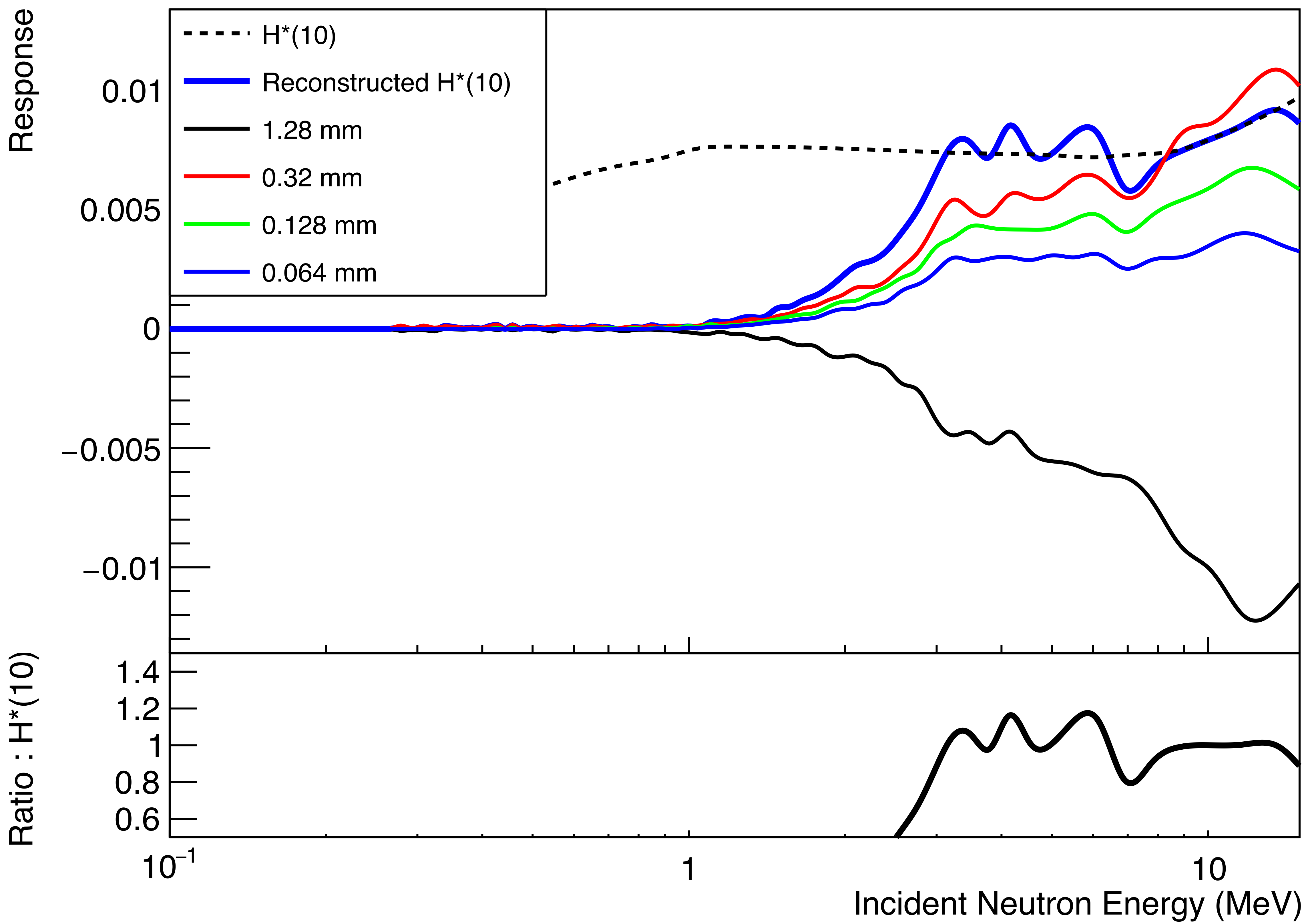


Raw Response (1.3 - 3.6 MeV)
Cts
Pixel (y)
Pixel (x)
Dots (Mostly Si recoils) (1.3 - 3.6 MeV)
Cts
Pixel (y)
Pixel (x)
Flat Field Derived from Dots
Pixel (y)
Pixel (x)
Normalised Response
Cts
Pixel (y)
Pixel (x)

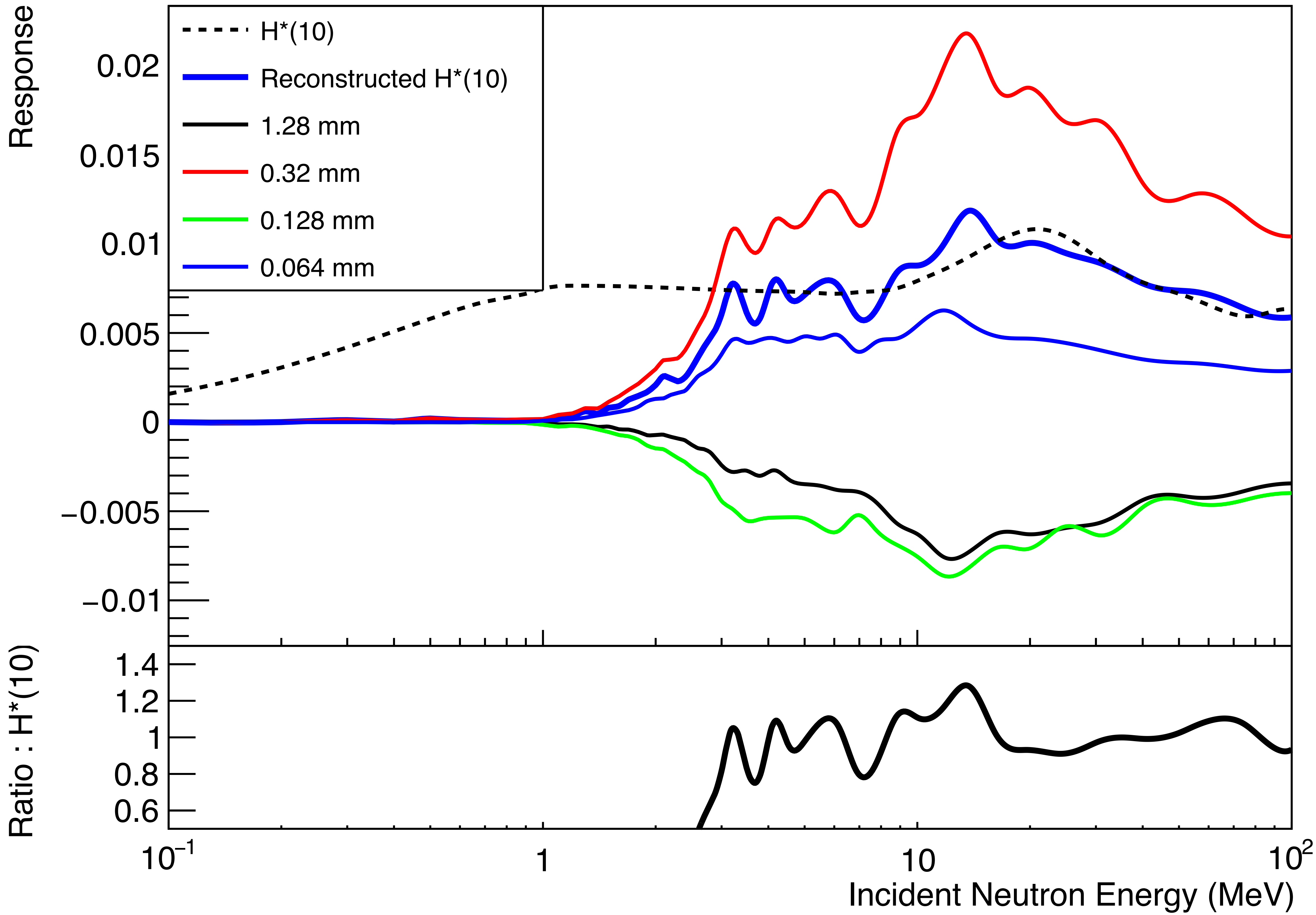


Net Responses after Flat Field
0.064mm
0.128mm
0.32mm
1.28mm
H*(10), Arb Units
Counts per Neutron (a.u.)
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
10^{-1}
1
10
10^{2}
Incident Neutron Energy (MeV)

Optimised responses (up to 15 MeV)



Optimised responses (up to 100 MeV)

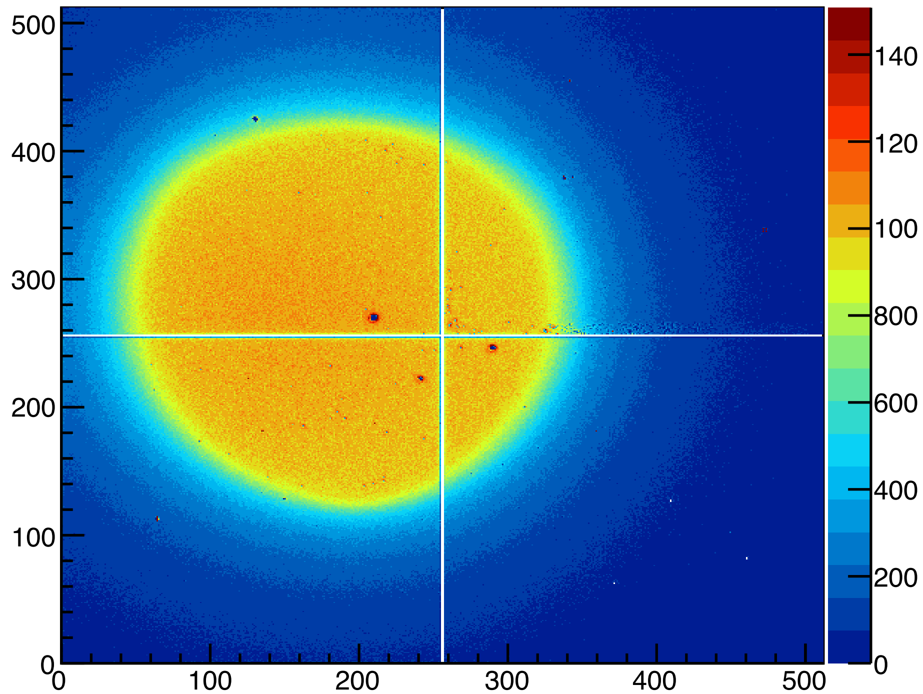


Conclusions

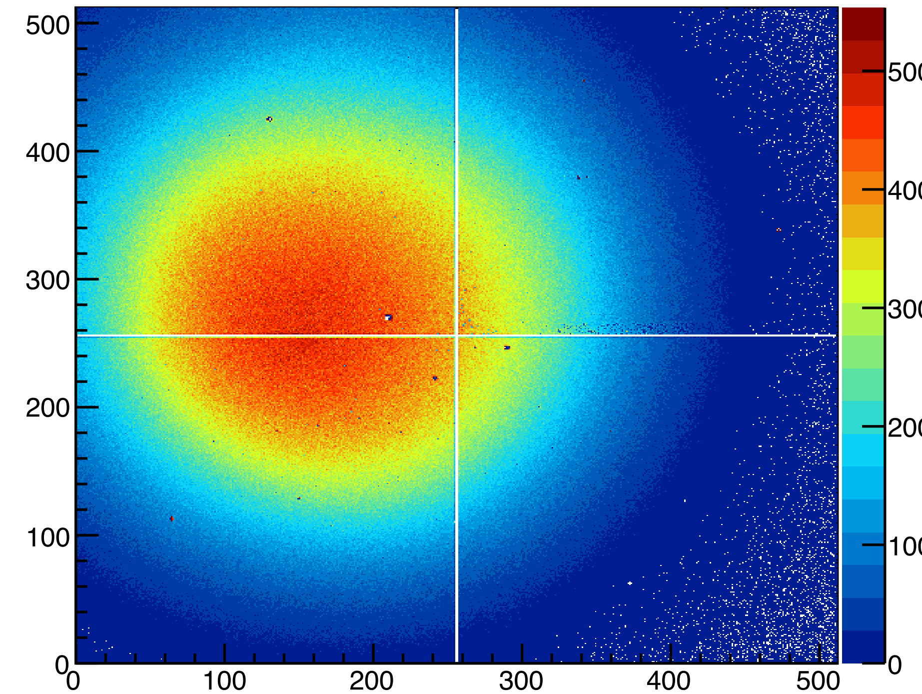
- Prototype dosimeter concept experimentally validated at NTOF
- Still needs absolute calibration using calibrated neutron sources.

nTOF Beam Profiles

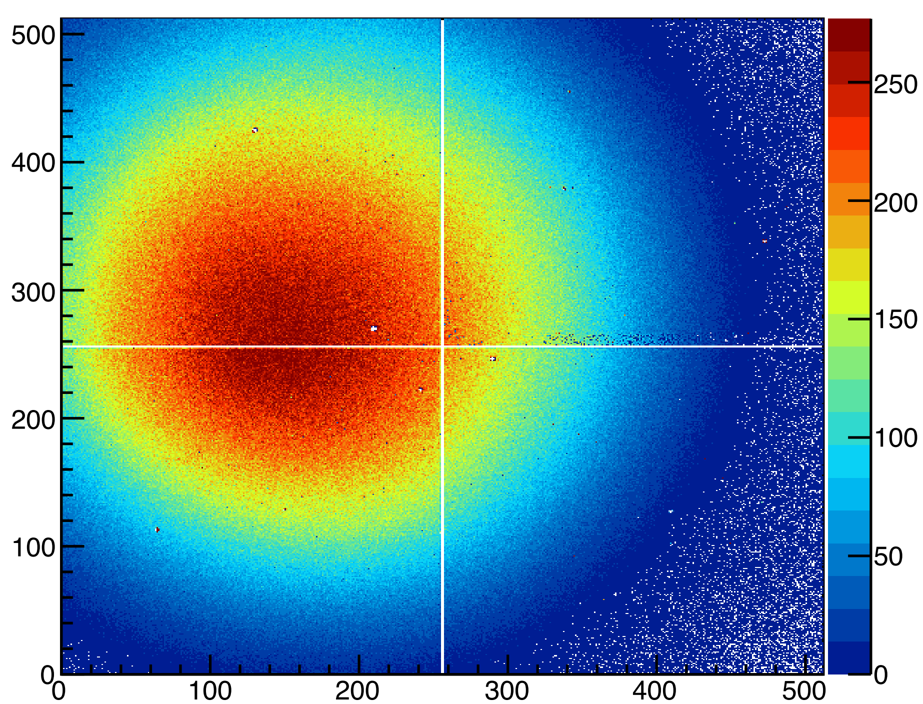
Position Neutrons (20 MeV and up)



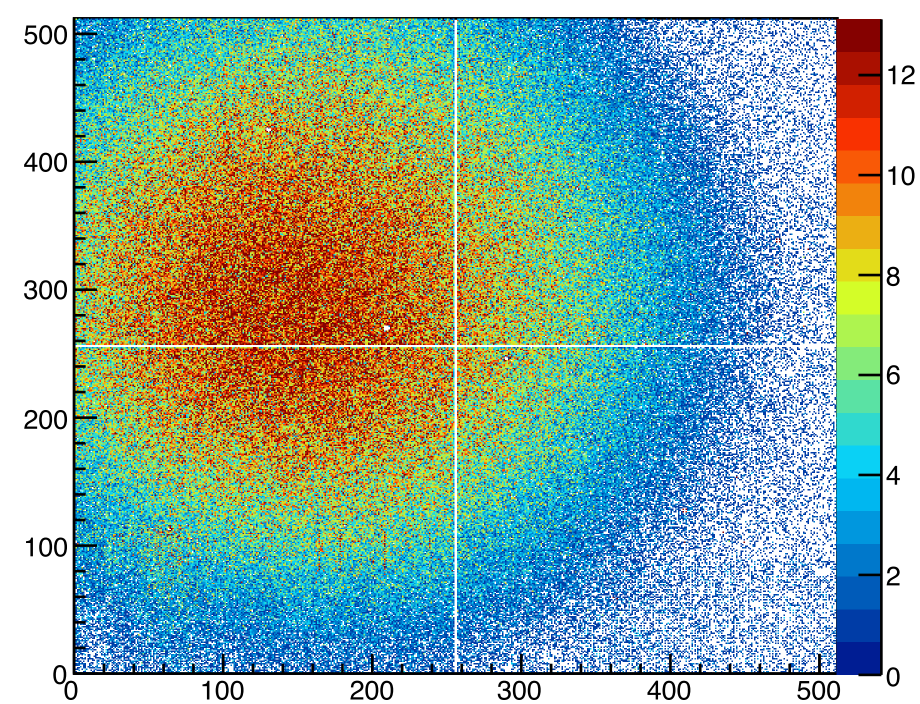
Position Neutrons (1 MeV- 20 MeV)



Position Neutrons (1 keV - 1 MeV)

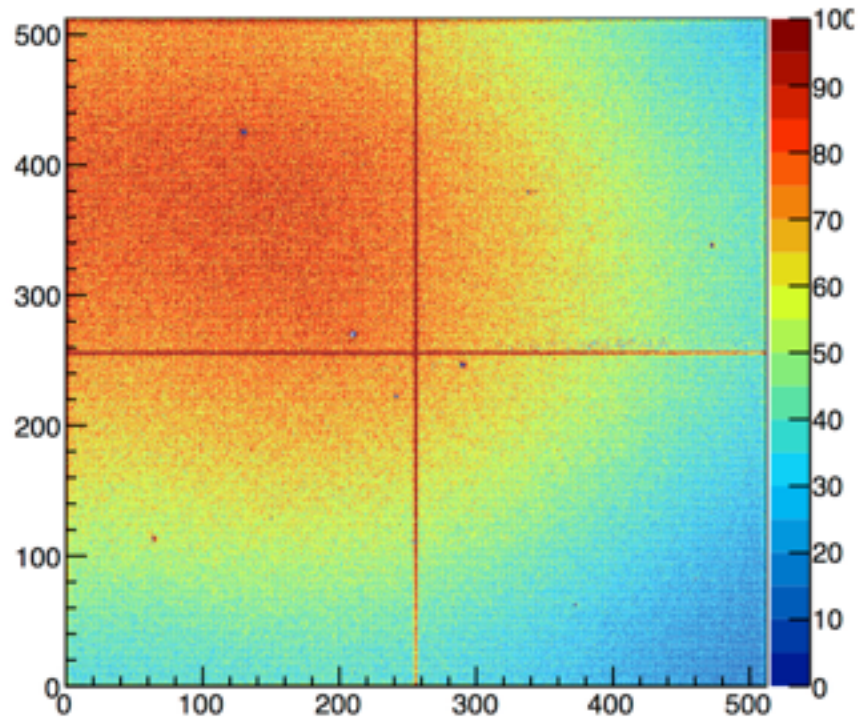


Position Neutrons (20 eV - 1 keV)

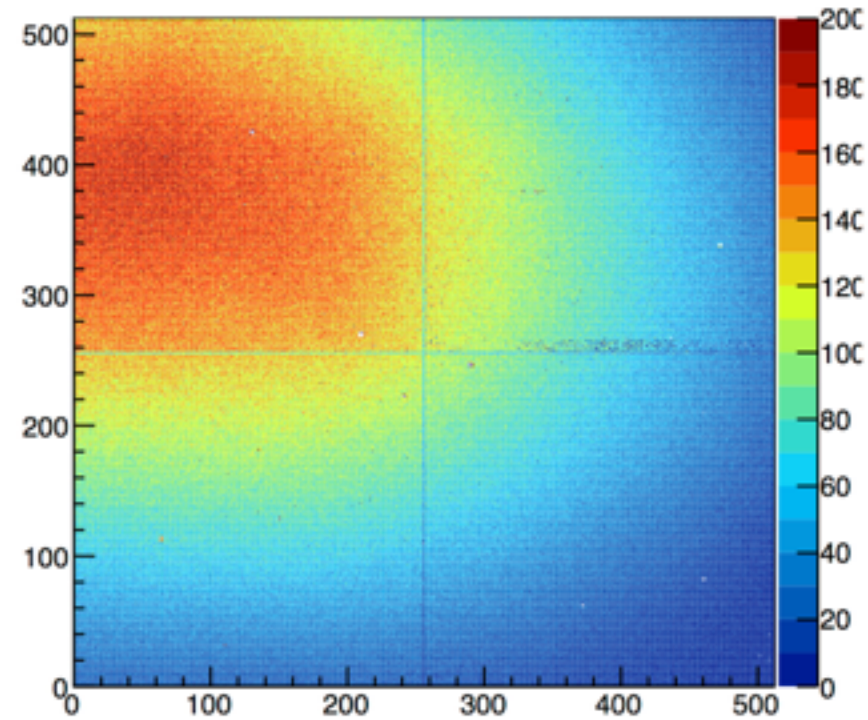


Beam Spot - NTOF 2

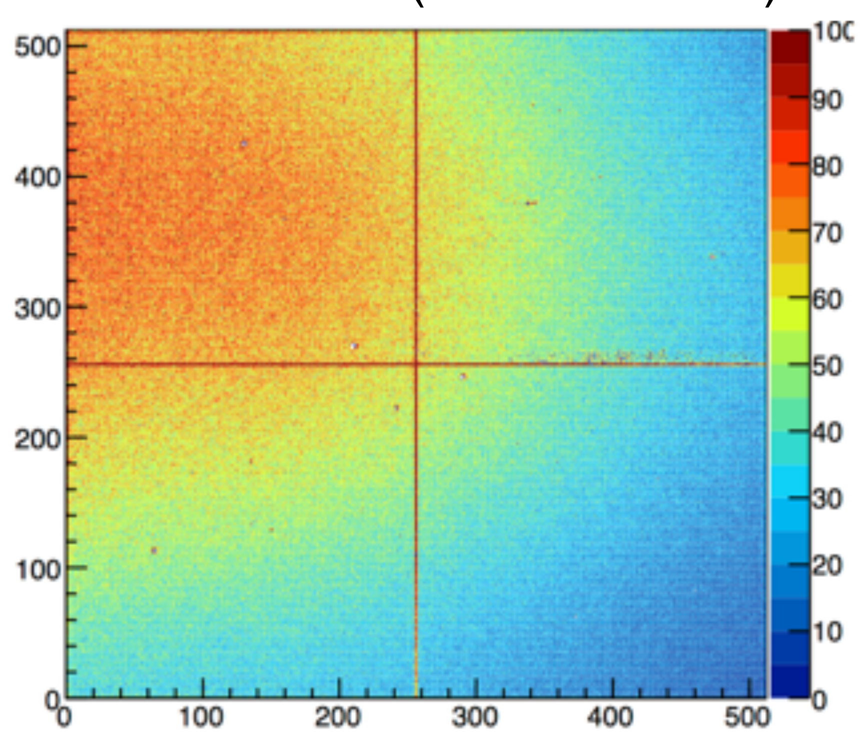
Position Tracks (20 MeV and up)



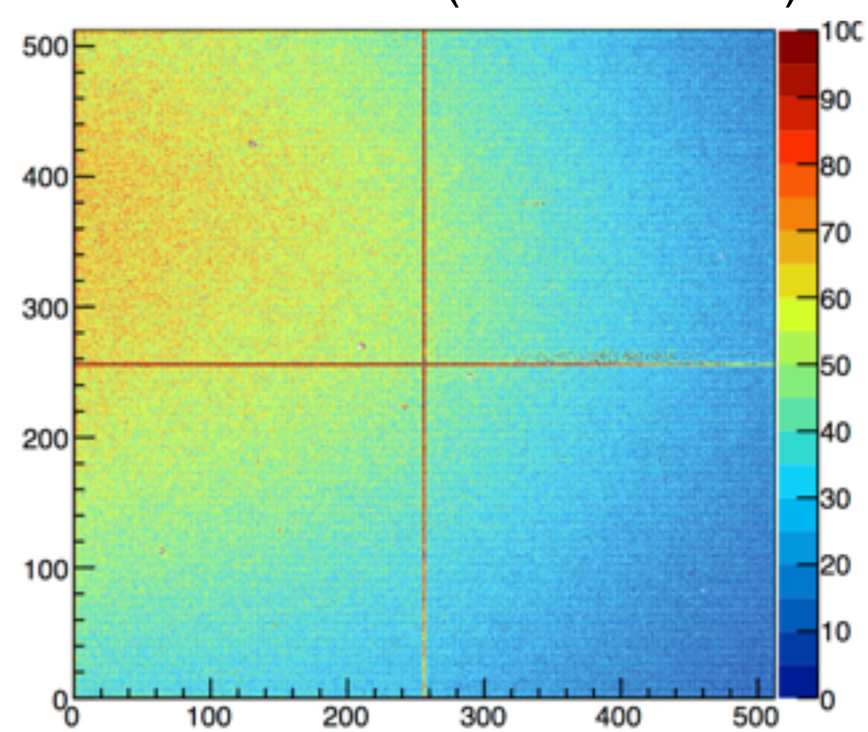
Position Tracks (1 MeV - 20 MeV)



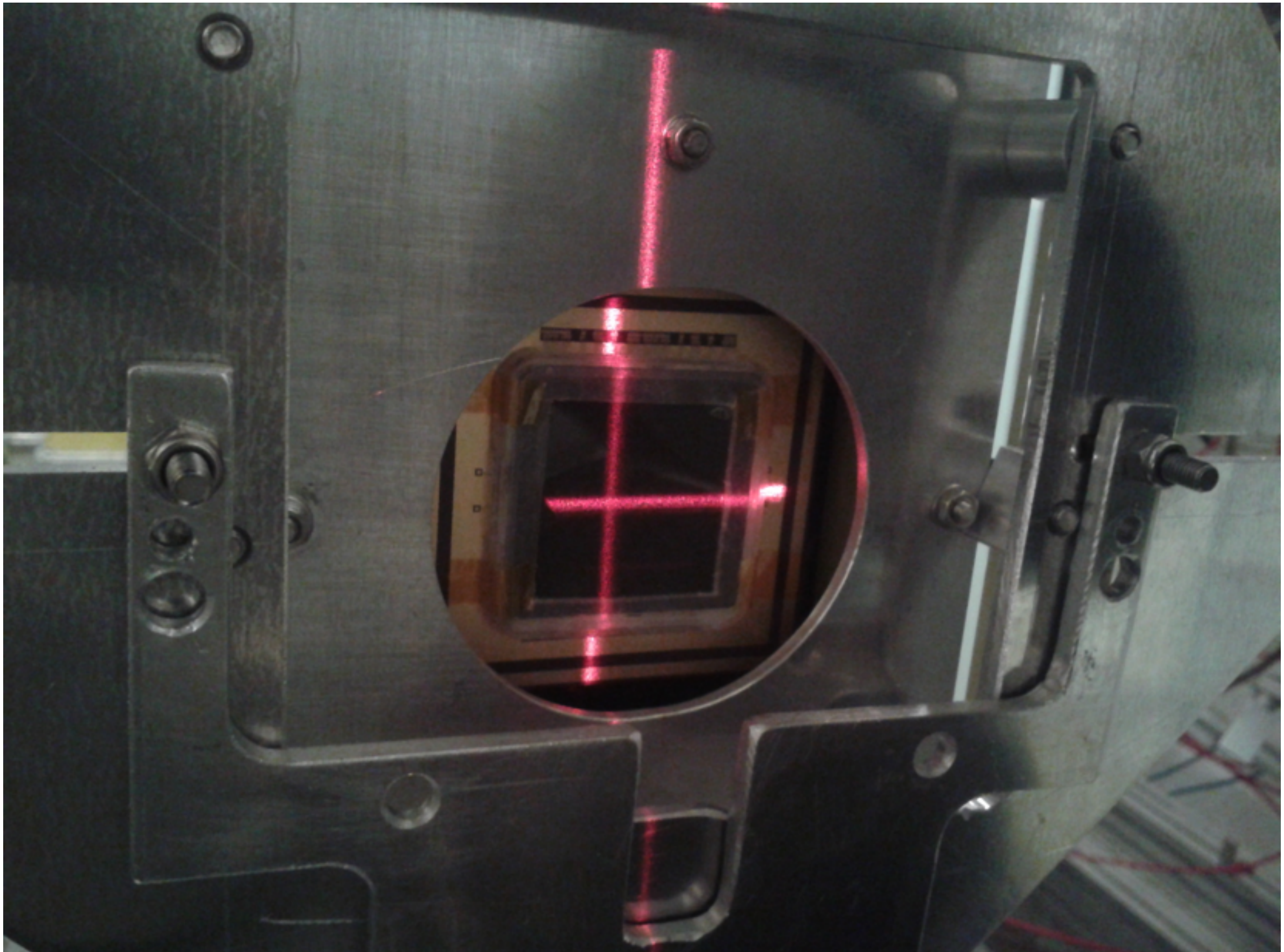
Position Tracks (1 keV - 1 MeV)



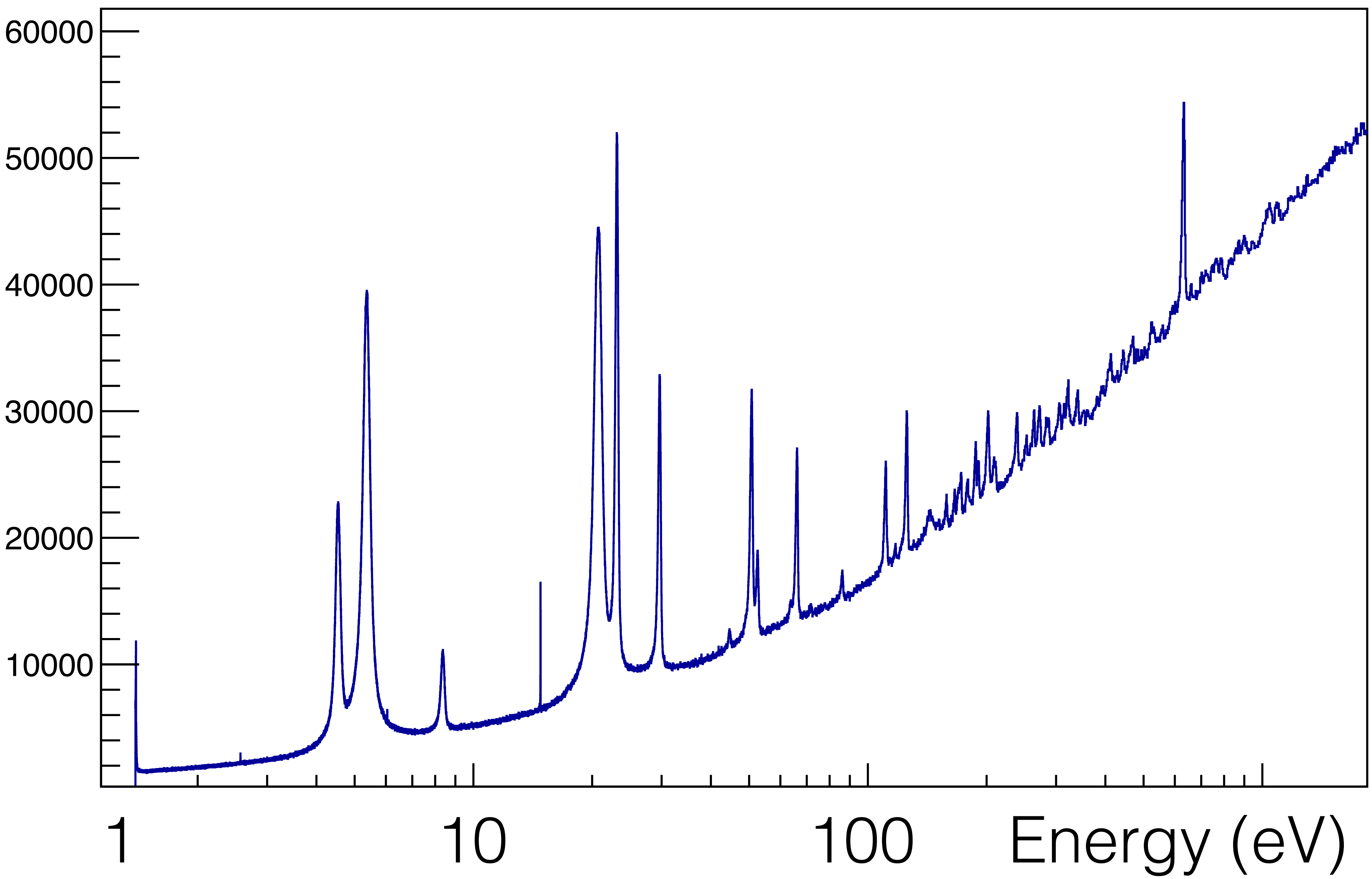
Position Tracks (20 eV - 1 keV)



Laser Alignment of Beam



Low Energy Structure



Neutron/gamma interactions with gold in the PCB board, lead in the solder bumps and gadolinium in the collimator

Thanks for your attention