15th Geant4 Space Users Workshop, December 5-7, 2023

Simulating a detector's response to solar flare polarization

Geant4 and the PADRE mission

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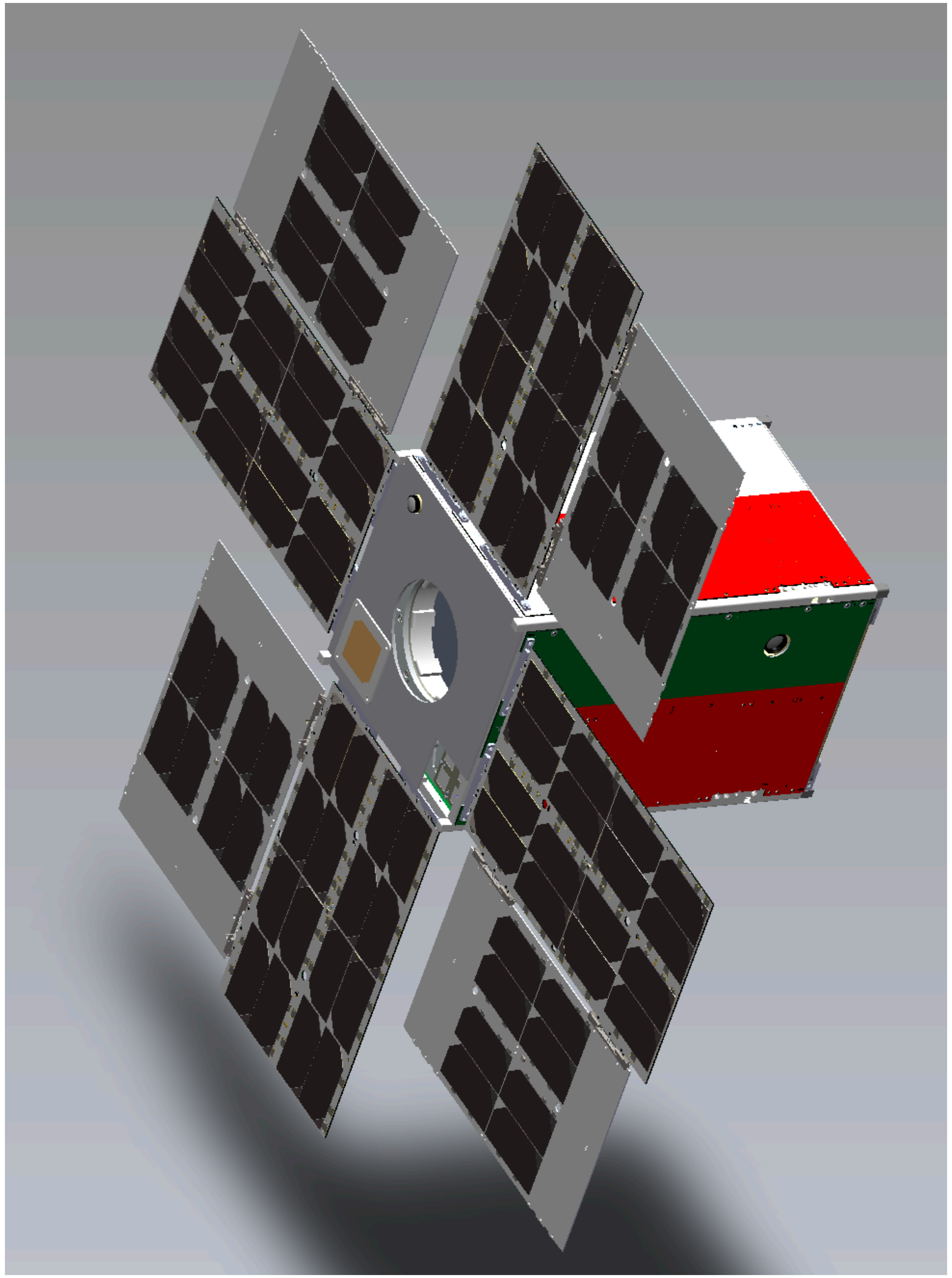
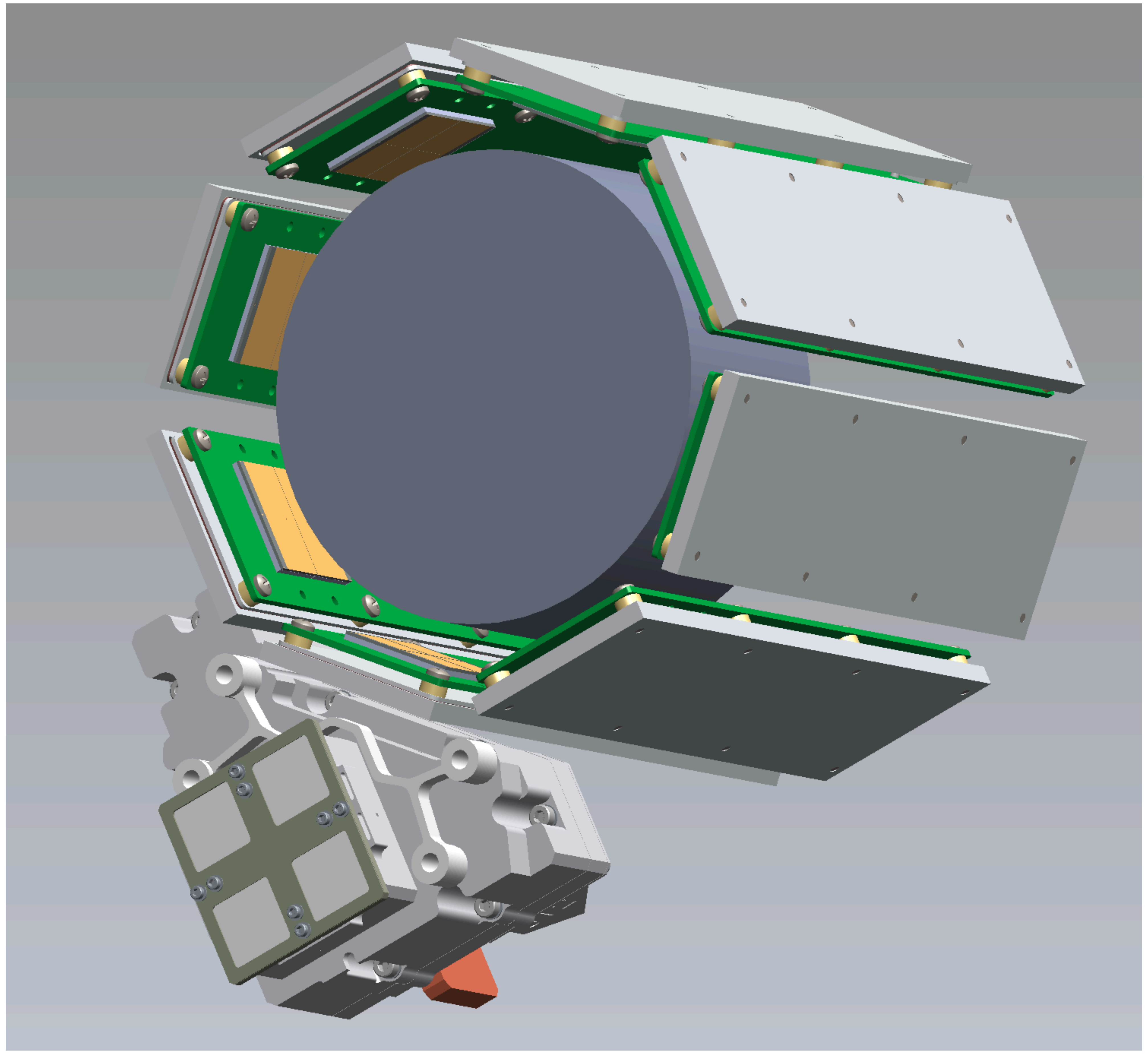
solar **P**ol**A**rization
and **D**irectivity X-
Ray **E**xperiment (PADRE)



Instruments:

Solar HARd X-ray Polarimeter (SHARP), consists of a cylindrical beryllium scatterer surrounded by 8 photon counting detectors



Measuring Directivity to Determine Electron Anisotropy (MeDDEA)

PADRE's Science Goal:

Investigate the dominant electron acceleration mechanisms in large solar flares

"How is the magnetic energy converted into electrons' kinetic energy during solar flares?"

How?

by determining the degree of beaming of accelerated electrons in large solar flares

But, how?

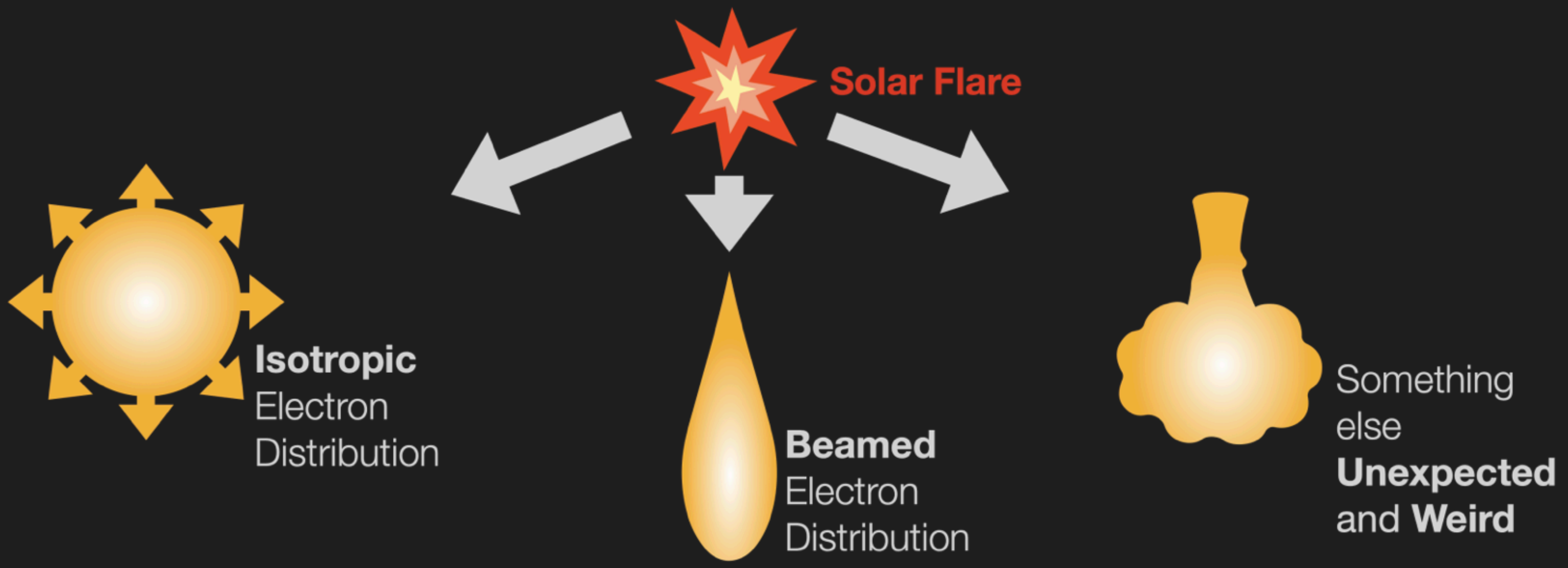
Implementing Two approaches:

- by measuring spatially-integrated spectro-polarimetric hard X-rays
- by coordinating with Solar Orbiter/STIX to make two point measurements of X-rays and determining their directivity.

PADRE will focus on determining the degree of beaming of accelerated electrons in large solar flares.

Why?

directivity of accelerated electrons is still poorly constrained



Validation Theory

Klein-Nishina formula, gives the differential cross section of photons scattered from a single electron

Formula for incoming polarized photons:

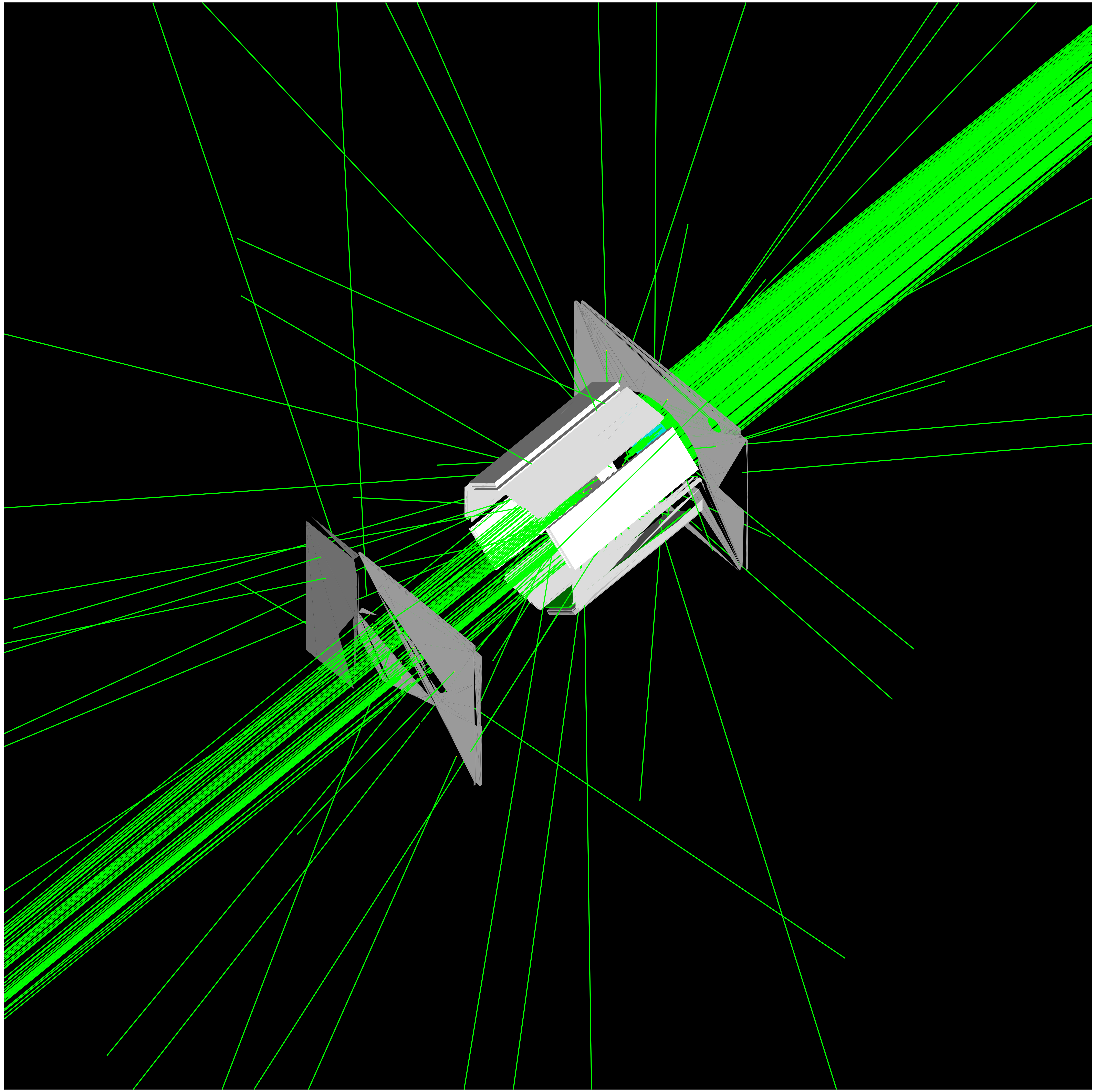
$$\frac{d\sigma}{d\Omega} = \frac{1}{2} r_e^2 \left(\frac{\lambda}{\lambda'}\right)^2 \left[\frac{\lambda}{\lambda'} + \frac{\lambda'}{\lambda} - 2\sin^2(\theta)\cos^2(\phi)\right]$$

Main takeaway is that the number of scattered photons as a function of phi (azimuthal angle) is sinusoidal and has maxima at 90 and 270 degrees and minima at 0 and 180 degree (with respect to the polarization vector)

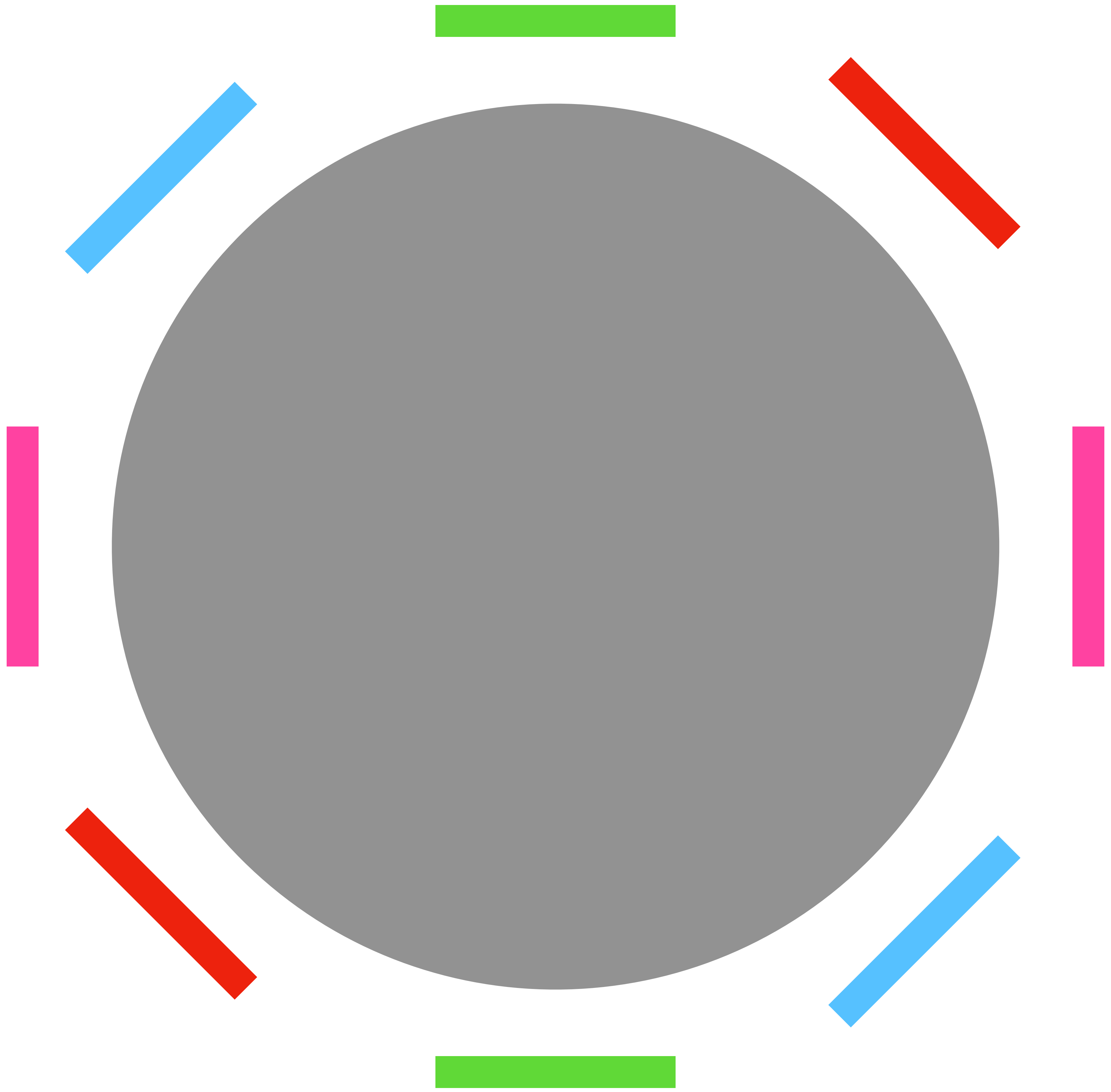
Validation Simulation

Sent beams of varying Stokes parameters (angle of photon polarization)

Used parameters corresponding to angles from 0 to 360 degrees, in steps of 5 degrees



Depiction of SHARP for understanding plots

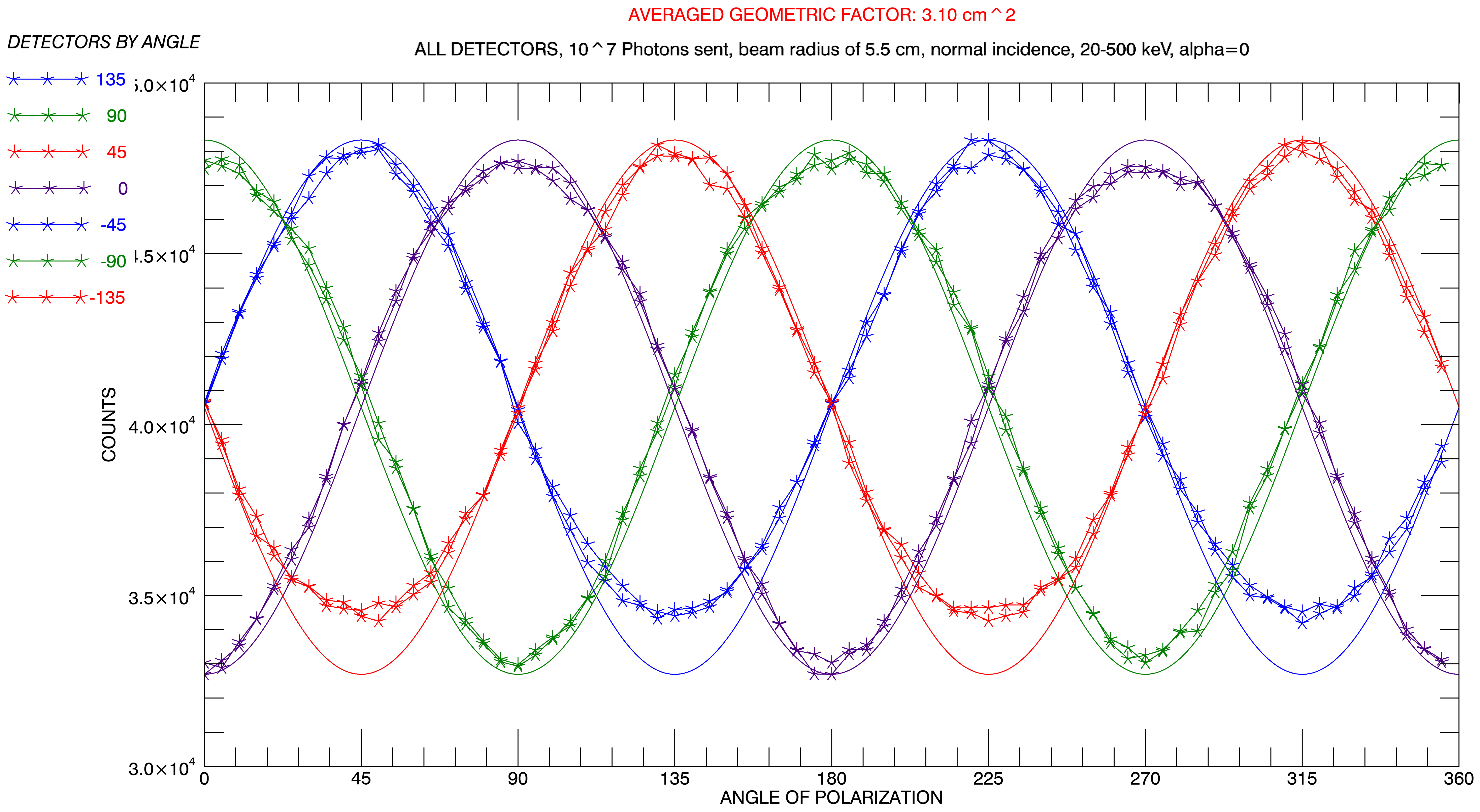


Detector pairs of same color should record similar counts to polarized photons.

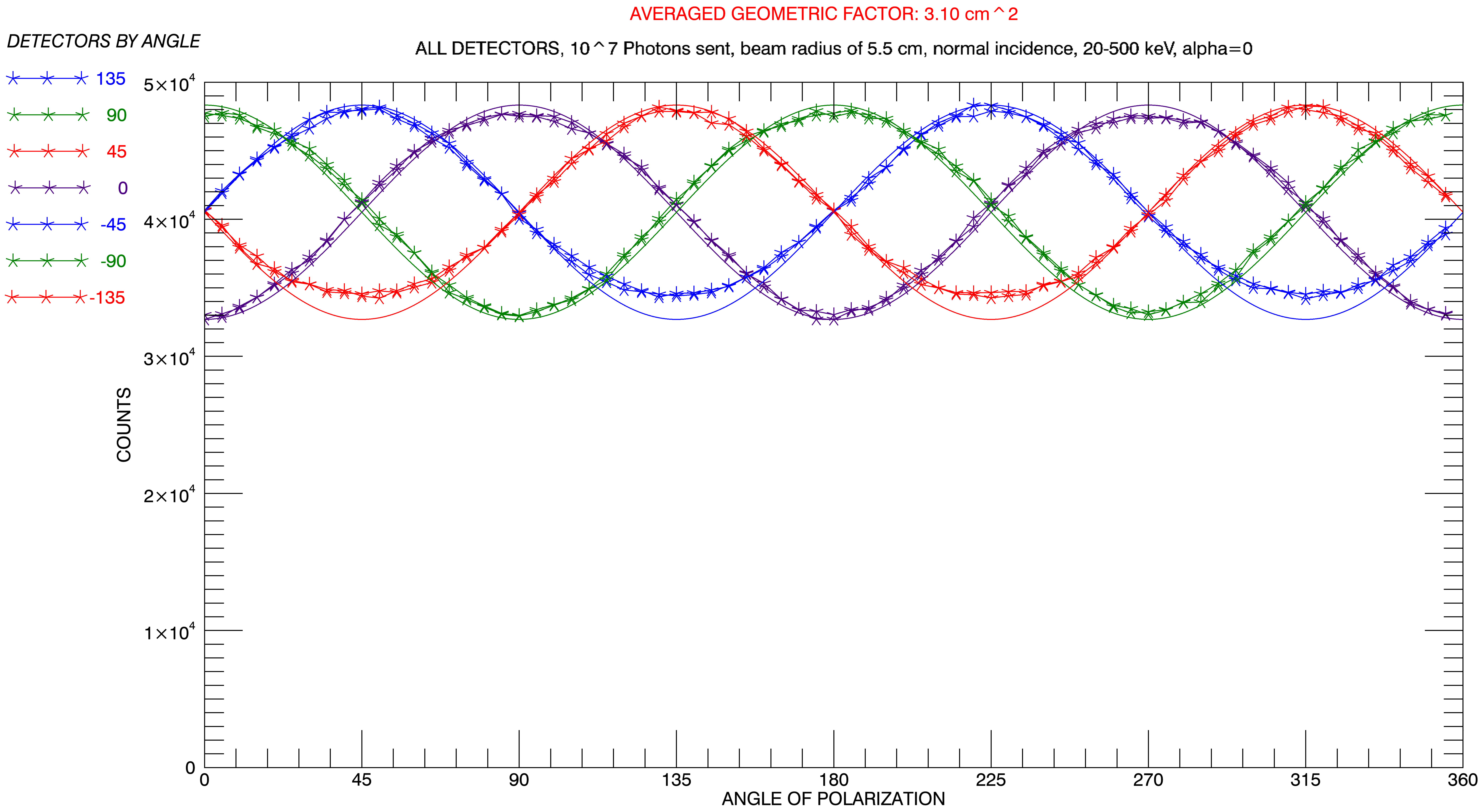
Surely, this is the most impressive depiction you've ever seen of a scatterer surrounded by detectors!

Validation Results

Up to 5% discrepancy between minima/maxima of detector pairs



Validation Results, zoomed out for perspective

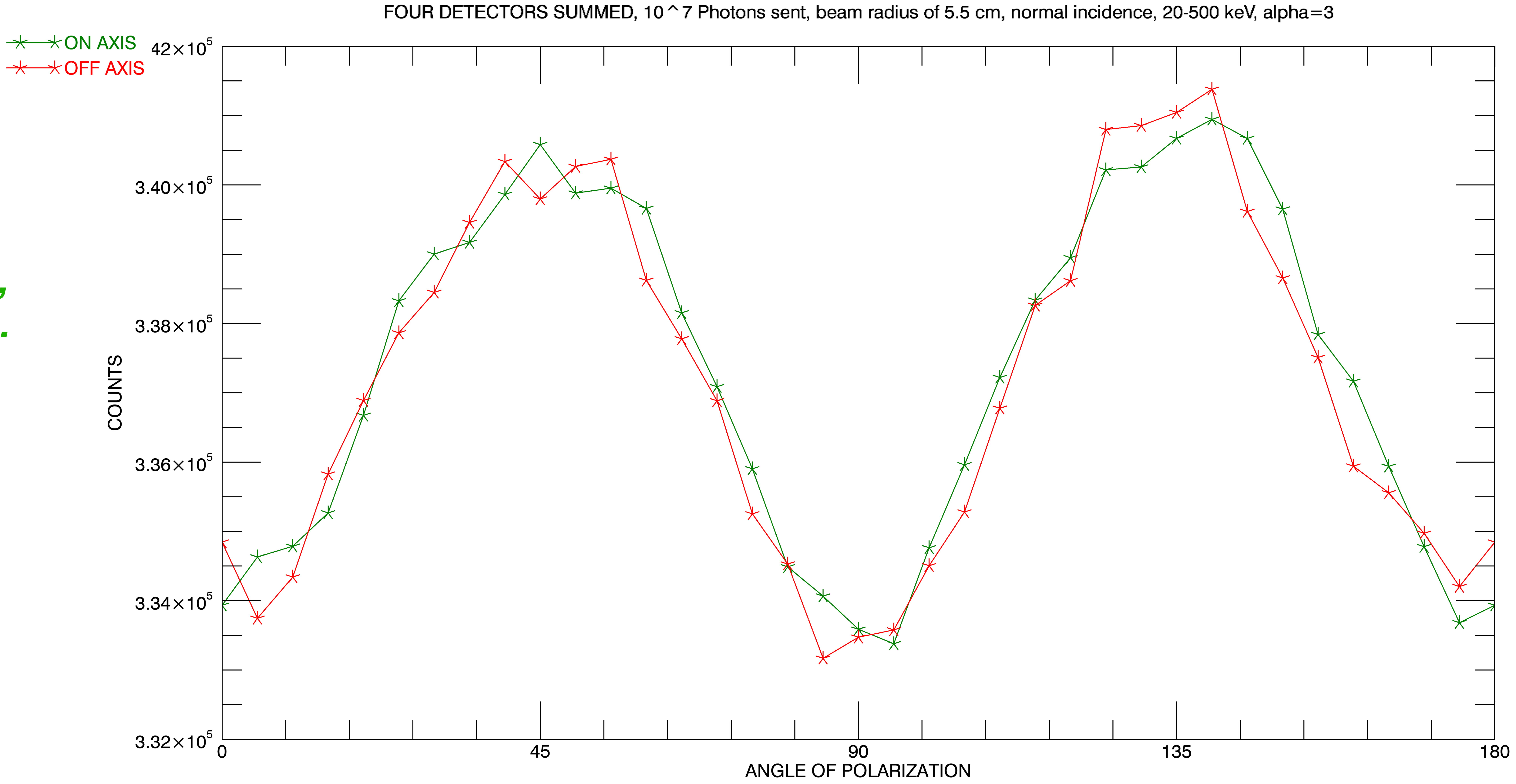


Validation Results, attempt to understand

Sinusoidal variation in total counts, sets of four detectors follow same curve

***ON AXIS* corresponds to detectors centered at 0, 90, 180, 270 degrees.**

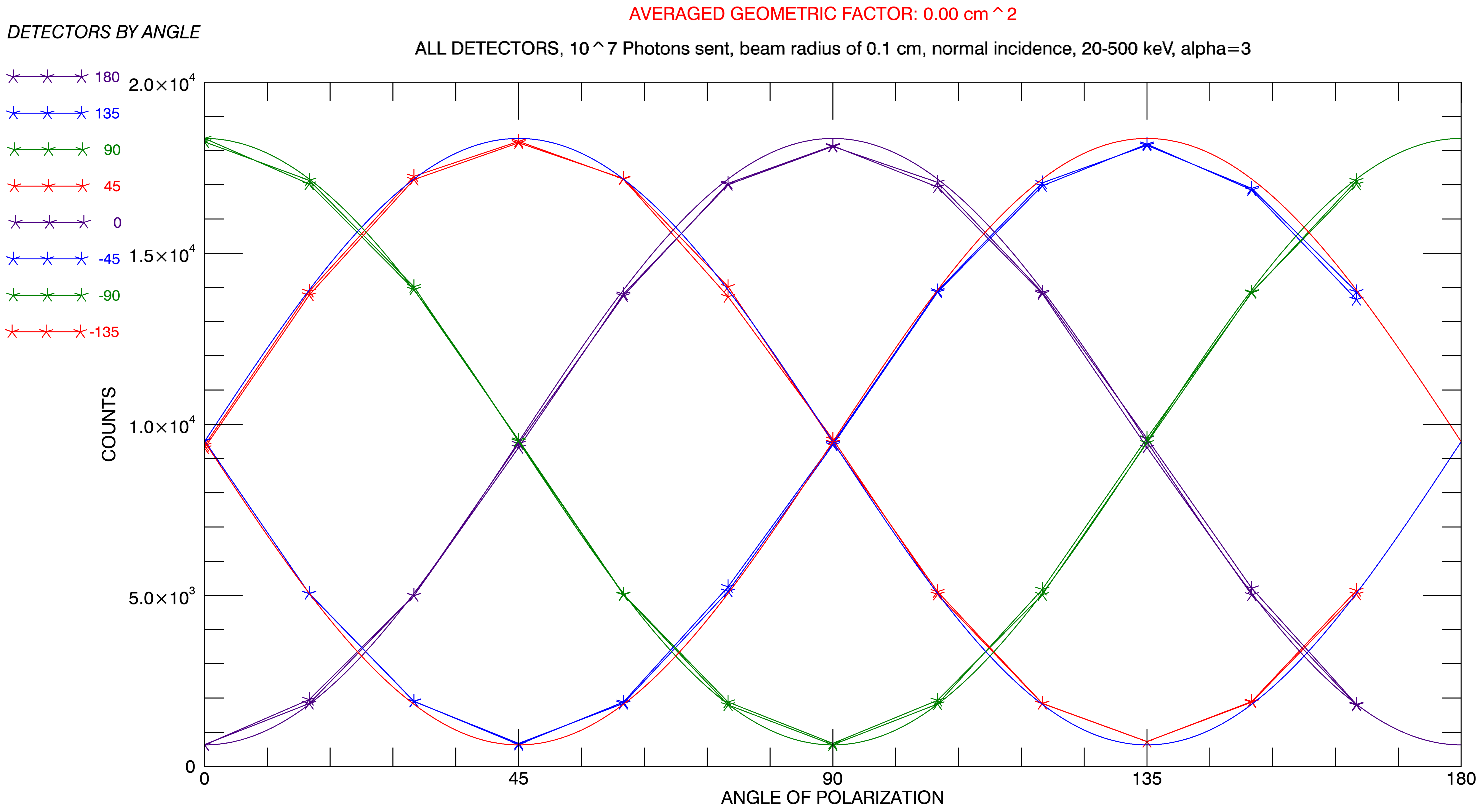
***OFF AXIS* corresponds to detectors centered at 45, 135, 225, 315 degrees.**



Validation Results, attempt to understand

Rotated detector in 15 degree increments, kept photon polarization angle the same throughout (0 degrees)

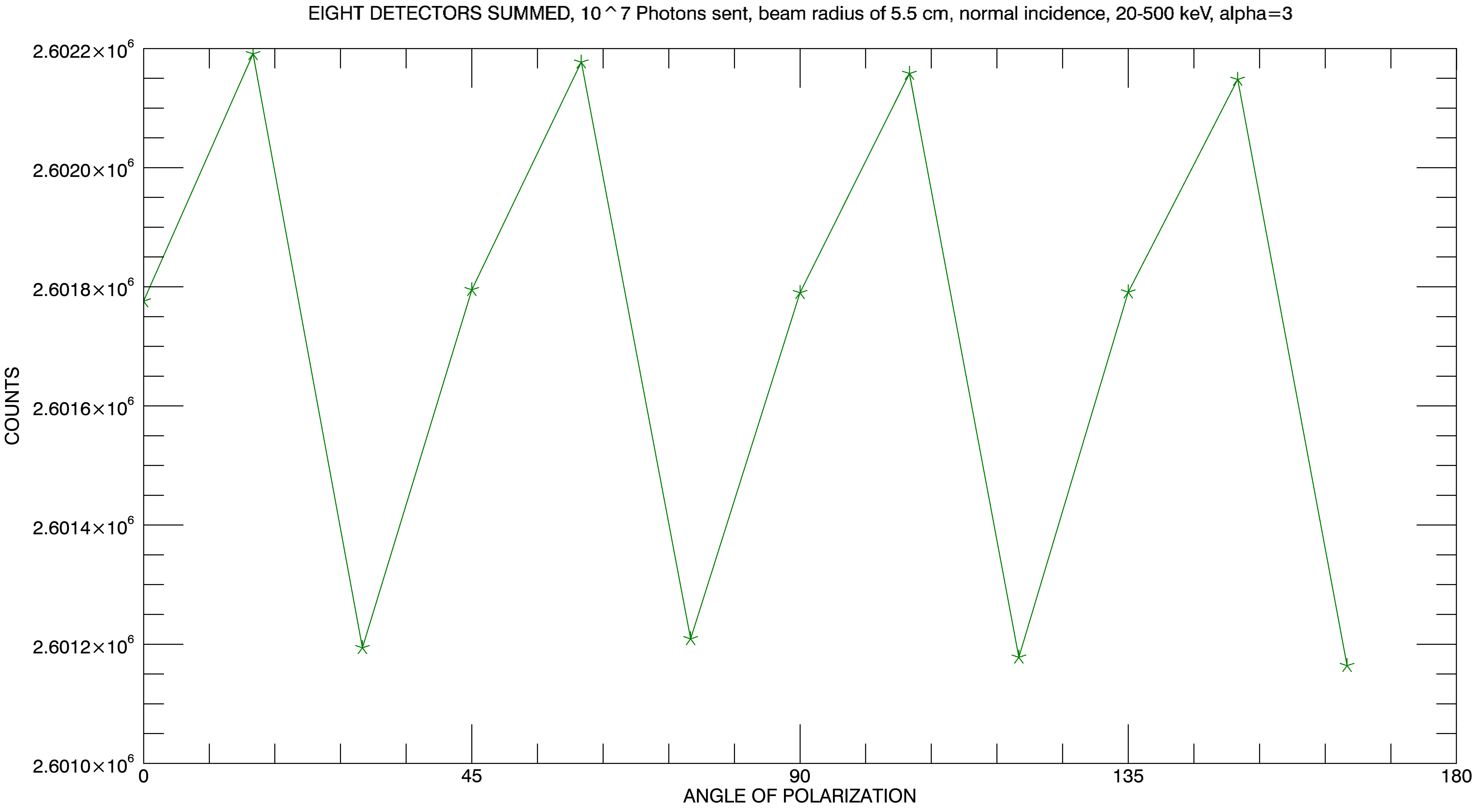
Results now match theory!



Colors of plot are incorrect, red and blue detectors were switched

Validation Results, attempt to understand

Variation in total counts now gone, slight variation due to changing angles resulting in non symmetry in geometry



Validation Results, inconclusive conclusion

1) *Rotate polarization angle of photons, keep detectors in place ==> slight discrepancy between results and theory*

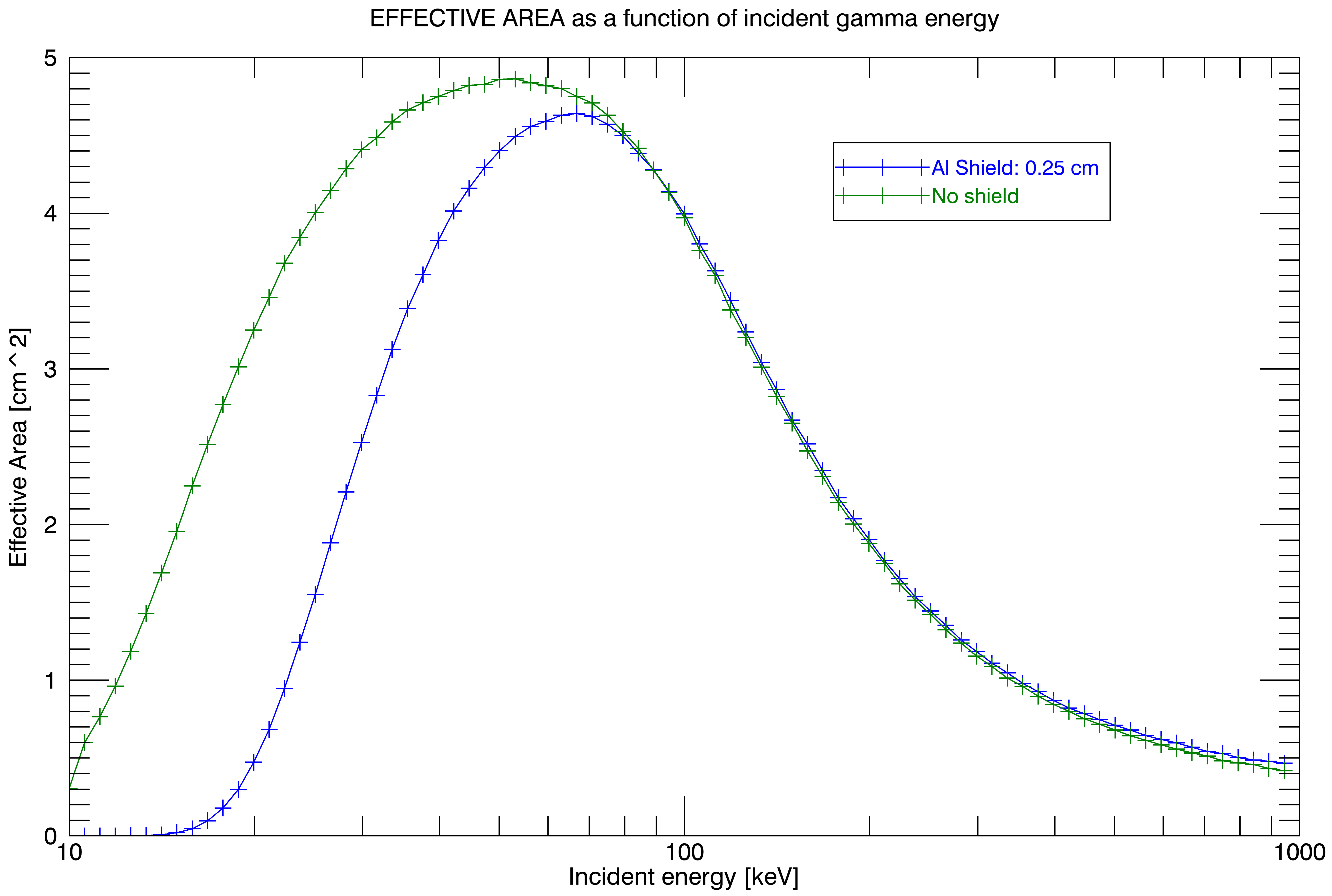
2) *Rotating detectors and maintain same polarization of photos throughout ==> agreement between results and theory*

Important calculations for polarization detectors

1) Effective area
2) Mu100
3) Minimum Detectable Polarization (MDP)
4) Uncertainty

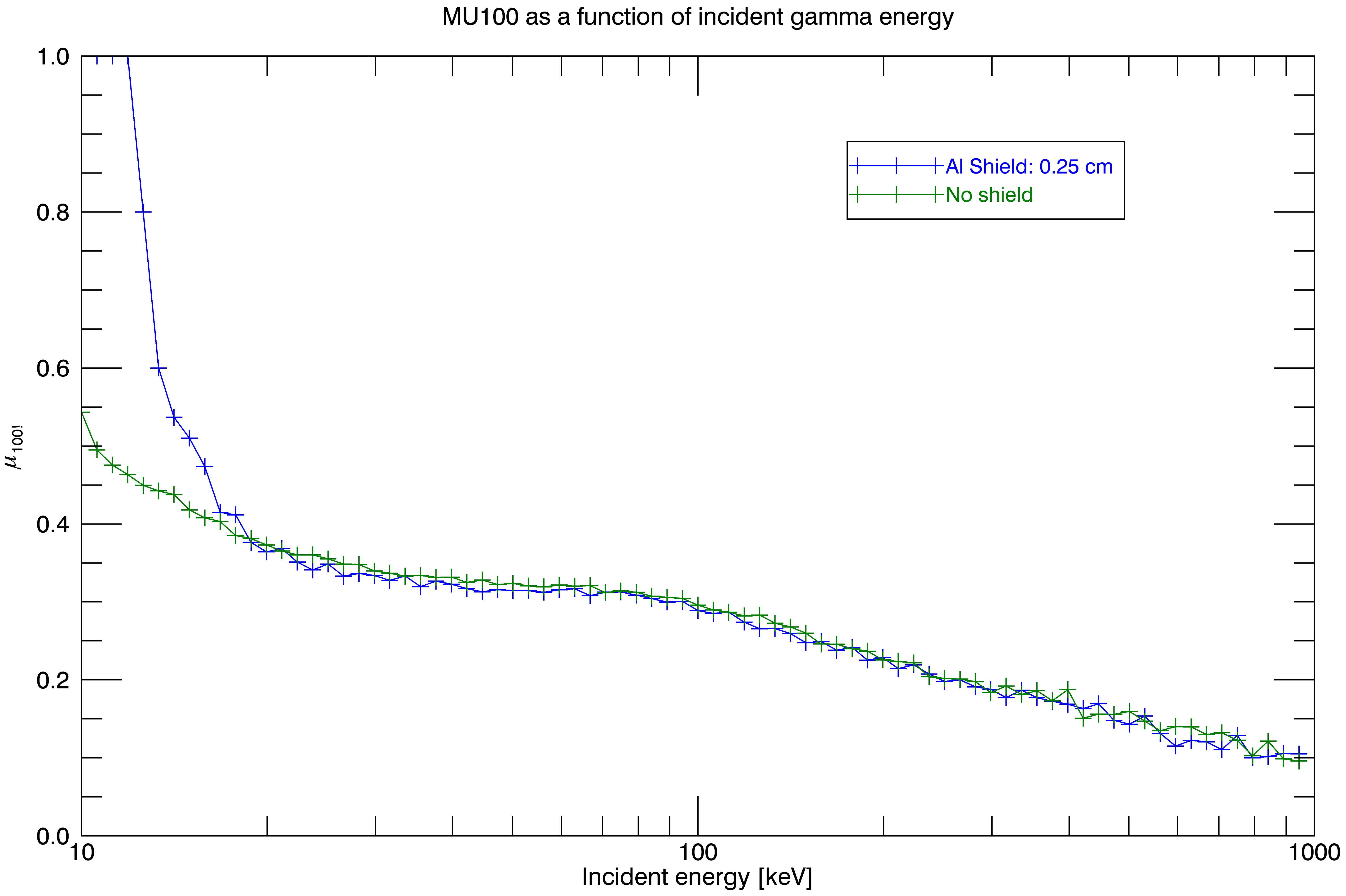
Effective area = *(total counts) / fluence*

Fluence = (particles sent) / (particle source area)



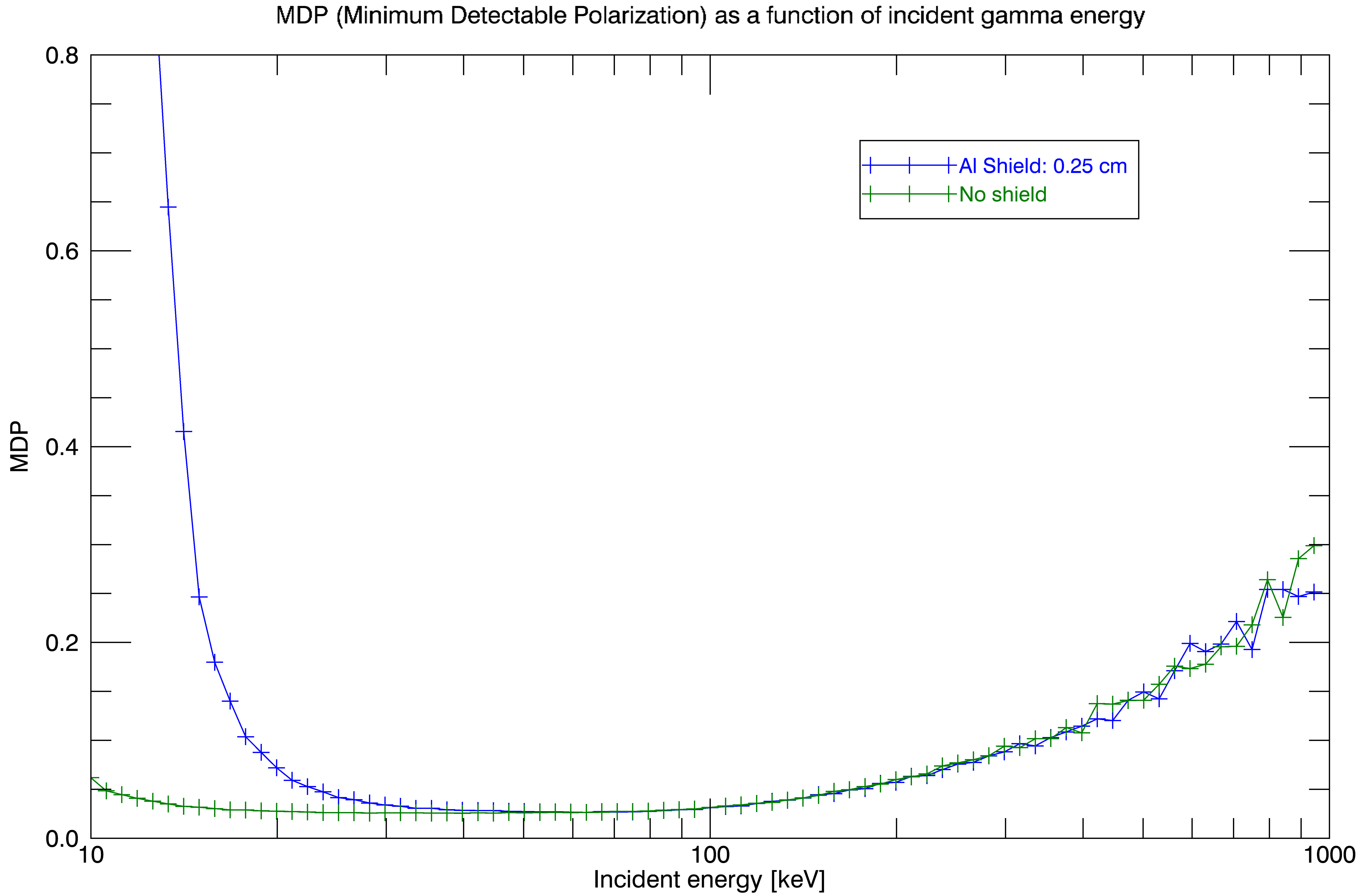
Mu100 = *(max counts - min counts) / (max counts + min counts)*

Gives the degree of the modulation factor:
1 = 100% in one direction, 0 = no favored direction

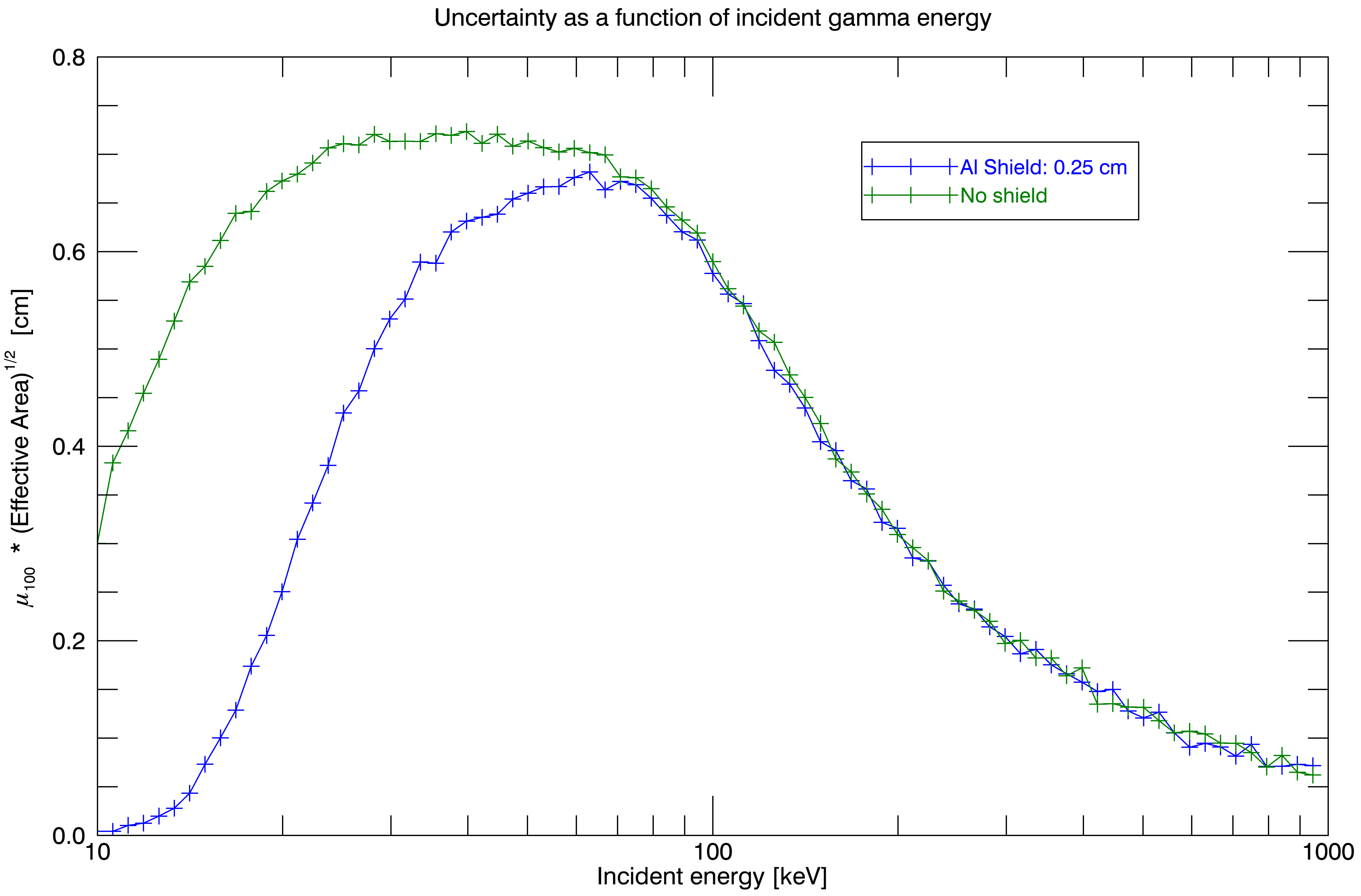


$MDP = 4.29 / [mu100 * sqrt(n)]$ *n = counts across all detectors*

Description of sensitivity of detector, how low of a polarization can be detected



Uncertainty inversely related to *mu100 * sqrt(effective area)*

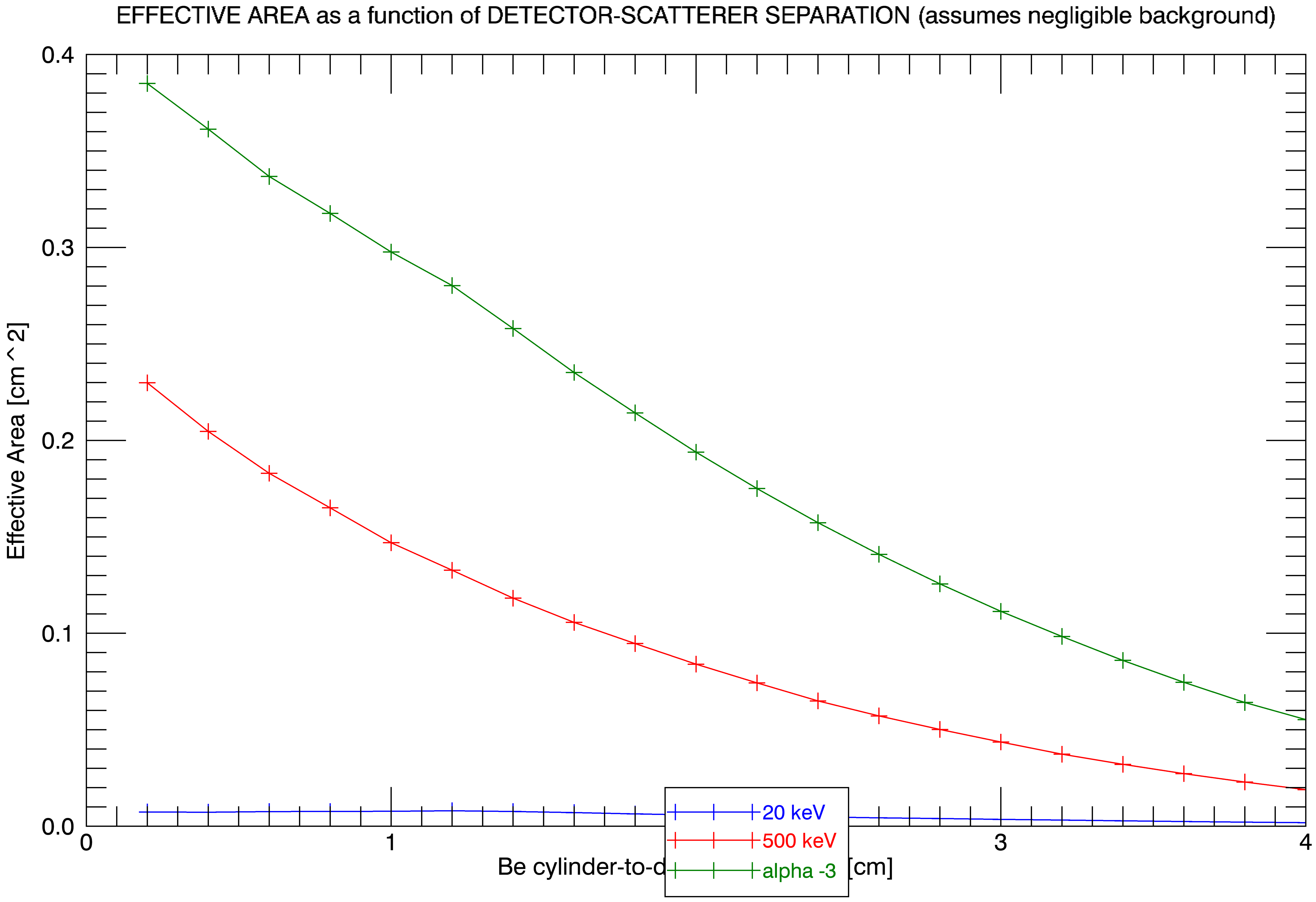


INSTRUMENT DESIGN

1) Scatterer radius (distance to detectors)

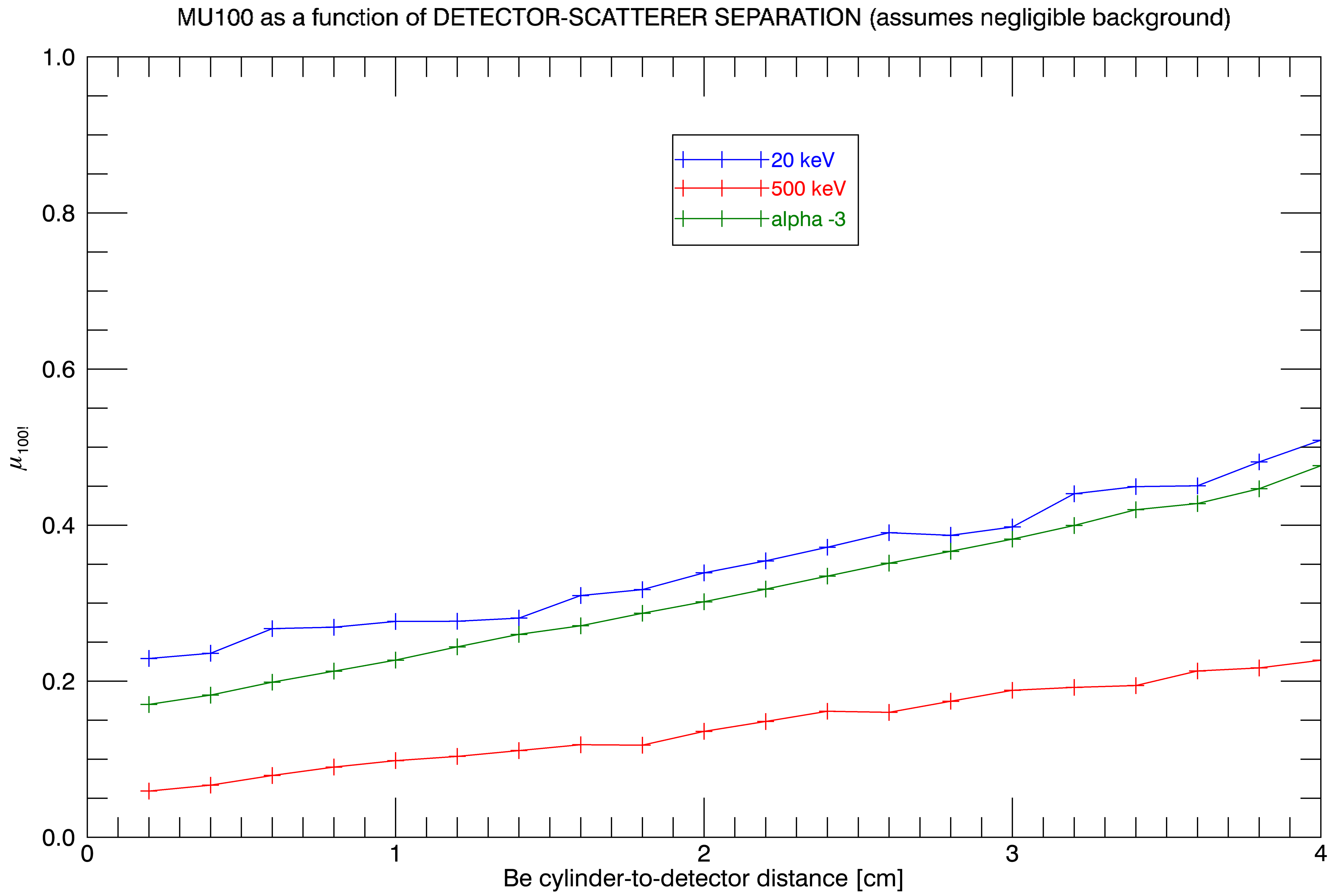
2) Shielding

Determination of optimal scattering radius



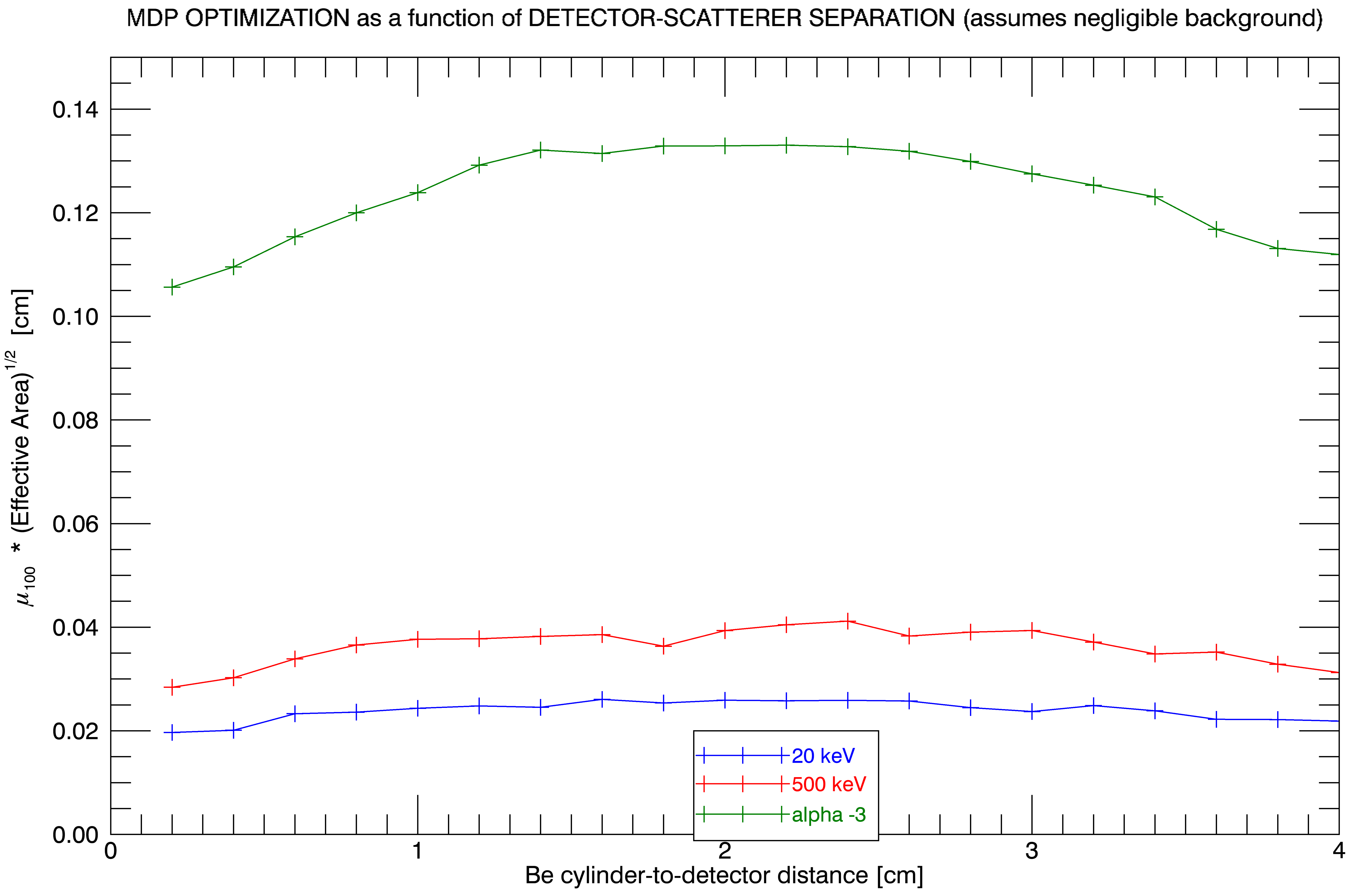
Determination of optimal scattering radius

Note that as effective area decreased with distance, mu100 increases, important to note for next plot for uncertainty (which we want to minimize)

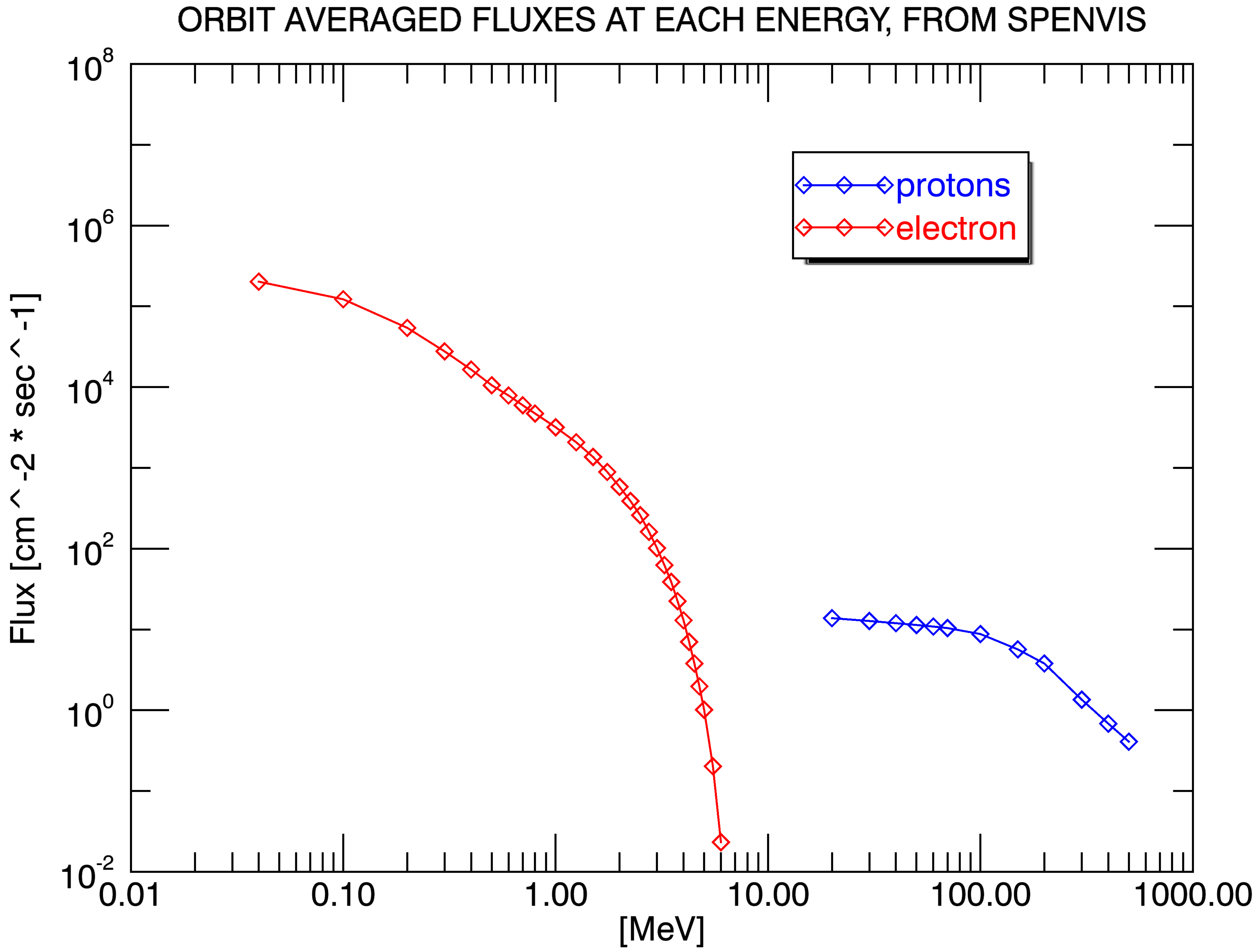


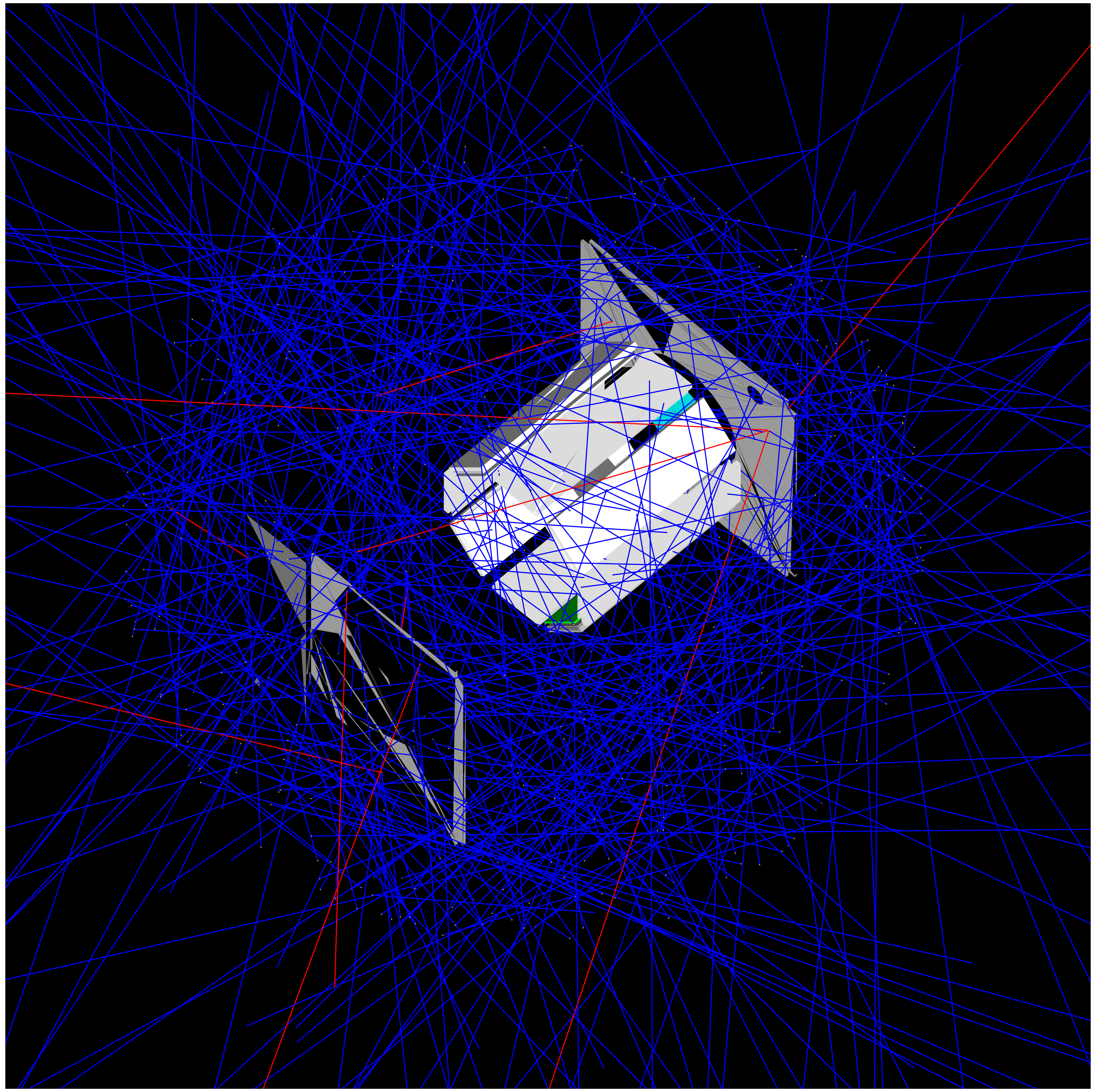
Determination of optimal scattering radius

Used these results to settle on distance of 2 cm (4.35 cm radius scatterer)



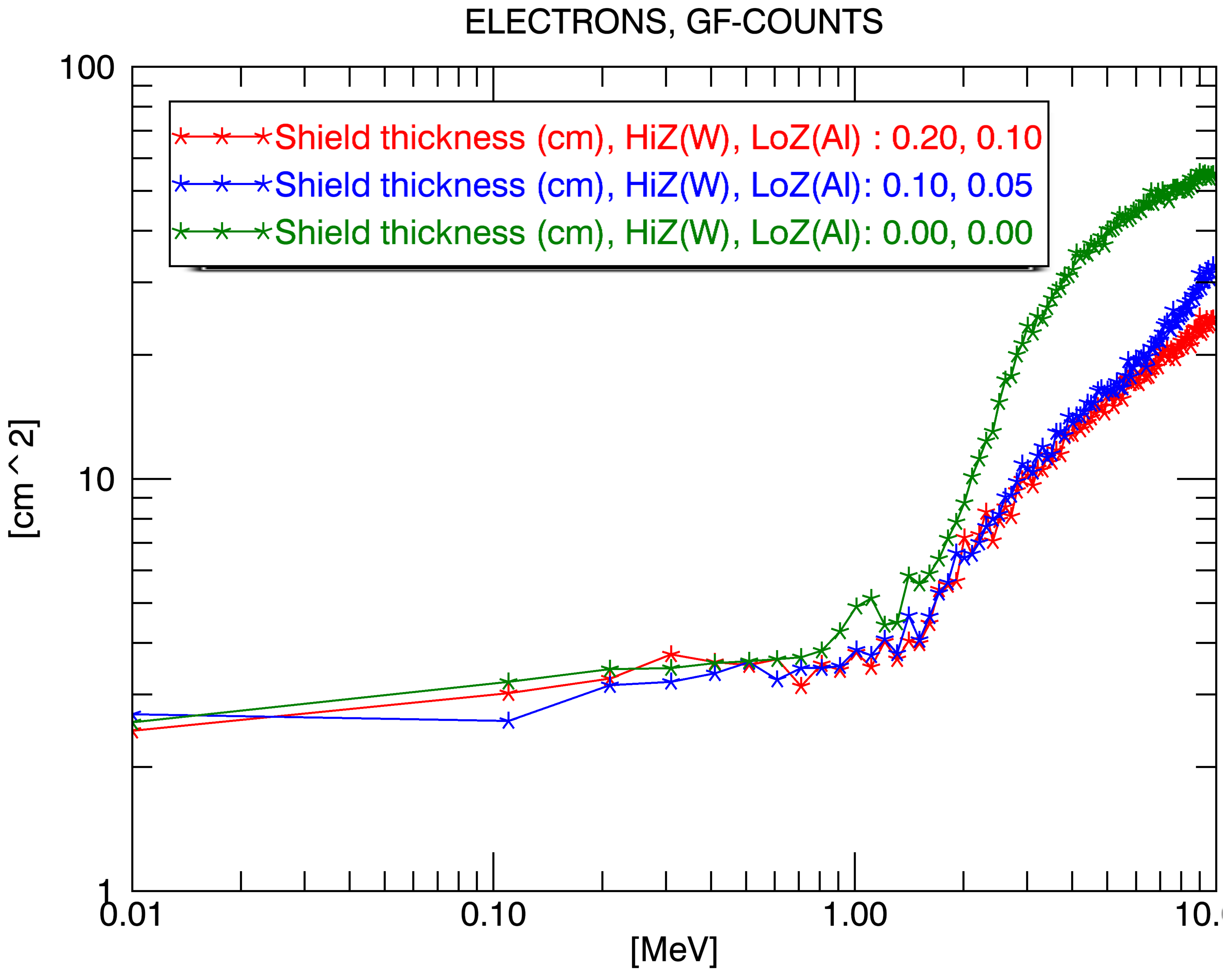
Shielding (graded Z) of each detector

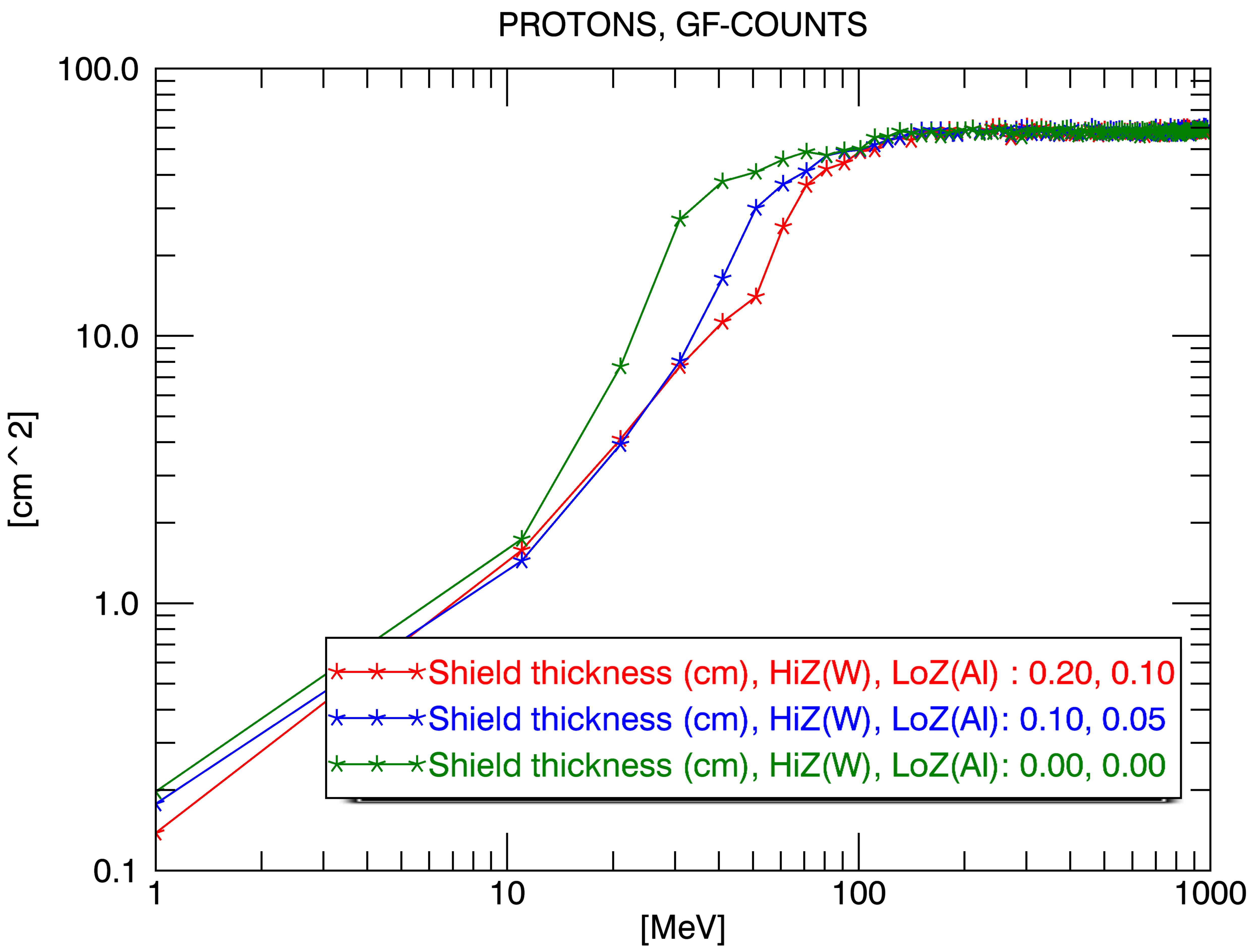




Shielding (graded Z) of each detector

Geometric factors

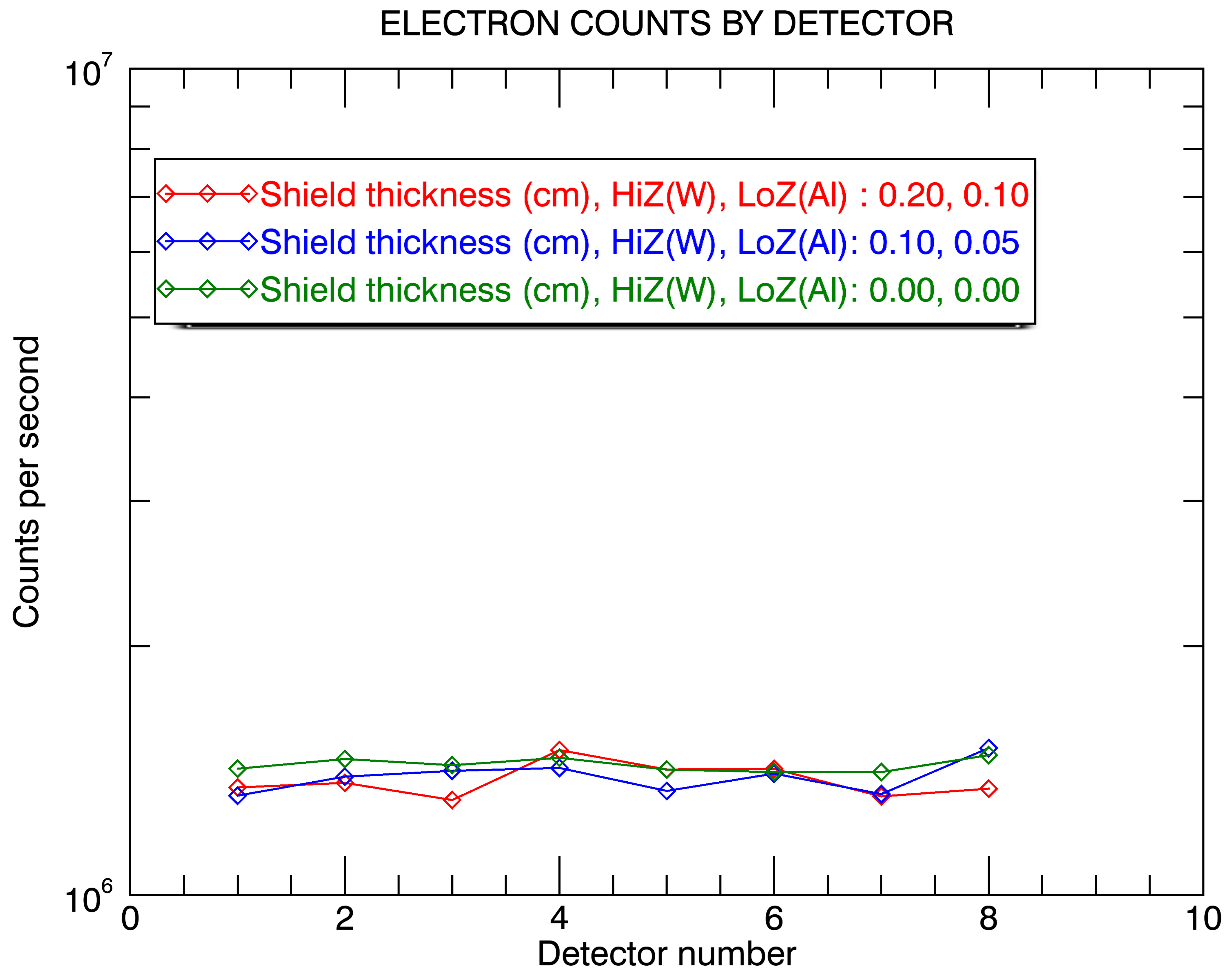


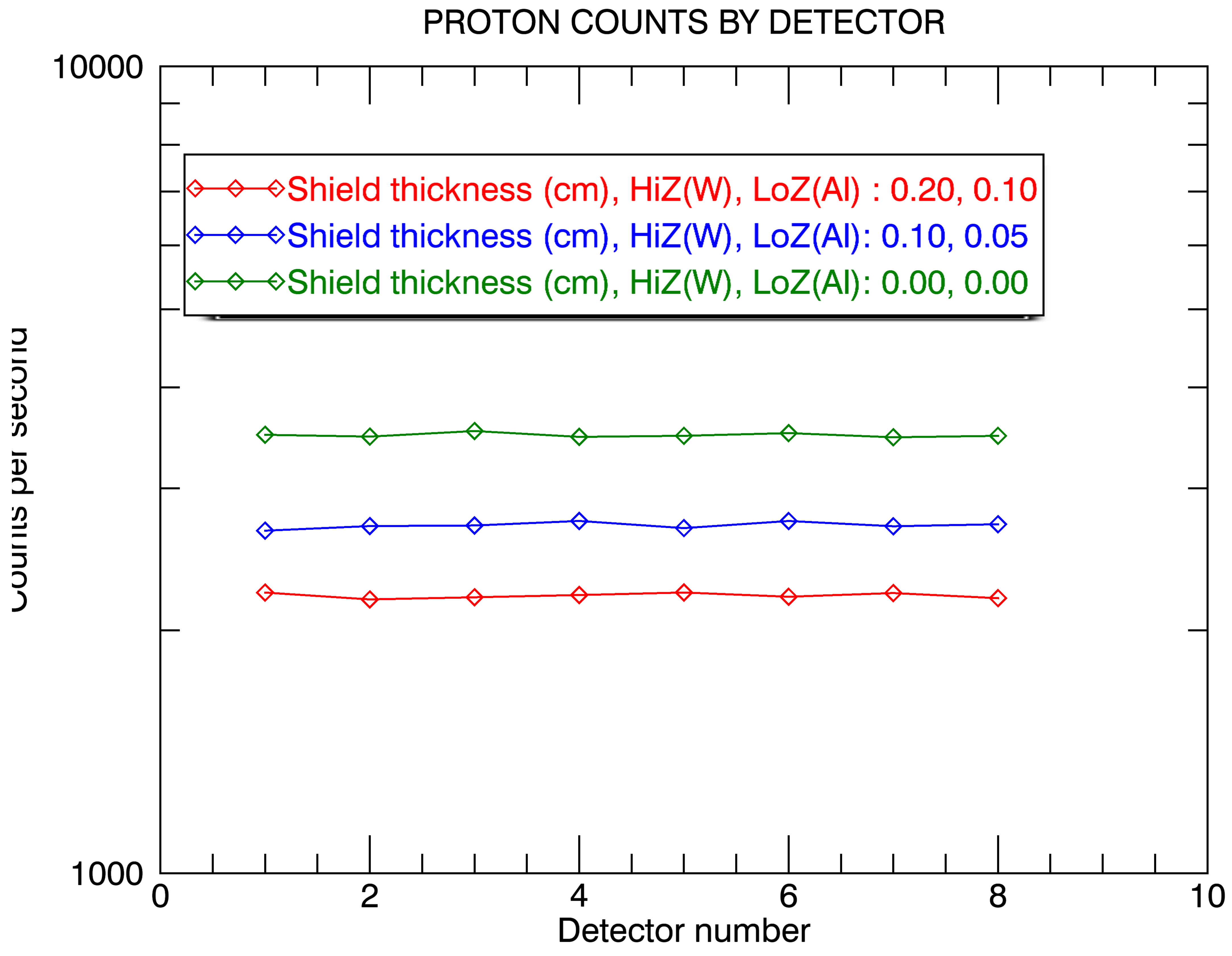


Always some shielding due to instrument structure, etc.

Shielding (graded Z) of each detector

Still working this out, but preliminary analysis shows little effect on electrons, some effect on protons in 10-100 MeV range.





NEXT STEPS

1) Continuing to add pieces to mass model

2) Currently purchasing FASTRAD to assist with mass model

3) Better understanding of fluorescence in Geant4 for purposes of shielding (are special physics lists required?)

4) Determine source of error in validation plots