# X-ray Polarimetry by Scattering and GEANT4

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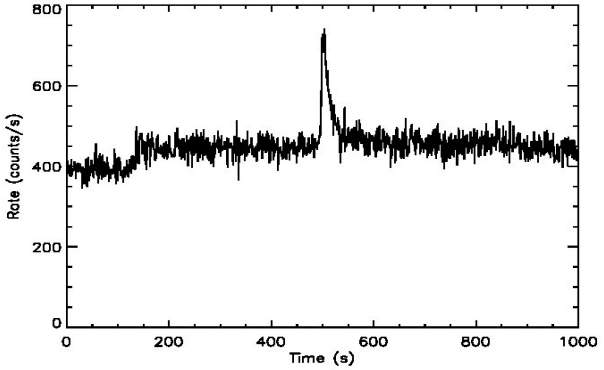
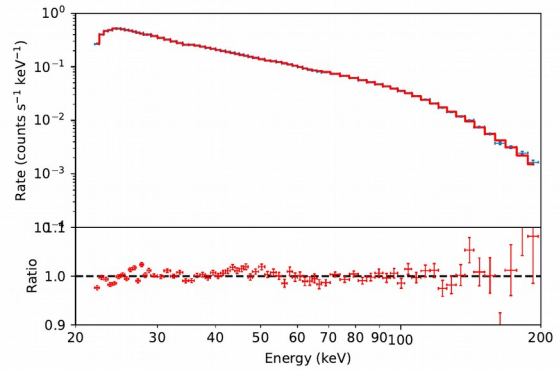
**1st National Workshop on GEANT4 and its application to High-Energy Physics and Astrophysics**
**05 - 09 Dec 2022**
**IUCAA Pune**

# Observations of astrophysical sources in X-rays








Time Position Energy

| | TIME<br>D<br>s | X<br>J<br>0.05 ARCSECONDS | Y<br>J<br>0.05 ARCSECONDS | PHA<br>I<br>CHAN | PI<br>I<br>CHAN |
|---|---|---|---|---|---|
| 1 | 9.506202266412E+07 | 23743 | 21330 | 423 | 1447 |
| 2 | 9.506202266412E+07 | 28728 | 21990 | 25 | 98 |
| 3 | 9.506202527717E+07 | 28176 | 31623 | 25 | 97 |
| 4 | 9.506202527717E+07 | 29829 | 30841 | 327 | 1131 |
| 5 | 9.506202527717E+07 | 23686 | 19319 | 541 | 1854 |
| 6 | 9.506203046611E+07 | 25510 | 32711 | 1810 | 6171 |
| 7 | 9.506203566620E+07 | 29814 | 28823 | 102 | 360 |
| 8 | 9.506203826626E+07 | 26635 | 30601 | 2062 | 7028 |
| 9 | 9.506204346625E+07 | 26429 | 20314 | 443 | 1519 |
| 10 | 9.506204606629E+07 | 20691 | 28728 | 1608 | 5471 |
| 11 | 9.506204606629E+07 | 27989 | 29777 | 202 | 700 |
| 12 | 9.506204606629E+07 | 21937 | 25667 | 117 | 402 |
| 13 | 9.506204866632E+07 | 28132 | 32491 | 462 | 1589 |
| 14 | 9.506204866632E+07 | 27204 | 29741 | 904 | 3095 |
| 15 | 9.506205126638E+07 | 22124 | 20257 | 290 | 994 |
| 16 | 9.506205906643E+07 | 23193 | 18795 | 1398 | 4771 |
| 17 | 9.506206166646E+07 | 23224 | 19326 | 276 | 950 |

# Another property of electromagnetic radiation: Polarization

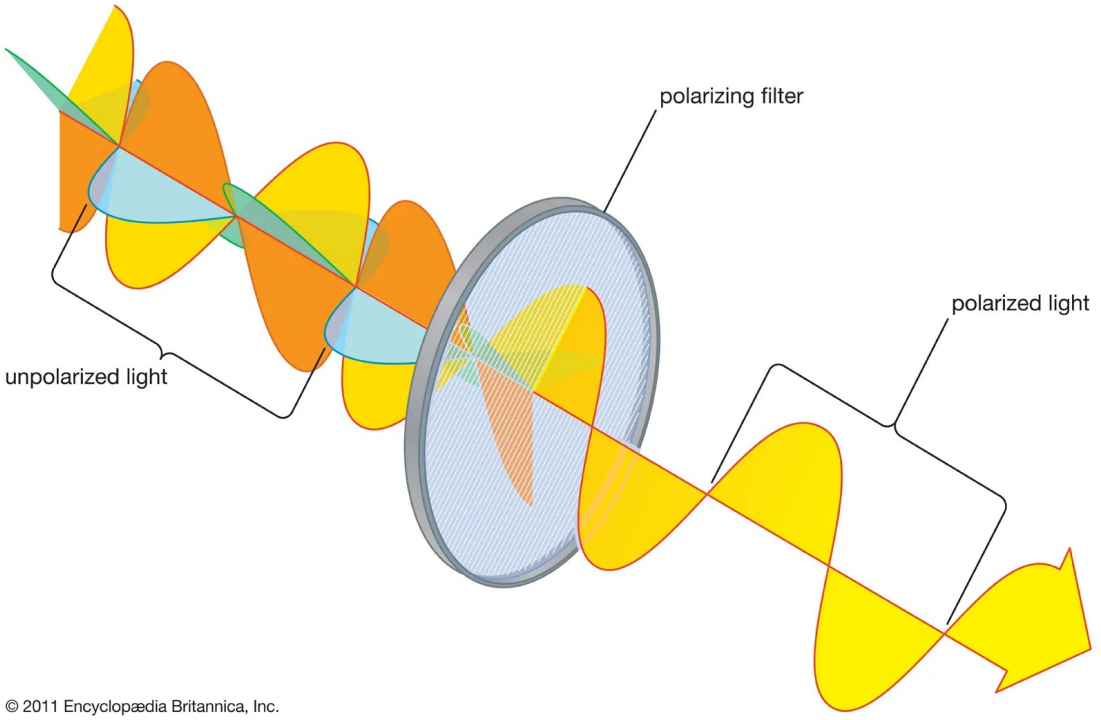



Figure from Encyclopædia Britannica

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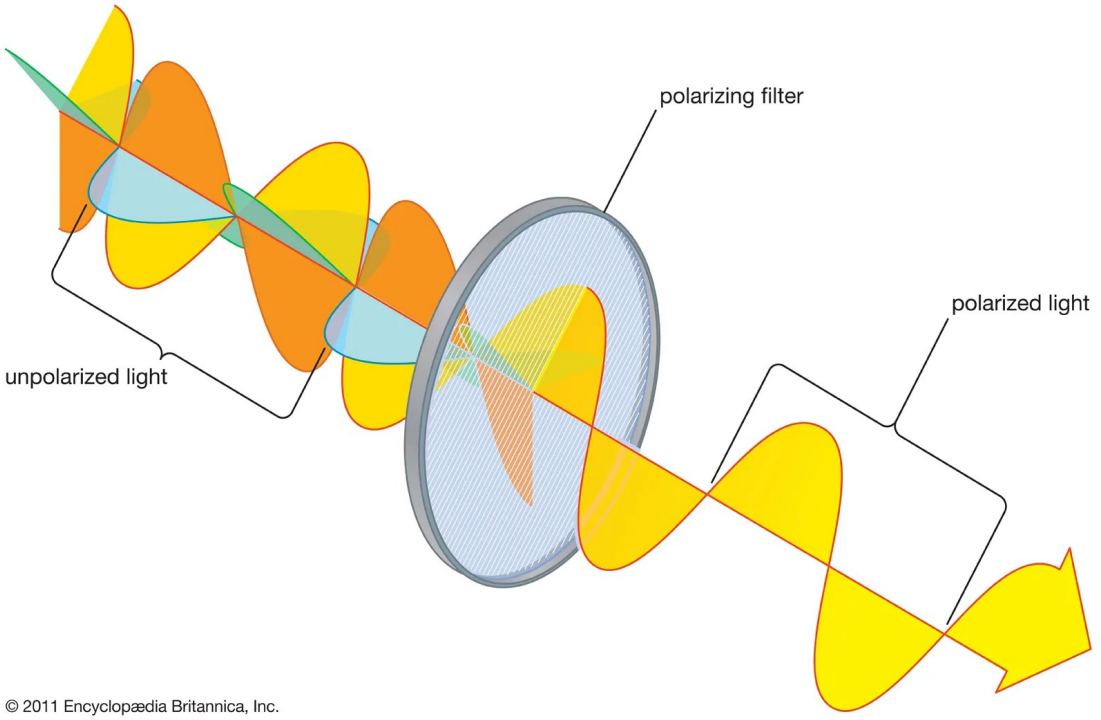


But should we care about measuring it?

Figure from Encyclopædia Britannica

# An example: Emission models of pulsars

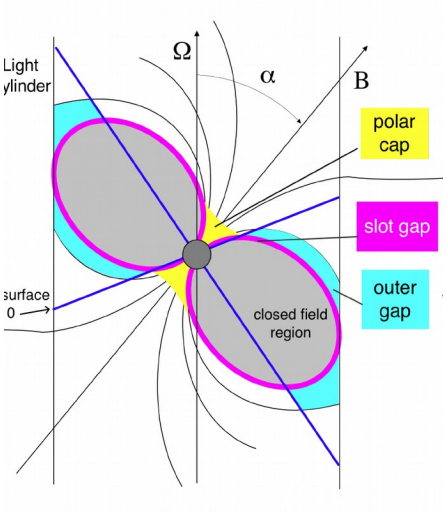


Figure from A K Harding

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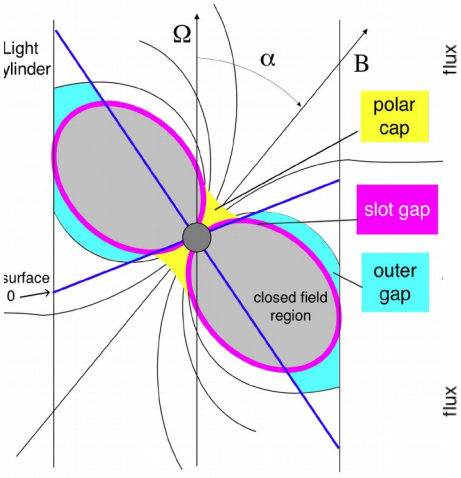
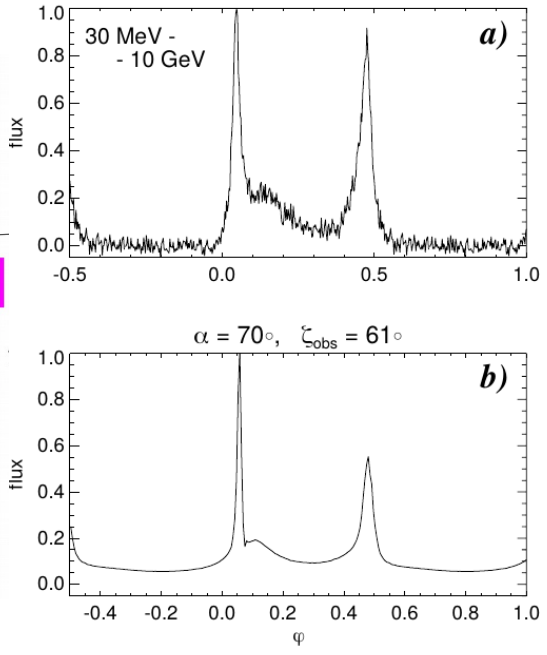


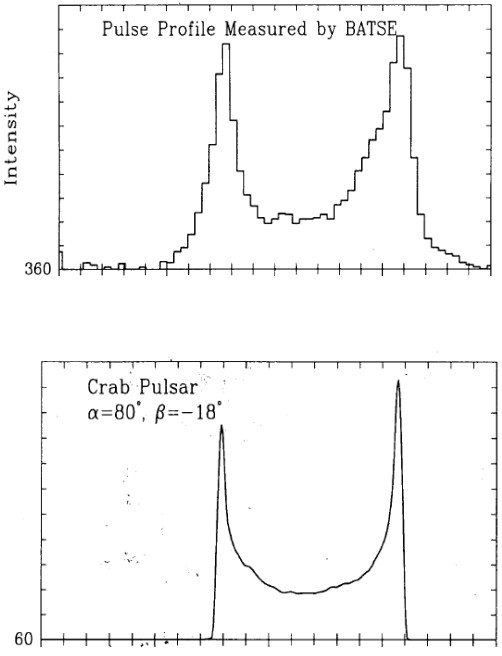

Figure from A K Harding

## Two-pole Caustic



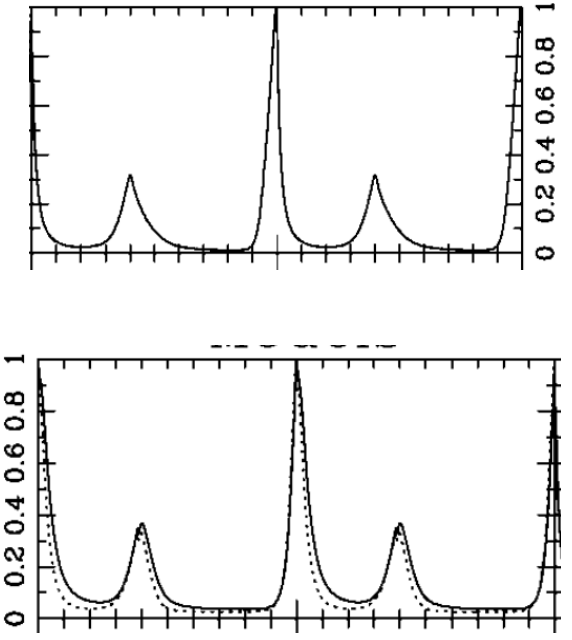

Dyks et al. (2003)

## Outer Gap




Romani et al. (1995)

## Striped wind



Petri & Kirk (2005)

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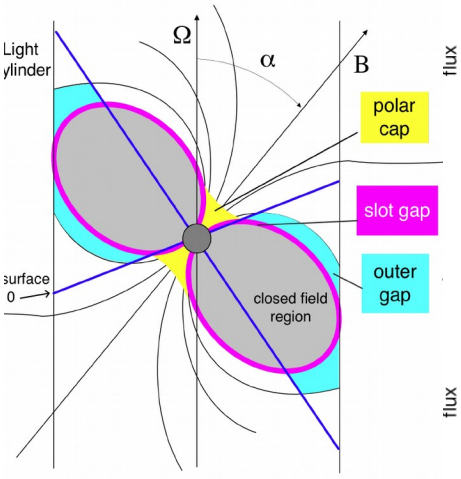


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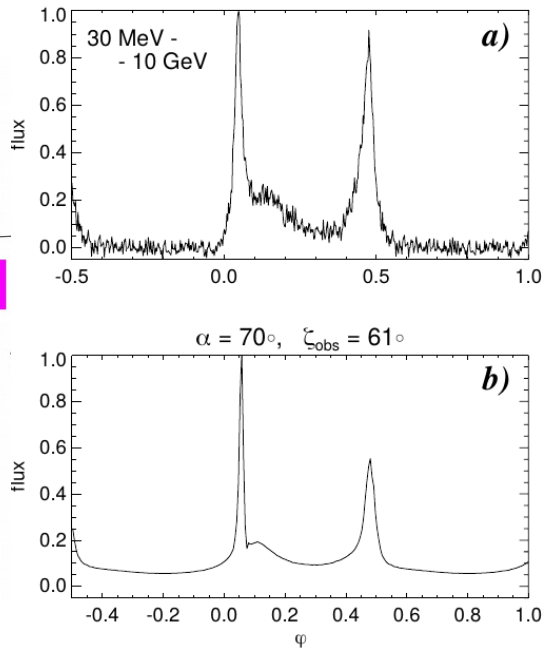


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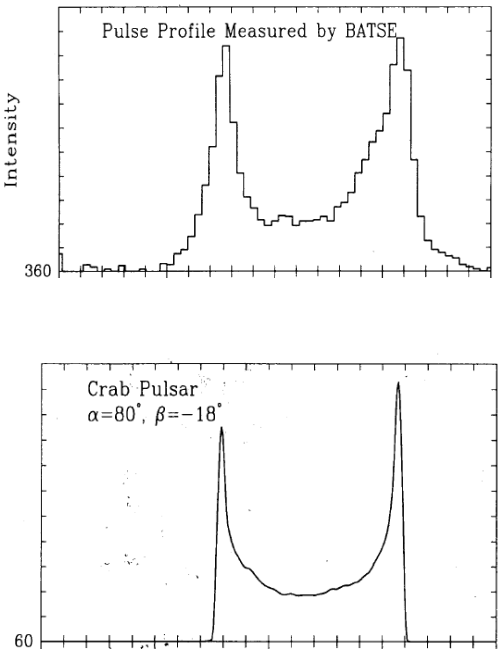


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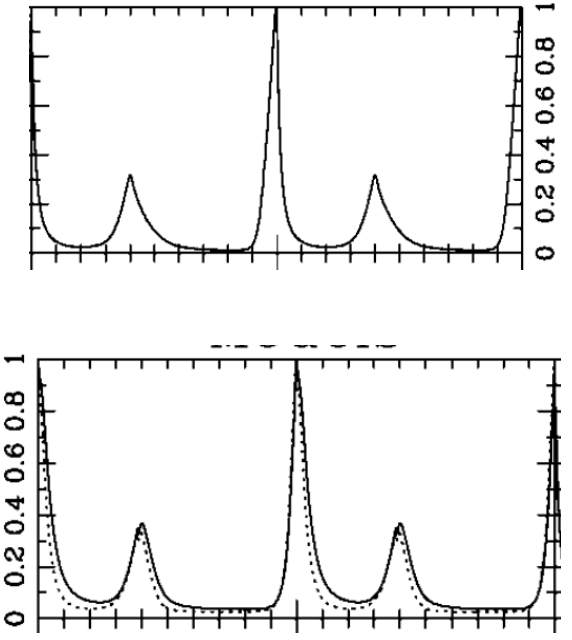
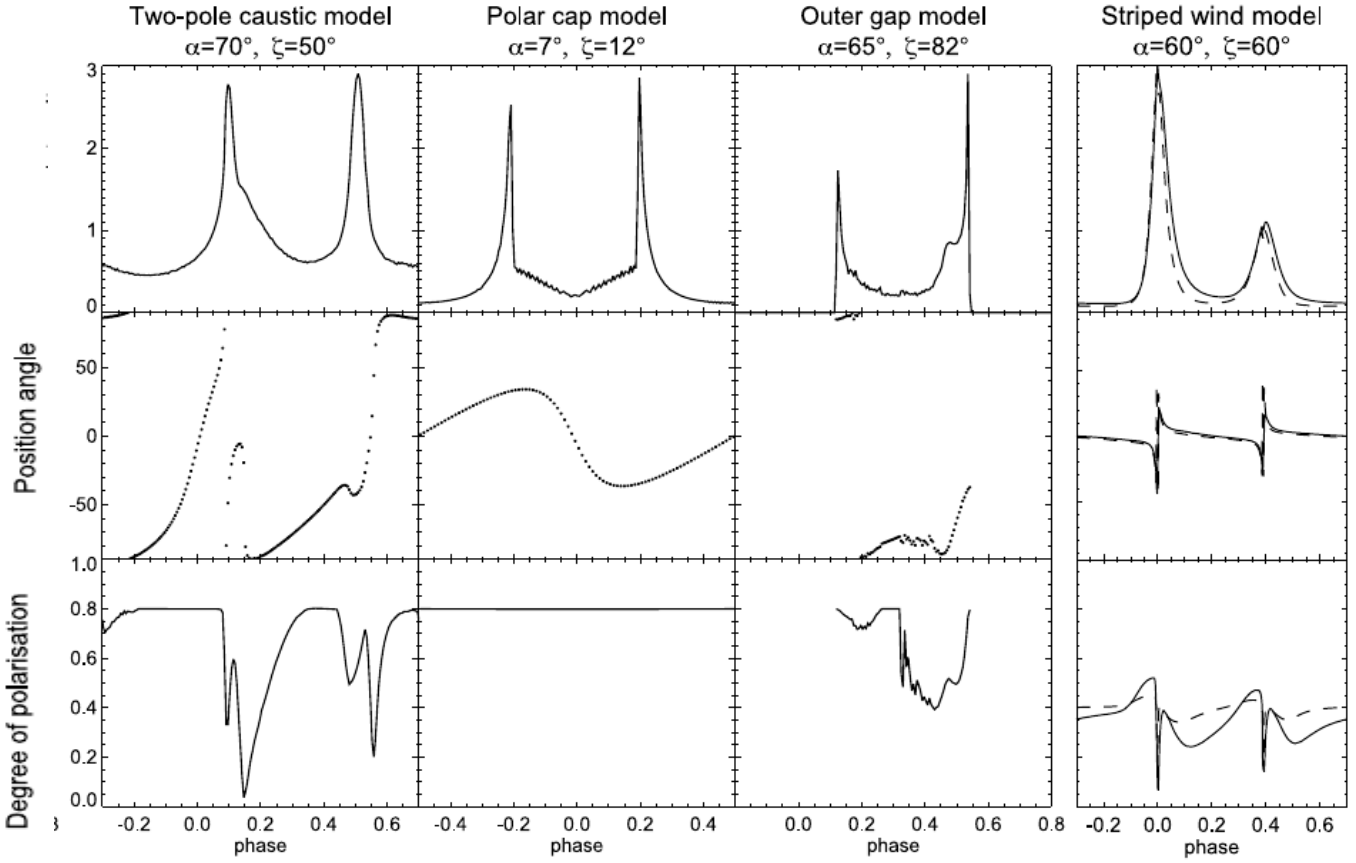


Petri & Kirk (2005)

All models are able to predict the observed pulse profiles to a great extent

# An example: Emission models of pulsars




Dyks et al. (2004), Petri &Kirk (2005)

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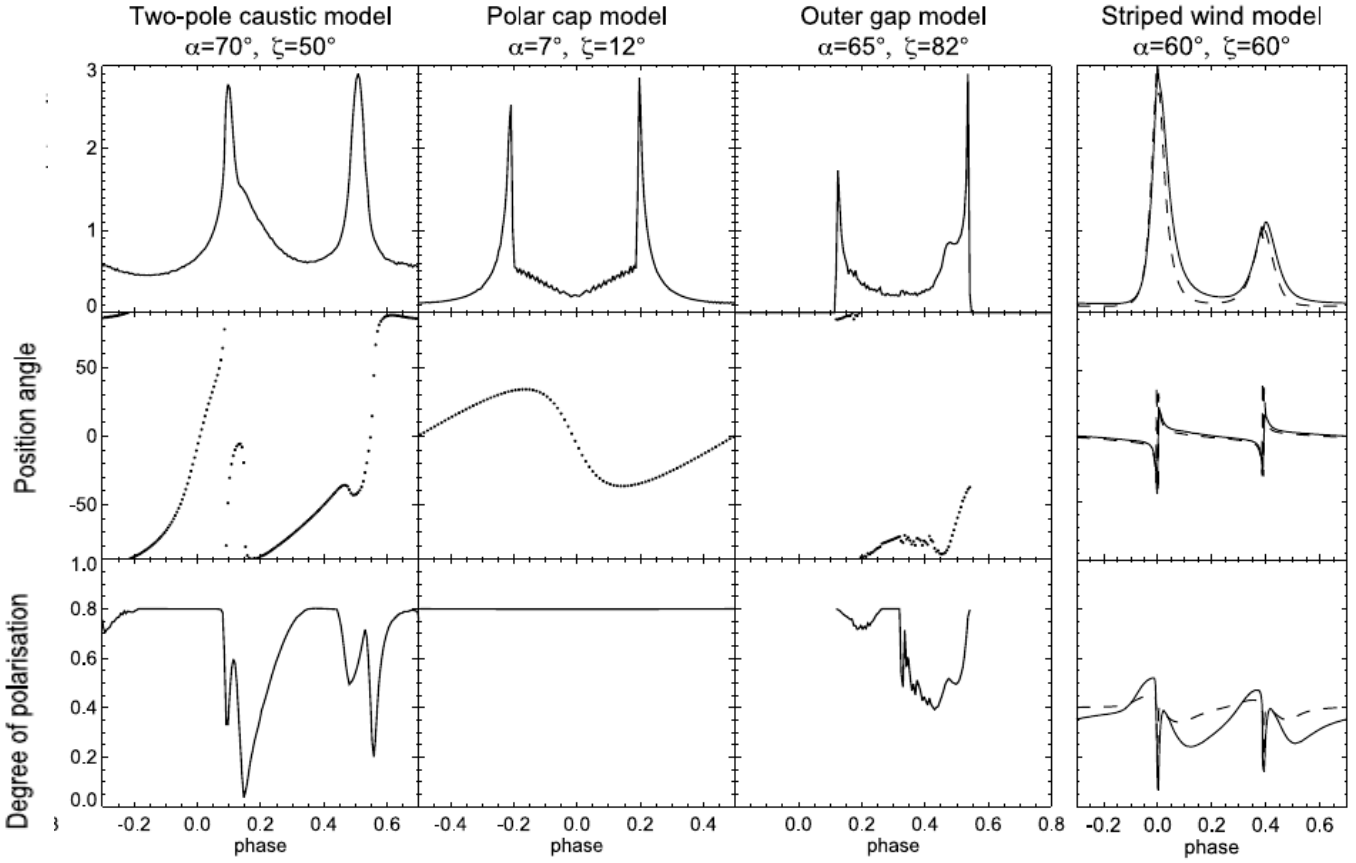


Dyks et al. (2004), Petri &Kirk (2005)

Phase-resolved polarization measurements to potentially break the degeneracy

# Science case for polarimetry

Pulsars was just an example – several cases for polarimetric observations in X-rays

Black-hole binaries and AGNs
Magnetars
Gamma Ray Bursts
The Sun!
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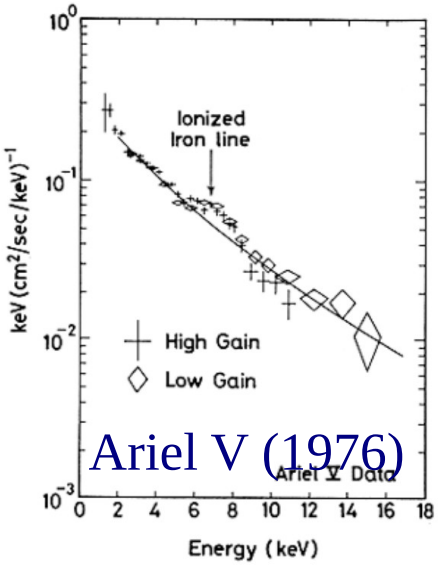
If it is so important, shouldn’t there be significant advances by now?

# Advances in X-ray Spectroscopy and Polarimetry in 40+ years!

Hot gas in Perseus Cluster




Ariel V (1976)

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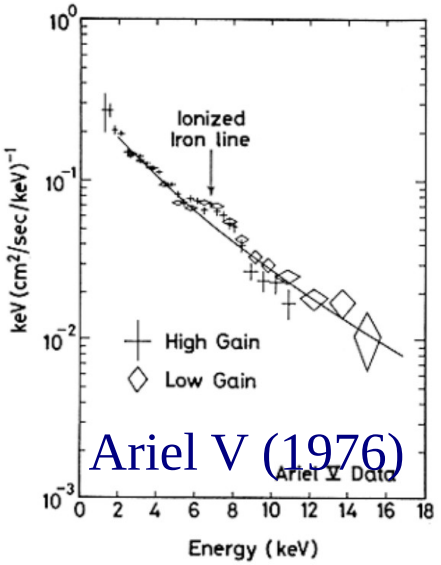


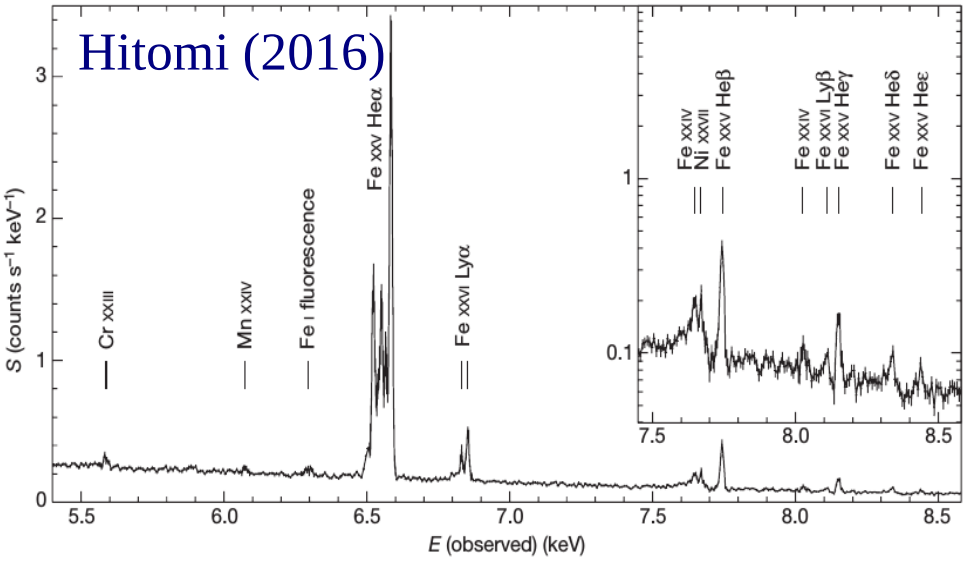

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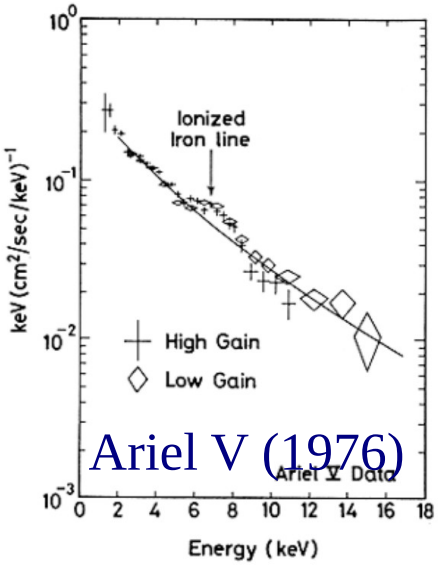


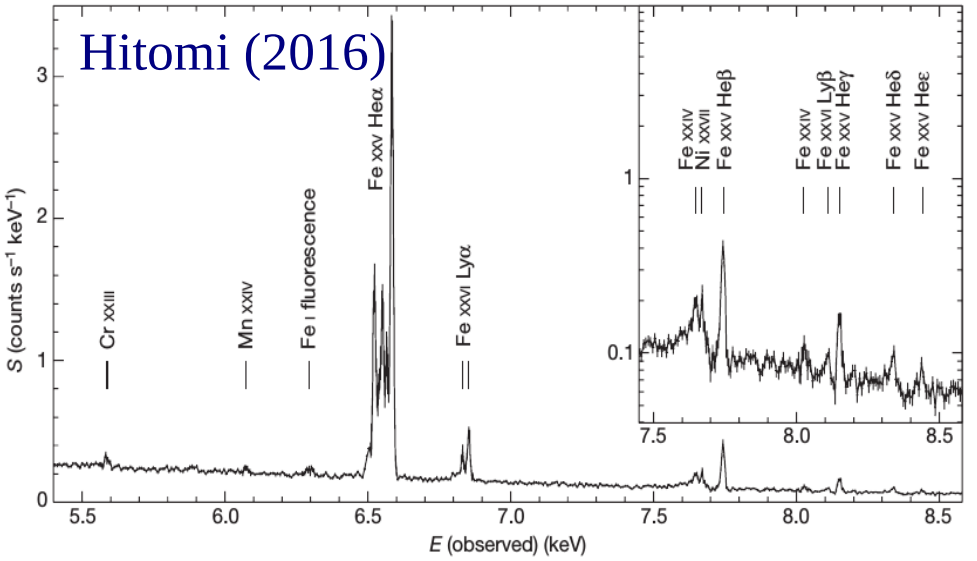


In comparison: First X-ray polarization measurement in 1978 and it was this year (2022) a dedicated X-ray polarimeter (in 2-8 keV) that has made some increase in number of sources with polarization measurement in X-ray energies

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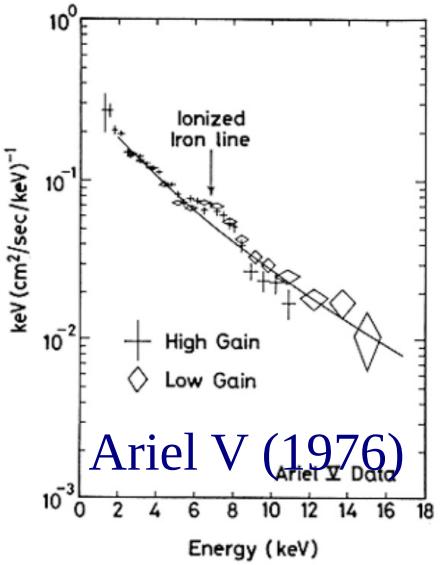


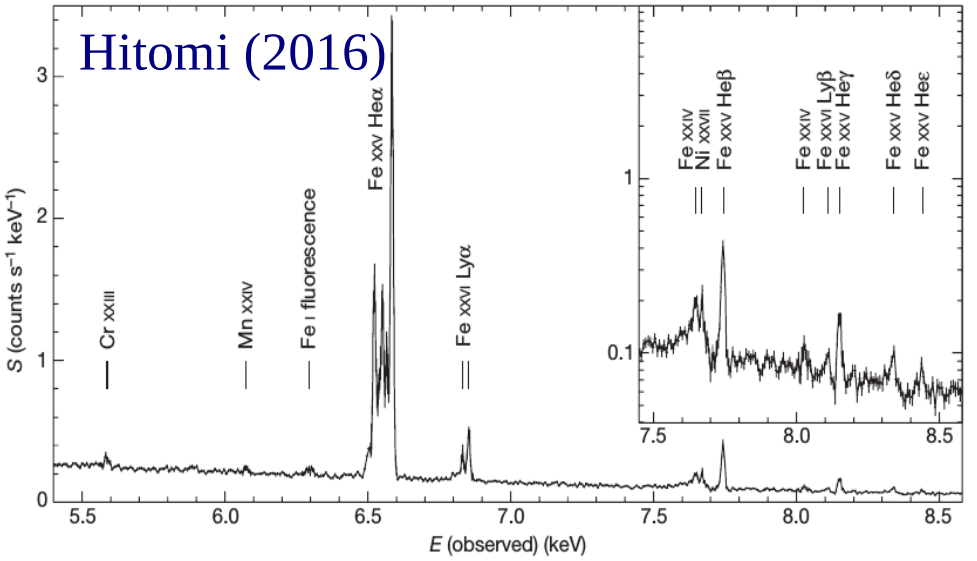


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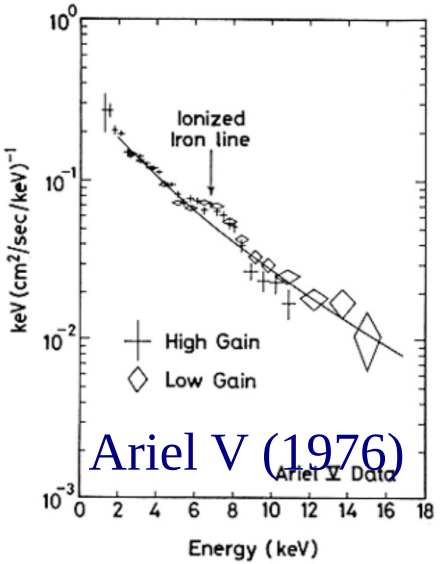


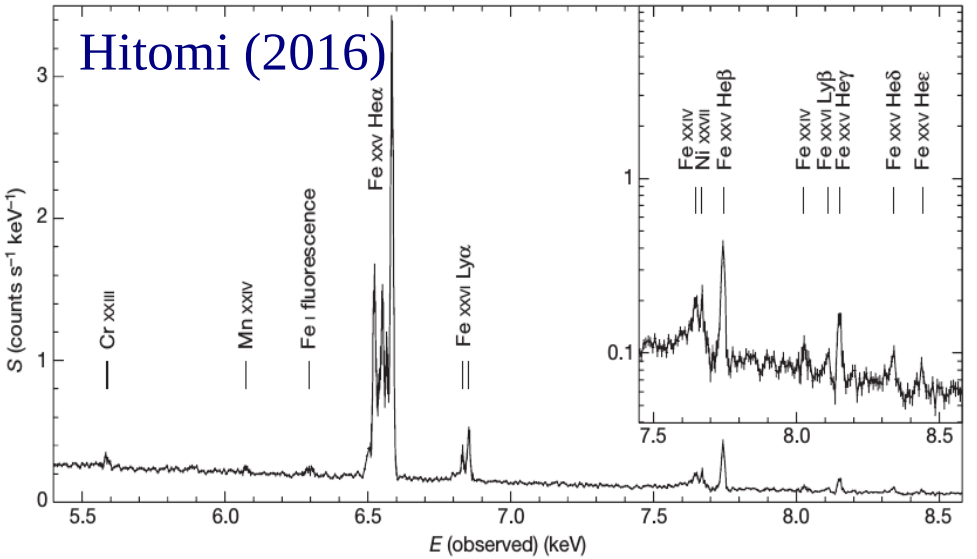


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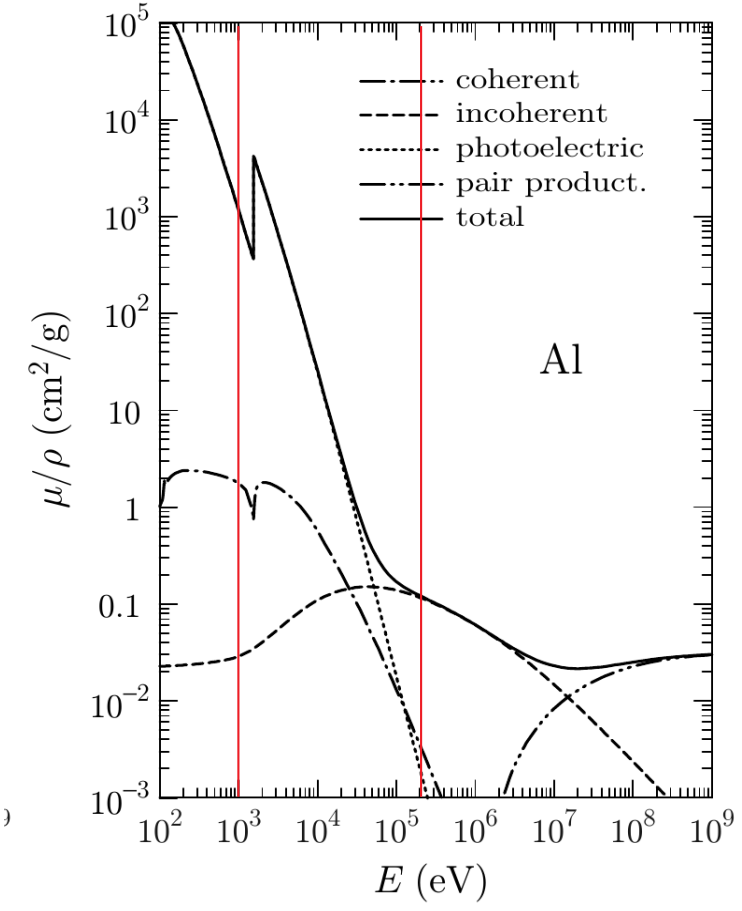
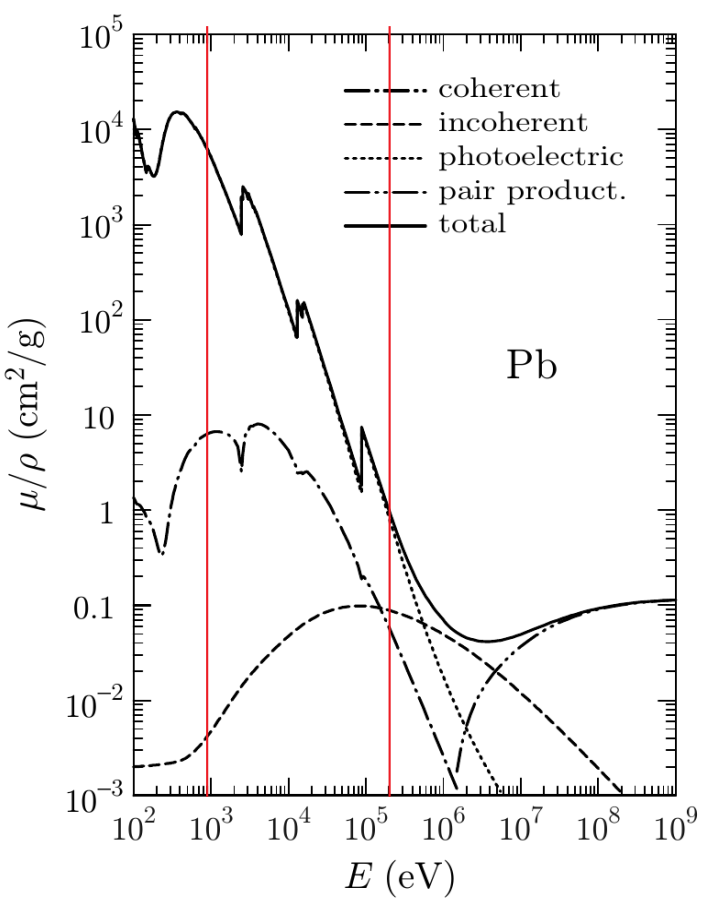
How do measure polarization?

# Interaction of photon with matter



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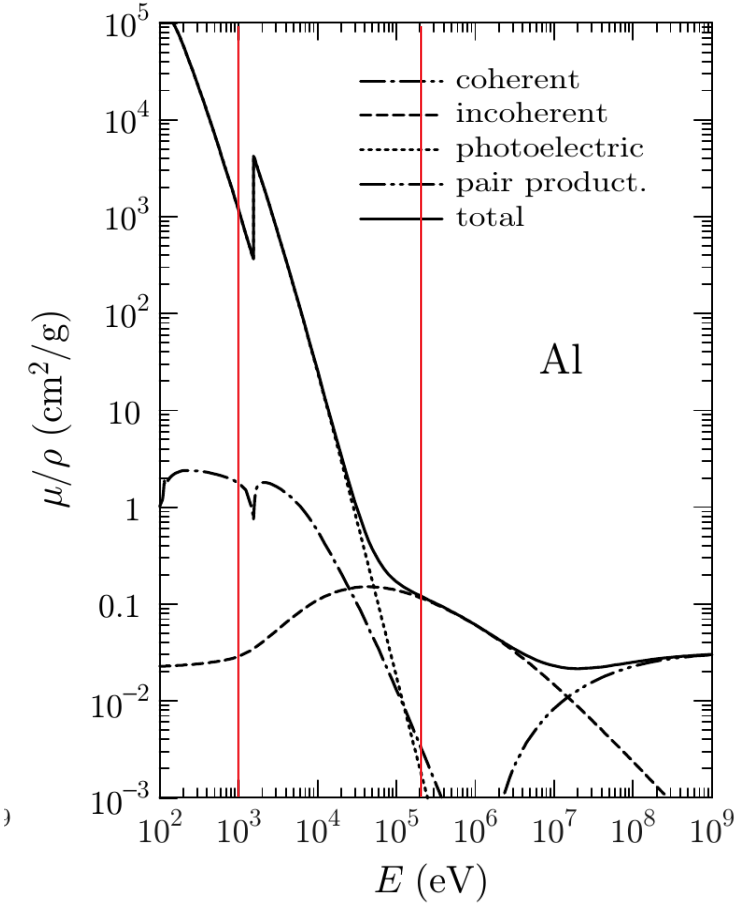


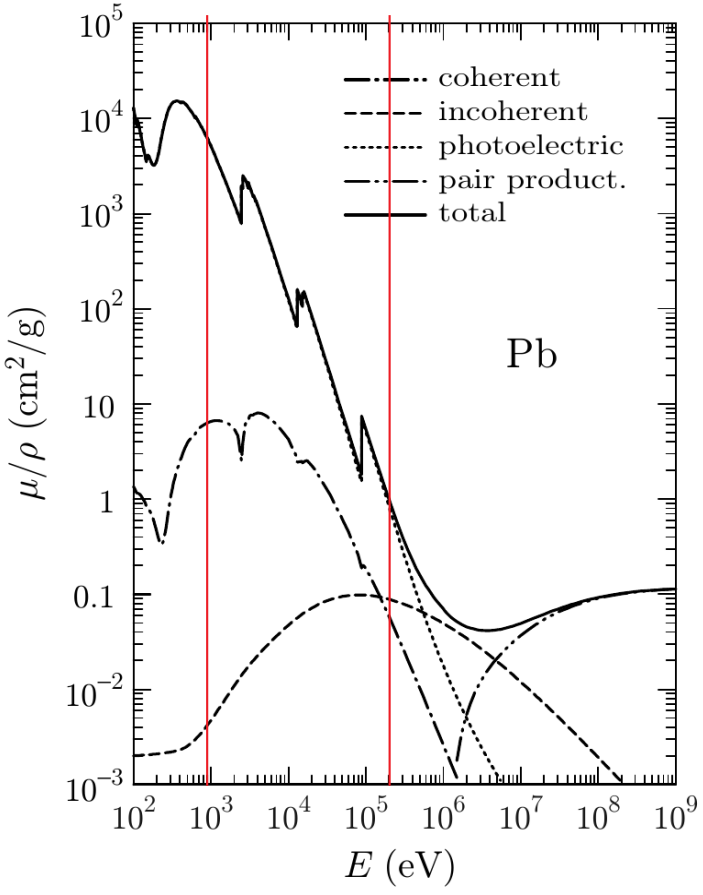


Energy depositions/total attenutation in materials: Not dependant on polarization

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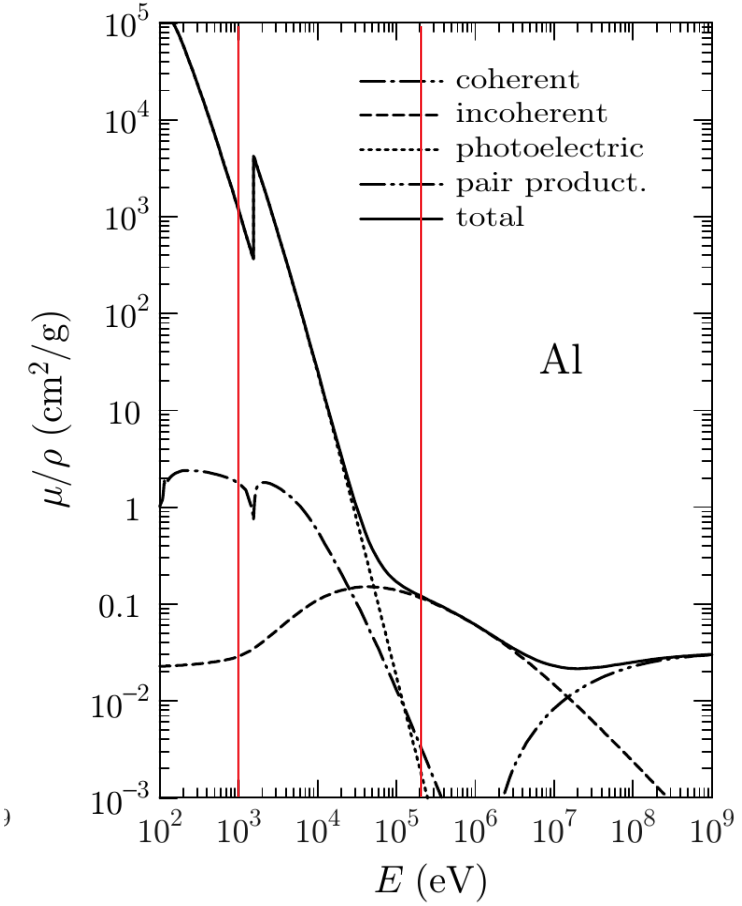
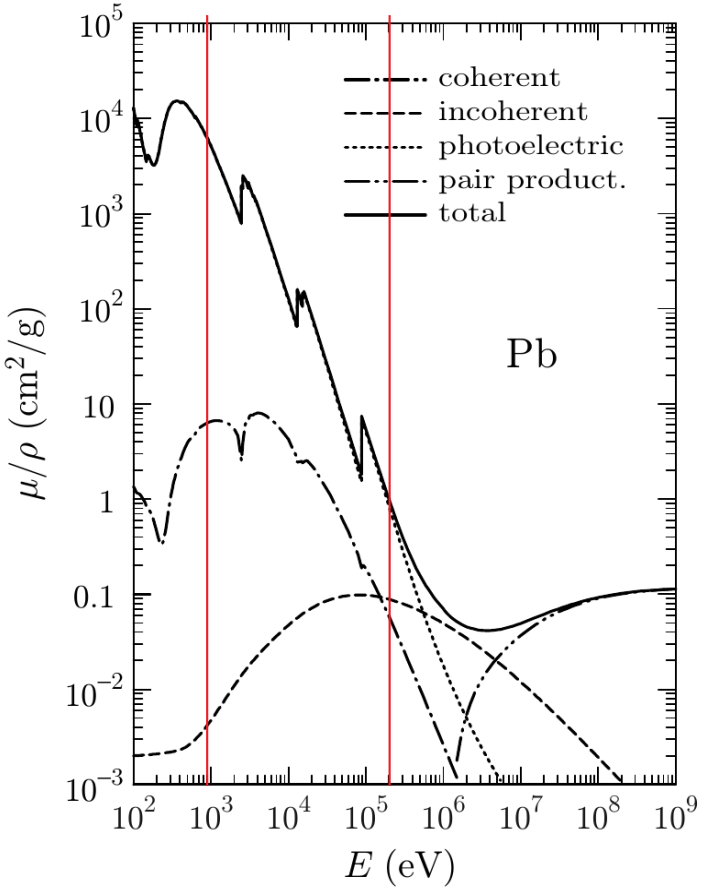
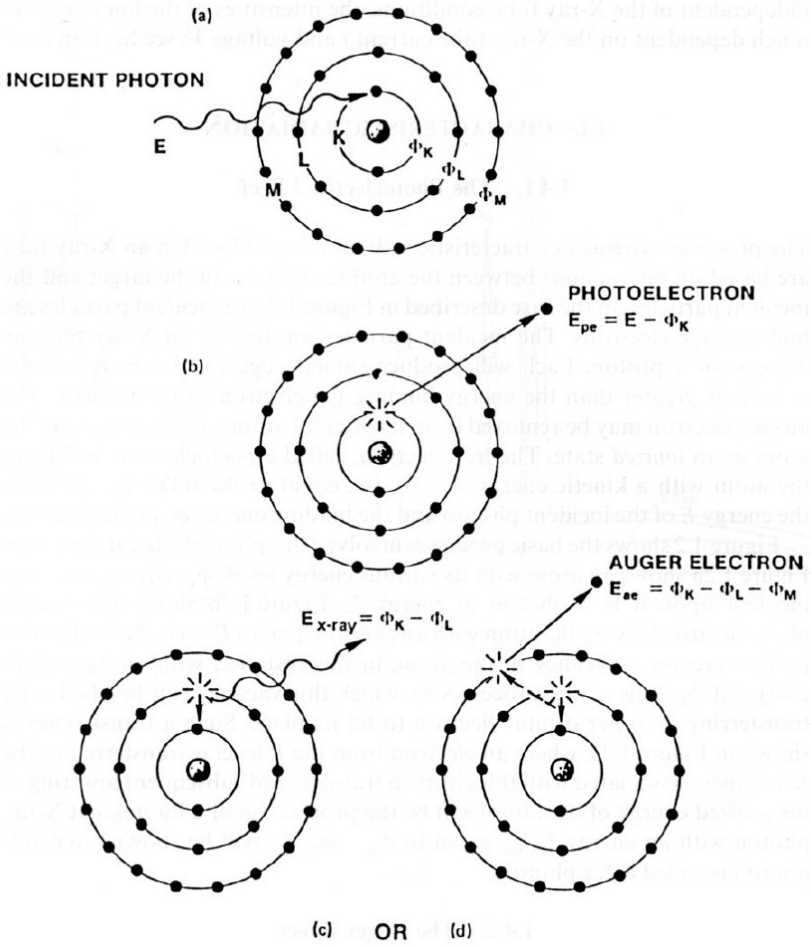



Energy depositions/total attenutation in materials: Not dependant on polarization

We need to go into the differential cross sections of the interaction

# Photoelectric interaction



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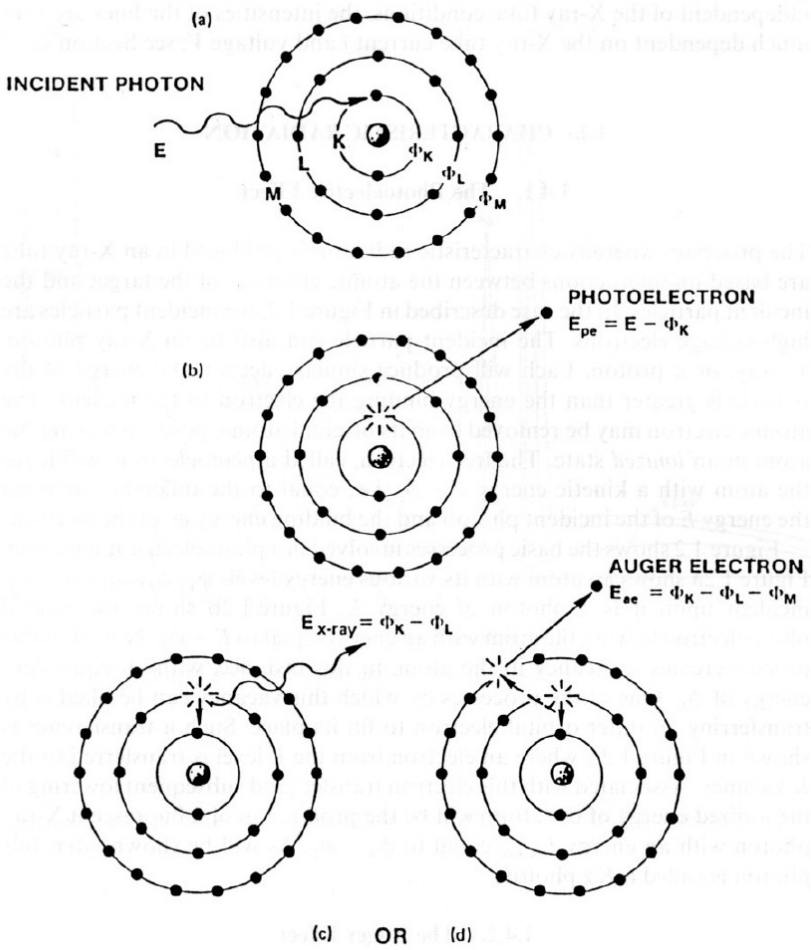
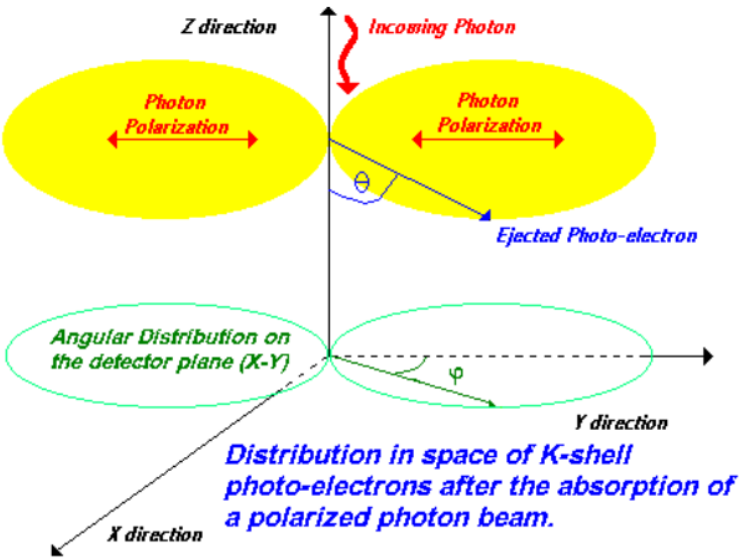
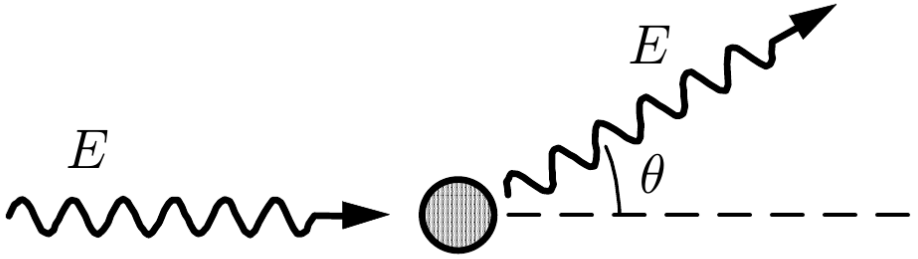


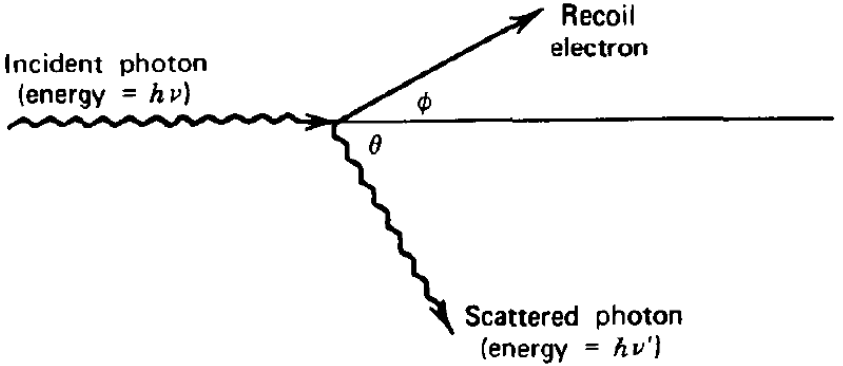

$$\frac{\partial\sigma}{\partial\Omega} = r_0^{\,2}\,\frac{Z^5}{137^4}\left(\frac{mc^2}{h\nu}\right)^{7/2}\frac{4\sqrt{2}\sin^2(\theta)\cos^2(\varphi)}{(1-\beta\cos(\theta))^4},$$




Costa et al (2002)

# Rayleigh and Compton Scattering




$$d\sigma = r_e^2 (1 - \sin^2\theta \cos^2\varphi) d\theta d\varphi$$

$$\frac{d\sigma}{d\Omega} = \frac{r_0^2}{2}\left(\frac{E'}{E}\right)^2\left(\frac{E'}{E} + \frac{E}{E'} - 2\sin^2\theta\cos^2\phi\right)$$

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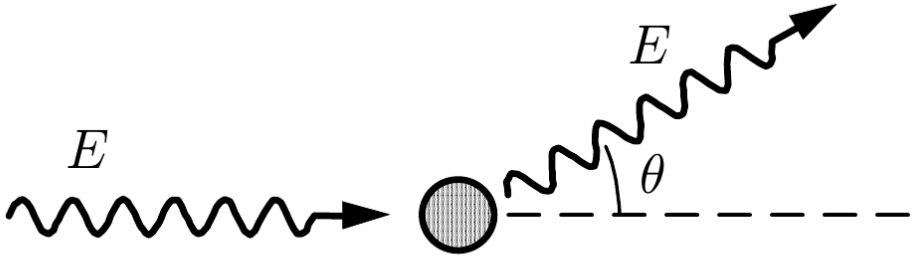


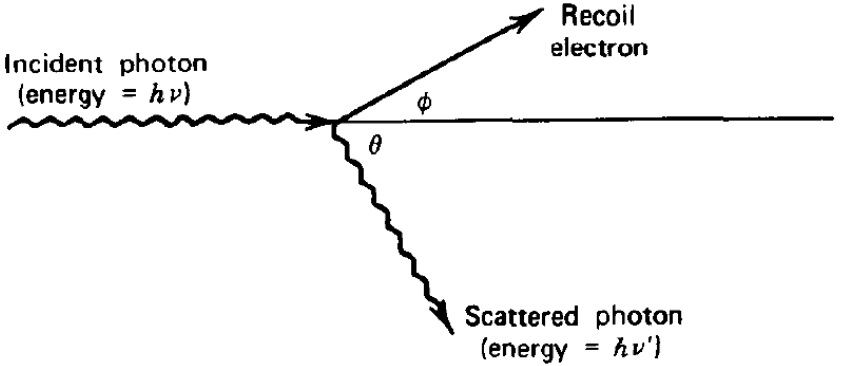


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Thomson scattering cross section and Klein Nishina cross section for free electrons

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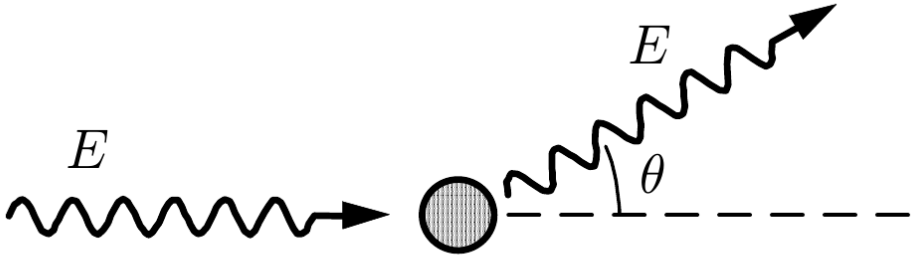


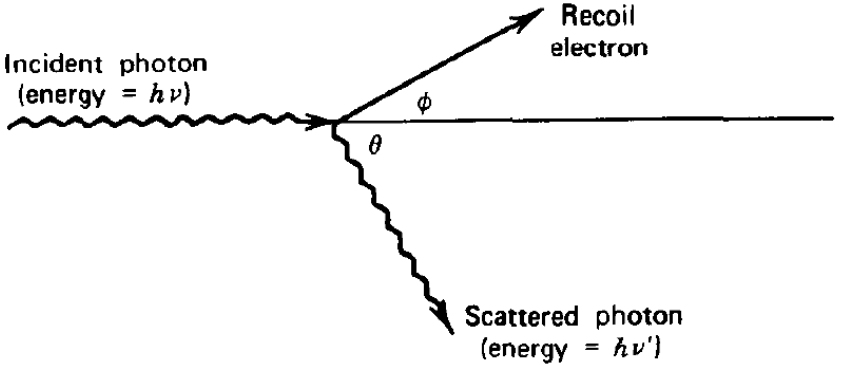


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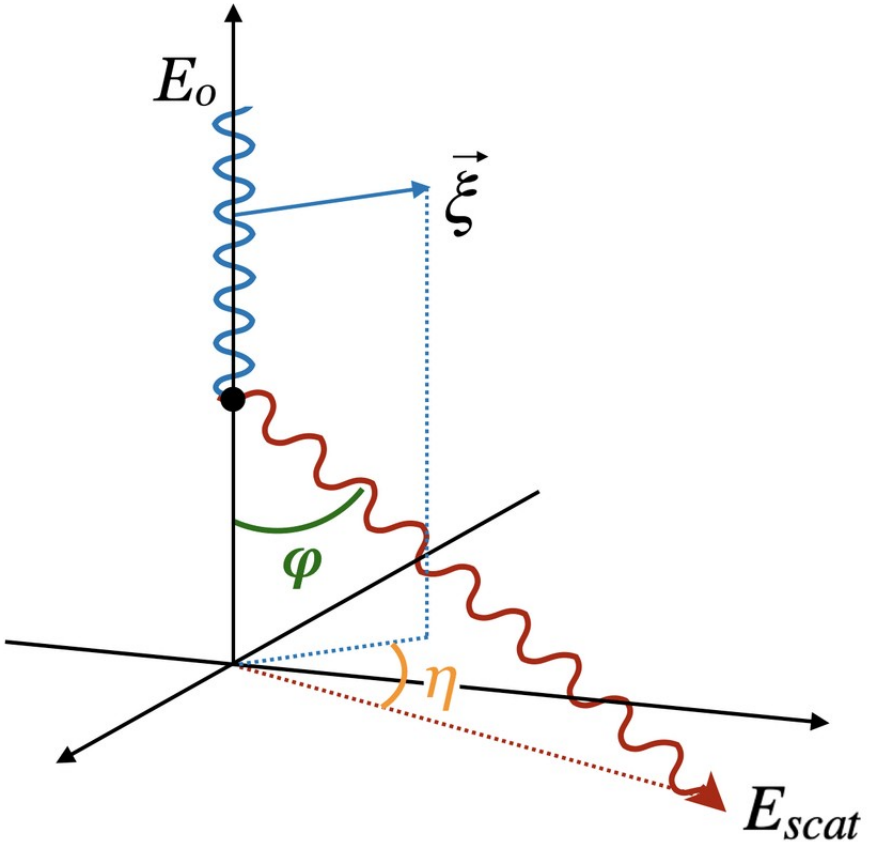
Thomson scattering cross section and Klein Nishina cross section for free electrons

Modified cross sections for bound electrons in atoms: But dependance on azimuthal angle remains the same

# Rayleigh and Compton Scattering




Keirans et al (2022)

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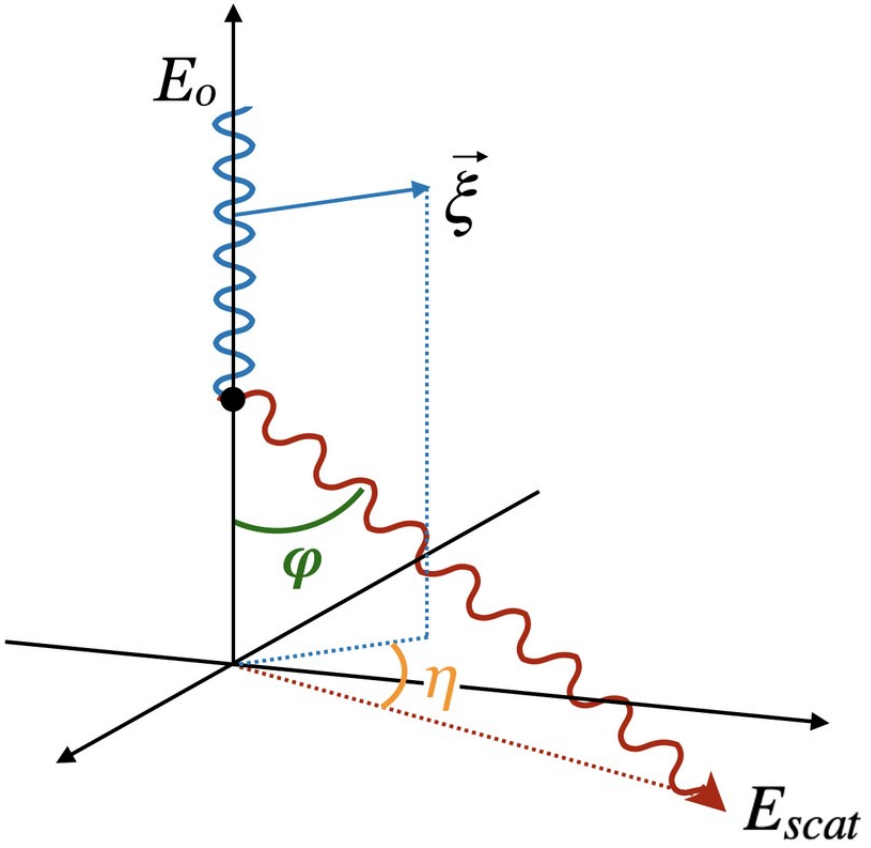
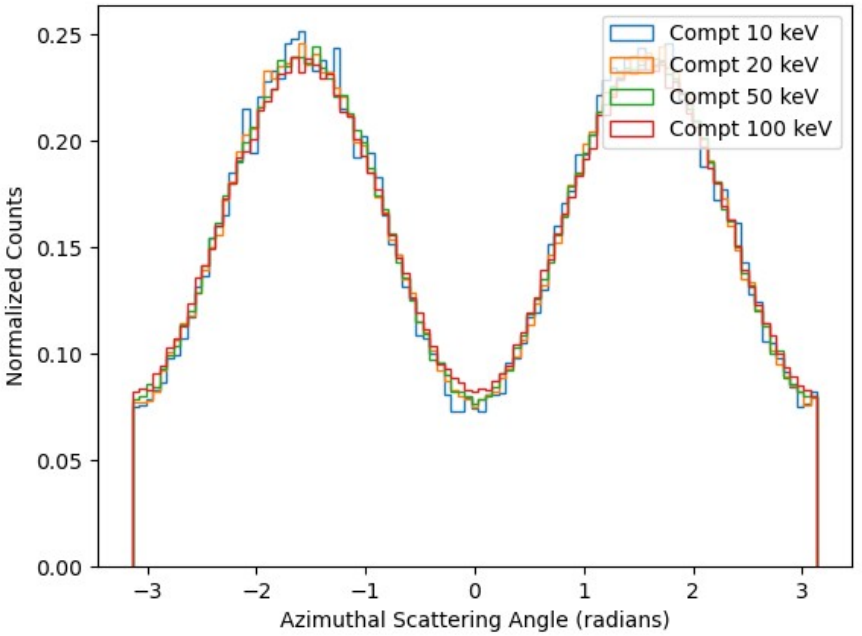



Keirans et al (2022)

One more technique: Bragg reflection – limited to very narrow energy range

# Obtaining polarization fraction from azimuthal angle distributions



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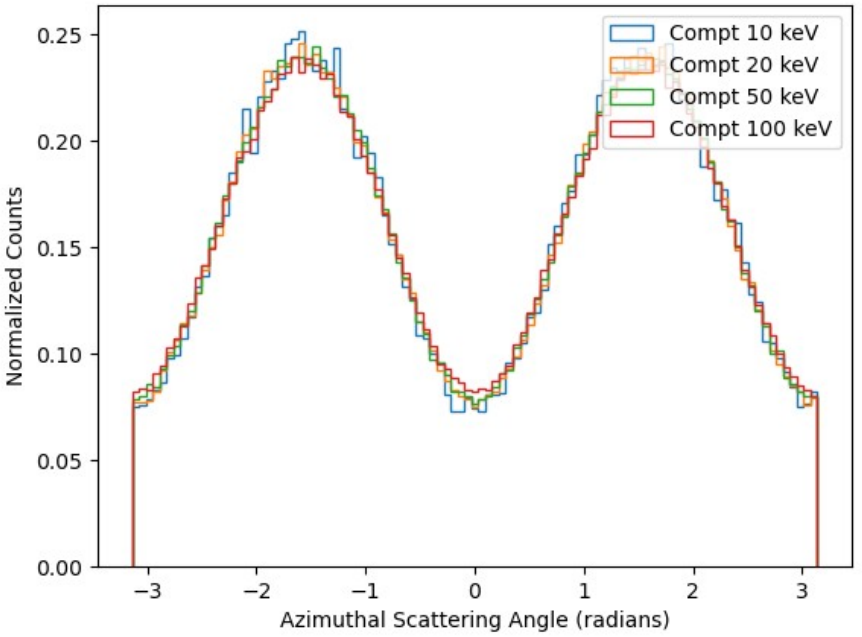


$$C(\varphi) = A\cos^2(\varphi - \varphi_0) + B$$

$$\mu = \frac{C_{\max} - C_{\min}}{C_{\max} + C_{\min}} \qquad P = \frac{\mu_P}{\mu_{100}}$$

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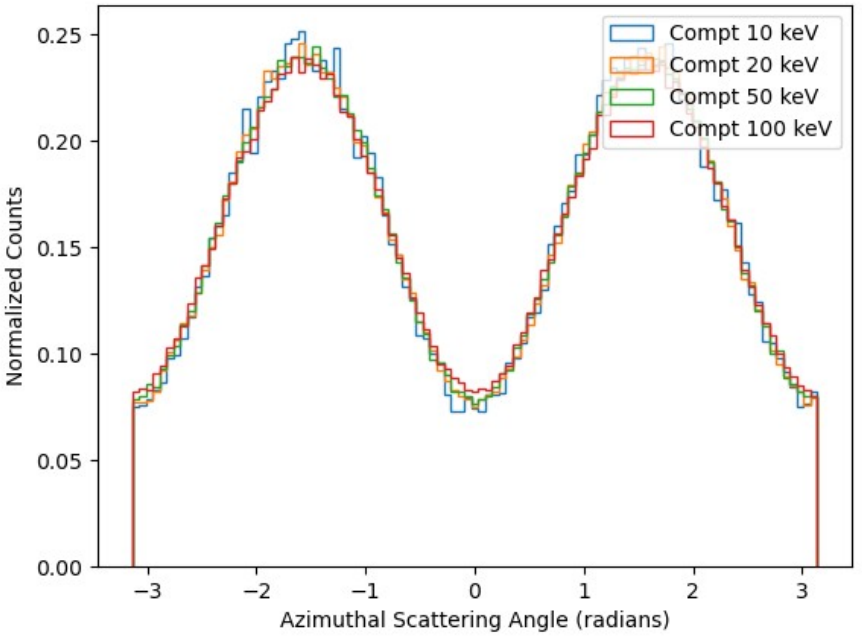


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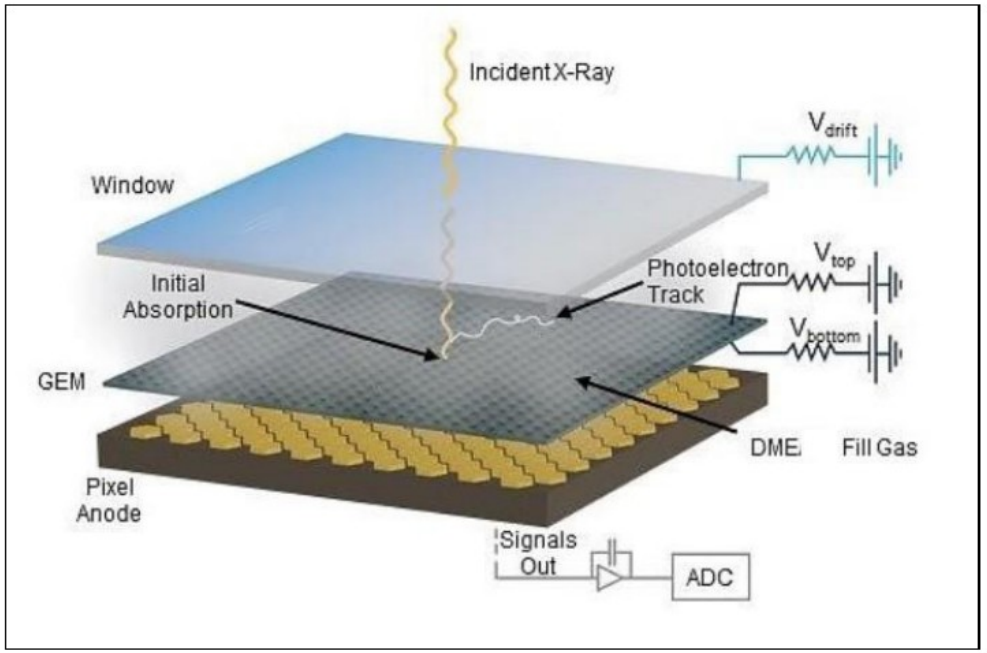
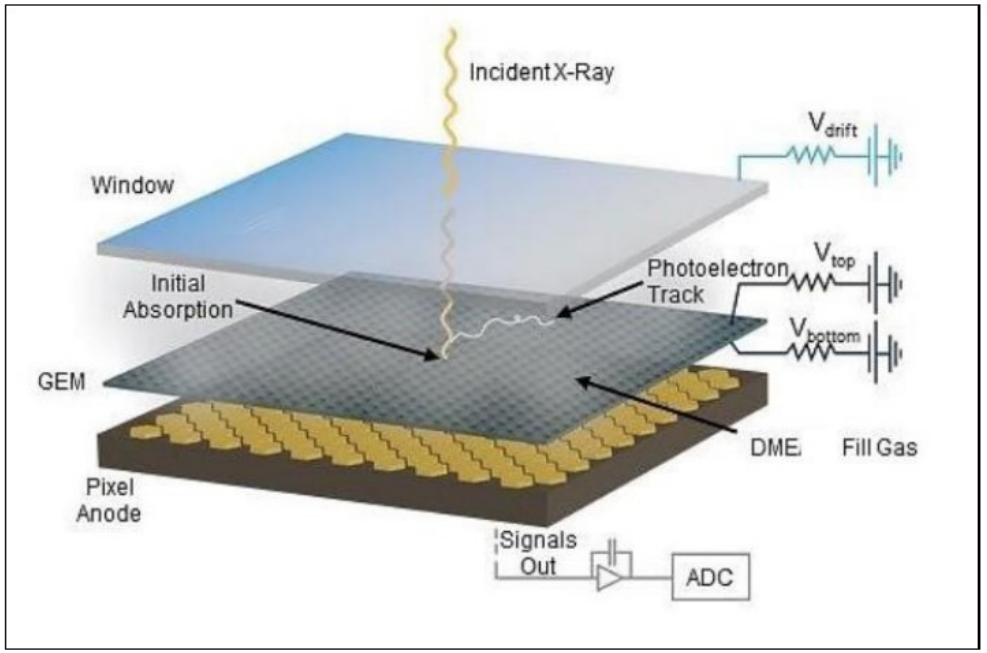
How to measure the azimuthal angle distribution of photo-electron or scattered photon?

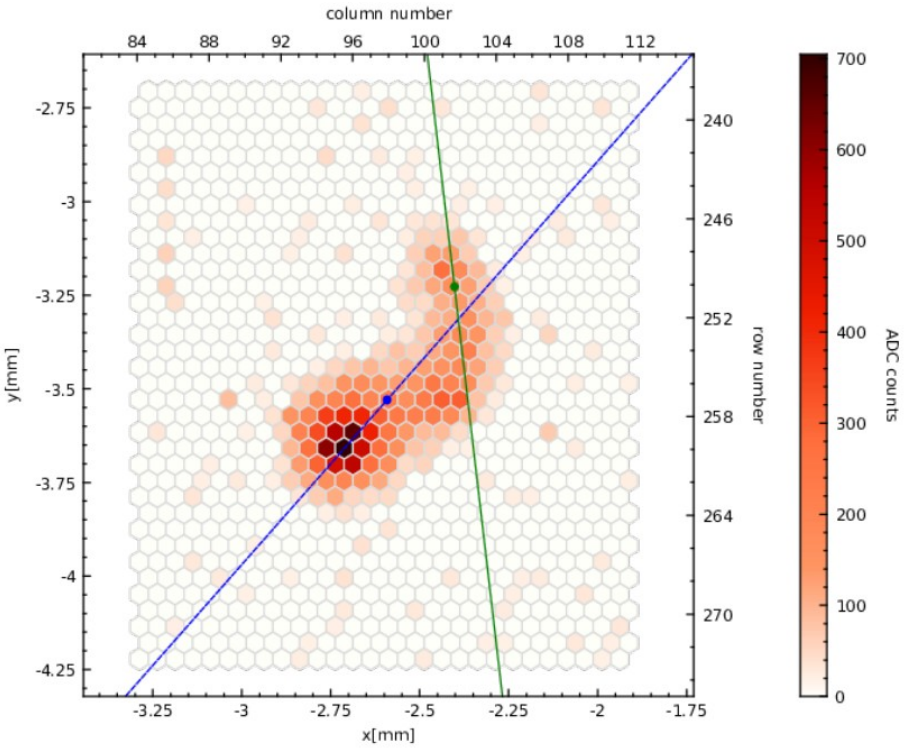
# Photo-electric polarimeters




Weisskopf et al (2022)

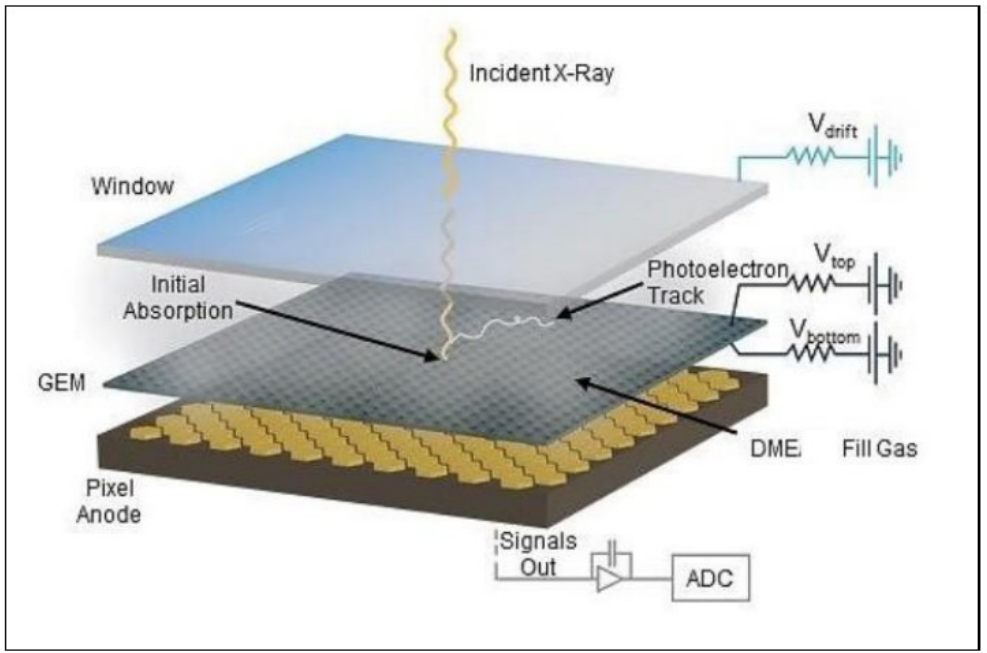
# Photo-electric polarimeters

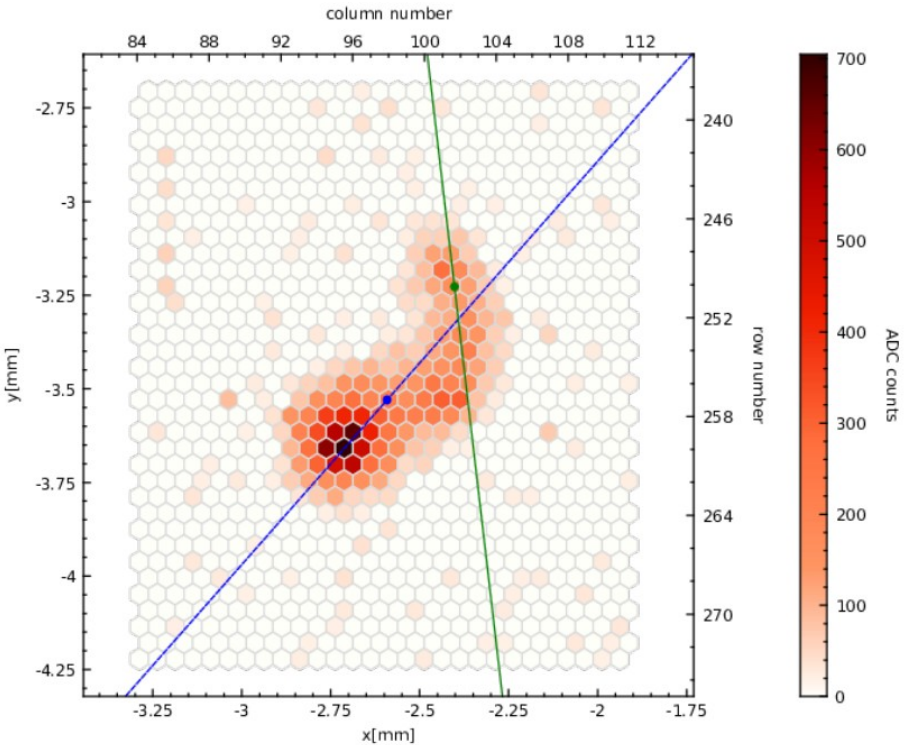



Weisskopf et al (2022)

# Photo-electric polarimeters



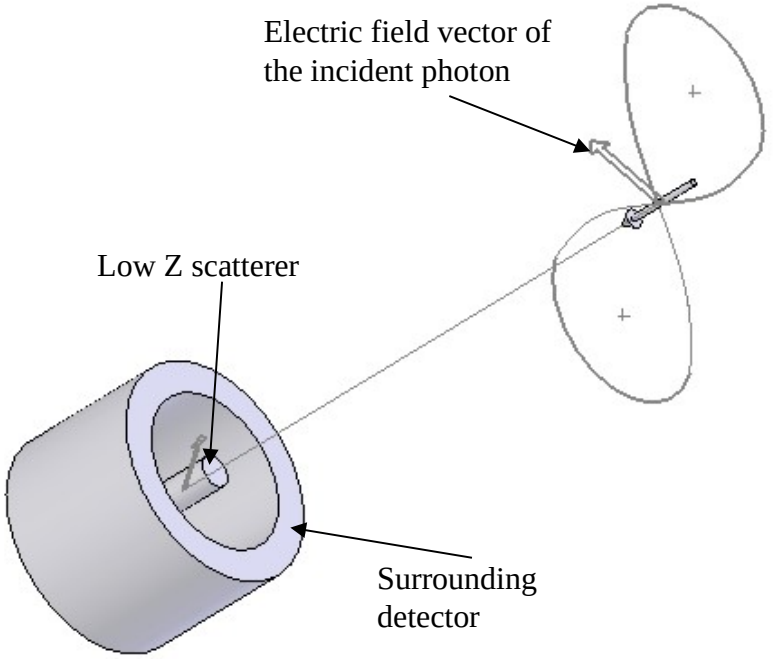




IXPE Detectors: Works at low energies, ie up to ~8 keV

Weisskopf et al (2022)

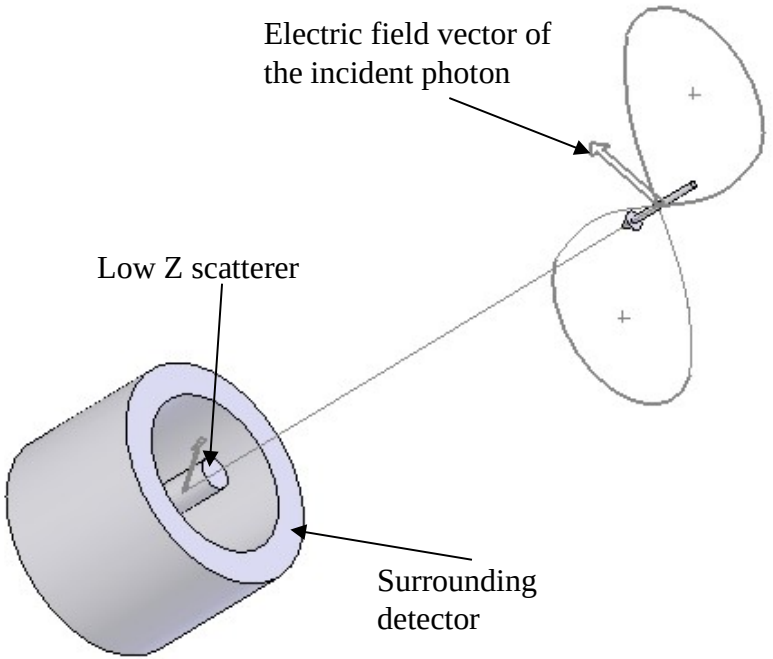
# Scattering polarimeters

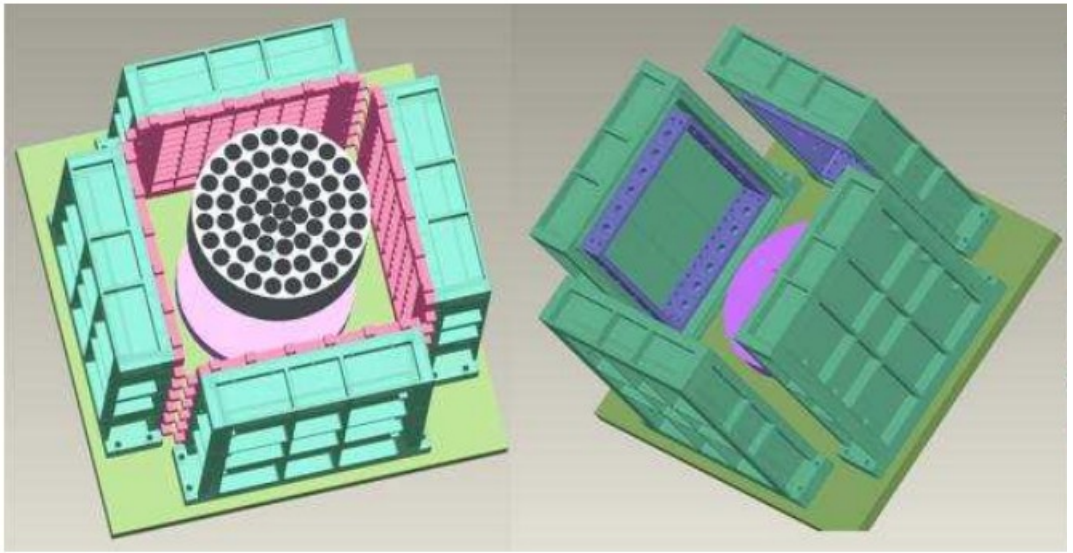
## An ideal polarimeter

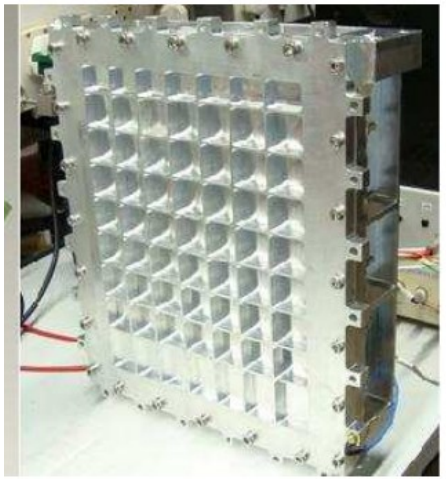


# Scattering polarimeters

## An ideal polarimeter



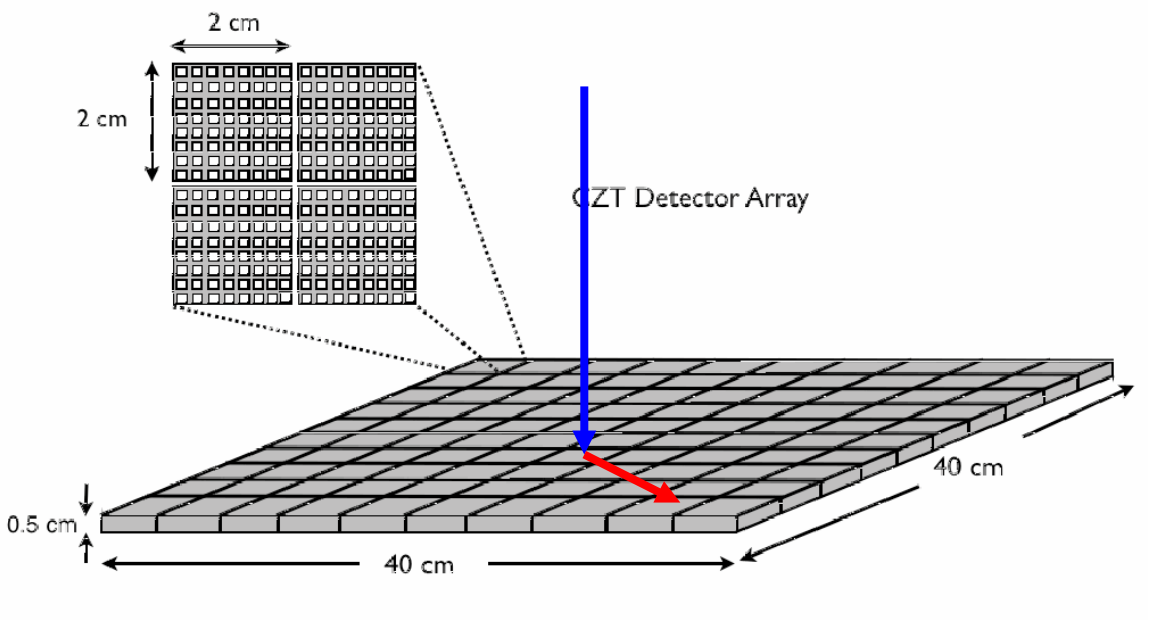


**POLIX: Rayleigh Scattering with Be scatterer**

**8-30 keV**

Rishin et al (2010)

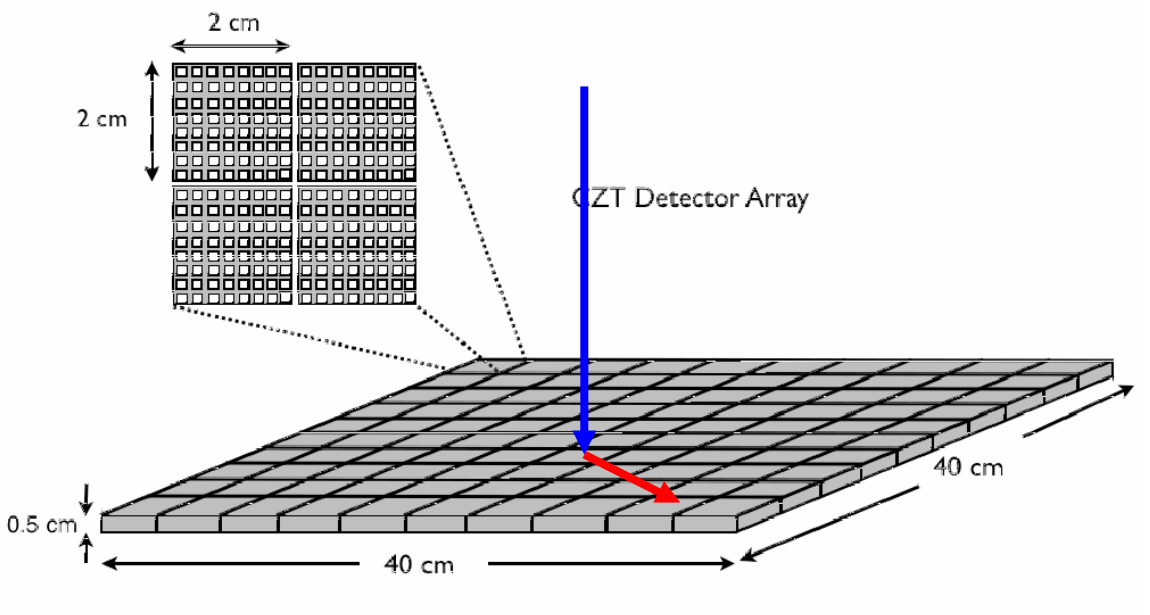
# Scattering polarimeters




AstroSat CZT-Imager: Compton

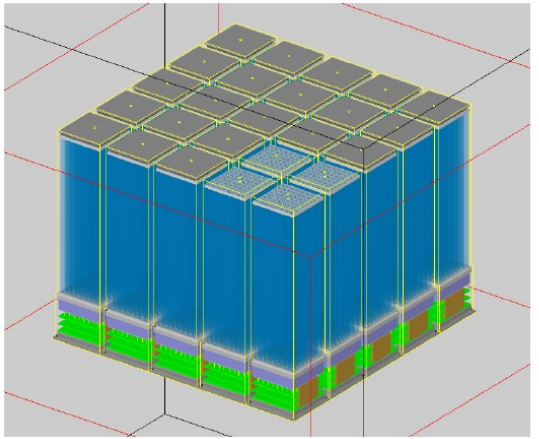
Above 100 keV

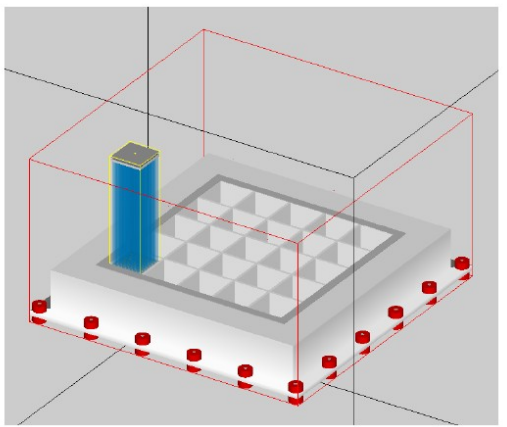
# Scattering polarimeters




AstroSat CZT-Imager: Compton

Above 100 keV

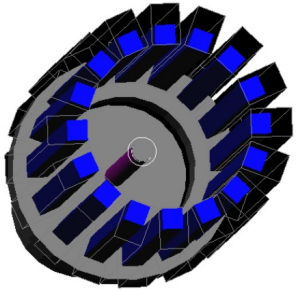


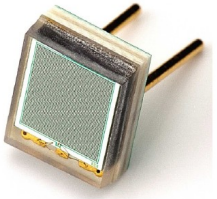


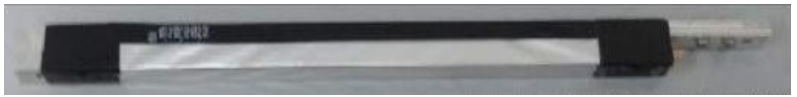
POLAR: Compton

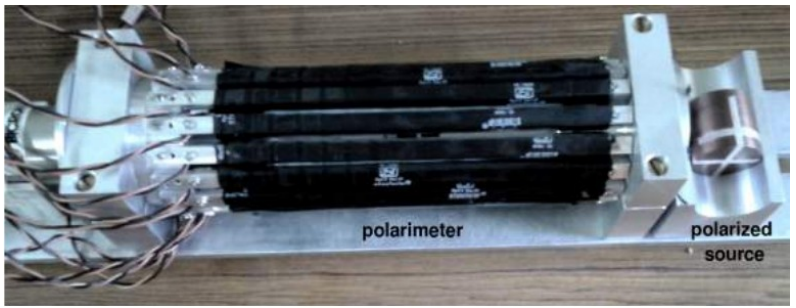
Li et al (2018)

# Scattering polarimeters: Compton polarimeter









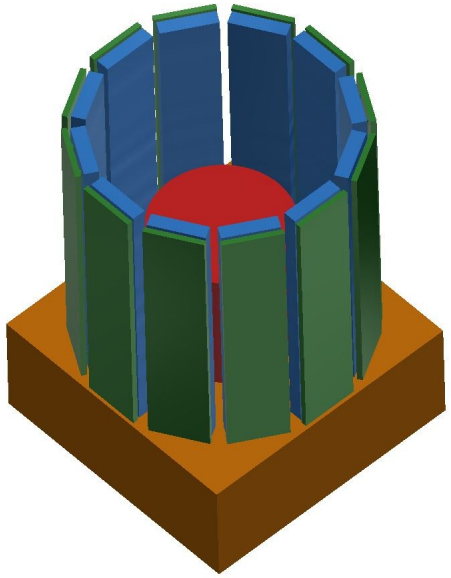

Plastic scintillator as scatterer

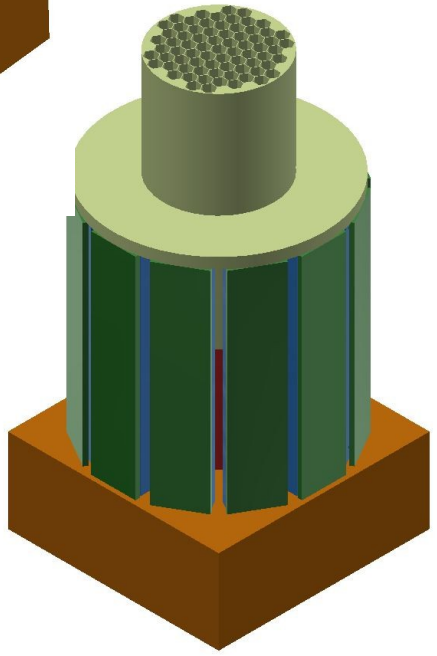
Csi/NaI scintillator read by SiPM as absorber

~20-200 keV

Chattopadhyay et al (2016)

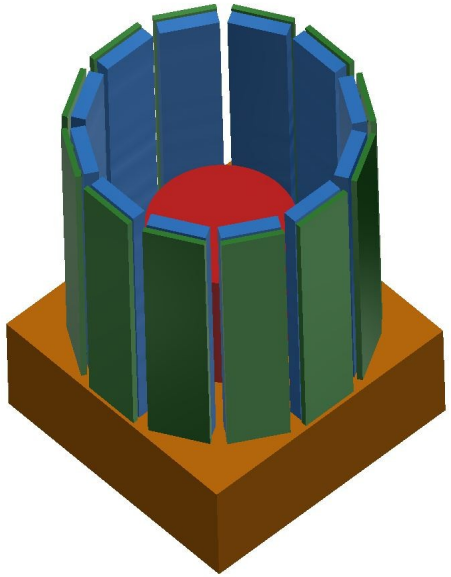
# Scattering polarimeters: Why we need GEANT4

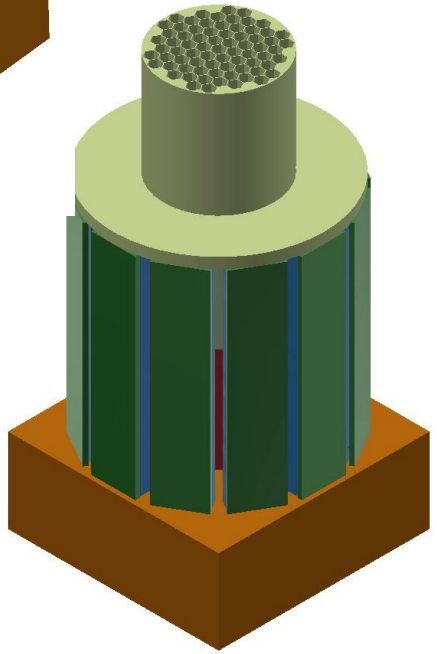




$\mu_{100}$ Modulation for 100% polarized photons

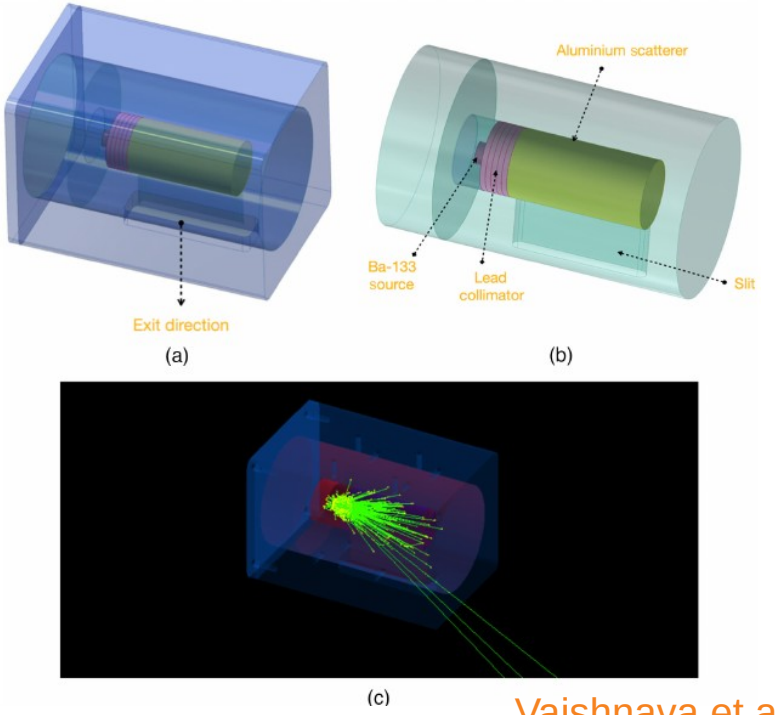
# Scattering polarimeters: Why we need GEANT4





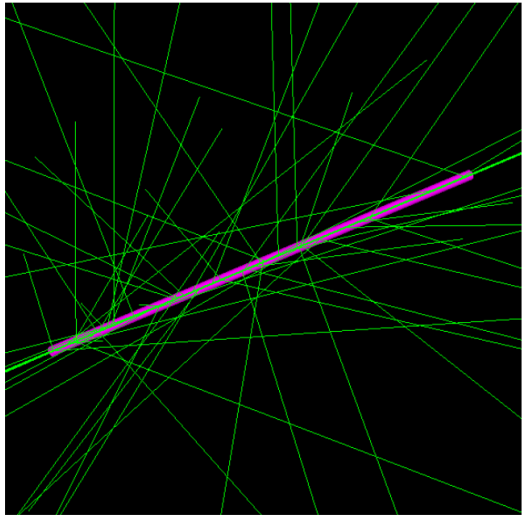
$\mu_{100}$ Modulation for 100% polarized photons

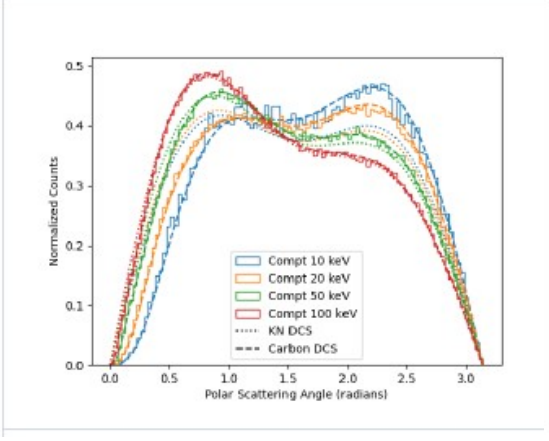
Making polarized X-rays

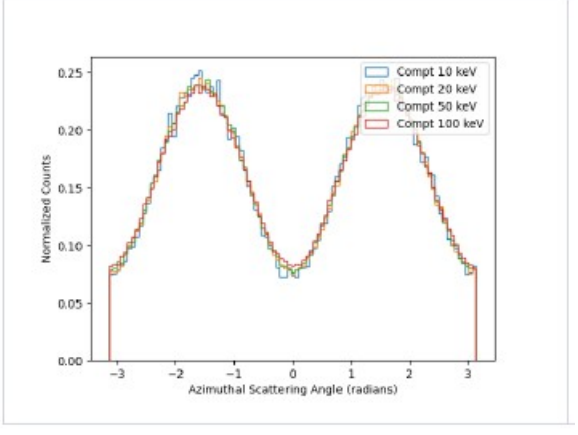



Vaishnava et al (2022)

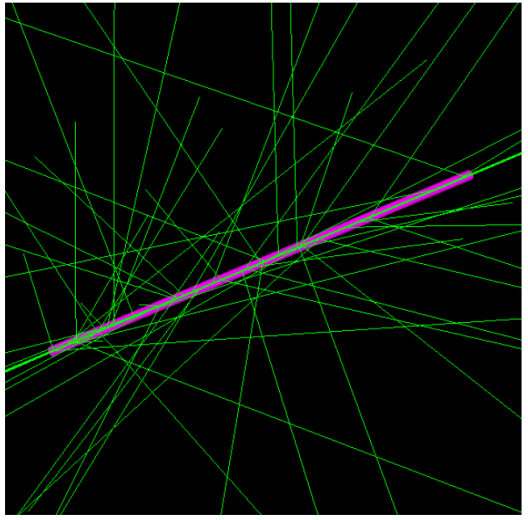
# Scattering polarimeter: The tutorial

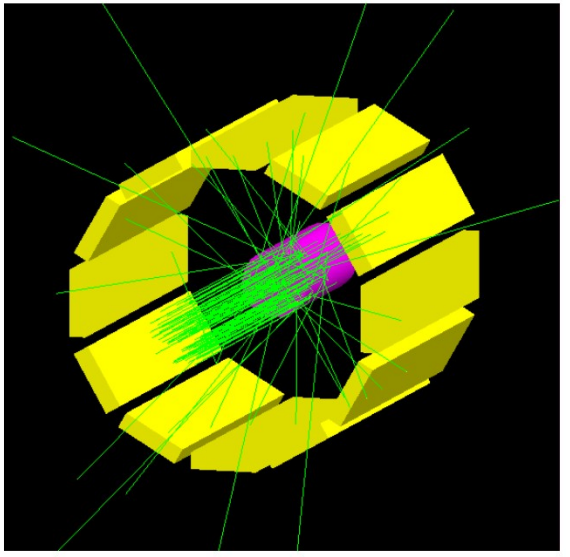


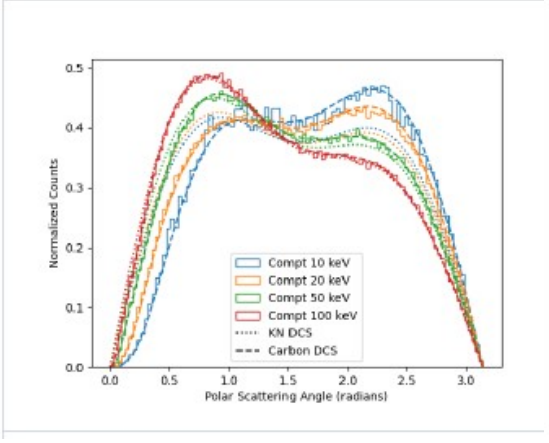


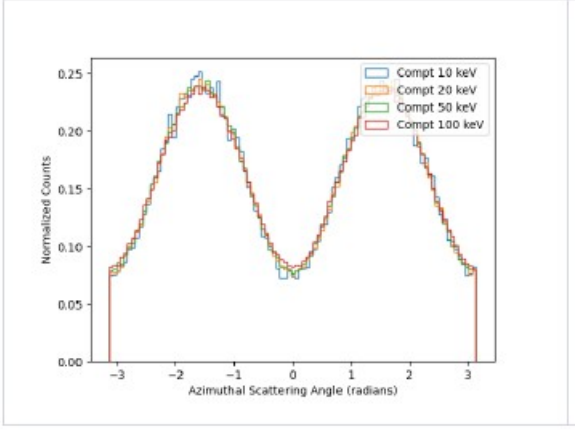



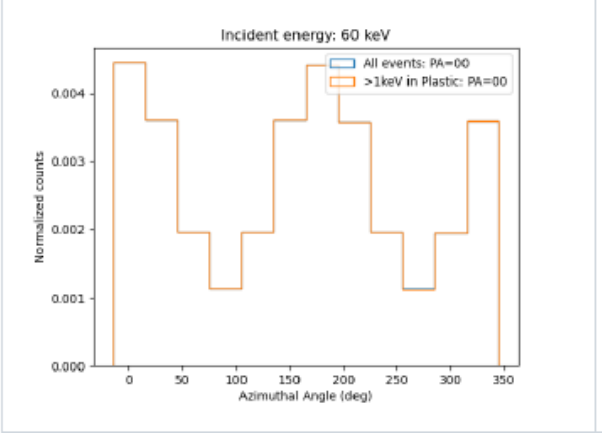
# Scattering polarimeter: The tutorial







Thank you!