The Future of High Energy Polarimetry

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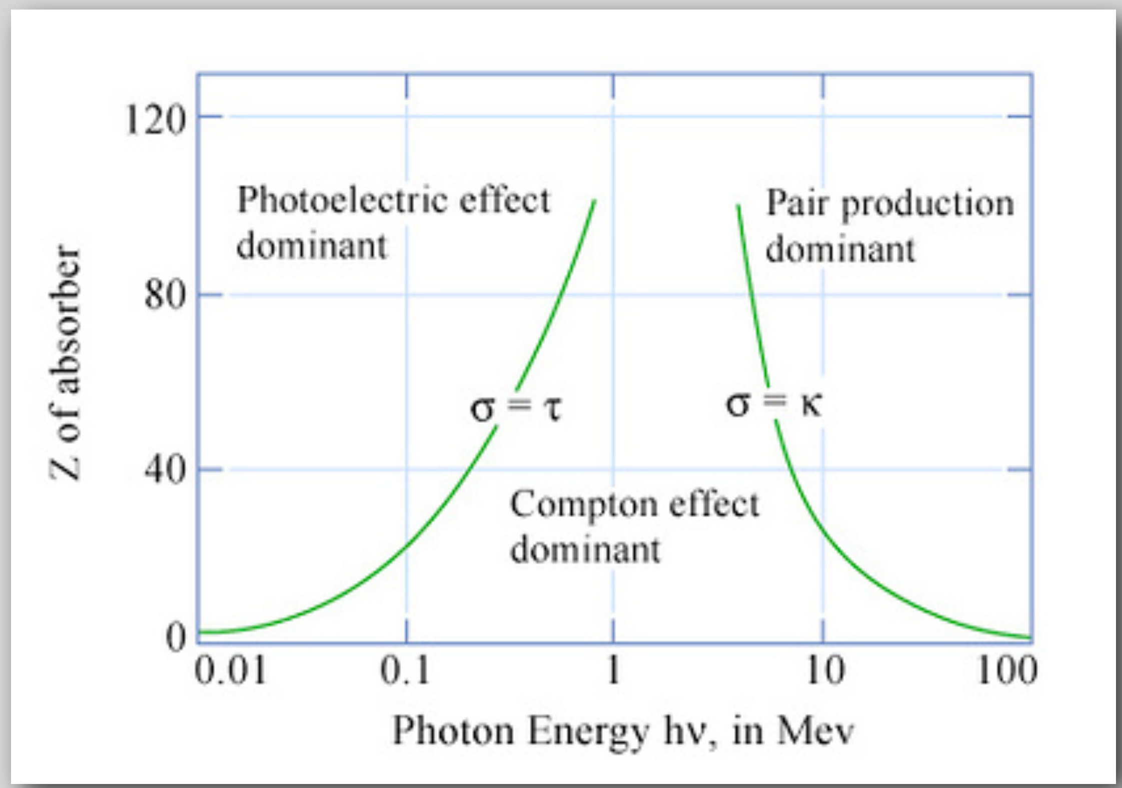
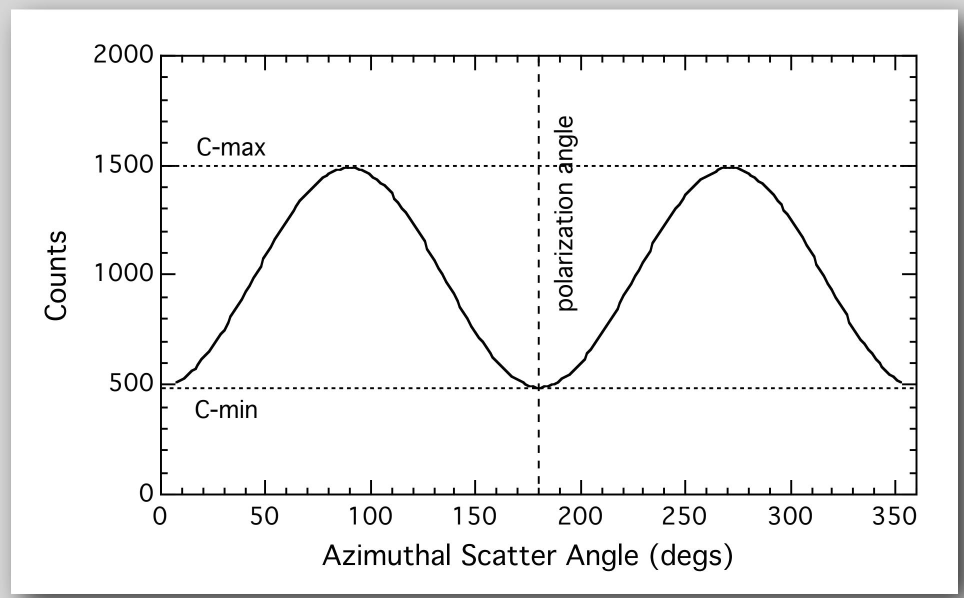
Measurement Methods

Measuring Linear Polarization

1 keV – 200 MeV

- ✦ Several techniques :
  - photoelectric effect
  - Compton scattering
  - pair production



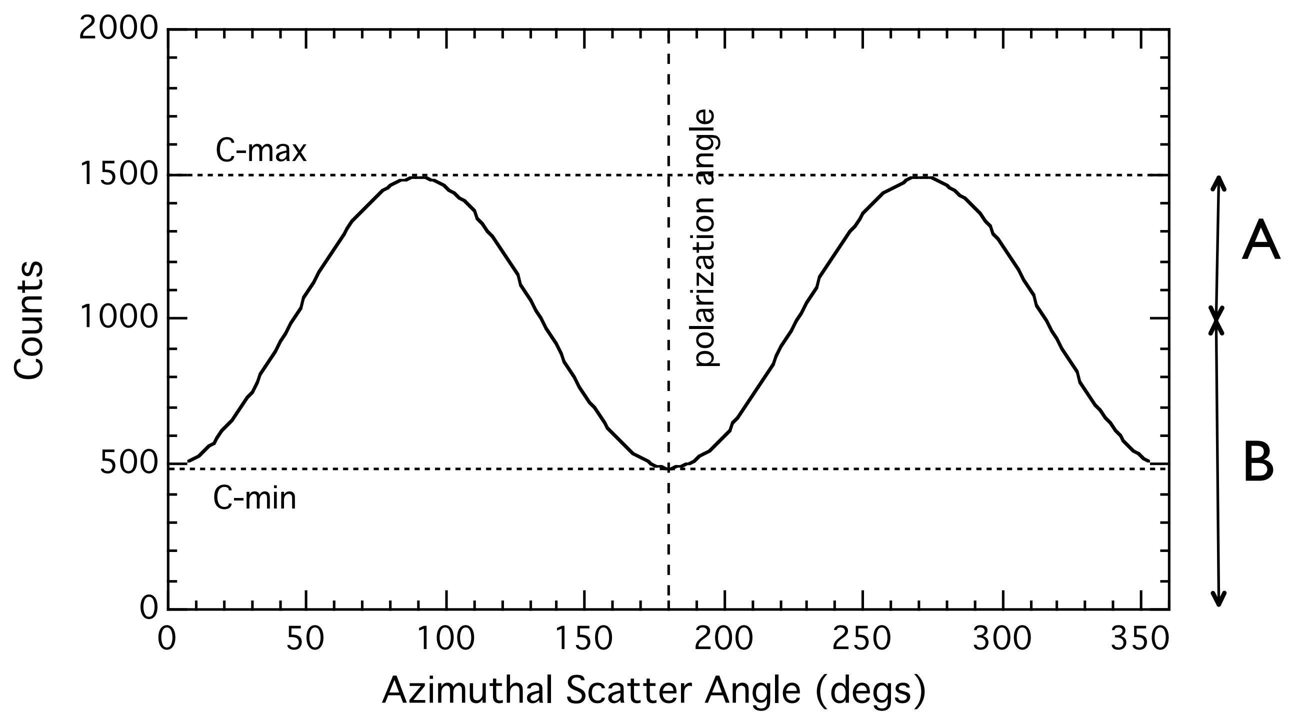


Compton scattering polarization signature.

All of these techniques rely on measuring some asymmetry in the scattered/secondary particle momenta.

The Polarization Signature

The azimuthal distribution of scattered/secondary particle momenta contains the polarization signature.



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

Modulation Factor for a 100% polarized beam represents a figure-of-merit for the polarimeter

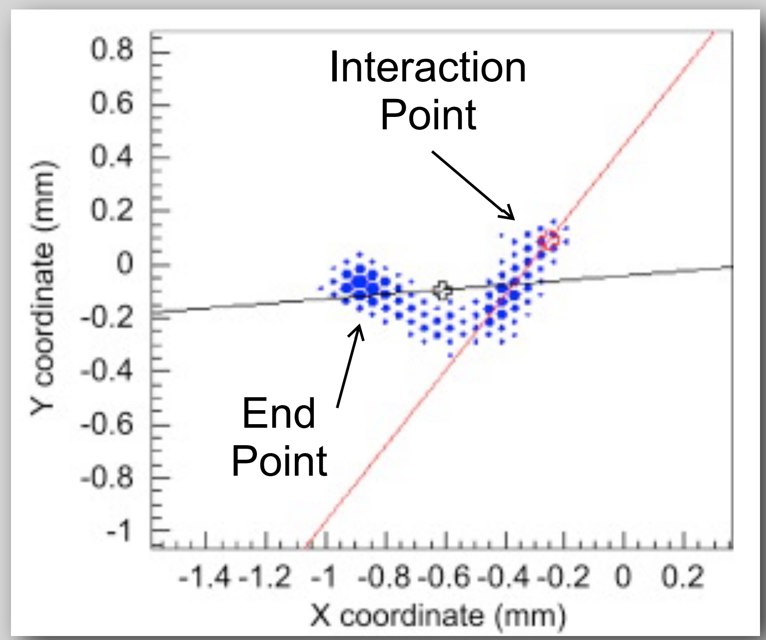
$$\mu_{100} = \frac{C_{max} - C_{min}}{C_{max} + C_{min}} = \frac{A}{B}$$

Amplitude defines the *level* of polarization.

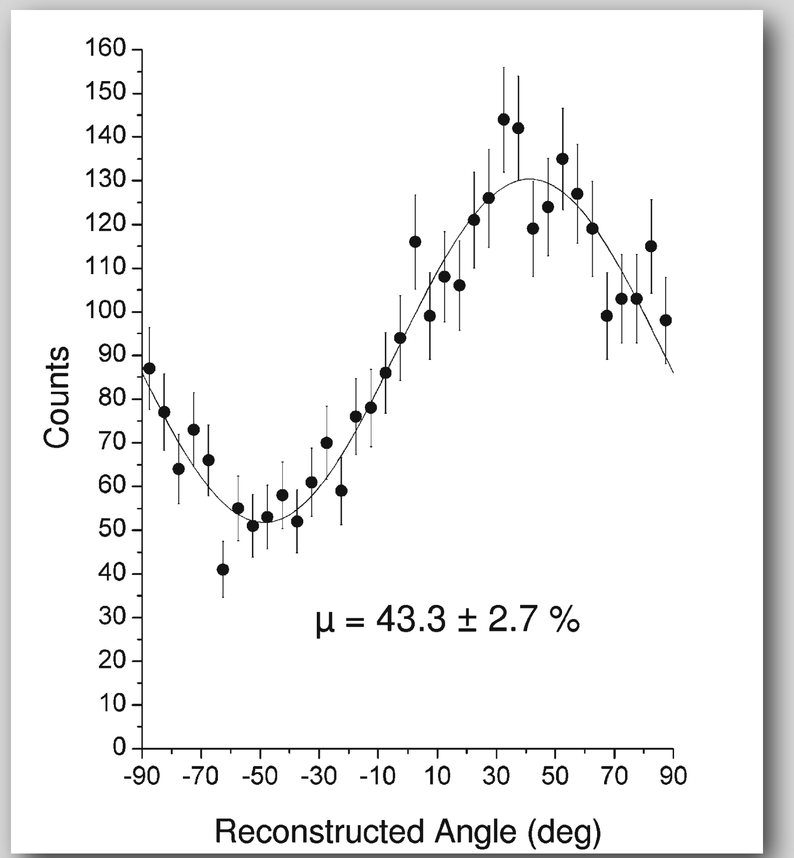
Minimum phase defines the *plane* of polarization.

Photoelectric Polarimetry

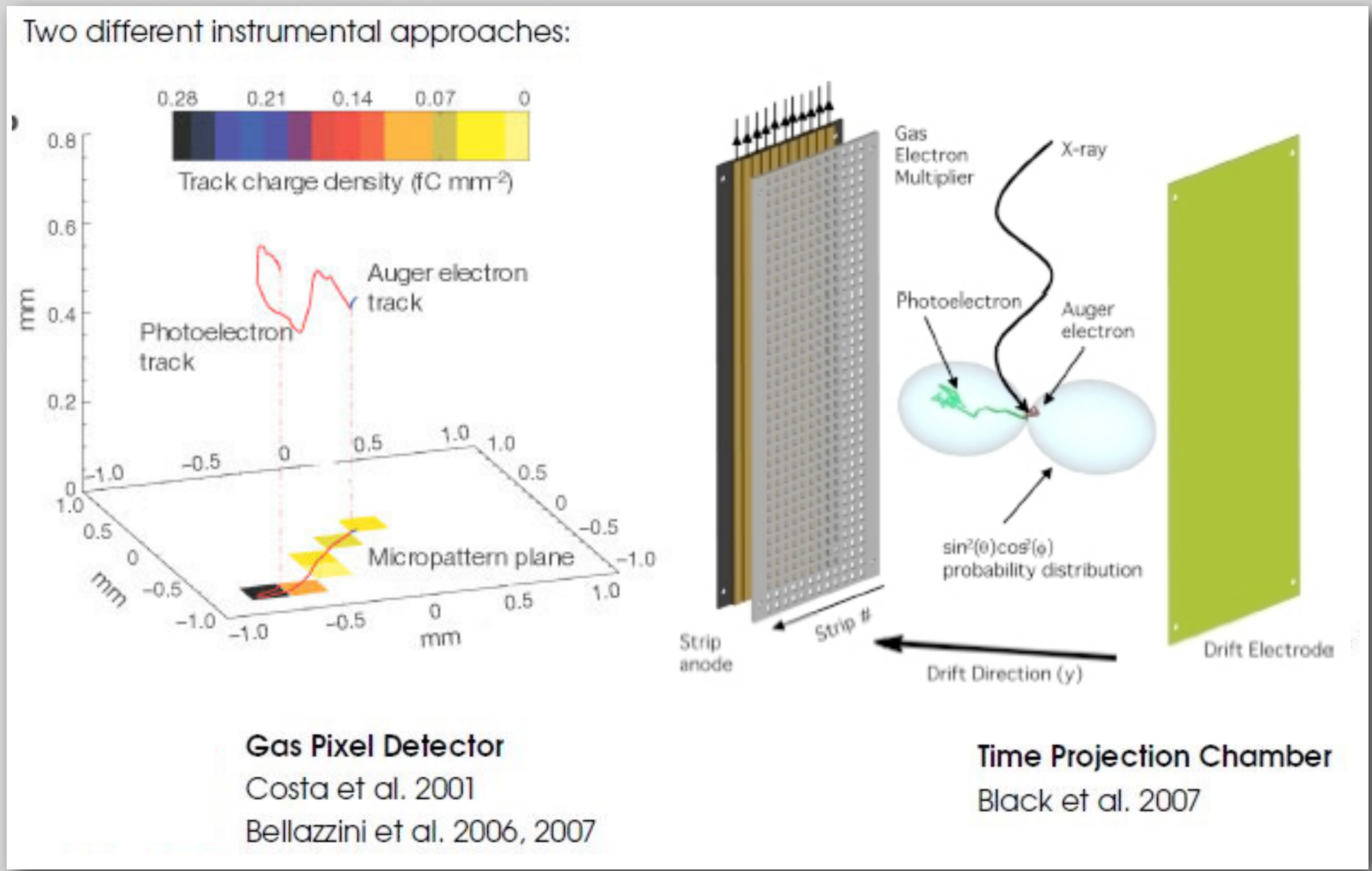
Energy Range ≈ 1-30 keV



- *Measurement Principle* :
  - Photoelectrons tend to be ejected in a direction parallel to the incident polarization vector.
- *Current Technologies :*
  - CCDs – typically thin, low efficiency
  - Gas Pixel Detectors (GPD)
  - Time Projection Chambers (TPC)
- *Challenges* :
  - Typical photoelectron range (in gas) is < 1000 μm
  - Determine initial direction of photoelectron
  - Scattering of photoelectron makes it hard to determine the initial direction.
  - Isotropically emitted Auger electron can also cause confusion.
  - Diffusion of the charge cloud can limit the detail.



Photoelectric Polarimetry



Couples a Gas Electron Multiplier (GEM) to amplify the ionization track with a finely segmented (2-D) pixel readout. Requires small pixel sizes (< 50 μm) and a large number of readout channels.

Uses time projection to form a 2-D track image from a 1-D strip readout. Geometry gives a diffusion that is independent of interaction depth. Can offer higher energy response.

Compton Scatter Polarimetry

Energy Range ≈ 5 keV - 30 MeV

✦ *Measurement Principle* :

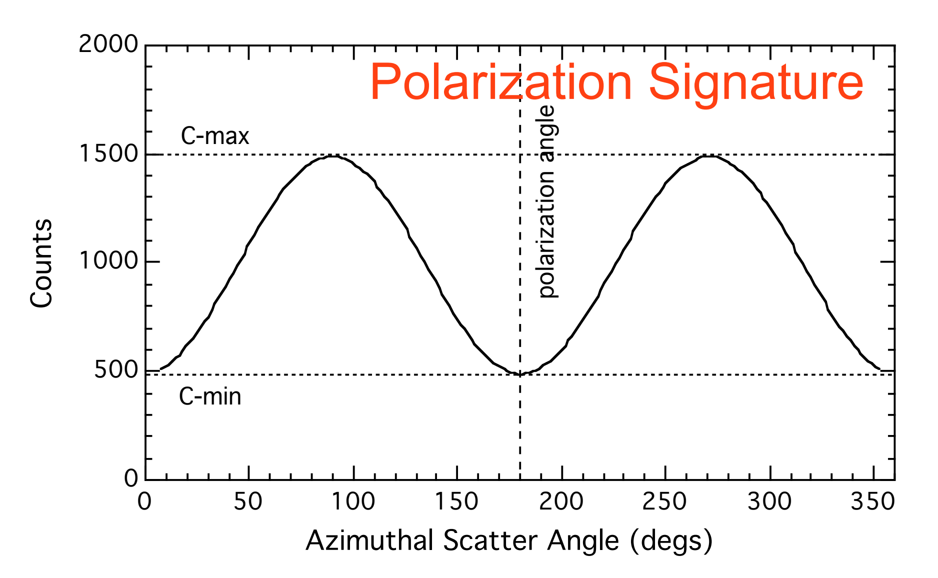
- Photons tend to scatter at right angles to the incident polarization vector.

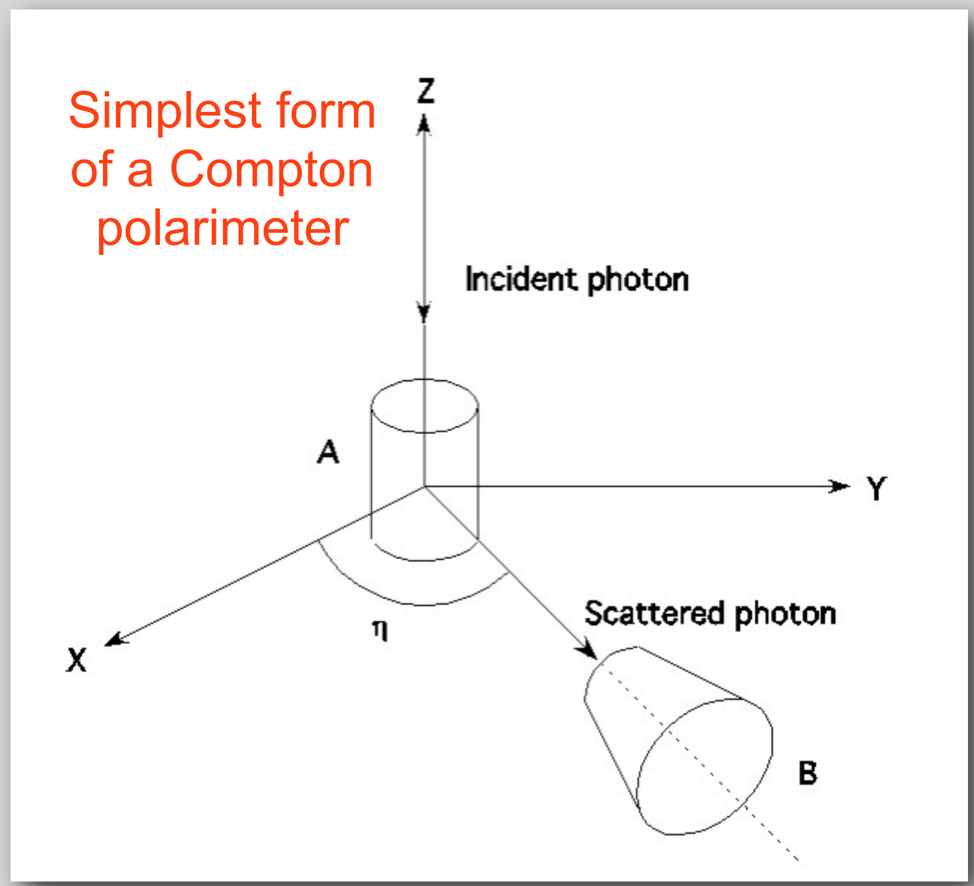
✦ *Current Technologies :*

- Scintillators
- Solid State Detectors (Si, Ge, CZT)
- Liquid Xe

✦ *Challenges* :

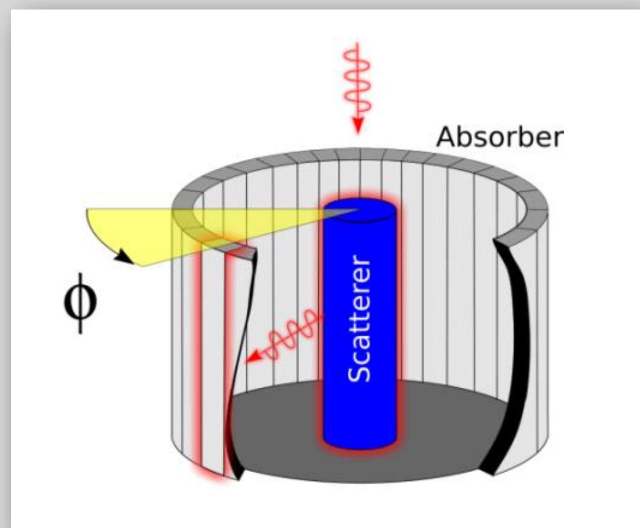
- Multiple scattering
- Fine spatial resolution (< 1 mm)
- Energy resolution
- Time resolution (nsec)
- Modulation decreases with energy.



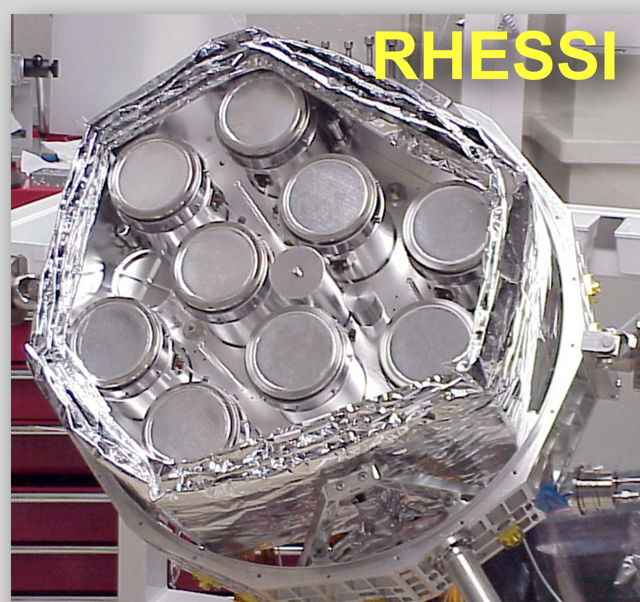


Compton Scatter Polarimetry

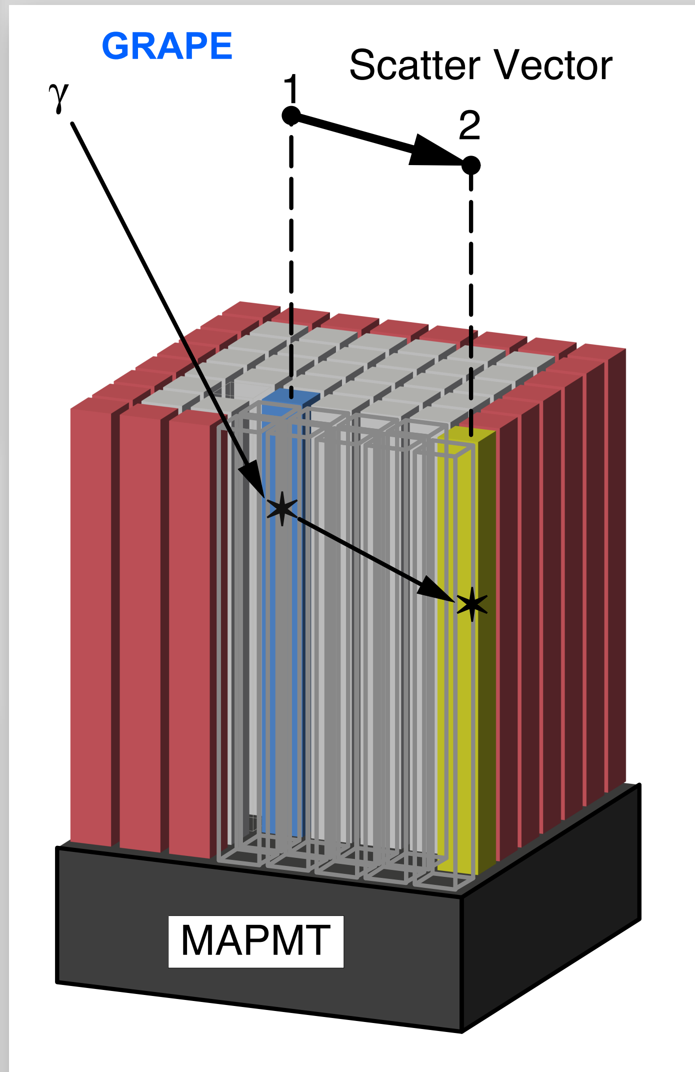
Energy Range ≈ 5 keV - 30 MeV



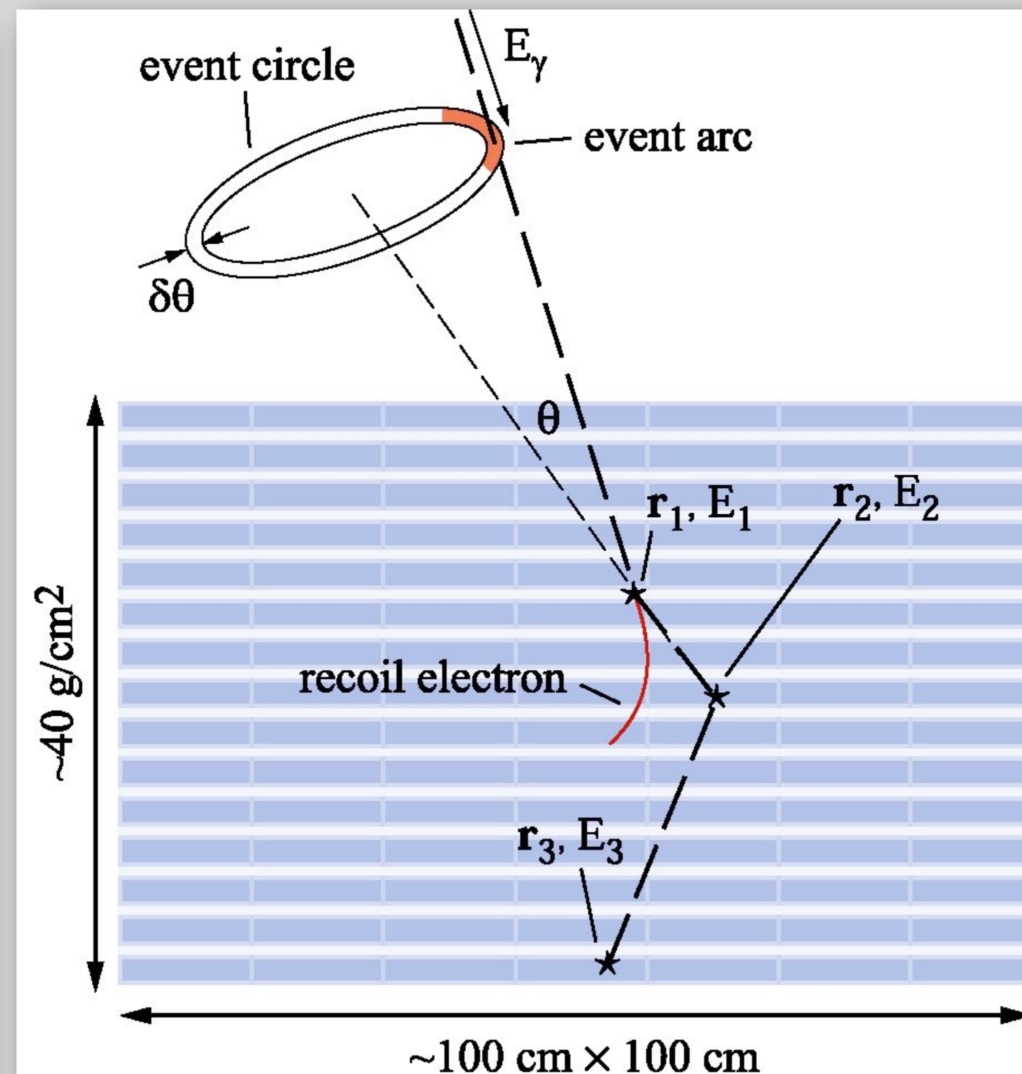
At low energies (Thomson regime) a passive scattering element is used.



At higher energies scattering between two active elements becomes possible.



Some Compton polarimeters are designed with a large FoV to capture GRBs. (McConnell et al. 2014)



More advanced designs permit the tracking of a photon through multiple scattering events. At higher energies, event reconstruction is required to determine polarization from initial scattering and to reduce background.

Pair Production Polarimetry

Energy Range ≈ 30 MeV – 300 GeV

✦ *Measurement Principle* :

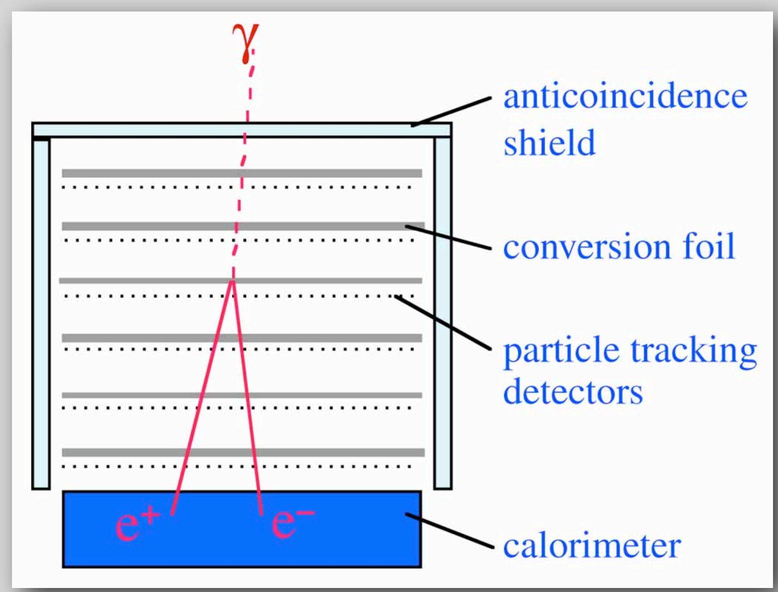
- The plane of the electron-positron pair is related to the incident electric field vector.

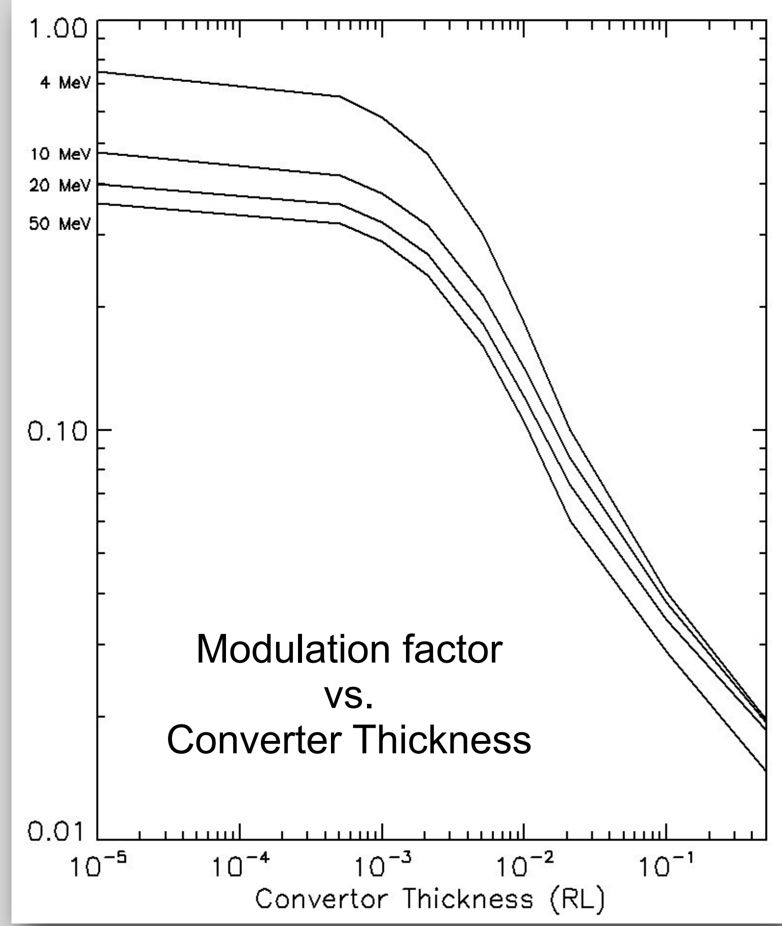
✦ *Current Technology* :

- Si tracking (e.g., Fermi)
- Micro well gas detectors

✦ *Challenges* :

- Determine initial directions of e+ and e-
- Need low density detector to minimize Coulomb scattering and thereby optimize angular resolution and polarization sensitivity
- Triplet production (measurable recoil momentum) offers possibility of stronger polarization signal.



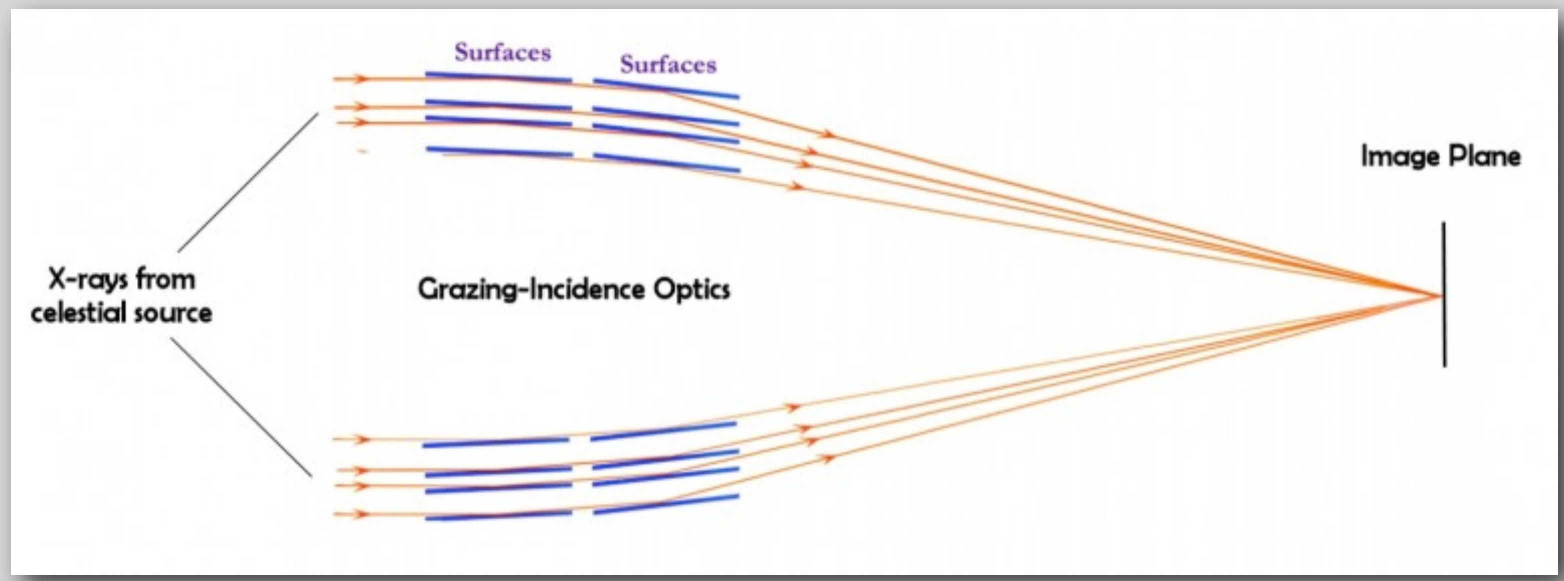


Imaging Spectropolarimetry

- Several polarimeter designs are either large FoV or collimated.
- It would be useful to have simultaneous imaging, spectroscopy and polarimetry.
- Imaging is not just a means to resolve fine detail, it is also a means to reduce background in a measurement and to distinguish sources in a crowded field.

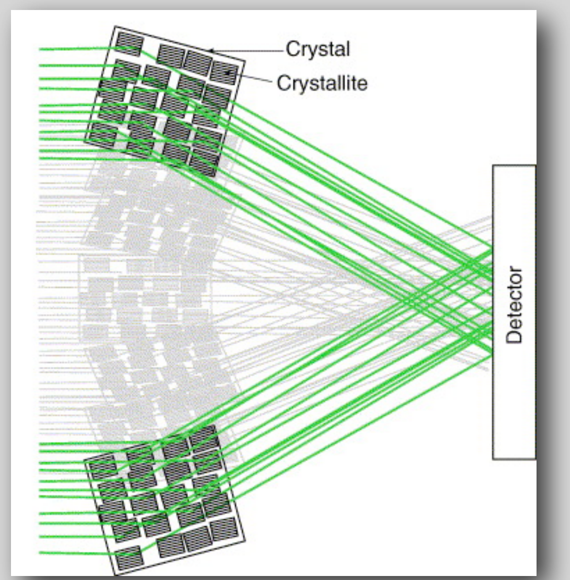
Imaging Spectropolarimetry

Some low-energy designs (e.g., GEMS, X-Calibur) place a polarimeter at the focal plane.



Grazing Incidence Imaging

Current technology can image up to ~80 keV, but higher energies may be possible.

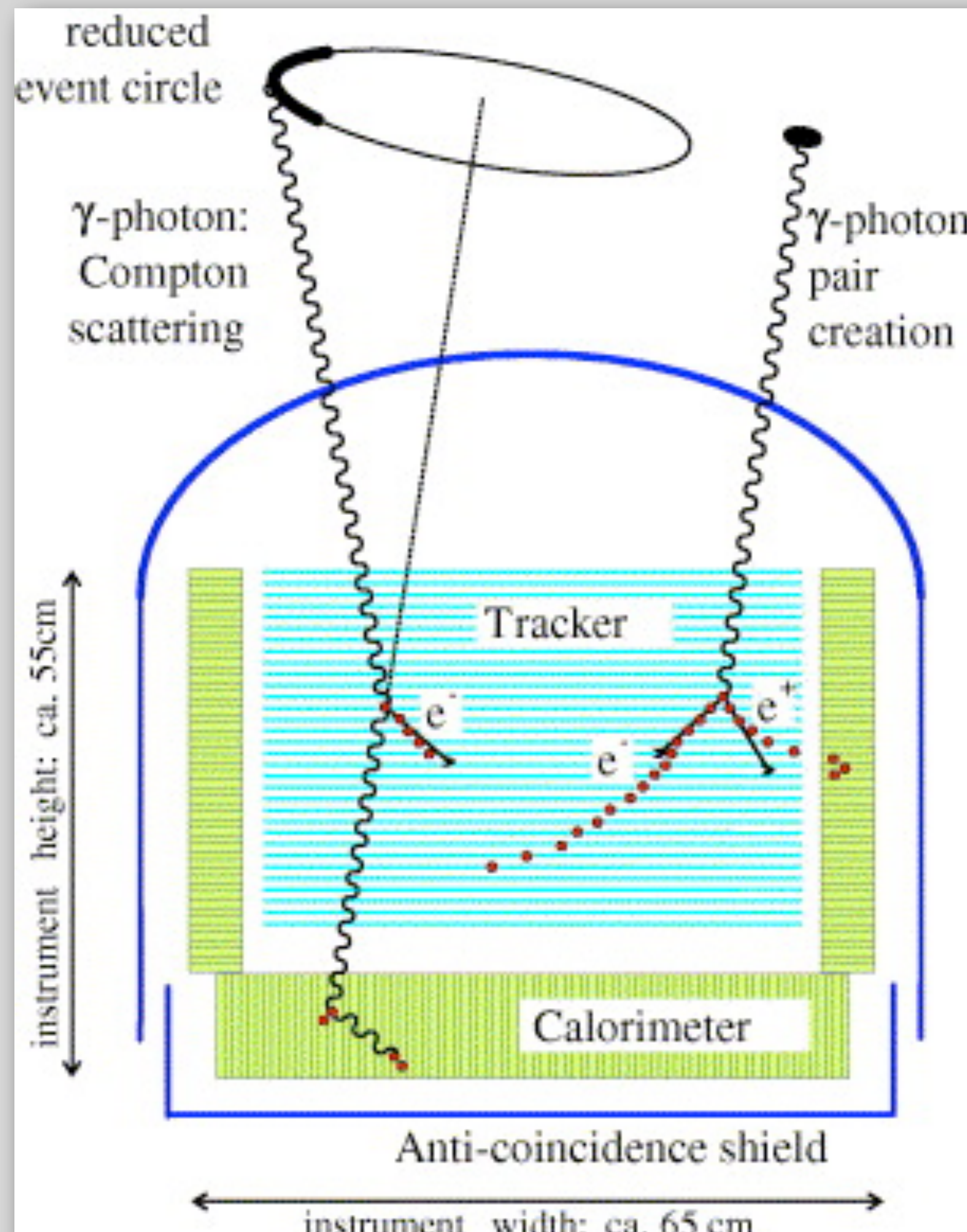


Laue Lens Imaging

Lenses can be designed for narrow-band ($\Delta E \approx 100$ keV) or broad-band ($\Delta E \approx 500$ keV) imaging at energies below 1 MeV, but can require very long focal lengths (20-100 m).

Imaging Spectropolarimetry

- ✦ In other cases, the imaging process itself provides the polarization measurement.
- ✦ Compton and pair production imaging can both cover a substantial fraction of the sky.



A design that utilizes both Compton Imaging and Pair Production Imaging.

Science Results

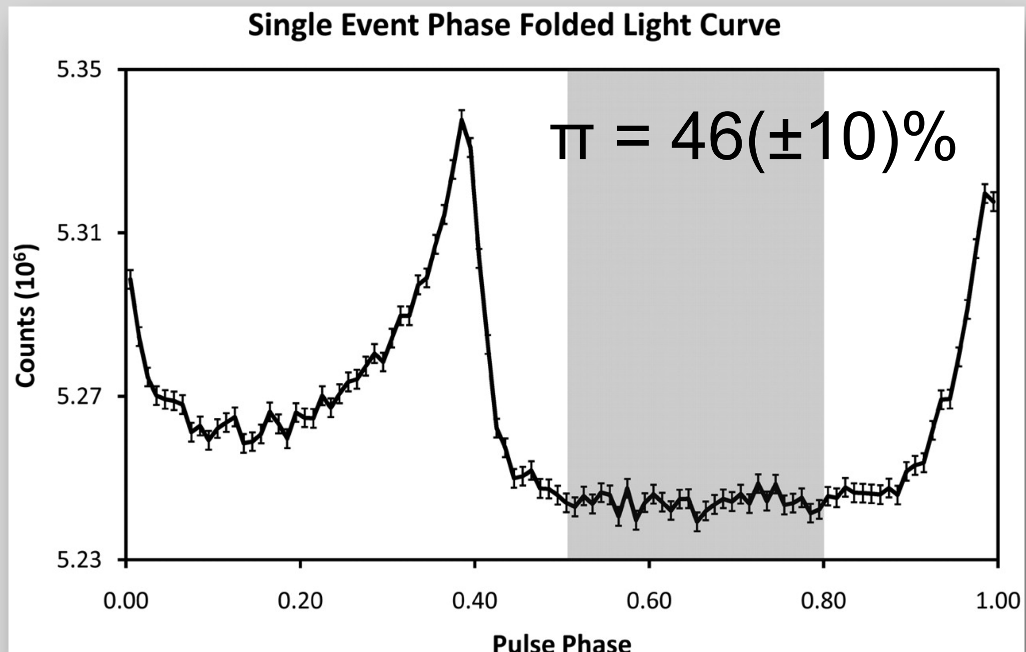
GRB Polarization Measurements

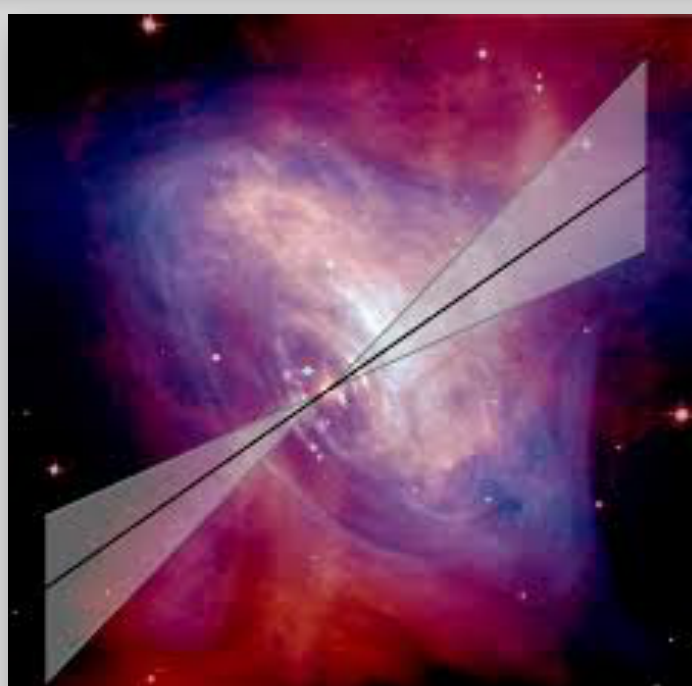
Several results suggest very high polarization levels, but all are of limited statistical significance.

Event	*Mission*	*Energy (keV)*	*Result*	*Reference*
GRB 930131	CGRO/BATSE	20 - 1000	(35-100%)	Willis et al. (2005)
GRB 960924	CGRO/BATSE	20 - 1000	(50-100%)	Willis et al. (2005)
GRB 021206	RHESSI	150 - 2000	80% ± 20%	Coburn & Boggs (2003)
GRB 041219a	INTEGRAL/SPI	100 - 350	98% ± 33%	Kalemci et al. (2007)
GRB 041219a	INTEGRAL/SPI	100 - 350	96% ± 40%	McGlynn et al. (2007)
GRB 041219a	INTEGRAL/IBIS	200 - 800	43% ± 25% (variable π)	Götz et al. (2009)
GRB 061122	INTEGRAL/IBIS	250 - 800	> 60%	Götz et al. 2013
GRB 100826a	IKAROS/GAP	70 - 300	27% ± 11% (variable PA)	Yonetoku et al. (2011)
GRB 110301a	IKAROS/GAP	70 - 300	70% ± 22%	Yonetoku et al. (2012)
GRB 110721a	IKAROS/GAP	70 - 300	80% ± 22%	Yonetoku et al. (2012)
GRB 140206a	INTEGRAL/IBIS	200 - 800	> 48%	Götz et al. (2014)

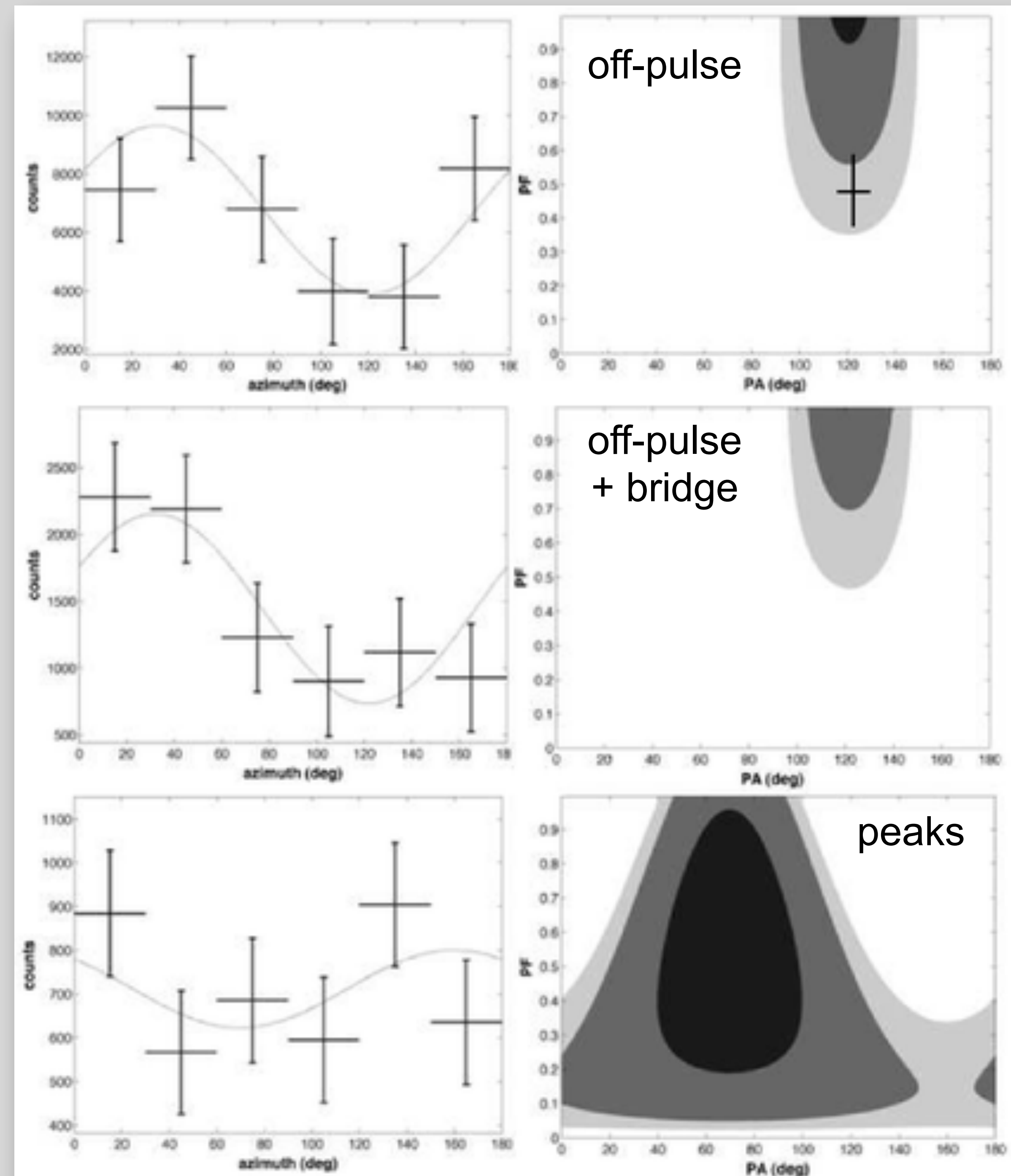
Crab Polarization

INTEGRAL/SPI (Dean et al. 2008)
100 keV - 1 MeV



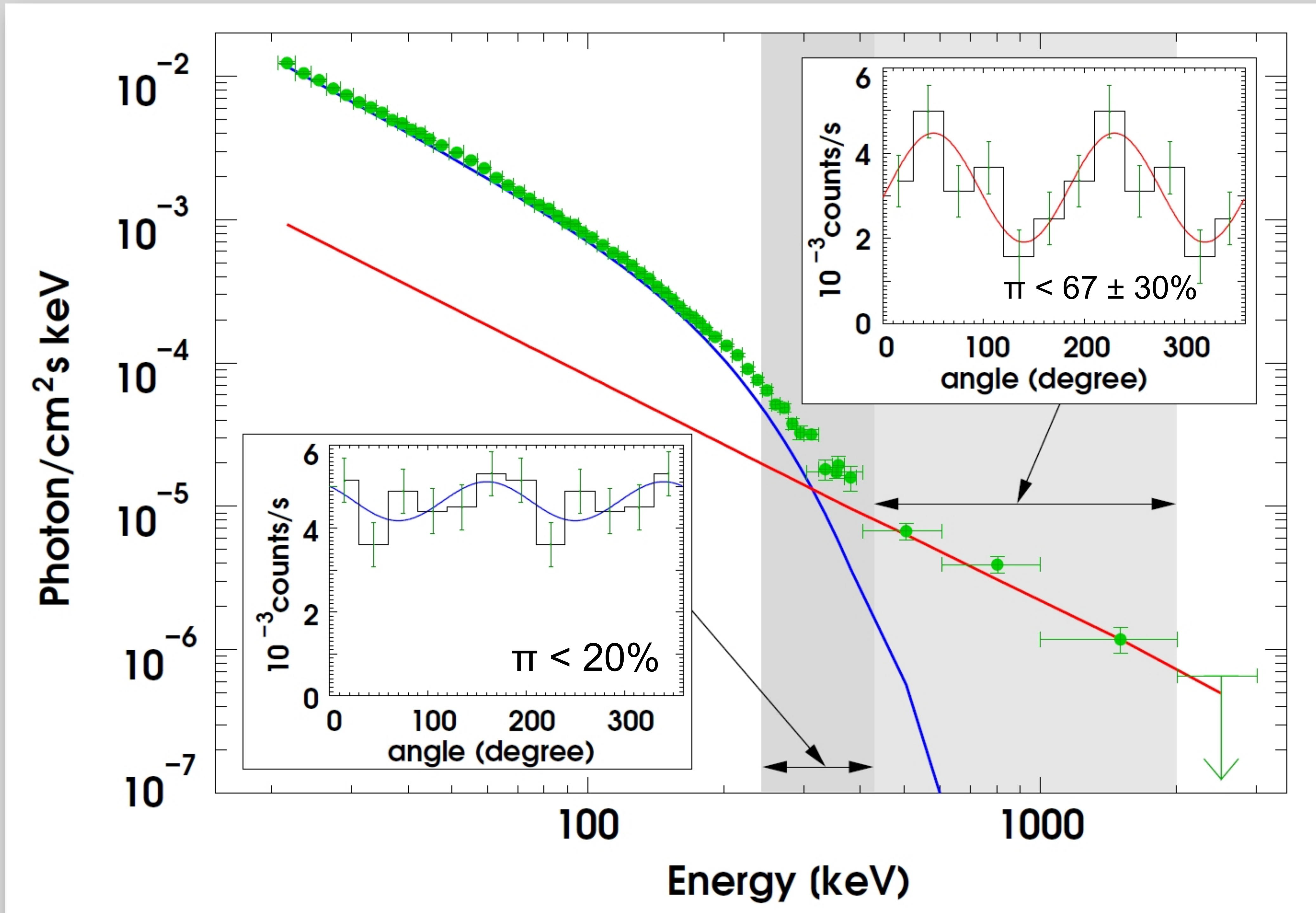


INTEGRAL/IBIS (Forot et al. 2008)
200 - 800 keV



Cygnus X-1

INTEGRAL / IBIS (Laurent et al. 2011)
[also INTEGRAL/SPI (Jourdain et al. 2012)]



Future Outlook

It is not yet clear what the next major step(s) in space-based gamma ray astronomy will be.

Several possibilities have been discussed.

They are all based on one (or more) of the three basic photon interaction mechanisms.

There seems to be general agreement that polarimetry is an important piece of any future mission.