SCATTERING POLARIMETRY IN THE HARD X-RAY RANGE

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Why Hard X-Ray Polarimetry?

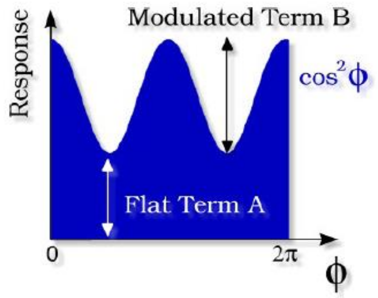
Paolo Soffitta has shown the outstanding results of IXPE.

He also mentioned how this technique can be extended to higher energies. A realistic boundary could be 25keV. Anyway at these pressures the absorption gap is highly transparent and many photons arrive to the bottom where they are lost.

The Formalism

Fit function: $\mathcal{M}(\phi) = A + B\cos^2(\phi - \phi_0)$

Modulation: $\dfrac{\mathcal{M}_{\max} - \mathcal{M}_{\min}}{\mathcal{M}_{\max} + \mathcal{M}_{\min}} = \dfrac{B}{B + 2A}$



Modulation curve

Polarization: $\dfrac{1}{\mu}\dfrac{B}{B + 2A}$

μ is the modulation factor, i.e. the modulation for 100% polarized radiation

Or by using Stokes Parameters

$$S(\varphi) = I + Qsin(2\varphi) + Ucos(2\varphi)$$

$$I = (A + \frac{B}{2}) \qquad U = \left(\frac{B}{2}\right) * \sin(2\varphi_0) \qquad Q = \left(\frac{B}{2}\right) * \cos(2\varphi_0)$$

$$P = \frac{\sqrt{Q2+U2}}{I} \qquad \varphi = \frac{1}{2} atan \frac{U}{Q}$$

Kislat et al. (2015) introduced the Stokes parameters from the direction of the single carrier of polarimetric observation

No V $\rightarrow$ no circular polarization with present techniques

The first limit: In polarimetry the sensitivity is a matter of photons

$$MDP = \frac{4.29}{\mu\, R_S}\sqrt{\frac{R_S + R_B}{T}}$$

Minimum Detectable Polarization (MDP)

R_S is the Source rate, R_B is the Background rate, T is the observing time
μ is the modulation factor: the response of the polarimeter to a 100% polarized beam (spanning from 0 or no sensitivity, to 1 or maximum sensitivity)

If background is negligible: $$\mathrm{MDP} = \frac{4.29}{\mu\sqrt{N_{ph}}}$$

To reach MDP=1% with μ=0.5: $$N_{ph} = \left(\frac{4.29}{\mu\,\mathrm{MDP}}\right)^2$$ = 736 10^3 ph

Source detection > 10 counts
Source spectral slope > 100 counts
Source polarization > 100.000 counts

Caution: the MDP describes the capability of rejecting the null hypothesis (no polarization) at 99% confidence. For a 3-sigma meaurement an observing time 2.2 times longer is needed while the 1-sigma error scales like : $28^o.5$/S/N

SYSTEMATICS

The attention to the statistics should not hide a serious problem of systematics.
The GPD is conceptually free from systematics. In practice it is to a modest level (<1.2% of spurious modulation) that anyway required months of hard work of calibration.

Scattering polarimetry for sure will have larger troubles.

The scattered photons travel between the scatterer and a set of absorbers. Some materials will be there (at least for mechanical mounting). Also the not cylindric geometry of the absorber will be a deviation from the circular symmetry.

In a payload/bus with low Z materials hard X-Ray/Soft γ-rays are difficult to stop or collimate. The back or side scattering of the passive materials can be itself a source of systematics. Also in calibration (!).

Different concepts

A polarimeter can be:

- Dispersive: All [many] angles together
- Not Dispersive: One angle at a time

- Dedicated: designed and built to perform polarimetry
- Byproduct: designed and built for some other purpose doing also some polarimetry

- Single instrument (typically narrow band)
- Combined Instruments (typically broad band)

In particular a Scattering Polarimeter can be:

- One phase: Same material for the analyzer (scatterer) and the absorber
- Two phases: Different materials for the analyzer and the absorber (typically lowZ/HighZ)

- Narrow field
- Wide Field

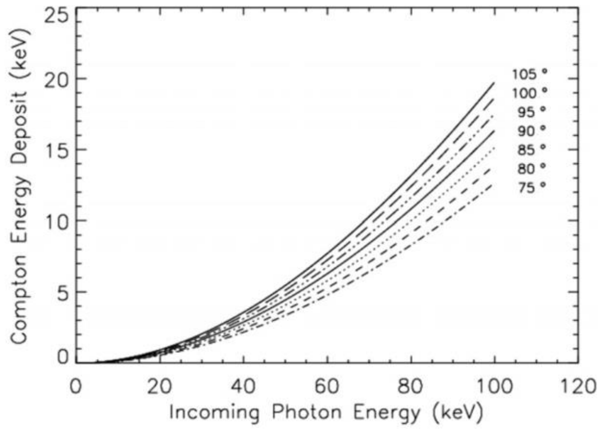
- Collimated
- Focal plane

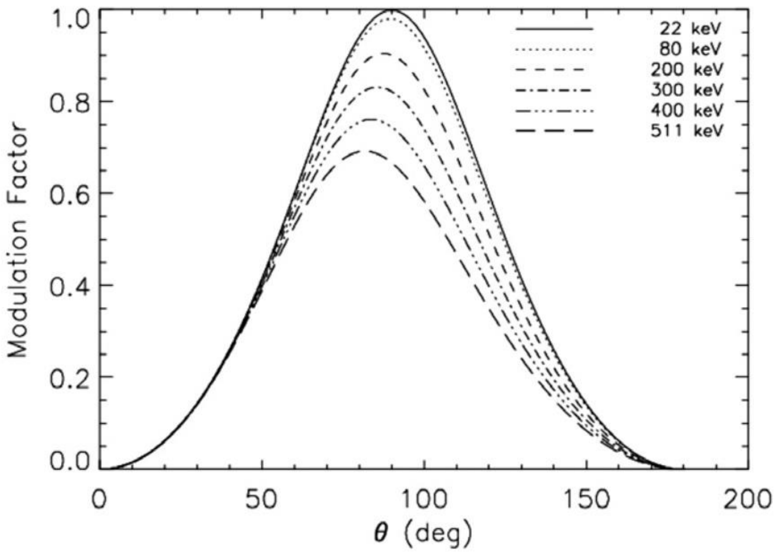
The Cross Section[s]

$$\frac{E'}{E} = \frac{1}{1 + \frac{E}{m_e c^2}(1 - \cos\theta)}$$

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

$$\mu(\theta) = \frac{N_{\max}(\theta) - N_{\min}(\theta)}{N_{\max}(\theta) + N_{\min}(\theta)} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_{\phi=\frac{\pi}{2}} - \left(\frac{d\sigma}{d\Omega}\right)_{\phi=0}}{\left(\frac{d\sigma}{d\Omega}\right)_{\phi=\frac{\pi}{2}} + \left(\frac{d\sigma}{d\Omega}\right)_{\phi=0}} = \frac{\sin^2\theta}{\frac{E}{E'} + \frac{E'}{E} - \sin^2\theta}$$





No $\boldsymbol{\gamma}$ here

Any Compton telescope for $\boldsymbol{\gamma}$ rays is also a polarimeter if the design is such to accept a reasonable amount of events scattered at large polar angles.

e.g. COMTEL aboard GRO was not a polarimeter because it was only accepting avents scattered forward. In practice polarimetry becomes difficult at $E \geq 1$ MeV.

Pair production polarimetry is also possible in principle but difficult in practice.

Here I only discuss polarimetry in the hard X-Ray range (<100 keV)

Some consequences of the cross section

Materials

Material	ρ (g/cm^3)	E scatt=photoe
Lithium	0.534	8.7
LiH	0.820	8.2
Beryllium	1.848	14
Plastic (PVT)	1.032	20

A scattering Polarimeter can be:

A scattering polarimeter is **Dispersive**: All [many] angles together. But some angles forbidden or covered not uniformly for mounting reasons

And can be:

- **Dedicated**: designed and built to perform polarimetry
- **Byproduct**: designed and built for some other purpose doing also some polarimetry

- **One phase**: Same material for the analyzer (scatterer) and the absorber
- **Two phases**: Different materials for the analyzer and the absorber (typically lowZ/HighZ)
  - Active Scatterer
  - Passive scatterer

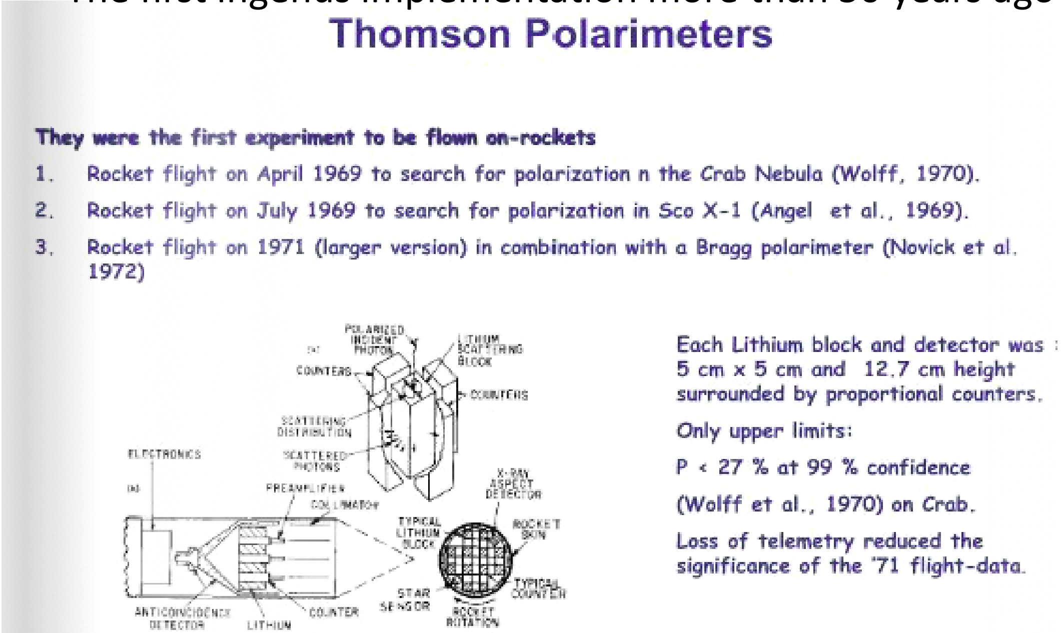
- **Narrow field**
  - Collimated
  - Focal plane of a Telescope
- **Wide Field**

- **Stand alone**
- **Combined** with other Instruments (typically broad band)

No optics-1

Passive scatterer[s] and absorber[s] → Modulation of counts with rotation

The first ingenus implementation more than 50 years ago


Thomson Polarimeters

They were the first experiment to be flown on-rockets
1. Rocket flight on April 1969 to search for polarization n the Crab Nebula (Wolff, 1970).
2. Rocket flight on July 1969 to search for polarization in Sco X-1 (Angel et al., 1969).
3. Rocket flight on 1971 (larger version) in combination with a Bragg polarimeter (Novick et al. 1972)

Each Lithium block and detector was : 5 cm x 5 cm and 12.7 cm height surrounded by proportional counters.

Only upper limits:

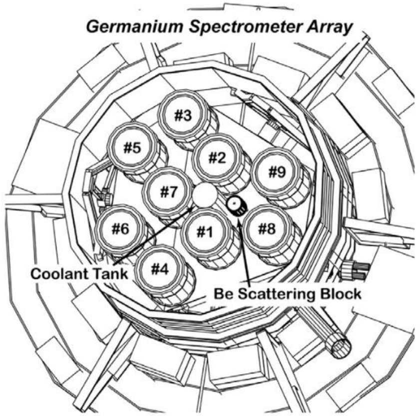
P < 27 % at 99 % confidence

(Wolff et al., 1970) on Crab.

Loss of telemetry reduced the significance of the '71 flight-data.

Angel+ 1969

Data showed that the Bragg was better. The technique was dropped

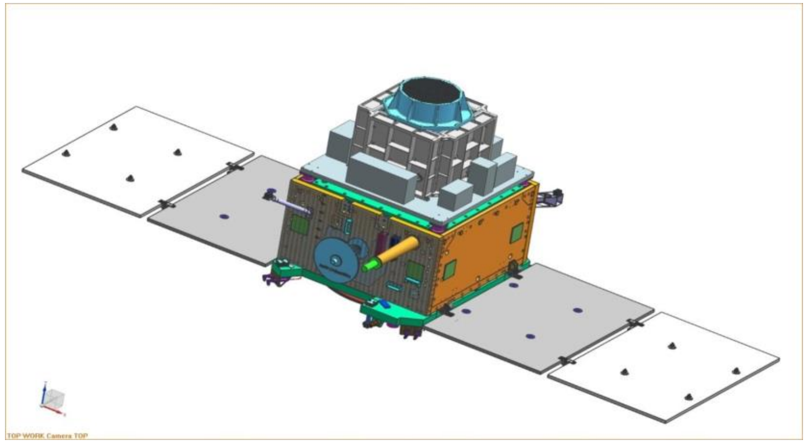


RHESSI

A littlee Beryllium scatterer surrounded with Ge detectors to perform polarimetry of Solar Flares. Only upper limits.

McCnnell 2017

But something new is arriving

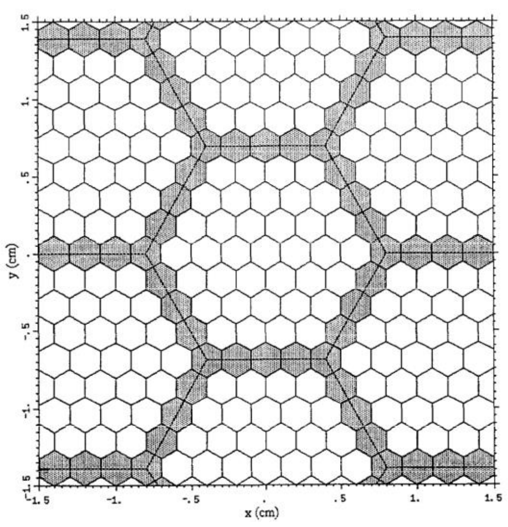


POLIX should be launched this year by ISRO
Collimator - Be Scatterer – 4 Proportional Counters, heritage of ASTROSAT
Nominal Range: 8-30 keV
Mainly aimed to study bright sources

No optics-2

A polarimeter could be conceived as a combination of detectors. A collimator would limit the direction of primary photons The coincidence would identify the path of the scattered photon to the final absorber. The sum of the two detected energies would be the energy. This for tens of years was merely conceptual.

E. Costa et al. / Nucl. Instr. and Meth. in Phys. Res. A 366 (1995) 161–172



Costa+1995

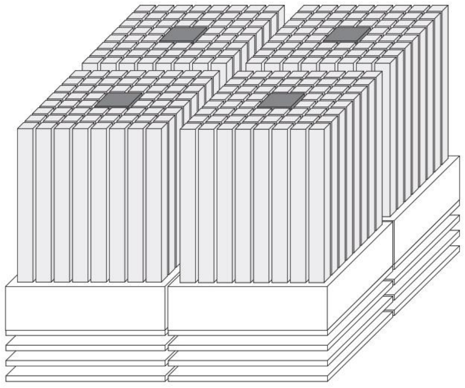
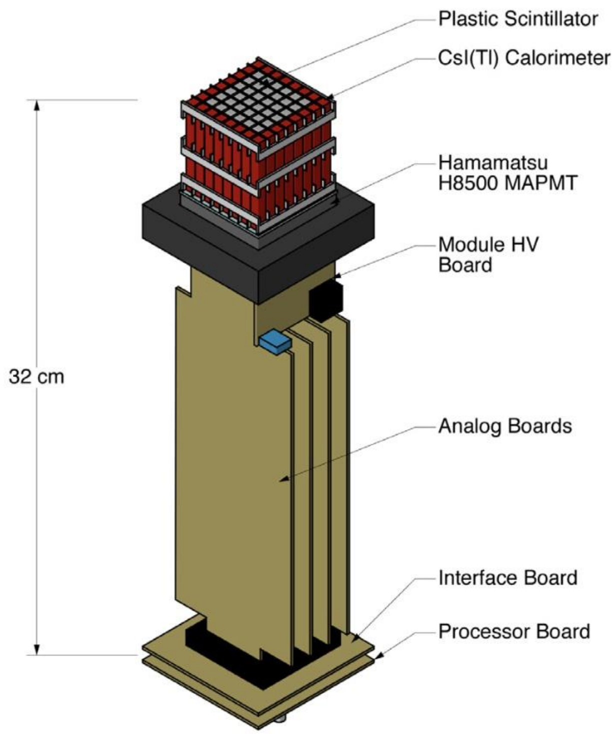


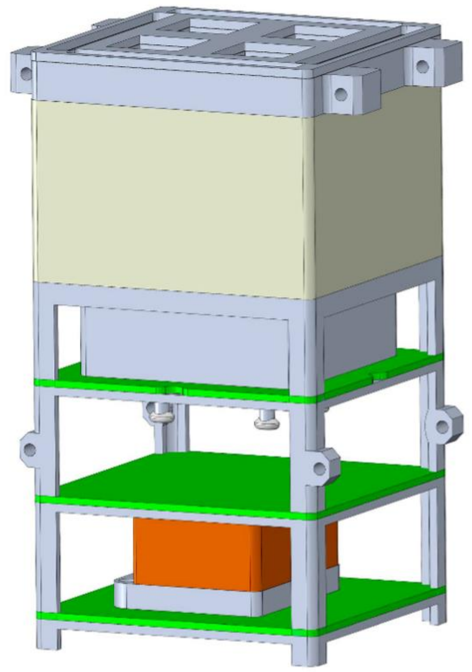
Fig. 3 The GRAPE design utilizes a flat-panel MAPMT for readout, shown here in a tiled configuration.

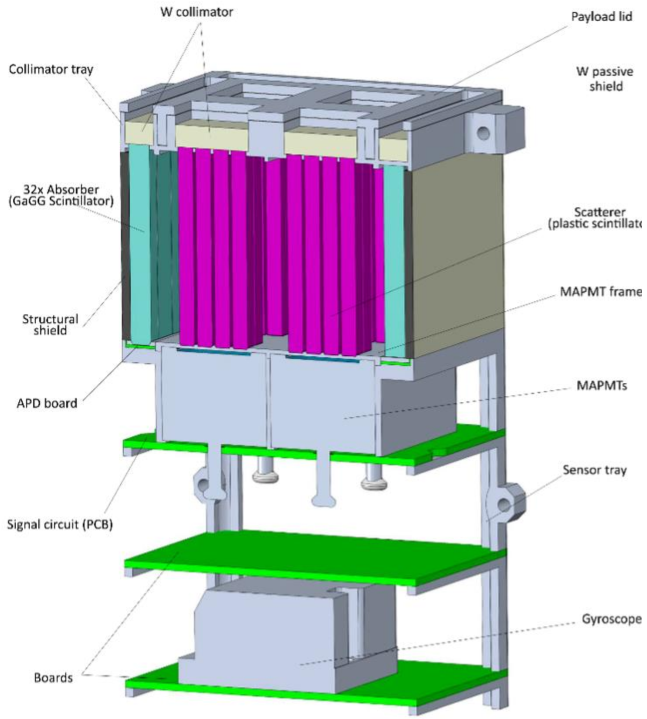
McConnell&Blowser2006

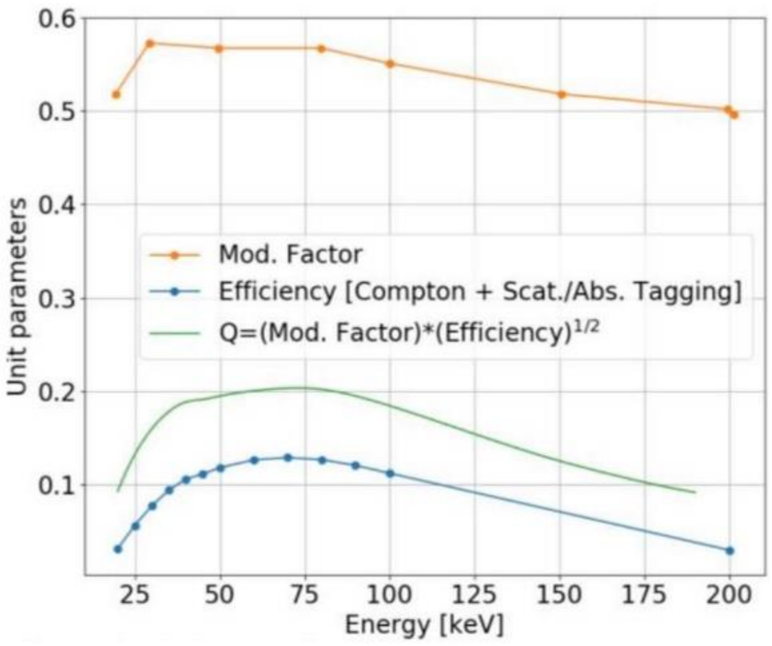


An evolved version of GRAPE named LEAP is proposed for the ISS

And one in the making at IAPS



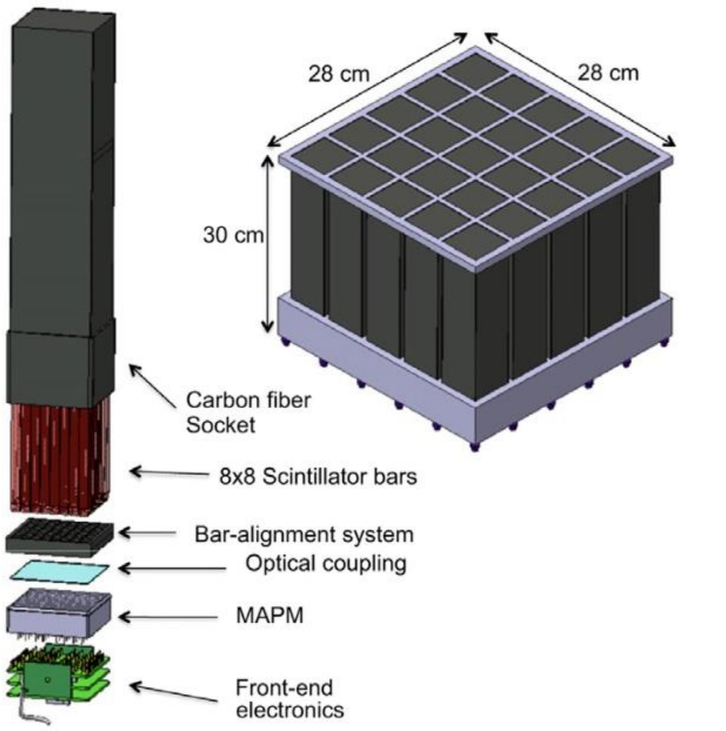




Fabiani+ 2022

The CUbesat Solar Polarimeter (CUSP) project aims to develop a constellation of two CubeSats orbiting the Earth to measure the **linear polarisation of solar flares** in the hard X-ray band by means of a Compton scat- tering polarimeter on board of each satellite.

Also one phase polarimeters

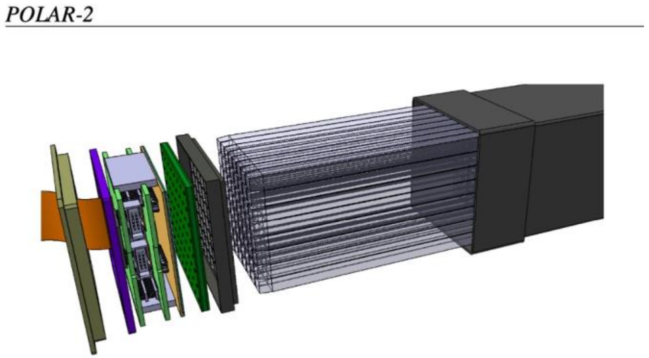


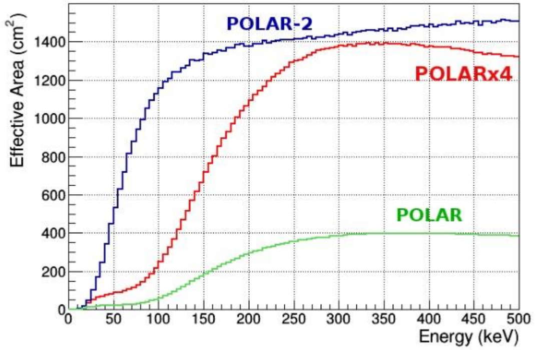
The attractive of one-phase is the use of the same array for all sensors. In the past multi-anode PMTs. Nowadays SiPMTs are the new favorite solution.

Caution: the energy measured is always $\lesssim E_{phot}$ and for the spectropolarimetry some problems are there.

POLAR (IHEP, Geneva Un. Et aal.) active on Tiangong-2 on 2016 – 2017 performed the polarimetry of 14 GRBs. Kole+2020.

POLAR-2 is the new version with 4 times the area, better sensitivity at lower energies (down to 50 keV). SiPMT instead of MAPMT





By-product Polarimetry

Some instruments designed and built for some other purpose doing also some polarimetry

Structured instruments sometimes include intermediate data that contain information on linear polarization. If these data are trasmitted (by original design or by late additions) the instrument can be used as a polarimeter.

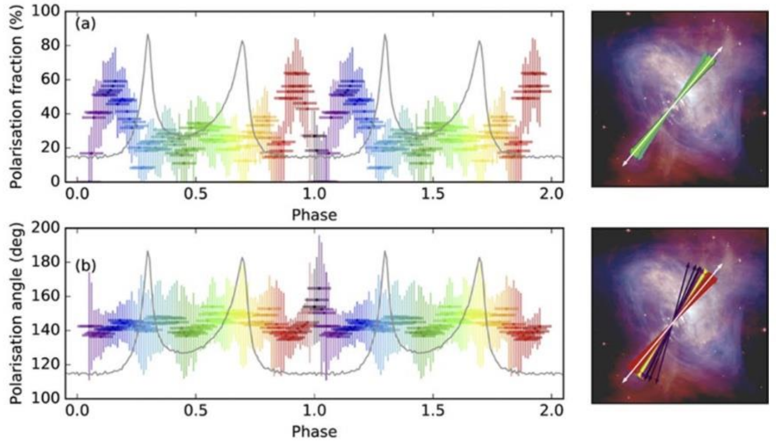
Given that polarization is more difficult to detect than spectra, images or timing the technique usually applies to a very limited subset of the brightest sources.

Moreover polarimetry requires an extreme (almost maniacal) care in the prevention of systematics that is absent in candidate byproduct polarimeters

In most case it does not work at all

The only substantial exception is ASTROSAT (Vadawale+2015).
Pixels of CZT 5mm thick have a reasonable fraction of Compton interactions at E>100keV.
Some of these scattered photons are absorbed by other pixels.
Laboratory tests showed that the corrected angular distribution is modulated by the polarization. Also the dependence of this modulation o the offset angle was easured and compared with simulations.

Vadawale2018



But it works only if Polarimetry is the core business

The turning point in X-Ray Astronomy

The optics was the turning point in X-Ray Astronomy

- Image extended sources
- Detect very weak sources because compares their flux with fluctuations of the background in the point spread function and not on the whole detector or ½ of that (as in experiments with collimators, modulation collimators or coded masks)

The Giacconi Revolution

Soon after the first discovery Giacconi sketched a strategy, based on the development of optics, to bring X-Ray Astronomy to the same level of other bands.

This strategy was in practice adopted by NASA

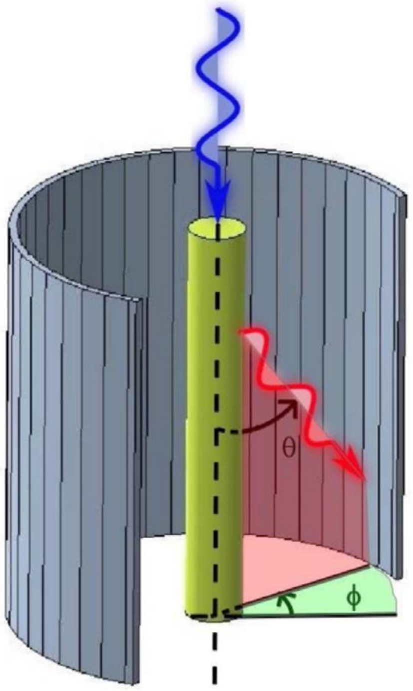
1) A satellite based on the same techniques of sounding rockets to have a first comprehensive view of X-Ray Sky → UHURU (1970)
2) A satellite with a first implementation of X.ray optics → Einstein (1978)
3) A satellite with a full exploitation of X-Ray optics (arcsecond resolution) → Chandra (1999)

Polarimetry started soon after with rockets (1971), Ariel-5 and and OSO-8 (1975) but missed the passage from 1) to 2).

A polarimeter was foreseen in the original design of Einstein but was removed
A polarimeter was foreseen in the original design of Chandra but was removed

The equivalent of Einstein was IXPE launched 43 years later!

Focal plane scattering?



A cylindric scatterer is positioned in the focus of a telescope. Scattered photons are detected by a set of vertical detectors around the scatterer.

The scatterer can be:
Li, LiH (encased with beryllium)
Beryllium
Plastic

Depending on the material of the scatterer the length of the scatterer and of the detector are optimized to maximize the sensitivity which is proportional to:

$$\boldsymbol{\varepsilon}^{1/2}\mu$$

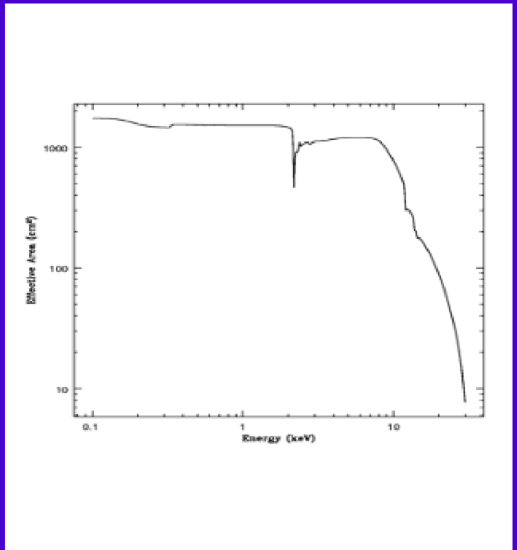
$$\rightarrow \boldsymbol{\varepsilon}\mu \text{ for } B \gg S$$

Historic Implementations (SXRP)

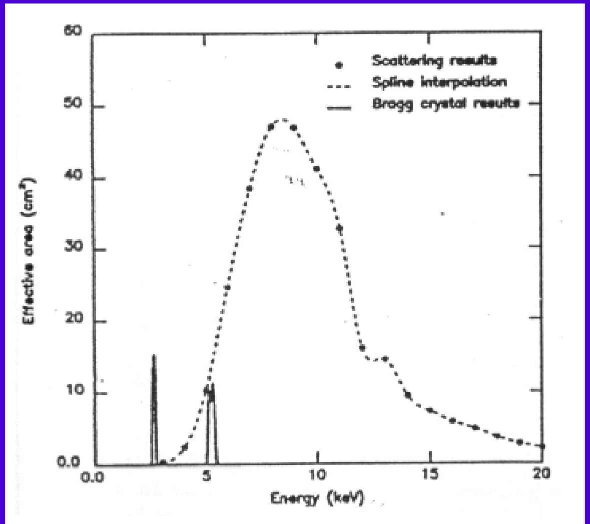
STELLAR X-RAY POLARIMETER
Aboard the SPECTRUM-X-γ MISSION

Harvard Smithsonian Center for Astrophysics, Columbia University,
Lawrence Livermore National Laboratories, Marshall Space Flight Center,
IASF-CNR Rome, IASFI-CNR Palermo.

SODART is an X-ray telescope with an effective area greater than 1000 cm^2 up to 8 keV. The effective area convolved with the response of the Bragg diffraction (15 cm2) and of the Thomson scattering (48 cm2) shows that the two methods are, very inefficient .



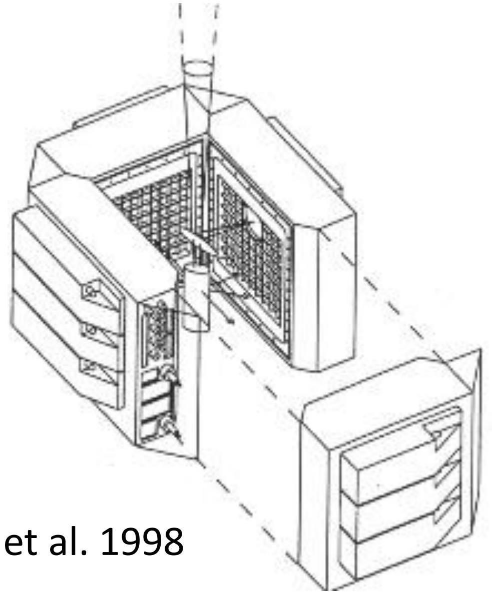
SODART effective Area



SXRP effective Area in the focus of SODART

An attempt to implement *classic* polarimetry as a focal plane science.

The detectors were proportional counters in a square well.



Soffitta et al. 1998

Starting from a telescope of > 1000cm^2 SXRP Bragg had an effective area of 15 cm^2 with a band width of 100 eV. At least it is imaging and the background is null.
The thomson polarimeter is "almost" 50 cm2 of area but the background was around 300 mCrab

This is not the way

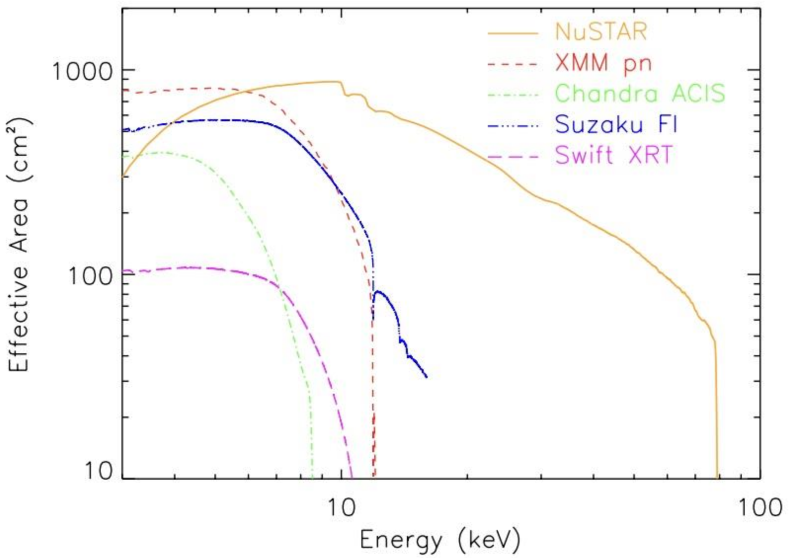
IXPE has shown that the focal plane is the solution.

Soffitta and Baracchini show that the Gas Photoelectric technique can be extended up to 20-25 keV

Clearly the room for focal plane polarimetry is in the hard X-Ray Range.

Can we use optics in Hard X-Rays?

With multilayer technique and with focal lengths of the order of 10 m the reflection of X-Rays can be extended to Higher energies. In practice up to the K edge of high Z elements (W, Pt,).



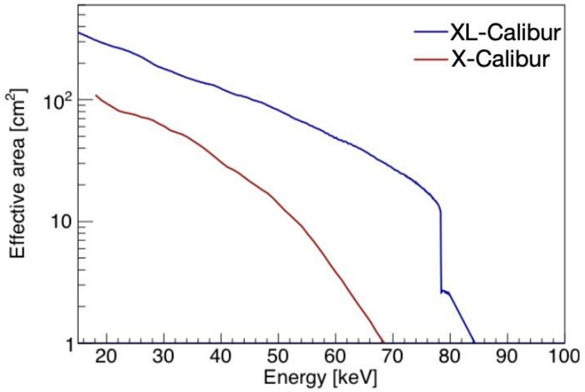
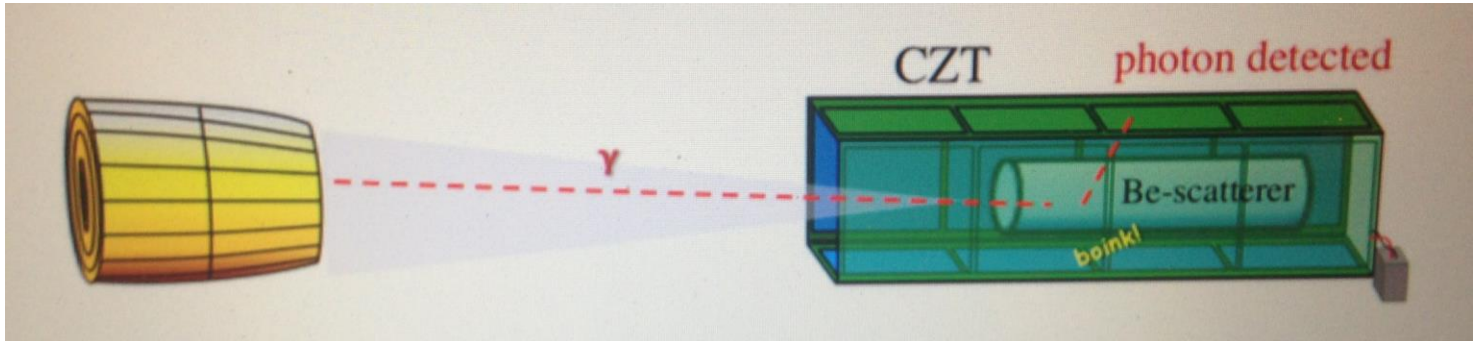


Figure 6: Energy-dependent effective areas of the *XL-Calibur* (*FFAST*) mirror (upper curve) and the *X-Calibur* (*InFOCμS*) mirror (lower curve) [40].

X-CALIBUR

X-Calibur is an experiment of Hard X-Ray Polarimetry designed to be flown aboard Long Duration Stratospheric Balloons. It is based on a Multi-layer Hrd X-Ray Optics with a focal length of 8m (TBC). A cylinder of Beryllium scatters photons near the foca plane. Scattered photons are absorbed by a Cadmium Zinc Telluride detectors disposed around to build a square well. From the angular distribution of the scattered photons the amount and angle of linear polarization is derived.
The sensitive range is 15 – 35 keV



X-CALIBUR is potentially of high interest to complement IXPE observations. Likely IXPE will not observe any cyclotron resonance frequency In the 15 – 35 keV a good number of them is included. Around the resonance the polarization should be very high. At lower energies 2 – 8 keV IXPE will be very sensitive. But some caution is needed.

X-Calibur has pointed GX301-2 on december 2008 for 8 hours with an equivalent time spent for background. The flight, planned to last weeks, aborted.

X-CALIBUR ACTUALLY

X-CALIBUR is potentially of high interest to complement IXPE observations. Likely IXPE will not observe any cyclotron resonance frequency In the 15 – 35 keV a good number of them is included. Around the resonance the polarization should be very high. At lower energies 2 – 8 keV IXPE will be very sensitive. But some caution is needed.

Only upper limits were detected with X-Calibur. But with a long duratio flight we could expect errors 4-5 times smaller. For a high polarization near the cyclotron frequency this should be interesting

Table 1. *X-Calibur* 15-35 keV polarization results. Errors on p and ψ are on 90% Confidence Level. The polarization angle of the third data set is unconstrained on the 90% confidence level.

Phase Interval	$\mathcal{Q}$ [%]	$\mathcal{U}$ [%]	Deviation from $p=0$ [σ]	p [%]	ψ [°]	Upp. Lim. p (90% CL) [%]
All (0-1)	18.4 ± 19.4	20.2 ± 19.4	1.41	27^{+38}_{-27}	21 ± 43	46.9
Main Pulse (0.8-1.14)	26.6 ± 21.2	16.1 ± 21.1	1.47	32^{+41}_{-32}	30 ± 40	52.3
Bridge and Sec. Pulse (0.14-0.8)	8.3 ± 33.5	24.6 ± 33.6	0.78	27^{+55}_{-27}	10	62.2

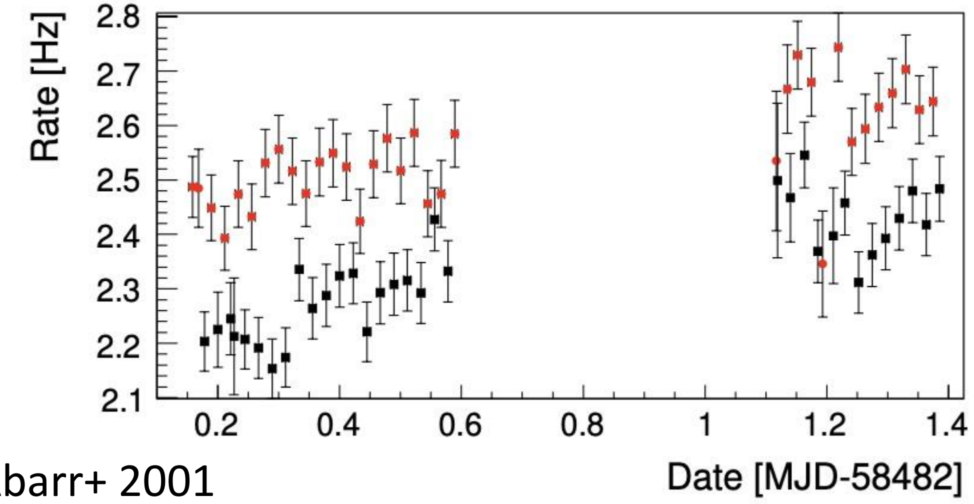
Also interesting Swift, NICER and Fermi/BAT pointed simultaneously.

If X-Calibur is active during IXPE a contemporary should be organized.
Anyway Kraszinski and Kislat are big part of TWG of IXPE

FIRST OBSERVATION WITH X-CALIBUR

Long Duration Balloons are only launched from Arctic or Antartic sites
McMurdo, Antartica 78°S   Longyearbyen, Svalbard 78° N
But the observation cannot be performed at too high inclination. Assuming that this must b < 35° we have that **δ**<-43° or **δ**>+43.
GX 301-2 is at **δ**=-62° . A good choice for sure but not completely free.

Our freedom to select the target is very limited. Anyway this is typical in all balloon experiments.



Abarr+ 2001

Figure 10. *X-Calibur* 15-35 keV detection rates on-source (red) and off-source (black) revealing an average source count rate of 0.23 Hz. The rates are raw rates in the sense that they have not been corrected for the flight altitude and elevation-dependent atmospheric absorption.

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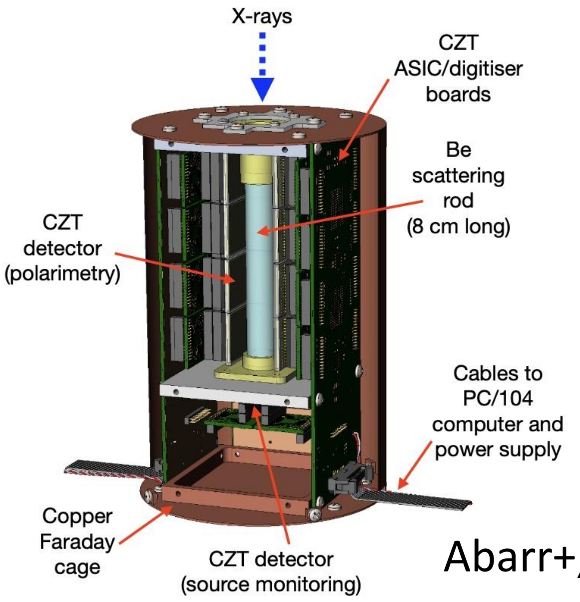
The background is the problem

The optics collect photons from (let us say) 500 cm^2 and focus them in a psf of $1mm^{2.}$ With an imaging detector the photons from the source are compared with the fluctuation of the background inside the psf.
With a scattering device the photons from the source are scattered all around and are to be compared with the fluctuations of the background proportional to the surface of the absorbing detectors.
In practice X-CALIBUR is wasting the advantage to be in the focus of an optics.

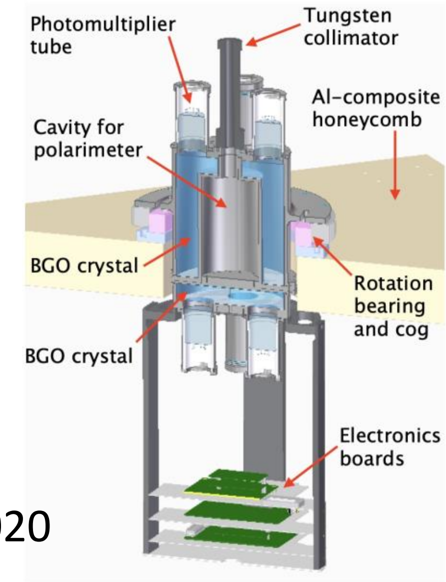
The Team is passing from
X-CALIBUR → XL-CALIBUR

A larger telescope
A much heavier anticoincidence shield

This new design should keep the BKG level below a good number of brighter sources.



Abarr+, 2020



Modern Implementations (XL-Calibur)

The only implementation of the concept of focal plane

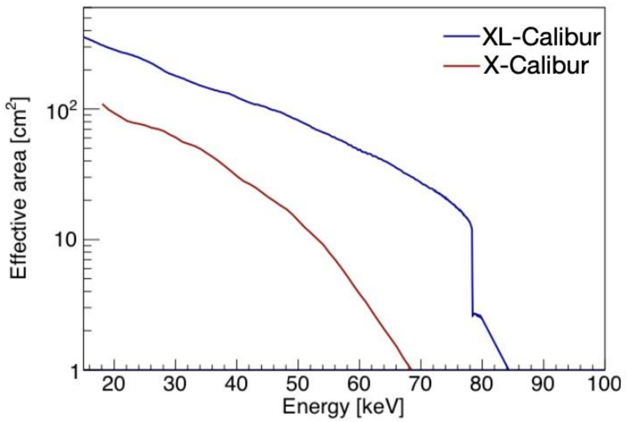


Figure 6: Energy-dependent effective areas of the *XL-Calibur* (*FFAST*) mirror (upper curve) and the *X-Calibur* (*InFOCμS*) mirror (lower curve) [40].

Abarr+, 2020

My view

The scatterer can be also for focal plane polarimeters a detector. The only viable choice is plastic scintillator. This technique has been studied in IAPS (Fabiani+ 2021) and in Ahmedabad (Chattopadhyay&Vadawale 2023). Both groups performed simulations and experiments.

If we remind the modulation factor vs polar angle

$$\mu(\theta) = \frac{N_{\max}(\theta) - N_{\min}(\theta)}{N_{\max}(\theta) + N_{\min}(\theta)} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_{\phi=\frac{\pi}{2}} - \left(\frac{d\sigma}{d\Omega}\right)_{\phi=0}}{\left(\frac{d\sigma}{d\Omega}\right)_{\phi=\frac{\pi}{2}} + \left(\frac{d\sigma}{d\Omega}\right)_{\phi=0}} = \frac{\sin^2\theta}{\frac{E}{E'} + \frac{E'}{E} - \sin^2\theta}$$

It is clear that the information is
In scattering around 50° to 130°.

But the energy given to the electron for scattering around 90° is very low.

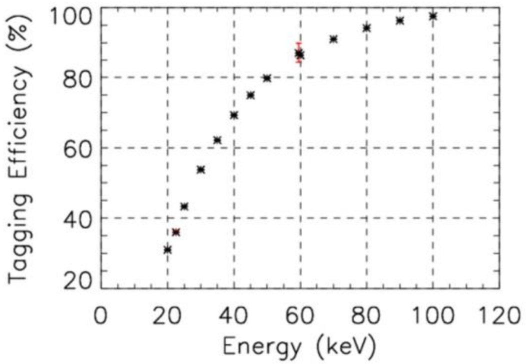


Fig. 13. Simulated tagging efficiency (black) plotted with measured one (red) for ^{109}Cd and ^{241}Am. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

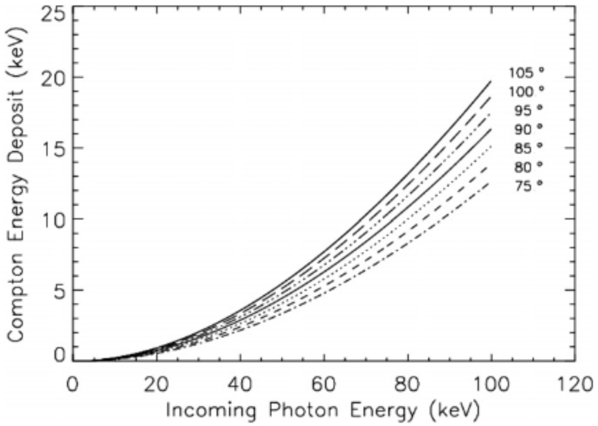


Fig. 3. Compton energy deposits calculated with Eq. (8) for some scattering angles around 90°.

Fabiani+ 2021

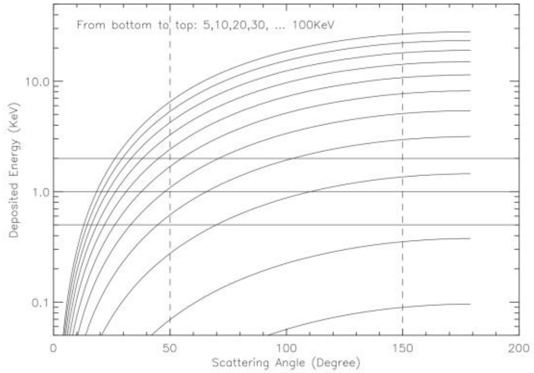


Fig. 2 Recoil energy of photon as function of scattering angle and incident photon energy. The curves from bottom to top are showing the electron energy for 5 KeV, 10 KeV, 20 KeV… 100 KeV respectively

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Ambitious

To fully exploit the advantage of optics, in terms of sensitivity, we should be able to detect in a cylinder of plastic scintillator signals of the order of 1 to 10 keV (hopefully 0.5 keV for 20 keV).

The coincidence with signals in the absorber and the compatibility in pulse height should lower the background to almost 0. The loss of efficiency will be widely compensated.

Futher improvements include:

- A cylindric design for the absorber
- Some shielding
- A vertical segmentation to exclude (or underweight) photon scattered a large angles. Easy for the absorber but very ambitious for the scatterer (Thin photodiode?).

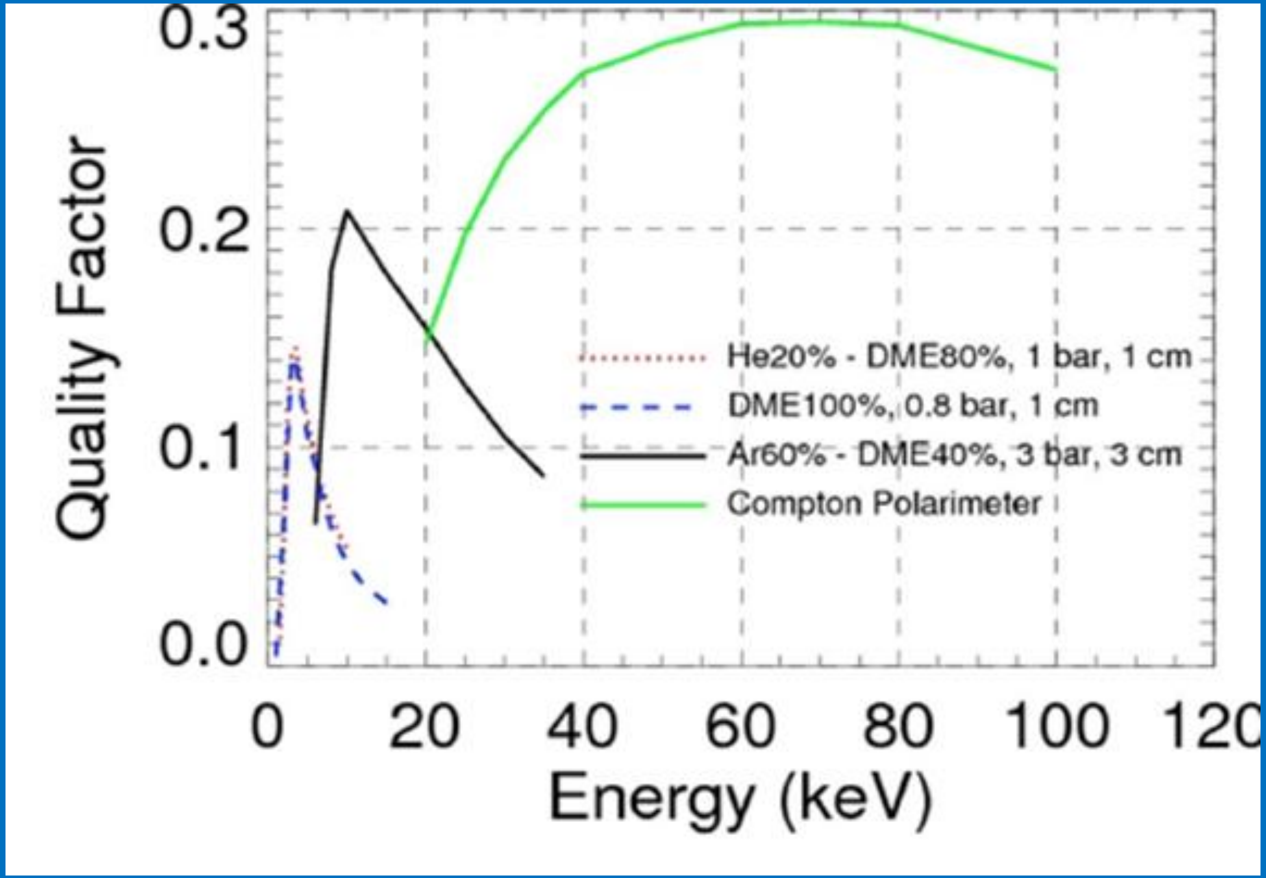
And anyway

If a Argon filled photoelectric detector is used up to 25 keV the scattering stage can be less effective at <30 keV. But definitely at >30 keV it will be much better than the passive configuration.

Detectors sensitive to different bands can be hosted side by side in a payload but, with a not trivial work of R&D some of them could be stacked

Even though the scatterer is long with a relevant effect of defocusing with a optics like NUSTAR a segmentation of the scatterer to do imagiung is feasible. But the cost in terms of band could be too much.

Three polarimeters for different energies



This is what we proposed more than 10 years ago following the NHXM proposal at ESA M2 and for eXTP

To resume

1. A multi-layer Optics with an active scatterer in the focus is the way in coincidence with a cylindric absorber
2. The first point to attack is the tagging efficiency, namely to lower the treshold in the scatterer, by optimizing the sensor[s].
3. Also other organic scintillators should be studied together with optimal wrapping (we tried polyterphenyle).
4. Stacking Photoelectric Gas Detector with Scattering should be studied.