CuPol: fitting a photoelectric X-ray polarimeter for solar flares in a CubeSAT

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On the behalf of the
High Energy Astrophysics and Related Technology Group
at the
INAF – IAPS (Rome, Italy)
in collaboration with
IMT (Rome, Italy)

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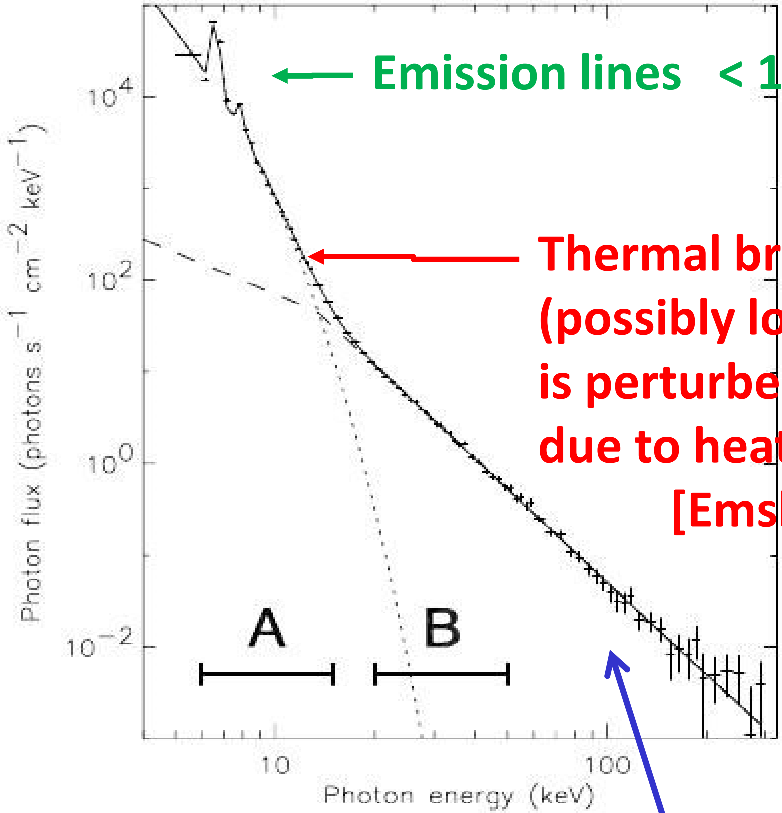
OUTLINE

- X-ray polarimetry as a diagnostics for solar flares
- Photoelectric polarimetry with the Gas Pixel Detector (GPD)
- Measurement simulations
- CuPol mission study

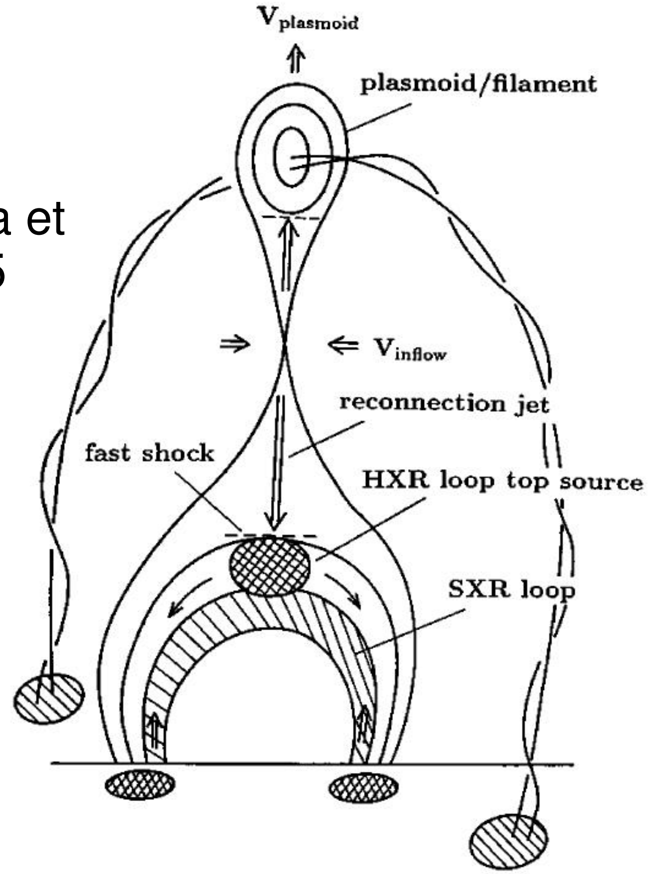
SOLA FLARES X-RAY POLARIMETRY



Emission lines < 10 keV [Doschek 2002]

Thermal bremsstrahlung up to 20 keV
(possibly low polarized if Maxwellian distribution of velocity is perturbed by plasma expansion along magnetic field lines due to heat propagation)
[Emslie & Brown 1980]

Non-thermal bremsstrahlung >20 keV
(highly polarized up to 40%)
[Zharkova et al. 2010]

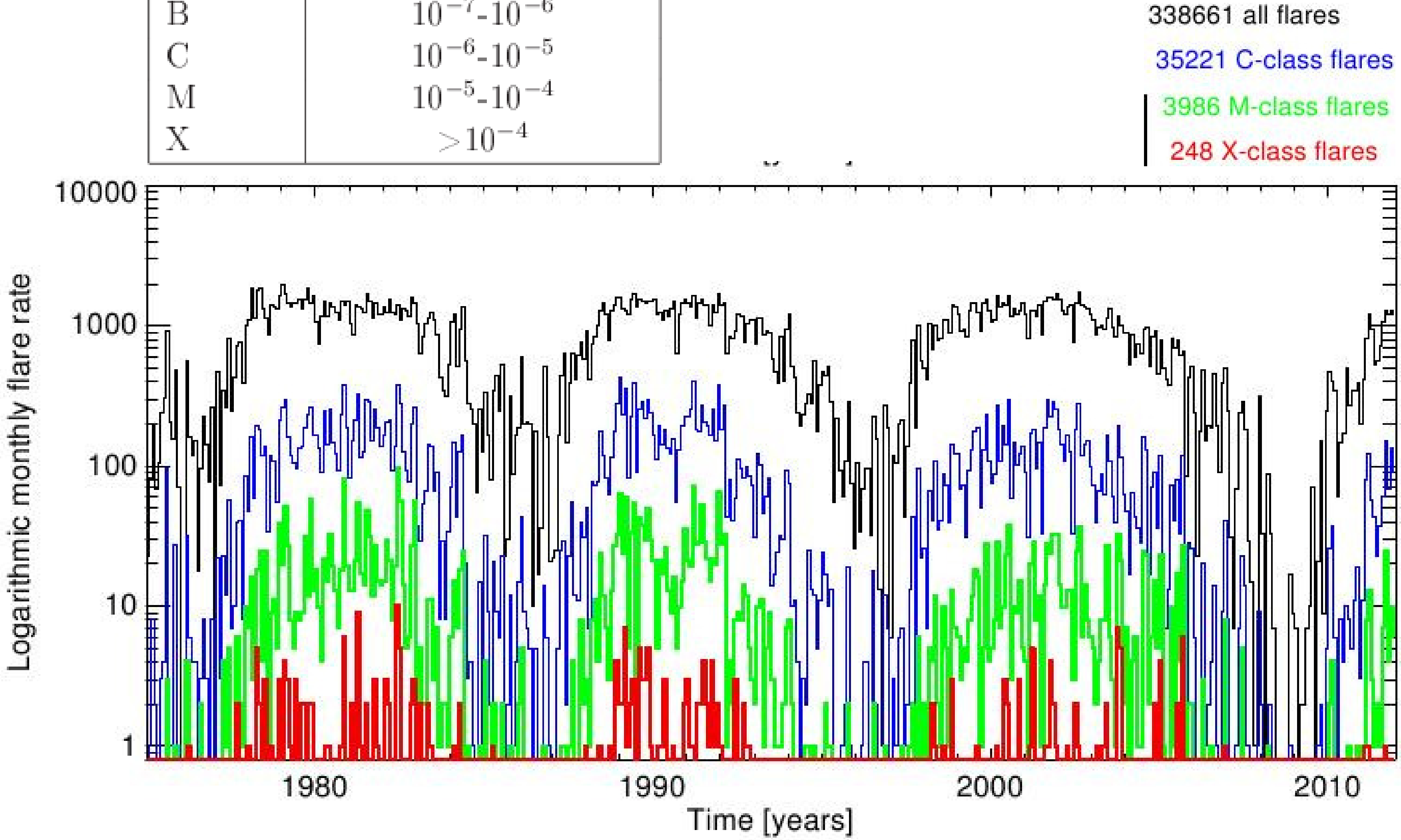


Shibata et al.1995

Moreover:
Scattering of radiation… therefore still polarization

MONTHLY FLARE RATE

Classes	Flux (peak) 0.1-0.8 nm [W/m^2]
A	10^{-8}-10^{-7}
B	10^{-7}-10^{-6}
C	10^{-6}-10^{-5}
M	10^{-5}-10^{-4}
X	$>10^{-4}$

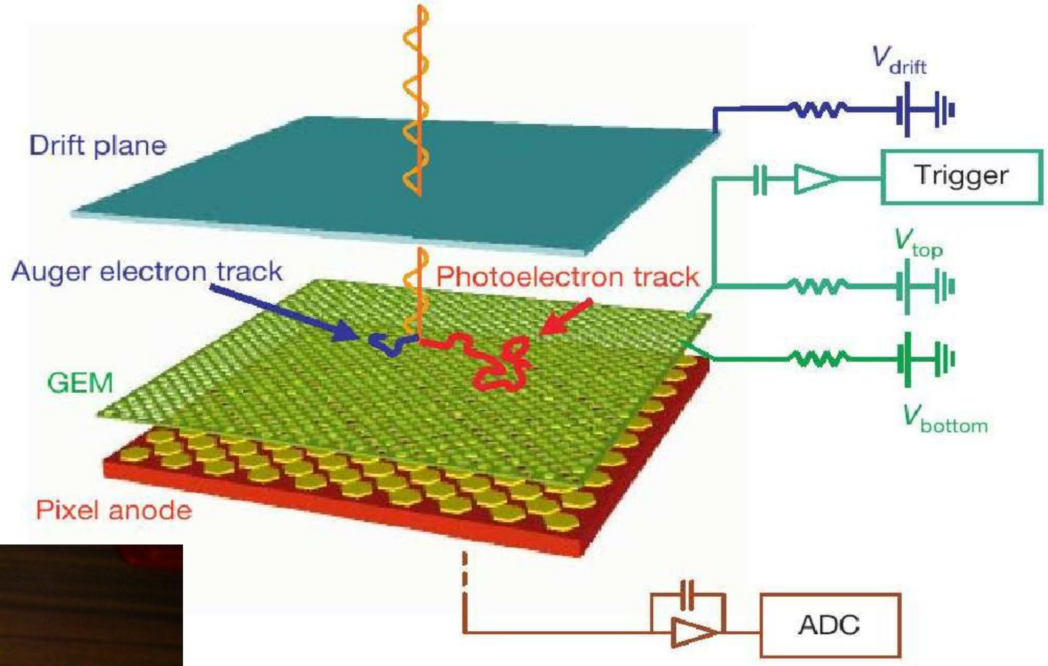


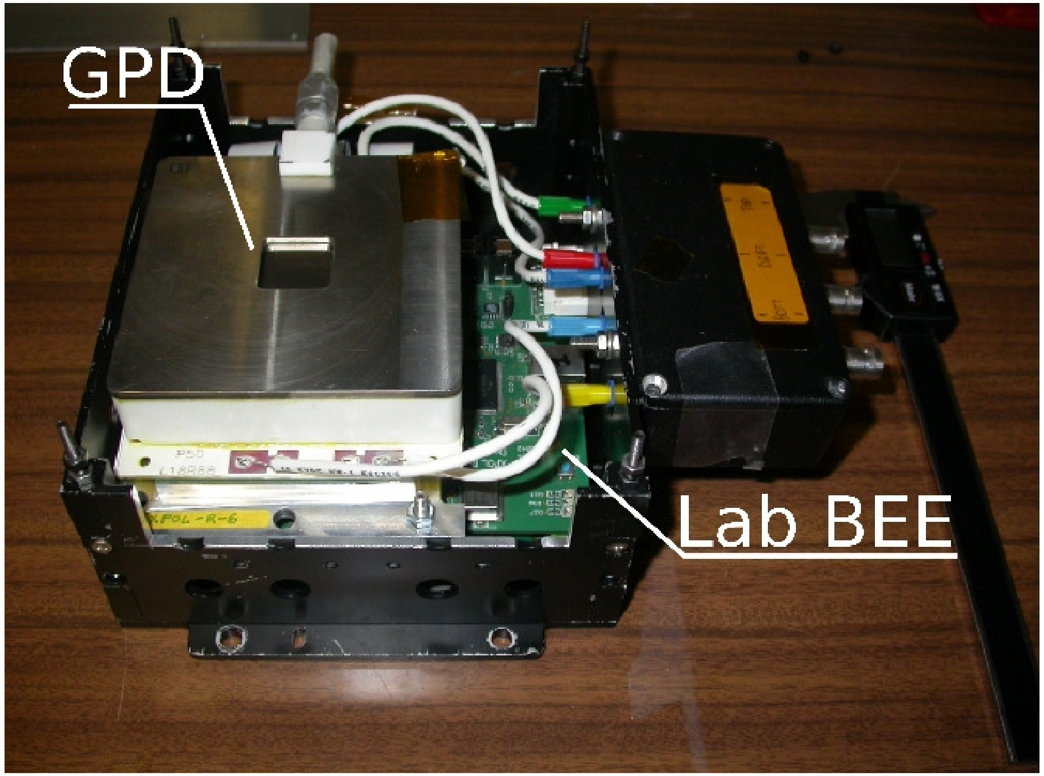
PHOTOELECTRIC POLARIMETRY: the GPD

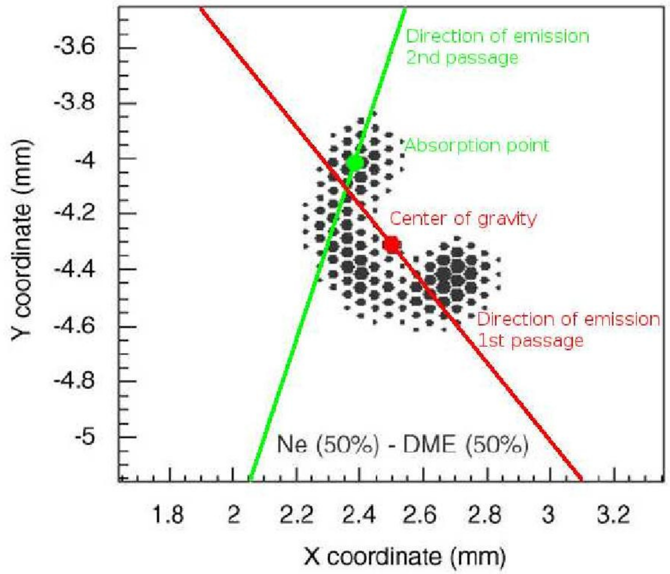
Cross section K-shell

$$\frac{d\sigma_K}{d\Omega} \propto \frac{3\sin^2\theta\cos^2\phi}{(1-\beta\cos\theta)^4} \propto \cos^2\phi$$

F: Azimuthal angle of emission of the photoelectron







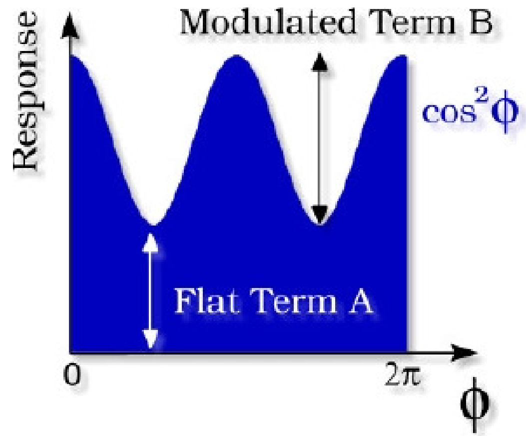
POLARIMETRY BASICS

Modulation curve

$$N(\phi) = A_{\mathrm{P}} + B_{\mathrm{P}} cos^2(\phi - \phi_0)$$

Polarization Degree

$$\mathcal{P} = \frac{1}{\mu}\frac{B_{\mathcal{P}}}{2A_{\mathcal{P}} + B_{\mathcal{P}}}$$



Minimum Detectable Polarization (at 99% confidence level) [Weisskopf et al. 2010]

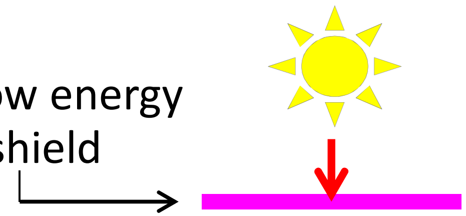
$$\mathrm{MDP} = \frac{4.29}{\mu \cdot R} \cdot \sqrt{\frac{R+B}{T}}$$

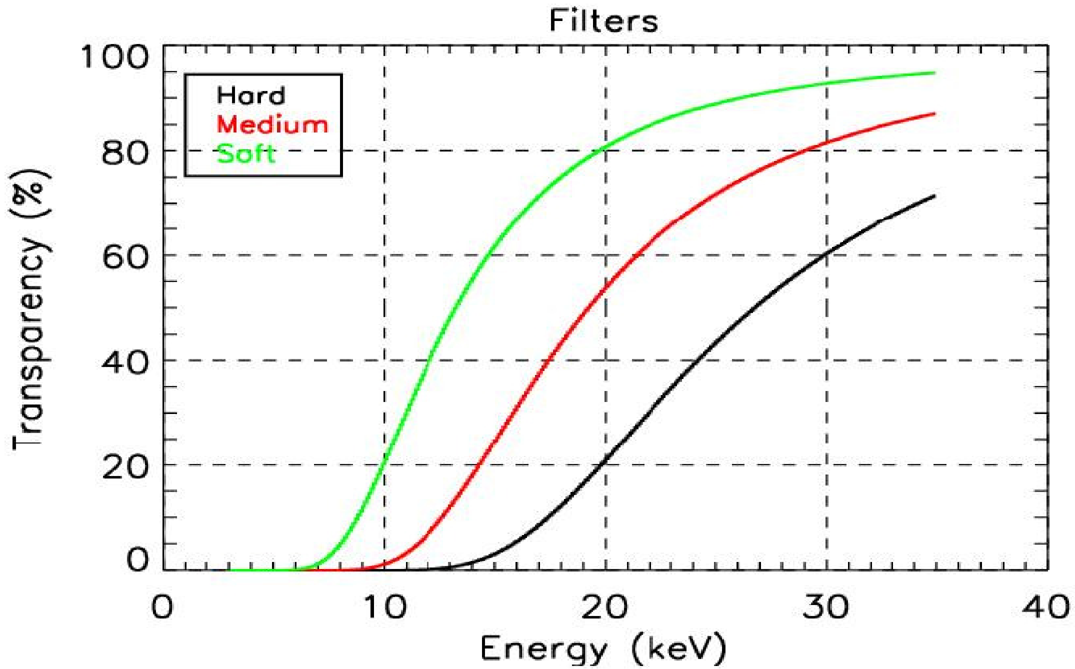
R : source rate
B : background rate
T : integration time

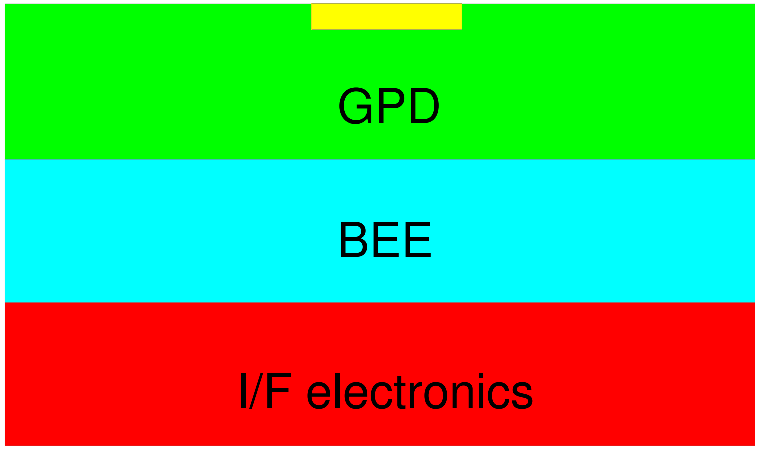
THE POLARIMETRIC PAYLOAD LAYOUT

1 GPD (MEP): Ar70%, DME30%,
3 atm, 3 cm, 2.25 cm^2
10-35 keV

Metallic low energy
radiation shield







Height (boards+GPD+HV)	< 10 cm
Total Weight	500 g
Total Power	< 5 W

MEASUREMENT SIMULATIONS

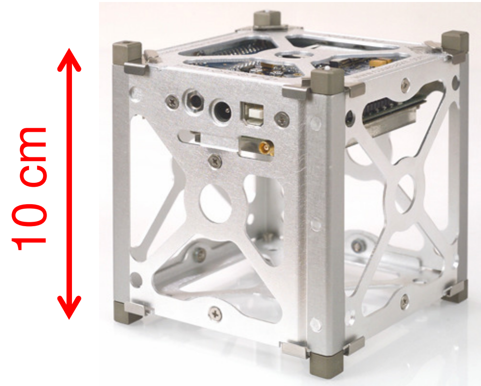
Preliminary results by assuming a constant 40% polarization degree of the non-thermal component (thermal component assumed unpolarized) of some real flares. Energy spectra from RHESSI data (coutesy of Prof. Sam Krucker)

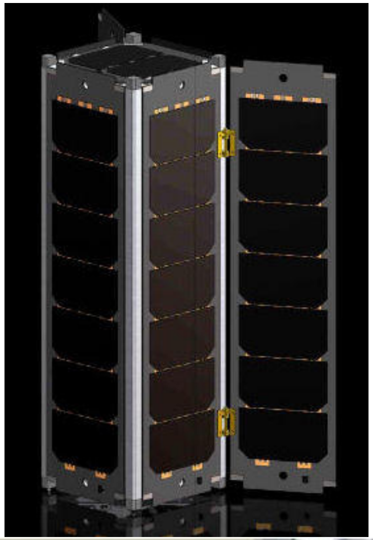
Flare Class	Filter type	Energy cuts (keV)	Rate (cts/s) [1GPD]	Counts [1GPD]	Measured pol. degree (%)	Measured pol. degree 1-σ error (%)	Measured pol. Degree significance	Measured pol. angle 1-σ error (deg)	MDP (%)

Tabel 4: Sensitivity estimation and simulation of measurements with real filters and cuts on photon energy. It is also shown the significance of the measured polarization degree (pol. degree/1-σ error).

WHAT ABOUT A CUBESAT?

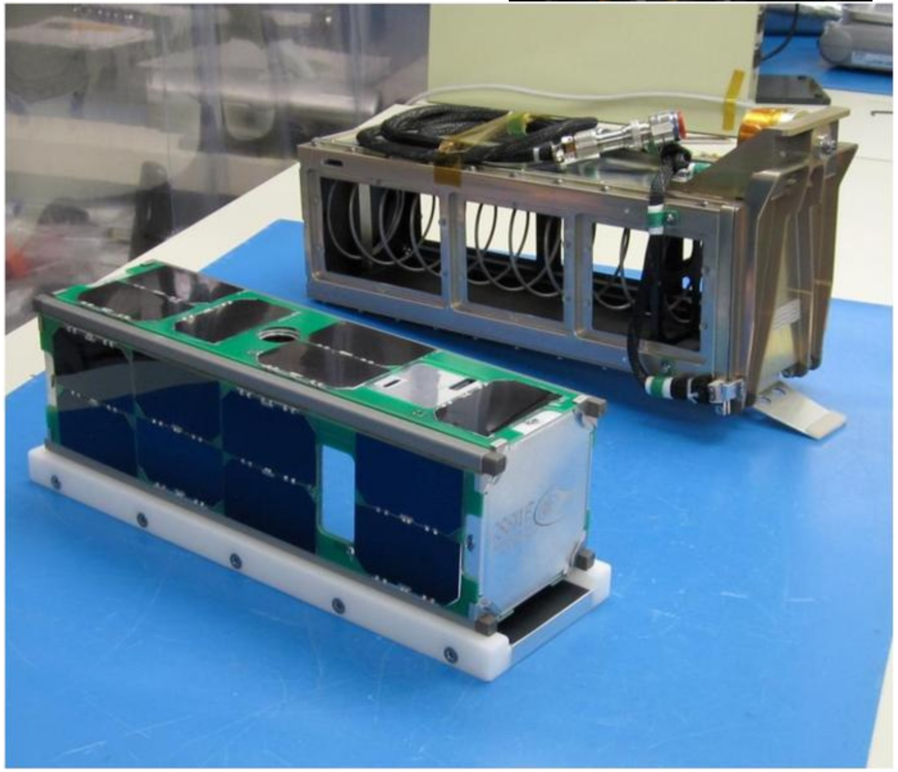
What is a cubesat?
- Very small satellite composed typically by 1, 2, 3, … units
- Each unit is a cube 10 cm of side
- Payload max : 1 Kg each unit
- Power : about 1W each face
- Costs: of the order of 1MEuro





Typical Cubesat Goals
- Mechanical and electronics testing
- University educational programs in collaboration with space agencies

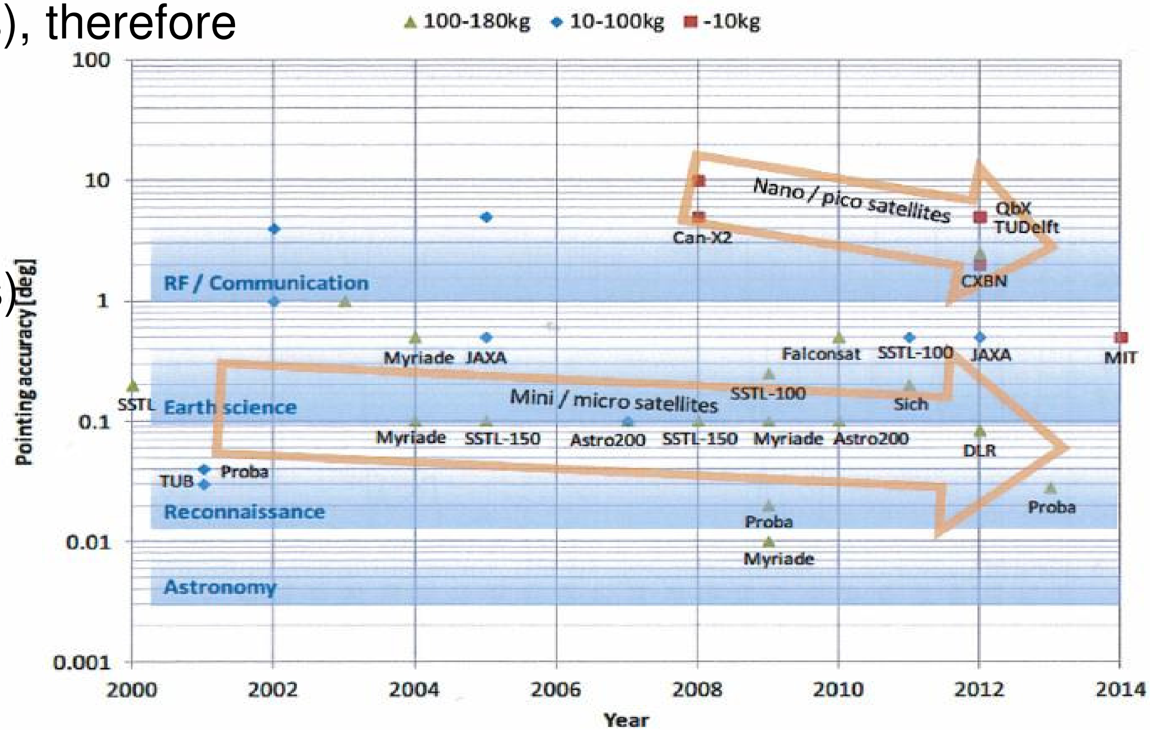
Our Goal
Use a Cubesat also for high level science by measuring solar flares X-ray polarization



Current status of the project
Phase study in collaboation between:
- INAF-IAPS in Rome (Italy) [Polarimetry payload]
- IMT industry in Rome specialized in Cubesat assemblement

MISSION CONCEPT

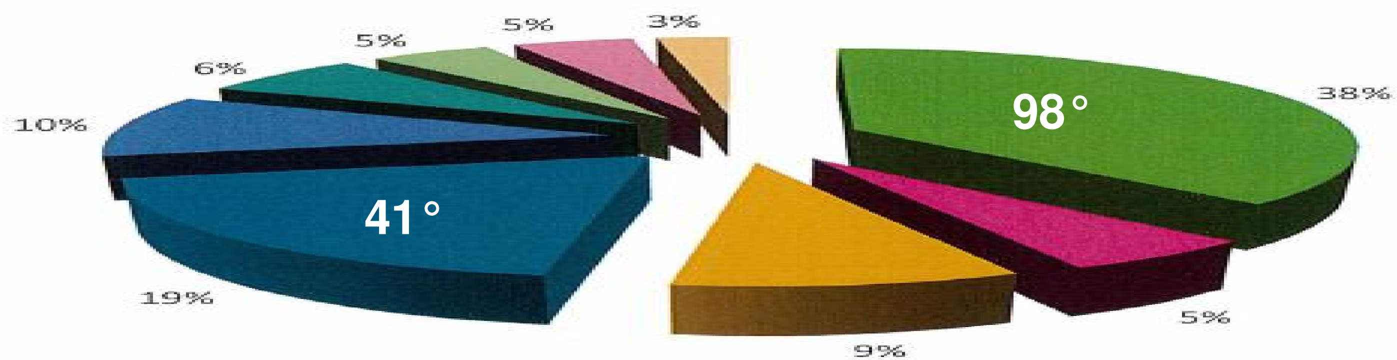
- 3U (preferred) or 6U in two possible configuration sudied
- About 2° of pointing accuracy
- On board computer manage the bus and payload operations
- Downlink of scientific data requires high data rate to download data from memory before its saturation due to new events (>500 kbps), therefore S or X band is needed
- Telemetry and housekeeping can be transmitted with a low data rate (UHF/VHF bands)
- Passive thermal control (or if needed active thermal control only during eclipses)



ORBIT PROBABILITY - inclination

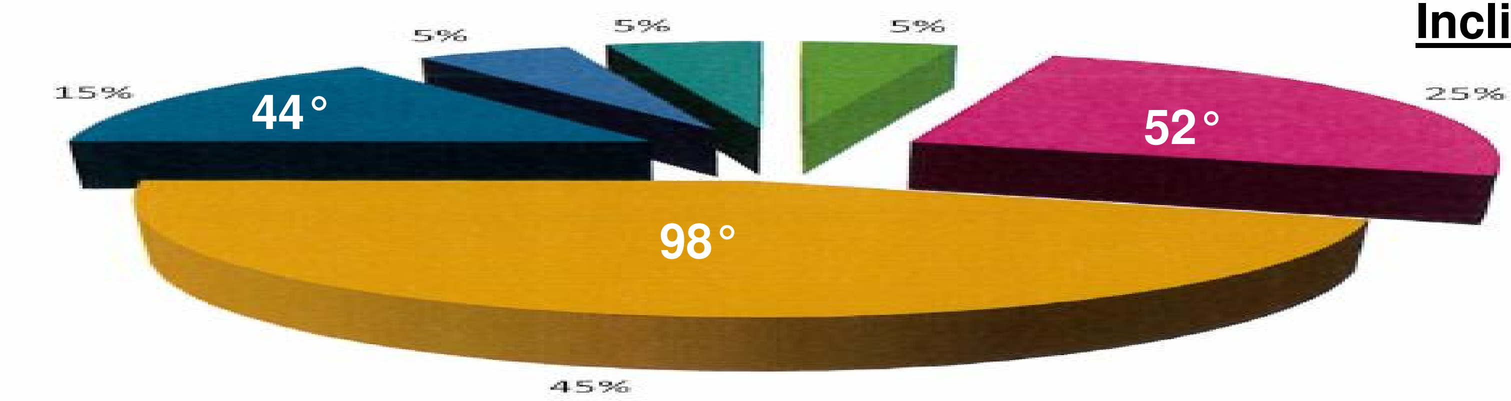
- Piggy back of other mission launches

- A statistical study on the past 109 cubesats launched was performed, as for the future 20 launches up to 2017 taking as reference these parameters:
    - orbital life time
    - disturbing torques
    - debris and micrometeoroids impacts
    - amount of data down link
    - orbital decay time larger then few years but no more then 25 years



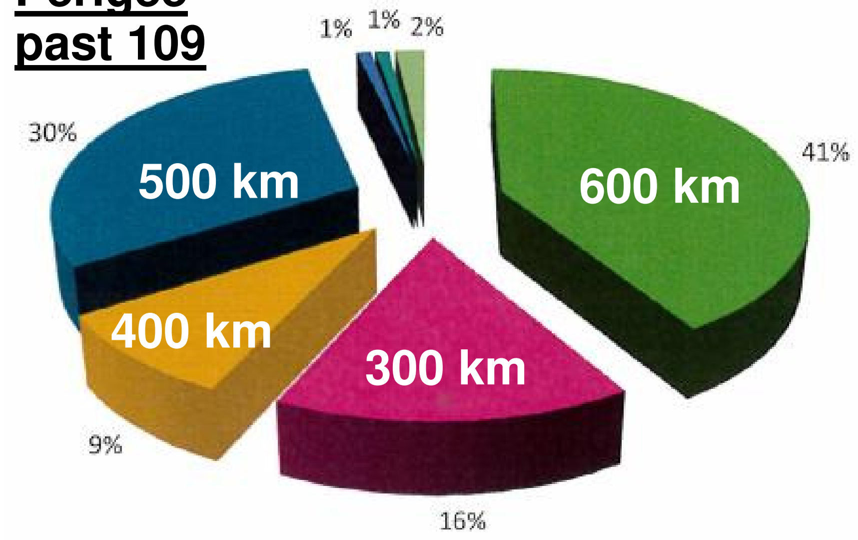
Inclination past 109

Inclination future 20

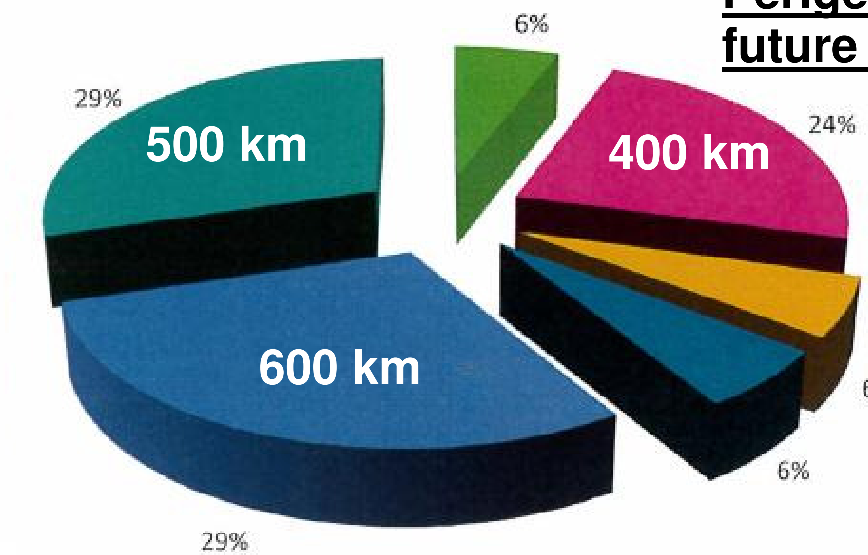


ORBIT PROBABILITY - perigee

Perigee past 109

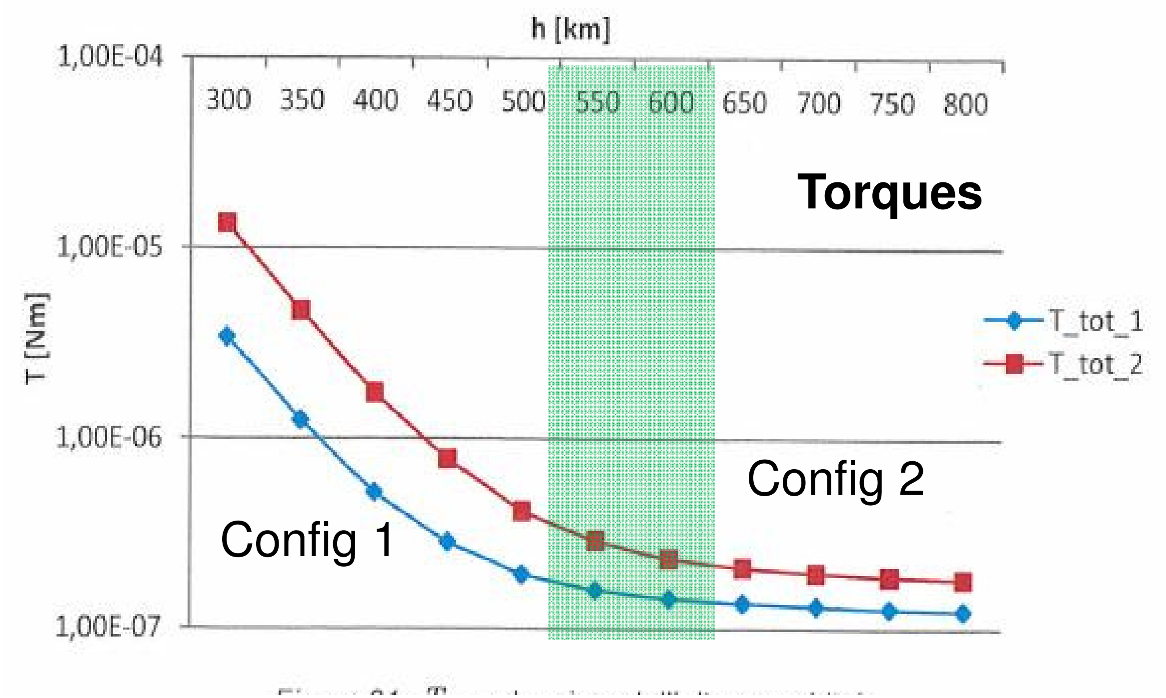


Perigee future 20



Typically Cubesats are launched with:

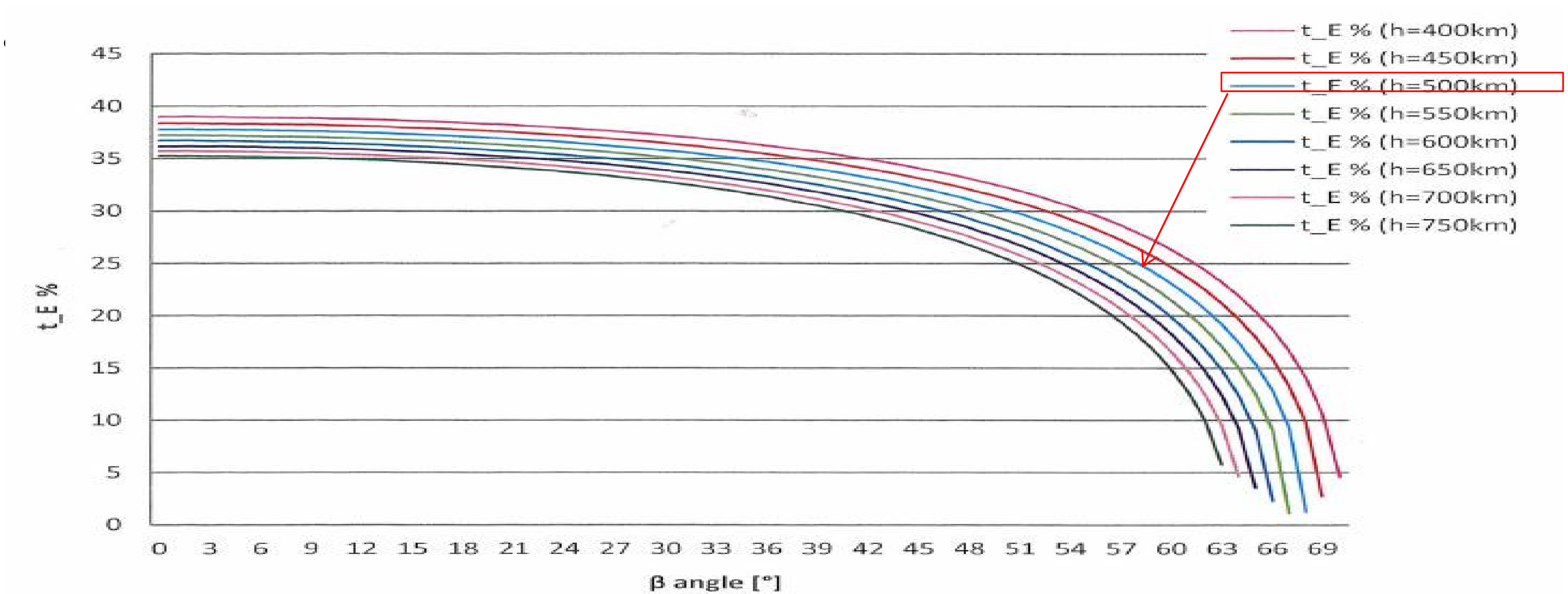
- orbital inclination 98° (SSO) or 40°-50°
- Quasi circular orbit with perigee of 500-600 km (LEO)



ORBIT PROBABILITY - β angle

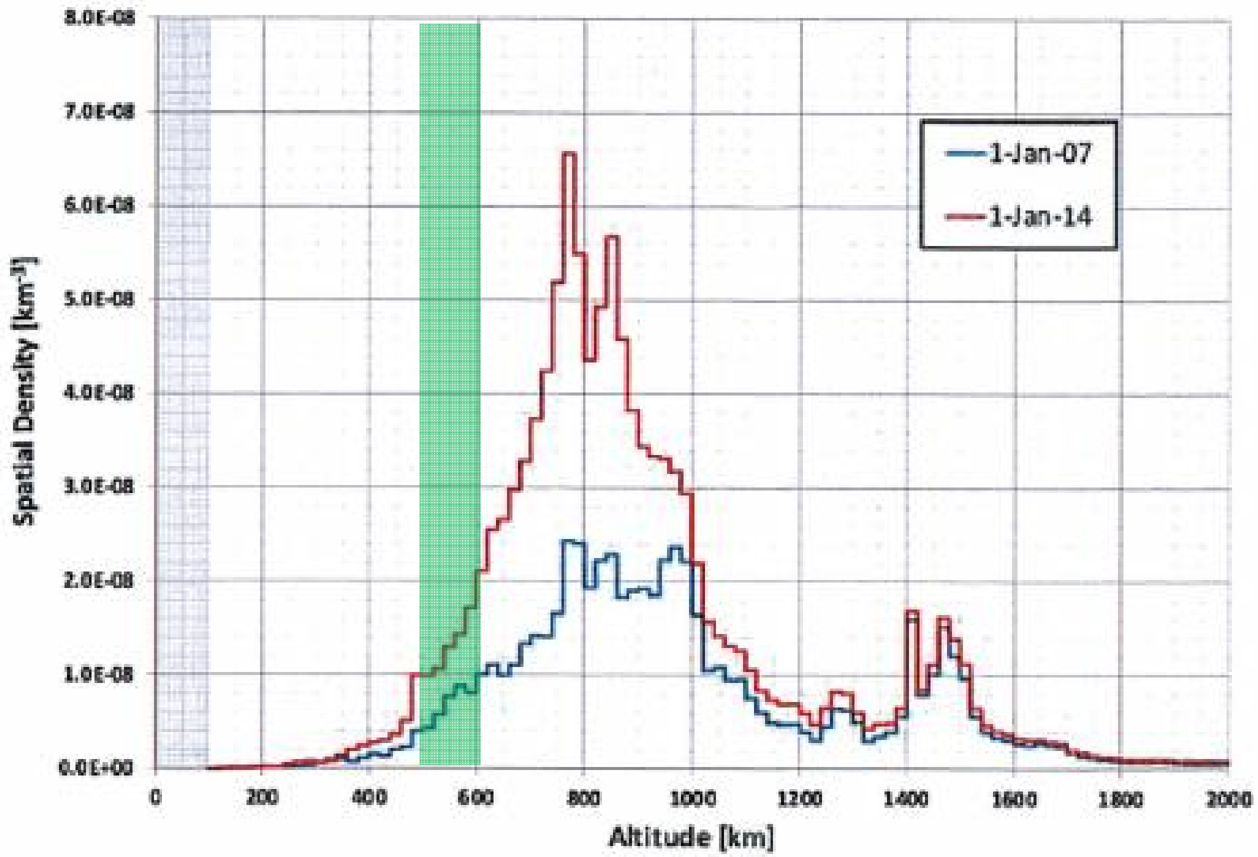
View from above Earth, looking down on N Pole (orbit i = 90°)

- The study of β angle allows to evaluate the fraction of time in eclipse.



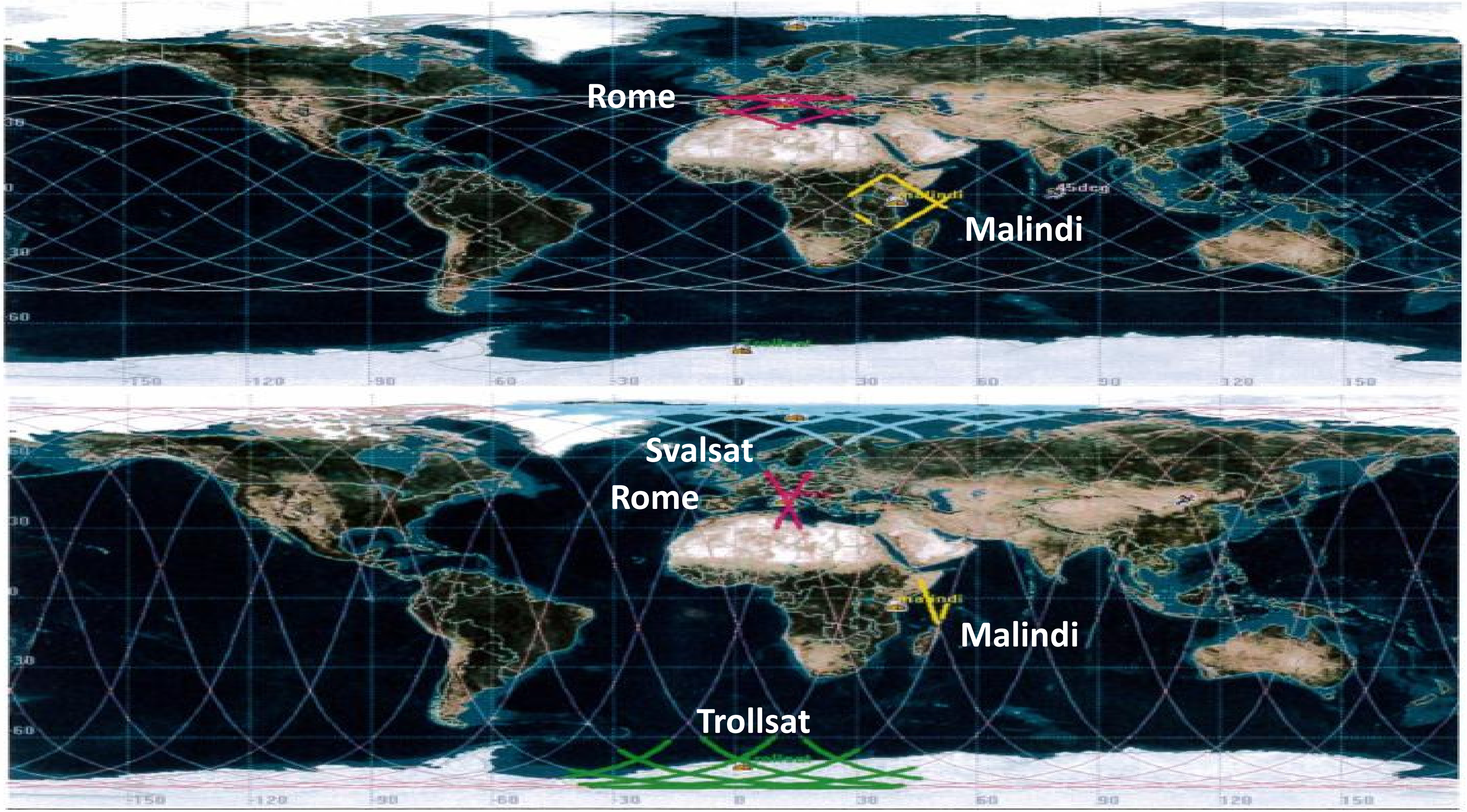
ORBIT PROBABILITY - debris

- The two configurations of cubesat are interested by the same incidence of impacts
- More probable small debris not penetrating the spacecraft (from 0.01 cm to < 0.1 cm)
- The probability of impact increase rapidly by incresing the orbit altitude
- Polar LEO induces a larger number of impacts with espect to a less inclined LEO
- An inclined circular LEO of 500 km of altitude with an inclinaiton of about 50° would be good and also probable



ORBIT PROBABILITY – data downlink

- Assumed one M5 flare each day and one X10 flare each month at solar maximum
- 7 MB/day for M5 flares
- 1GB/month for X10 flares
- Possible ground stations are: Rome (private IAPS/IMT to built), Malindy (ASI), Svalsat and Trollsat (KSAT Norwegian private company)



CONCLUSIONS

- CuPol is a cubesat mission that would allow to measure X-ray polarization of X-class and M-class solar flares with high significance
- The scientific goals can be reached within the cubesat mission framework
- A mission study is in progress to define a mission proposal and be ready for future calls
- <u>Thanks to COST for the support of this research in particular by funding 3 STSMs I attended and the participations to COST meetings.</u>

X-RAY POLARIMETRY OF SOLAR FLARES

SOLAR FLARES X-RAY EMISSION

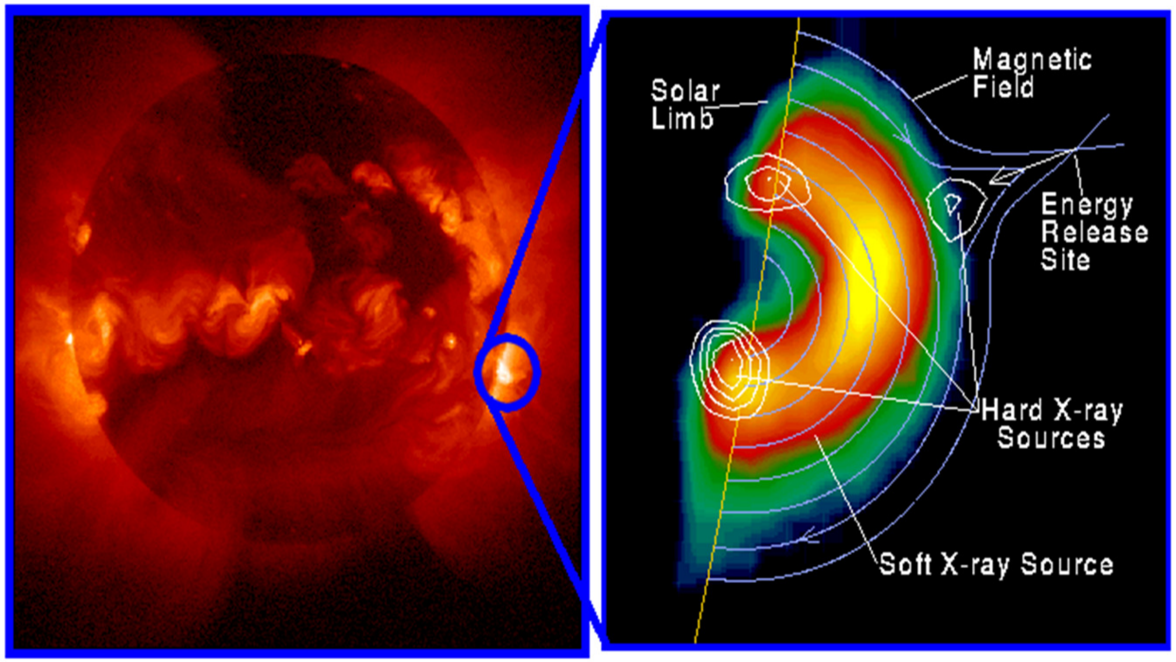
- Magnetic reconnection
- Acceleration of particles

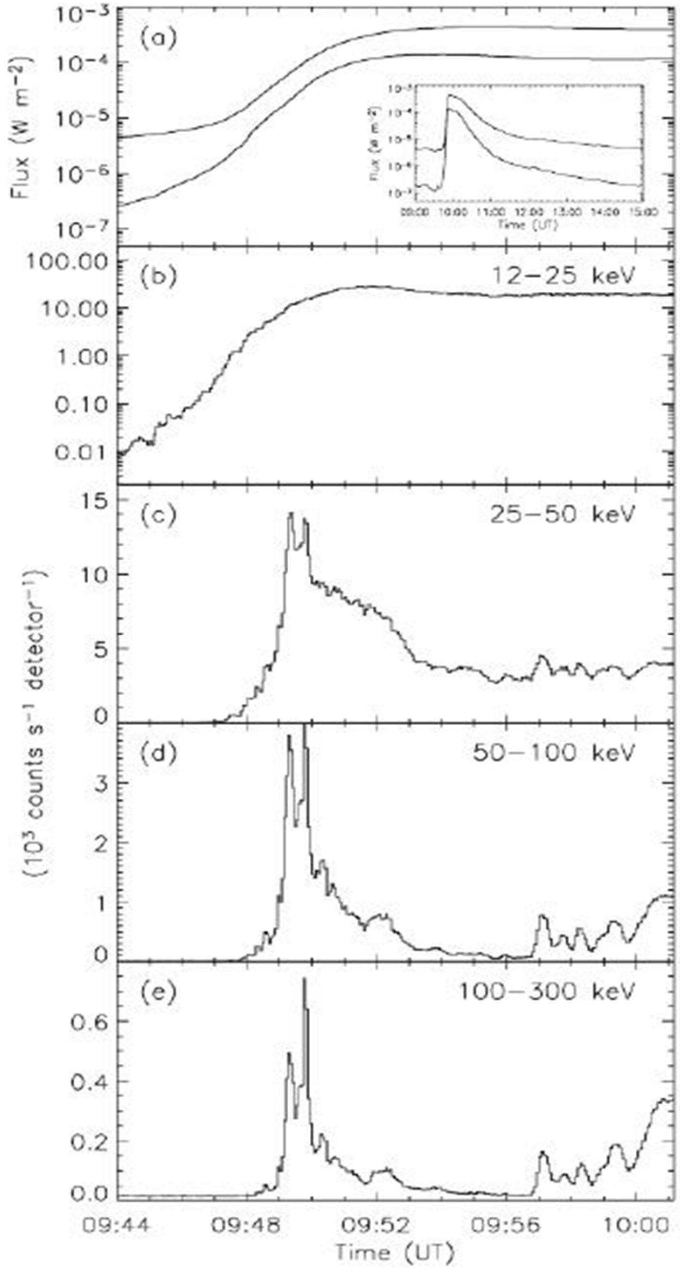
(lower atmosphere and solar wind)

- Plasma heating

X-RAY POLARIZATION

- Non-thermal Bremsstrahlung polarized emission,
- Local magnetic field geometry,
- Active regions environment





PRESENT RESULTS

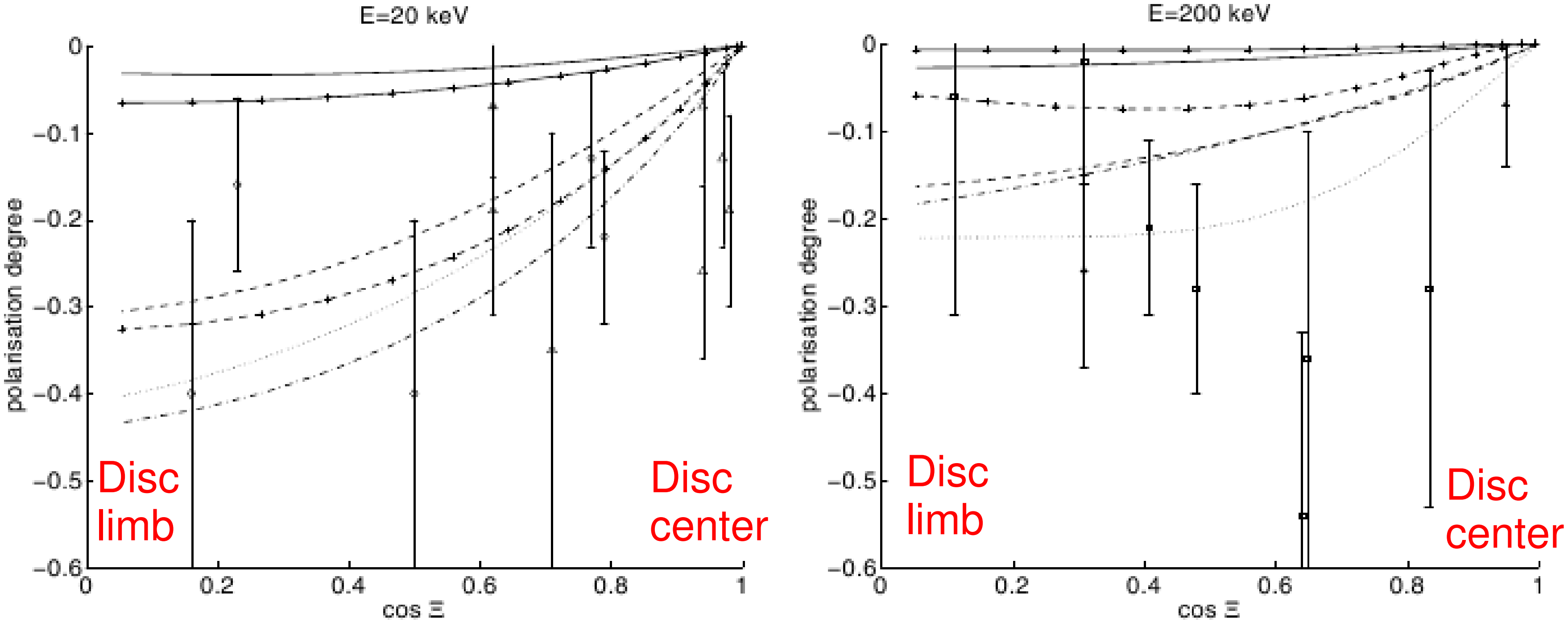


Fig. 10. Comparison of the simulations of HXR bremsstrahlung polarization for 20 keV (*left plot*) and 200 keV (*right plot*) produced for different position angle on the solar disk ($\cos\Xi = 1$ in the disk center and 0 on the limb) by a wider electron beam with $\Delta\mu = 0.2$ and the energy flux of 10^{10} erg cm^{-2} s^{-1} ($\gamma = 3$: C+E model – solid line, C+E+B model – solid line with crosses; $\gamma = 7$: C+E model – dashed line, C+E+B model – dashed line with crosses) and by more collimated ($\Delta\mu = 0.02$) electron beam (C+E model) with $\gamma = 7$ and the initial energy fluxes of 10^{10} (dot-dashed lines) and 10^{12} erg cm^{-2} s^{-1} (dotted lines). The observation results are plotted as follows: diamonds correspond to the observations of Tindo et al. (1970, 1972a,b) at 15 keV, triangles – to the observations of Tramiel et al. (1984) at 16-21 keV, squares – to the observations of Suarez-Garcia et al. (2006) at 100−350 keV, and asterisks – to the observations of Boggs et al. (2006) at 200−400 keV.

Models

C = particle collisions

E = beam electron self induced electric field (Zharkova et al. 2010)

B= magnetic field convergence

PRESENT RESULTS

Small Effective Area and high signal threshold:

→ ***RHESSI*** (spectrometer, Compton scattering among Ge rods
to try to measure polarization).
Summary of results by Suarez-Garcia et al. 2006

→ Compton events in the photoelectric/Compton cross-section transition
(Energy range 100-350 keV)

→ High probability to scatter X-ray photons out of the detector active region

Flare number (RHESSI)	2072301	3110221	4111002	5011710	5011911	5012005	5082502
Date	July 23, 2002	November 2, 2003	November 10, 2004	January 17, 2005	January 19, 2005	January 20, 2005	August 25, 2005
ϕ (deg)	151 ± 195	96 ± 12	104 ± 24	71 ± 29	170 ± 11	66 ± 14	102 ± 104
Π (%)	2 ± 14	28 ± 12	36 ± 26	28 ± 25	54 ± 21	21 ± 10	6 ± 25

. Π is the polarization degree of the flare, and ϕ its polarization angle given in heliocentric coordinates.

Signal dominated by background:

→ ***SPR-N*** on board CORONAS-F (Thomson scattering polarimeter), Zhitnick et al. 2006

→ Energy range 20-100 keV

→ Large geometric area (50cm^2) scatterer, small effective area

→ Passive scatterer, no background reduction. Signal dominated by background.

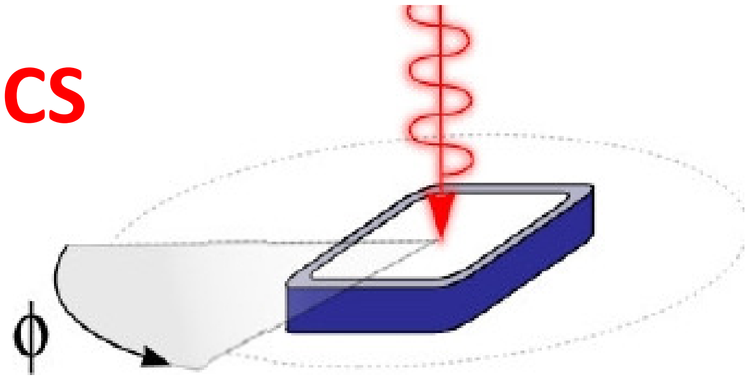
→ Signal heavily affected by radiation background especially when passing near
the poles (h=500 km, incl. 82.5 °)

POLARIMETRY BASICS

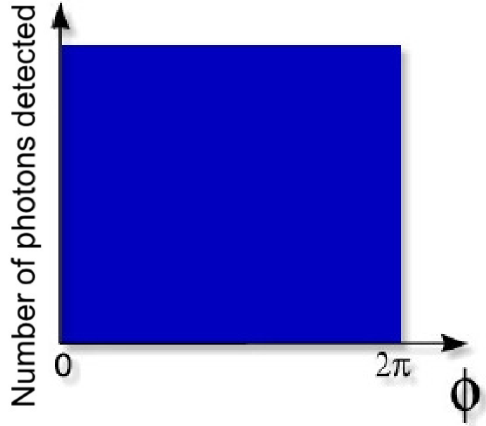
Polarimeter = Analyser + Detector

Analyser : For analysing different angles of polarization

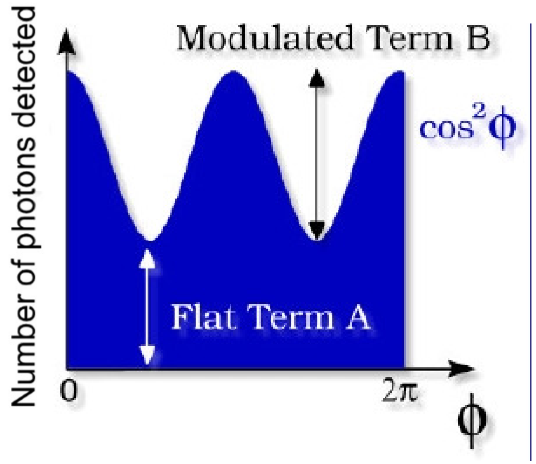
Detector : To detect photons for each angle



Unpolarized radiation → flat response



Polarized radiation → Modulated response



$$N(\phi) = A_{\mathrm{P}} + B_{\mathrm{P}} cos^2(\phi - \phi_0)$$

MODULAITON FACTOR (measured with 100% pol. rad.)

$$\mu = \frac{N_{100\%}^{\max} - N_{100\%}^{\min}}{N_{100\%}^{\max} + N_{100\%}^{\min}} = \frac{B_{100\%}}{2A_{100\%} + B_{100\%}}$$

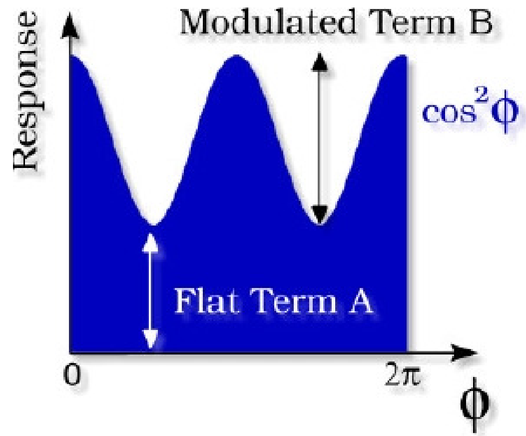
POLARIMETRY BASICS

Modulation curve

$$N(\phi) = A_{\mathrm{P}} + B_{\mathrm{P}} cos^2(\phi - \phi_0)$$

Polarization Degree

$$\mathcal{P} = \frac{1}{\mu}\frac{B_{\mathcal{P}}}{2A_{\mathcal{P}} + B_{\mathcal{P}}}$$



Minimum Detectable Polarization (at 99% confidence level) [Weisskopf et al. 2010]

$$\mathrm{MDP} = \frac{4.29}{\mu \cdot R} \cdot \sqrt{\frac{R+B}{T}}$$

R : source rate
B : background rate
T : integration time

POLARIMETRY BASICS

$$I = \frac{1}{2\pi}\int_0^{2\pi} N(\phi), d\phi = A_{\mathcal{P}} + \frac{B_{\mathcal{P}}}{2}$$

$$Q = \frac{1}{\mu}\frac{B_{\mathcal{P}}}{2}\cos 2\phi_0$$

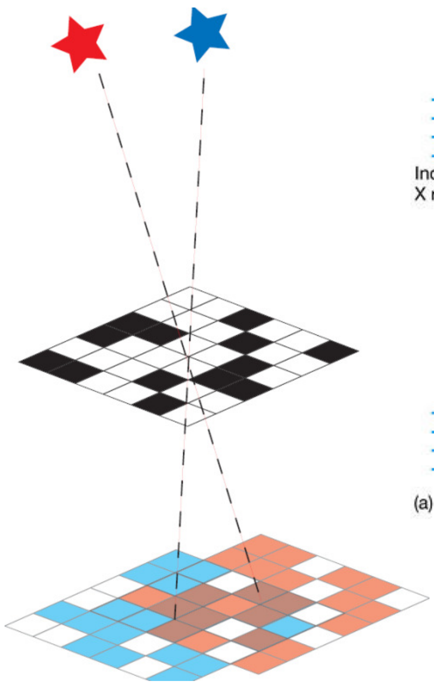
$$U = \frac{1}{\mu}\frac{B_{\mathcal{P}}}{2}\sin 2\phi_0$$

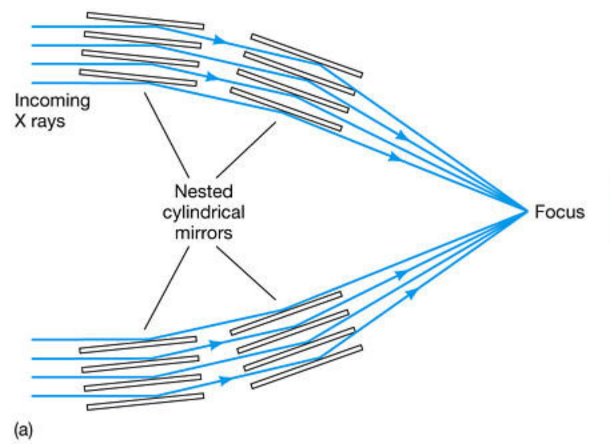
$$\mathcal{P} = \frac{\sqrt{Q^2 + U^2}}{I} = \frac{1}{\mu}\frac{\sqrt{\frac{B_{\mathcal{P}}}{4}^2 \cos^2\phi_0 + \frac{B_{\mathcal{P}}}{4}^2 \sin^2\phi_0}}{A_{\mathcal{P}} + \frac{B_{\mathcal{P}}}{2}} = \frac{1}{\mu}\frac{B_{\mathcal{P}}}{2A_{\mathcal{P}} + B_{\mathcal{P}}}$$

PHOTOELECTRIC POLARIMETRY: the GPD

<u>To derive the image of the source the detector must be coupled with:</u>

- Grazing incidence
  X-ray telescope
- Coded mask aperture
- Rotating modulation
  collimator





<u>If no imaging is required:</u>

- Collimator
- Field angular delimiter