Future prospects for solar flare (*but not only*) X-ray polarimetric missions

Sergio Fabiani
INFN – Trieste

On the behalf of the
High Energy Astrophysics and Related Technology Group
at the
INAF – IAPS (Rome)

INFN Istituto Nazionale di Fisica Nucleare

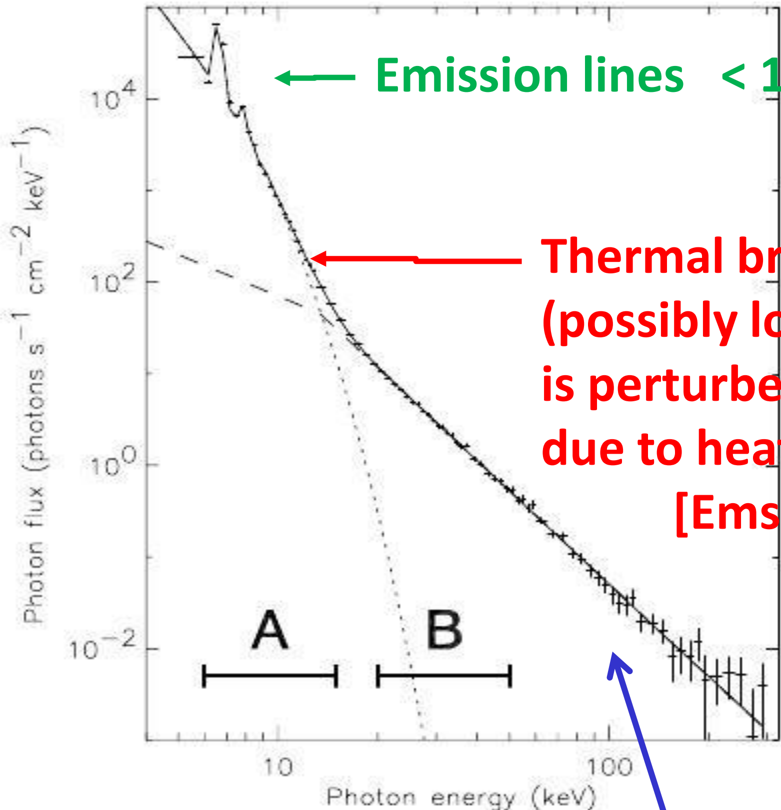
IAPS

5-8 May 2014, Prague

OUTLINE

- **X-ray polarimetry as a diagnostics for solar flares**
- **Photoelectric polarimetry with the Gas Pixel Detector (GPD)**
- **Mission proposals and collaborations**
- **More to come: Compton polarimetry**

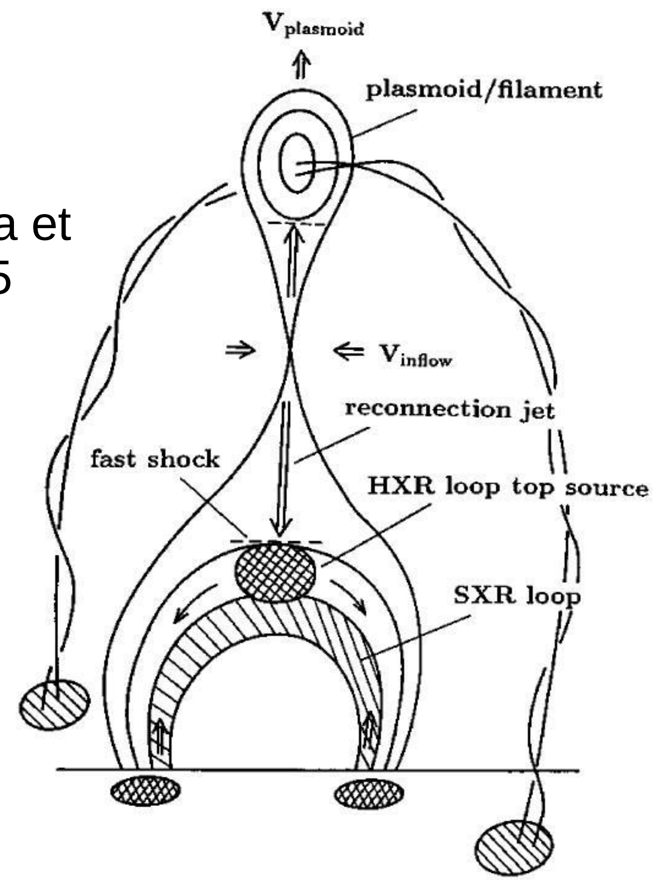
SOLA FLARES X-RAY POLARIMETRY



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]

Shibata et al.1995



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

Moreover:
Scattering of radiation… therefore still polarization

PRESENT RESULTS

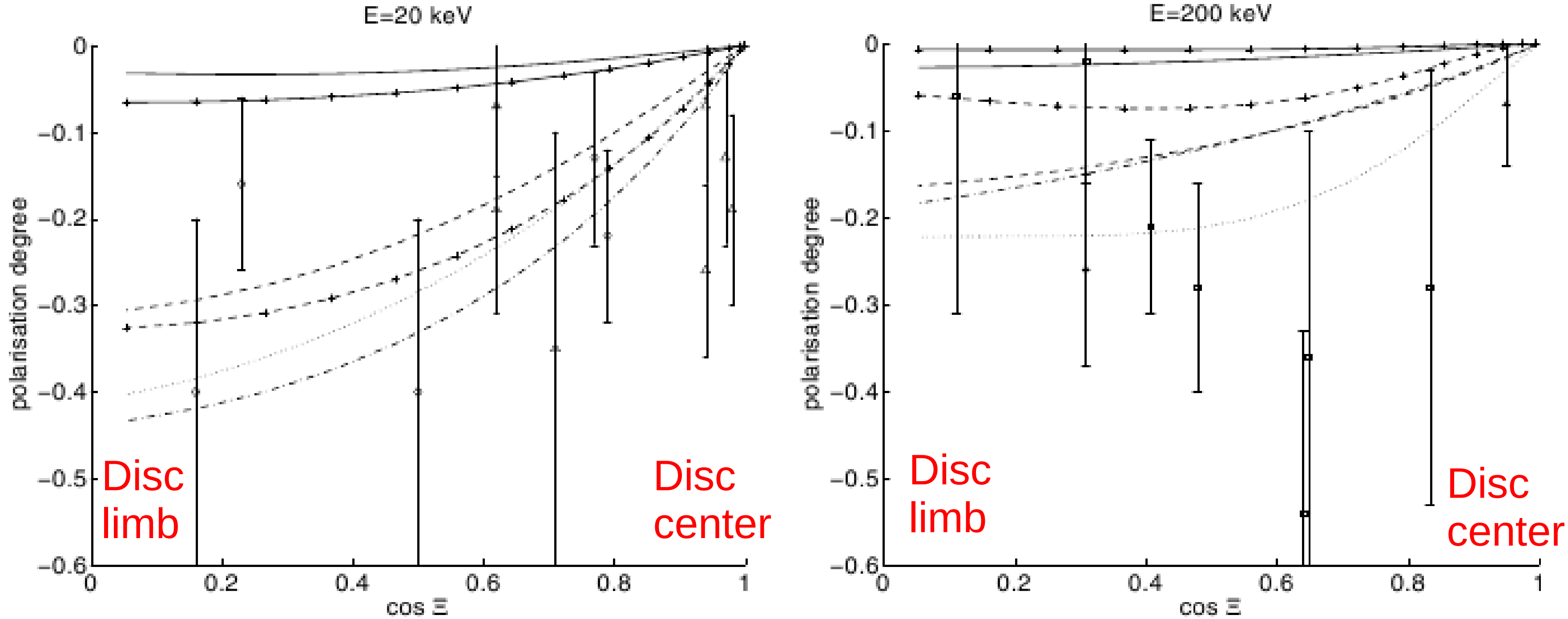


Fig. 10. Comparison of the simulations of HXR bremsstrahlung polarization for 20 keV (*left plot*) and 200 keV (*right plot*) produced for different position angle on the solar disk ($\cos \Xi = 1$ in the disk center and 0 on the limb) by a wider electron beam with $\Delta\mu = 0.2$ and the energy flux 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.

<u>Models</u>

C = particle collisions

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

B= magnetic field convergence

Solar flare polarimetry…What do we need?

Soft X-rays (high flux, contamination by thermal emission):

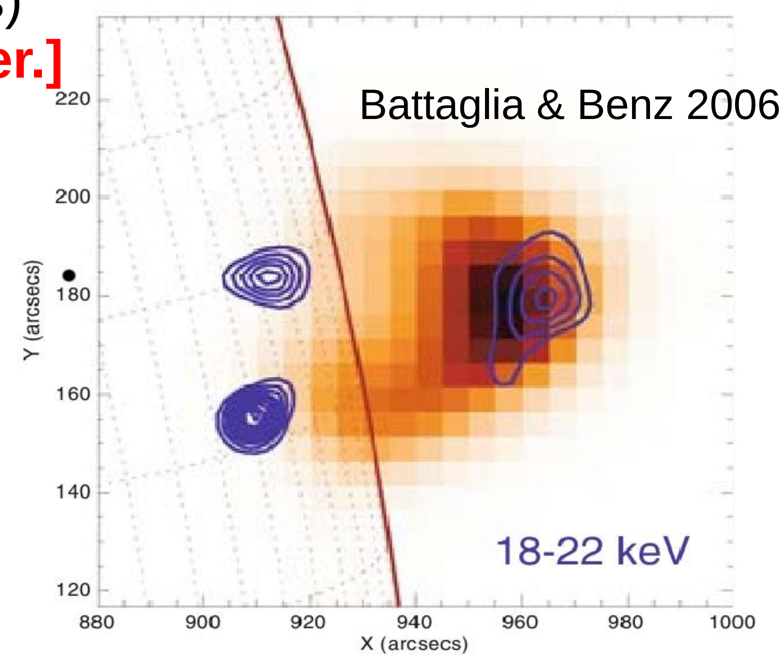
Photoelectric polarimetry (high efficiency in SXRs)
[Fabiani et al. 2012, Adv. in Sp. & Res.]

Hard X-rays (low flux, only non-thermal emission):

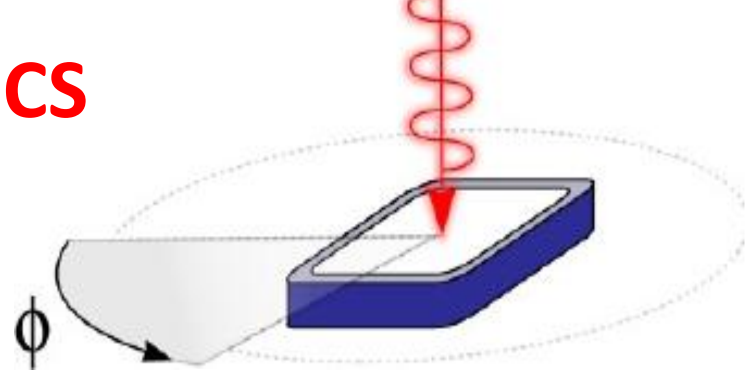
Compton polarimetry (high efficiency in HXRs)
[Fabiani et. al. 2012, Jour.of Phys. Conf. Ser.]

Nice to have:

Imaging capability with angular resolution (<= 10 arcseconds) to separate solar flare emitting regions (footpoints and looptop) and perform imaging-polarimetry



POLARIMETRY BASICS

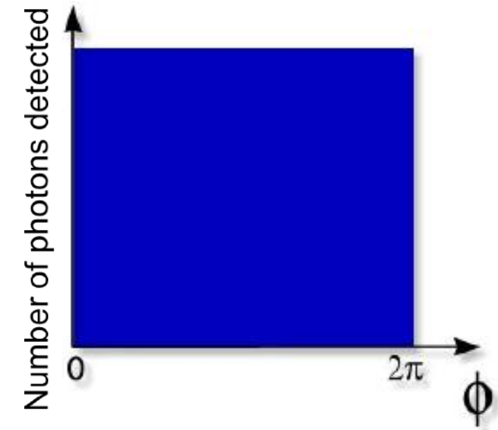


Polarimeter = Analyser + Detector

Analyser : For analysing different angles of polarization

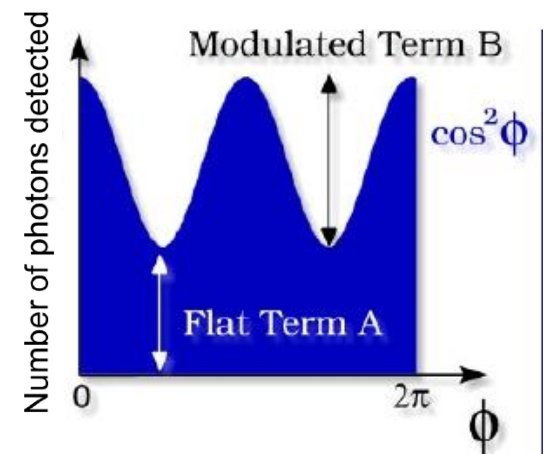
Detector : To detect photons for each angle

Unpolarized radiation → flat response



Polarized radiation → Modulated response

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



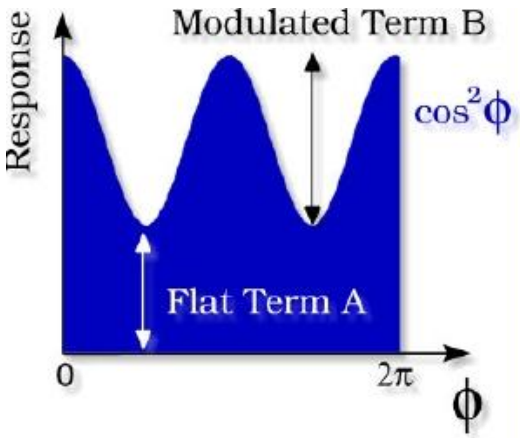
MODULAITON FACTOR (measured with 100% pol. rad.)

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

POLARIMETRY BASICS

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

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

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

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

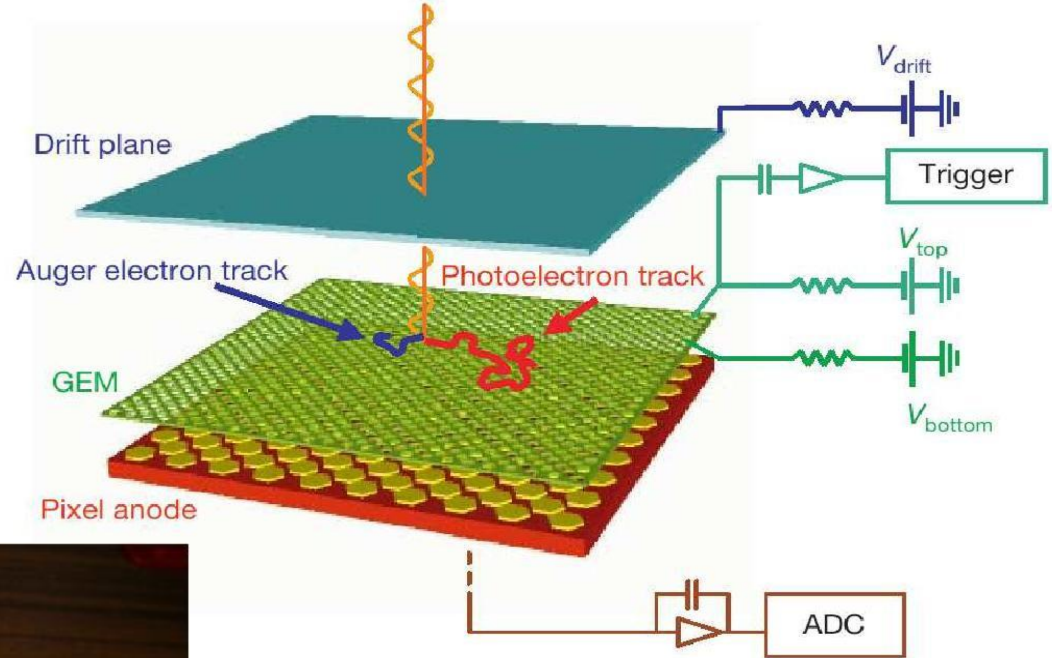
$$\mathcal{P} = \frac{\sqrt{Q^2+U^2}}{I} = \frac{1}{\mu}\frac{\sqrt{\frac{B_{\mathcal{P}}}{4}^2\cos^2\phi_0 + \frac{B_{\mathcal{P}}}{4}^2\sin^2\phi_0}}{A_{\mathcal{P}} + \frac{B_{\mathcal{P}}}{2}} = \frac{1}{\mu}\frac{B_{\mathcal{P}}}{2A_{\mathcal{P}} + B_{\mathcal{P}}}$$

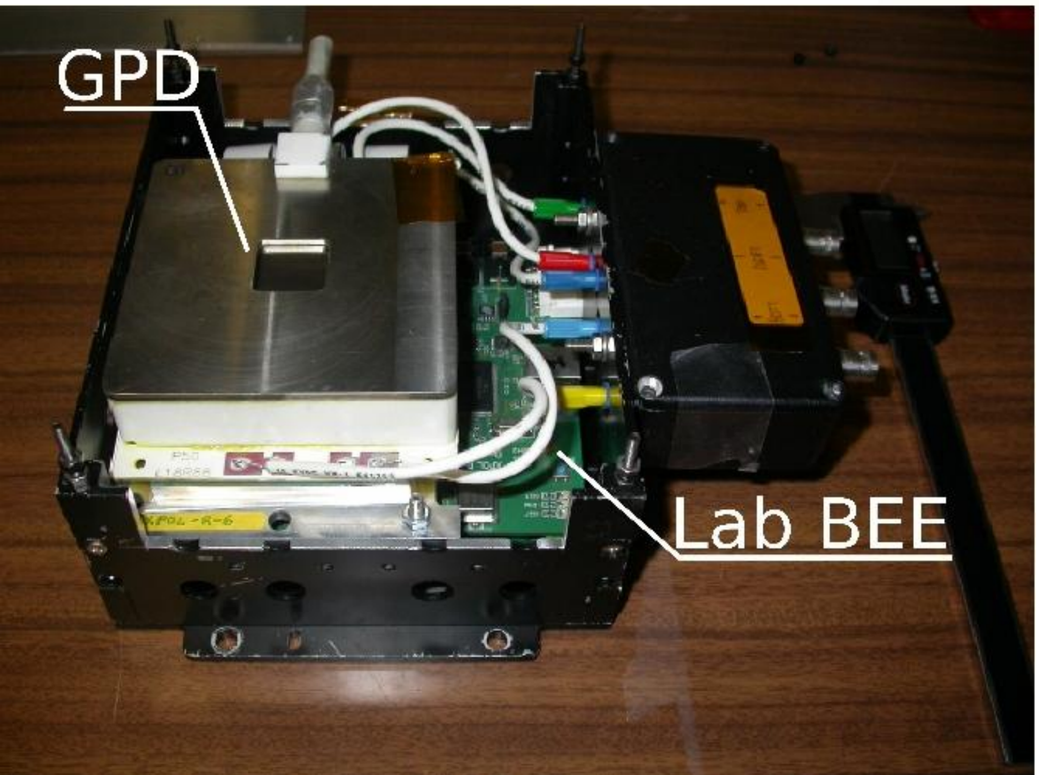
PHOTOELECTRIC POLARIMETRY: the GPD

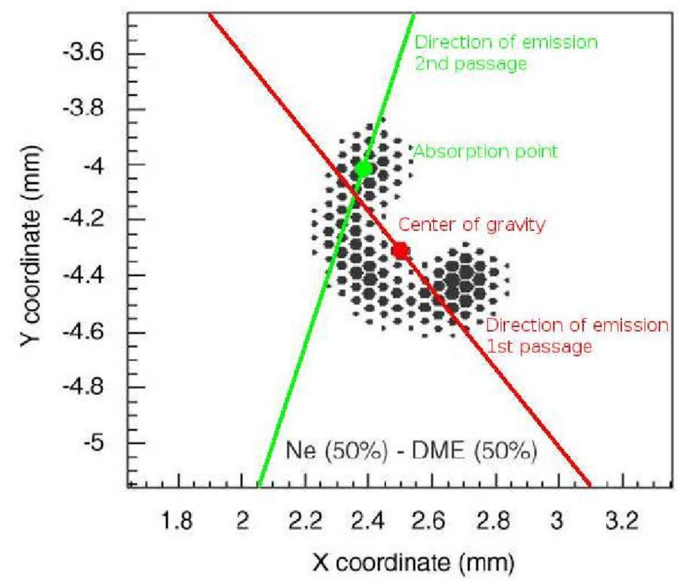
Cross section K-shell

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

Φ: Azimuthal angle of emission of the photoelectron







PHOTOELECTRIC POLARIMETRY: the GPD

1. Polarimetry: degree and angle
2. Moderate spectroscopy: 20% at 6 keV
3. Imaging: impact point detection
   (LEP: Spatial Resolution FWHM **70**mm, measured by Soffitta et al. 2012, NIMA)
4. Timing: photon by photon detection (some us)

Low Energy Polarimeter (LEP) 2-10 keV:

He based gas mixtures

Medium Energy Polarimeter (MEP) 6-35keV:

Ar based gas mixtures

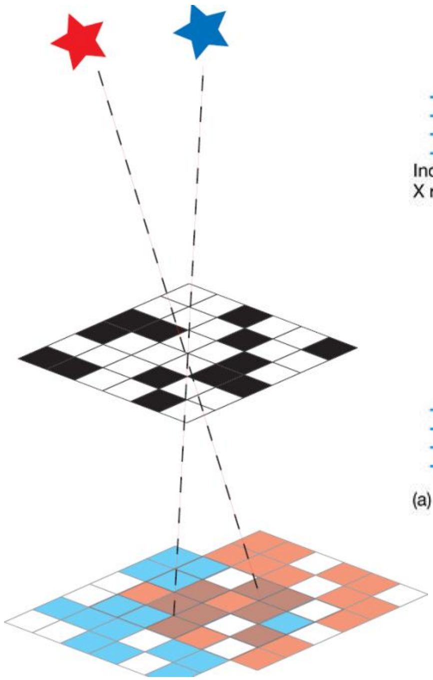
Good for solar flares polarimetry,

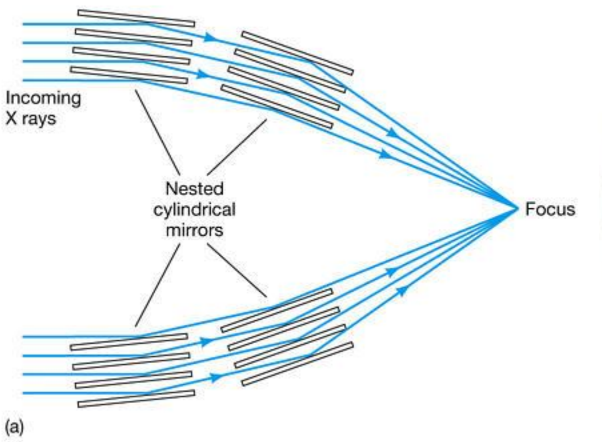
[Fabiani et al. 2012, Adv. in Sp. & Res.]
[Fabiani et. al. 2012, SPIE]

PHOTOELECTRIC POLARIMETRY: the GPD

To derive the image of the source the detector must be coupled with:

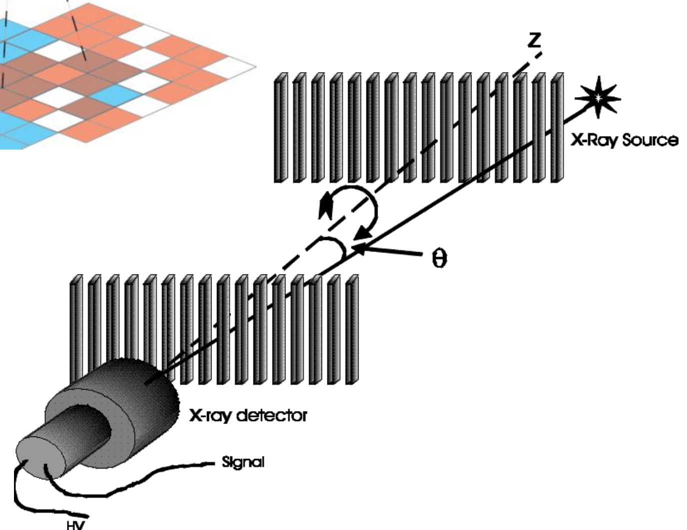
- Grazing incidence
  X-ray telescope
- Coded mask aperture
- Rotating modulation
  collimator





If no imaging is required:

- Collimator
- Field angular delimiter



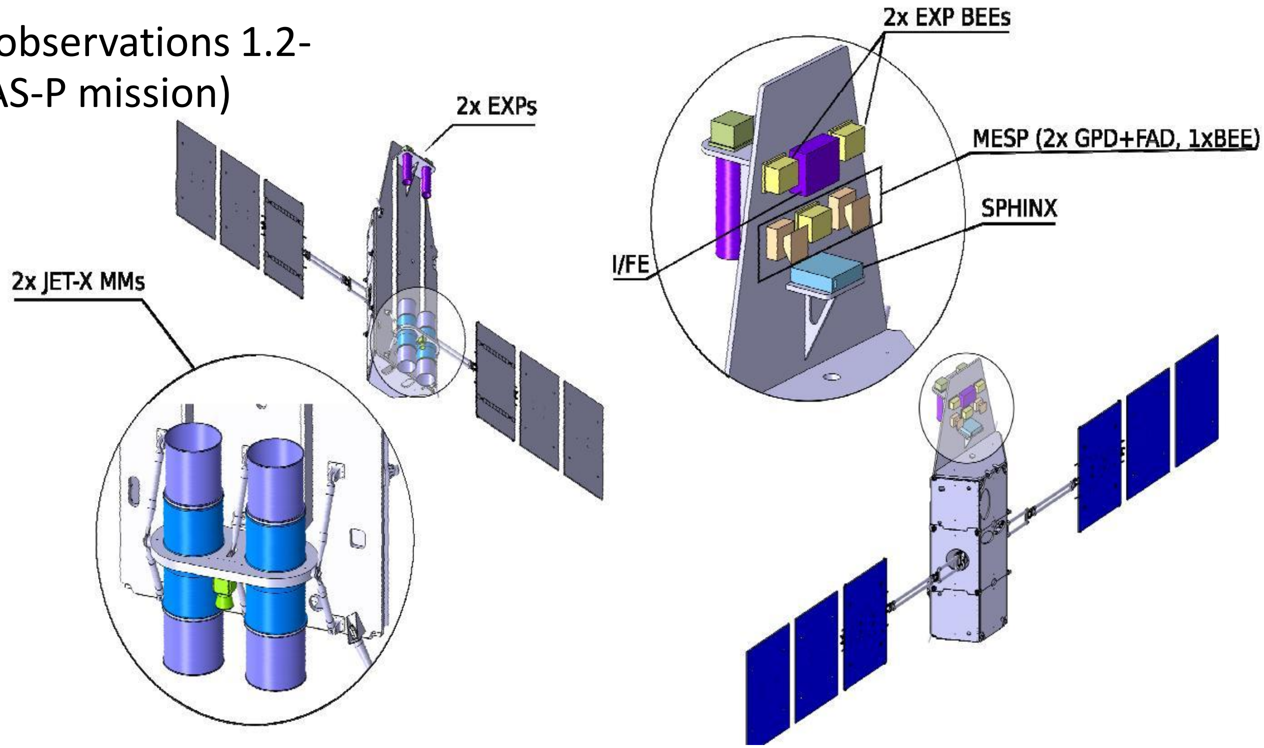
MISSION PROPOSAL: 2012 ESA call for a small mission

X-ray Imaging Polarimeter Explorer (XIPE)

2 LEP 20%He-80%DME coupled to 2 optics module of **JET-X telescope** (HEW 15arcsec @ 1.5 keV) for non-solar sources. Energy band 2-10 keV (MDP 14% in 100ks for 1mCrab)

2 MEP 60%Ar-40%DME with a field angular delimiter for solar flares observations (Energy band 15-35keV)

SPHINX – photometer for solar observations 1.2-15 keV (recurrent from CORONAS-P mission) [SRC-PAS Wrocław (Poland)]



MISSION PROPOSAL: 2012 ESA call for a small mission

X-ray Imaging Polarimeter Explorer (XIPE)

XIPE Solar Polarimeter sensitivity

Flare Class	MDP (%)	Integration Time (s)
X10	0.6	748
X5.1	1.3	989
X1.2	4.8	239
M5.2	6.6	489
M1	46.4	128

Spectra from Saint-Hilaire et al. 2008

TWO MISSION PROPOSALS: 2012 ESA call for a small mission

X-ray Imaging Polarimeter Explorer (XIPE)

BHs: Polarization angle rotation with energy

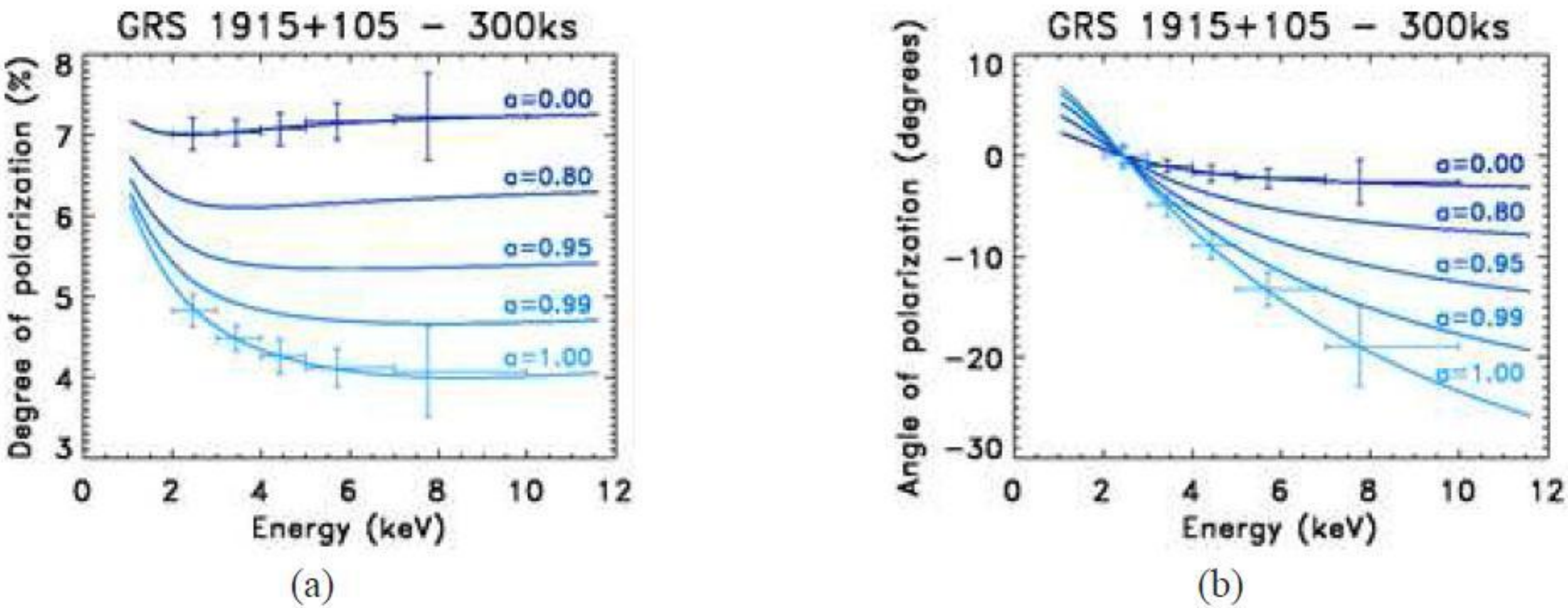
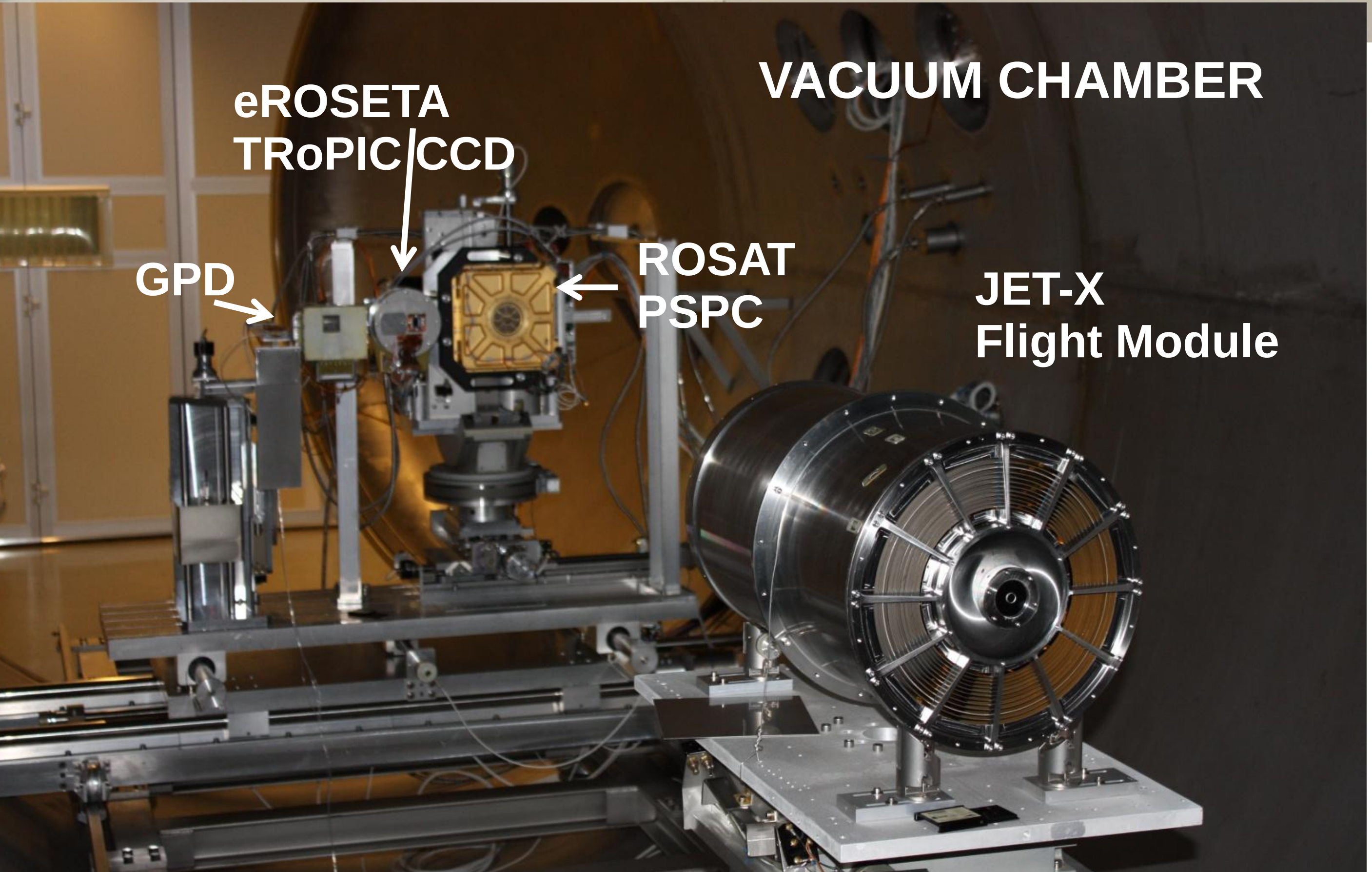


Fig. 6 (**a**). Expected variation of the polarization degree with energy in GRS1915+105 simulating an observation of 300 ksec The model is from Dovčiak et al (2008) while the errors are evaluated for the case of an observation with XIPE). (**b**). Polarization angle rotation with energy in the same observation.

Soffitta et al. 2013, Exp. Astron.

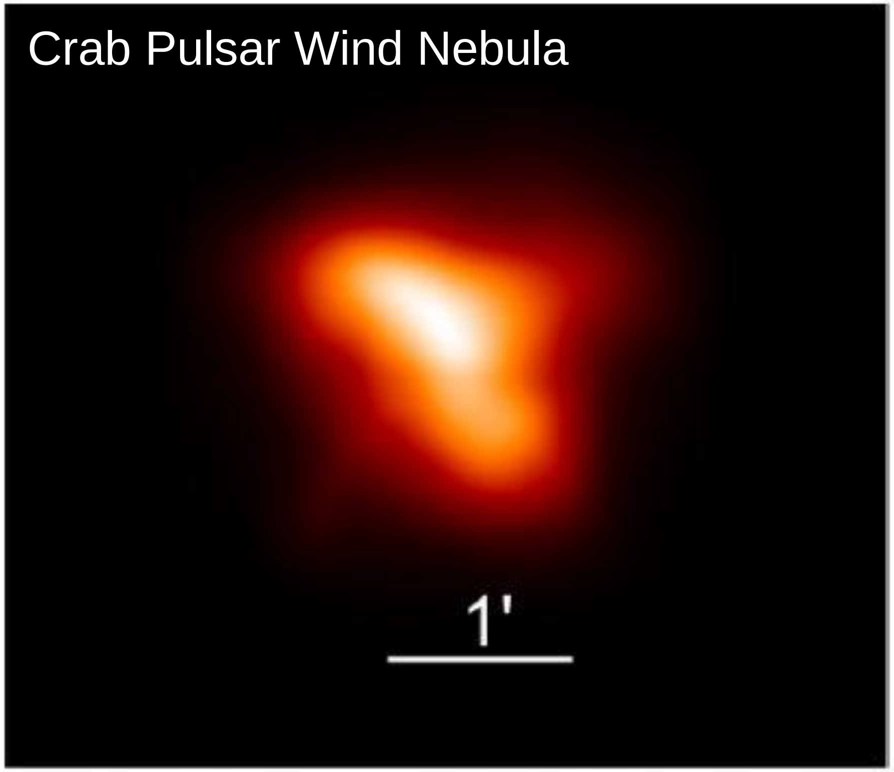
Calibrations at PANTER (27 Nov-1 Dec 2012)

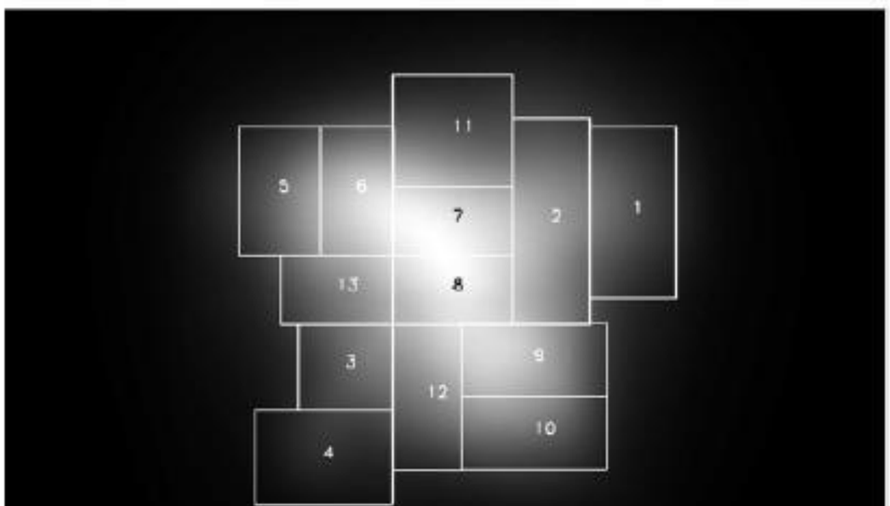


PSF measurement of GPD+telescope optics

At present angular resolution is limited by optics, not by the detector

Fabiani et al. 2014, ApJ Suppl., in Press





Fabiani et al. 2014, ApJ Suppl., in Press

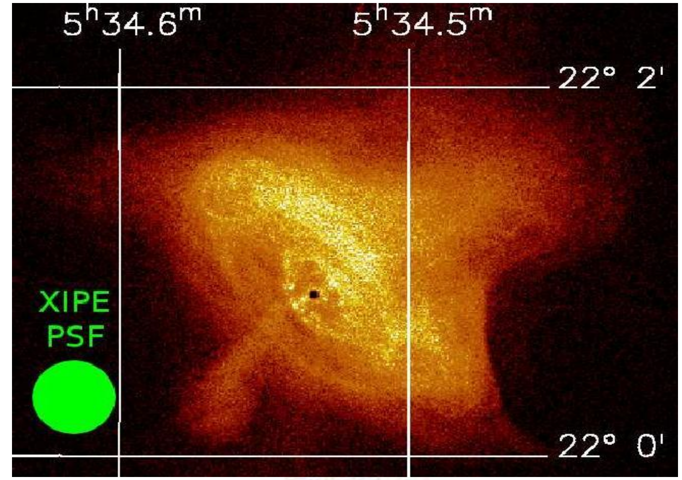


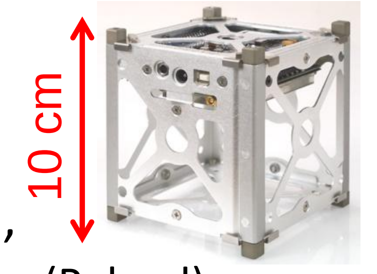
Table 4
Simulation of a Polarization Measurement for the Crab

Region No.	σ_{degree} (%)	σ_{angle} (deg)	MDP (%)
1	0.7	1.1	2.2
2	0.5	0.8	1.5
3	0.8	1.3	2.5
4	1.0	1.6	3.2
5	0.7	1.1	2.2
6	0.5	0.9	1.7
7	0.5	0.8	1.6
8	0.5	0.8	1.6
9	0.5	0.9	1.7
10	0.7	1.1	2.2
11	0.6	1.0	1.9
12	0.6	1.0	1.9
13	0.7	1.1	2.2

Notes. The source is subdivided in 13 regions as shown in Figure 11 (bottom panel). The uncertainties of the degree and angle of polarization are listed, assuming a polarization degree of 19% (Weisskopf et al. 1978) in the energy range 2–10 keV for a 100 ks observation.

FUTURE PROSPECTS FOR X-RAY POLARIMETRY:

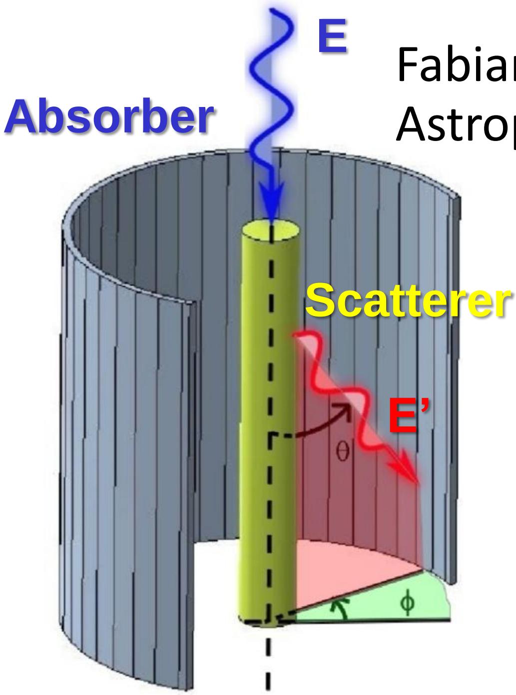
- **ESA-CAS proposals:**
  - **XILPE: A Light (=descooped) version of XIPE:**
    - No solar polarimeters. One telescope only.
    - JET-X optics will be reproduced with modern technology (a lighter optics module, possibly larger effective area)
    - http://sci.esa.int/science-e/www/object/doc.cfm?fobjectid=53868
  - **SEELPE (Solar Energetic Emission and Particle Explorer):**
    - High Energy Band Spectrometer (HEBS) (10 keV- 600 MeV)
    - Solar X-ray Polarimeter (15-35 keV)
    - Electron-Proton and High-Energy Telescopes (EPT-HET)
    - Supra-Thermal Electrons & Protons (STEP)
    - http://sci.esa.int/science-e/www/object/doc.cfm?fobjectid=53887
- **Next NASA SMEX call:**
  - **X-ray Polarimetry dedicatd mission with GPD (no solar polarimeter)**
    - Weisskopf et al. 2013, SPIE
- **Next ESA Cubesat call:**
  - nano-satellite composed by 3 cubes 10 cm of side (!!)
  - 1 solar GPD (IAPS, INFN-Pisa, Univ. of Rome «Tor Vergata»),
  - X-ray solar photometer (SRC-PAS in Wrocław , Univ. of Wrocław (Poland)



MOVING TOWARDS COMPTON POLARIMETRY: polarimeter concept

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

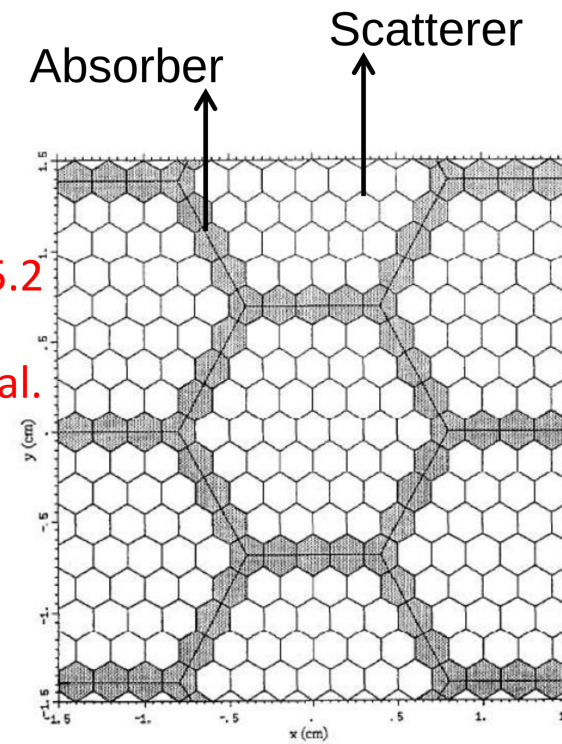
Focal plane configuration



Fabiani et al. 2013, Astroparticle Physics

MDP=10% for 10mCrab in 100ks @ 1 NuStar optics module (3 cm scatterer length tested in lab but not optimized)

Non Focal plane configuration



MDP=4.2% for M5.2 class flare (spectra by Saint-Hilaire et al. 2008)

Costa et al. 1995

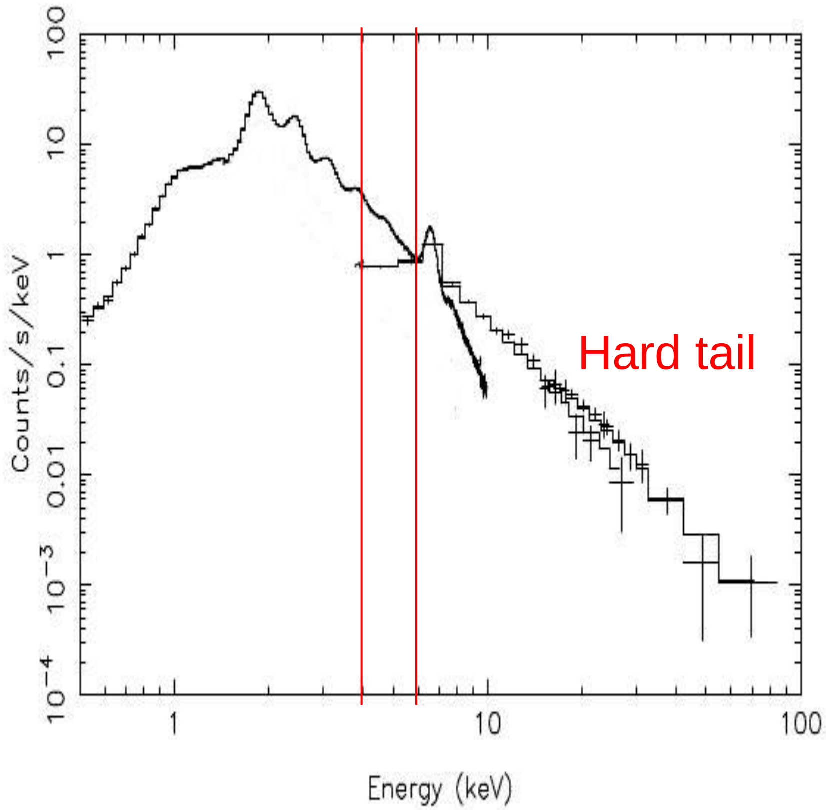
CONCLUSIONS

- Precise polarimetry in X-rays is now feasible
- Solar flare X-ray polarimetry would allow to drive plasma and magnetic field properties in solar atmosphere, contributing to present studies
- A wide population of astrophysical sources charcterized by polarized mission are suitable to be observed:
  - See the paper about XIPE by Soffitta et al. 2013, Experimental Astronomy, Vol.36, pp.523 «XIPE: the X-ray imaging polarimetry explorer» for an updated review about science targets of photoelectric polarimetry

AND…

Thanks to COST Action MP1104 that funded the STSMs of

- Sergio Fabiani and Fabio Muleri to join the calibration of the GPD at the PANTER X-ray test facility (Germany) in 2012
- Sergio Fabiani to visit the Solar Physics Division of the Polish Accademy of Science in Wrocław (Poland) to start a collaboration for future proposals about solar flare X-ray polarimetry missions (Cubesat) in 2013



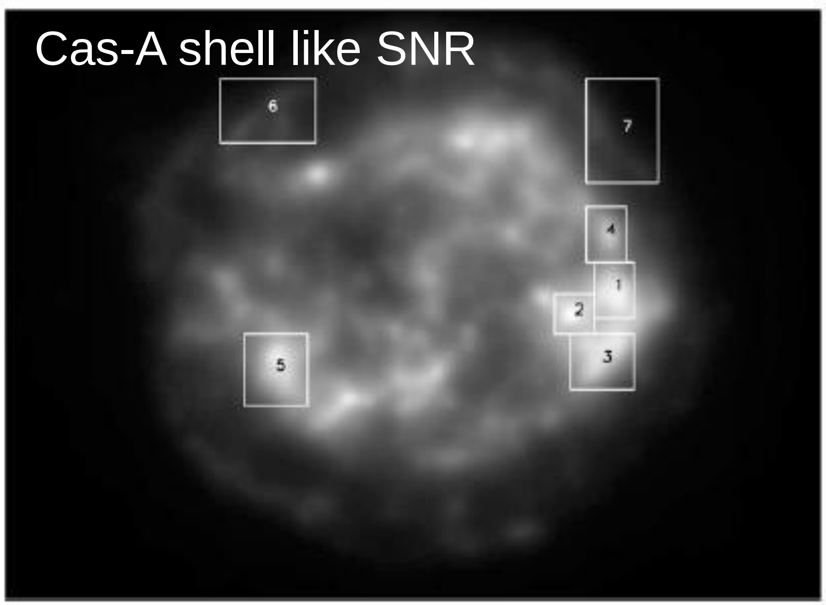


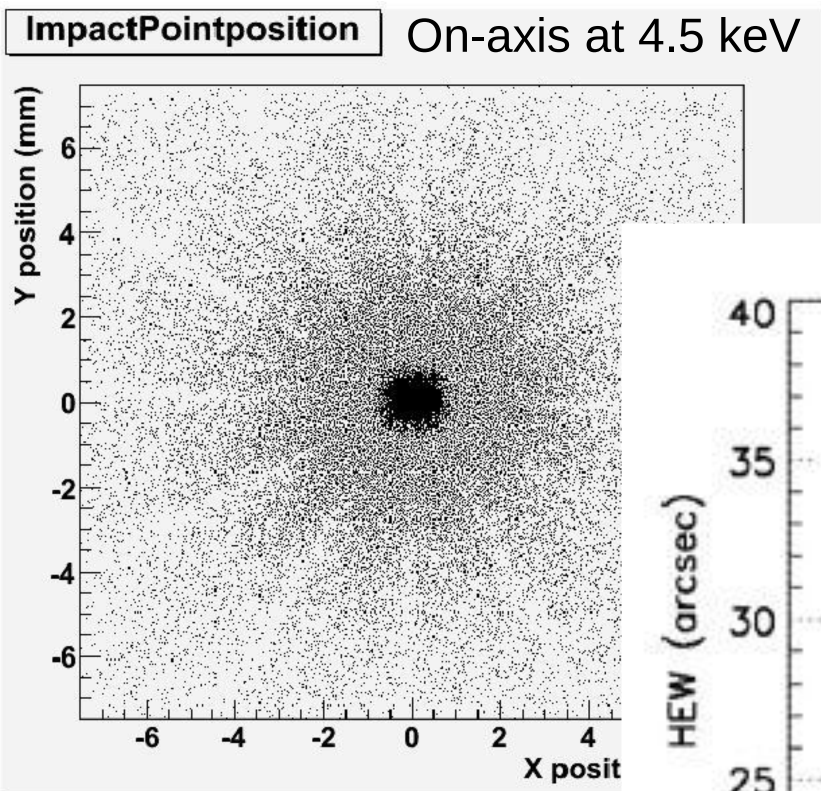
Table 5
Simulation of a Polarization Measurement for Cas-A

Region No.	σ_{degree} (%)	σ_{angle} (deg)	MDP (%)
1	2.4	6.6	7.7
2	2.7	8.3	8.8
3	2.1	5.9	6.7
4	2.9	7.8	9.5
5	1.9	5.3	6.1
6	3.5	11.0	11.1
7	3.6	11.0	11.6

Notes. The source is subdivided in 7 regions as shown in Figure 12 (bottom panel). The uncertainties of the degree and angle of polarization are listed, assuming a polarization degree of 11% in the energy range 4–6 keV for a 2 Ms observation. Regions 4, 6, and 7 are probably dominated by the non-thermal component, therefore the polarization arising from their emission should be higher with respect to regions 1, 2, 3, and 5 in which the thermal component is dominant.

Fabiani et al. 2014, ApJ Suppl., in Press

Calibrations at PANTER (27 Nov-1 Dec 2012)



Fabiani et al. 2014, ApJ Suppl., in Press

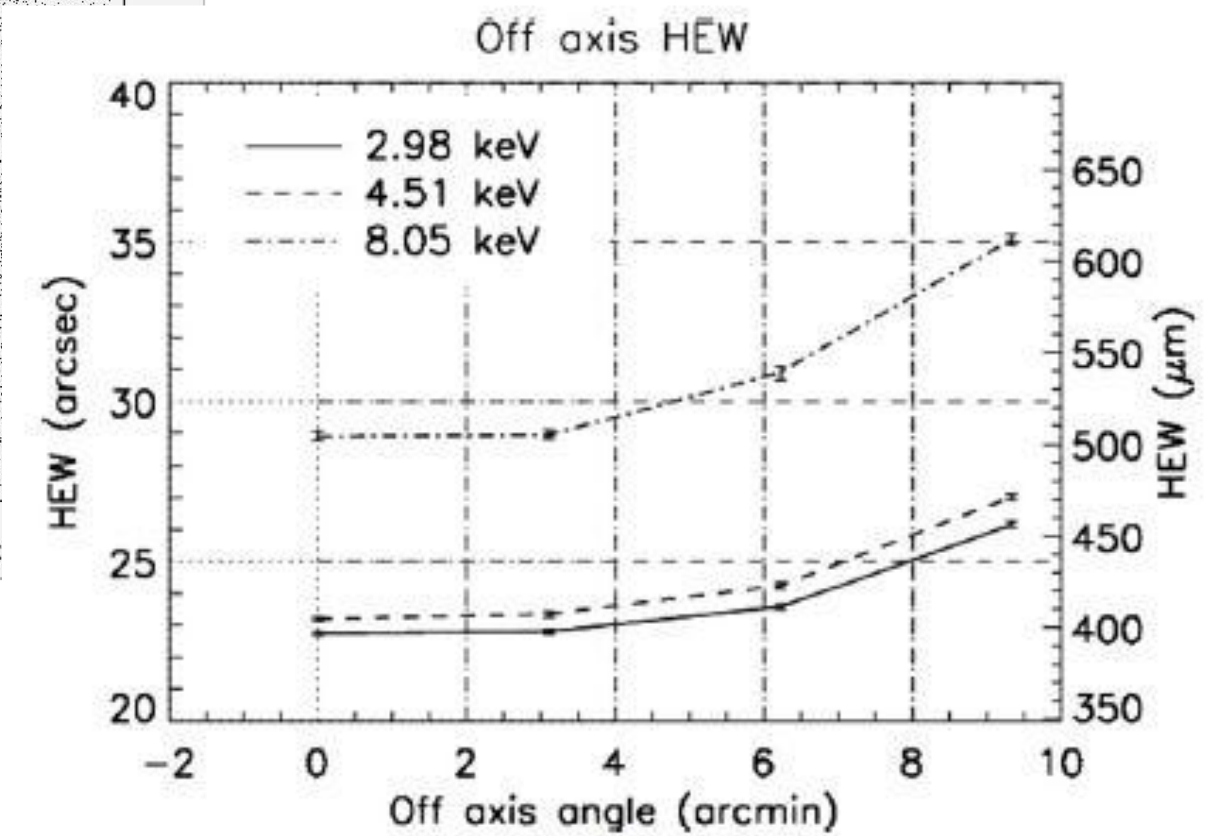
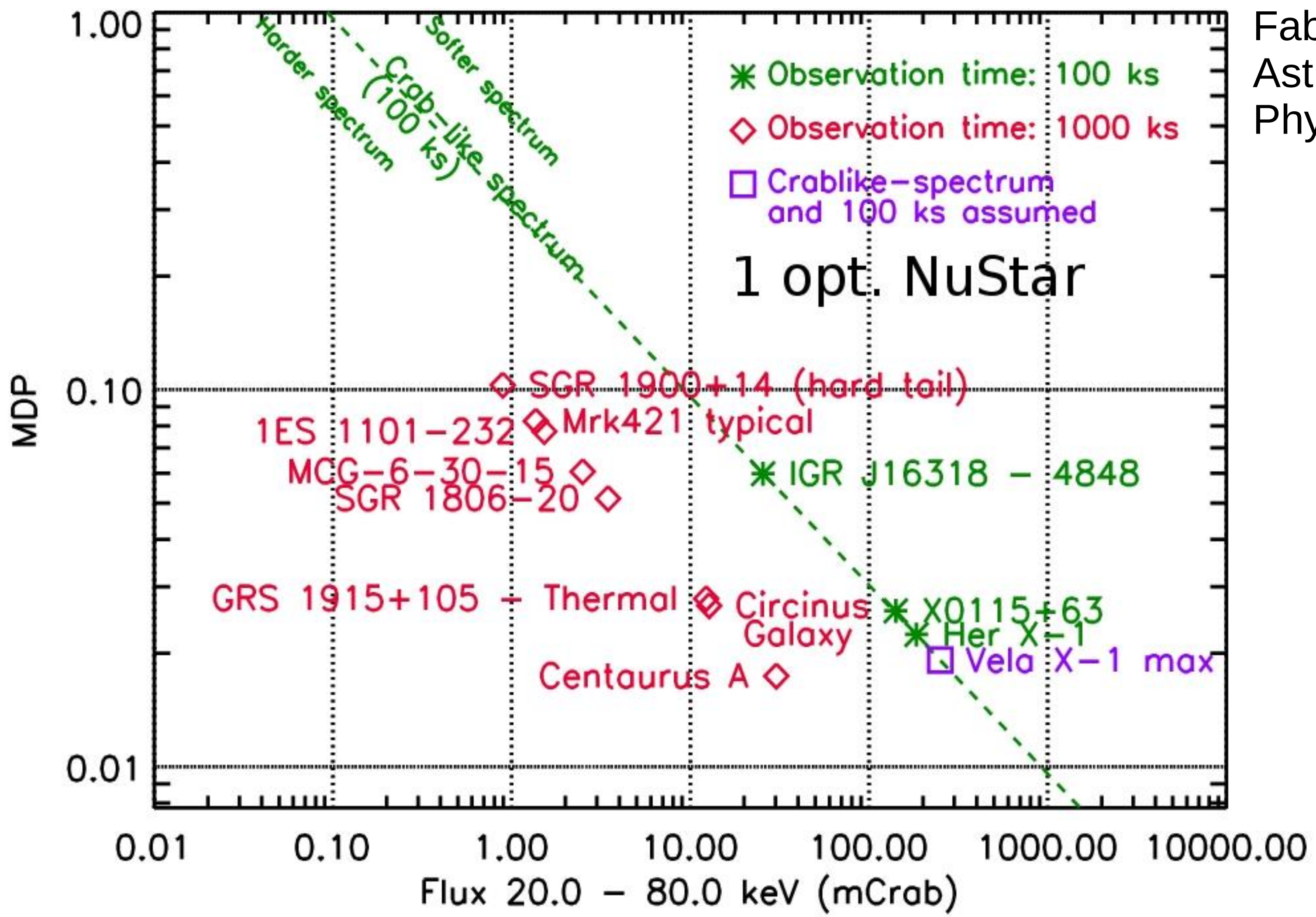


Figure 10. Off-axis HEW at 2.98, 4.51, and 8.05 keV. Plotted values are listed in Table 3. The FOV of JET-X coupled with the GPD (see Table 1) corresponds to an angle of 10.4 arcmin from the image center to the corner along the diagonal.

MOVING TOWARDS COMPTON POLARIMETRY



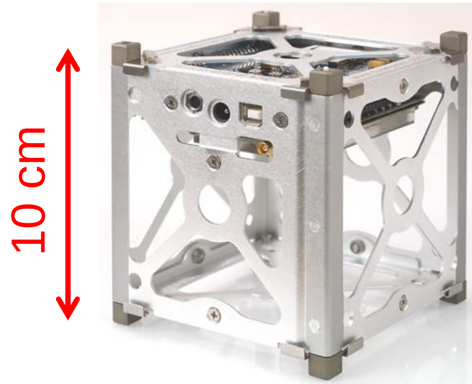
Fabiani et al. 2013, Astroparticle Physics

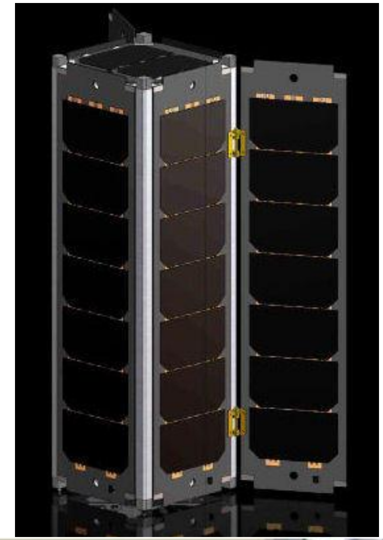
Polarimeter geometry is based on the laboratory set-up (3cm scint. rod) that is not optimized for polarimetric observations, but... MDP=10% for 10mCrab in 100ks !!

[1Crab in 20-80keV is $1.5*10^{-8}$ erg cm^{-2} s^{-1}]

FUTURE PROSPECTS FOR X-RAY POLARIMETRY:

A CUBESAT FOR SOLAR FLARE POLARIMETRY





What is a cubesat?

- Very small satellite composed typically by 1, 2 or 3 units
- Each unit is a cube 10 cm of side (gross dimension !!)
- Payload max : 1 Kg each unit
- Power : about 1W each face
- Costs: of the order of 1MEuro

Typical Cubesat Goals

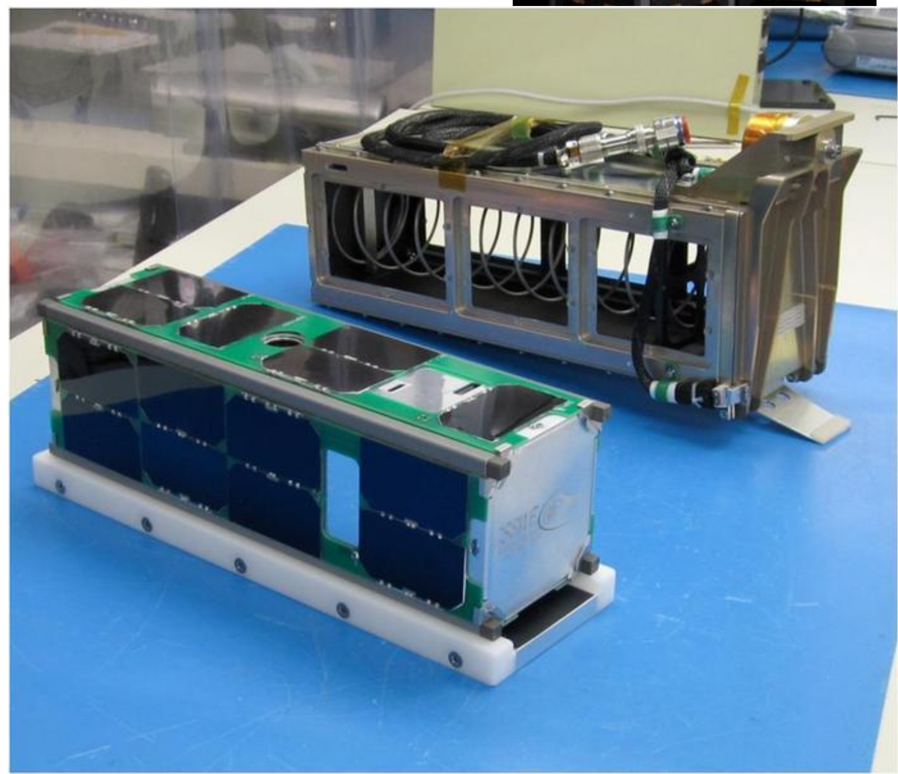
- Mechanical and electronics testing
- University educational programs in collaboration with space agencies

Our Target

ESA call for Cubesats (educational program)
next call on the beginning of 2014

Involved Institution

INAF-IAPS in Rome (Italy) [Polarimeter]
INFN Section of Pisa (Italy) [Polarimeter]
SRC-PAS in Wrocław (Poland) [Photometer]
Univ. of Wroclaw (Poland) [Photometer]
Univ. of Rome «Tor Vergata» (Italy) [bus services]



FUTURE PROSPECTS FOR X-RAY POLARIMETRY:
A CUBSEAT FOR SOLAR FLARE POLARIMETRY

3 Units Cubesat

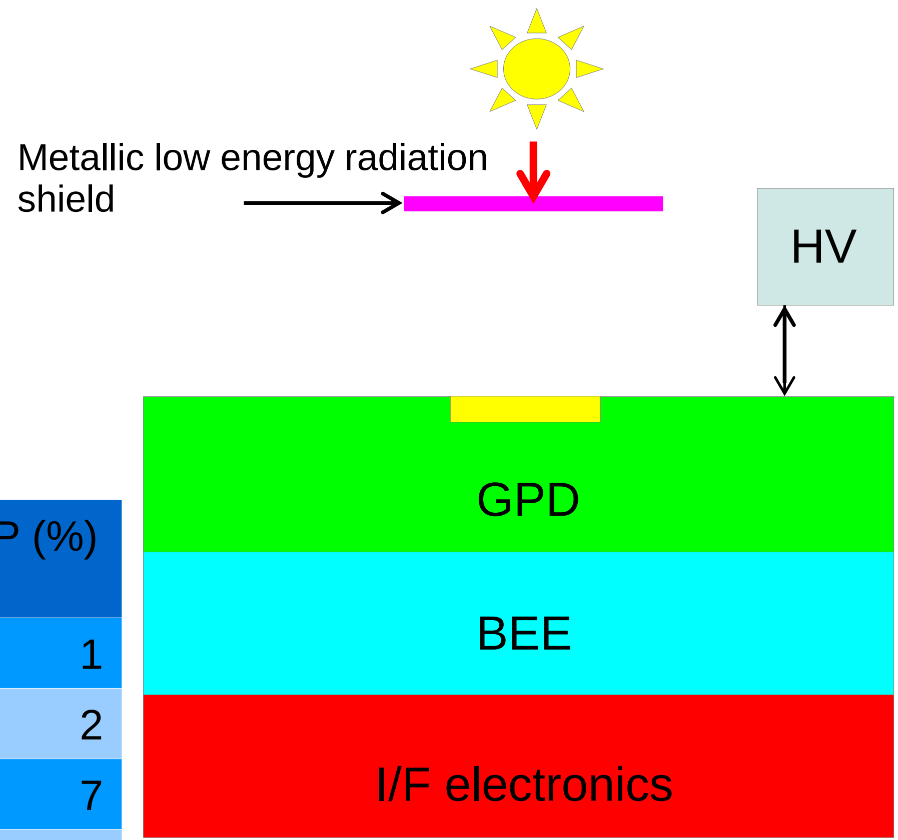
Polarimetry	Spectro/Photometry	Bus Services
Solar Flare Polarimeter (GPD - MEP) 15-35 keV	Solar Photometer (SPHINX upgrade: Si, CdTe)	Pointing control
<u>Instrumental team</u> • INFN Sezione di Pisa • INAF-IAPS • AMDL (GPD fast electronics) **<u>Theory and modeling</u>** • Univ. of Northumbia (UK) (Prof. Valentina Zharkova)	**<u>Instrumental and theory</u>** • SRC-PAS Wroclaw (Poland) • Univ. of Wroclaw (Poland) • Lebedev Inst. of Moskow (Russia) [possibly]	• Univ. of Rome "Tor Vergata"
		Telemetry, Mass memory, Pawer distribution, etc.

…and for all you need go on…

THE POLARIMETRIC PAYLOAD LAYOUT

1 GPD (MEP): Ar70%, DME30%,
3 atm, 3 cm, 2.25 cm^2
15-35 keV

Height (boards+GPD+HV) 7.4 cm
Total Weight 500 g
Total Power 2 W



Flare Class	Avg. Rate (c/s)	Int.Time (s)	MDP (%)
X10	1348	749	1
X5.1	203	989	2
X1.2	63	240	7
M5.2	17	489	9

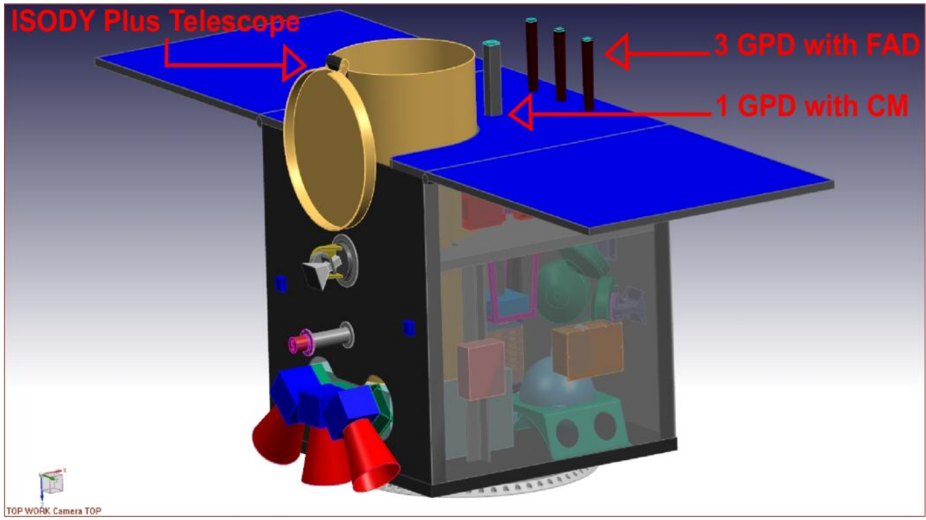
MDP evaluated from spectra in web additional material of Saint-Hilaire et al. 2008

About 1-2 flares per month between class M5 and X10 in 2016

TWO MISSION PROPOSALS: 2012 ESA call for a small mission

ADvanced Astronomy for HELIophysics Plus (ADAHELI Plus)

Visible – NIR payload:
Observations of the solar photosphere and chromosphere at high-temporal rate and high spatial and spectral resolutions.
→ *50cm Gregorian type telescope*
→ *Fabry-Pérot interferometer* with piezoelectric actuators to match cavity length with radiation wavelength.



X-ray payload:
4 MEP, 1 coupled with a coded mask aperture to allow the flare localization onto the solar disc, 3 coupled with a field angular delimiter.

Flare Class	MDP (%)	Integration Time (s)
X10	0.5	748
X5.1	1.0	989
X1.2	3.7	239
M5.2	5.0	489
M1	35.5	128

Spectra from Saint-Hilaire et al. 2008

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

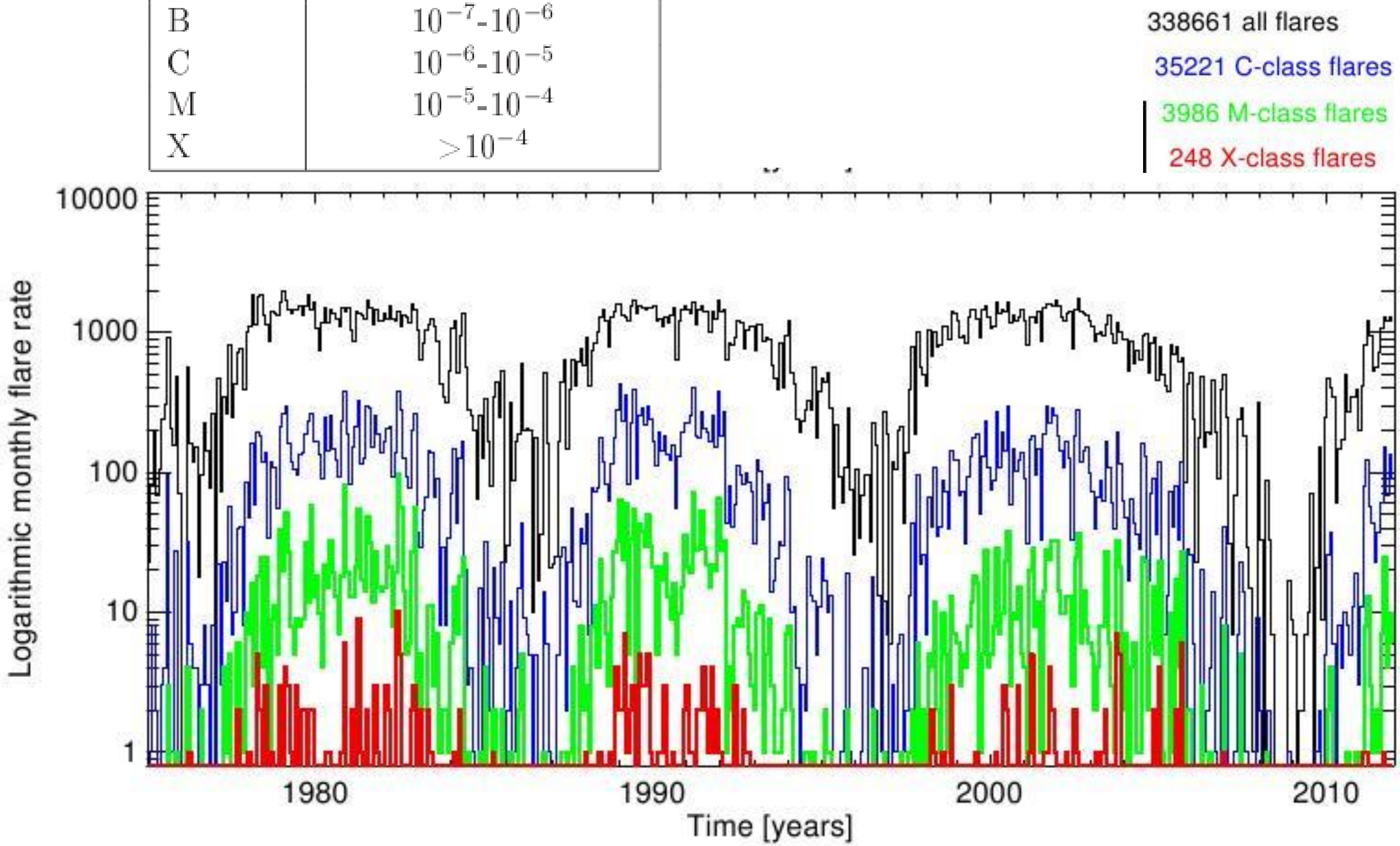
. Π is the polarization degree of the flare, and ϕ its polarization angle given in heliocentric coordinates.

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°)

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	$>10^{-4}$



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