

Solar Flare Hard X-ray Polarimetry with the CUBesat Solar Polarimeter (CUSP)

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Nicolas De Angelis – nicolas.deangelis@inaf.it

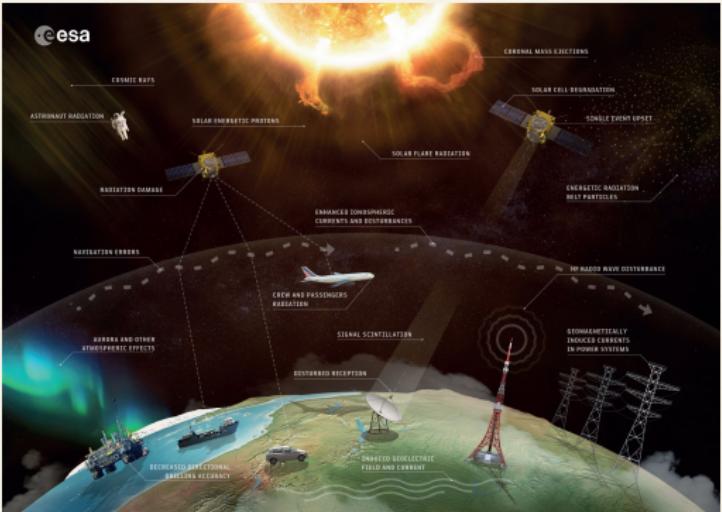
INAF-IAPS, Rome, Italy



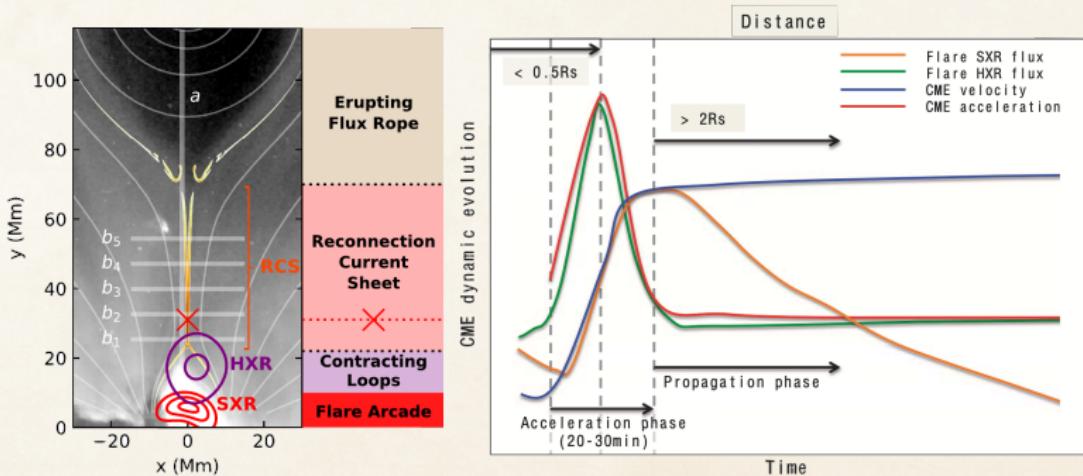
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- Solar activity, including **Solar flares (SFs)**, can be disruptive for human technological activities in space and on ground
- The occurrence of SFs is very often associated to **Coronal Mass Ejection (CME)** and **Solar Energetic Particle (SEPs)** events on the ground
- SF **can also occur alone** producing a **direct acceleration** of particles towards the Earth



- Most powerful eruptions associated to powerful flares
- HXRs are related to CME acceleration \Rightarrow **HXR polarimetry** could improve the knowledge of the **initial conditions** of the eruption of most powerful CME
- SXRs are related to CME velocity
- The rapid CME development in the lower corona during the acceleration phase strongly correlates with the associated flare activity.

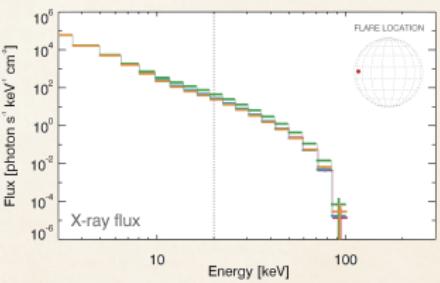
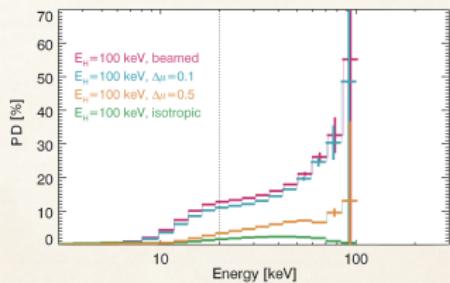


Chen B. et al. (2020), Nat. Astron.

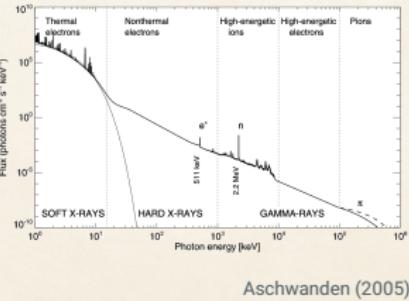
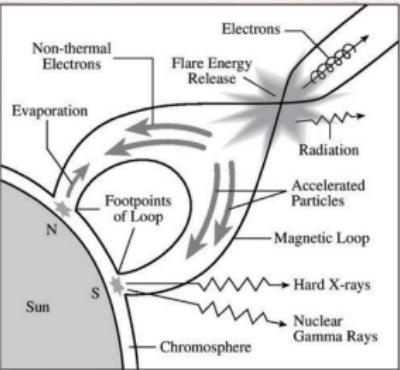
Temmer (2016), Astron. Nachr.

Motivation for X-ray Polarimetry of SFs

- SFs originate from **magnetic reconnection** in loop structures in solar corona
- SFs energy spectrum in the X-rays is dominated by:
 - thermal Bremsstrahlung (due to plasma heating, expected weakly polarized by Emslie&Brown 1980) + emission lines < 10 keV
 - non-thermal Bremsstrahlung (at the loop top and footprints, due to particle acceleration along magnetic field lines) expected highly polarized [Zharkova+ 2010] >10-20 keV
- (Linear) X-ray polarimetry would allow to **disentangle degeneracies in models** of particle beaming and magnetic field structure (also without imaging of the SF)



Jeffrey+ 2020 (A&A)



Aschwanden (2005)

- The polarization degree is expected to be correlated with the fraction of non-thermal electrons
- Hard X-ray Polarimetry will allow to probe the fraction of accelerated electrons

THE ASTROPHYSICAL JOURNAL LETTERS

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The Efficiency of Electron Acceleration during the Impulsive Phase of a Solar Flare

Eduard P. Kontar, A. Gordon Emslie, Galina G. Motorina, and Brian R. Dennis
Published 2023 April 14 • © 2023. The Author(s). Published by the American Astronomical Society.

[The Astrophysical Journal Letters, Volume 947, Number 1](#)

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Solar flare accelerates nearly all electrons in a large coronal volume

Gregory D. Fleishman , Gelu M. Nita, Bin Chen, Sijie Yu & Dale E. Gary

[Nature](#) **606**, 674–677 (2022) | [Cite this article](#)

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About the same flare that occurred on September 10, 2017:

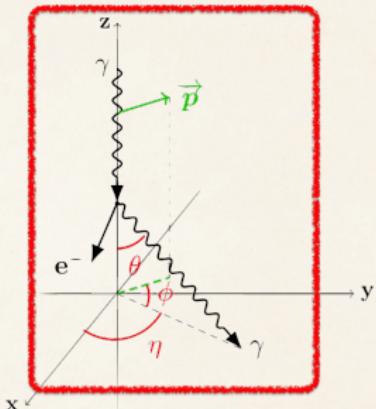
- Kontar et al.: "Our results strongly indicate that the fraction of accelerated electrons in the coronal region at any given time is relatively small..."
- Fleishman et al.: "...a volume filled with only (or almost only) non-thermal electrons while being depleted of the thermal plasma, implying that all electrons have experienced a prominent acceleration there."

- Photons interact with matter through three processes:

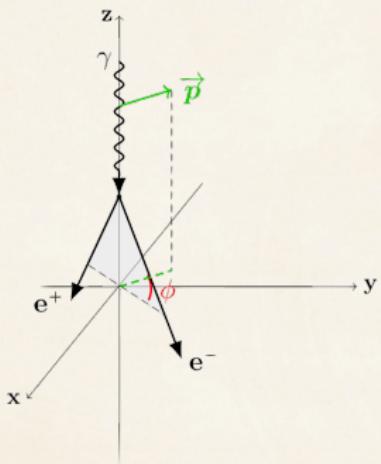
Photo-electric effect



Compton scattering



Pair production



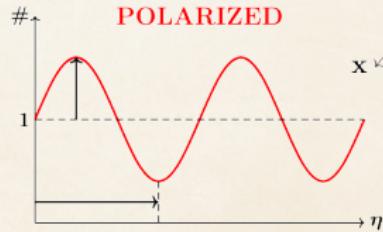
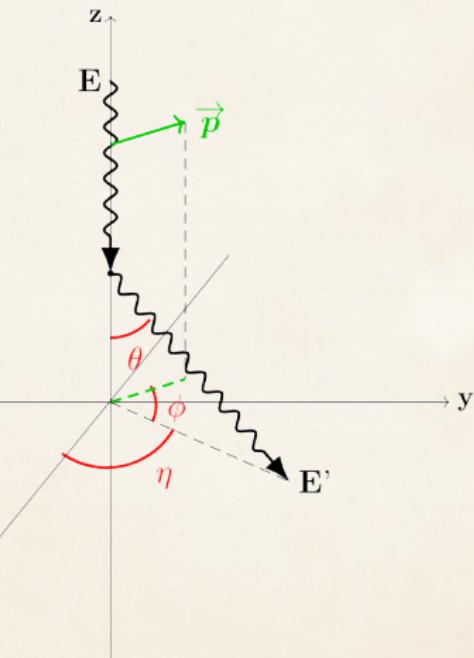
- Each process is dominant at different energies
- The azimuthal distribution of the secondary products is correlated with the polarization direction of the primary photon: $\frac{d\sigma}{d\Omega} \propto 1 + \mu \cos(2\phi)$
- **Compton scattering** is the dominant process in the energy band where the SF non-thermal emission lies (20-100 keV)

Compton scattering can be used to determine the polarization of a source:

- Azimuthal scattering angle distribution provides information on PD and PA
- Modulation curve parameterized by the Klein-Nishina cross-section:

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

- Relative amplitude \leftrightarrow PD, phase \leftrightarrow PA

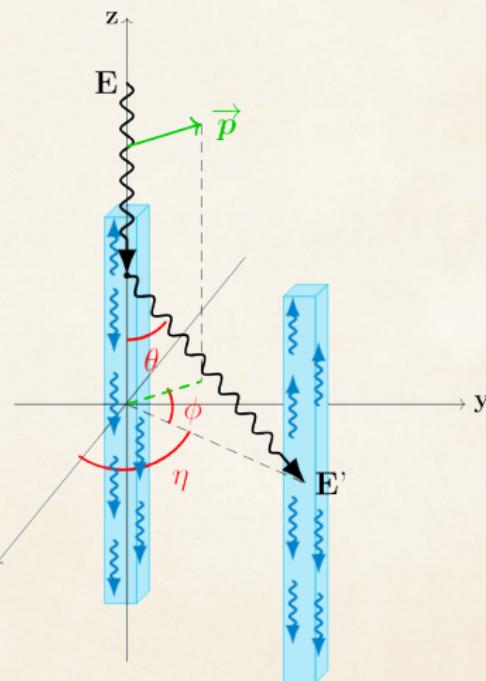
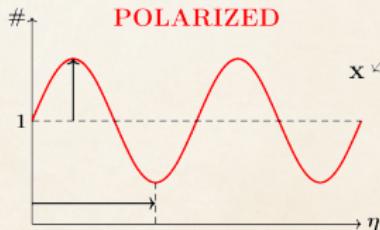
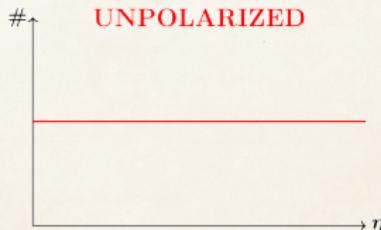


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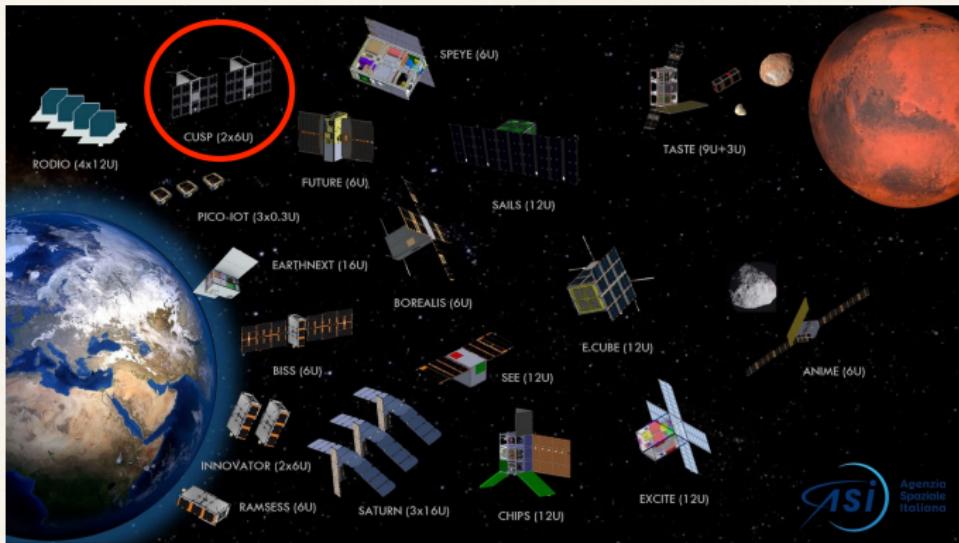
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- Relative amplitude \leftrightarrow PD, phase \leftrightarrow PA
- A segmented array of scintillators can be used to measure the scattering angle distribution (aka modulation curve)



The Project Framework

- The **Italian Space Agency (ASI)** started a new national program named **Alcor** for funding the development of CubeSat technologies and missions
- **CUSP** is one of the 20 selected missions among 49 proposals
- 22 participants from Research Institutes and Universities and 78 companies, mainly Small and medium-sized ones
- Currently in a 1-year **Phase B** until December 2025



The CUSP Team

- **INAF: IAPS-Roma:** Prime contractor, PI-ship, and Payload; **OAS-Bologna:** Detector Simulation; **OAR-Roma:** Lab SW Support
- **IMT s.r.l.:** Satellite Platform
- **deda connect s.r.l.:** Payload Electronics
- **Università di Bologna – CIRI AERO:** Mission Analysis
- **Università della Tuscia:** Ground Segment
- **Italian Space Agency (ASI):** Project Control



Websites: <https://www.iaps.inaf.it/it/missioni-spaziali/cusp>

<https://www.asi.it/tecnologia-ingegneria-micro-e-nanosatelliti/micro-e-nanosatelliti/il-programma-alcor/>

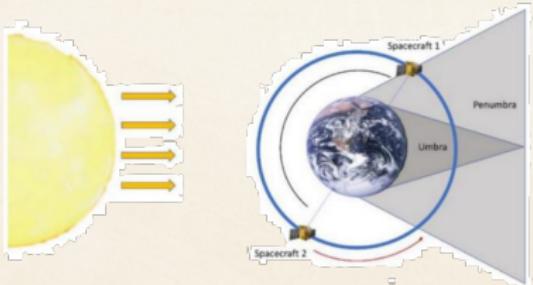
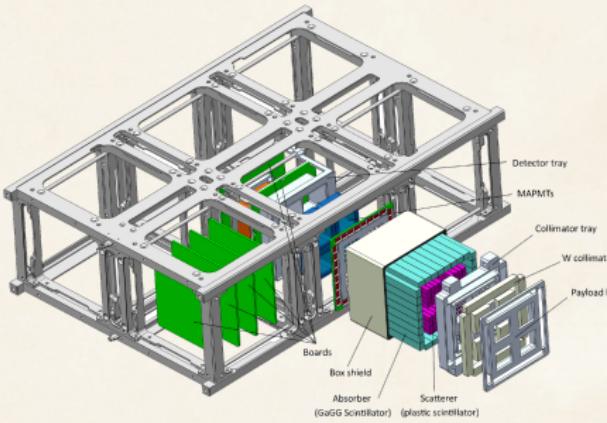


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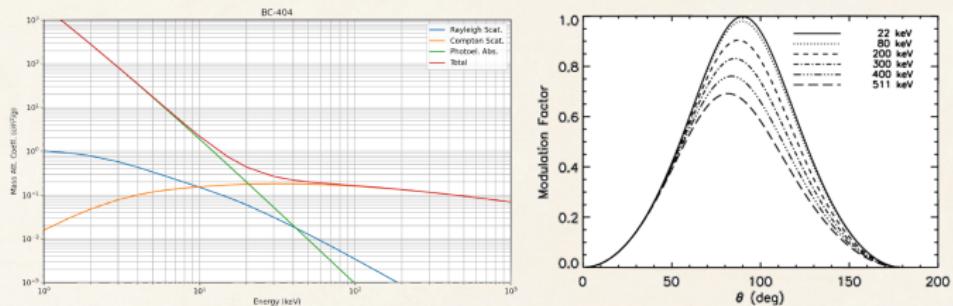


The CUSP Mission Preliminary Design

- Mission proposal: **Constellation of two 6U-XL CubeSats** orbiting the Earth on SSO orbit (\sim 500-600 km) to observe the Sun
- Monitoring of the Sun with a time fraction $>68\%$ during the 3 years nominal life-time
- X-ray polarimetry of Solar Flares in the 25-100 keV energy band
- Each satellite hosts a **dual-phase Compton scattering polarimeter** that exploits **coincidence** measurements between plastic (scatterer) and inorganic (absorber) scintillator rods
- **1 RPM rotation** of the spacecraft around the polarimeter symmetry axis pointing the Sun allows to reduce the systematic effect known as spurious polarization



- High probability of **scattering in plastic** material (4 MAPMTs read out with a MAROC-3A ASIC by WEEROC)
- 90° scattering produces maximum modulation of the signal
- @20 keV only 750 eV of Compton energy deposit for scattering at 90° , PMT needed (1-3 optical photons to collect)



NIST XCOM

Fabiani & Muleri 2014

- High probability of **photoelectric absorption** in the absorber (**GAGG**) material (32 APDs read out with a SKIROC-2A ASIC by WEEROC)
- Measurement of **coincidences** Scatterer/Absorber allows effective **background reduction**
- **Fast schedule, no R&D possible**, we need heritage and space proven items as much as possible. We selected APDs from past TSUBAME mission unfortunately lost in 2015 and similar MAPMTs (Y. Yatsu 2014, SPIE Proc.)

- **Minimum Detectable Polarization** (Weisskopf+ 2010, SPIE, Strohmayer & Kallman 2013, ApJ) in the 25-100 keV energy band (CBE based on benchmark SFs from Saint-Hilaire et al. (2008), Sol. Phys. 250, 53–73)

Flare Class	Integration time (s)	MDP (%) (25-100 keV)
M5.2	284	10.2
X1.2	240	5.0
X10	351	1.1

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

$$Q = \mu \sqrt{\varepsilon}$$

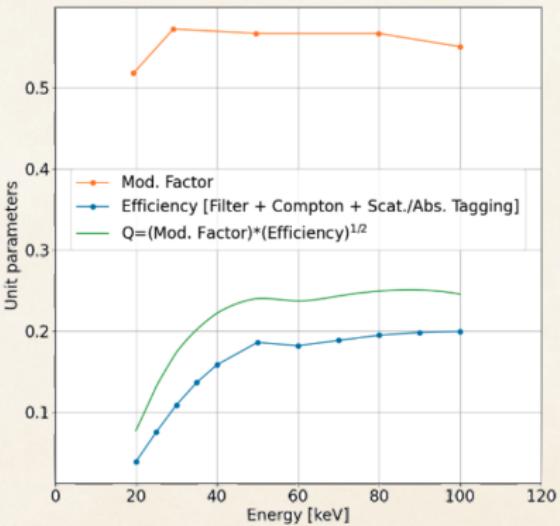
R: source rate

B: background rate

T: integration time

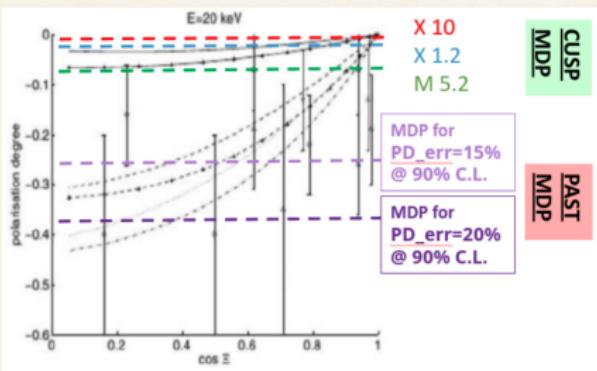
μ : modulation factor

ε : quantum efficiency



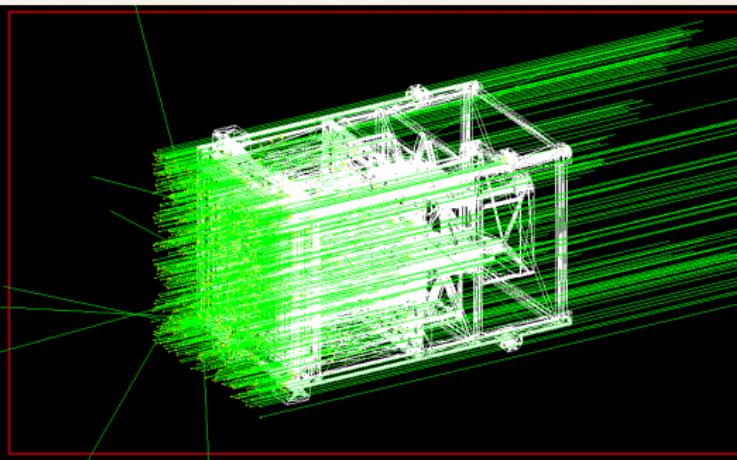
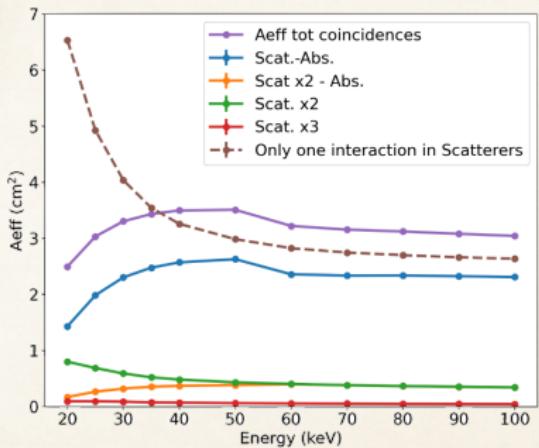
Single Satellite Polarimetric Sensitivity

- MDP $\sim 3\sigma$ for 1 parameter measurement (Strohmayer & Kallman 2013, ApJ)
- PD errors of about:
 - 15% with a C.L. of 90% ($\sim 1.645\sigma$) correspond to an MDP $\sim 27\%$
 - 20% corresponds to an MDP $\sim 37\%$
- **CUSP will reduce significantly the MDP wrt past observations.**
- Flares are **expected to be polarized at tens of %**, few minutes of integration time allow to measure with high significance their polarization



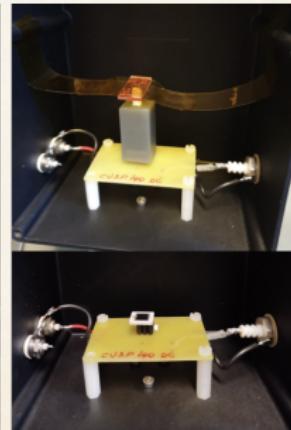
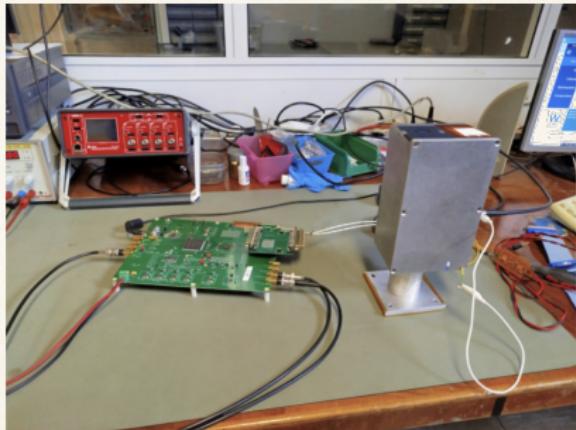
Zharkova+ 2010 (A&A)

- Analysis of the **effective area** (A_{eff}) in progress for design and analysis optimization
- We are currently working on getting the **spurious modulation** and **modulation factor** from simulations



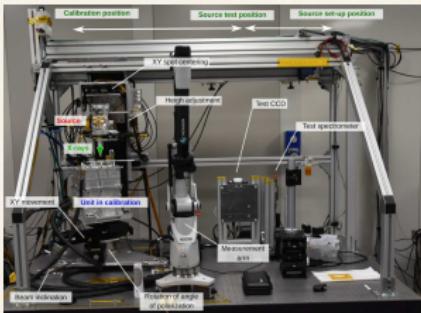
Laboratory Test of the Acquisition Chains

- CUSP is employing **2 acquisition chains** for the **Absorbers** (GAGG + APD + SKIROC-2A) and **Scatterers** (Plastic + MA-PMTs + MAROC-3A)
- Preliminary tests are being conducted based on ASIC Test Boards (WEEROC) and single scintillator bars coupled to sensors



Payload Calibration Plan

- Currently using **calibration sources** (Fe55 – 5.9keV, Cd109 – 22 and 88 keV, Am241 – 59.5 keV, Co57 – 123 keV) with single channel absorber/scatterer read out by ASIC development boards provided by WEEROC
- Soon building a reduced version of the instrument with **4×4 scatterers surrounded by 16 absorbers** to be read out by a **custom FEE** embedding both ASICs and an FPGA to apply the coincidence trigger logic
- This reduced module will be **calibrated in-house using calibration facilities** developed for IXPE's GPD calibration based on X-ray tubes combined with Bragg diffraction crystals to get a highly polarized X-ray flux
- Possibility of **calibration at Synchrotron facilities** with highly polarized beam in CUSP's energy range (e.g. ESRF in Grenoble, France)



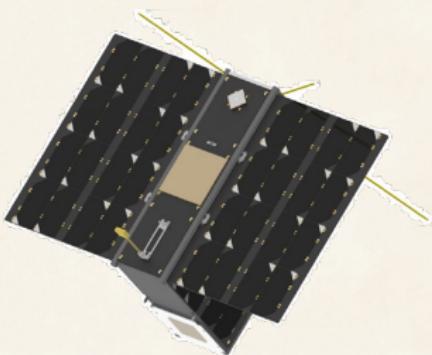
ICE setup @INAF-IAPS

- A **constellation of 2 6U-XL Cubesats** has been proposed in the frame of ASI's Alcor project
- Its main scientific goal is to perform **hard X-ray polarimetry of solar flares**, allowing to better understand the physics of coronal mass ejection and to probe magnetic reconnection sites in the Sun's atmosphere
- The **12 months Phase B** started in December 2024 to define a preliminary design and deliver a representative prototype of the polarimeter
- Next step would be to propose a **15 months combined Phase C/D**
- Model Philosophy:
 - 1 detector prototype at the end of Phase B. Representative of the detector front-end (from TRL 3 to TRL 4)
 - 1 payload sub-system Structural Model at the end of Phase B (scintillator bars holding system)
 - 1 payload EQM (design phase B, production and test phase C). Representative of the payload (from TRL 4 to TRL 7)
 - Trade-off assessment to allow ASI to decide if to continue with a 2 CubeSats constellation or with a single CubeSat. Depending on the outcome of the trade-off:
 - 1 Proto-flight Model (PFM). To qualify at proto-qualification level
 - If second satellite approved: 1 additional Flight Model (FM). To qualify at acceptance level
- Current launch window: **late 2027/early 2028**

The Satellite Platform and Ground Station

- BUS designed and produced by **IMT s.r.l.** company
- **6U-XL CubeSat** platform based on the heritage of the HORTA and EOSS platforms (funded by Italian regional POR / FESR 2014-20 projects of Lazio and Puglia regions, respectively)

Peak Power	~ 30 W with Deployable Panels in Sun Pointing
Battery	Up to 84 Wh (baseline 42 Wh)
Pointing accuracy	$\pm 2^\circ$ @ 1σ
Operative frequencies	S-Band downlink; UHF-Band uplink / downlink
Downlink throughput	Up to 5 Mbps
Available interfaces	CAN Bus, I2C, UART, SPI, RS485
Regulated bus	3,3V, 5V e 12V
Not regulated bus	16V (12V-16.8V)
Available volume for the payload	2.5U
Nominal life time	3 years in LEO



- Ground station located at the Università della Tuscia in Viterbo, Italy
- Available antennas and bands: VHF and UHF for uplink; VHF, UHF, and S-band for downlink