Solar Flare polarimetry with the CUbesat Solar Polarimeter (CUSP) mission

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on behalf of the CUSP Team

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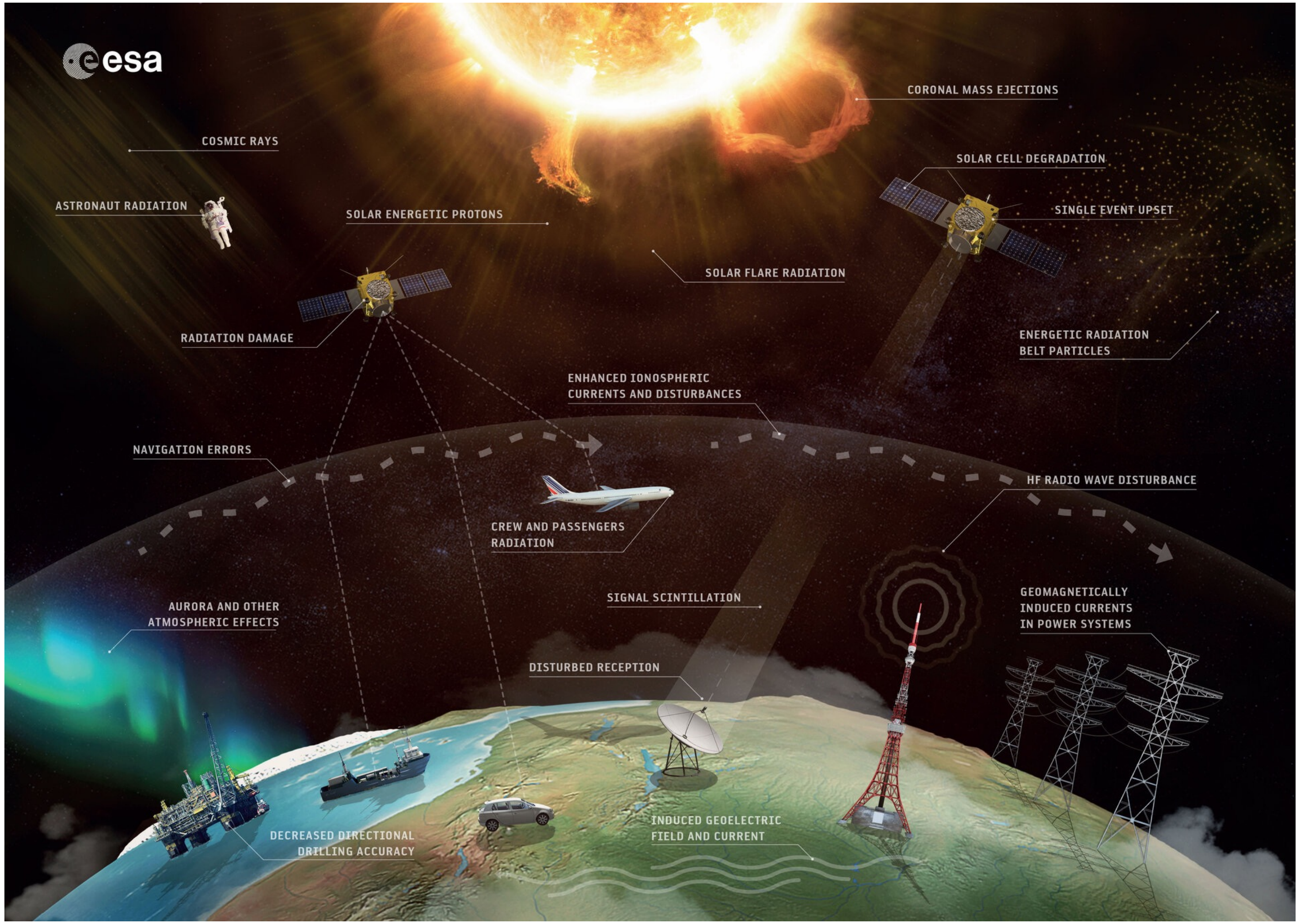
Solar Flares: Heliophysics and Space Weather

- 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**



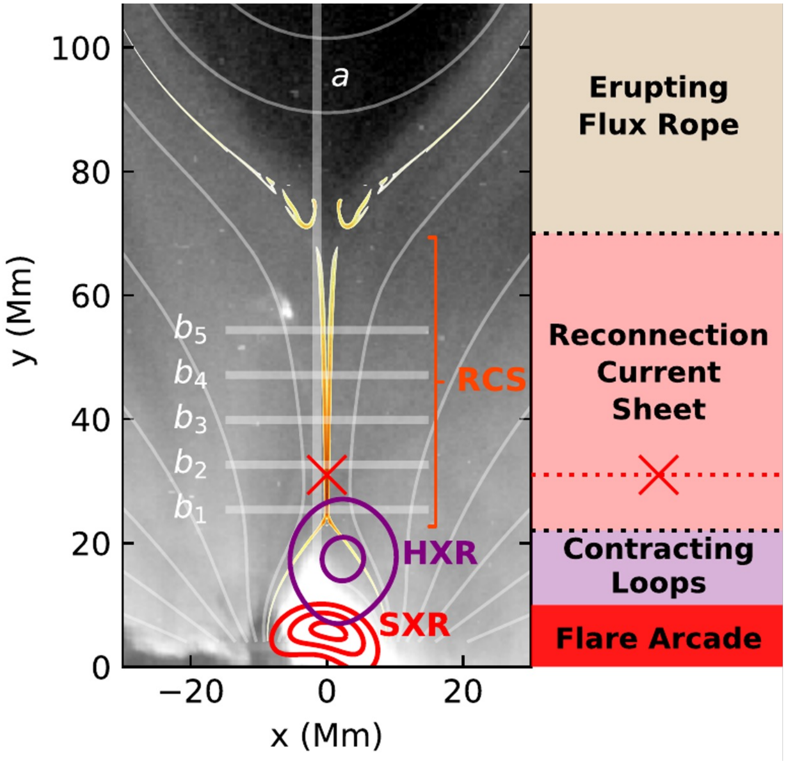
Solar Flares - CME feedback

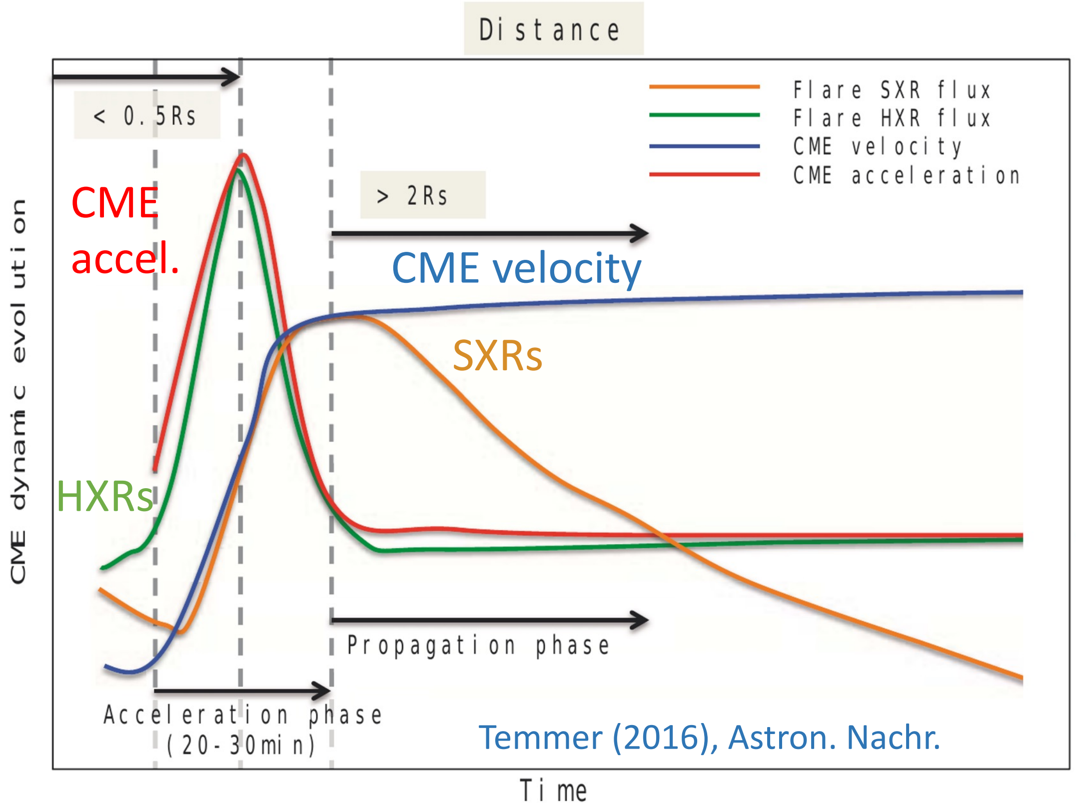
- Most powerful eruptions associated to powerful flares
- HXRs are related to CME acceleration

→ **HXR polarimetry** could improve the knowledge of the **initial conditions** of the eruption of most powerful CME

- SXRs are related to CME velocity

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





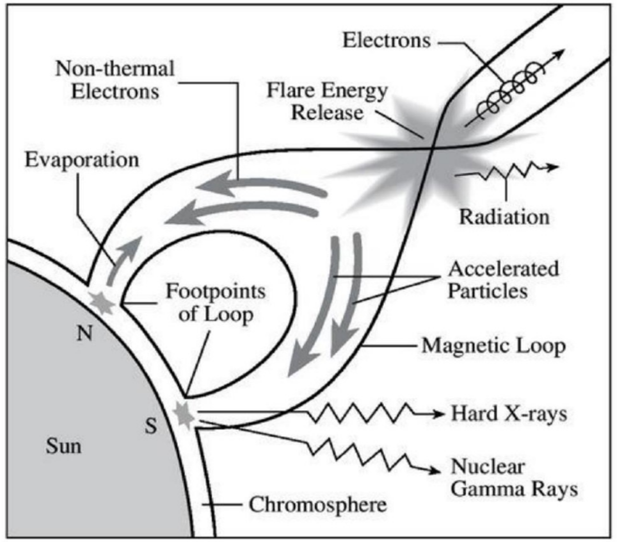
Temmer (2016), Astron. Nachr.

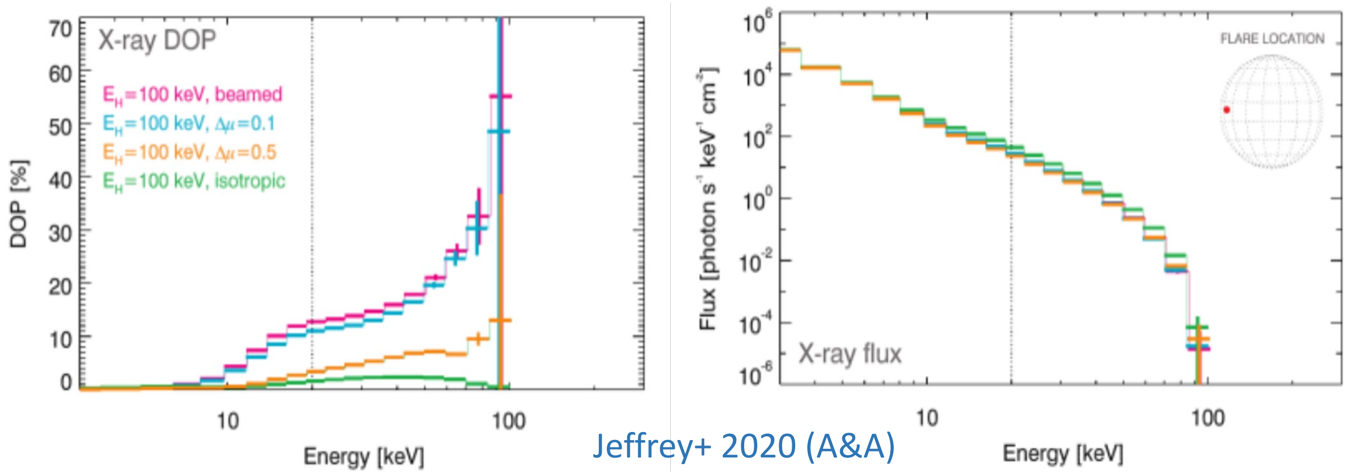
See also:
Zhang et al. (2001, 2004), ApJ;
Chen & Krall (2003), JGR;
Maričić (2007), Sol. Phys.
Temmer et al. (2008), ApJ Lett.;
Temmer et al. (2010), ApJ.
Berkebile-Stoiser et al., 2012

The rapid CME development in the lower corona during the acceleration phase strongly correlates with the associated flare activity.

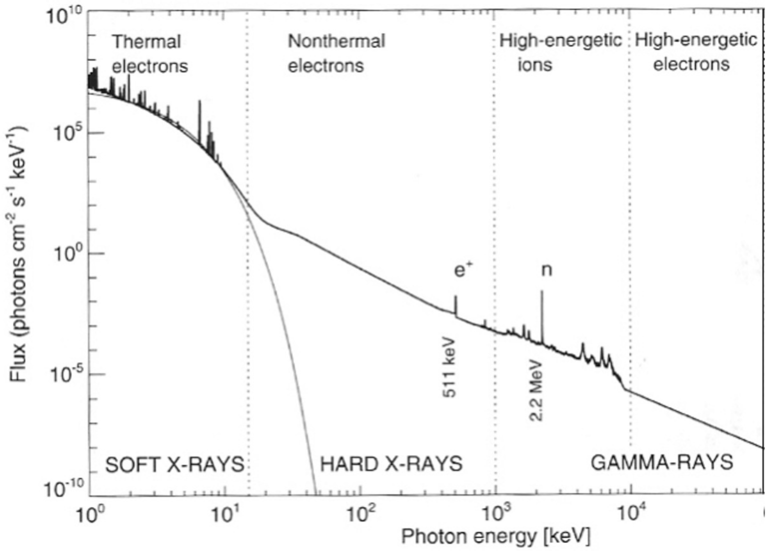
Why Hard X-ray polarimetry of Solar Flares?

- 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
- **X-ray polarimetry** (linear) would allow to **disentangle degeneracies** in **models** of particle beaming and magnetic field structure (also without imaging of the SF)





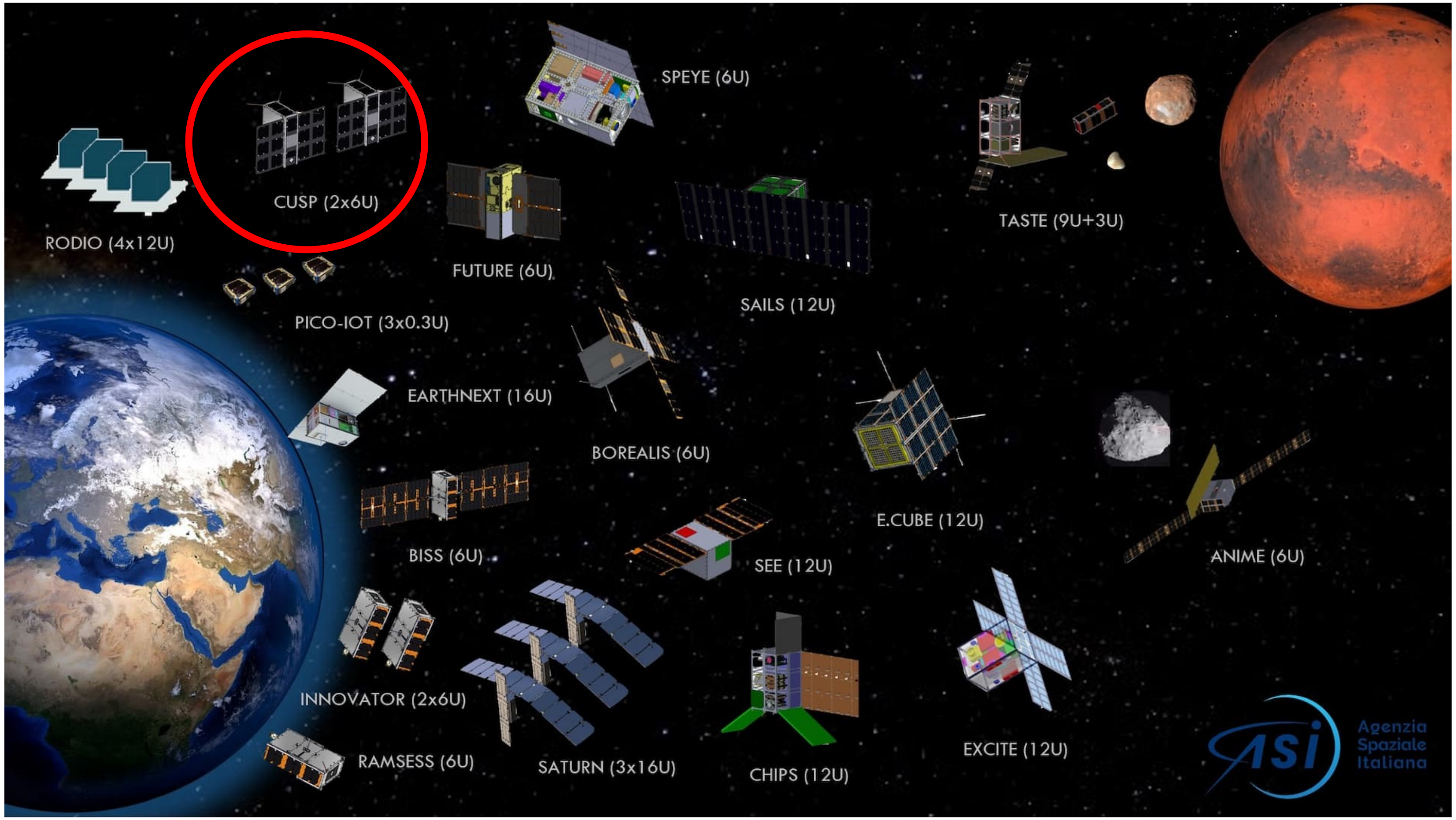
Jeffrey+ 2020 (A&A)



Aschwanden (2005)

The 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



CUSP Team

- INAF
  - IAPS (Prime and Payload)

    Sergio Fabiani (PI), Enrico Costa, Nicolas De Angelis, Ettore Del Monte, Sergio Di Cosimo, Alessandro Di Marco, Giuseppe Di Persio, Pasqualino Loffredo, Giovanni Lombardi, Gabriele Minervini, Fabio Muleri, Monia Rossi, Alda Rubini, Emanuele Scalise, Paolo Soffitta
  - OAS-Bologna (Detector Simulation)

    Riccardo Campana, Giovanni De Cesare
  - OAR (Lab-SW support)

    Mauro Centrone
- IMT s.r.l. (Platform)

  Massimo Perelli, Sergio Bonomo, Giovanni Cucinella , Andrea Negri
- SCAI Connect s.r.l. (Payload Electronics)

  Andrea Del Re, Giulia De Iulis, Paolo Leonetti, Alessandro Zambardi
- Università di Bologna – CIRI AERO (Mission Analysis)

  Paolo Tortora, Andrea Curatolo, Alfredo Locarini, Dario Modenini
- Università della Tuscia (Ground Segment)

  Pierluigi Fanelli, Ilaria Baffo

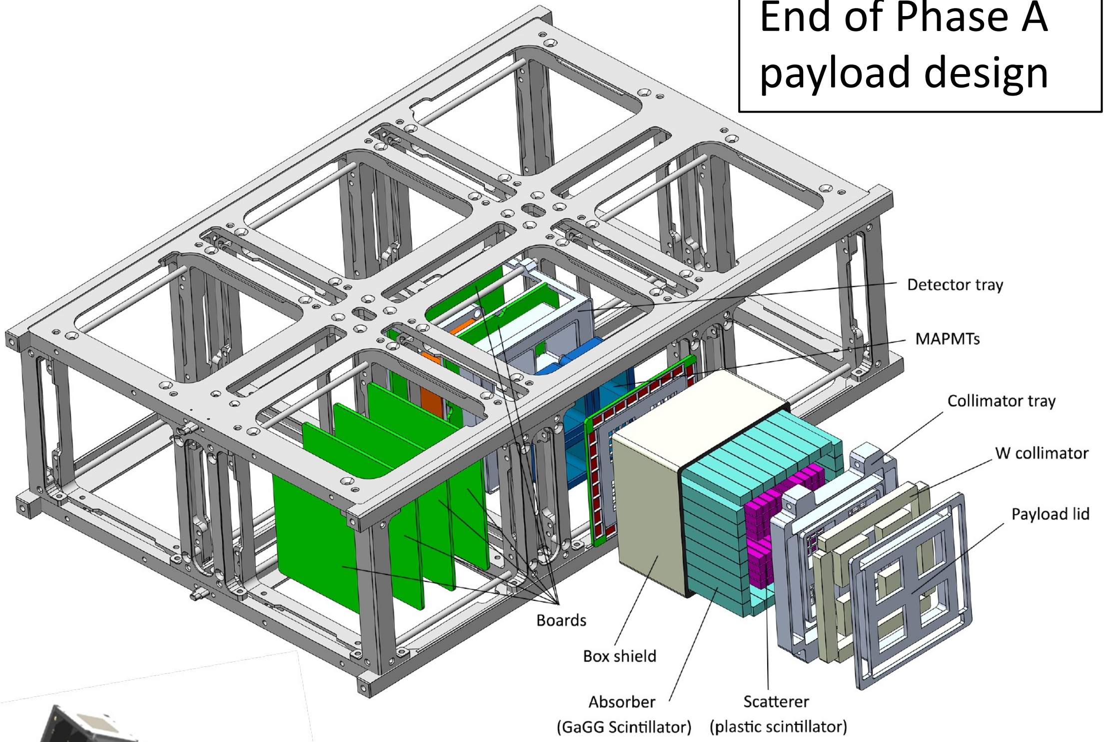
- ASI (Project Control)

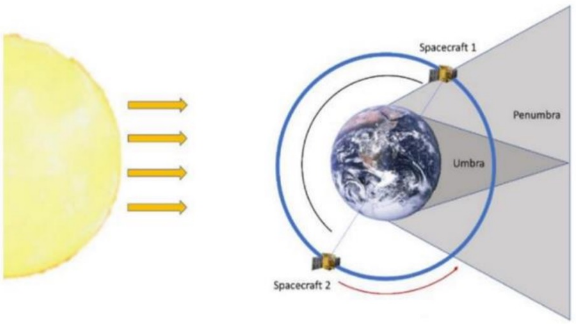
  Silvia Natalucci, Daniele Brienza, Immacolata Donnarumma, Andrea Terracciano, Emanuele Zaccagnino

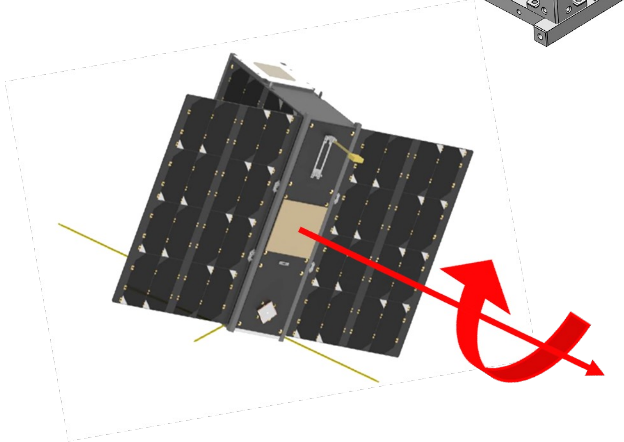
The payload

- **Constellation** of **two 6U CubeSats** orbiting the Earth on SSO orbit (~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

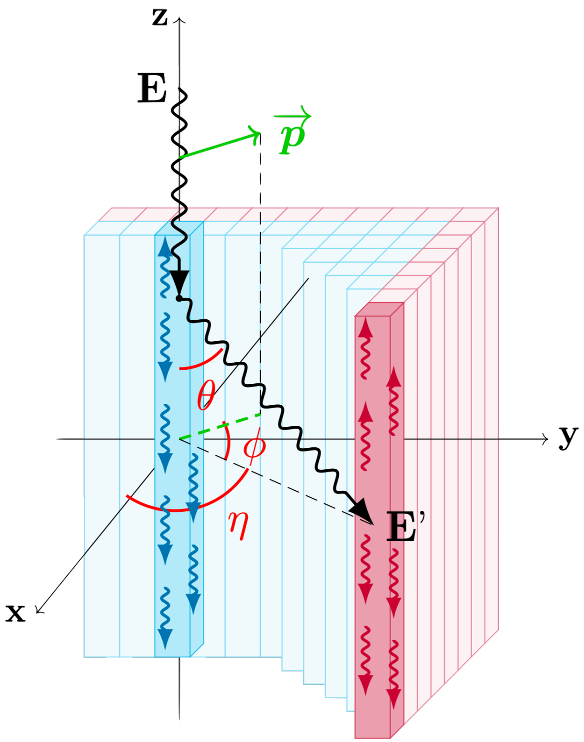
End of Phase A payload design

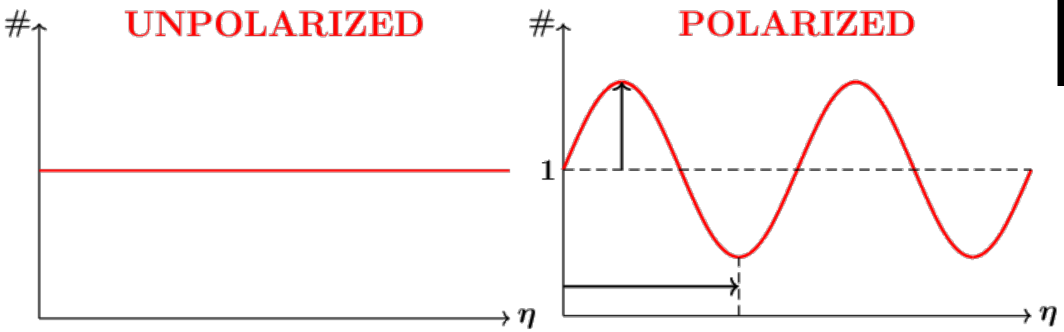


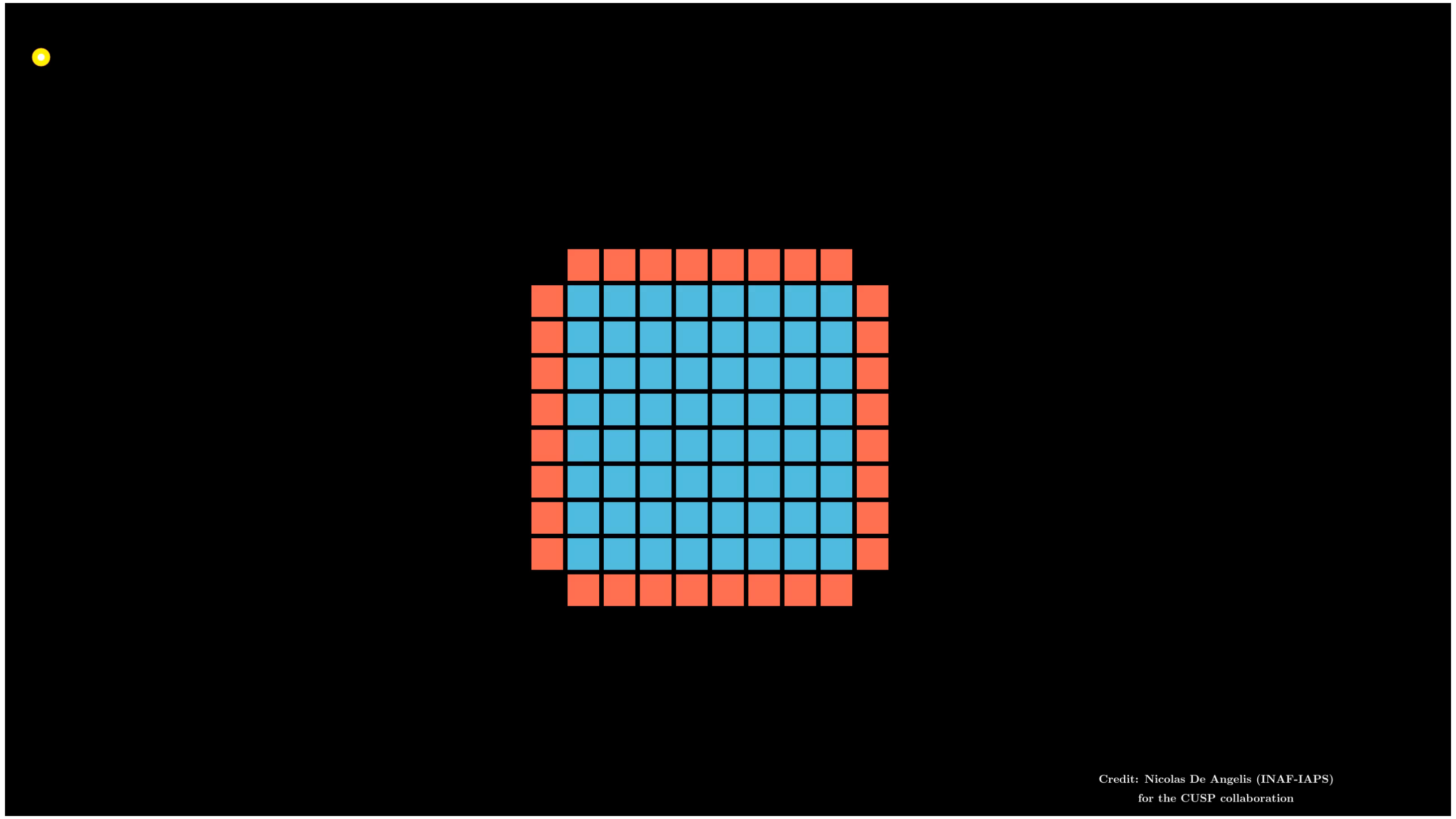




Compton polarimeter working principle





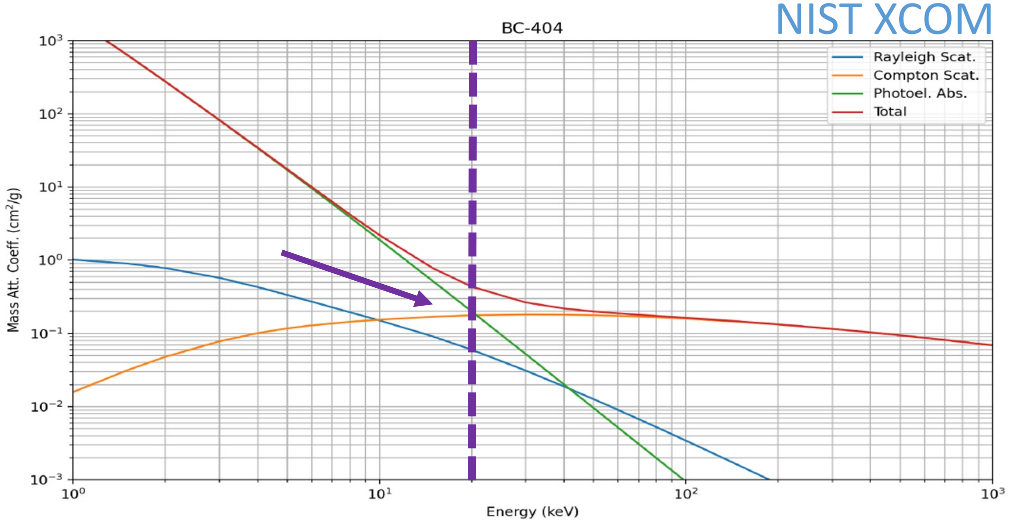


Klein-Nishina: $$\frac{d\sigma}{d\Omega} = \frac{r_e^2}{2}\left(\frac{E'}{E}\right)^2\left[\frac{E'}{E} + \frac{E}{E'} - 2\sin^2(\theta)\boxed{\cos^2(\phi)}\right]$$

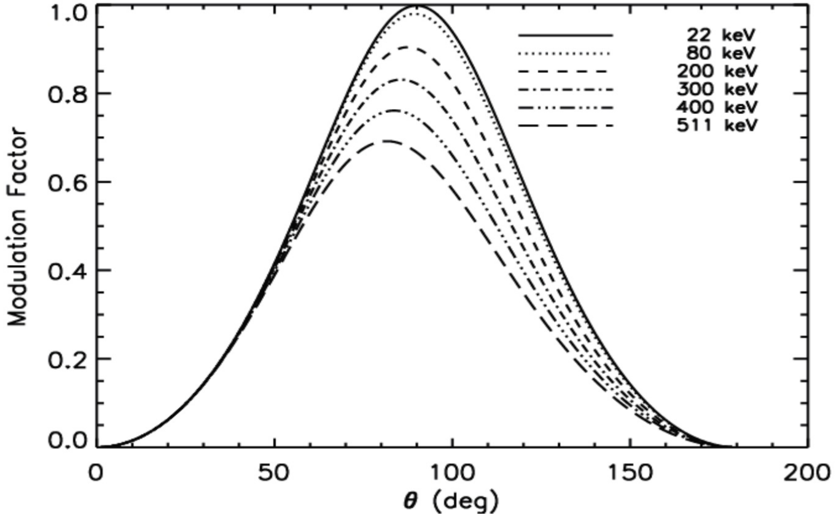
Our dual-phase design

- 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 unfortuantely lost in 2015 (and similar MAPMTs) by Hamamatsu (Japan - Yoichi Yatsu 2014, SPIE Proc.)

The payload sensitivity

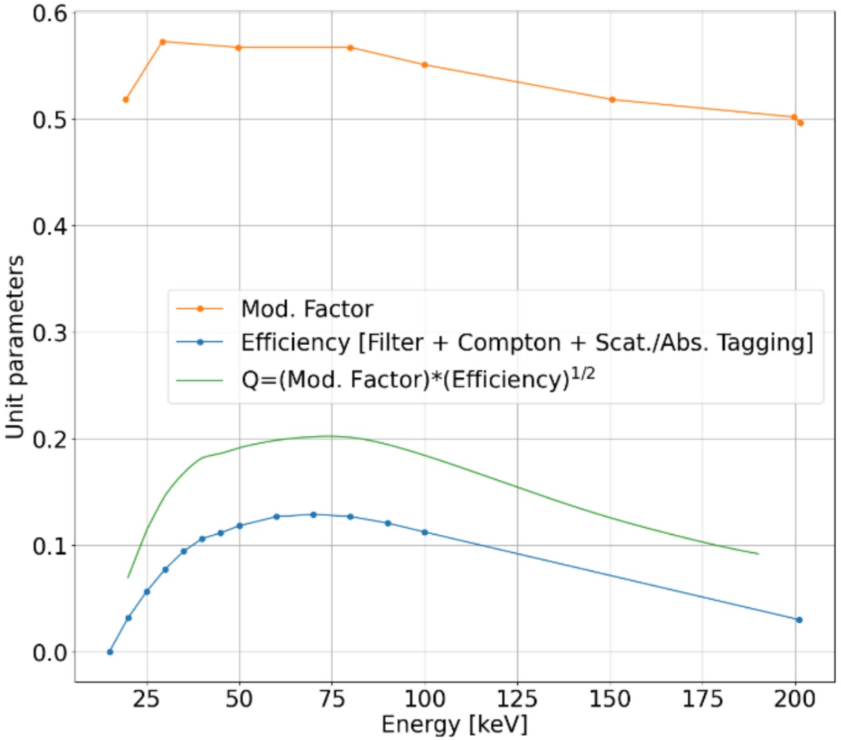
- **Minimum Detectable Polarization** (Weisskopf+ 2010, SPIE, Strohmayer & Kallman 2013, ApJ) in the 25-100 keV energy band (CBE based on benchmark SFs from Saint-Hilaire et al. (2008), Sol. Phys. 250, 53–73)

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



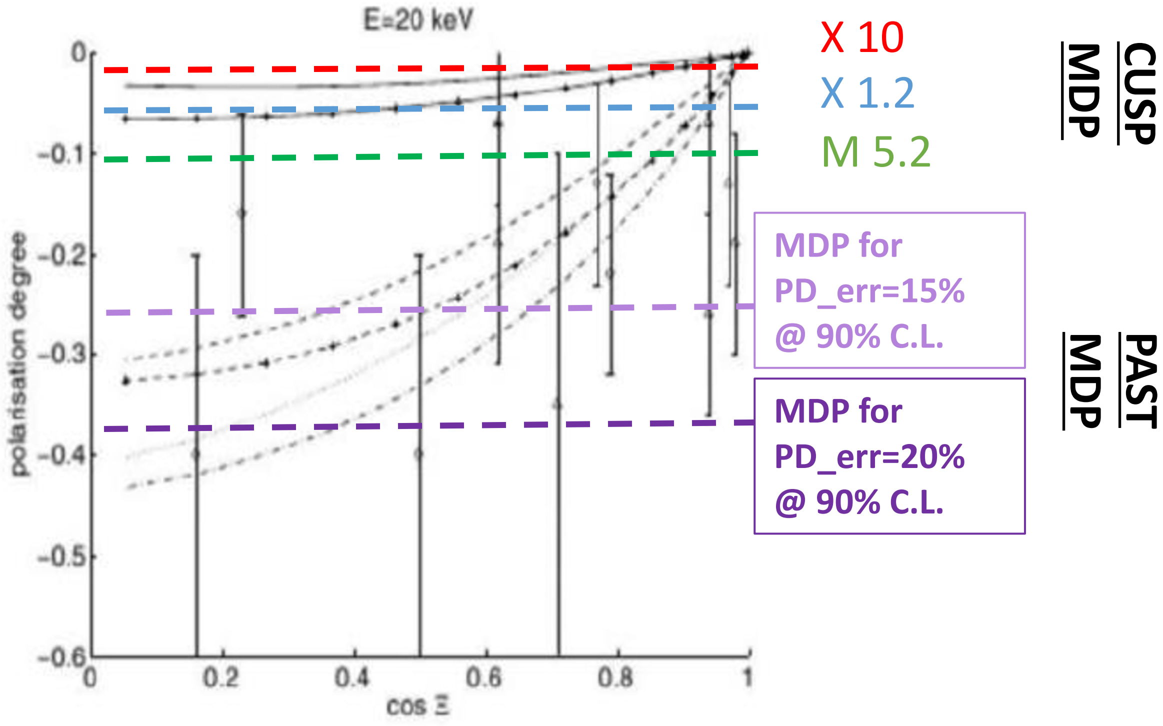
Tagging efficiency by Fabiani+ 2013 Astrop.Phys ., is the probability to detect a scattering event in the plastic if the scattered photon is detected in the absorber.

The payload sensitivity

- MDP~3σ for 1 parameter measurement
  (Strohmayer & Kallman 2013, ApJ)
- PD errors of about:
  - 15% with a C.L. of 90% (~ 1.645 σ) correspond to an MDP ~27%
  - 20% corresponds to an MDP ~37%

- **CUSP will reduce significantly the MDP wrt past observations.**

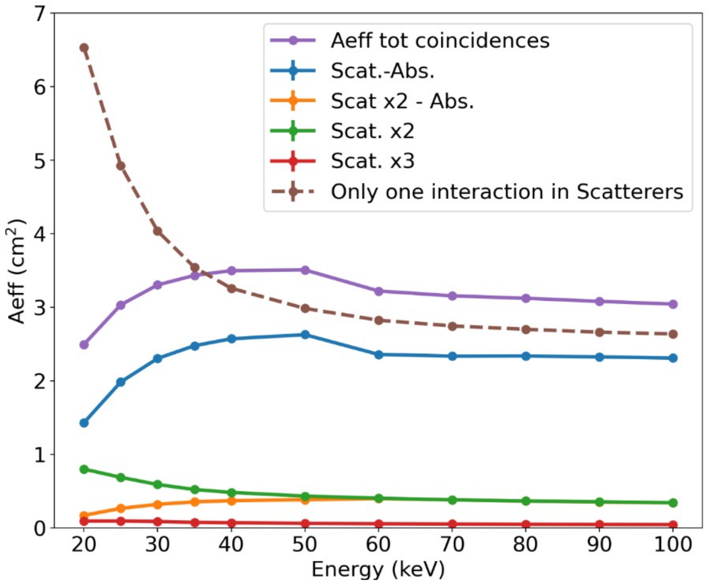
- Flares are expected to be **polarized at tens of %**, few minutes of integration time allow to measure with high significance their polarization

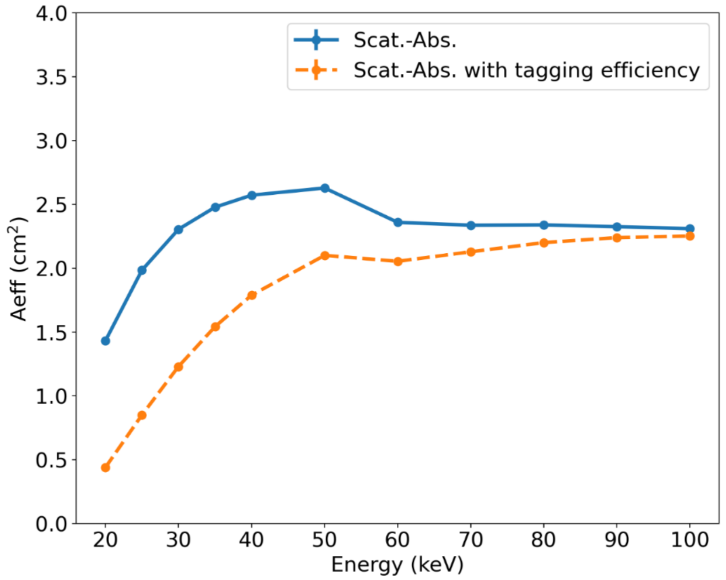


Zharkova+ 2010 (A&A)

Design optimization: Geant4 simulations

- Analysis of the **effective area (Aeff)** in progress for design and analysis **optimization**
- Next to come **spurious modulation** and **modulation factor**



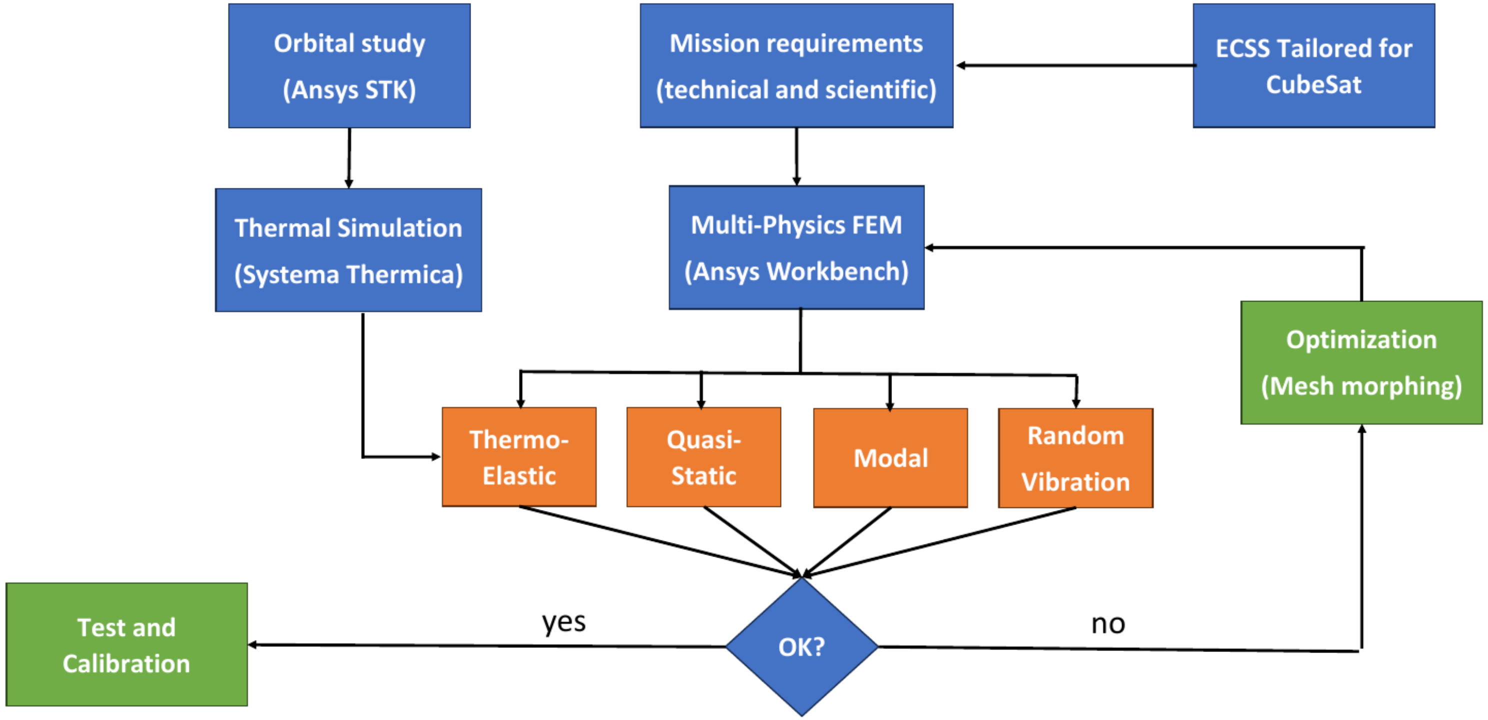


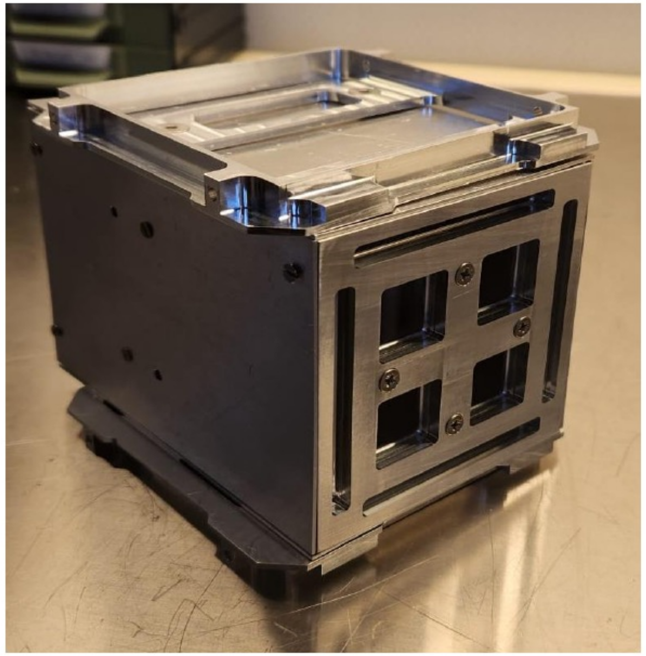
Tagging efficiency by Fabiani+ 2013 Astrop.Phys .

- **De Cesare et al.** SPIE2024 13093-311, “The evaluation of the CUSP scientific performance by a GEANT4 Monte Carlo simulation”

Thermo-mechanical optimization

- Implementation of a **multi-physical thermo-mechanical simulation method** to apply **during next phase B** already allowed some hypothesys of improvement of the mechanical design

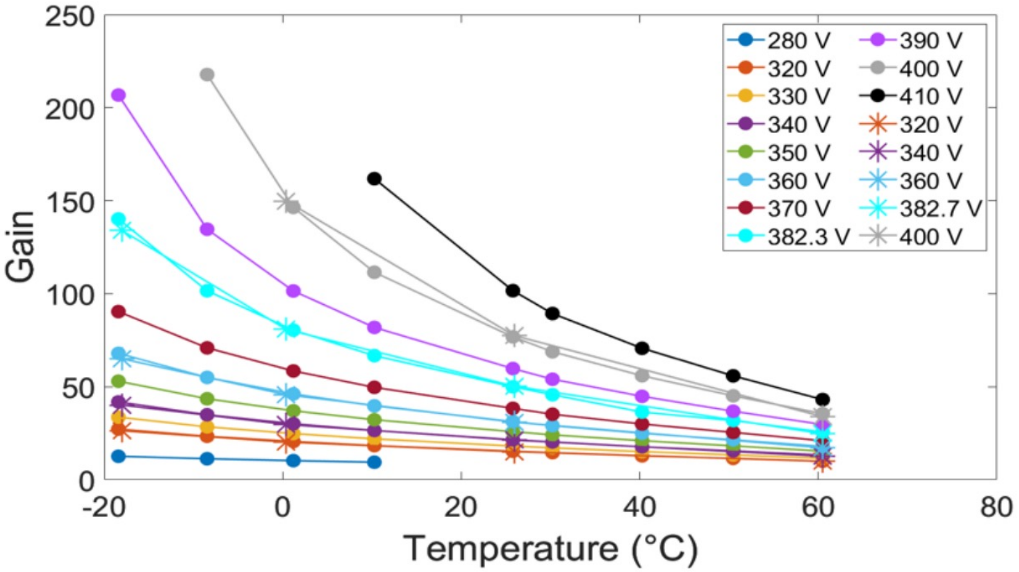


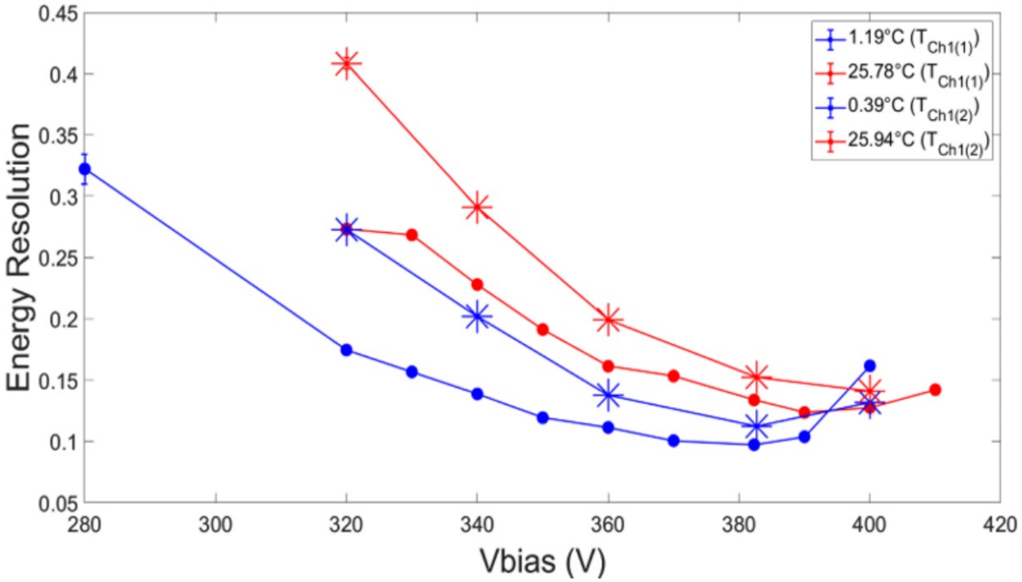


- **Lombardi et al. SPIE 2024** 13093-307, "The payload thermo-mechanical design of the CUbesat Solar Polarimeter (CUSP), for Space Weather and Solar flares X-ray polarimetry."

Characterization of the light sensors

- Test and characterization of the APDs @ INAF-IAPS
- APD gain is strongly dependent on the temperature



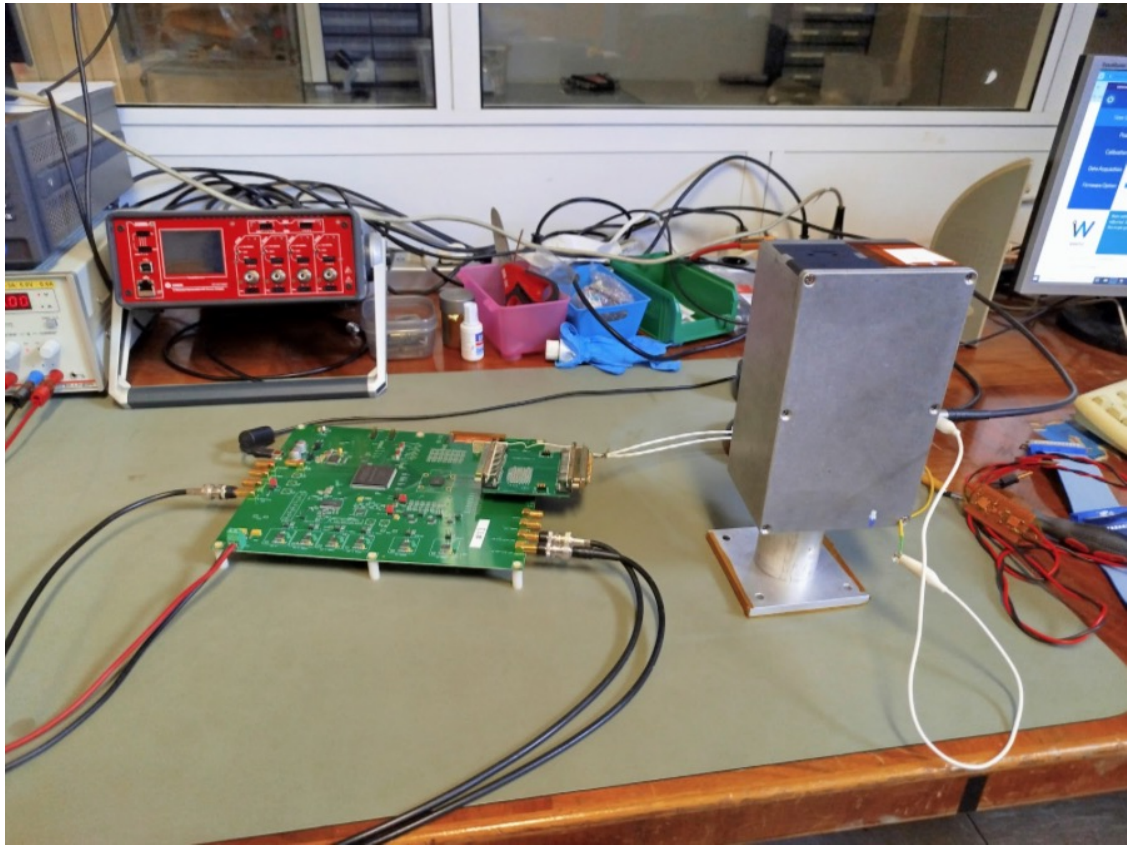


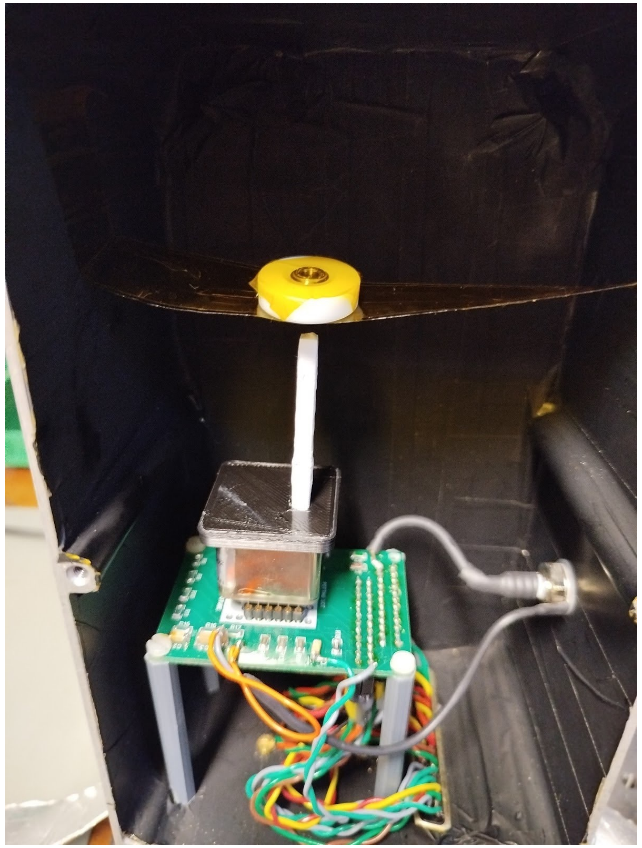
APD directly illuminated with a ^{55}Fe source

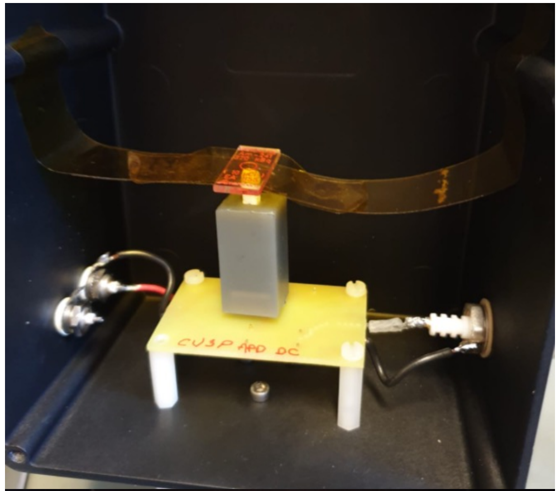
- **Alimenti et al.** Sensors 2024 "Design and test of a calibration system for avalanche photodiodes used in X-ray Compton polarimeters for space"

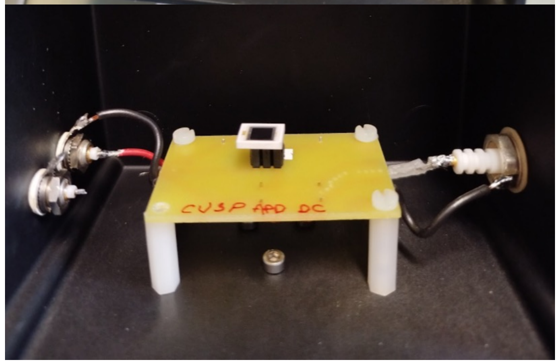
Testing of the two acquisition chains

- 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









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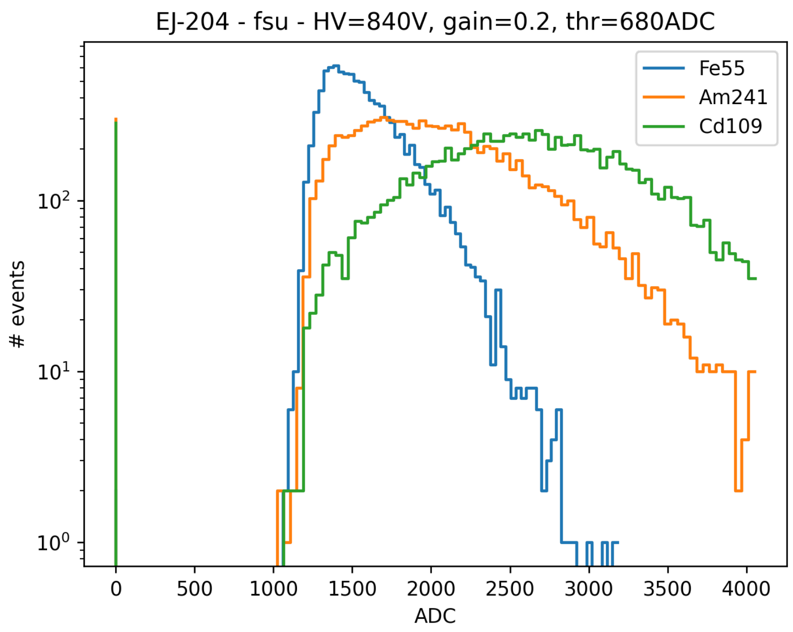
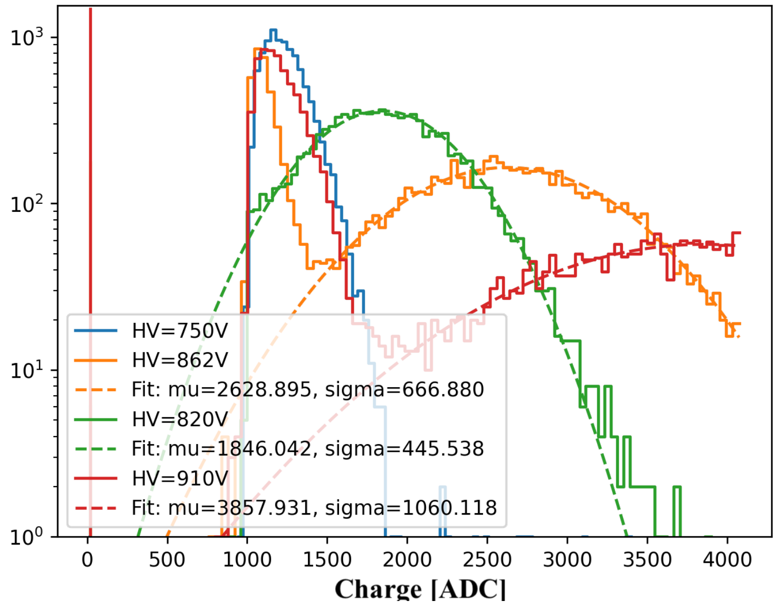
- Preliminary tests are being conducted based on ASIC Test Boards (WEEROC) and single scintillator bars coupled to sensors
- Measuring preliminary performances: energy range, noise optimization and energy threshold, noise rejection with coincidences between the two systems

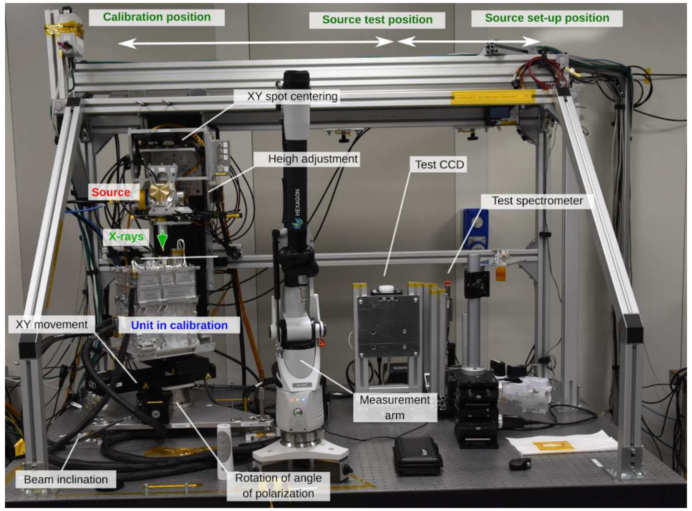




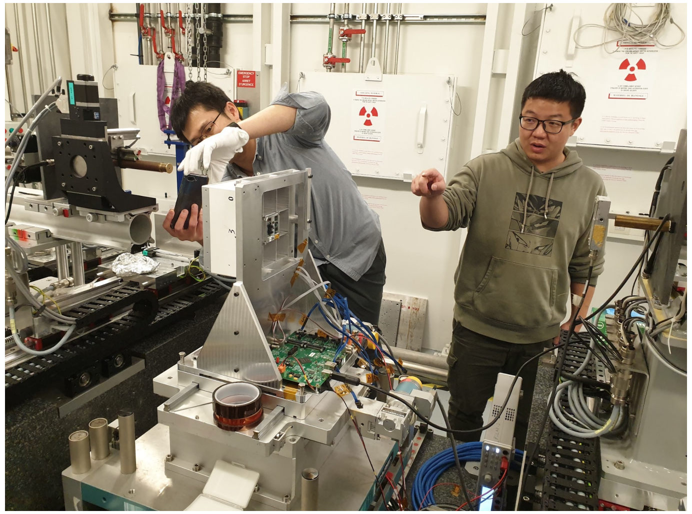
Impinging Energy (keV)	Scattering angle (deg)	Compton energy deposit (keV)
20	90	0.753
25	90	1.17
30	90	1.66
40	90	2.90
50	90	4.46
60	90	6.31
80	90	10.8
100	90	16.4
	65	10.2

Calibration plans of the phase B prototype

- 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 **4x4 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 ESRF** (France) with synchrotron polarized beam in the 20-500 keV range, such beam line has already been used for calibration of POLAR as well as prototypes modules from POLAR-2 HPD and BSD



ICE setup @INAF-IAPS

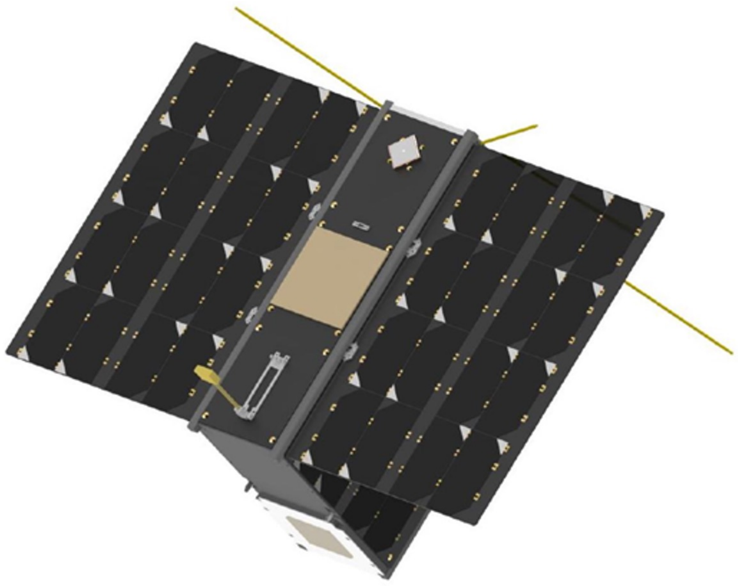


POLAR-2 HPD/BSD ESRF beam test

The satellite platform

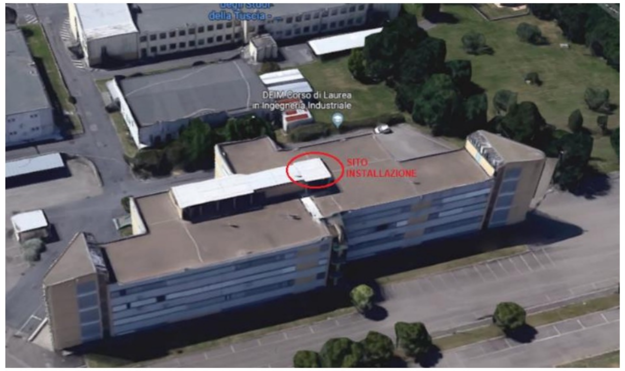
- Designed and prduced by **IMT s.r.l.** Italian company
- **6U CubeSat** platform based on the heritage of the HORTA and EOSS platforms (funded by Italian regional POR / FESR 2014-20 projects of Lazio and Puglia regions, respectively).

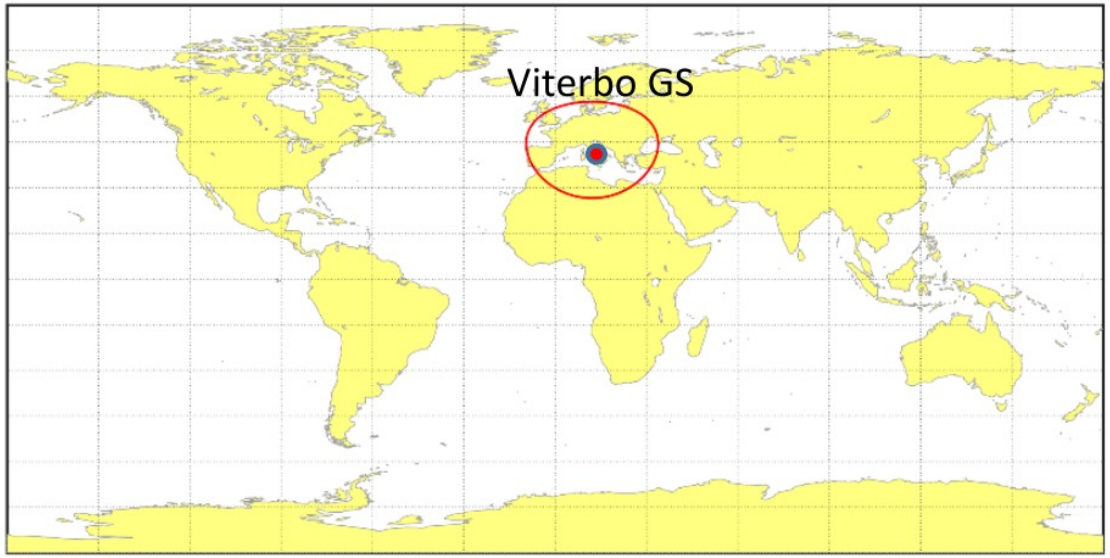
Peak Power	$\sim$ 30 W with Deployable Panels in Sun Pointing
Battery	Up to 84 Wh (baseline 42 Wh)
Pointing accuracy	$\pm 2^\circ$ @ 1σ
Operative frequencies	S-Band downlink; UHF-Band uplink / downlink
Downlink throughput	Up to 5 Mbps
Available interfaces	CAN Bus, I2C, UART, SPI, RS485
Regulated bus	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



The Ground Station

- Located on a building of the **Università della Tuscia in Viterbo (Lazio, Italy)**
- Built in 2019 for the HORTA project (funds POR/FESR 2014-2020 by Lazio Region)
- Available antennas and bands:
  - VHF: Uplink and Downlink
  - UHF: Uplink and Downlink
  - S-band: Downlink
- UHF/VHF bandwith:
  - Downlink: default 9.6 kbps (available also 1.2/2.4/4.8 kbps)
  - Uplink: default 1.2 kbps (available also 2.4/4.8/9.6 kbps)
- S-band bandwith:
  - Downlink: up to 1 Mbps





Conclusions & Project Status

- **CUSP** will measure linear X-ray polarization of solar flares for **Heliophysics** and **Space Weather**, with a better MDP w.r.t. past missions. A better understanding of magnetic reconnection processes can also be precious for studying the physics of energetic astrophysical sources
- The 12 months **Phase B** should be starting in **October/November 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 1 CubeSat
  - Depending on the trade-off 1 or 2 CubeSats:
    - 1 Proto-flight Model (PFM). To qualify at proto-qualification level
    - 1 additional Flight Model (FM). To qualify at acceptance level
- **Calibration** of the Hard X-ray Polarimeter of each CubeSat will be carried out at INAF-IAPS calibration facility (+ possibility for measurements at Synchrotron facilities like ESRF)

High Solar Activity and the May 2024 Events

ROMATODAY

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Redazione

11 maggio 2024 07:41

Si parla di

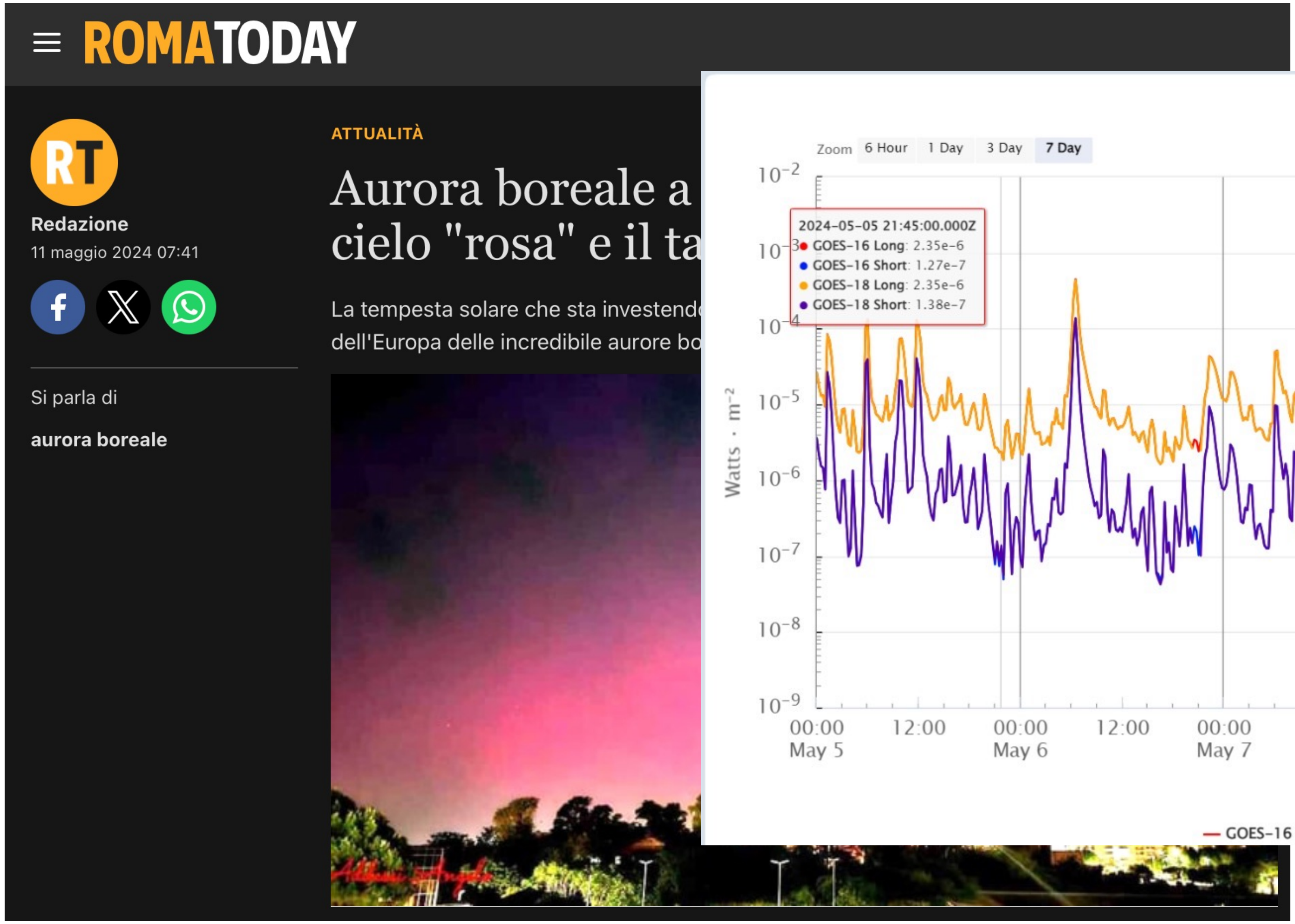
aurora boreale

ATTUALITÀ

Aurora boreale a Roma, lo spettacolo del cielo "rosa" e il tam tam sui social

La tempesta solare che sta investendo la terra sta facendo apparire nei cieli di buona parte dell'Europa delle incredibile aurore boreali

High Solar Activity and the May 2024 Events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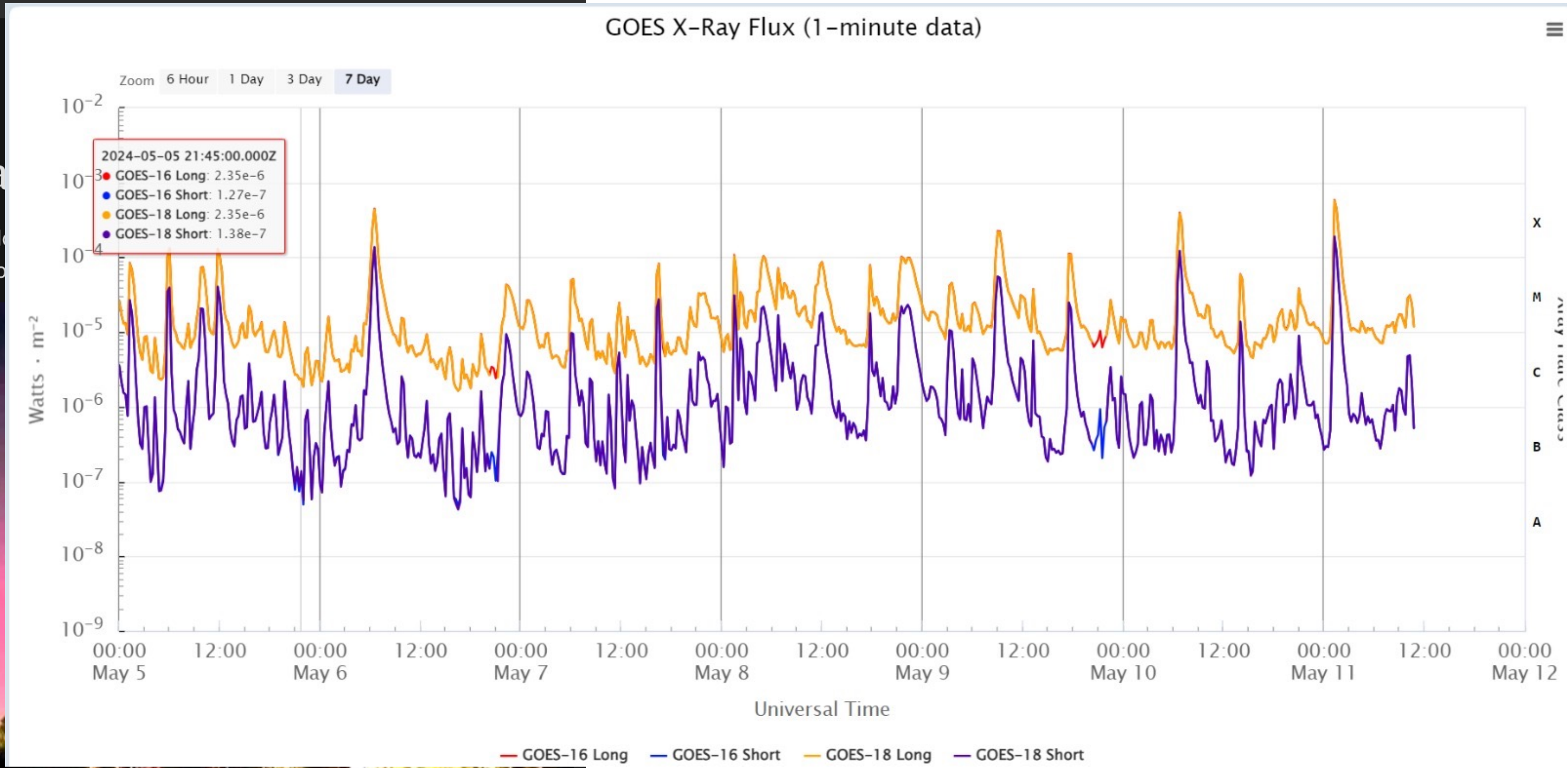

https://www.swpc.noaa.gov/

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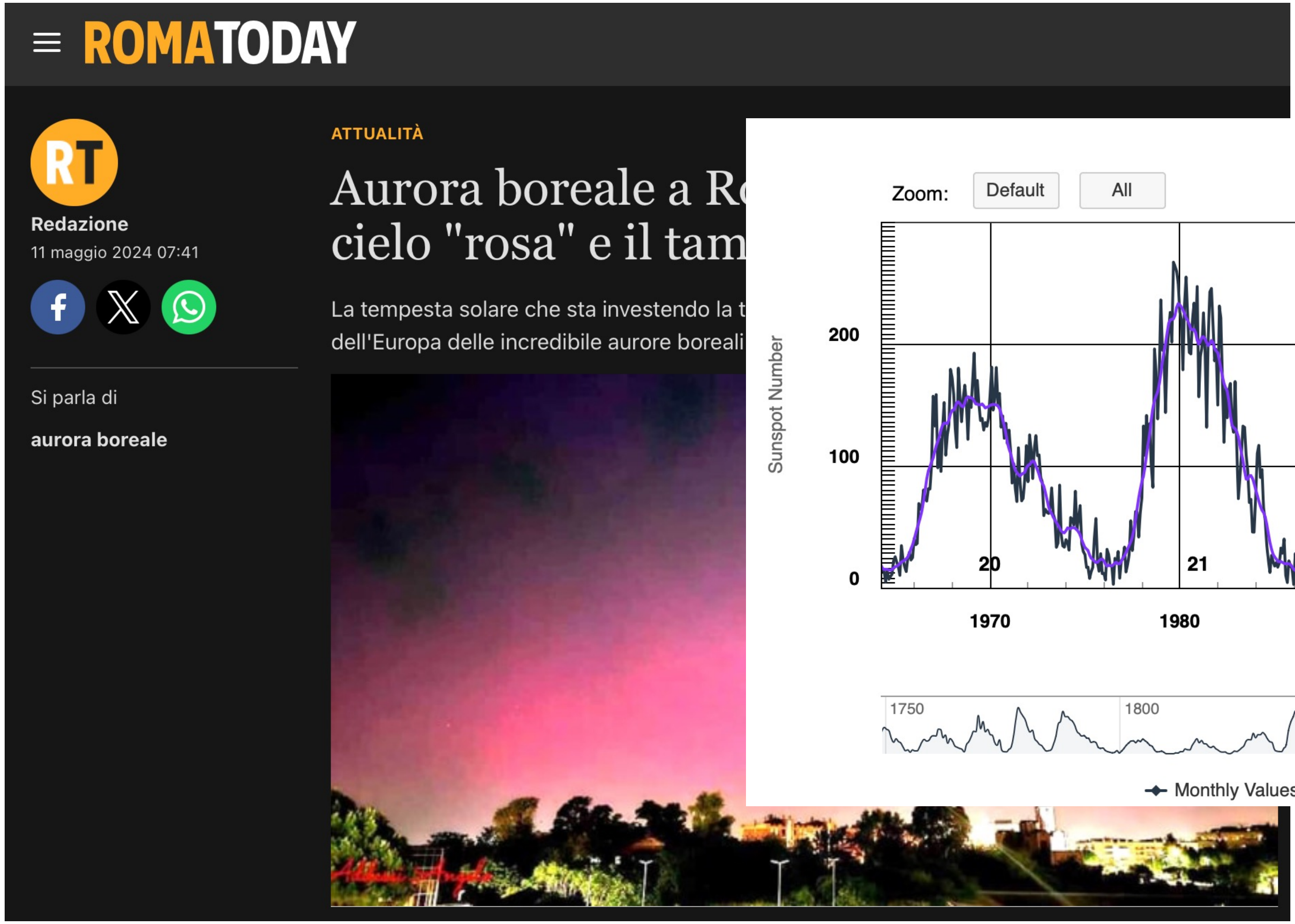

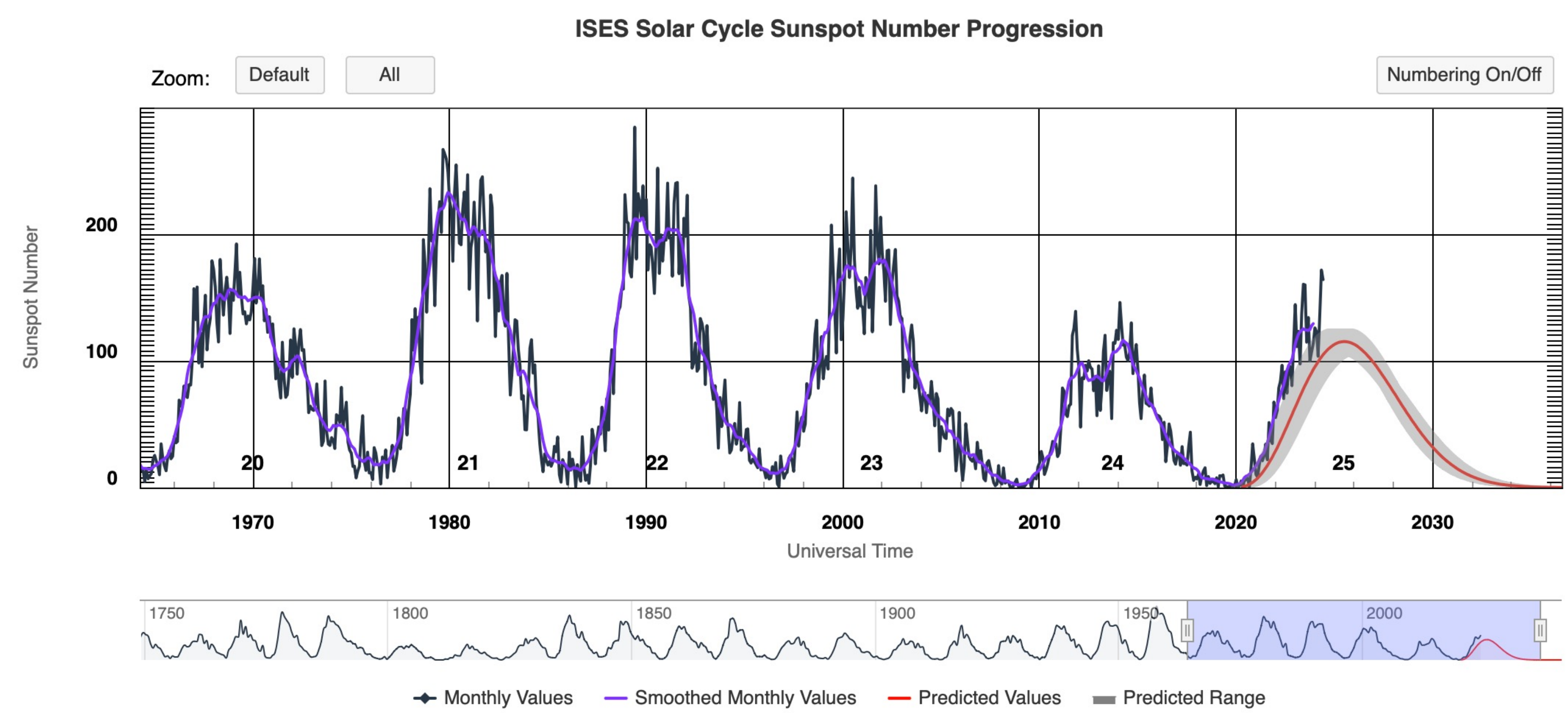

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