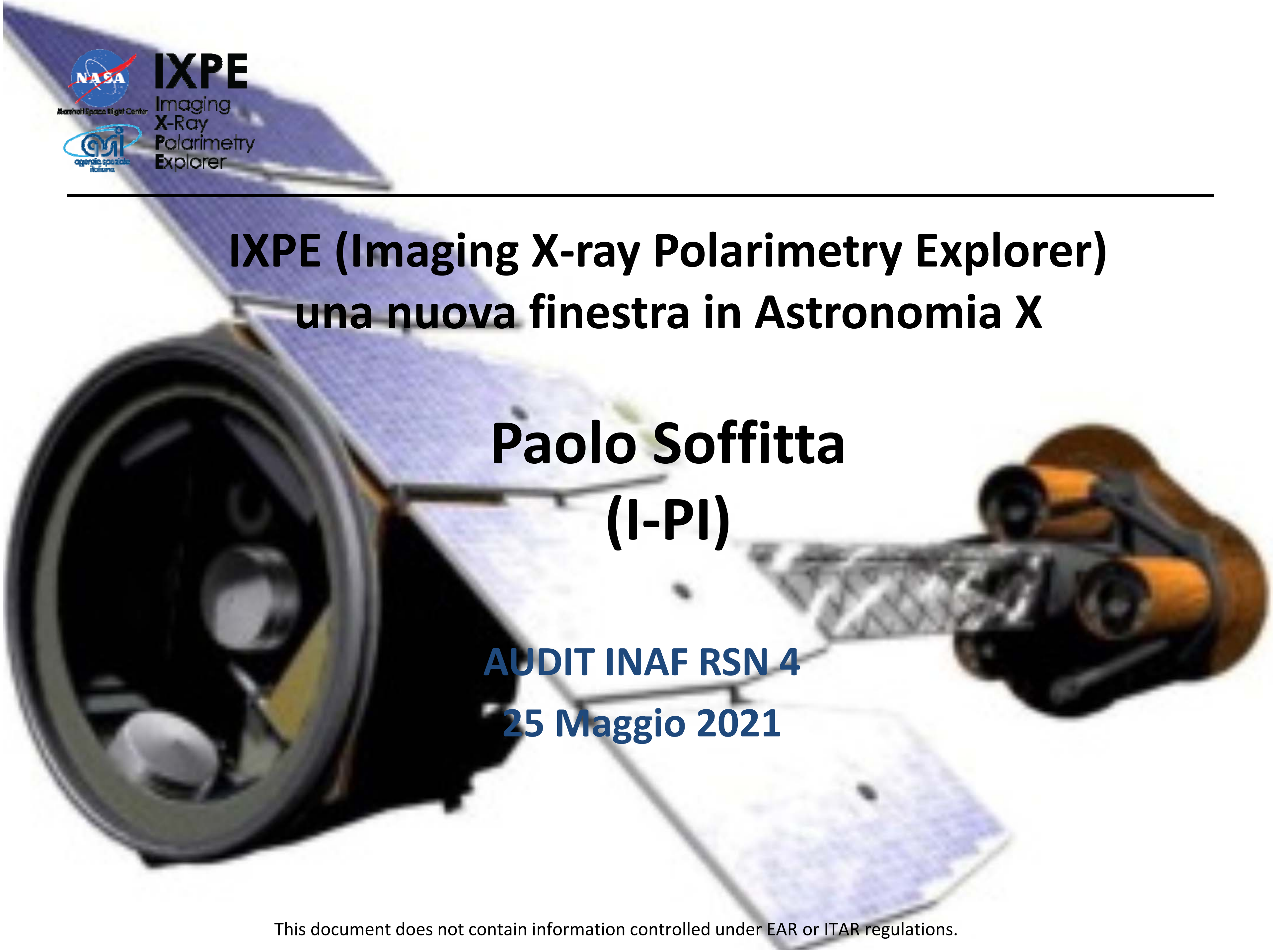


IXPE (Imaging X-ray Polarimetry Explorer) una nuova finestra in Astronomia X

Paolo Soffitta
(I-PI)

AUDIT INAF RSN 4

25 Maggio 2021

Why X-ray Astrophysical Polarimetry ?

Polarization from celestial sources may derive from:

- **Emission processes themselves: cyclotron, synchrotron, non-thermal bremsstrahlung**

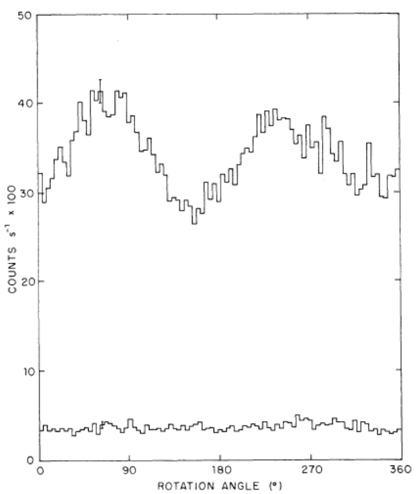
(Westfold, 1959; Gnedin & Sunyaev, 1974; Rees, 1975)

- **Scattering on aspherical accreting plasmas: disks, blobs, columns.**

(1975; Sunyaev & Titarchuk, 1985; Mészáros, P. et al. 1988)

- **Vacuum polarization and birefringence through extreme magnetic fields**

(Gnedin et al., 1978; Ventura, 1979; Mészáros & Ventura, 1979)



Notwithstanding the theoretical previsions the polarization of only one source was detected so-far by OSO-8 back in the '70:

Positive measurement: of X-ray polarization of the Crab Nebula without pulsar contamination
(by lunar occultation, Weisskopf et al., 1978).

P = (19.2 ± 1.0) %; θ = 156°.4 ± 1°.4 (2.6 keV)

P = (19.5 ± 2.8) % ; θ = 152°.6 ± 4°.0 (5.2 keV)

The technique was the limit !

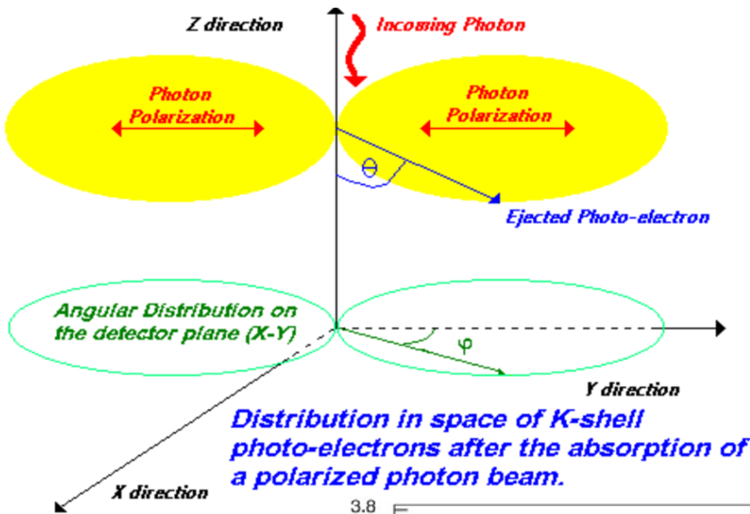
Many proposals different leadership in majority italian

IXPE
Imaging
X-Ray
Polarimetry
Explorer

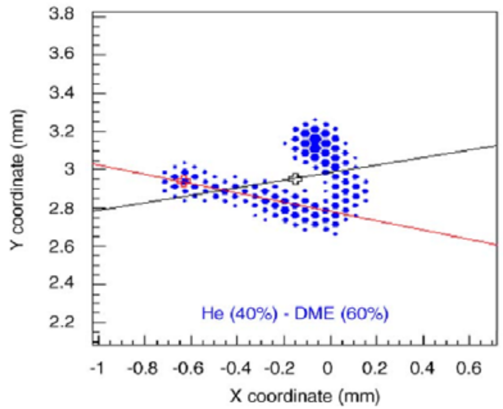
In 2001 we developed a tecnique that allows sensitive polarimetry using photoelectric effect

Mission	Date	PI
XMM	Late 80’	G.W. Fraser (UK)
SXRP /SRG	Late 80’ Early 00’	R.Novick (USA)
XEUS/IXO	2007-2012	R. Bellazzini (IT)
POLARIX	2007-2008	E. Costa (IT)
IXPE (OLD)	2007	M. Weisskopf (USA)
HXMT	2007-2009	E. Costa (IT)
NHXM	2011	G. Tagliaferri (IT)
LAMP	2013	H. Feng (China)
XIPE (Small)	2014	E. Costa (IT)
ADAELI+	2014	F. Berrilli (IT)
SEEPE (ESA-CAS)	2014	S.Liu-P. Soffitta
XIPE M4	2014-2017	P. Soffitta (IT)
IXPE	2014+	M. Weisskopf (USA)

$$\frac{\partial\sigma}{\partial\Omega} = r_o^2 \frac{Z^5}{137^4}\left(\frac{mc^2}{h\nu}\right)^{7/2} \frac{4\sqrt{2}\sin^2(\theta)\cos^2(\varphi)}{(1-\beta\cos(\theta))^4}$$



Costa et al., 2001



Energy, space and time resolved X-ray polarimetry

XIPE & IXPE

In 2014 **ESA** and **NASA** issued an AOO respectively for the 4th Scientific Mission of Medium Size (M4) with a budget of 450 M€ (+ national contributions launch 2029) and for SMEX (budget of ~ 175 M$ Launch 2021)

XIPE and IXPE performed competitive phase A among three mission each

IXPE was selected first in January 2017 and this caused the XIPE non-selection:

We lost the PI-Ship (still INAF I-PI) but the data will be avaiable 8 years in advance

IXPE is only slightly less sensitive than XIPE and the NASA Standing Review Board wrote in the Mission –System Requirement Rreview final report:

"Value and quality of the Italian contribution raises the total return on investment such that the mission is closer to a MIDEX"

Imaging X-ray Polarimetry Explorer

Classificazione:

RSN 4, RNS 5

Obiettivo Tecnologico:

Utilizzare l’ effetto fotoelettrico in gas per misurare la polarizzazione dei raggi X.

Obiettivi Scientifico:

Migliorare la conoscenza di come funziona l’universo nella banda delle alte energie inclusa la determinazione della geometria delle sorgenti compatte

Risultati e prospettive:

Attualmente i risultati ottenuti sino a qui permettono di affermare che i requisiti scientifici di alto livello quali la sensibilita’ dichiarata in fase di proposta sono rispettati al lancio previsto per il 17 novembre 2021. Il commissioning durera’ un mese. Durante i primi tre mesi i dati verranno rilasciati dopo un mese. Successivamente i dati verranno rilasciati dopo una settimana dal completamento dell’ osservazione.

IXPE

IXPE Imaging X-Ray Polarimetry Explorer

Principal Investigator: **M. C. Weisskopf (MSFC)**

Co-Investigators: *Brian D. Ramsey, Paolo Soffitta (IPI), Ronaldo Bellazzini, Enrico Costa, Stephen L. O'Dell, Allyn Tennant, Herman Marshall, Fabio Muleri, Jeffery Kolodziejczak, Roger W. Romani, Giorgio Matt, Victoria Kaspi, Ronald Elsner, Luca Baldini (I-CoPI), Luca Latronico, Stephen Bongiorno, Wayne Baumgartner*

Marshall Space Flight Center: PI team, project management, SE and S&MA oversight, mirror module fabrication, X-ray calibration, science operations, and data analysis and archiving	IAPS, INAF, INFN, OAC, OHB Italia: Polarization-sensitive imaging detector systems
	LASP: Mission operations
ASI: Detector system funding, ground station	Roma Tre, Stanford University: Scientific theory
	McGill: Co-Investigator
Ball: Spacecraft, payload structure, payload, observatory I&T	Massachusetts Institute of Technology: Co-Investigator

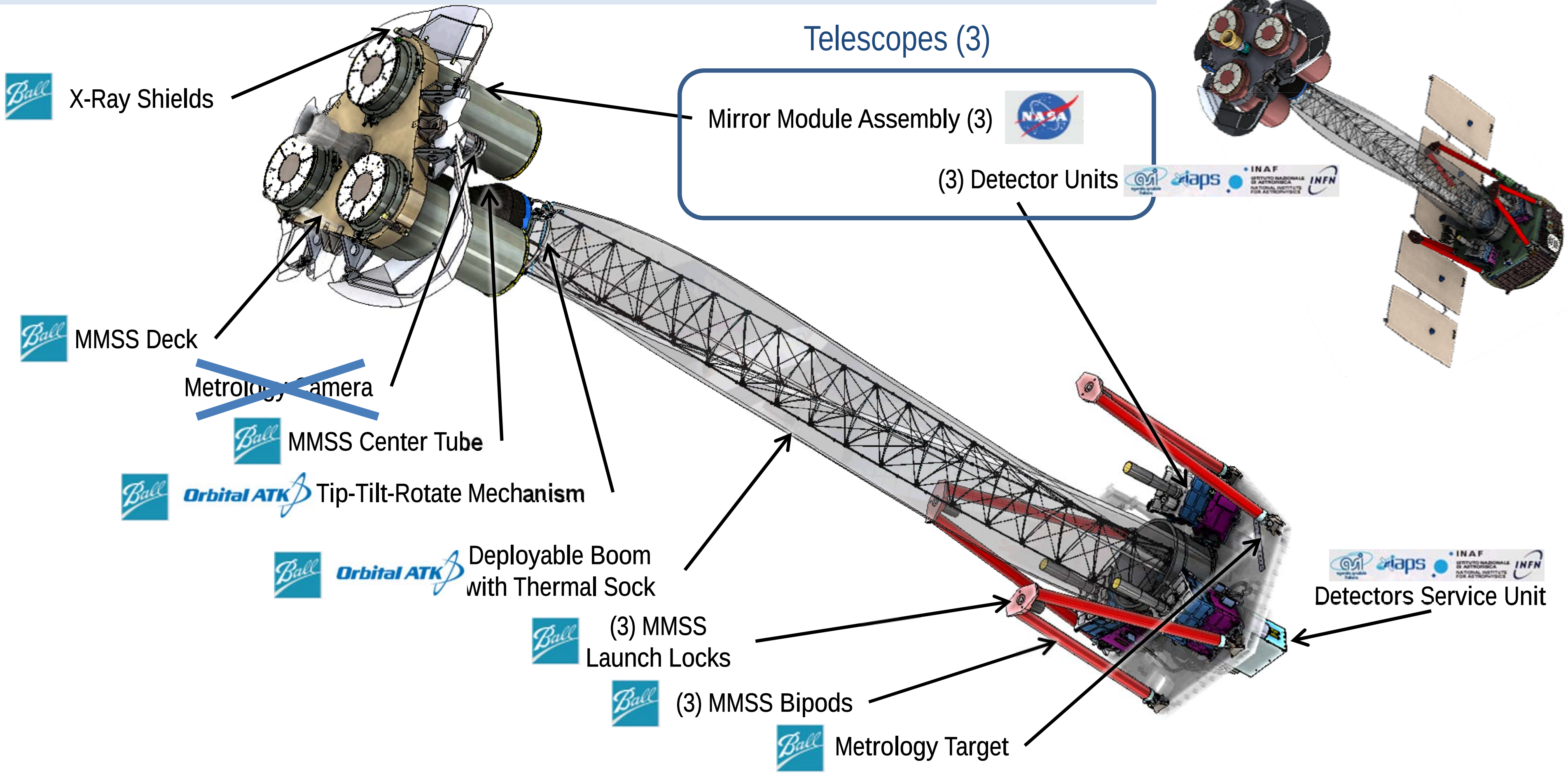
Science Advisory Team

- **Falcon 9 Launcher**
- **600-km circular orbit at 0.1° inclination**
- **2 year baseline mission, 1 year SEO**
- **Dithering at known targets**
- **Science Operations Center at MSFC**
- **Mission Operations Center at CU/LASP**
- **Malindi ground station (Singapore Backup)**

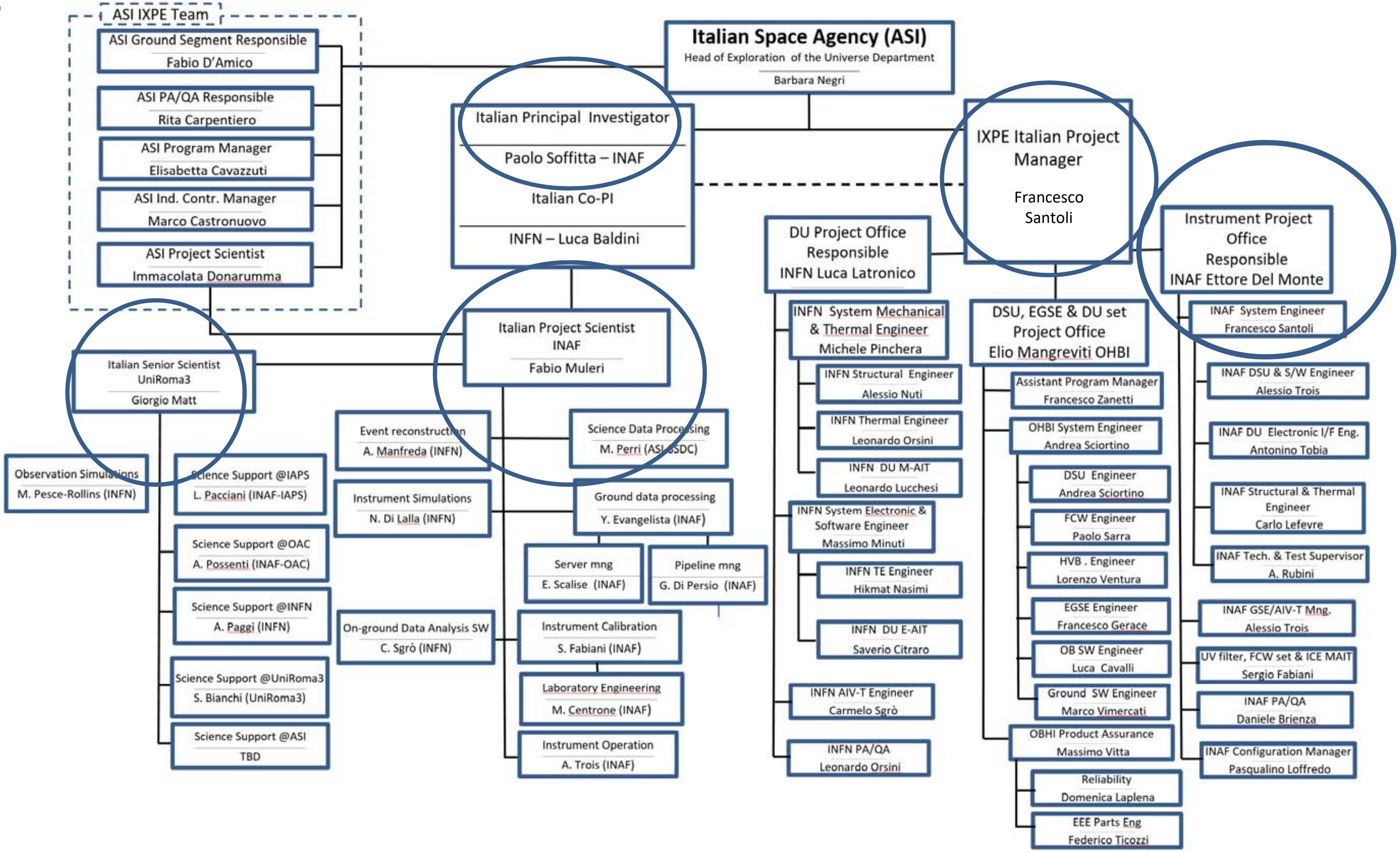
IXPE
Imaging X-Ray Polarimetry Explorer

PAYLOAD COMPONENTS

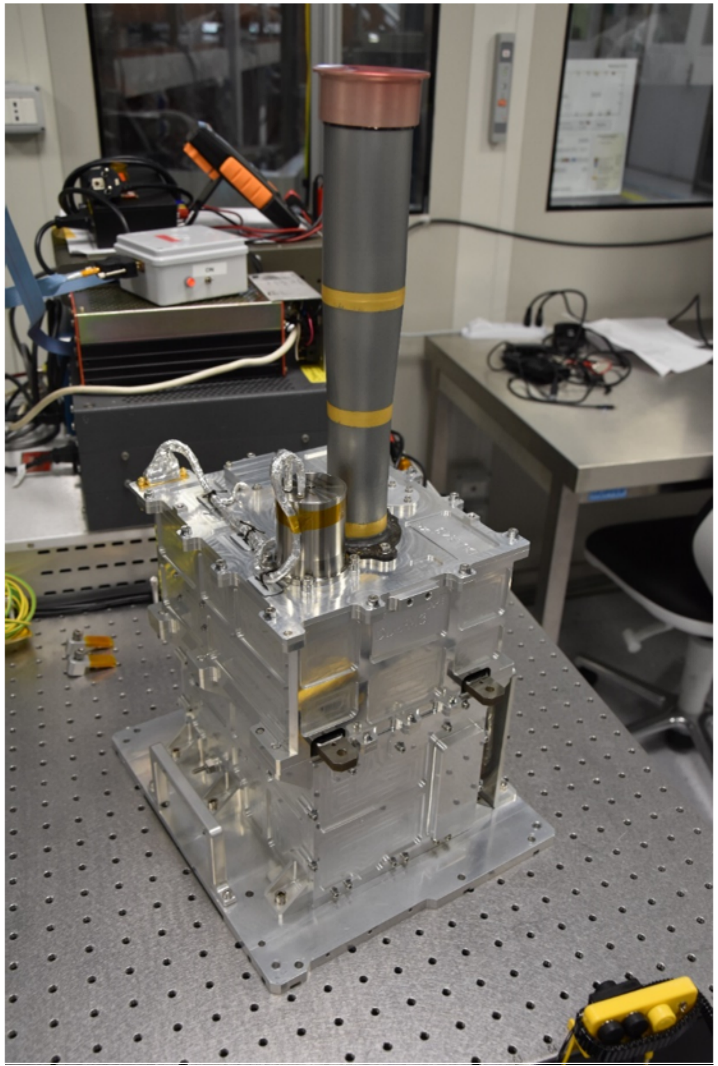
Accomplish the science through integrated system of Telescopes and structure alignment components.



The Instrument management tree



3 flight Detector Units + 1 spare



- Stray-light collimator made of carbon fiber molybdenum and gold-coating
  (The x-ray sky is very bright and we have no tube)
- Filter and calibration (wheel)
  - 7 position
  - 4 calibration sources
- Gas Pixel Detector
- DAQ Board
- HV board

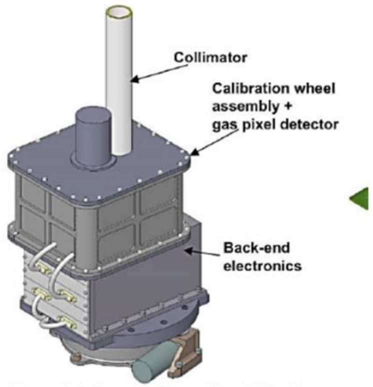
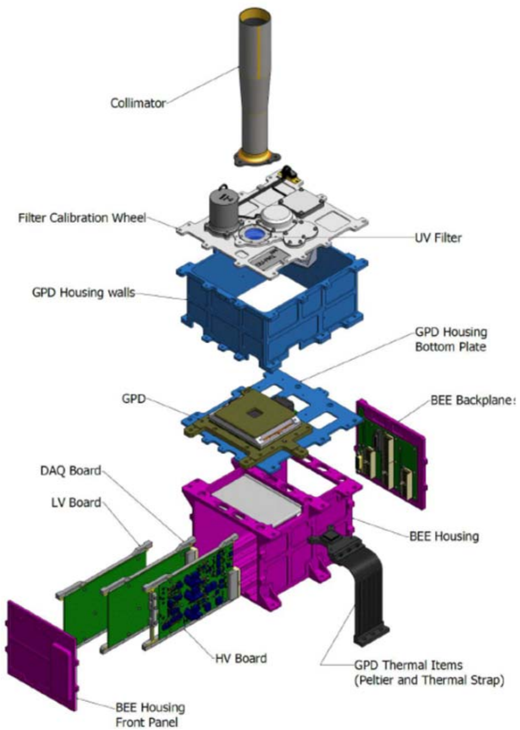


Figure E-4: Detector Assembly with Back-End Electronics on Turntable



INAF Contribution (part)

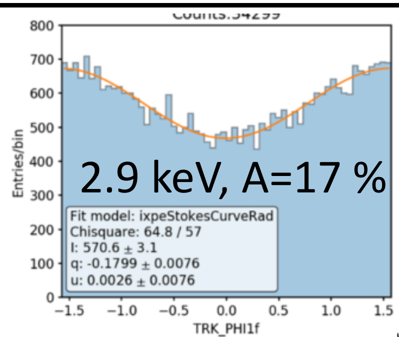
INAF contribution so far: from the proposal to the design, to the implementation, to the calibration & test and Astrophysics

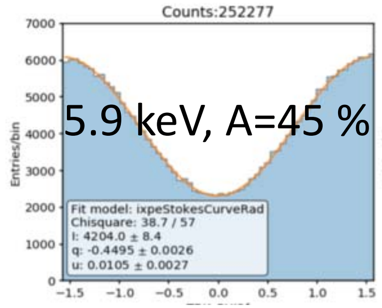
- Astrophysical Requirement
- Instrument requirement definition
- Instrument architecture in collaboration with INFN and OHB-I
- Instrument design
- Instrument Project Office
- Reference institution in relevant teleconf and meeting (PSET, Tech Team, Risk boards, PCB, Eeekly, Monthly and Quarterly Review, M-SRR, M-PDR, M-CDR, M-SIR
- Full participation and definition of telescope calibration activities
- Analysis and interpretation of Ground Data

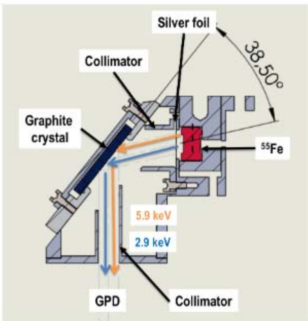
IXPE INAF Contribution (1A/5)

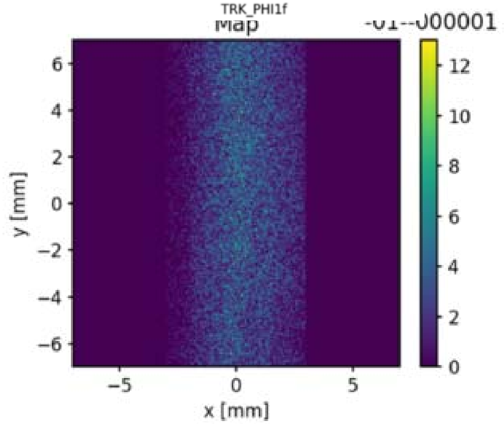
Filter Calibration-set&Test, UV-ion Filter&Test

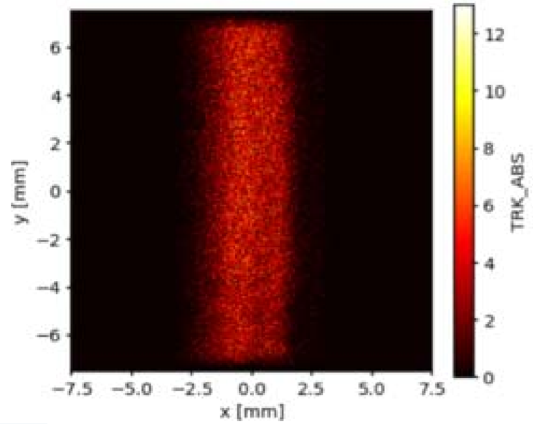
- Design validation test
- Acceptance test
- In vacuum test @ 20 °C during TVAC (2.9 & 5.9 keV)

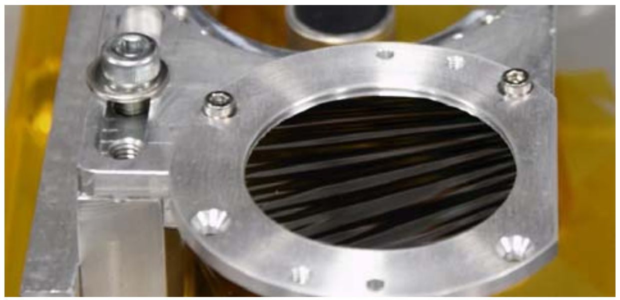












- UV Filter

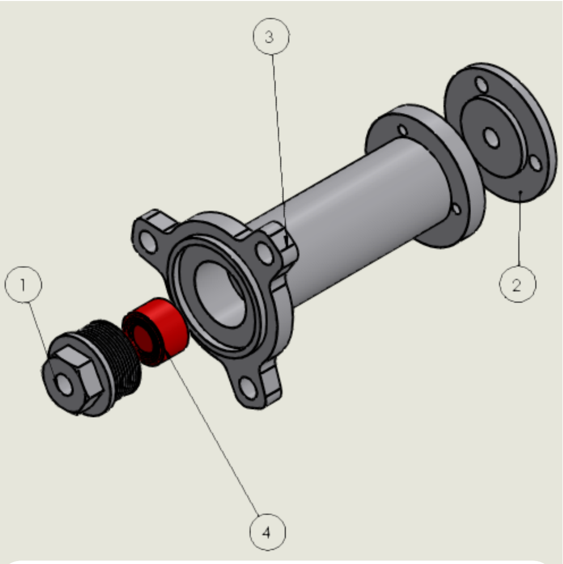
Source	Flight expected rate [c/s]
CalA FM2 @ 2.9 keV	1.4
CalA FM2 @ 5.9 keV	17
CalB FM2	48
CalC FM2	90
CalD FM2	76

Modulation factor, gain & spurious modulation checks

INAF Contribution (1b/5)
Cal B, Cal C and Cal D sources

Cal B

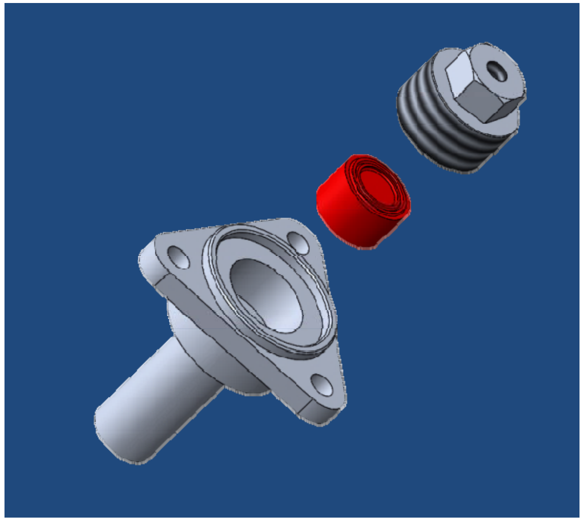
- Unpolarized at 5.9 keV
- Collimated to a 3 mm spot
- Check the absence of spurious signal to a very low level
- Counting rate 48 c/s (flight source)



Cal B: 5.9 keV collimated non polarized

Cal C

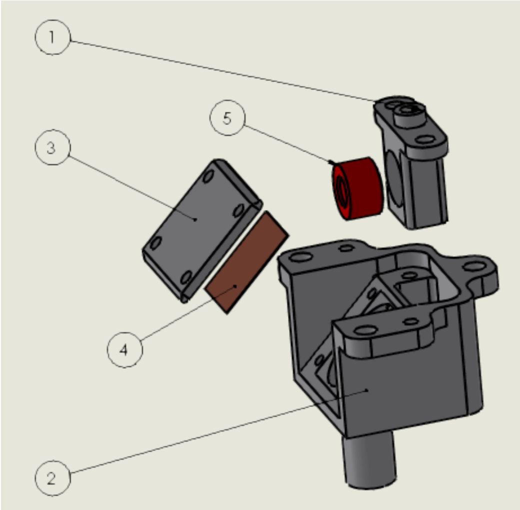
- Unpolarized at 5.9 keV
- Map the GPD gain at 5.9 keV
- Non collimated, full illumination of the GPD
- Counting rate 90 cts/s (flight source)



Cal C: 5.9 keV non collimated non polarized

Cal D

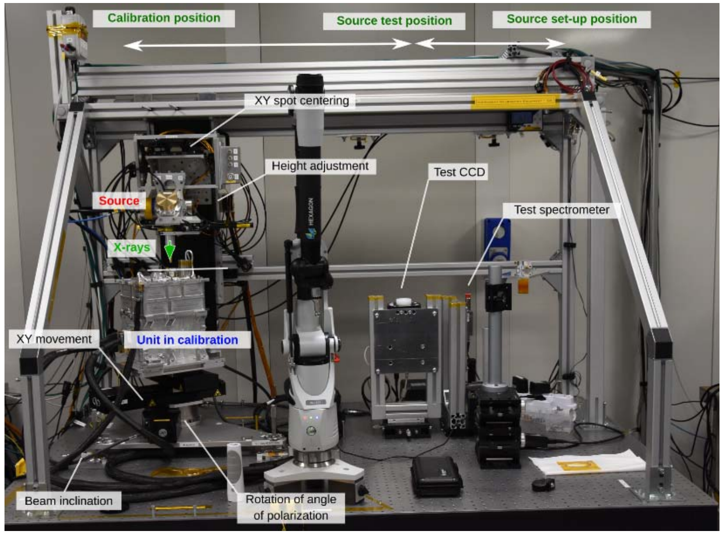
- ^{55}Fe source extracting fluorescence from a silicon target
- Map the GPD gain at 1.7 keV
- Full illumination of the GPD
- Counting rate ~46 cts/s (flight source)



Cal D: 1.7 keV non collimated non polarized

INAF CONTRIBUTION 2A/5 INTRUMENT CALIBRATION EQUIPMENT (ICE)AND AIV

CALIBRATION EQUIMENT

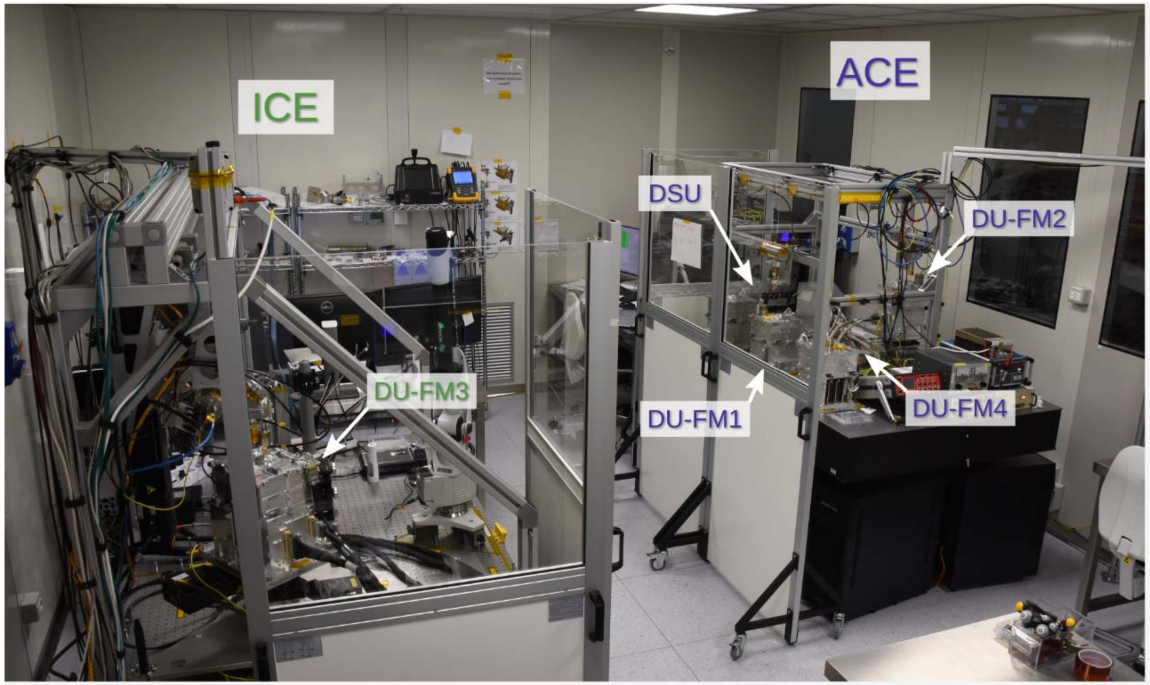


- Design of the facilities
- Procurement of X-ray generators, bragg crystals and ancillary detectors and measurement arm.
- Design and machining of monochromatic and polarized sources and detector mechanical parts
  Integration and test of parts

A busy clean room:

Two facilities operating at the same time.

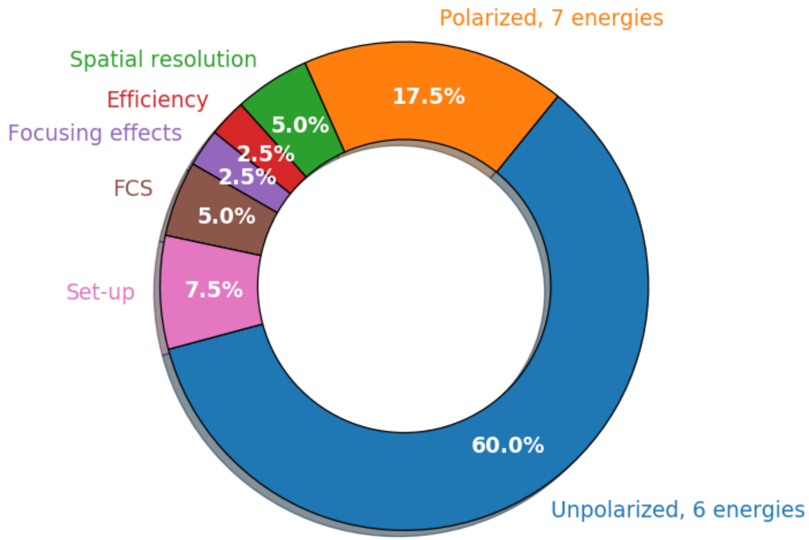
While calibrating DU-FM3 the Instrument was integrating



IXPE clean room (ISO7) @ INAF-IAPS in November 2019

INAF CONTRIBUTION (2B/5)
ACCEPTANCE TEST OF GPDS & CALIBRATION OF DUS

- **Calibration of DU are being carried out in Italy at INAF-IAPS, before Instrument integration and delivery to USA**
- **40 days for each DU (3 flight + 1 spare units)**
  - Up to 24/7 data acquisition
- **First unit started calibration on 26th July, DU-FM2 started on 6th Sep 2019, DU3 on 23 Oct. 2019, DU 4 on 16 Dec. 2019**
- **60% of time dedicated to characterization of the response to unpolarized radiation at 6 energies**
- **17.5% of time dedicated to measurements of modulation factor at 7 energies**
- **Remaining time to calibrate other parameters of interest**
- **Energy calibration and dead-time are by-product of previous measurements**



Calibration started at 26/07/2019
Calibration ended at 3/02/2020
Delta Calibration ended 22/03/2020

To absorb the delay of INFN and OHB-I e OXFORD Ins. Tech. Oy we run the calibration facility 24 hours a day for 7 days a week for 40 days/DU

Delivery of DU 2 & EGSE

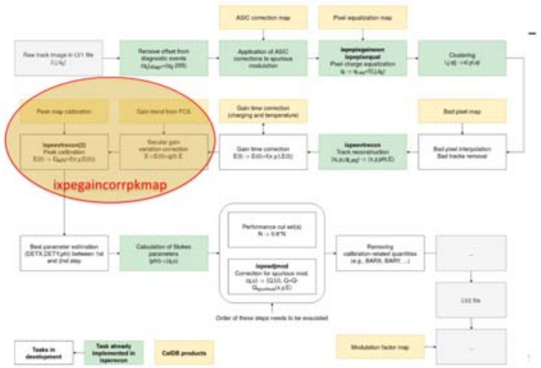
INAF CONTRIBUTION 3/5

- **Block diagram of the IXPE Flight Pipeline**

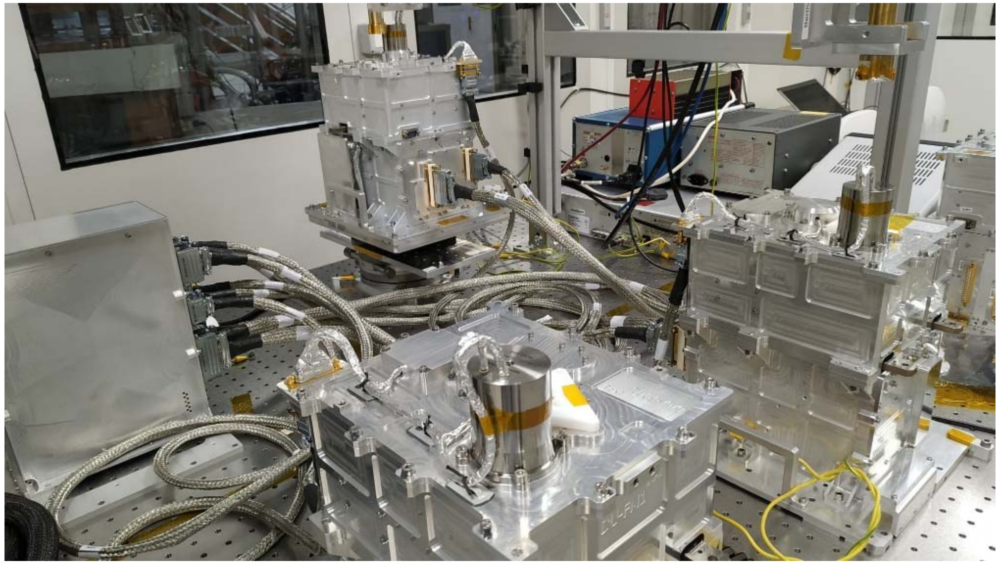
- **Implementing of CalDB and crucial task in the flight pipeline:**
(ixpeevtrecon,ixpeadjmod,xpegaincorrtemp) with contribution of SSDC (see SSDC card)

- **Ground pipeline and storage of calibration data**

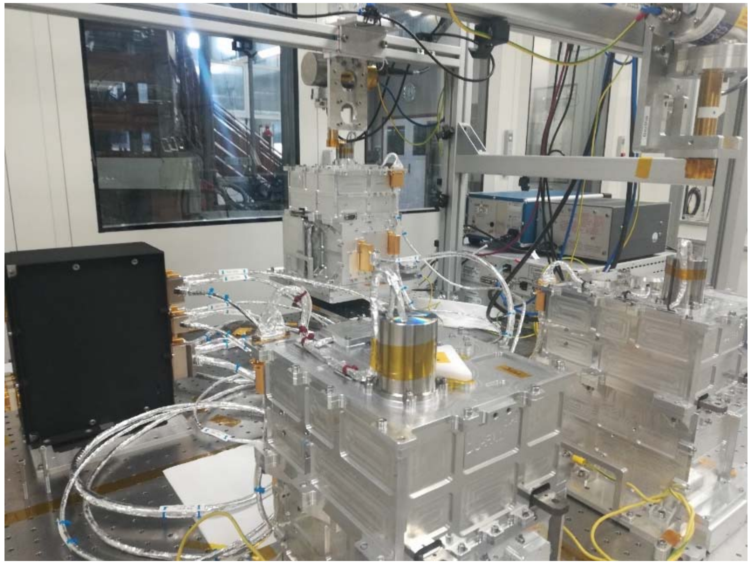
- **Definition of tasks for the Detector Service Unit (OHB-I contribution) and the instrument as a whole:**
  - **Timing architecture based on the GPS use (heritage from AGILE)**
  - **'Orphan removal' algorithm to reduce the telemetry rate**
  - **Payload mode philosophy**



INAF Contribution (4/5)
Bench Integration of the Instrument



DSU EM

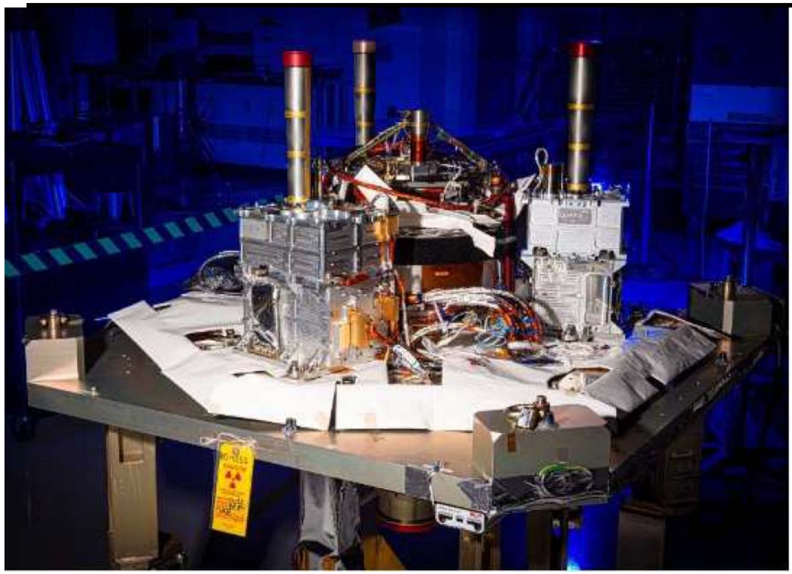


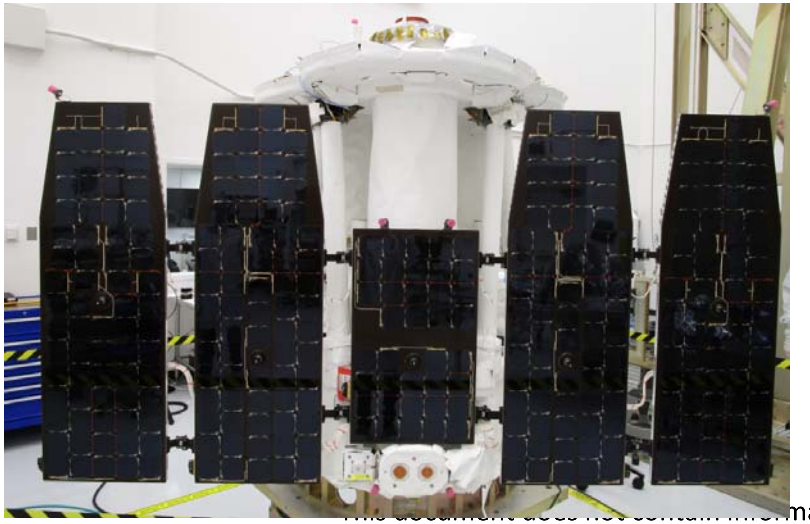
DSU PFM

- Preliminary DSU-EM
- Instrument DSU-PFM (nominal & redundant), DU FM1, DU FM3, DU-EM or DU FM4
- Delta (after DSU-reworking), DSU-PFM, DU FM1, DU FM3, DU FM4

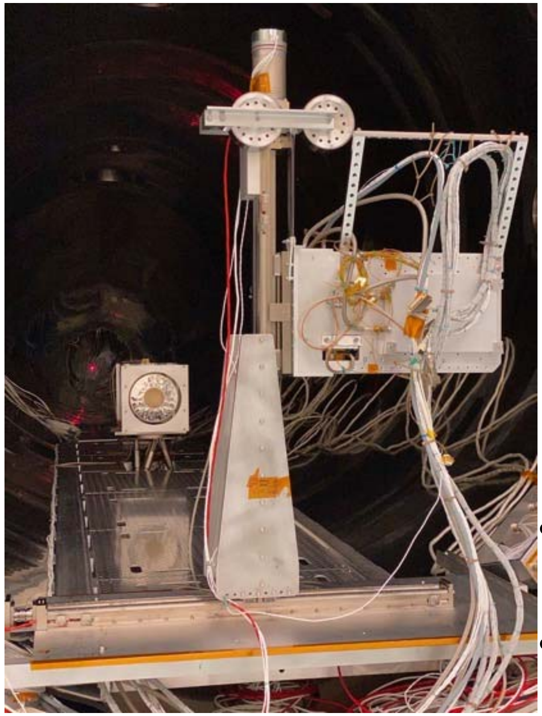
DU, DSU Power on/off, HK rate, memory check and man. , Pixel scan, ASIC Ped. Cal., FCW Control, Instrument Nominal Acquisition, Instrument, SAA, Alarm, Timing, Performance (orbital cycles)

THE INSTRUMENT, THE OPTICS & THE BOOM

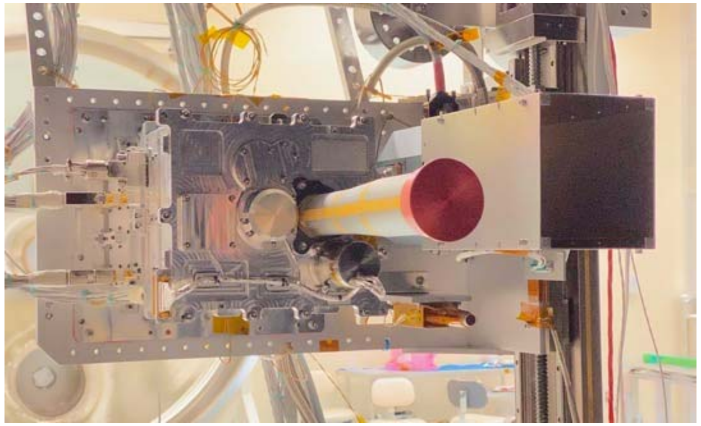




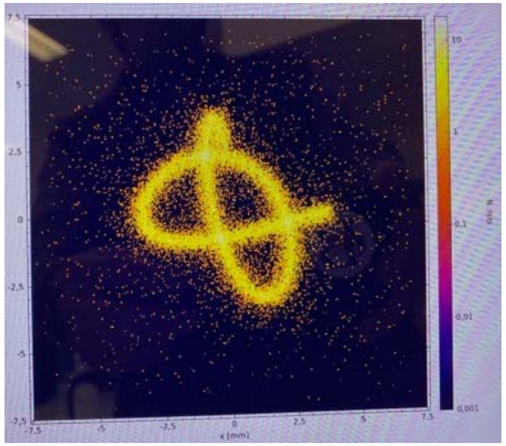
MSFC TELESCOPE CALIBRATION



SLTF Telescope Calibration configuration



DU-FM1 and other detectors mounted inside SLTF



Dither pattern in progress on DU

- The mirror effective area evaluated with the SDD is consistent with the mirror effective area evaluated with the DU-1.
- The modulation factor measured at INAF-IAPS for detector DU-1 is fully consistent with the modulation factor measured with the telescope and at MSFC without mirror: the mirrors do not indroduce extra-polarization.
- The spurious modulation measured at INAF-IAPS with and is fully consistant with that measured at MSFC.

We can fully use the ground calibration at INAF-IAPS and the mirror calibration to infer their joint performance during flight.

IXPE Imaging X-Ray Polarimetry Explorer

Programmazione

Milestone	Date	
I-SRR	30-10-2017	
I-PDR	05-03-2018	
I-CDR	14-05-2018	
M-PDR	26-06-2018	
KDP-C	01-11-2018	
M-CDR	24-06-2019	
Calibration Started	26-07-2019	
Delivery DU-2	15-11-2019	
Calibration ended	03-02-2020	
Lock-down in Italy started	**09-03-2020**	
Delta Calibration ended	22-03-2020	
Delivery DU-3,DU4, DSU (DRB;actual shipment)	31-06-2020;23-06-2020	
M-SIR	22-09-2020	
Delivery DU-FM1	06-10-2020	
KDP-D	02-11-2020	
MRR		17 Agosto 2021
MRR/KDP-E		1 November 2021
M-PSR		5 Novembre 2021
Launch		17 Novembre 2021

Test	Date
Vibration Test	24/5-3/6 2021
Shock Test	8-9/6/2021
Acustic Test	17-18/6/2021
TVAC Test	15-31/7/2021

Science WGs e Topical Working Groups

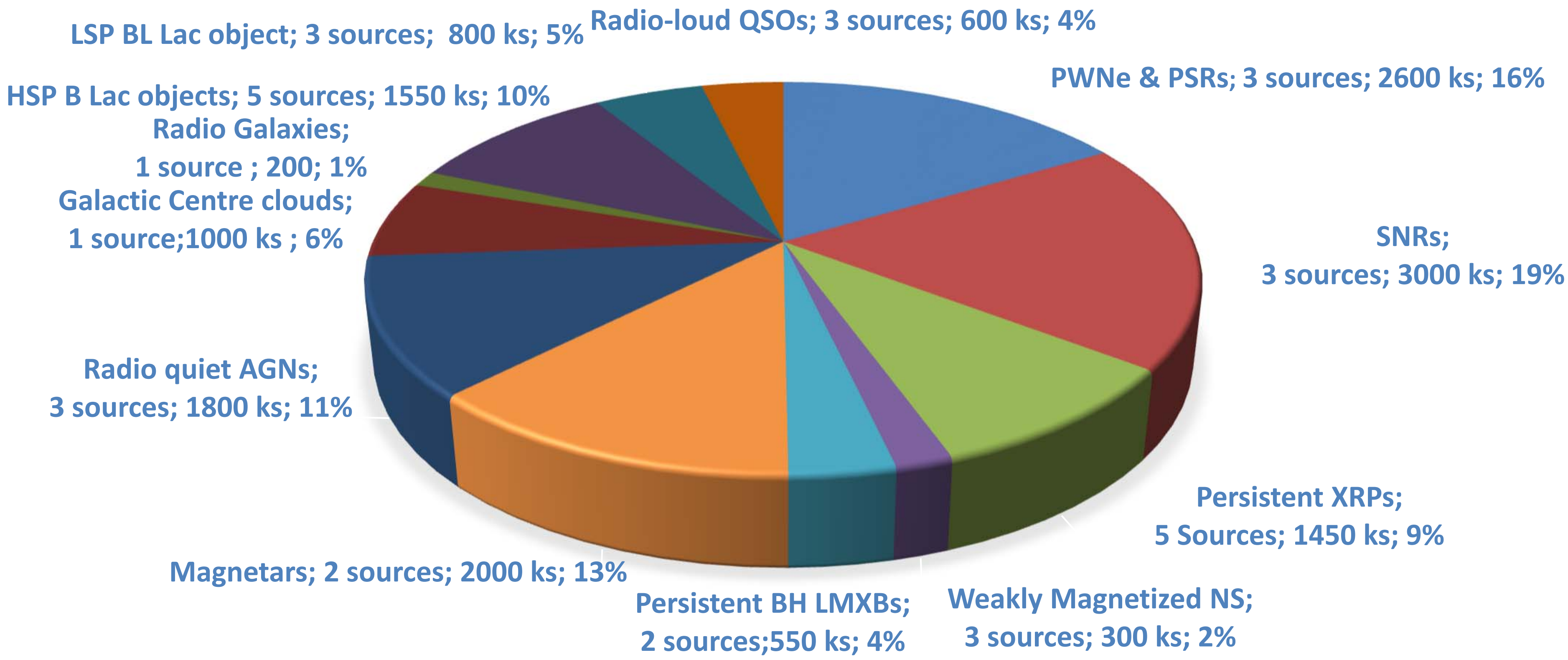
1. Wayne Baumgartner: **Science Calibration WG** (Co-Chair Fabio Muleri IAPS/INAF
2. Allyn Tennant: **Science Data Processing WG** (Co-Chair Matteo Perri INAF c/o SSDC
3. Luca Baldini: **Science Analysis and Simulation WG** (Co-Chair Herman Marshall MIT)
4. Giorgio Matt (Universita' Roma Tre) and Roger Romani (Stanford): **Science Advisory Team** chairs

Topical Working Groups

1. Niccolò Bucciantini (O. Arcetri): **Pulsar Wind Nebulae and isolated pulsars**
2. Patrick Slane (Harvard Univ.) : **Super Nova Remnants**
3. Michal Dovčiak (Czech Academy of Sciences): **Accreting stellar-mass BH**
4. Juri Poutanen (Tuorla Obs.): **Accreting NS & WD**
5. Roberto Turolla (Padua Univ.): **Magnetars**
6. Frédéric Marin (Astron. Obs. of Strasbourg): **Radio-quiet AGN & Sgr A***
7. Alan Marscher (Boston Univ.): **Blazars & radio galaxies**

All data are made public one week after the accomplishment of the observation by HEASARC

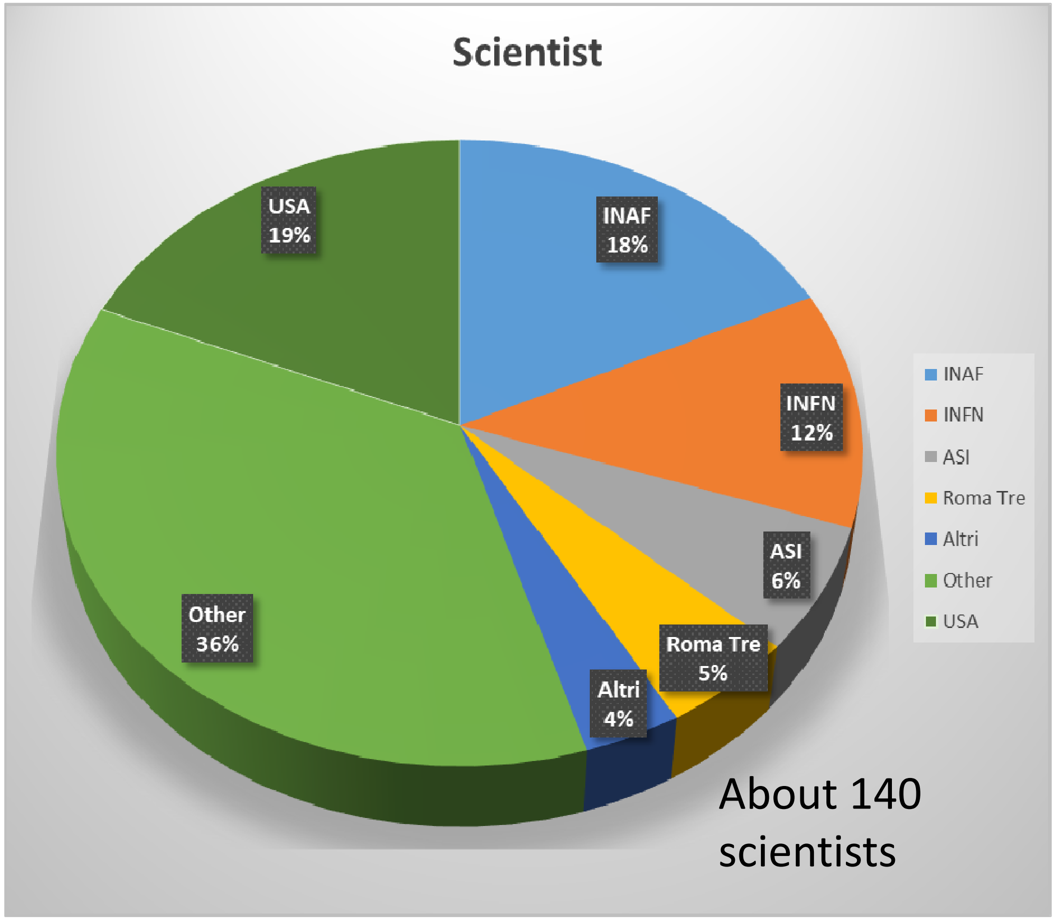
First year: fraction of the observing time



INAF CONTRIBUTION (5/5): SCIENTIFIC ACTIVITIES (PART)

- High level analysis software for ground calibration
- Health monitor & analysis of HK.
- Analysis of the DU calibration, of the telescope calibration and of environmental test data
- Validation of the Neural Network algorithm with calibration data
- Estimation of background
- Extended source study (Molecular Clouds, PWNe, SNRs)
- Anomalous X-ray Pulsars
- Pulsar study
- BH-Binaries studies
- Polarization from scattering off the companion star in binary systems.
- Radio-quiet Sy2 AGNs
- Blazar

The chart of IXPE scientists



Costo totale c.a 200 M$ Costo ASI 19 M€ Costo ASI-INAF 4.2 M€

Termine contratto attuale (fase B-D) 10 giugno 2022

IXPE FTEs

Nome	Ruolo nel Progetto	FTE 2021-2023
Paolo Soffitta	Italian PI	3
Argan Andrea	Management	0,3
Ettore Del Monte	Instrument Project Office Manager	0,9
Francesco Santoli	Instrument Project Manager	0,3
Fabio Muleri	Italian Project Scientist	1,5
Sergio Fabiani	Calibration scientist, Science	1,5
Yuri Evangelista	Web Site Manager	0
Carlo Lefevre	Mechanical/Therma engineering	0,1
Luigi Pacciani	Science	0,3
Alessandra De Rosa	Science	0,3
Fiamma Capitanio	Science	0,9
Elisabetta De Angelis		0
Massimo Cocchi	Science	0,4
Giuseppe Di Persio	IT Manager	0,9
Alessandro Di Marco	Calibration scientist, Science	3
Fabio La Monaca	Laboratory set-up	3
Pasqualino Loffredo	Laboratory set-up	1,3
Fei Xie	Science, Simuation	3
Riccardo Ferrazzoli	Science, Simulation	3
John Rankin	Calibration scientist, Science	3

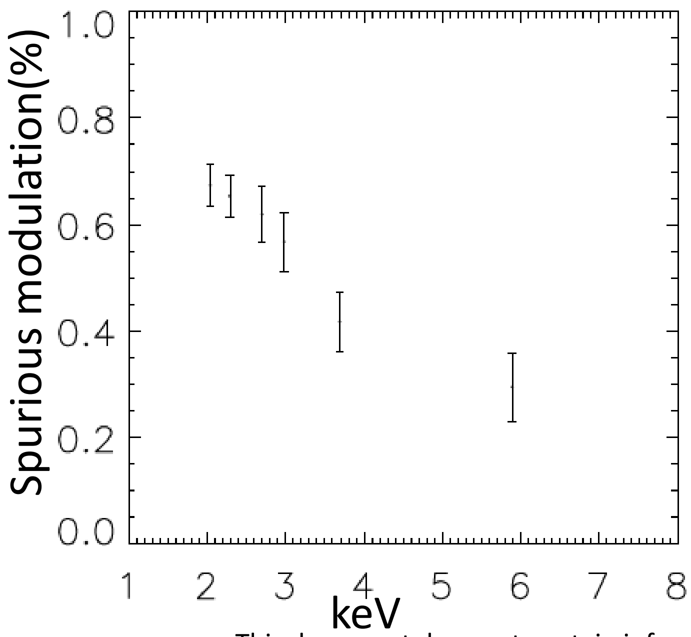
Nome	Ruolo nel Progetto	FTE 2021-2023
Mauro Centrone	Tecnician	0
Ajay Ratheesh	Science	3
Andrea Possenti	Science	0,3
Alessio Trois	AIV/Manager	0,6
Matteo Bachetti	Science, Software	0,3
Maura Pilia	Science	0,3
Matteo Perri	Scientific Pipeline Manager	0
Niccolò Bucciantini	Science	0,5
Fabrizio Tavecchio	Science	0,3
Giorgio Matt	Science	1,5
Stefano Bianchi	Science	0,3
Roberto Taverna	Science	0,2
Francesco Tombesi	Science	0,6
Francesco Massaro	Sience	0,6
Immacolata Donnarumma	Project Scientist ASI	0
Enrico Costa	Senior Co-I	0
Enrico Massaro	Science	0
Alda Rubini	Electronics Enginneer	0
Sergio Di Cosimo	Contract Manager	0

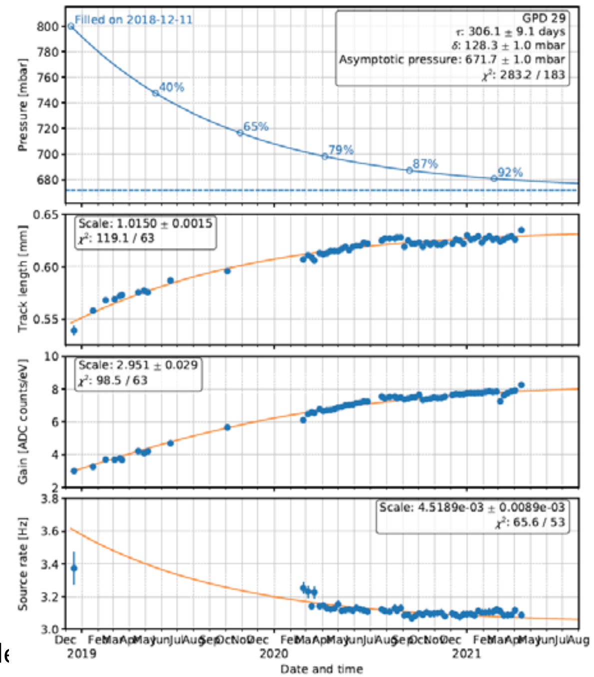
35 FTE on three years (2021-2023)

Criticita’ di progetto 1/2

- Scoperta della modulazione spuria a bassa energia: introdotto il dithering del satellite per mitigarne l’effetto. Richiesto gran parte di tempo di calibrazione. Studi sono stati necessari per verificarne la stabilita’ temporale e in temperature della modulazione spuria
- Scoperta del decadimento di pressione interna per assorbimento del gas e ottiche meno efficienti (10%) di quanto previsto:

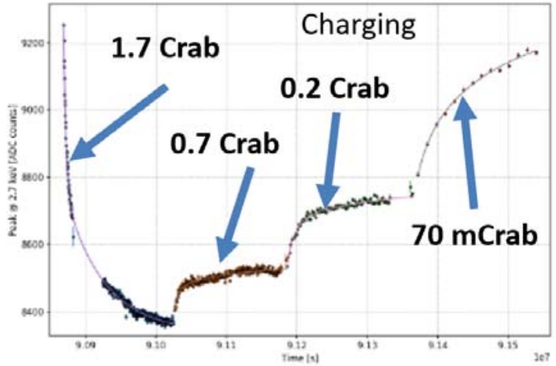
INAF ha trovato come compensare introducendo i pesi nell’analisi delle traccie





Criticita’ di progetto 2/2

- A causa del processo di caricamento del piano di moltiplicazione il guadagno varia con il tempo:



- A causa dei ritardi OHB ed INFN le calibrazioni delle detector units si sono compresse a parita’ di statistica fino a 40 giorni h24 7 giorni su 7.

- A causa della ‘variazione di guadagno secolare’ e del ‘fenomeno di caricamento’ i tools di processamento ed analisi devono tener conto degli andamenti temporali delle prestazioni.
- Scoperta una criticita’ sul serraggio dell’ albero delle ruote porta filitri. E’ stato necessario smontarle e ridistribuirle fra le 4 DU per motivi si schedula.

Criticita’ programmatche

- Per via dell’ emergenza CoViD le attivita’ di integrazione, test e calibrazione del telescopio sono effettuate con la presenza di I2T in remoto. Le attivita’ ad Huntsville (MSFC) -7 ore e Boulder (Ball) -8 ore richiedono una presenza continua tra le 16 e le 24 durante i test e le calibrazioni

- La rendicontazione ASI e’ diventata molto laboriosa
  - La RA6 e’ slittata di un anno. I rendicontatori dell’ ASI hanno questionato sia sui singoli items (WEBEX, Dispositivi per camera pulite, voci di personale (Tecnologo vs Ricercatore) spese di bollo.
  - Richiesta da parte dei rendicontatori di dettagliare le spese fino ad arrivare ai singoli componenti elettronici e meccanici dalle fatture e non dagli impegni di spesa.

- Alcuni items con tempi di procurement lunghi hanno imposto la formazione di un team integrato Italia-USA dedicato al procurement.

- Difficolta’ di reperire e mantenere personale tecnico e di management per espletare il ruolo di Prime

IXPE performances

Parameter	2.69 keV	6.40 keV
Modulation factor	30.3 % ± 0.4 %	56.4 % ± 0.4 %
Efficiency (expected during flight)	13.5%	1.68%
Gray filter transparency	17.4 %	88.0 %
UV Filter transparency	(95.94 ± 0.25)%	(99.38 ± 0.38) %
Spurious modulation	(1.01 ±0.03) %	(0.37 ±0.04) %
Systematic error on the P.A. determination	$(0.143 \pm 0.094)^{\circ}$	$(0.186 \pm 0.097)^{\circ}$
Energy resolution	(22.2±0.5)%	(16.3±0.1)%
Position resolution	(115.02 ± 0.22) μm	119 ± 0.22) μm
Dead Time	1.1 ms	1.2 ms

Parameter	Value
Timing accuracy	1-2 μs (by means of the use of the PPS)
Timing resolution	1 μs
Common FoV	9′
Dithering radius	1′.6 standard (or 0′.8 or 2′.6 or no-dithering)
Expected background rate (2-8 keV)	1.9 10^{-3} c/s/cm^2/keV
Expected Crab nebula rate (2-8 keV)	285 c/s
Expected Crab nebula rate (1-12 keV)	480 c/s

Lancio 17 novembre 2021. Ma un possibile slittamento e’ probabile secondo il PI

TOP SCIENTIFIC REQUIREMENTS OF IXPE

Table 1. IXPE Scientific Requirements

Physical Parameter	Observable	Property	Value
Linear Polarization	Degree Π, angle ψ	Sensitivity $MDP_{99}(F_{2-8} = 10^{-11}$ cgs, $\Delta t = 10$ d)	$\leq 5.5\%$
		Systematic error in polarization degree Π (5.9 keV)	$\leq 0.3\%$
		Systematic error in position angle ψ (6.4 keV)	$\leq 1°$
Energy dependence	$F(E)$, $\Pi(E)$, $\psi(E)$	Energy band E_{min}–E_{max}	2–8 keV
		Energy resolution ΔE (E = 5.9 keV), $\propto \sqrt{E}$	≤ 1.5 keV
Spatial dependence	$F(k)$, $\Pi(k)$, $\psi(k)$	Angular resolution HPD (system-level)	$\leq 30''$
		Field of view FOV >> HPD	$\geq 9'.0$
Time dependence	$F(t)$, $\Pi(t)$, $\psi(t)$	Time accuracy << source pulse periods	≤ 0.25 ms
Areal background rate	R_B/A_{det}	$R_B/A_{det} << R_S/A_S$ for faint source (2-8 keV, per DU)	$< 0.004\ s^{-1}cm^{-2}$

Observative life: 2 years (+1)

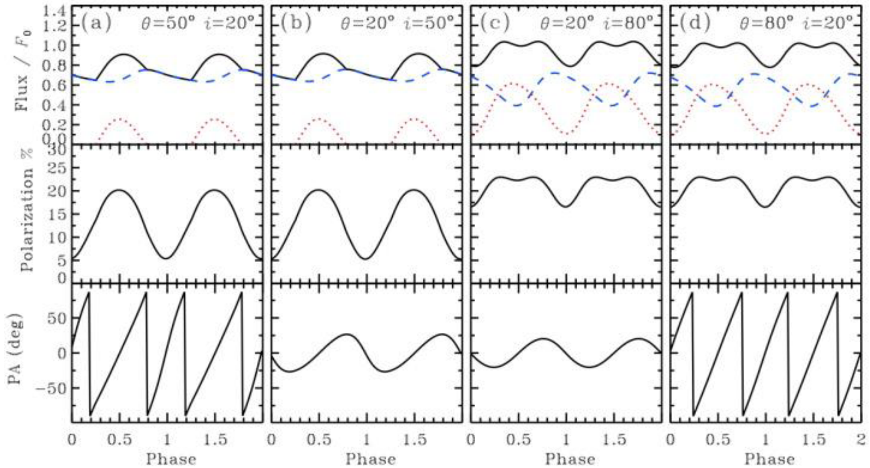
IXPE Imaging X-Ray Polarimetry Explorer

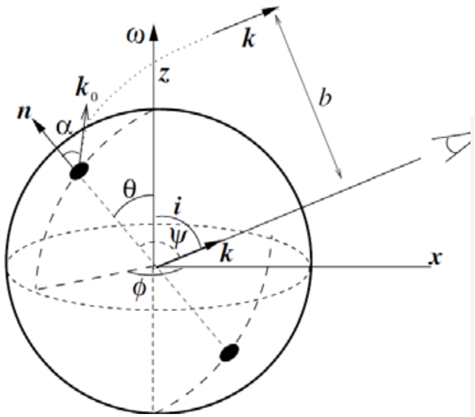
e.g. Accreting Millisecond Pulsars

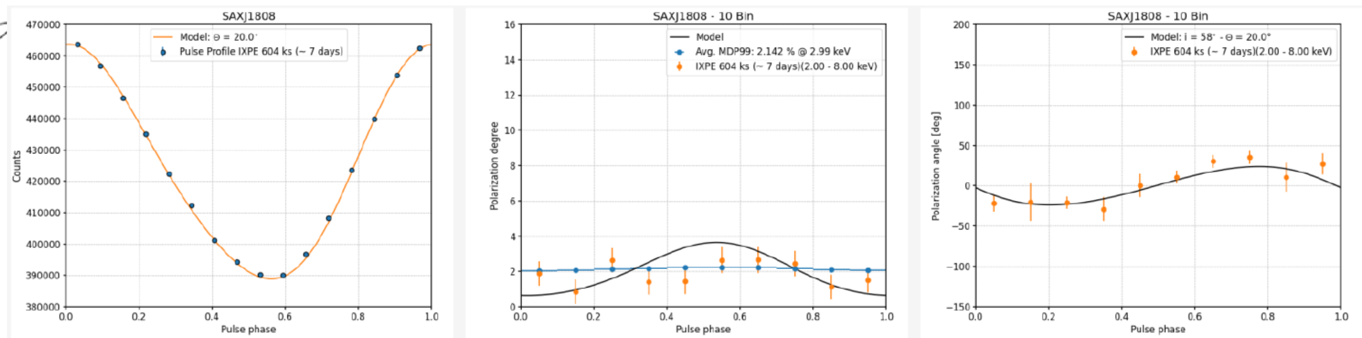
Emission due to scattering in hot spots ⇒

Phase-dependent linear polarization

Viironen & Poutanen 2004







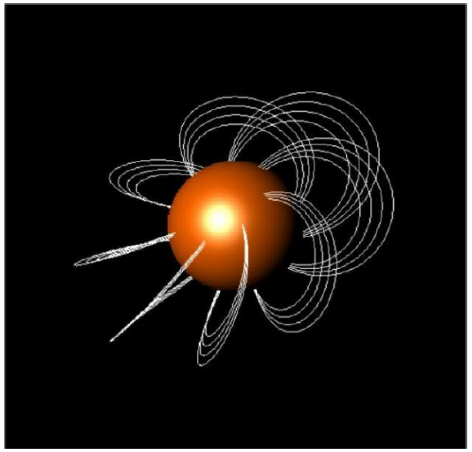
Courtesy of A. Di Marco, A.Papitto & M.Pilia

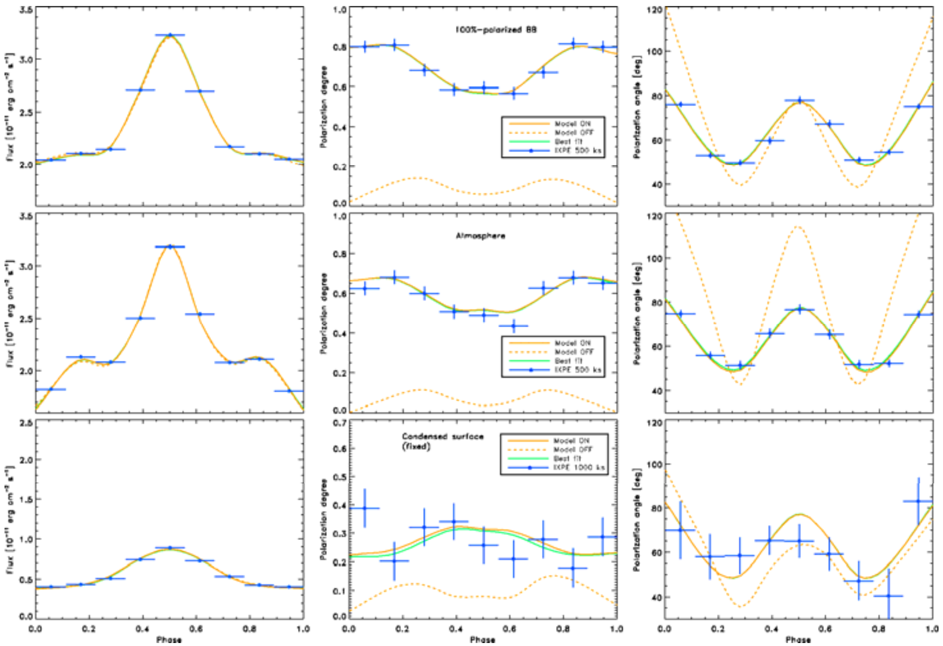
Polarization measurements determine the geometrical parameters of the system.

IXPE
Imaging X-Ray Polarimetry Explorer

e.g. QED effects in Magnetars

- **Magnetar is a neutron star with magnetic field up to 10^{15} Gauss**
  - Billion times the strongest laboratory field
  - Non-linear QED predicts magnetized-vacuum birefringence
    - Refractive indices different for the two polarization modes
    - Impacts polarization and position angle as function of pulse phase
    - Can exclude QED-off at better than 99.9% confidence

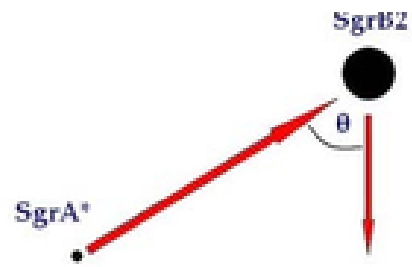


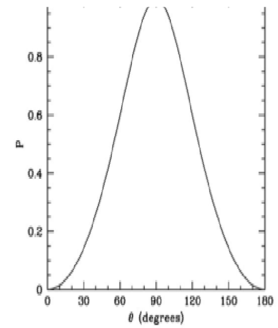


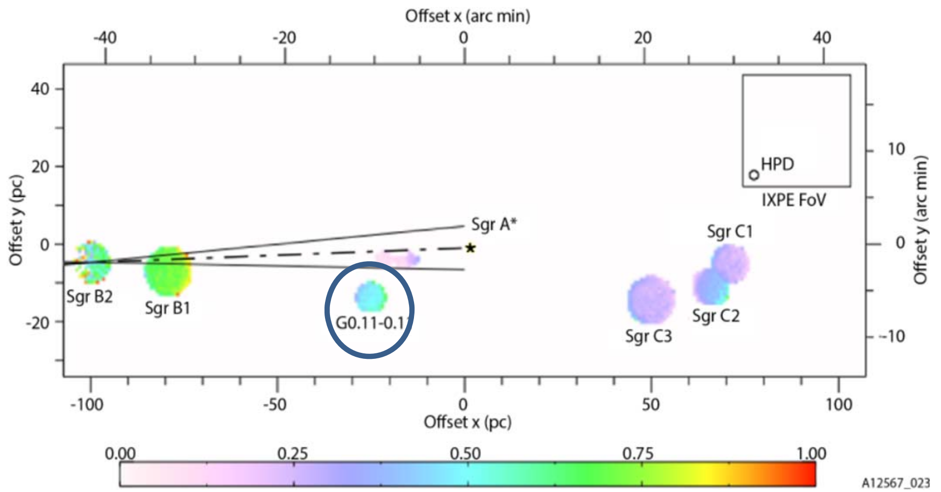
Taverna et al. 2020

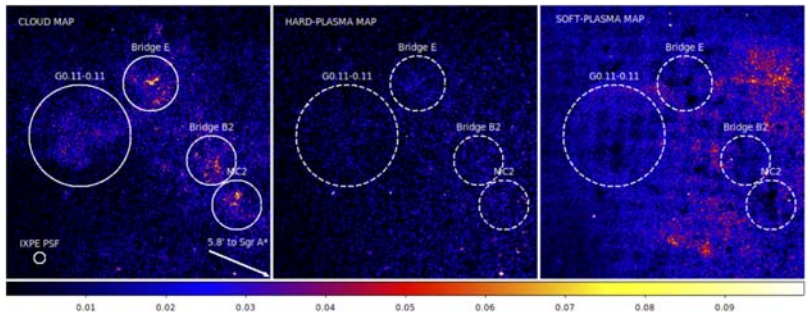
e.g. was the galactic center active a few century ago ?

- **Galactic Center molecular clouds (MC are known X-ray sources**
  - Are MCs reflecting X-rays from Sgr A (supermassive black hole in the GC)
    - X-radiation would be *highly polarized* perpendicular to plane of reflection and indicates the direction back to Sgr A*
    - Sgr A* X-ray luminosity was 10^6 larger ≈ 300 years ago









Di Gesu et al. 2020

IXPE Imaging X-Ray Polarimetry Explorer

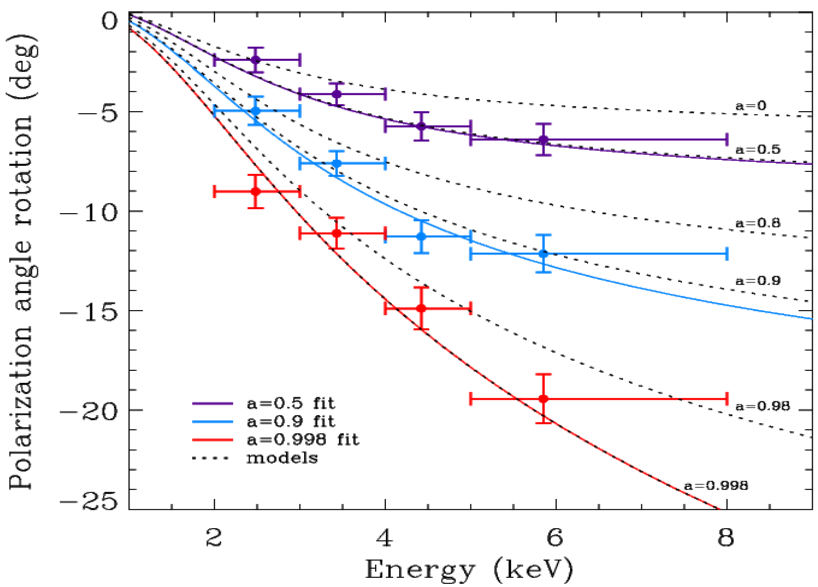
e.g. The spin of the black hole in microquasars

- **For an accreting Galactic BH in the soft state**
  - Scattering polarizes the thermal disk emission
  - Polarization angle rotates due to GR effects
    - Polarization rotation is greatest for emission from inner disk
    - Inner disk is hotter, producing higher energy X-rays

Why another method, besides the three ones already in use?

J1655-40:

QPO	=	**0.290±0.003**
Continuum	=	**0.7±0.1**
Iron line	>	**0.95**



200 ks IXPE observation of GRS1915+105

FINE