IXPE
Imaging
X-Ray
Polarimetry
Explorer

Marshall Space Flight Center

High Energy Polarimetry

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IXPE Italian PI

(INAF-IAPS)

Giornate INAF

Osservatorio Astronomico di Capodimente Napoli 2-5 Maggio 2023

Why High Energy Polarimetry

Polarization from celestial sources may derive from:

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

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

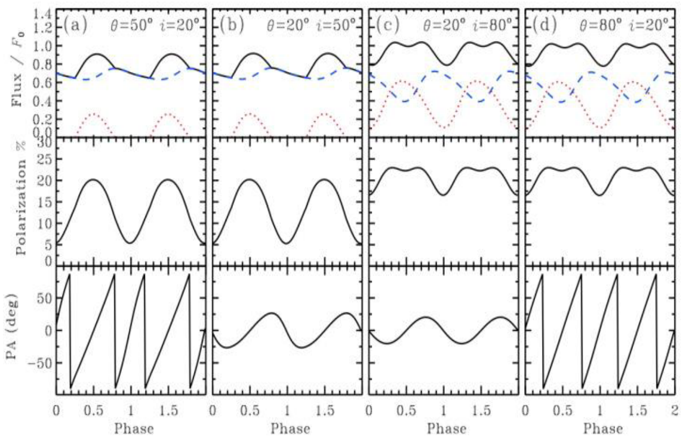
- **Scattering on aspherical accreting plasmas:**
disks, blobs, columns.

(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)

Just one example: solving ambiguity in geometry of compact objects



Viironen & Poutanen 2004

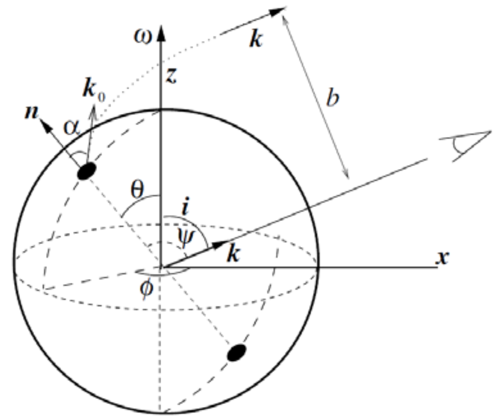
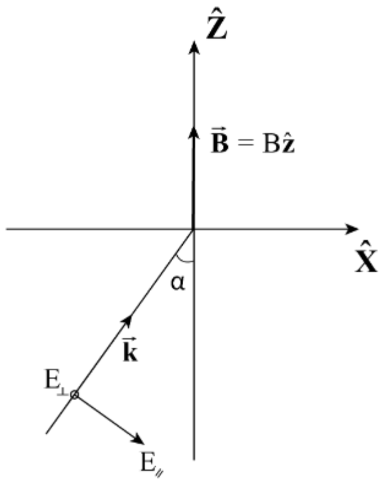
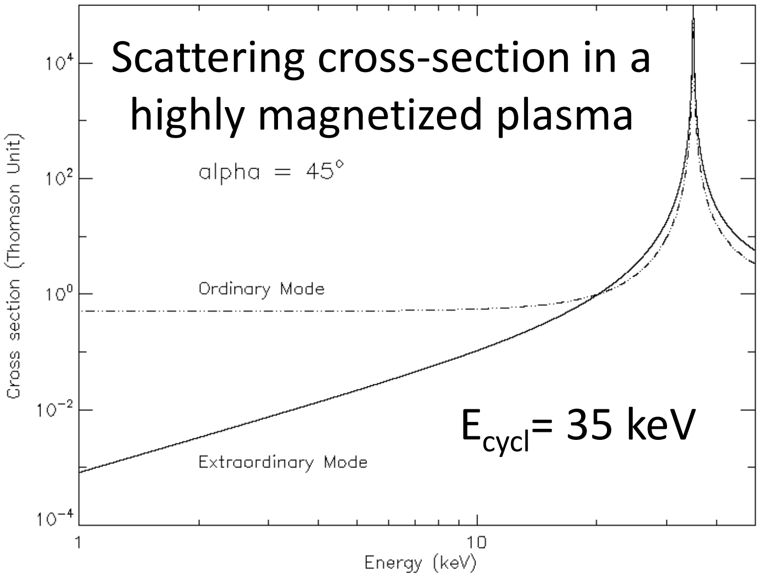


Fig. 1. Geometry of the problem.

Polarimetry resolves the degeneracy of lightcurves with respect to the geometry of accreting neutron stars

What happens in a highly magnetized plasma





Two modes, with very different scattering cross sections

Ordinary mode: E field parallel to the k-B plane

Extraordinary mode: E field perpendicular to the k-B plane

Caiazzo & Heyl., 2020

The radiation emerging from a highly magnetized atmosphere very likely is mostly in extraordinary mode because the scattering cross-section is smaller.

The first criticality: In high energy polarimetry the sensitivity is a matter of photons

$$MDP = \frac{4.29}{\mu R_s}\sqrt{\frac{R_s + R_b}{T}}$$ **Minimum Detectable Polarization (MDP)**

R_S is the Source rate, R_B is the Background rate, T is the observing time
μ is the modulation factor: the response of the polarimeter to a 100% polarized beam (spanning from 0 or no sensitivity, to 1 or maximum sensitivity)

If background is negligible: $$\mathrm{MDP} = \frac{4.29}{\mu\sqrt{N_{ph}}}$$

To reach MDP=1% with μ=0.5: $$N_{ph} = \left(\frac{4.29}{\mu\,\mathrm{MDP}}\right)^2$$ = 736 10^3 ph

Source detection > 10 counts
Source spectral slope > 100 counts
Source polarization > 100.000 counts

Caution: the MDP describes the capability of rejecting the null hypothesis (no polarization) at 99% confidence. For a 3-sigma meaurement an observing time 2.2 times longer is needed while the 1-sigma error scales like : 28°.5/S/N

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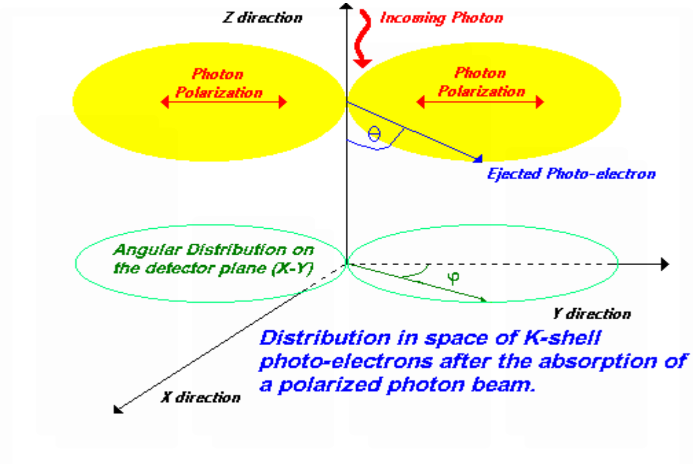
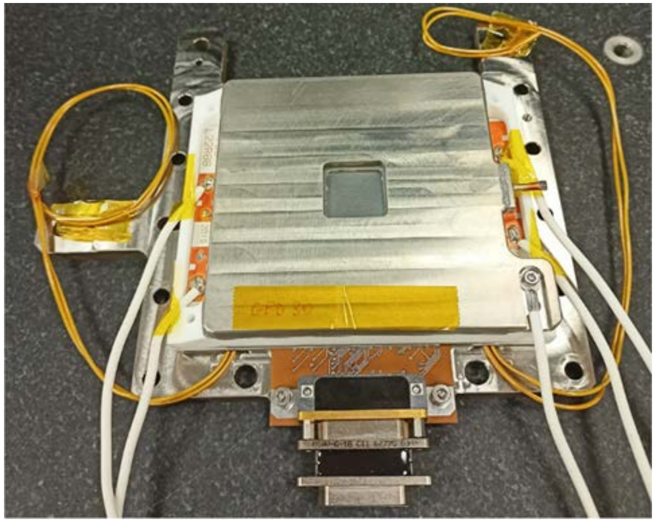
Photoelectric effect for X-rays polarimetry

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	**2017+**	**M. Weisskopf (USA)**

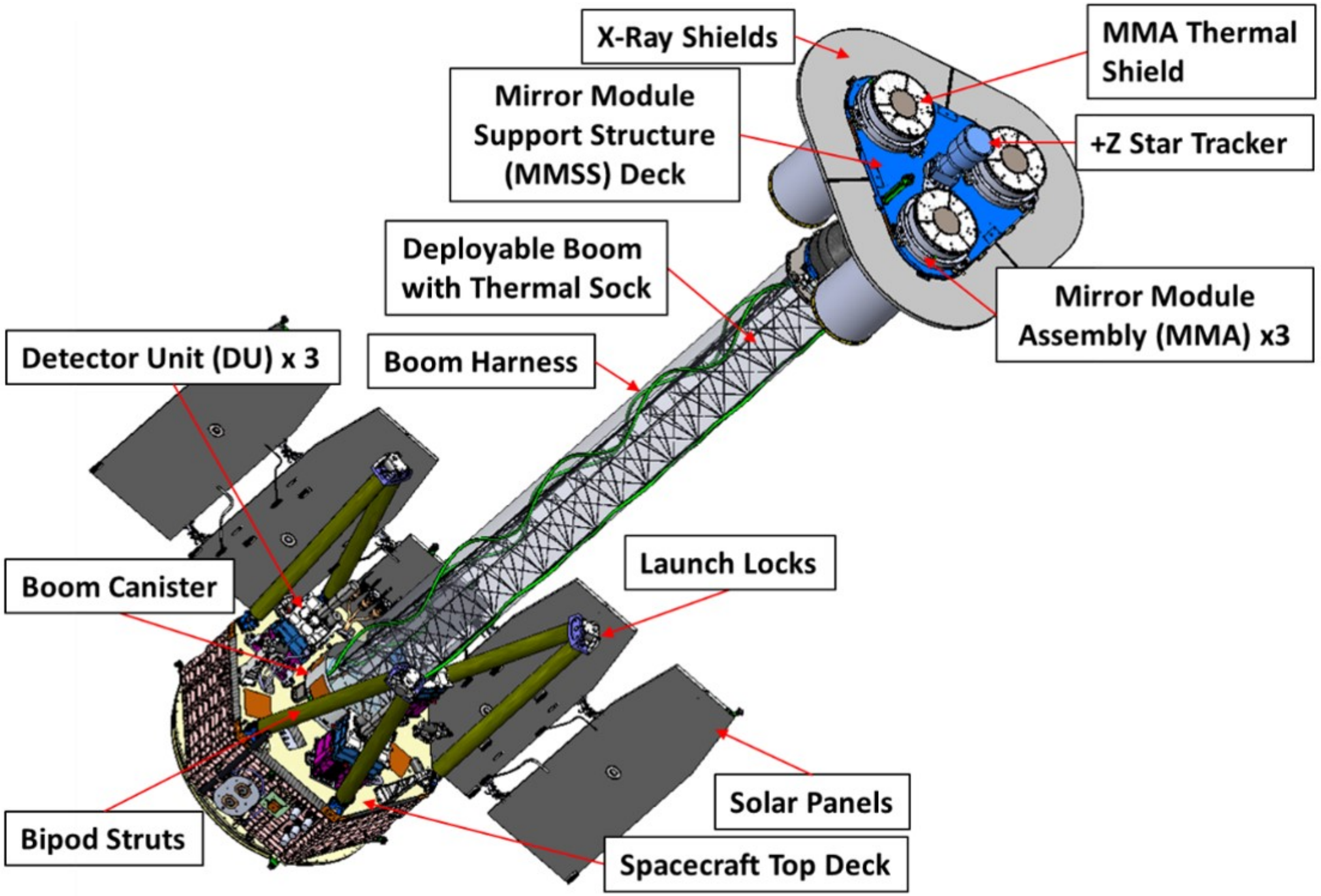


Costa et al., 2001



At the 13th proposal IXPE was selected for flight!
Selecten in Jan. 2017.
Launched on 9th December 2021.

The IXPE Observatory



CALIBRATION OF 3 FLIGHT DUS + 1 SPARE, AIV&T

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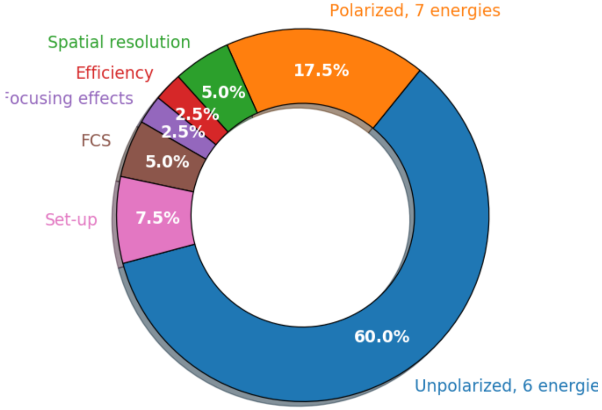
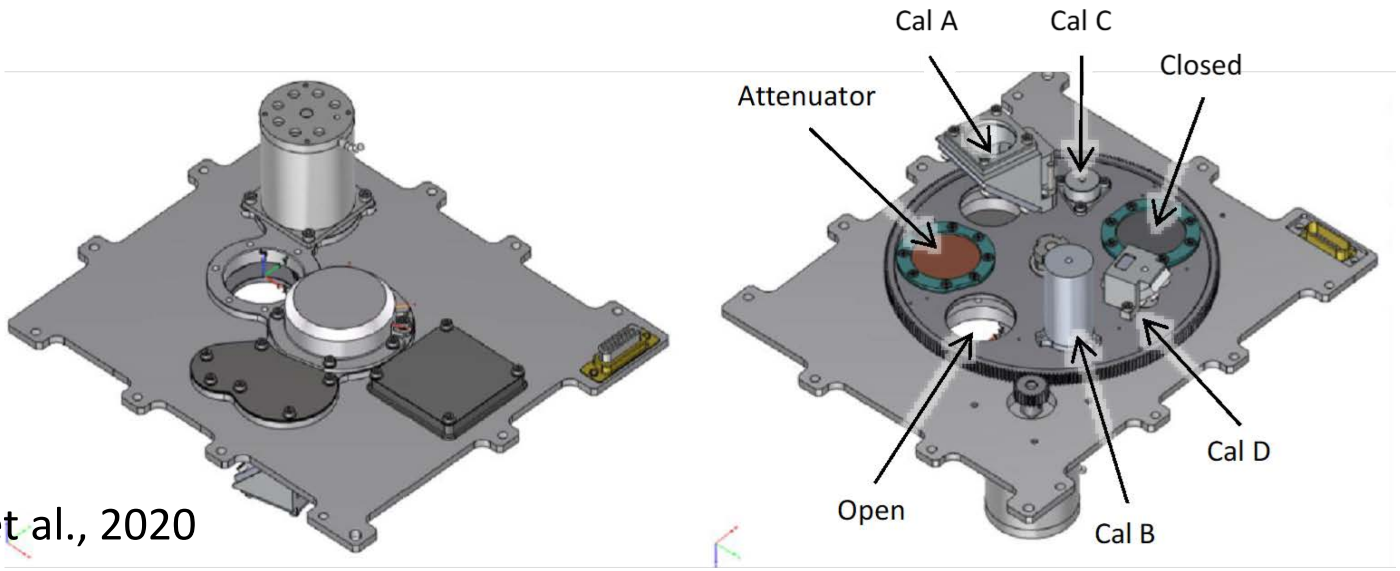
- **Calibration of DU have been carried out in Italy at INAF-IAPS, before Instrument integration and delivery to USA**
- **40 days for each DU (3 flight + 1 spare units)**
  - Up to 24/7 data acquisition
- **First unit started calibration on 26th July, DU-FM2 started on 6th Sep 2019, DU3 on 23 Oct. 2019, 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**



Muleri et al., 2022

Lesson learned: Larger number of energies at low and at high energy ends.
Smaller duration (less ASIC dead-time) of calibration: no always available such time.

Filter Calibration Wheel Assembly



Ferrazzoli et al., 2020

Filter and Calibration Wheel (FCW), providing open, attenuator, and closed positions, plus four ^{55}Fe-powered calibration sources:

- **Cal A – Bragg-reflected polarized 2.98-keV (Ag-Lα fluorescence) and 5.89-keV (Mn-Kα)**
- **Cal B – unpolarized 5.89-keV spot**
- **Cal C – unpolarized 5.89-keV flood**
- **Cal D – unpolarized 1.74-keV (Si-Kα fluorescence) flood**

Calibration is performed once per orbit during occultation of celestial sources by the Earth

TOPICAL WORKING GROUPS

Science Advisory Team (chaired by Giorgio Matt and Roger Romani)

Coordinates science activities required for planning, analyzing, interpreting, and reporting IXPE observations

Organized into seven Topical Working Groups

- *TWG1 Pulsar Wind Nebulae, led by Niccolò Bucciantini (INAF-Arcetri)*

Obtain polarimetric imaging to constrain the magnetic-field geometry of the nebula and the phase-dependent polarization of the pulsar

- *TWG2 Supernova Remnants, led by Pat Slane (CfA)*

Obtain spectral polarimetric imaging of Supernova Remnants (SNR) to constrain the magnetic-field structure of the X-ray emitting regions

- *TWG3 Accreting Black Holes, led by Michal Dovčiak (CAS-ASU)*

Obtain spectral polarimetry of microquasars to constrain the value of the black-hole spin parameter (if in soft state), or constrain the geometry of the corona (if in hard state)

- *TWG4 Accreting Neutron Stars, led by Juri Poutanen (Turku)*

Obtain phase-dependent polarimetry of accreting X-ray pulsars (high-magnetic-field binaries) to constrain models and geometries for the pulsing emission. Obtain polarimetry of non pulsating accreting NS to constrain the geometry of the system

- *TWG5 Magnetars,* led *by Roberto Turolla (Uni Padua)*

Obtain phase-dependent polarimetry of magnetars to constrain the effects of vacuum polarization (birefringence in a strong magnetic field)

- *TWG6 Radio-Quiet AGN & Sgr A, led by Frédéric Marin (Strasbourg)*

Obtain polarimetry of RQ AGN to constrain the geometry of the emitting regions

- *TWG7 Blazars & Radio Galaxies, led by Alan Marscher (Boston U)*

Obtain polarimetry of Blazars and RG to study jet emission

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STATUS OF TECHNICAL PAPERS (REF. JOURNALS)

Author	Journal	Topic	Status	Year
Weisskopf, Soffitta et al.,	JATIS	IXPE Mission	Published	2022
Soffitta et al.,	AJ	IXPE Instrument	Published	2021
Baldini et al.	Astrop. Phys.	IXPE GPD	Published	2021
Di Marco et al.	AJ	Weghted Analysis	Published	2022
Di Marco et al.	AJ	Calibration Pol. Rad.	Published	2022
Di Marco et al.	AJ	IXPE Background	Published	2023
Rankin et al.	AJ	Spurious Modul. Correction	Published	2022
Rankin et al.	AJ	Gain Equalization	Published	2023
Muleri et al.	Astrop. Phys.	Instrument Calibration Equip.	Published	2022
Ferrazzoli et al.	JATIS	On-board Calibration Sources	Published	2020
Peirson, Romani	ApJ	Neural Network	Published	2021
Peirson et al.	NIM A	Neural Network	Published	2021

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STATUS OF THE ASTROPHYSICAL PAPERS 1/2

Sorgente	Tipo	Primo autore	Rivista	Stato
4U 0142+61	Magnetar	Roberto Taverna	Science	Published
Mrk 501	Blazar (HBL)	Yannis Liodakis	Nature	Published
Cen A	Radio Galaxy	Stephen Ehlert	ApJ	Published
Cas A	Supernova Remnant	Jacco Vink	ApJ	Published
Her X-1	Accreting neutron star	Viktor Doroshenko	Nature Astronomy	Published
Vela PWN	Pulsar Wind Nebula	Fei Xie	Nature	Published
Cyg X-1	Black Hole Binary	Henric Krawczinsky	Science	Published
4U 1626-67	Accreting neutron star	Herman Marshall	ApJ	Published
Crab PWN	Pulsar Wind Nebula	Niccolo' Bucciantini	Nature Astonomy	Pubblicato
MCG-5-23-16	Radio Quiet AGN	Andrea Marinucci	MNRAS	Pubblicato
Mrk 421	Blazar (HBL)	Laura DI Gesu	ApJ Letter	Pubblicato
GS 1826-238	Weakly Magnetized Neutron Star	Fiamma Capitanio	ApJ	Sottomesso
Cen X-3	Accreting neutron star	Sergey Tsiganov	ApJ letter	Published
Cyg X-2	Accreting neutron star	Ruben Farinelli	MNRAS	Pubblicato
Circinus Galaxy	Radio Quiet AGN (Seyfert 2)	Francesco Ursini	MNRAS	Pubblicato
BL Lac	Blazar	Riccardo Middei	ApJL	Accettato
Sgr A* Complex	Molecular Clouds in the Gal. Center	Frèdèric Marin	Nature	Accepted

STATUS OF THE ASTROPHYSCIAL PAPER 2/2

Sorgente	Tipo	Primo autore	Rivista	Stato
Tycho	Supernova Remnant	Riccardo Ferrazzoli	Nature Astronomy	Pubblicato
Vela X-1	Accreting neutron star	Juri Poutanen	ApJL	Published
GRB 221009A	Gamma Ray Burst (Prompt & Aft)	Michela Negro	ApJL	pubblicato
1 RXS J1708	Magnetar	Silvia Zane	ApJL	Published
Mrk 421 (B)	Blazar (HBL)	Laura di Gesu	Nature Astronomy	submitted
BL Lac blazar (B)	Blazar (LBL)	Lawrence Pearscon	ApJ	submitted
XTE J1701-462	Accreting Neutron Star	Massimo Cocchi	A&A Letters	submitted
GRO J1008-57	Accreting Neutron Star	Sergey Tsygankov	A&A	Submitted
NGC 4151	Radio Quiet AGN	Elvezia Gianolli	MNRAS	Submitted
LMC X-1	Black-Hole Binary	Jakub Podgorny	MNRAS	Submitted
X-Persei	Accreting Neutron Star	Alexander Mushtukov	MNRAS	Submitted
GX 9-9	Accreting Neutron Star	Francesco Ursini	A&A	Submitted
4U 1630-472	Black Hole Binary	Ajay Ratheesh	Nature Astronomy	Submitted
EXO 2030+275	Accreting Neutron Star	Christian Malacaria	A&A	Submitted

About at least 31 astrophysical papers submitted by the collaborations. 18 papers have an Italian first author

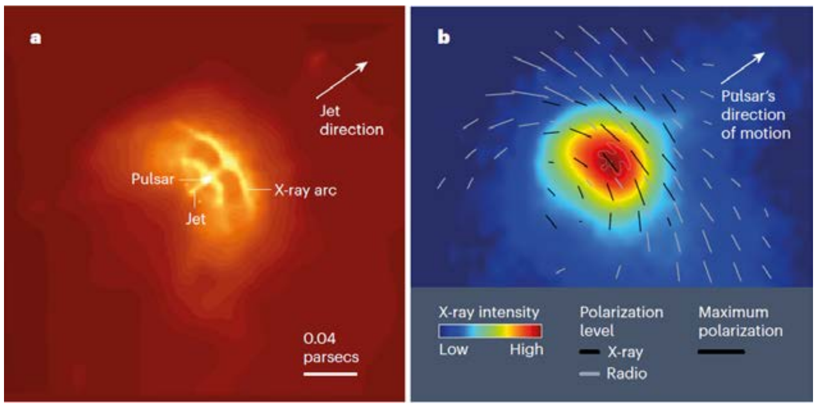
From Quick-look analysis

19 Detections at more than 6-sigma on 46 Sources

Source	Type
Crab	PWN
Vela PWN	PWN
MSH 15-52	PWN
Cyg X-1	Accreting stellar black-hole
4U-1630-47	Accreting stellar black-hole
Cyg X-3	Accreting stellar black-hole
Her X-1	Accreting Neutron Star
Cen X-3	Accreting Neutron Star
XTE 1701-46	Accreting Neutron Star
GRO J1008-57	Accreting Neutron Star
4U 0142+61	Magnetar
1RXS j170849	Magnetar
Mrk 501	Blazar
Mrk 421	Blazar
1ES1959+650	Blazar
Cyg X-3	Accreting Stellar Black-Hole
GRO J1008-57	Accreting Neutron Star
LSV 44-17	Accreting Neutron Star
GX 5-1	Accreting Neutron Star

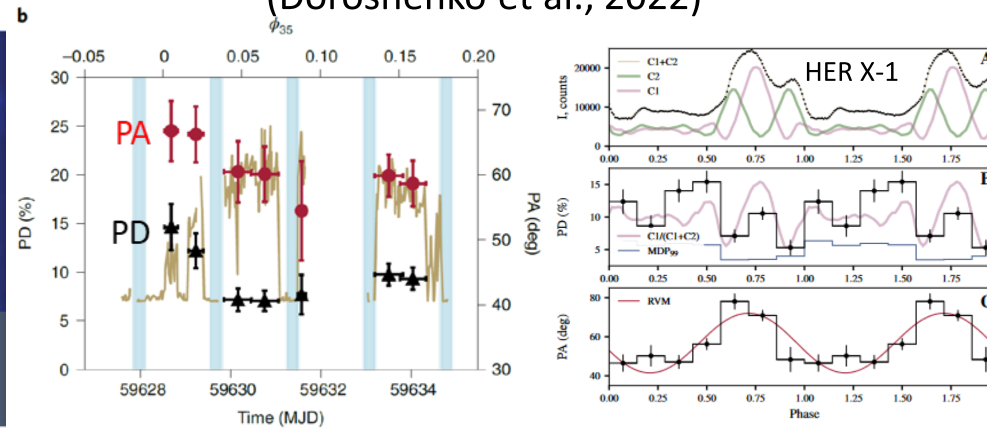
Some results from IXPE changed the game

(Xie et al., 2022)



Vela PWN showed a polarization close to the synchrotron limit

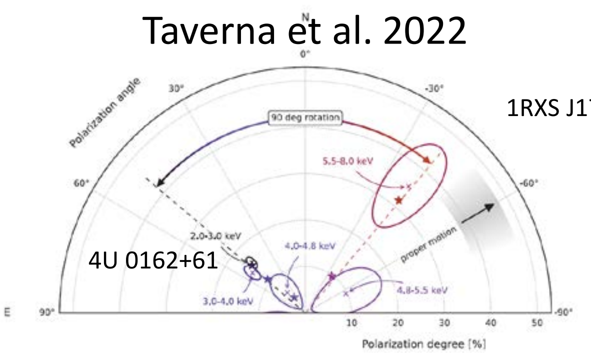
(Doroshenko et al., 2022)

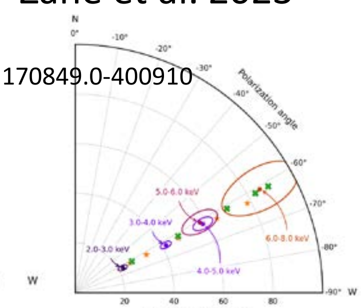


X-ray binary pulsars much less polarized than expected.

Taverna et al. 2022

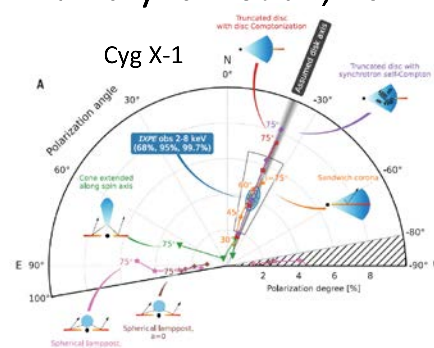
Zane et al. 2023



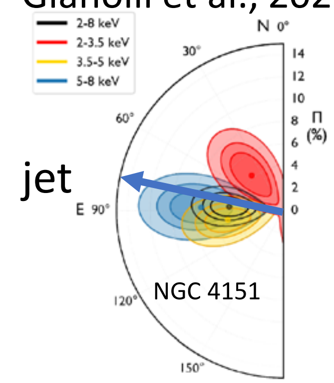


Two magnetars: two different behaviors of energy-resolved polarimetry challenge models

Krawczynski et al., 2022



Gianolli et al., 2023



Polarization in Cyg X-1 larger then expected. Sandwich corona for both Cyg X-1 and NGC 4151

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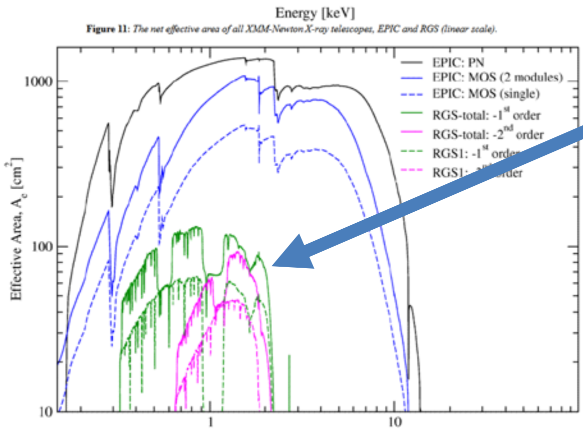
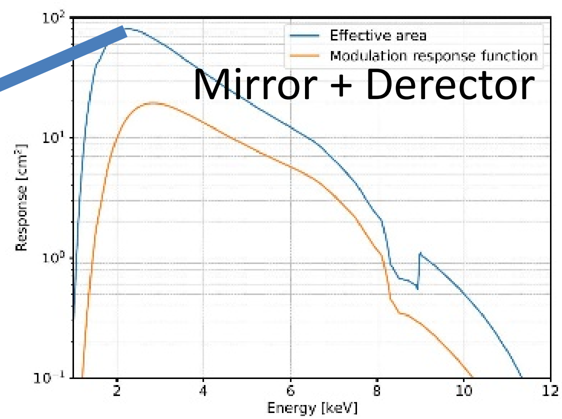
Improving and expanding the capabilities of X-ray Polarimetry beyond IXPE

Larger Effective area & Point Spread Function

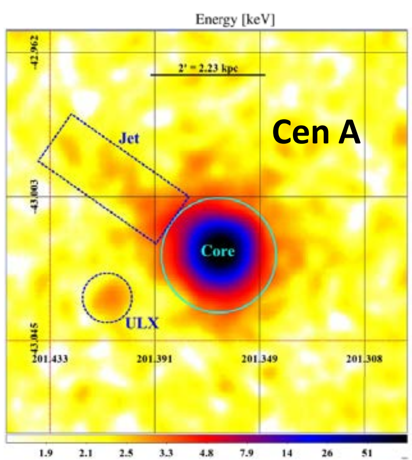




Larger mirror effective area

Larger detector Q.E.-> electro-negative mixtures

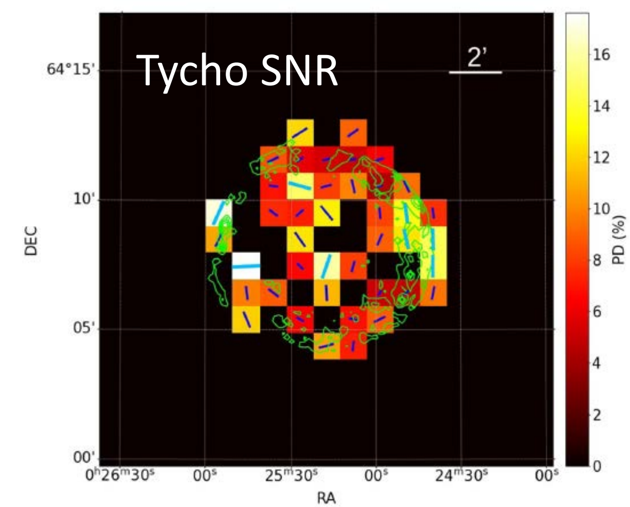
Better than 30' HEW



36 % MDP on the jet (100 ks)

Ehlert et al., 2022

Two magnetars showed different behavior with 1 Ms net observing time (20 days each). Needed a large area to improve the sensitivity.



Ferrazzoli et al., 2023

Few pixels showed significant polarimetry

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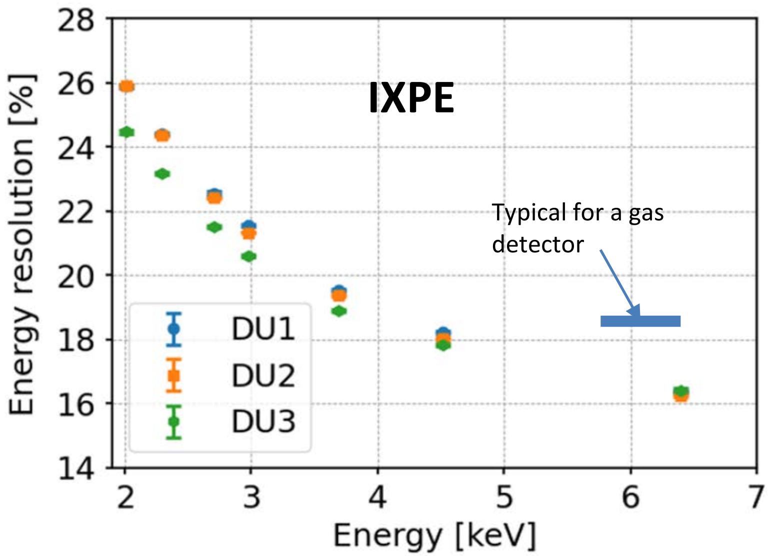
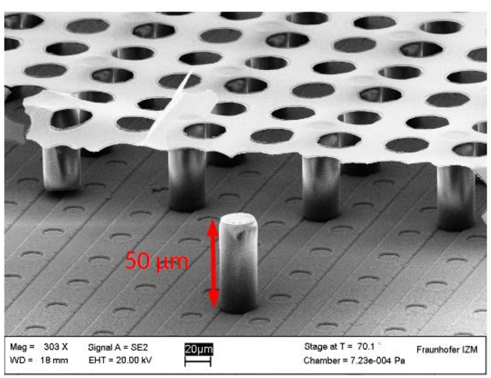
Energy resolution

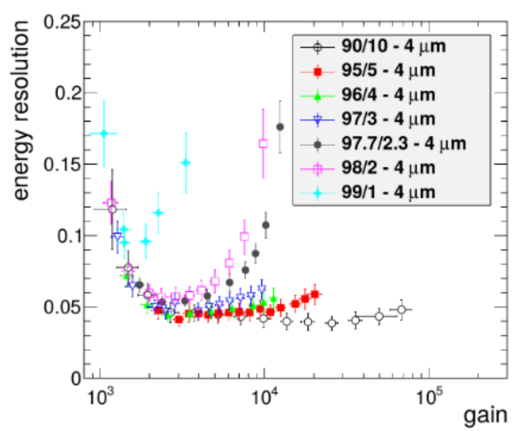


Weisskopf et al., 2022

The energy resolution is already better than that the typical proportional counter



Kaminski 2017



An energy resolution down to 10 % can be reached with GridPIX technologies at 6 keV

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Algorithms

$$MDP_{99} = 5.5\ \% \sqrt[2]{\frac{1}{\frac{T}{10\ days} * \frac{F}{0.5\ mCrab})}}\ (2\text{-}8\ keV)$$

Requirement

- The mirror effective area after construction is about 20 % smaller than expected.
- The detector is about 20 % less efficient than expected (but larger modulation factor)

$$MDP_{99} = 6.2\ \% \sqrt[2]{\frac{1}{\frac{T}{10\ days} * \frac{F}{0.5\ mCrab}}}$$

Unweighted analysis

$$MDP_{99} = 5.5\ \% \sqrt[2]{\frac{1}{\frac{T}{10\ days} * \frac{F}{0.5\ mCrab}}}$$

Weighted analysis
Di Marco et al., 2022 AJ

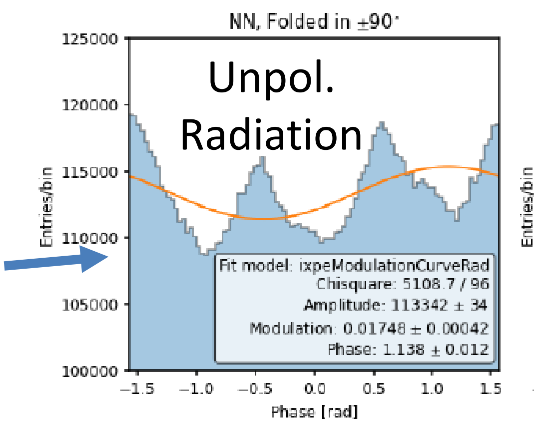
$$MDP_{99} = 5.0\ \% \sqrt[2]{\frac{1}{\frac{T}{10\ days} * \frac{F}{0.5\ mCrab}}}$$

Convolutional Neural Network
(Peirson& Romani, 2021 ApJ)

?

Visual Transformer & Graph Neural Network

Di Marco et al., 2022



Neural Networks seems promising techniques. They need to be validated with real calibration data because Monte Carlo training can hide a non uniform response to unpolarized radiation. Measuring flat response to unpolarized radiation is very difficult.

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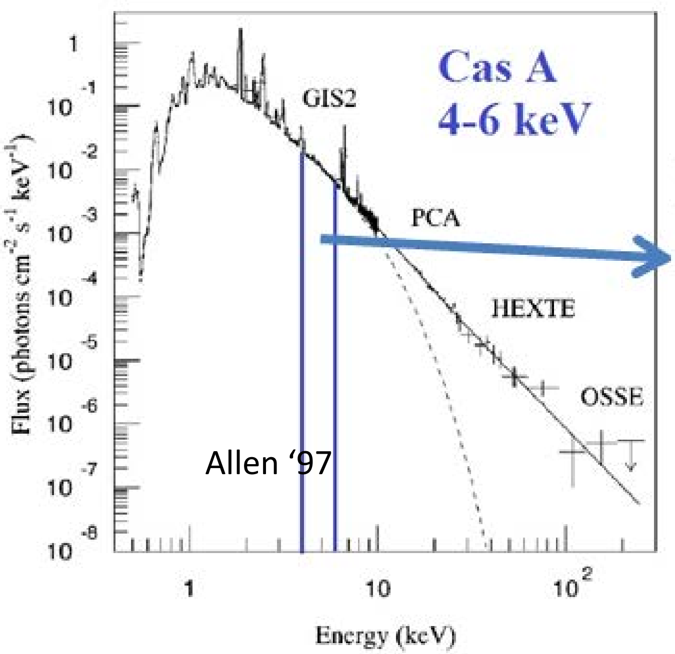
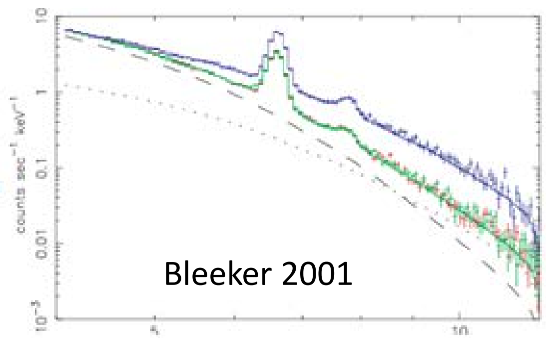
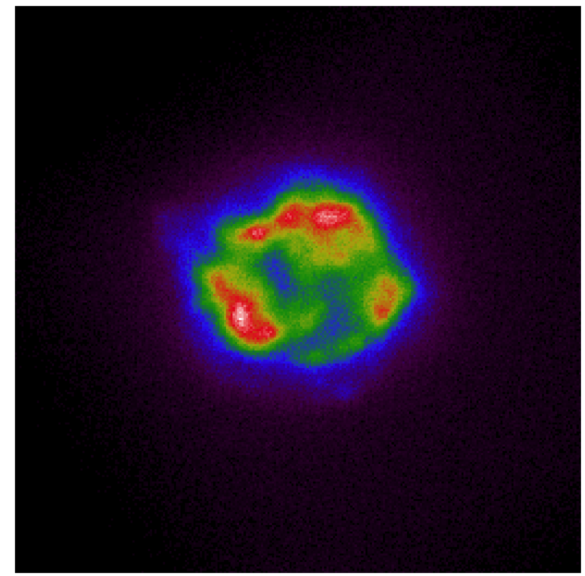
IMPROVING AND EXPANDING THE CAPABILITIES OF X-RAY POLARIMETRY BEYOND IXPE

Wider energy band & imaging for Supernova Remnants







Rotating each photon with respect to the center and selecting the energy range between the calcium line and the Iron line we demonstrated that, as in radio, the polarization angle is perpendicular to the radius of the SNR as in radio band *(Vink et al. 2022)*

Imaging polarimetry beyond 6.4 keV will measure polarization directly of the non-thermal emission due to synchrotron

10 m focal length will impose multiple observations for Tycho Supernova a single observation for Cas A

IMPROVING AND EXPANDING THE CAPABILITIES OF X-RAY POLARIMETRY BEYOND IXPE

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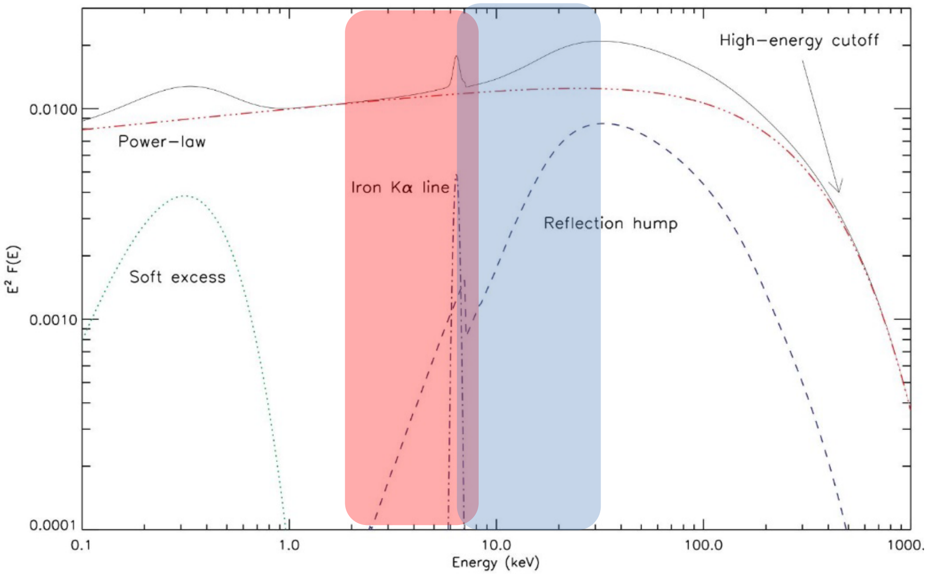
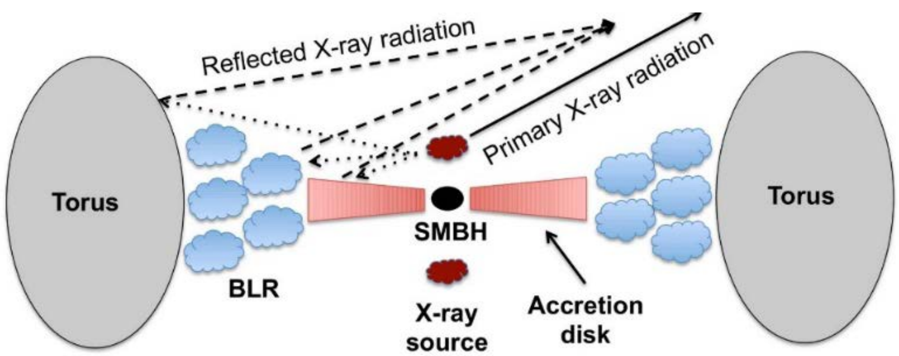


Wider energy band & imaging for AGNs



Credit Ricci, C.

IXPE energy band

Future Hard X-ray imaging polarimetry

Polarimetry above 6 keV to study reflection phenomena suffers of both a small detector quantum efficiency/mirror effective area. Reflection phenomena are poorly constrained

Improving and expanding the capabilities of X-ray Polarimetry beyond IXPE

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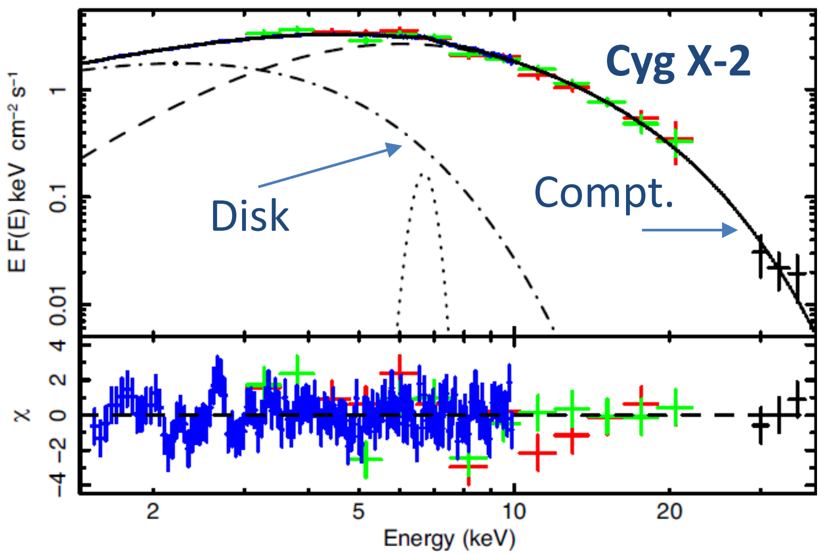
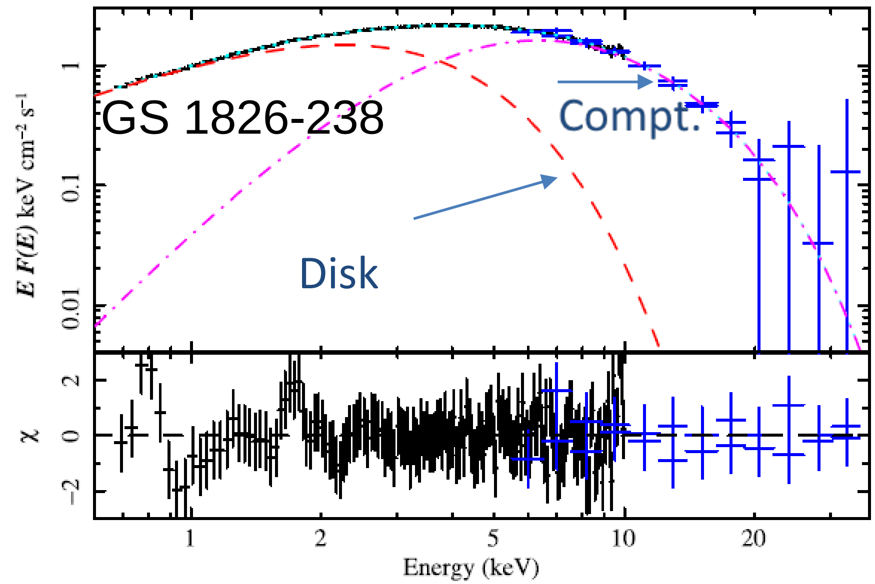
Wide energy band and no imaging for Low Magnetized Neutron Stars



Farinelli et al., 2022

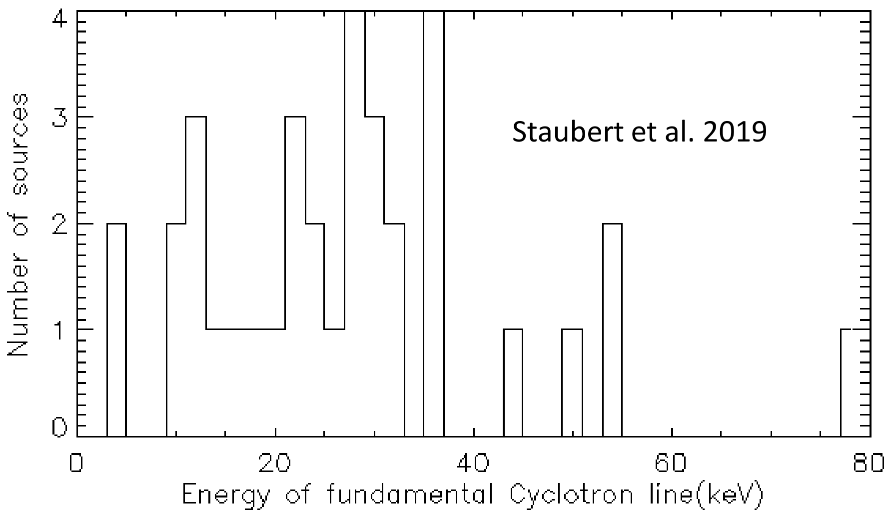


Capitanio et al., 2022

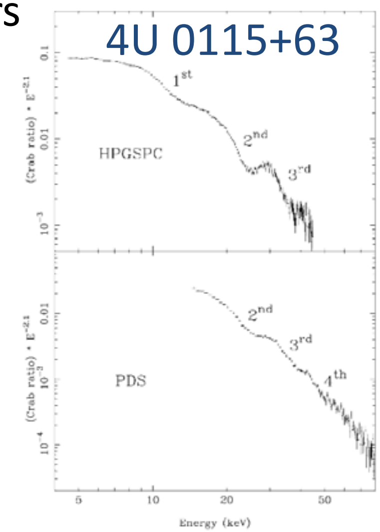
Comptonization extends up to 20-30 keV. It might be interesting to explore polarimetry in this energy band. It might help to constrain the geometry of the reflecting elements

IMPROVING AND EXPANDING THE CAPABILITIES OF X-RAY POLARIMETRY BEYOND IXPE

Wide energy band and no imaging for binary X-ray pulsars



4U 0115+63



In outburst now!
But not visible by IXPE ☹

MAXI/GSC observation of brightest outburst of the Be/X-ray binary pulsar 4U 0115+63 in 27 years

ATel #15975; *M. Nakajima, H. Negoro (Nihon U.), W. Iwakiri (Chiba U.), K. Kobayashi, M. Tanaka, Y. Soejima (Nihon U.), T. Mihara, T. Kawamuro, S. Yamada, T. Tamagawa, M. Matsuoka (RIKEN), T. Sakamoto, M. Serino, S. Sugita, H. Hiramatsu, H. Nishikawa, A. Yoshida (AGU), Y. Tsuboi, J. Kohara, S. Urabe, S. Nawa, N. Nemoto (Chuo U.), M. Shidatsu, M. Iwasaki (Ehime U.), N. Kawai, M. Niwano, R. Hosokawa, Y. Imai, N. Ito, Y. Takamatsu (Tokyo Tech), S. Nakahira, S. Ueno, H. Tomida, M. Ishikawa, T. Kurihara (JAXA), Y. Ueda, S. Ogawa, K. Setoguchi, T. Yoshitake, K. Inaba, Y. Nakatani (Kyoto U.), M. Yamauchi, T. Sato, R. Hatsuda, R. Fukuoka, Y. Hagiwara, Y. Umeki (Miyazaki U.), K. Yamaoka (Nagoya U.), Y. Kawakubo (LSU), M. Sugizaki (NAOC)*

on 3 Apr 2023; 14:28 UT

High Energy Polarimeter (Scattering)

Medium Energy Polarimeter (Photoelectric)

Most of the cyclotron fundamental lines can be probed by photoelectric imaging Polarimeters (Pressurized Argon, Medium Energy). The higher energy end requires Active Compton scattering polarimeter

To conclude

Beside a larger effective area and better HEW mirror

TECHNICAL IMPROVEMENTS IN THE IXPE BANDS

How IXPE could be made better

- **Thermal deformation of the boom -> metrological system**
- **Larger accessible sky (Multivavelength and ToO’s) -> more solar panels**
- **Constant gas pressure -> better studies of detector materials.**
- **Ground segment better staffed (more ToO’s)**

… and in the future

- **Less charge build-up -> multiplication stage different from Gas Eelectron Multiplier**
- **Less spurious modulation -> New ASIC generation**
- **Less dead-time -> New ASIC generation**
- **Avoid dithering (If possible).**
- **Tagged calibration source (If possible).**

THE FUTURE (ALL FUNDED PROJECTS)

New Generation of 3D photoelectric detectors for high throughput optics (very low dead-time)

2-8 keV Classical energy band polarimetry (Imaging, DME based)
6-30 keV Hard-X polarimetry (Imaging, Argon based)

New Generation of photoelectric large area detector for a collimated small experiment (much less costly than IXPE)

2-8 keV Classical energy band polarimetry (DME based)
6-30 keV Hard X-ray polarimetry (Argon based)

By-side science

Wide field GRB polarimetry:

Based on active scattering 20-200 keV (SWEPE, Muleri F.)
Based on photoelectric effect (2-8 keV or 6-30 keV)

Solar flare polarimetry **Based on active scattering (20-200 keV) (CUSP, Fabiani S.)**
Based on photoelectric effect (10-30 keV)

Conclusive remarks

X-ray polarimetry deserves a much larger mission

Future X-ray telescopes should include an X-ray polarimeter

Meanwhile we are working to improve the instrument and the analysis tools

END