Possible Directions for a Wide Band Polarimetry X-ray Mission

Frascati Workshop 2025
Multifrequency Behaviour of High Energy Cosmic Sources - XV
Mondello, Italy – 13th June 2025

Nicolas De Angelis – nicolas.deangelis@inaf.it

INAF-IAPS, Rome, Italy

Outline

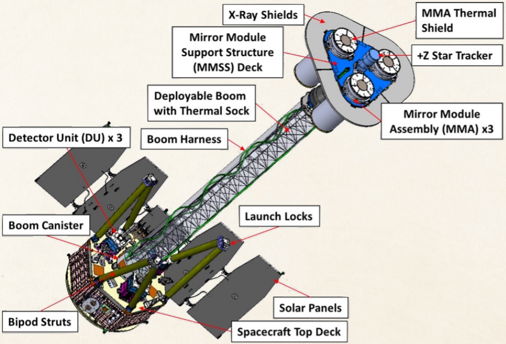
1. State-of-the-art of X-ray polarimetry: IXPE
2. Polarimetry in the sub-keV Band
3. Extending Photoelectric Polarimetry to 2-30 keV
4. Higher Energies with Compton Polarimetry
5. Proposed Wide-Band X-ray Polarimetry Missions
6. Wide Band and Wide FoV Polarimeters for Transients

Section 1

State-of-the-art of X-ray polarimetry: IXPE

State-of-the-art of X-ray polarimetry: IXPE

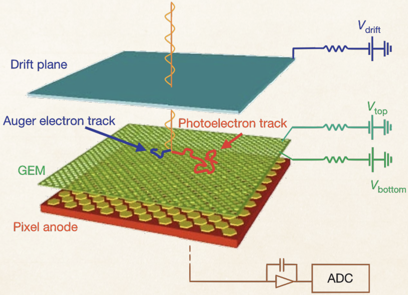
- Imaging X-ray Polarimetry Explorer (IXPE)
- NASA-ASI SMEX mission launched in Dec 2021
- Spectro-polarimetric imaging of X-ray sources in the 2-8 keV range

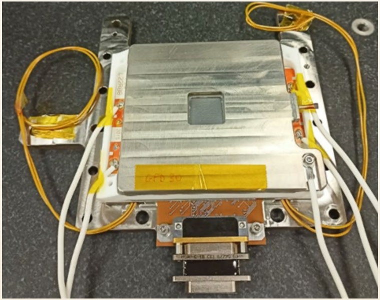


NASA IXPE Webpage, Weisskopf et al. 2022, Soffitta et al. 2021, Baldini et al 2021

Photoelectric polarimetry

- IXPE’s Gas Pixel Detector (GPD): sealed gas chamber with a Berylium entrance window, red out by an XPOL-I ASIC by INFN
- An X-ray will be converted into a (photo)electron whose emission direction in the gas is correlated to the polarization vector of the incoming photon
- An electric field is applied in the gas chamber to drift the photoelectron track towards the pixaled ASIC
- IXPE is made of 3 Detector Units (DUs) mounted 120° w.r.t. each other
- Costa et al. 2001, Bellazzini et al 2005, 2006, Baldini et al. 2021, Soffitta et al. 2022





IXPE Energy Range and Observations

Science case	Sources	$<$ 1 keV	1–10 keV	$>$ 10 keV
Acceleration phenomena	PWN	yes (but abs.)	yes	yes
	SNR	no	yes	yes
	Jet (Microquasars)	yes (but abs.)	yes	yes
	Jet (Blazars)	yes	yes	yes
Emission in strong magnetic fields	WD	yes (but abs.)	yes	difficult
	AMS	no	yes	yes
	X-ray pulsator	difficult	yes (no cyclotron?)	yes
	Magnetar	yes (better)	yes	no
Scattering in aspherical geometries	Corona in XRB & AGNs	difficult	yes	yes (difficult)
	X-ray reflection nebulae	no	yes (long exposure)	yes
Fundamental Physics	QED (magnetar)	yes (better)	yes	no
	GR (BH)	no	yes	no
	QG (Blazars)	difficult	yes	yes
	Axions (Blazars, Clusters)	yes?	yes	difficult

Table from Paolo Soffitta

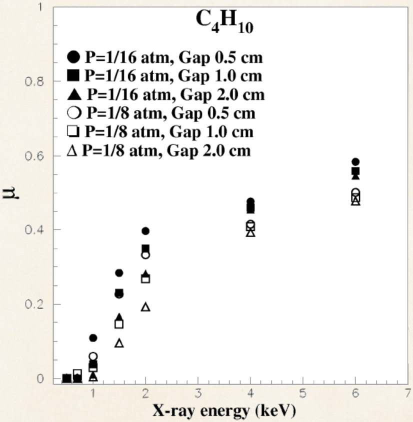
7 PWNe and isolated pulsars:	Crab PWN, Vela PWN, MSH 15-52, PSR B0540-69, G21.5, 3C 58, PSR B1259-63
6 SNRs (7 pointings):	Cas A, Tycho's, SN1006 NE, RCW 86, RX J1713.7-3946, Vela Jr, SN1006 SW
14 Accreting stellar-BH:	Cyg X-1, 4U 1630-472, Cyg X-3, LMC X-1, SS433, 4U 1957-115, SS 433 Lobes, LMC X-3, SWIFT J1727.8-1613, 4U 1957+115, Swift J0243.6+6124, Swift J1727.8-1613, GX 339-4, SWIFT J151857.0-572
33 Accreting NS & WD:	Cen X-3, Her X-1, GS1826-67, Vela X-1, Cyg X-2, GX 301-2, Xpersei, GX 9-9, 4U 1820, GRO J1008-57, XTE 1701-46, EXO 2030+375, LS V+44 17, GX 5-1, 4U 1624-49, Sco X-1, Cir X1, GX13+1, SMC X-1, SRGA J144459.2-604207, 4U 1538-52, V395 CAR, PSR J1023+00, GX 340+0, GX 3+1, 4U 1728-34, PSR J1723-2837, 4U 1735-44, GX 9+1, GX 349+2, 4U 1538-52, GX 17+2
5 Magnetars:	4U 0142+61, 1RXS J170849, SGR 1806-20, 1E 2259+586, 1E 1841-045
5 Radio-quiet AGN & 1 Sgr A*:	MCG 5-23-16, Circinus Galaxy, NGC 4151, IC 4329 A, Sgr A* Complex, NGC 1068, NGC 4945
17 Blazars & radio galaxies:	Cen A, S5-0716-714, 1ES 19-59-650, Mrk 421, BL Lac, 3C 454, 3C 273, 3C 279, 1ES 0229-200, PG 1553 -113, S4 0954+65, 1E 2259+586, RGB J0710+591, H 1426+428, 1ES 1101-232, PICTOR A WEST

Section 2

Polarimetry in the sub-keV Band

Low Efficiency of Photoelectric below 2 keV

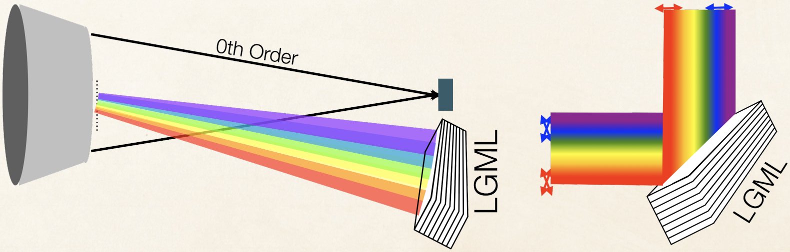
- Modulation factor μ is the response of the polarimeter to a 100% polarized beam, spanning from 0 – no sensitivity to 1 – perfect polarimeter
- Pushing down the photoelectric effect in energy doesn't allow polarimetric sensitivity below 0.8-1 keV
- Low-pressure/small-drift length required for low energy applications: larger incomplete low-energy tail expected due to incomplete charge collection



Pacciani et al. 2003

Bragg diffraction Extending energies below 2 keV

- Polarimetry based on Bragg diffraction, very high modulation factor (almost 100 %), very good energy resolution, polarimetry in the 0.1-0-7 keV band
- X-ray focusing mirror + Grading system to disperse light according to energy + Laterally Graded Multi-Layer (LGML) mirrors + CCD
- 0-th order light directly collected by a CCD, 1th-order dispersed light reflected by LGML to a CCD
- LGML reflectivity highly dependent on polarization (only reflecting s-polarzation), one can measure I, Q, U (linear Stokes polarization) with 3 instruments at 120° or with a rotating telescope
- 30+ yr of concept work & 15+ yr lab work in MIT Kalvi: Marshall 2007, 2008; Marshall et al. 2009, 2018
- R&D ongoing using twisted crystals to go up to 1 keV

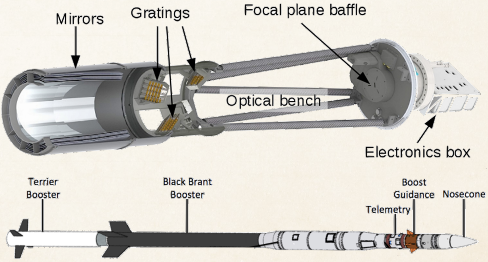


Marshall et al. 2018 JATIS

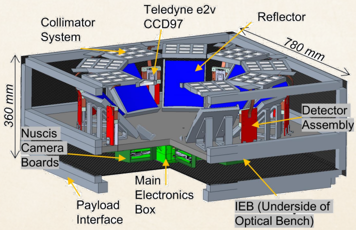
REDSoX: Sounding rocket demonstrator selected for a 2027 launch, 0.18-0.4 keV (Marshall et al.), 3 assemblies, 5 mn flight observing one blazar

GOSoX: Orbiter version of REDSoX, proposed to the NASA Astrophysics Pioneer 2025 call (Marshall et al.), 1 assembly with rotation at 1°/s, using sCMOS instead of CCD

StokeSat: More compact telescope which does not require optics, energy band is very narrow (few eV around 275 eV) but large effective area, proposed to the NASA Astrophysics Pioneer 2025 call (DeRoo et al.)



Marshall et al. 2018 JATIS



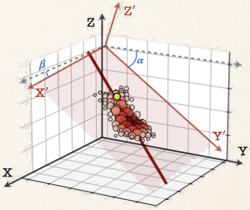
C. DeRoo & StokeSat collab.

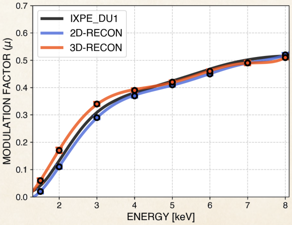
Section 3

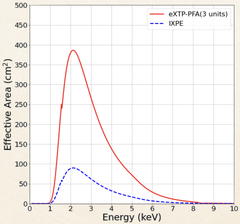
Extending Photoelectric Polarimetry to 2-30 keV

Possible Improvements in the IXPE Band (2-8 keV)

- Room for improvement: modulation factor (polarimeter), energy resolution (polarimeter), angular resolution (mirrors), effective area (mirrors + detector's deadtime)
- R&D project in INAF-IAPS to use CERN's Timepix chip for 3D photoelectron track reconstruction (with timing) to improve the modulation factor
- Future eXTP's Polarimetry Focusing Array (PFA) with improved effective area
- Possibility of using Time Projection Chambers (TPCs), e.g. design for the GEMS proposal (track readout with 1D + timing, no imaging possible)





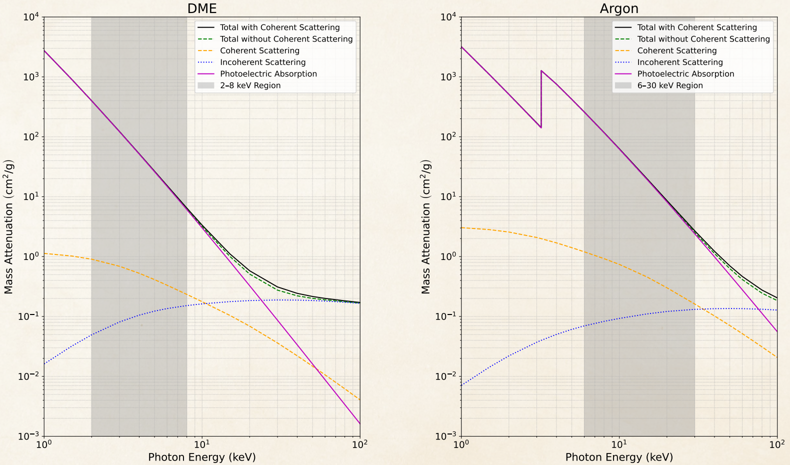


Kim et al. 2024 JINST

Zhang et al. 2025 arXiv:2506.08101

Higher energies with gas polarimeters From 6 to 30 keV

- Dimethyl Ether (CH3OCH3) $\rightarrow$ Argon
- K-edge energies: 543 eV for DME and 3.2 keV for Argon
- A 2-bars Ar-DME GPD has already be built and tested (Fabiani et al. 2012)

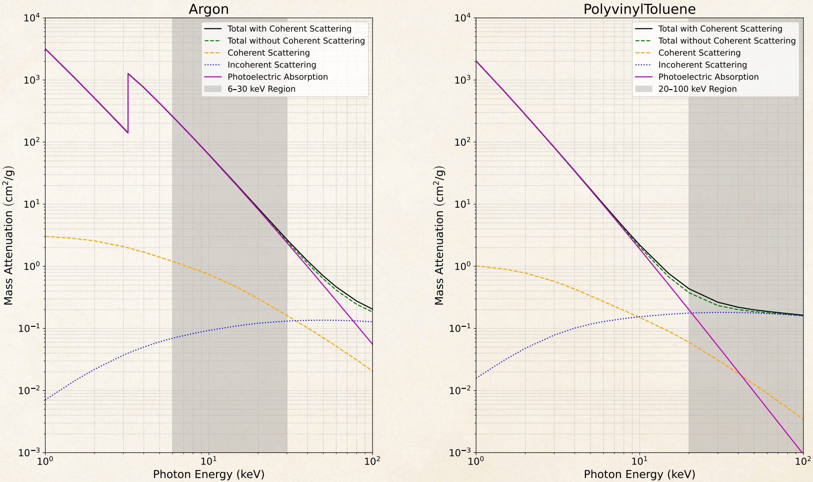


Data from NIST XCOM

Section 4

Higher Energies with Compton Polarimetry

- **Photoelectric** polarimetry → **Compton** scattering polarimetry
- Low-Z scintillators (e.g. plastic) are required to maximize Compton cross section down to low energies (lowering the energy threshold)



Data from NIST XCOM

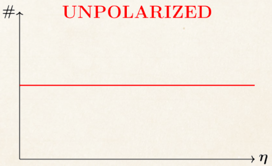
Compton Polarimetry Beyond 20 keV

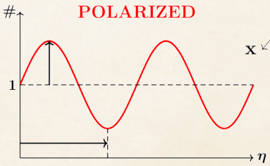
Compton scattering can be used to determine the polarization of a source:

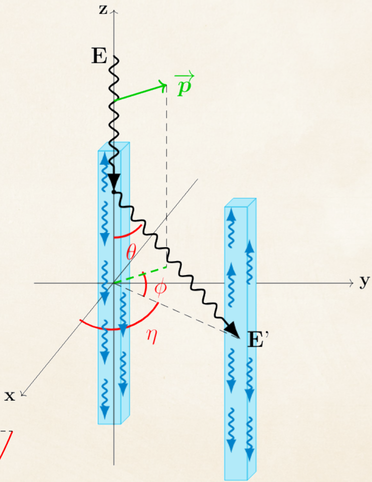
- Azimuthal scattering angle distribution provides information on PD and PA
- Modulation curve parameterized by the Klein-Nishina cross-section:

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

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

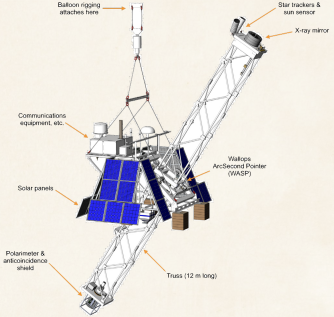


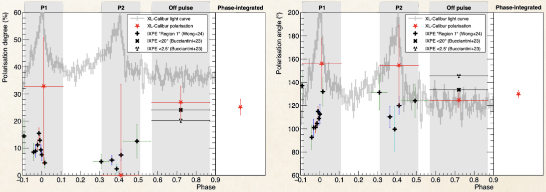




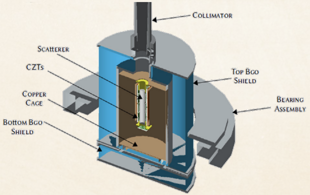
Example of Compton Polarimetry Mission XL-Calibur

- Zero Pressure Balloon flight in July 2024 from Sweden to Canada for 5d 20h
- Be scatterer surrounded by pixelated CZT absorber, encapsulated in an anti-coincidence shield
- Polarimeter placed at the focus of spare Hitomi X-ray optics, 12 m focal length
- Energy range 15-80 keV
- Observed Crab and Cyg X-1
- Other example of Compton polarimeter: see next talk by Sergio Fabiani on the **CUSP** Solar Flare polarimeter





Awaki et al. 2025 MNRAS



Iyer et al. 2023 NIM-A

Section 5

Proposed Wide-Band X-ray Polarimetry Missions

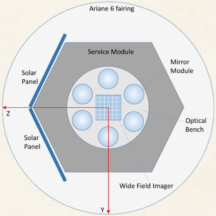
Proposed Missions EXPO – ESA M8 call

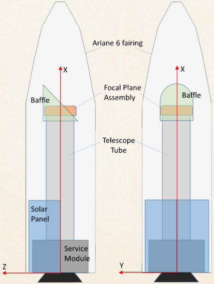
- The **Enhanced X-ray Polarimetry Observatory** (EXPO) proposed as an M8 mission by Soffitta et al.
- **6 telescopes + 1 wide field imager**
  - Multi-layer mirrors with 10 m focal length
  - Sensitive to polarization from $\sim$1 to $\sim$100 keV
- 1 telescope for spectro-imaging, 5 for polarimetry
- Stacked design: a photoelectric polarimeter (LEP or MEP) on top of a Compton one (HEP)

Mirror #	1	2	3	4	5	6
Front	LEP	LEP	MEP	MEP	MEP	MEP
Behind	HEP	HEP	HEP	HEP	HEP	SIC

Low Energy Polarimeters, Ne/DME filled	2–8 keV
Medium Energy Polarimeters, Ar/DME filled	6–30 keV
High Energy Polarimeters, Compton	20–80 keV
Spectrometer-Imager Camera	$<2 - >80$ keV

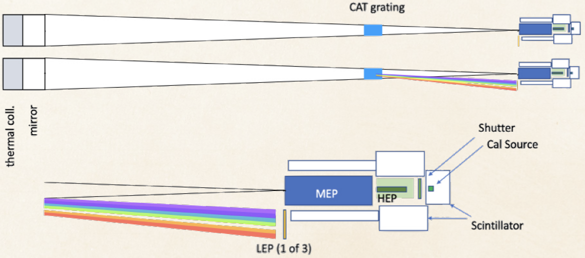
- Reduction of observing time with respect to IXPE at low energy over a factor 4
- *Swift*-like autonomous re-pointing capabilities
- Ariane 6 to launch in L2 in 2041





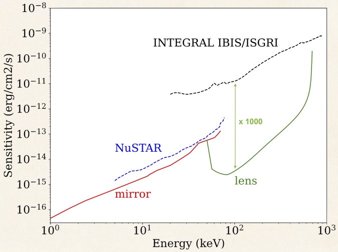
Proposed Missions XPP

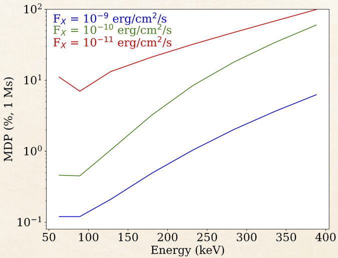
- The **X-ray Polarimetry Probe** will be composed of 4 types of polarimeters:
  2x MIT's REDSoX design (0.15-1.0 keV)
  2x GSFC's Time Projection Chamber (photoelectron tracker, 2-8 keV)
  1x INAF-INFN's Gas Pixel Detector (photoelectron tracking imager, 2-8+ keV)
  2x U. Washington's CZT & LiH scatterer (XL-calibur, 5-50 keV)
- 3 $\sim$2000 cm^2 mirror assemblies (1x 15" HPD for GPD, 2x 60" for other detectors), 10 m focal length
- Spinning at 1 rph, >5 years life time, HEO orbit
- White paper: Jahoda et al. 2019, 2020 Astrophysics Decadal review



INAF ISTITUTO NAZIONALE DI ASTROFISICA
IAPS ISTITUTO DI ASTROFISICA E PLANETOLOGIA SPAZIALI

- The **Polarimetric High Energy Modular Telescope Observatory** (PHEMTO) proposed as an ESA M8 mission by Laurent et al.
- Optics: X-ray mirrors + Laue lenses
- Focal Plane Assembly made of Low Energy Detector (LED): Si-based matrix 1-20 keV, and High Energy Detector (HED): CdTe pixelated detector (8-400 keV) + Anti-Coincidence shield
- Compton polarimetry above 50 keV with coincidence b/w LED and HED
- 20 m focal length, formation flight with 2 spacecraft (optics + detectors)
- White paper: Laurent et al. 2021 Exp. Astron.



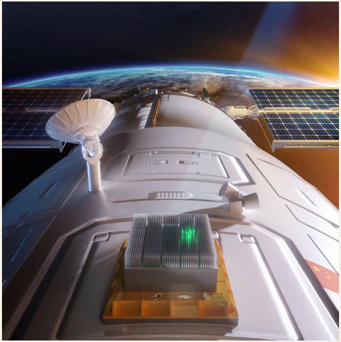


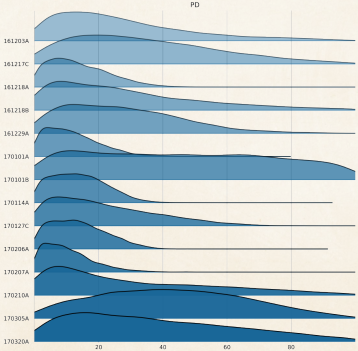
Section 6

Wide Band and Wide FoV Polarimeters for Transients

The POLAR GRB Polarimeter

- POLAR was a dedicated gamma polarimeter composed of a 40×40 plastic scintillator bars read out by Multi-Anode PMTs
- Optimized for Compton scattering polarimetry in the 50-500keV range
- 30kg instrument, half-sky FoV, $\sim 300 cm^2$ effective area at 400 keV
- Instrument design: Produit et al. 2018 NIM-A
- Launched in Sept 2016 on the Tiangong-2 space lab, operated for 6 months
- Observed 55 GRBs, the 14 brightest shown low levels of polarization

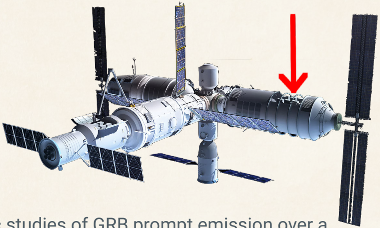




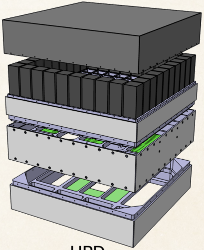
A&A 644, A124 (2020)

Wide FoV Wide Band Polarimetry POLAR-2/HPD-LPD-BSD

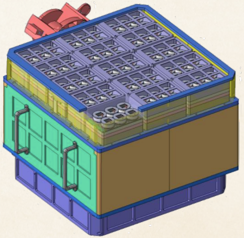
- Successor mission called **POLAR-2** (led by Unige, CH), scheduled for launch to China Space Station mid-2027
- Wider band Compton Polarimeter (**HPD**): 50-500 keV → 20-800 keV
- Equipped with two additional instruments for broader band spectro-polarimetry: Photoelectric Polarimeter (**LPD**) led by GuangXi University, Nanning & Broad-band Spectrometer (**BSD**) led by IHEP, Beijing



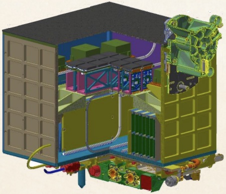
- **Scientific motivation:** energy-dependent polarimetric studies of GRB prompt emission over a wide interval is much more powerful than integrated analysis as a diagnostic tool to probe emission mechanism, jet structure, magnetic field configuration



HPD



LPD



BSD

Summary

- Widening the energy band of X-ray polarimetry is of high interest for astrophysics
- Sensitivity improvements in the current 2-8 keV IXPE bands are possible or currently investigated, upper energy boundary can be pushed using other gas mixture
- Sub-keV polarimetry can be achieved using Bragg technique, and above 10-20 keV using Compton scattering
- Several wide band focal plane polarimetry missions proposed, future generation of wide FoV GRB polarimeters also employing several polarimetry technique to widen the energy band

galaxies MDPI

Review

Considerations on Possible Directions for a Wide Band Polarimetry X-ray Mission

Paolo Soffitta [1,*], Enrico Costa [1,*], Nicolas De Angelis [1], Ettore Del Monte [1], Klaus Desch [2], Alessandro Di Marco [1], Giuseppe Di Persio [1], Sergio Fabiani [1], Riccardo Ferrazzoli [1], Markus Gruber [2], Takahashi Hiromitsu [3], Saba Imtiaz [1,4], Philip Kaaret [5], Jochen Kaminski [2], Dawoon E. Kim [1,6,7], Fabian Kislat [8], Henric Krawczynski [9], Fabio La Monaca [1,6,7], Carlo Lefevre [1], Hemanth Manikantan [1], Herman L. Marshall [10], Romana Mikusincova [1], Alfredo Morbidini [1], Fabio Muleri [1], Stephen L. O'Dell [5], Takashi Okajima [11], Mark Pearce [12,13], Vladislavs Plesanovs [2], Brian D. Ramsey [5], Ajay Ratheesh [1], Alda Rubini [1], Shravan Vengalil Menon [9] and Martin C. Weisskopf [5]

DOI:*10.3390/galaxies12040047*

Backup slides

Science Motivations for Wider-Band Polarimetry 1

INAF ISTITUTO NAZIONALE DI ASTROFISICA
IAPS ISTITUTO DI ASTROFISICA E PLANETOLOGIA SPAZIALI

Below 2 keV:

- **Isolated pulsars** with spectrum peaking at 0.1-0.3 keV, 100 out of 1800 known rotation-powered pulsars emit thermal X-rays $10^5 - 10^6$ K
- Sub-keV thermal emission from surface of **isolated neutron stars** (including magnetars), notable 10 cataloged magnetars at high galactic latitudes (absorption is a problem in the galactic plane at these energies)
- About a dozen of **black hole binaries** at high galactic latitudes
- **High synchrotron peaked blazars** (HSP) may have peak energy in 0.1-10 keV, determine if smooth transition from low polarization in optical/IR/millimeter to potentially high polarization in X-ray

Science Motivations for Wider-Band Polarimetry 2

INAF ISTITUTO NAZIONALE DI ASTROFISICA
IAPS ISTITUTO DI ASTROFISICA E PLANETOLOGIA SPAZIALI

2-8 keV:

- Improving the instrument performances in the already probed IXPE band would allow a **reduced exposure time** to reach the same sensitivity, hence allowing to observe more sources within the mission's life time
- Increase of reachable extragalactic sources with **higher effective area**
- More detailed morphology studies of PWN with **better angular resolution**, also useful for SNRs (although not the best energy band)

Science Motivations for Wider-Band Polarimetry 3

Above 10 keV:

- **AGNs** above 6 keV: dominated by scattering on the disk for **Seyfert-1**, and by scattering from ionization cones or surrounding molecular torus for **Seyfert-2** galaxies
- **SNR** polarimetry is difficult in the IXPE range due to large thermal emissions and lines, imaging polarimetry of SNRs above iron lines will help studying the synchrotron non-thermal emission
- Further probe emission regions from **magnetars**
- **Binary pulsars** cyclotron line polarimetry
- Cleaner and more sensitive tomography of **galactic center** as the significance in the IXPE band is highly impacted by the presence of warm and bright plasma emitting around few keV