IXPE
Imaging
X-Ray
Polarimetry
Explorer

IXPE First Results

- Imaging X-ray Polarimetry Explorer -

Sergio Fabiani (INAF-IAPS)

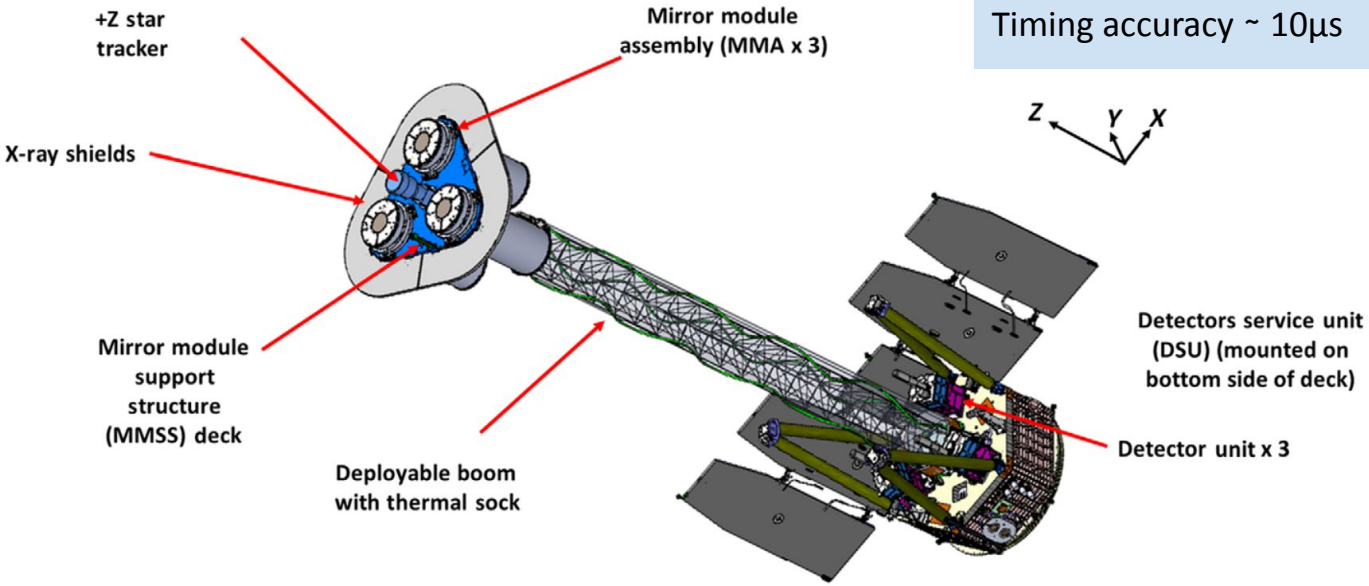
on behalf of the IXPE Science Team (https://ixpe.msfc.nasa.gov/partners_sci_team.html)

Vulcano Workshop 2022, “Frontier Objects in AstroPhysics and Particle Physics”, Elba, September 26th - October 1st

IXPE in a nutshell - the Observatory

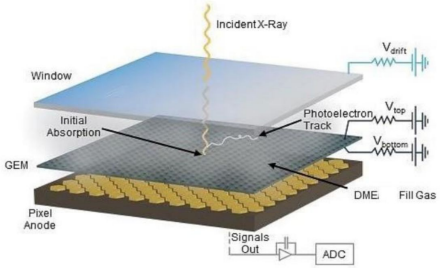
NASA Small Explorer Mission
NASA / ASI partnership
ASI funded the “focal plane”, the scientific detectors
INAF-IAPS and INFN developed them
Launched December 9th 2021

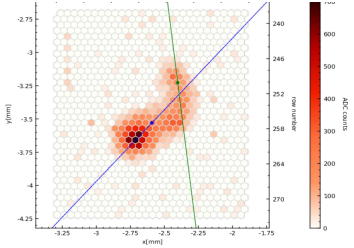
Energy range: 2–8 keV
Polarimetry: MDP>5.5% in 10 days for 0.5 mCrab
Focal length: 4m
Angular Resolution: HEW < 30 arcsec
Energy resolution <20% at 5.9 keV
Timing accuracy ~ 10µs



IXPE in a nutshell - the Payload

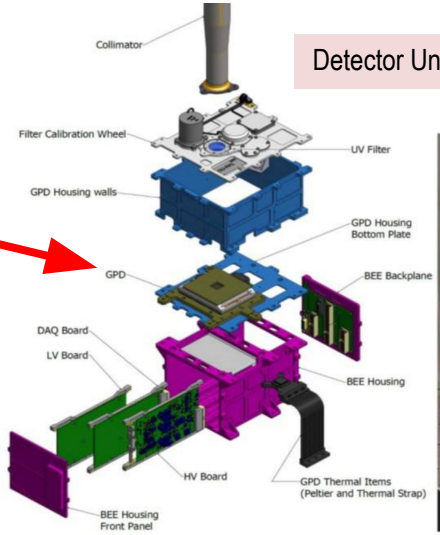
Gas Pixel Detector

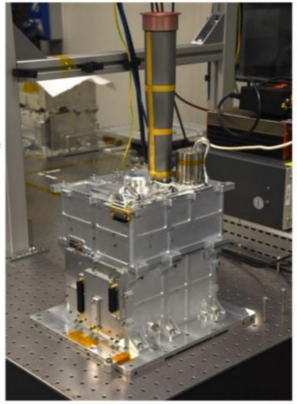




Photoelectron Track

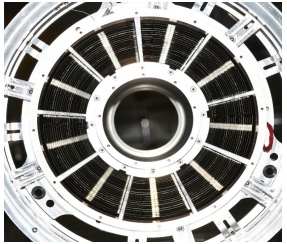
Detector Unit

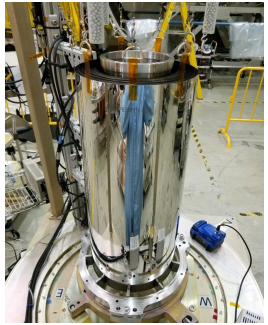




4 Detector Units (1 spare), 1 Detector Service Unit:
- INAF-IAPS, INFN
- Industry OHB-I

Mirror Module Assemblies



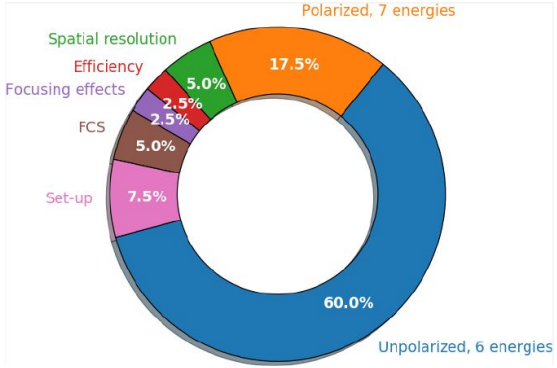


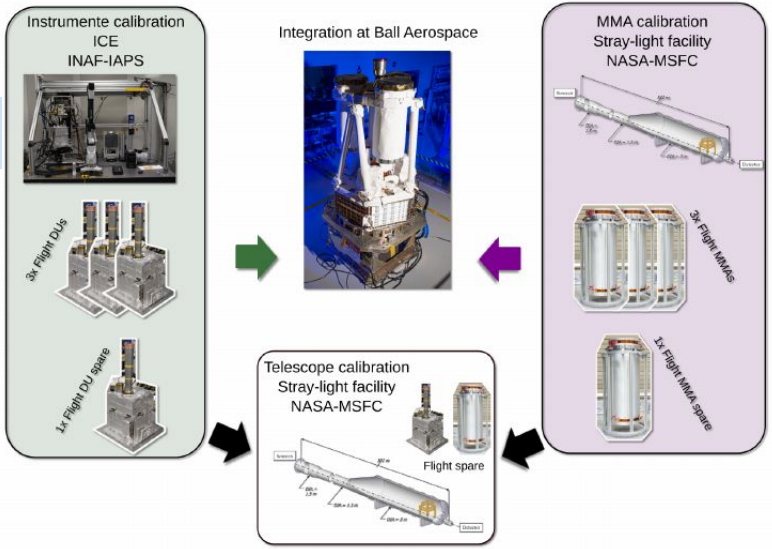
4 Mirror Module Assemblies (1 spare):
- NASA-MSFC
- Industry Ball Aerospace

IXPE in a nutshell - calibration and integration

- **All DUs and MMAs** on board IXPE were calibrated **separately** in Italy at **INAF-IAPS** and at the **Stray Light Test Facility (SLTF) of MSFC**, respectively
- The **spare DU with the spare MMA** were, moreover, calibrated also in the **Telescope configuration** at the **SLTF of the MSFC** with the support of INAF and INFN Italian team during Covid-19 emergency

Time allocation of DU calibration measurements





Integrated IXPE @ Ball Aerospace, Boulder (Colorado, USA)

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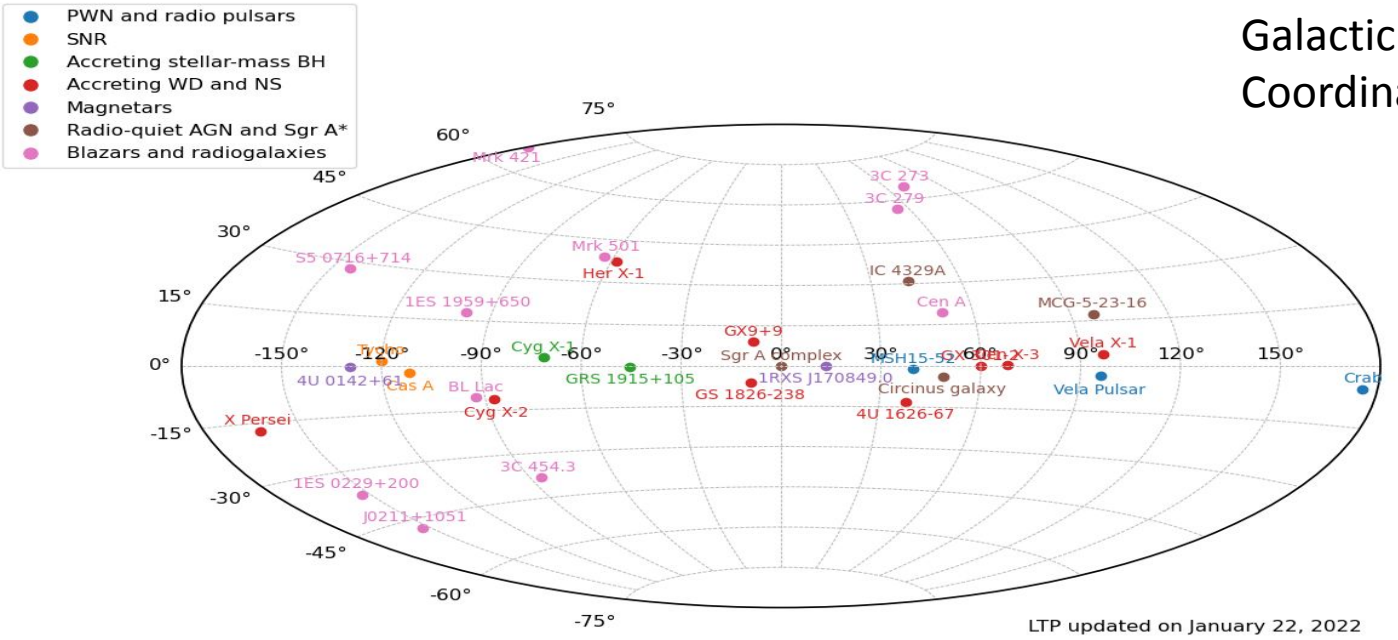
Imaging X-Ray Polarimetry Explorer

Mission Planning and data availability

- **Science Mission Planning**
  - 2-year mission, based upon recommendations by IXPE's Science Advisory Team
  - Extended mission (if approved), dependent upon HEASARC administered General Observer program
  - Detailed observation scheduling on weekly basis
  - Rework of schedule when needed to accommodate targets of opportunity
- **Science Data Processing**
  - Ground Station Malindi (Kenya) by ASI
  - MOC (Mission Operation Center, at LASP in Boulder - Colorado) aggregates science and engineering data
  - SOC (Science Operation Center, at NASA/MSFC in Huntsville - Alabama) run these data through a pipeline (contribution from INAF-IAPS, INFN and ASI/SSDC) to generate science data products:
    - Low-level data to the Instrument Team (in Italy: INAF-IAPS and INFN) for monitoring and trends analysis
    - Level-1 data, including electron track images and event lists in detector coordinates
    - Level-2 data, including event lists in sky coordinates for detailed scientific analysis (gain calibrated and spurious modulation subtracted, downloadable from HEASARC archive)
  - Maintenance of a Calibration Database (CalDB), which is needed for detailed scientific analysis
- **Science Data Archiving**
  - IXPE CalDB to the High-Energy Astrophysics Science Archive Research Center (HEASARC)
  - For each observation, science data products transmitted to the HEASARC within 1 week of end of observation
  - Test of HEASoft tools provided by the HEASARC for analysis of IXPE data (HEASoft 6.30.1 now available)

1st-year targets

Galactic Coordinates



Archive of observed sources https://heasarc.gsfc.nasa.gov/docs/ixpe/archive/
Updated long term observing plan: https://ixpe.msfc.nasa.gov/for_scientists/ltp.html

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How IXPE data work

- Each photoelectron is associated to a "pseudo"-Stokes parameter depending on the reconstructed initial direction φ_i and energy dependent modulation factor μ_i
- Spurious modulation (a detector systematic effect) is subtracted in this Stokes space, depending also on the event position on the detector image
- q, u and thus the polarization degree (PD) and angle (PA) are obtained

$$q = \langle (2\cos(2\varphi_i) - q_i^{sm})/\mu_i \rangle$$
$$u = \langle (2\sin(2\varphi_i) - u_i^{sm})/\mu_i \rangle$$

$$\Pi = \sqrt{Q^2 + U^2}/I = \sqrt{q^2 + u^2}$$
$$\psi = \frac{1}{2}\tan^{-1}\left(\frac{Q}{U}\right) = \frac{1}{2}\tan^{-1}\left(\frac{q}{u}\right)$$

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How polarization results are reported

- **Polarization results can be reported in terms of**
  - Normalized Stokes parameters Q/I and U/I which are assumed independent and Gaussian distributed
  - PD and PA which are not independent
- **PD and PA can be reported as 1-D values, but the more appropriate representation for a joint measurement of PD and PA are 2-D contour plots at a certain confidence levels**
- **2-D (PD,PA) contour plots can be drawn:**
  - on the basis of the statistics of N collected events

    Weisskopf et al. (2010), doi: 10.1117/12.857357;

    Strohmayer & Kallman (2013), doi: 10.1088/0004-637X/773/2/103

    Muleri (2022), https://arxiv.org/abs/2204.12739
  - with XSPEC spectral fitting tool (in this case a spectral model is needed)

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Some rules…

- These charts include results currently under embargo rules of different journals, **please do not**:
  - **take pictures**
  - **make recordings**
  - **post on social media**
  - **make press releases**

- I report results from published and submitted papers
- Many submitted papers already available on arXiv

Magnetic field structure in extended sources: PWN

- **Crab PWN by Bucciantini et al. arXiv:2207.05573**

- The **Crab pulsar (PSR) and nebula (PWN)** are the only astrophysical system for which integrated and/or phase-resolved X-ray and optical polarisation has been reported by various instruments:

  OSO-8: Weisskopf et al. 1978

  Isaac Newton Telescope (La Palma): Smith et al 1988

  Nordic Optical Telescope: Słowikowska et al 2009

  INTEGRAL/IBIS: Forot et al. 2008

  HST: Moran et al. 2013

  INTEGRAL SPI: Chauvin et al. 2013

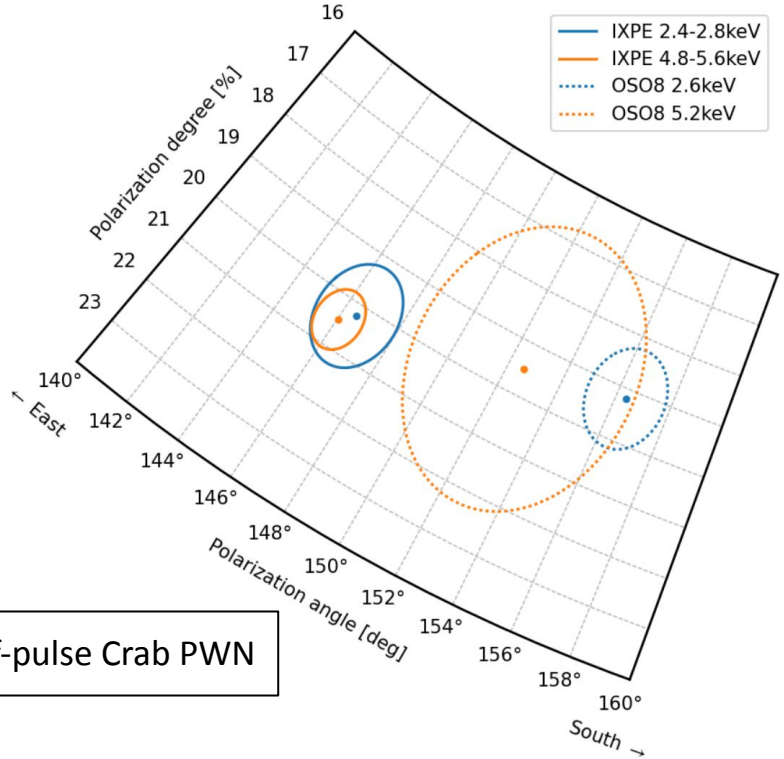
  PoGO+: Chauvin et al. 2017

  AstroSat CZT Imager: Vadawale et al. 2018

  PolarLight: Feng et al. 2020

  PolarLight: Long et al. 2021

  POLAR: Li et al. 2022



Off-pulse Crab PWN

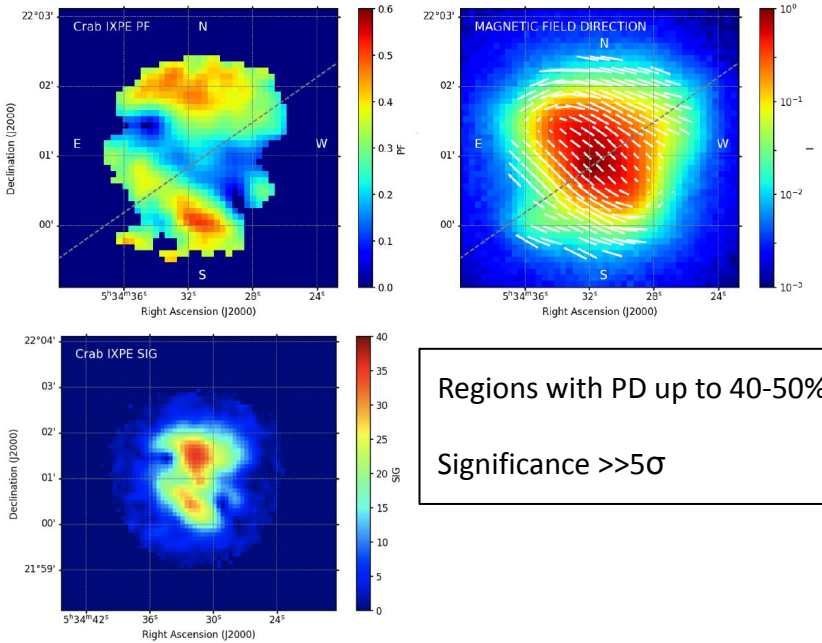
Magnetic field structure in extended sources: PWN

- **Crab PWN by Bucciantini et al. arXiv:2207.05573**
- **Vela PWN discovery paper by Xie et al. Submitted**

- **Crab PWN** magnetic field map (mg. field orthogonal to polarization) confirm the general expectation for PWNe, where the synchrotron emission takes place in the (mostly) toroidal magnetic field, originating from the pulsar wind and compressed in the nebula, which sets the symmetry axis of the jet-torus structure.

- **Vela PWN** integrated PD is (44.6±1.4)% and PA (from north through east) of -(50.0±0.9)◦

Crab PWN



Regions with PD up to 40-50%

Significance >>5σ

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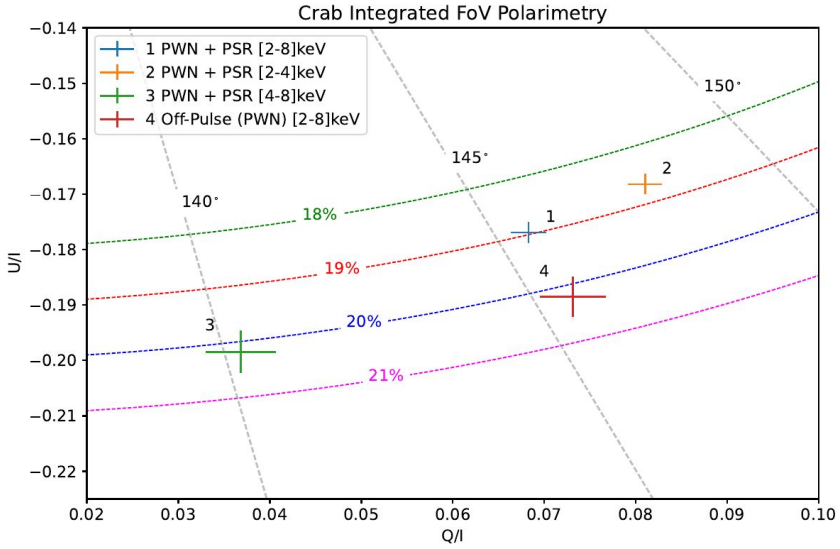
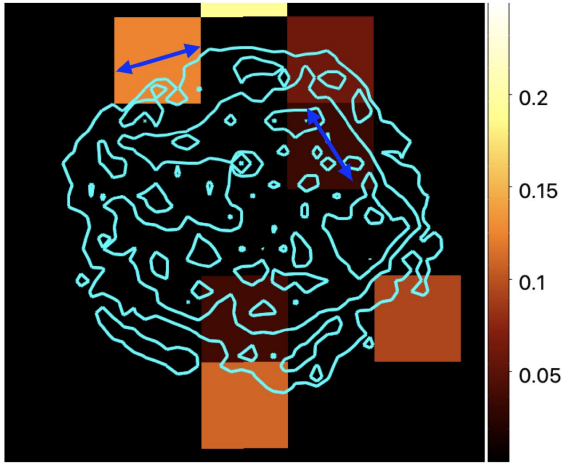
Crab PWN



Magnetic field structure in extended sources: Cas A

- **Cas A SNR by Vink et al. accepted (ApJ), arXiv:2206.06713**

- In Radio PD ~5%, PA tangencial (radially-oriented magnetic field… young SNR, ~350 yrs)
- In X-rays search for polarization in 3-6 keV energy band (Synchrotron dominated continuum wrt lines)
- Few single regions at ~ 3σ
  - turbulence on scales smaller than the angular resolution.



-Marginally significant polarization in small regions, false positive detection cannot be excluded

-Only regions with pre-trial confidence levels above 2σ are shown.

- Regions above 3σ PA indicated with blue arrows (errors ~ 8◦)

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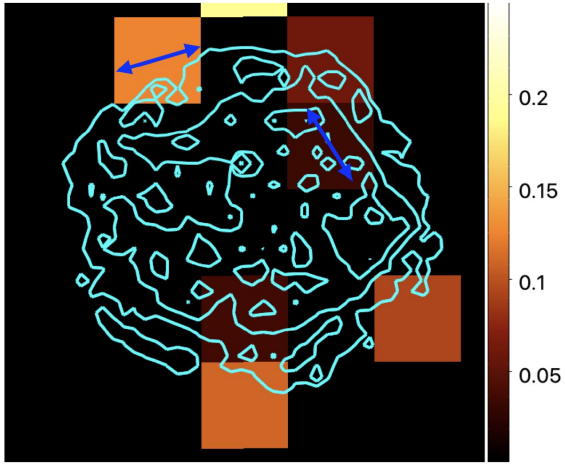
- In X-rays search for polarization in 3-6 keV energy band (Synchrotron dominated continuum wrt lines)
- Few single regions at ~ 3σ
  - turbulence on scales smaller than the angular resolution.
- By summing over a large region, assuming circular symmetry (angle rotation photon by photon), the overall PD = (1.8 ± 0.3)%



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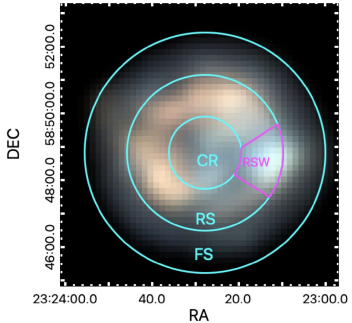

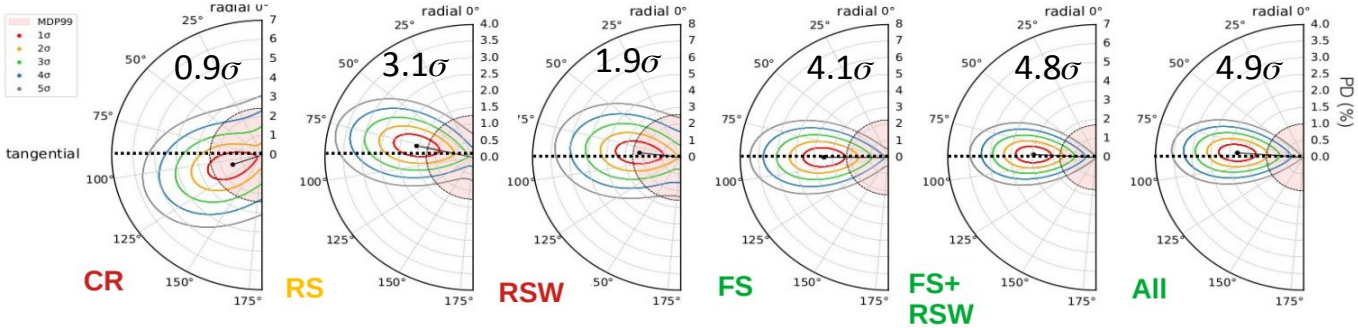

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What do we learn from SNRs vs PWNe ?

- Synchrotron radiation is intrinsically highly polarized at the ~ 70% level (Ginzburg & Syrovatskii 1965), with the PA related to magnetic field orientation (they are orthogonal) and PD related to magnetic field uniformity

- In Cas A there is a clear evidence of presence of turbulence (low PD, few %)
  (next to come Tycho and SN 1006, already observed)

- In PWNe there is a clear evidence of an almost negligible turbulence (high PD, tens %)
  (Crab PWN and Vela PWN)

- This has an impact on models for particle acceleration at VHE

Jet physics in AGNs: BL Lac objects

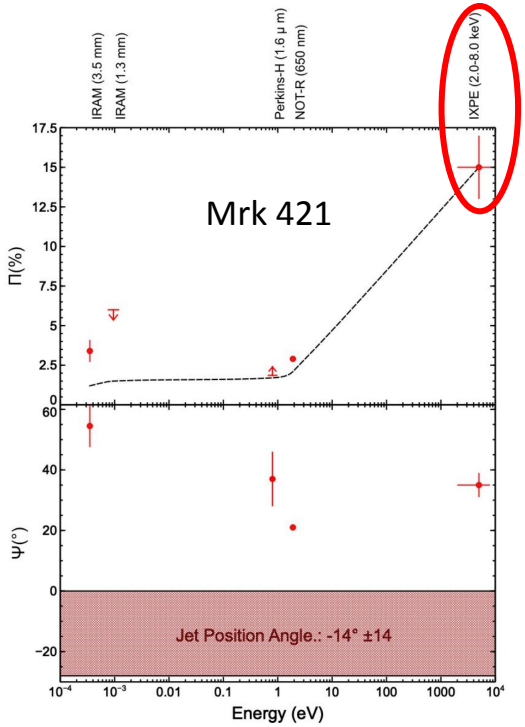
- **BL Lac objects**
  - **Mrk 421 by Di Gesu et al. accepted (ApJL), arXiv:2209.07184**
  - **Mrk 501 by Liodakis et al. accepted (Natur), arXiv:2209.06227**

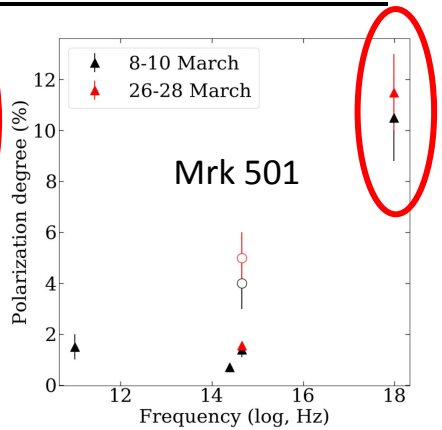
- Jet aligned towards our line of sight

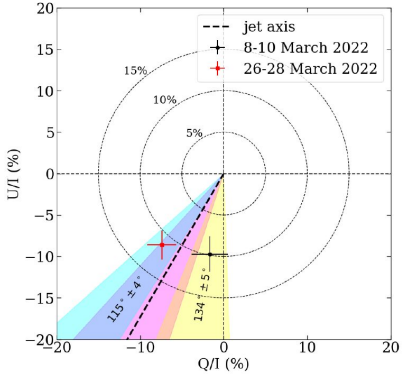
- The degree of polarization at optical, infrared, and millimeter wavelengths is lower

- The higher level of PD compared to longer wavelengths, and the absence of significant polarization variability, suggest a shock as the most likely X-ray emission site

- Energy-stratification model is favored. Particles are emitting in X-rays closer to the acceleration





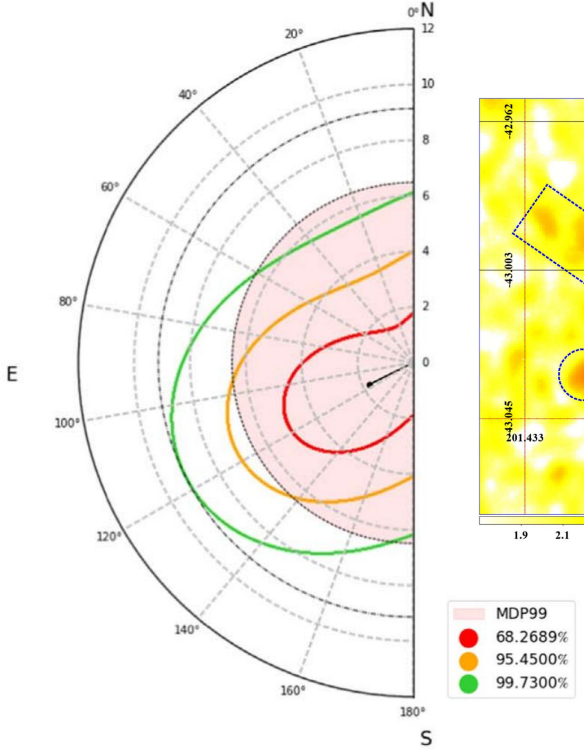


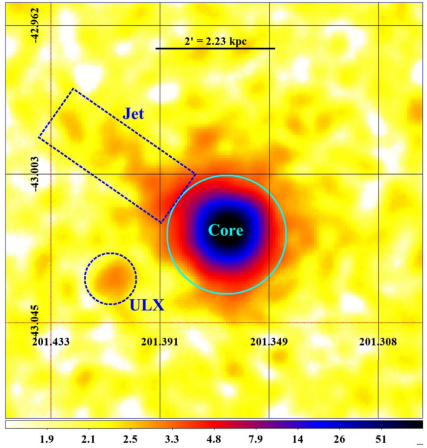
Jet physics in AGNs: Cen A Radio Galaxy

- **Cen A by Ehlert et al. 2022, ApJ 935:116**

- No statistically significant PD detected

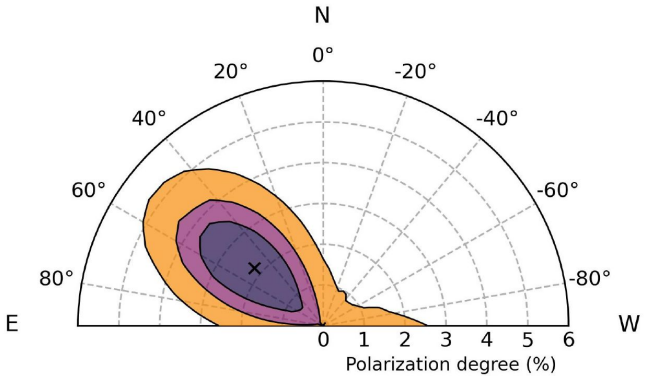
- Core Upper limit consistent with the predictions of Compton scattering:
  - The low PD and the relative lack of variability in the Fe Kα emission line support a picture where **electrons are accelerated in a region of highly disordered magnetic fields surrounding the innermost jet**

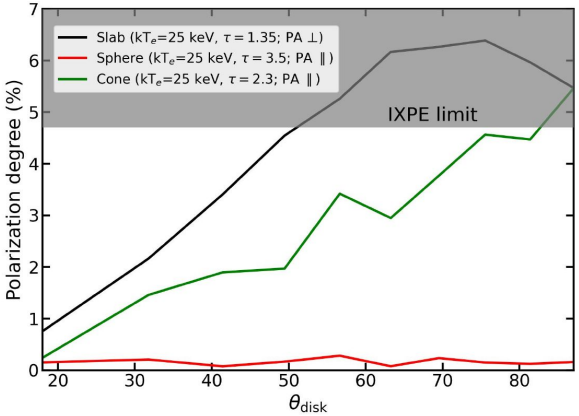




X-ray Corona in AGN: MCG-05-23-16 Seyfert Galaxy

- **MCG-05-23-16 by Marinucci et al. accepted (MNRASL), arXiv:2207.09338**
- PD < 4.7% (at the 99% c.l.)
- Polarized X-rays produced in radio quiet sources are thought to be produced by the inverse Compton mechanism, occurring within tens of gravitational radii from the central black hole. Different geometries of the scattering medium, depending on the degree of asymmetry, will result in a different degree of polarization
- **Monte Carlo simulations shows that**
  - a **lamp-post and a conical** geometry of the corona are consistent with the observed upper limit
  - a **slab** geometry is allowed only if the inclination angle of the system is less than 50°





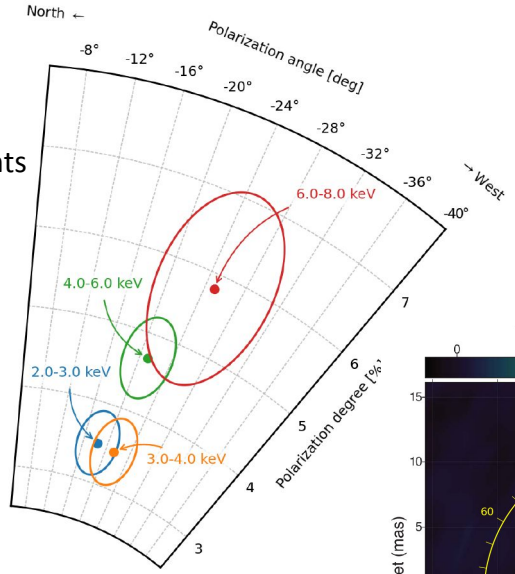
Disk - jet in BH binaries: Cyg X-1

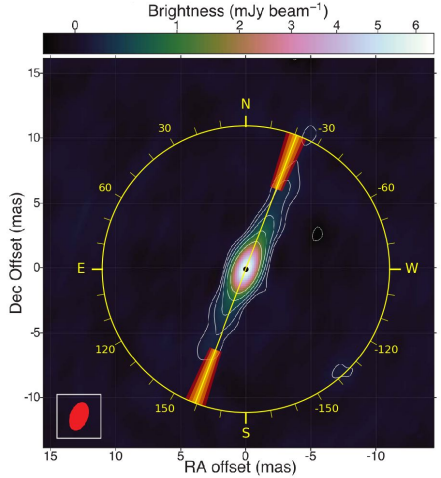
- **Cyg X-1 by Krawczynski et al. arXiv:2206.09972**

- Observed in the hard state:
  - polarization of Comptonized emission (flux ~90% of total) constraints properties of corona as well as the inner accretion disk
  - The reflection component (flux ~10% of total) is expected to be polarized as well
  - fluorescence line at 6.4 keV (flux <1% of total)

- PD = 4.0 ± 0.2% in 2-8 keV energy band
  - higher than expected (< 1%)
  - it implies a more edge-on viewing angle than inferred from the orbital parameters

- PA aligned with radio jet:
  - jet is launched from the inner X-ray emitting region
  - jet perpendicular to the disc





NS LMXBs accretion and geometry

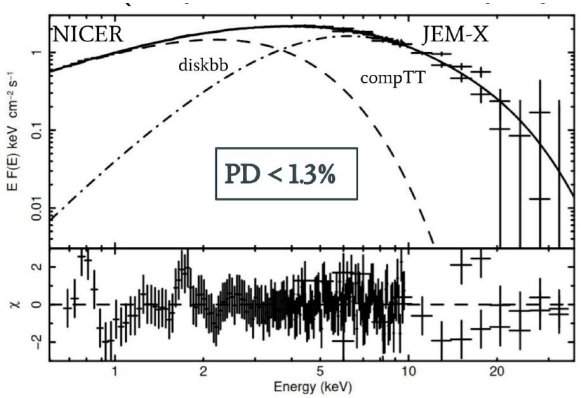
- **GS 1826-238 by Capitanio et al. submitted**
- **Cyg X-2 by Farinelli et al. submitted**

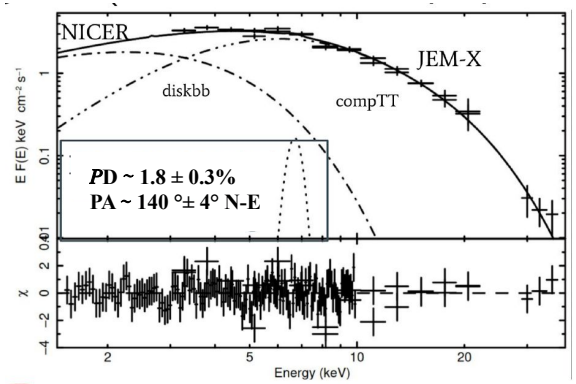
- Both observed in soft state

- Weakly magnetized NS-LMXB accrete via Roche-lobe overflow from a stellar companion, in a similar fashion as BH-LMXB

- GS 1826-238 upper limit on polarization degree implies a low disc inclination (almost face-on view)

- Cyg X-2 detection of polarization confirms the disc is viewed inclined
  - Results strongly favour a spreading layer at the neutron star surface as the main source of the polarization signal





A strongly magnetized Ultracompact LMXB

- **4U 1626-67 by Marshall et al. submitted**

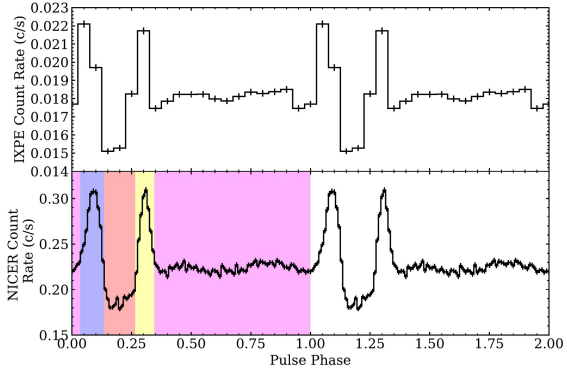
- NS around a very LM companion, 42 minutes orbital period
- The only UCXB hosting a persistent, strongly magnetized X-ray pulsar (B~(3-4) × 10^{12} G, cyclotron resonance scattering feature (CRSF) at ~37 keV)
- 7.66 s pulsations detected by IXPE

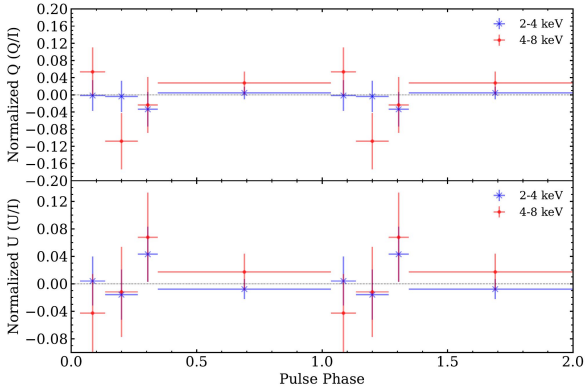
- Expected to be highly polarized due to high magnetic field

- Upper limit on the pulse-averaged linear polarization <4% (at 95% confidence)

- Marginal detection of polarization of the power-law spectral component at the 4.8±2.3% level (90% confidence)

- Posterior probability assessment suggest (with caution given the large uncertainties) a preference for larger values of θ (magnetic obliquity, the angle between the magnetic dipole axis and the spin axis)
- It suggests that a single-geometry picture is insufficient to characterize the accretion geometry around the pulsar



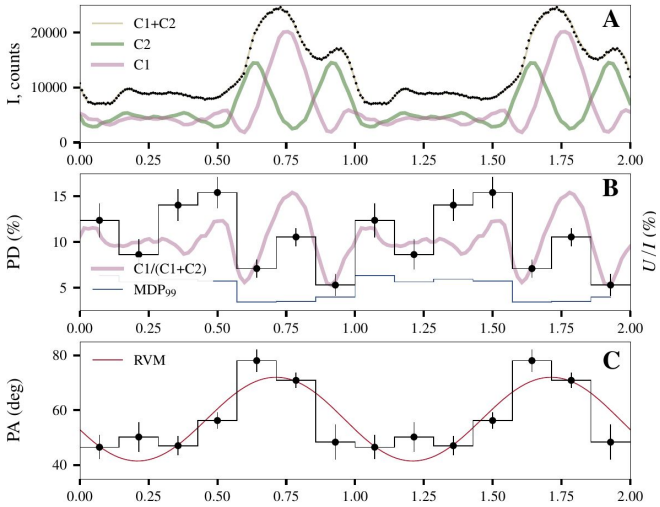


Phase resolved polarimetry with X-ray pulsars

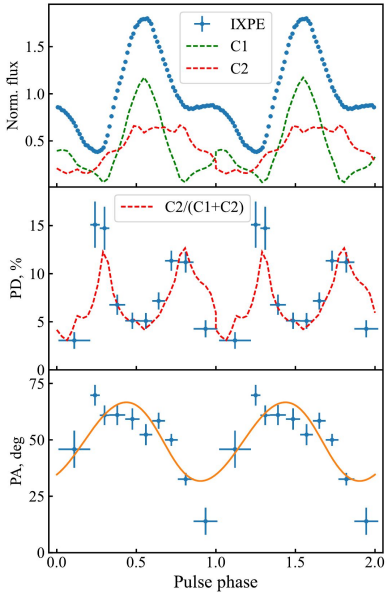
- **Her X-1 by Doroshenko et al. accepted (NaturAstro), arXiv:2206.07138**
- **Cen X-3 by Tsygankov et al. submitted, arXiv:2209.02447**

- **Her X-1, the first time phase resolved polarimetry in X-rays**
- PD and PA exhibit variability with pulse phase, which allowed to measure the pulsar spin position angle and magnetic obliquity of the neutron star
- **The most direct proof that Polarimetry can disenagle geometry from physics with a direct measurement of angles**
- High magnetic field, plasma birefringence
- PD far below the theoretical expectations (60%-80% in Caiazzo & Heyl, 2021 [MNRAS 501(2021)129])
- Low PD can be explained by the upper layers of NS atmosphere overheated by the accreted matter (Basko & Sunyaev 1975; Becker et al. 2012; Mushtukov et al. 2015, 2021).
- Another possible reason is mixing of emission from two magnetic poles seen at different angles

Her X-1
2-7 keV



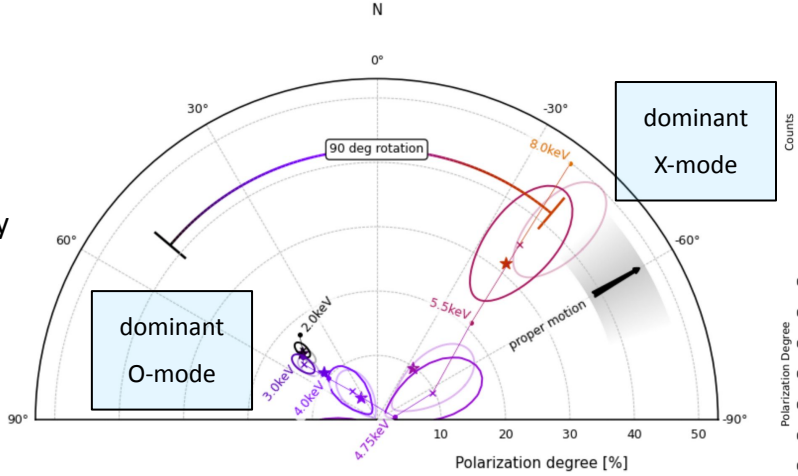
Cen X-3
2-8 keV



Strong magnetic field in magneters

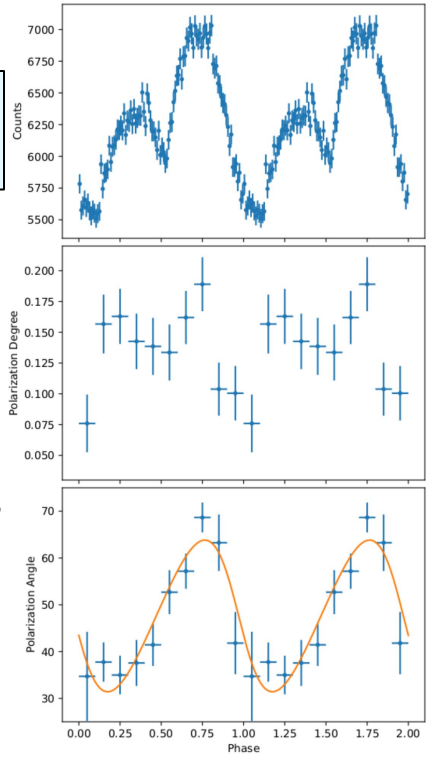
- **AXP 4U 0142+61 by Taverna et al. arXiv:2205.08898**

- Surface emission from highly magnetized NSs is expected to be linearly polarized into two normal modes: ordinary (O) and extraordinary (X), with polarization vector either **parallel** or **perpendicular** to the <u>plane of the photon direction</u> and the <u>(local) magnetic field.</u>
- Strong magnetic fields due to QED E makes the vacuum around the star birefringent
- The polarization vectors follow the magnetic field direction, thus observed polarization degree is close to the emitted one
- The energy dependent polarization behaviour provides evidence of the 90° swing between two polarization modes



- The energy dependent most favorable explanation (B ~ 10^{14} G) foresees radiation from an iron condensed surface from an equatorial belt resulting in predominant O-mode photons at low energies. Reprocessing by Resonant Compton Scattering then produces an excess of X-mode photons at higher energies (thus 90° angle rotation)

Phase resolved polarimetry

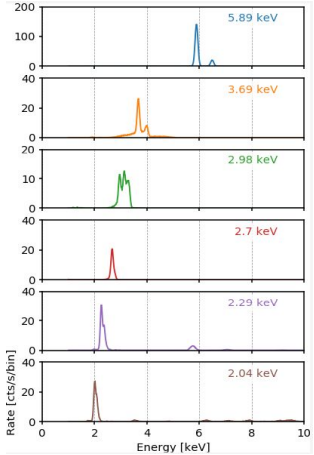


~~Conclusions~~ Summary and next to come…

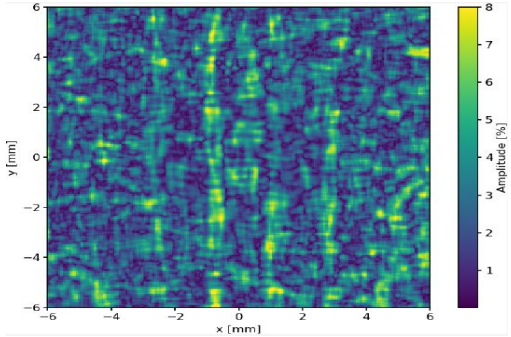
- IXPE definitely opened the polarization window in X-ray Astronomy
- Polarimetry directly explores magnetic field and geometry (breck of symmetry) of sources
- IXPE is bringing to us many confirms, unexpected results and it is opening to many new questions
- X-ray polarimetry is now fully included among observational techniques in Astrophysics

Instrument calibration with unpolarized radiation: spurious modulation

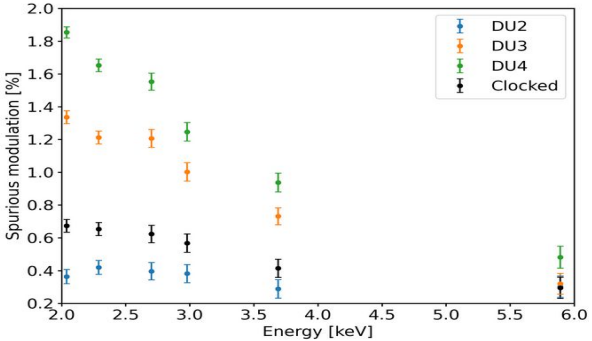
- **Unpolarized measurements at 6 energies:**
  - Commercial X-ray tubes or ^{55}Fe: direct or fluorescence
  - Use of filters to select the desired energy
- **Residual polarization (due to Bremsstrahlung continuum and X-ray tube geometry, diffraction on fluorescence target) removed by summing up two measurements rotated by 90° (residual polarization and Spurious Modulation sum differently for the two measurements)**
- **Spurious modulation removed by SOC pipeline thanks to calibration (Rankin et al. 2022)**

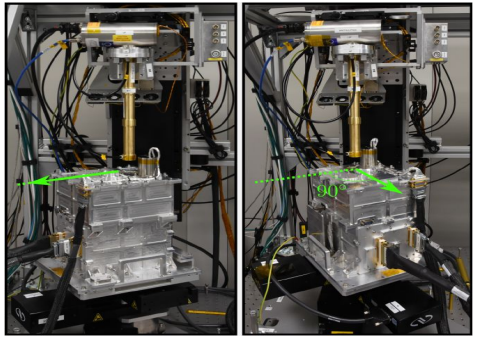


Map of SM @ 2.7 keV for DU-FM2



SM vs energy in a 3 mm diameter spot

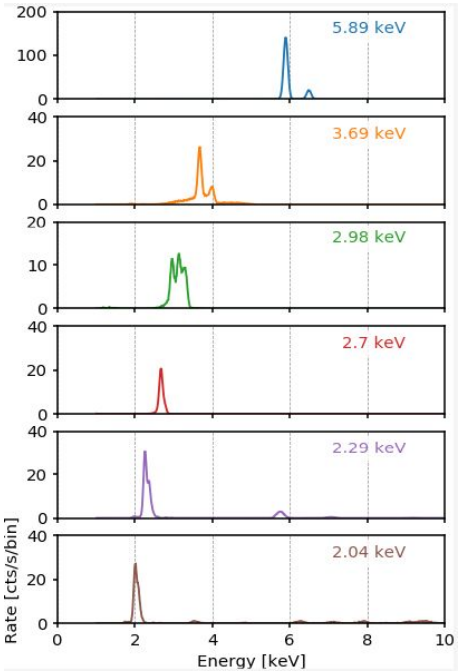




Instrument calibration with unpolarized radiation: spurious modulation

Table 2. Residual polarization of the ICE "Unpolarized" X-ray sources.

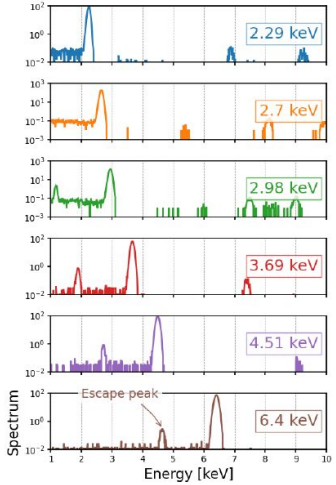
Nominal Energy (keV)	Source Set-Up	Measured Polarization (%)
2.04	Fluorescence of Zn target illuminated by Rh X-ray tube	1.02 ± 0.19
2.29	Fluorescence of Mo target illuminated by Ag X-ray tube	0.73 ± 0.12
2.70	Direct X-ray tube with Rh anode with a PVC filter	6.29 ± 0.10
2.98	Direct X-ray tube with Ag anode with an Ag filter	13.02 ± 0.09
3.69	Direct X-ray tube with Ca anode	Undetected MDP(99%)=0.23%
5.89	^{55}Fe nuclide, 4mCi	Undetected MDP(99%)=0.22%



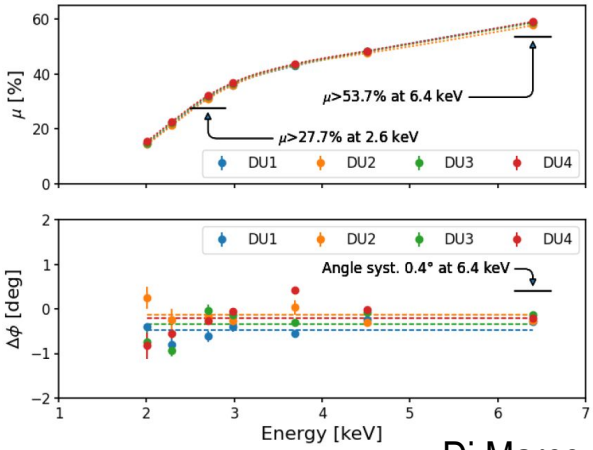
Fabiani et al. 2021, SPIE

Instrument calibration with polarized radiation: modulation factor

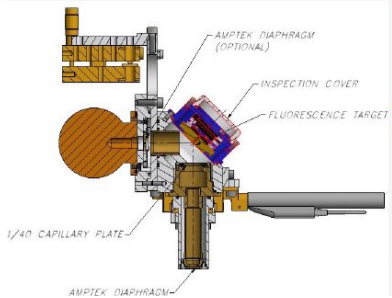
- **Commercial X-ray tubes coupled to custom designed monochromator-polarizers exploiting Bragg diffraction at nearly 45°**
  - Different crystals to diffract photons at different energies
  - Up to five polarization angles for each energy

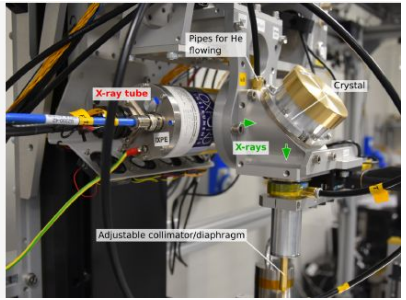


Modulation Factor vs Energy



Di Marco et al., 2022, AJ

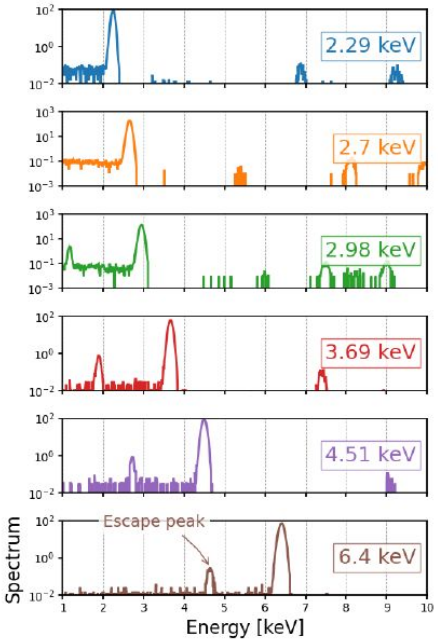




Instrument calibration with polarized radiation: modulation factor

Table 1. Set-ups and energies of the polarized sources available on the ICE. In black color the set-ups used for IXPE DU-FMs calibration.

Crystal	X-ray tube	Energy (keV)	2d	Diffraction angle (deg)	Rp/Rs	Polarization (%)
PET(002)	Continuum	2.01	8.742	45.000	0.0000	~ 100.0
ADP(200)	Mo Lα	2.29	7.500	46.209	0.0027	99.46
InSb(111)	Mo Lα	2.29	7.481	46.361	0.0034	99.32
Graphite(0002)	Continuum	2.61	6.708	45.000	0.0000	~ 1000.0
Ge(111)	Rh Lα	2.70	6.532	44.877	0.0024	99.53
Si(111)	Ag Lα	2.98	6.271	41.562	0.0252	95.08
Al(111)	Ca Kα	3.69	4.678	45.909	0.0031	99.38
CaF_2(220)	Ti Kα	4.51	3.840	45.716	0.0023	99.54
Si(220)	Ti Kα	4.51	3.840	45.716	0.0023	99.54
LiF(220)	Fe Kα	6.40	2.848	42.859	0.0529	~ 89.95
Si(400)	Fe Kα	6.40	2.716	45.511		~ 100.0



Fabiani et al. 2021, SPIE