Neutron stars in X-ray binaries as observed by the Imaging X-ray Polarimetry Explorer

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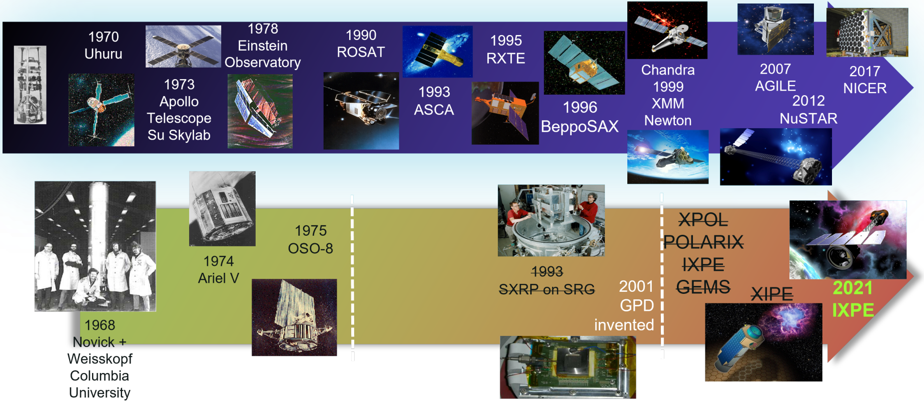
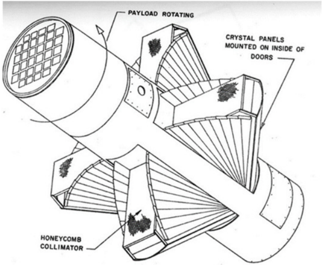
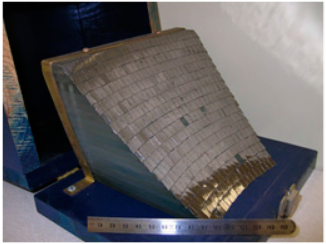
X-ray polarimetry...

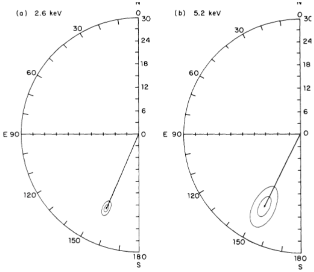
While X-ray astrophysics evolved... X-ray polarimetry took longer time to evolve



From Weisskopf, Galaxies 2018, 6, 33







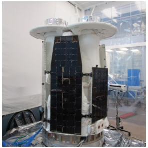
- Polarization detected for the Crab [Weisskopf+ ApJL 220 (1978) 117]
- Sco X-1 $PD < 2.7\%$ at 2.6 keV
- Upper limits for Cyg X-2, Cyg X-1, Cen X-3 and Her X-1

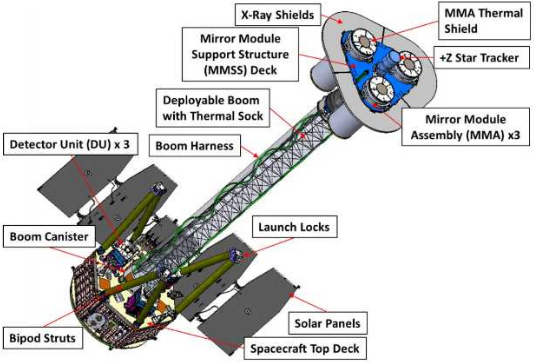
Imaging X-ray Polarimetry Explorer (IXPE)

- NASA-ASI SMall EXplorer mission dedicated to (linear) X-ray imaging polarimetry

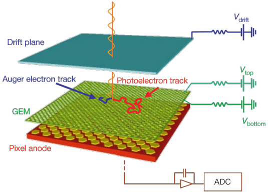
IXPE launch on
9 December 2021

Stowed Configuration





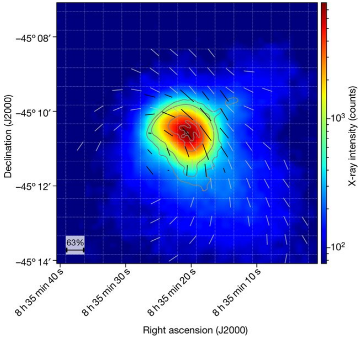
- Energy range: 2–8 keV
- 3 identical telescopes
  - ➥ Grazing-incidence X-ray mirrors (3+1 spare)
  - ➥ Imaging X-ray photoelectric polarimeters based on Gas Pixel Detector design (3+1 spare)
  - ➥ The two are separated by an extensible boom



[Weisskopf+ JATIS, 8 (2), 2022]

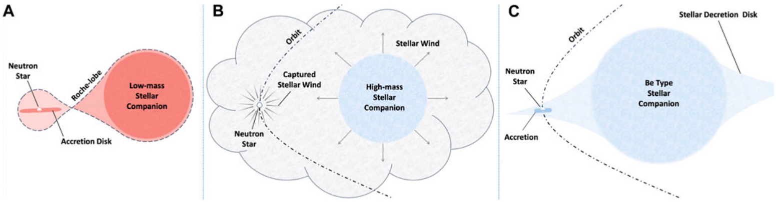
Where polarization come from?

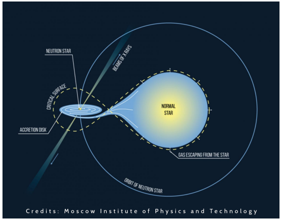
- Polarization is a vector
  - ➥ measures geometry Electric vector position angle (EVPA)
- Synchrotron radiation gives EVPA perpendicular to magnetic field lines and $PD = (p+1)/(p+7/3)$ up to 70%
- Scattering gives EVPA perpendicular or parallel to scattering plane and PD$\sim$ few percent
- Reflection gives EVPA perpendicular to scattering plane and PD up to 20–30%
- Strong magnetic fields gives EVPA transported along magnetic field orientation
- Strong gravitational fields gives EVPA parallel-transported along space-time geodesics



Xie+, Nature 612 (2022) 658

Accreting NS in X-ray binaries





[R. M. Ludlam et al., FASS 10, 1292500, 2023]

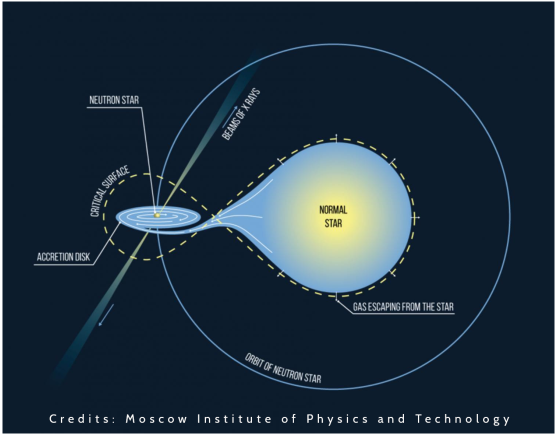
A) LMXB system where the NS accretes from a stellar companion via Roche-lobe overflow forming a disk

B) NS in a HMXB that accretes from material captured from stellar winds that are launched from the companion

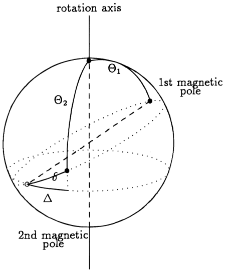
C) NS accreting from the decretion disk of a Be-type stellar companion

D) NS accreting matter from a High Mass Stellar companion via funneling

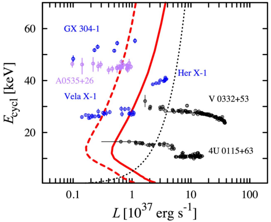
Classic X-ray pulsars



- Luminosity $\sim 10^{37}$ erg/s
- Pulsation periods 1–1000 s
- Accretion flow ($\dot{M} \sim 10^{17}$g/s) driven by magnetic field
- Accretion in the polar caps, disk disruption by magnetic field



Kraus et al., ApJ 467, 794, 1996



Mushtukov et al., MNRAS 447, 1847, 2015

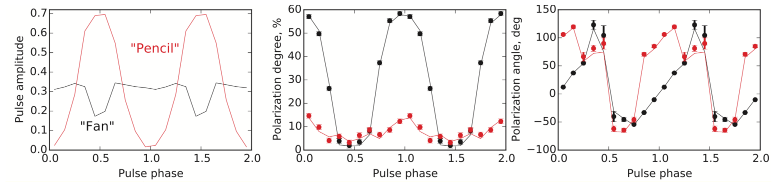
- Several efforts for pulse profile decomposition
  - ➥ Based on assumption that observed asymmetry of pulse profiles is due superposition of two symmetric components displaced wrt each other

- Cyclotron lines can allow to measure B

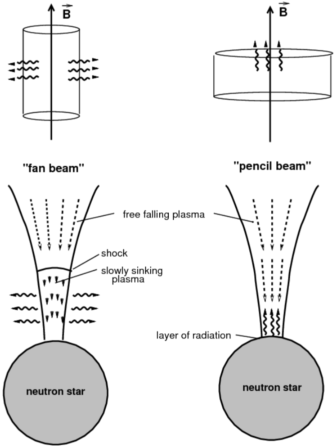
$$E_{cyc} \sim \frac{n}{1+z} 11.6\ [\text{keV}] B\ [10^{12}\ \text{G}]$$

  - ➥ E_{cyc} dependence on luminosity used to distinguish the pencil/fan beam regimes

What polarimetry can do?

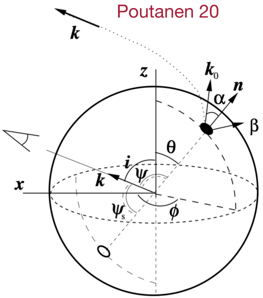


Meszaros et al. ApJ 324, 1056, 1988



- Cyclotron lines (birefringence) + pulsations = polarization in X-rays
- Early models assume homogeneous slab/column predicting ∼10–100% polarization degree
- Detailed models do not exist yet
  - ➥ QED effects both within atmosphere and magnetosphere are important
- An attempt for a detailed model before IXPE launch [Caiazzo, Heyl, MNRAS 501, 129, 2021] predicted PD> 50%

What polarimetry can do?



- Pulsar geometry can be costrained by modeling polarization variations with spin-phase
- Naively PA is expected to be aligned with magnetic field
  - ➥ expect PA of a rotating dipole to follow RVM model [Radhakrishnan & Cooke AL, 3, 225, 1969]
  - ➥ PA alignment due to vacuum polarization expected to result in similar behaviour
  - ➥ PA is less sensitive to details of radiative transfer close to the surface

- PA dependence allows to constrain geometry with the rotating vector model (RVM)

$$\tan(PA - \chi_p) = \frac{-sin\theta \sin(\phi - \phi_0)}{\sin i_p \cos\theta - \cos i_p \sin\theta \cos(\phi - \phi_0)}$$

Observed targets by IXPE

- **X-Ray Pulsars**:
  - **Cen X-3** *S. Tsygankov et al., ApJL 941, L14, 2022*
  - **Her X-1** *V. Doroshenko, et al., Nature Astronomy 6, 1433, 2022*
  - **4U 1626–67** *H. Marshall, et al., ApJ 940, 70, 2022*
  - **Vela X-1** *S. Forsblom, et al., ApJL 947, L20, 2023*
  - **GX 301-2** *V. Suleimanov, et al., A&A 678, A119, 2023*
  - **X Persei** *A. Mushtukov, et al., MNRAS 524, 2004, 2023*
  - **GRO J1008–57** *S. Tsygankov, et al., A&A 675, A48, 2023*
  - **EXO 2030+375** *C. Malacaria, et al., A&A 675, A29, 2023*
  - **LS V +44 17** *V. Doroshenko, et al., A&A 677, A57, 2023*
  - **Her X-1** *J. Heyl, et al., Nature Astronomy 8, 1047, 2024*
  - **SMC X-1** *S. Forsblom et al., A&A, 691, A216 2024*
  - **Swift J0243.6+6124** *J. Poutanen et al., A&A, 691, 123, 2024*
  - **PSR B1259–63** *P. Kaaret et al., ApJL, 974, 1, 2024*
  - **4U 1538-52** *V. Loktev et al., A&A, 698, 22, 2025*
  - **4U 1907+09** *M. Zhou et al., A&A, 700, 283, 2025*
  - **4U 1700-377** *N. Kaito et al., PASJ, 77, 49, 2025*
  - **H 1417-624***M. Zhou et al., arXiv:2508.16417*
- Before IXPE no significant detection of polarization available

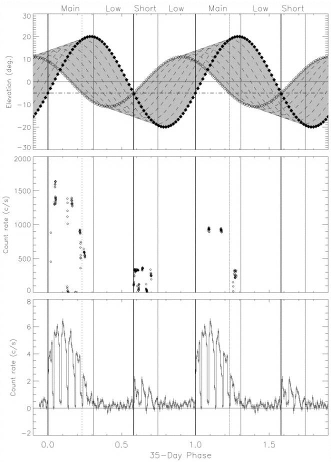
Hercules X-1

V. Doroshenko, et al., Nature Astronomy 6, 1433, 2022

- Her X-1 is the second X-ray pulsar ever discovered
  - spin period of $\sim 1.24\,\mathrm{s}$
  - intermediate mass X-ray binary at a distance of $\sim 7\,\mathrm{kpc}$ with nearly circular orbit
  - $P_{orb} \sim 1.7$ d
  - having a surprisingly stable $\sim 35\,\mathrm{d}$ super-orbital variability

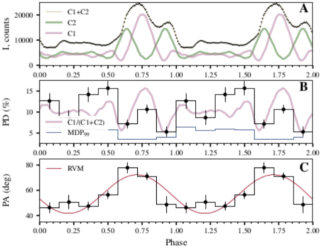
- IXPE observed Her X-1 on 2022 February 17–24
  - at the beginning of the 35 d precession cycle
  - in the so-called "main-on" state,

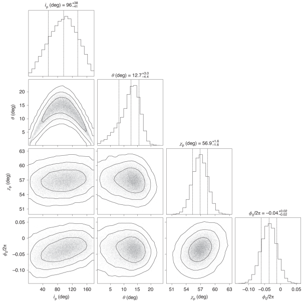
- **IXPE obtained the first highly significant detection of polarization signal from Her X-1:**
  - $\mathrm{PD} = (8.6 \pm 0.5)\%$
  - $\mathrm{PA} = (62 \pm 2)^\circ$ (measured from north to east)



[D. M. Scott, et al., ApJ, 539, 392, 2000]

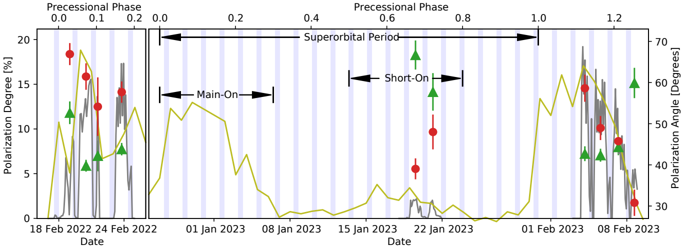
- **IXPE detected for the first time polarization resolved in phase**
  - PD approach $\sim 15\%$ with phase dependence rather complex
  - PA shows simpler, roughly sinusoidal dependence
- **PA dependence allows to costrain geometry with the rotating vector model (RVM):**
  - magnetic obliquity (i.e. co-latitude of the magnetic pole): $\theta = (12.7^{3.0}_{-4.4})^{\circ}$
  - inclination $i_p = (96^{+38}_{-41})^{\circ}$
  - position angle $\chi_p = (56.9 \pm 1.6)^{\circ}$
  - phase $\phi_0 = -2\pi(0.04 \pm 0.02)$
- **PD significantly lower than the predicted 60–80% [Caiazzo & Heyl, MNRAS 501(2021)129]**

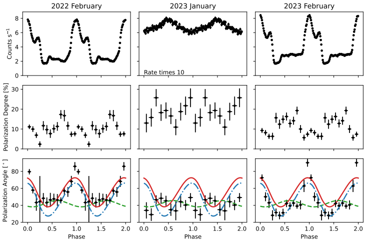




Her X-1: observations along the superorbital period

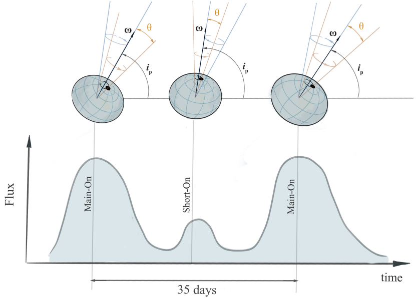
J. Heyl, et al., Nature Astronomy 8, 1047, 2024





- IXPE observed Her X-1 along the superorbital period aiming to test precession models
  - First main-on: 2022 February 17–24
  - Short-on: 2023 January 18–21
  - Second main-on: 2023 February 3–8
- **RVM analysis shows a variation in geometry along the different pointings**

	Mean PD [%]	$\chi_{\rm p}$ [deg]	θ [deg]	$i_{\rm p}$ [deg]	$\phi_0/2\pi$	Prec. Phase
First Main-On	9.5 ± 0.5	55.4 ± 1.6	$14.5^{+3.0}_{-4.0}$	58^{+28}_{-22}	$0.19^{+0.03}_{-0.02}$	0.088
Early	8.6 ± 0.6	57.9 ± 2.1	$16.3^{+3.5}_{-4.1}$	64^{+25}_{-22}	$0.19^{+0.03}_{-0.02}$	0.073
Late	9.3 ± 0.7	52.2 ± 2.7	$15.9^{+3.6}_{-4.0}$	85^{+35}_{-37}	$0.22^{+0.05}_{-0.05}$	0.162
Short-On	17.8 ± 1.4	41.9 ± 2.2	$3.7^{+2.6}_{-1.9}$	90^{+30}_{-30}	$0.85^{+0.18}_{-0.20}$	0.687
Second Main-On	9.1 ± 0.5	46.8 ± 1.5	$16.0^{+3.1}_{-4.3}$	56^{+24}_{-20}	$0.20^{+0.02}_{-0.02}$	0.159



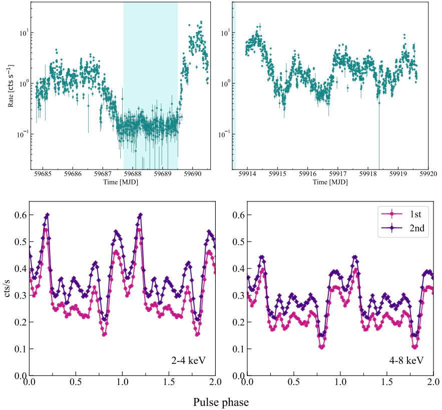
- **geometry variation compatible with precession**
  - ➥ uncertainty on the inclination is very large
  - ➥ for the same superorbital phase the geometrical parameters are well in agreement

- Polarization degree always much smaller than expectations

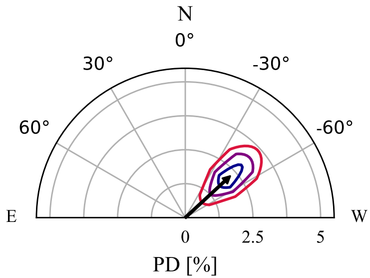
Vela X-1

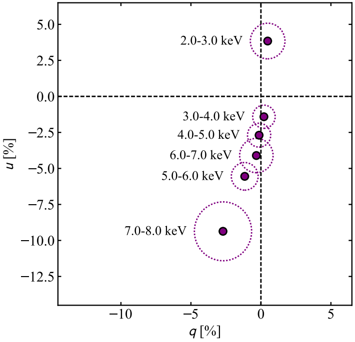
S. V. Forsblum et al., ApJL 947, L20, 2023

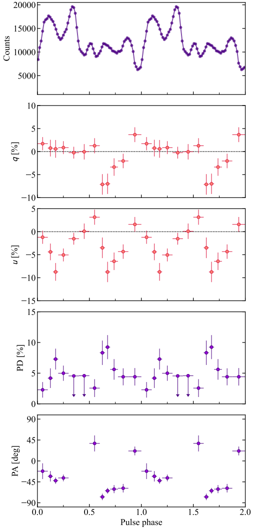
- Vela X-1 is one of the bright persistent XRPs and one of first the HMXB discovered
- Vela X-1 is a bright eclipsing source, displaying strong X-ray pulsations
  - ➥ spin period 283 s
  - ➥ orbital period 8.964 d
- **IXPE observed Vela X-1 in the period April 15 –22 and November 30 – December 6, 2022**
  - ➥ eclipse period removed from the analysis



Vela X-1: energy resolved polarization



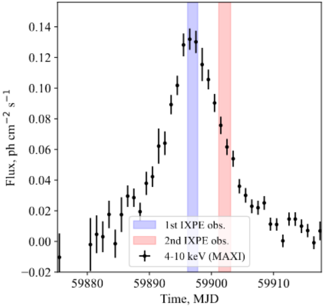


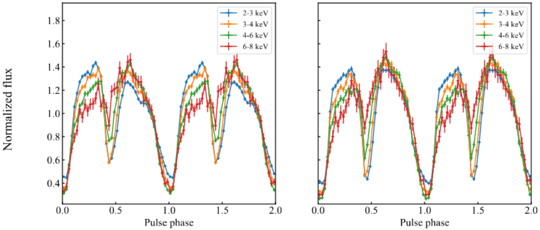


- IXPE detected PD and PA at $> 4\sigma$CL.
  - ➥ PD $= (2.3 \pm 0.4)\%$
  - ➥ PA $= -(47.3 \pm 5.4)^\circ$
- Evidence for polarization variation with energy
- Evidence for polarization variation with phase

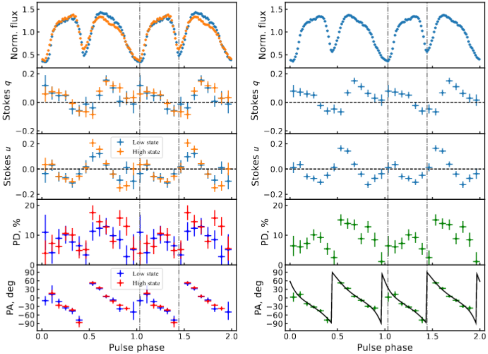
S. Tsygankov et al., A&A 675, A48, 2023

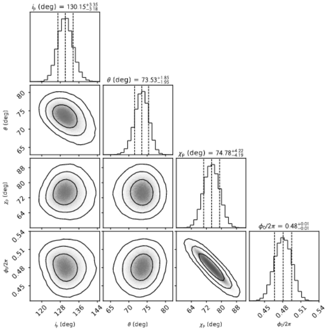
- GRO J1008–57 is one of the most predictable and best-studied Be/XRPs
  - discovered in '93 by the BATSE instrument on board the Compton Gamma-Ray Observatory as a transient XRP
  - $P_{\mathrm{spin}} = 93.587(5)$ s
- showing giant Type II and Type I (associated with the periastron passage) outbursts, related to the Be type of the optical companion (B1-B2 Ve star)
  - $P_{orb} \sim 249.48(4)$ d
- IXPE observations:
  - 2022 Nov 13–14 and Nov 18–20





GRO J1008–57: Polarization spin-phase resolved

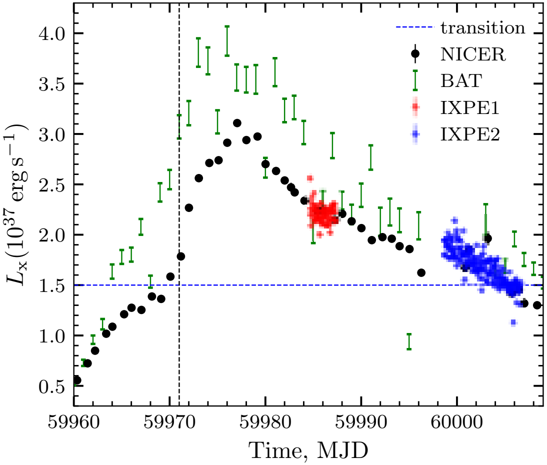




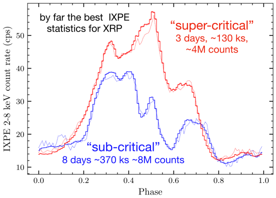
- GRO J1008–57: average polarization at 3.9±0.5%
- phase resolved polarization allows to obtain information on its geometry
  - ➥ Magnetic obliquity $\theta \simeq 73.5^\circ$ **almost orthogonal rotator, different from Her X-1 and Cen X-3**
  - ➥ Pulsar rotation axis position angle $\chi \simeq 75^\circ$
  - ➥ $i_P \sim 130^\circ$

LS V +44 17/RX J0440.9+4431

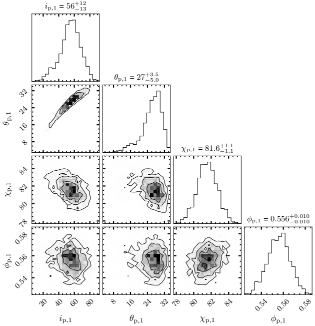
V. Doroshenko, et al., A&A 677, A57, 2023

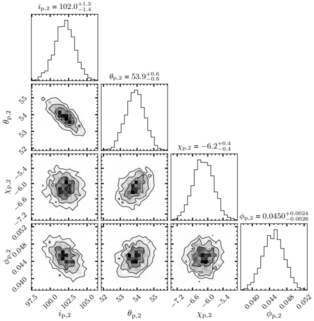


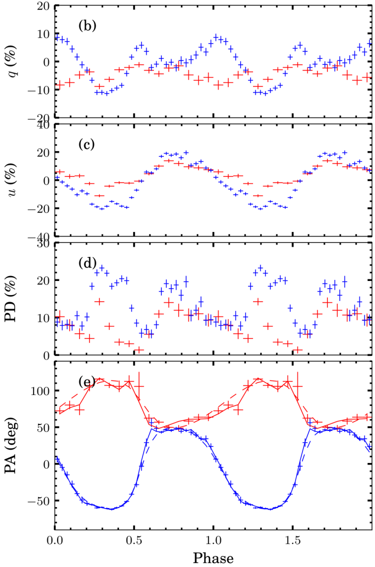
- LS V +44 17/RX J0440.9+4431 is a BeXRB
  - discovered in 1997 by ROSAT
  - pulsations period ∼206 s
  - orbital period ∼ 150 d
  - system in which accretion continues during quiescence (L∼ 10^{34} erg/s) likely powered by a cold, non-ionized disk or wind.
- Active for the first time since 2010-11
- Giant (Type II) outburst in Jan 2023 L∼ 4×10^{37} erg/s
- IXPE observed the source in two pointings of 130 ks and 373 ks



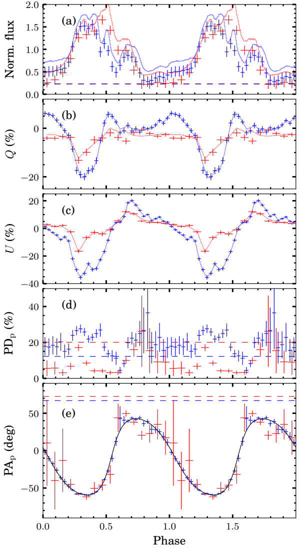
- **Geometry is dramatically different between the two pointings**







LS V +44 17: geometry variation?

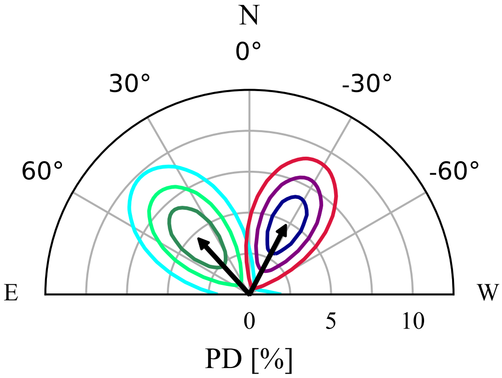


- **RVM reveals no significant variability of angles within either observation**
  - Variation only between first and second pointing
- **90° change in χ can be due to the change of dominant polarization mode O/X upon super-sub critical transition but what about other angles?**
- RVM - QED angles defined by dipole field component is not working fine?
- crazy precession or complete re-arrangement of the magnetic field or emission region?

- Alternative idea:
  - Polarization having a constant component + a pulsed component following RVM model
  - 10–40% of flux due to this component? where comes from?

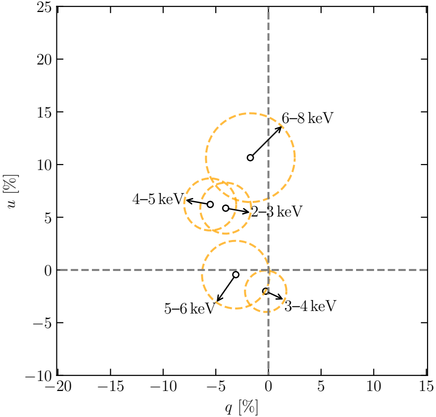
4U 1538-52

V. Loktev et al., A&A, 698, 22, 2025



4U 1907+09

M. Zhou et al., A&A, 700, 283, 2025

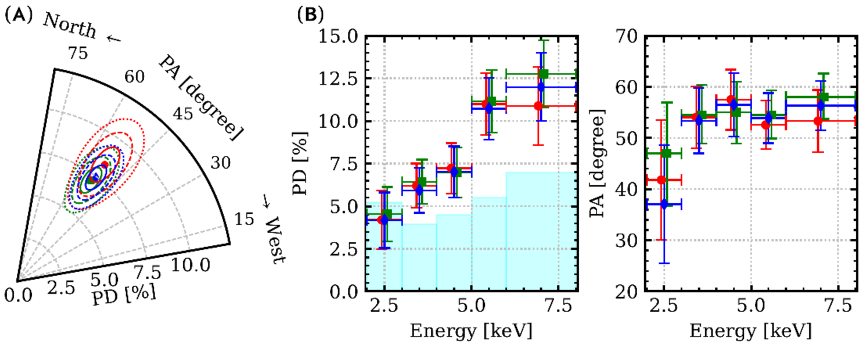


2-3 keV (blue) vs 4-8 keV (red)

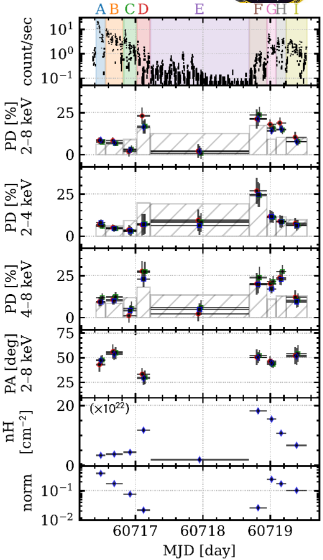
Both showing energy dependance and needing for multi-component RVM

4U 1700–377 polarization Pre- and Post-Eclipse I

- 4U 1700–377 is a wind-fed HMXB
  - ➥ orbital period 3.4 days with an eclipse duration of ∼1.1 days
  - ➥ mass accretion $\dot{M} \sim 10^{-5} \mathrm{M}_{\odot} \mathrm{yr}^{-1}$
- Wind-fed HMXBs in eclipses expected to be polarized at ∼20% [Kallman+ ApJ 815 (2015) 53]



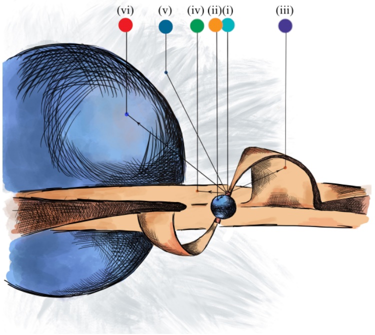
4U 1700–377 polarization Pre- and Post-Eclipse II



- PD is energy dependent
- PD varies with time and increases just before and after the eclipse

- Scattering in the wind?
- Partial obscuration?
- Reflection on the companion and/or its wind?

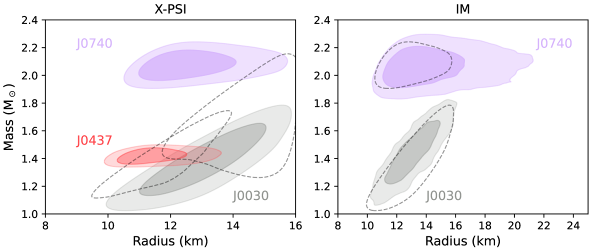
- XRP show a measured PD below the theoretical expectations
- IXPE polarimetric observations provide previously unavailable information on these sources:
  - first phase resolved polarization properties
  - first direct costrain on their geometry
- A full interpretation of the observed polarization and a full assessment on the possible scenarios requires a deeper understanding of the accretion physics and the emission mechanisms in these objects
  - **Intrinsic polarization from the hotspot**
  - **Reflection from the NS surface**
  - **Reflection from the accretion curtain**
  - **Reflection from the accretion disk**
  - **Scattering by the stellar wind**
  - **Reflection by the optical companion**



Millisecond pulsars

Polarimetry of millisecond pulsars I

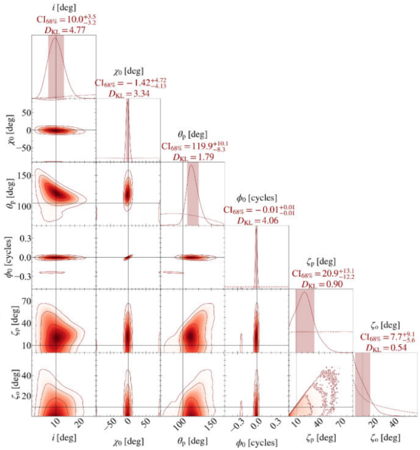
- Simultaneous measurement of the mass M and the equatorial radius R_{eq} of NSs
  - ➥ paramount importance for constraining their equation of state
- Modeling the X-ray pulse profiles of MSPs depends on several geometrical and spectral parameters **[See Lecture by A. Papitto]**
- Rotational millisecond pulsars require Ms of NICER exposure time to achieve constrain



Chatziioannou et al., arXiv:2407.11153v1

Polarimetry of millisecond pulsars II

- Accreting millisecond pulsars (AMSPs) intriguing alternative given their **higher luminosity** with respect to rotating MSPs
- X-ray polarimetry might provide key information on geometrical parameters of the spots
- Soft photons from the NS surface are up-scattered by hot electrons in the accretion shock achieving PD from a few per cent up to 10–20%
- Several theoretical models and code to study polarization in AMSP were proposed/developed (Poutanen A&A 641, A166 (2020), Salmi et al., A&A 646, A23 (2021)2021, Di Marco et al., Proceedings IAU Symposium No. 363, 2023, Bovrikova et al., A&A 678, A99 (2023))



X-PSI now includes X-ray polarimetry [Salmi+, MNRAS 538 (2025) 2562]

Accepting millisecond pulsar

- **SRGA J144459.2–604207** *A. Papitto et al., A&A, 694, 37, 2025*
- **SAXJ1808.4–3658**

Transitional millisecond pulsar

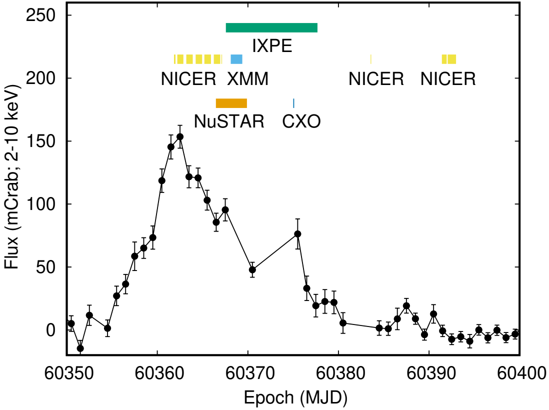
- **PSR J1023+0038** *M. C. Baglio et al., ApJL 987, 19, 2025*

Spider pulsar

- **PSR J1723–2837** *M. Negro et al., arXiv:2509.05240*

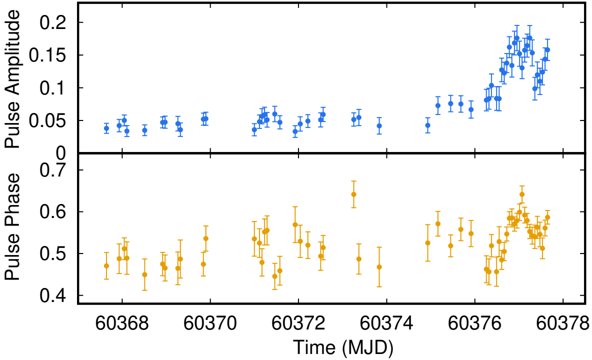
A. Papitto et al., A&A, 694, 37, 2025

- Discovered in outburst on 2024 February 21 (ATel #16464) by *Mikhail Pavlinsky* ART-XC [Molkov arXiv:2404.19709]
  - relatively bright: 4–12 keV X-ray flux of $2 \times 10^{-9}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$
  - pulsations at 447.9 Hz, orbital period a 5.2 h [Ng et al., ApJL 2024 968 L7]
  - shows type-I X-ray bursts quite regularly (ATel #16475) with a recurrence time increasing from 1.6 to 2.2 h as the X-ray flux decreases
- First AMSP observed by IXPE in the context of a campaign which included also NICER, *XMM-Newton* and *NuSTAR*

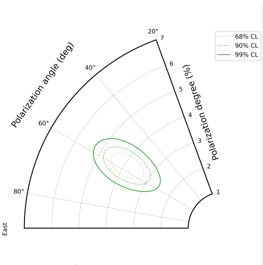


SRGA J144459.2-604207: X-ray pulse timing

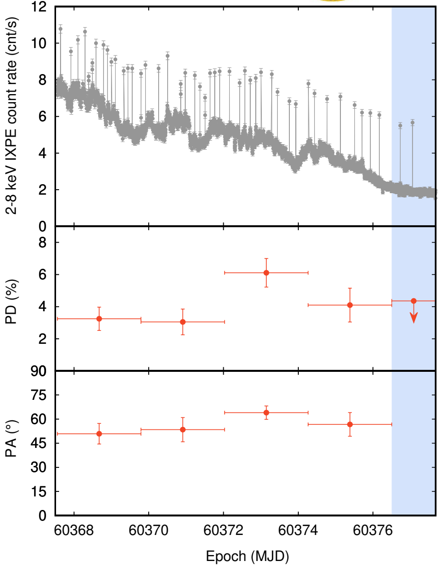
	IXPE
Interval (MJD)	60367.615–60377.619
$\phi(T_0)$	0.37(1)
$\nu(T_0)$ (Hz)	447.87156138(8)
$\dot{\nu}$ (Hz s^{-1})	$< 3.0 \times 10^{-13}$
$a_1 \sin i/c$ (lt-s)	0.650486(13)
$P_{\rm orb}$ (s)	18803.665(4)
$T_{\rm asc}$ (MJD)	60361.641310(5)
e	$< 1.0 \times 10^{-4}$
χ^2 (d.o.f.)	121.3 (53)



- Starting by NICER ephemeris solution [Ng et al., ApJL 2024 968 L7] new ephemeris from IXPE data were obtained
- An increase of pulse amplitude is observed from 4% to 15% after MJD 60736.5

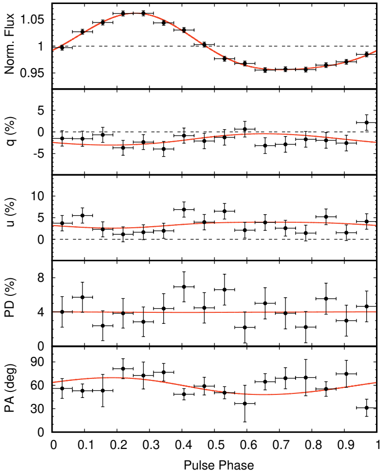


- Burst are removed from the data
- 2–8 keV average polarization (significance $\sim 5.3\sigma$):
  - $\mathrm{PD} = 2.3\% \pm 0.4\%$ and $\mathrm{PA} = 59^\circ \pm 6^\circ$
- Between 2 and 3 keV and above 6 keV, no significant detection of PD
- In the 3–6 keV energy range PD is highly detetcted:
  - $\mathrm{PD}_{3-6} = 4.0\% \pm 0.5\%$ and $\mathrm{PA}_{3-6} = 57^\circ \pm 3^\circ$
- No significant variations with time observed



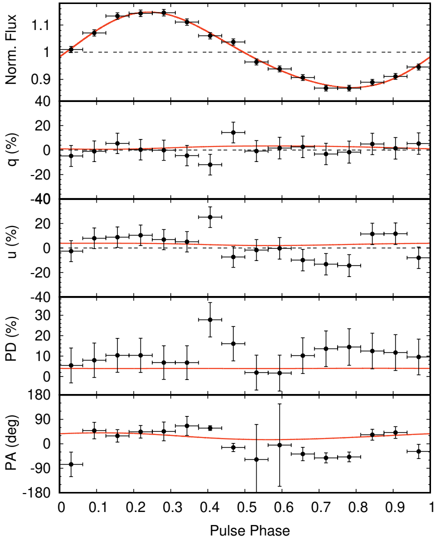
Phase-resolved polarimetry before MJD 60376.5

- Phase-resolved analysis in $n = 16$ phase bins in the 3–6 keV energy band
- Stokes parameters Q and U did not show significant variability, a fit with a constant function gave on 15 d.o.f.:
  - ➥ $q = Q/I = -1.6\% \pm 0.5\%$ ($\chi^2 = 16.6$)
  - ➥ $u = U/I = 3.5\% \pm 0.4\%$ ($\chi^2 = 15.6$)
- h set to -0.3 but reasonably good fit achievable for any value of h between 0 and -1
- Best-fit: $i = (74.1^{+5.8}_{-6.3})^\circ$, $\theta_1 = (11.8^{+2.5}_{-3.5})^\circ$, $\theta_2 = (172.6^{+2.0}_{-1.0})^\circ$, $\phi_0 = 0.57(4)$, $N = 6.90(6) \times 10^4$ cnt, $p_1 = 4.0\% \pm 2.0\%$, $\chi_\mathrm{p} = 57.2^\circ \pm 0.5^\circ$



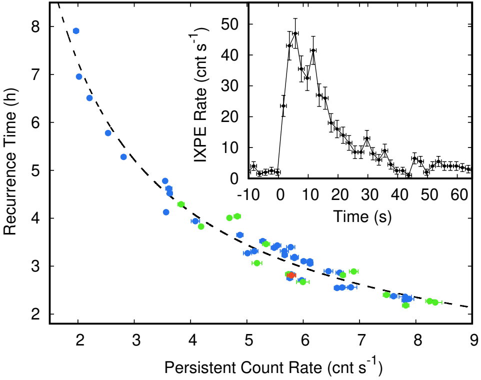
Phase-resolved polarimetry after MJD 60376.5

- Phase-resolved analysis in $n = 16$ phase bins in the 3–6 keV energy band
- **Stokes parameters** Q **and** U **did not show significant variability**, a fit with a constant function gave on 15 d.o.f.:
  - ➥ $q = Q/I = 0.5\% \pm 1.4\%$ ($\chi^2 = 10.2$)
  - ➥ $u = U/I = 2.4\% \pm 2.7\%$ ($\chi^2 = 18.7$)
- The increase of the pulsed fraction (MJD 60376.5) to $A_1 = 18.7\% \pm 0.8\%$ can be qualitatively explained:
  - ➥ magnetic inclination of the two spots varies by $\delta\theta_1 \simeq -\delta\theta_2 \simeq 10^\circ$

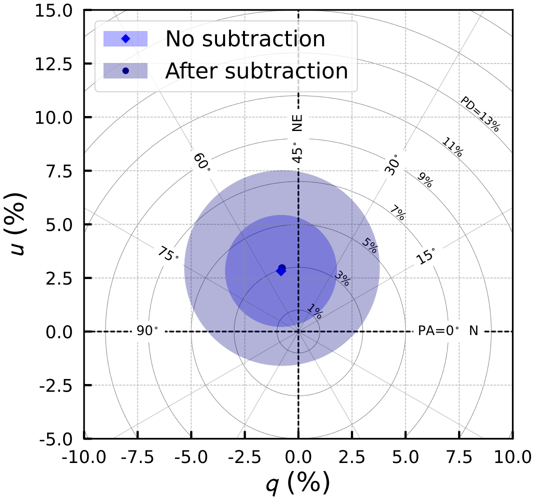


- During the observation IXPE detected 52 type-I X-ray bursts which shared similar properties
- Average peak count rate 38.7 $\mathrm{cnt\,s^{-1}}$ with standard deviation 2.9 $\mathrm{cnt\,s^{-1}}$
- Fluence very similar (649 cnt) and only slightly increased for bursts occurring when the persistent count rate had decreased below 3 $\mathrm{cnt\,s^{-1}}$

- Stacking all the observed bursts and fitting the observed spectra with the sum of a thermal component and the two-component model used to fit the persistent spectrum we get $\langle kT_{\rm burst}\rangle = 1.83 \pm 0.05$ keV and $R_{\rm burst} = (6.2 \pm 0.2) d_8$ km
- Defining the burst duration as $\tau = \mathcal{F}/F_{\rm peak}$, and neglecting variations of the spectrum throughout the burst: $\tau = 16.8 \pm 1.6$ s



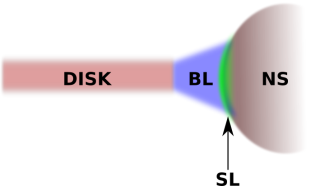
- To search for a polarized signal during the X-ray bursts we stacked the emission observed during all the events retaining 32 s after the onset of each burst (total exposure 1664 s) after subtracting the contribution from persistent emission we measured:
  - ➥ $\tilde{q}_{\rm b} = -0.7\% \pm 3.9\%$
  - ➥ $\tilde{u}_{\rm b} = 3.0\% \pm 3.9\%$
  - ➥ $PD_{\rm UL} = 8.5\%$ (90% c.l.)



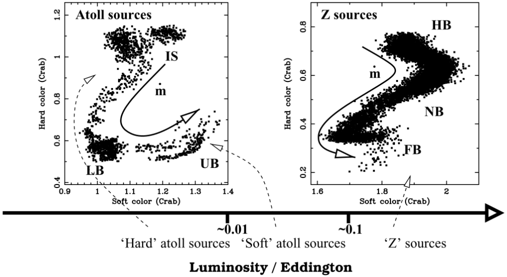
Conclusions

- IXPE observed for the first time an accreting millisecond pulsar obtaining a significant detection of polarization in 3–6 keV
- Phase resolved analysis allowed to obtain geometrical parameters, even if no strong variability on Q and U are observed
- 52 Type-I X-ray bursts have been detected obtaining an upper limit on the polarization of 8.5% at 90% CL
- Further studies are ongoing

Weakly magnetized NS in LMXB



- Binary systems having a NS ($B < 10^{10}\,G$) and a companion star ($M < M_{\odot}$)
- Accreting matter via Roche lobe overflow (similar to BH)
- Classified in:
  - **Z-sources** with luminosities 0.1–1 L_{Edd}
  - **Atoll-sources** with luminosities 0.01–0.1 L_{Edd}



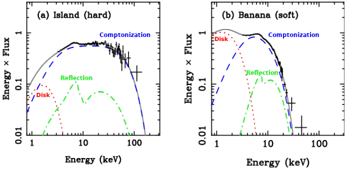
[Migliari & Fender 2006]

QPOs and spectra

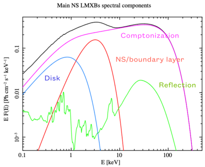
- Eastern model [Mitsuda et al., 1989]
  - Soft: accretion disk
  - Hard: Comptonization from BL
- Western model [White et al., 1988]
  - Soft: NS surface or BL
  - Hard: Comptonization from accretion disk
- Hybrid model [Lin et al., 2007]
- Presence of reflection
  - Allow to study inner disk radius and a new method to constrain EoS

- Energy-resolved Fourier spectra point towards the Eastern scenario
- Highly inclined ADC sources favor western/Birmingham model

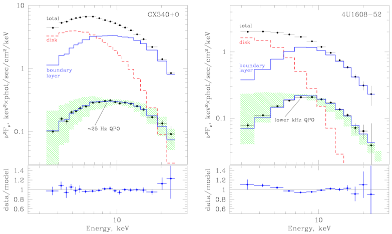
see lectures by A. Marino



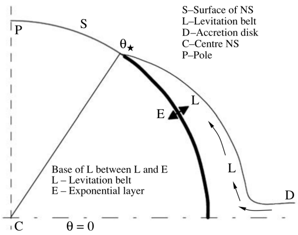
[Done+ 2007]



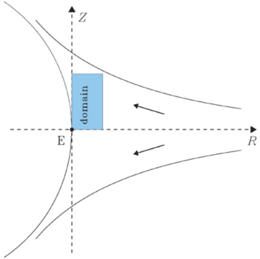
[Marino CNOC2022]



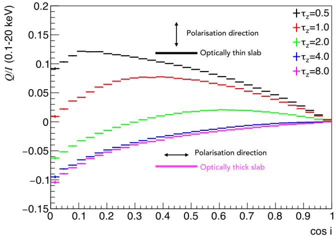
[Gilfanov et al., A&A 410, 217, 2003]



Spreading Layer [Inogamov & Sunyaev 2010]

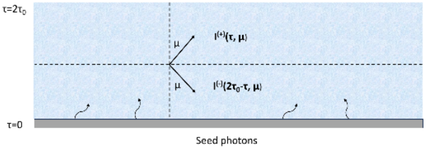


Boundary Layer [Babkovskaia+ 2008]

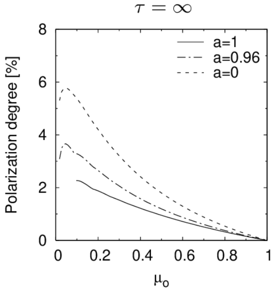


[Tomaru+ 2024]

- Spectral models (Eastern/Western/Hybrid) can be degeneracy
- Timing support SL/BL as in Eastern scenario
- Sco X-1 marginal detection of polarization show a PA aligned with radio-jet direction
- **Polarization can help to study "corona" geometry**
  - Accretion disk PA expected parallel to the disk (orthogonal to radio-jet)
  - BL PA expected parallel or perpendicular to the disk depending on τ

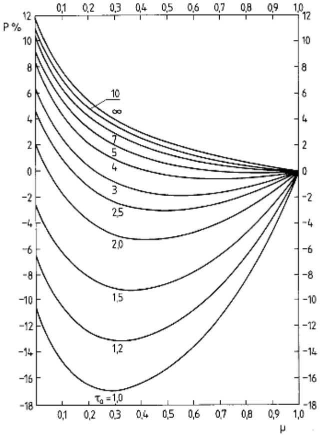


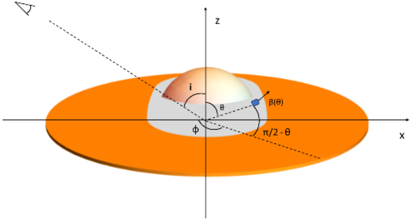
- **Accretion disk** expected to have low polarization ($< 6\%$) parallel to the disk
  - Chandrasekhar S. 1960, Radiative Transfer (New York: Dover)
  - Dovciak+ MNRAS 391 (2008) 32
  - Loktev+ A&A 660 (2022) 25

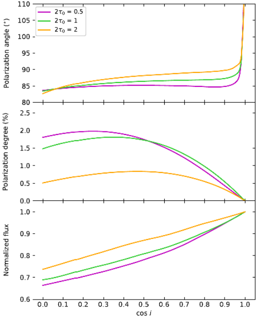


Polarization from each component II

- **Boundary layer** expected to have polarization $< 10\%$ **parallel to the disk if optically thick**, while an **optically thin slab** can have higher polarization (up to $\sim 18\%$) and it is expected to be **orthogonal to the disk plane**
  - ➥ Sunyaev & Titarchuk A&A 143 (1985) 374







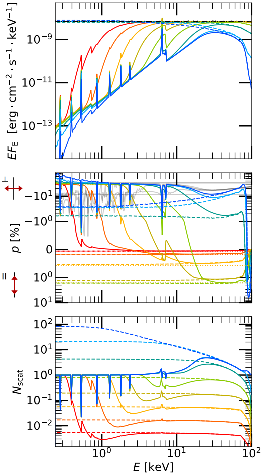
- **Spreading layer** (or vertically extended boundary layer) polarization up to 3% and polarization angle flipped by 90°with respect to boundary layer
  - Farinelli+ A&A 684 (2024) 62
  - Bobrikova+ A&A 696 (2025) 181

Polarization from each component IV

- **Reflection component** is polarized up to 20-30% with unpolarized fluorescence lines
  - ➥ Matt MNRAS 260 (1993) 663
  - ➥ Poutanen+ MNRAS 283 (1996) 892
  - ➥ Podgorny+ MNRAS 524 (2023) 3853
  - ➥ Podgorny A&A, 702, A43 (2025)

- **Scattering in the wind** can be polarized up to 20%
  - ➥ Tomaru+ MNRAS 527 (2024) 7047
  - ➥ Nitindala+ A&A 694 (2025) 230

- **Accretion disk corona** can be polarized up to 20%
  - ➥ Di Marco+ ApJL 979 (2025) 47
  - ➥ Tomaru+ arXiv:2509.26147



Observed targets by IXPE

Z-sources

- **Cyg X-2** *Farinelli, Fabiani, Poutanen, et al., MNRAS 519, 3681, 2023*
- **GX 5−1** *Fabiani, Capitanio, Iaria et al., A&A 684, A137, 2024*
- **GX 340+0 HB** *La Monaca, Di Marco, Ludlam et al., A&A 691, A253, 2024*
- **GX 340+0 NB** *La Monaca, Di Marco, Coti Zelati et al., A&A 702 (2025) 101*
- **Sco X-1** *La Monaca, Di Marco, Poutanen et al., ApJL 960, L11, 2024*
- **GX 349+2** *La Monaca, Bobrikova, Poutanen et al., A&A 702 (2025) 40*

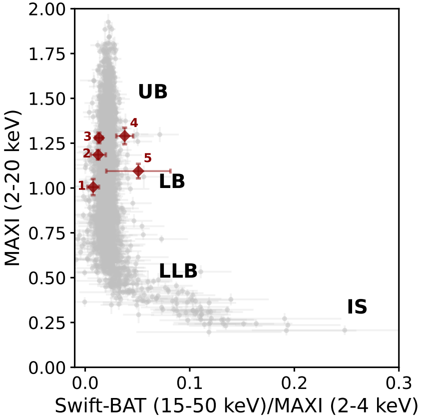
Atoll-sources

- **GS 1826–238** *F. Capitanio et al., ApJ 943, 129, 2023*
- **GX 9+9** *F. Ursini et al., A&A 676, A20, 2023*
- **4U 1820–303** *A. Di Marco et al., ApJL 953, L22, 2023*
- **4U 1624–49** *M. L. Saade et al., ApJ 963, 133. 2024*

Transients and peculiar sources

- **XTE J1701–462** *M. Cocchi et al., A&AL 674, L10, 2023*
- **Cir X-1** *J. Rankin et al., ApJL 961, L8, 2024*
- **GX 13+1** *A. Di Marco et al., ApJL 979, 47, 2025*

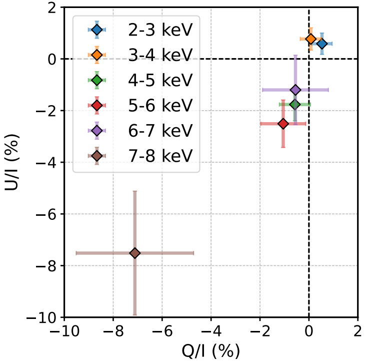
A. Di Marco, F. La Monaca, J. Poutanen et al., ApJL 953, L22, 2023

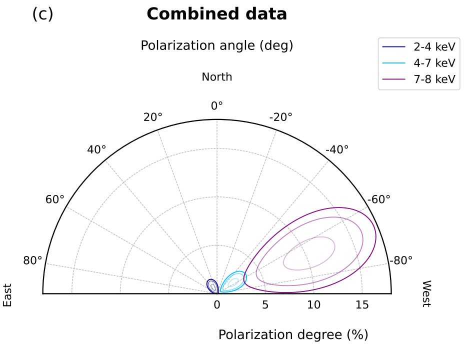


- LMXB consisting of a He WD accreting onto an ultracompact NS
- First identified source of type I X-ray bursts (bursts only around the flux minima)
- LMXB with the shorter orbital period (685 s)
- Superorbital period of $\simeq$ 170 days

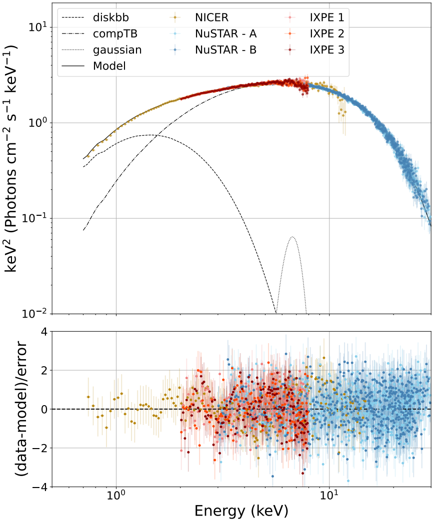
- Previous tentative to measure of X-ray polarization
  - PD $<$ 4.7% at 2.6 keV and $<$ 10.8% at 5.2 keV (99% CL) by OSO-8 ApJ 280(1984)255
- IXPE observed the source two times in the LB state

4U 1820–303: polarization as a function of the energy





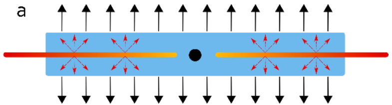
- Polarization results to be energy dependant
- Energy bin 7–8 keV **highly significant (99.99%CL)**
- PA rotation of 90 deg at 96% CL at $\simeq$4 keV



Polarimetric components		polconst*diskbb + polconst*comptb	polconst*diskbb + pollin*comptb	polconst*diskbb + polpow*comptb
diskbb	PD (%)	9.8 ± 4.2	$8.1^{+7.1}_{-6.8}$	$3.2^{+3.0}_{-2.9}$
	PA (°)	32 ± 13	-59^{+13}_{-26}	43 ± 35
comptb	PD / A_1 (%)[a]	5.31 ± 0.24	5.7 ± 2.4	$0.46^{+9.63}_{-0.46} \times 10^{-3}$
	$A_{\rm slope}$ (% keV^{-1})	–	-1.9 ± 0.6	–
	$A_{\rm index}$	–	–	$-4.9^{+1.6}_{-2.6}$
	PA / ψ_1 (deg)[a]	-63 ± 11	38 ± 7	-63 ± 7
	$\psi_{\rm slope}$ (deg keV^{-1})	–	0 (f)[b]	–
	$\psi_{\rm index}$	–	–	0 (f)[b]
	χ^2/dof	724/662 = 1.094	699/661=1.057	697/661=1.054

- soft disk component not well determined
- hard component due to boundary layer shows higher linear-dependent polarization
- the two components are rotated by 90°

4U1820-303: possible interpretations



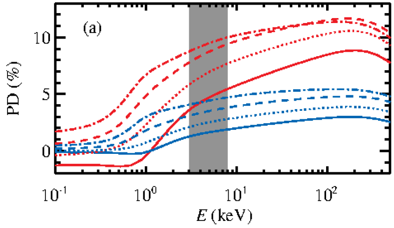


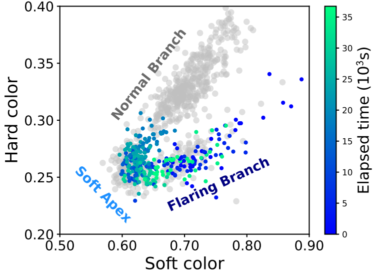
Figure: Blue (red) corresponding to inclination 30°(60°) for different outflow velocities β_0: 0 (solid), 0.2 (dotted), 0.4 (dashed), 0.6 (dotted–dashed).

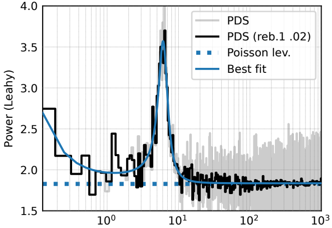
- **From Poutanen et al., (ApJL 949:L10, 2023) a PD increase with energy is expected for slab geometry** in the presence of relativistic outflows but inclination should be higher to explain the fast increase of PD
- **Energy spectrum dominated by Comptonization** as in the hard state, thus we can study corona properties
- PD increasing with energy is associated with a corona with slab geometry, where PD can reach $10\% - 20\%$ for an optical thin corona, but in our case $\tau > 10$ expected PD of few % **some non-standard corona geometry required**
- reflection component negligible ($< 5\%$) with respect to Comptonization ($> 90\%$) in the total flux
  - ➥ Max PD for reflection $\simeq 30\% \rightarrow$ cannot explain the results

Scorpius X-1

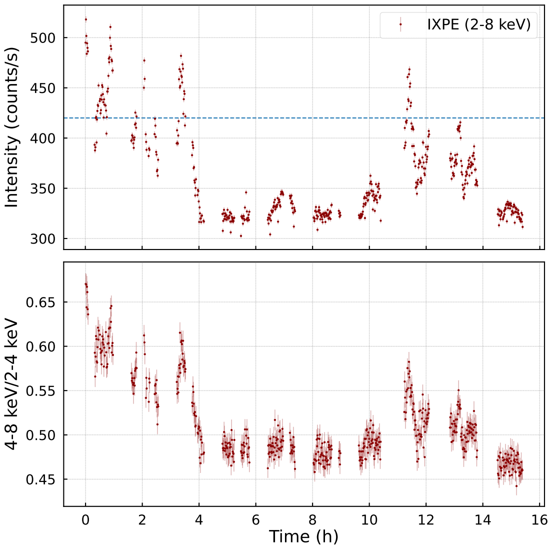
F. La Monaca, A. Di Marco, J. Poutanen, et al., ApJL 960, L11, 2024

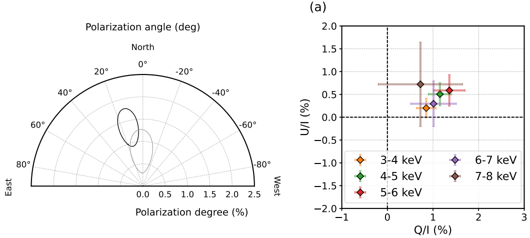
- First X-ray extra-solar source discovered and the brightest in the X-ray sky
  - ➥ peak luminosity near the Eddington-limit
- First X-ray binary where radio emission was detected:
  - ➥ VLBI spatially resolved radio jet at position angle $\sim 54^\circ$ [Fomalont et al., 2001]
- Previous attempts to measure X-ray polarization by OSO-8 [Long+ 1979] and PolarLight [Long+ 2022]
  - ➥ marginal detection
  - ➥ long exposure time without possibility to clearly distinguish the source state
- Observation campaign simultaneous with **IXPE**: **Nicer**, **NuSTAR** and **insight-HXMT**





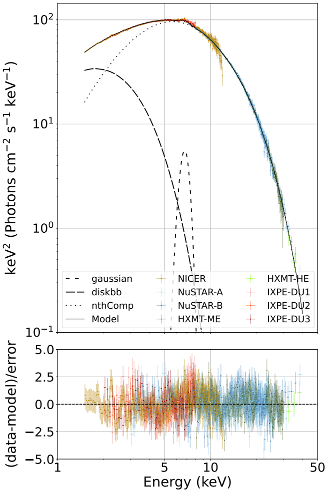
Sco X-1: Polarimetric results



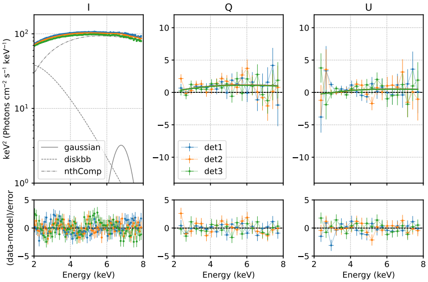


- Polarization for flaring and non-flaring states compatible at 90% CL
- **No evidence of PD or PA variation with energy**
  - ➥ PD smaller than expectations: the geometry can be compatible with a **sandwich corona geometry** (Poutanen et al., ApJL 949:L10, 2023)

Sco X-1: spectro-polarimetric results



- **Spectral fit**:
  - ➥ continuum with `tbabs*(diskbb+nthcomp)`
  - ➥ clear broad Fe line at ∼6.7 keV as a reflection feature modeled with a **Gaussian line** or with a complete reflection model **relxillNS**
- **Highly significant polarization** in 2–8 keV energy band (PD=1.0%±0.2% and PA=8°±6°)
- **Spectropolarimetric analysis for the model with Gaussian line**:
  - ➥ PD of the disk < 3% **compatible with expectations from (Chandrasekhar, 1960)** for an inclination ∼44°
  - ➥ PD of the Comptonized component of 1.3% ± 0.4%, **compatible with a coplanar BL/corona having** $\tau_{\rm T}$**∼7 and** $kT_{\rm e}$**∼3 keV** [Sunyaev & Titarchuk, 1985]

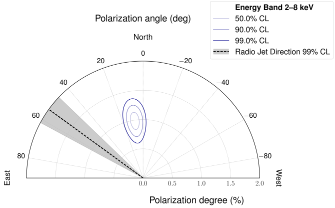


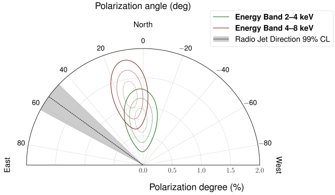
- **Spectropolarimetric analysis for model with Reflection**:
  - ➥ A clear polarimetric disentanglement of the three spectral components is not possible with the present data
  - ➥ Fixing PD of the disk and Comptonized component, PD of the reflection component is about 14% **compatible with predicted values (Matt+ 1993 and Poutanen+ 1996)**

	Disk		Comptonization		Reflection	
Case A	$< 1.9\%$	–	$< 8.2\%$	–	$< 66\%$	–
Case B	1.1%	-40°	0%	–	$14\% \pm 5\%$	$15^\circ \pm 7^\circ$

Sco X-1: polarization angle VS radio-jet direction

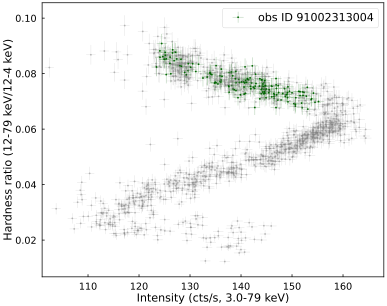
- **Sco X-1 shows a PA rotated of ∼46° with respect to the radio-jet position angle**. In contrast:
  - previous OSO-8 and PolarLight observations
  - IXPE results for Cyg X-2 (Farinelli+ 2023)
- **The PA variation/rotation may be due to relativistic precession or HR variations**:
  - **relativistic precession**: radio-jet observed in a few sources to change up to 36° on short timescales (Miller-Jones+ 2019), likely related to the relativistic Lense-Thirring precession of the accretion disk
  - Cir X-1 showed variations of the orientation of the radio jet over time, first time for an NS (Cowie+, in prep.)
  - **variation of the corona geometry** in the different states of the source with PA variations up to ∼70°: Cir X-1 (Rankin+ 2023), GX 13+1 (Bobrikova+ 2024a,b; Di Marco et al., 2025), XTE J1701-462-80 (Di Marco, 2025)





[*La Monaca, Astron. Nachr. e20240107, 2024*, La Monaca, arXiv:2504.07181]

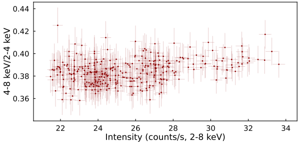
GX 340+0: a Cyg-like source



- Z source belonging to **Cyg-like sub-class**
- Inclination of the system:
  - ➥ expected intermediate inclination between Cyg-like and Sco-like systems
  - ➥ from the reflection modeling inclination $\sim 35^\circ$ (D'Aì et al., 2009; Miller et al., 2016; La Monaca et al. 2024; Li et al. 2025):
  - ➥ Seifina et al. (2013) proposed a model with a Comptonized corona that puffs up while the source changes state from HB through the NB to the FB, allowing to explain the dipping FB
- No spatially resolved radio-jet
- Spectral Joint fit NICER+IXPE+NuSTAR

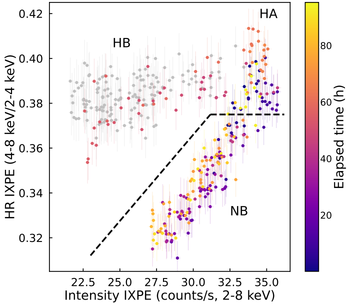
IXPE HID: First observation

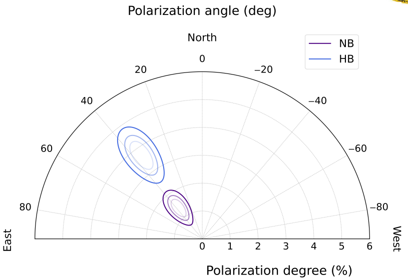
F. La Monaca, A. Di Marco, R. M. Ludlam et al., A&A 691, A253, 2024



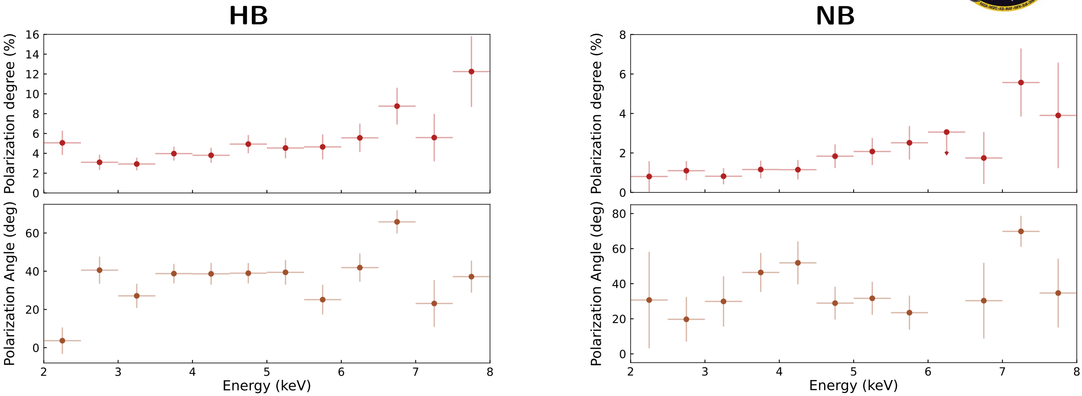
IXPE HID: Second observation

La Monaca, Di Marco, Coti Zelati et al., A&A 702 (2025) 101



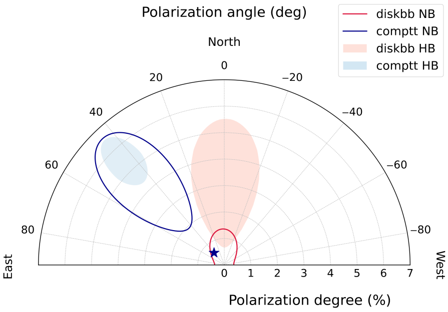


- GX 340+0 observed in the **HB** and in the **NB**
  - ➥ **Polarization in the HB** ($\sim 11\sigma$ CL):
    $\mathrm{PD} = 4.3\% \pm 0.4\%$ at $\mathrm{PA} = 36^\circ \pm 3^\circ$
  - ➥ **Polarization in the NB** ($\sim 5.6\sigma$ CL):
    $\mathrm{PD} = 1.4\% \pm 0.3\%$ at $\mathrm{PA} = 37^\circ \pm 5^\circ$
- **PD of the HB is higher than NB** in line with other IXPE results (XTE J1701−462, GX 5−1, GX 349+2)
- **Compatible PAs in the two branches**



- **PD increasing with energy**: up to ∼ 12% in the HB and up to ∼ 6% in the NB
- PA variation of ∼40° is observed between the soft and high energy bins in the HB; not observed in the NB
- Variation of polarization confirmed by spectropolarimetric analysis favouring `XSPEC pollin` or `polpow` model both in HB and NB

GX 340+0: spectropolarimetric analysis



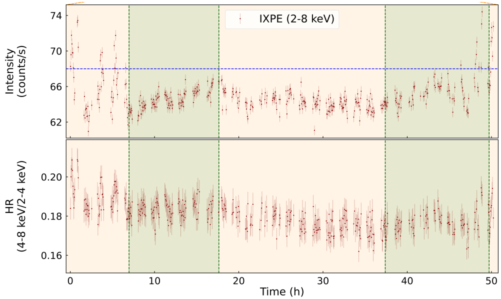
[*La Monaca, Di Marco, Coti Zelati et al., A&A in press, arXiv:2508.13278*]

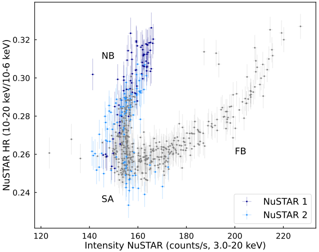
- Spectropolarimetric models with independent polarization for soft and Comptonized components with unpolarized Gaussian
- PD of the Comptonized emission from an optically thick and relatively narrow SL expected to be <0.6% (Bobrikova+ 2025)

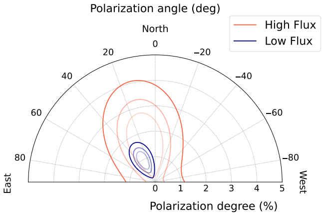
- **Uncommon PA difference of** $\sim 40^\circ$ between the two spectral components: misalignment of the disk/BL axis with the NS axis?
- PD of the Comptonised component remains **constant at** $\sim$**4% between the HB and the NB**
- The high **polarization from Comptonization requires inclination higher than 70°**
- **Reflection points to inclination** $\sim$**37°**
- Possible other explanation for the high PD:
  - **Scattering of the source emission in the equatorial wind** (Nitindala+ 2025); wind features observed (Miller+ 2016)
  - **presence of an extended accretion disk corona (ADC)**, which may contribute as an additional component of polarized emission (Di Marco et al. 2025). XRISM observation favours this scenario (Ludlam+ 2025)

GX 349+2: a Sco-like source

La Monaca, Bobrikova, Poutanen et al., A&A 702 (2025) 40

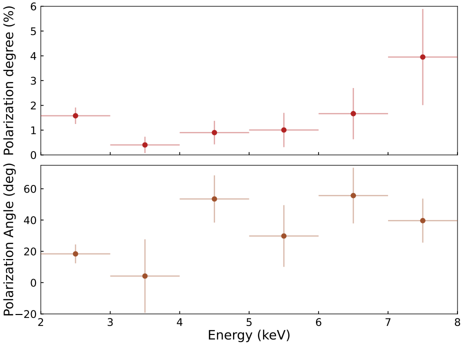






- **GX 349+2 was observed mainly in the NB** (joint NuSTAR observation)
- Polarization results ($\sim 4.2\,\sigma$): PD $= 1.1\,\% \pm 0.3\,\%$ at PA $= 29\,^\circ \pm 7\,^\circ$
- **PD compatible with other sources observed in the NB** (Cyg X-2, GX 5−1, XTE J1701−462, GX 340+0)
- No significant variability of polarisation in time and flux has been observed

GX 349+2: energy-resolved and spectropolarimetric analysis



Spectral component		GX 349+2	GX 340+0 NB	GX 340+0 HB
`diskbb`	PD (%)	1.0 ± 0.7	< 1.2	3.1 ± 1.7
	PA (°)	6^{+24}_{-23}	–	-1 ± 16
`Comptonization`	PD (%)	3.7 ± 3.0	4.3 ± 1.8	5.2 ± 1.0
	PA (°)	68 ± 26	44 ± 13	44 ± 5

- Gaussian assumed unpolarized

[*F. La Monaca, A. Bobrikova, J. Poutanen et al., A&A in press, arXiv: 2507.07163*]

- **Complex variability for PD/PA with energy**; similar trend for PD in GX 340+0
- Spectropolarimetric analysis confirmed the polarization variability with energy: `XSPEC pollin` model favored respect to a PD constant behaviour with energy
- **PD of the Comptonized emission exceeds the theoretical predictions** (Bobrikova+ 2025)
- **Polarimetric results align more closely with the Cyg-like system GX 340+0 of similar inclination**

Polarization of the reflection component

Sco X-1

Component		Model C1	Model C2
diskbb	PD (%)	< 1.9	[1.1]
	PA (°)	—	[−40]
nthcomp	PD (%)	< 8.2	[0]
	PA (°)	14 ± 8	—
rellxillNS	PD (%)	$< 66\%$	14 ± 5
	PA (°)	—	15 ± 7

[*F. La Monaca, A. Di Marco, J. Poutanen et al., ApJL 960, L11, 2024*]

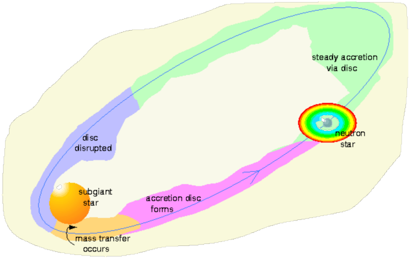
GX 349+2

Component		Model B1	Model B2	Model B3
diskbb	PD (%)	0.9 ± 0.7	[1.0]	[1.0]
	PA (°)	5^{+25}_{-23}	[6]	[6]
bbodyrad	PD (%)	< 4	[3.7]	[0]
	PA (°)	—	[68]	—
relxillNS	PD (%)	< 62	< 9	11 ± 5
	PA (°)	—	—	68^{+12}_{-13}

[*F. La Monaca, A. Bobrikova, J. Poutanen et al., A&A in press, arXiv: 2507.07163*]

- **Similar results for GX 340+0**: PD of the reflection up to 30% depending on the assumption and showing that to constrain the PD of the reflection, PD of the Comptonized component has to be $> 1\%$
- A clear polarimetric disentanglement of the three spectral components is not possible with the present data, **confirming the degeneracy of the polarization of Comptonization and reflection**
- **PD of the reflection component compatible with predicted values** (Matt 1993 and Poutanen+ 1996)

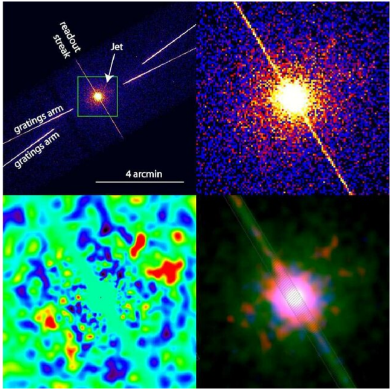
Circinus X-1

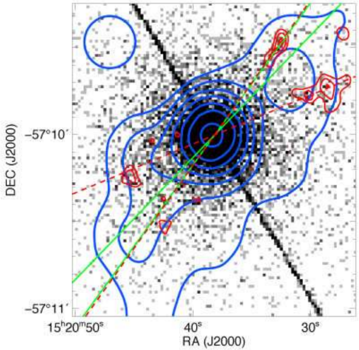


- Circinus X-1 is a peculiar weakly magnetized neutron star X-ray binary system
  - ➥ Discovery of Type I X-ray bursts proved that the compact object is a neutron star (Tennant+ 1986)
- Very young system (< 5000 yr, Heinz+ 2015) since the supernova explosion

- Historically went through both Z and atoll states (Schulz+ 2019)
- Accretion flow strongly related to its eccentric ~ 16.6 days orbit, during which its flux and spectrum change
- During periastron the disk is perturbed causing an X-ray outburst (Johnston+ 1999)

Jets in Circinus X-1



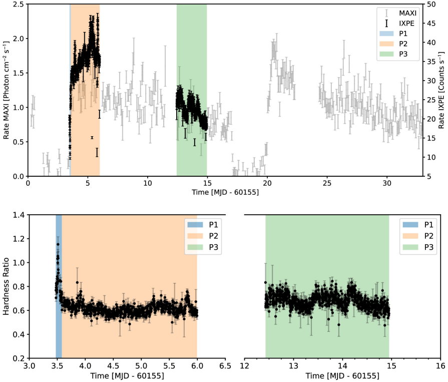


Heinz+ 2007

- Circinus X-1 shows X-ray jet in Chandra images
- Cir X-1 has also a detected radio jet

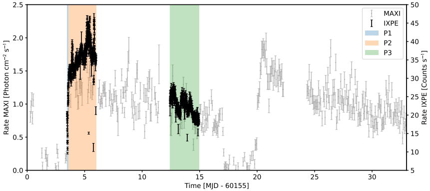
- The two jets in Heinz+ 2008 resulted to be almost aligned

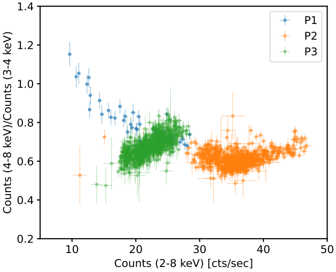
J. Rankin, F. La Monaca, A. Di Marco, et al., ApJL 961, L8, 2024



- IXPE observed Cir X-1 in two pointings for a total exposure time of 263 ks:
  - ➥ 2023-08-02–04
  - ➥ 2023-08-11–13
- IXPE first observation starts at the exit from the dip and covered the **flaring** phase
- IXPE second observation peformed during the **transition** from the high to the low flux states covering the **stable** phase

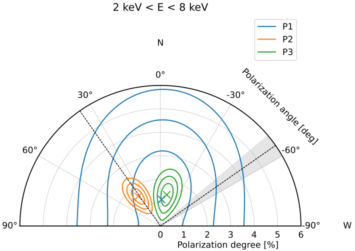
Polarization of Circinus X-1 along the orbit

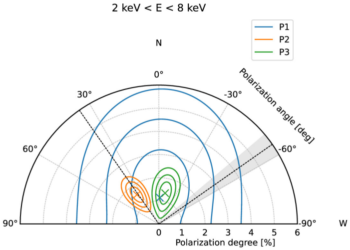


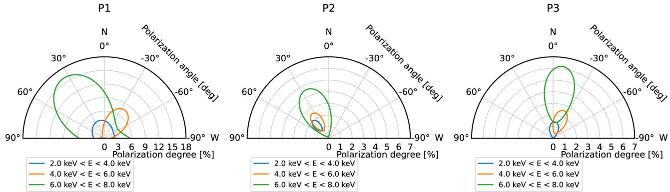


- IXPE data were divided into 3 phases of the orbital period
  - ➥ P1: fast rise of the flux
  - ➥ P2: flaring
  - ➥ P3: stable

- Not significant detection of polarization in P1
- PD almost constant in P2 and P3, while PA changed

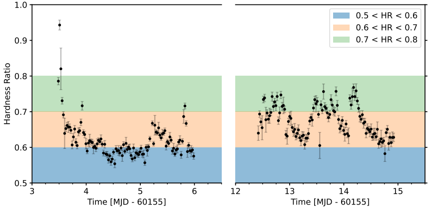


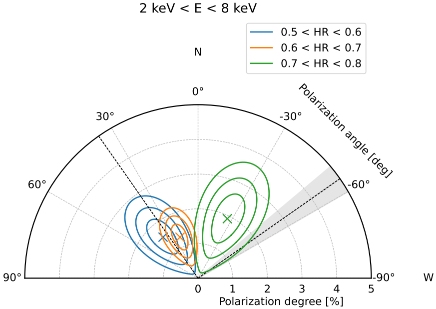




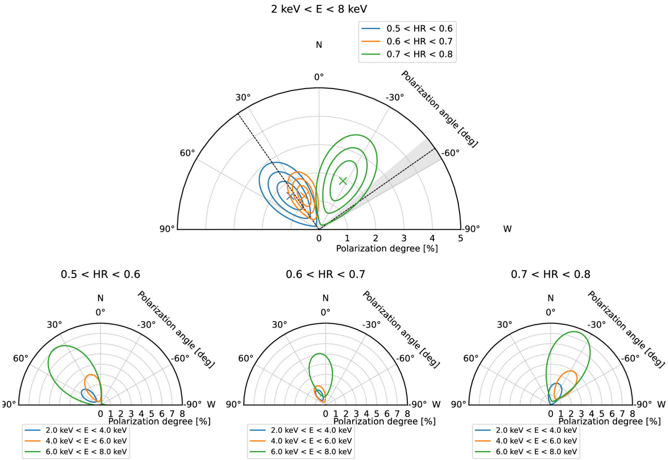
- P1 not statistically significant
- P2 no visible energy trend and PA orthogonal to the radio-jet position angle in each energy bin
- P3 hint at 90% CL for energy increase of PD, while PA is almost constant

Polarization of Circinus X-1 at different HR



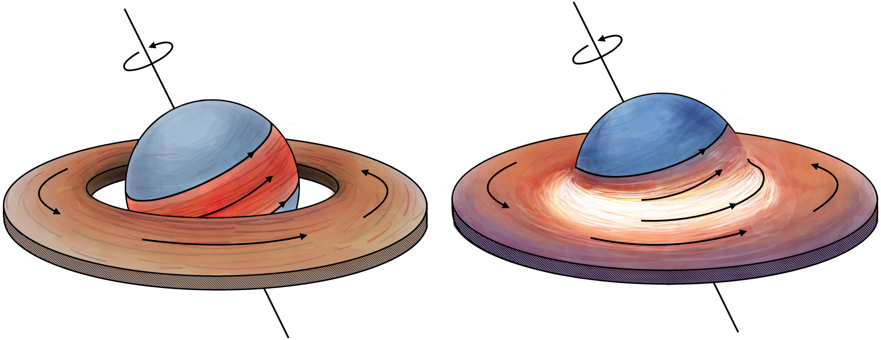


- IXPE data were divided into 3 HR bins
  - ➥ HR1: $0.5 < HR < 0.6$ is the softer bin
  - ➥ HR2: $0.6 < HR < 0.7$ intermediate HR
  - ➥ HR3: $0.7 < HR < 0.8$ harder bin
- This analysis is used to try to disentangle contribution due to different spectral components
  - ➥ HR1: aligned ortogonally to the radio-jet
  - ➥ HR3: approaching to the jet direction



- No indication for energy dependencies in any HR bin

Circ X-1 results

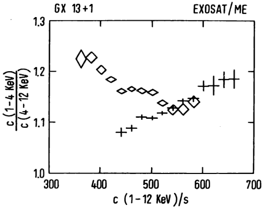


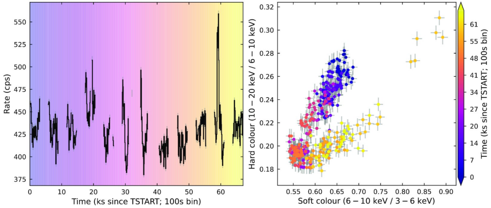
- **Cir X-1 PA variation along orbit and HR**
- Boundary layer dominant at high accretion rates (PA aligned with accretion disc)
- Spreading layer dominant at low accretion rates (PA parallel to rotation axis)
- Relativistic effects can cause rotations but not so large
  - ➥ **misalignment of neutron star angular momentum and orbital axis**

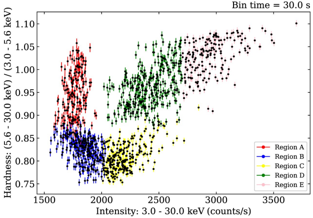
J. Rankin, F. La Monaca, A. Di Marco, et al., ApJL 961, L8, 2024

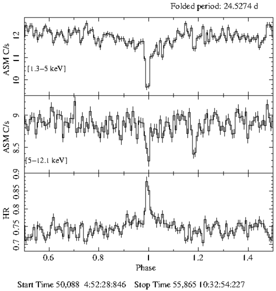
GX 13+1 I

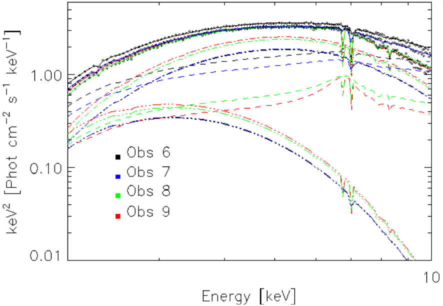
- Peculiar source, unique position between atolls and Z-sources:
  - ➥ Bright as Z-source (up to 0.5 L_{edd}) and persistent radio emission
  - ➥ CCD shape closer to atolls source
- 24.5 d periodic flux variation due to orbital movement (the longest between NS-LMXB) with almost regular short dips of $\sim$1 ks (expected for high inclination)





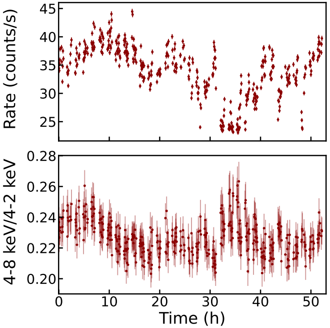




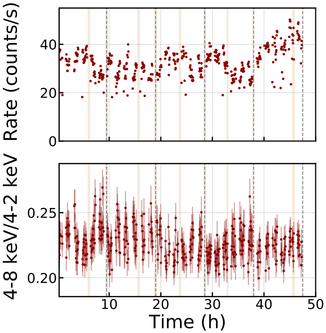


- Source showing dips (inclination $> 60°$)
  - A 24.5 d periodic dip is observed
- Complex spectrum (Díaz Trigo et al. 2012):
  - common continuum deconvolution
  - **reflection features**
  - **seven absorption features coming from the interaction of the radiation in the wind above the disk**

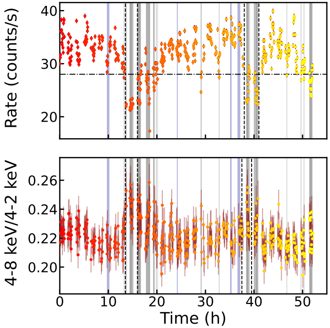
GX 13+1: IXPE observations



First observation performed in October 2023 (*A. Bobrikova, S. Forsblom, A. Di Marco, et al., A&A 688, A170, 2024*)

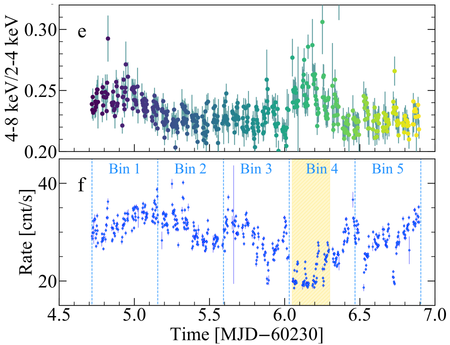


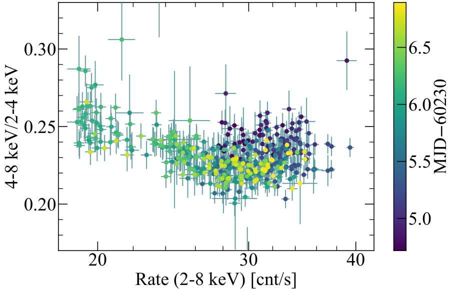
Second observation performed in February 2024 (*A. Bobrikova, A. Di Marco, F. La Monaca et al., A&A, 688, A217, 2024*)



Third observation performed in April 2024 (*A. Di Marco, F. La Monaca, A. Bobrikova, et al., ApJL, 979, L47, 2025*)

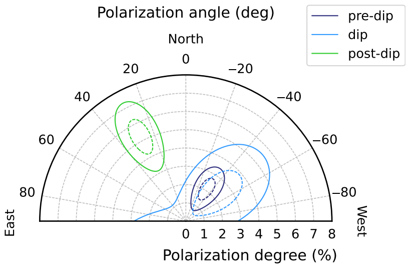
First observation



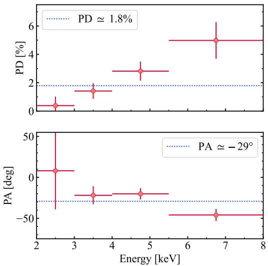


- First observation performed in October 2023 (*A. Bobrikova, S. Forsblom, A. Di Marco, et al., A&A 688, A170 (2024)*)
- Exposure time: $\sim 100\,\text{ks}$
- Measured a significant polarization
  - ➥ PD=$1.4\% \pm 0.3\%$
  - ➥ PA=$-2^\circ \pm 6^\circ$

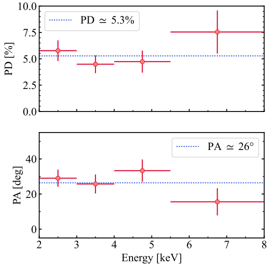
GX 13+1: around the dip



Pre-dip



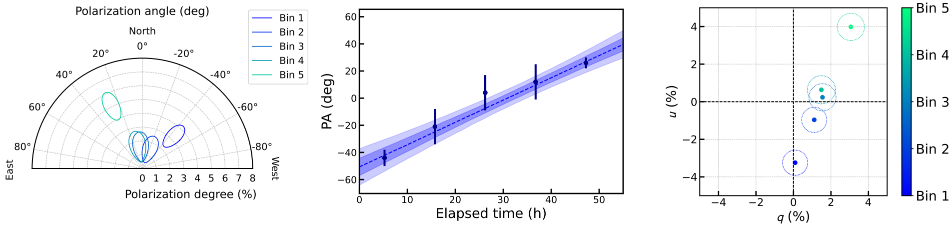
Post-dip



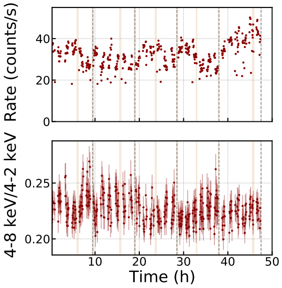
- Study of different parts of the observation based on the light curve: pre-dip, dip, and post-dip
- **Pre-dip and post-dip parts completely different behaviour**:
  - PD pre-dip hint for energy dependence
  - PD post-dip almost constant with energy
  - PA doesn't show significant energy dependency but is changed $\sim 60^\circ$ apart between pre-dip and post-dip
- dip polarization up to 7.5%(1.7%) with PA -51°(7°)

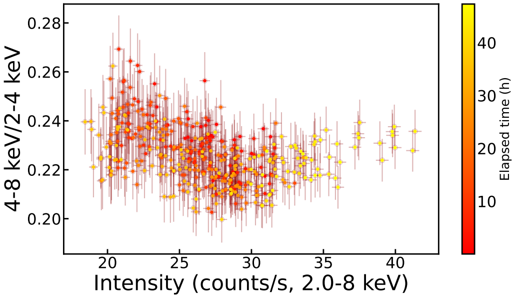
GX 13+1: time evolution

- We **split data into five equal time bins** (10.55 h each)
- rotation of the PA with time with a slope of $1^\circ.64$ per hour and the **total rotation angle exceeding 70°**
- The evolution of the source in the q-u plane shows a straight line
- PD is relatively high at the beginning and at the end of the observation

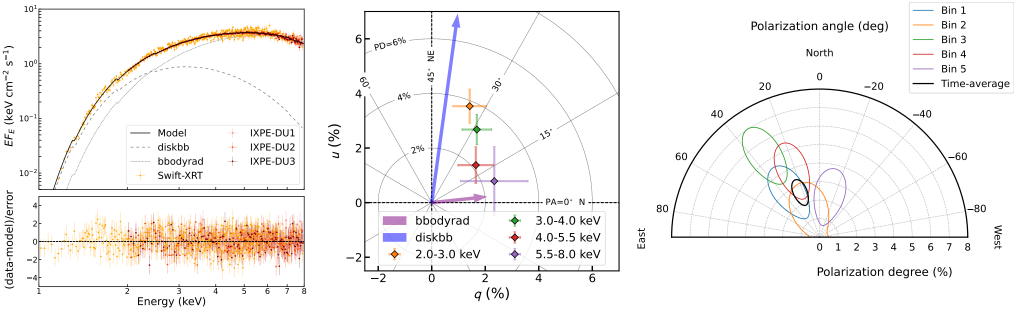


Possible contribution from wind/obscuration of the source?





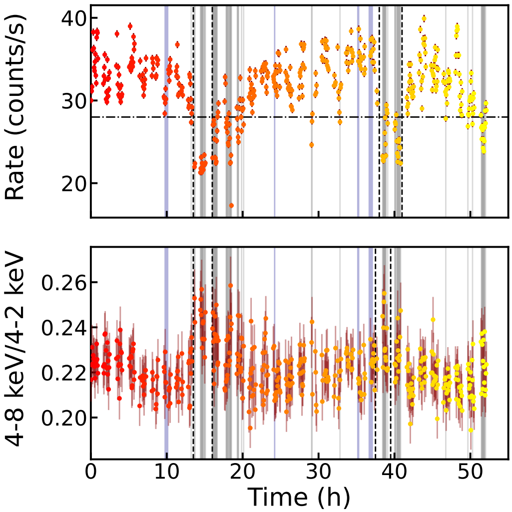
- Second observation performed in February 2024 (*A. Bobrikova, A. Di Marco, F. La Monaca et al., A&A, 688, A217, 2024*)
- Exposure time: $\sim 90\,\mathrm{ks}$ covered with 10 Swift-XRT snapshots
- Measured a significant polarization
  - PD=$2.6\% \pm 0.5\%$
  - PA=$23^\circ \pm 5^\circ$



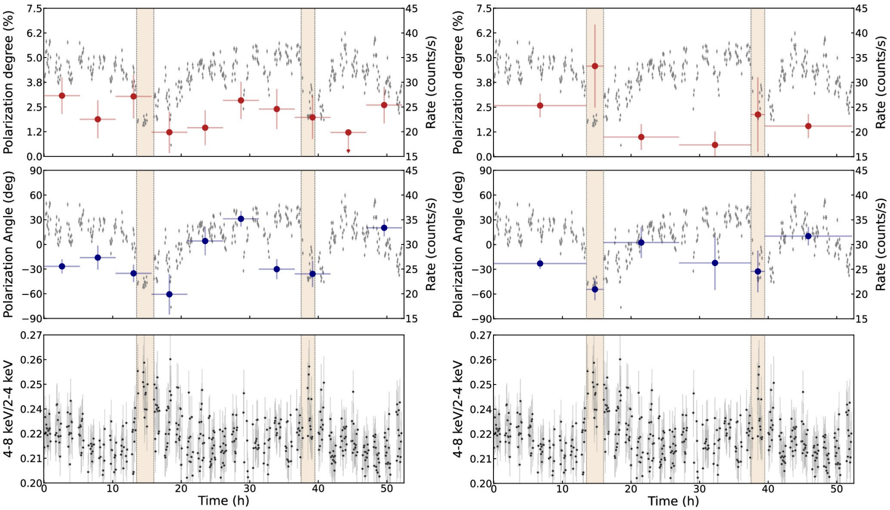
- Swift-XRT data allowed for a better spectral modelling and for spectropolarimetric analysis
- `diskbb` and `bbodyrad` polarization are not orthogonal
- Time variability of the PD, while PA is almost constant

GX 13+1 third observation

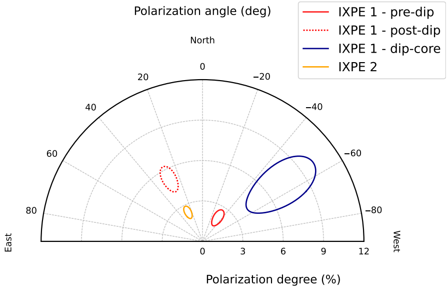
- Third observation performed in April 2024 (*A. Di Marco, F. La Monaca, A. Bobrikova, et al., ApJL, 979, L47, 2025*)
  - ➥ Exposure time ~ 100 ks
  - ➥ Two dips during the observation
  - ➥ partial coverage by NICER
- Significant polarization detected
  - ➥ PD=$1.4\% \pm 0.3\%$
  - ➥ PA=$-11^\circ \pm 7^\circ$

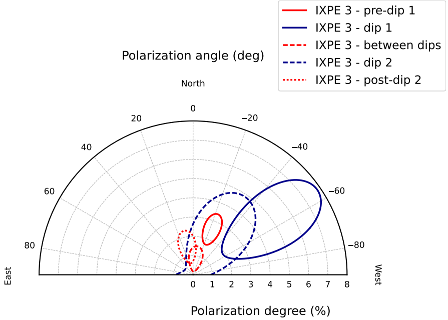


GX 13+1 polarization vs time



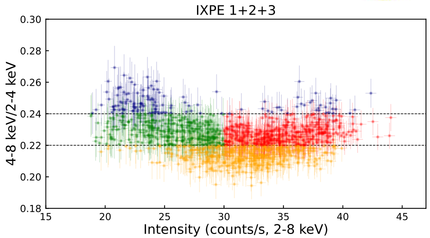
GX 13+1 comparison of different observations



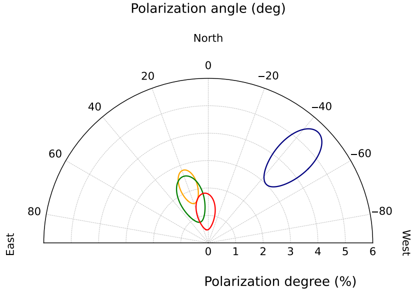


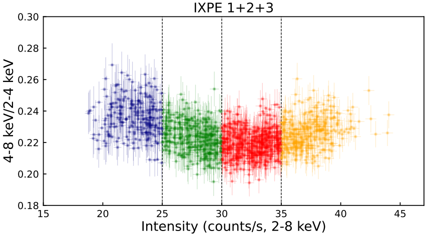
- Dips seems to show the same PA and higher PD
- Out of the dip PD smaller and PA changes

Polarization resolved in HR

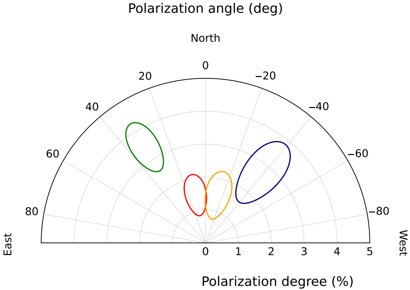


- 3 equally spaced HR bins
- softer bin and harder one show PA difference of $\sim 70^\circ$



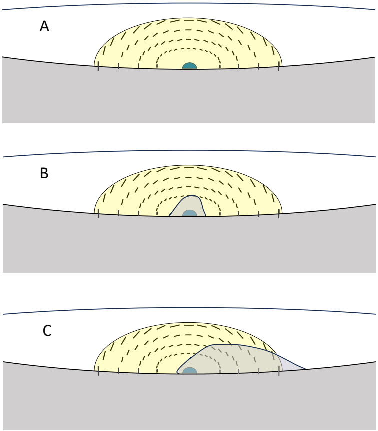


- 4 equally spaced intensity bins
- PA span on $\sim 70^{\circ}$ interval
- higher intensity approach the PA of the lower intensity bin



Conclusions

- $\sim 70^\circ$ rotation during the first IXPE observation could be related to different obscuration of the different emitting regions
- Both HR resolved and intensity resolved polarization show PA variations spanning on $\sim 70^\circ$
- During dips the central region (NS+BL/SL) is obscured
  - ➥ accretion disk corona polarization contribution increases
  - ➥ optical depth varying with time in the wind



[*A. Di Marco, F. La Monaca, A. Bobrikova, et al., ApJL, 979, L47, 2025*)]

IXPE results on WMNS

- Compatible PD results for Cyg-like and Sco-like sources
  - ➥ Polarization is not governed by the subclass to which the source belongs
- Polarization variation with the accretion flow
- Harder state (HB) appears to be highly polarised and probably dominated by emission from an ADC or wind
- Softer states (NB and FB) are probably dominated by disk and BL emissions
- Atolls have lower average polarization and polarization variation with energy

Cir X-1, Sco X-1 and GX 13+1 show a PA rotation with time/state of the source

Open questions:

- **Shape and geometry of the region responsible for the strong Compton feature dominating the hard spectra**
- **Polarization correlation with the accretion rate?**
- **What is its role of the reflection in the total PD?**
- **Cyg X-2 PA aligned with Radio-jet, why not Sco X-1?**

Since IXPE launch several papers on modeling Loktev+ 2022, Gnarini+ 2022, Poutanen+ 2023, Farinelli+ 2024, Tomaru+ 2024, Bobrikova+ in prep.

Conclusion

- IXPE is providing new amazing results and information not available before

- As Meszaros+ wrote in 1988:
  "A doubling of the observational parameter space from the present two (frequency and time) to four, however, is definitely feasible. It is possible to add the two extra dimensions provided by ***X-ray polarimetry****, namely the direction and magnitude of polarization, to the previous two parameters. This* ***would be currently, and for the near future, our most direct way of seeking a quantum leap in our understanding*** *of the nature and structure of compact objects"*

After 35 years, we are in the quantum leap!

Next talk about IXPE results on April 3rd by R. Ferrazzoli