INAF ISTITUTO NAZIONALE DI ASTROFISICA

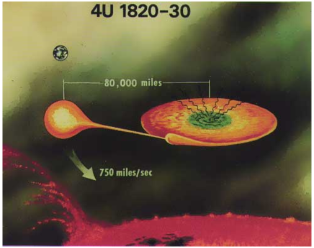
IAPS ISTITUTO DI ASTROFISICA E PLANETOLOGIA SPAZIALI

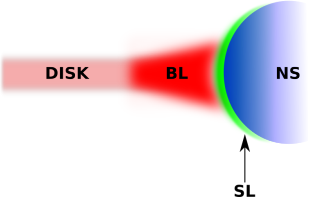
The IXPE View of NS-LMXBs: New Insights from X-ray Polarimetry into Emission Geometry and Accretion Physics

Alessandro Di Marco alessandro.dimarco@inaf.it
INAF-IAPS, Italy

High Energy Astrophysics and Cosmology in the era of all-sky surveys – Yerevan, Armenia June 15-19 2026

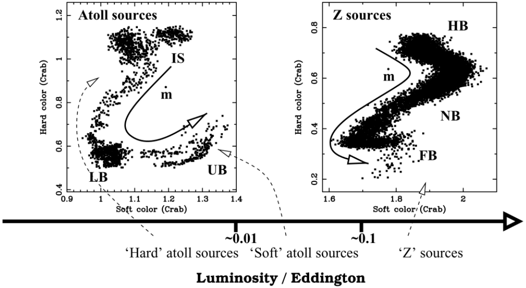
2026 June 19





[*La Monaca, PoS FRAPWS2024, 39, 2025*]

- 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}
  - **Peculiar sources**

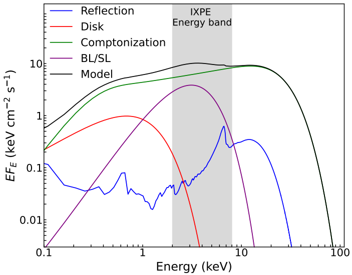


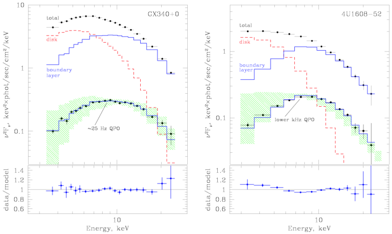
[Migliari & Fender 2006]

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

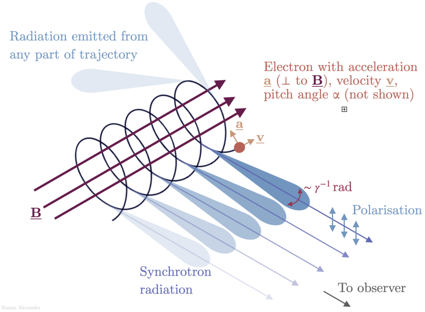
- Energy-resolved Fourier spectra point towards the Eastern scenario
- Highly inclined ADC sources favor western/Birmingham model





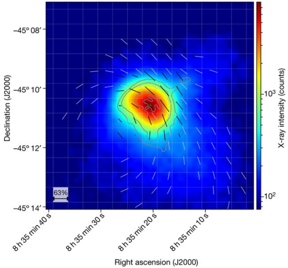
[Gilfanov et al., A&A 410, 217, 2003]

- **Polarization is a vector** → measures geometry
  Electric vector position angle = EVPA or simply PA
- **Synchrotron radiation** → PA perpendicular to magnetic field lines
- **Scattering/reflection** → PA parallel/perpendicular to scattering plane
- **Strong magnetic fields** → PA transported along magnetic field orientation
- **Strong gravitational fields** → PA parallel-transported along space-time geodesics



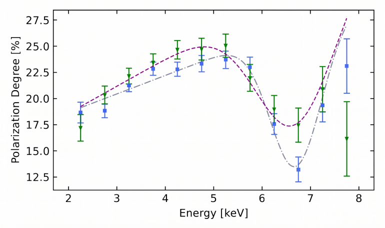
Polarization variations to track source variations

Spatial variability



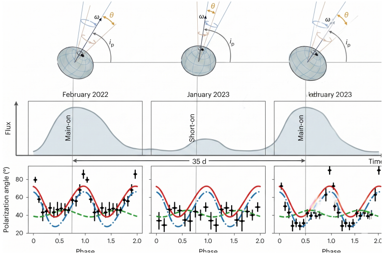
Maps of magnetic fields
F. Xie, **Di Marco**+ Nature 612(2022)658

Energy variability



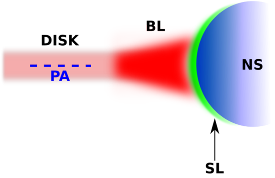
Break spectral degeneracy
R. Mikusinkova+
(**incl. Di Marco**)
arXiv:2512.12879, accpted ApJ

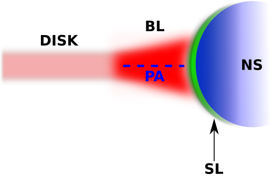
Time variability

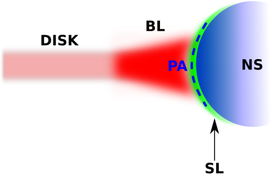


Track geometrical variations in the emitting regions
J. Heyl+ (**incl. Di Marco**)
Nat. Astro. 8(2024)1047

Polarization in WMNSs: what could we expect?







- **Accretion disk**: PD<6% and **PA parallel to the disk**
  - Chandrasekhar 1960
  - Loktev+ A&A 660, 25, 2022
- **Boundary layer**: PD<10% and **PA parallel to the disk**
  - Sunyaev & Titarchuk A&A 143, 374, 1985
- **Spreading layer**: PD<2% and **PA flipped by 90° with respect to BL/disk**
  - Bobrikova+ A&A 696, 181, 2025
- **Other sources of polarized radiation**
  - **Reflection component**: PD up to 20-30% (Poutanen+ MNRAS 283, 892, 1996): unpolarized fluorescence lines
  - **Scattering in the wind**: PD up to 20% (Nitindala+ A&A 694, 230, 2025)
  - **Extended accretion disk corona**: PD max 20% in the case $\tau = 1$ (Brown & McLean A&A, 57, 141, 1977; **Di Marco**+ ApJL 979, 47, 2025)

Observed WMNSs by IXPE

Z-sources

- **Sco-like**
  - **Sco X-1** *La Monaca+ ApJL 960, L11, 2024*
  - **GX 349+2** *La Monaca+ A&A 702, A40, 2025*
  - **GX 17+2** *Kashyap+ ApJ 994,221, 2025*
- **Cyg-like**
  - **Cyg X-2** *Farinelli+ MNRAS 519, 3681, 2023*
  - **GX 5–1** *Fabiani+ A&A 684, A137, 2024*
  - **GX 340+0** *La Monaca+ A&A 691, A253, 2024*
    La Monaca+ A&A 702, A101, 2025

Atoll-sources

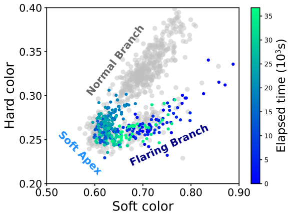
- **GS 1826–238** *Capitanio+ ApJ 943, 129, 2023*
- **GX 9+9** *Ursini+ A&A 676, A20, 2023*
- **4U 1820–303** *Di Marco+ ApJL 953, L22, 2023*
- **4U 1624−49** *Saade+ ApJ 963, 133, 2024*
- **Ser X-1, GX 3+1, 4U 1728−34, 4U 1735−44, GX 9+1, 4U 0614+091**

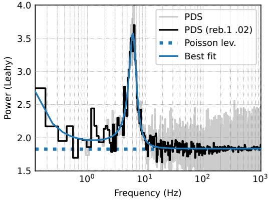
Peculiar sources

- **Cir X-1** *Rankin+ ApJL 961, L8, 2024*
  La Monaca+ in preparation
- **GX 13+1** *Bobrikova+ A&A 688, A170, 2024*
  Bobrikova+ A&A 688, A217, 2024
  Di Marco+ ApJL, 979, L47, 2025
  Di Marco+ in preparation
- **XTE J1701–462** *Cocchi+ A&AL 674, L10, 2023*
- **2S 0921-630 (V395 Car)** *Tomaru+ MNRAS 2026*

20 WMNSs observed by IXPE!

La Monaca, A. Di Marco, J. Poutanen et al., ApJL 960, L11, 2024
La Monaca, AN 346, e20240107, 2025 La Monaca, PoS FRAPWS2024, 39, 2025

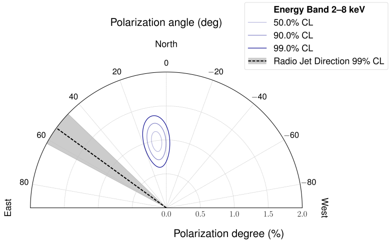


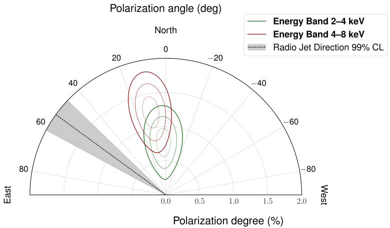


[*La Monaca+ ApJL 960, L11, 2024*]

- 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)
- An ideal candidate to **attempt to measure X-ray polarization**: OSO-8 satellite (Long et al., 1979) and PolarLight (Long et al., 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: polarization angle VS radio-jet direction



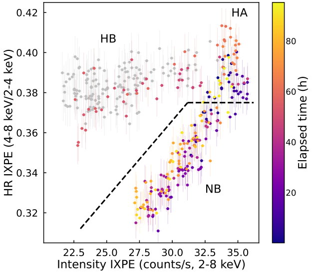


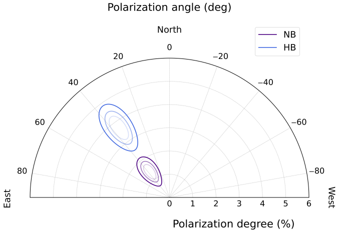
[*La Monaca, AN 346, e20240107, 2025*]

- **IXPE Sco X-1 measurement shows a PA rotated of $\sim 46^\circ$ with respect to the radio-jet position angle and previous OSO-8 and PolarLight observations**
- **The rotation of the PA may be due to relativistic precession or HR variations?**:
  - **relativistic precission**: Cir X-1 showed variations of the orientation of the radio jet over time, first time observed for an NS (Cowie+ 2025)
  - **variation of the geometry in the different states** see later Cir X-1 and GX 13+1
- **new simultaneous radio + IXPE observation**

GX 340+0: a Cyg-like source

La Monaca, Di Marco, Ludlam, Bobrikova, Poutanen et al., A&A 691, A253, 2024
La Monaca, Di Marco, Coti Zelati, Bobrikova, Ludlam, Poutanen et al., A&A 702, A101, 2025

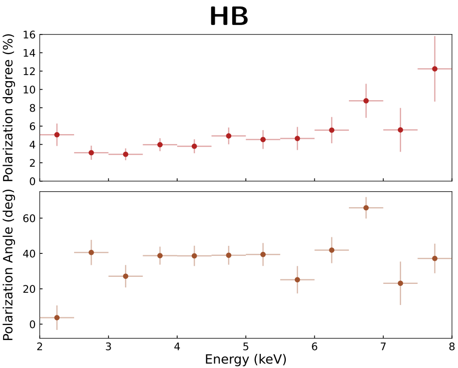




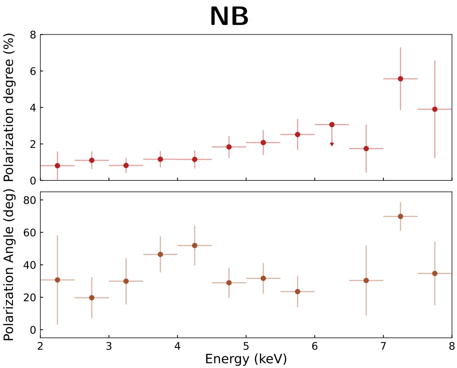
- Z source belonging to **Cyg-like sub-class**: intermediate inclination $\sim 35°$ from the reflection model
- No evidence of spatially resolved radio-jet

- **Polarization in the HB** ($\sim 11\sigma$ CL): $\mathrm{PD} = 4.3\% \pm 0.4\%$ at $\mathrm{PA} = 36° \pm 3°$
- **Polarization in the NB** ($\sim 5.6\sigma$ CL): $\mathrm{PD} = 1.4\% \pm 0.3\%$ at $\mathrm{PA} = 37° \pm 5°$
- **PD of the HB is higher than NB**
- **Compatible PAs in the two branches**

GX 340+0: energy-resolved polarization analysis

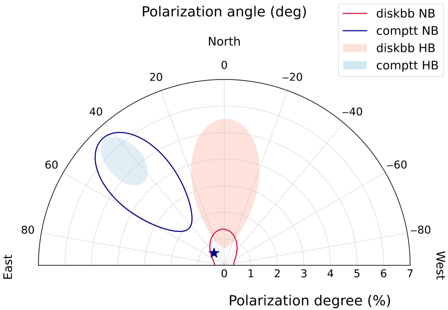


[*La Monaca, Di Marco, Ludlam+ A&A 691, A253, 2024*]



[*La Monaca, Di Marco, Coti Zelati+ A&A 702, A101, 2025*]

- **PD increasing with energy**: up to $\sim 12\%$ in the HB and up to $\sim 6\%$ in the NB
- PA variation of $\sim 40^\circ$ is observed between the soft and high energy bins in the HB; not observed in the NB



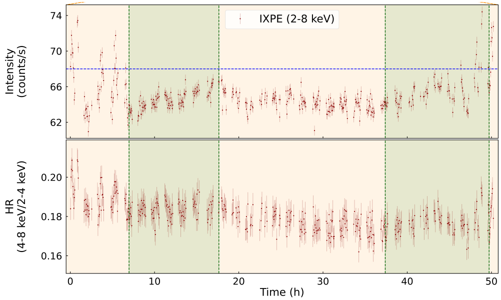
[*La Monaca, Di Marco, Coti Zelati+ A&A 702, A101, 2025*]

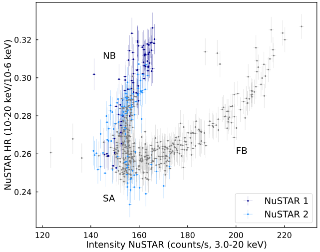
- Spectropolarimetric models with independent polarization for soft and Comptonized components with unpolarized Gaussian
- PD of the Comptonized emission from an optically thick and relatively narrow SL expected to be <0.6% (Bobrikova+ 2025)

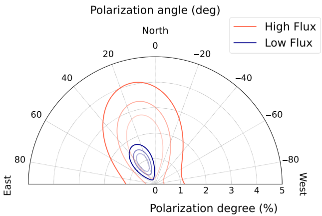
- **Uncommon PA difference of** $\sim 40^{\circ}$ between the two spectral components: misalignment of the disk/BL axis with the NS axis?
- PD of the Comptonized component remains **constant at** $\sim$**4% between the HB and the NB**
- The high **polarization from Comptonization requires inclination 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

F. La Monaca, A. Bobrikova, J. Poutanen et al., A&A 702, A40, 2025

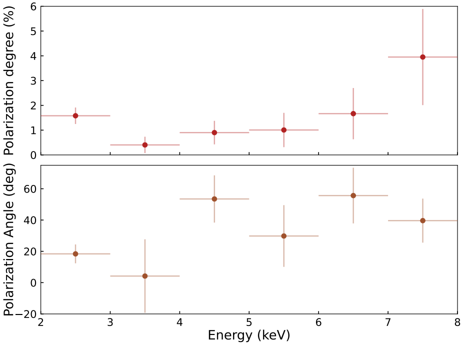






- **GX 349+2 was observed mainly in the NB** (joint NuSTAR observation)
- Polarization results ($\sim$4.2 σ): PD $= 1.1\,\% \pm 0.3\,\%$ at PA $= 29\,^\circ \pm 7\,^\circ$
- **PD compatible with other sources observed in the NB** (Cyg X-2, GX 5$-$1, XTE J1701$-$462, GX 340+0)
- No significant variability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

GX 349+2: spectropolarimetric analysis



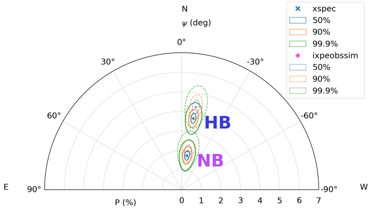
Spectral component		GX 349+2	GX 340+0 NB	GX 340+0 HB
diskbb	PD (%)	1.0 ± 0.7	< 1.2	3.1 ± 1.7
	PA (°)	6^{+24}_{-23}	–	-1 ± 16
Comptonization	PD (%)	3.7 ± 3.0	4.3 ± 1.8	5.2 ± 1.0
	PA (°)	68 ± 26	44 ± 13	44 ± 5

- Gaussian assumed unpolarized

[*La Monaca, Bobrikova, Poutanen et al., A&A 702, A40, 2025*]

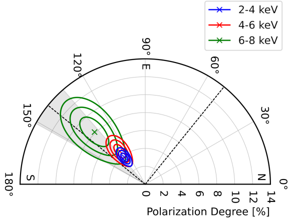
- **Complex variability for PD/PA with energy**; similar trend for PD in GX 340+0
- Spectropolarimetric analysis confirmed the polarization variability with energy: `XSPEC pollin` model favored respect to a PD constant behaviour with energy
- **PD of the Comptonized emission exceeds the theoretical predictions**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

GX 5-1



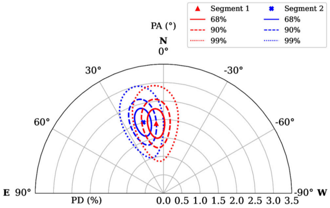
[*Fabiani+ (incl. Di Marco)+ A&A 684, A137, 2024*]

Cyg X-2



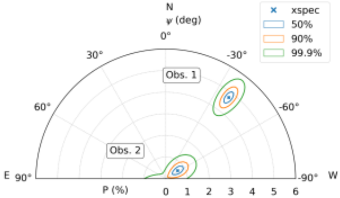
[*Farinelli (incl. Di Marco)+ MNRAS 519, 3681, 2023*]

GX 17+2



[*Lavanya+ MNRAS 549, 1–12, 2026*]

XTE J1701−462



[*Cocchi (incl. Di Marco)+ A&A 674, L10, 2023*]

Sco X-1

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

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

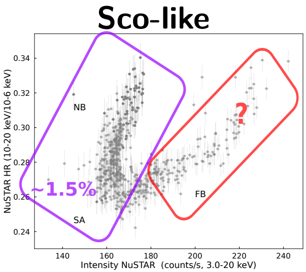
GX 349+2

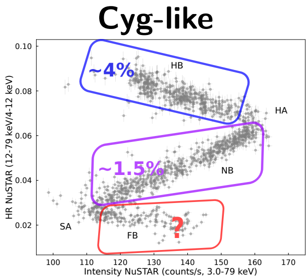
Component		Model B1	Model B2	Model B3
diskbb	PD (%)	0.9 ± 0.7	[1.0]	[1.0]
	PA (°)	5^{+25}_{-23}	[6]	[6]
bbodyrad	PD (%)	< 4	[3.7]	[0]
	PA (°)	—	[68]	—
relxillNS	PD (%)	< 62	< 9	11 ± 5
	PA (°)	—	—	68^{+12}_{-13}

[*La Monaca, Bobrikova, Poutanen et al., A&A 702, A40, 2025*]

- **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 $> 1\%$. Similar results for Cyg X-2 (Liu+ JHEA 51, 100548, 2026),
- 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)

Polarization in Z sources

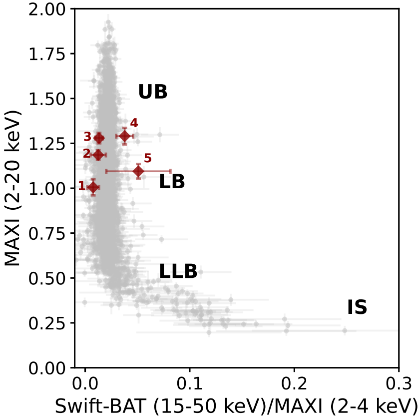




- Average polarization as expected is typically low, **but higher than atoll sources**
- Compatible PD results for Cyg-like and Sco-like sources: **polarization is not governed by the subclass**
- **polarization variation with the accretion flow**
- **PD is higher in the HB and lower in the NB**

Branches	Z-sources	PD (2–8 keV)
NB	Cyg X-2, XTE J1701-462, GX 5-1, Sco X-1, GX 340+0, GX 349+2, GX 17+2	~1.5%
HB	XTE J1701-462, GX 5-1, GX 340+0	~4%

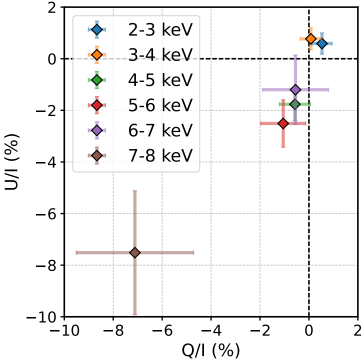
A. Di Marco, F. La Monaca, J. Poutanen et al., ApJL 953, L22, 2023

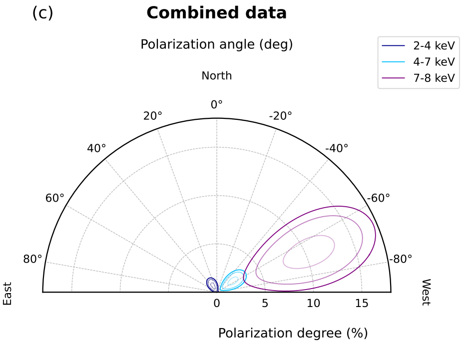


- LMXB consisting of a He WD accreting onto an ultracompact NS
- First identified source of type I X-ray bursts (bursts only around the flux minima)
- LMXB with the shorter orbital period (685 s)
- Superorbital period of $\simeq$ 170 days

- 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, 255, 1984*)
- IXPE observed the source two times in the LB state

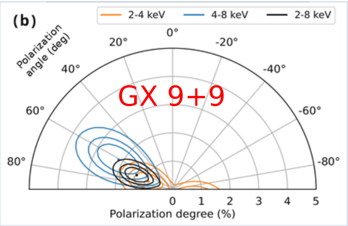
4U 1820–303: polarization as a function of the energy

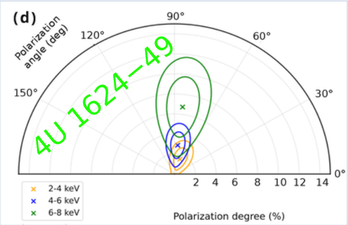




[*Di Marco, La Monaca, Poutanen et al., ApJL 953, L22, 2023*]

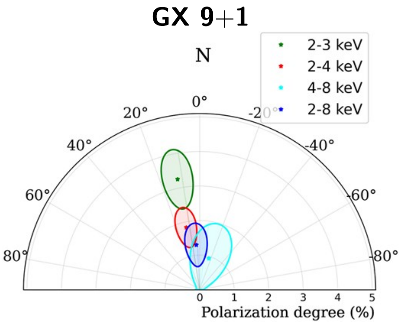
- Polarization results to be energy dependant
- Energy bin 7–8 keV **highly significant (99.99%CL)**
- PA rotation of 90 deg at 96% CL at $\simeq$4 keV





GX 9+9 *Ursini+ (incl. Di Marco) A&A 676, A20, 2023*

4U 1624−49 *Saade+ (incl. Di Marco) ApJ 963, 133, 2024*

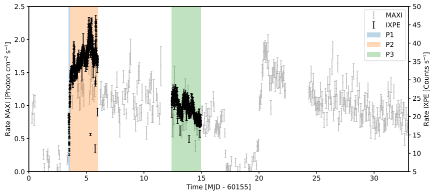


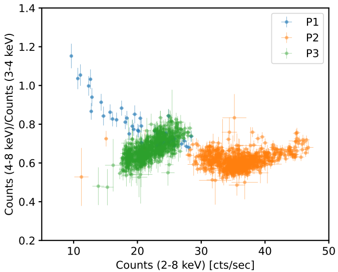
[*Prakash+ MNRAS 540, 1578, 2025*]

- **Atoll sources polarization in 2-8 keV smaller than Z sources**
- **Atoll sources show an energy trend of PD only 4U 1820−303 shows indication of PA rotation**

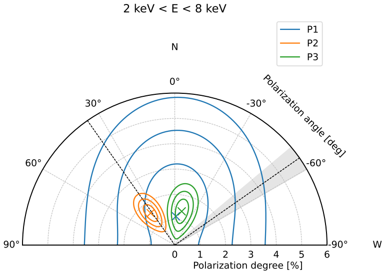
Circinus X-1

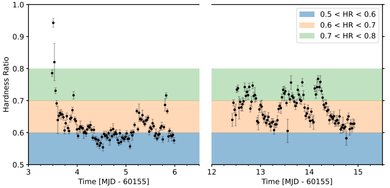
J. Rankin, F. La Monaca, A. Di Marco et al., ApJL 961, L8, 2024

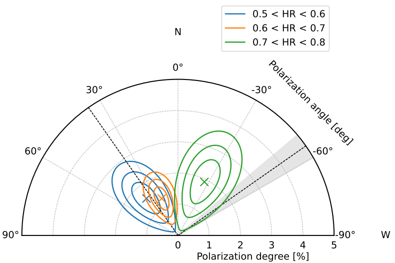




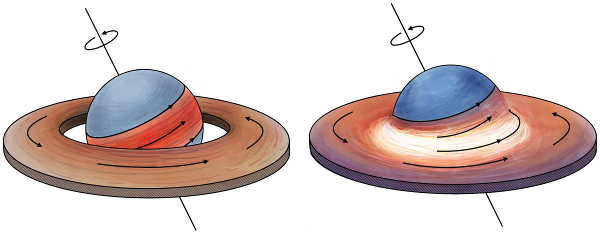
- Peculiar XRB: historically went through Z and atoll states
- Young XRB having eccentric $\sim$16.6 days orbit, during which its flux and spectrum change
- X-ray and radio jets: almost aligned (Heinz+ 2008)
- IXPE observation starts at the exit from the dip during the **transition** from the high to the low flux states and covered the **flaring** phase and the **stable** one



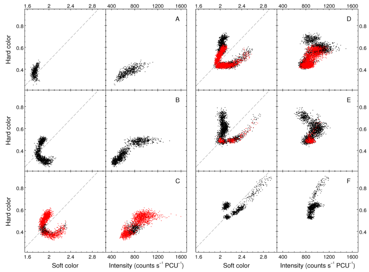




[*Rankin, La Monaca, Di Marco et al., ApJL 961, L8, 2024*]

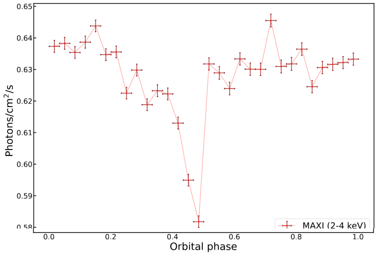


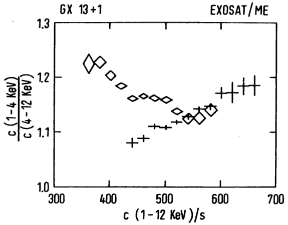
- **Cir X-1 continuous state variations during orbit**
- Boundary layer dominant at high accretion rates (PA aligned with accretion disc)
- Spreading layer dominant at low accretion rates (PA parallel to rotation axis)
- Relativistic effects can cause rotations, but not so large
  - ➥ **misalignment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

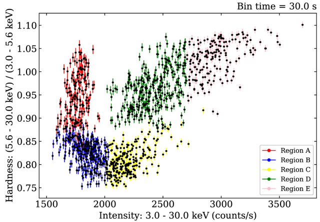


[Fridriksson+ ApJ809(2015)52]

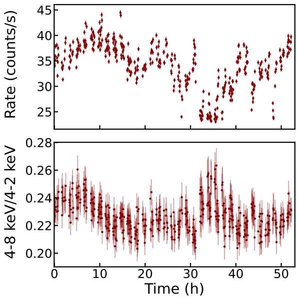
- Peculiar source, unique position between atolls and Z-sources:
  - ➥ Bright as Z-source (up to 0.5 L_{edd}) and persistent radio emission
  - ➥ CCD shape closer to atolls source
- 24.5 d periodic flux variation due to orbital movement (the longest between NS-LMXB) with almost regular short dips of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



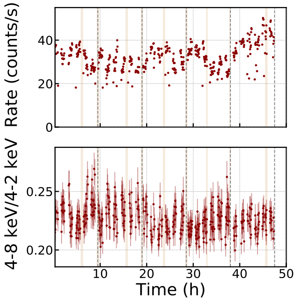




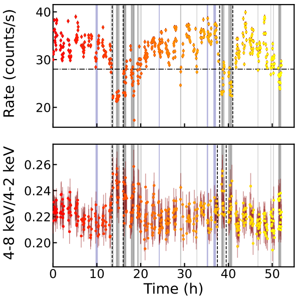
GX 13+1: IXPE observations



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*)



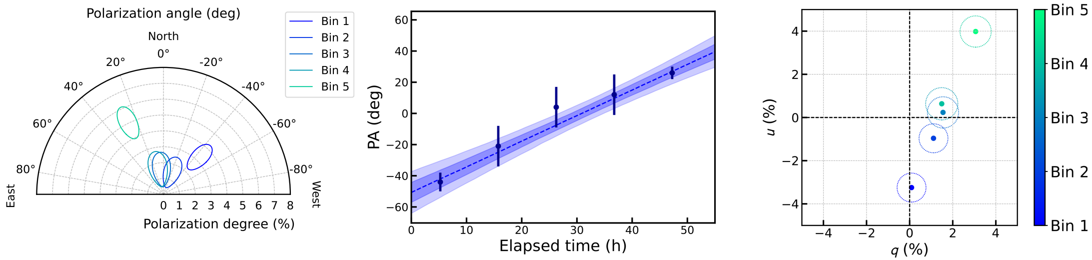
Third observation performed in April 2024 (*A. Di Marco, F. La Monaca, A. Bobrikova, et al., ApJL, 979, L47, 2025*)

Plus a fourth observation performed on October 2025

GX 13+1: time evolution in the first observation

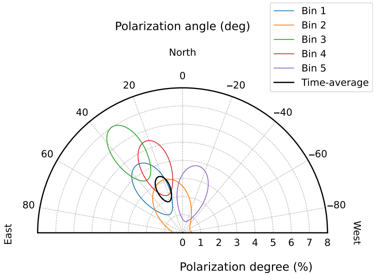
A. Bobrikova et al., A&A 688, A170, 2024

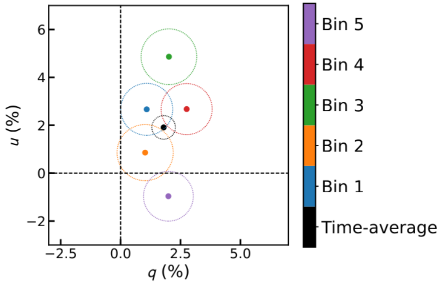
- We **split data into five equal time bins** (10.55 h each)
- rotation of the PA with time with a slope of 1°.64 per hour and the **total rotation angle exceeding 70°**
- The evolution of the source in the q-u plane shows a straight line
- PD is relatively high at the beginning and at the end of the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



Possible contribution from wind/obscuration of the source?

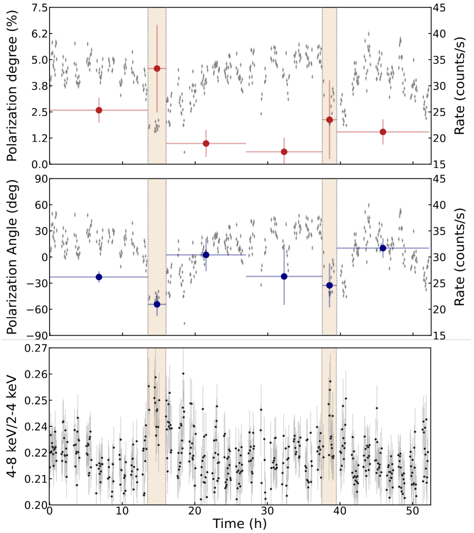
A. Bobrikova et al., A&A, 688, A217, 2024





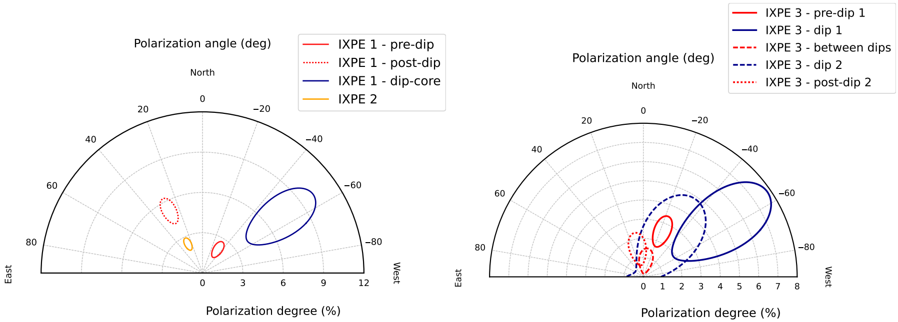
- Measured a significant polarization in a peculiarly absorbed state
  - ➥ PD$=2.6\% \pm 0.5\%$
  - ➥ PA$=23^\circ \pm 5^\circ$
- Time variability of the PD, while PA is almost constant

GX 13+1: time evolution in the third observation



- Polarization related to flux variations?
- Higher PD during dips
- PA rotation during dips

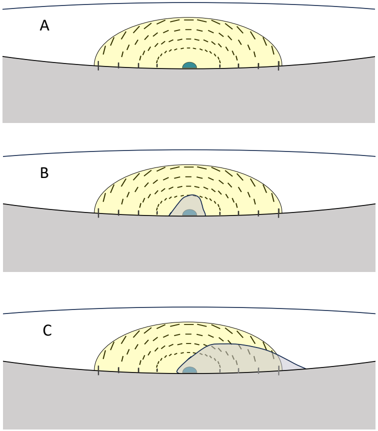
GX 13+1 comparison of different observations



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

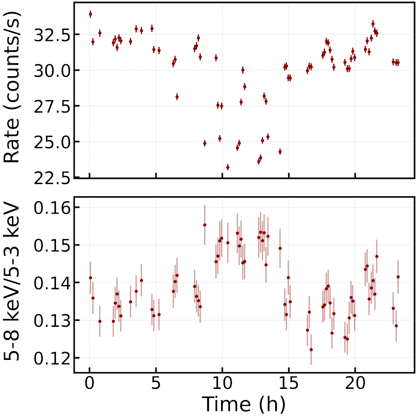
GX 13+1: geometrical constraint

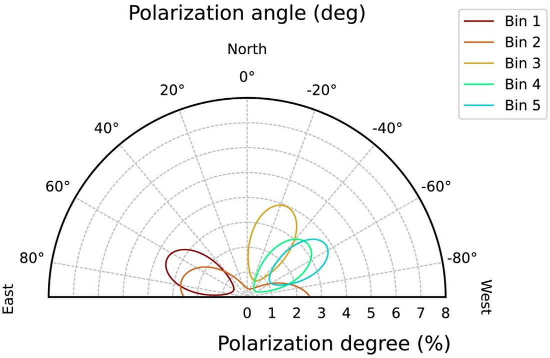
- PA rotations could be explained with different obscuration of the different emitting regions
- During dips the central region (NS+BL/SL) is obscured
  - ➥ accretion disk corona polarization contribution increases
  - ➥ optical depth varying with time in the wind



[*Di Marco et al., ApJL, 979, L47, 2025*]

- First source observed by IXPE showing polarization changing with the spectral state passing from HB to NB
- Hint for PA rotation during the NB





[*Di Marco, Astron. Nachr. 346:e20240126, 2025*]

Millisecond pulsars observed by IXPE

Accreting millisecond pulsar

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

Transitional millisecond pulsar

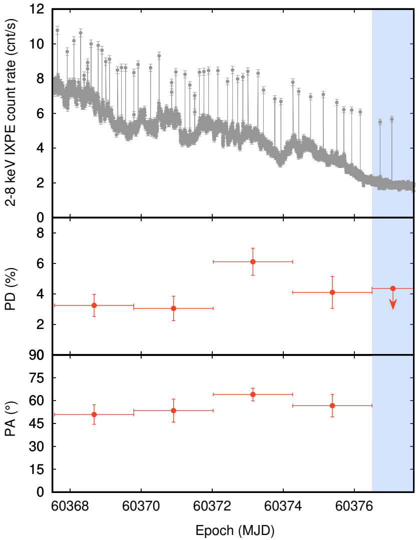
- **PSR J1023+0038** *M. C. Baglio et al., ApJL 987, 19, 2025*

Spider pulsar

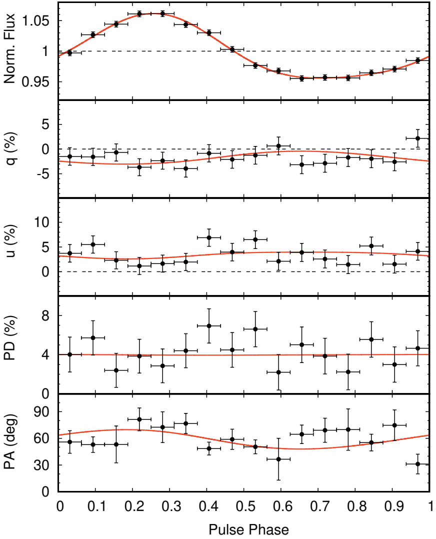
- **PSR J1723–2837** *M. Negro et al., ApJ 999, 207, 2026*

SRGA J144459.2-604207: Polarization as a function of time

- 52 **Type I X-ray bursts** detected and removed from the data (PD<8.5% at 90% CL)
- **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 significant**:
  - ➥ $\mathrm{PD}_{3-6} = 4.0\% \pm 0.5\%$ and $\mathrm{PA}_{3-6} = 57^\circ \pm 3^\circ$
- No significant variations with time observed on longer time scales

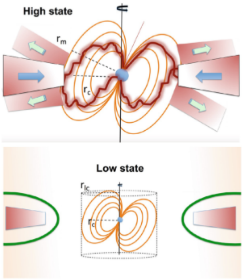


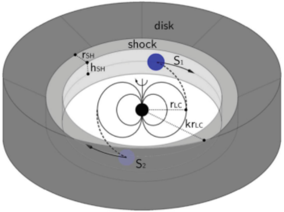
Phase-resolved polarization before MJD 60376.5



- Phase-resolved analysis in $n = 16$ phase bins in the 3–6 keV energy band
- Stokes parameters Q and U are compatible with a constant:
  - $q = Q/I = -1.6\% \pm 0.5\%$ ($\chi^2/dof = 16.6/15$)
  - $u = U/I = 3.5\% \pm 0.4\%$ ($\chi^2/dof = 15.6/15$)
- Best fit for two hot spots provides $\chi^2/dof = 38.8/41$ [Papitto+, A&A 694(2025)37]:
  - $i = (74.1^{+5.8}_{-6.3})^\circ$
  - $\theta_1 = (11.8^{+2.5}_{-3.5})^\circ$
  - $\theta_2 = (172.6^{+2.0}_{-1.0})^\circ$
  - $\chi_p = 57.2^\circ \pm 0.5^\circ$
  - $\phi_0 = 0.57(4)$
  - $N = 6.90(6) \times 10^4$ counts
  - $p_1 = 4.0\% \pm 2.0\%$

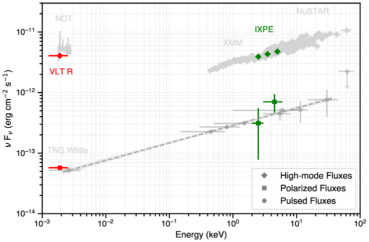
Baglio, Zelati, Di Marco et al.,ApJL 987 (2025) L19

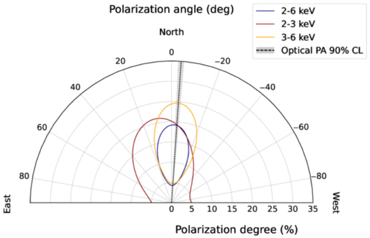


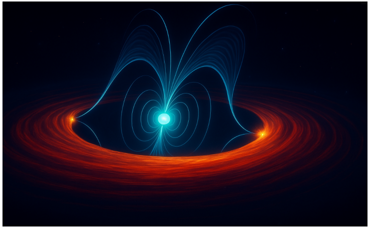


- Mini pulsar wind nebula scenario:
  - ➥ High mode: the radio pulsar is active; the wind interacts with the innermost accretion flow in a region of shock. The dissipation at the shock produces most of the X-ray emission via synchrotron, and is responsible for coherent pulsations from optical up to X-raya
  - ➥ Low mode: the shock moves outwards; X-rays are lower and pulsations are washed out
  - ➥ Flaring mode: the shock increases its dimension, giving origin to episodes of high X-ray fluxes.

X-ray polarization of PSR J1023+0038







- Results provide direct evidence that the polarized and pulsed emissions both originate from synchrotron radiation at the shock formed where the pulsar wind interacts with the inner regions of the accretion disk
- Similarities between J1023 and PWNe:
  - ➥ High-energy emission attributed to synchrotron radiation produced by electrons accelerated within highly ordered, predominantly toroidal magnetic fields shaped by the pulsar wind
  - ➥ Polarization degree observed in a few PWNe is higher than in J1023: distinct geometries and scales of PWNe compared to J1023 may play a crucial role in the observed differences

Conclusion and future perspectives

- Average polarization is typically low, but **time- and energy- resolved analysis showed enhancements in PD**
- **Z-sources show a common PD pattern with branches**

- Radio-jet misalignment and PA variations were unexpected
- **Misalignment disk/BL axis and NS axis?** it can be possible for young systems as Cir X-1
- **PA rotation with time in GX 13+1 and XTE J1701−462** could be explained with presence of dips
  - ➥ Possible contribution from scattering in disk wind or extended accretion disk corona

- **IXPE observed two AMSPs: phase-resolved analysis provided no highly significant variation**

For more information: