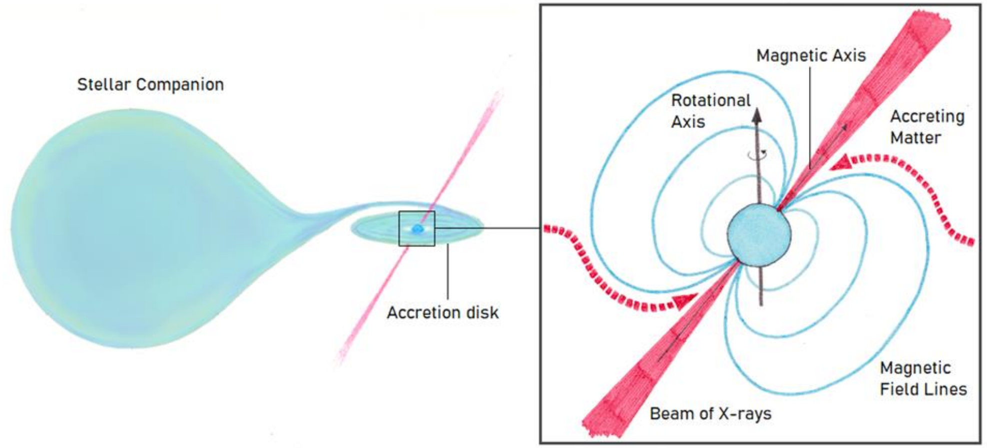
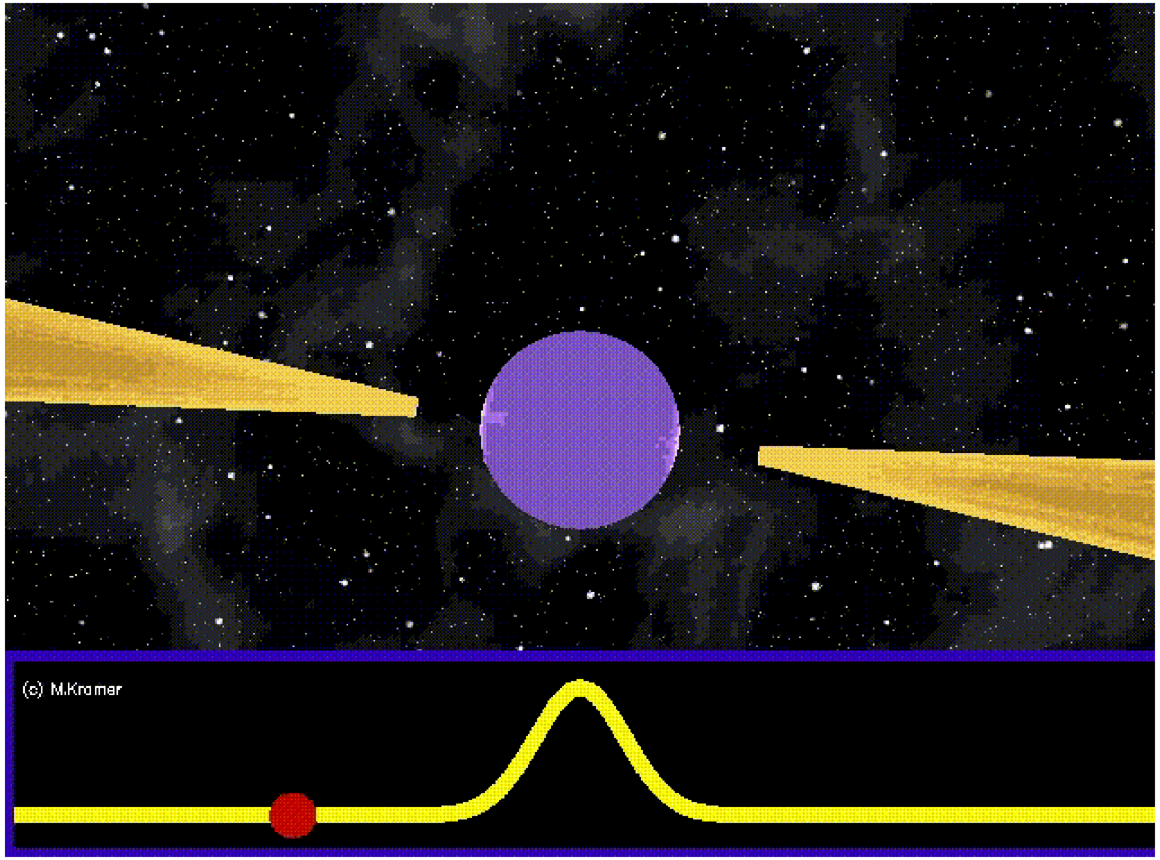
Polarized emission from X-ray pulsars probed by IXPE

Sofia V. Forsblom, + …
University of Turku

X-Ray Pulsars

X-RAY PULSARS are highly magnetized (B ≈ $10^{11\text{-}13}$ G) neutron stars accreting matter from a close stellar companion





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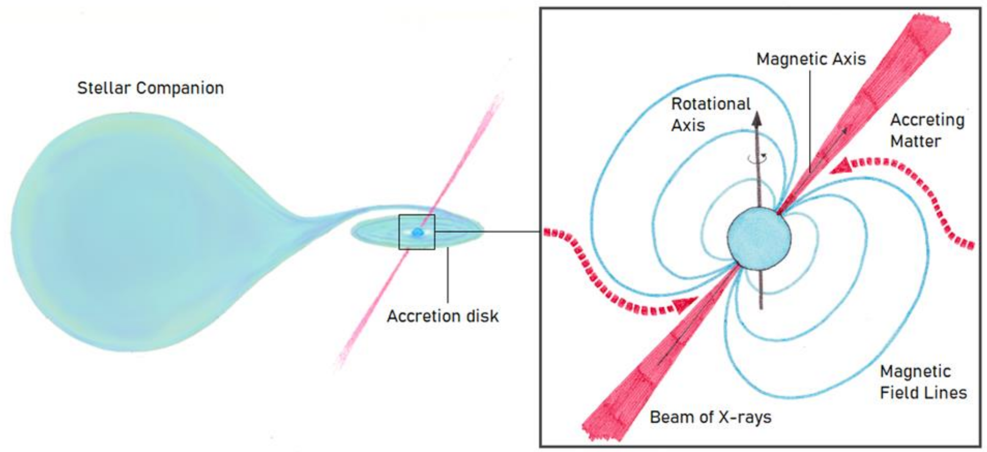
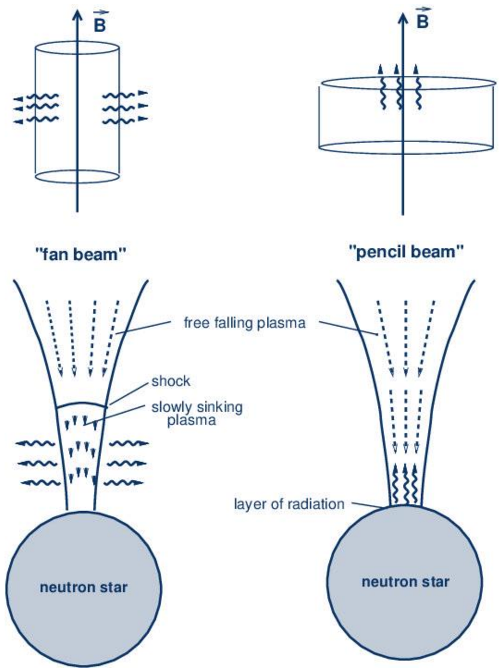


The beam pattern of the emerging radiation is determined by the emission region geometry

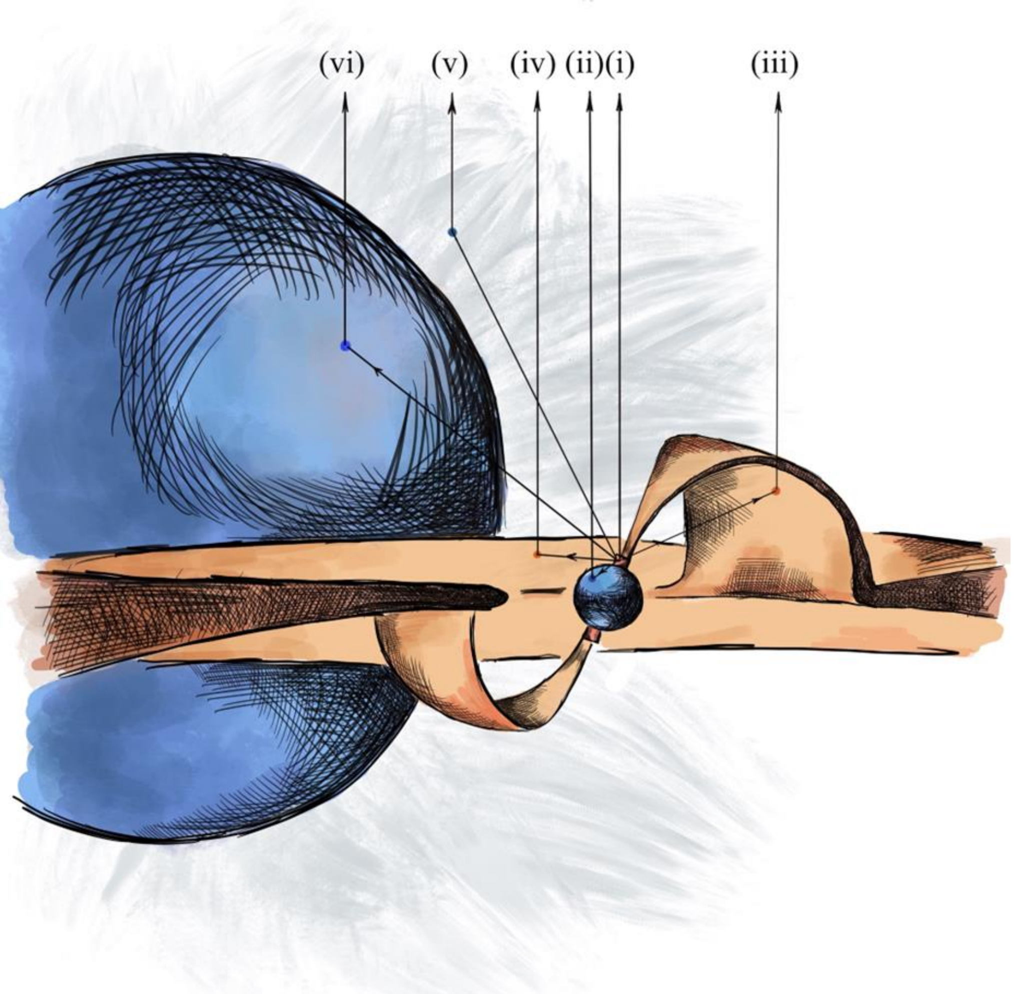
Two main configurations:

High mass accretion rates = ACCRETION COLUMN = "fan beam"



Low mass accretion rates = HOT SPOT = "pencil beam"

X-Ray Pulsars



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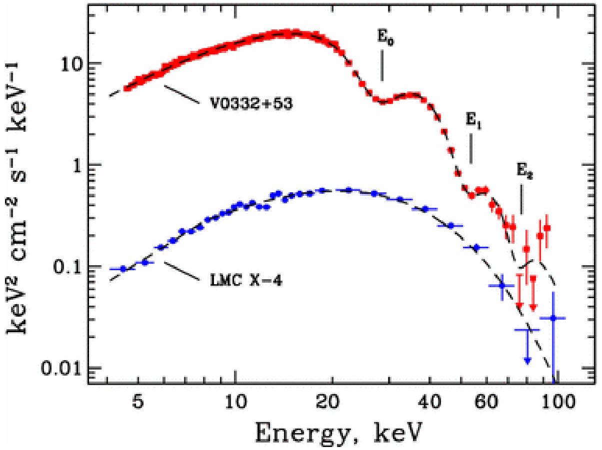
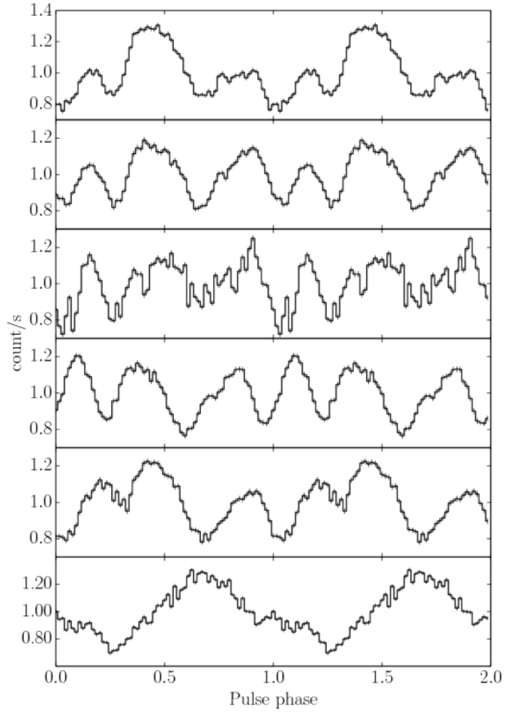
Spectral



Timing



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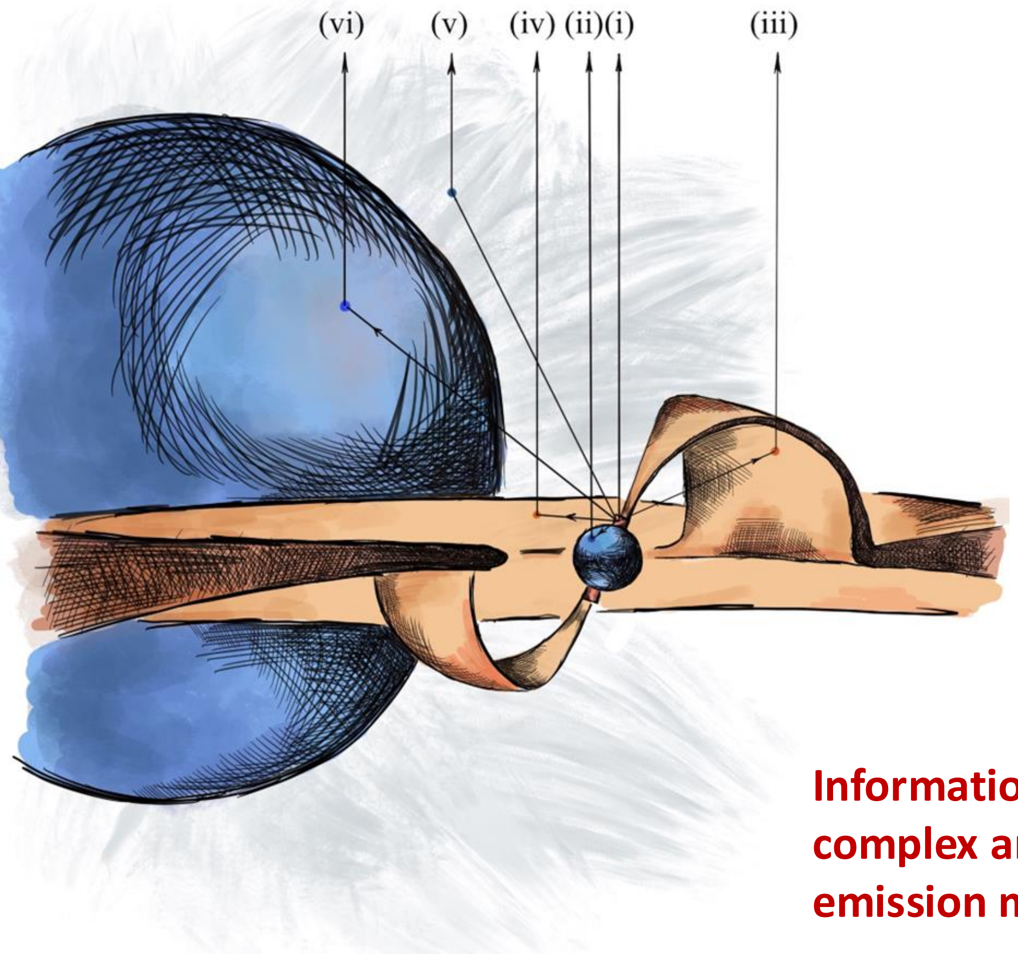

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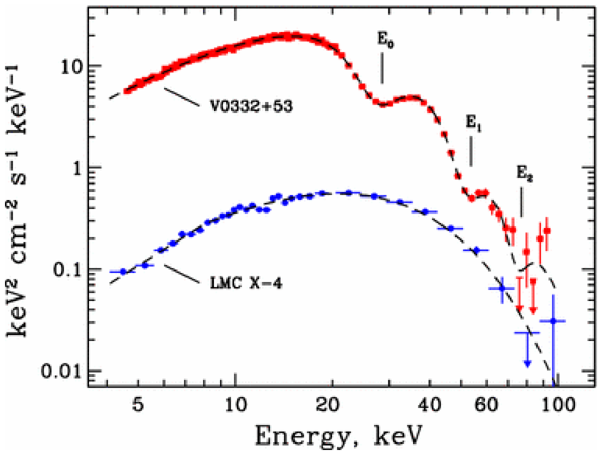

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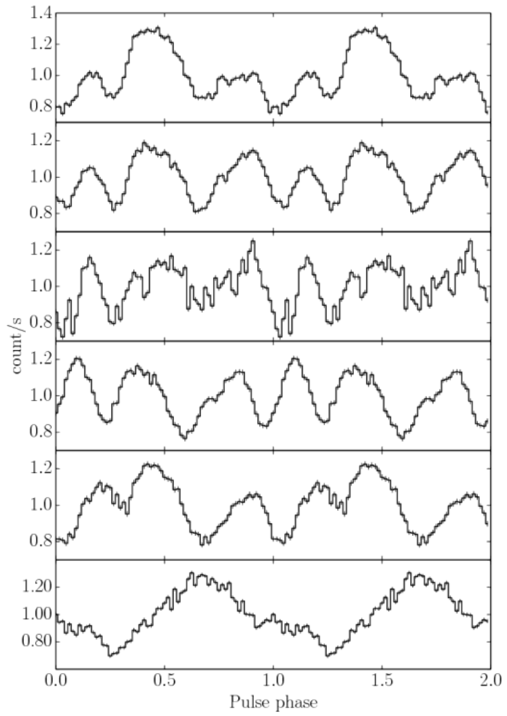
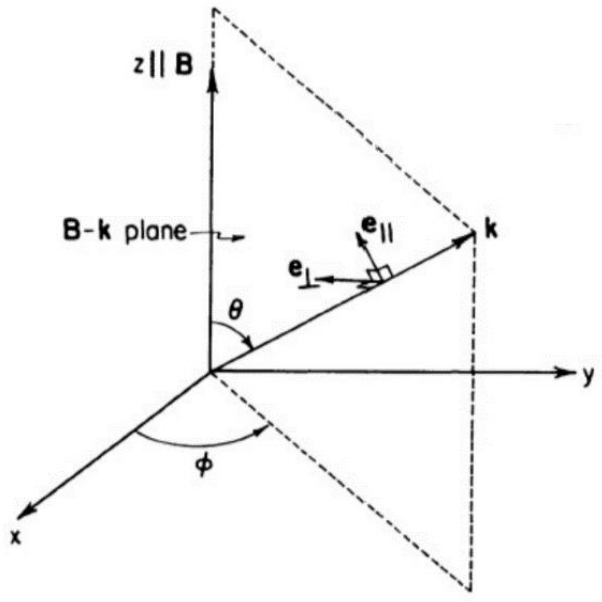


Information is heavily degenerate with complex and uncertain physics of emission mechanisms

X-RAY PULSARS - POLARIZATION

The magnetic field of the neutron star is the main cause of the polarized X-ray emission

The birefringence of highly magnetized plasma allows us to treat the polarization in terms of two normal polarization modes:



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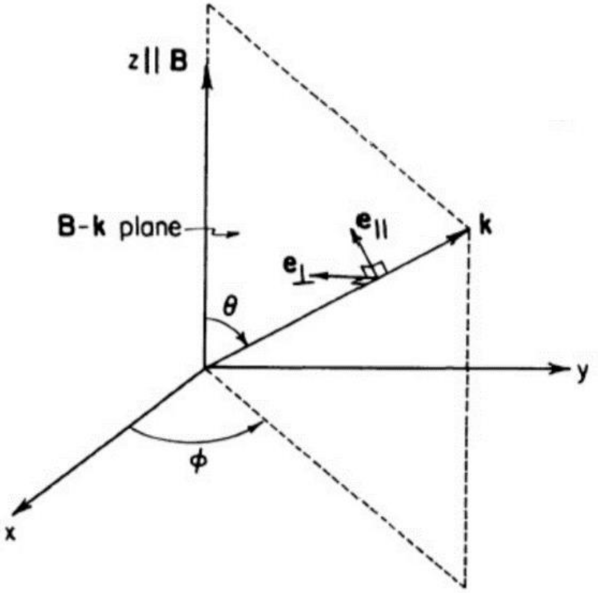
E-vector oscillates in the k-B plane



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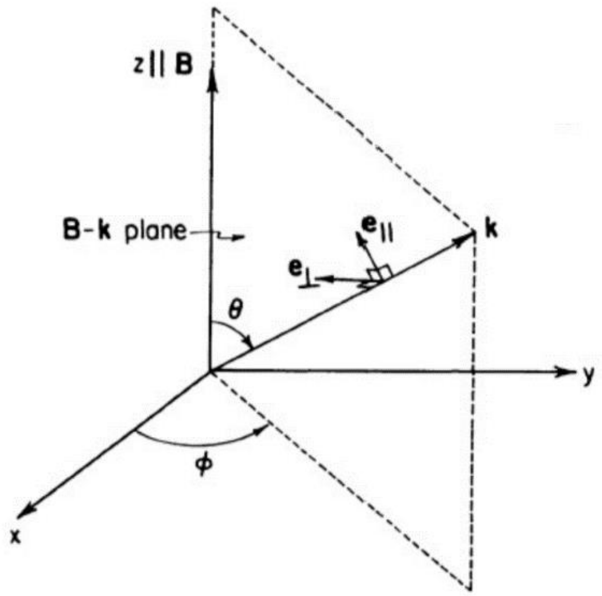

X-Ray Pulsars - Polarization

IXPE
Imaging X-Ray Polarimetry Explorer

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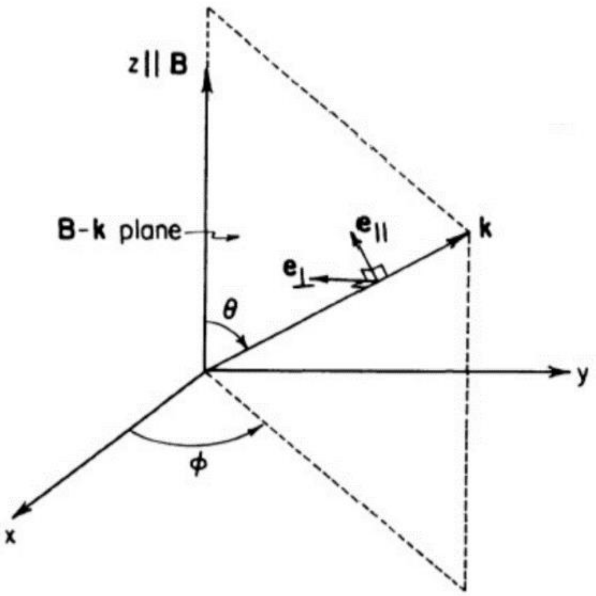
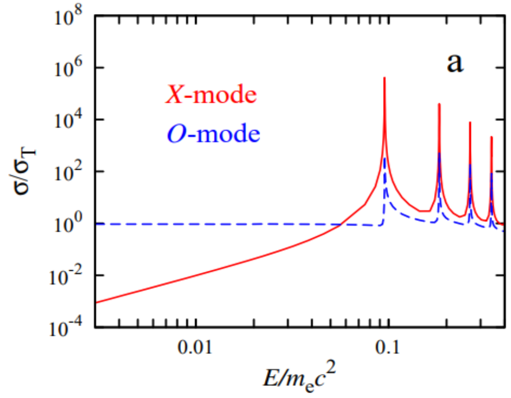




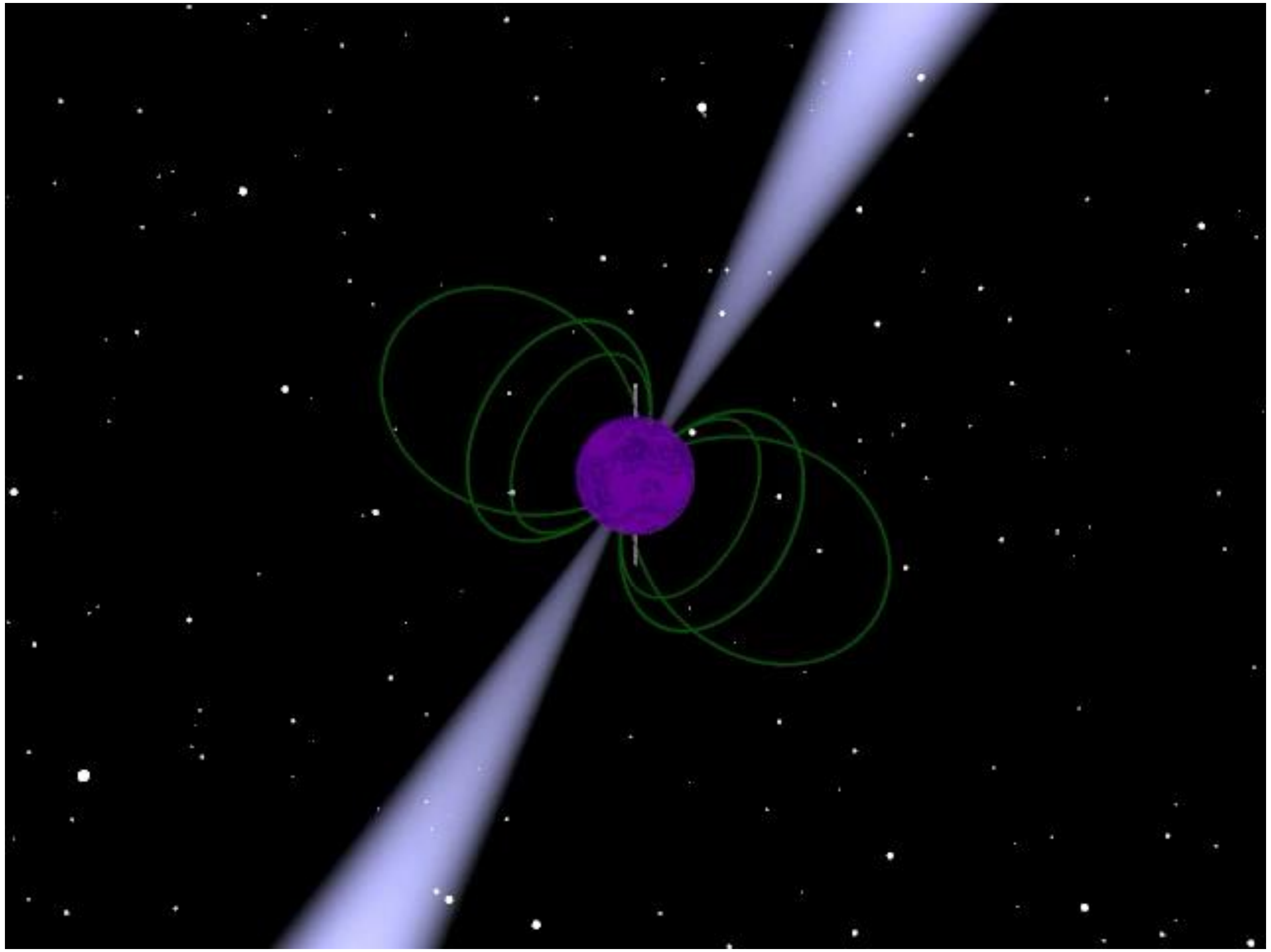
Mushtukov et al. 2016

Scattering of photons in a highly magnetized plasma is expected to result in a strong polarization of emerging X-rays:

Linear polarization can reach up to 80% (for favorable orientations)

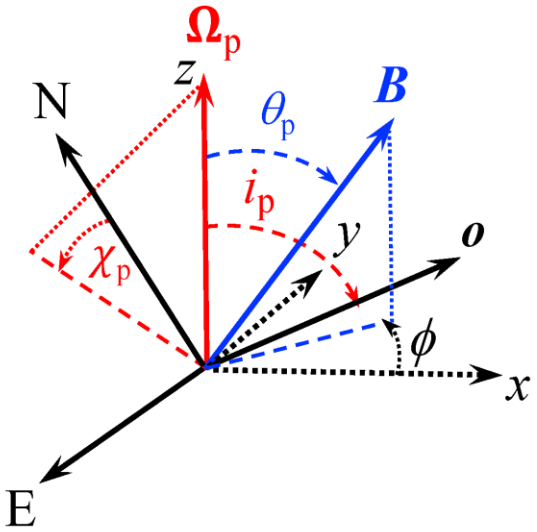
(Meszaros et al. 1988)

ROTATING VECTOR MODEL (RVM)



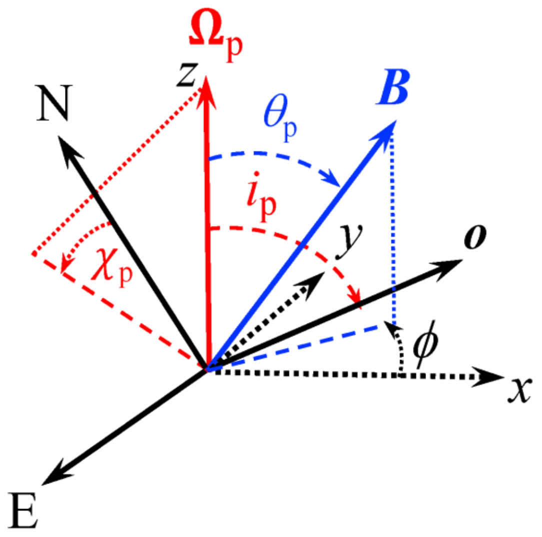
In the RVM, the evolution of the PA with pulse phase is related to the projection of the magnetic dipole on the plane of the sky:

$$\tan(\mathrm{PA} - \chi_\mathrm{p}) = \frac{-\sin\theta\ \sin(\phi - \phi_0)}{\sin i_\mathrm{p} \cos\theta - \cos i_\mathrm{p} \sin\theta \cos(\phi - \phi_0)}$$



Poutanen+ 2024

RVM ⟶ PULSAR GEOMETRY



Position angle of pulsar angular momentum

$$\tan(\mathrm{PA} - \chi_\mathrm{p}) = \frac{-\sin\theta\ \sin(\phi - \phi_0)}{\sin i_\mathrm{p}\ \cos\theta - \cos i_\mathrm{p}\ \sin\theta\ \cos(\phi - \phi_0)}$$

Inclination of pulsar spin with respect to line of sight

Magnetic obliquity

IXPE Imaging X-Ray Polarimetry Explorer

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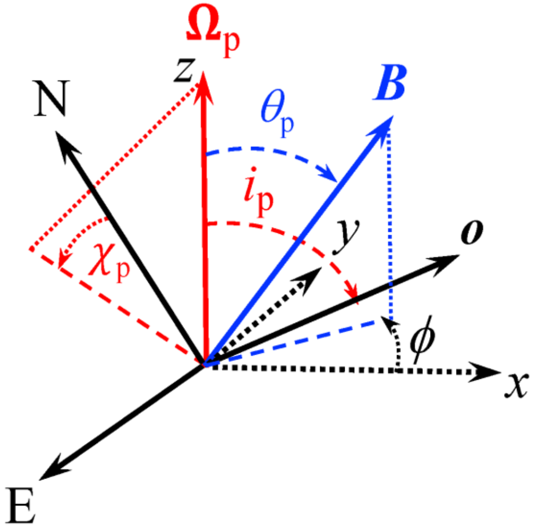

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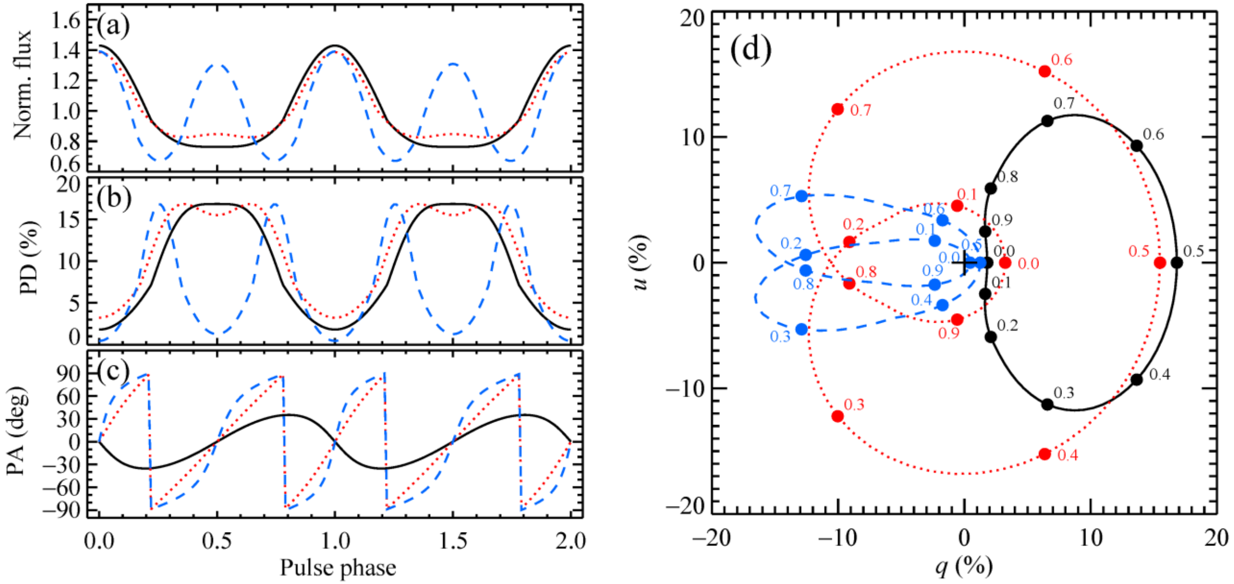

(i,θ)

(60°, 30°)
(30°, 70°)
(70°, 85°)

IXPE – X-Ray Pulsars

1. Her X-1
2. Cen X-3
3. 4U 1627-67
4. Vela X-1
5. X Persei
6. GX 301-2
7. GRO J1008-57
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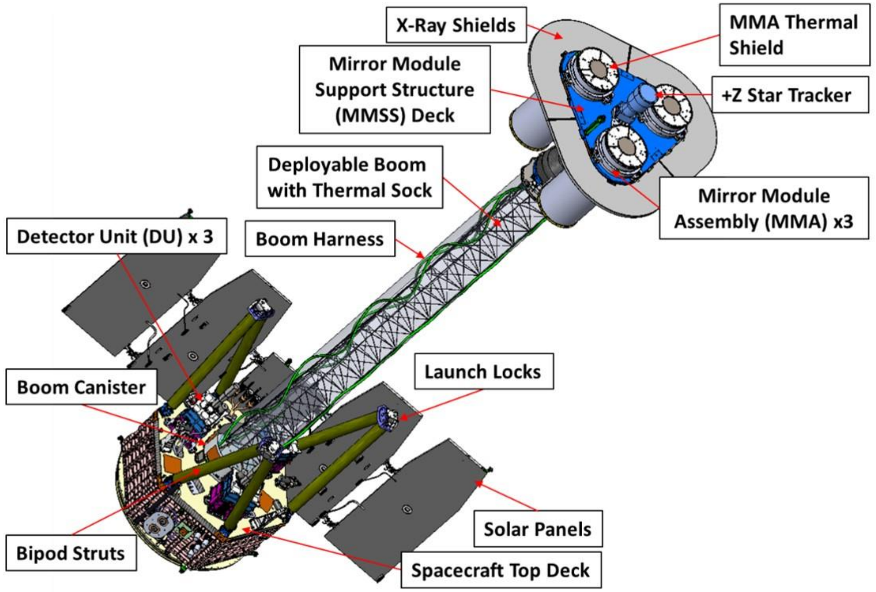

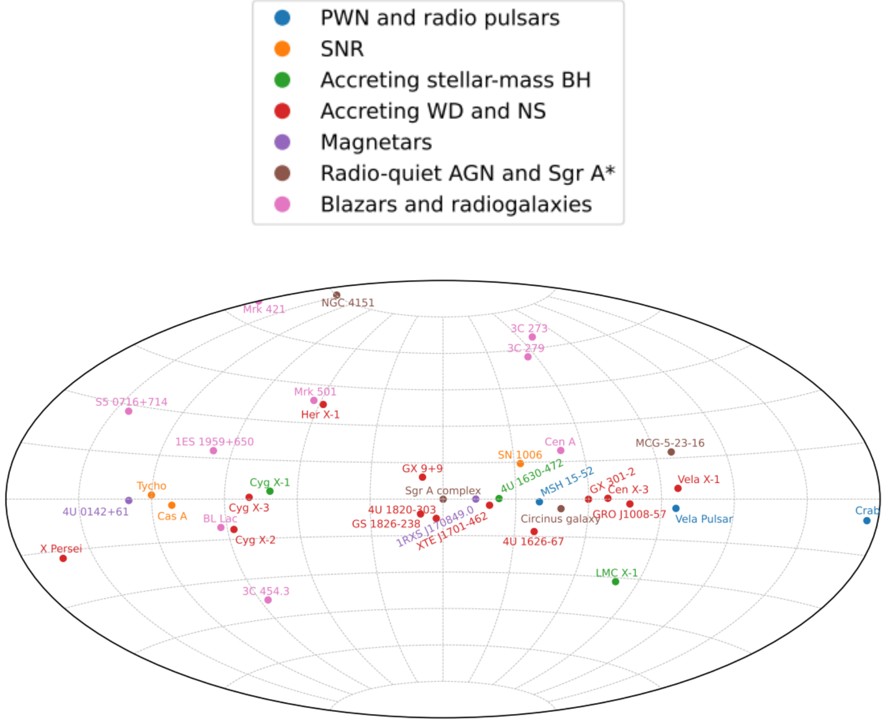

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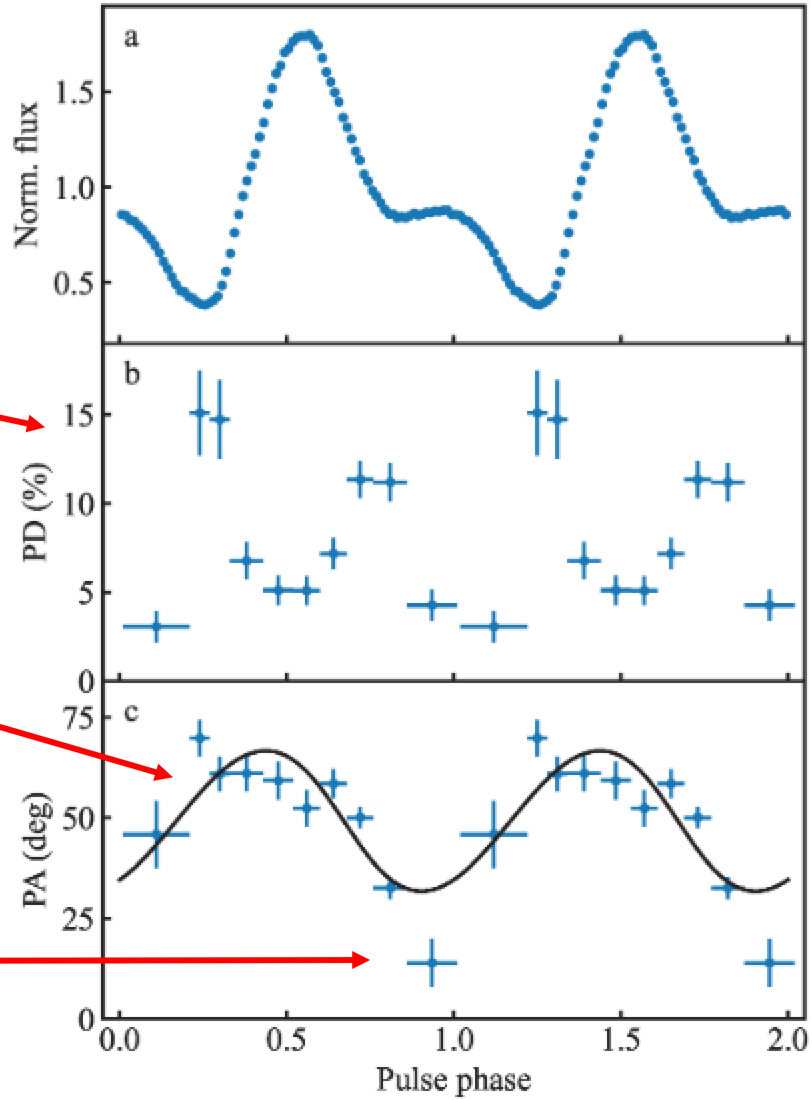
X-RAY PULSARS - POLARIZATION

Typical display of IXPE results for X-ray pulsars

LOW POLARIZATION DEGREE

ROTATING VECTOR MODEL (RVM)

RVM DEVIATION

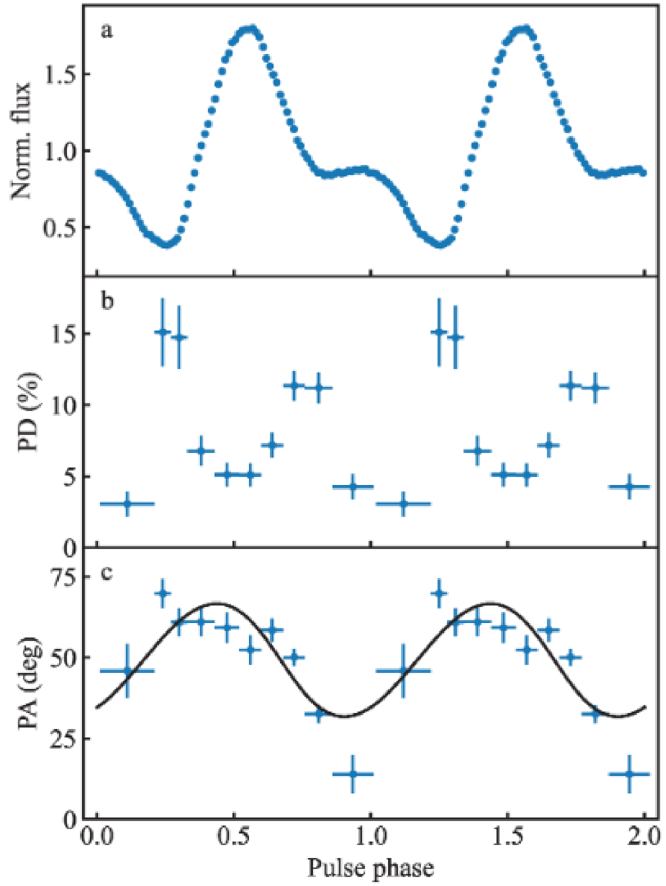


Cen X-3

Tsygankov+, 2022, ApJL

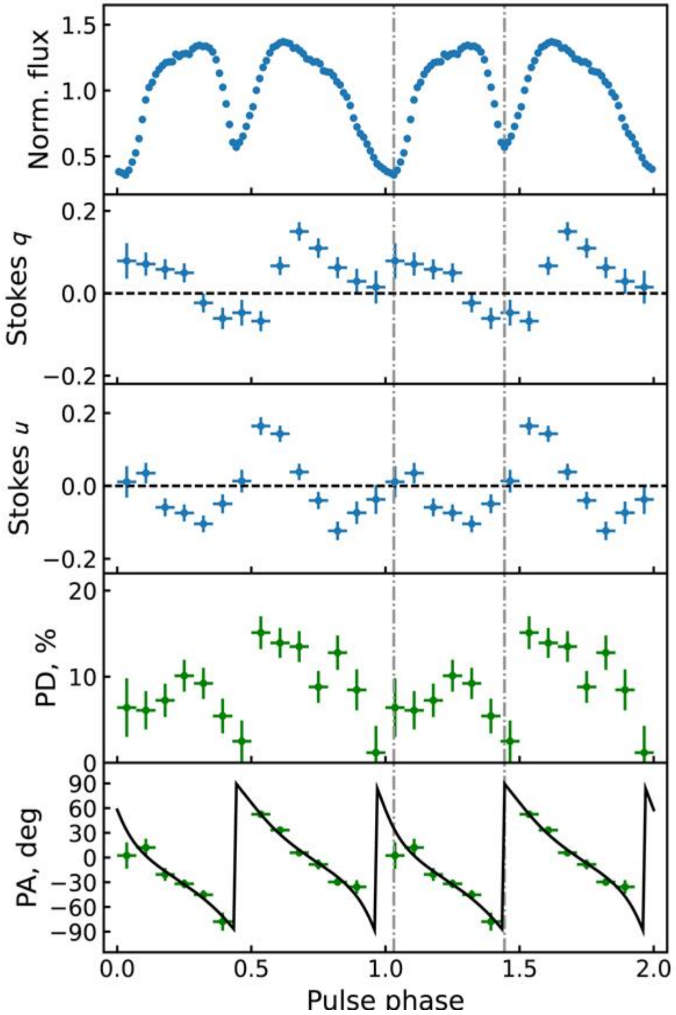
GEOMETRIES OF DIFFERENT XRPS

Cen X-3



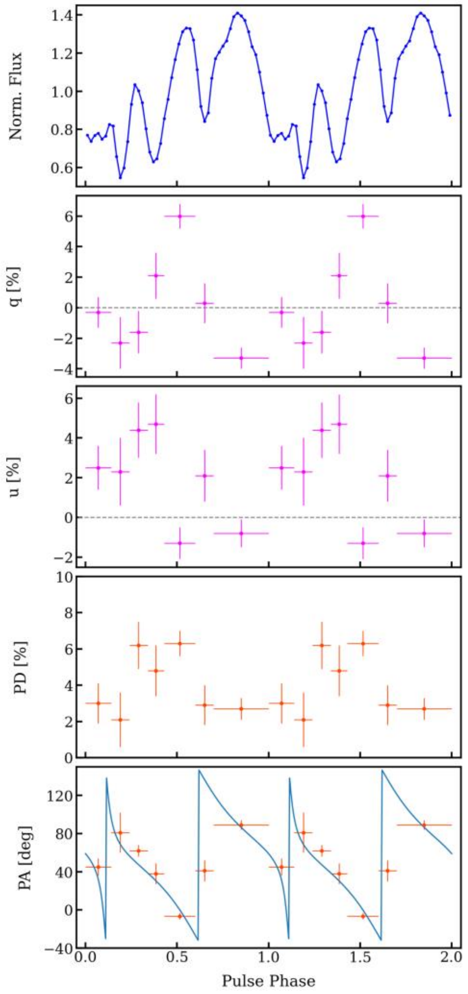
Tsygankov+, 2022, ApJL

GRO J1008-57



Tsygankov+, 2023, A&A

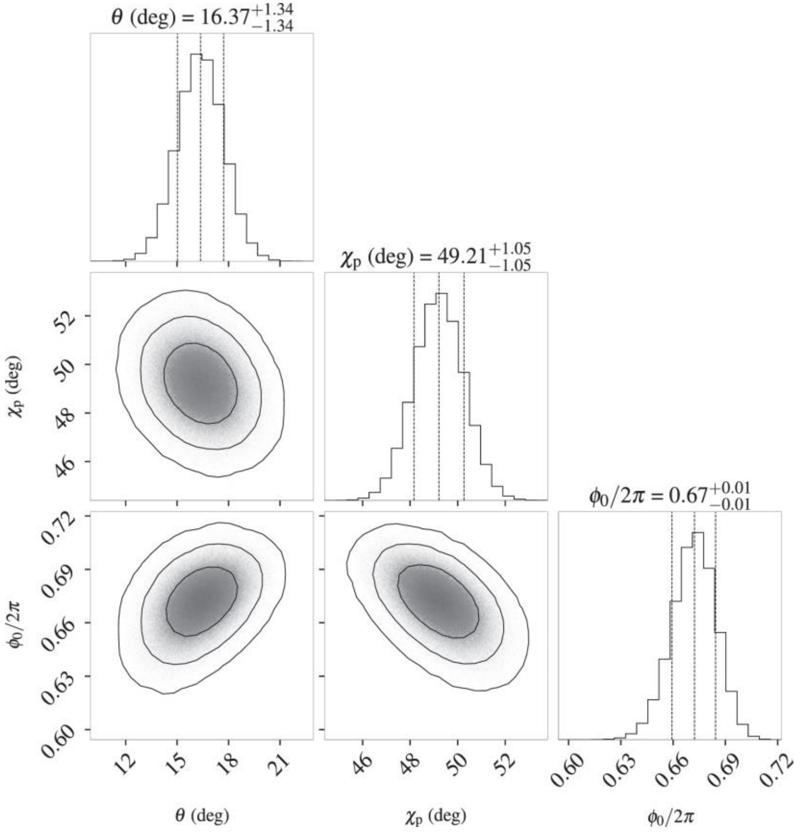
EXO 2030+375



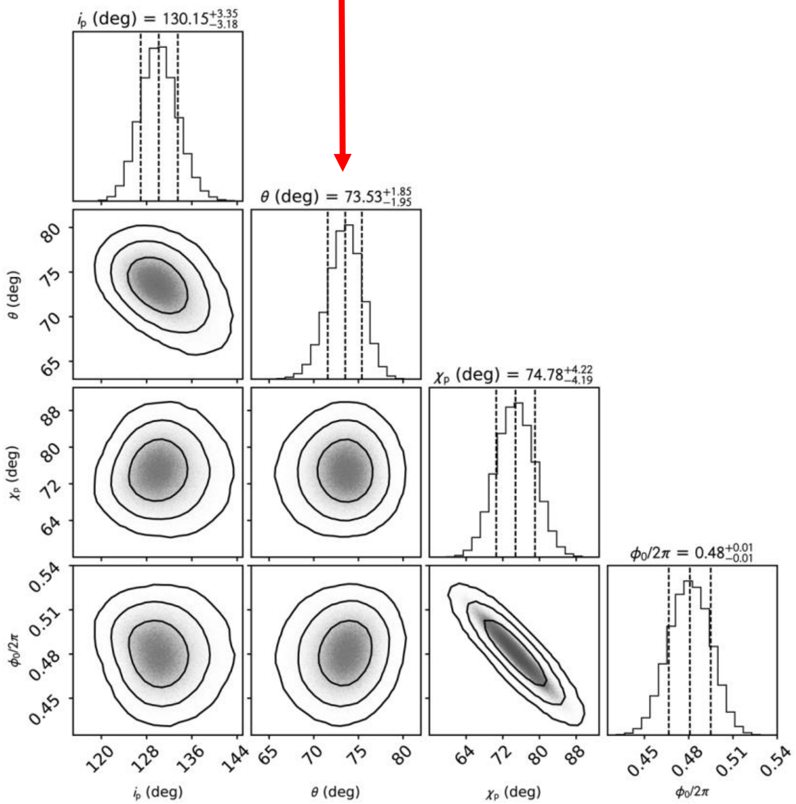
Malacaria+, 2023, A&A

GEOMETRIES OF DIFFERENT XRPs

Cen X-3



GRO J1008-57
Orthogonal rotator



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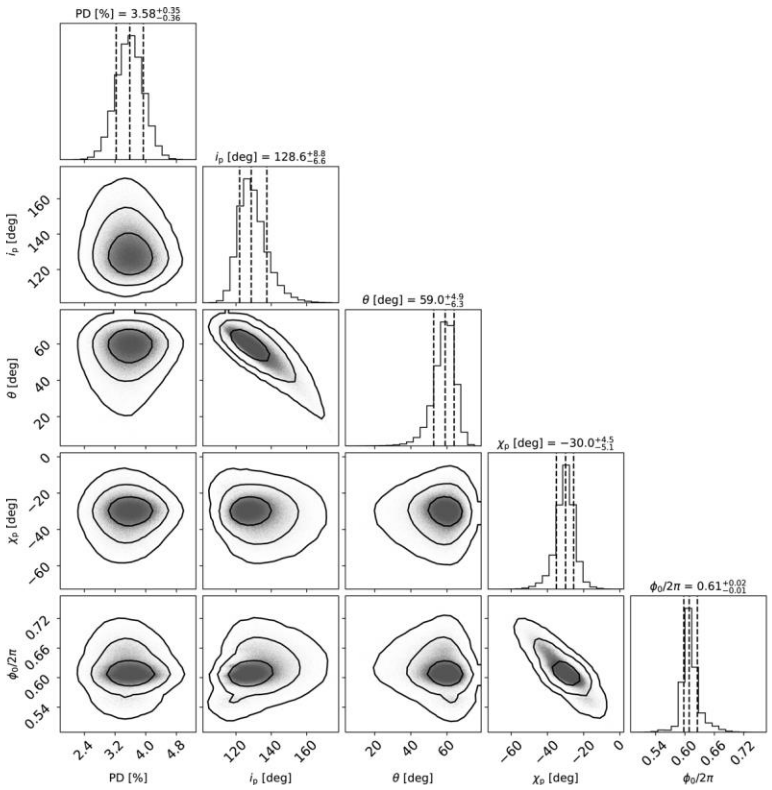

ADDITIONAL POLARIZED COMPONENTS

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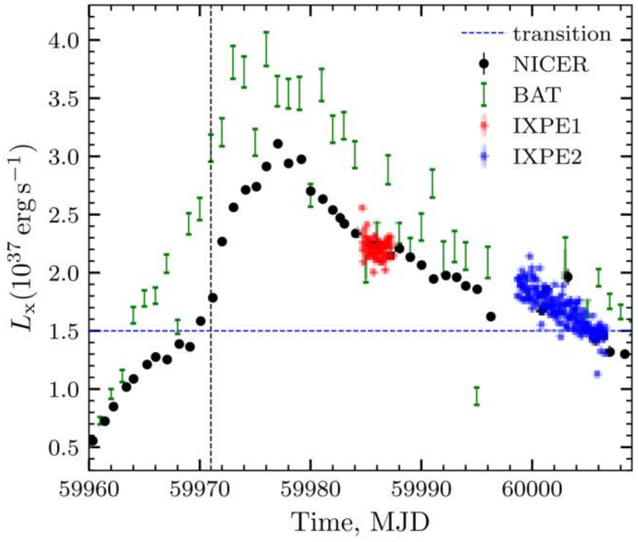

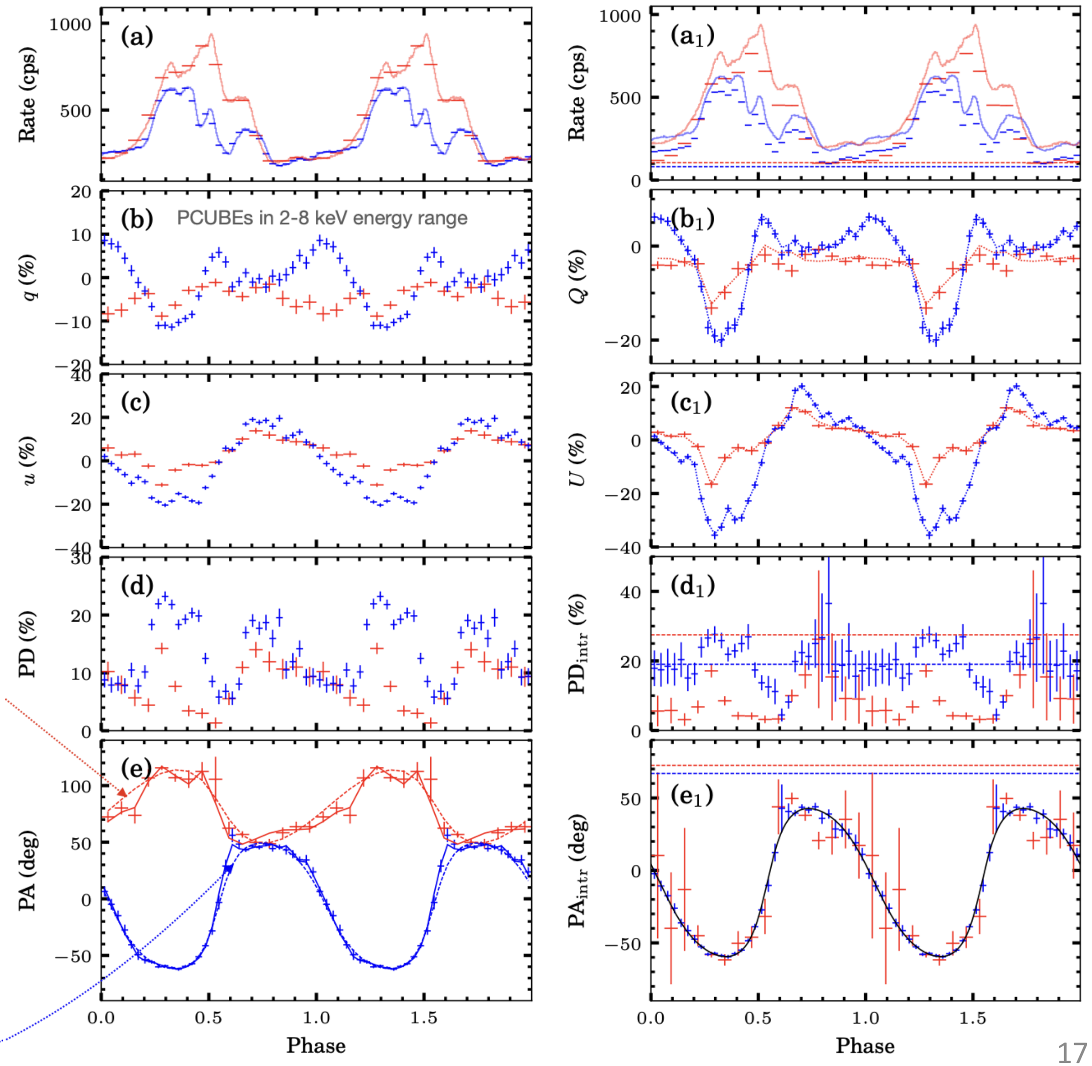

Doroshenko+, 2023, A&A

Geometry is dramatically different.
The angles changed by

$$\Delta i_p \sim 46^\circ$$
$$\Delta \theta_p \sim 30^\circ$$
$$\Delta \chi_p \sim 90^\circ$$
$$\Delta \phi_0 \sim 0.5$$

...in 10 days

(after subtracting constant component)

IXPE Imaging X-Ray Polarimetry Explorer

Complex energy-dependence

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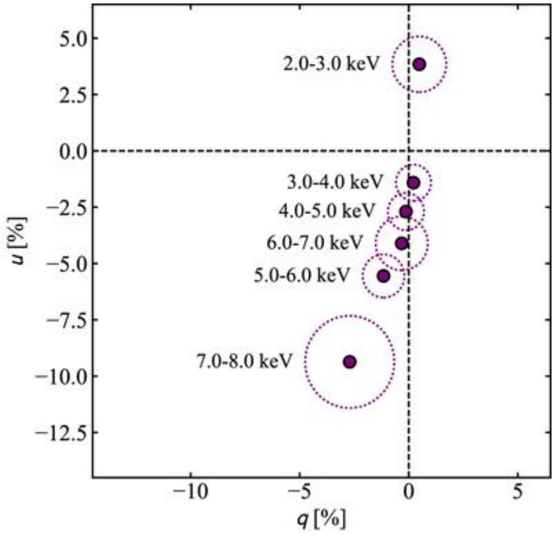
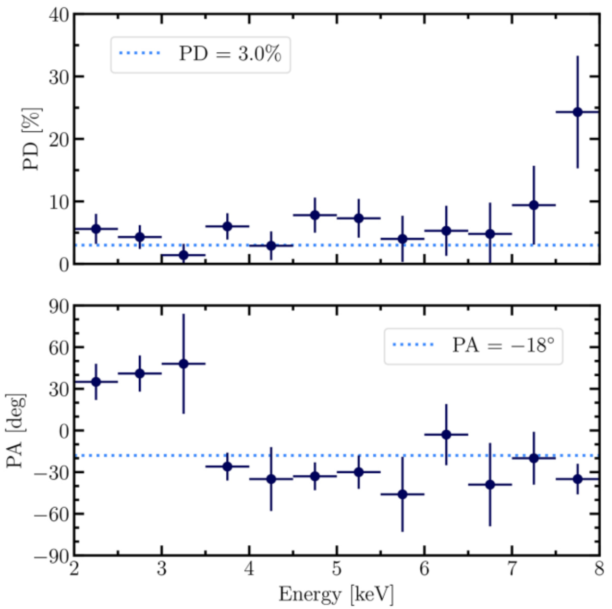
Vela X-1



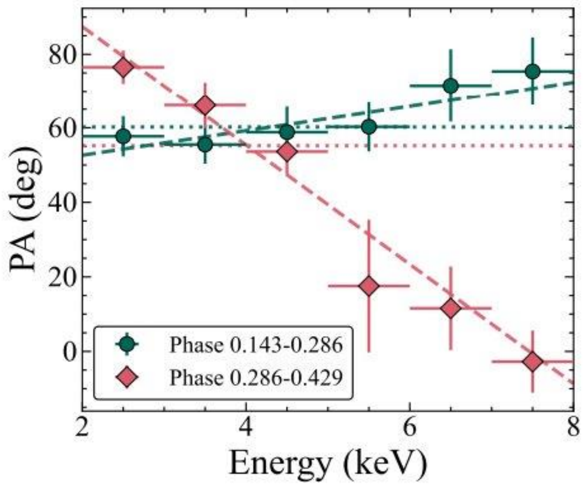
Forsblom+, 2023, ApJL

4U 1538-52



Loktev+, 2025, A&A

Cen X-3



Zhao+ A&A 2026

Tsygankov+, 2022, ApJL

= the energy-dependence of the polarization properties varies in complexity between these sources

PRECESSION?

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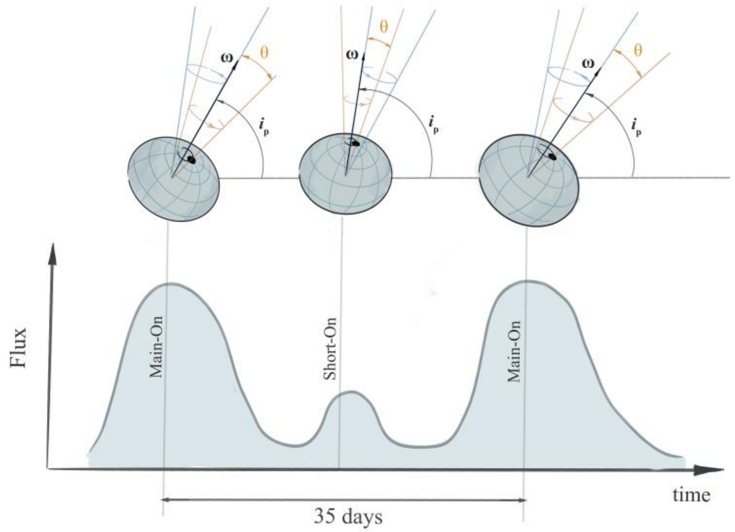
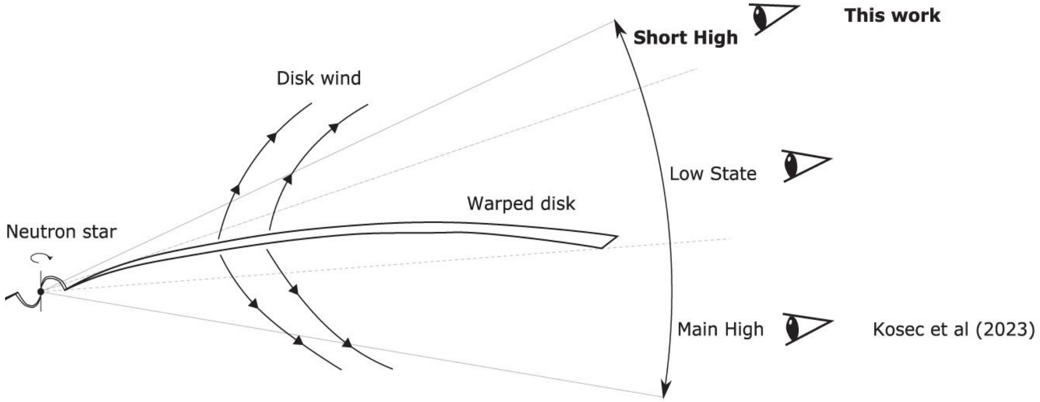




HER X-1

Quick facts:

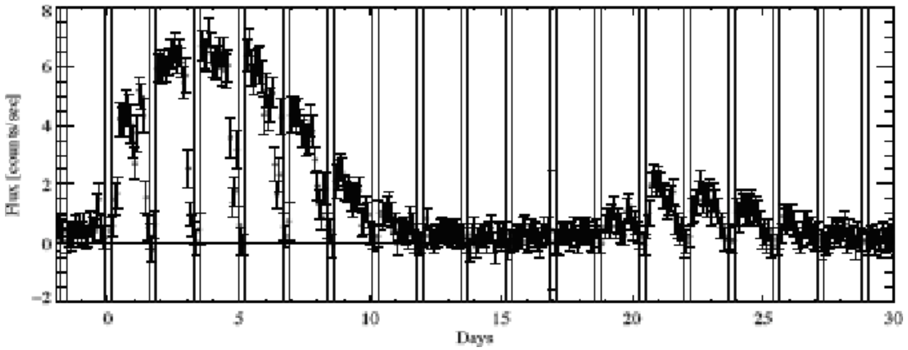
- **Her X-1** is the second XRP ever discovered and one of the most studied
- **Her X-1/HZ Her** is an **IMXB** consisting of a **persistently accreting NS and a B3 donor star**
- **35-day "on-off" cycle due to precession of accretion disk**
- **Two different on-states: Main-On and Short-On**

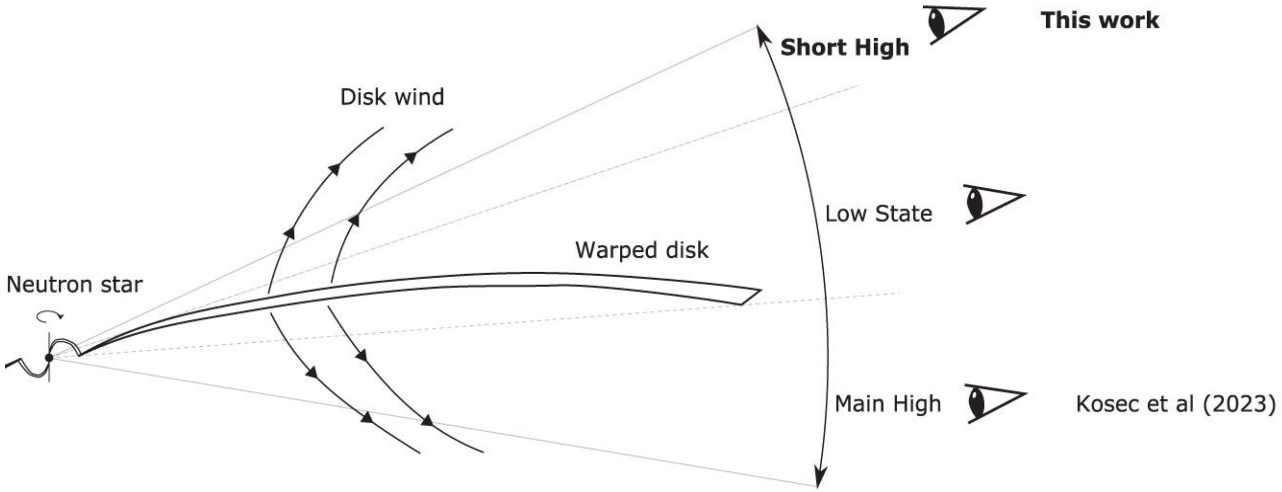
Spin period: 1.24 s

Orbital period: 1.7 d

Super-orbital period: 35 d

Jones et al. 1976





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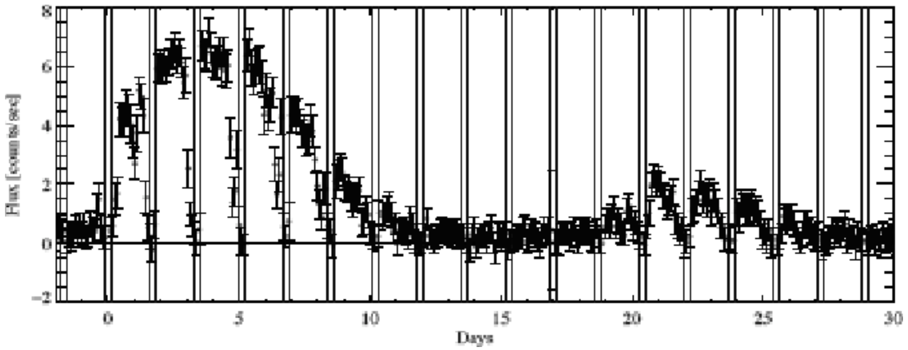
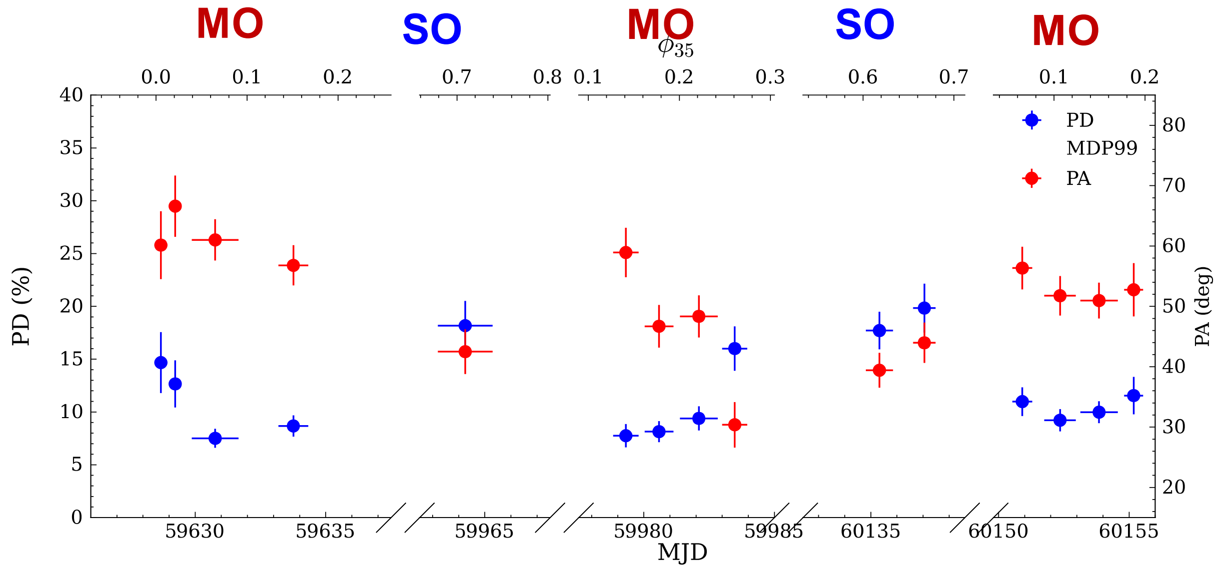




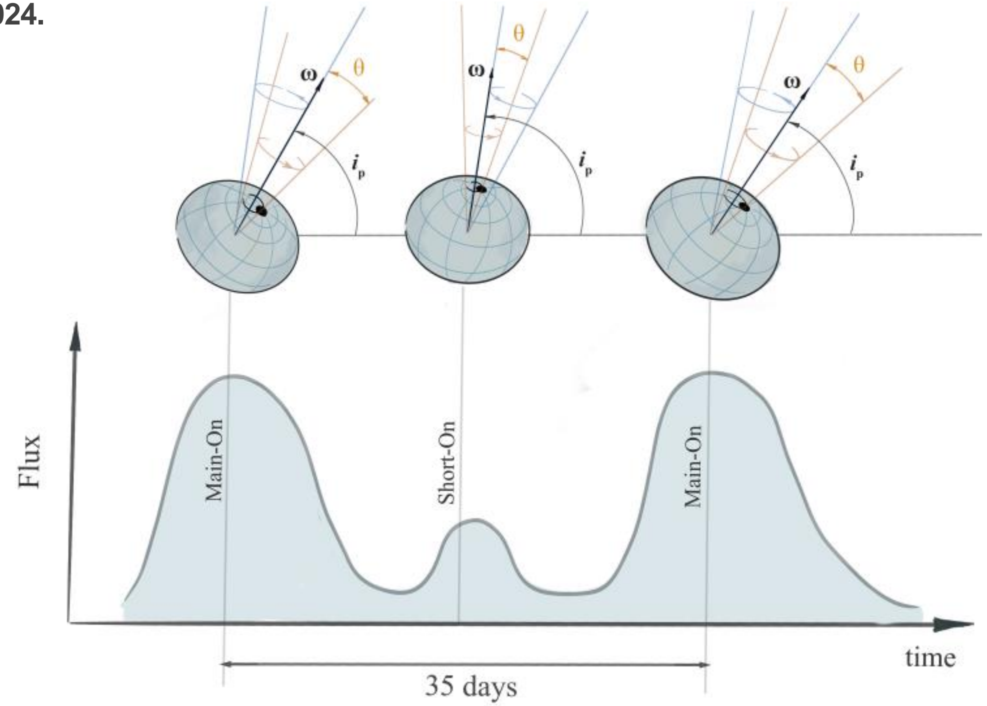
Doroshenko+, 2022, NatAst; Heyl+, 2024, NatAst; Zhao+, 2024, MNRAS

Her X-1 – Free Precession

	Mean PD (%)	i_p (deg)	θ (deg)	χ_p (deg)	ϕ_0 (%)	Prec. Phase (%)
First Main-On	9.5 ± 0.5	58^{+28}_{-22}	$14.5^{+3.0}_{-4.0}$	55.4 ± 1.6	$19.0^{+2.7}_{-2.2}$	8.8
Early	8.6 ± 0.6	64^{+25}_{-22}	$16.3^{+3.5}_{-4.1}$	57.9 ± 2.1	$19.0^{+2.6}_{-2.4}$	7.3
Late	9.3 ± 0.7	85^{+35}_{-37}	$15.9^{+3.6}_{-4.0}$	52.2 ± 2.7	$21.7^{+4.5}_{-5.0}$	16.2
Short-On	17.8 ± 1.4	90^{+30}_{-30}	$3.7^{+2.6}_{-1.9}$	41.9 ± 2.2	85.1^{+18}_{-19}	68.7
Second Main-On	9.1 ± 0.5	56^{+24}_{-20}	$16.0^{+3.1}_{-4.3}$	46.8 ± 1.5	$19.8^{+2.3}_{-2.0}$	15.9

Heyl+, NatAst, 2024.

The data allowed us to conclude that the observed 35-day period in Her X-1 is set by the free precession of the NS



This implies that its shape is slightly asymmetric, by a few parts per ten million

SMC X-1 & LMC X-4 – PRECESSION?

SMC X-1:

HMXB in the SMC; one of a few SGXBs known for Roche lobe overflow
Luminosity varies between 10^{37} erg/s to over 5 x 10^{38} erg/s

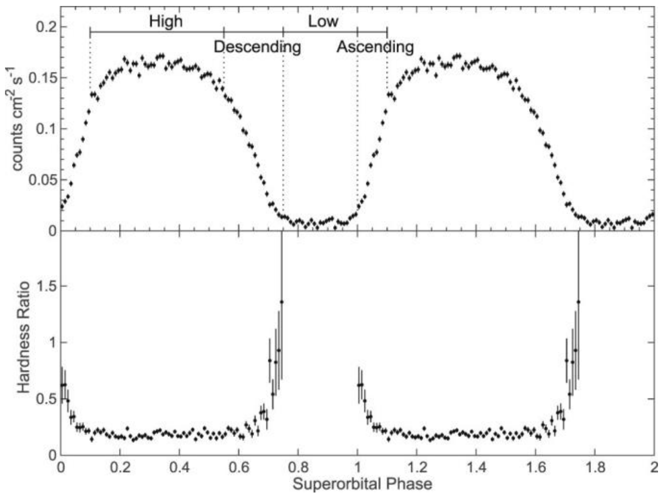
Spin period: 0.7 s
Orbital period: 3.9 d
Super-orbital period: average 55 d (40 — 65 d)

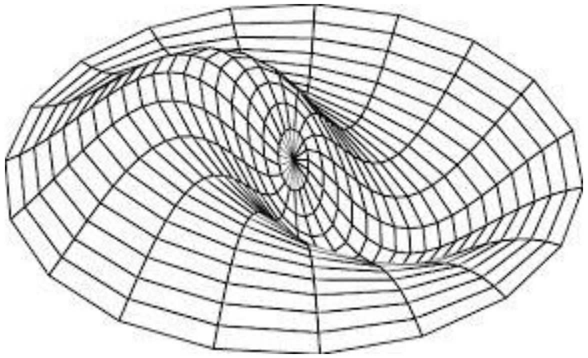
LMC X-4:

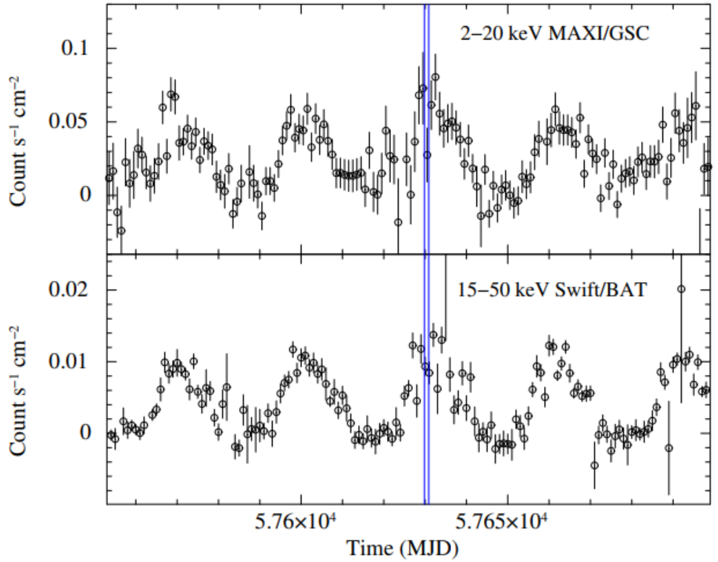
HMXB in the LMC
Luminosity varies between 10^{36} erg/s to over 4 x 10^{38} erg/s

Spin period: 13.5 s
Orbital period: 1.4 d
Super-orbital period: 30.5 d (stable)

Chin-Ping Hu et al., 2019, ApJ

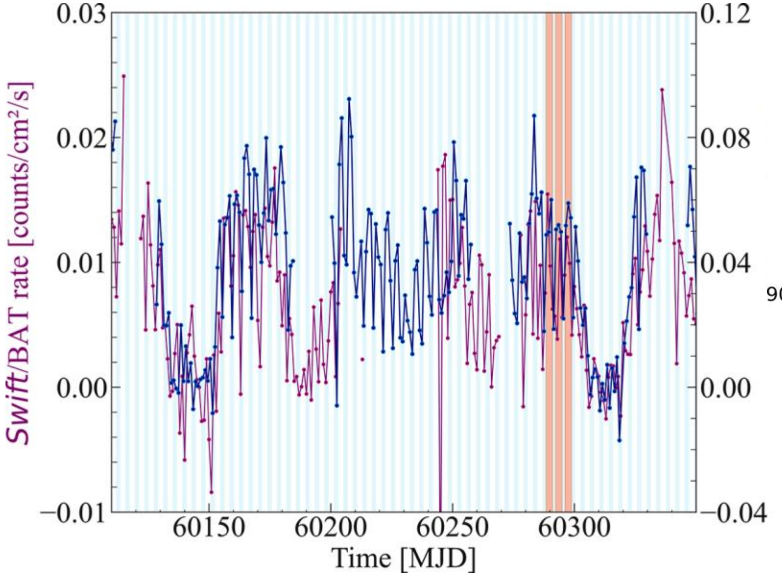


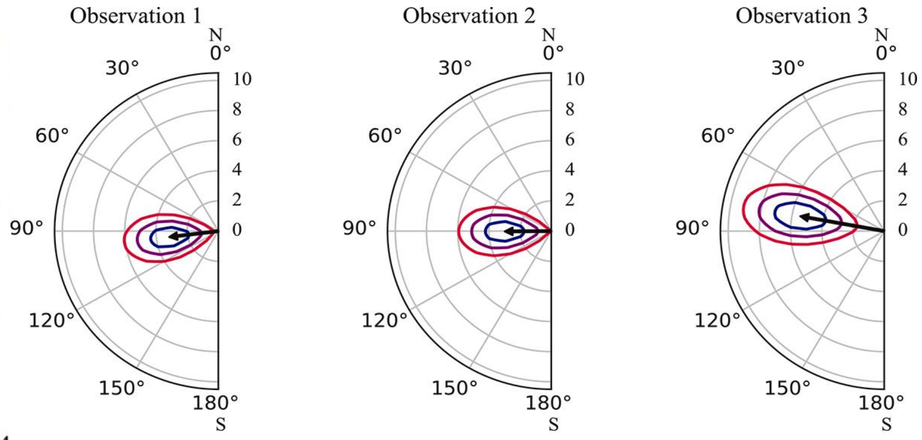


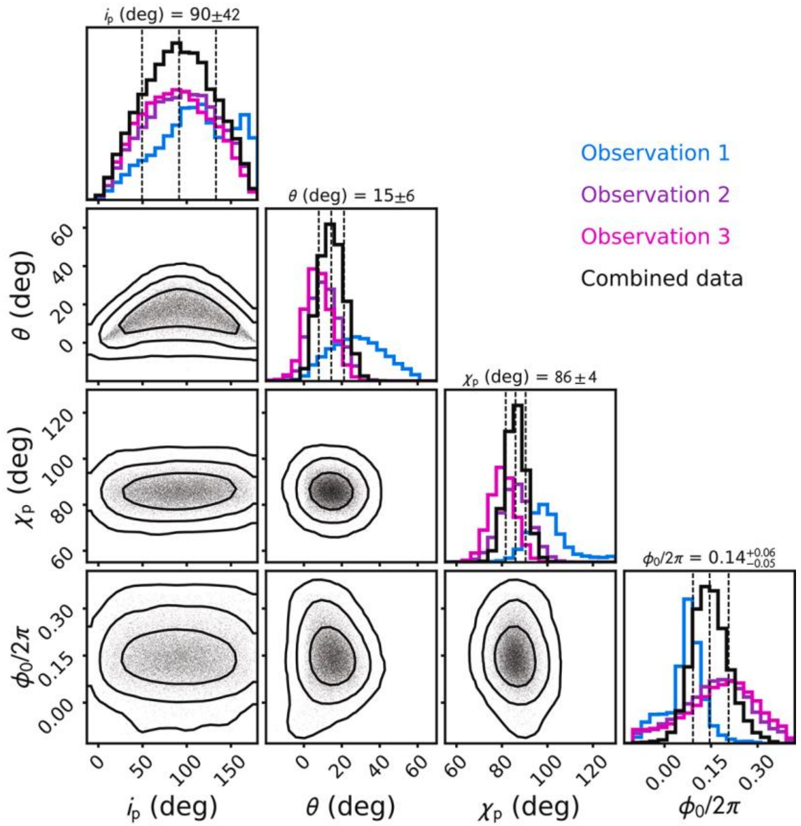


Sharma et al., 2022, MNRAS

SMC X-1 – PRECESSION?



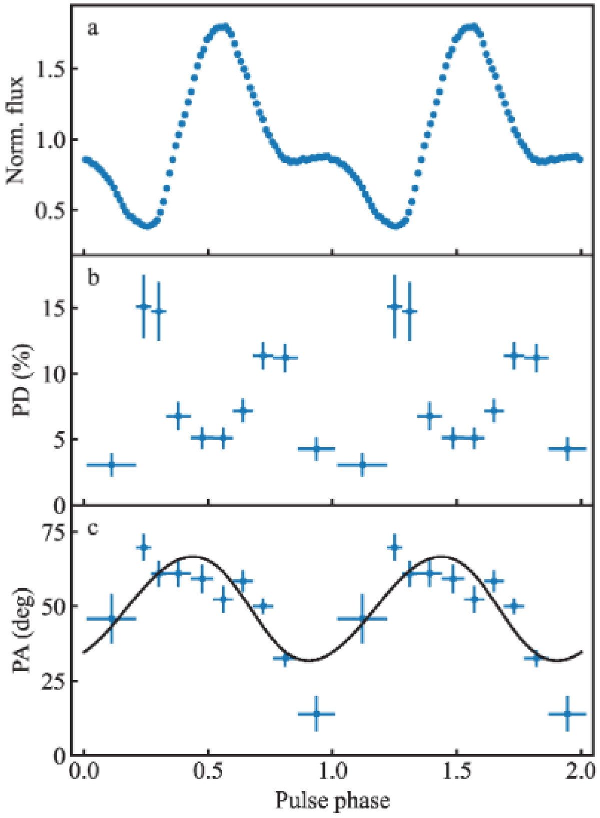




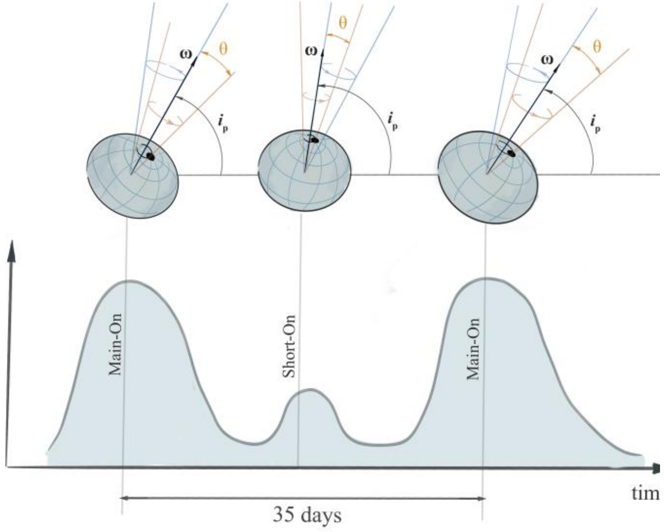
Forsblom+, 2024, A&A

IXPE Overview of X-ray Pulsars

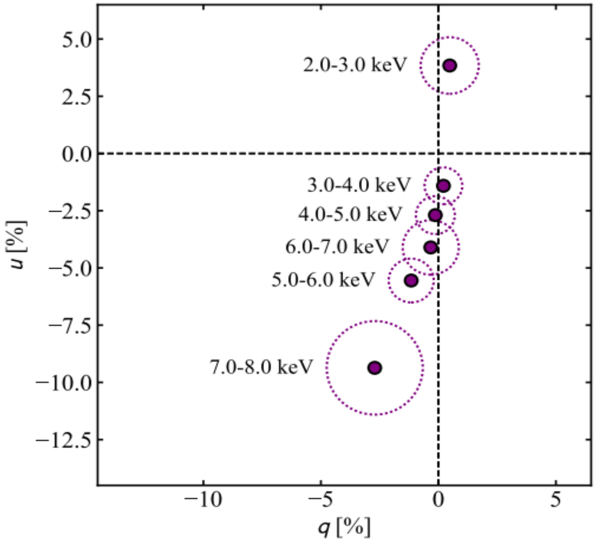
NS Geometries



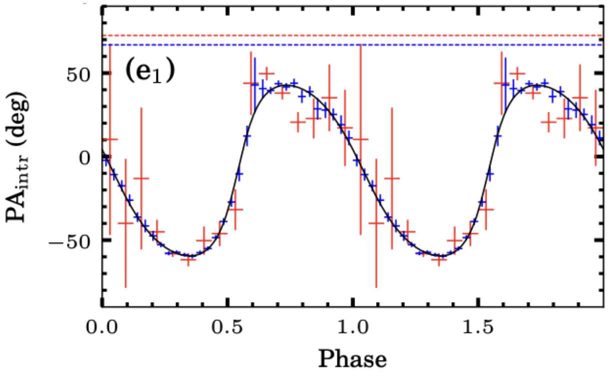
Precession?



Complex energy-dependence



Additional polarized components



(after subtracting constant component)

BACK-UP SLIDES

IXPE Imaging X-Ray Polarimetry Explorer

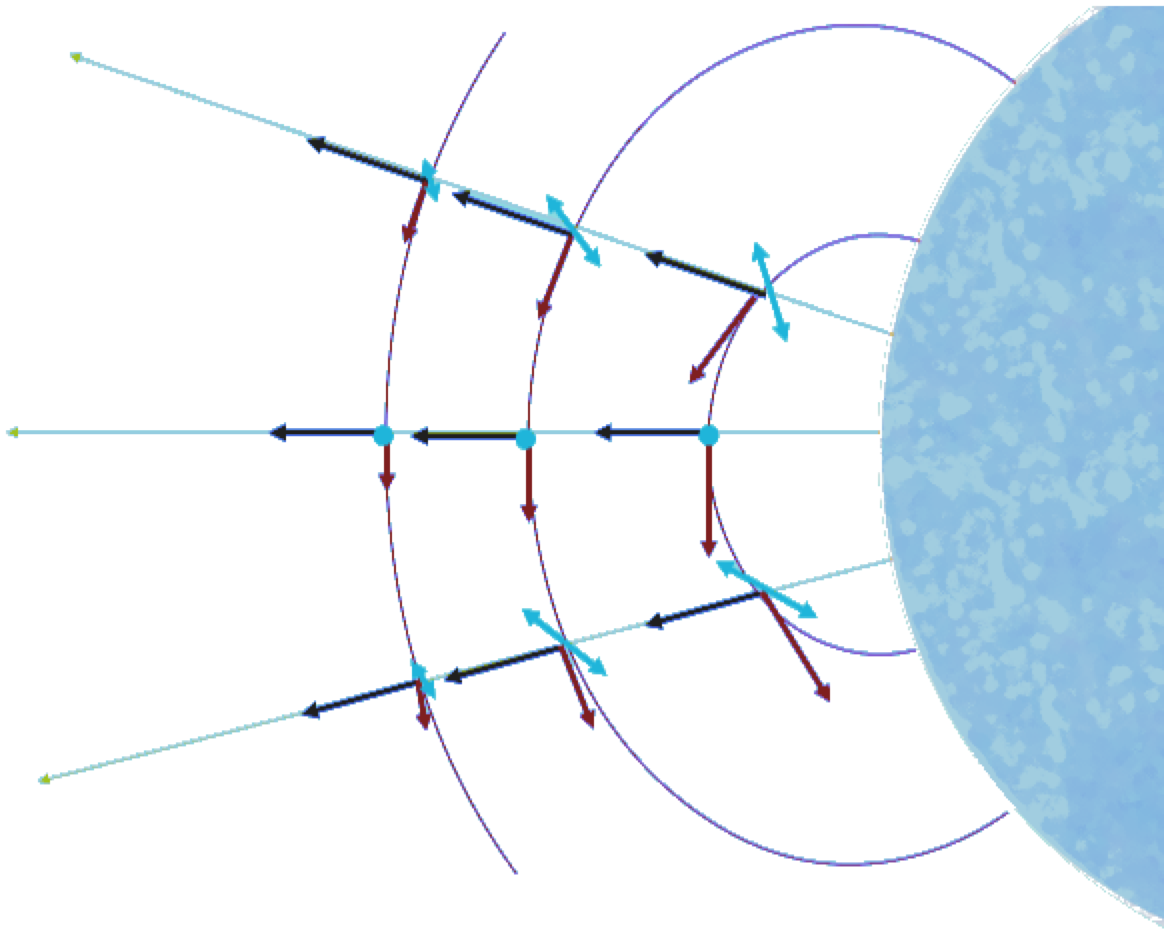
X-RAY PULSARS - POLARIZATION

QED vacuum polarization effects:

- The limit within which polarization modes are preserved depends on the star magnetic field strength and photon energy:

$$\frac{r_{\rm pl}}{R_{\rm NS}} \simeq 4.3 \left(\frac{B_{\rm p}}{10^{11}\ {\rm G}}\right)^{2/5} \left(\frac{E}{1\ {\rm keV}}\right)^{1/5} \left(\frac{R_{\rm NS}}{10\ {\rm km}}\right)^{1/5} (\sin\alpha)^{2/5},$$

- Photons can have different PAs at the NS surface initially, but we expect vacuum birefringence to align them to a preferred direction



Heyl+, 2003, MNRAS

IXPE Imaging X-Ray Polarimetry Explorer

X-Ray Pulsars - Polarization

QED vacuum polarization effects:

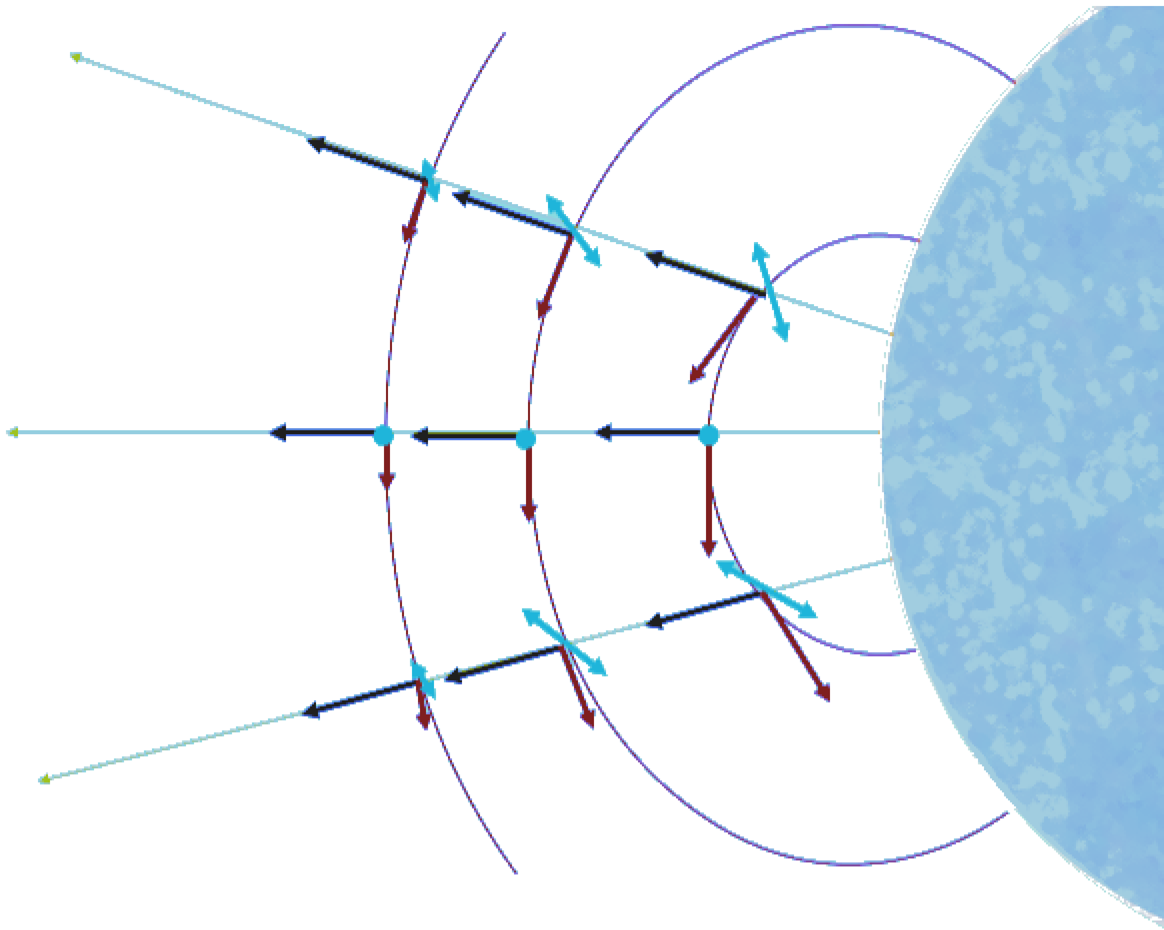
- The limit within which polarization modes are preserved depends on the star magnetic field strength and photon energy:

Typical B for XRPs gives about 20 NS radii

$$\frac{r_{\rm pl}}{R_{\rm NS}} \simeq 4.3 \left(\frac{B_{\rm p}}{10^{11}\ {\rm G}}\right)^{2/5} \left(\frac{E}{1\ {\rm keV}}\right)^{1/5} \left(\frac{R_{\rm NS}}{10\ {\rm km}}\right)^{1/5} (\sin\alpha)^{2/5},$$

We don't expect strong energy dependence of PA

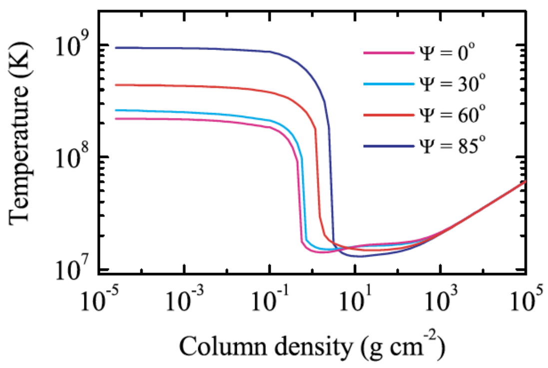
- Photons can have different PAs at the NS surface initially, but we expect vacuum birefringence to align them to a preferred direction

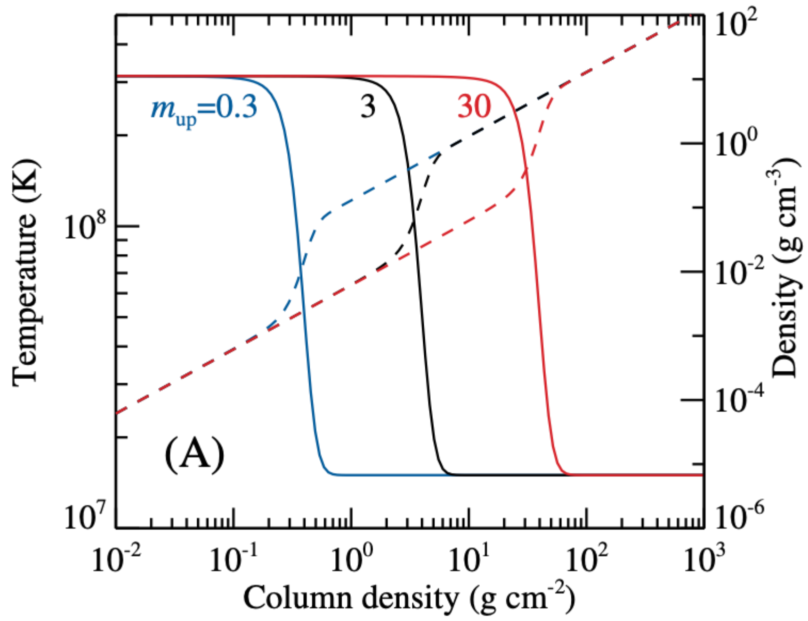


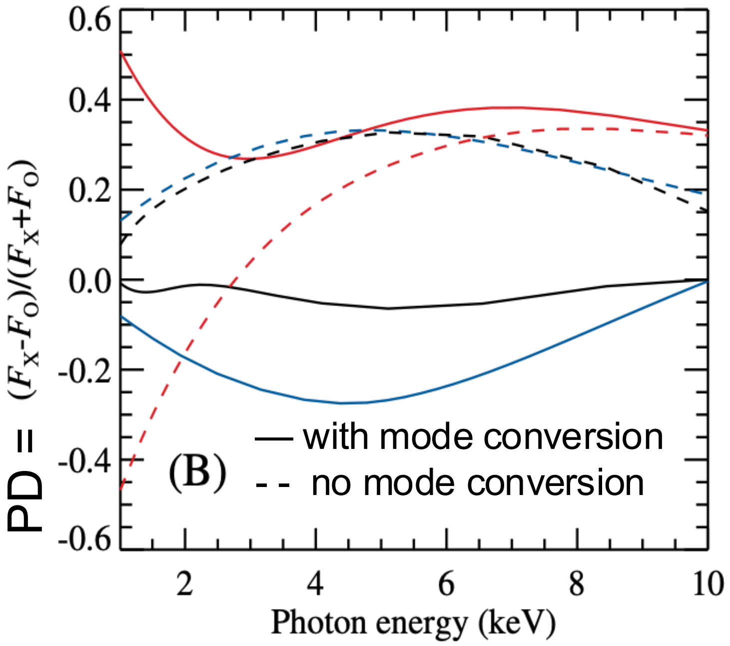
Heyl+, 2003, MNRAS

LOW POLARIZATION DEGREE

- Normally T decreases going outwards
- X-mode photon photosphere is deeper than the O-mode -> X-mode dominates flux
- Particle bombardment produces inverted T gradient, O-mode photons escape at a larger temperature, and may dominate the outgoing flux
- Polarization depends on the thickness of the heated layer







Doroshenko+, 2022

IXPE OBSERVATIONS OF LS V +44 17/RX J0440.9+4431

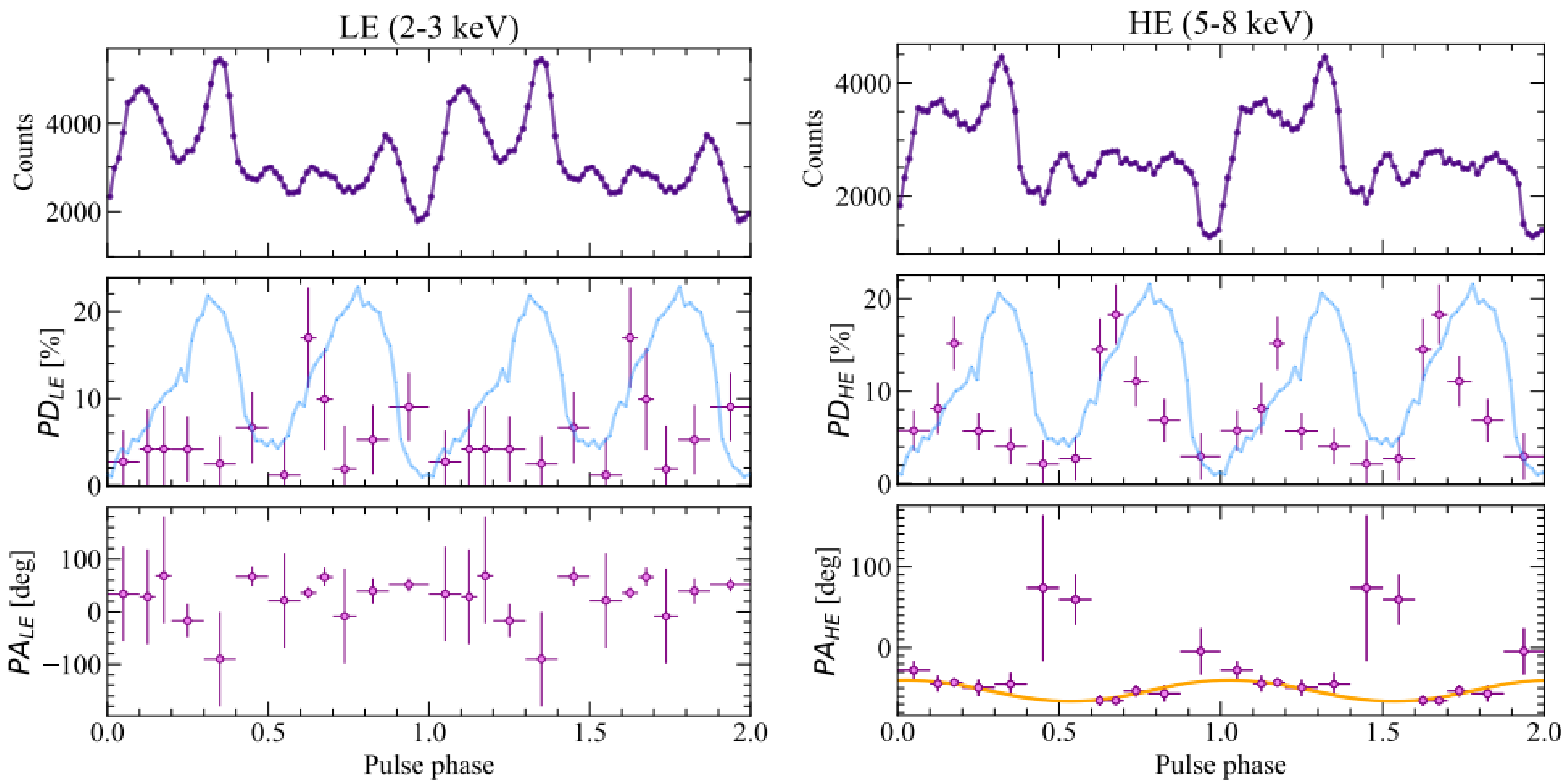
Three questions:

1. what is it?
2. can it give 10-40% of observed flux?
3. 30% polarisation?

Unpulsed = relatively far away from NS: scattering in disk/disk wind?

- **PD up to ~33%** due to comptonization in accretion disk atmosphere (Sunyaev&Titarchuk 1985) or outflows
  - **~20% polarization** observed in Cyg X-3/Circinus (scattering)
- There's evidence for presence of strong disk outflows in BeXBs from radio and X-ray data (Jaisawal et al. 2019; Doroshenko et al 2020, van den Eijnden et al. 2019, 2022; Chatzis et al. 2022; van den Eijnden et al. 2022) with **up to 20% flux in reflected/scattered component** (although at higher L_x).
- LS V +4417 is viewed **~edge-on**, polarization due to scattering is expected to be high (i.e. fraction of scattered emission may remain low)

VELA X-1 – ENERGY DEPENDENT POLARIZATION



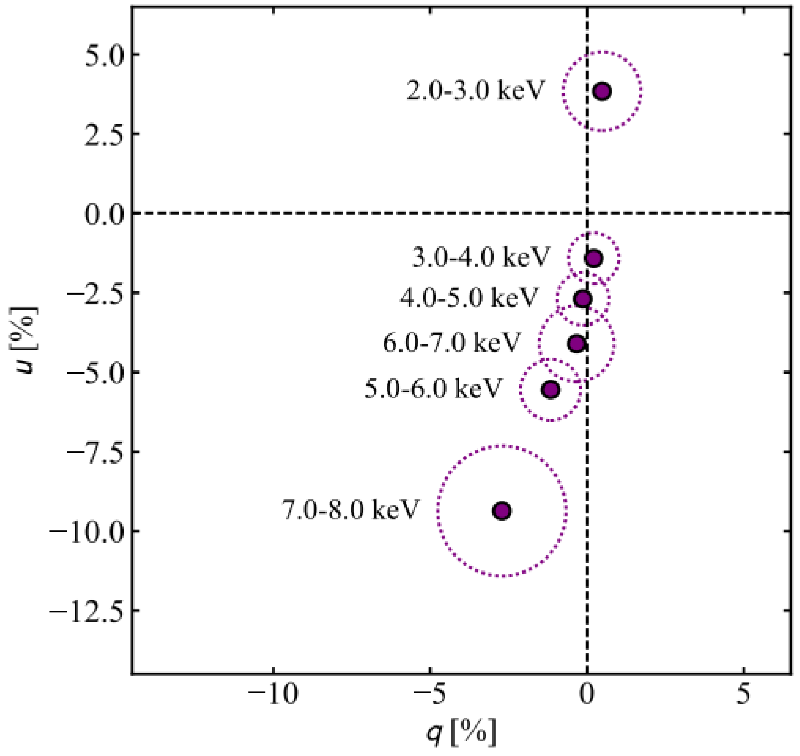
Forsblom+, 2025, A&A

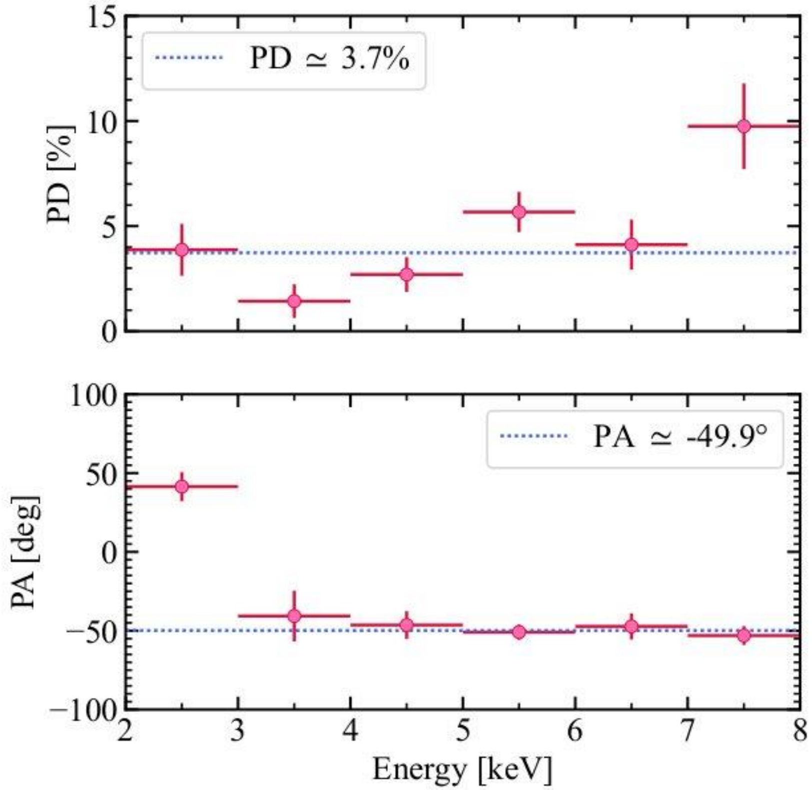
Fig. 3. Results of the phase-resolved spectro-polarimetric analysis of Vela X-1 based on the IXPE data at low energies (LE; 2−3 keV; *left*) and high energies (HE; 5−8 keV; *right*). *Top panels*: Pulse profiles (in counts) corresponding to the low- and high-energy ranges. *Middle* and *bottom panels*: Pulse-phase dependence of the PD and PA, respectively. The *NuSTAR* pulse profile in the 15−45 keV energy band is displayed in the PD panels (light blue). The orange curve in the PA panel shows the best-fit RVM to the data in the high-energy range.

VELA X-1 – ENERGY DEPENDENT POLARIZATION

Possible explanations:

- Spectral component that diminishes at higher energies and generally has a PA orthogonal to that of the dominant high-energy component



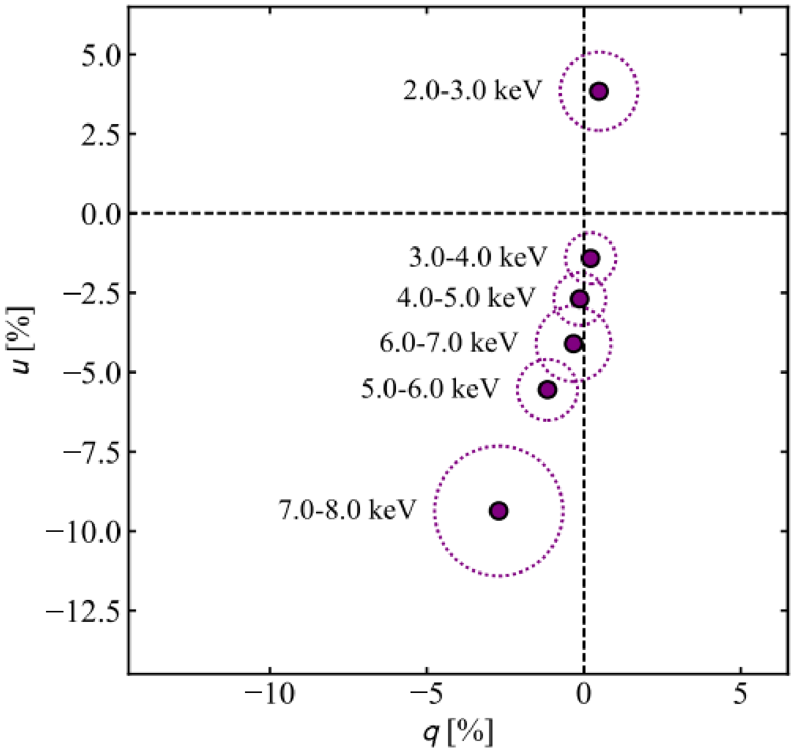


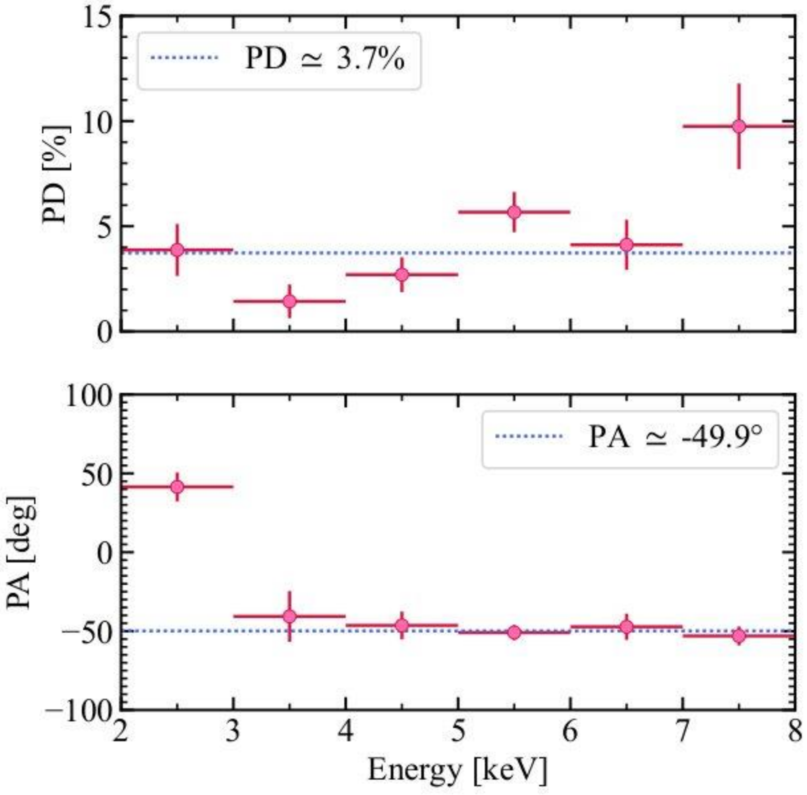
Forsblom+, 2023, ApJL

Vela X-1 – Energy Dependent Polarization

Possible explanations:

- Spectral component that diminishes at higher energies and generally has a PA orthogonal to that of the dominant high-energy component
- Vacuum resonance, in which one polarization mode converts into another, resulting in a 90 deg shift in the PA at some preferable energy





Forsblom+, 2023, ApJL