

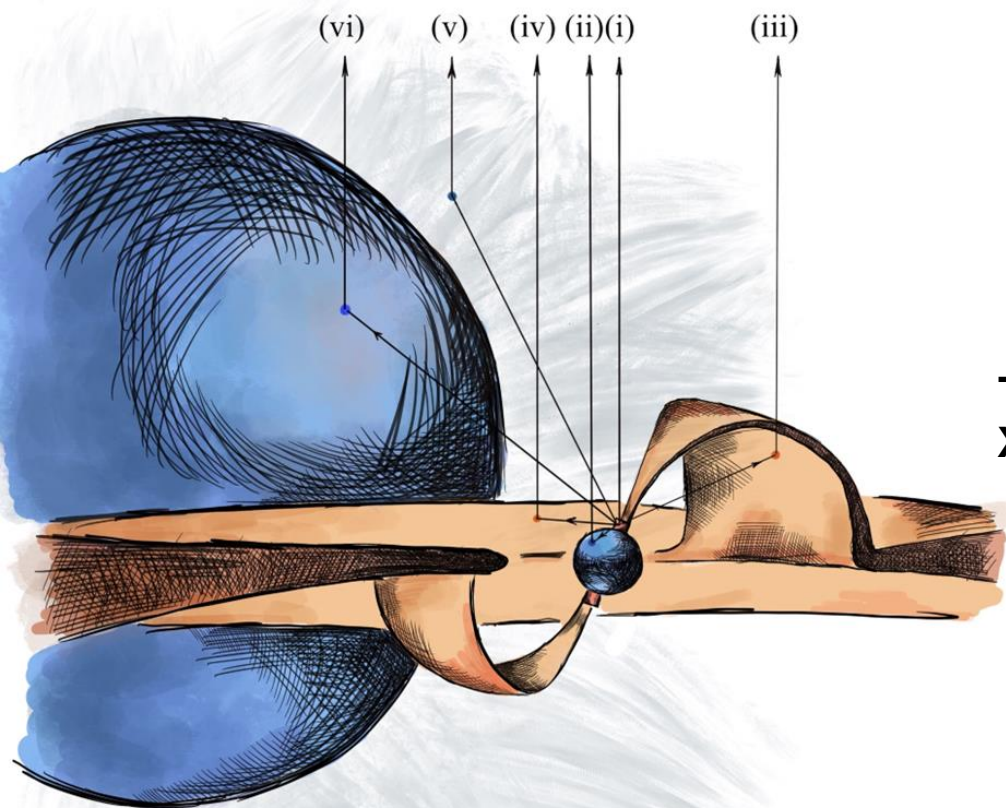
Energy-dependent polarization properties in X-ray pulsars probed by IXPE

Sofia V. Forsblom, + ...



University of Turku

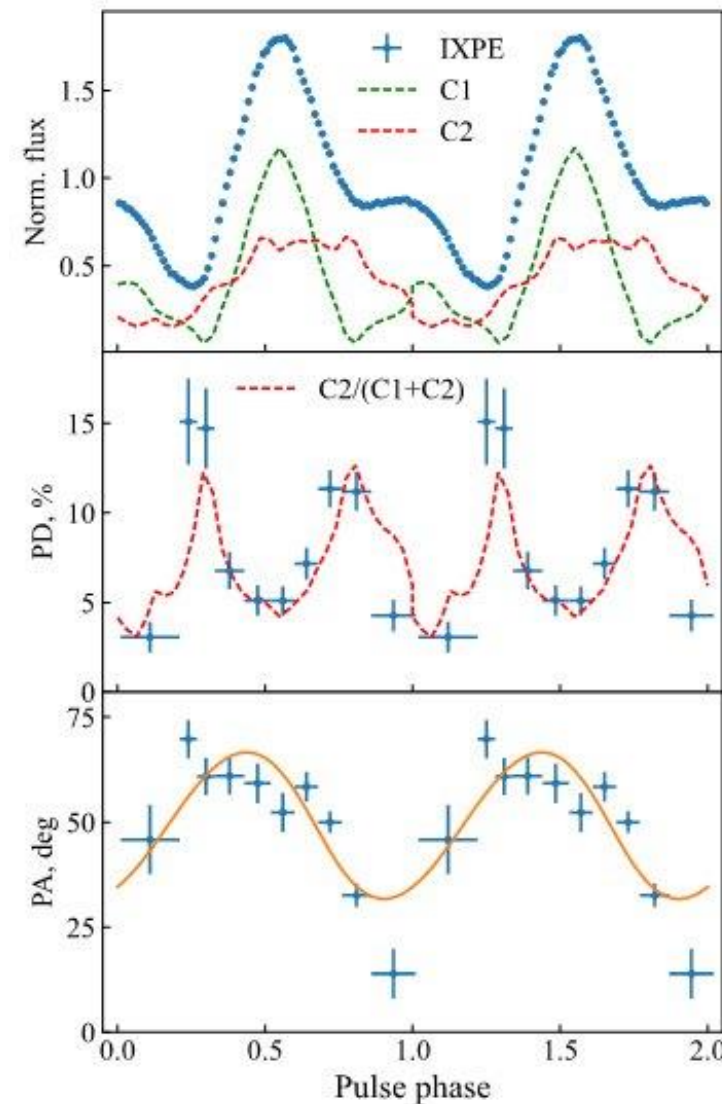
X-RAY PULSARS



Typical display of IXPE results for X-ray pulsars

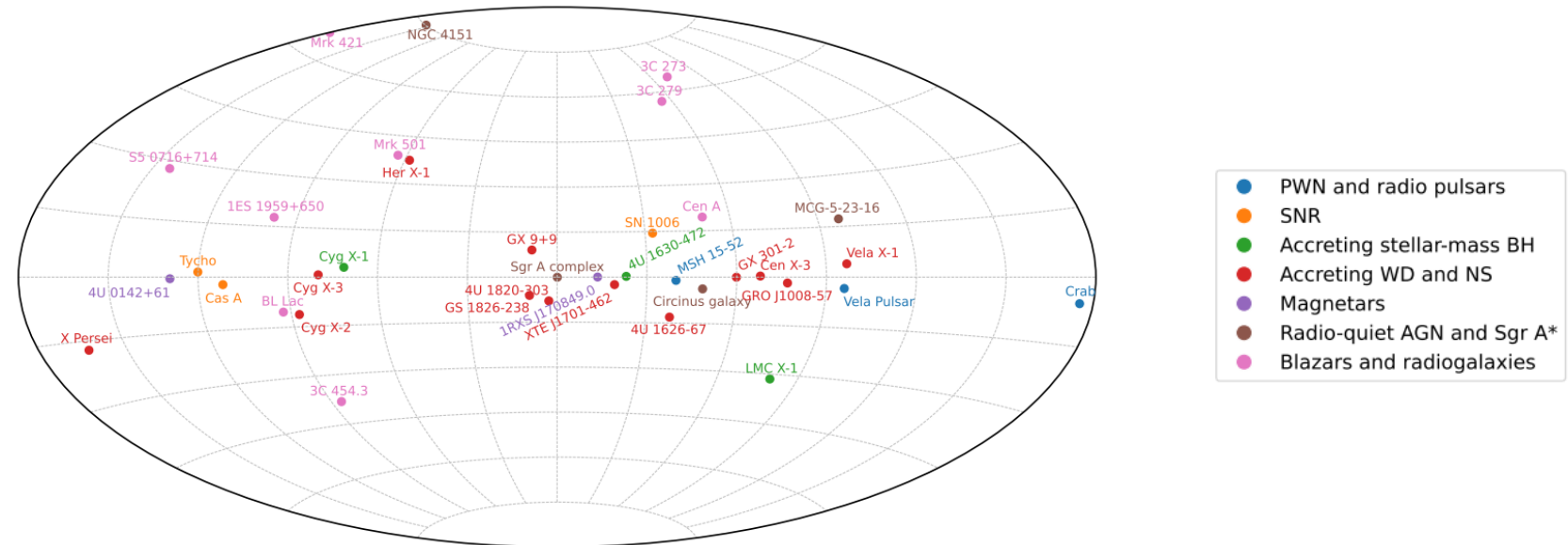


PD tells us something about the emission region; **PA** gives us the geometry of the NS



Targets in the initial IXPE LTP, displayed in galactic coordinates

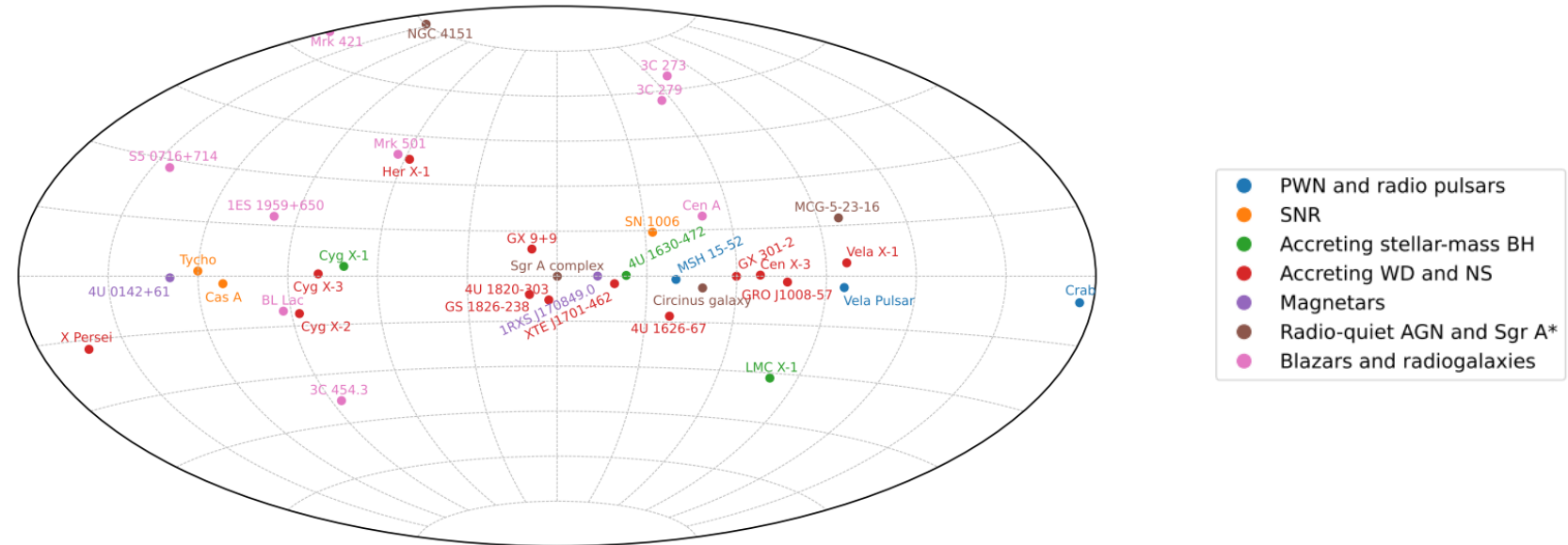
1. Her X-1
2. Cen X-3
3. 4U 1627-67
4. Vela X-1
5. X Persei
6. GX 301-2
7. GRO J1008-57
8. EXO 2030+375
9. LSV +44 17
10. Swift J0243.6+6124
11. SMC X-1
12. 4U 1538-52
13. 4U 1907+09
14. 4U 1954+319



Generally, some energy-dependence of the polarization degree, but the polarization angle remains consistent over energy

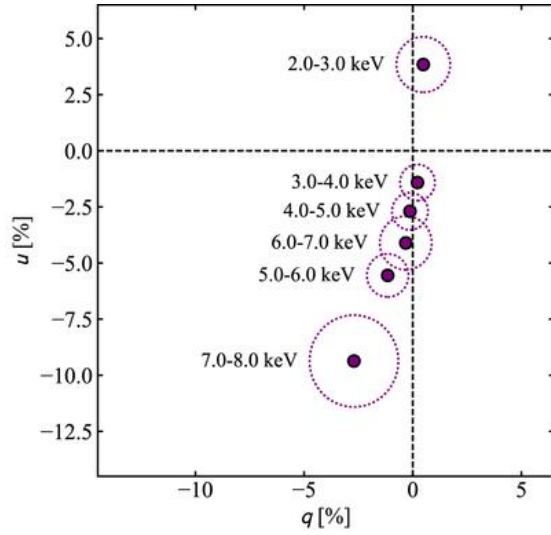
Targets in the initial IXPE LTP, displayed in galactic coordinates

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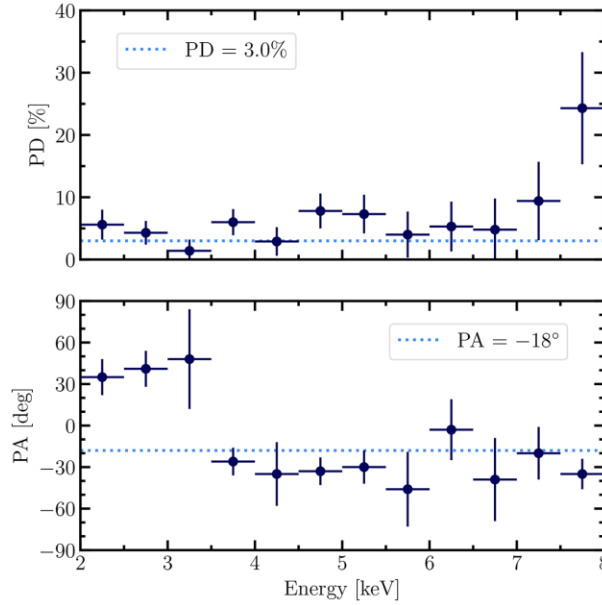


However, some sources display a clear energy dependence of both PD and PA

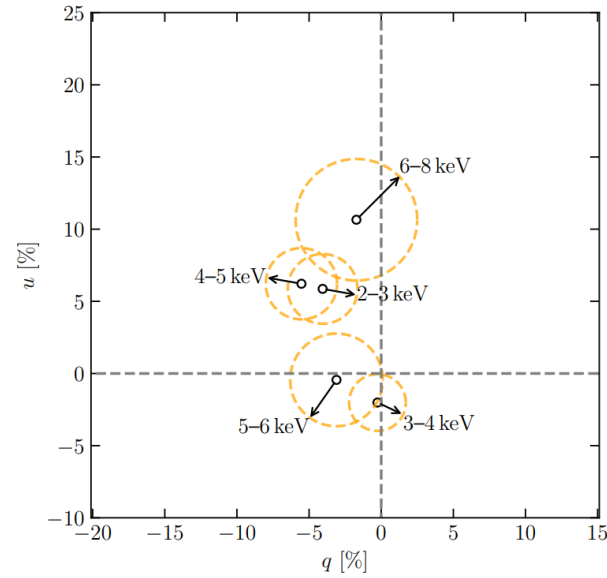
ENERGY DEPENDENCE OF DIFFERENT XRPs



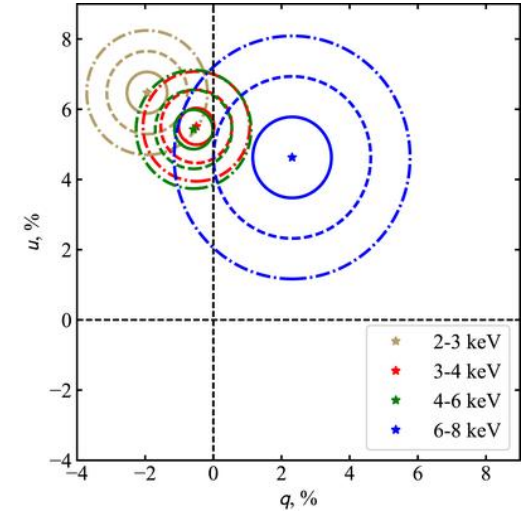
Vela X-1



4U 1538-52



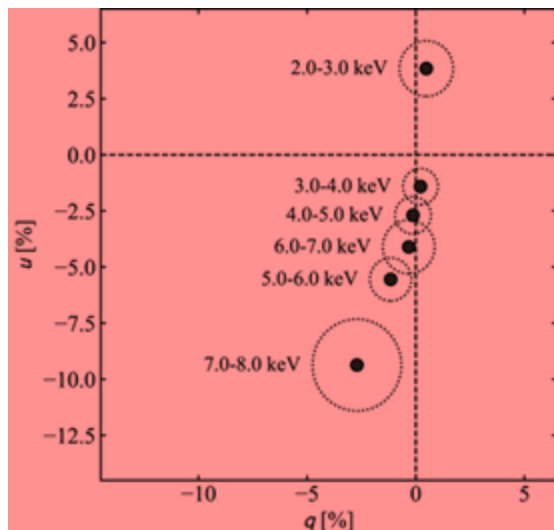
4U 1907+09



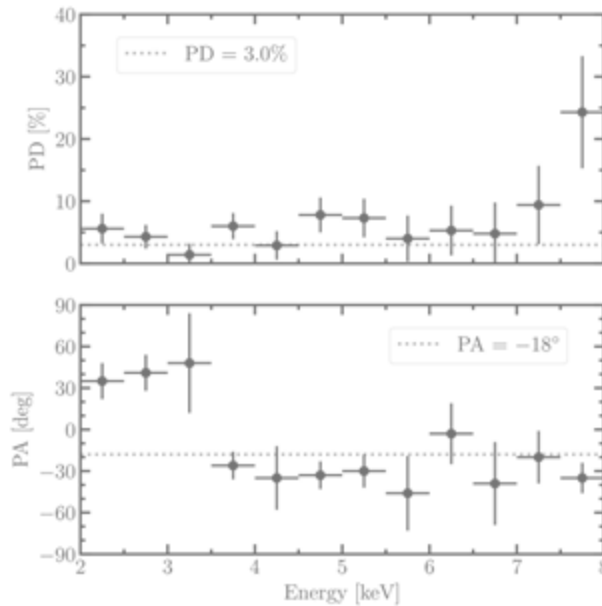
Cen X-3

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

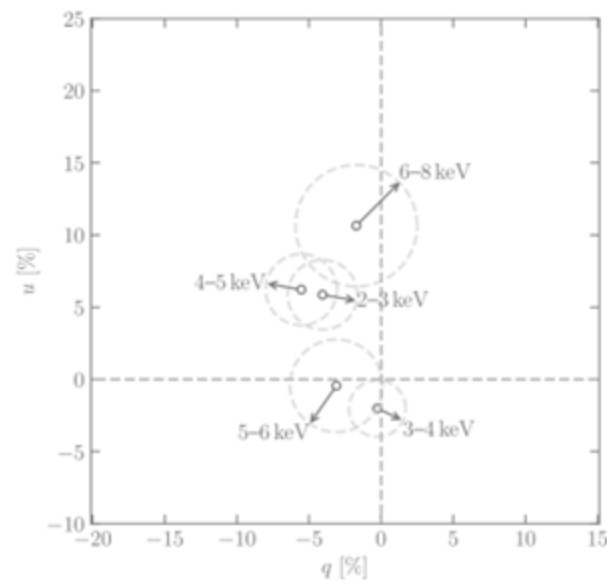
ENERGY DEPENDENCE OF DIFFERENT XRPCs



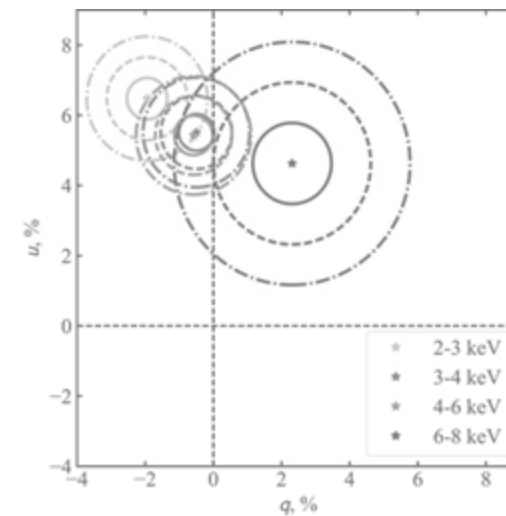
Vela X-1



4U 1538-52



4U 1907+09



Cen X-3

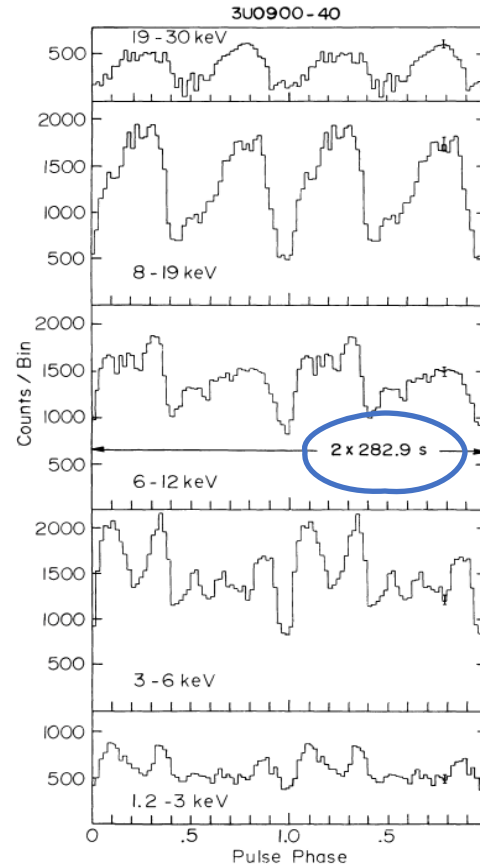


Increased complexity

VELA X-1 – QUINTESSENTIAL WIND ACCRETOR

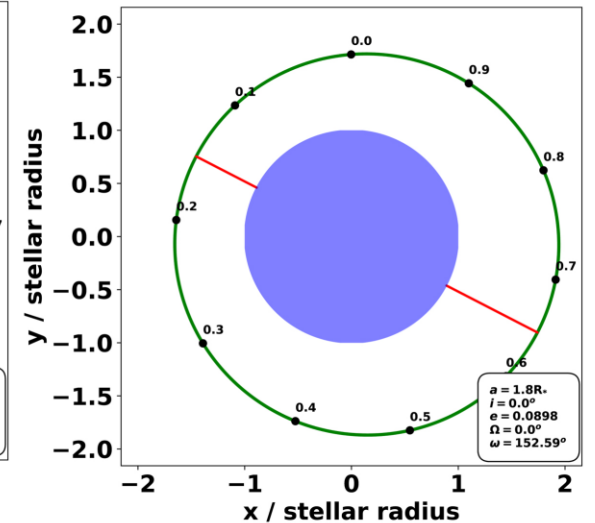
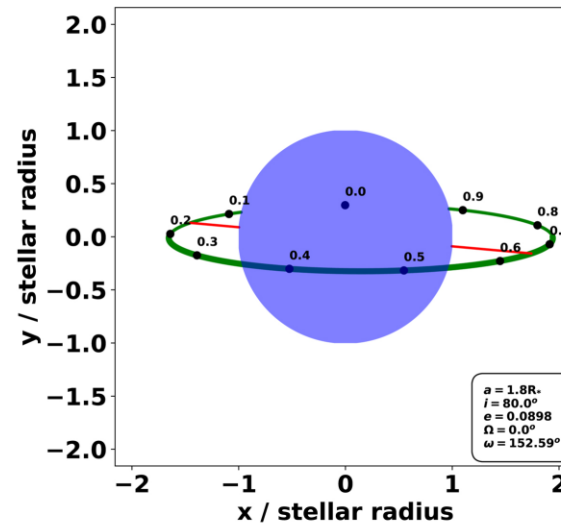
Quick facts:

- Discovered as one of the first X-ray sources in the early years of X-ray astronomy (Chodil et al. 1967)
- Pulse period of **283 s** discovered in 1975 (McClintock et al. 1976)
- Orbital period **8.964 d**
- Eclipses lasting about **1.7 d**



McClintock et al. 1976

- Bright, persistent wind-accreting XRP
- Separation between the NS and its companion star GP Vel only ~ 1.7 stellar radii
- Deeply embedded in the stellar wind



Kretschmar et al. 2021

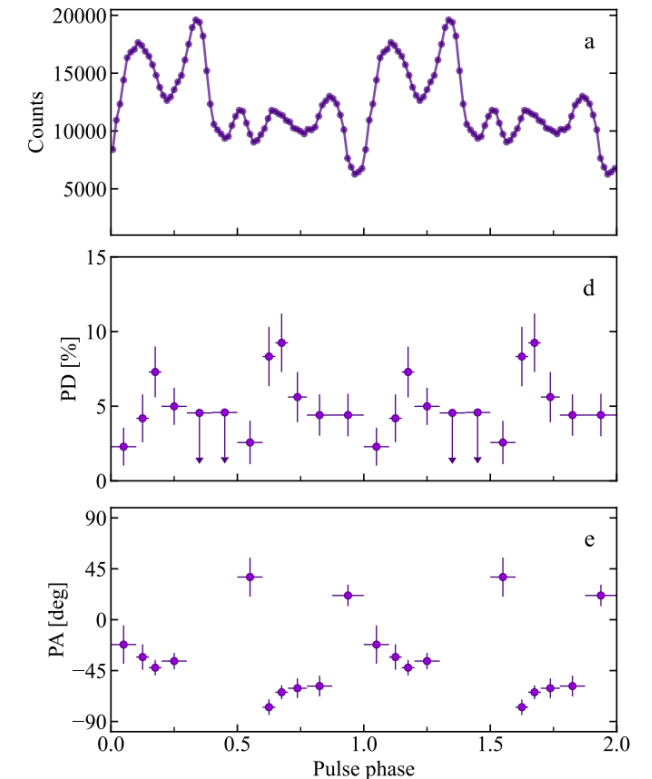
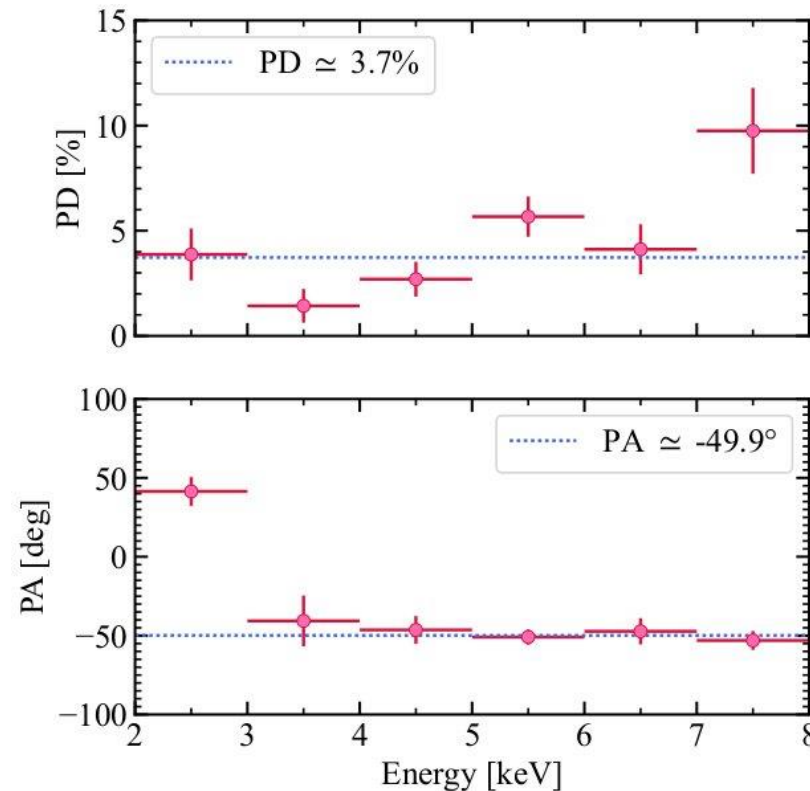
VELA X-1 – ENERGY DEPENDENT POLARIZATION

Energy-resolved analysis:

- At higher energies, the PD reaches 6-10%, with the PA differing by 90° from that below 3 keV

⇒ 90° swing unique to Vela X-1 among XRPs

- Unable to fit the **RVM** to the phase-resolved PAs in the full energy range



Forsblom+, 2023, ApJL

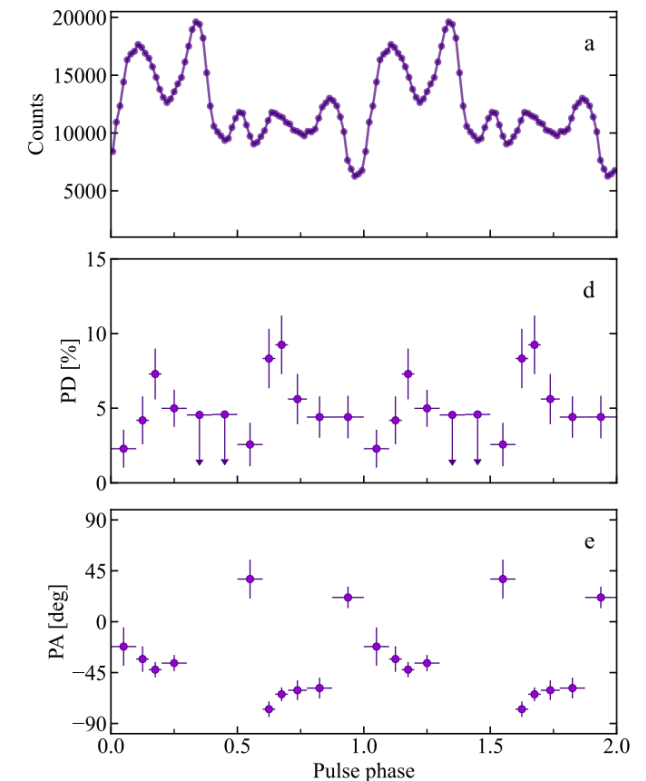
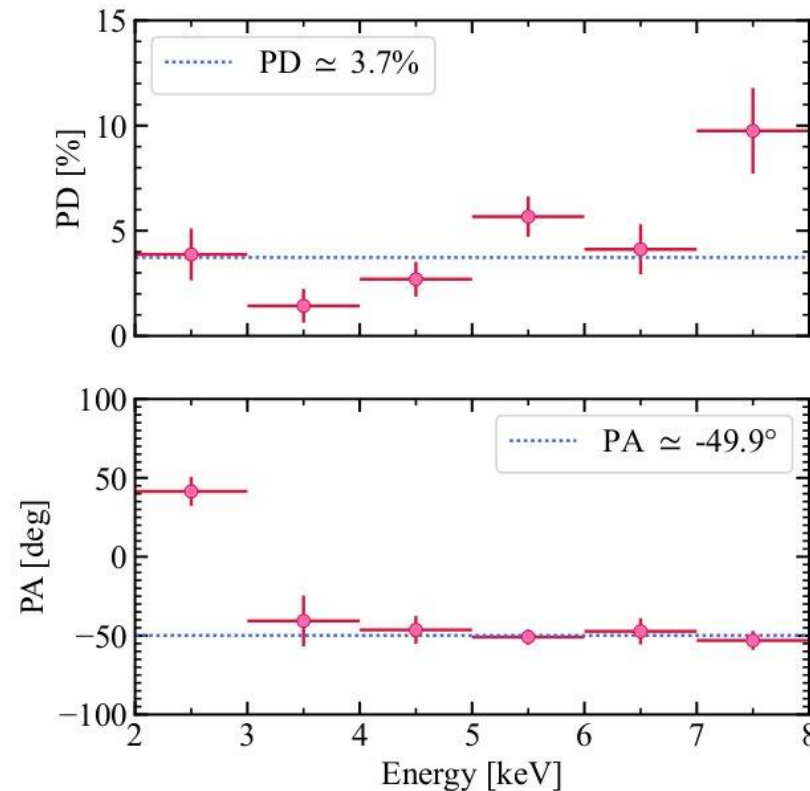
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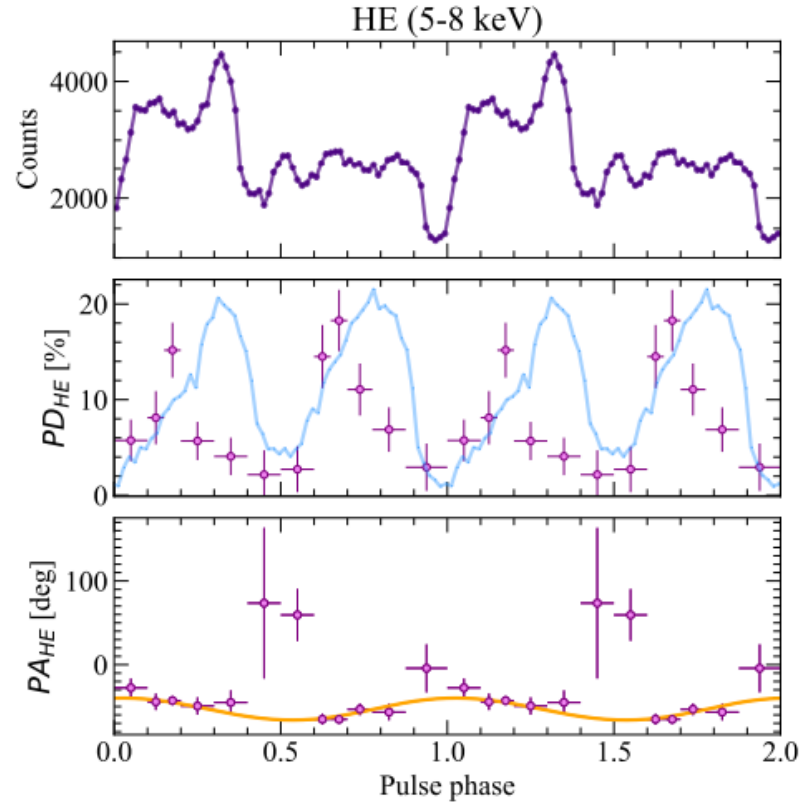
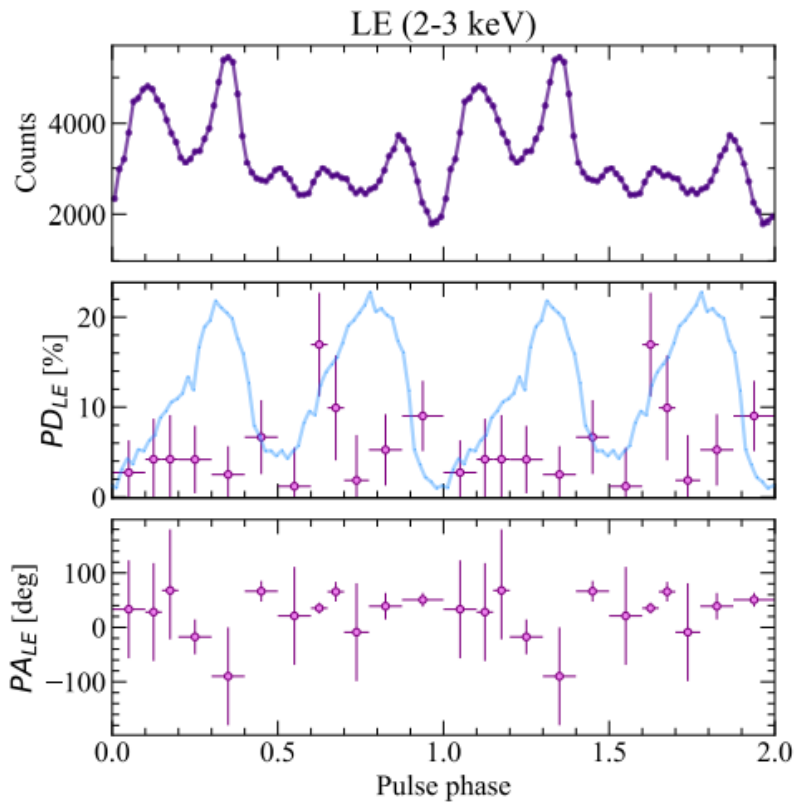
- Unable to fit the **RVM** to the phase-resolved PAs in the full energy range



Forsblom+, 2023, ApJL

Instead, look at phase-resolved properties at low (2-3 keV) and high (5-8 keV) energies separately:

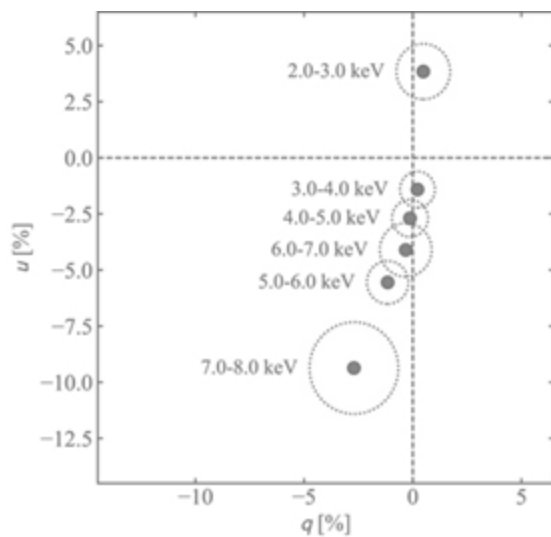
VELA X-1 – ENERGY DEPENDENT POLARIZATION



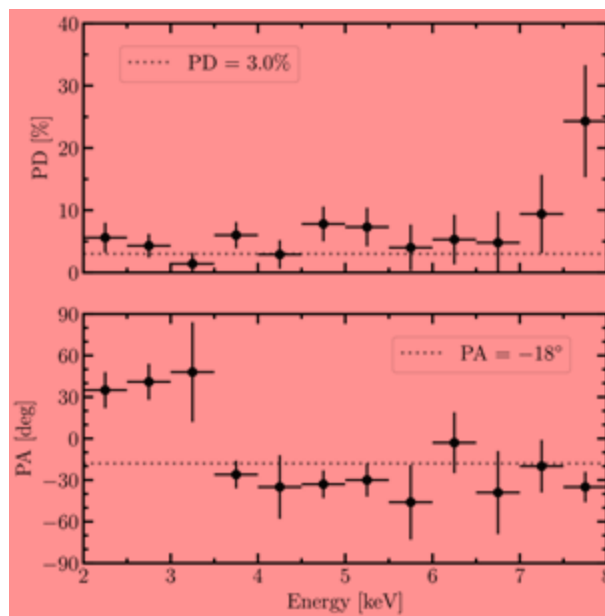
Possible explanations:

- 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

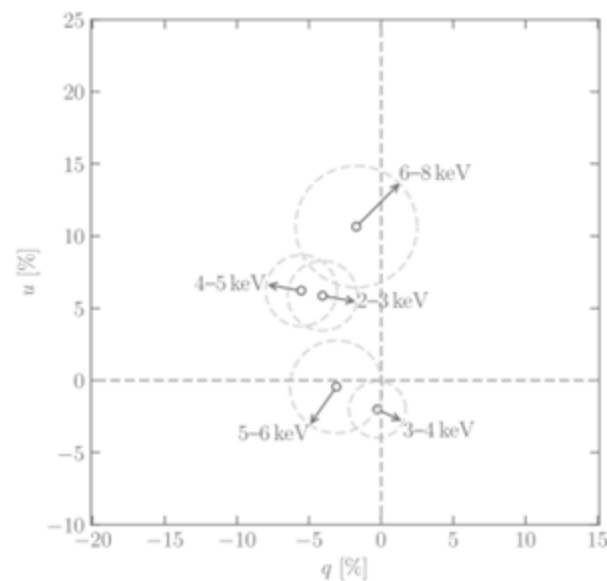
ENERGY DEPENDENCE OF DIFFERENT XRPCs



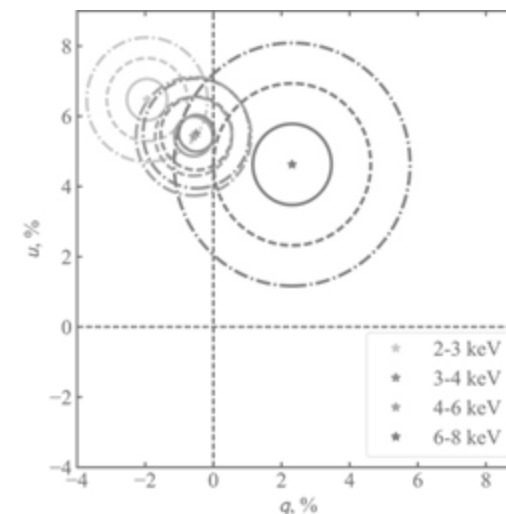
Vela X-1



4U 1538-52



4U 1907+09



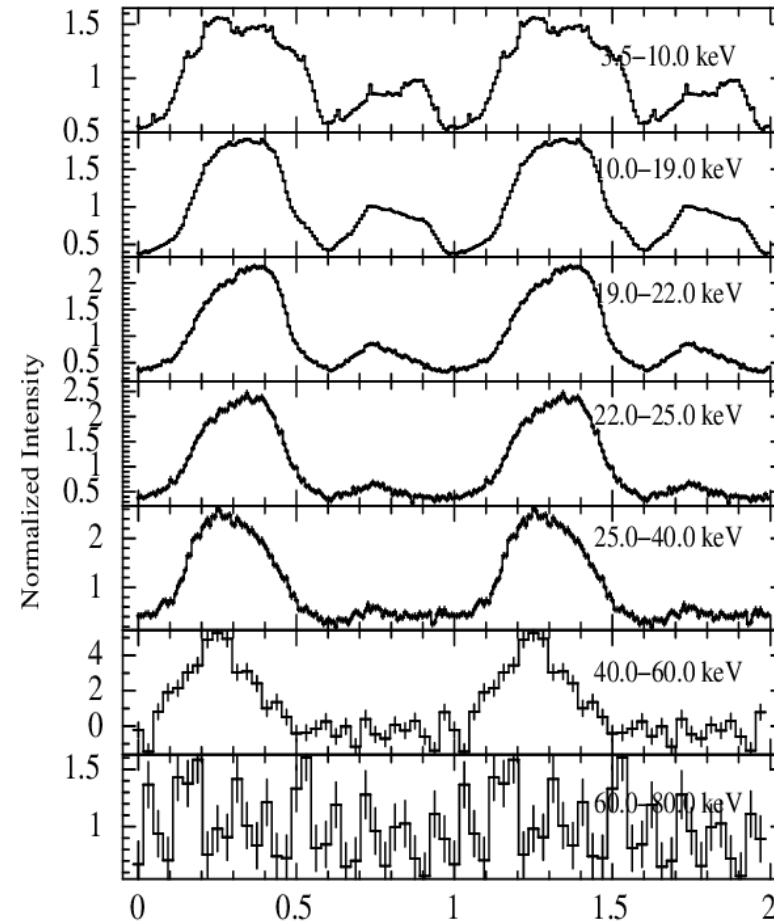
Cen X-3



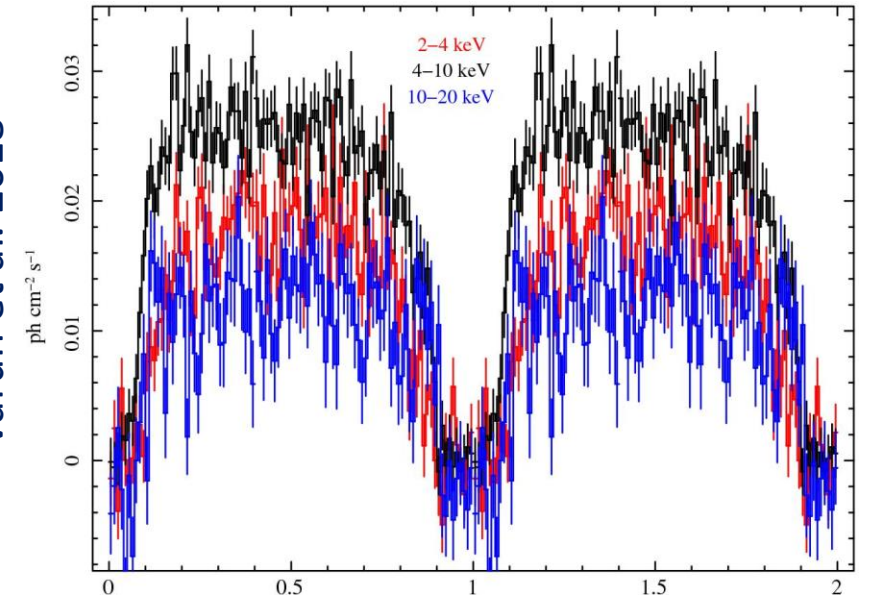
Increased complexity

Quick facts:

- Persistent XRP, considered "twin system" to Vela X-1, with similar properties
- Pulse period of **529 s** (Becker et al. 1977; Davison 1977)
- Orbital period **3.73 d**
- Eclipsing binary



Varun et al. 2018



J. J. Rodes-Roca et al. 2015

4U 1538-52 – ENERGY DEPENDENT POLARIZATION

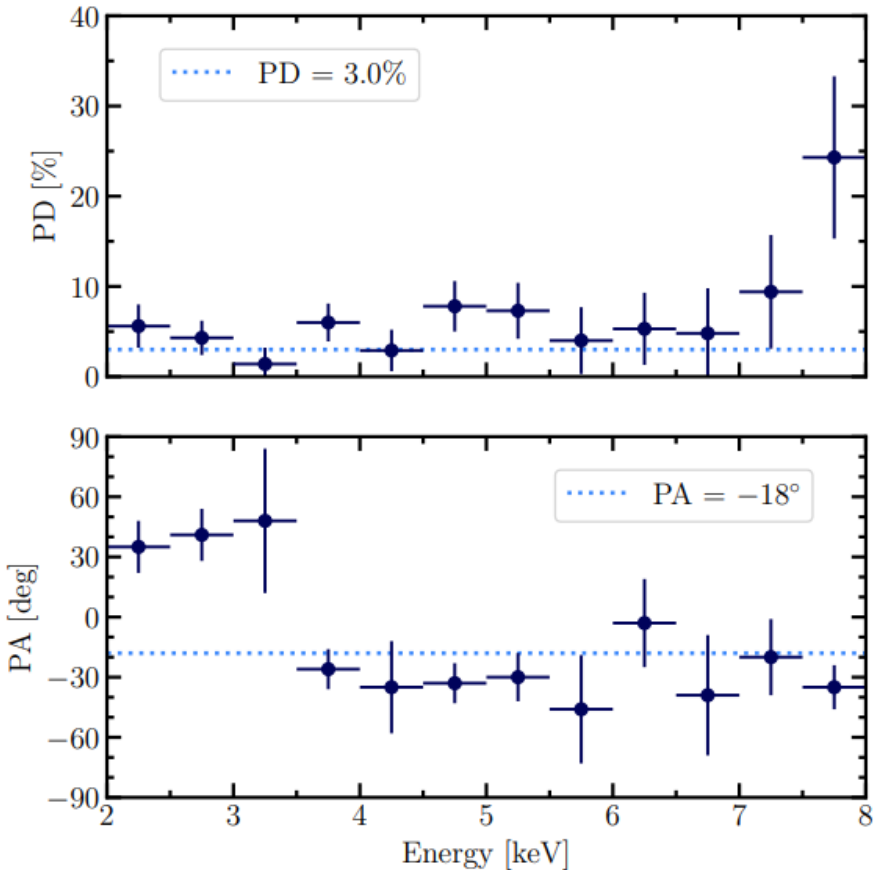


Fig. 3. Energy dependence of the PD and PA for the combined set of data (excluding dip), obtained with the pcube algorithm.

Clear energy-dependence of the PA, with an about 70 deg span of the PA values between low and high energies

Similar to Vela X-1, with switch at around 3 keV

Separate the phase-resolved analysis into low (2-3 keV) and high (4-8 keV) energy bands, excluding the 3-4 keV energy range in order to minimize the contribution from the adjacent energy band with different PA

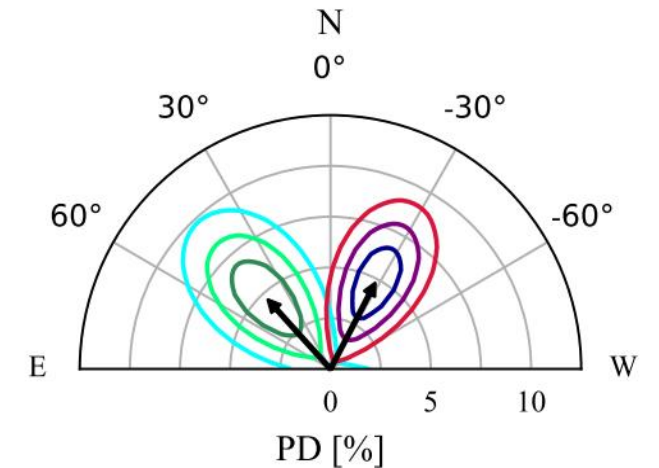
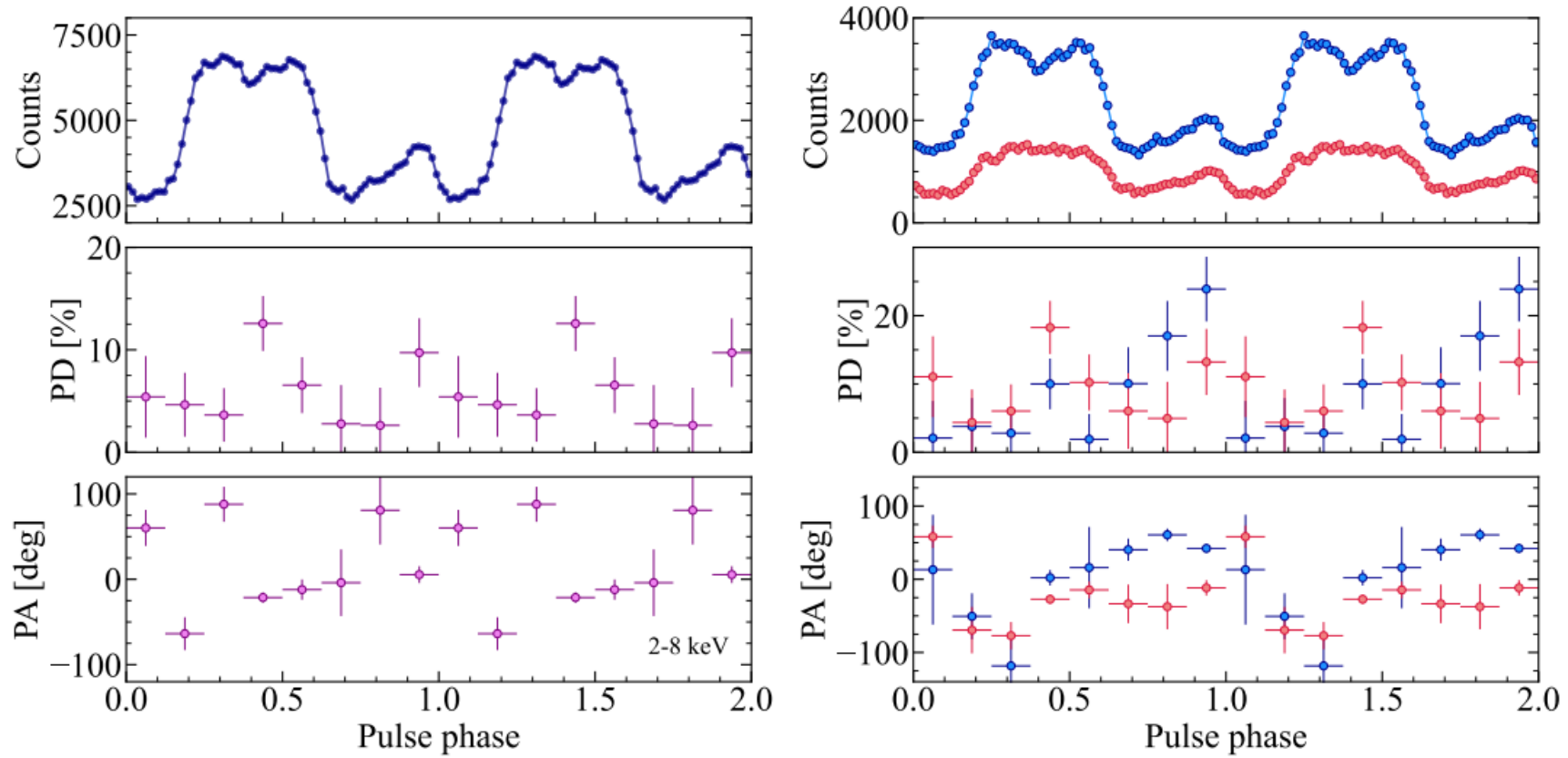


Fig. 5. Polarization vectors of 4U 1538-52 from the results of the phase-averaged spectro-polarimetric analysis of the combined data set. Contours at 68.3%, 95.45%, and 99.73% c.i. calculated for two degrees of freedom are shown in shades of blue for 2-3 keV and in shades of red for 4-8 keV.

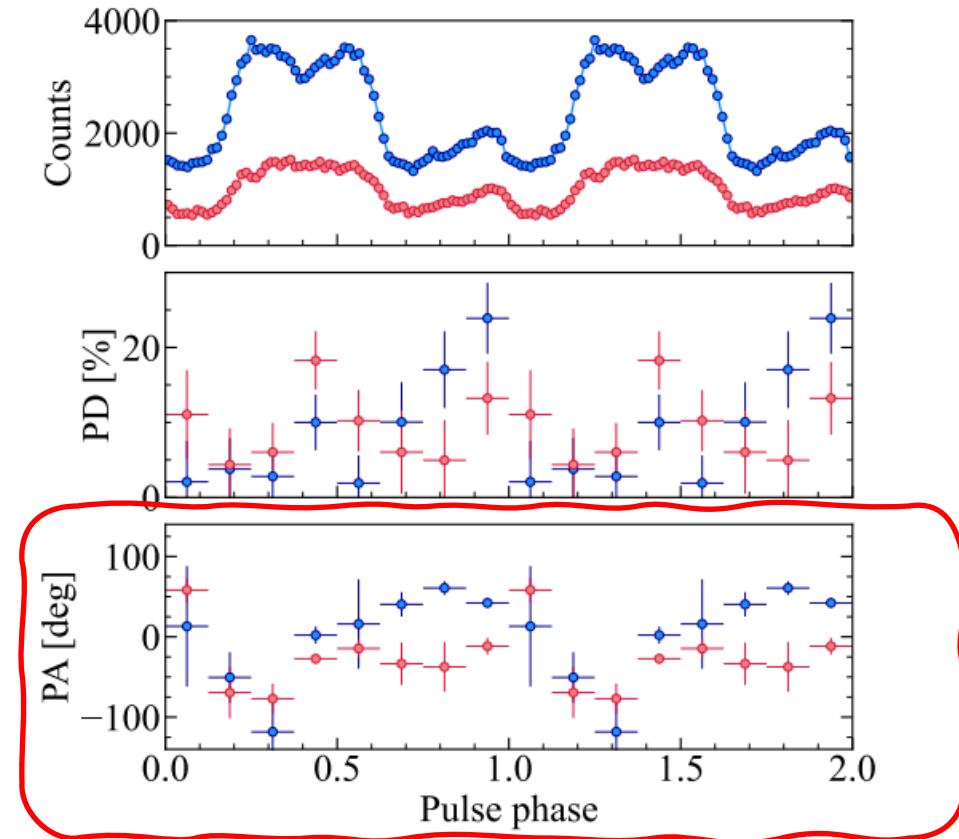
4U 1538-52 – ENERGY DEPENDENT POLARIZATION



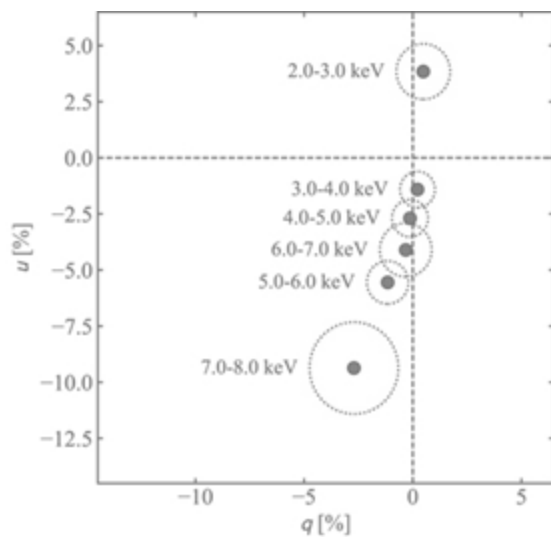
4U 1538-52 – ENERGY DEPENDENT POLARIZATION

At low energies (2–3 keV), the PD spans from ~2% up to ~18%, accompanied by large-amplitude swings in the PA.

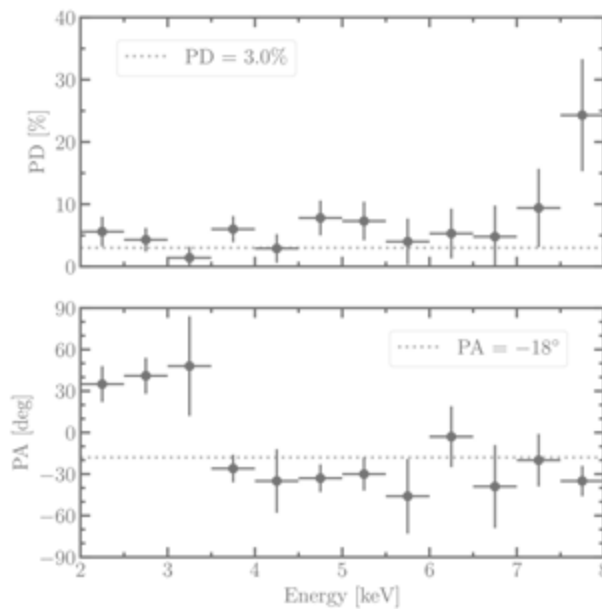
At higher energies (4–8 keV), the PD varies between ~3% and ~12%, and the PA not only is similarly highly variable but also **exhibits a markedly different phase dependence**



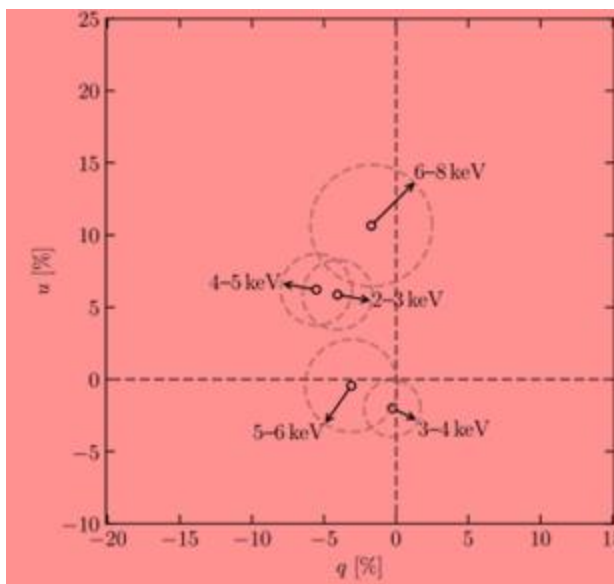
ENERGY DEPENDENCE OF DIFFERENT XRPCs



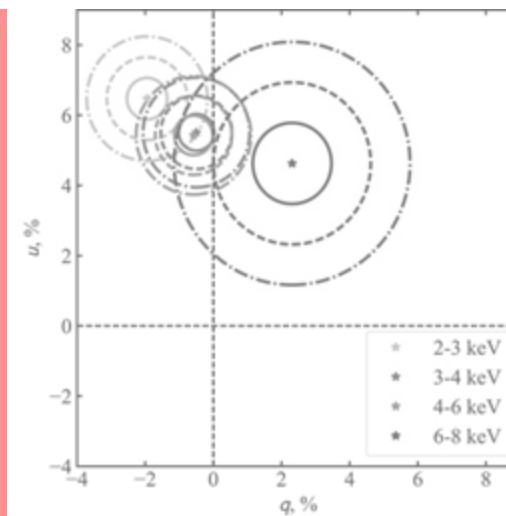
Vela X-1



4U 1538-52



4U 1907+09



Cen X-3

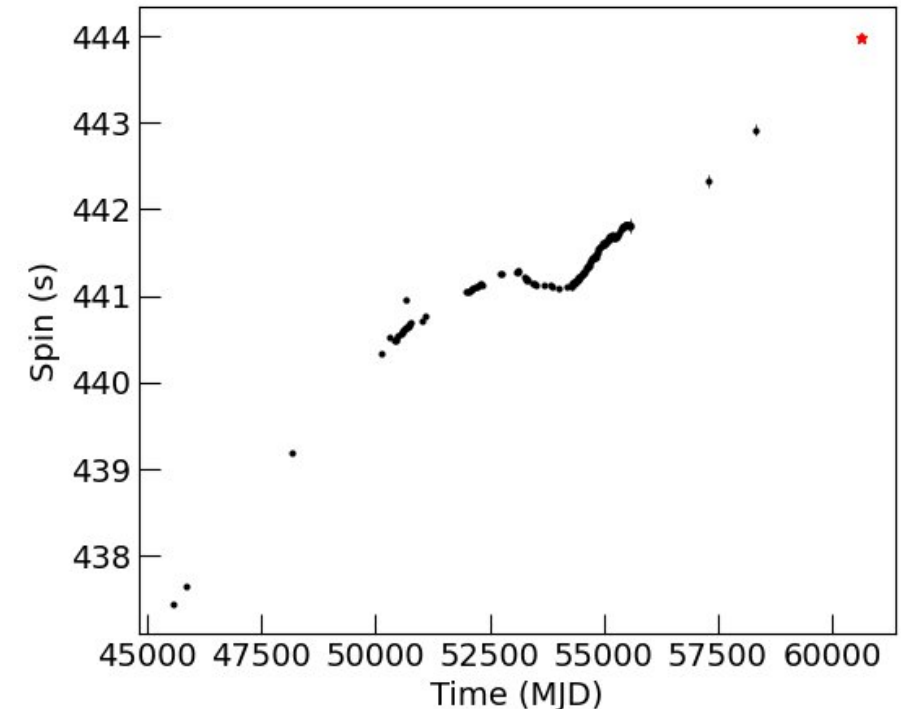
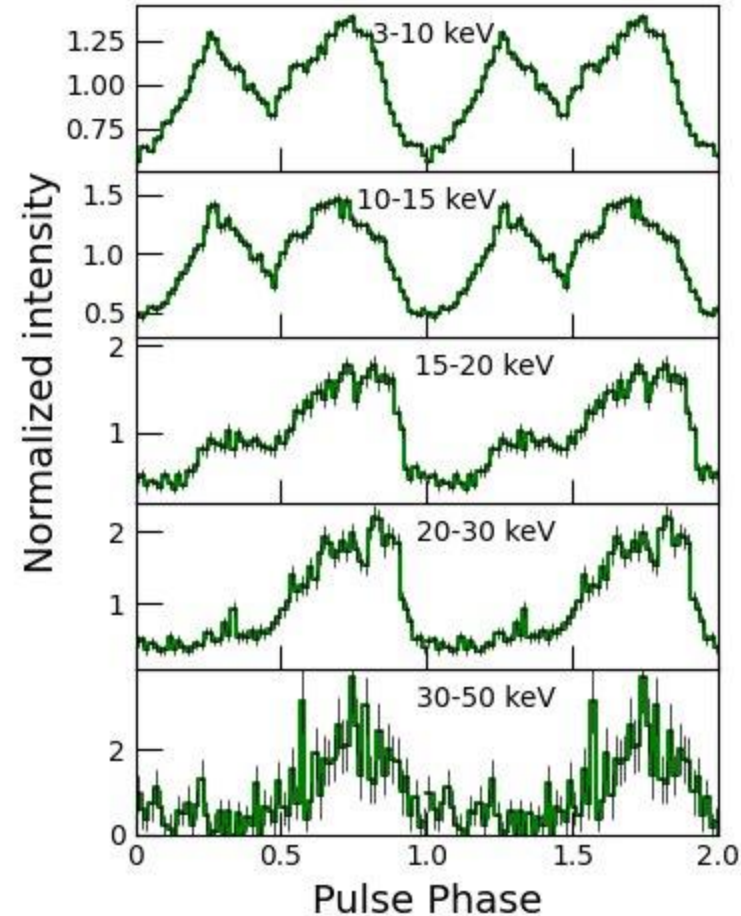


Increased complexity

4U 1907 – INCREASED COMPLEXITY

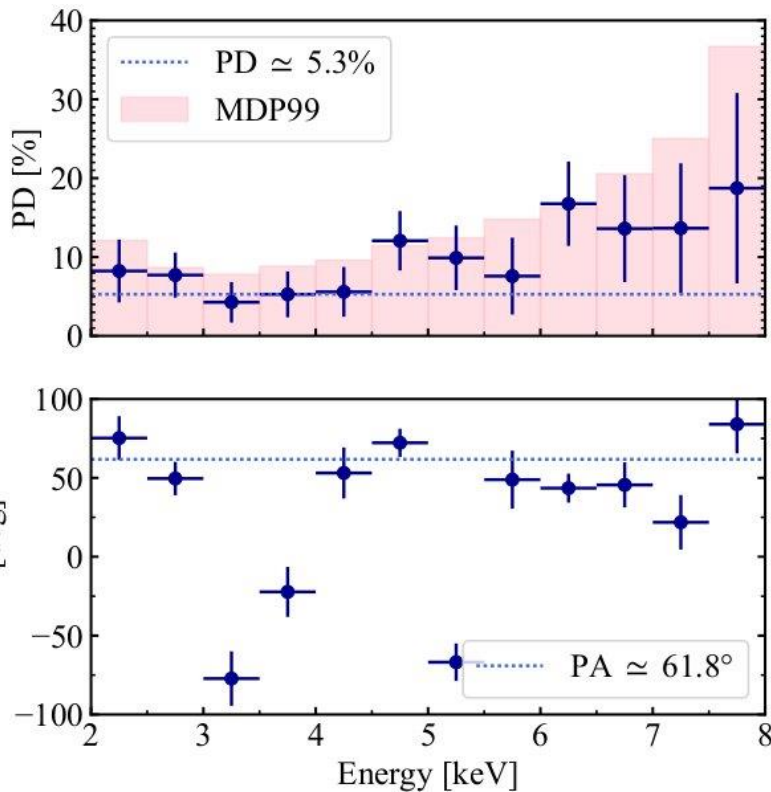
Quick facts:

- First detected in the third Uhuru survey and subsequently confirmed as a HMXB (Giacconi et al 1971; Forman et al. 1978)
- Pulse period of **437.5 s** (Makishima et al. 1984)
- Orbiting a highly reddened companion in an eccentric orbit with a period **8.3753 d**
- Complex pulse profile that depends on both energy and luminosity



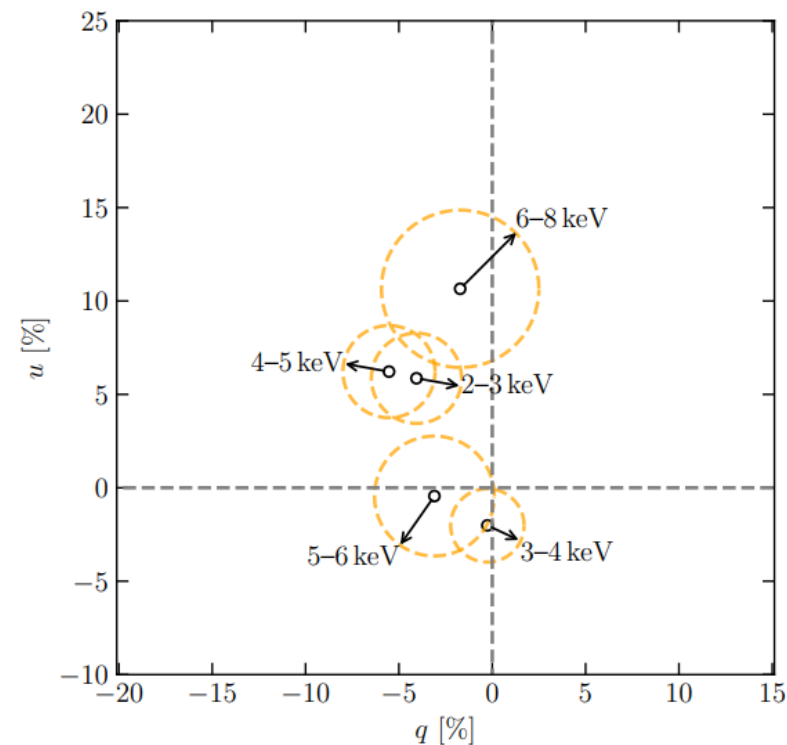
Kumar et al. 2025

4U 1907 – ENERGY DEPENDENT POLARIZATION

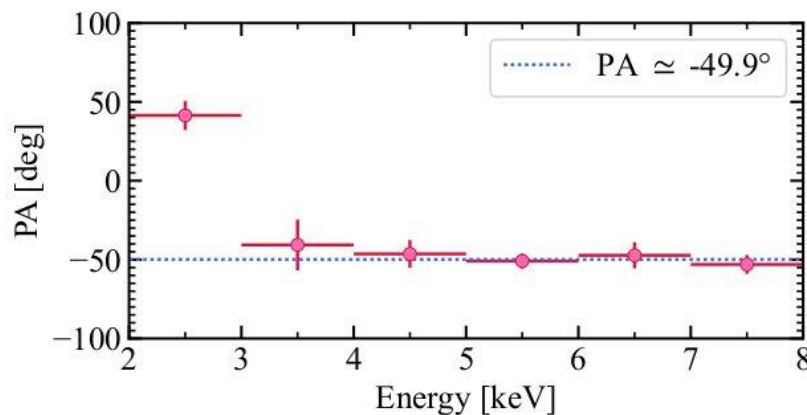
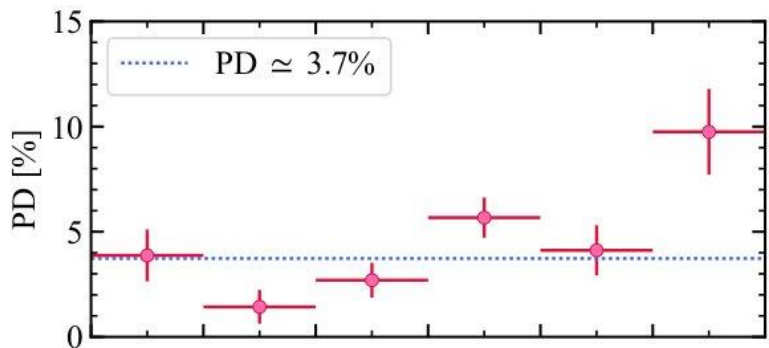


Complex energy dependence, with polarimetric detections in different energy bands exhibiting distinct PAs

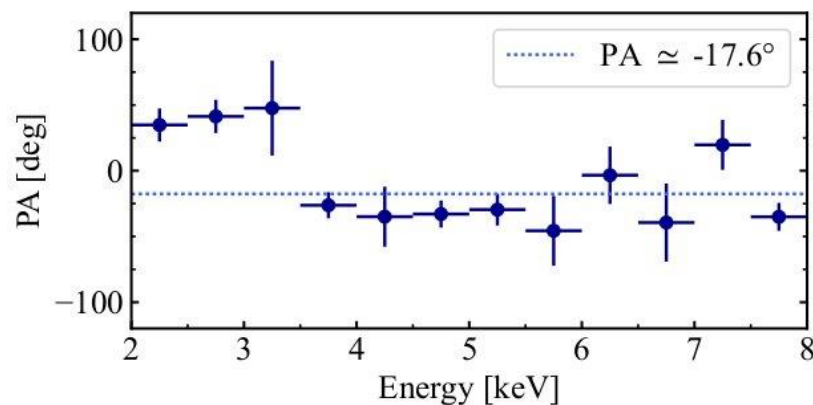
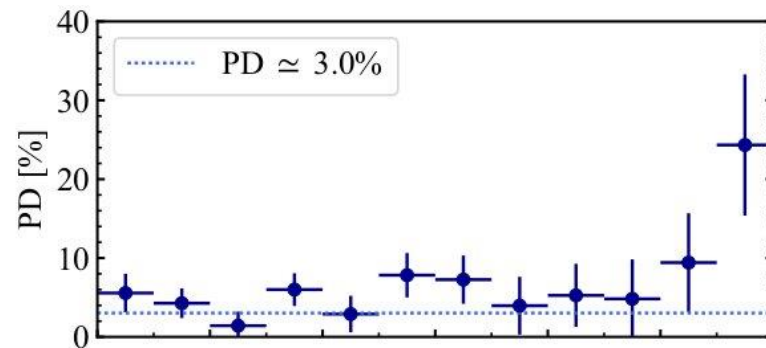
Normalized Stokes q and u for each energy band highlight these polarization discrepancies across energy bands



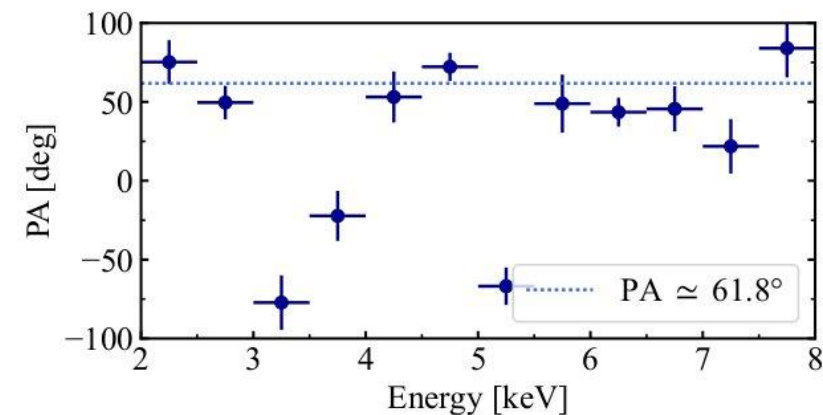
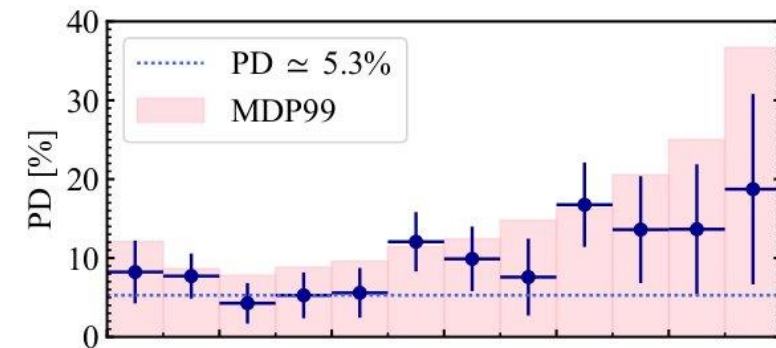
Vela X-1



4U 1538-52

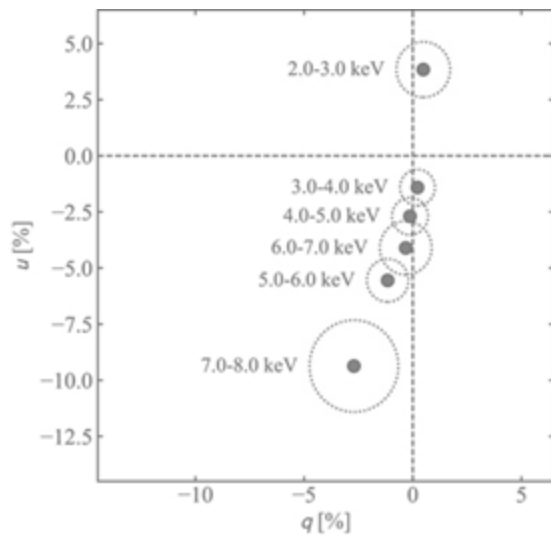


4U 1907+09

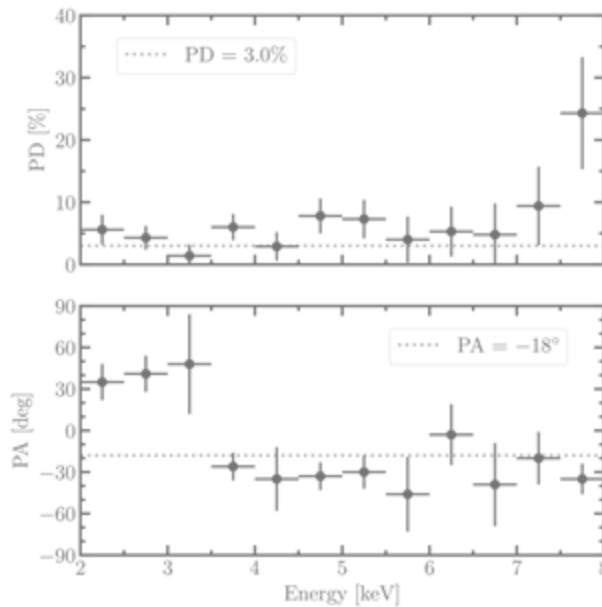


However, the absence of a distinct PA transition at a specific energy precludes the application of an energy-resolved RVM fit

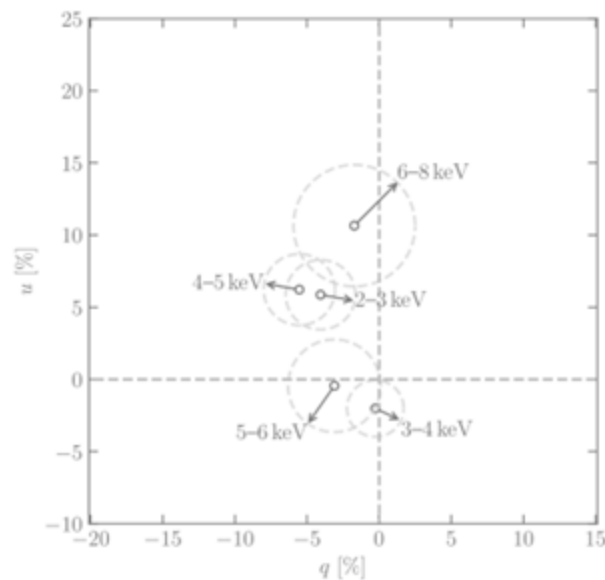
ENERGY DEPENDENCE OF DIFFERENT XRPs



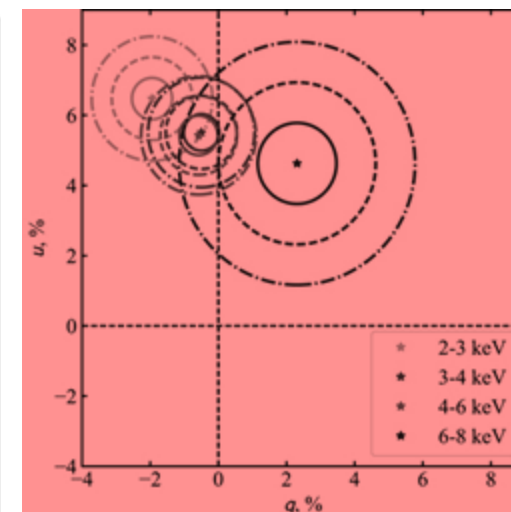
Vela X-1



4U 1538-52



4U 1907+09



Cen X-3



Increased complexity

CEN X-3 – THE FIRST X-RAY PULSAR

Quick facts:

First X-ray pulsar ever discovered

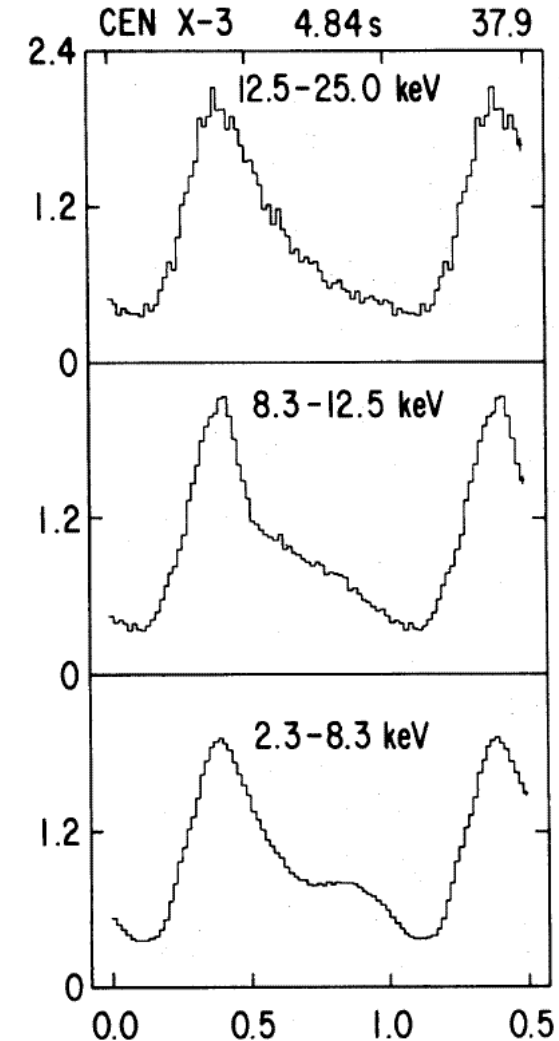
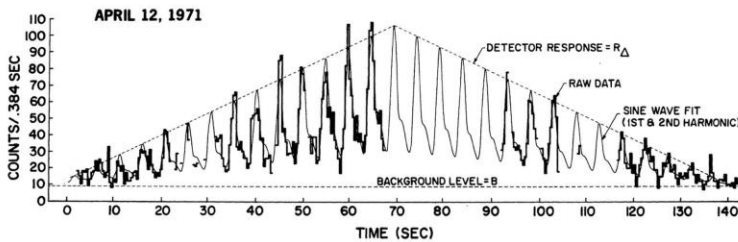
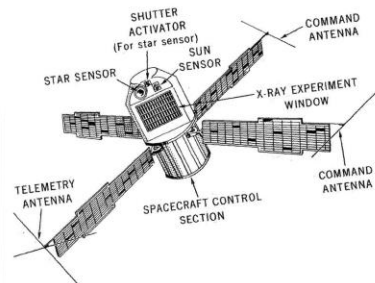
Persistent X-ray pulsar with almost circular orbit ($e < 0.0016$) around O6–8 III supergiant V779 Cen

Ash et al. (1999) determined the inclination of the system to be $70^\circ.2 \pm 2^\circ.7$.

Spin period $P_s = 4.8$ s

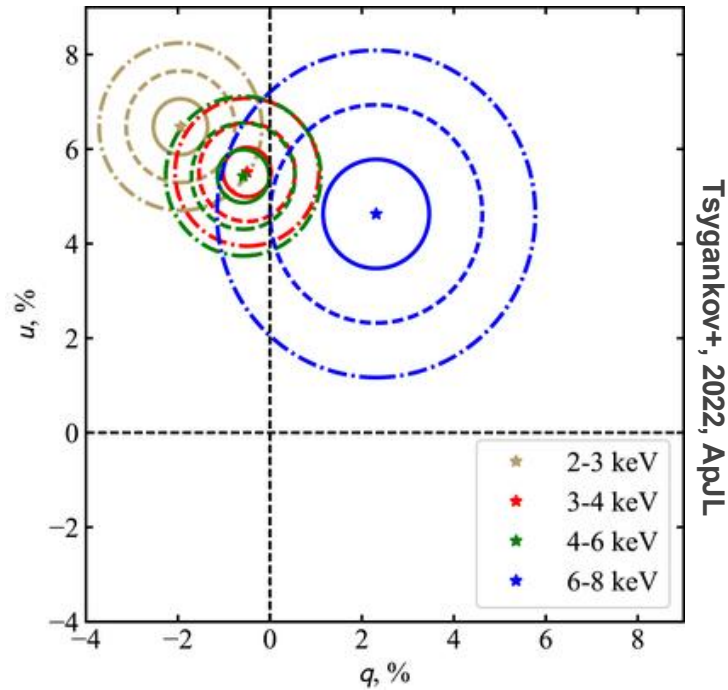
Orbital period $P_{orb} = 2.09$ d

Distance $d = 6.4^{+1.0}_{-1.4}$ kpc

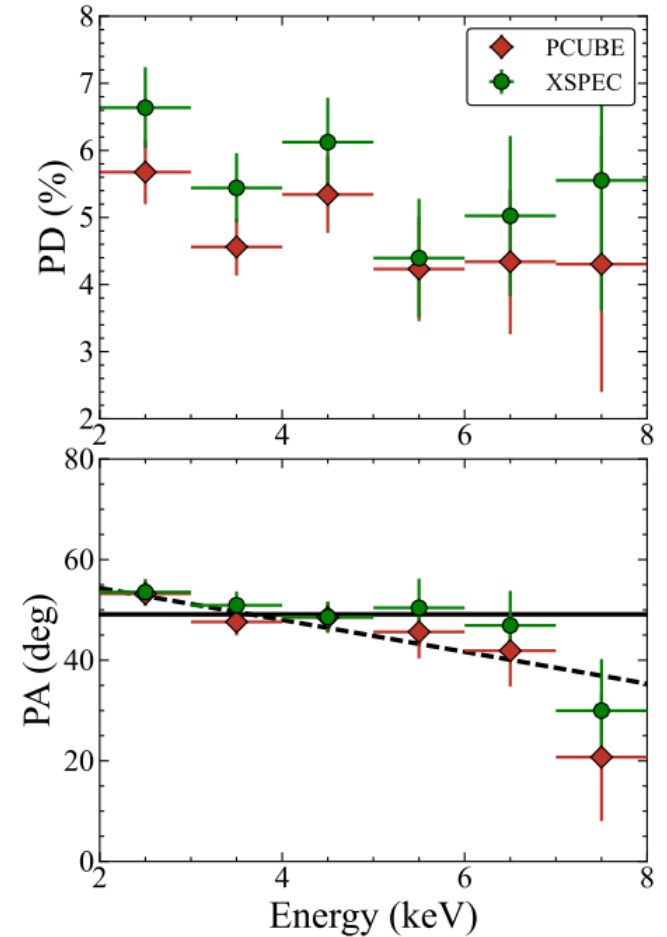


White et al. 1982

CEN X-3 – ENERGY DEPENDENT POLARIZATION

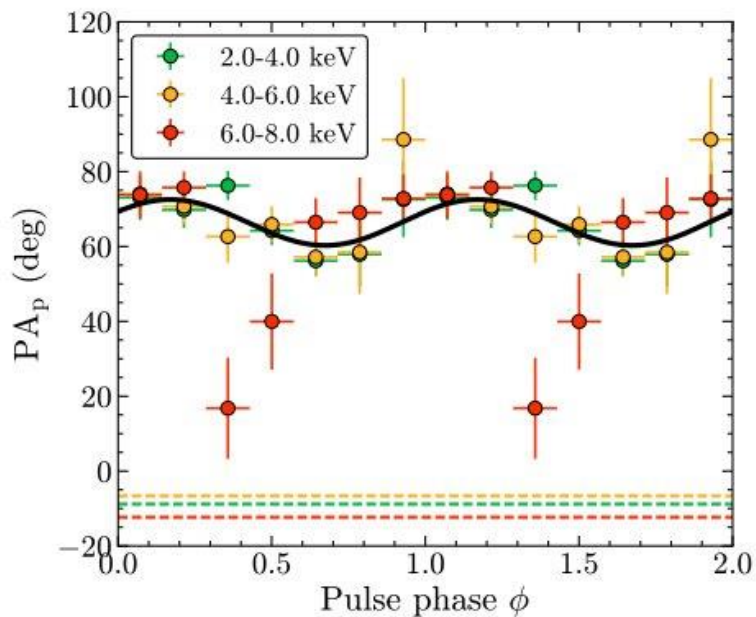


Contrary to the previous examples, no significant energy-dependence of polarization properties in the phase-averaged, energy-resolved analysis



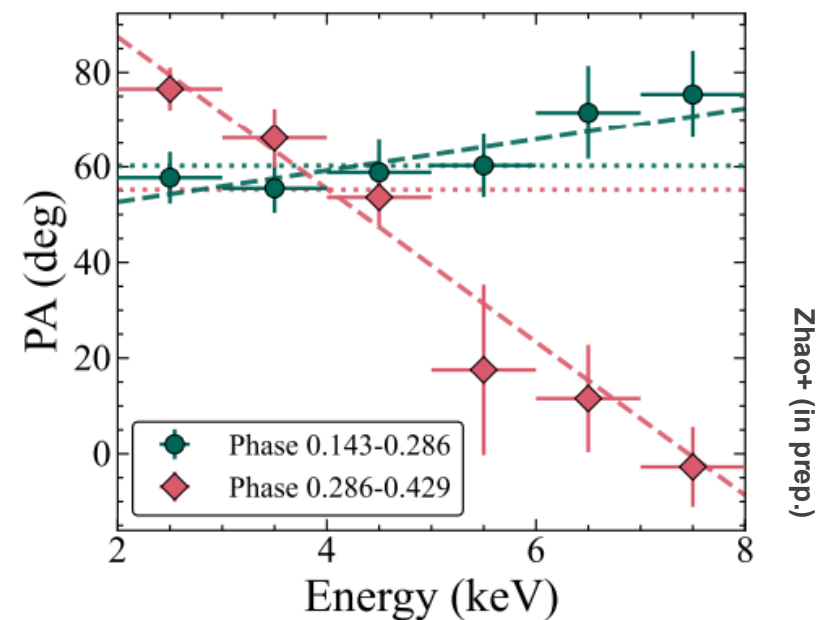
Zhao+ (in prep.)

CEN X-3 – ENERGY DEPENDENT POLARIZATION



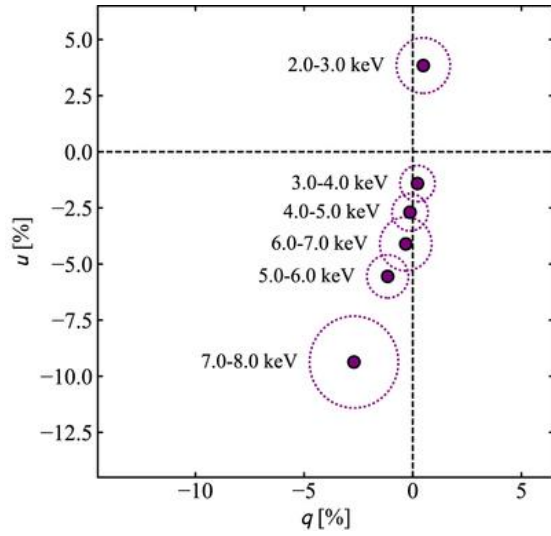
The phase-resolved analysis reveals that the energy dependence of the PA is strongly phase-dependent,

with dramatic variations visible in a few specific phase intervals



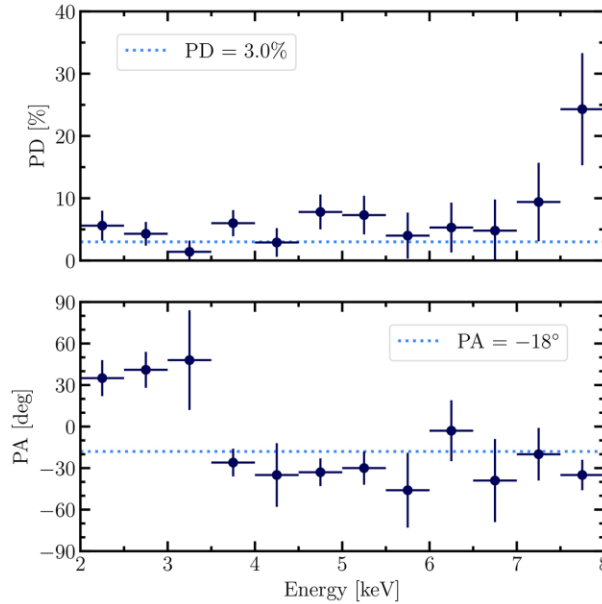
Zhao+ (in prep.)

CONCLUSIONS/DISCUSSION



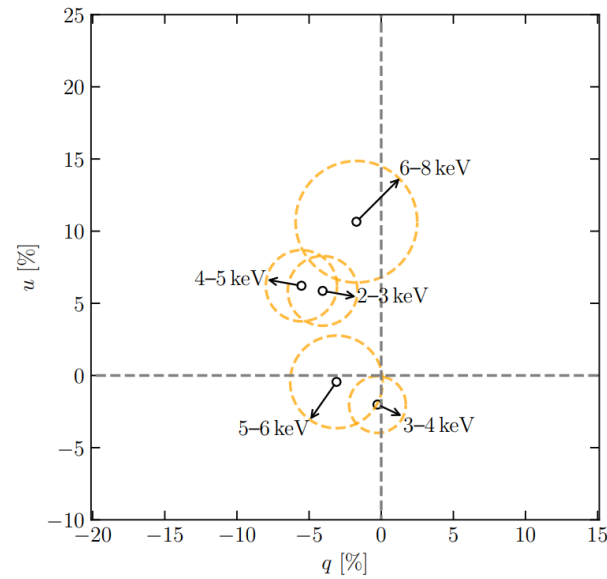
Vela X-1

Clear 90 deg shift in PA between low and high energies, can be explained by difference in modes*



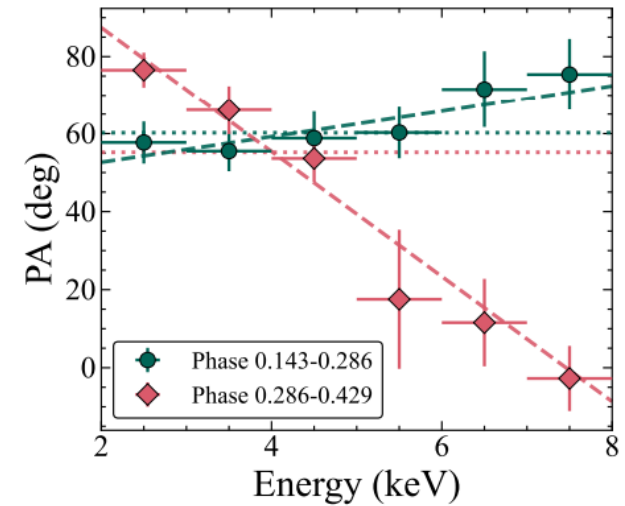
4U 1538-52

Sharp switch in PA at around 3 keV presents a particular challenge, as it is not consistent with the right-angle switch seen in Vela X-1



4U 1907+09

Very complex behavior, and the absence of a distinct PA transition at a specific energy precludes the application of an energy-resolved RVM fit



Cen X-3

No significant energy dependence in phase-averaged, but complex behavior observed in energy phase bins