Variability of X-ray polarization of Cyg X-1

Vadim Kravtsov (University of Turku)
A. Bocharova, A. Veledina, J. Poutanen, A. K. Hughes, M. Dovčiak et al. 2025

15 September 2025

UNIVERSITY OF TURKU

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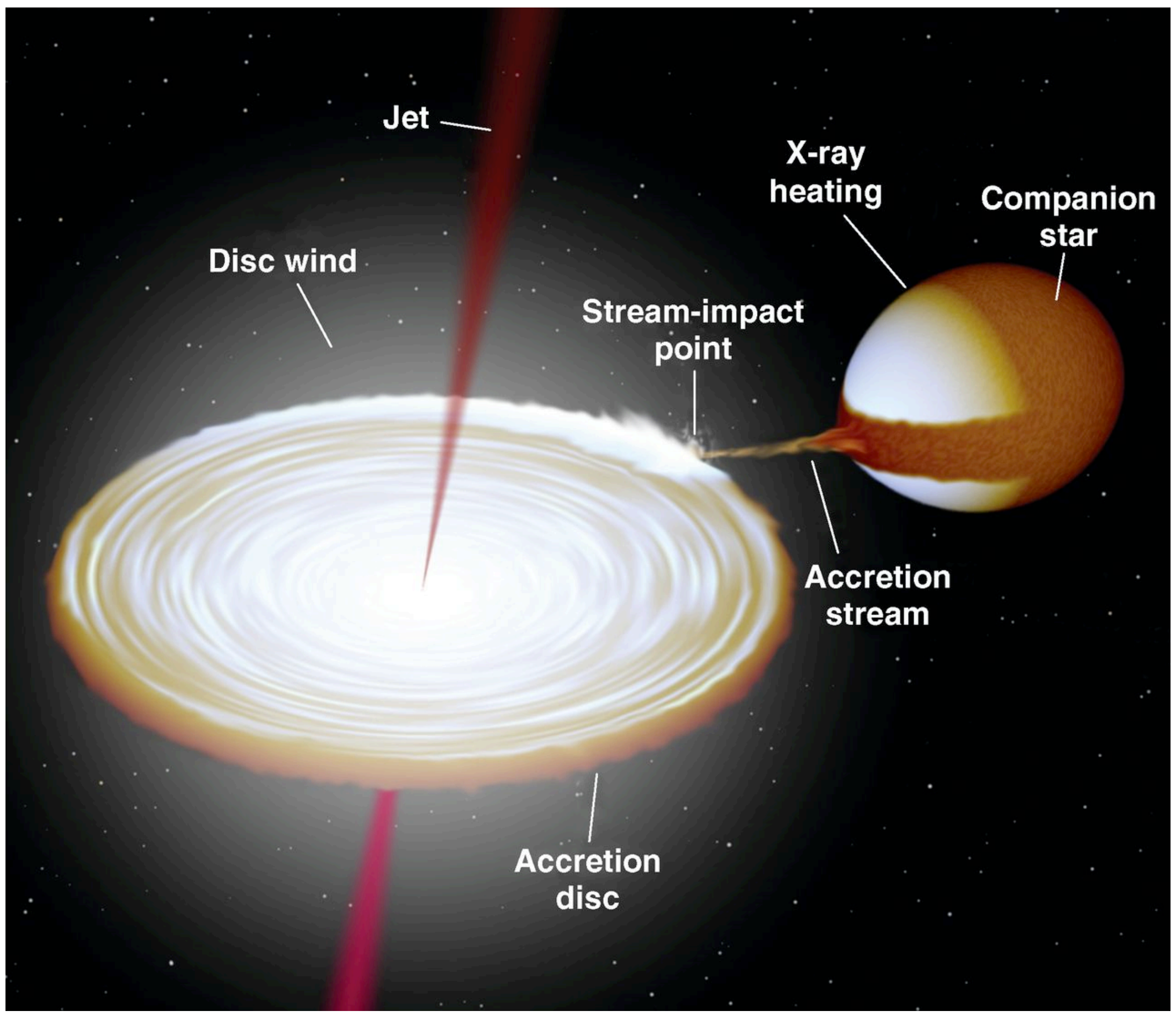
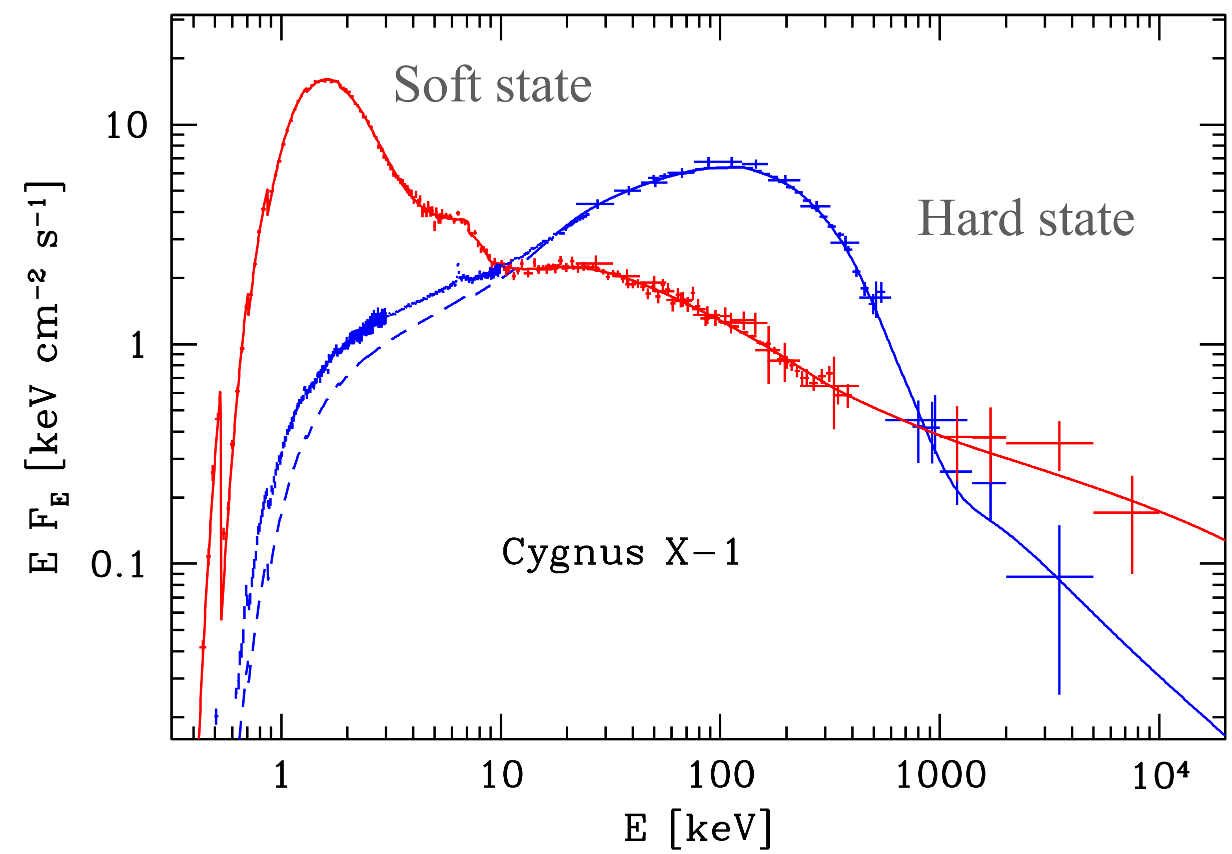
Introduction

Introduction

Spectrum of X-ray binary – product of a complex interplay between contributions of several components.



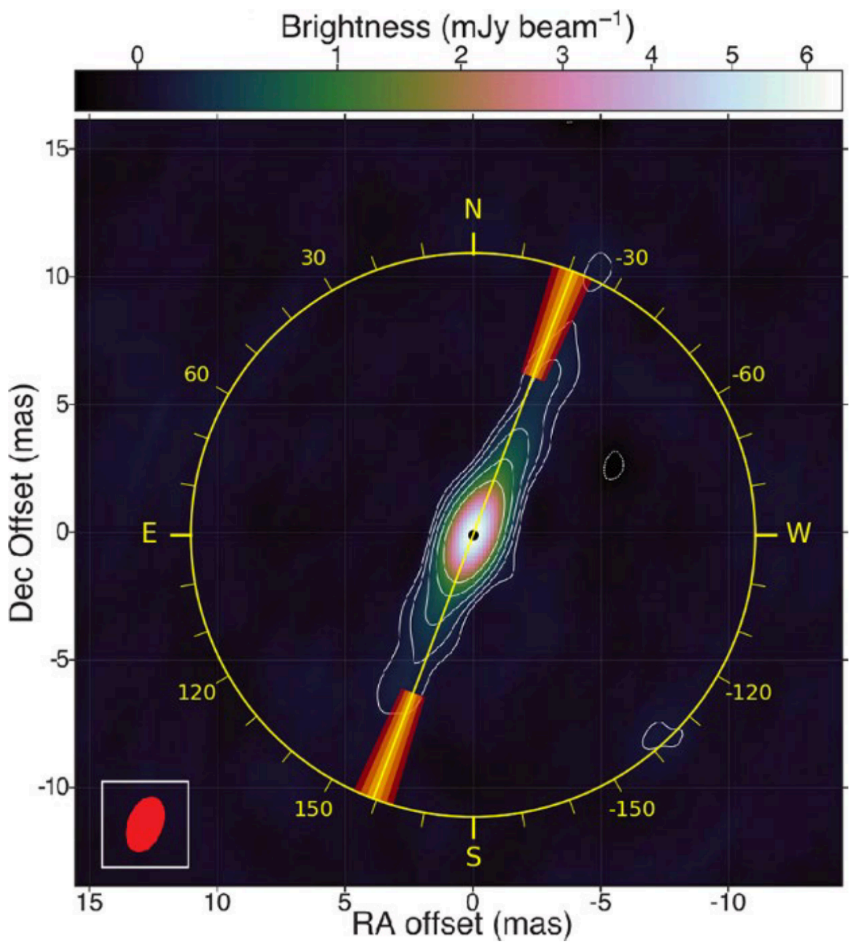
[Image produced with BinSim by Rob Hynes]



McConnell et al. 2002

Introduction

First IXPE observation of Cyg X-1



Krawczynski et al., 2022

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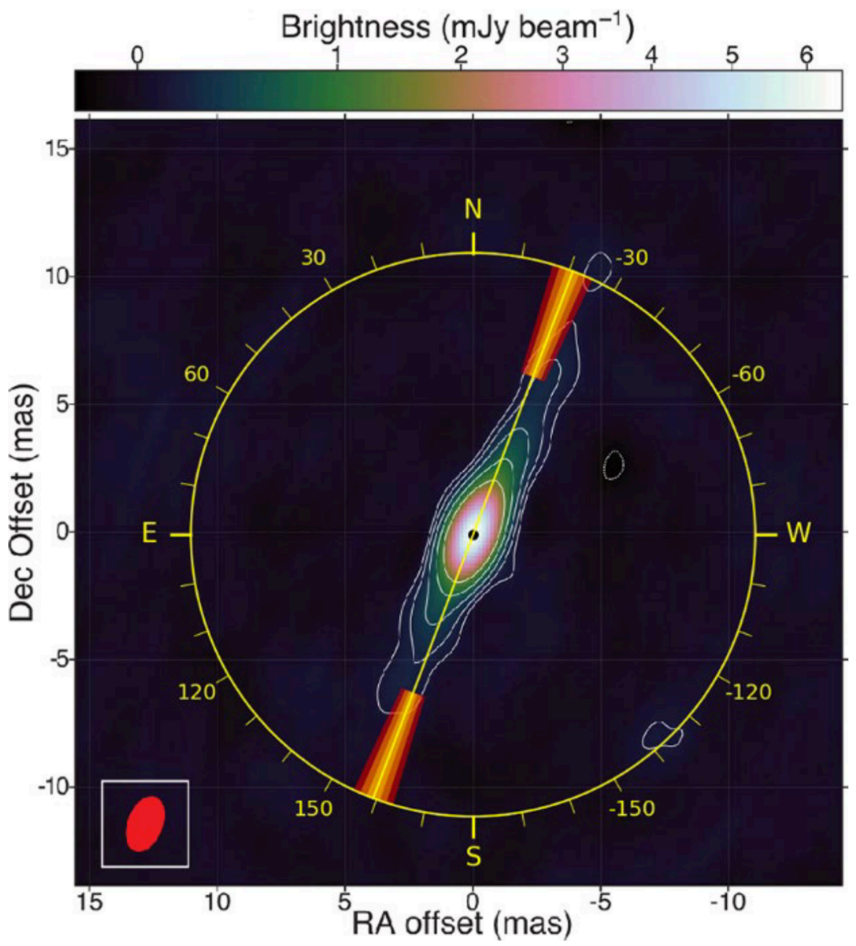

Krawczynski et al., 2022

PD > 4% required high (i > 45°) inclination of the X-ray bright region

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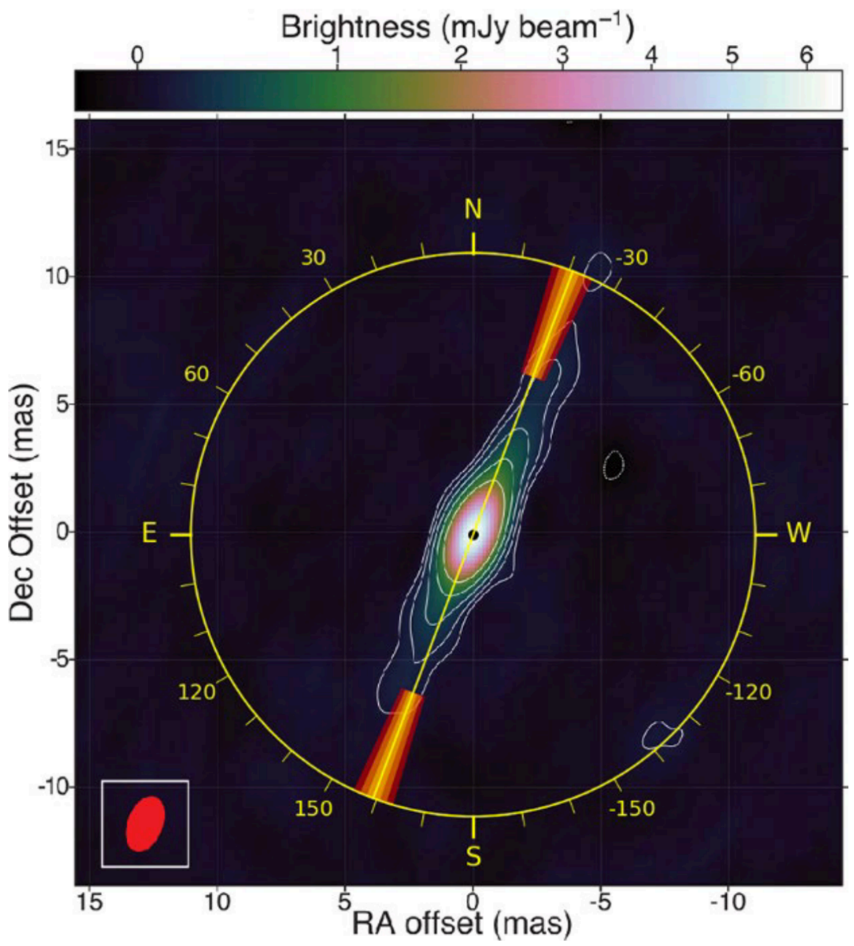

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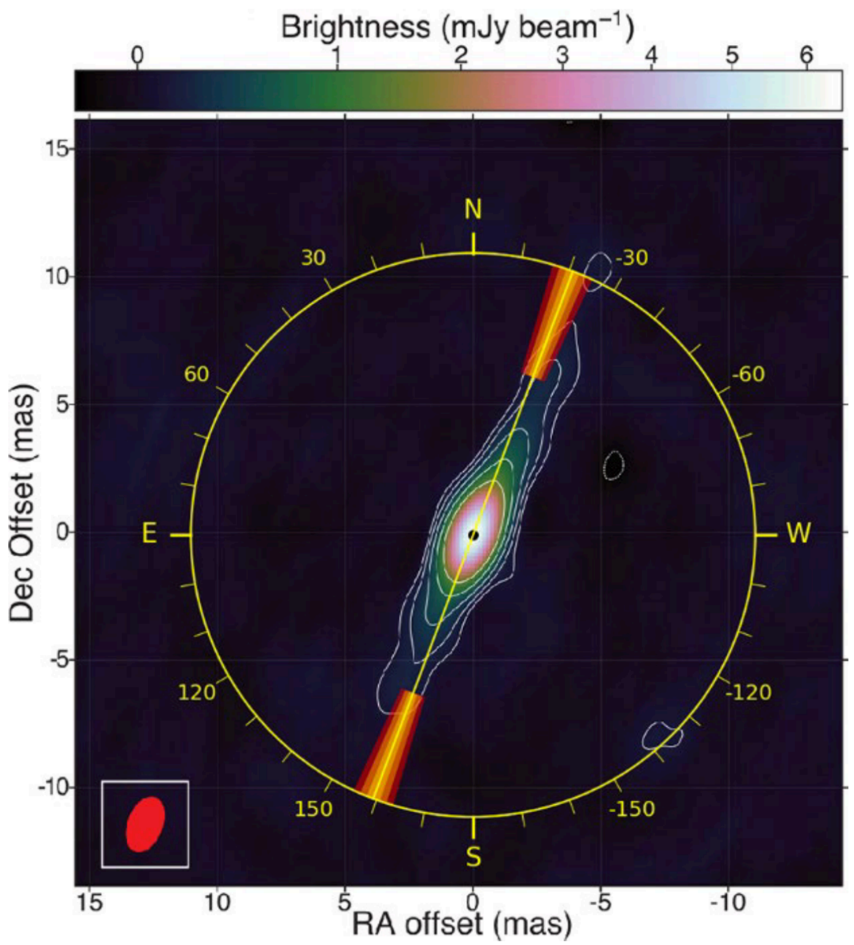
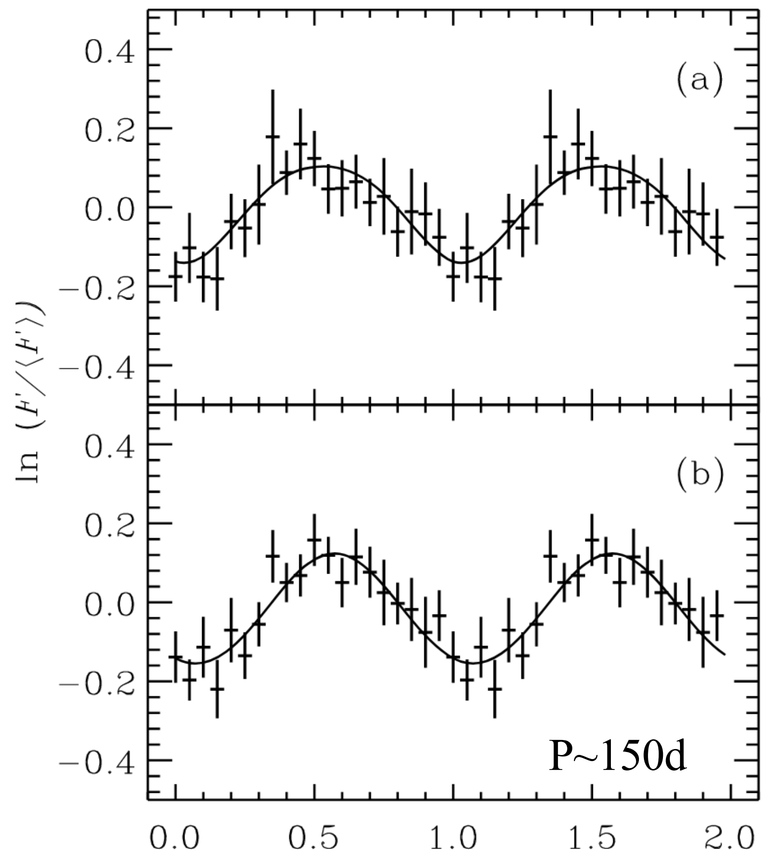


Krawczynski et al., 2022

RXTE/ASM data



Ibragimov et al. 2007

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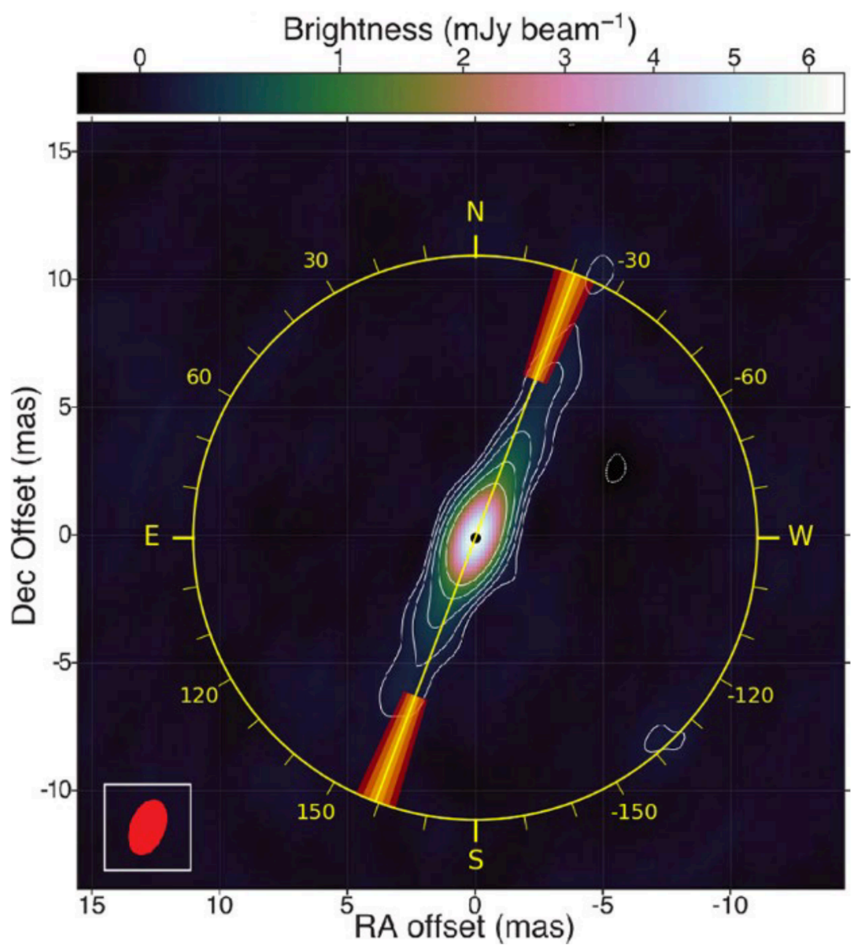

Krawczynski et al., 2022

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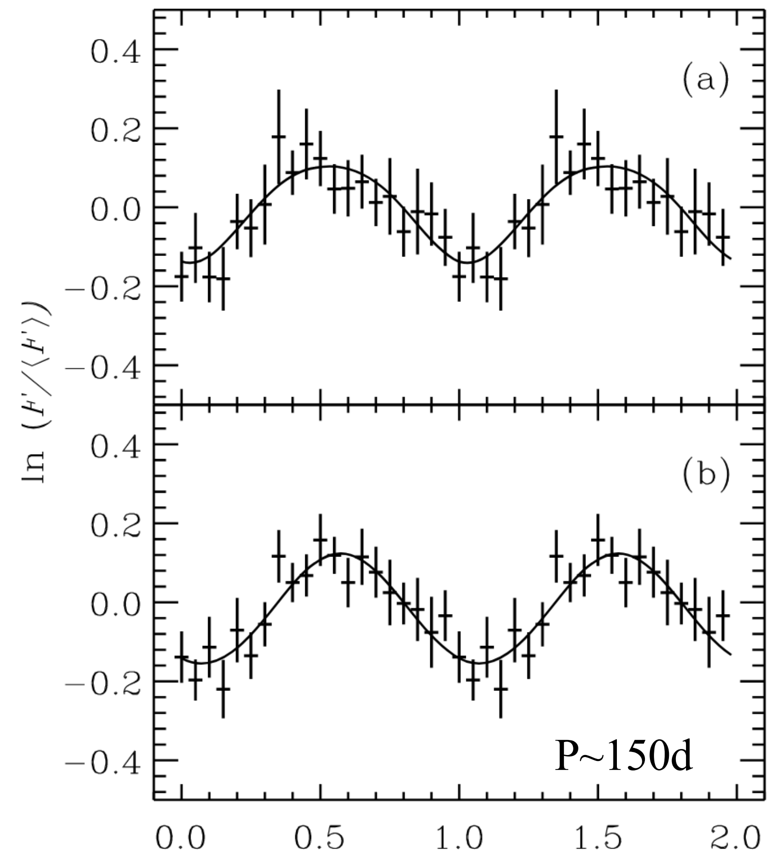
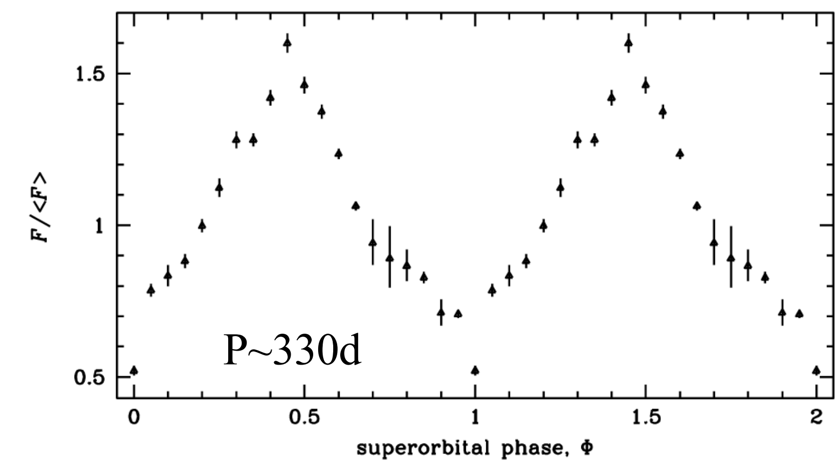


Ibragimov et al. 2007

AMI data



Zdziarski et al. 2011

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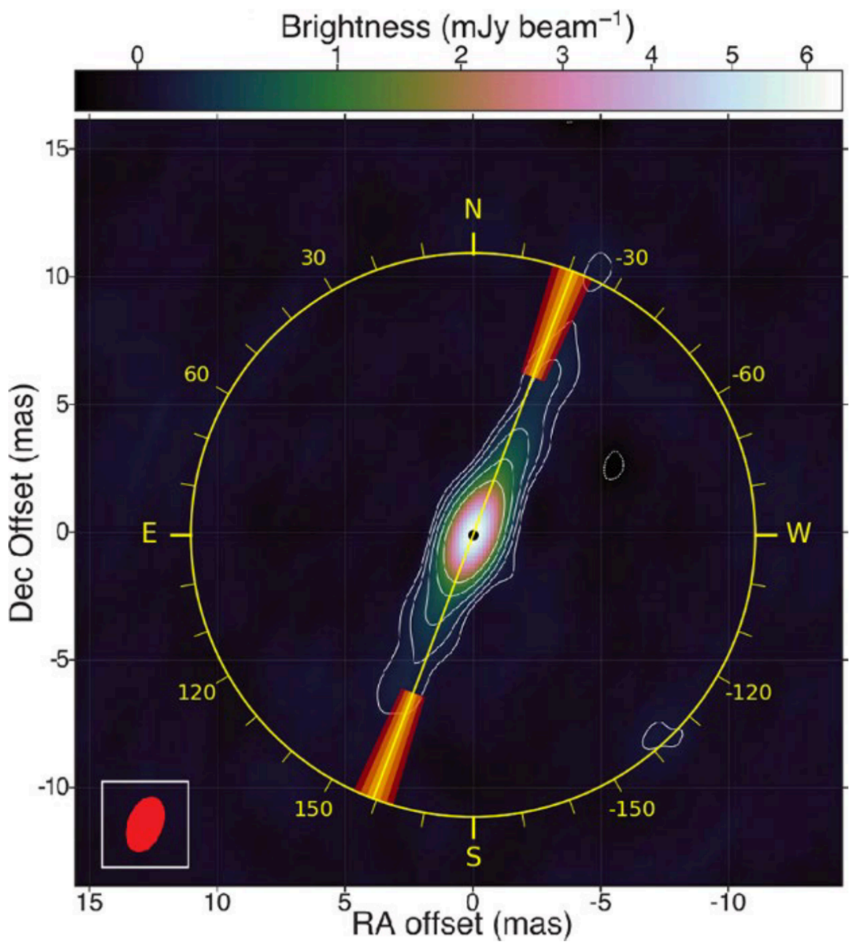

Krawczynski et al., 2022

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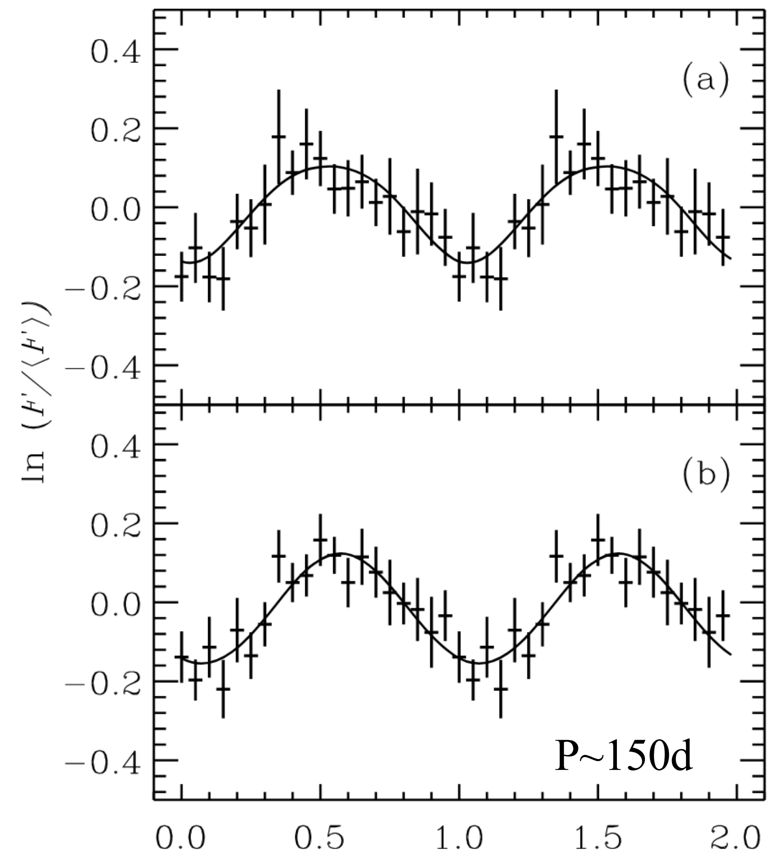

Ibragimov et al. 2007

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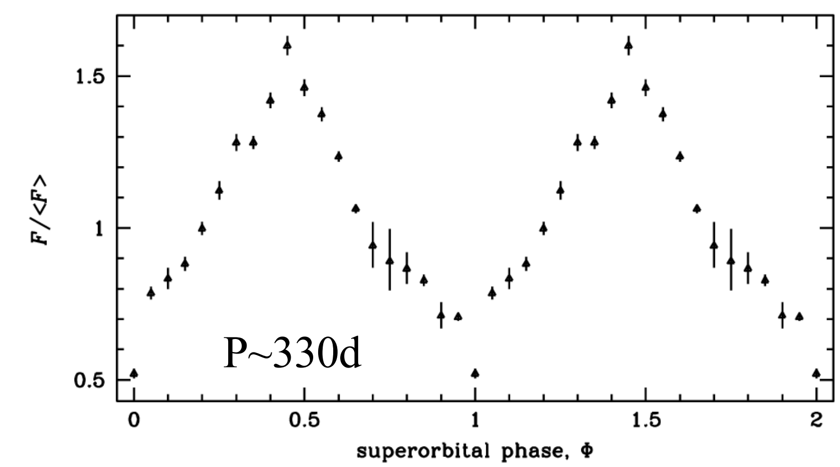
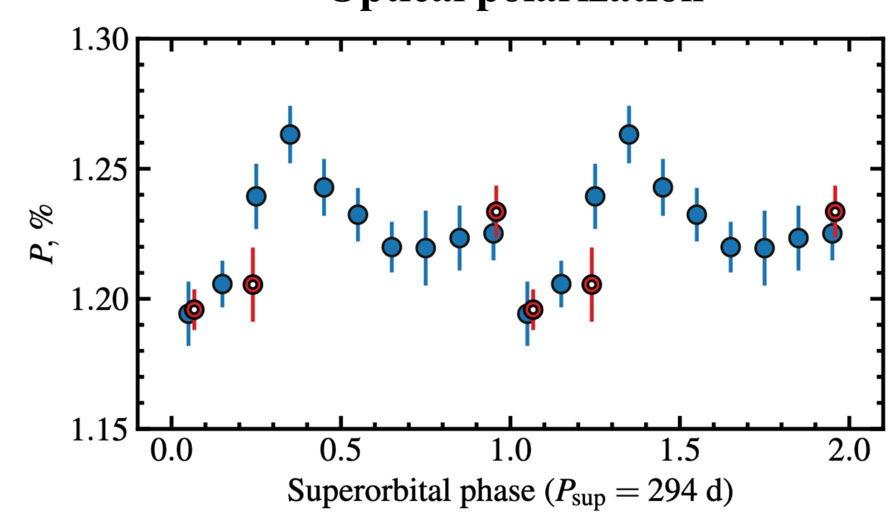


Zdziarski et al. 2011

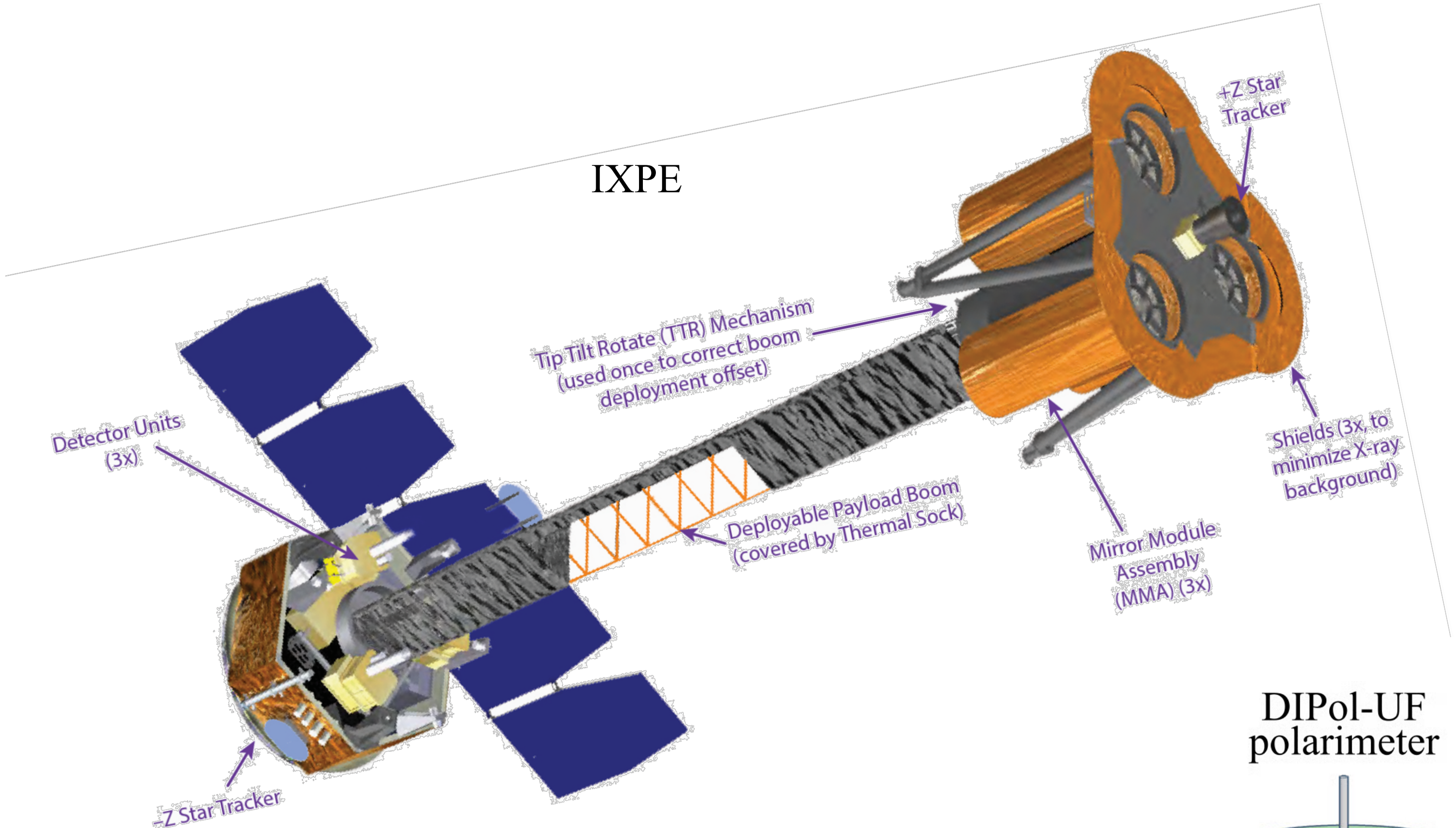
Optical polarization



Kemp et al., 1983 (blue); Kravtsov et al. 2023 (red)

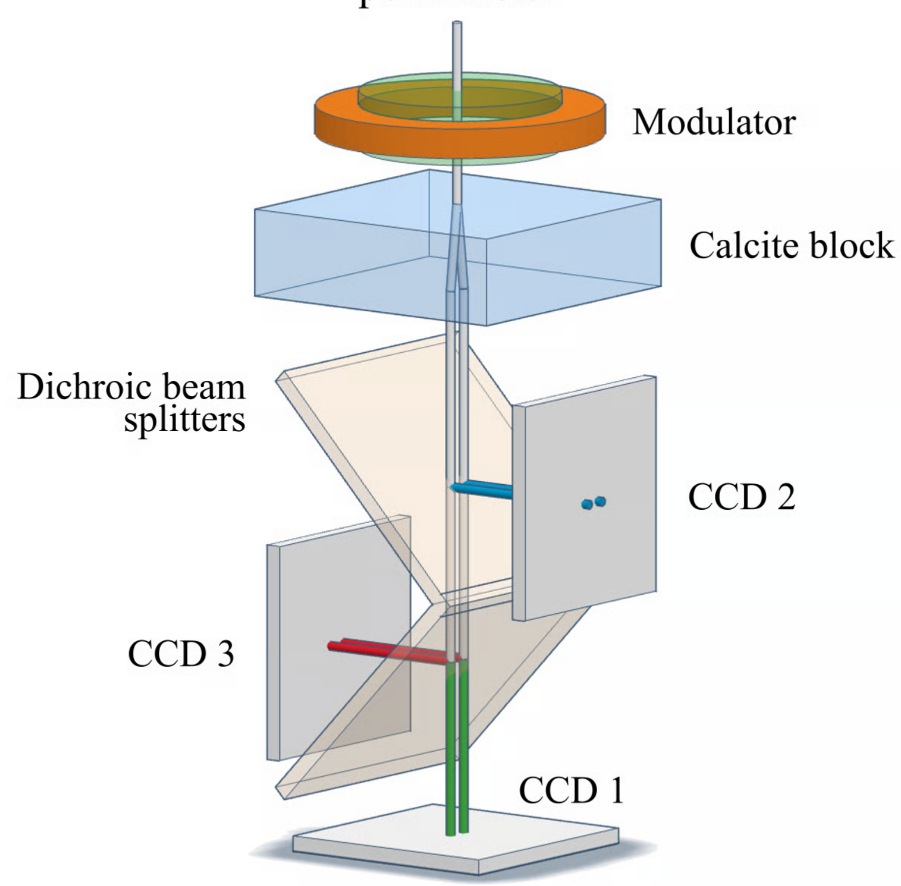
PD > 4% required high (i > 45°) inclination of the X-ray bright region

Observations

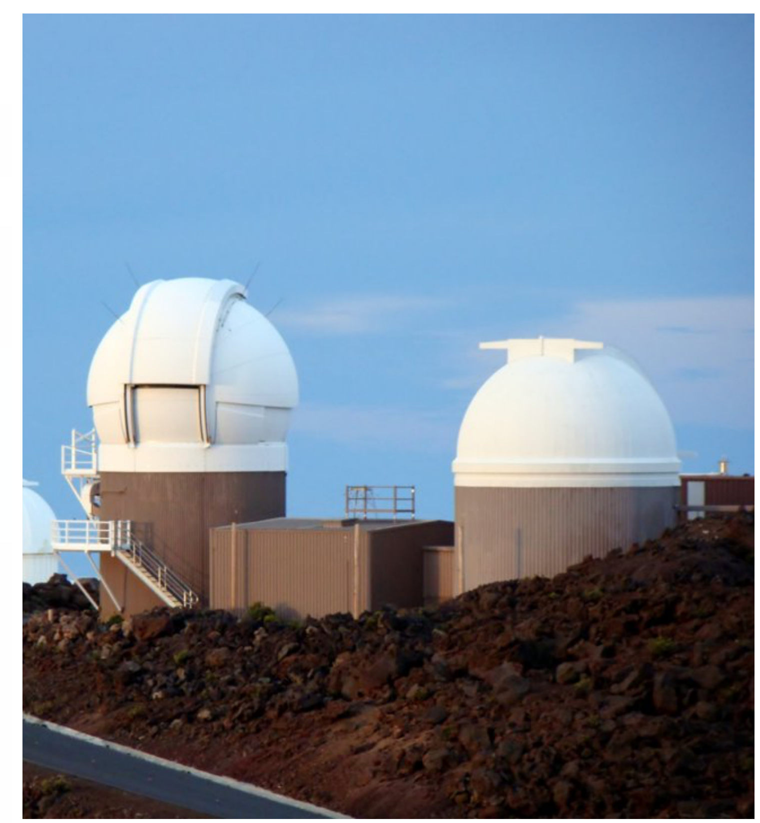


Very Large Array (N.Mex, US) - A. Hughes, F. Carotenuto

DIPol-UF polarimeter



Haleakala Observatory (Hawaii, US)



Additional coverage:

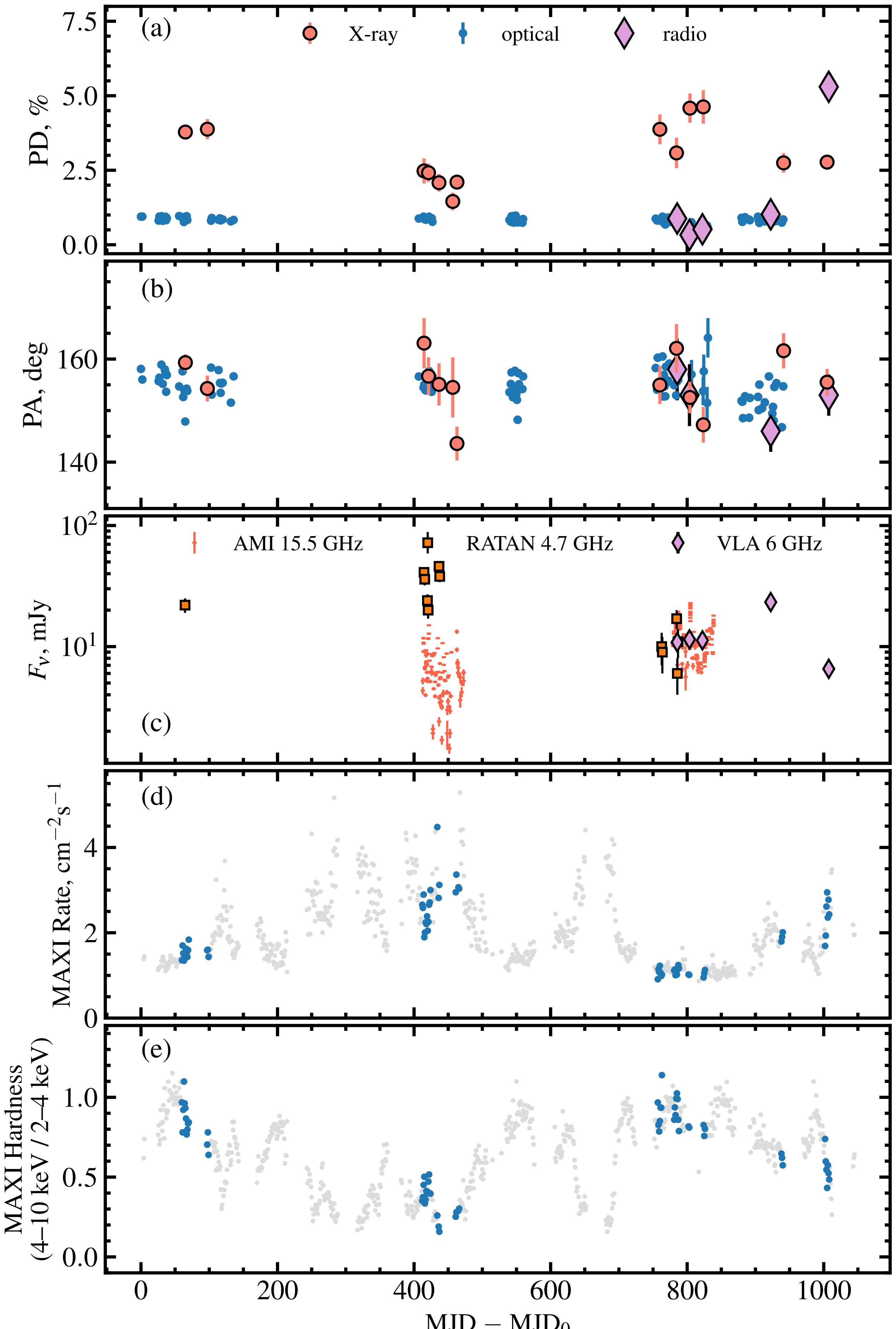
- **AMI** (D. Green, J. Bright, L. Rhodes)
- **RATAN-600** (S. Trushkin)
- **RoboPol** (Y. Liodakis, D. Blinov, N. Mandarakas)

Observations

13 IXPE pointings during 3 years

Epoch		Date	State	PD (%)	PA (deg)
1	2022	May 15	H	4.0 ± 0.2	−21 ± 2
2		June 18	H	3.9 ± 0.3	−26 ± 3
3	2023	May 2	S	2.5 ± 0.4	−17 ± 5
4		May 9	S	2.4 ± 0.3	−23 ± 4
5		May 24	S	2.1 ± 0.3	−25 ± 4
6		June 13	S	1.5 ± 0.3	−26 ± 6
7		June 20	S	2.1 ± 0.2	−36 ± 3
8	2024	April 12	H	3.9 ± 0.5	−25 ± 4
9		May 6	H	3.1 ± 0.5	−28 ± 5
10		May 26	H	4.6 ± 0.5	−28 ± 3
11		June 14	H	4.6 ± 0.6	−33 ± 3
12		October 10	S	2.8 ± 0.3	−18 ± 3
13		December 12	S	2.8 ± 0.2	−25 ± 3

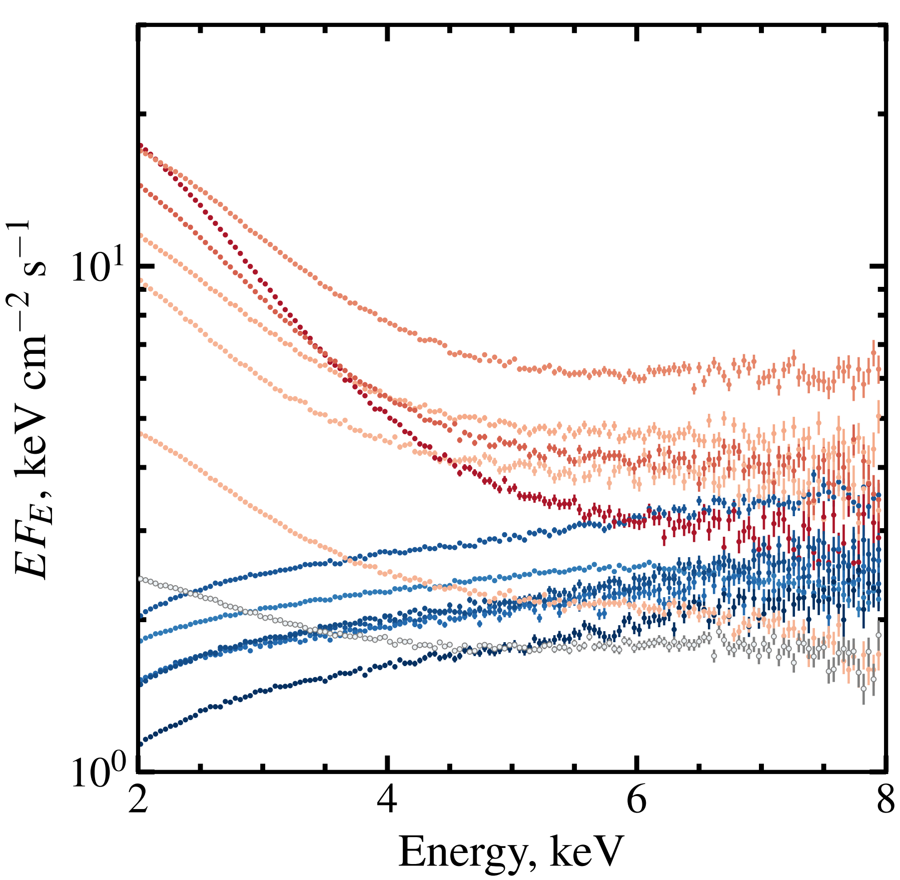
[1-2] Krawczynski et al. 2022
[3-7] Steiner et al. 2024, Jana et al. 2024
[8-10] Dovčiak et al. 2024



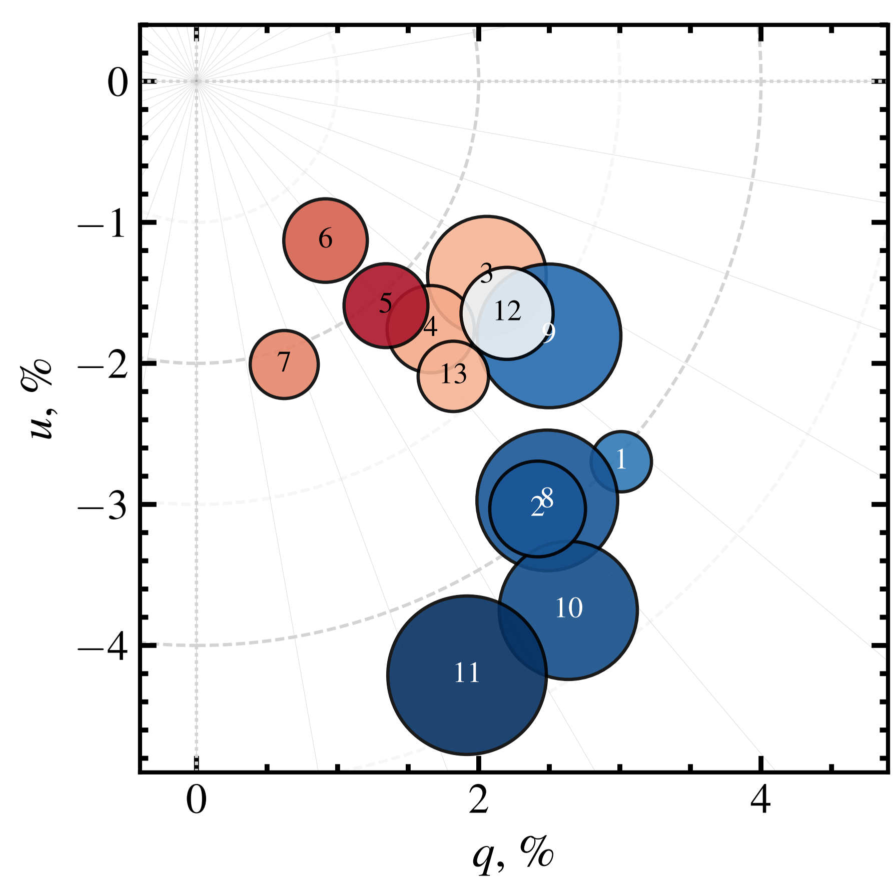
Results

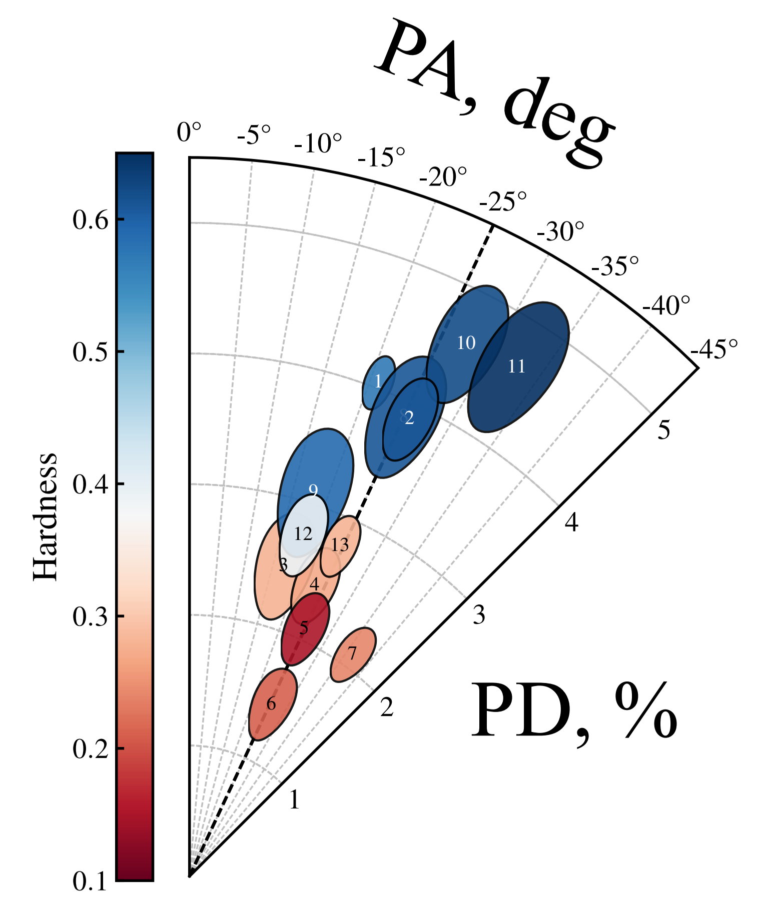
13 observations across all spectral states

X-ray spectra



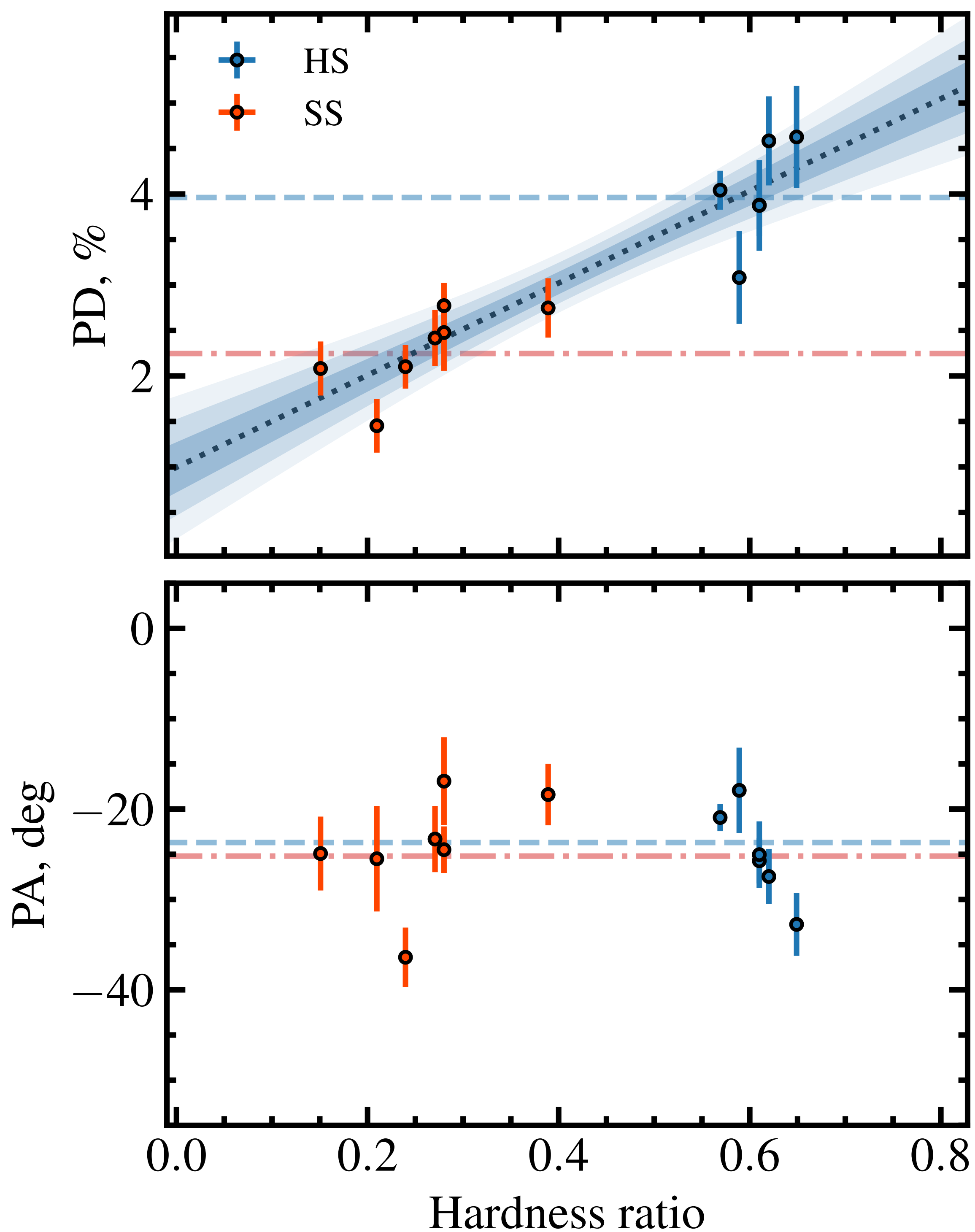
Stokes parameters





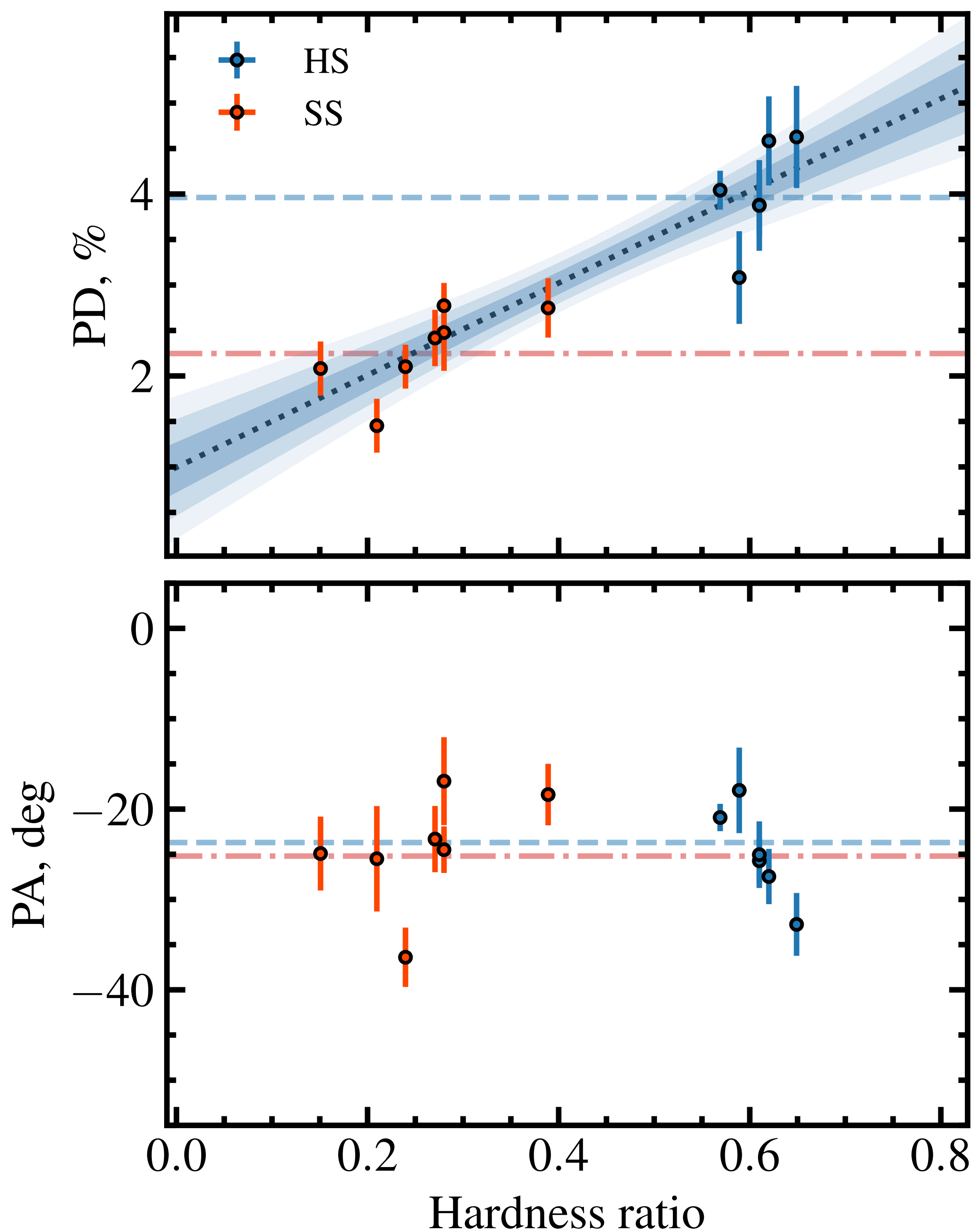
Results

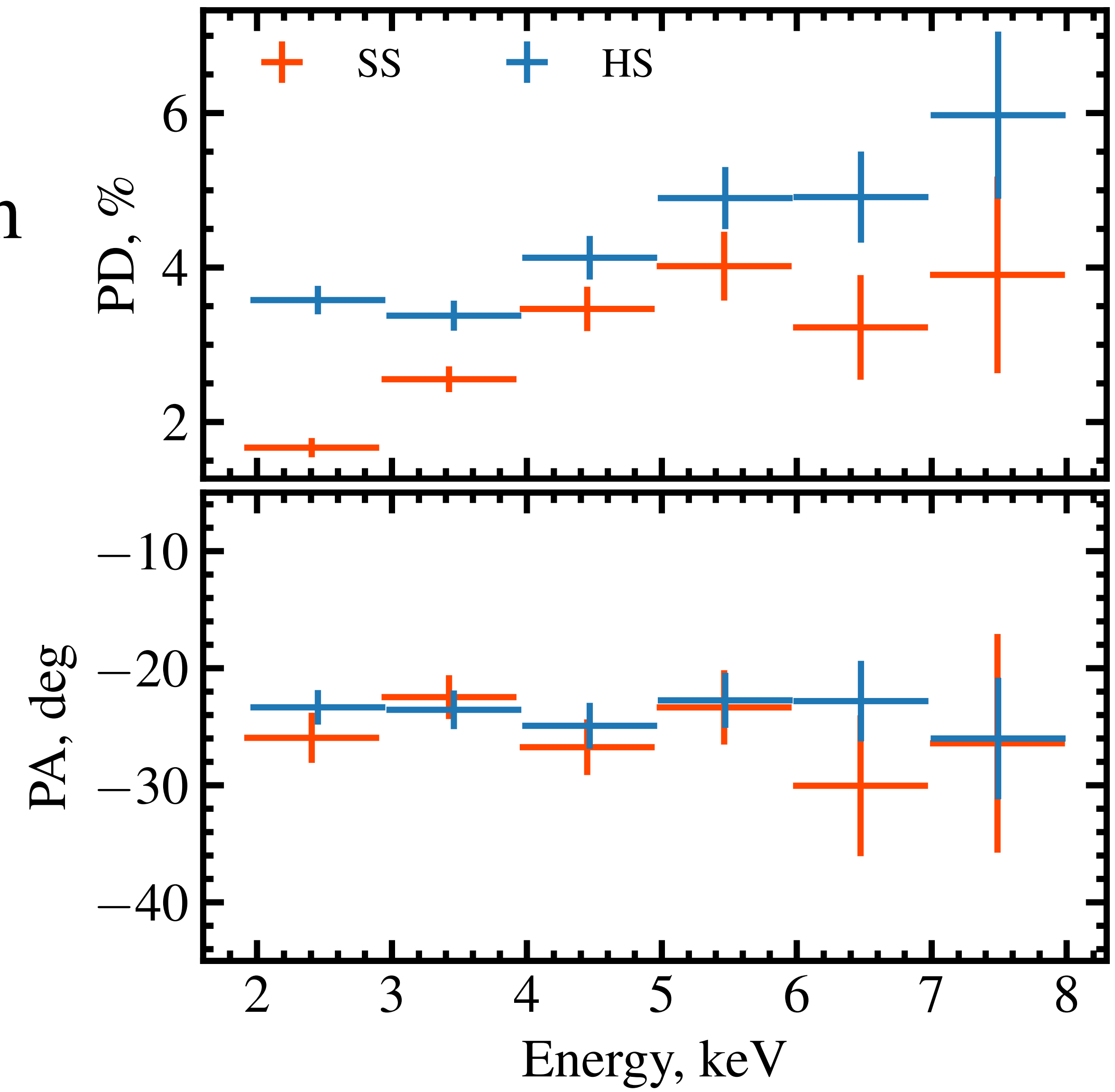
PD-HR relation



Results

PD-HR relation, polarization spectrum





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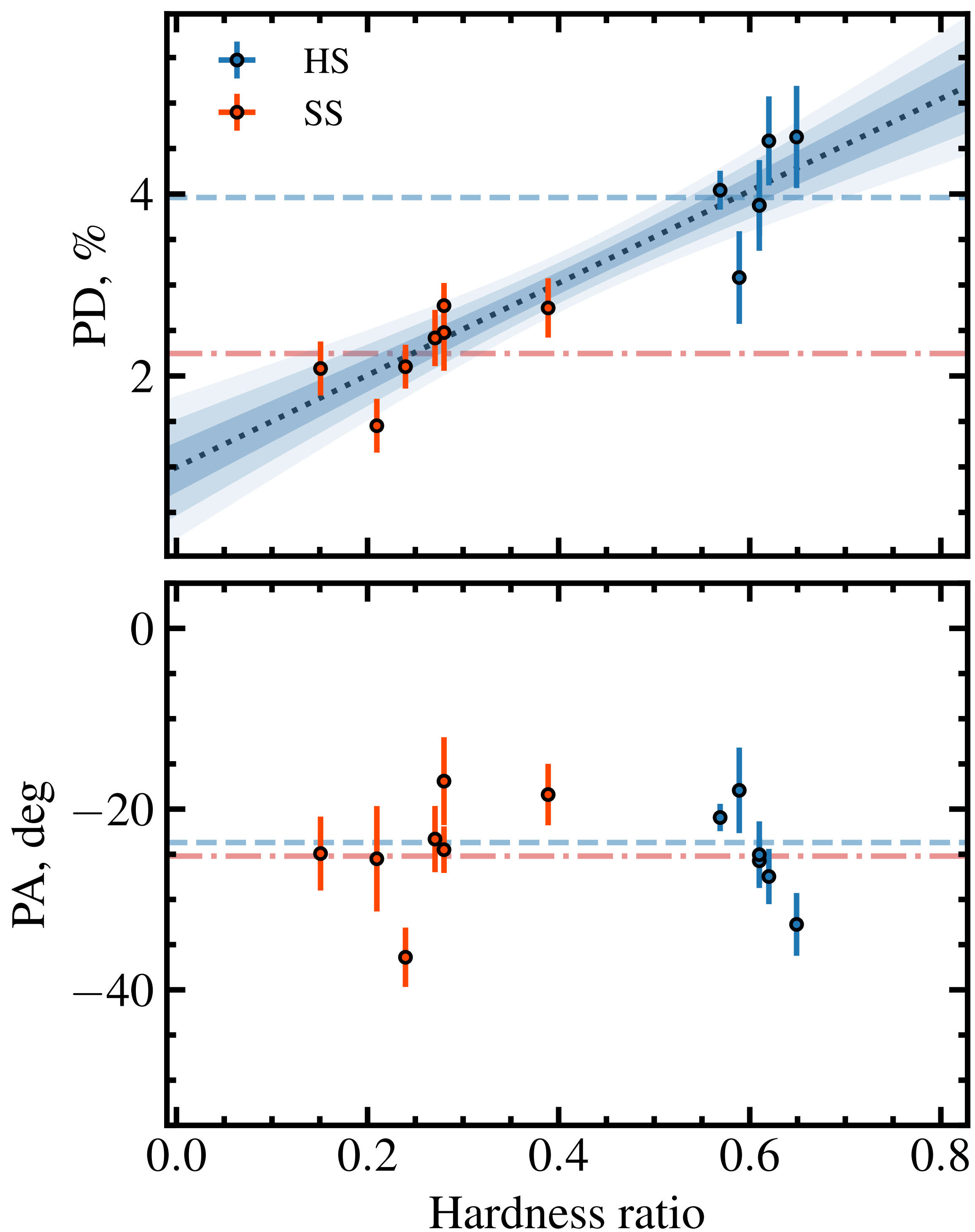
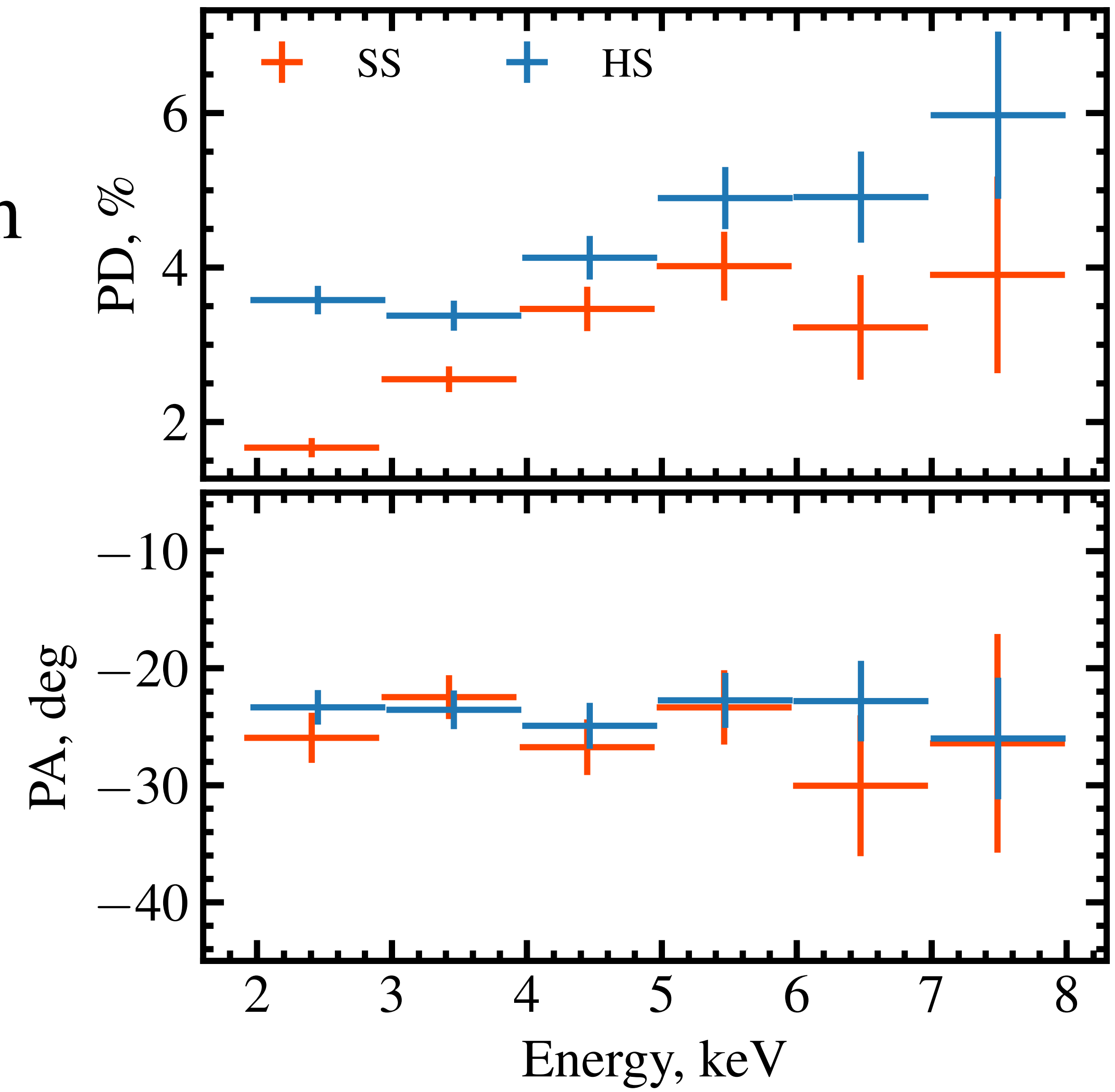
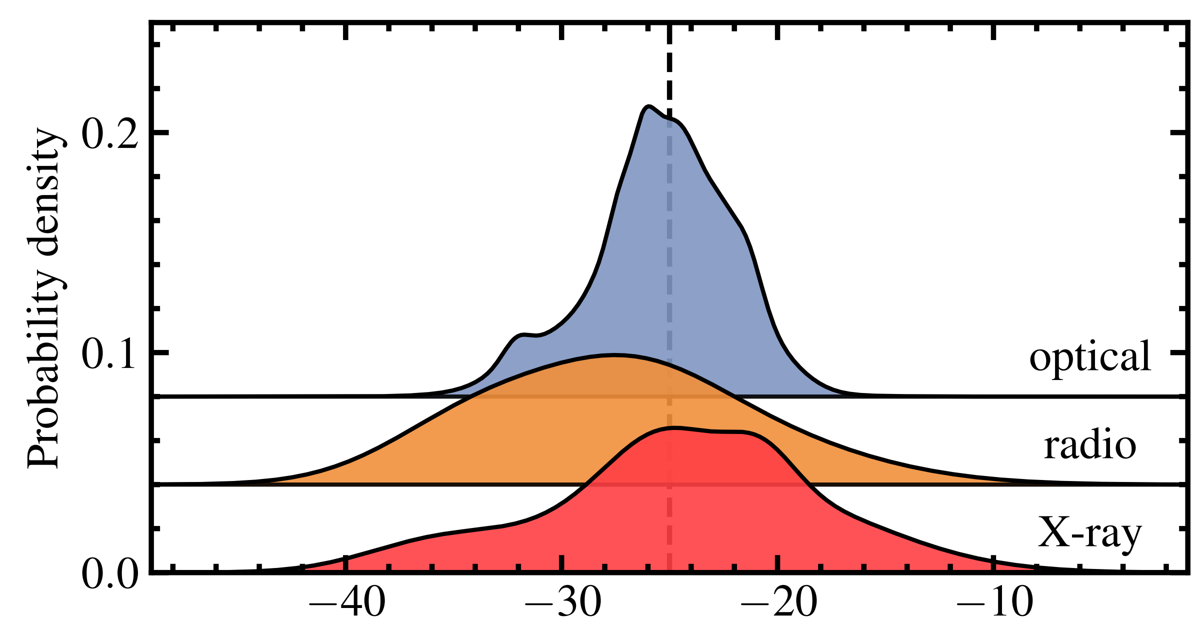
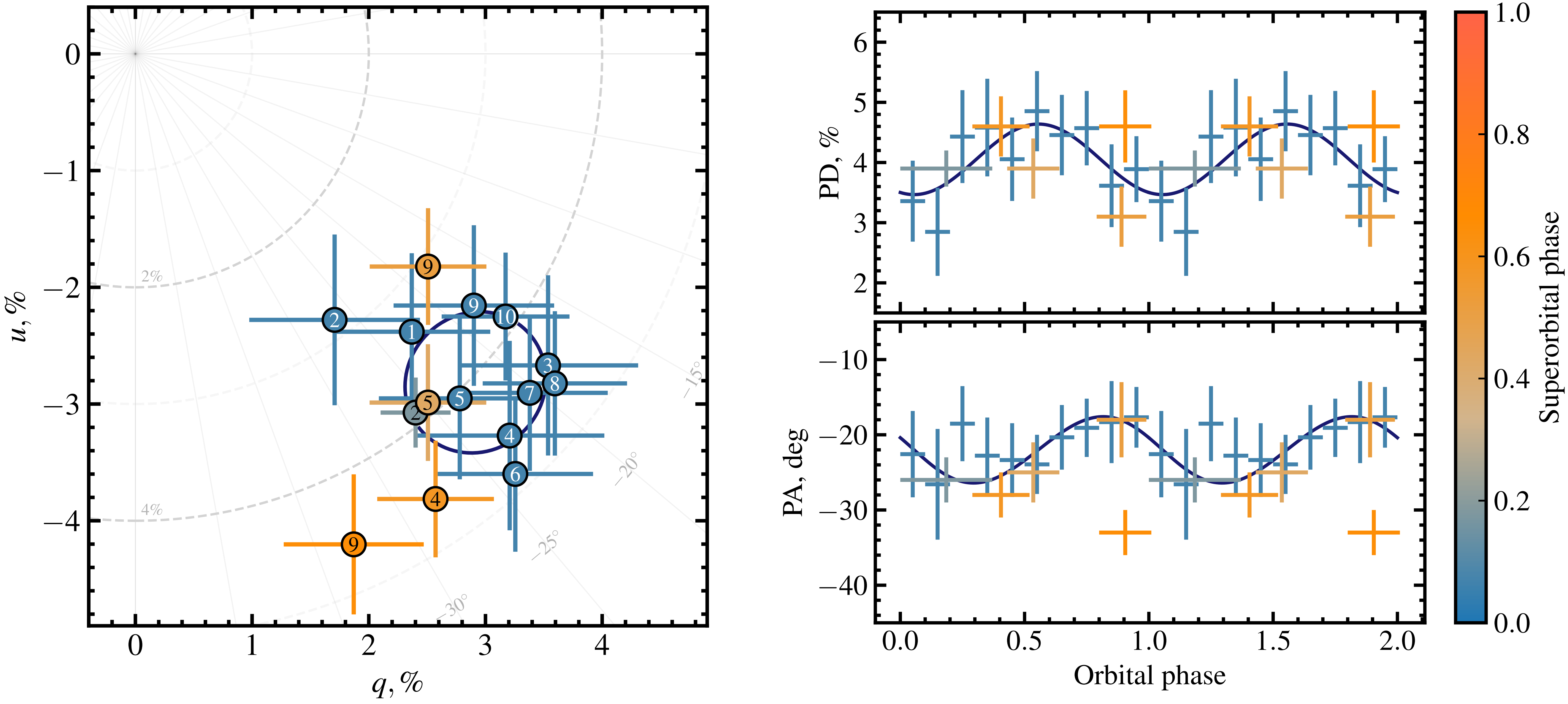






Results

Orbital variability of X-ray polarization



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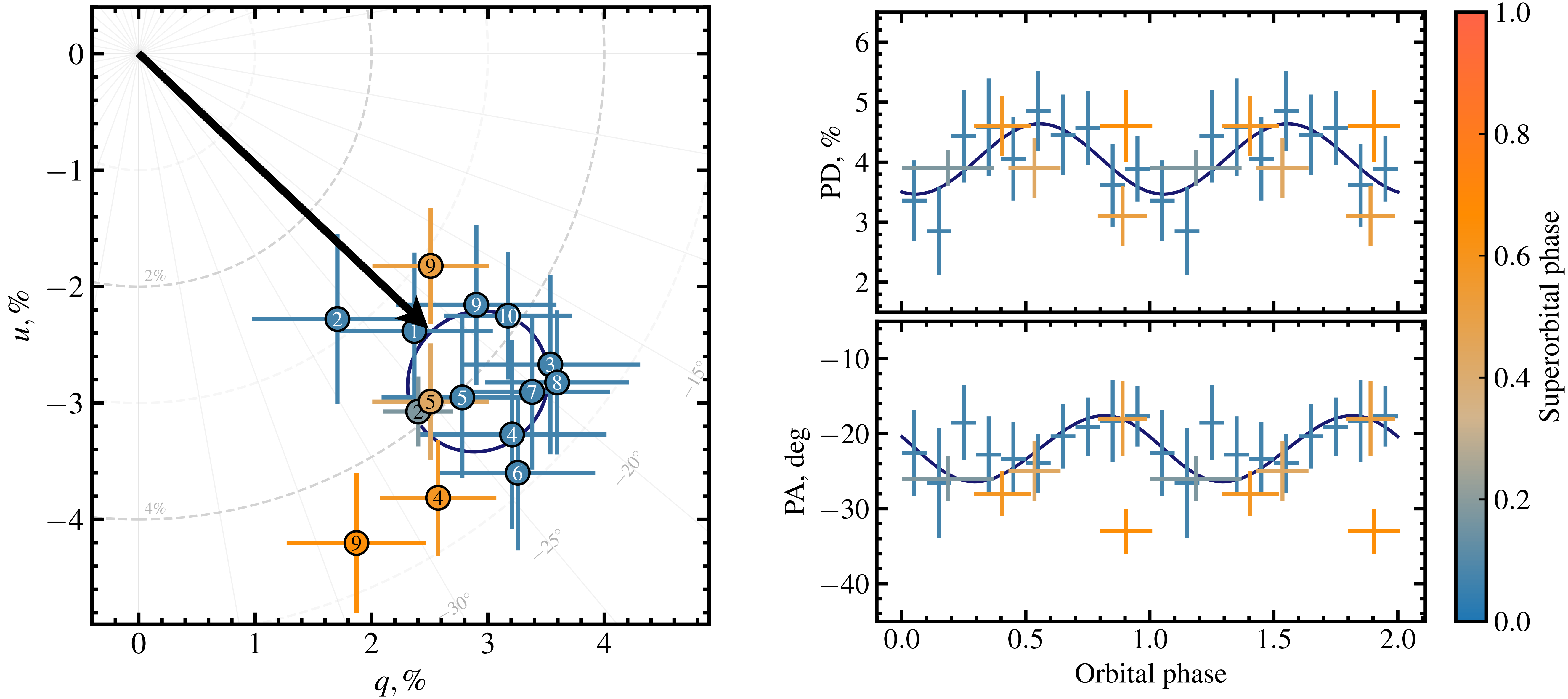

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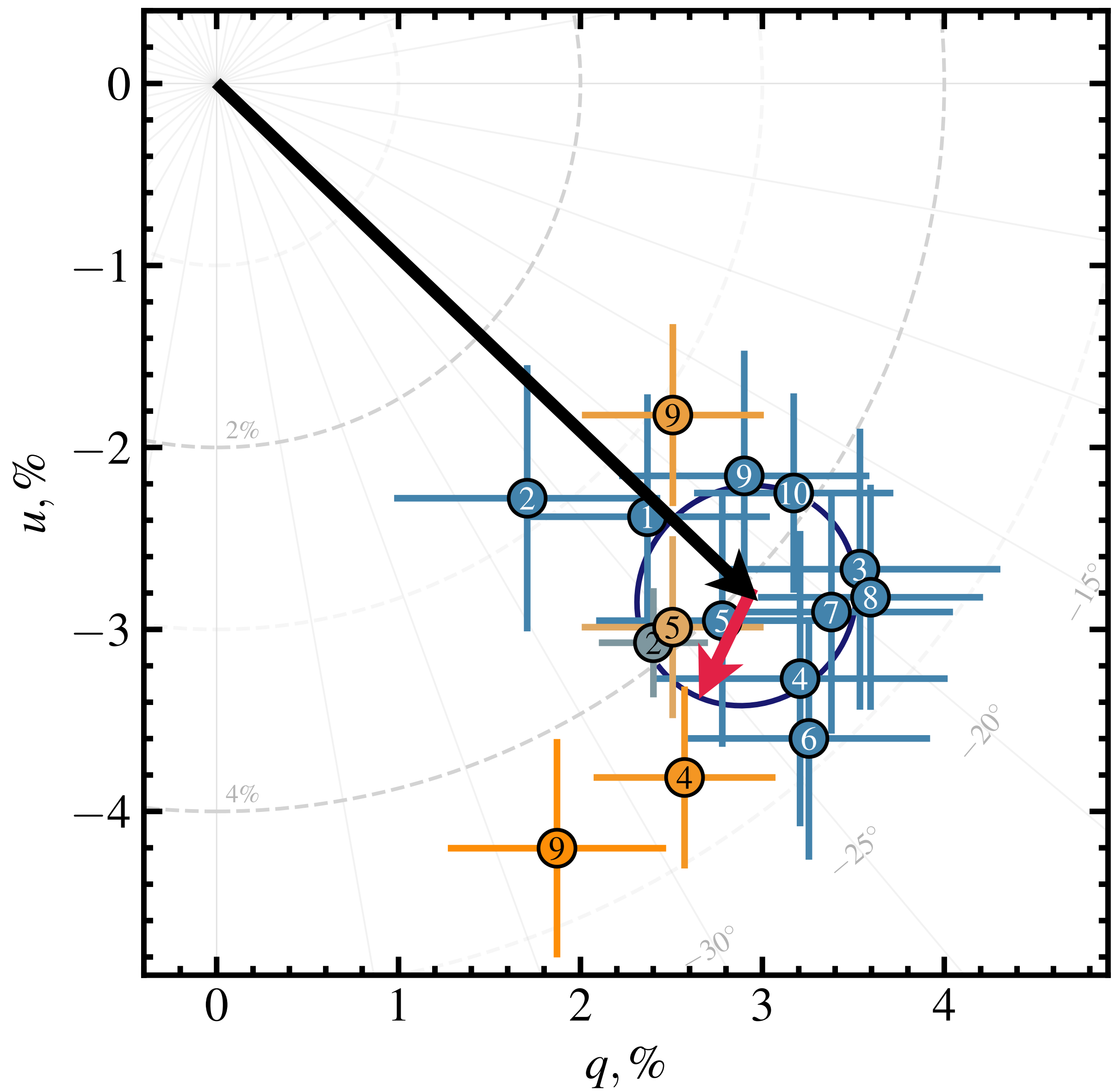
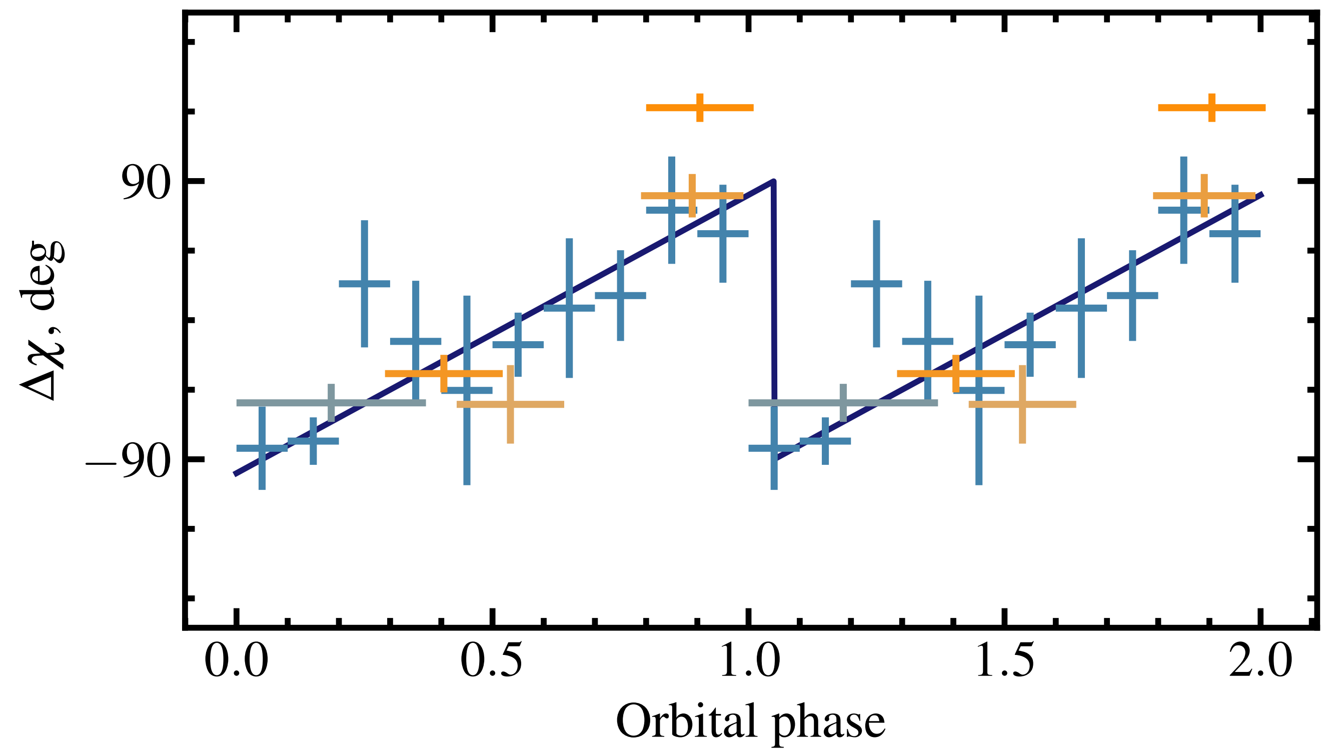


$\Delta\chi = \mathrm{PA_v} - \langle \mathrm{PA} \rangle$



Marginal detection of orbital variations with confidence of ~4σ

Interpretation

Two families of models

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$$p = p(2\phi)$$

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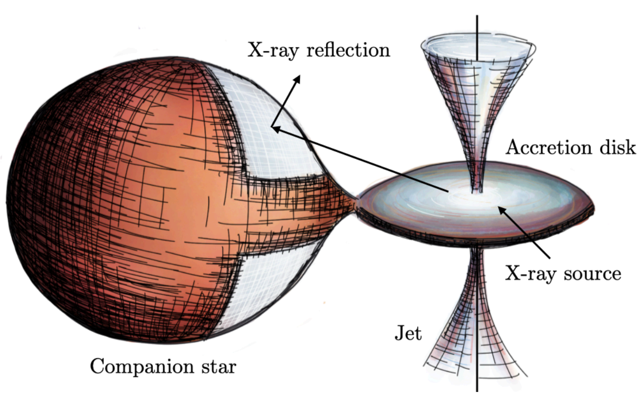
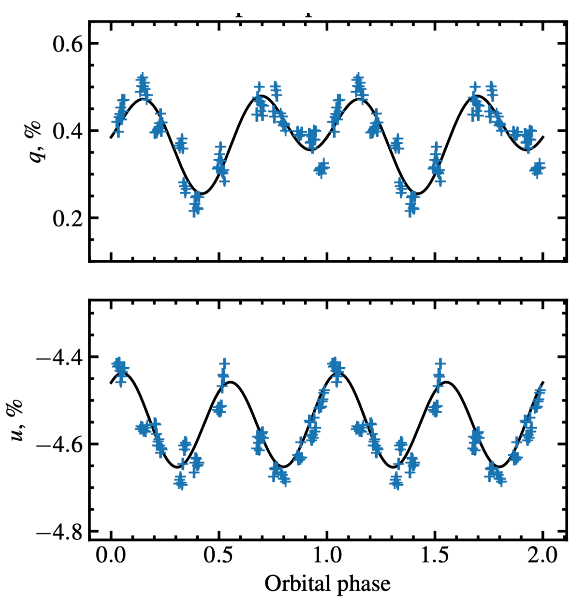
- Reflection from a companion star
(Ahlberg, Kravtsov, Poutanen 2024)
- Optically thin scattering in a circumbinary matter
(Brown, McLean, Emslie 1978; Kravtsov et al. 2020)



Ahlberg et al., 2024



Kravtsov et al., 2023

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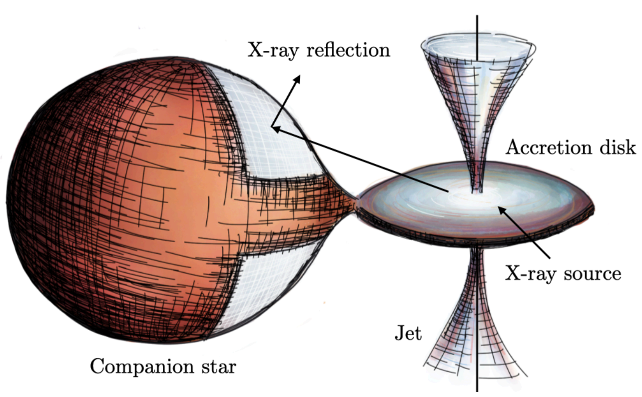

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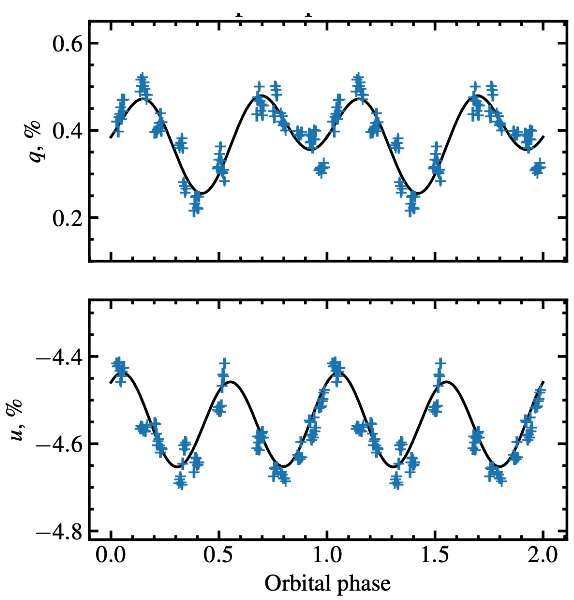

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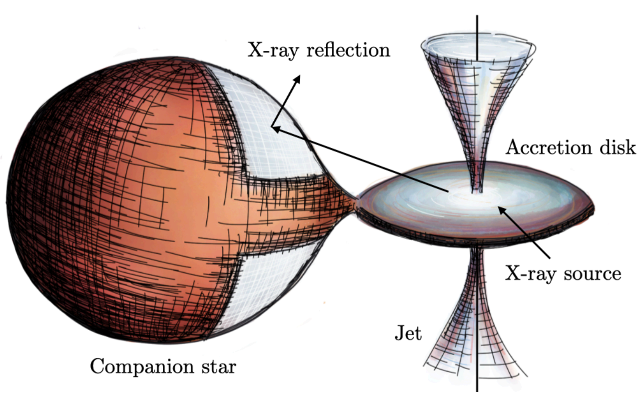
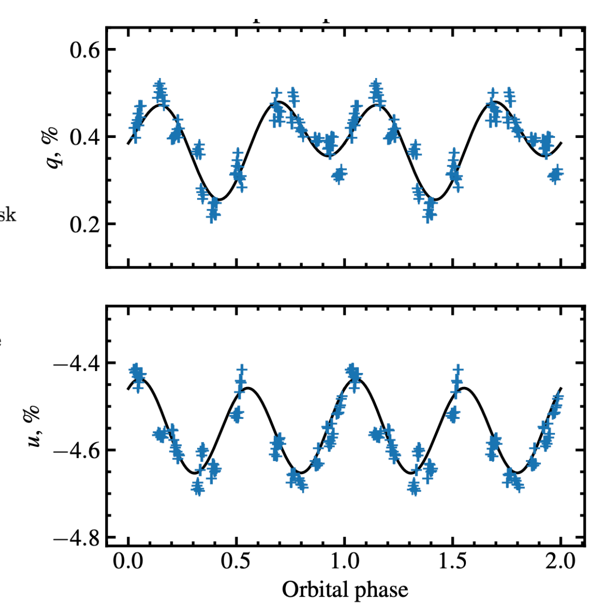
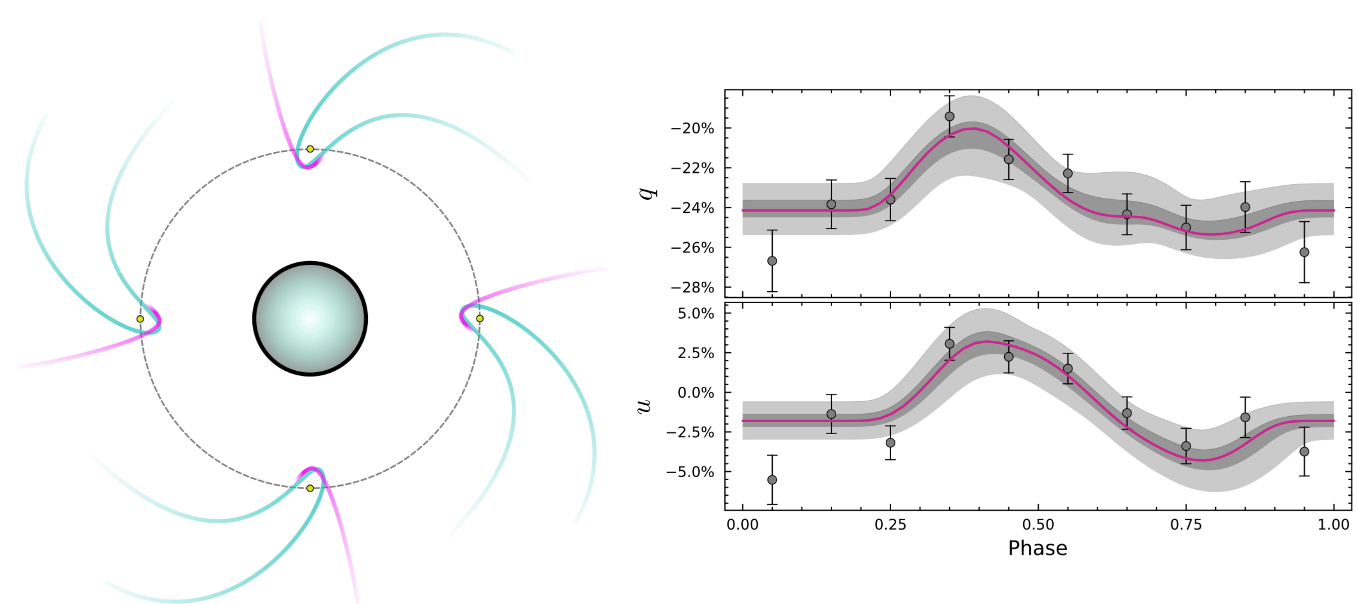
- **Rotating vector model (RVM)**
(Radhakrishnan & Cooke 1969; Meszaros et al. 1988)
- **Scattering in the asymmetric shock/wind**
(Ahlberg, Bocharova, Veledina 2025)



Ahlberg et al., 2024



Kravtsov et al., 2023



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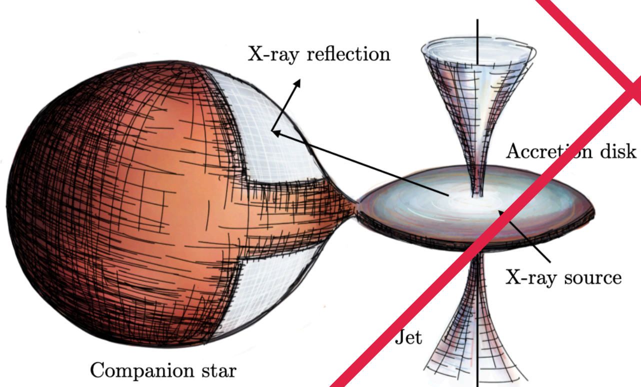
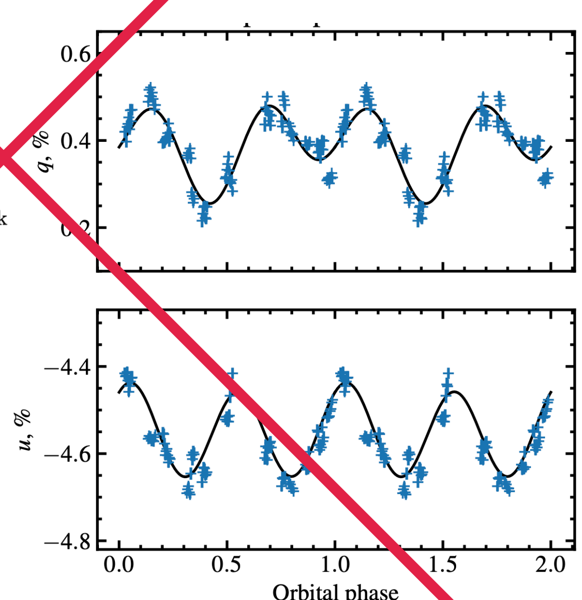


Ahlberg et al., 2024



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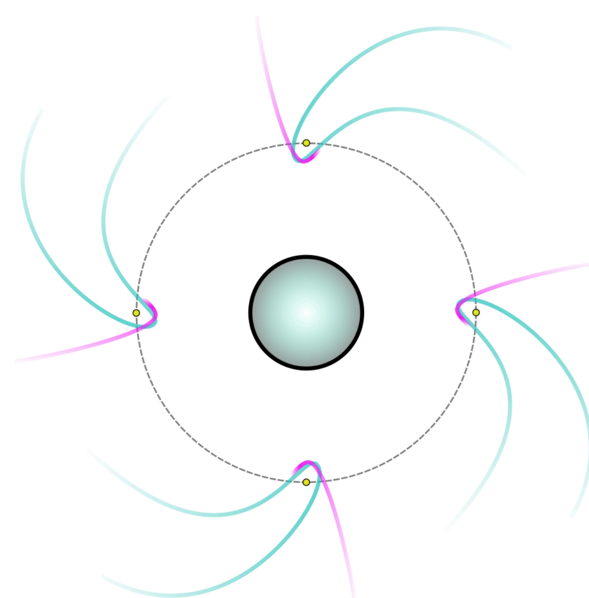

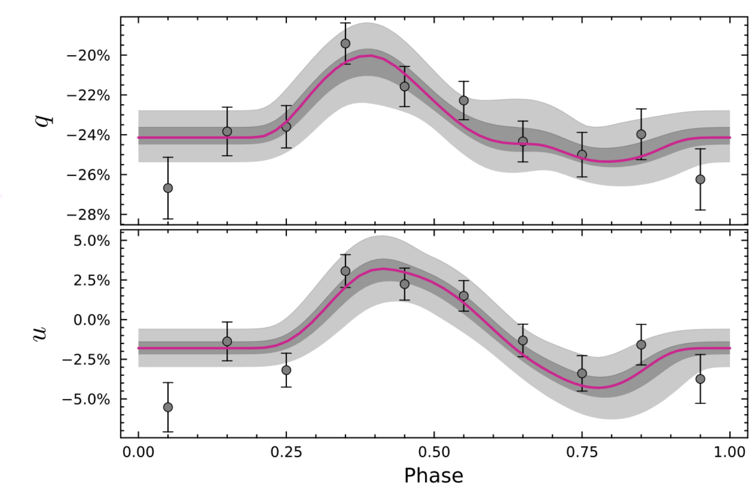

Ahlberg et al., 2025

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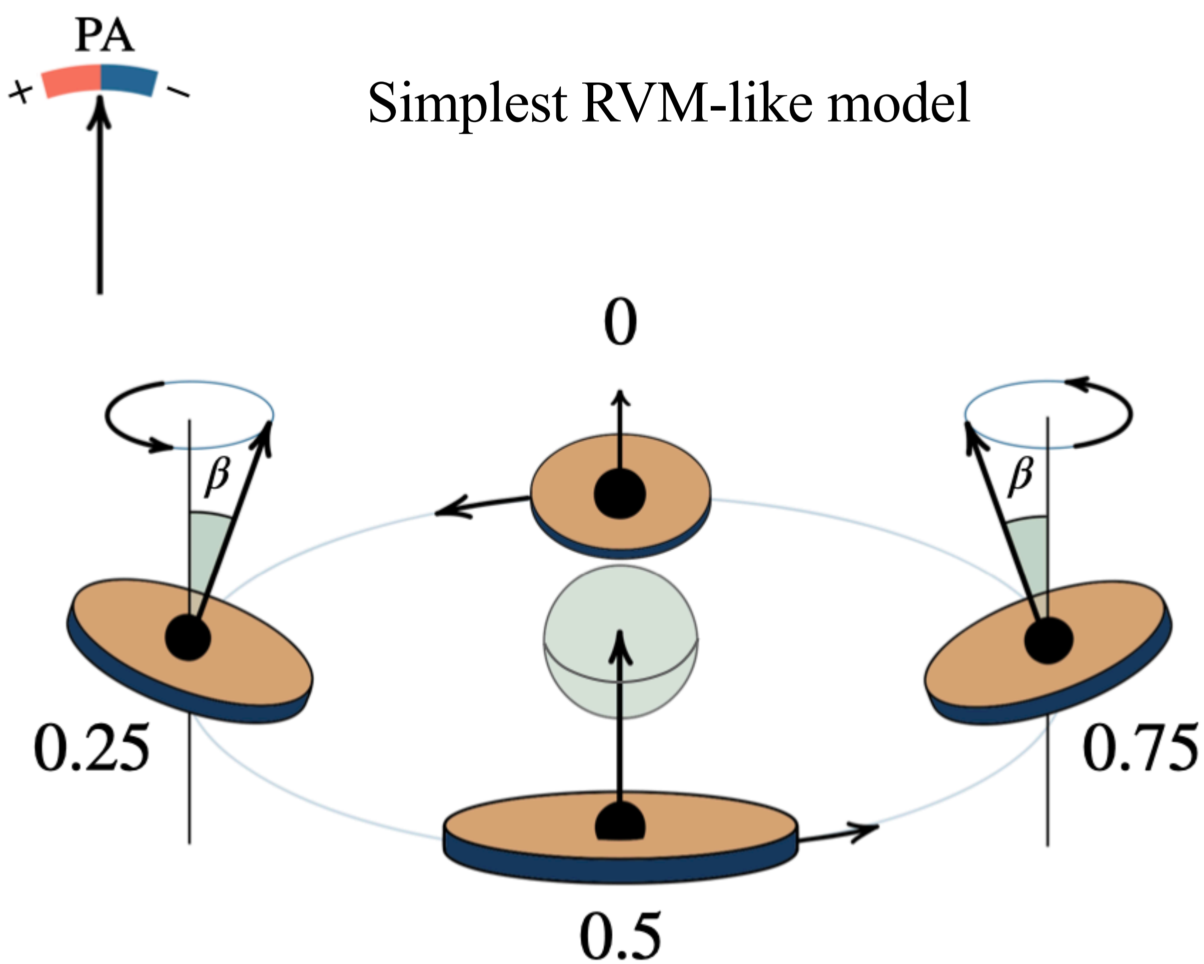
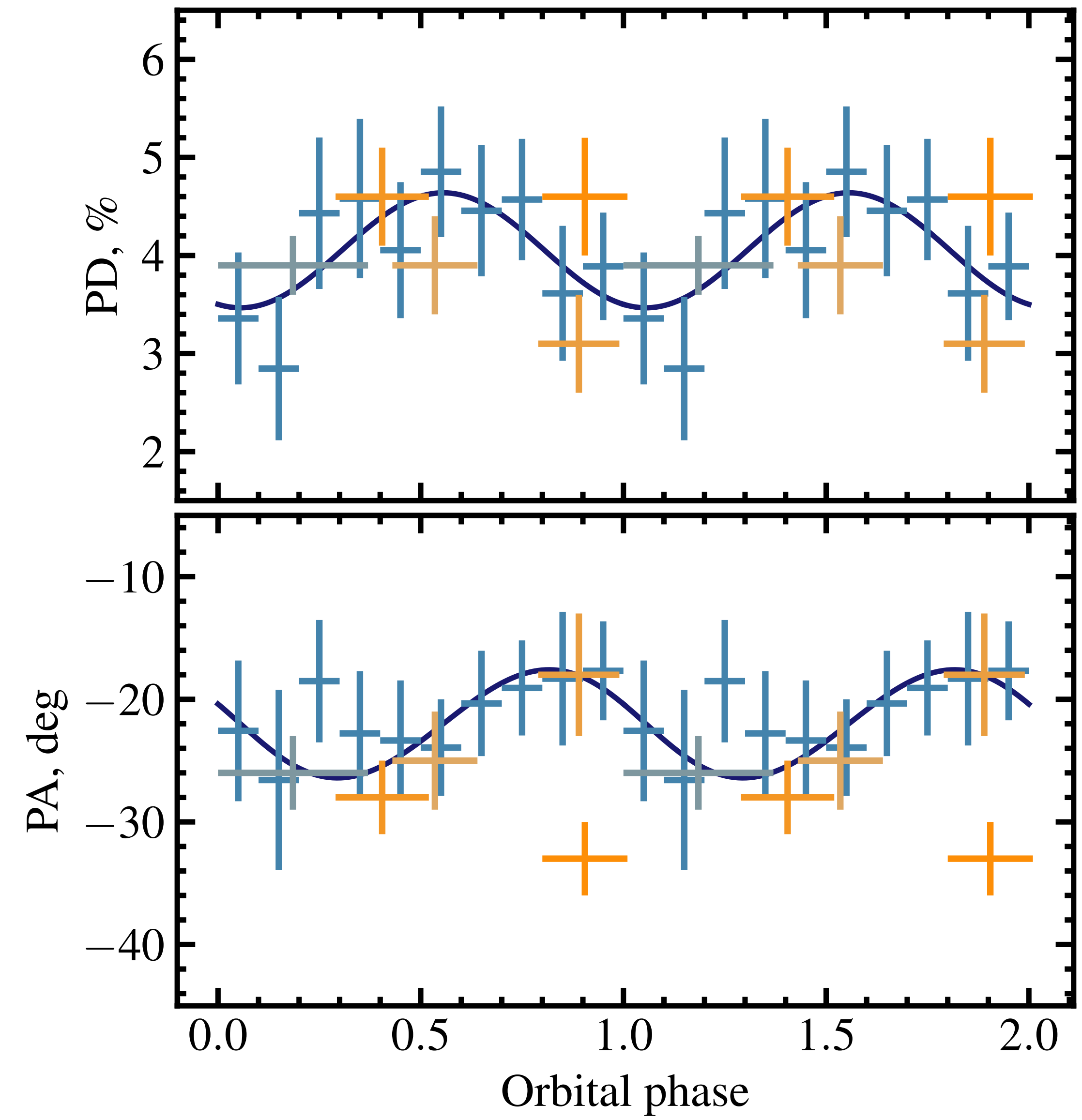
Simplest RVM-like model



$$P = P_{\max}(1-\mu)$$

$$\mu = \overrightarrow{n_{\mathrm{d}}} \cdot \vec{o} = cos(\theta)$$



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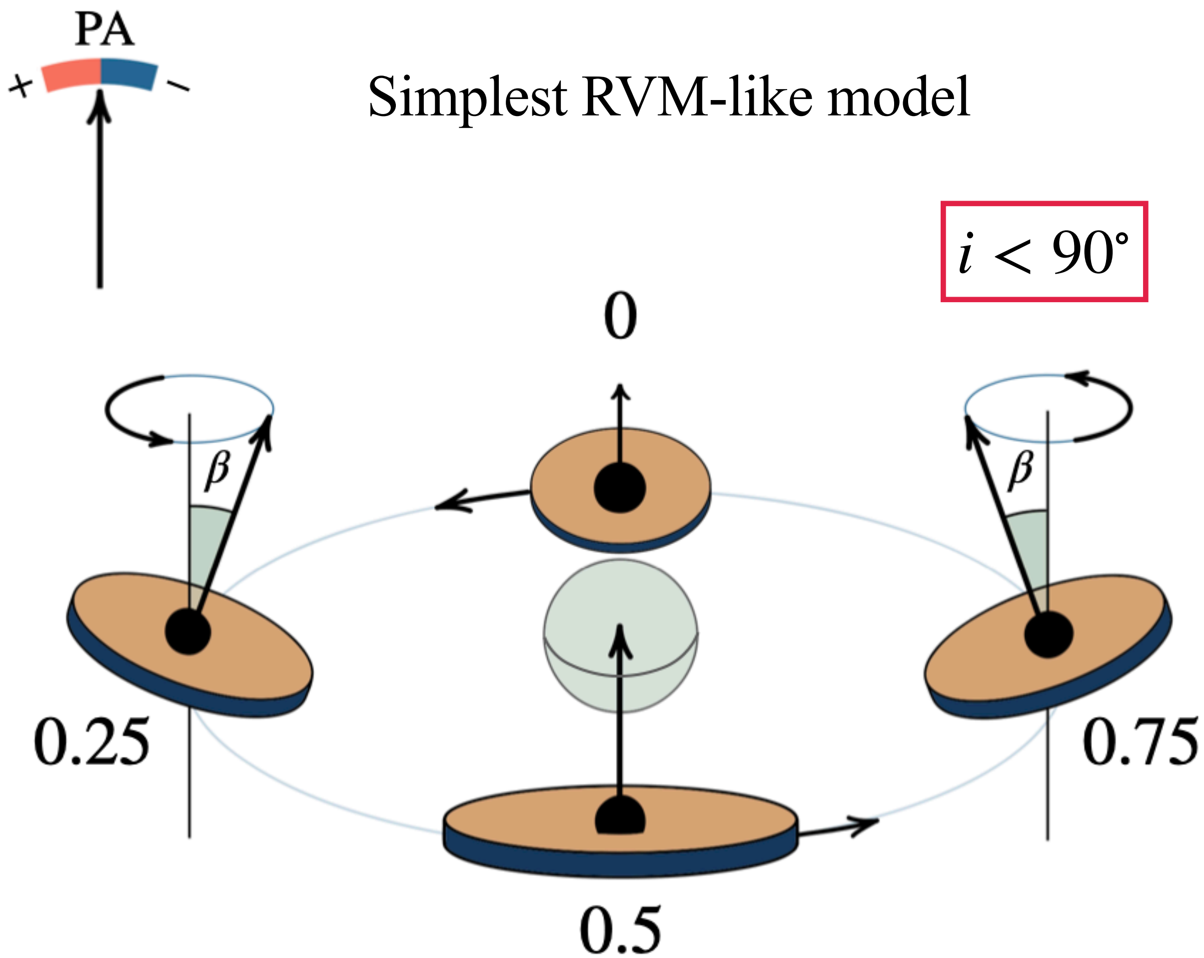

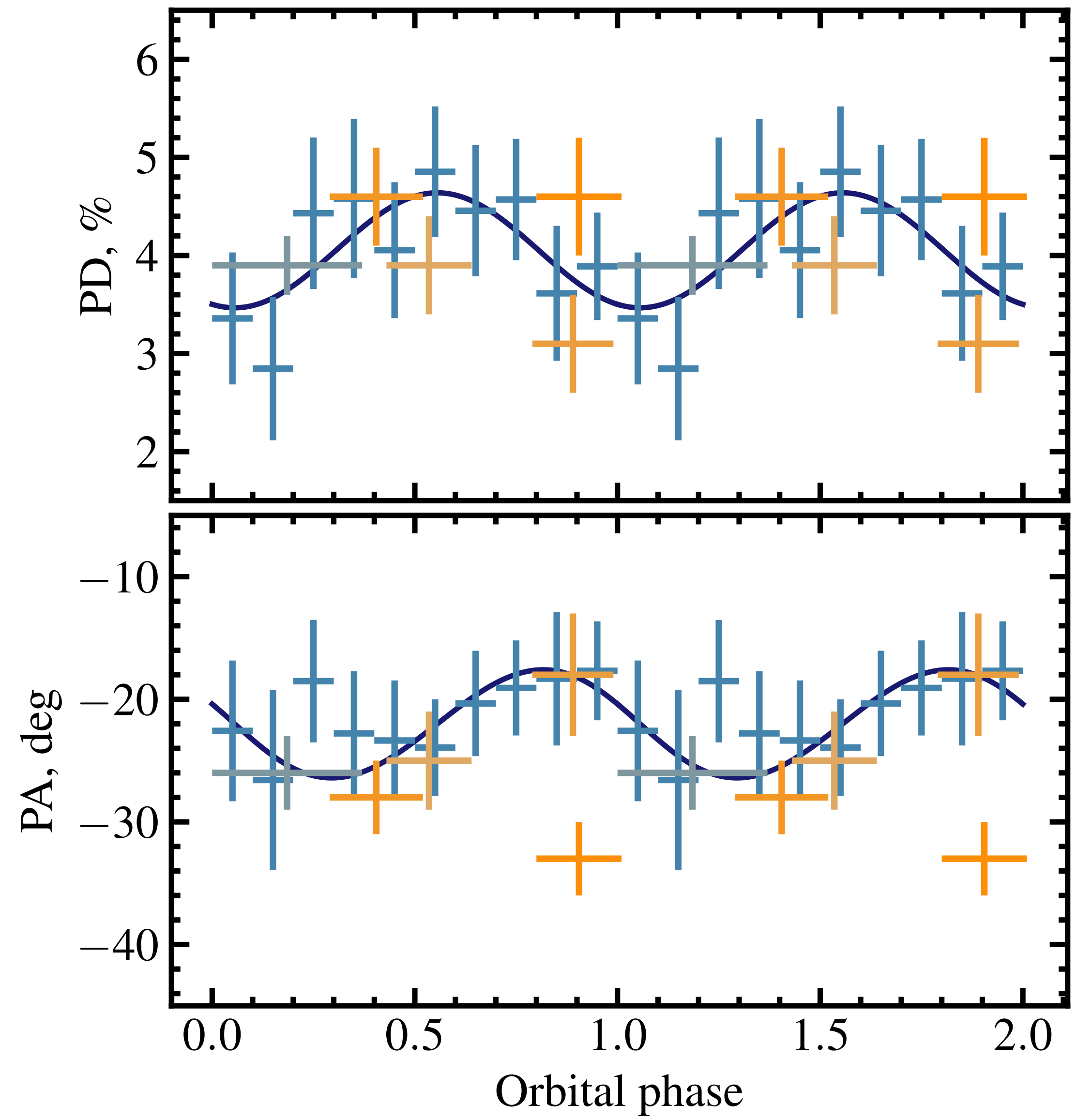

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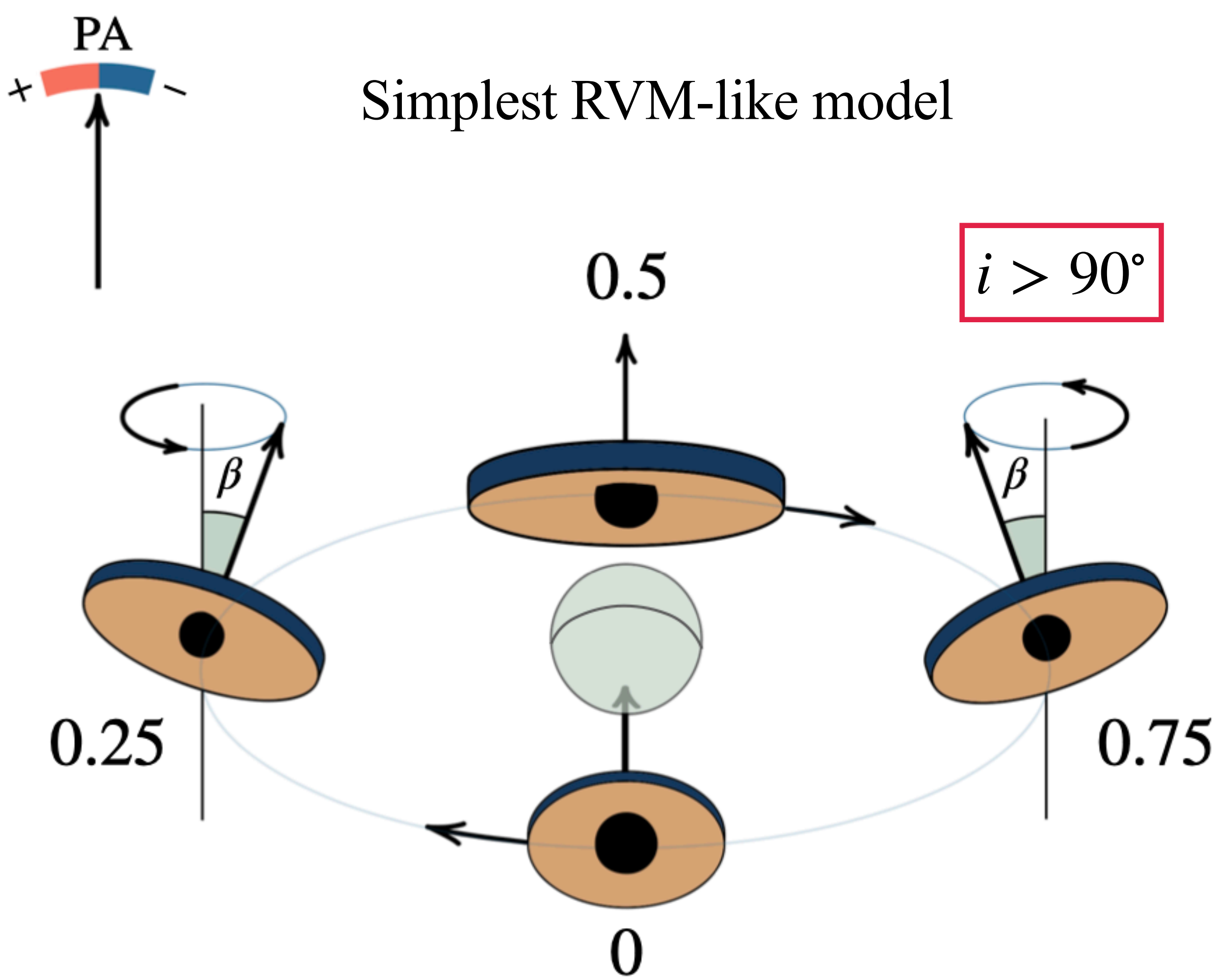

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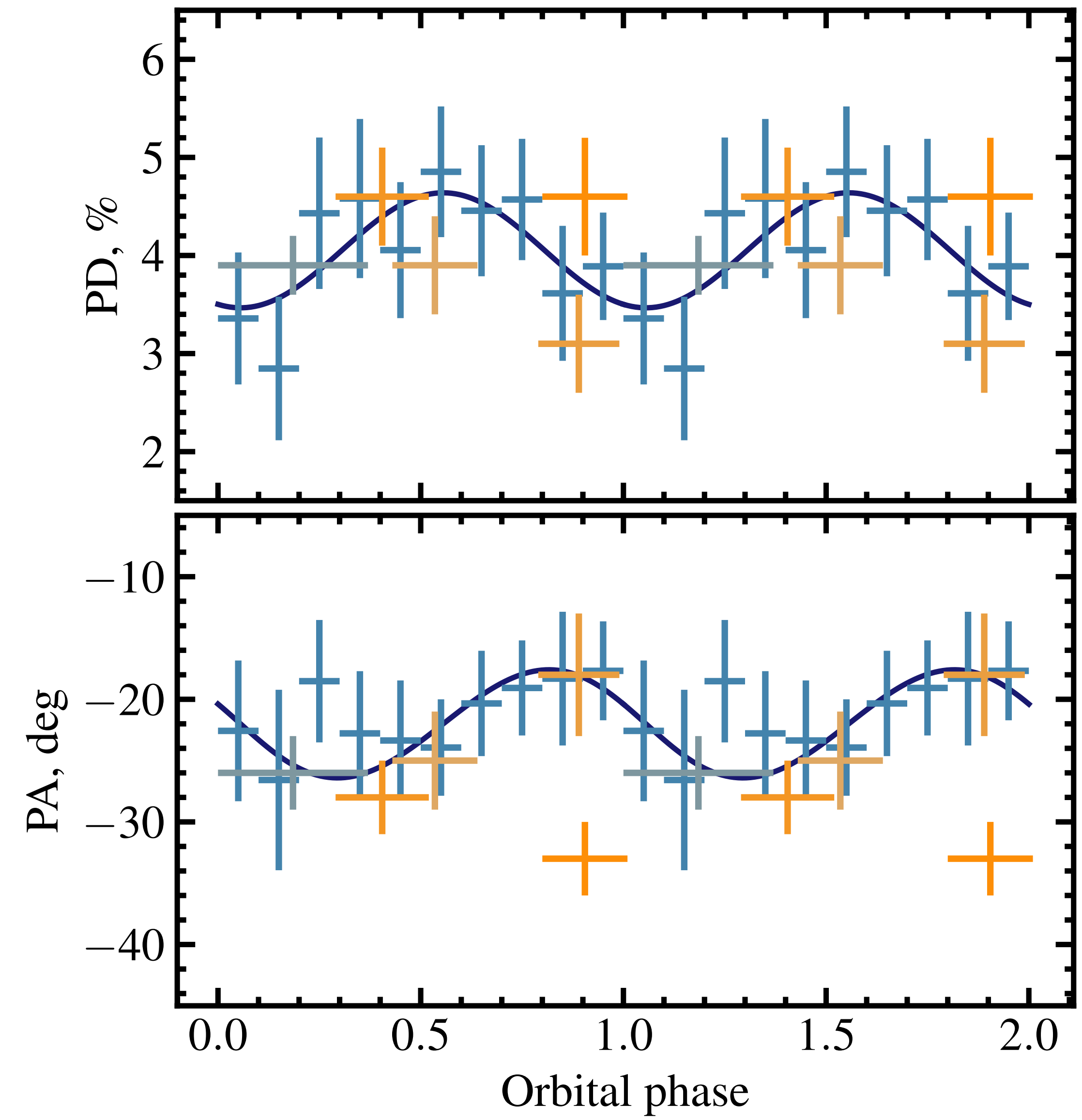

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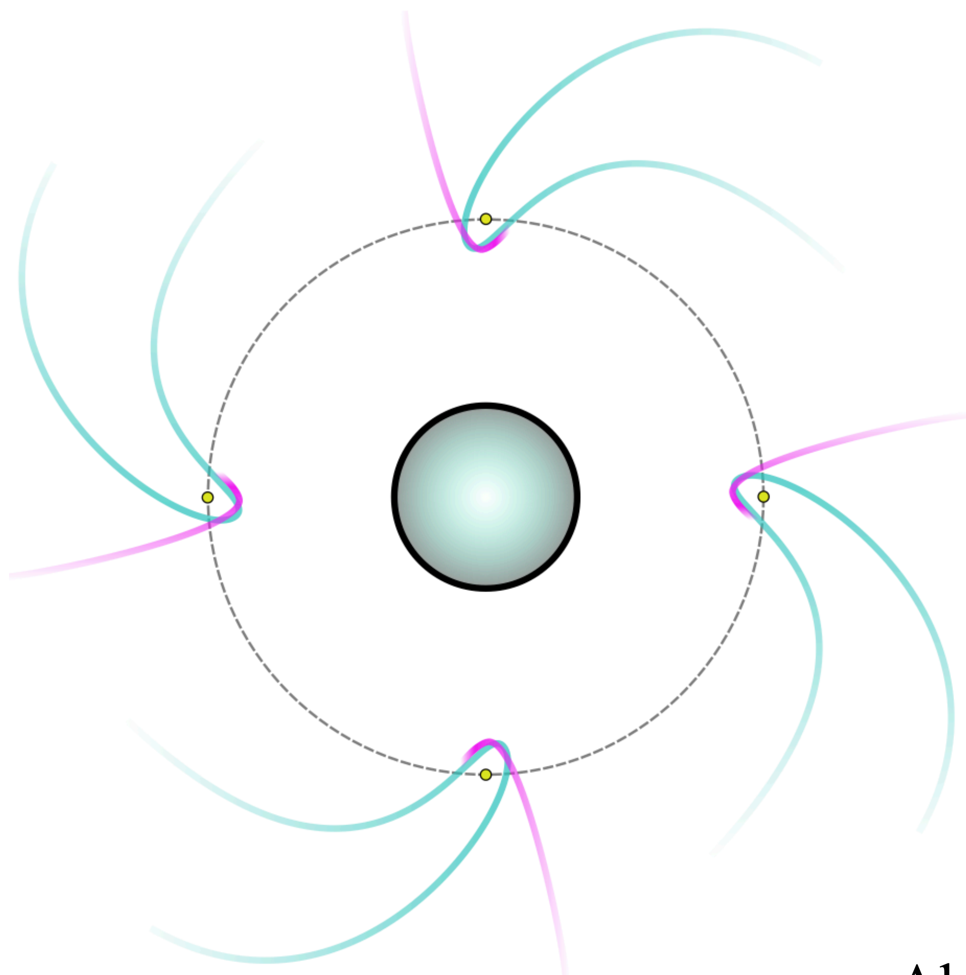

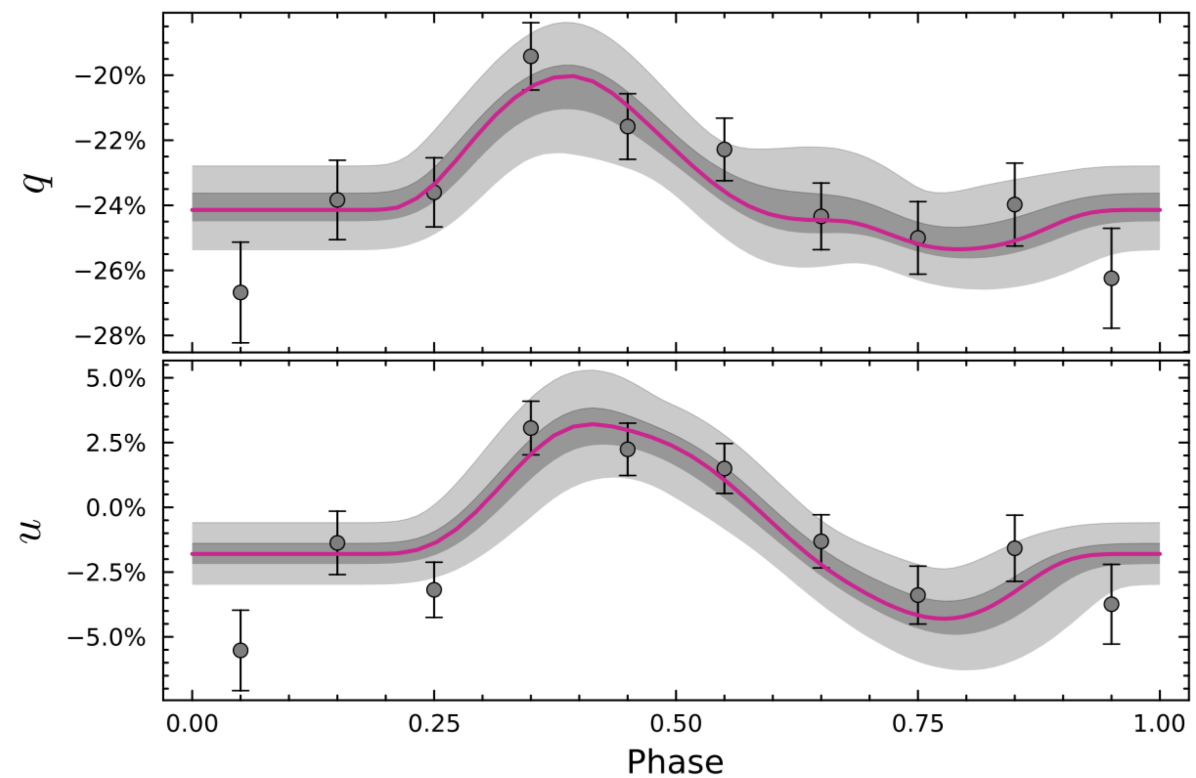

Ahlberg et al., 2025

But better data is needed to compare proper models!

Summary

- We track Cyg X-1 in X-ray polarization **across all spectral states**.
- We **detect orbital variations of X-ray polarization** of Cyg X-1 with marginal significance of $\sim 4\sigma$.
- We find **no evidence of superorbital (P = 294 d) variability** and put an upper limit of 5° on the possible disk tilt.
- We detect Cyg X-1 in **radio polarization for the first time** and find radio PA to be aligned with optical and X-ray PA.
- We discuss possible sources of phase-dependent polarization, but **more precise data is needed to discriminate between different models**.

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Variability of X-ray polarization of Cyg X-1

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(Affiliations can be found after the references)

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ABSTRACT

We present the results of a three-year X-ray, optical, and radio polarimetric monitoring campaign of the prototypical black hole X-ray binary Cyg X-1, conducted from 2022 to 2024. The X-ray polarization of Cyg X-1 was measured 13 times with the Imaging X-ray Polarimetry Explorer (IXPE), covering both hard and soft spectral states. The X-ray polarization degree (PD) in the hard state was found to be ≈4.0%, roughly twice as high as in the soft state, where it was around 2.2%. In both states, a statistically significant increase in PD with the energy was found. Moreover, a linear relation between PD and spectral hardness suggests a gradual and continuous evolution of the polarization properties, rather than an abrupt change of polarization production mechanism between states. The polarization angle (PA) was independent of the spectral state and showed no trend with the photon energy. The X-ray PA is well aligned with the orientation of the radio jet, as well as the optical and radio PAs. We find significant orbital changes of PA in the hard state, which we attribute to scattering of X-ray emission at the intrabinary structure. No significant superorbital variability in PD or PA was found at the period $P_{so} = 294$ d. We detect, for the first time in this source, polarization of the radio emission, with the PA aligned with the jet, and a strong increase of the PD at a transition to the soft state. We also find no correlation between the X-ray and optical polarization; if any, there is a long-term anti-correlation between the X-ray PD and the radio PD.

Key words. accretion, accretion disks – polarization – stars: black holes – stars: individual: Cyg X-1 – X-rays: binaries

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