

Exploring polarization and geometry in the X-ray pulsar 4U 1538-52

Vladislav Loktev

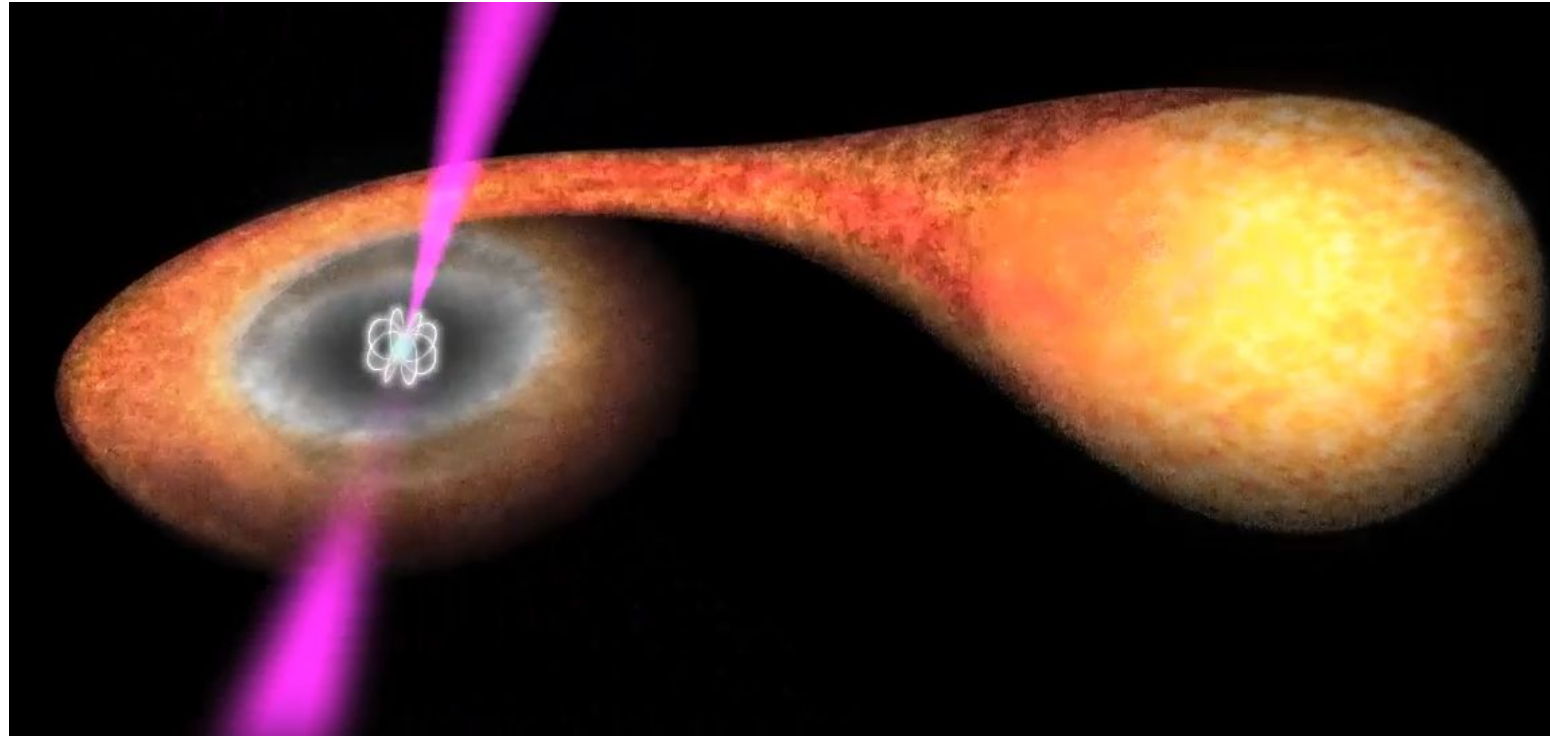
University of Turku, University of Helsinki

with Sofia V. Forsblom, Sergey S. Tsygankov, Juri Poutanen, etc.



X-ray Pulsars in polarization

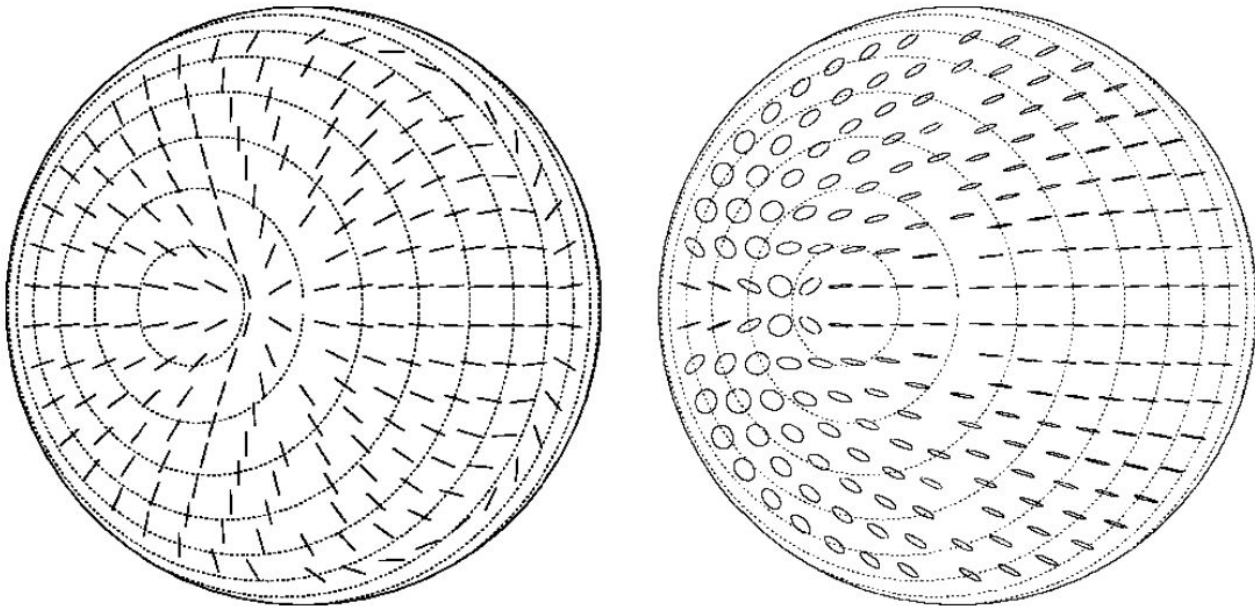
- High magnetic field NS
- Accretion (e.g. wind)
- X-ray pulsations
- mission: to understand the geometry and physical processes
- X-ray Polarimetry has proven to be a window into the geometrical properties



credit: ESA

X-ray Pulsars in polarization

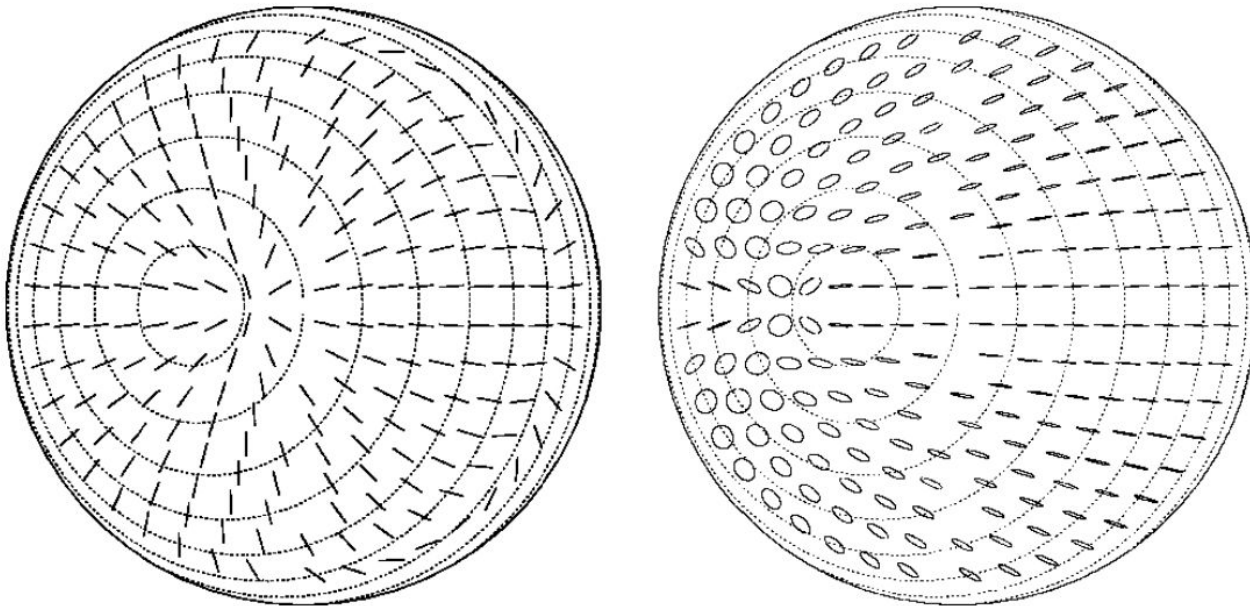
- Vacuum birefringence in high magnetic field of the NS is presumably aligns X-ray polarization to the field lines at a dozen NS radii



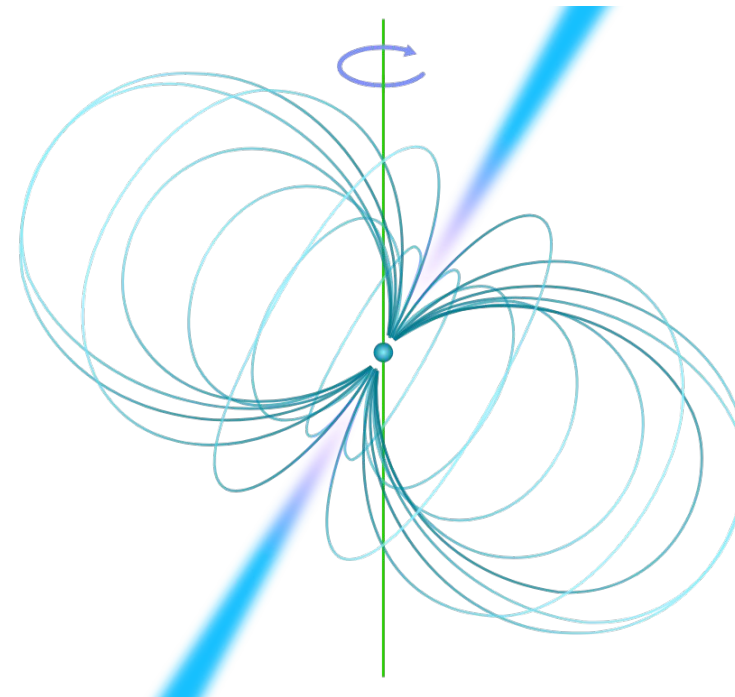
e.g. (Heyl & Shaviv 2002)

X-ray Pulsars in polarization

- Vacuum birefringence in high magnetic field of the NS is presumably aligns X-ray polarization to the field lines at a dozen NS radii
- The field is presumably dominated by dipole. The rotation of the NS then produces a regular swing for the polarization angle.

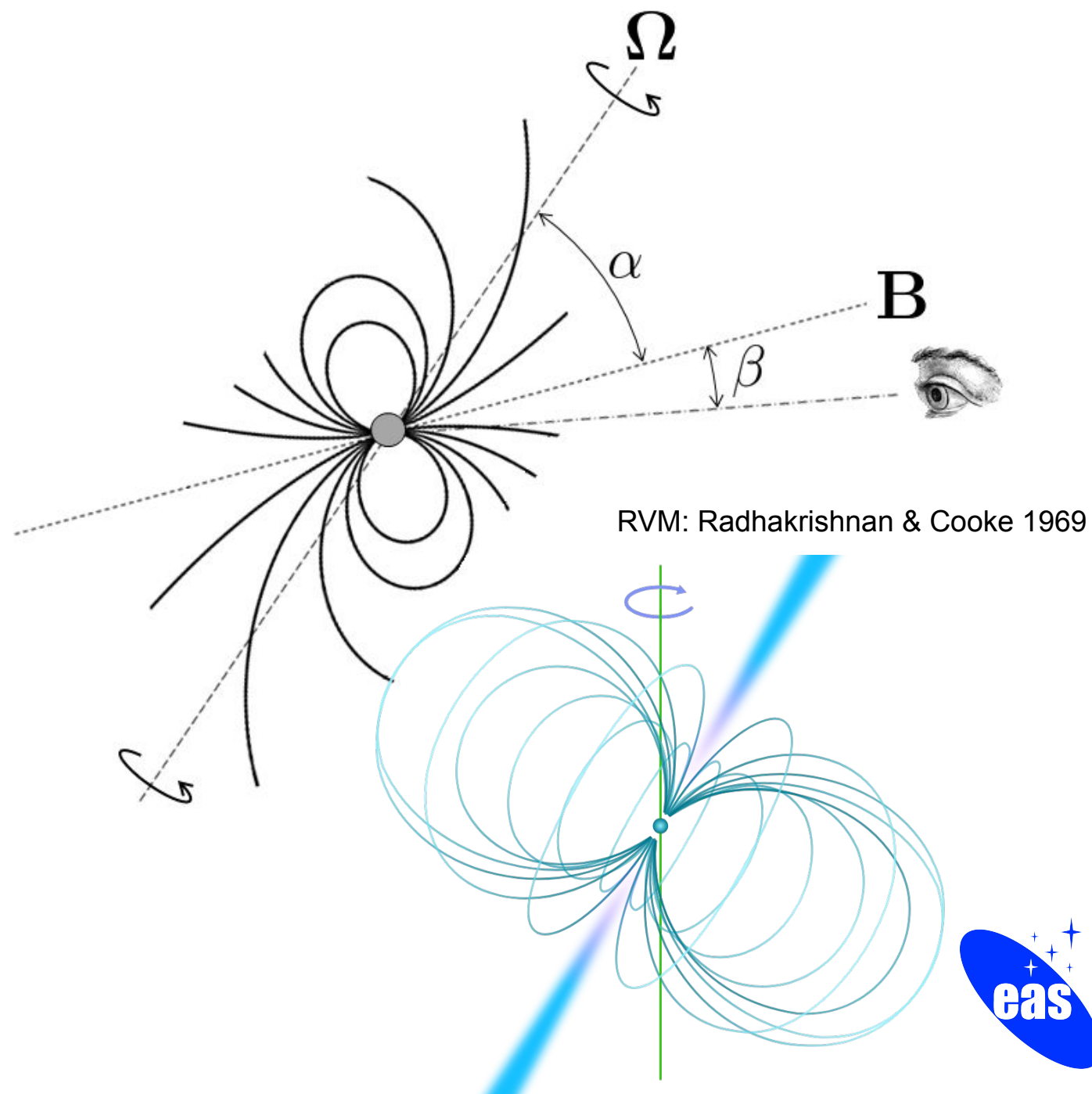


e.g. (Heyl & Shaviv 2002)



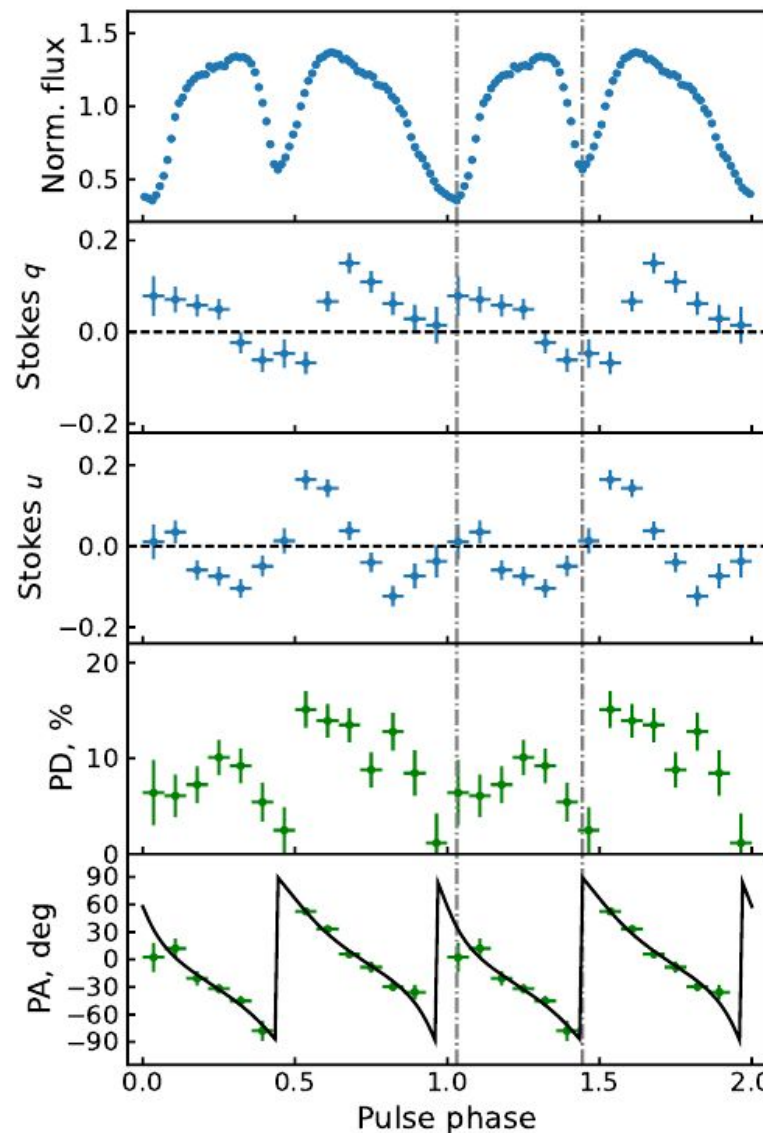
Rotating Vector Model

- RVM describes the behavior of the position angle of linear polarization as a projection of a rotating vector onto the image plane

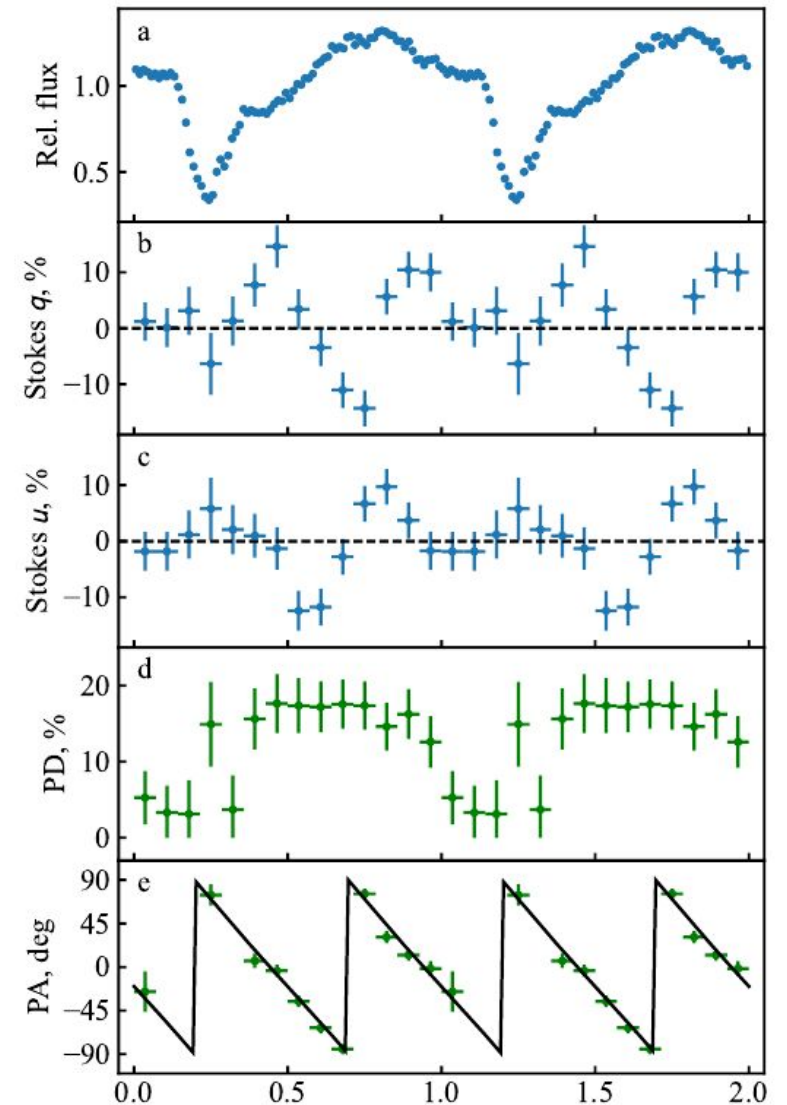


Rotating Vector Model

- RVM describes the behavior of the position angle of linear polarization as a projection of a rotating vector onto the image plane
- RVM was successfully applied to many X-ray pulsars observed by IXPE with few corrections



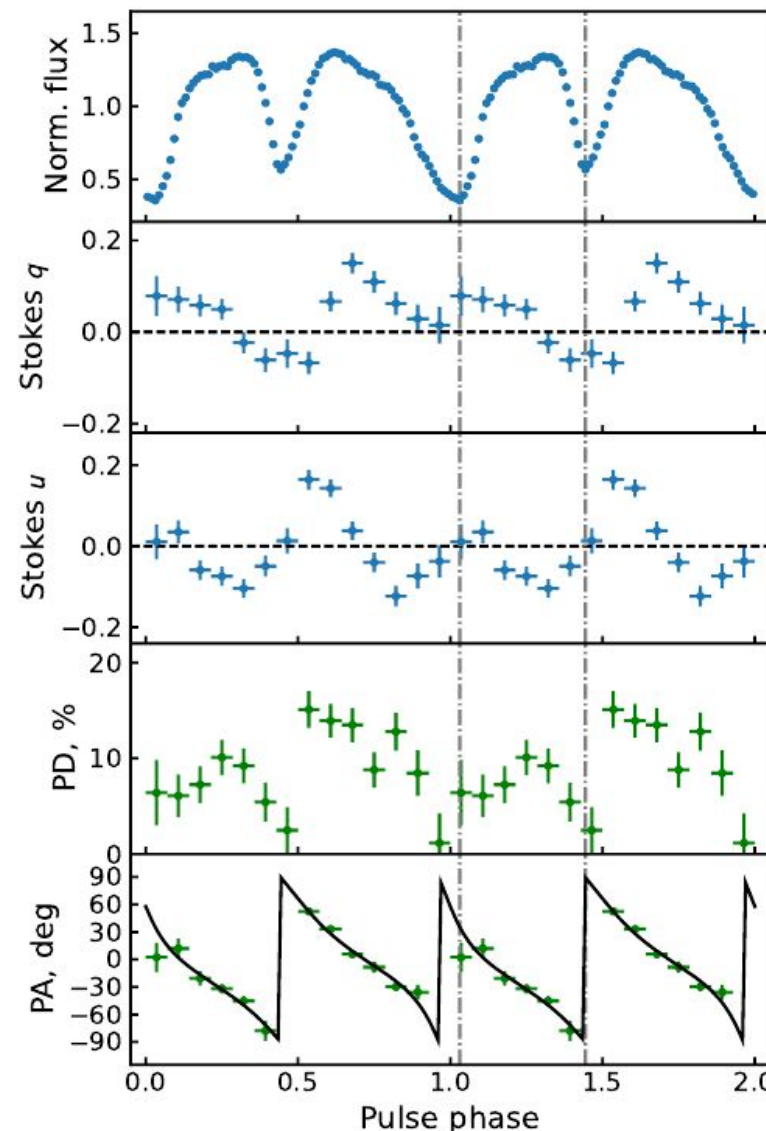
IXPE pulse profile of GRO J1008-57
(Tsygankov et al. 2023)



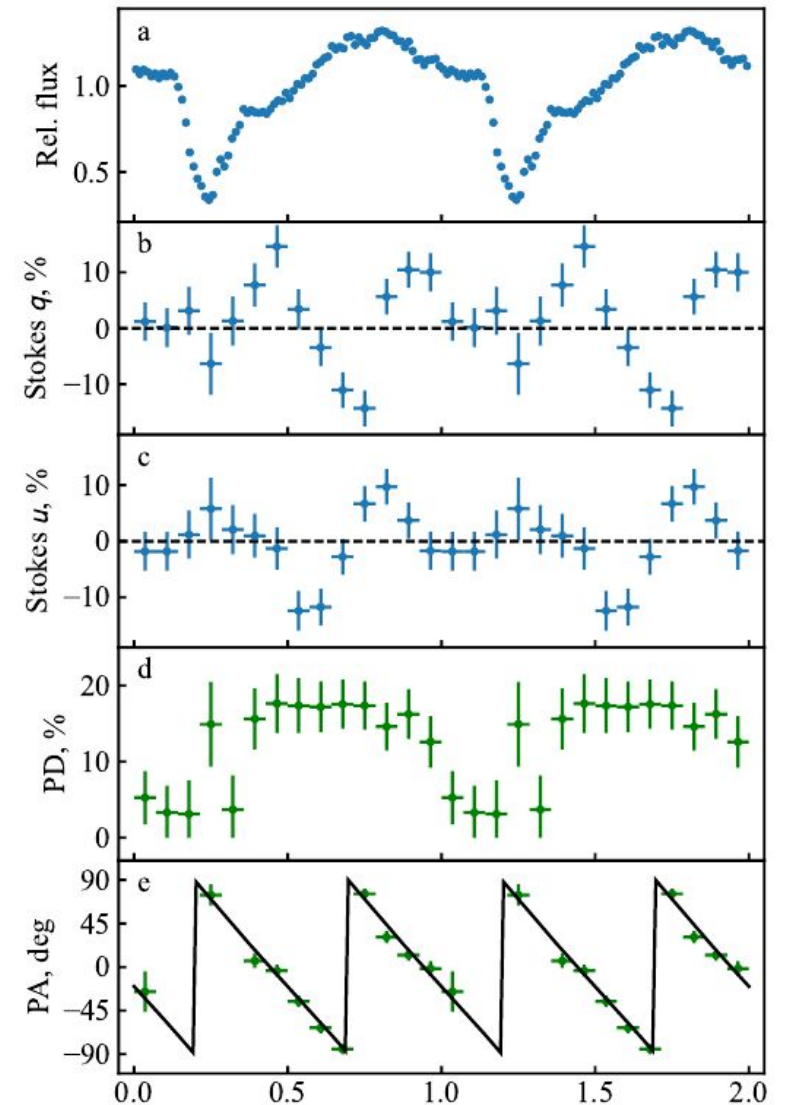
IXPE pulse profile of X Persei
(Mushtukov et al. 2023)

Rotating Vector Model

- RVM describes the behavior of the position angle of linear polarization as a projection of a rotating vector onto the image plane
- RVM was successfully applied to many X-ray pulsars observed by IXPE with few corrections
- One notable exception was the ‘archetypical’ wind-fed source Vela X-1



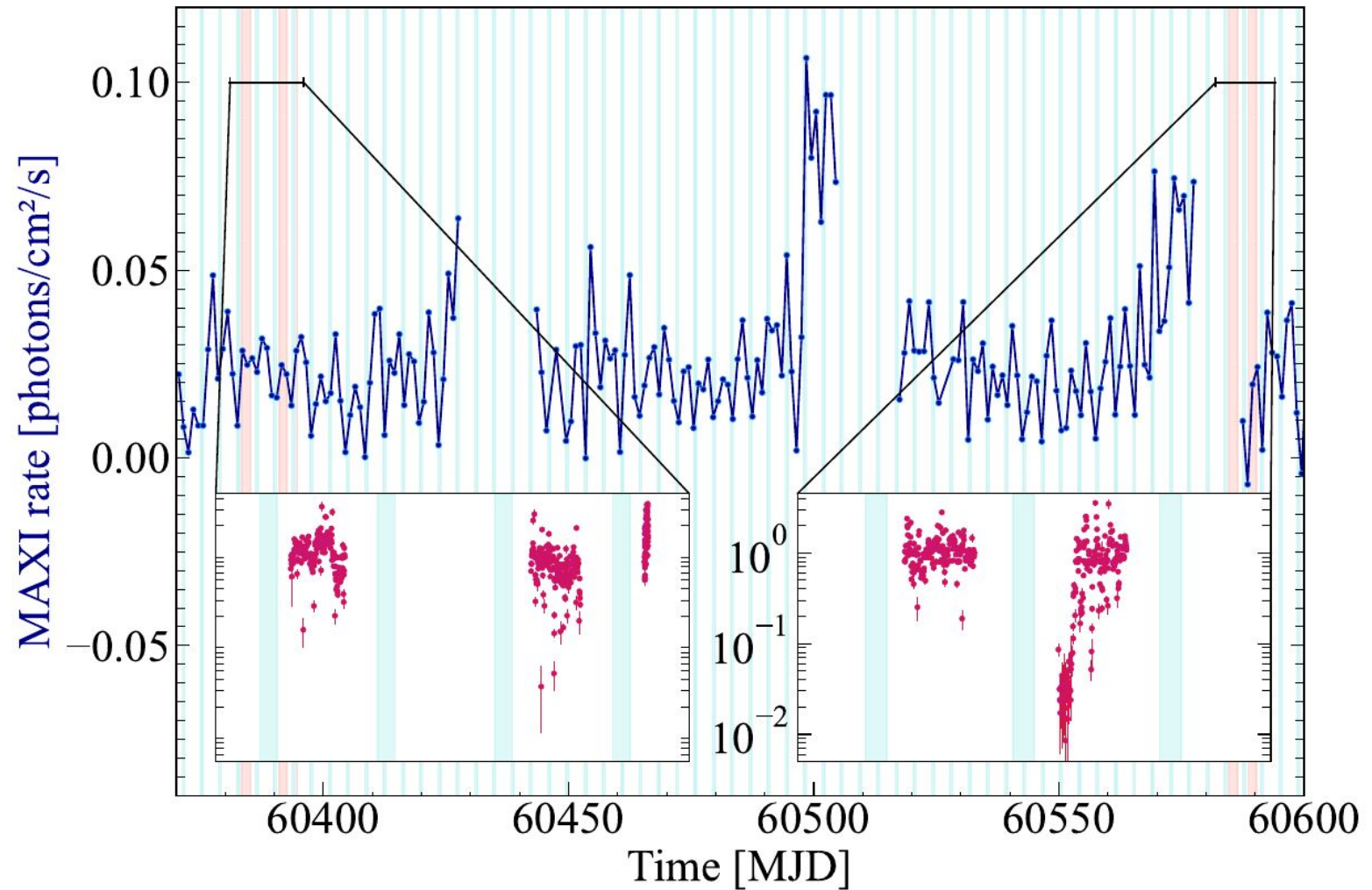
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Observation of 4U 1538-52

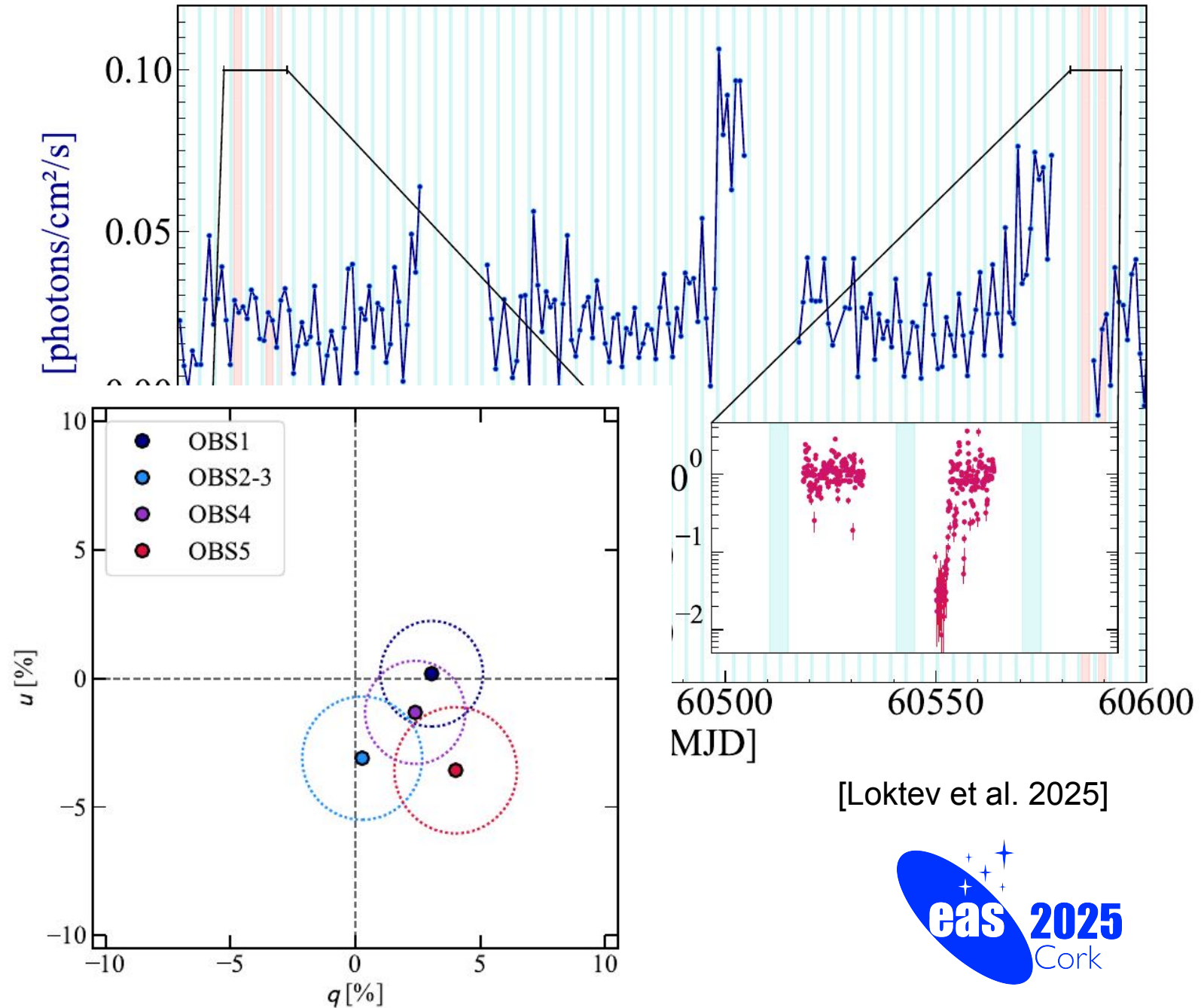
- 5 (4.1) observations of total ~ 360 ks :
2.1 in spring and another 2 in fall 2024



[Loktev et al. 2025]

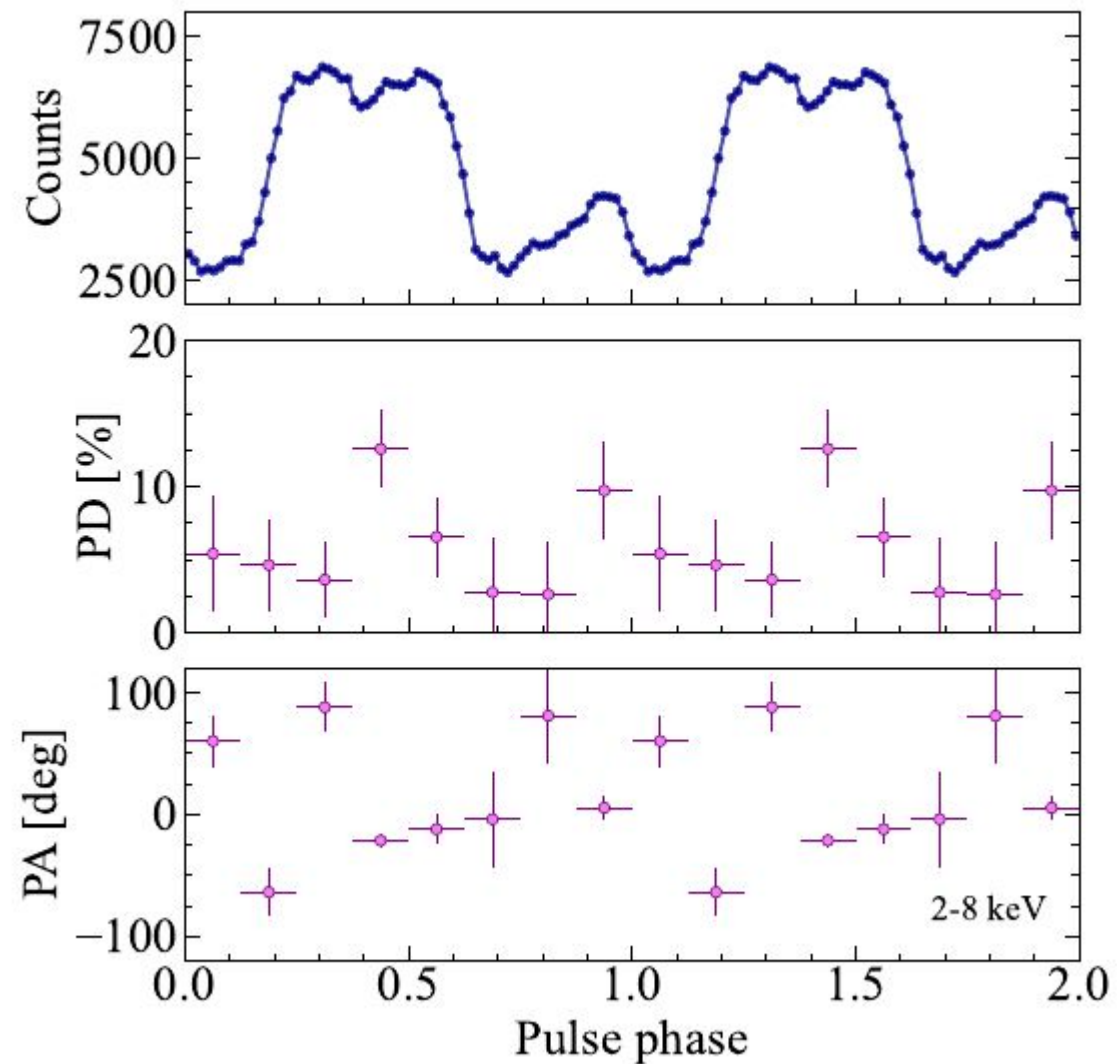
Observation of 4U 1538-52

- 5 (4.1) observations of total ~ 360 ks :
2.1 in spring and another 2 in fall 2024
- No irregular activity (except small dip in the beginning of OBS5) and similar spectral and polarimetric properties between observations



Pulse phase and energy-resolved analysis

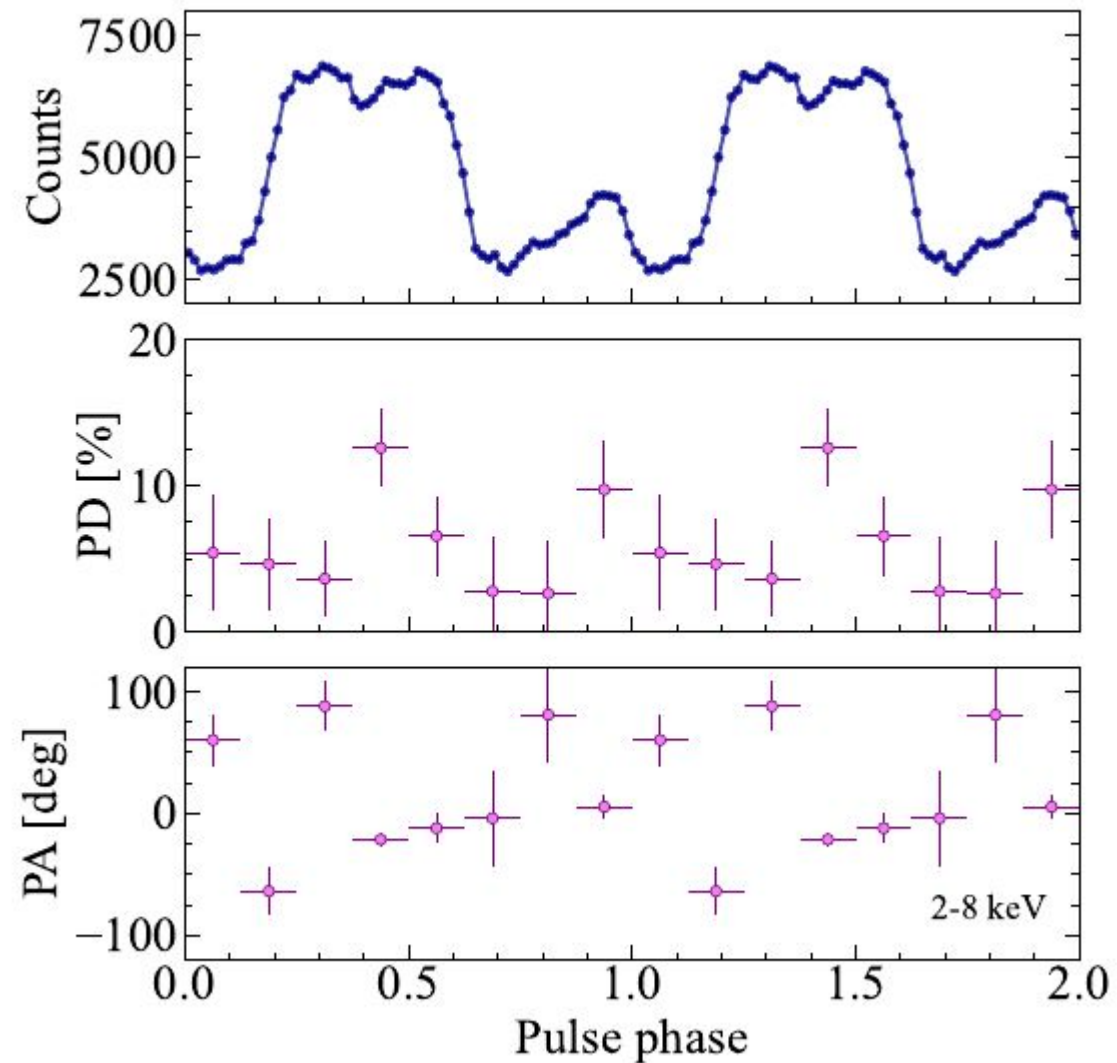
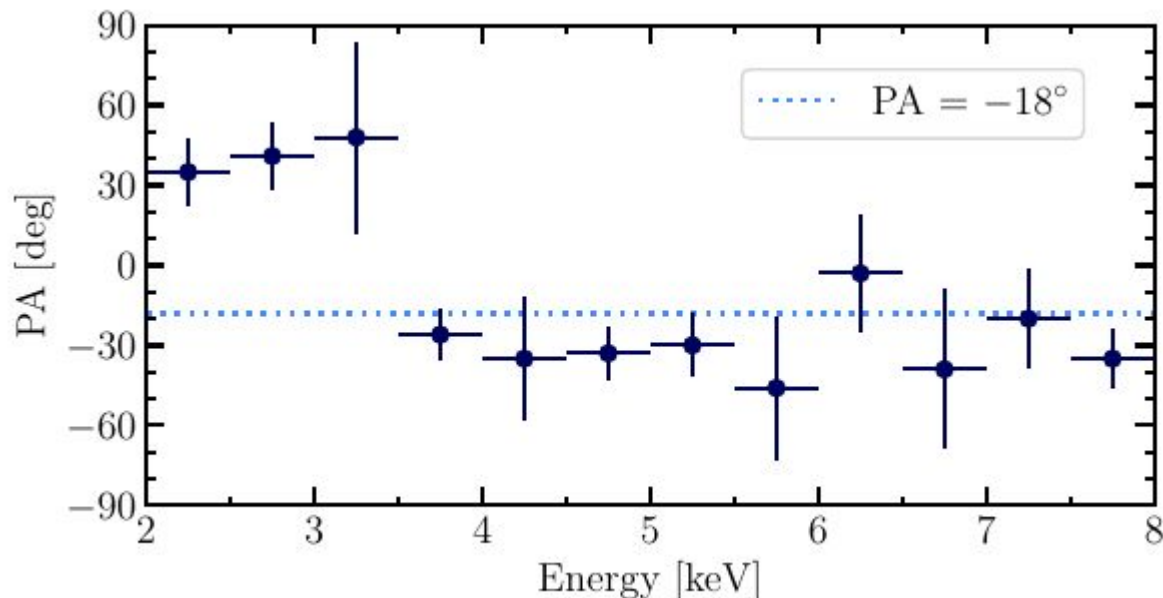
- The phase-resolved polarimetric analysis did not show a regular PA behavior describable by RVM.



[Loktev et al. 2025]

Pulse phase and energy-resolved analysis

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- Instead, similar to Vela X-1, we discovered a change in average PA between lower and higher energies:

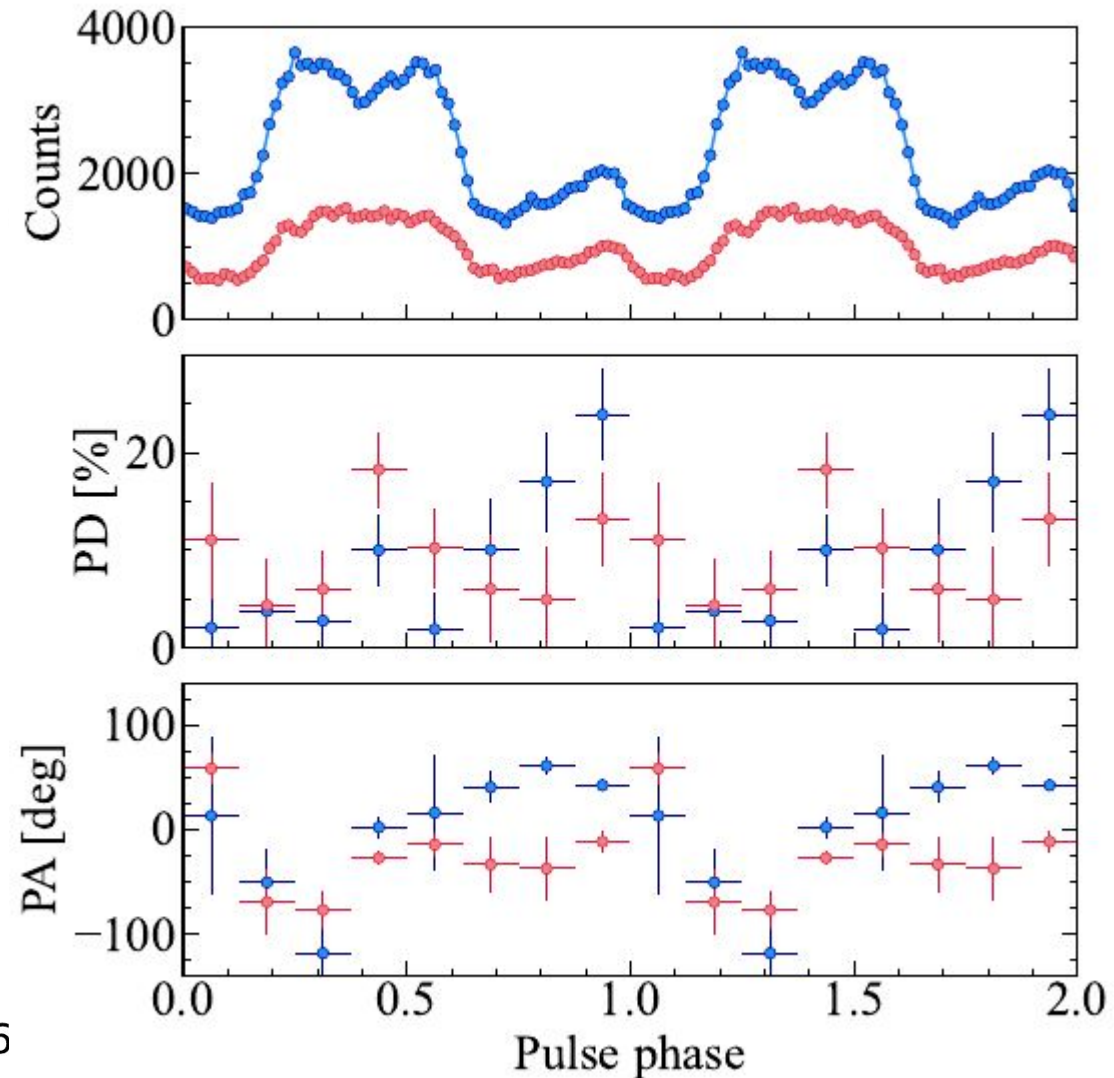
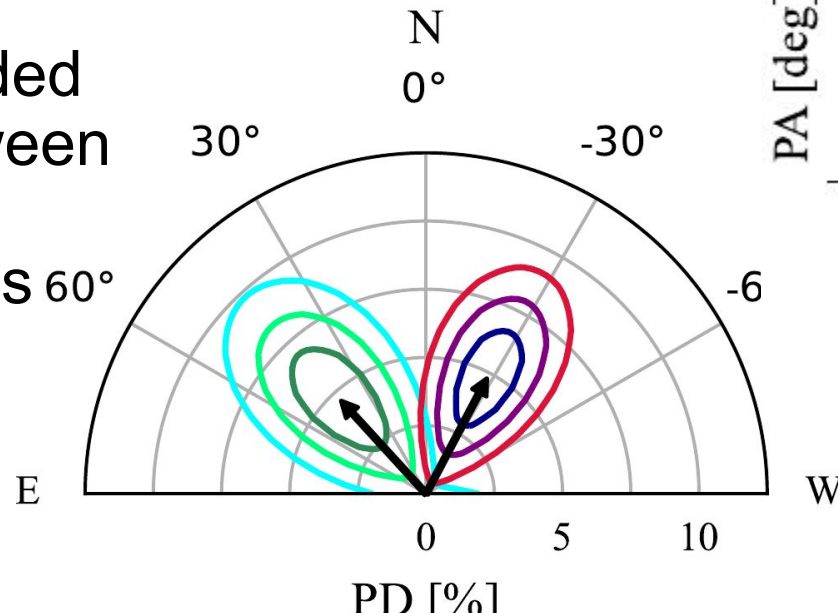


[Loktev et al. 2025]

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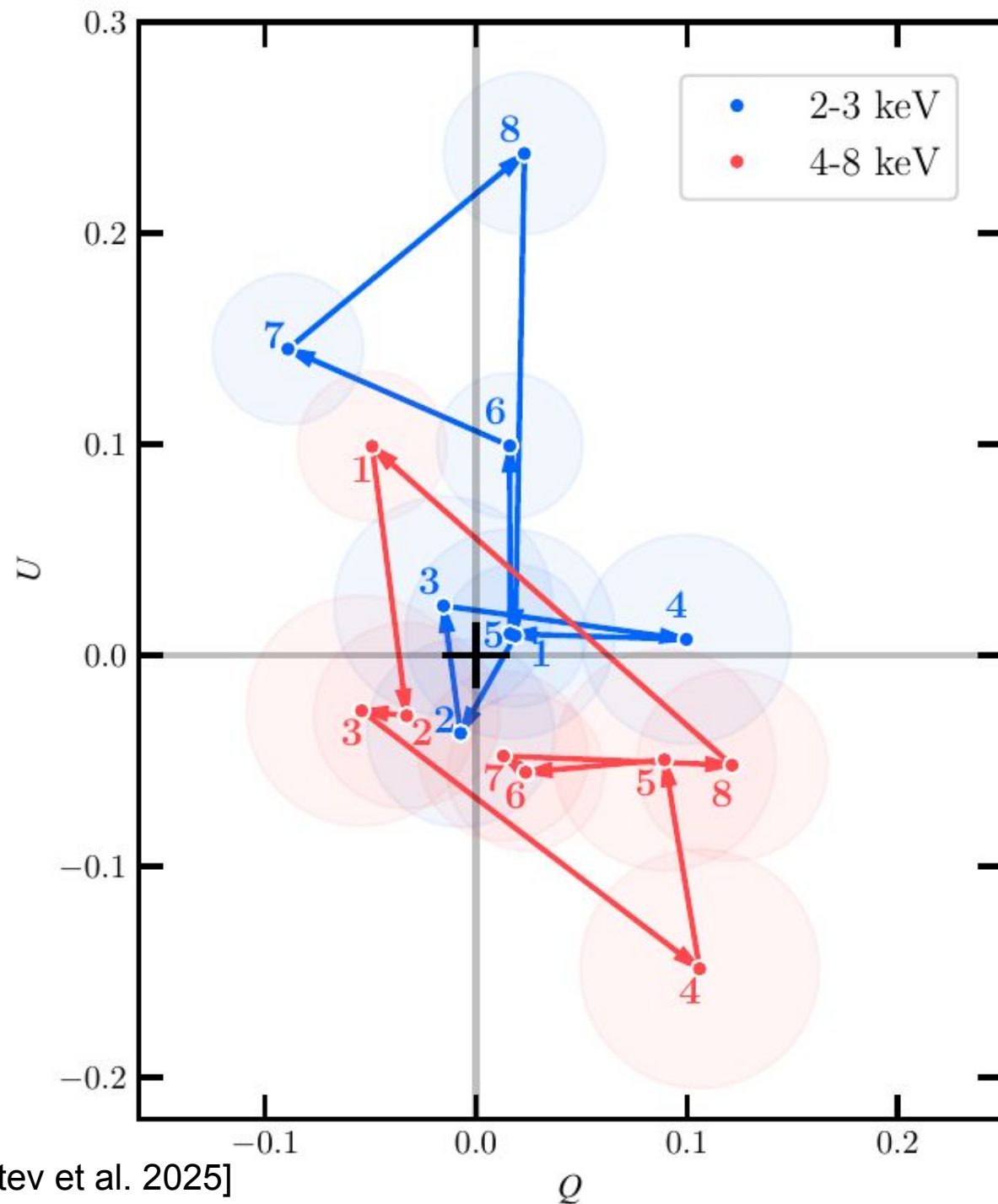
- Thus we divided the data between 2-3 keV and 4-8 keV bands



[Loktev et al. 2025]

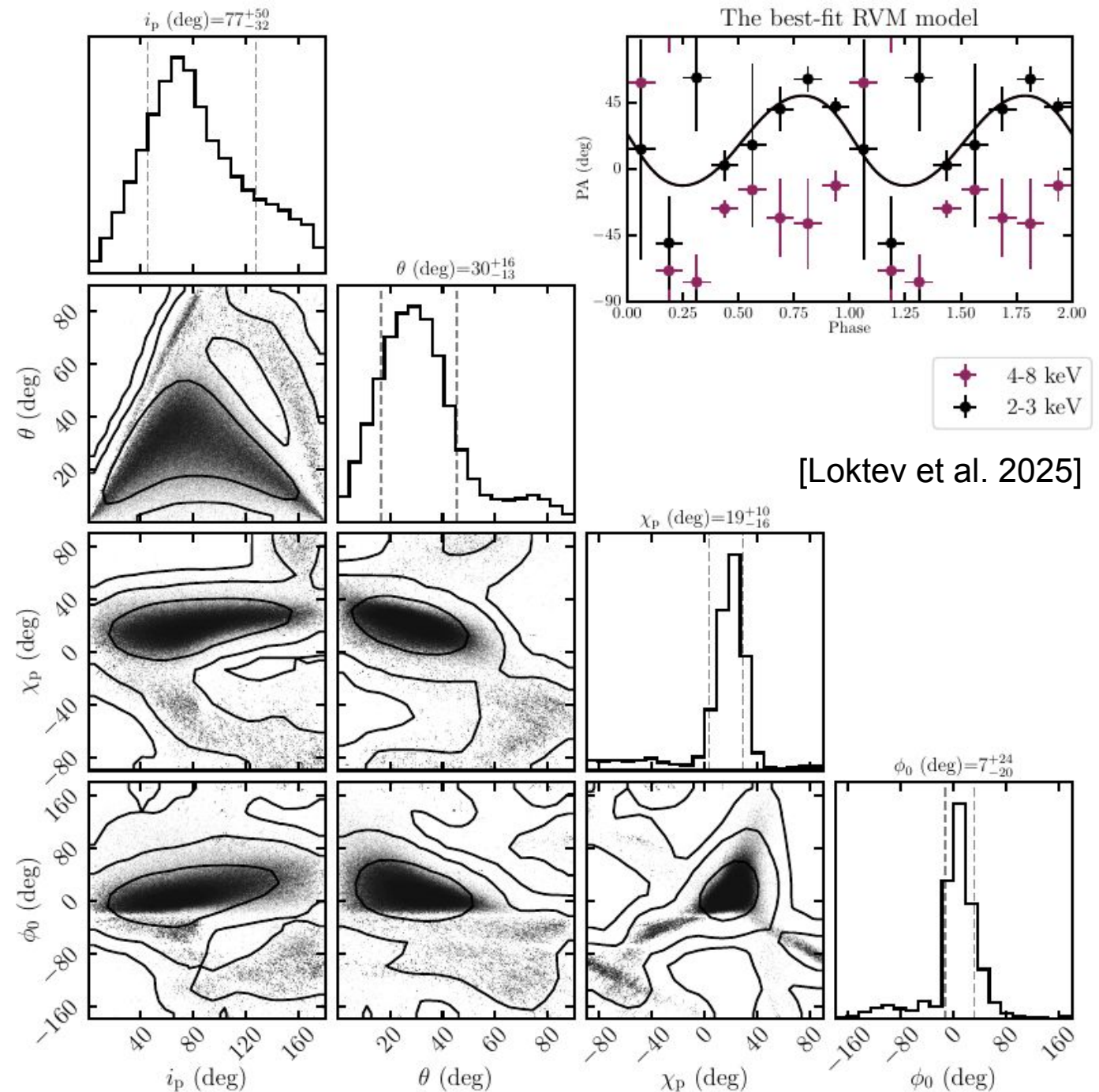
Main takeaway: it is a mess

- Q and U Stokes fluxes in two energy bands and eight pulse phase bins:
- On the Q-U plane the two bands do not show a coherent behavior



MCMC fitting

- yet, the RVM fitting to the softer band data returns constraints on the geometrical parameters of the ‘magnetosphere’
- favors high inclination, consistent with system inclination
- The harder band data could not be fitted independently neither could jointly



Vela X-1 vs 4U 1538-52

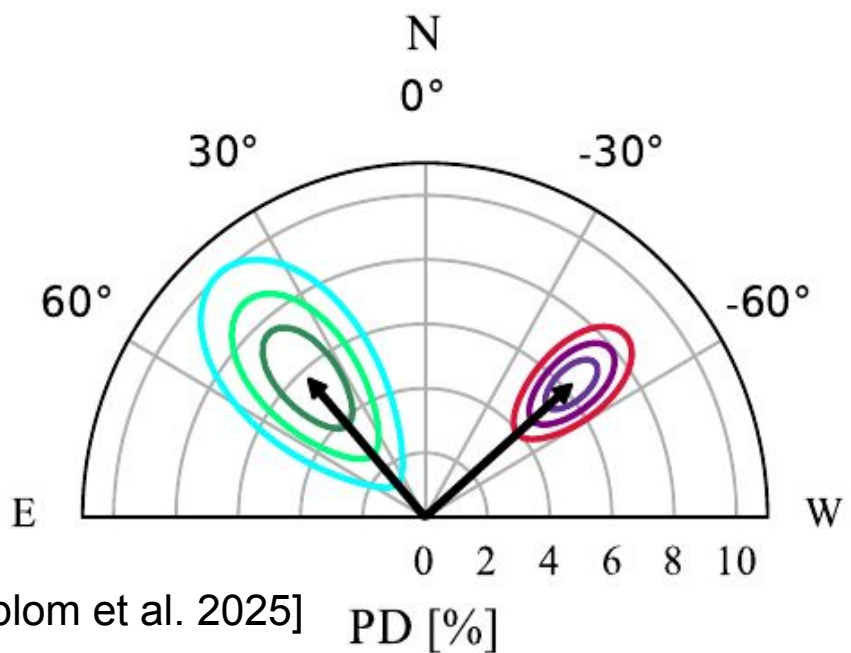
$P_{\text{orbit}} \sim 9 \text{ d}$	$P_{\text{orbit}} \sim 4 \text{ d}$
$P_{\text{spin}} \sim 283 \text{ s}$	$P_{\text{spin}} \sim 529 \text{ s}$
B estimate 2×10^{12}	$B \sim 2 \times 10^{12}$

Nearly twin systems:

- Wind fed X-ray pulsars;
- Long spin periods, short orbital periods;
- Stellar companions of spectral type B0-0.5 I.

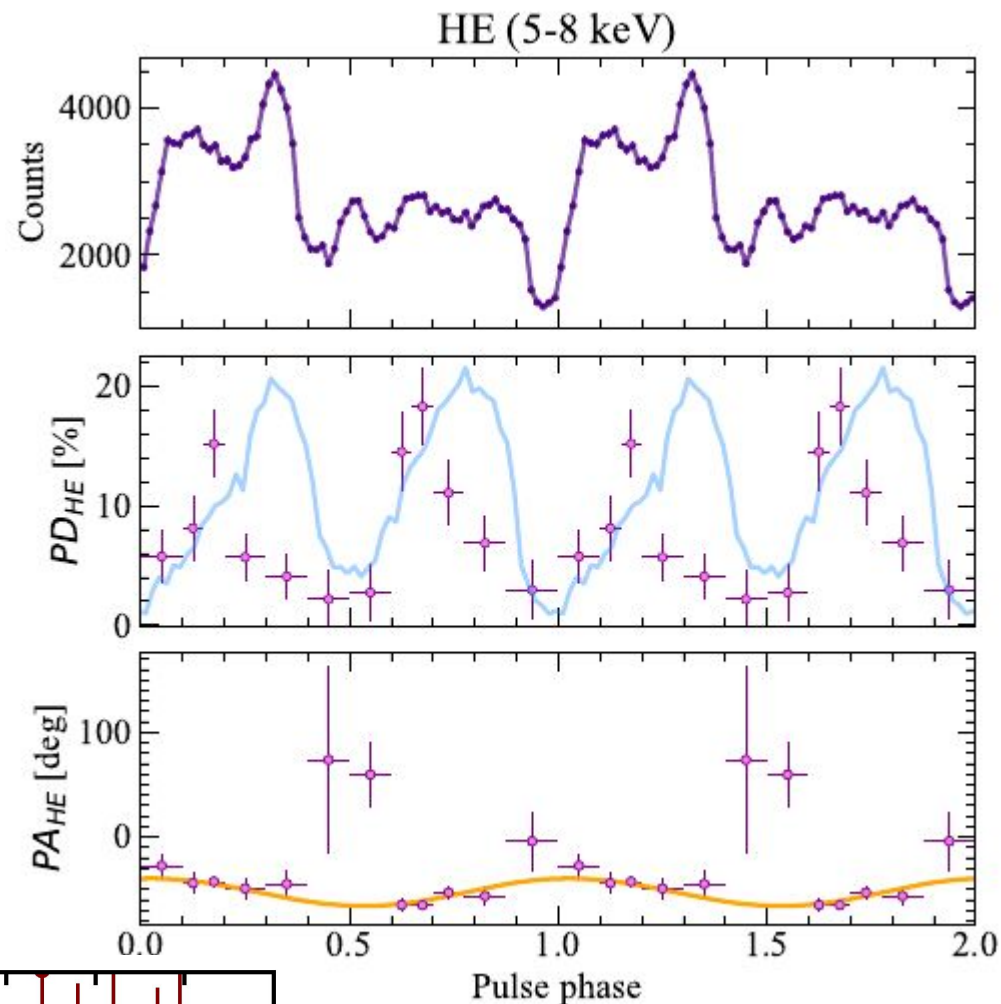
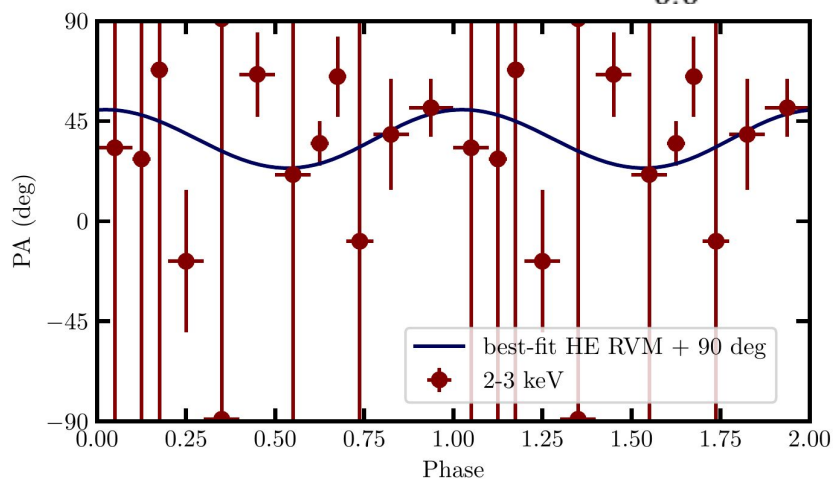
Vela X-1 vs 4U 1538-52

Vela X-1 has almost precisely orthogonal components;
consistent with phase resolved PA (mostly unconstrained, but still)



[Forsblom et al. 2025]

LE (2-3 keV)

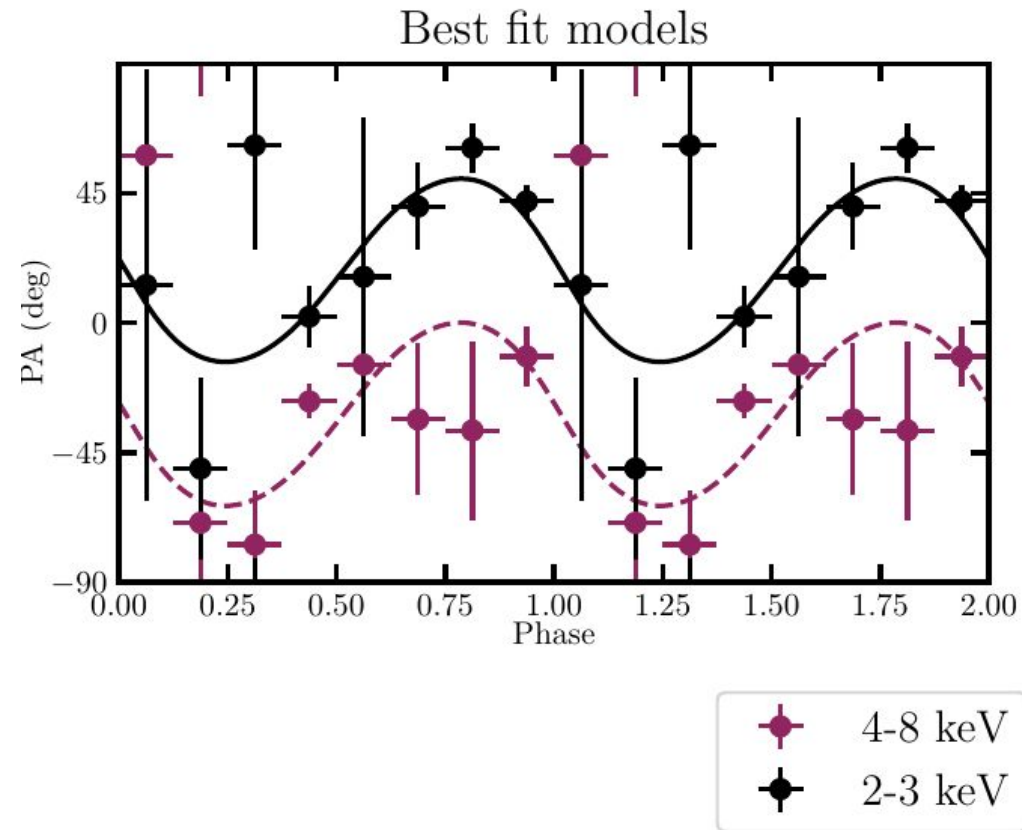
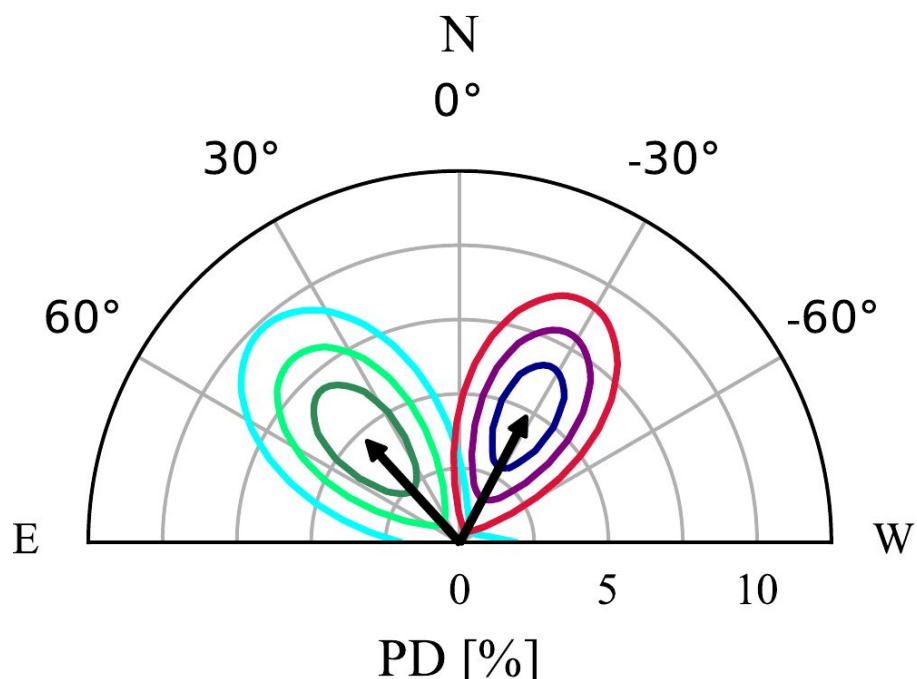


[Forsblom et al. 2025]

Vela X-1 vs 4U 1538-52

4U 1538-52 has two components ~70 degrees apart

PA consistent with 45 degrees difference (unphysical)



IN CONCLUSION

- ★ 4U 1538-52 exhibits pulse phase variability in polarization, but also behavior is different between energy bands
- ★ Similar to the wind fed pulsar Vela X-1 but also different
- ★ Possibly some process outside of adiabatic radius of the magnetosphere
- ★ 4U 1538-52 needs more attention for simultaneous timing spectrography and polarimetry analysis

