Peering into the tilted heart of Cyg X-1 with high-precision optical polarimetry

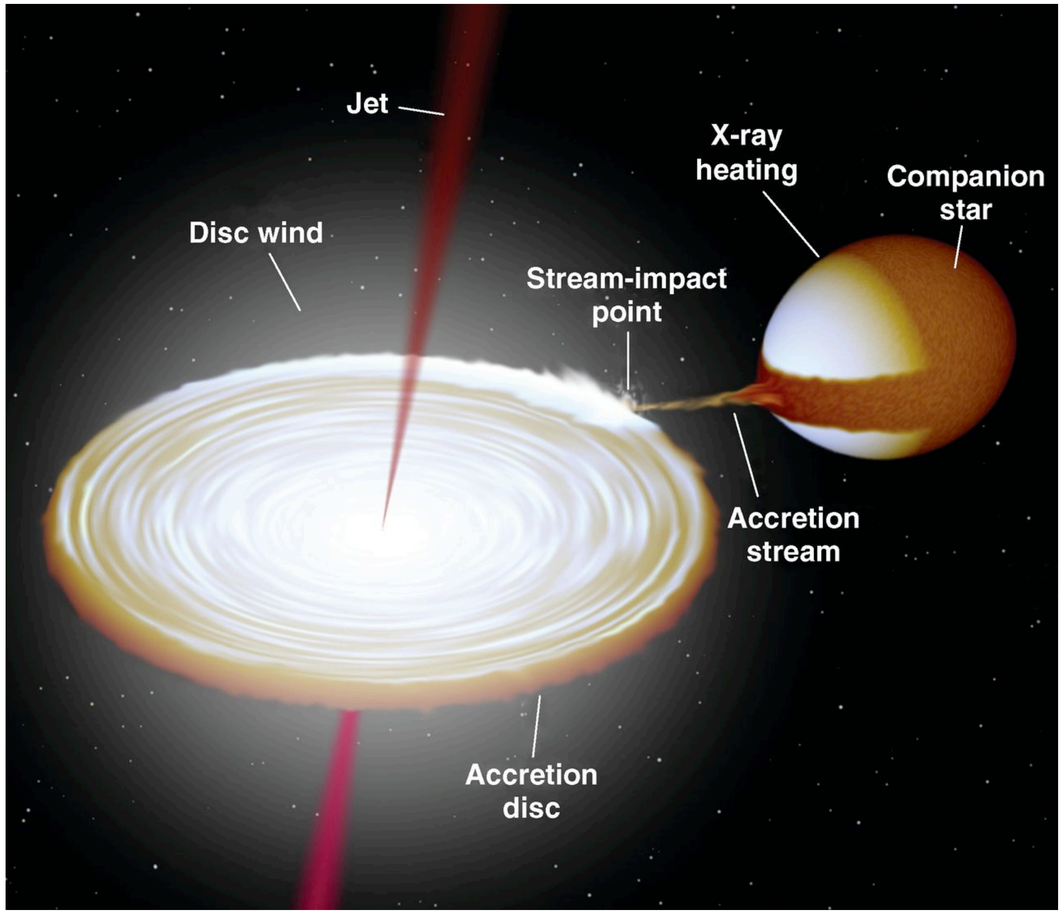
Vadim Kravtsov, University of Turku, Finland
Alexandra Veledina
Andrei Berdyugin
Andrzej Zdziarski
Juri Poutanen
and others....

10th Microquasar Workshop
Crete, Greece
22 – 26 May 2023

UNIVERSITY OF TURKU

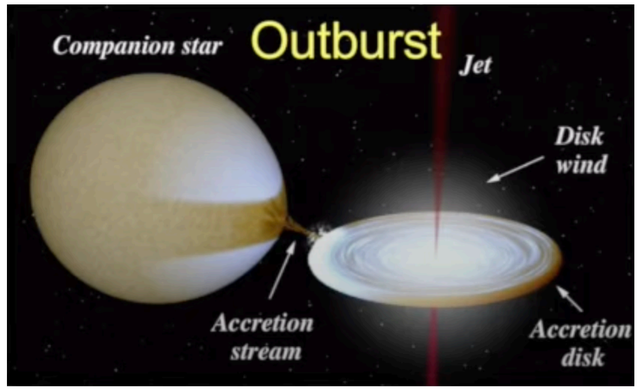
Motivation

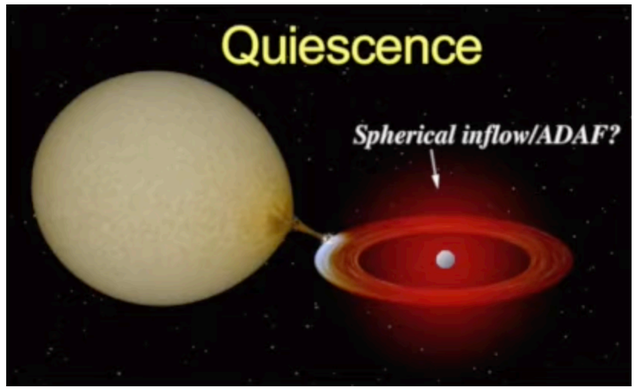
Geometry of black hole X-ray binaries (BHXRBs)



[Image produced with BinSim by Rob Hynes]

Spectrum of BHXRB – product of a complex interplay between contribution of several components.





Optical and infrared (OIR) emission

jet + wind + irradiated disc + + hot accretion flow	optical companion + accretion disc/flow + hotspot/line + jet

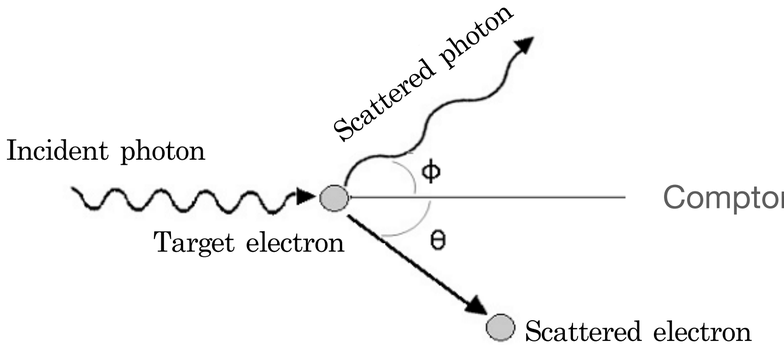
The identification of the different spectral components is essential for understanding the accretion physics in BHXRBs.

Motivation

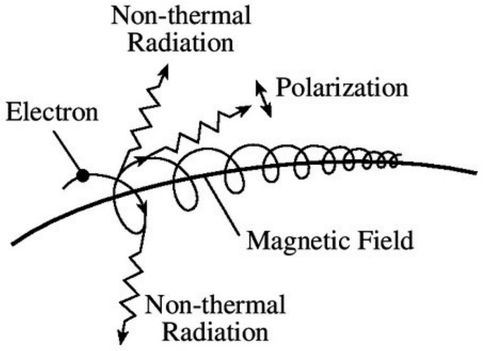
Choice of a tool

There are **several methods** that can be used to study the geometry of X-ray binary systems: *photometry, spectroscopy, imaging, timing, and **polarimetry**.*

Why **polarimetry**?



Compton scattering



Synchrotron radiation

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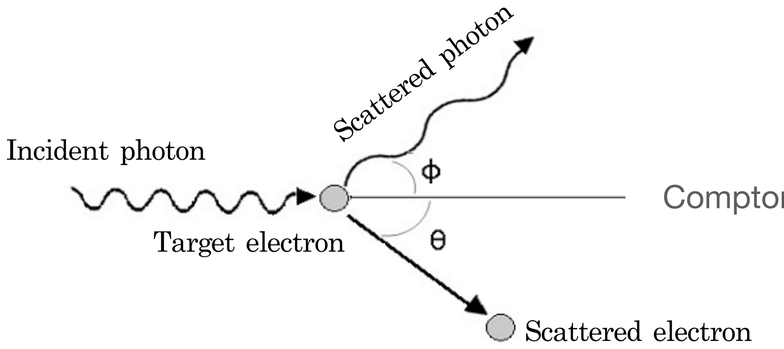

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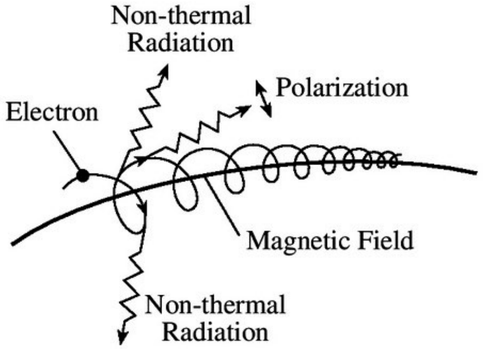

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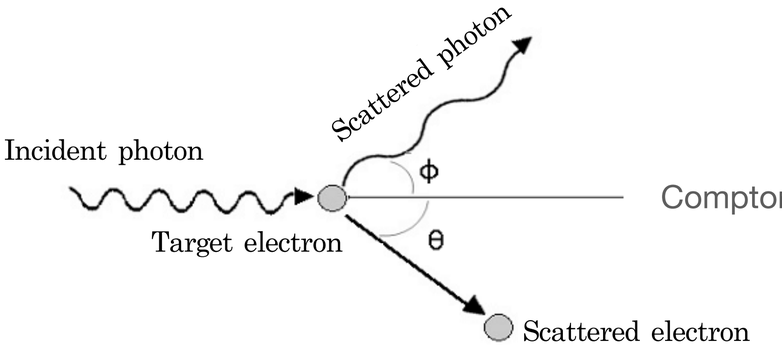

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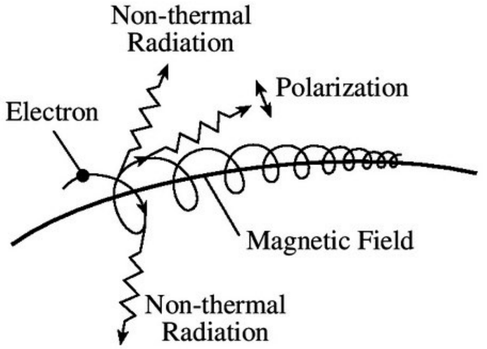

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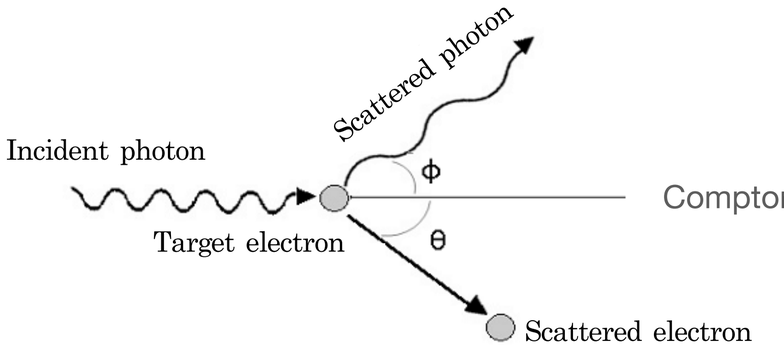
- **Each component has different polarization properties** (or no polarization at all).



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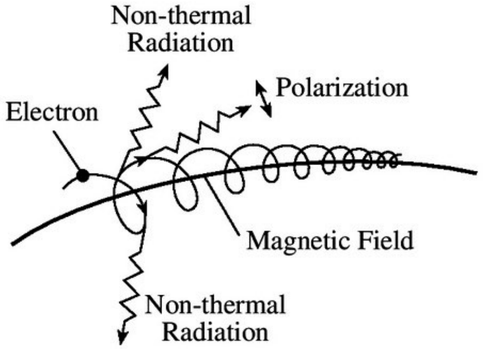
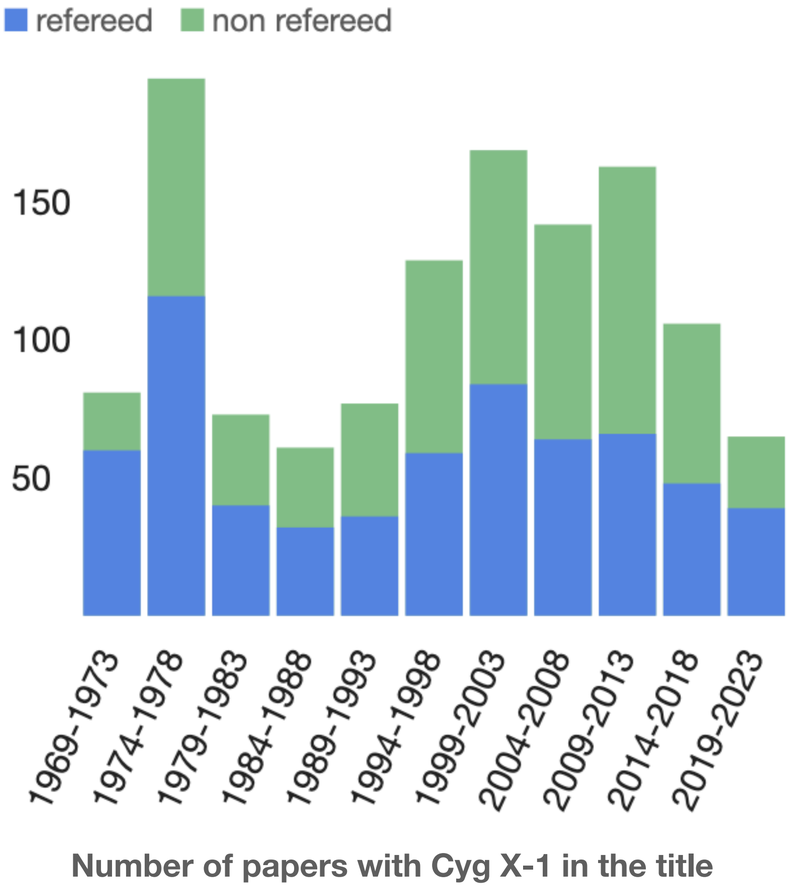


Synchrotron radiation

Microquasar Cyg X-1

The best-studied X-ray binary to date

More than **1300 articles** with "Cyg X-1" in the title.
Or about **1-2 articles every month** since 1960s.



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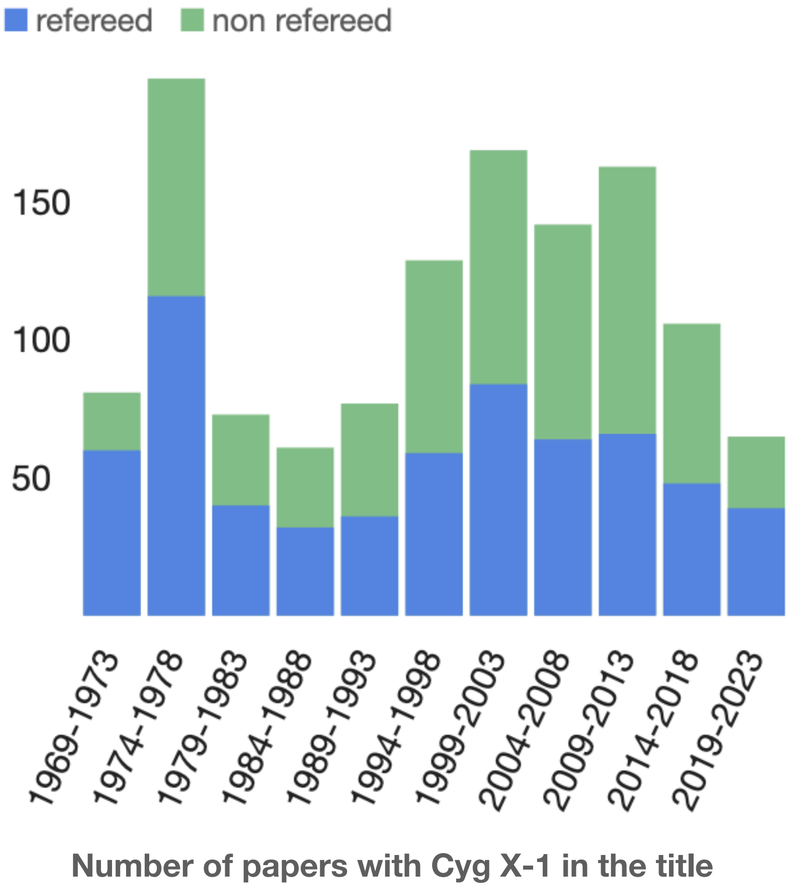

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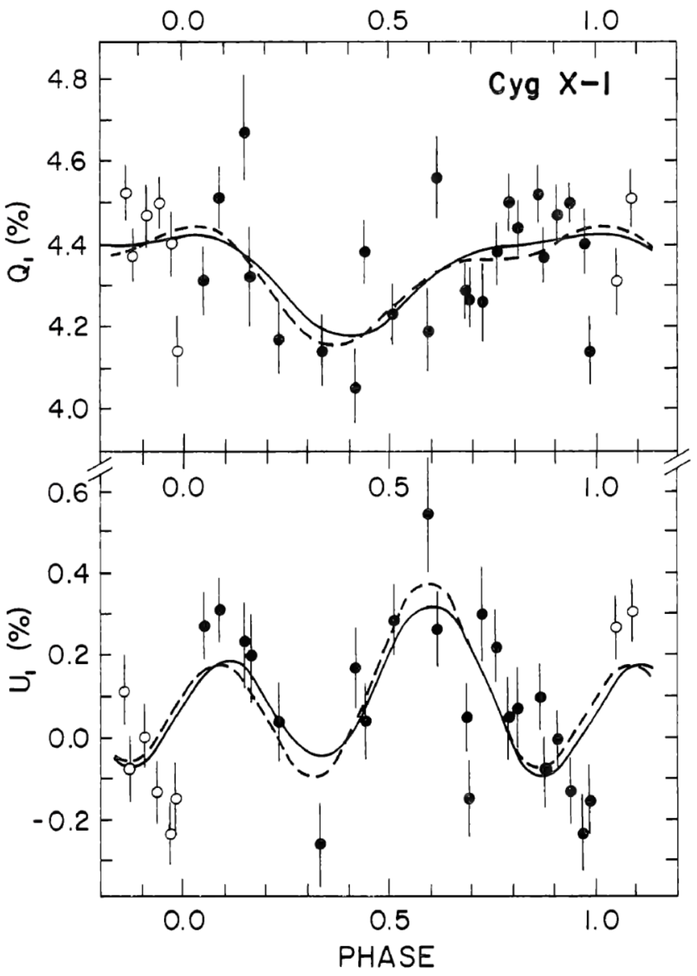

Nolt et al., 1975

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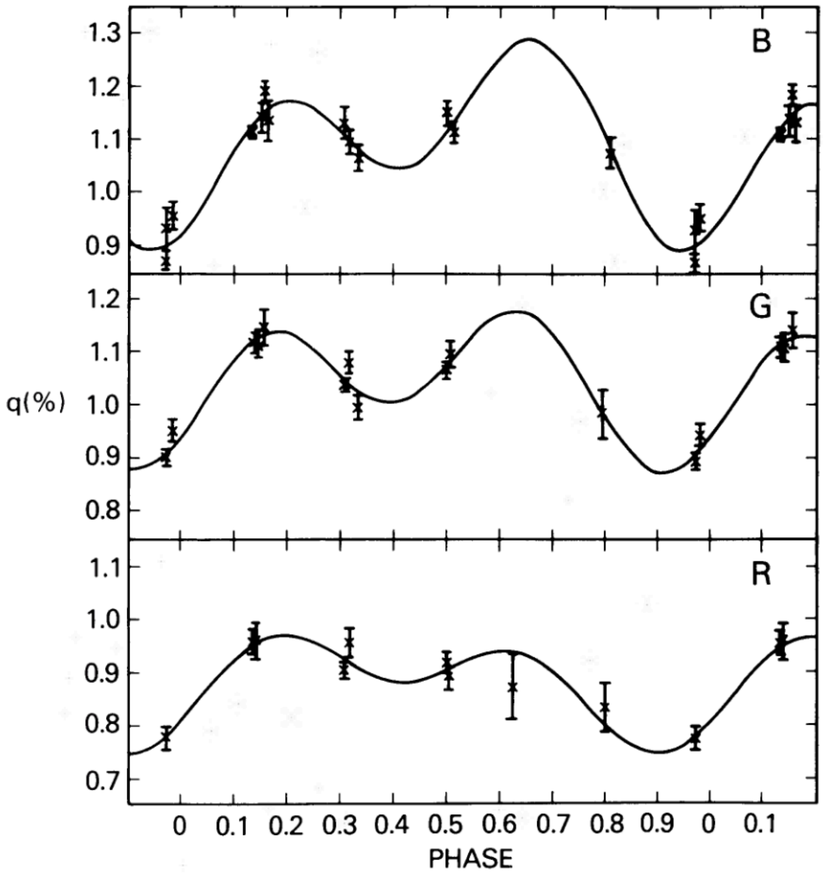

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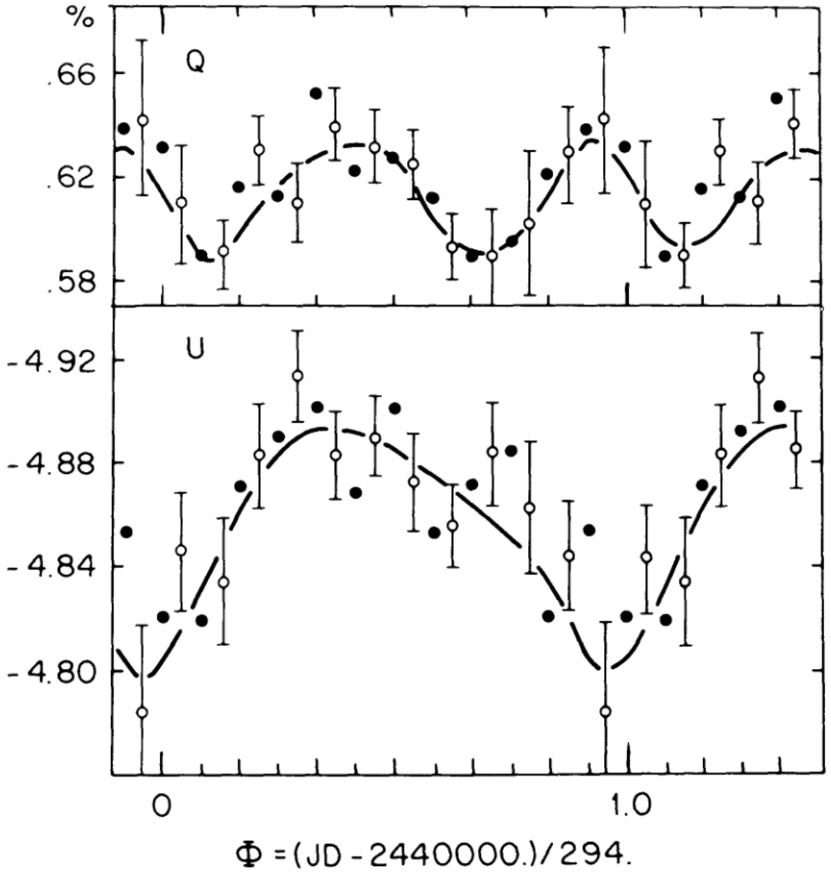

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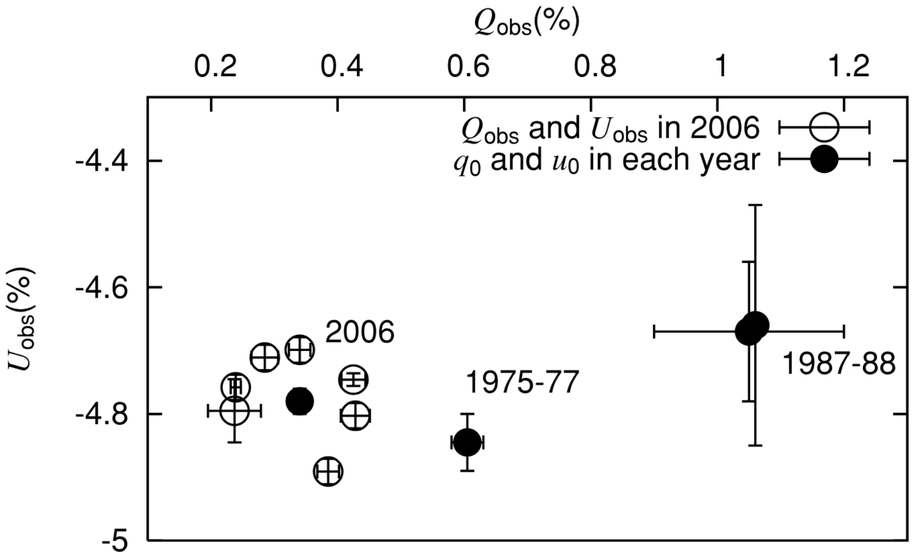

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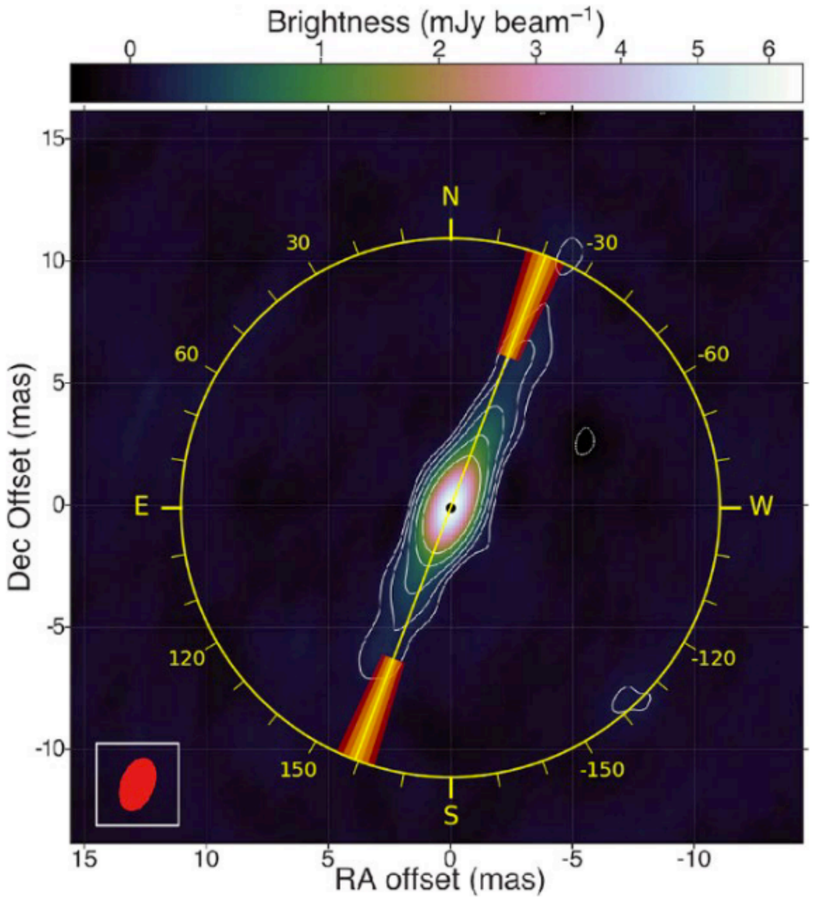
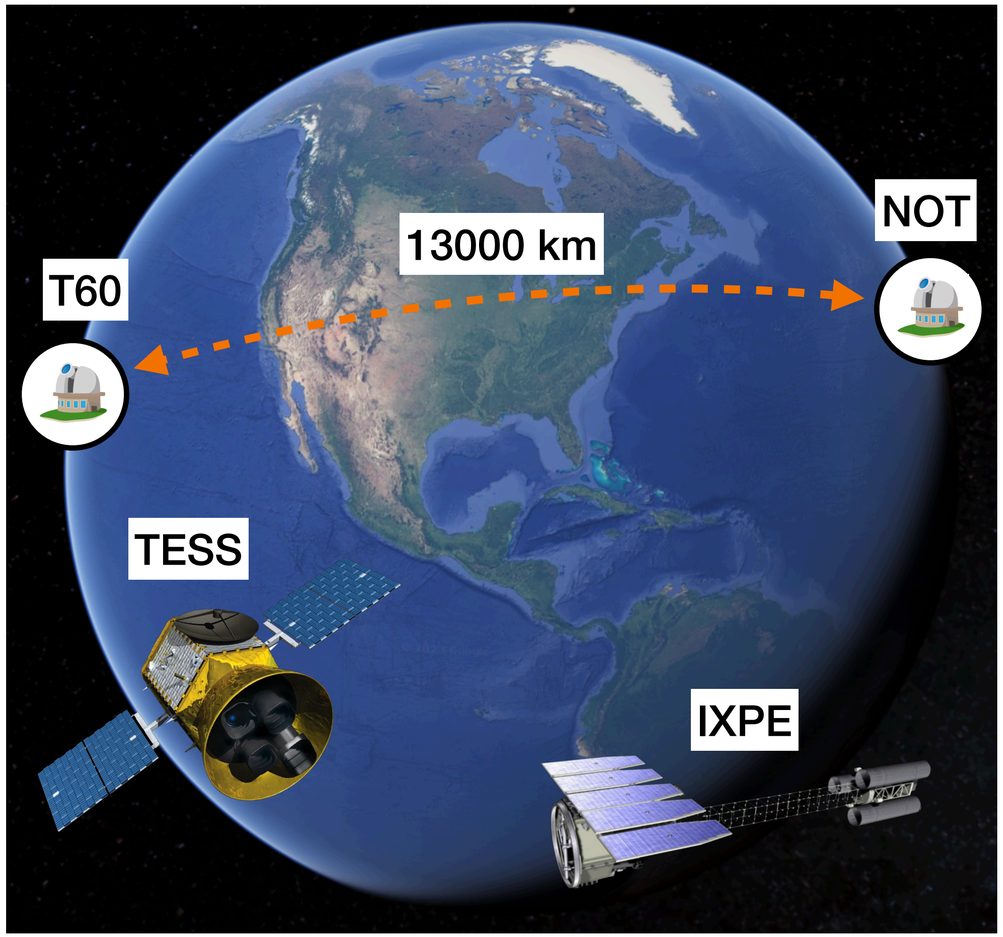
- First robust **detection of X-ray polarization** with IXPE (*Krawczynski et al., 2022*)



Krawczynski et al., 2022

Our observations

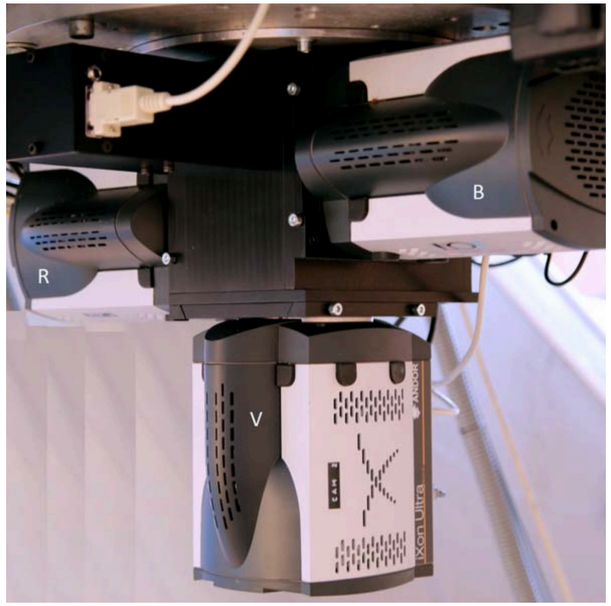
The telescopes and instruments we used



Nordic Optical Telescope (NOT)

La Palma, Canary Islands, Spain

DIPol-UF polarimeter, mounted on NOT



Simultaneous Three-color (*BVR*) polarimeter

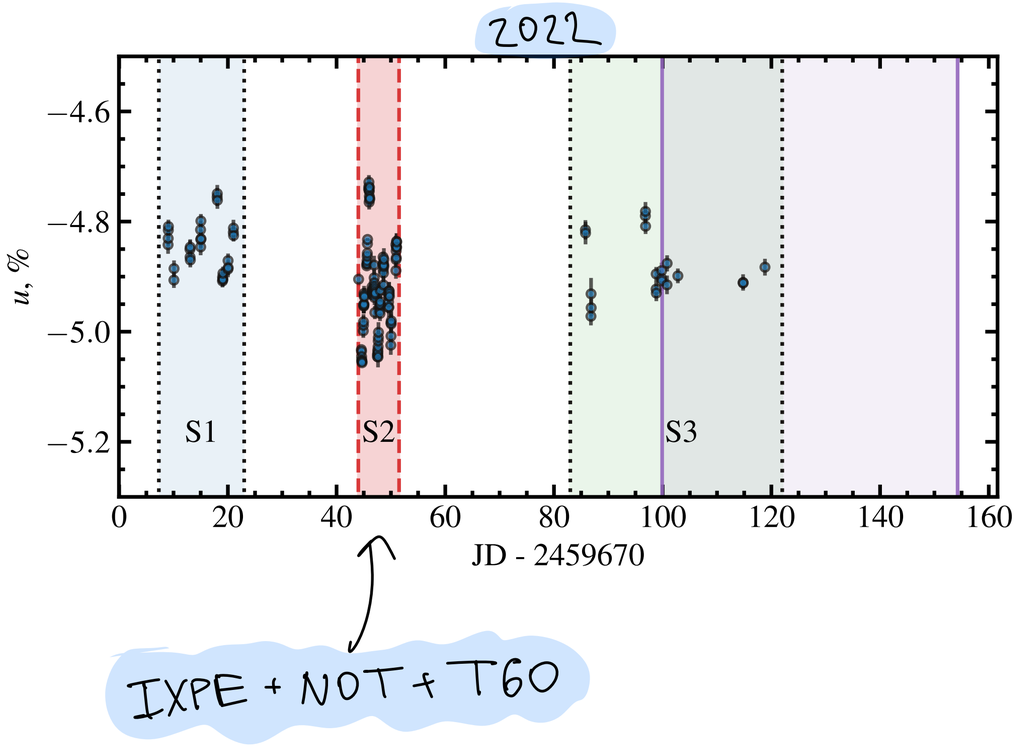
Why DIPol-UF/2?

- Precision up to 10^{-5} ($\Delta P \sim 0.001\,\%$)
- **Simultaneous** three-band (*BVR*) polarimetry
- **Sky polarization is optically eliminated!**

Piirola et al., 2020

Our observations

High-precision optical polarization and flux measurements



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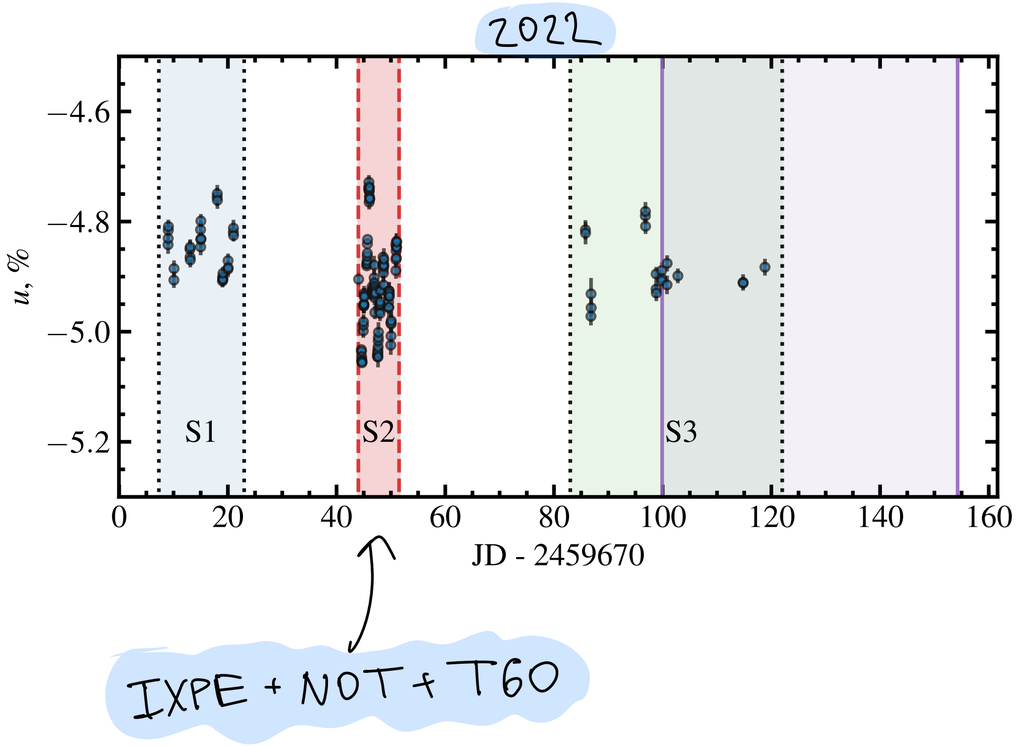

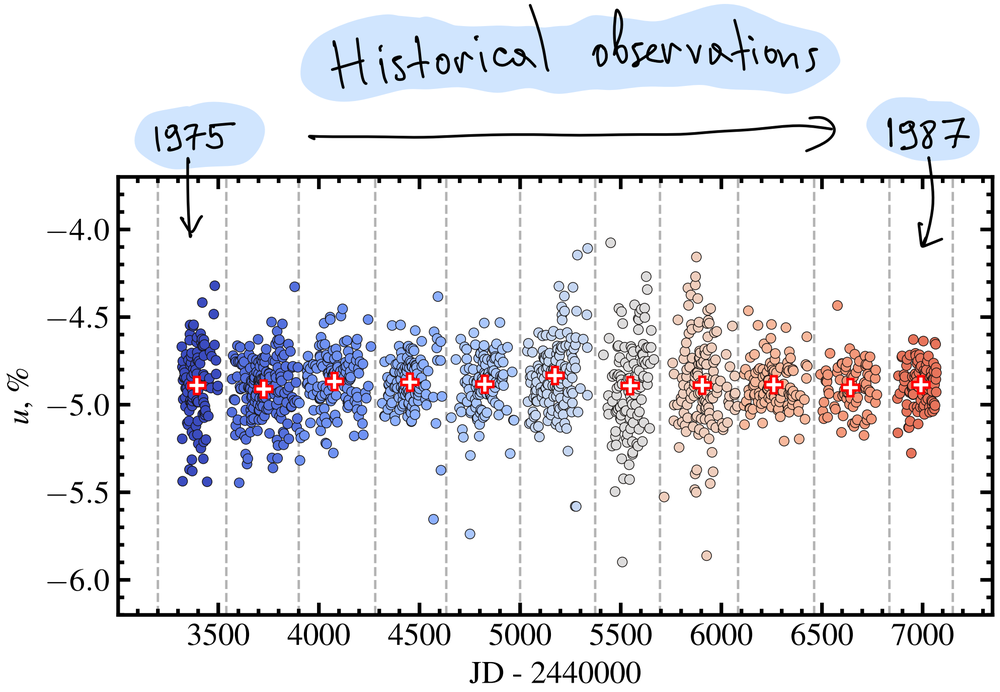

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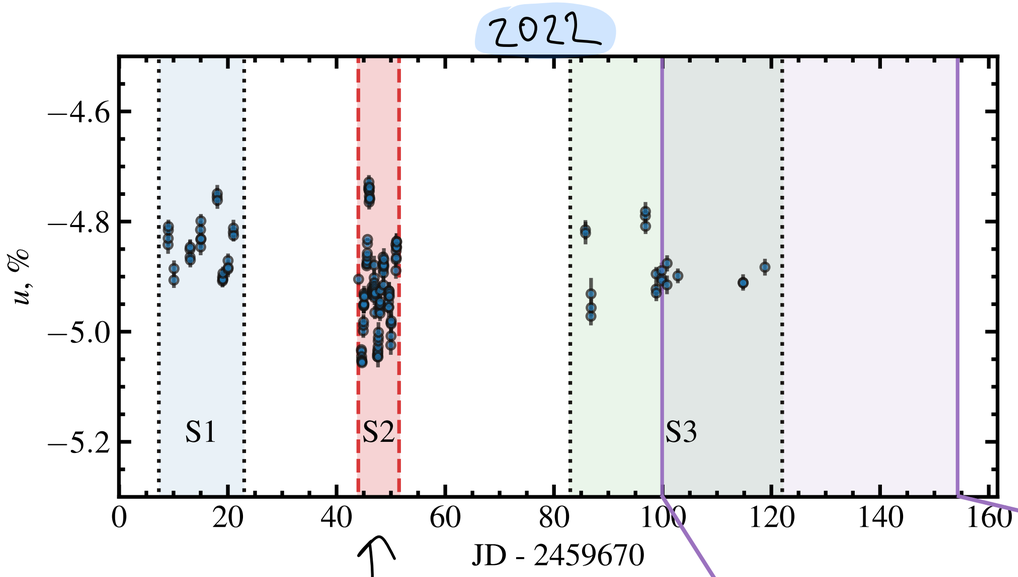
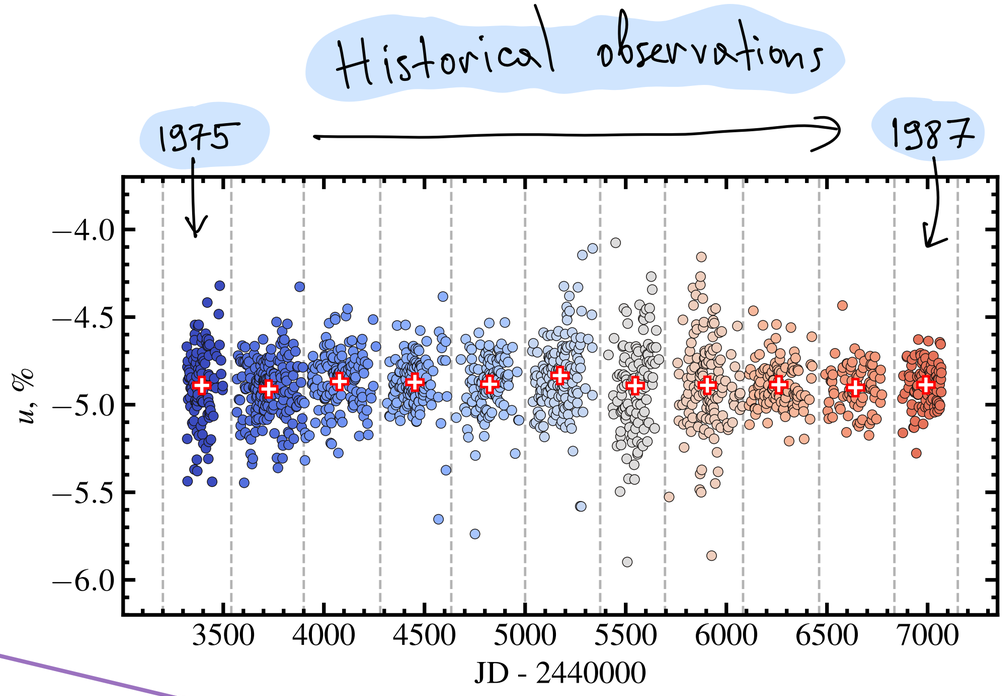
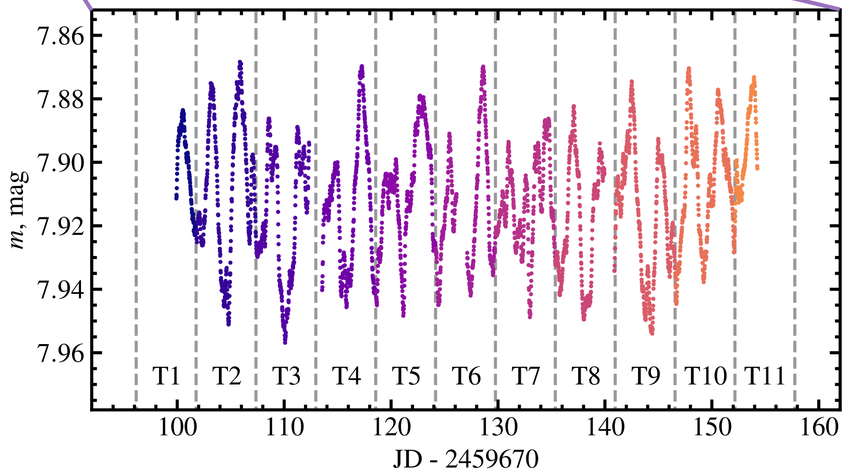


IXPE + NOT + T60

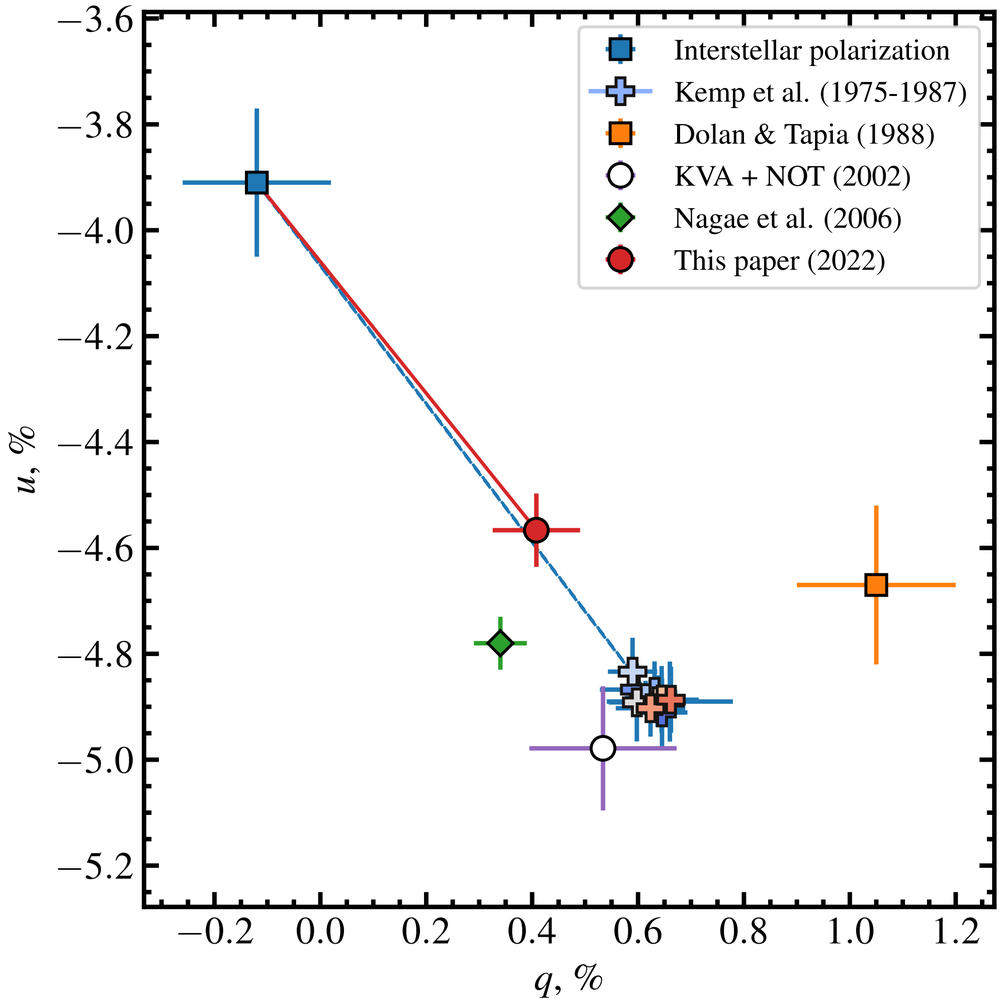




TESS photometry

Results

Intrinsic polarization estimation



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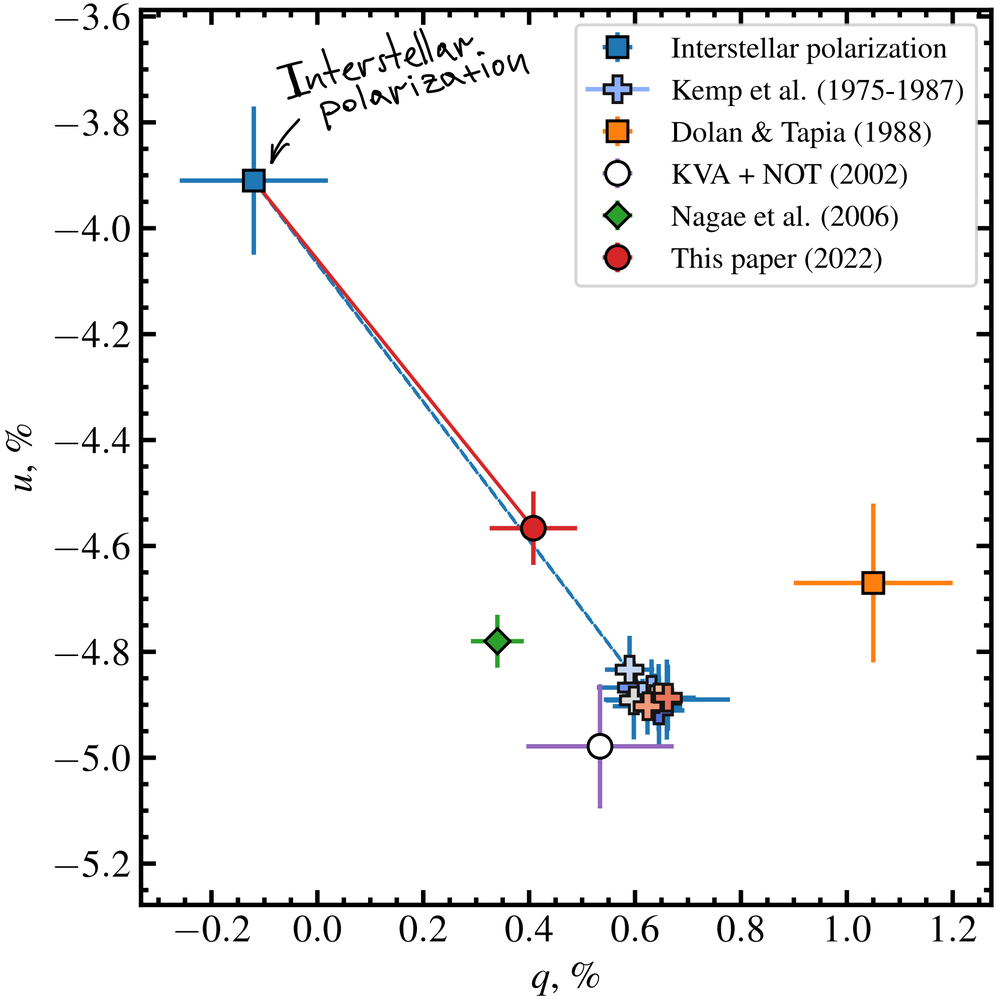

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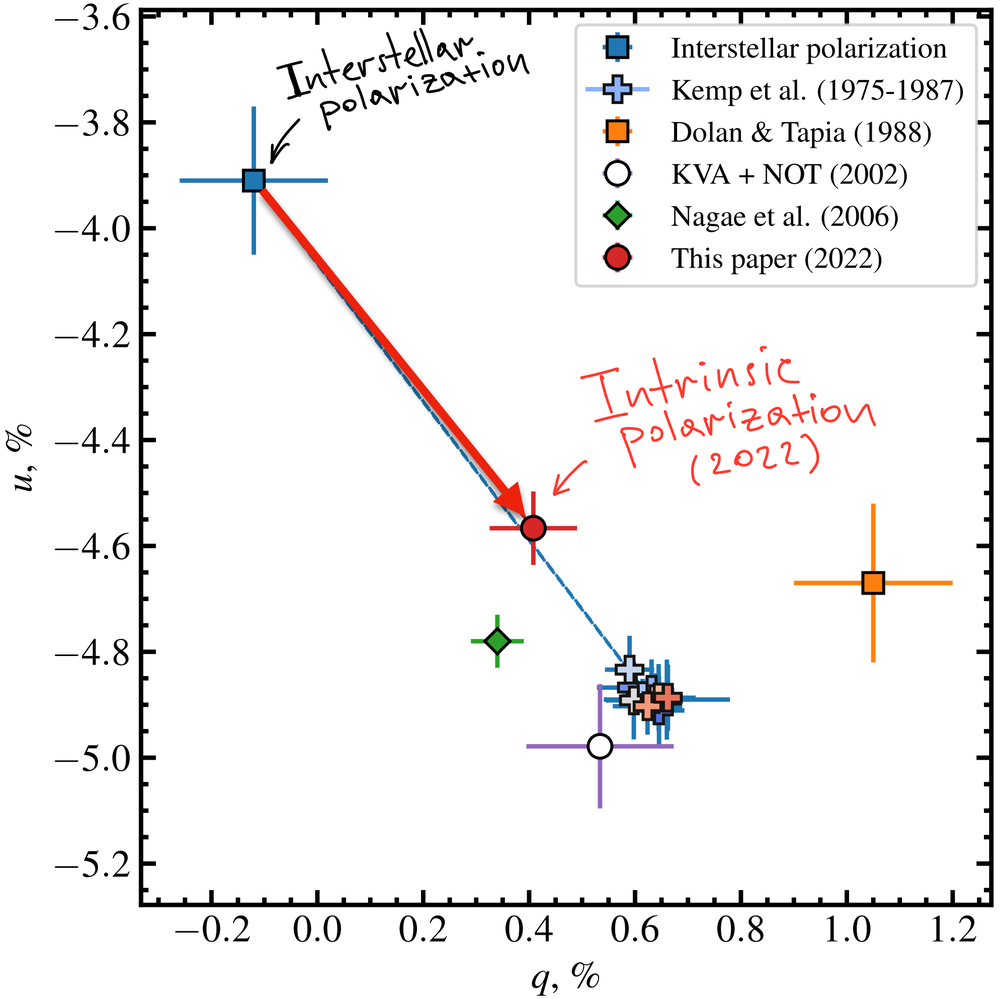

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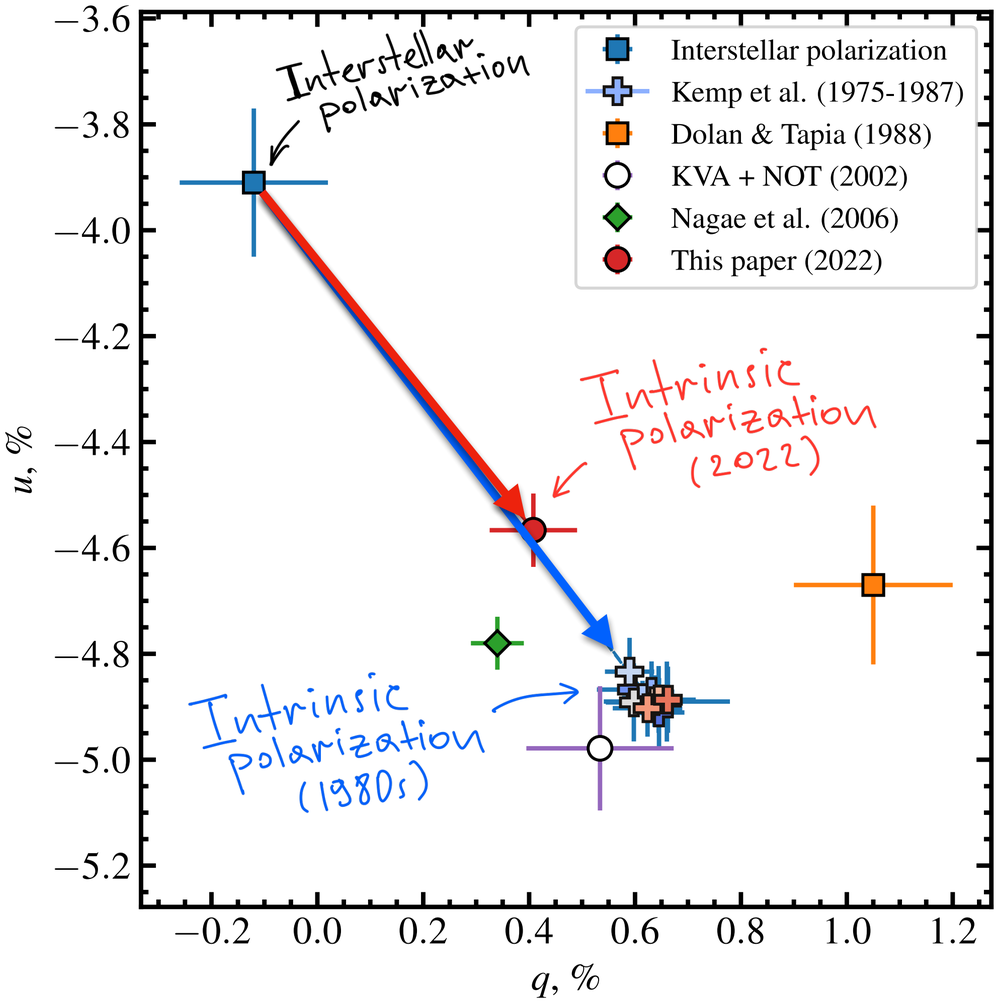

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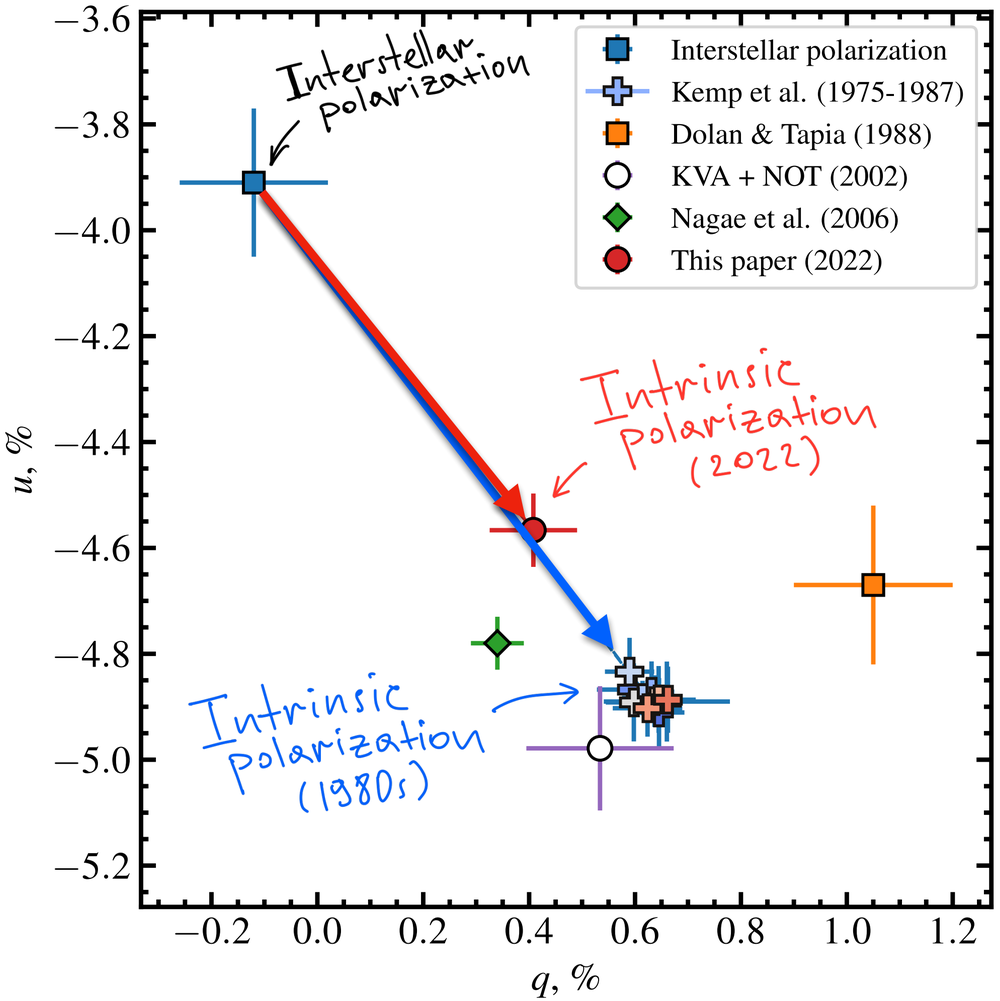

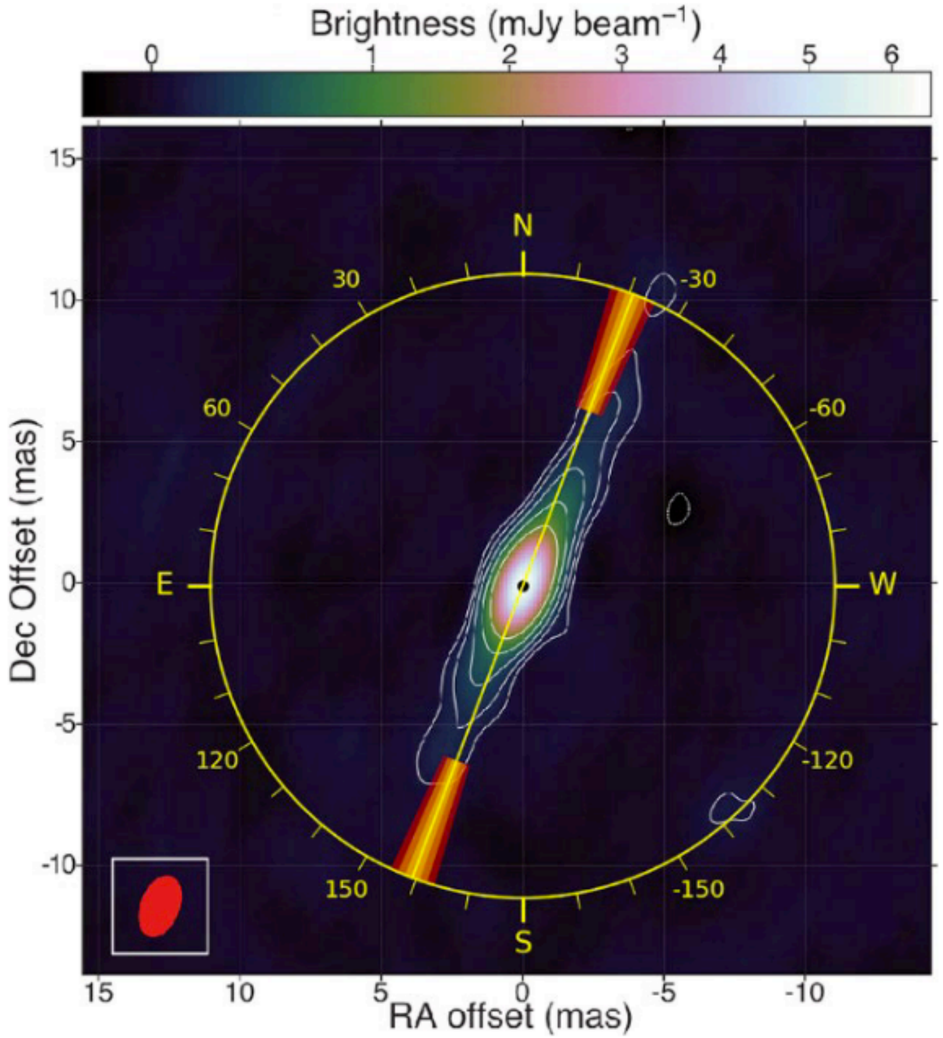

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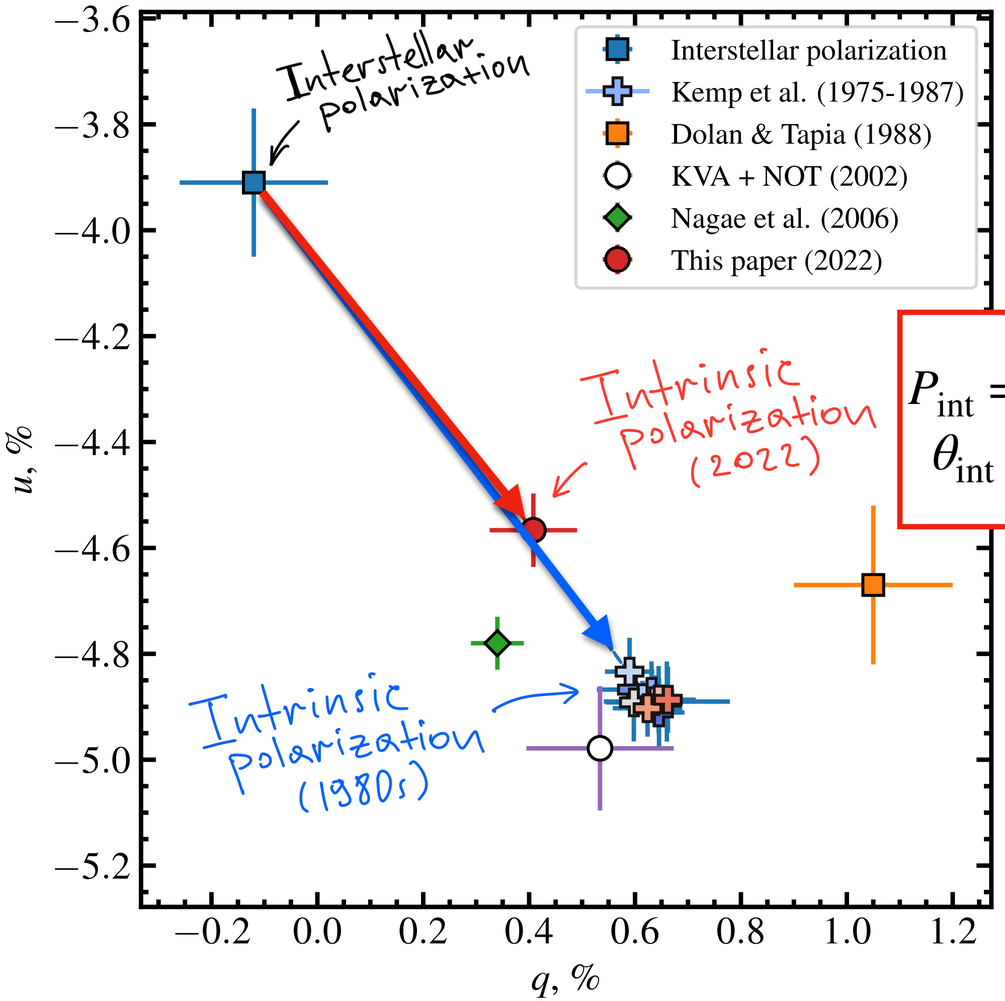
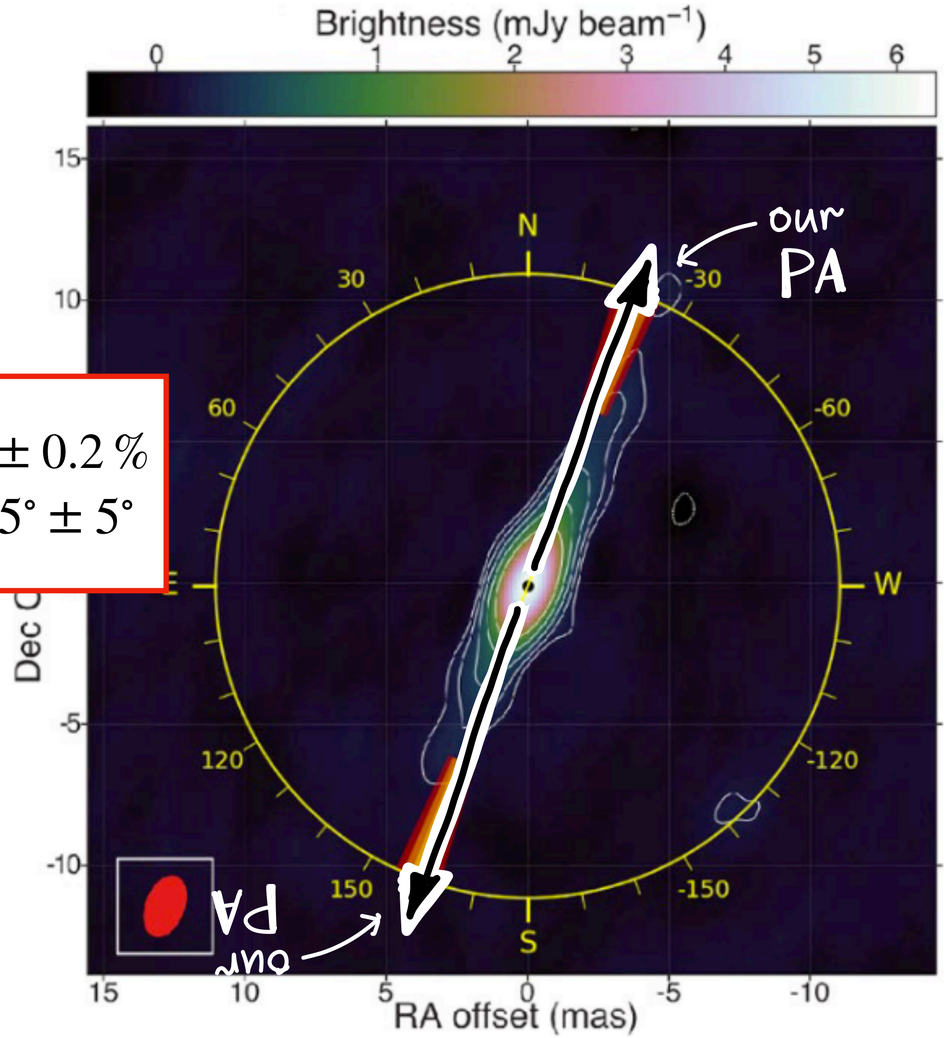
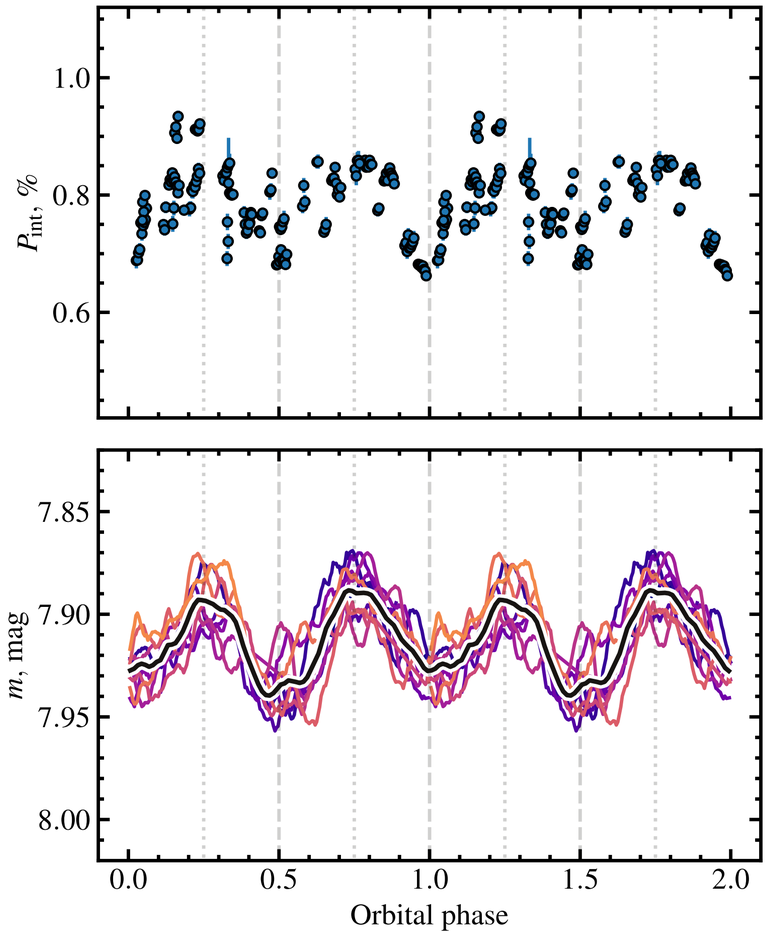


$$P_{\rm int} = 0.8 \pm 0.2\,\%$$
$$\theta_{\rm int} = 155^\circ \pm 5^\circ$$



Results

Variability of Cyg X-1 in optical part of the spectrum



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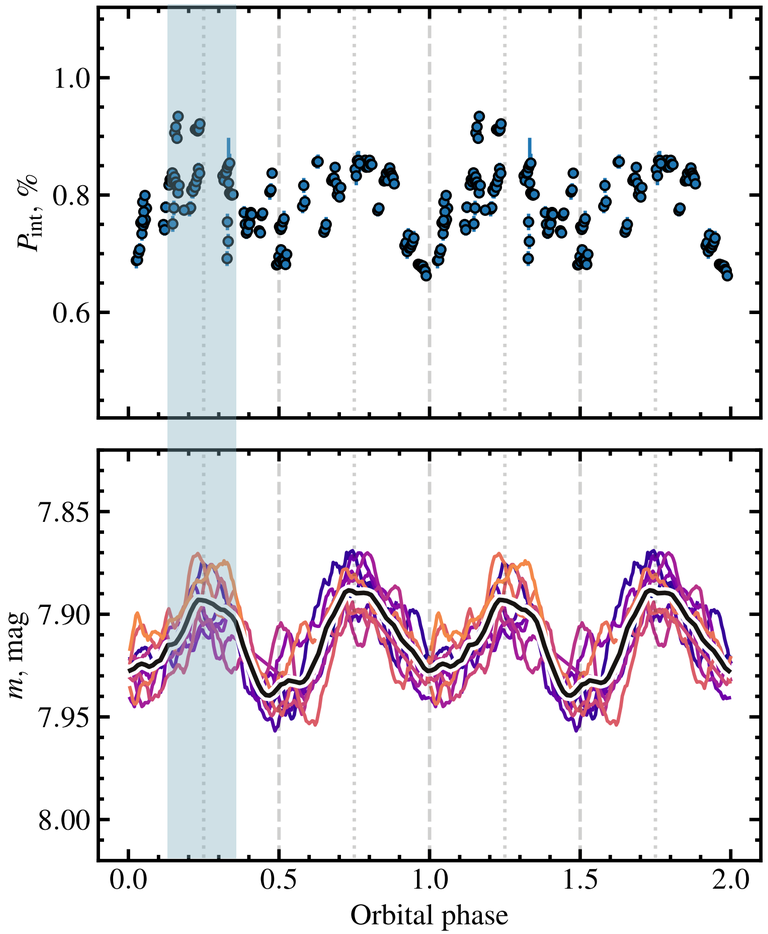
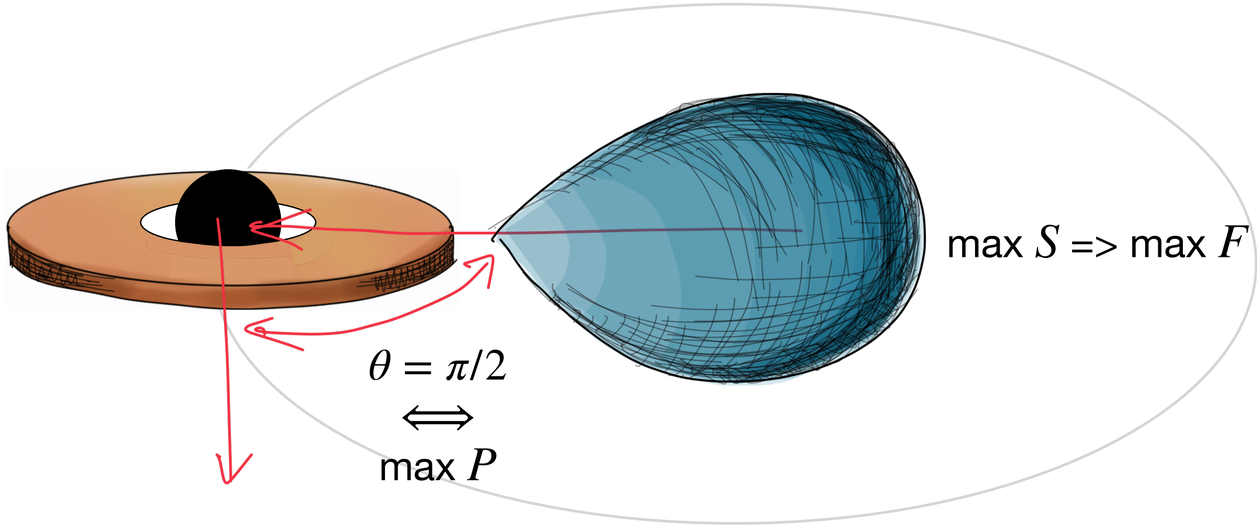


Flux $F \propto$ Visible area of the star S

$$P = \frac{1-\mu^2}{1+\mu^2},\ \mu = \cos\theta$$

$$P = 1 \iff \mu = 0 \iff \theta = \pm\pi/2$$



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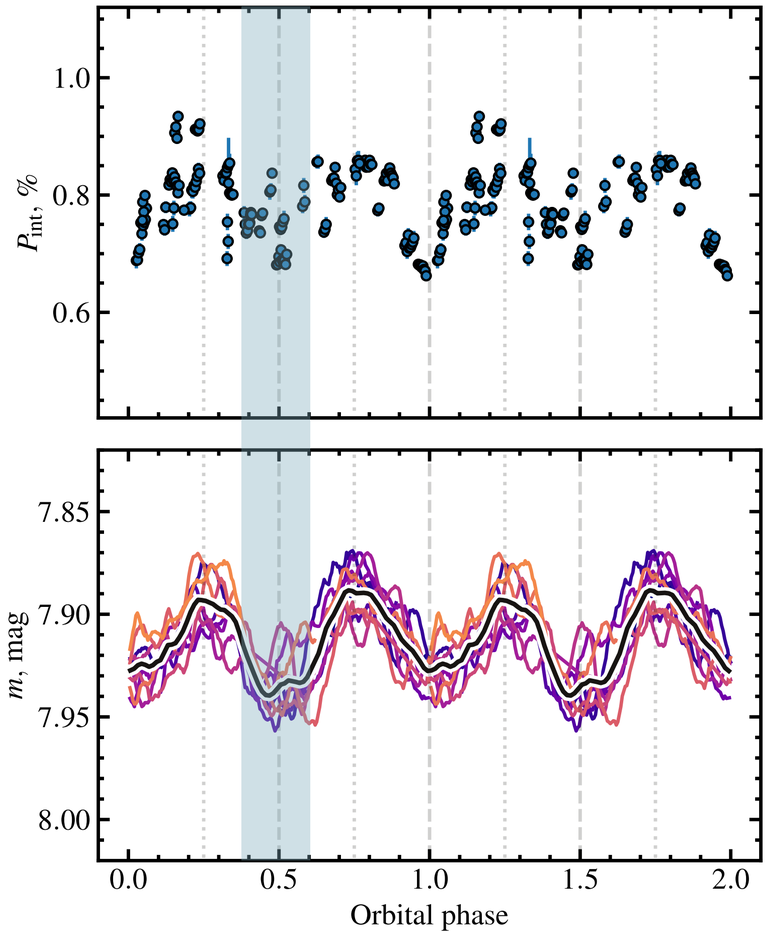

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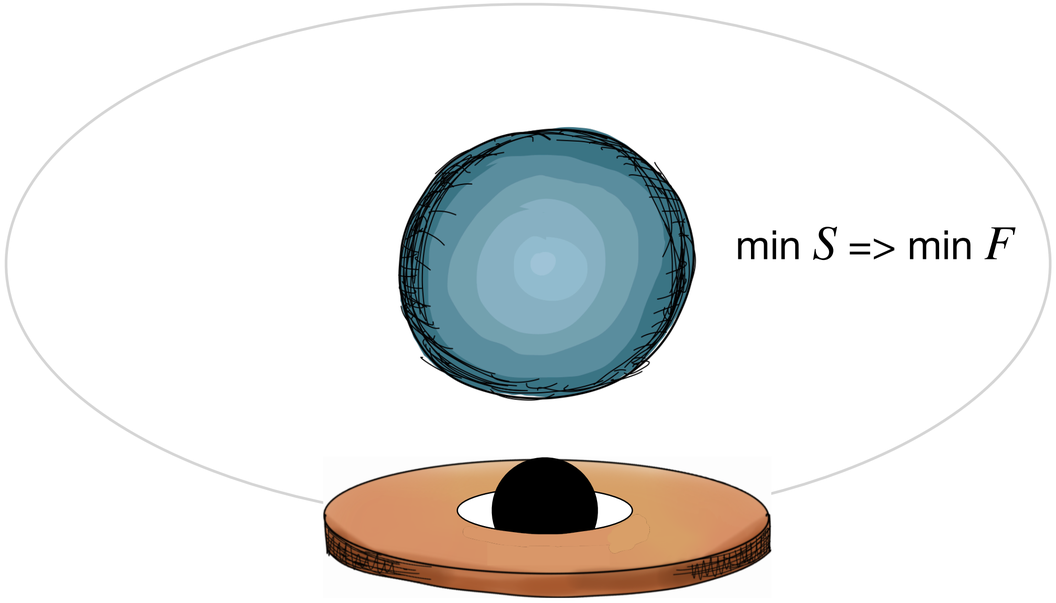

min S => min F

min/max θ $\iff$ min P

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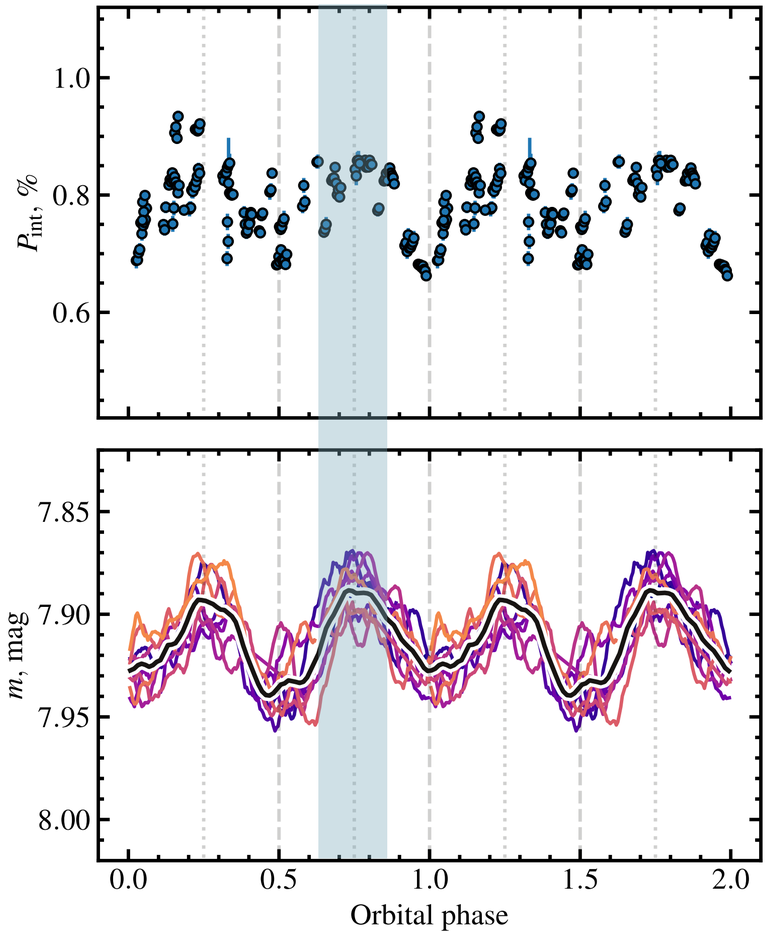

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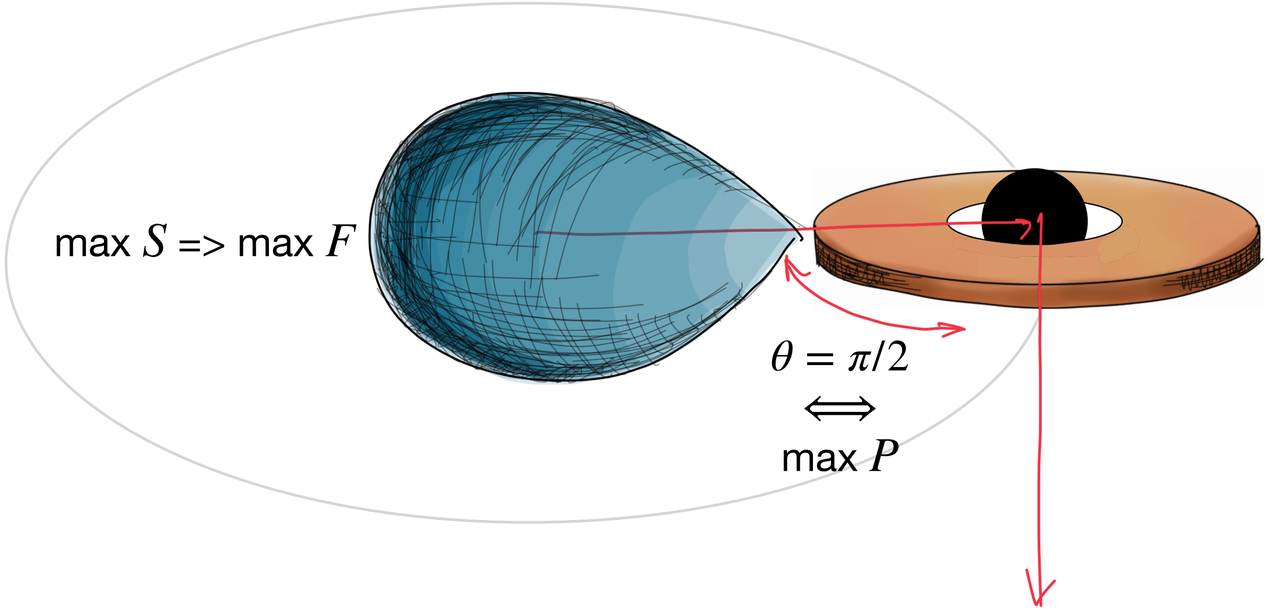

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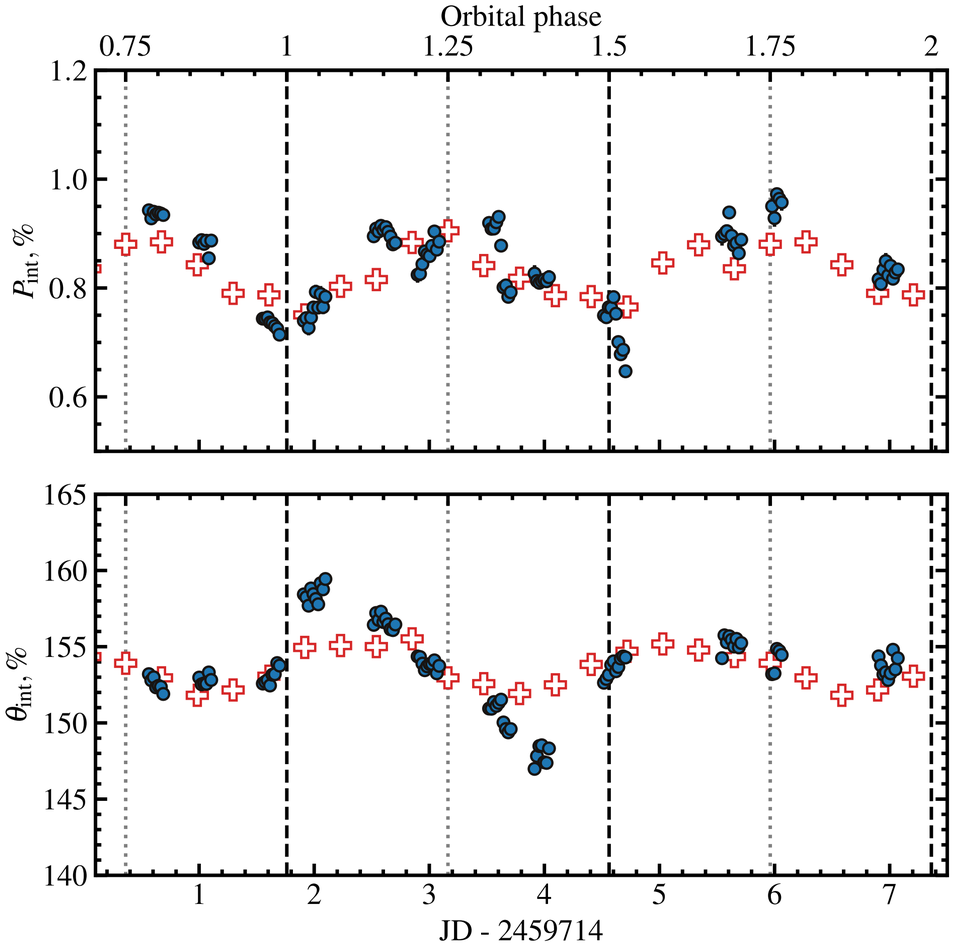

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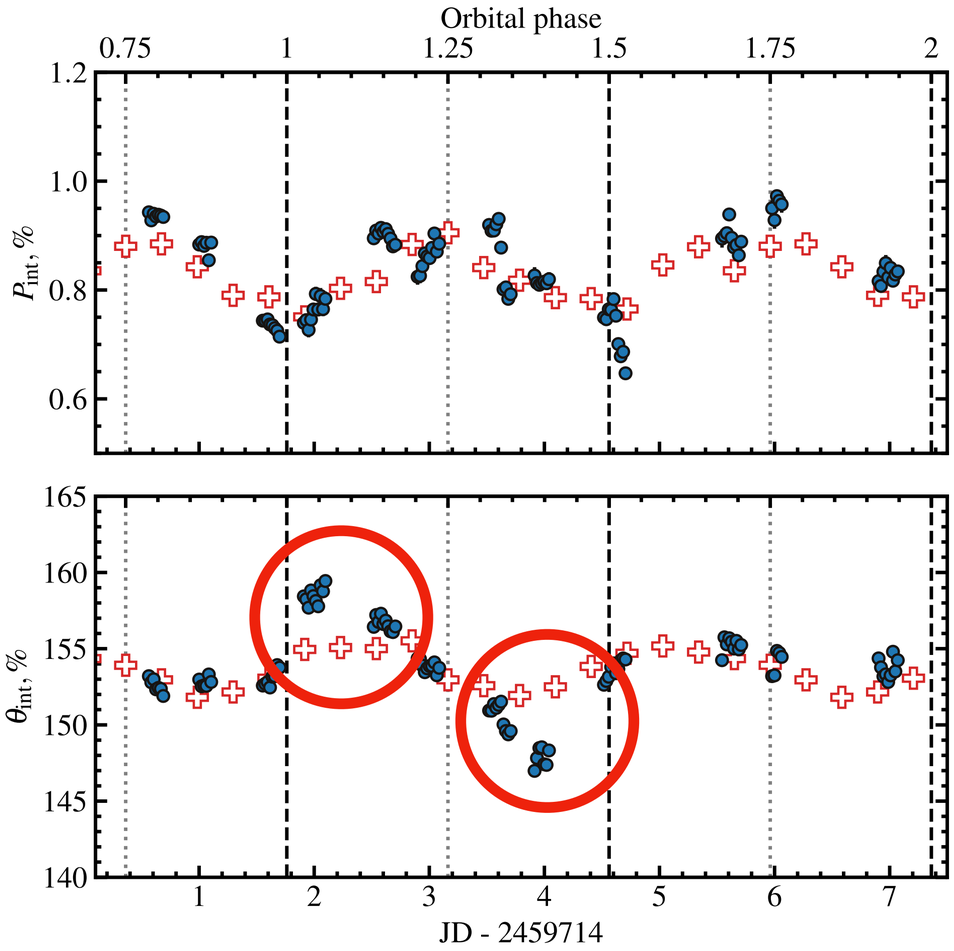

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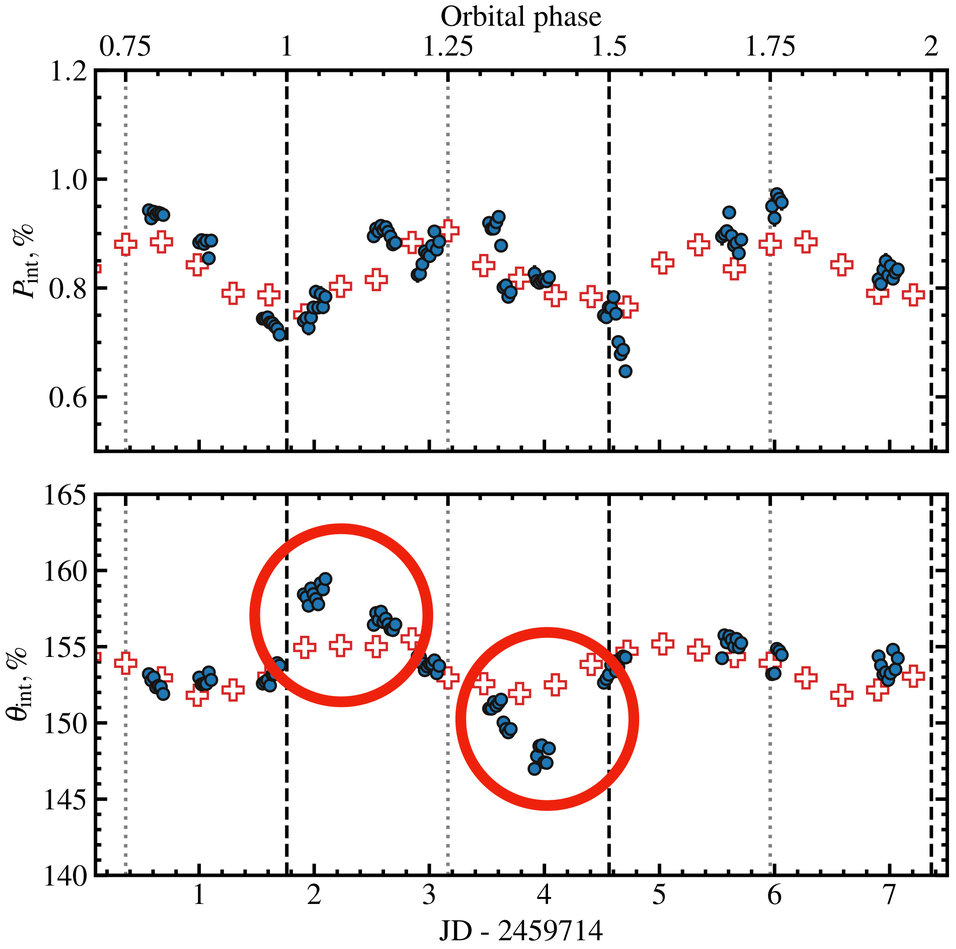
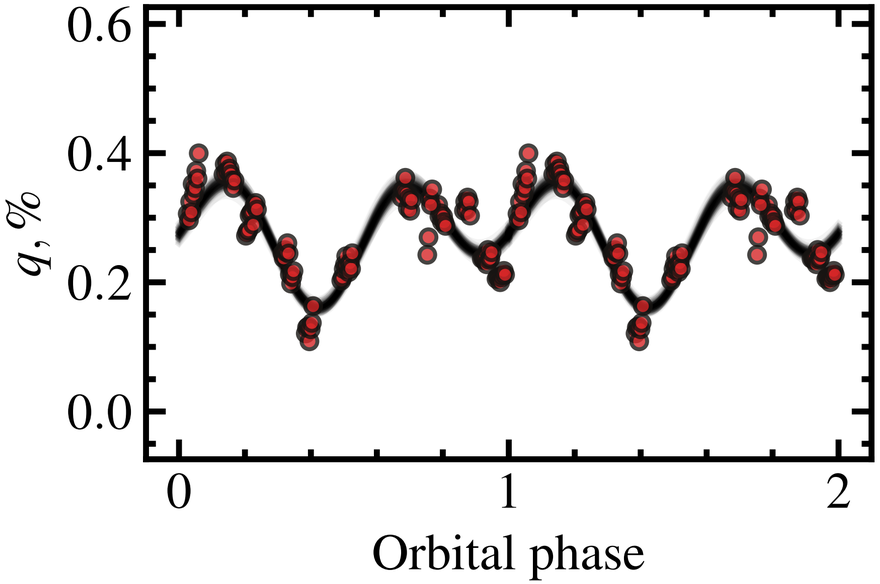
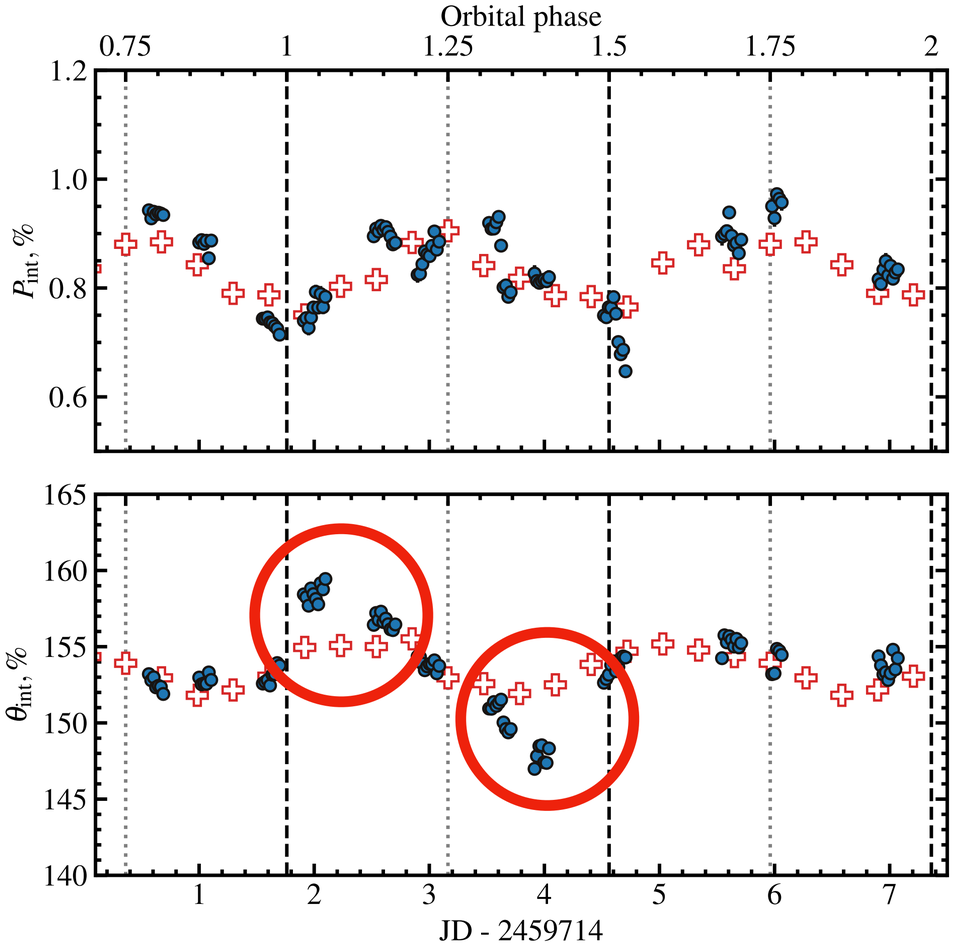
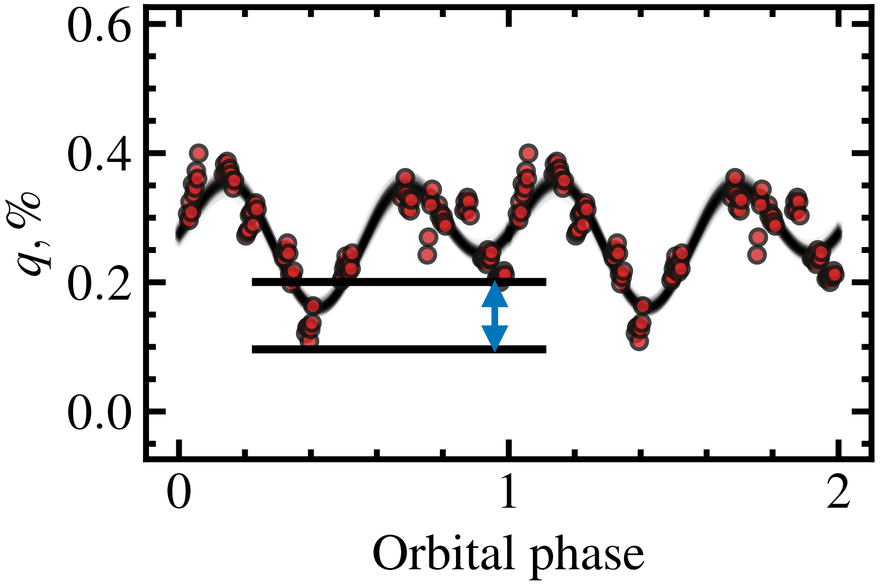




Results

Best single orbit coverage to date





Results

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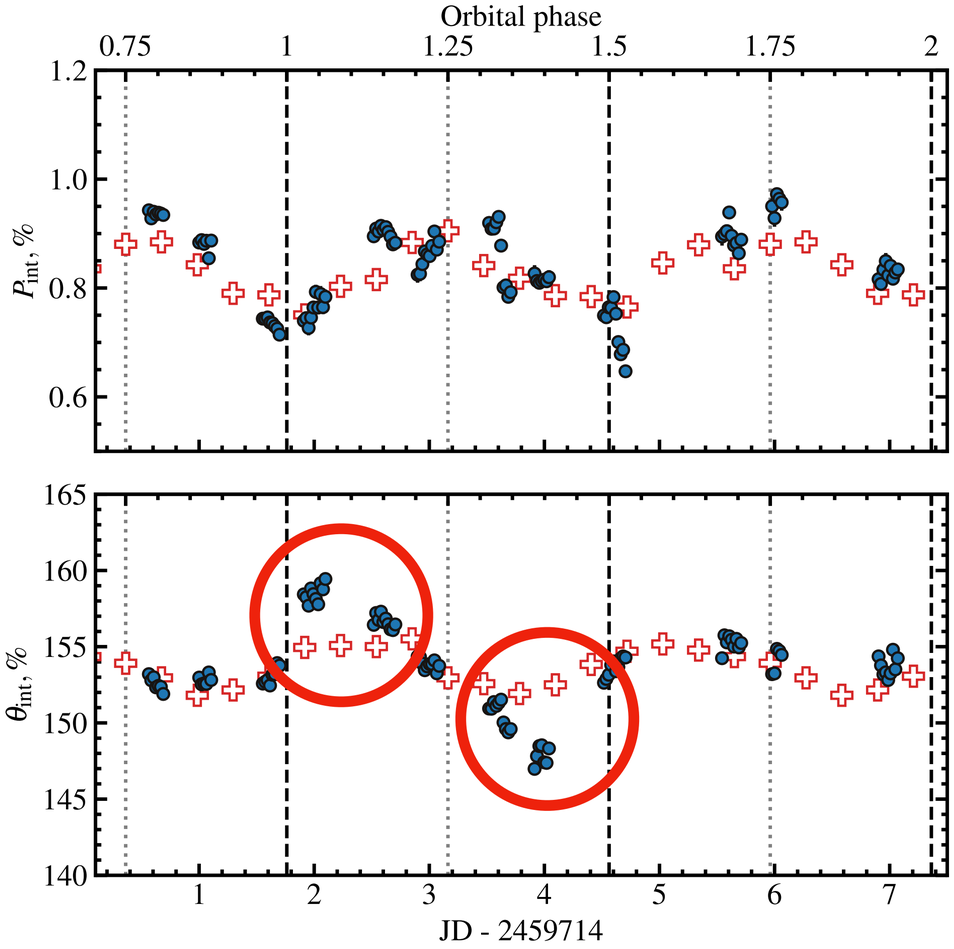
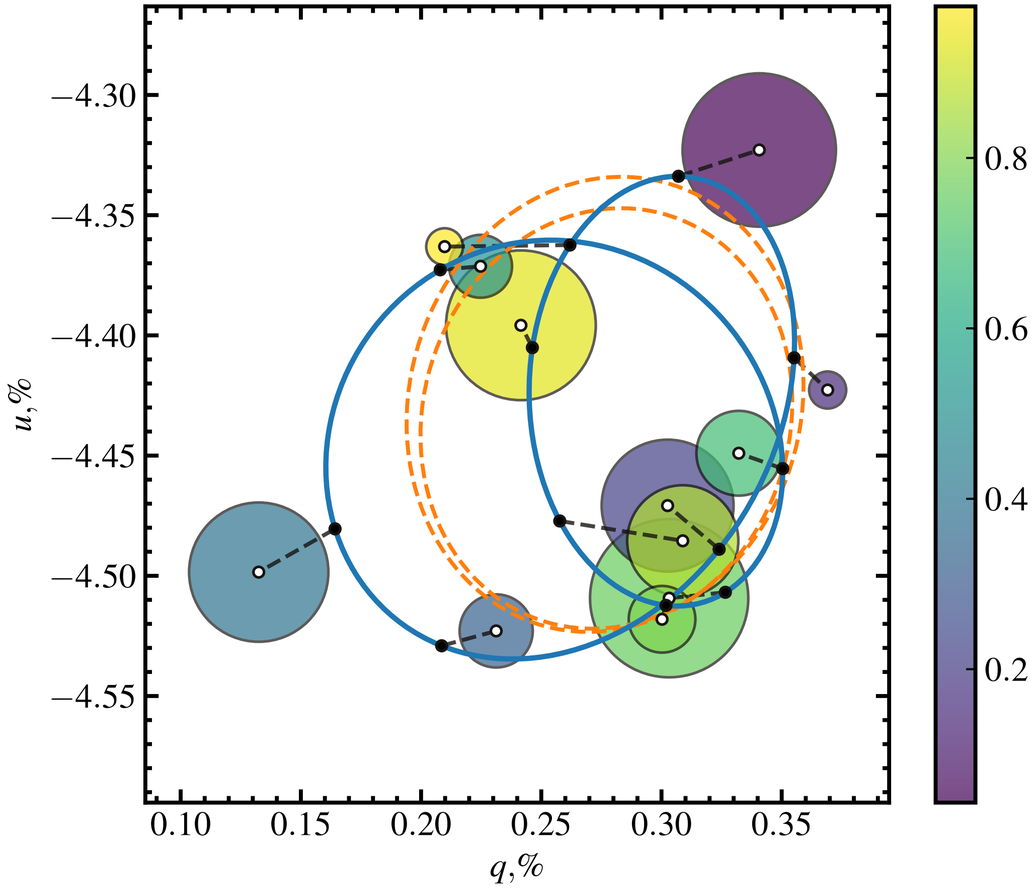
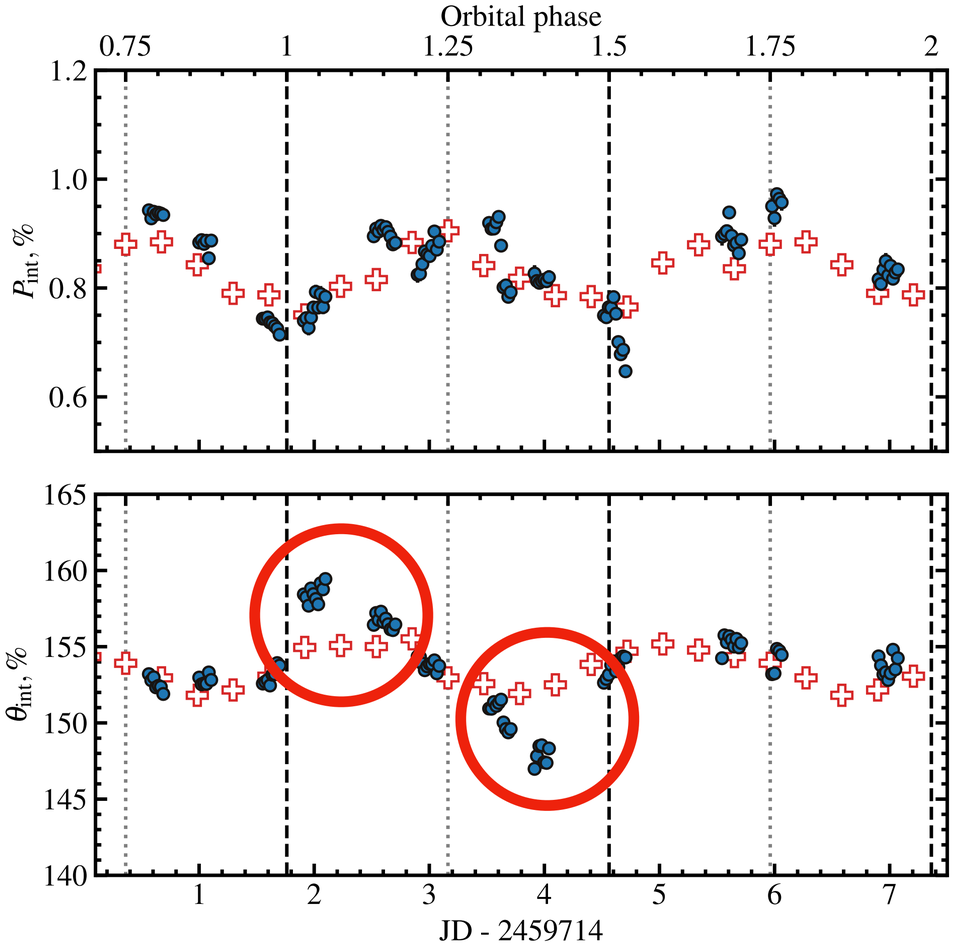
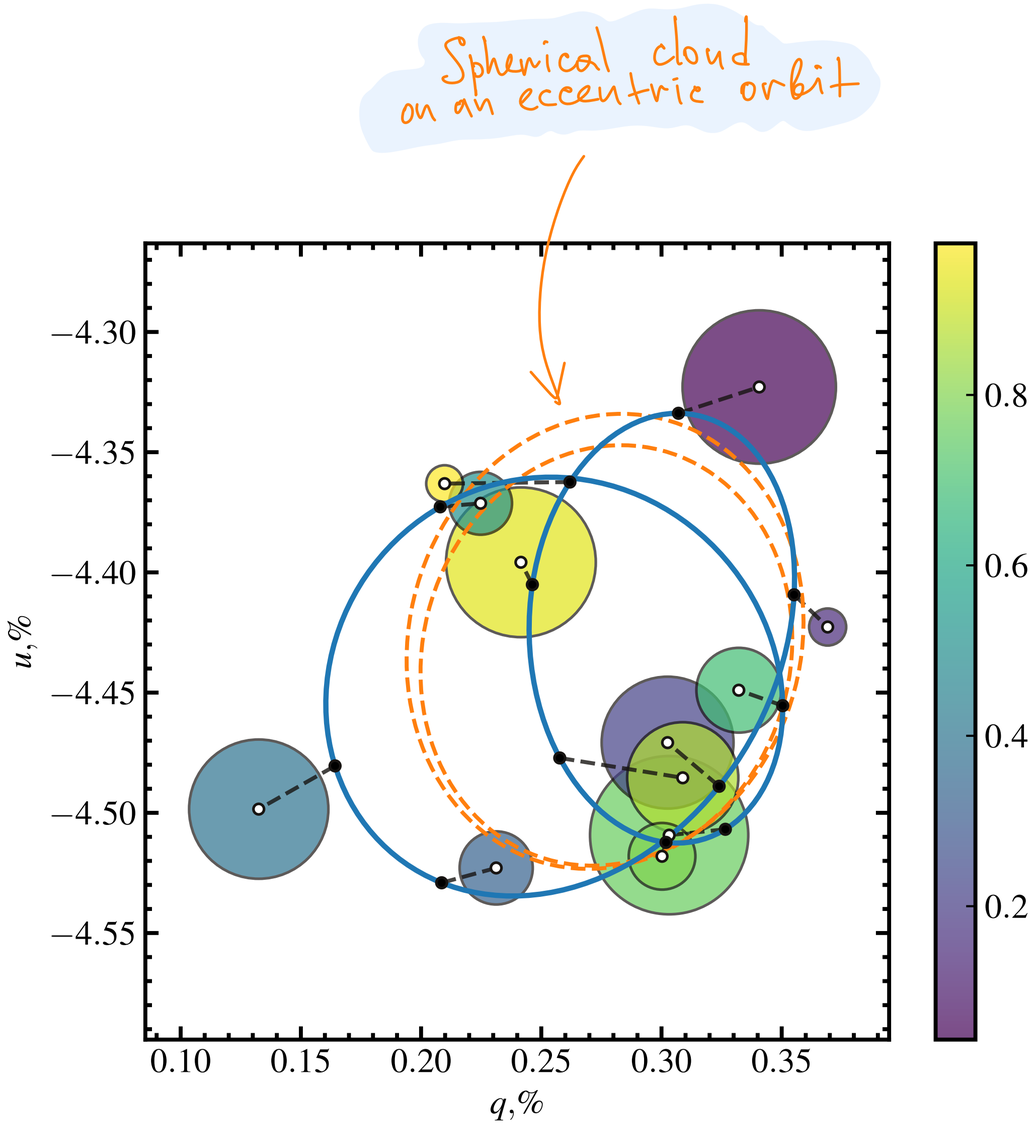




Results

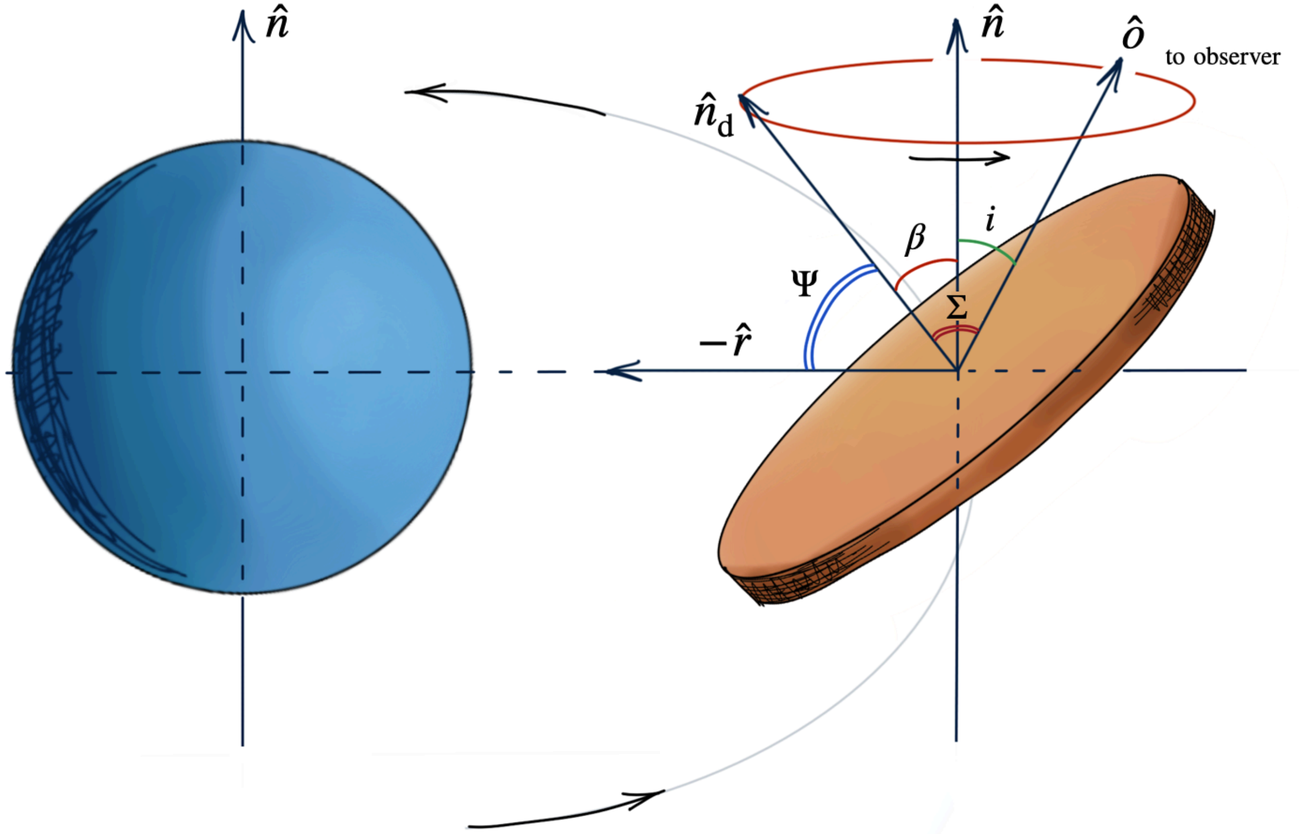
Best single orbit coverage to date

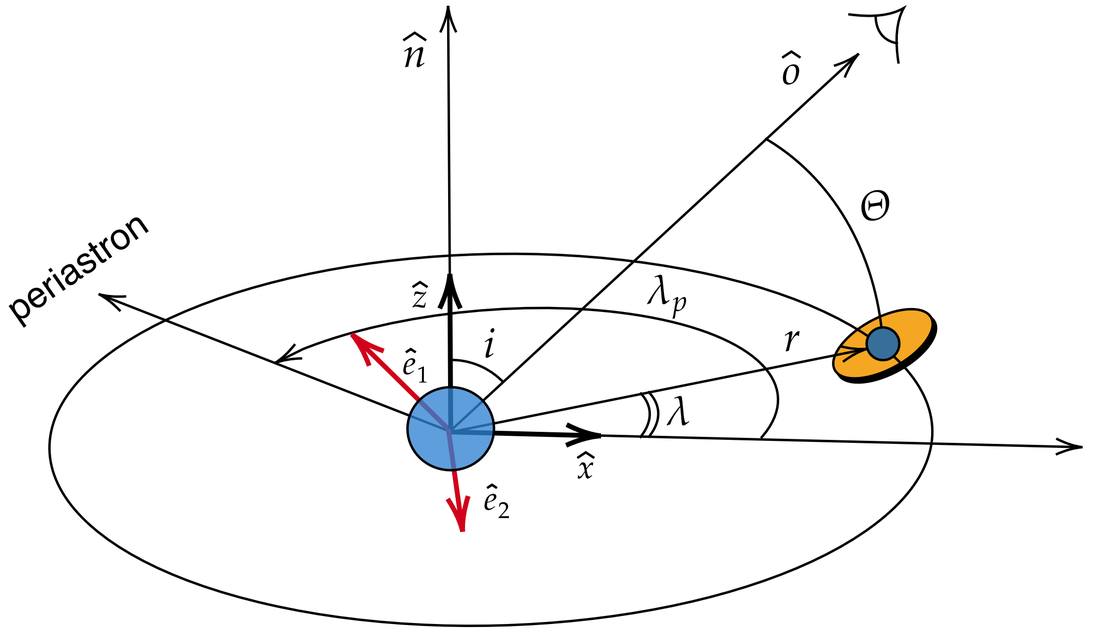




Results

Model of Thomson scattering off tilted accretion disk

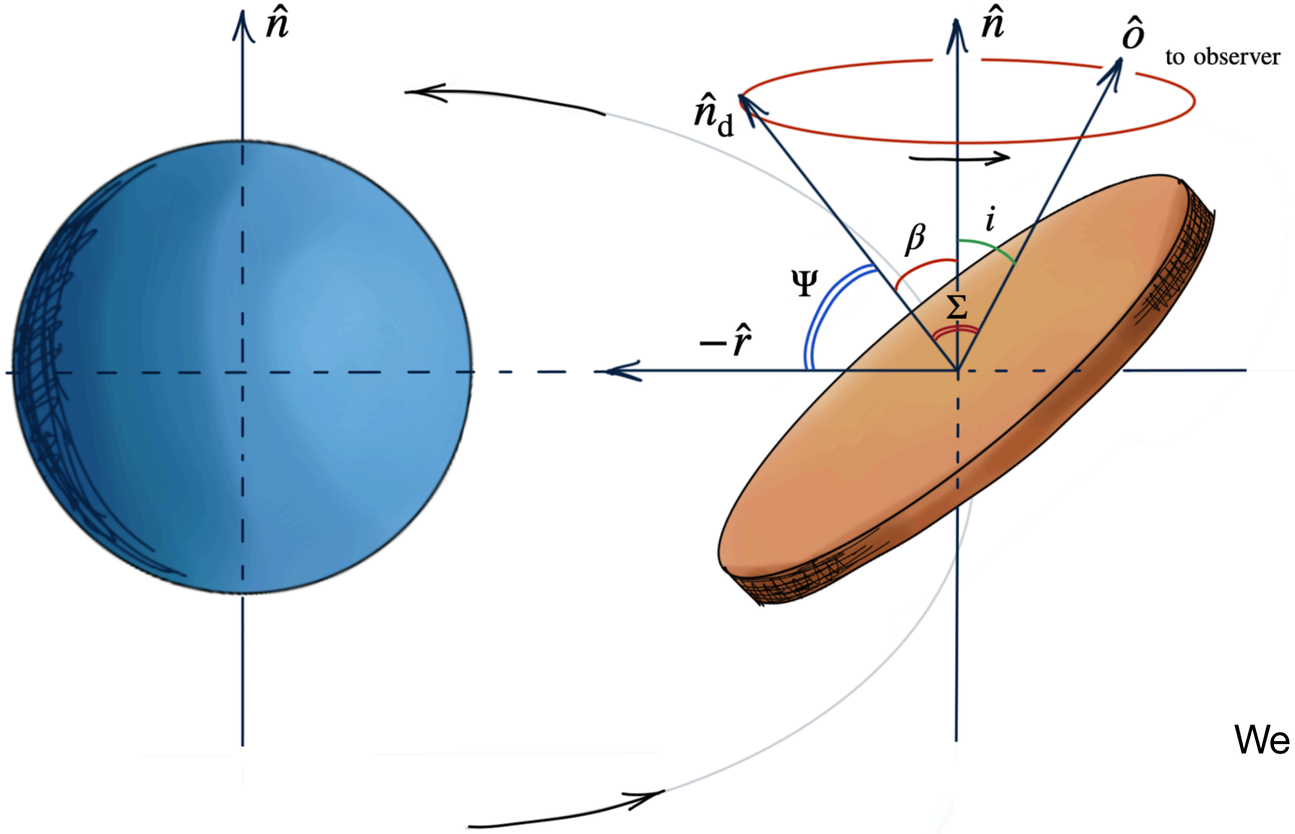


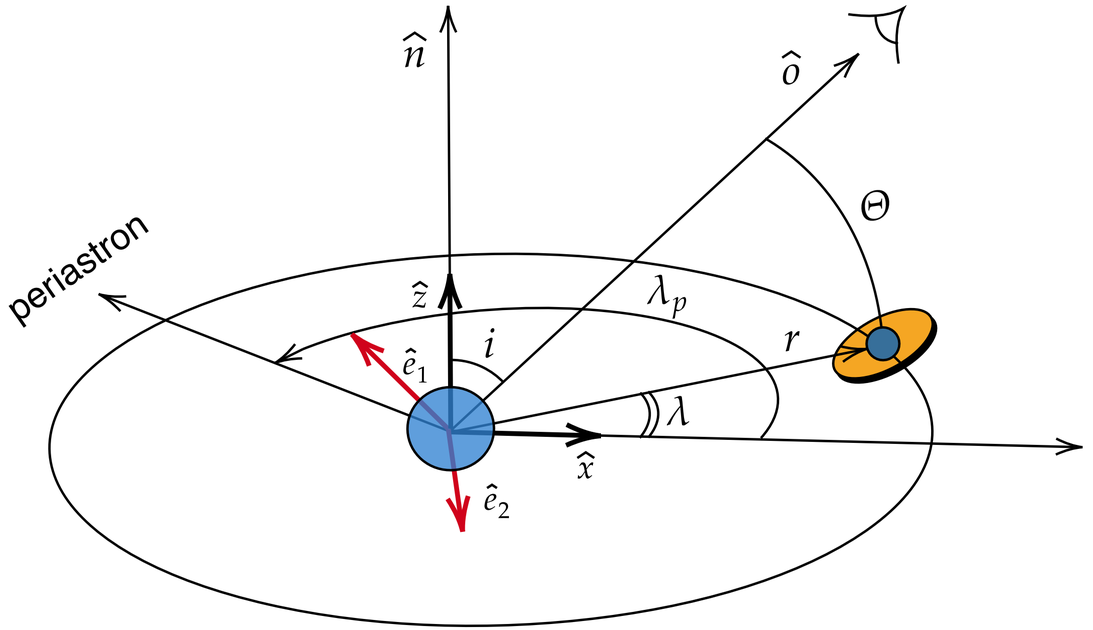


$$(q, u) = f(\phi, e, i, \Omega, \ldots, \beta)$$

Results

Model of Thomson scattering off tilted accretion disk



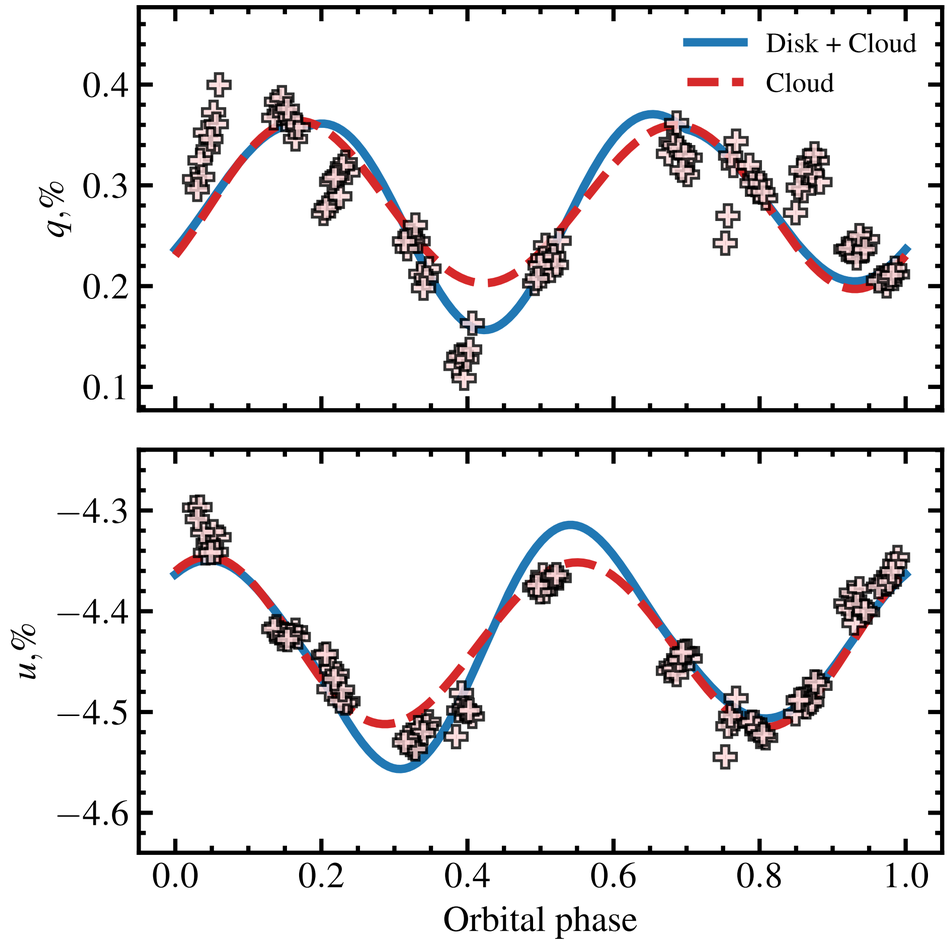


$$(q, u) = f(\phi, e, i, \Omega, \ldots, \beta)$$

We put here the orbital parameters from *Miller-Jones et al., 2021* (e, i, Ω) and disk, inclined on $\beta = 15°$.

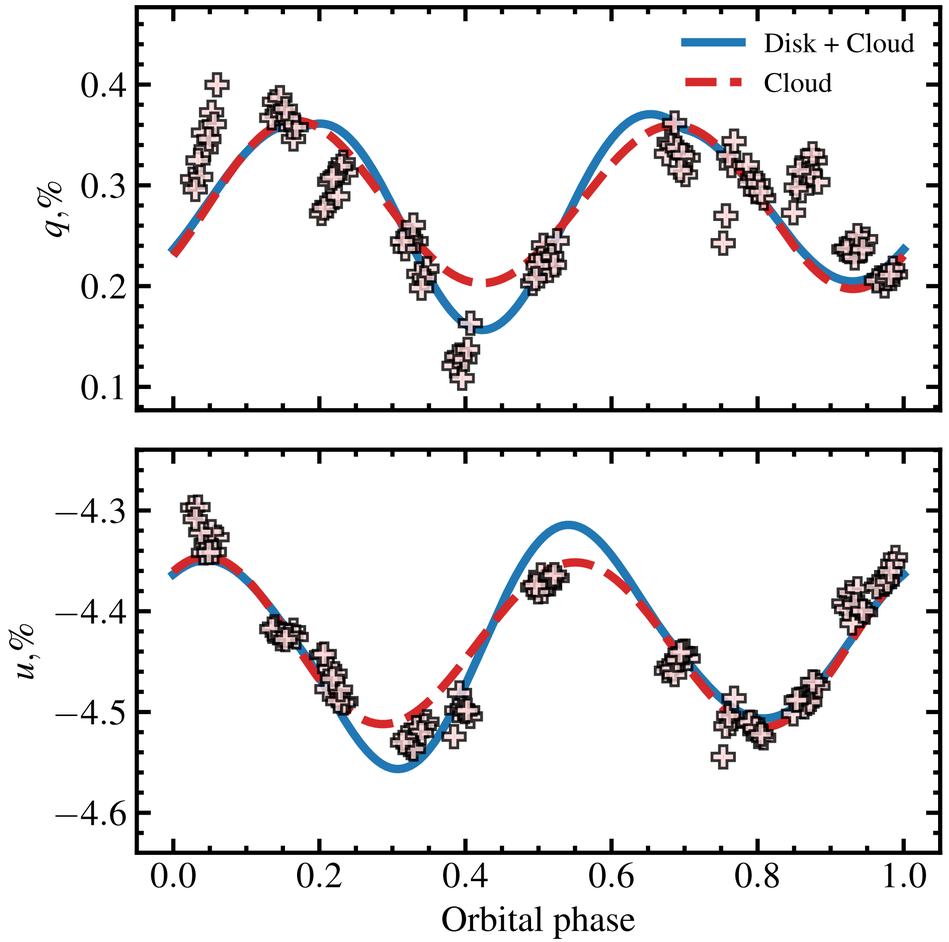
Results

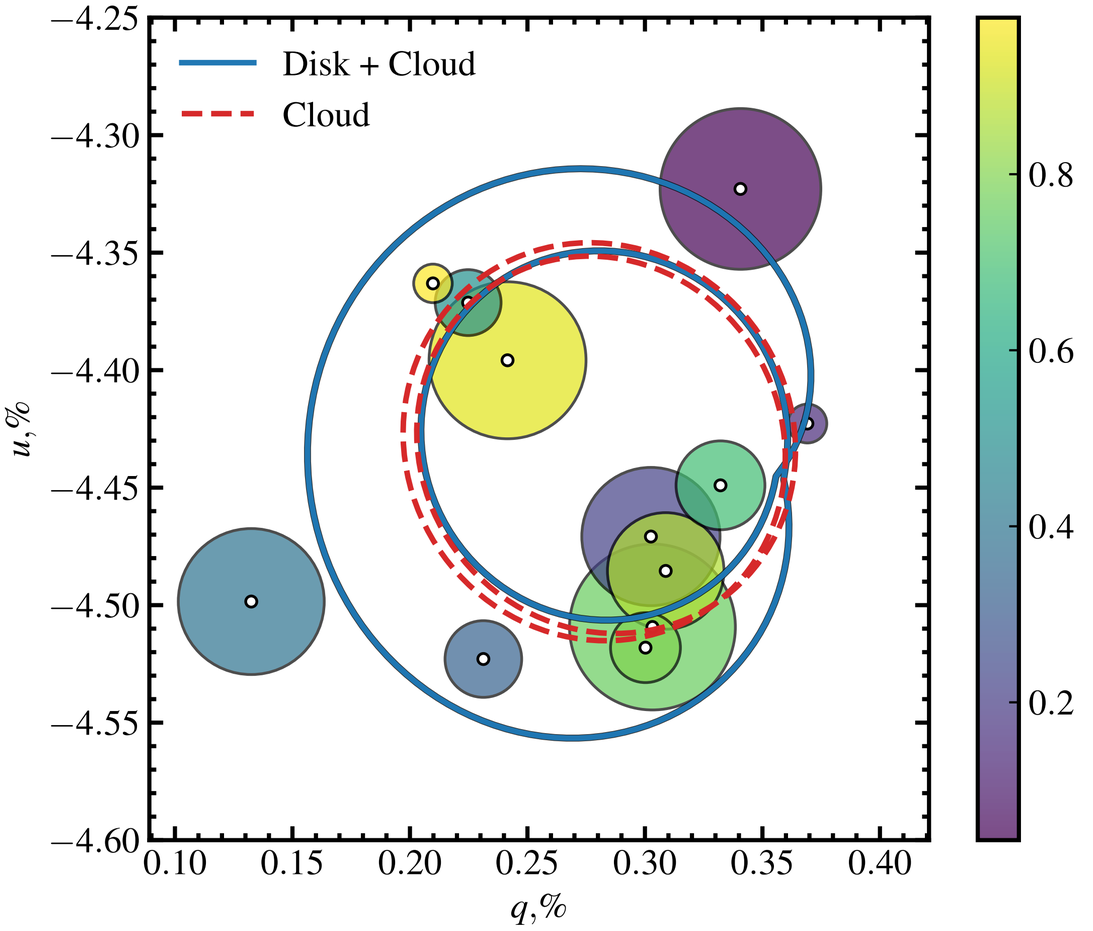
Model of Thomson scattering off tilted accretion disk



Results

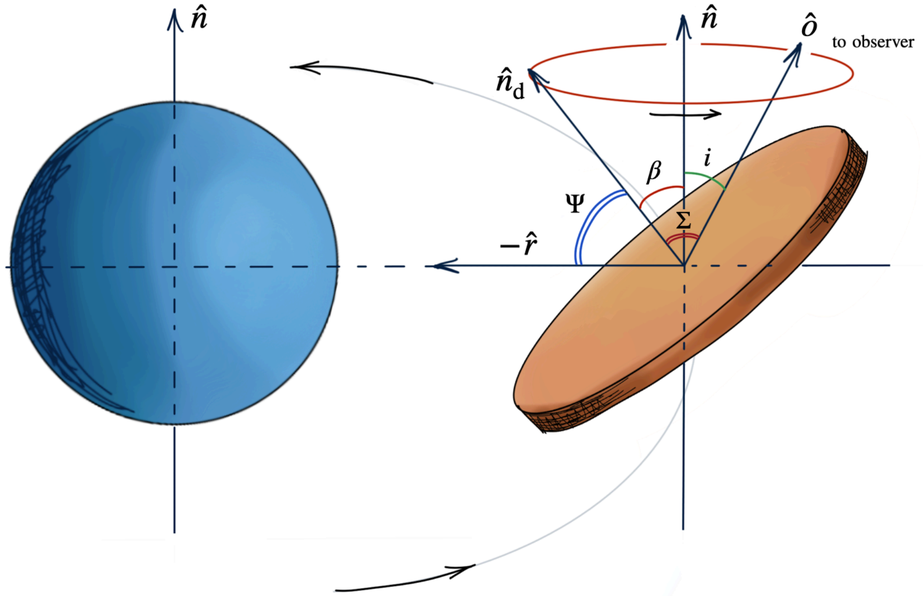
Model of Thomson scattering off tilted accretion disk





Summary

- We determined the **intrinsic polarization** of Cyg X-1.
- We performed high-precision optical polarimetry of Cyg X-1 with the **best single orbit coverage to date**.
- We constrained the **inclination** $i > 120^\circ$ and **eccentricity** $e < 0.08$ of Cyg X-1.
- We found the **asymmetry of the orbital profiles of Stokes parameters**, which implies the asymmetry of the scattering material about the orbital plane.
- We propose simple analytical model of Thomson **scattering of the tilted accretion disk** with $\beta \sim 15^\circ$ that can reproduce the data.

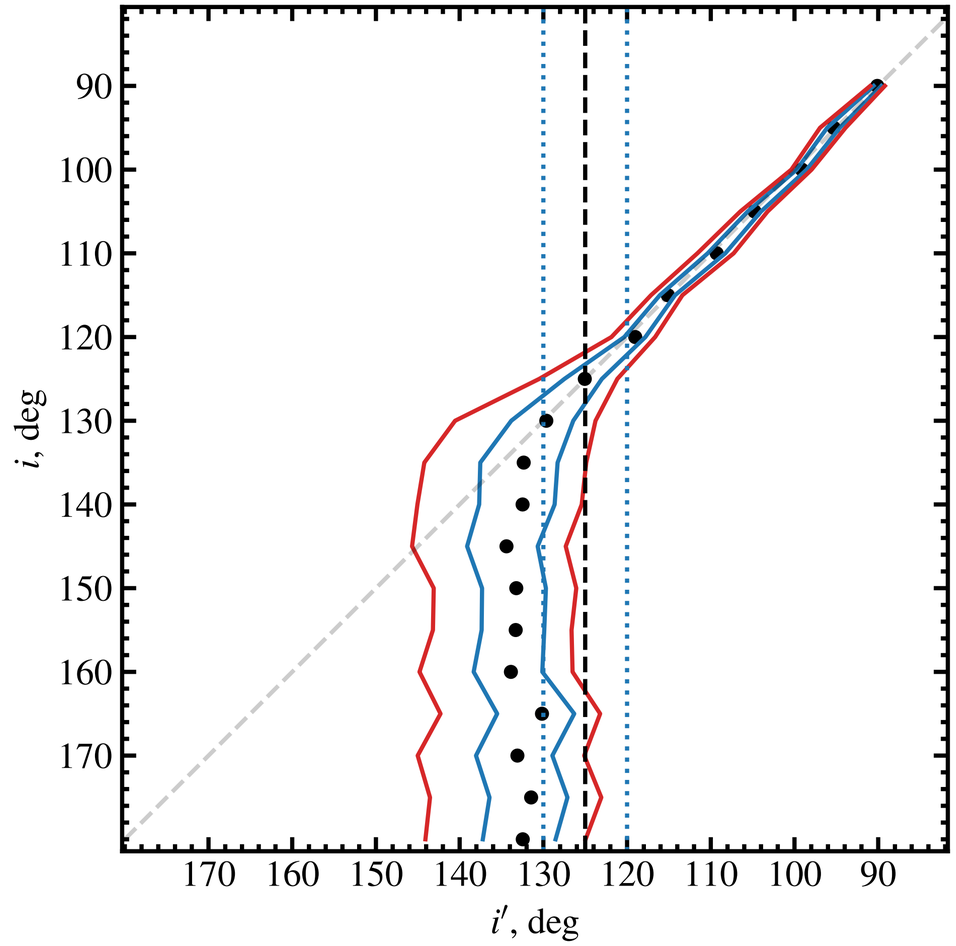


Thank you for your attention!

sites.google.com/view/**vakrav**

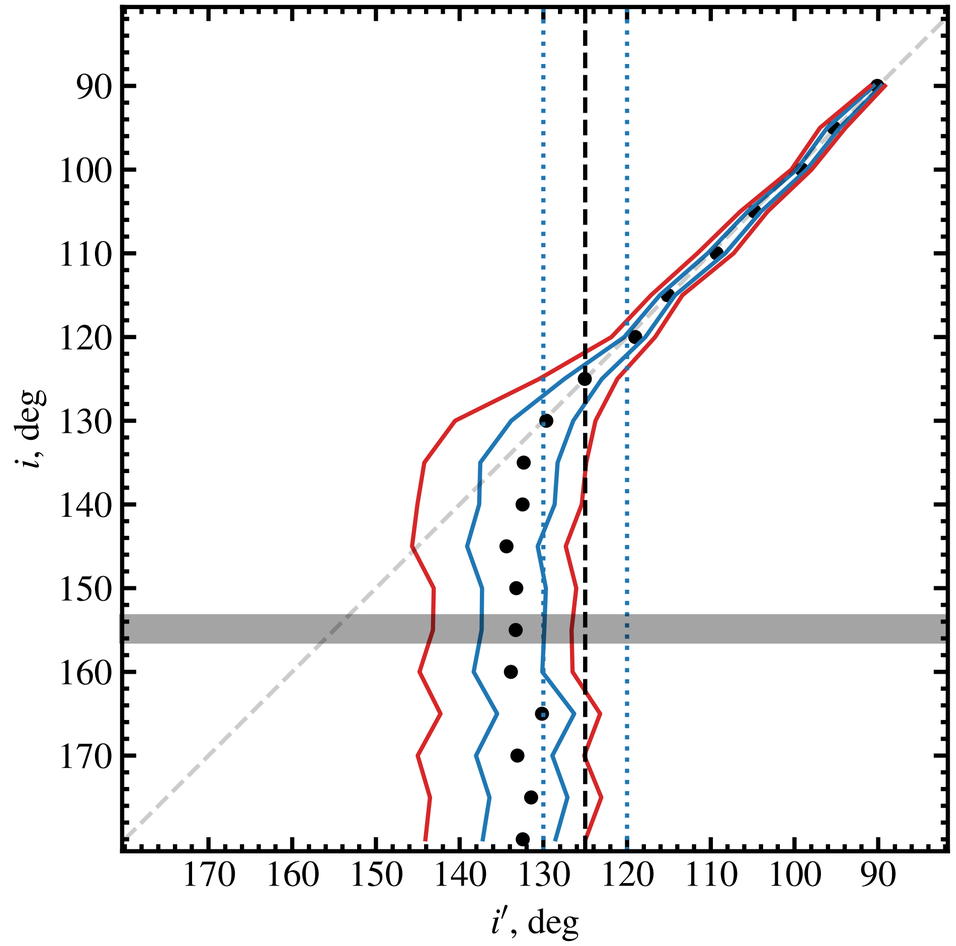
Results

Orbital parameters constraints



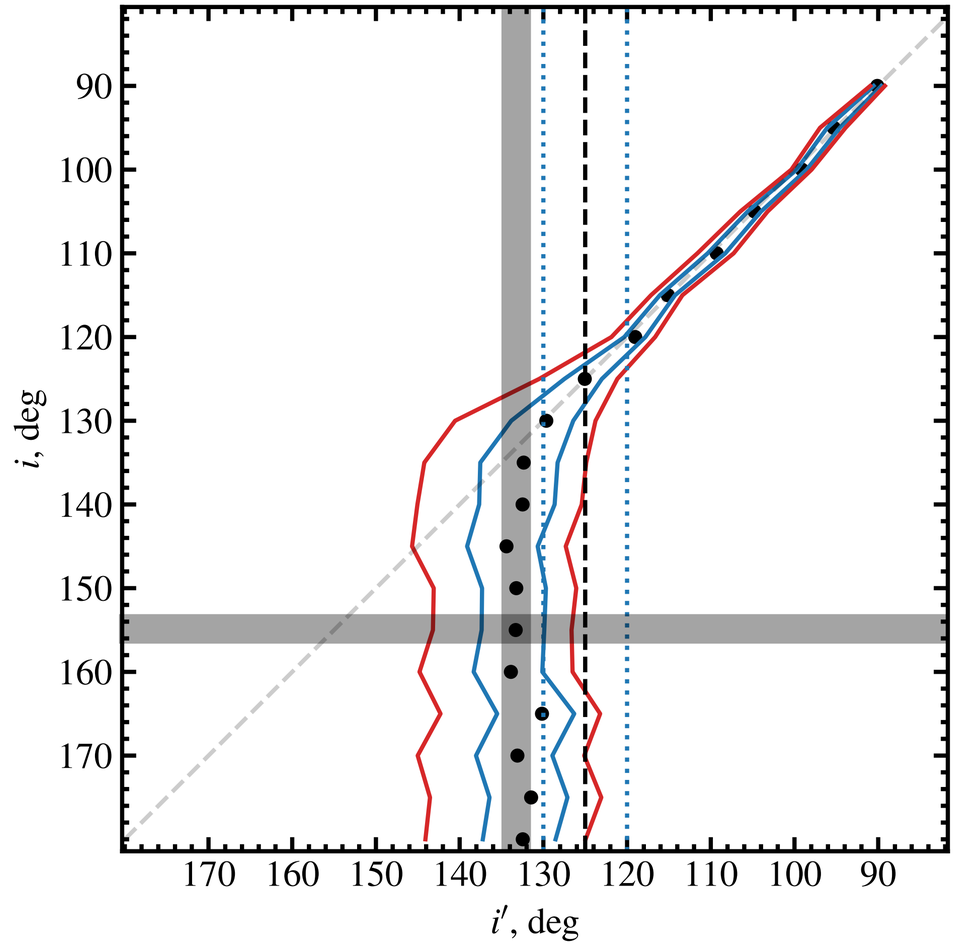
Results

Orbital parameters constraints



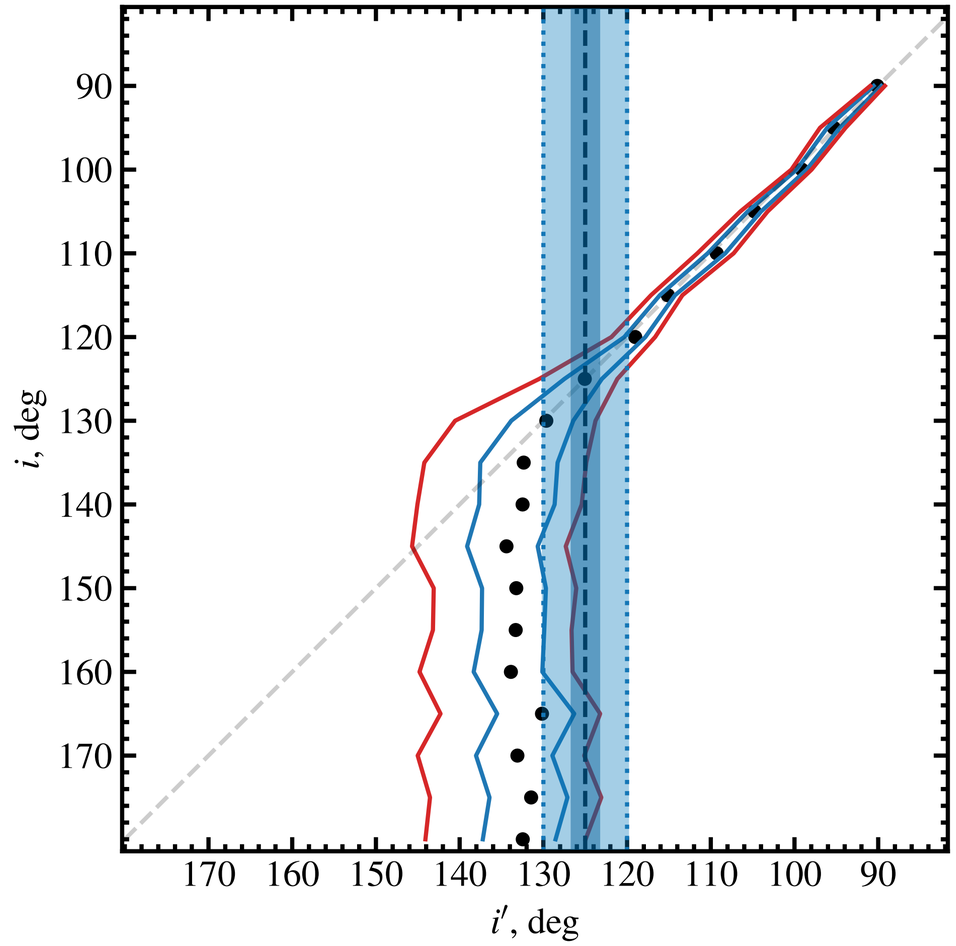
Results

Orbital parameters constraints



Results

Orbital parameters constraints



We constrained the **inclination** $i > 120^{\circ}$ and **eccentricity** $e < 0.08$ of Cyg X-1.

Results

Orbital parameters constraints