Probing the geometry of X-ray binaries with high-precision polarimetry

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Andrei Berdyugin
Andrzej Zdziarski
Juri Poutanen
and others....

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Hotel Scandic Vaasa
Vaasa, Finland
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UNIVERSITY OF TURKU

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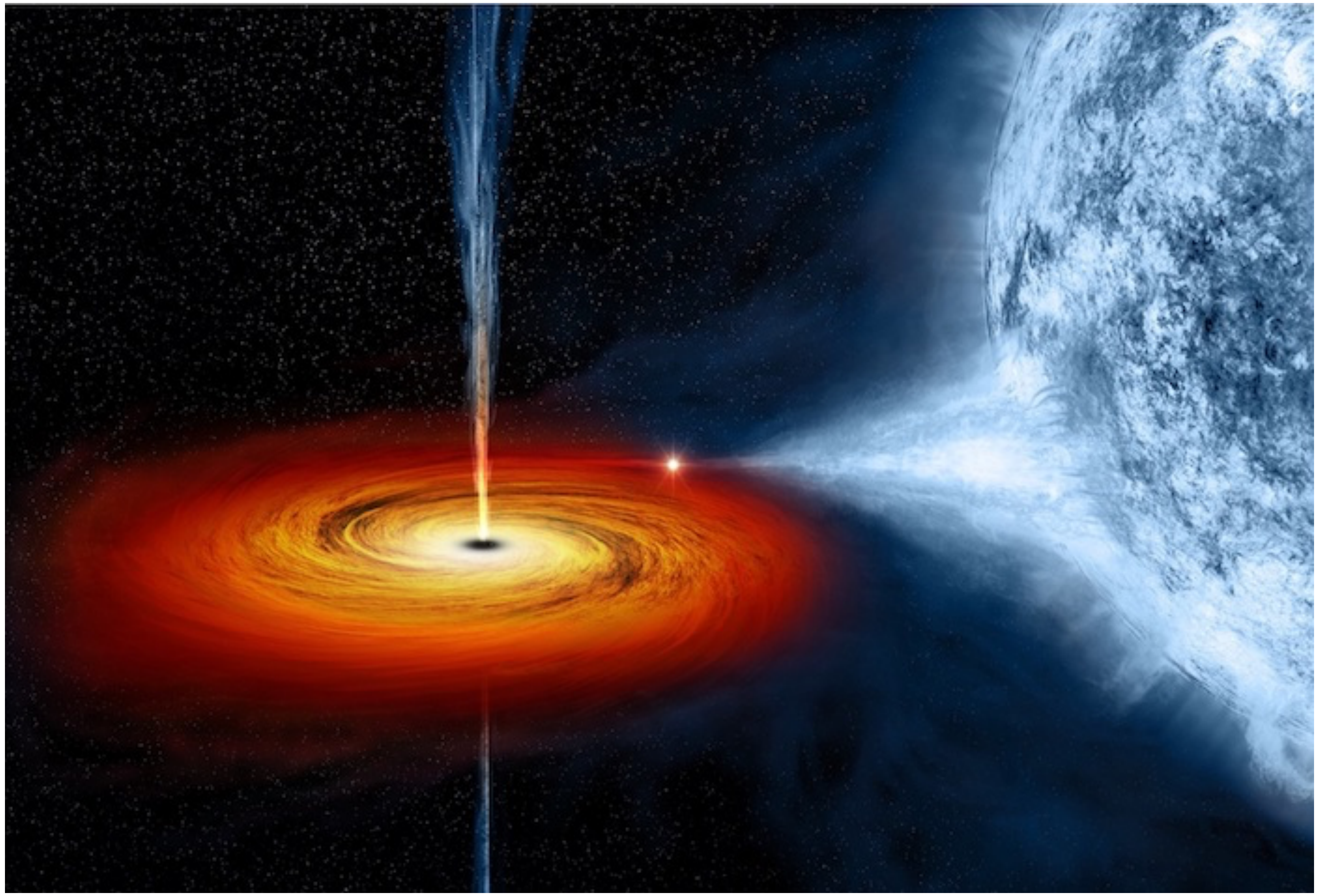
Introduction

Introduction

Definition of X-ray binary star



To be considered as an X-ray binary, a star must be:

- **a binary star**
- **luminous in X-rays**

The observed X-ray luminosity can be explained **only** if we assume that it is produced by the **most effective source of energy** – by accretion of matter onto the compact massive object.

$$\eta = \frac{E(m)}{mc^2}$$ – measure of efficiency

$$\eta_{\mathrm{nuc}} < 1\,\% \qquad \eta_{\mathrm{acc}} \sim 10\,\%$$

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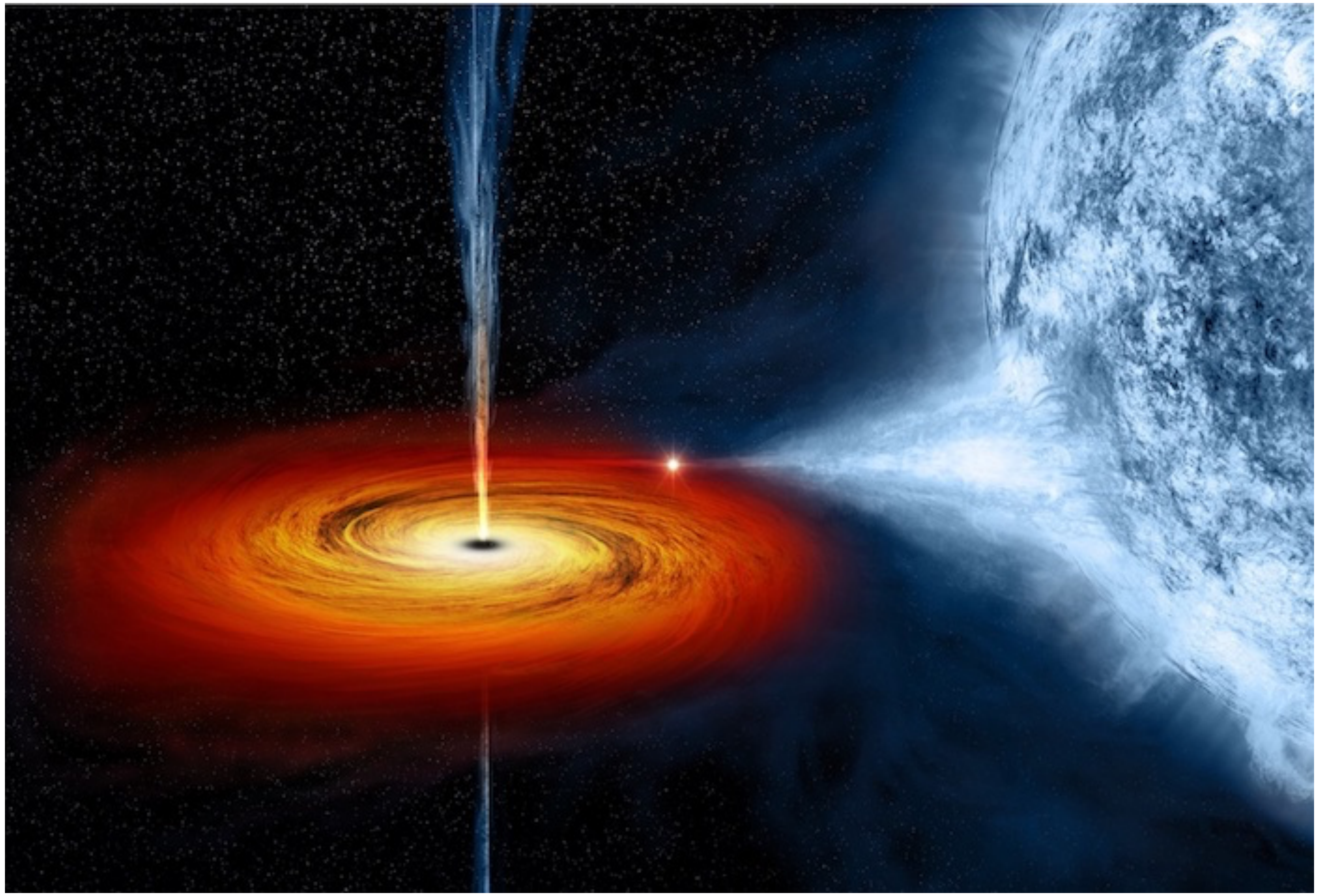


To produce X-rays via accretion, we should have:

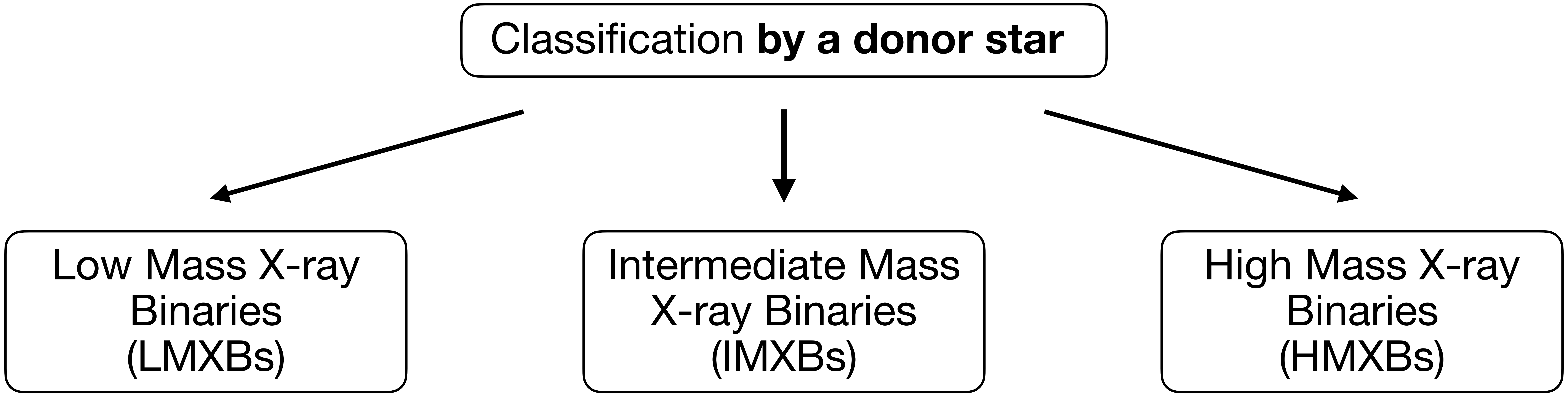
- **some matter to accrete**
- **the object on which the matter is accreted**

The matter is provided by a **donor star**.

The accretion is done by an **accretor**.

Introduction

Classification of X-ray binaries

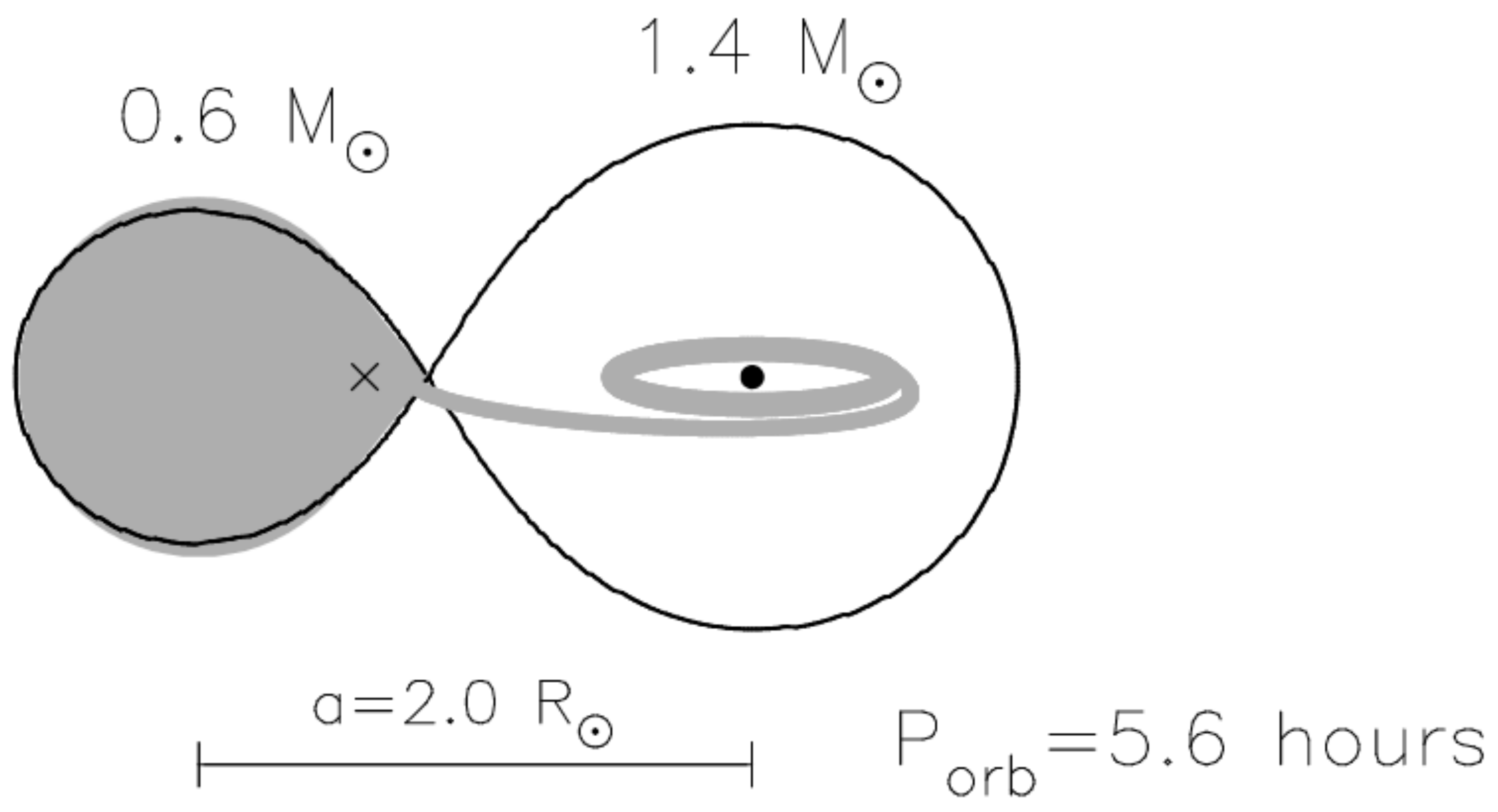


Introduction

Classification of X-ray binaries

Classification **by a donor star**

- Low Mass X-ray Binaries (LMXBs)
- Intermediate Mass X-ray Binaries (IMXBs)
- High Mass X-ray Binaries (HMXBs)



Introduction

Classification of X-ray binaries

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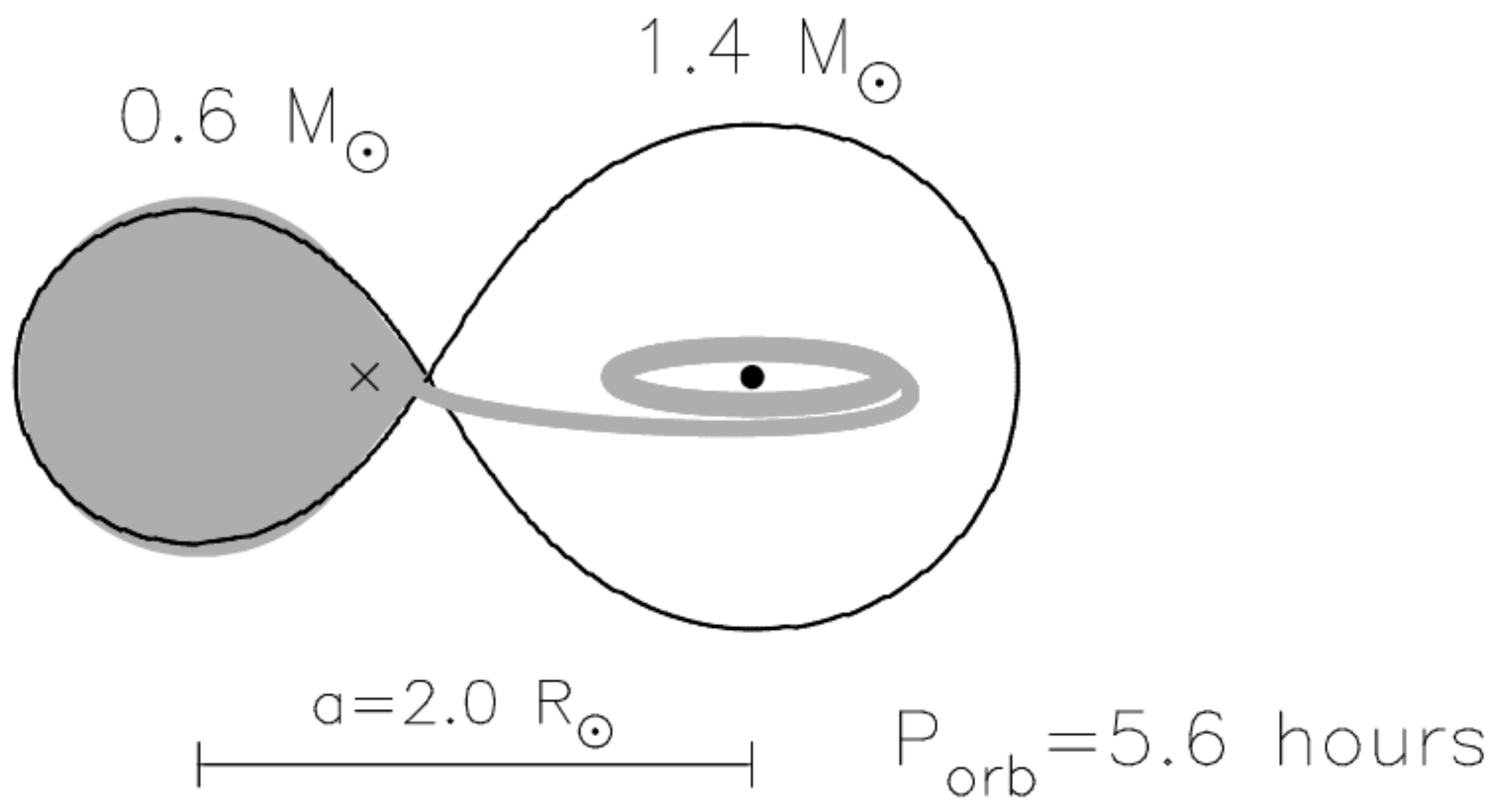

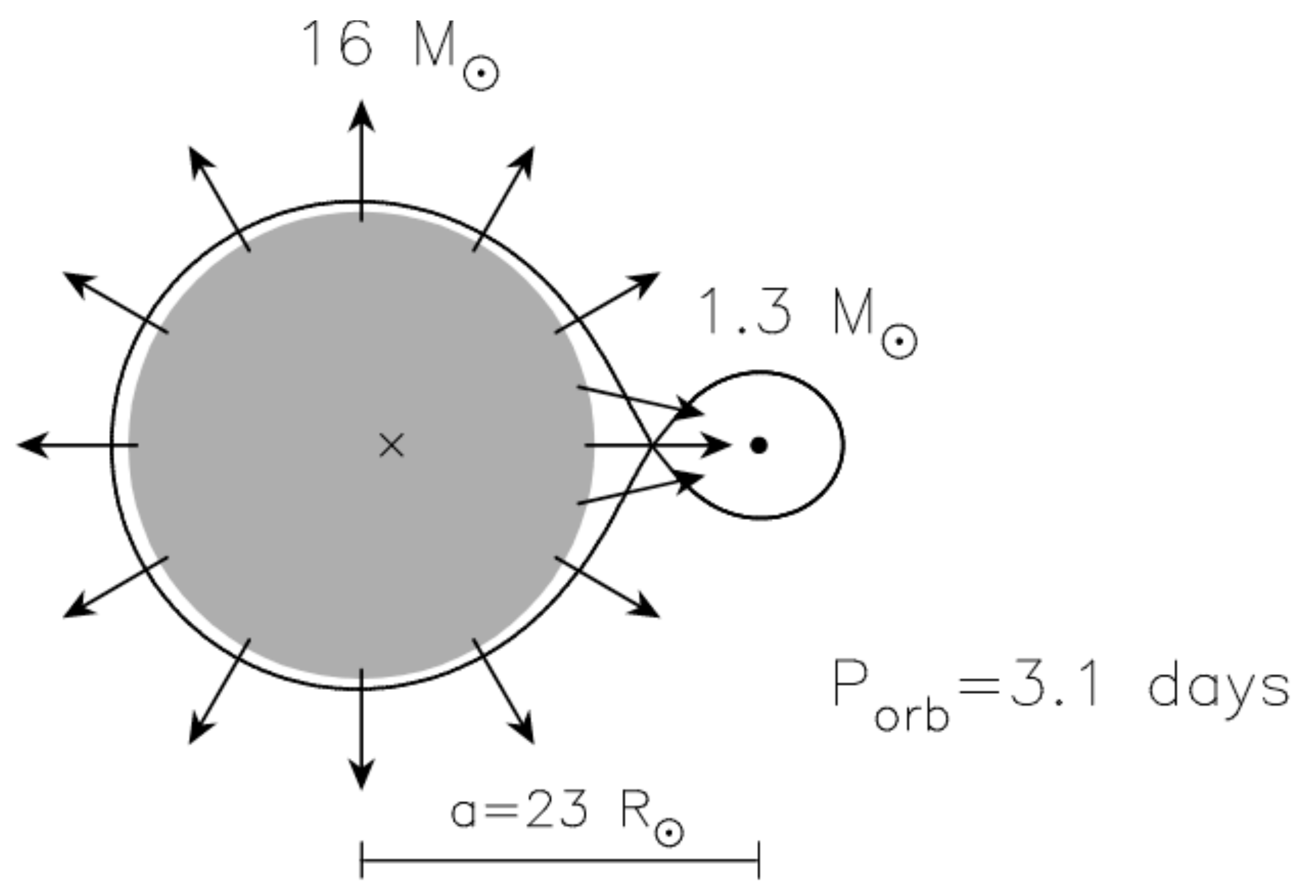

Introduction

Classification of X-ray binaries

Classification **by an accretor**

Neutron Star X-ray binary (NSXRBs)

Black Hole X-ray binary (BHXRBs)

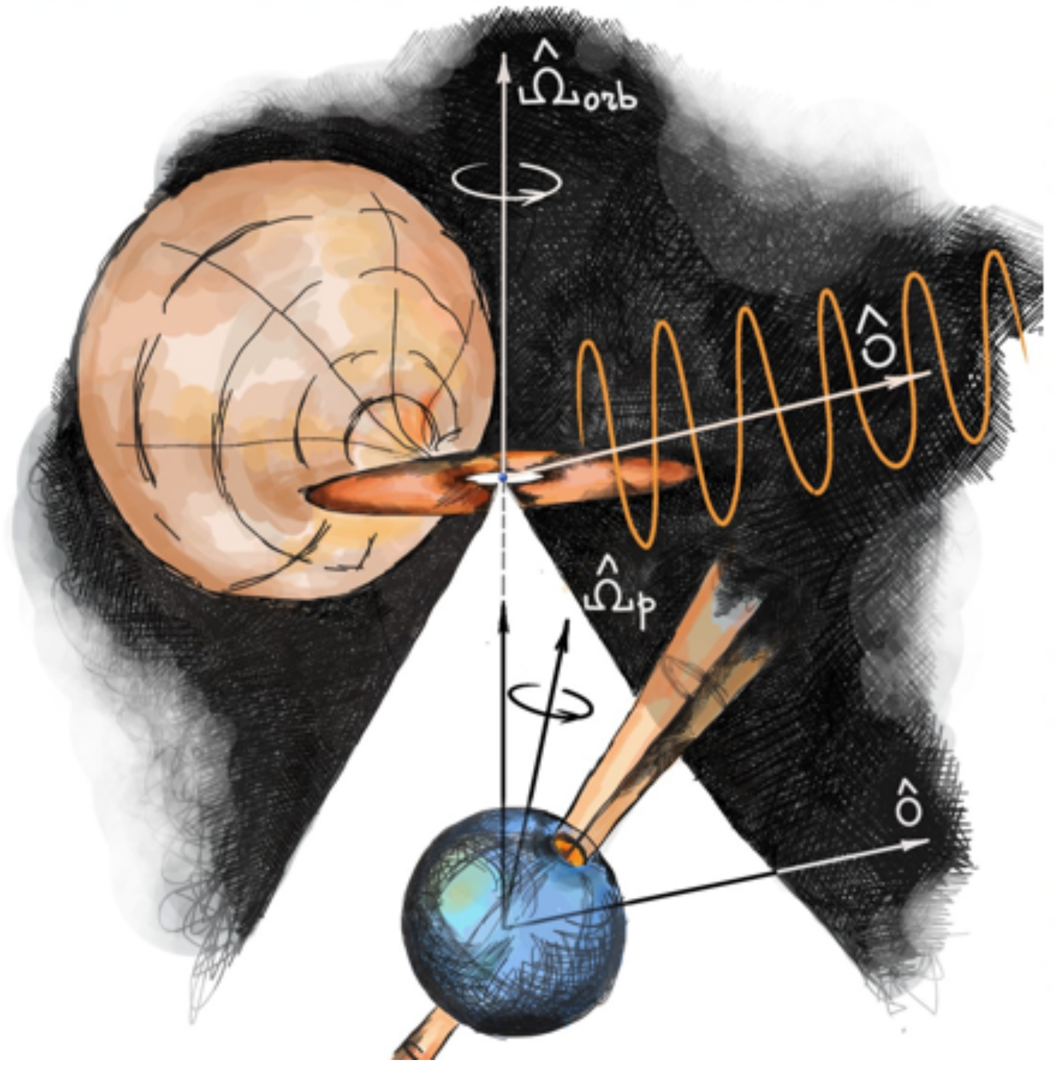

Image: Alexander Mushtukov

Introduction

Classification of X-ray binaries

Classification **by an accretor**

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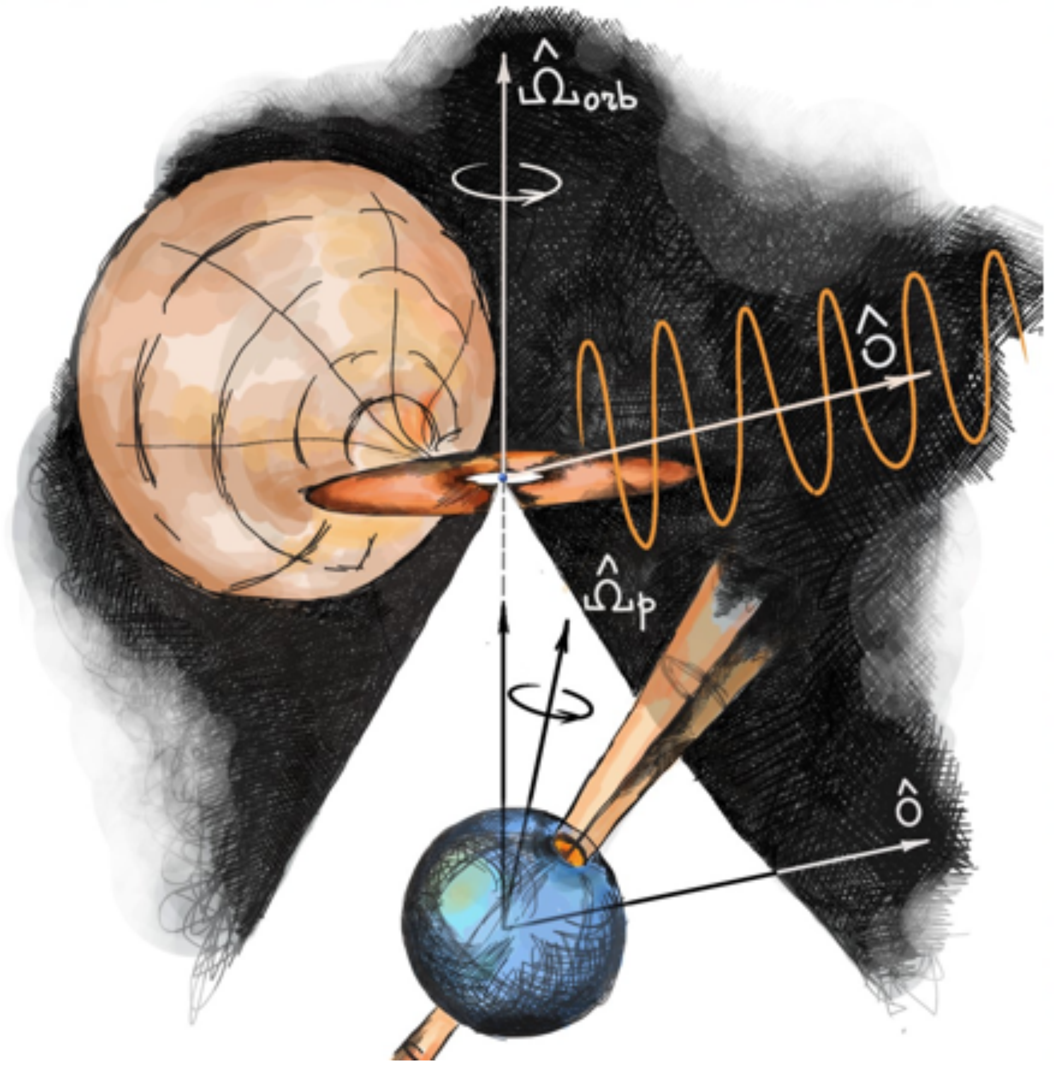
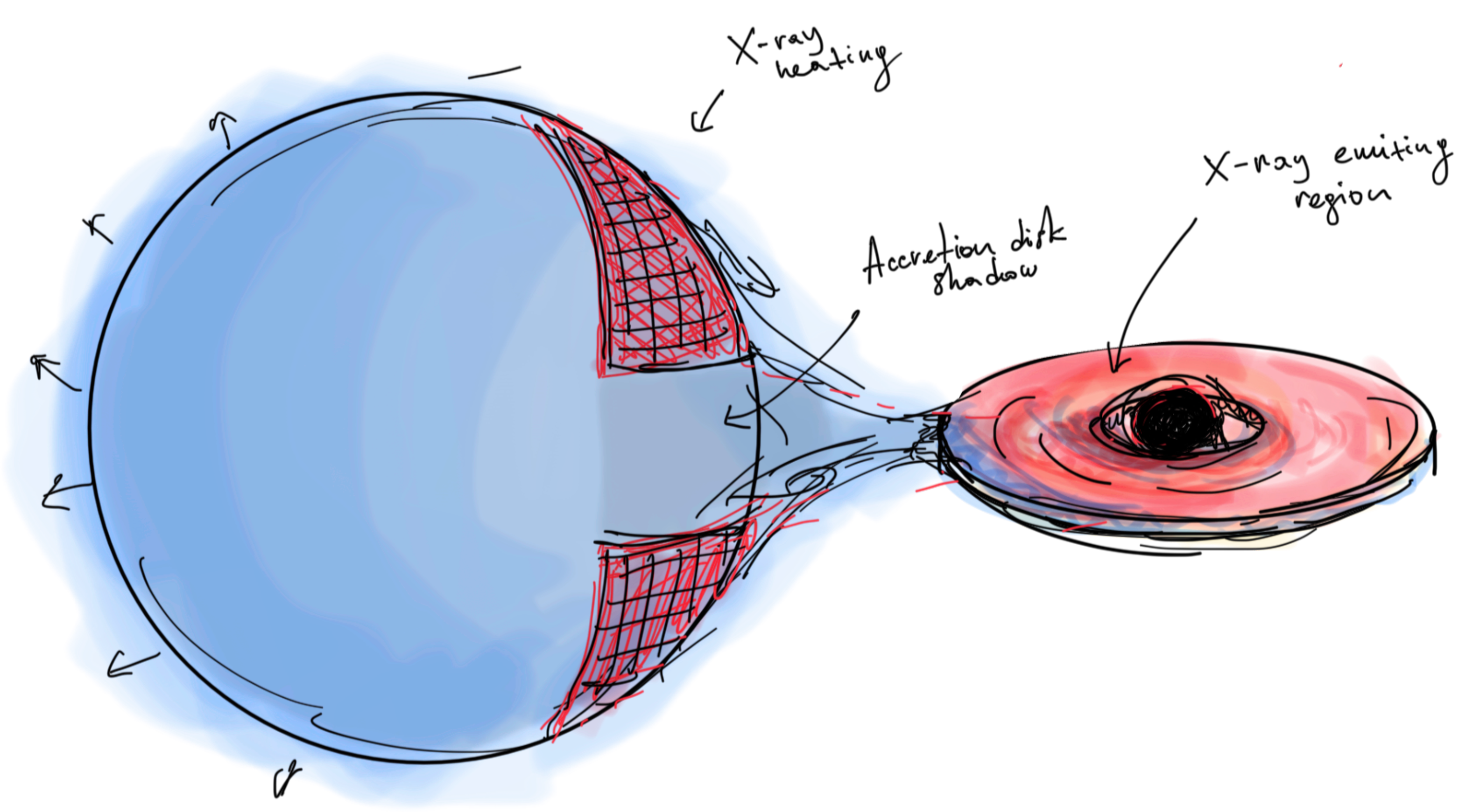
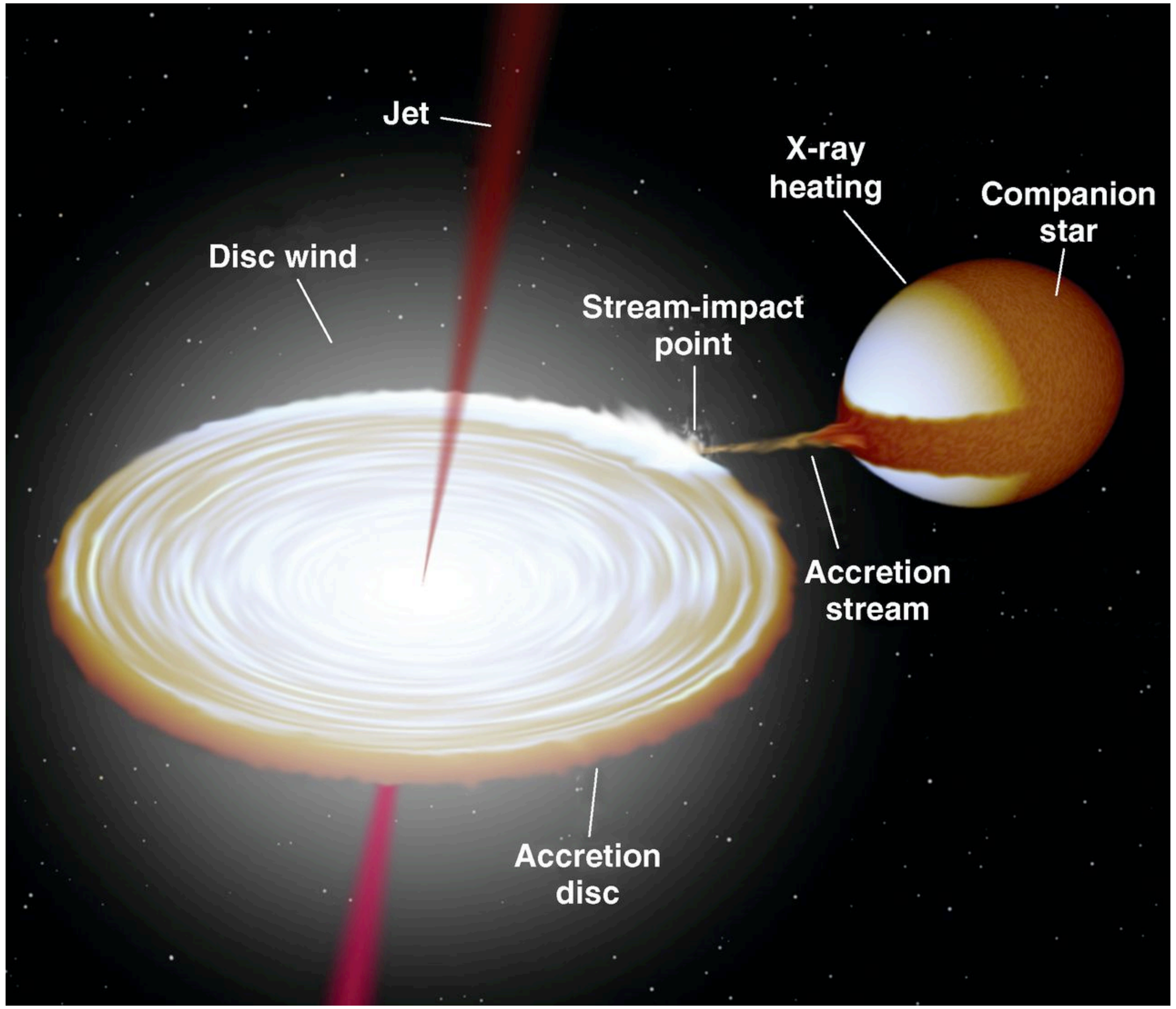


Image: Alexander Mushtukov



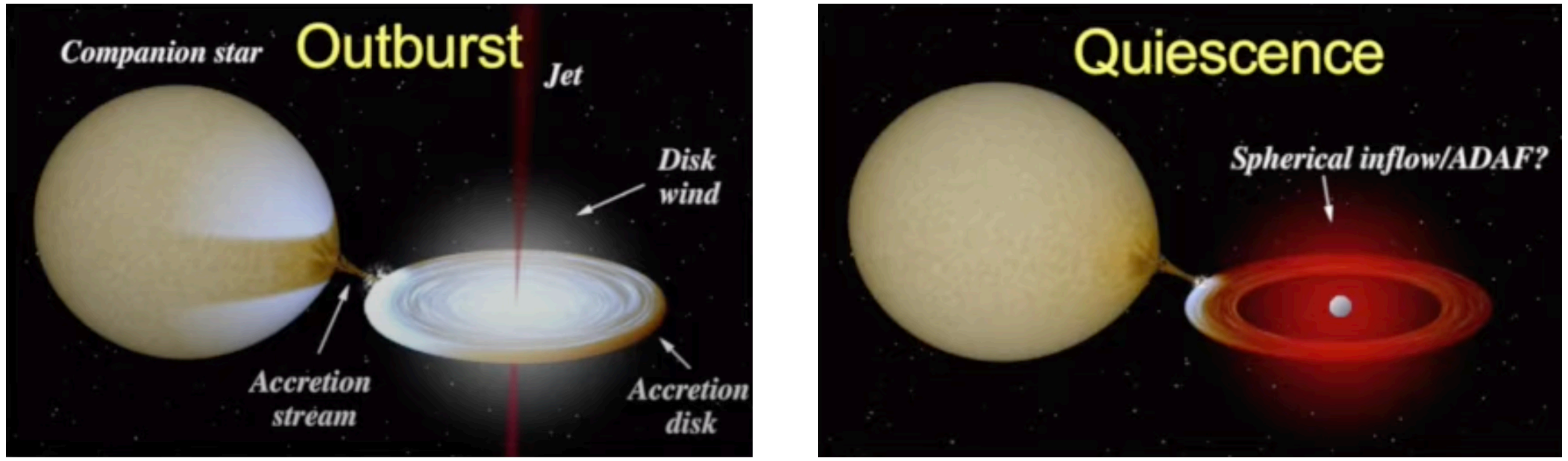
Introduction

Geometry and spectra of X-ray binaries

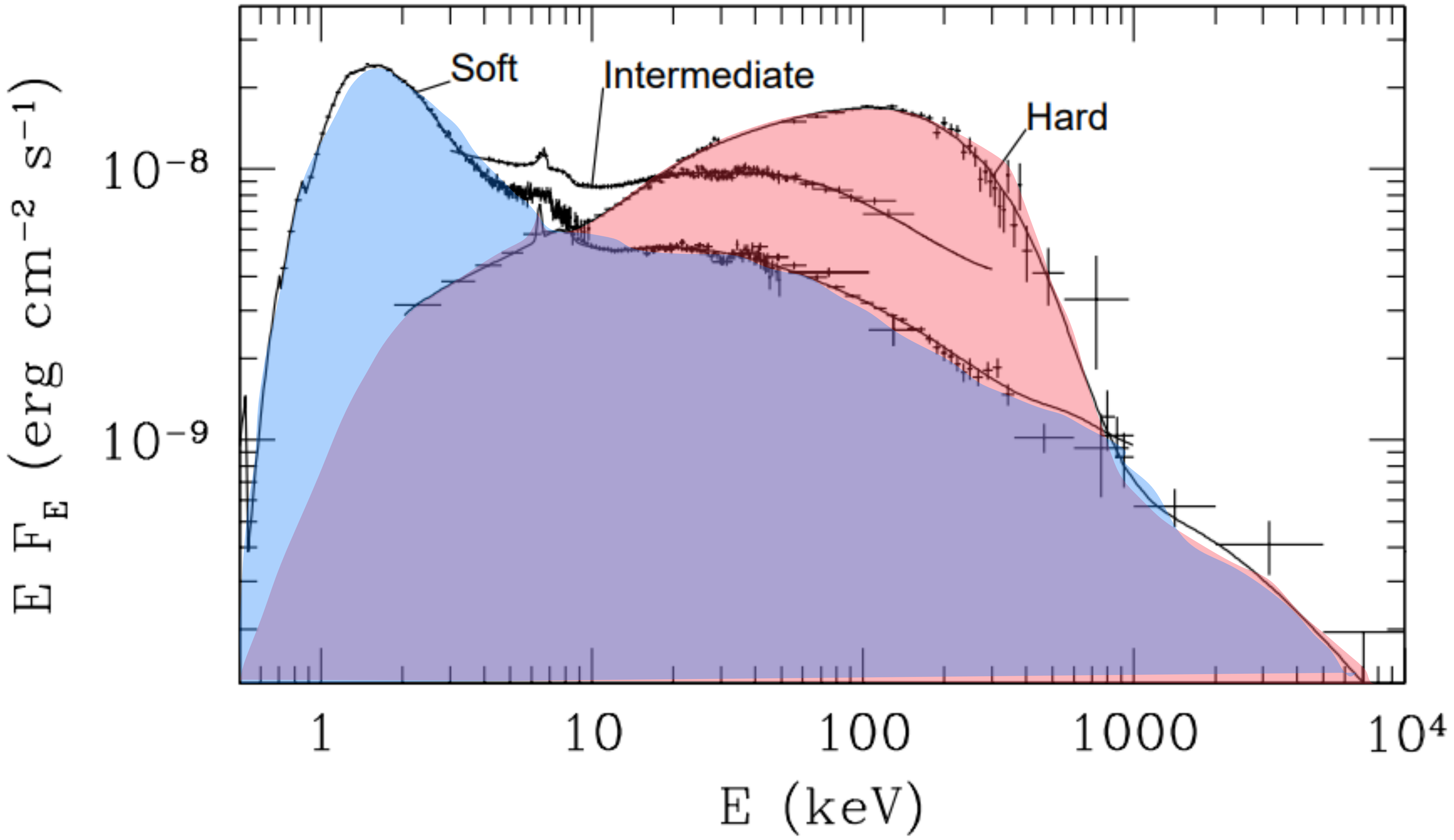


[Image produced with BinSim by Rob Hynes]

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



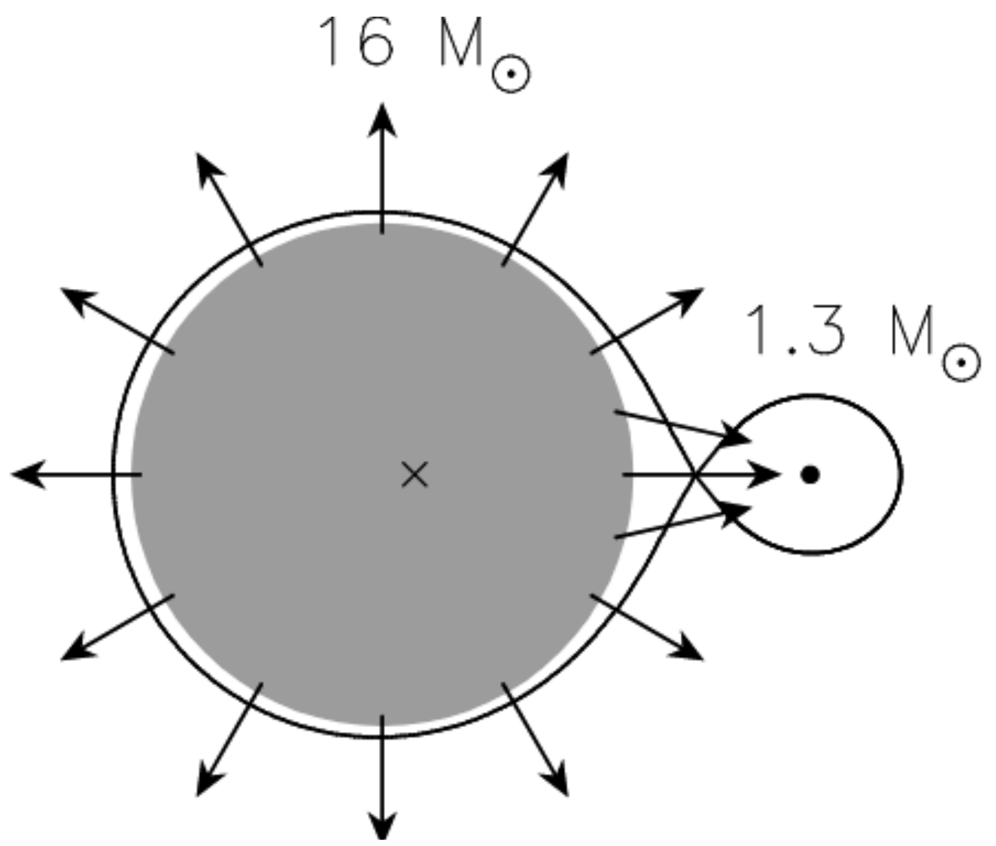
optical star + accretion disk + jet + wind + hot accretion flow + ...



Results of my studies

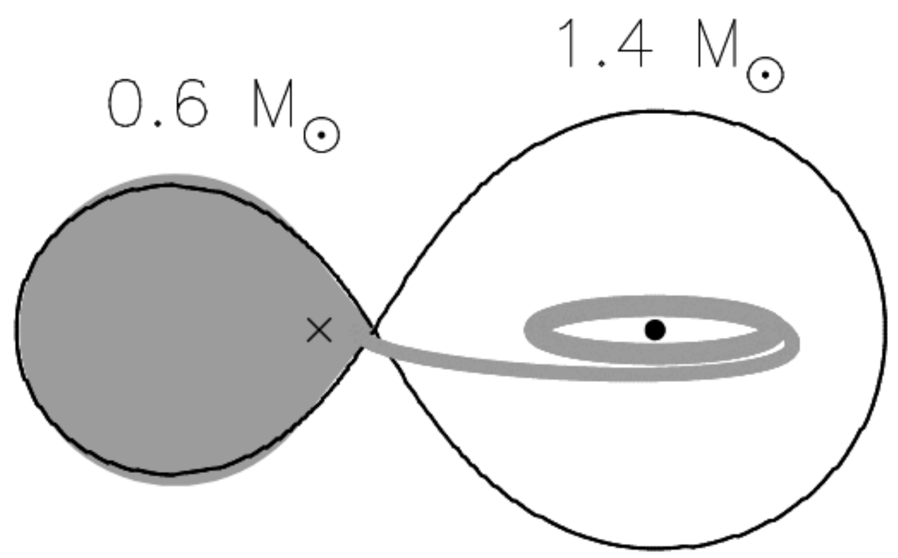
Our sample of X-ray binaries

High Mass X-ray Binaries



Cyg X-1
LS I +61 303
LS V +44 17
LS 5039
1A 0535+262

Low Mass X-ray Binaries



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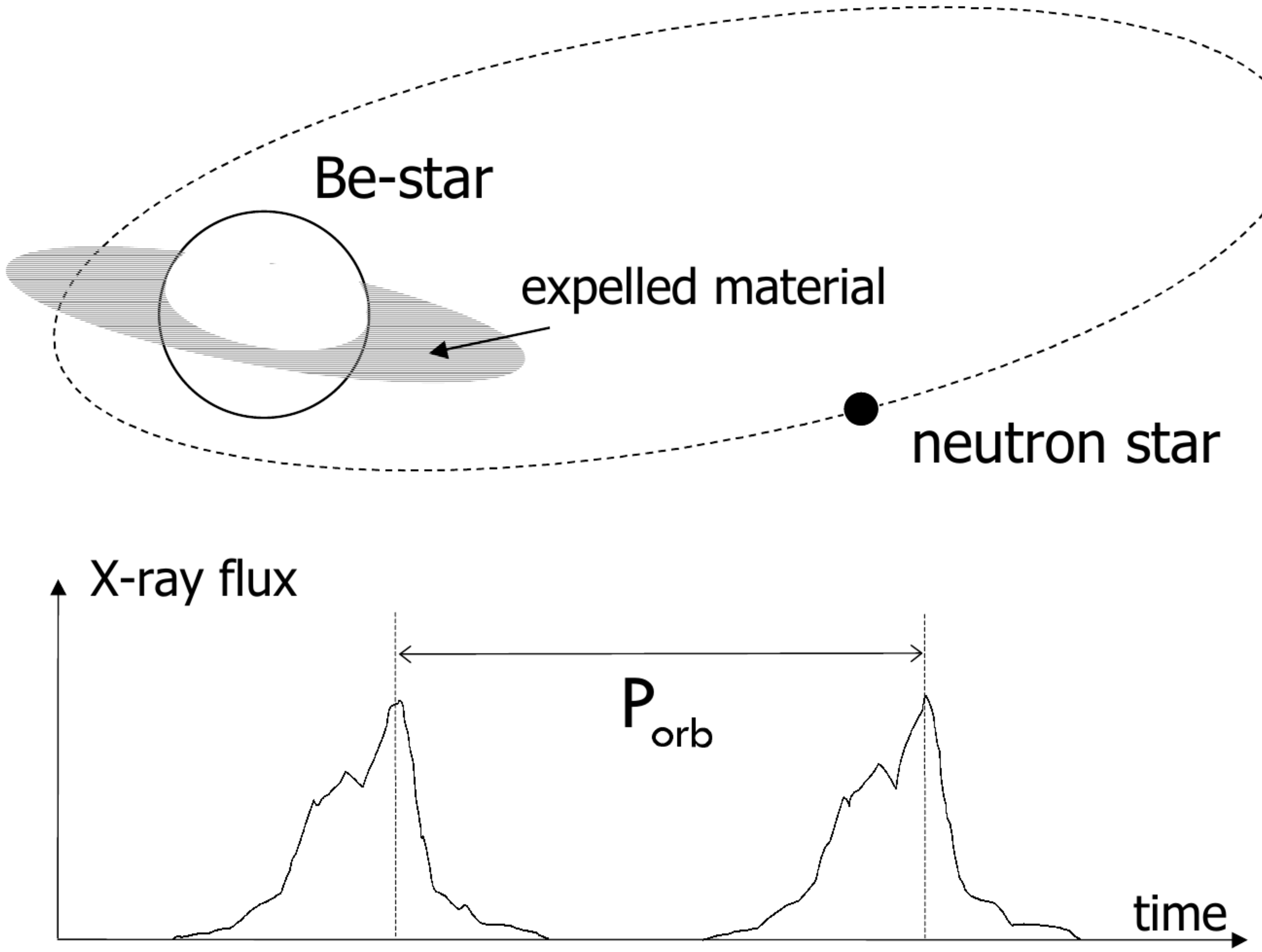
MAXI J1820+070
V404 Cyg
4U 1957+115
LS V +44 17
XTE J1118+480
MAXI J0637–430
Swift J1357.2–0933
Swift J1727.8–1613

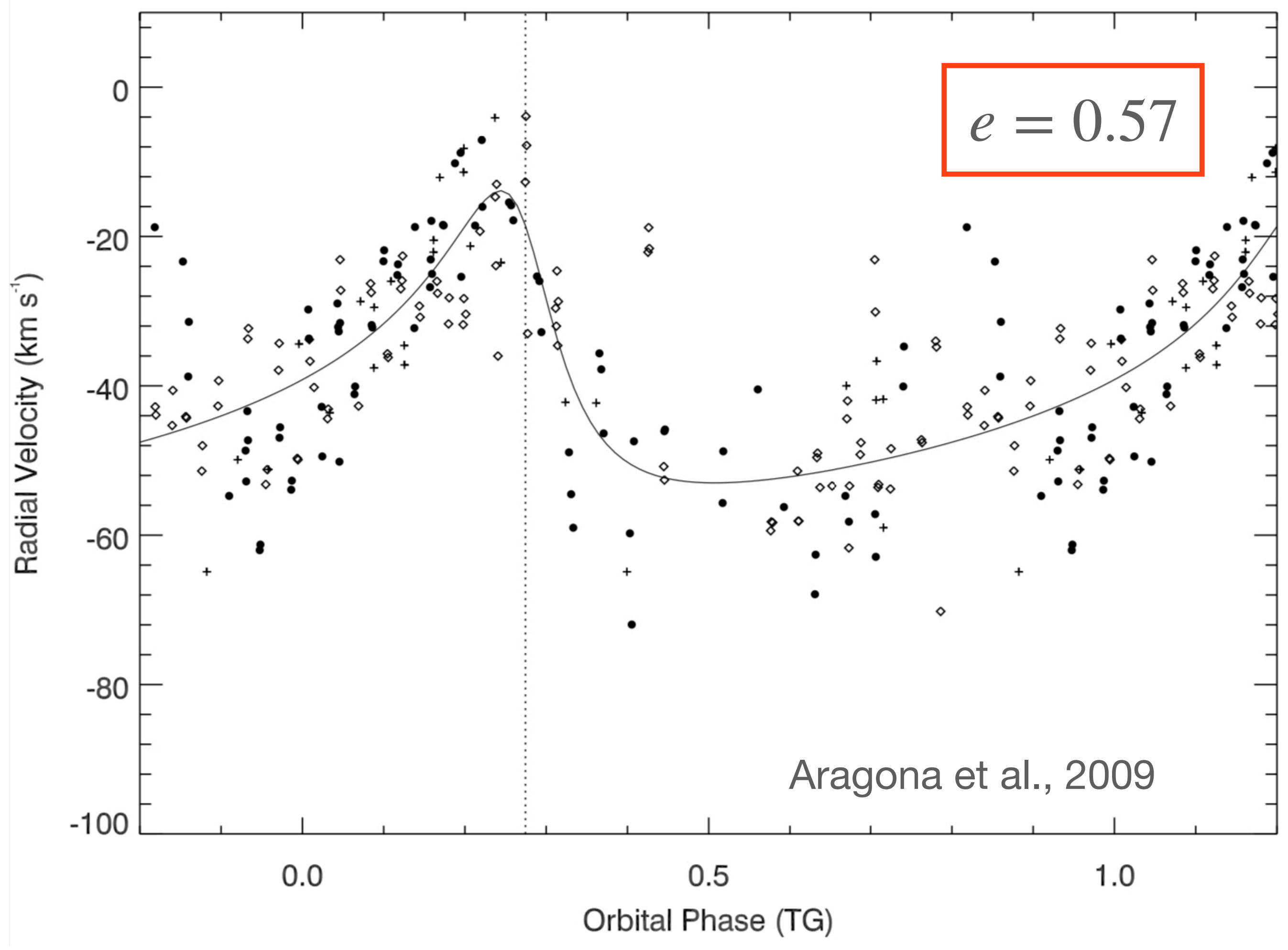
Project 1: orbital variations of the polarization of HMXBs

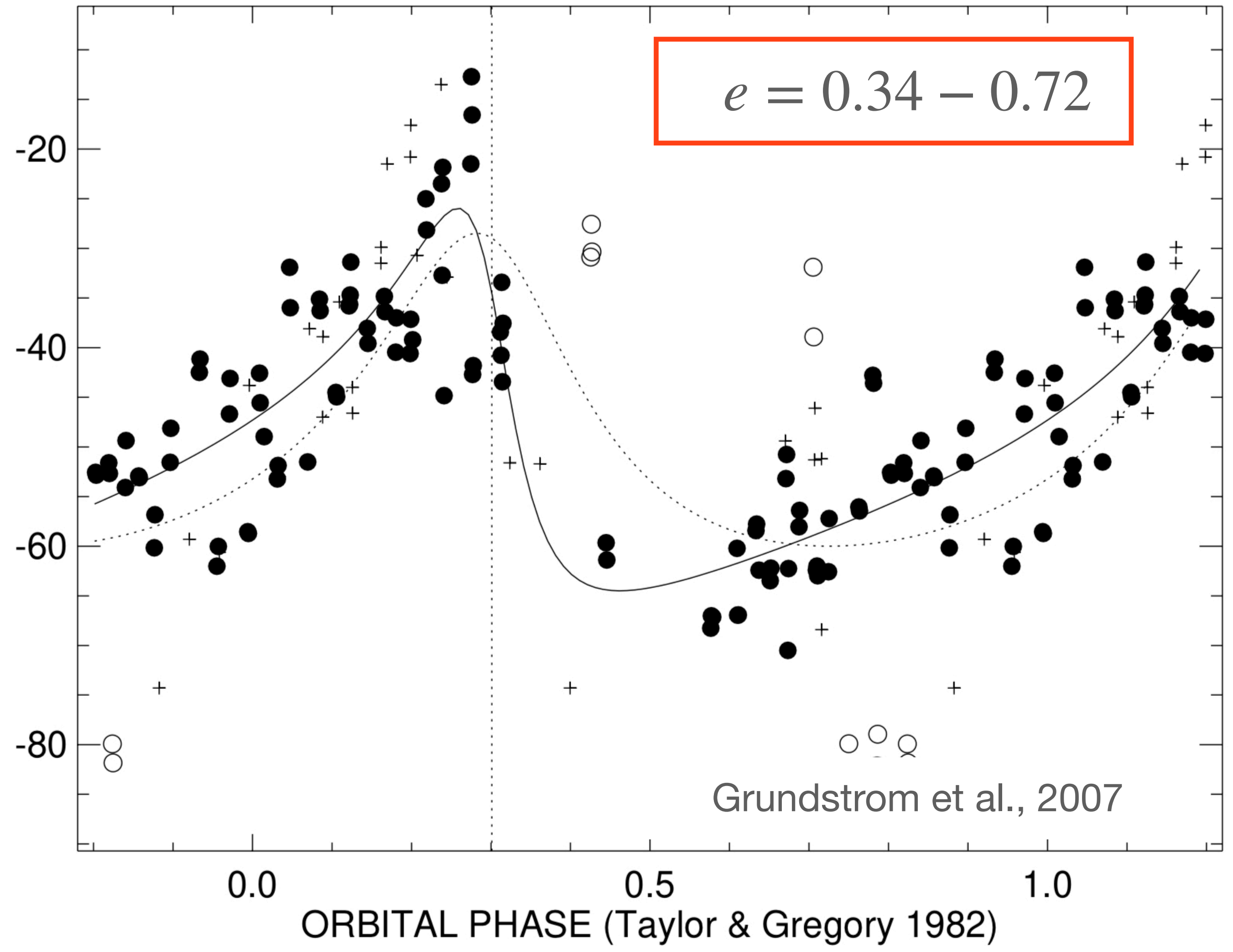
Microquasar LS I +61 303

Be star + neutron star (?)



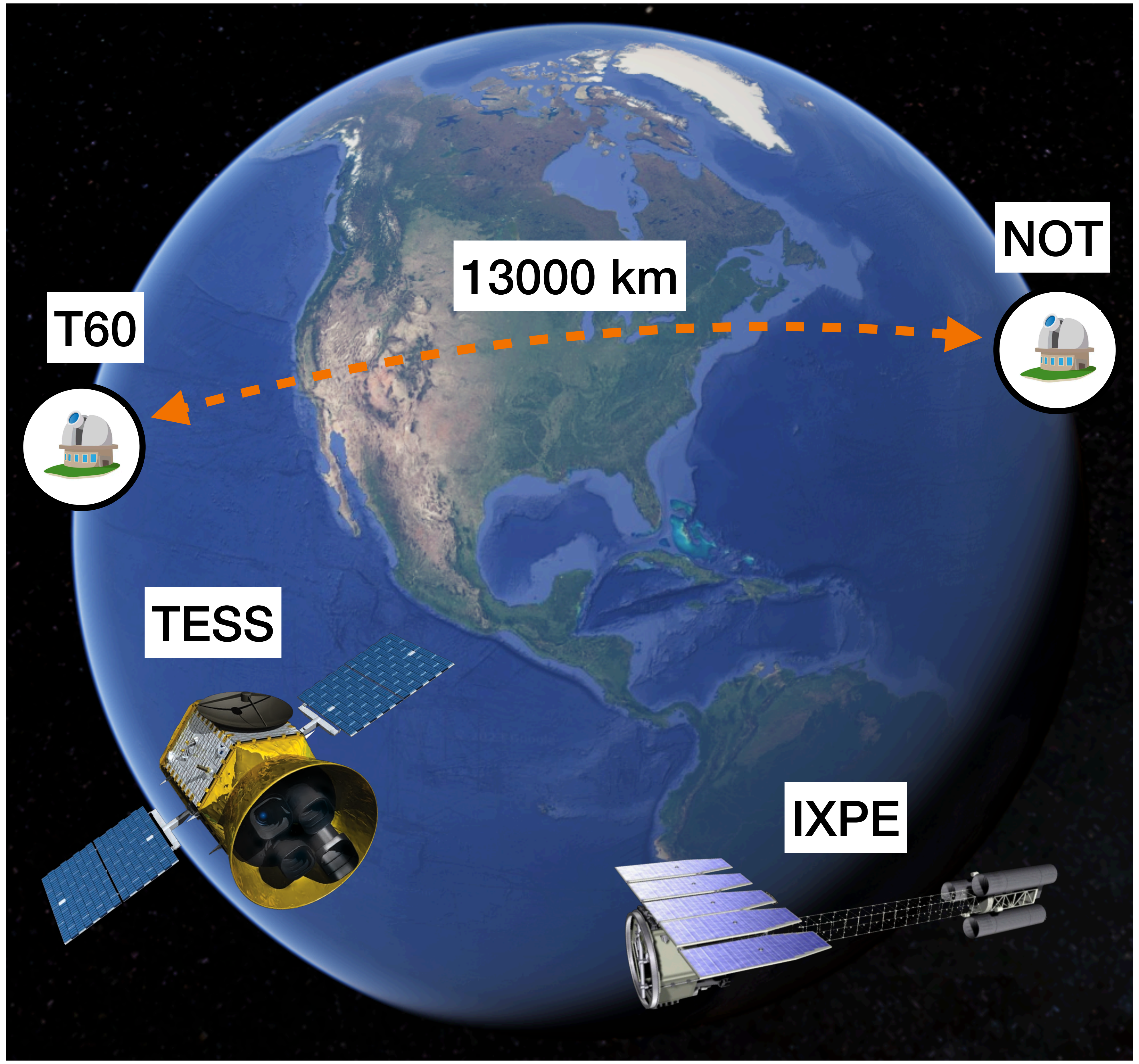
RV curves of LS I +61 303





Our observations

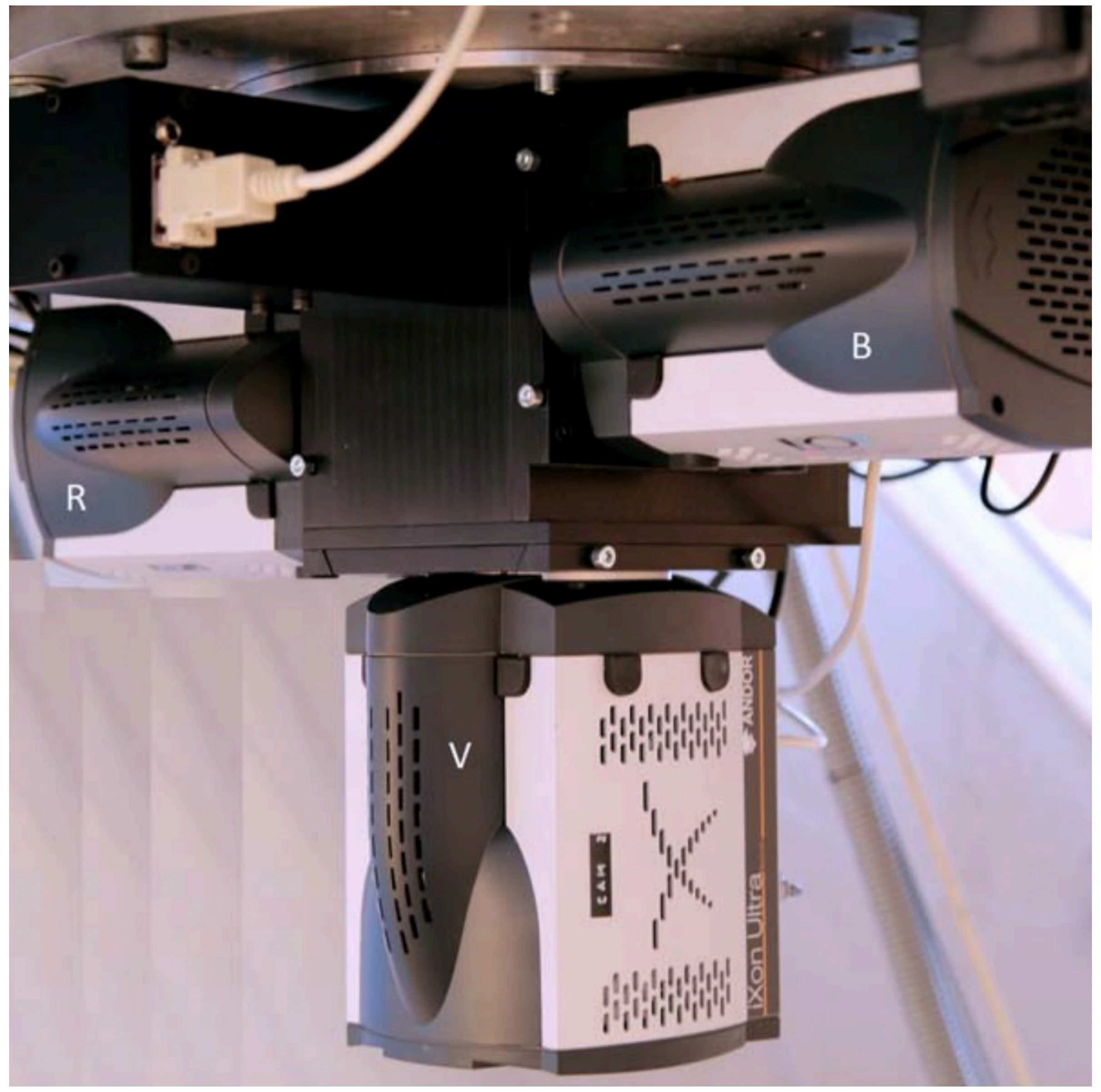
The telescopes and instruments we used



Nordic Optical Telescope (NOT)

La Palma, Canary Islands, Spain

DIPol-UF polarimeter, mounted on NOT



Simultaneous Three-color (*BVR*) polarimeter

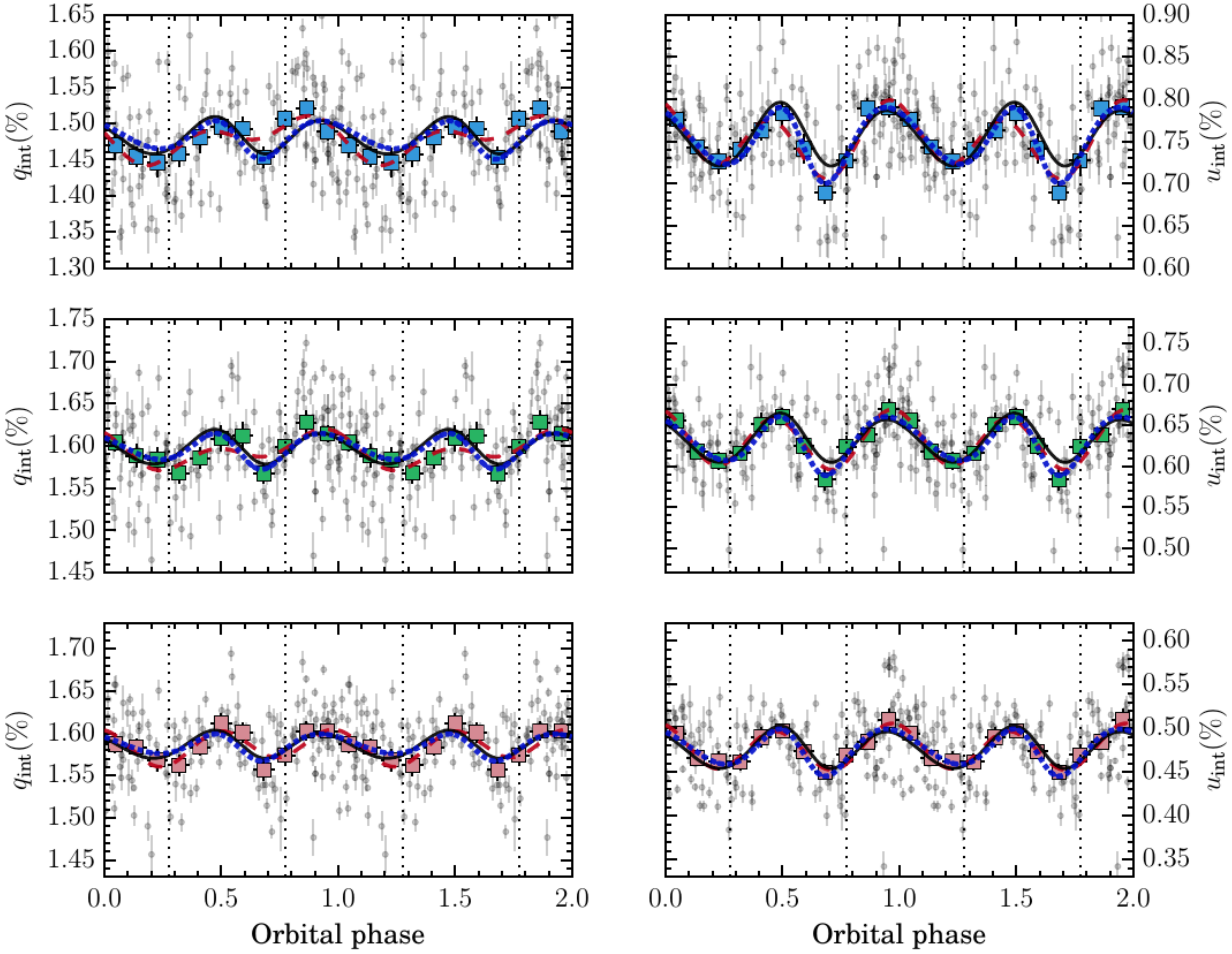
Why DIPol-UF/2?

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

Piirola et al., 2020

Microquasar LS I +61 303

Orbital variability of the polarization



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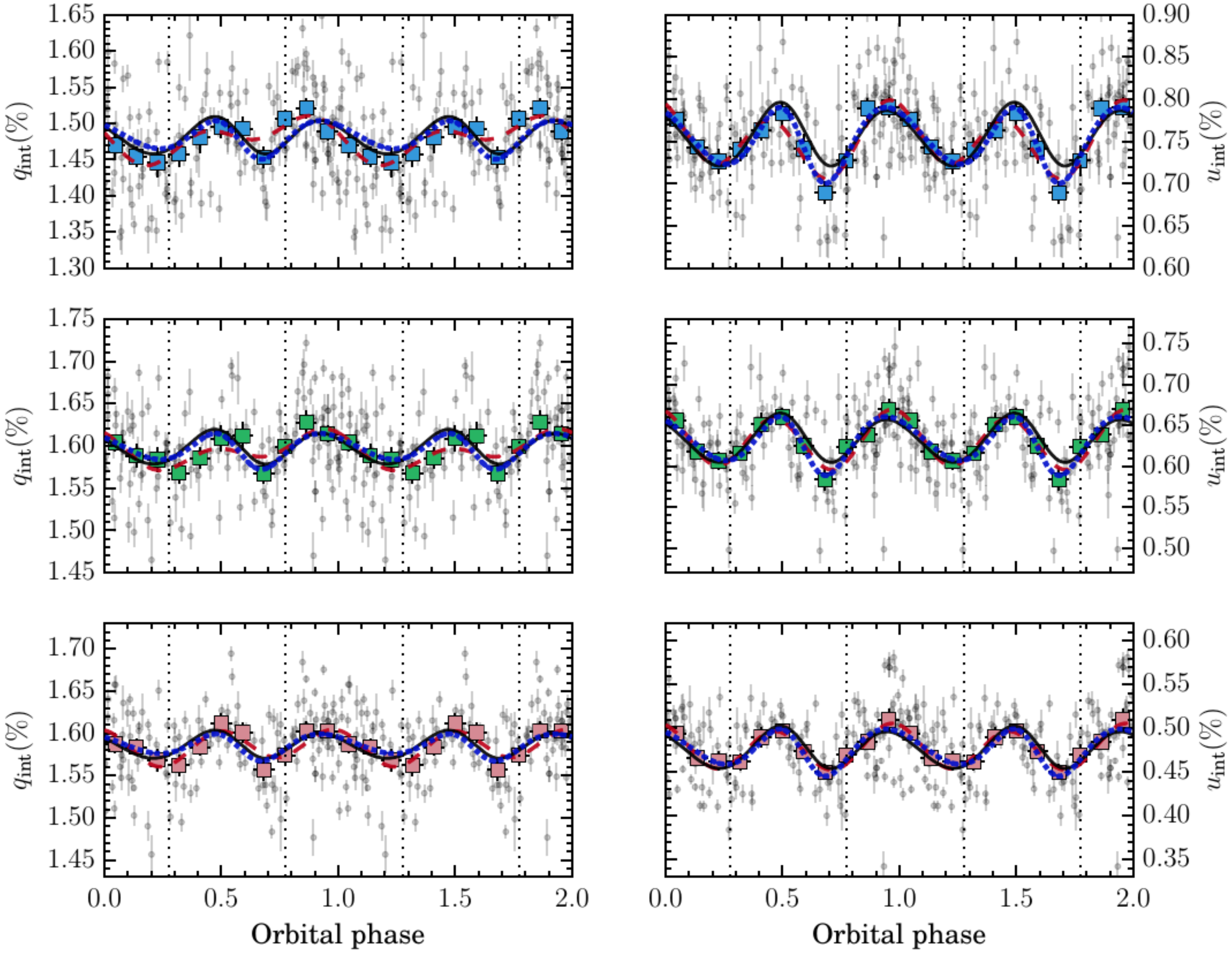

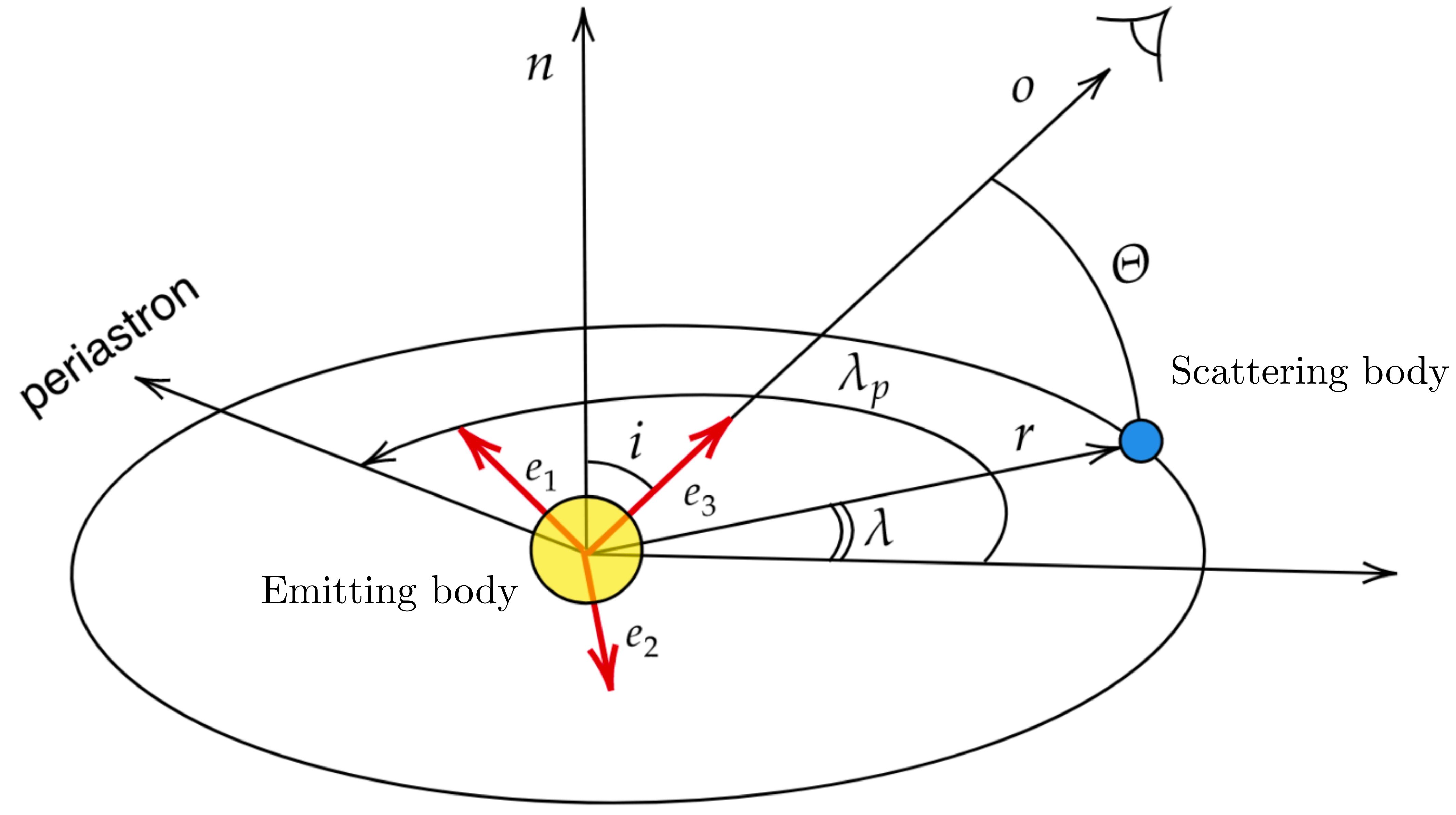

$$q = \frac{3f_0}{16}\left[\sin^2 i - \left(1+\cos^2 i\right)\cos 2\lambda\right]\left[1+e\cos\left(\lambda-\lambda_{\rm p}\right)\right]^2,$$
$$u = \frac{3f_0}{8}\left[-\cos i\ \sin 2\lambda\right]\left[1+e\cos\left(\lambda-\lambda_{\rm p}\right)\right]^2.$$

Kravtsov et al., 2020

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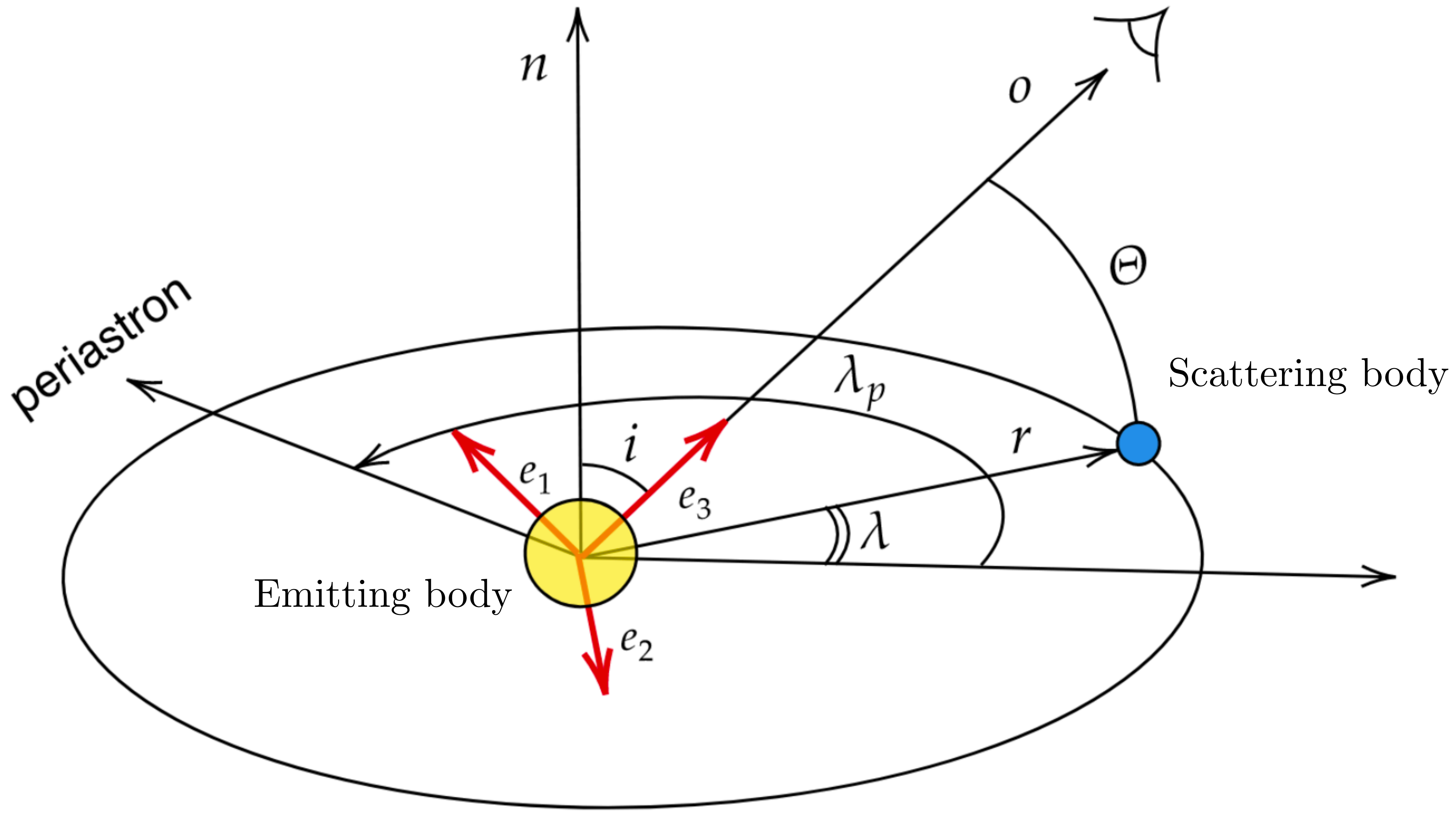

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Kravtsov et al., 2020

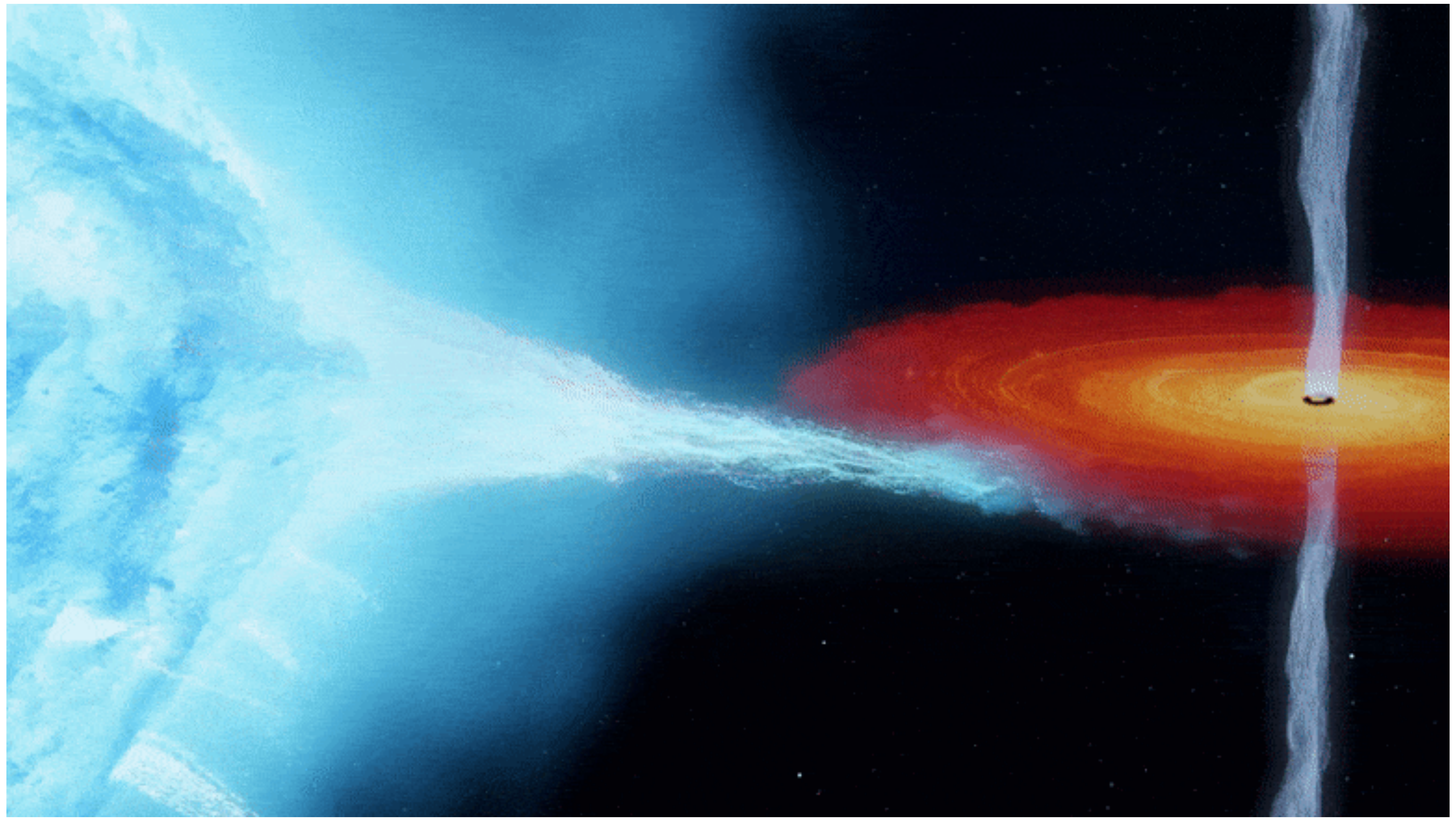
Main results: simple analytical model for variable polarization production and new upper limit on eccentricity of LS I +61 303

$$e < 0.15$$

(instead previous $e = 0.34 - 0.72$)

Microquasar Cyg X-1

The best-studied X-ray binary to date



Basic information:

$P_{\rm orb} = 5.6$ days

$M_{\rm BH} \sim 21\ M_\odot$

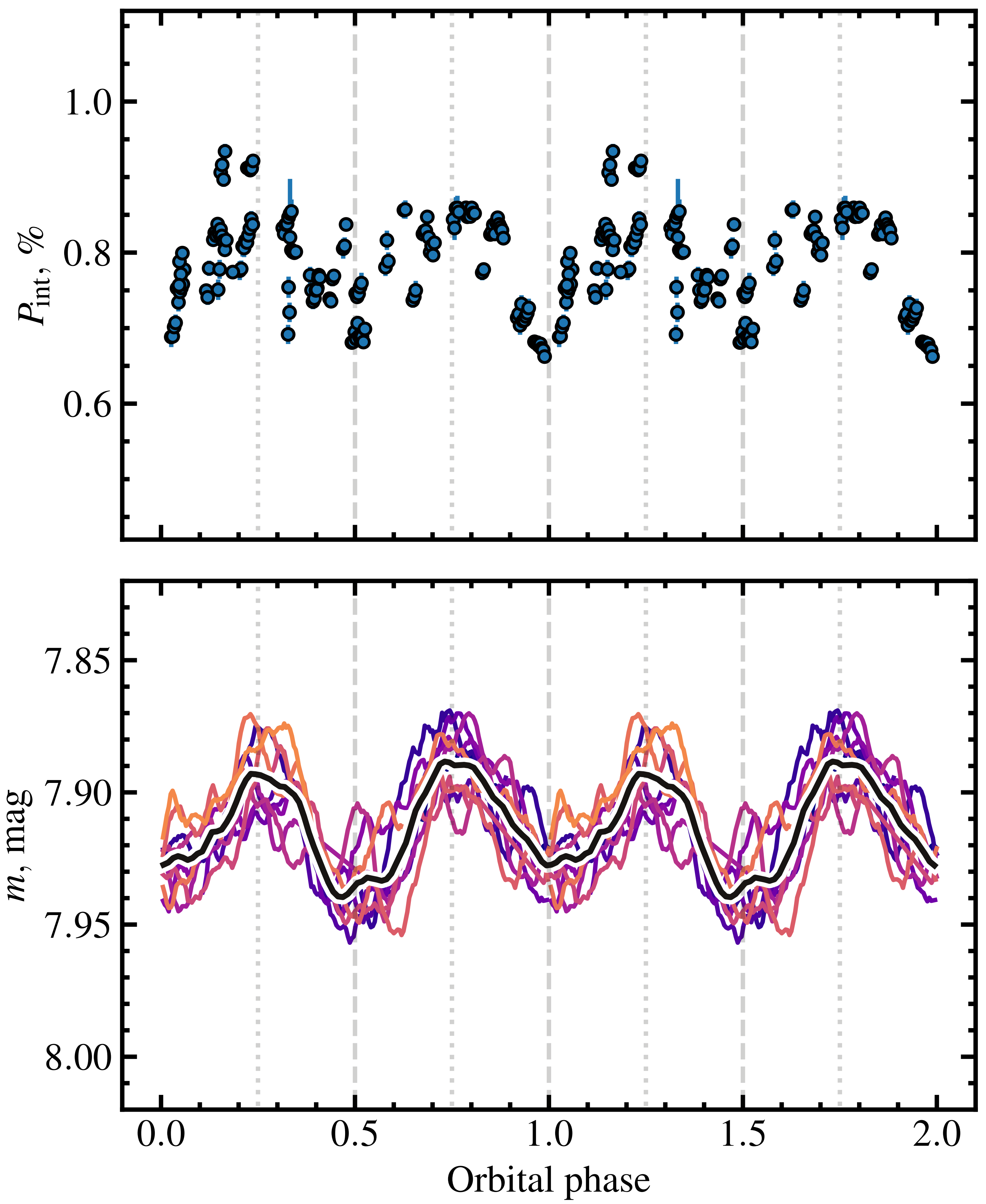
$M_{\rm C} \sim 40\ M_\odot$

$i \sim 150^\circ$

Cyg X-1

Results

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



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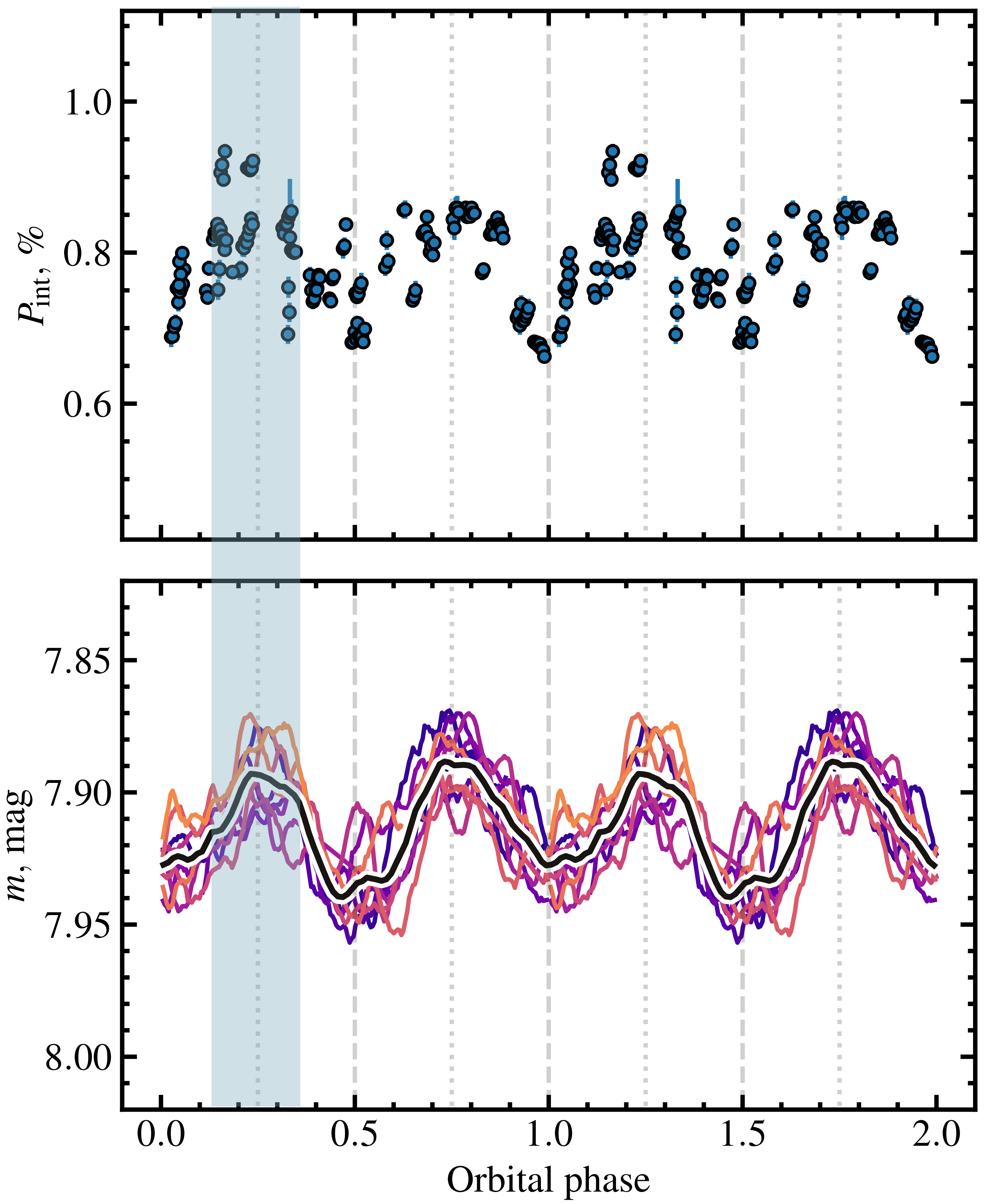
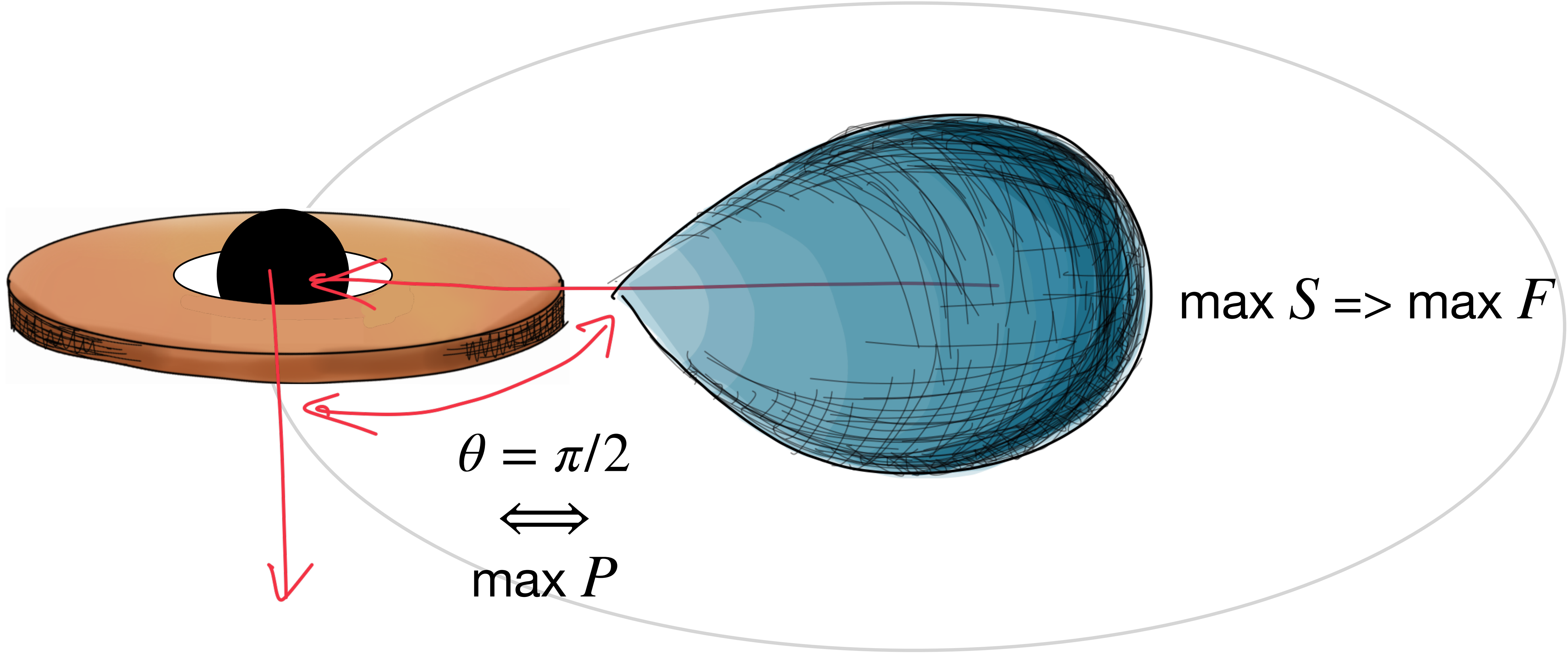


Flux $F \propto$ Visible area of the star S

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

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



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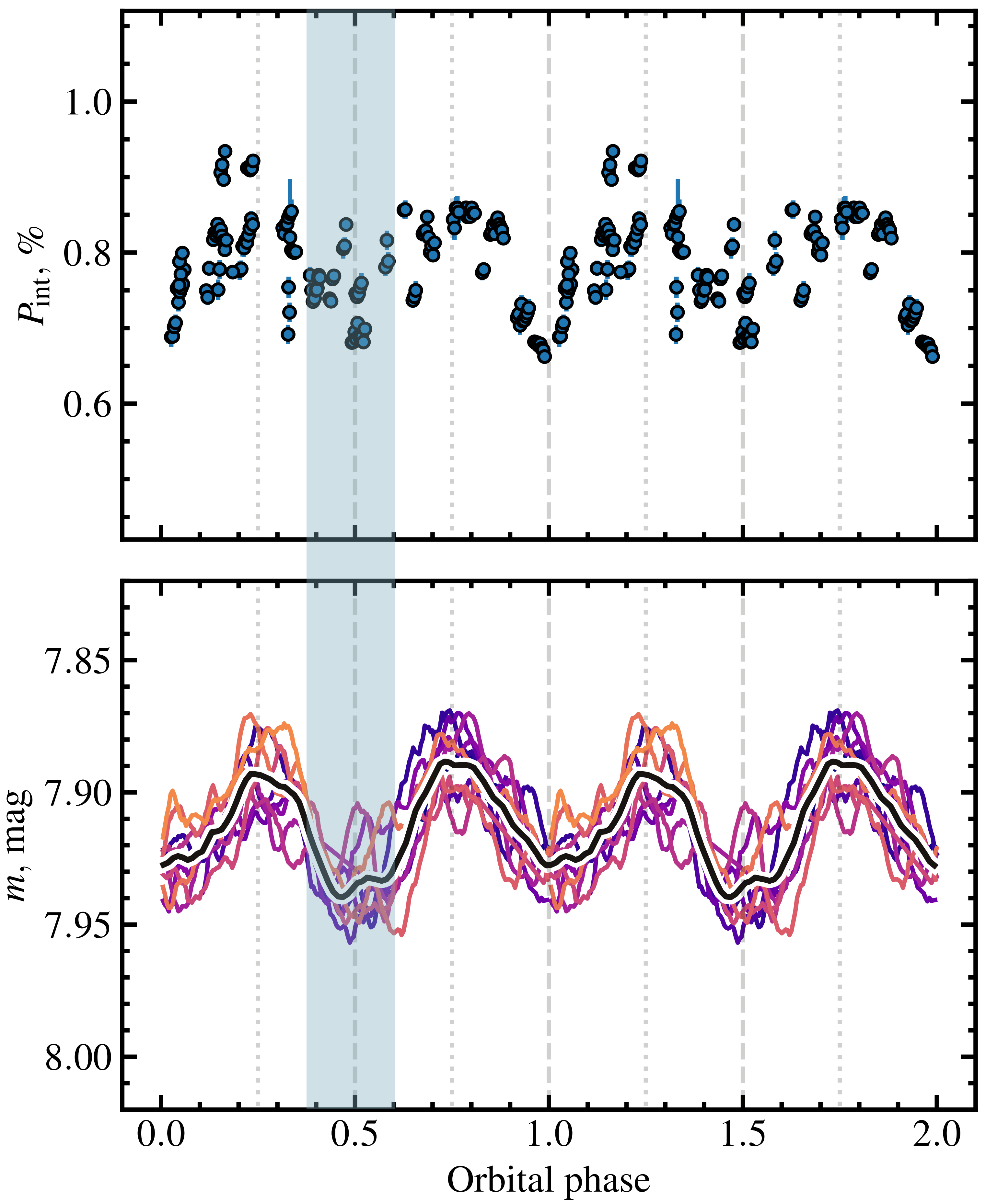

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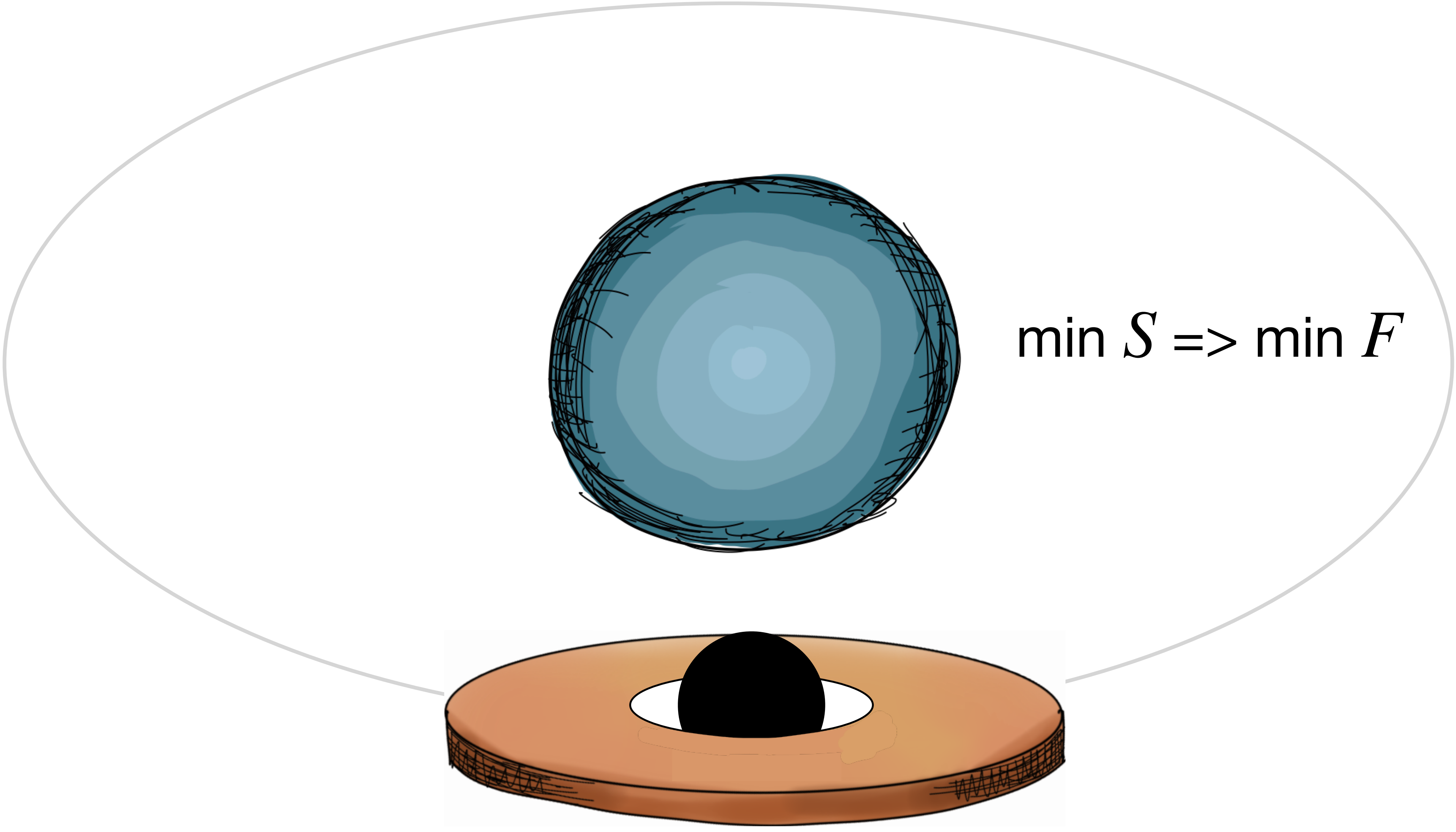
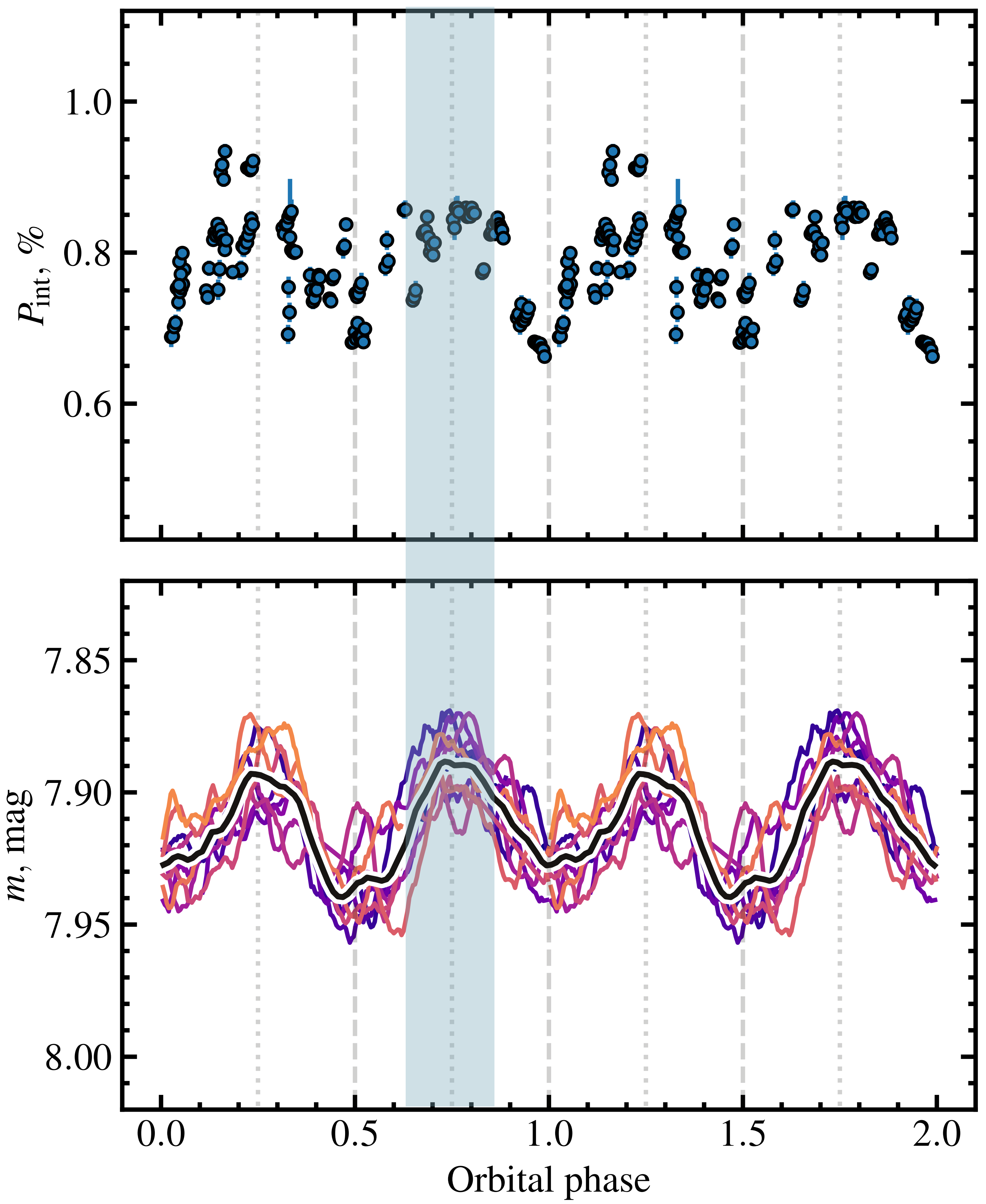


min/max $\theta \iff$ min P

Results

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



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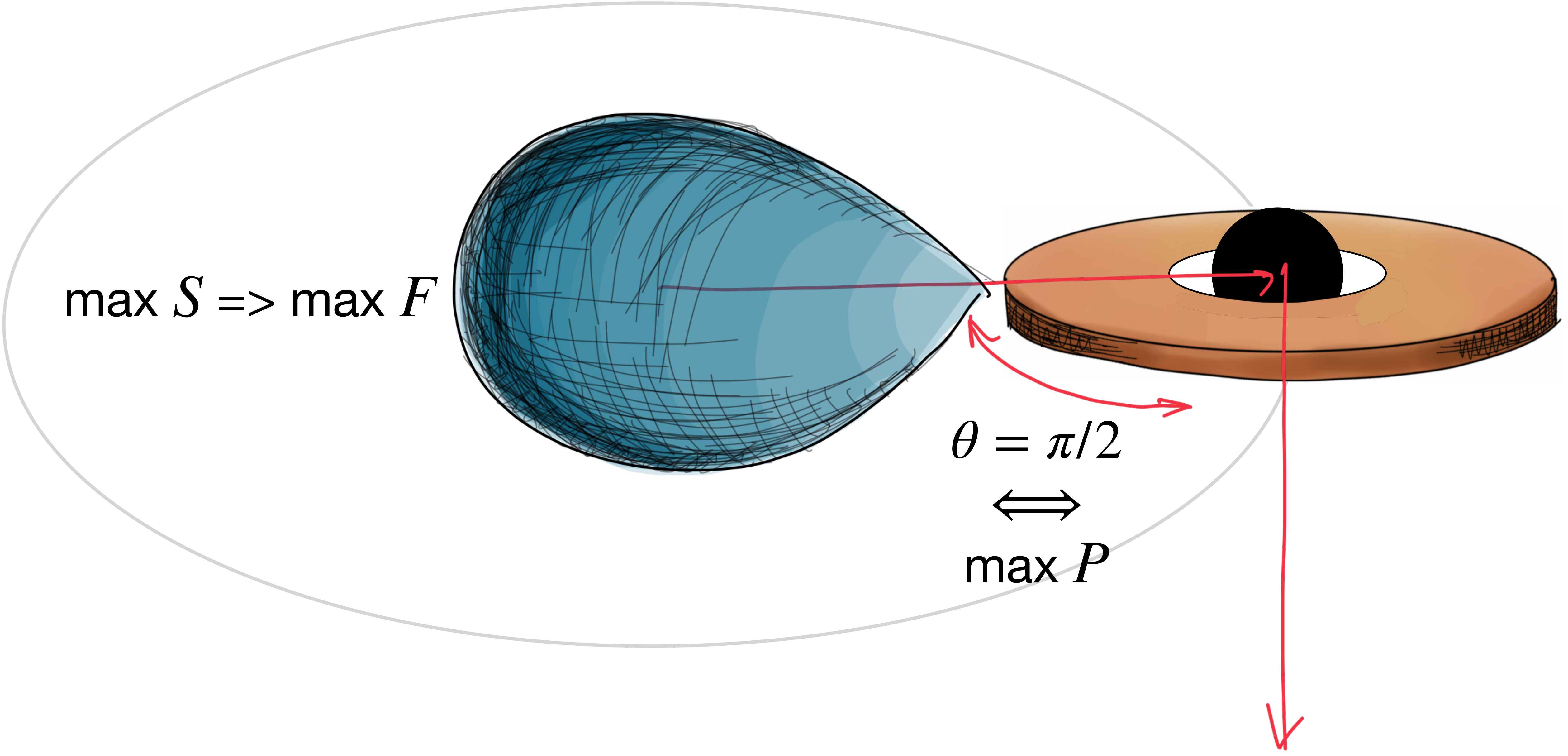
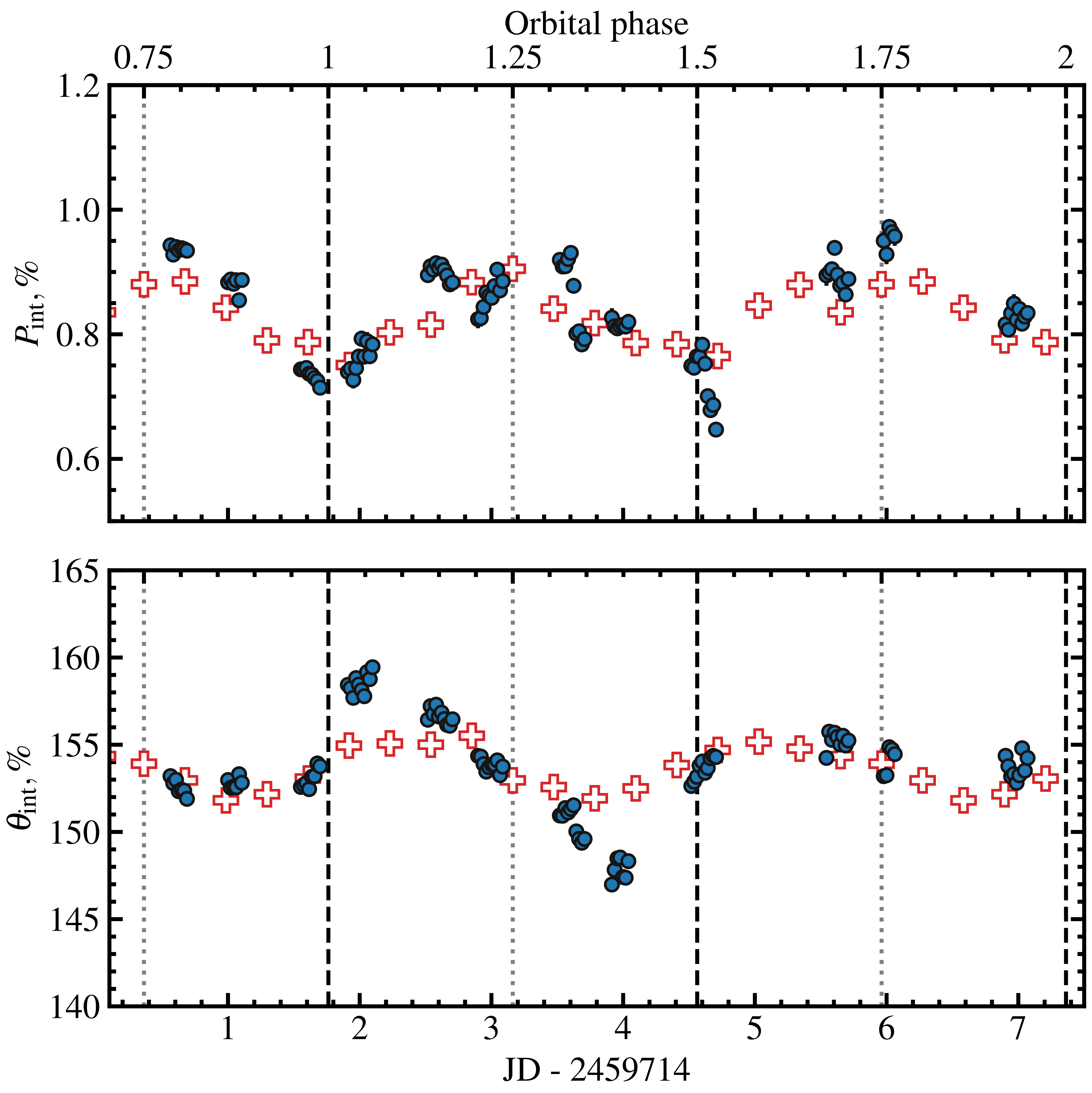


Results

Best single orbit coverage to date



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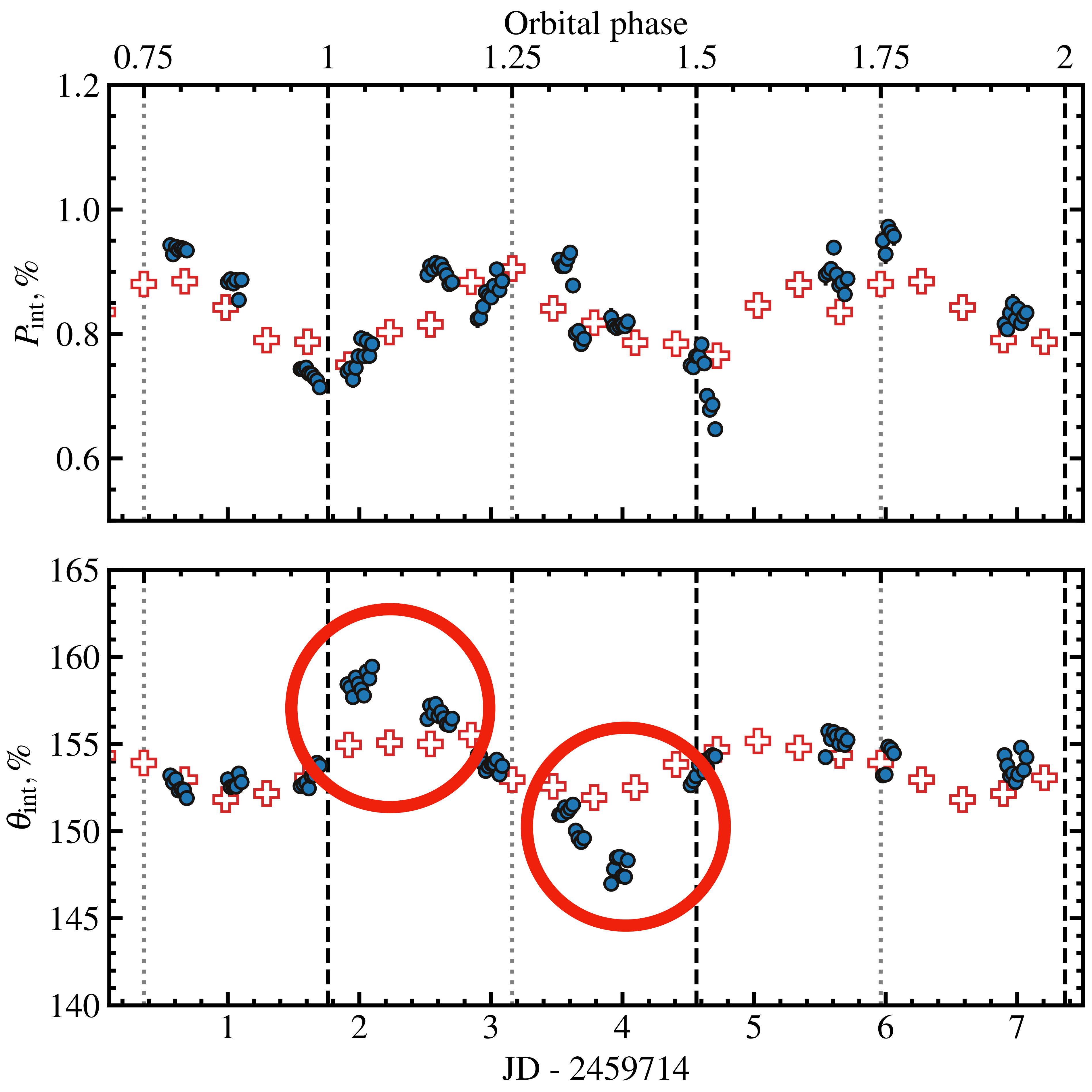

arXiv:2305.10813

Results

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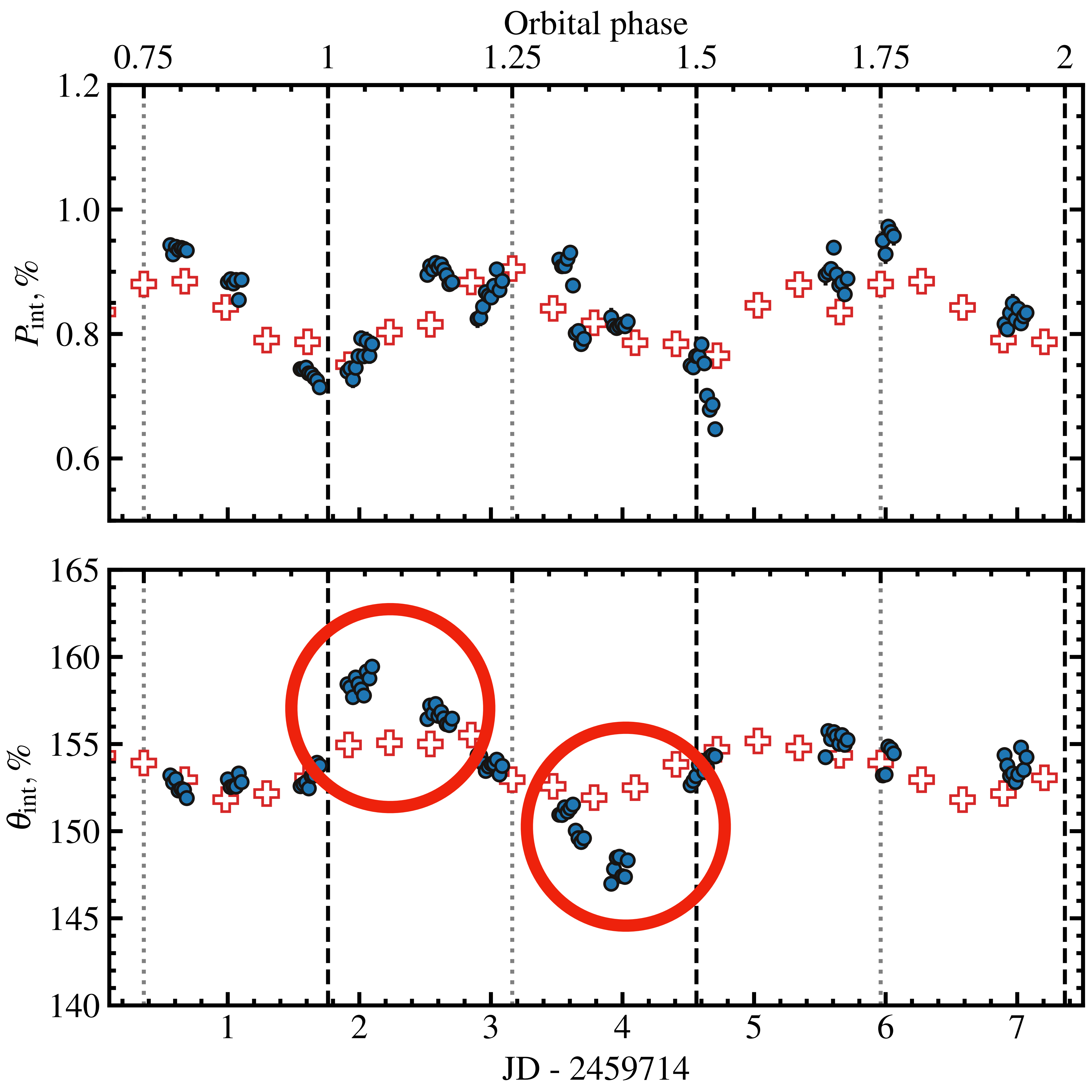

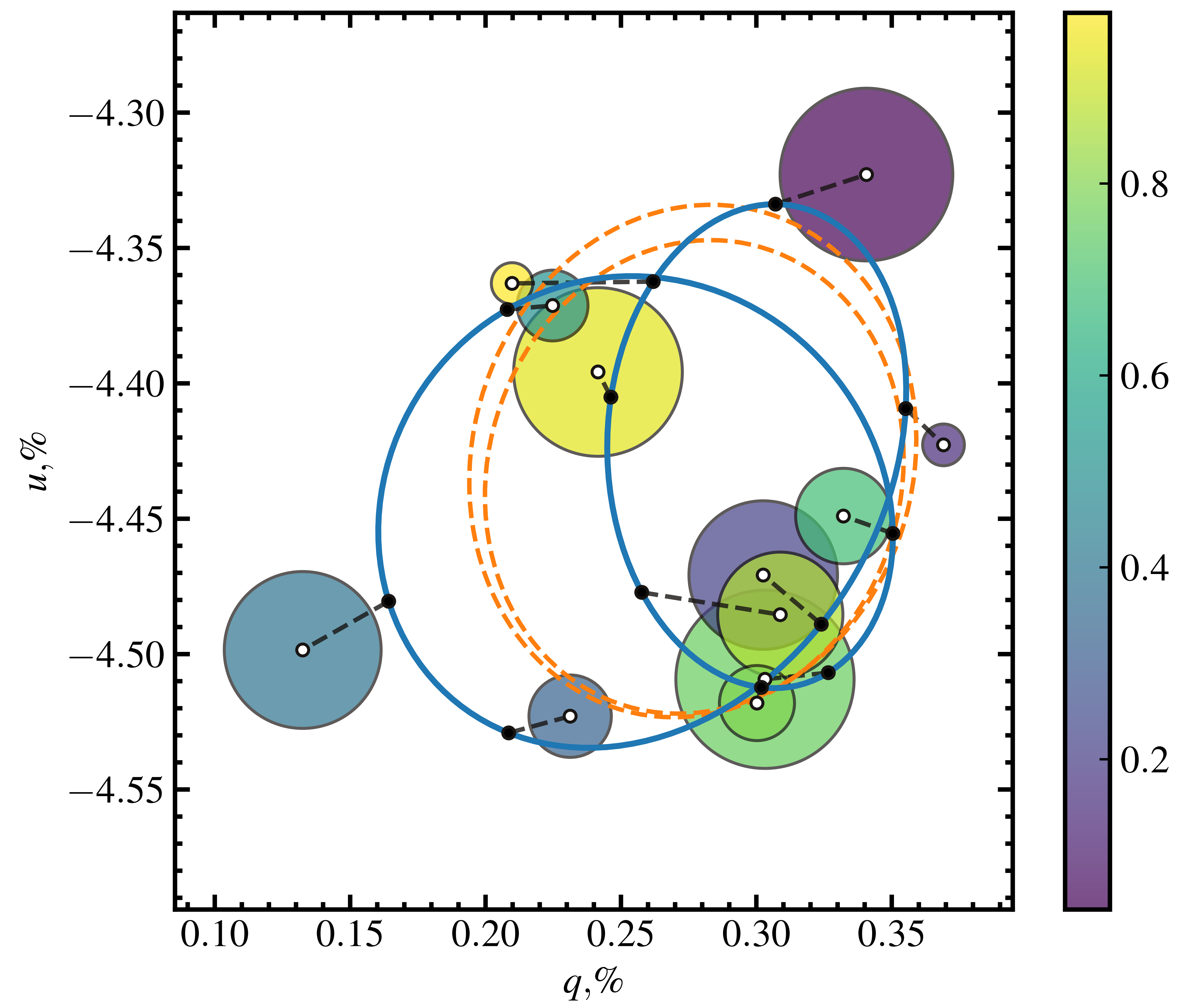

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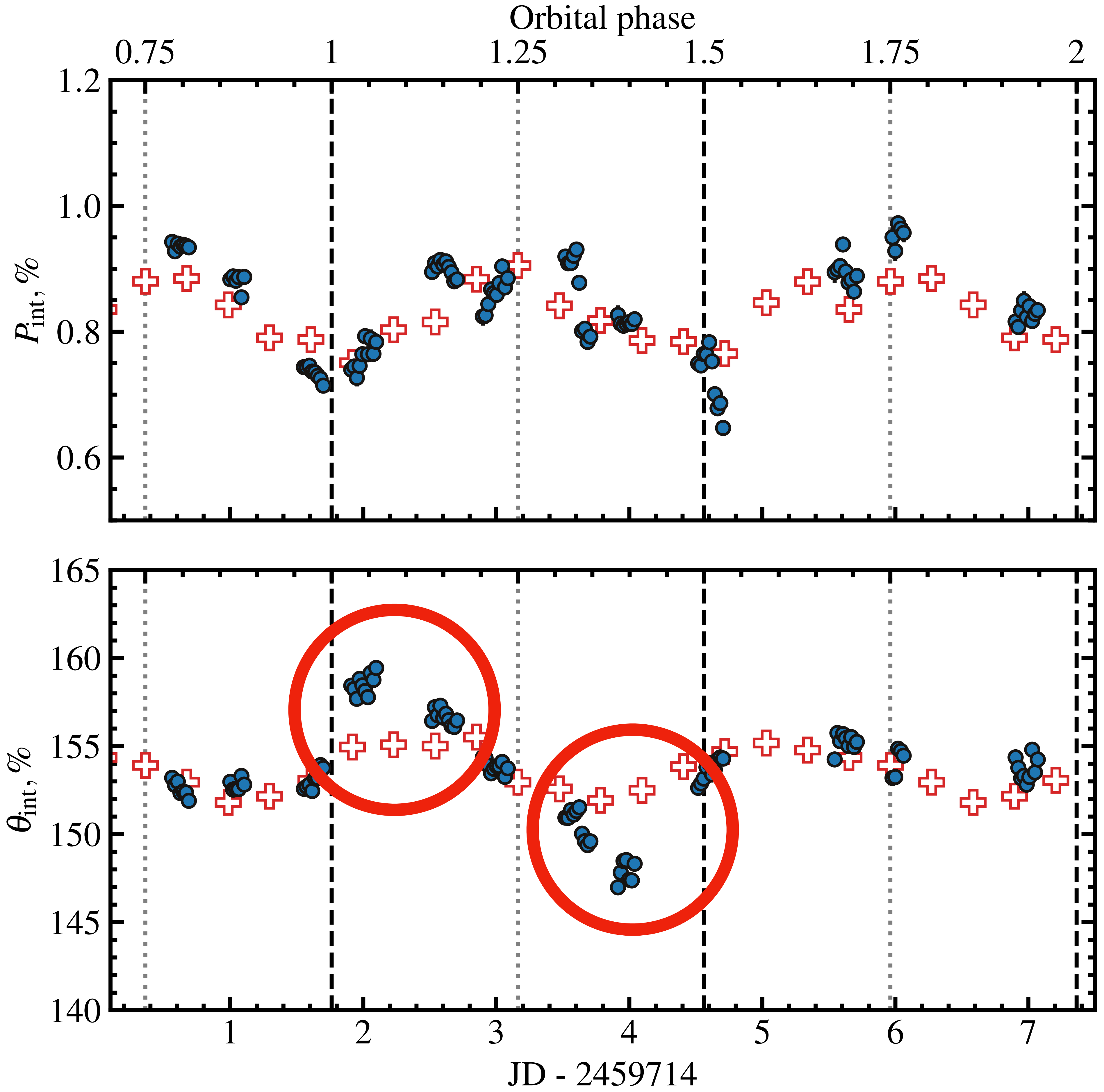
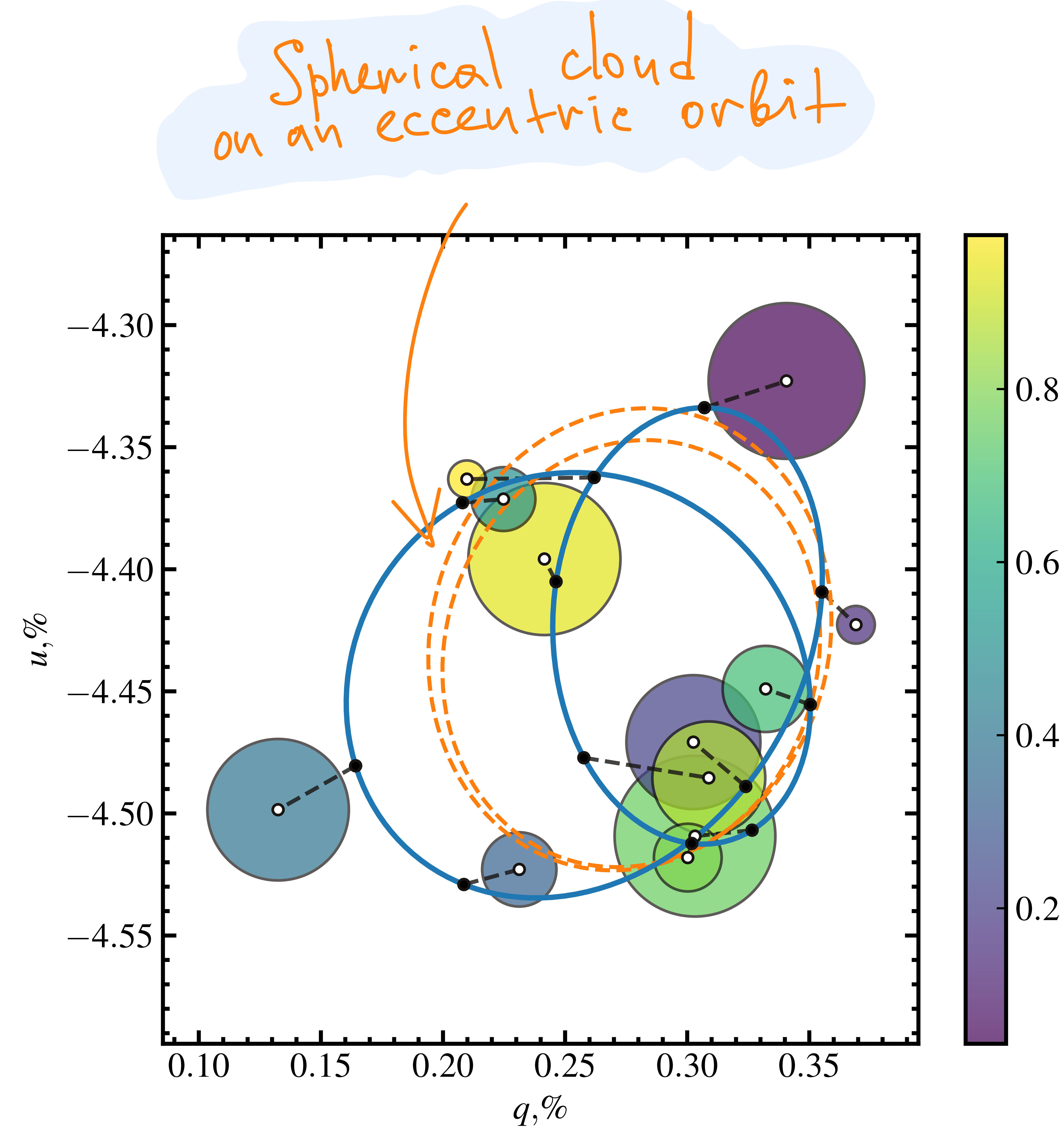
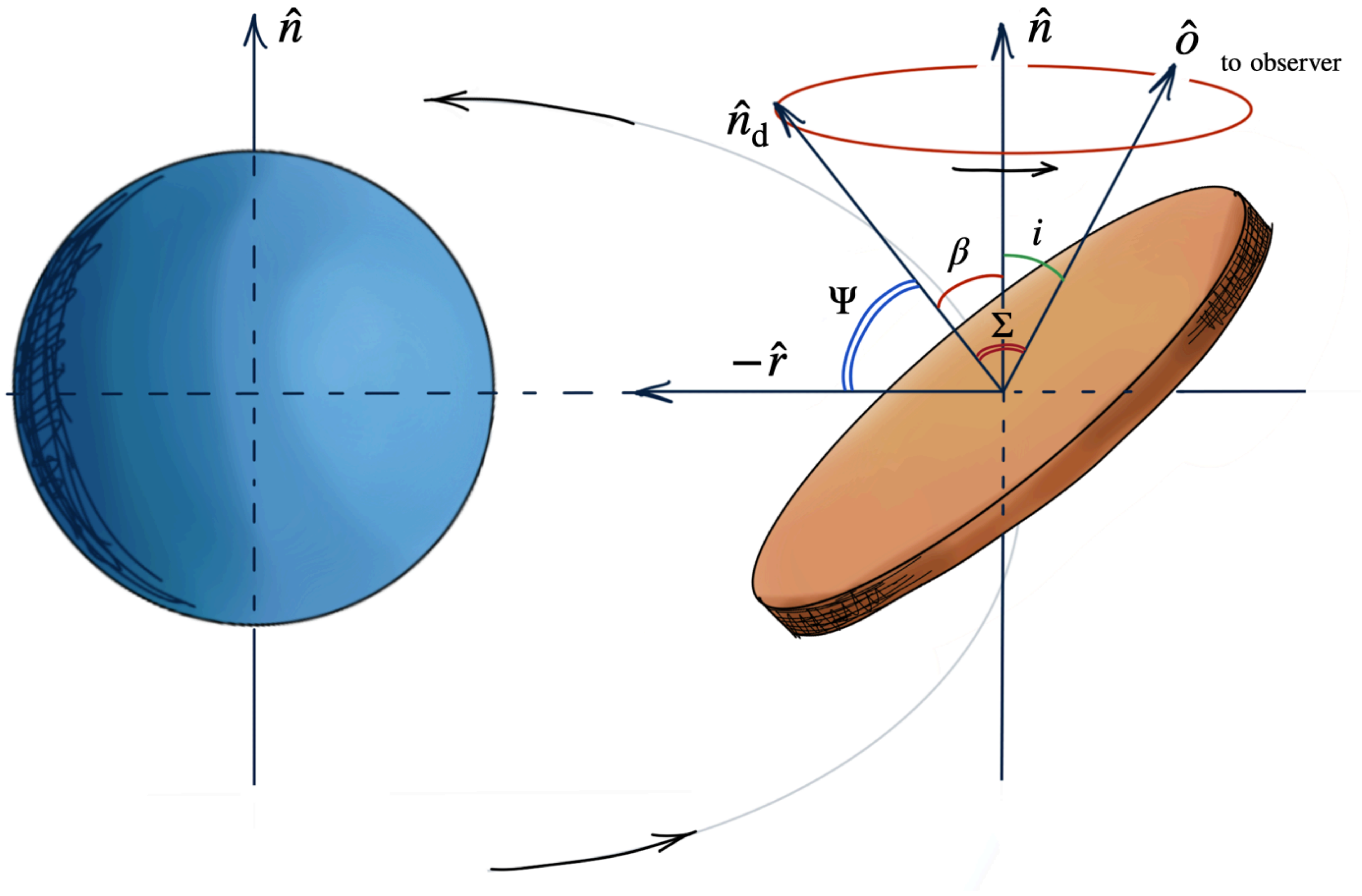
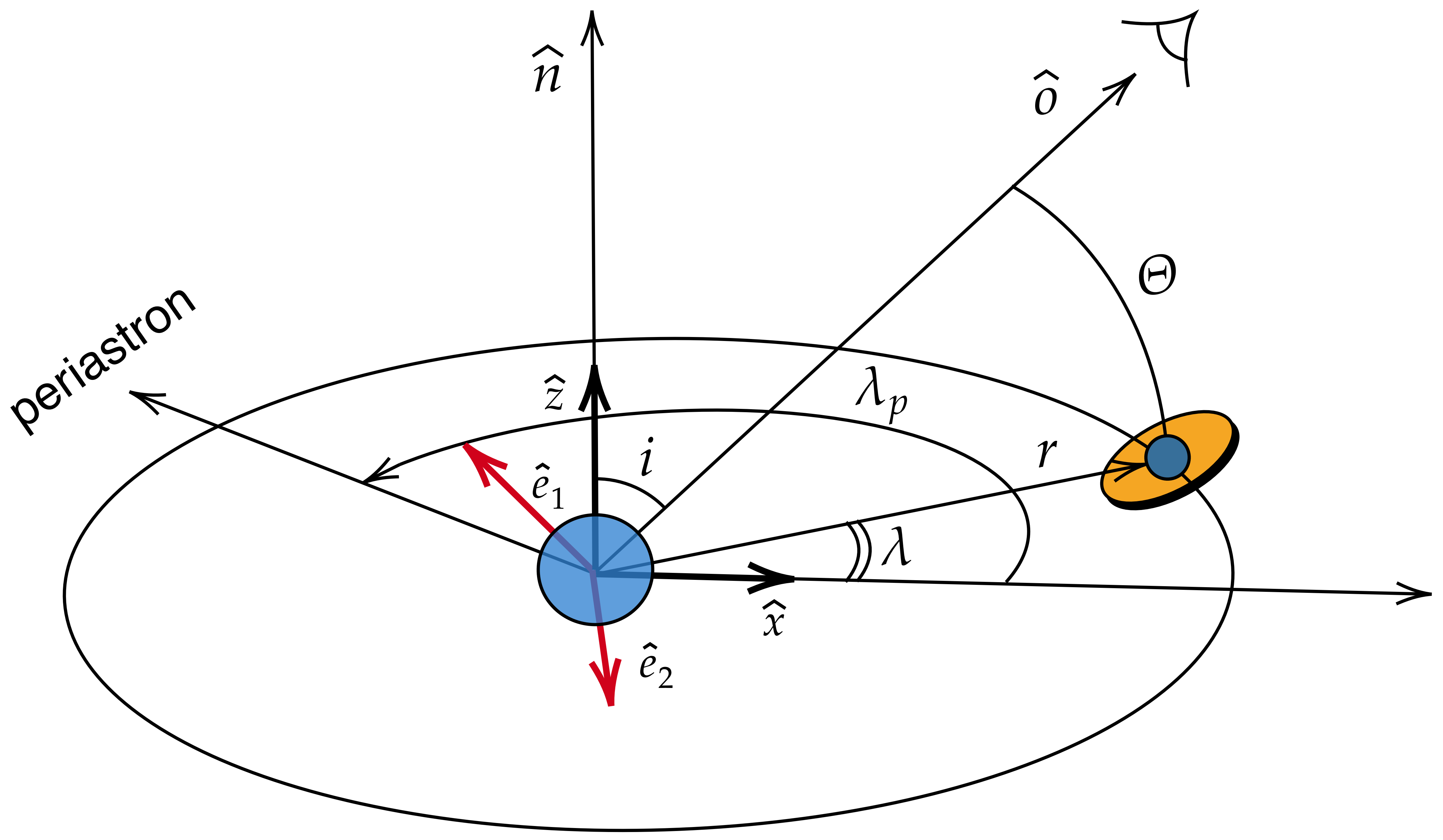




Results

Model of Thomson scattering off tilted accretion disk

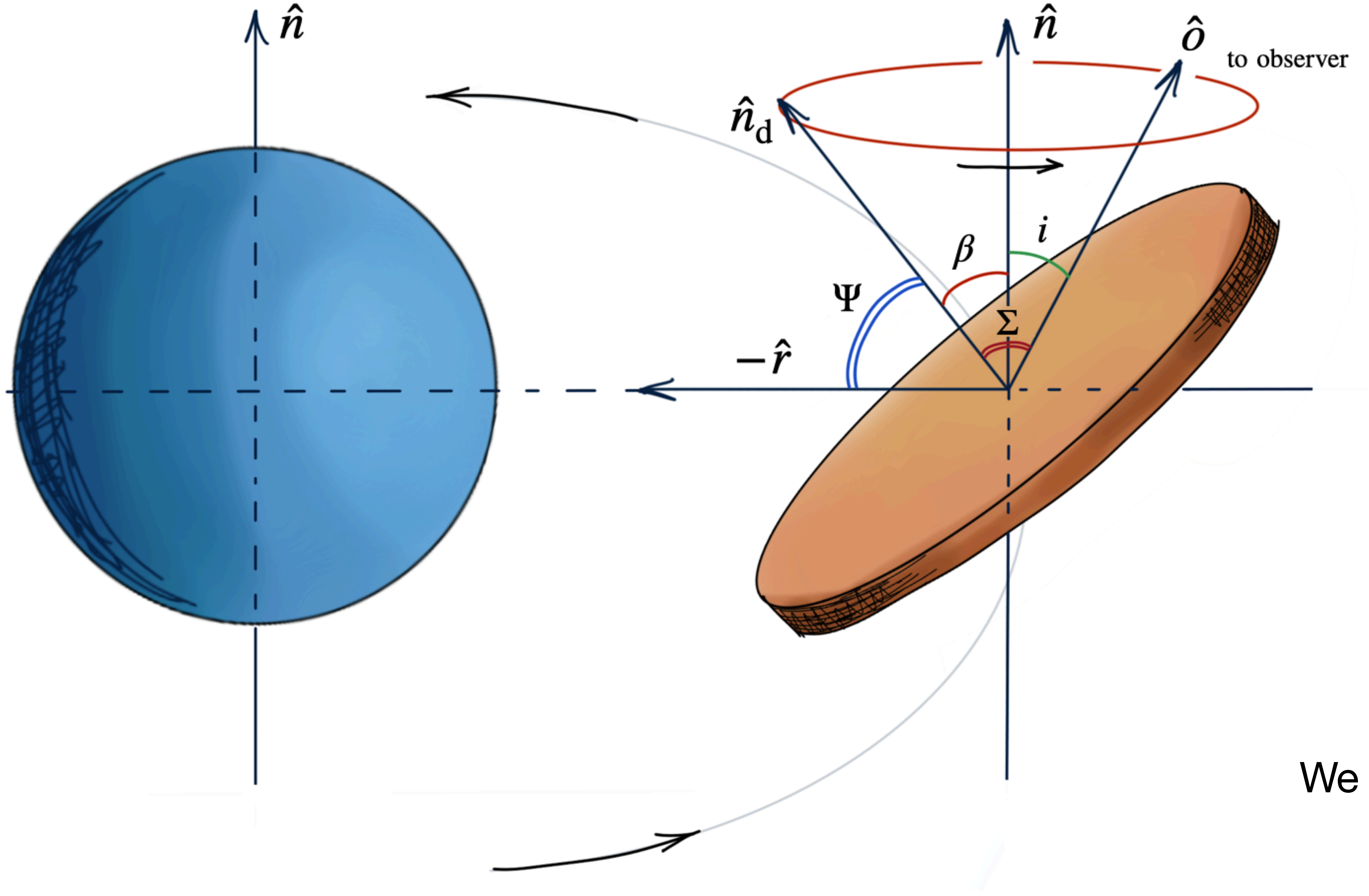


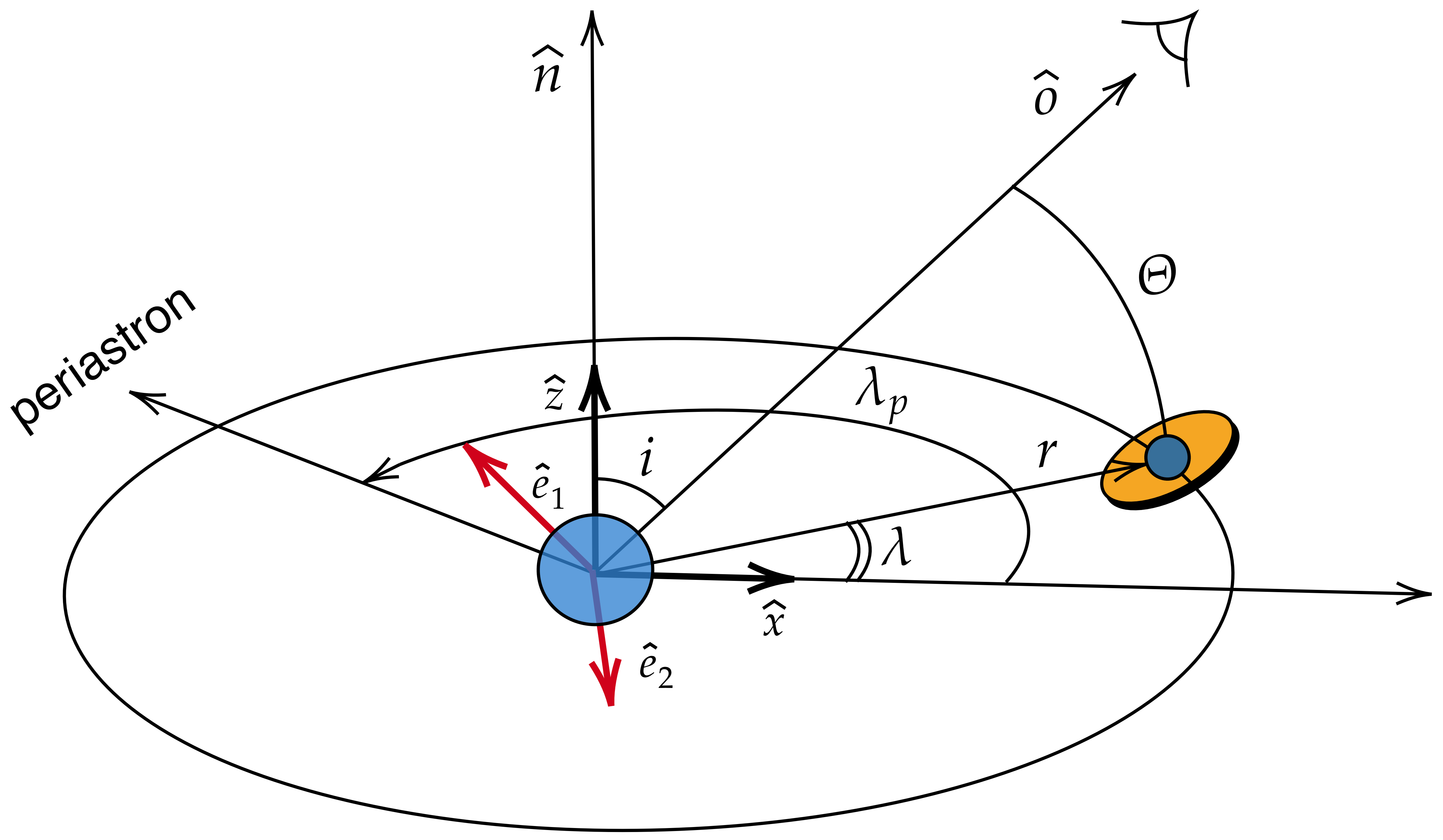


$$(q, u) = f(\phi, e, i, \Omega, \ldots, \beta)$$

Results

Model of Thomson scattering off tilted accretion disk



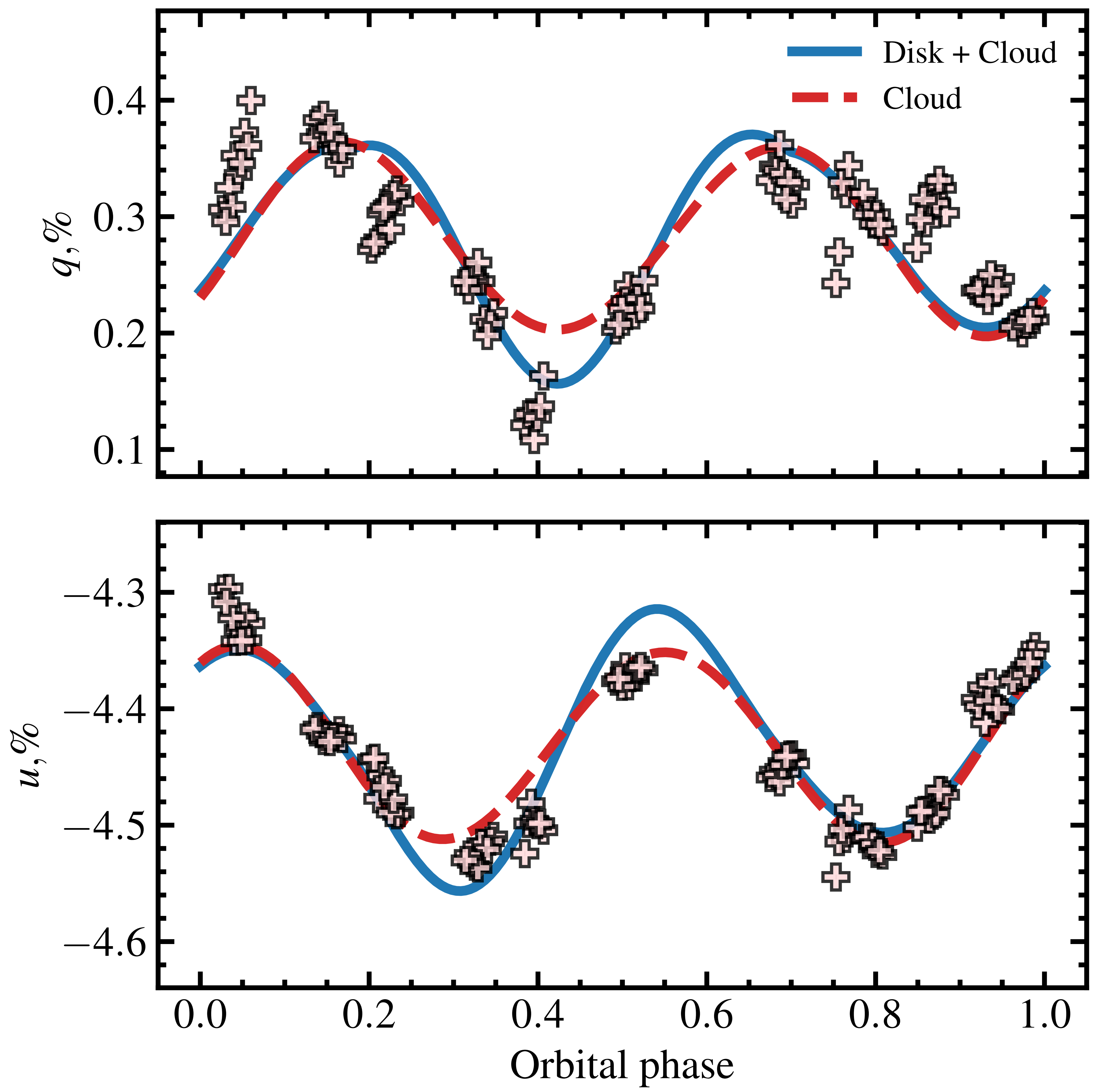


$$(q, u) = f(\phi, e, i, \Omega, \ldots, \beta)$$

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

Results

Model of Thomson scattering off tilted accretion disk



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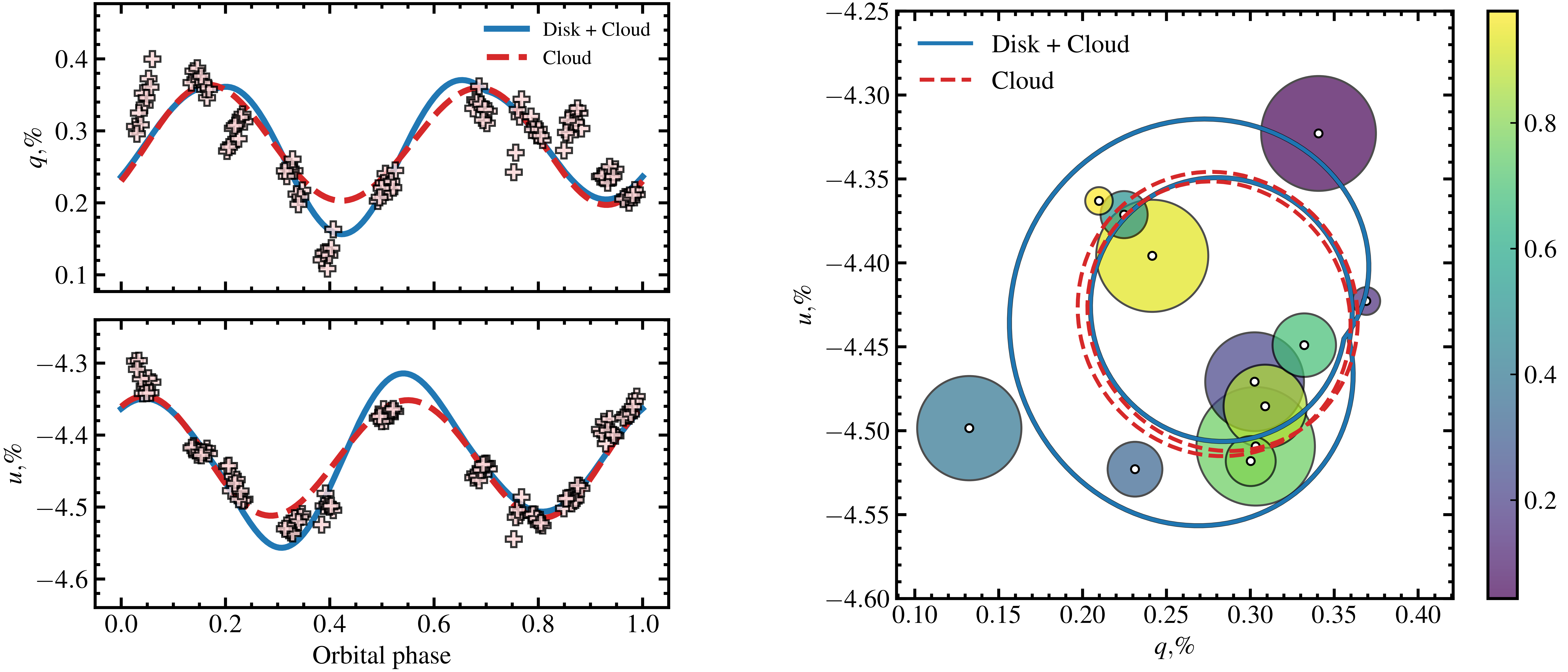


Project 2: polarization of low mass BHXRBs

Our sample of X-ray binaries

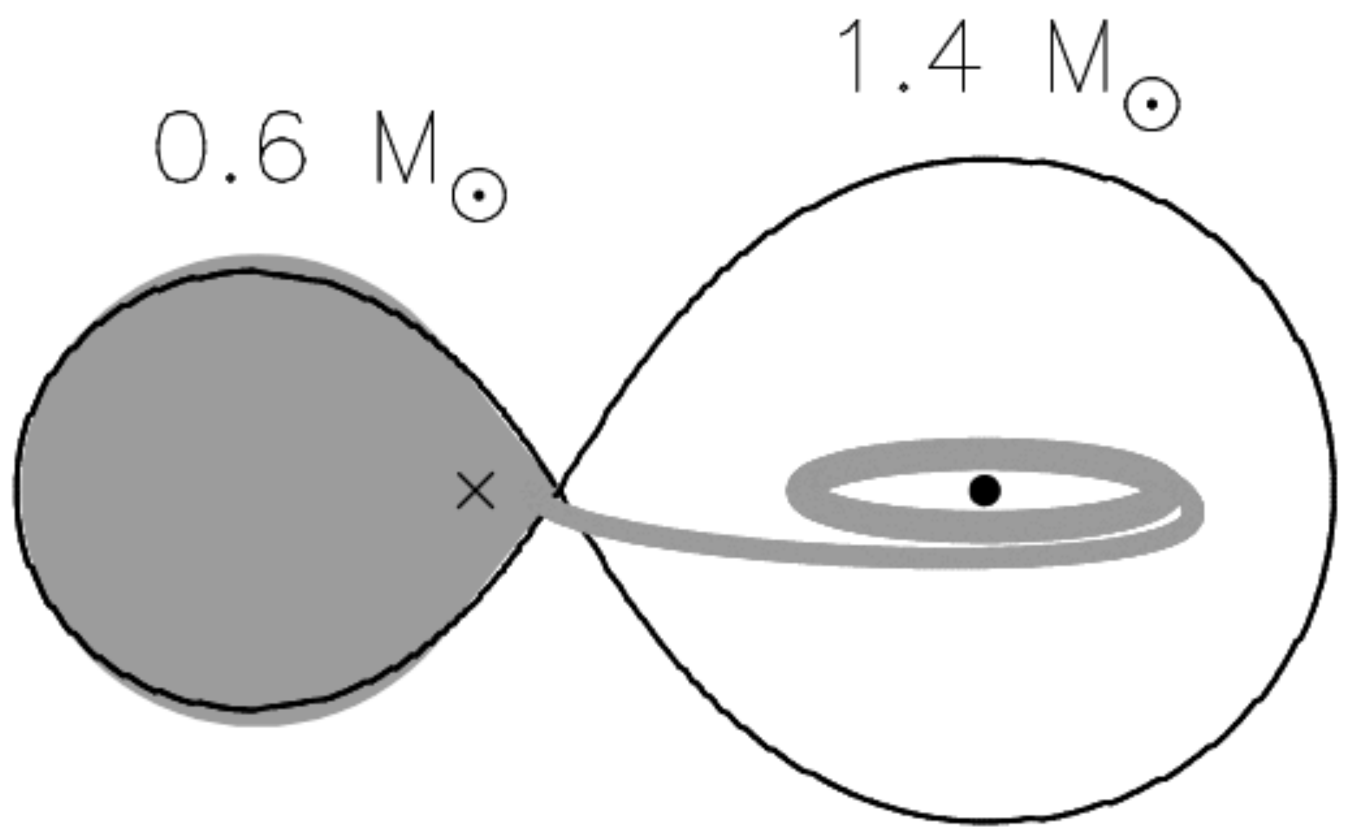
No significant polarization detected

- V404 Cyg
- 4U 1957+115
- LS V +44 17
- XTE J1118+480
- MAXI J0637–430
- Swift J1357.2–0933
- Swift J1727.8–1613

Exceptional sources!

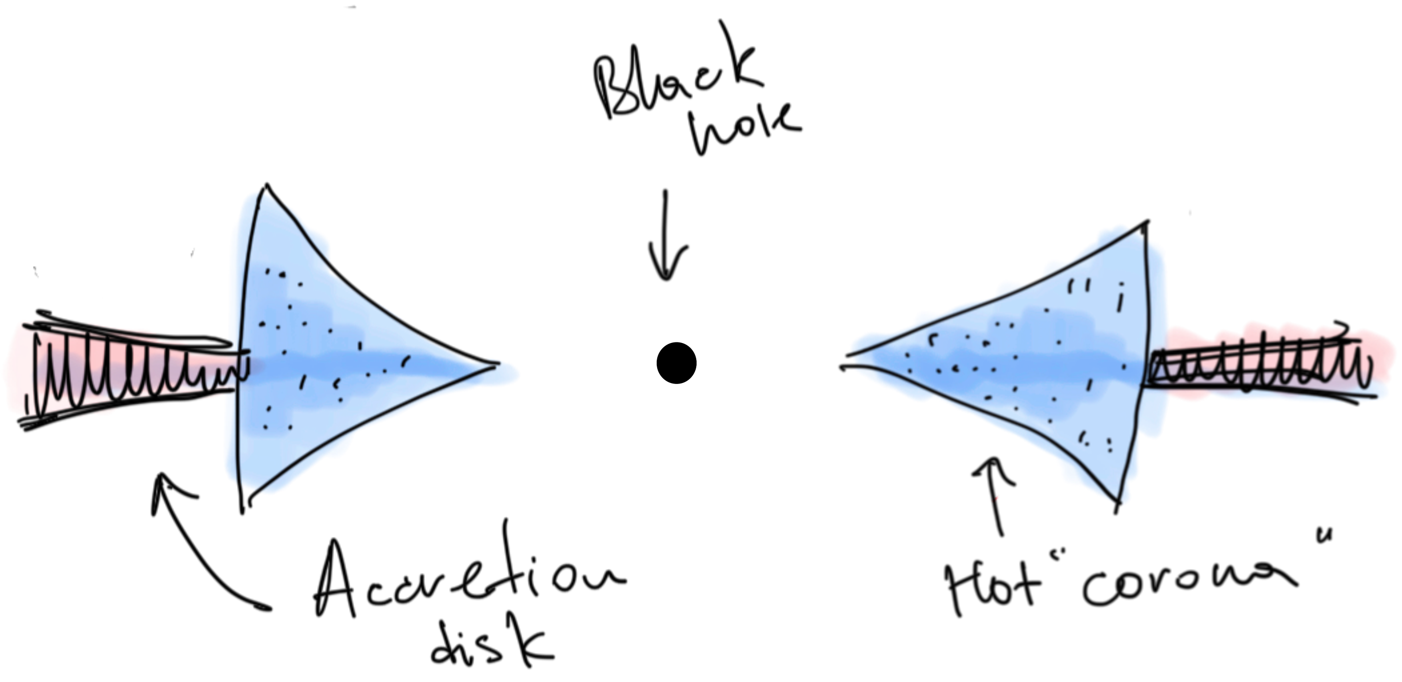
- 1A 0620–00
- MAXI J1820+070

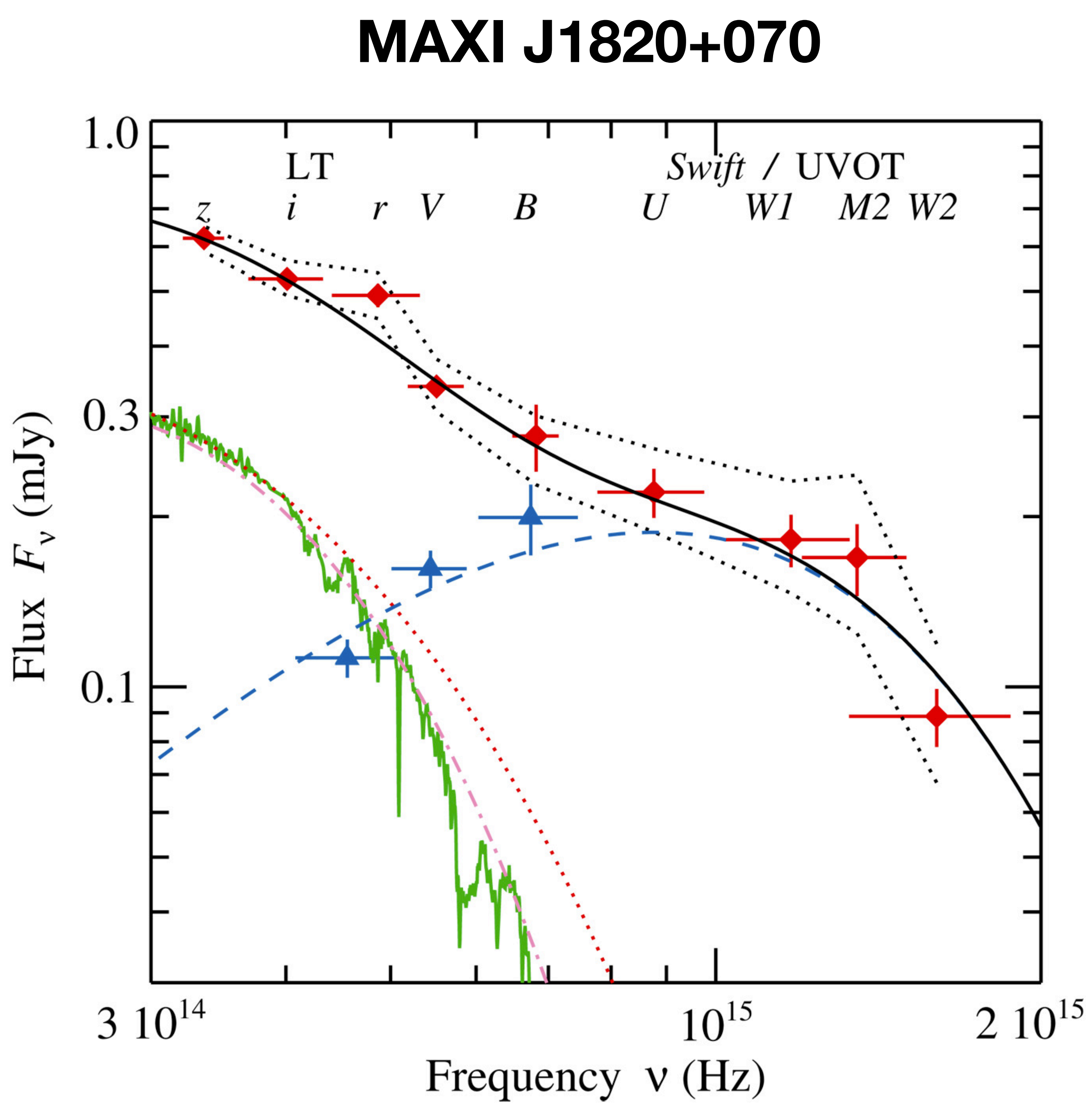
Low Mass X-ray Binaries



Exceptional sources: MAXI J1820+070

- **MAXI J1820+070:** Poutanen et al., 2022 – polarization up to P_{int}~5% with the position angle changed by 40°(!) relative to the value in outburst, non-synchrotron origin, jet-spin misalignment(!)





Poutanen et al., 2022, Science

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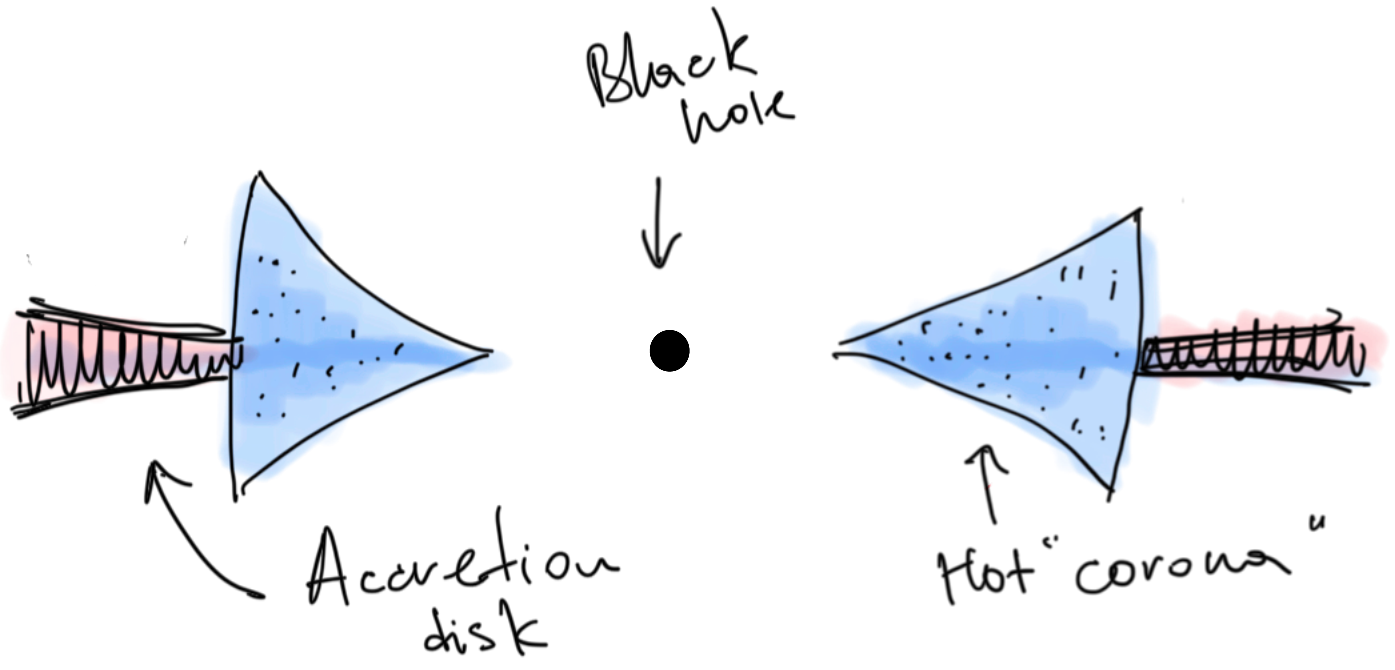
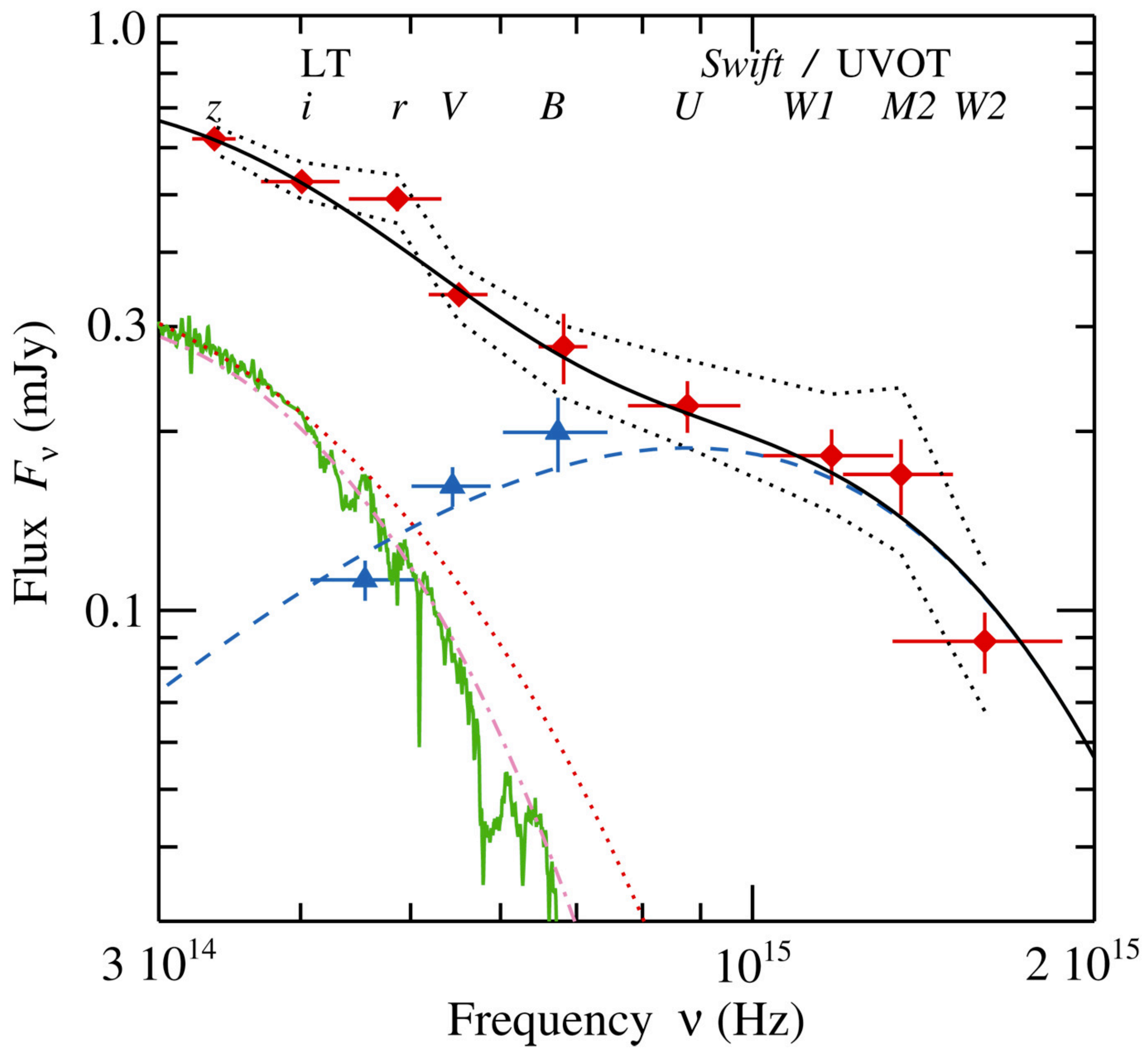
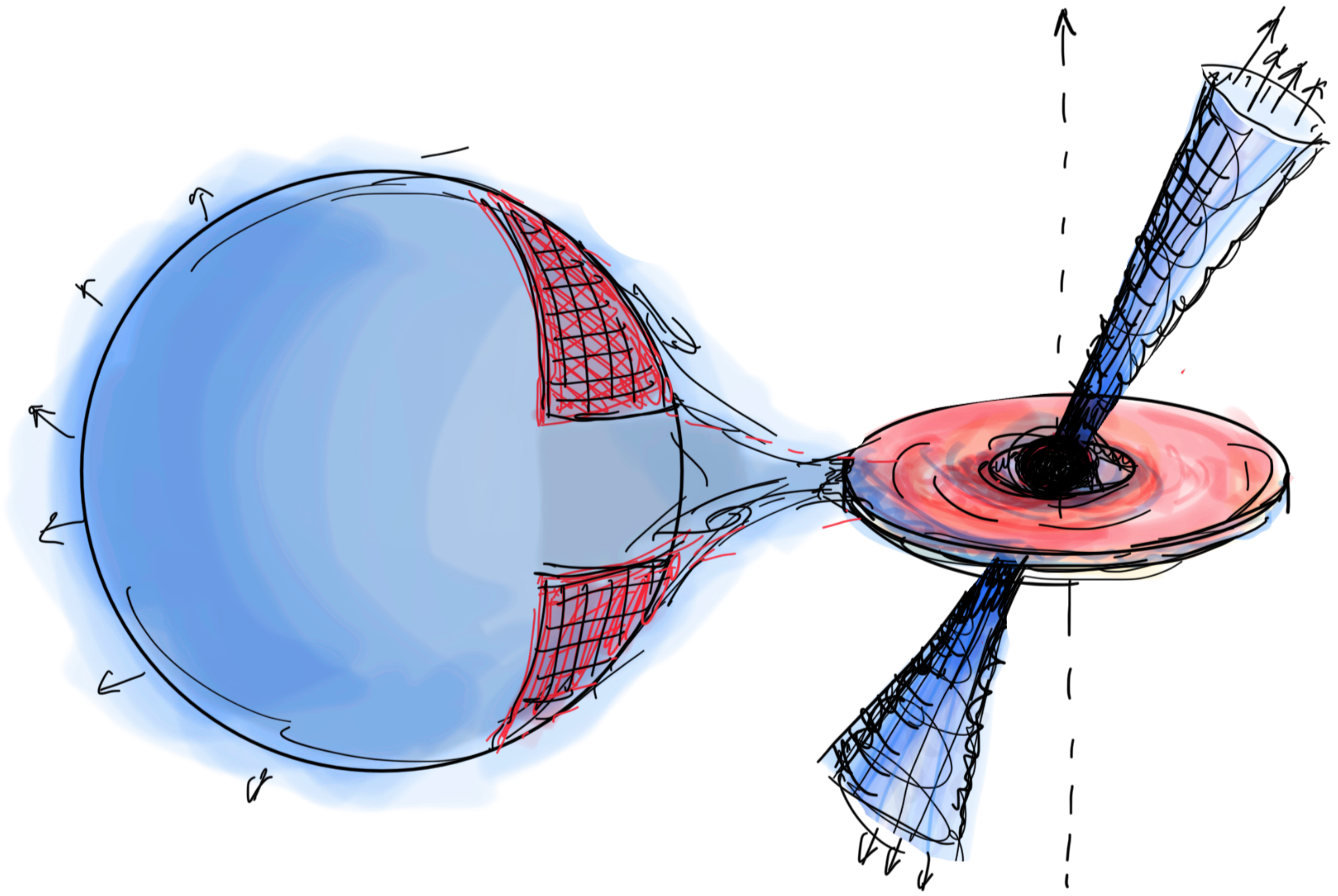


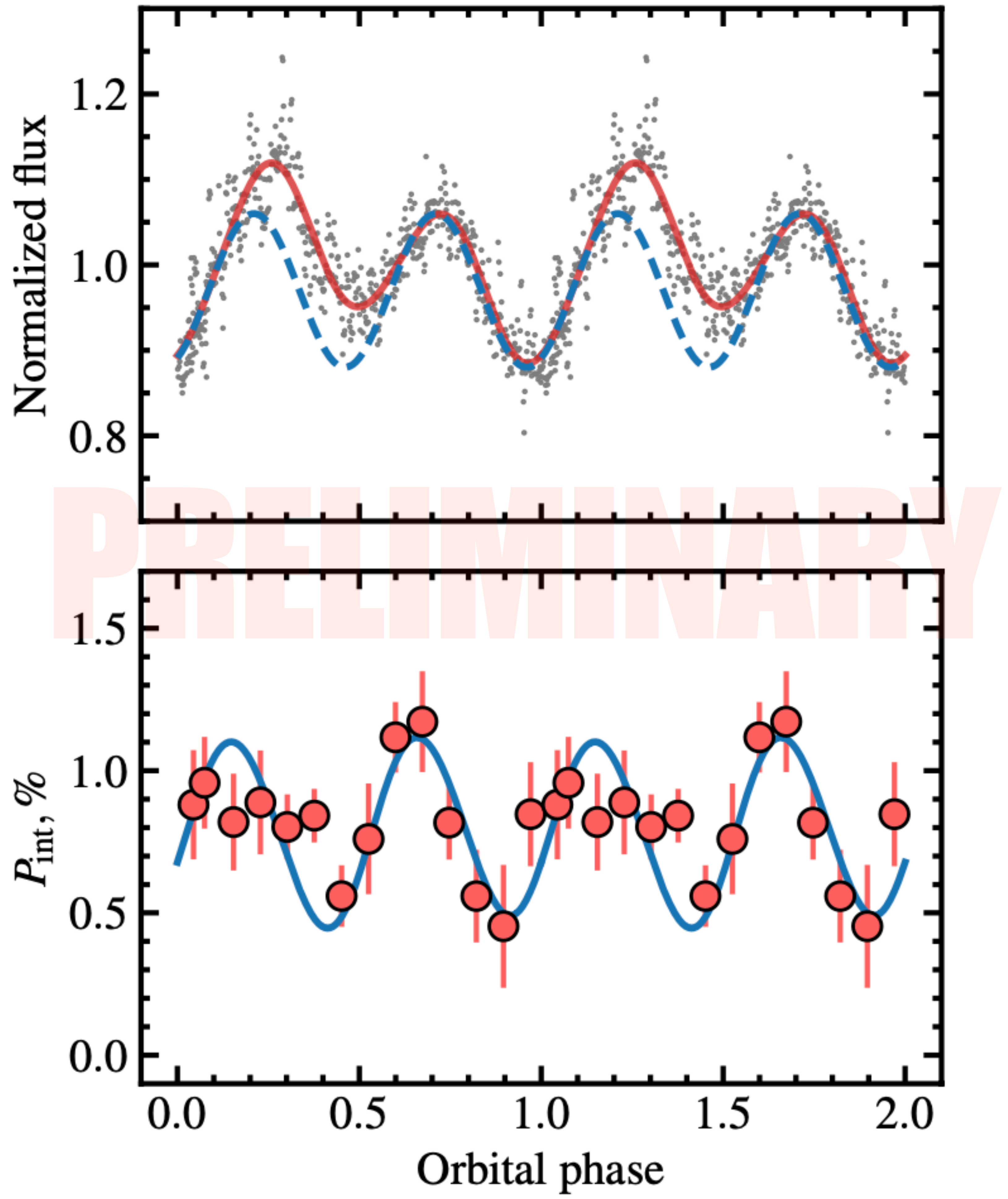
MAXI J1820+070

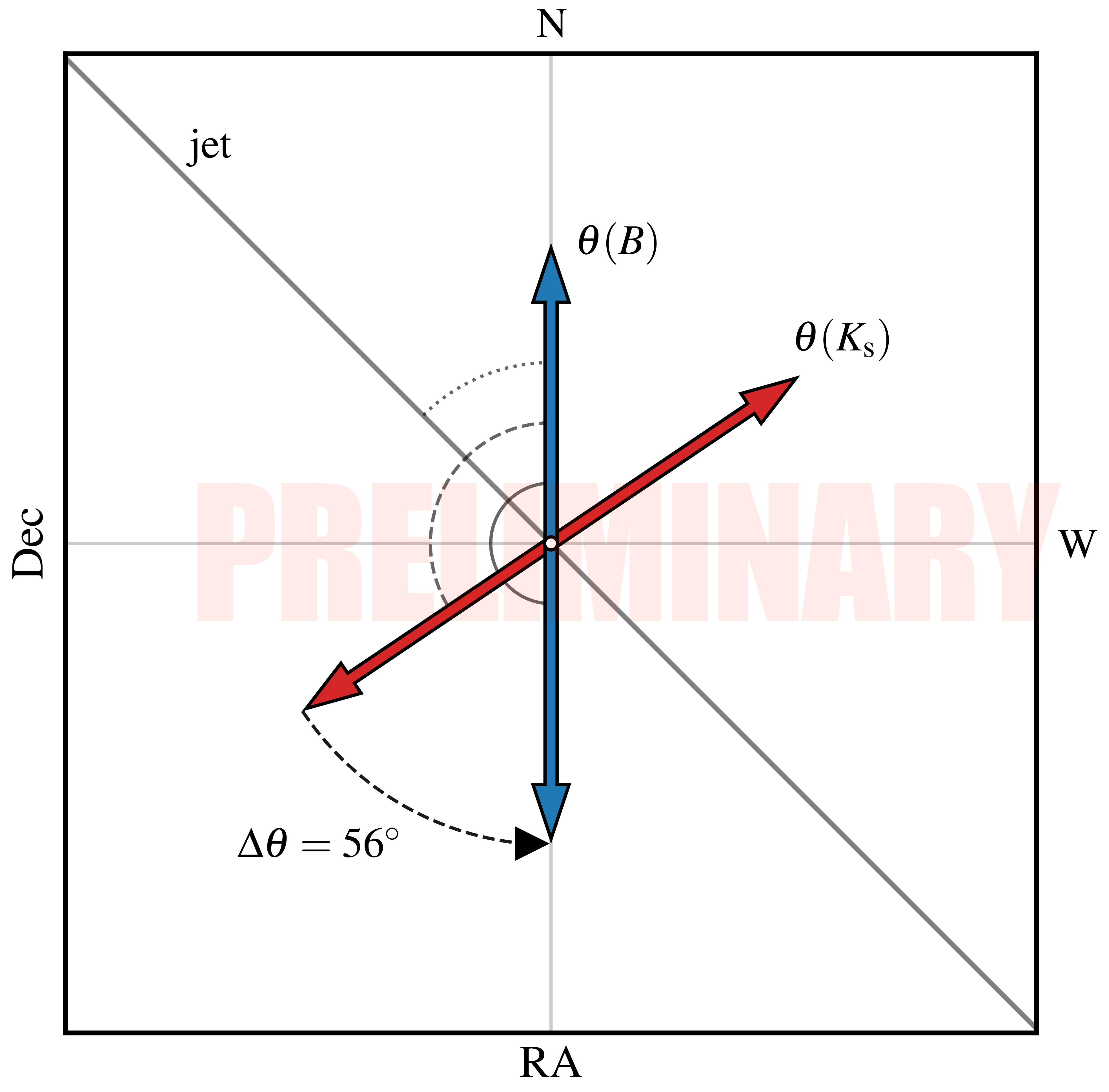


Poutanen et al., 2022, Science



Exceptional sources: A0620–00





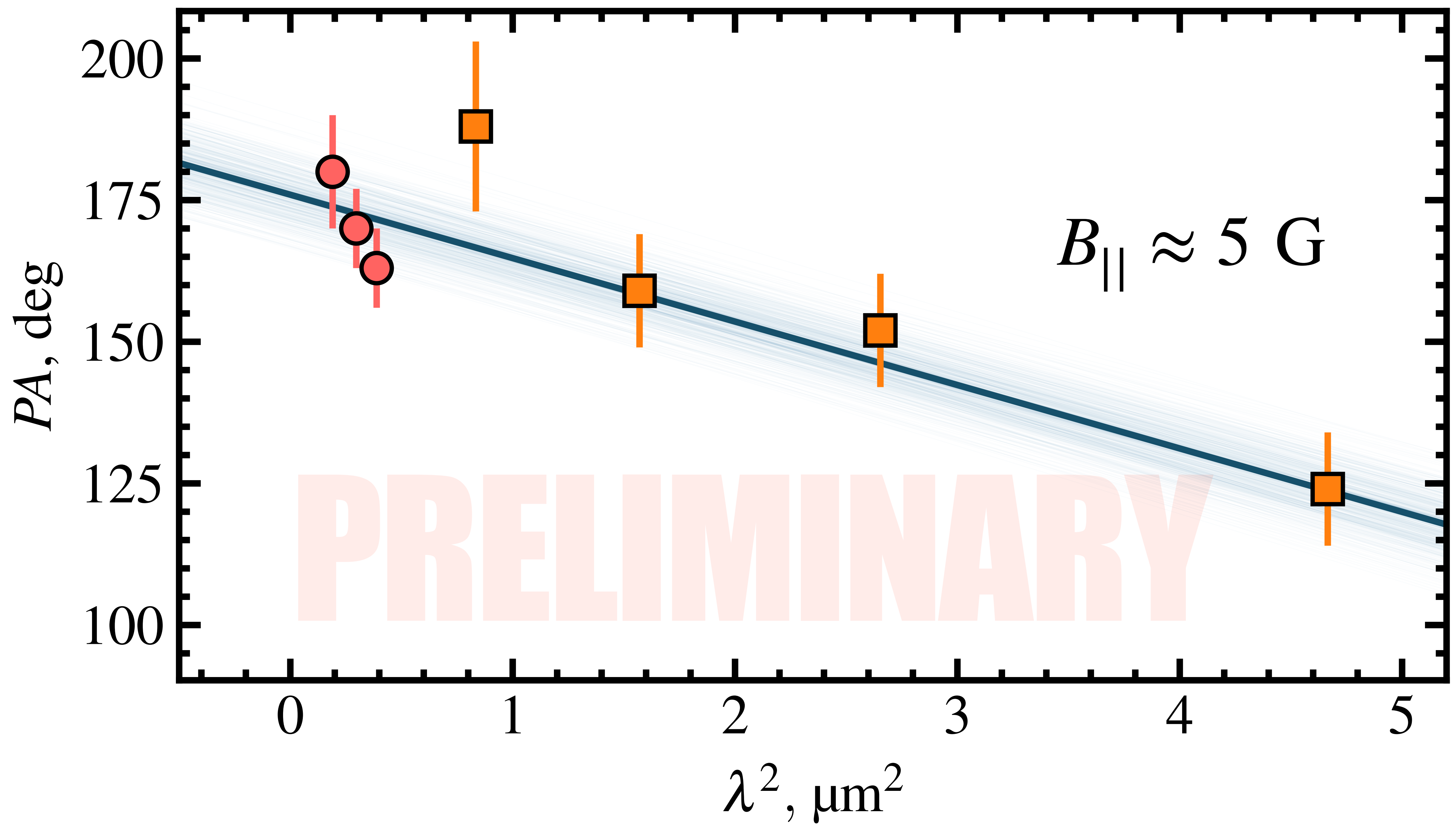
Puzzling polarization of A0620–00

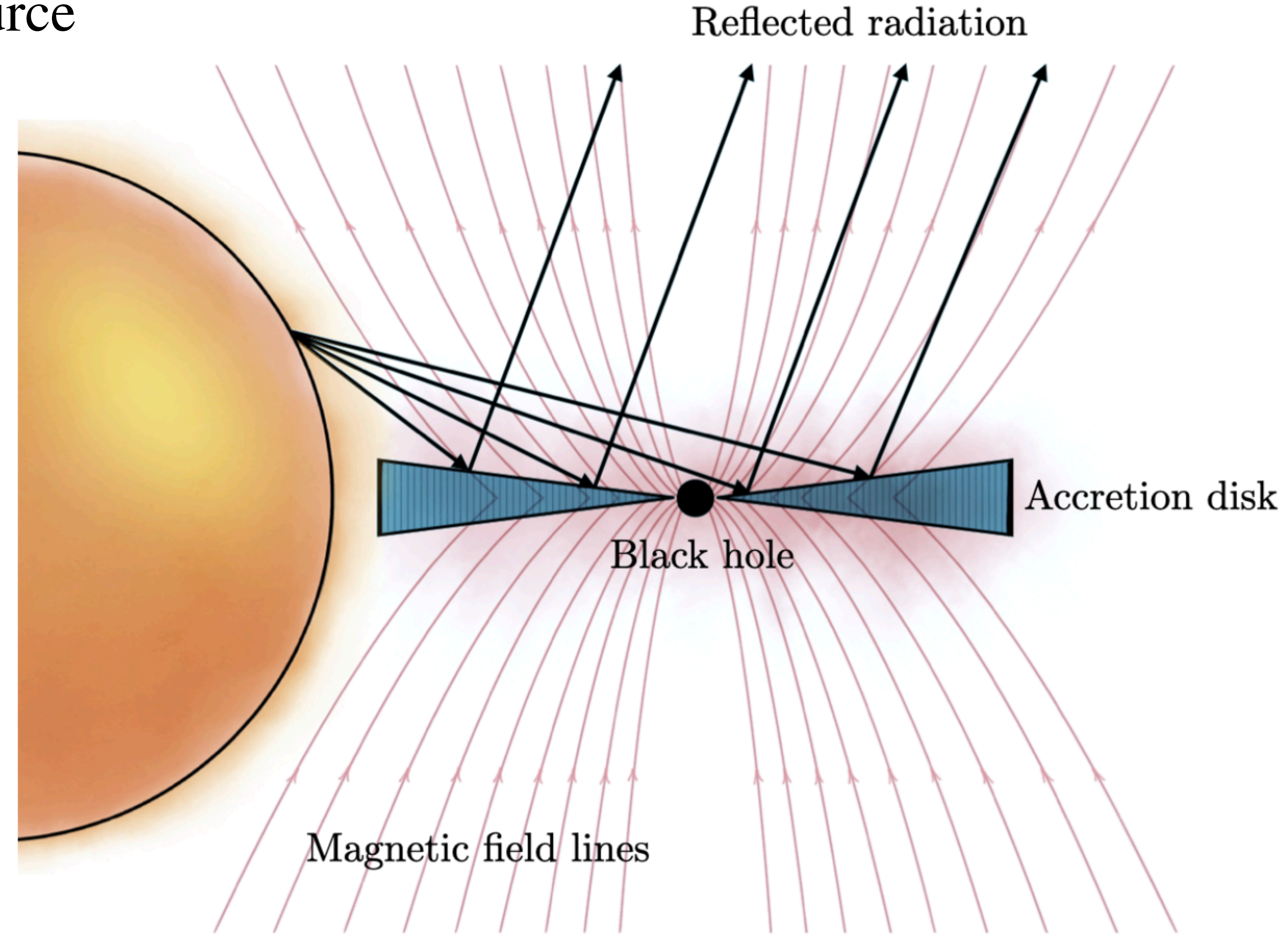
Kravtsov et al., 2024 (in prep)

Why angle rotates?

Faraday rotation?

$$\Delta\theta = \mathrm{RM}\lambda^2 \qquad RM = \frac{e^3}{2\pi m^2 c^4}\int_{\mathrm{source}}^{\mathrm{observer}} n_e(l)B_{||}(l)dl \approx 0.4\tau B_{||}\ \mathrm{rad}\ \mu\mathrm{m}^{-2}$$





Puzzling polarization of A0620–00

Kravtsov et al., 2024 (in prep)

Conclusions

- We used high precision optical polarimetry **to study the geometry of black hole binary systems**
- We have done probably the most comprehensive analysis of the polarization properties of X-ray binaries in a variety of spectral states
- Combined with the X-ray polarimetry, high precision optical polarimetry **put constraints on the accretion mechanisms in X-ray binaries**
- Our studies resulted in **9 referred papers published**, including 2 papers in Science