

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

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Andrzej Zdziarski

Juri Poutanen

and others....

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**Aalto University**

**Espoo, Finland**

**17 January 2024**

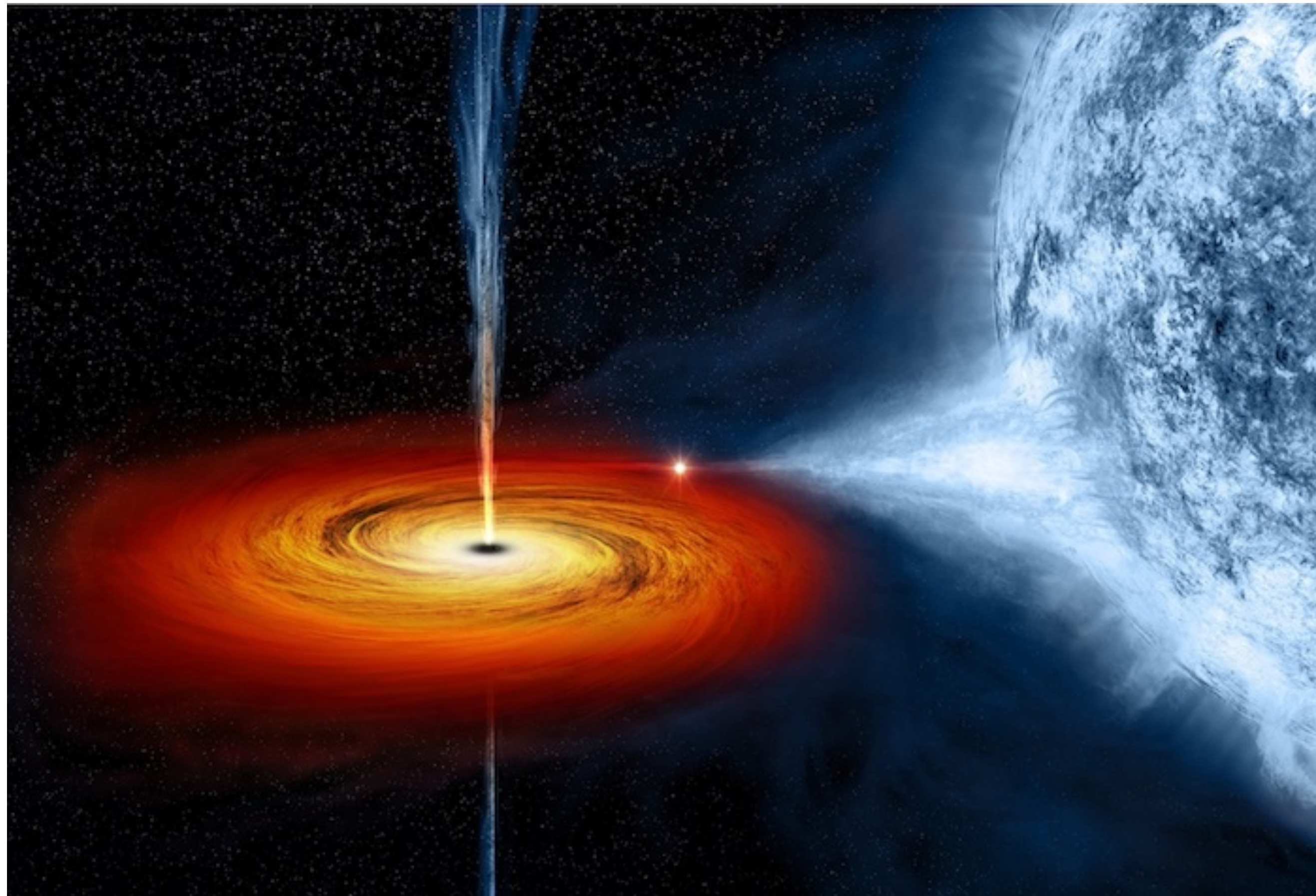


[www.vakrau.com](http://www.vakrau.com)

# Introduction

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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**

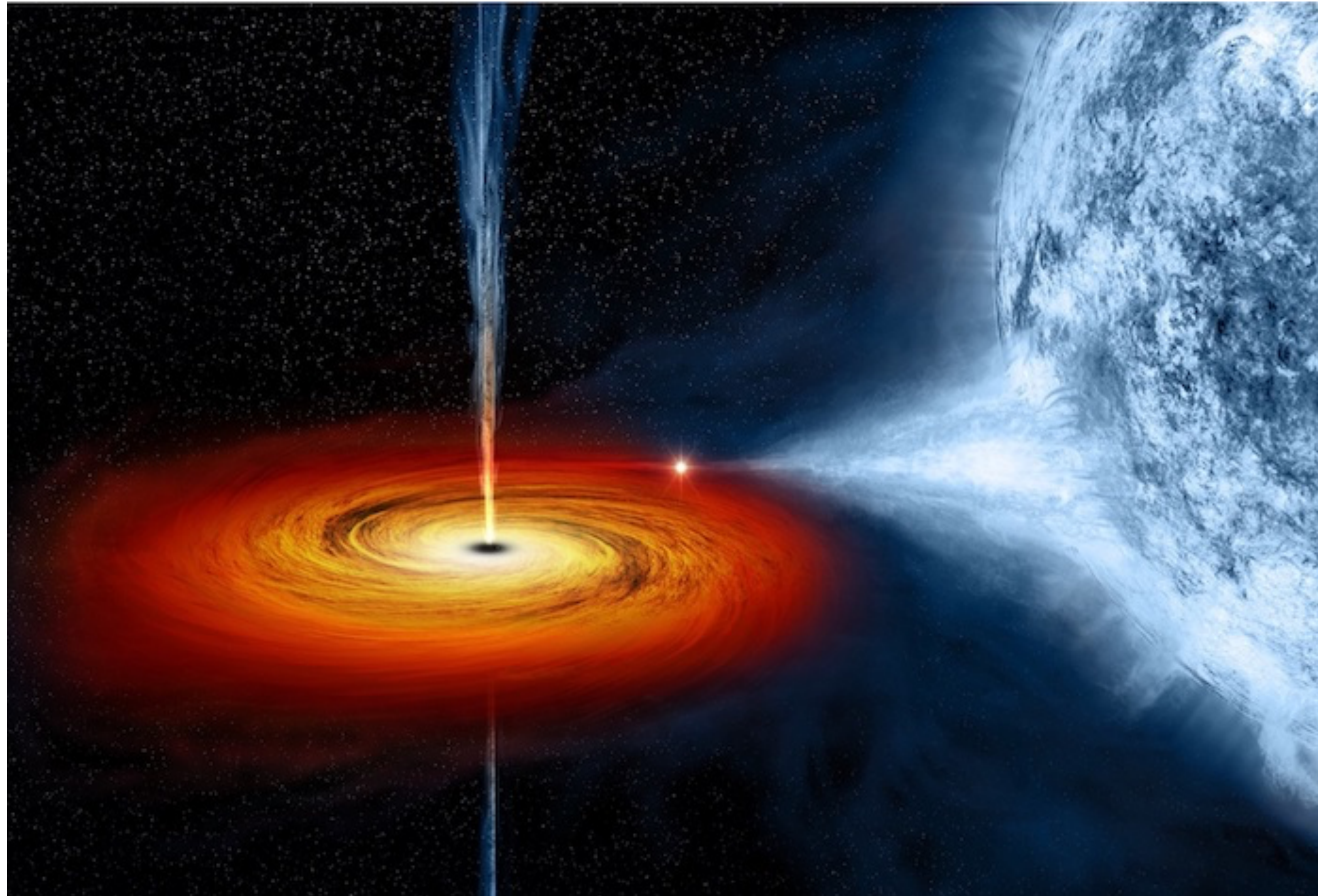
The observed X-ray luminosity can be explained **only** if we assume that it is produced by the **most effective source of energy** – by accretion of matter onto the compact massive object.

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

$$\eta_{\text{nuc}} < 1\% \quad \eta_{\text{acc}} \sim 10\%$$

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Definition of X-ray binary star



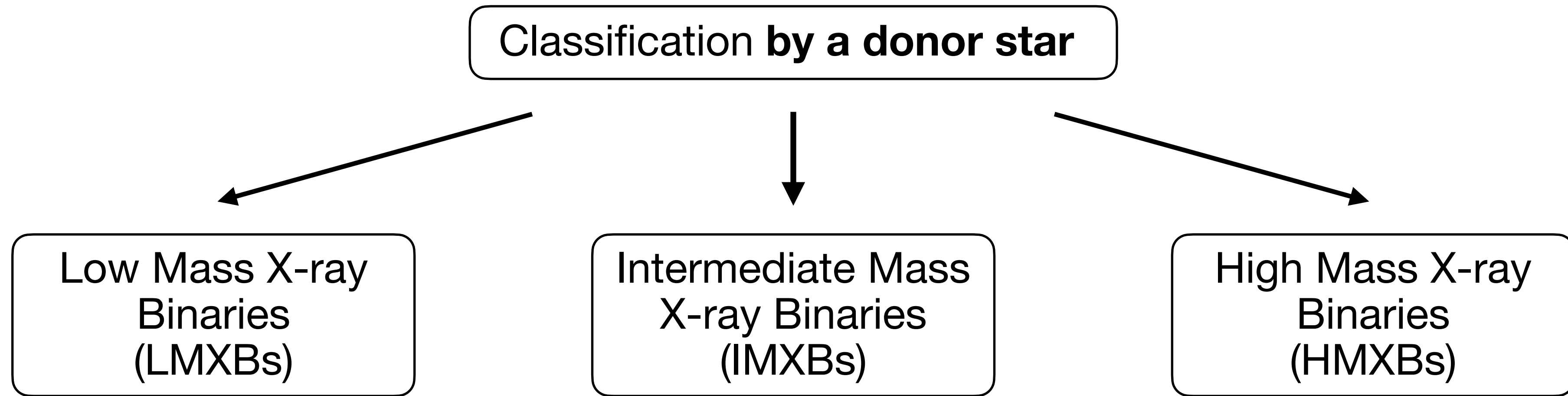
To produce X-rays via accretion, we should have:

- **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**.

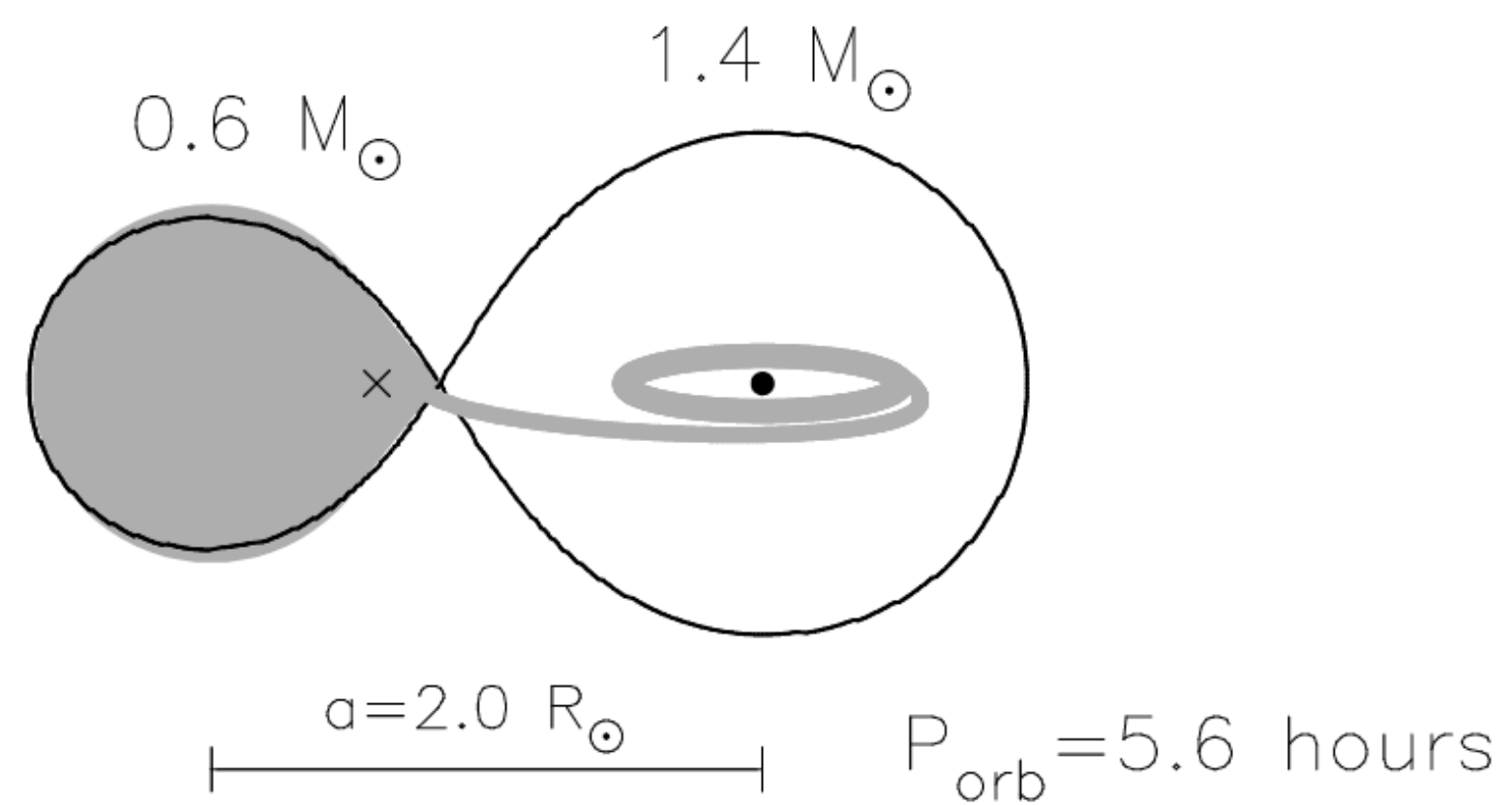
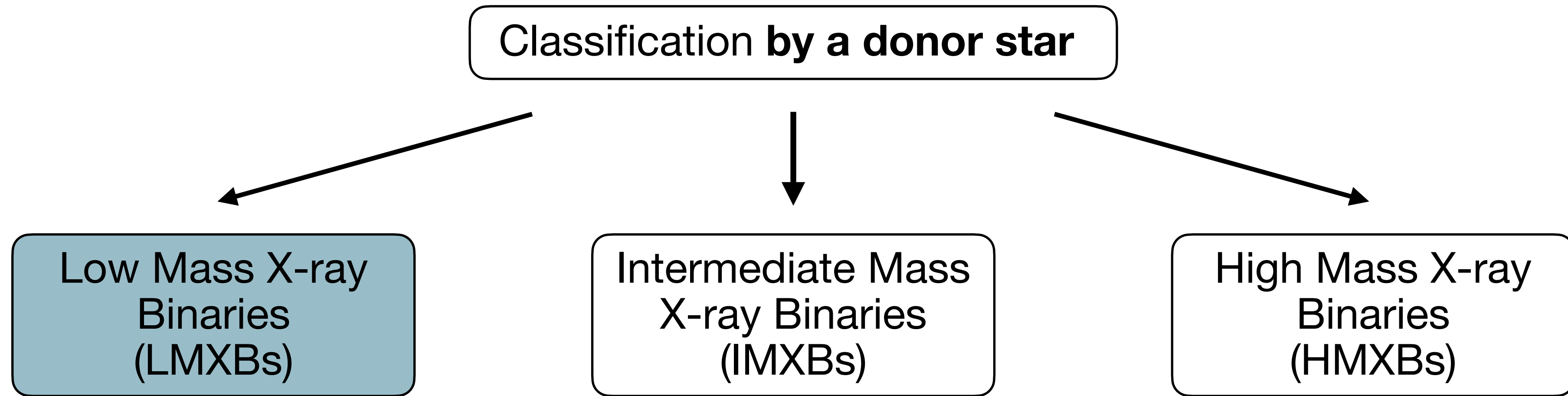
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Classification of X-ray binaries



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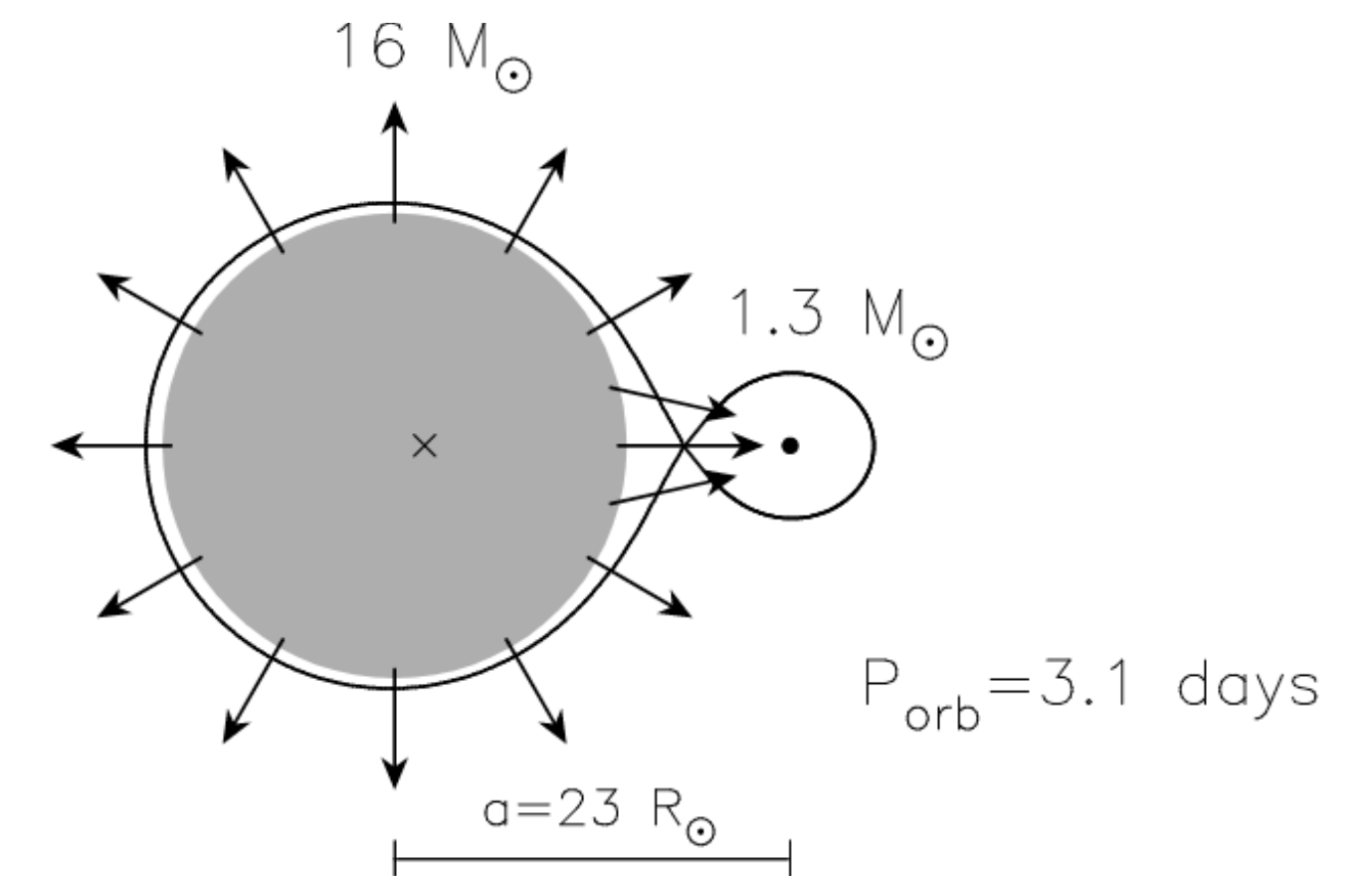
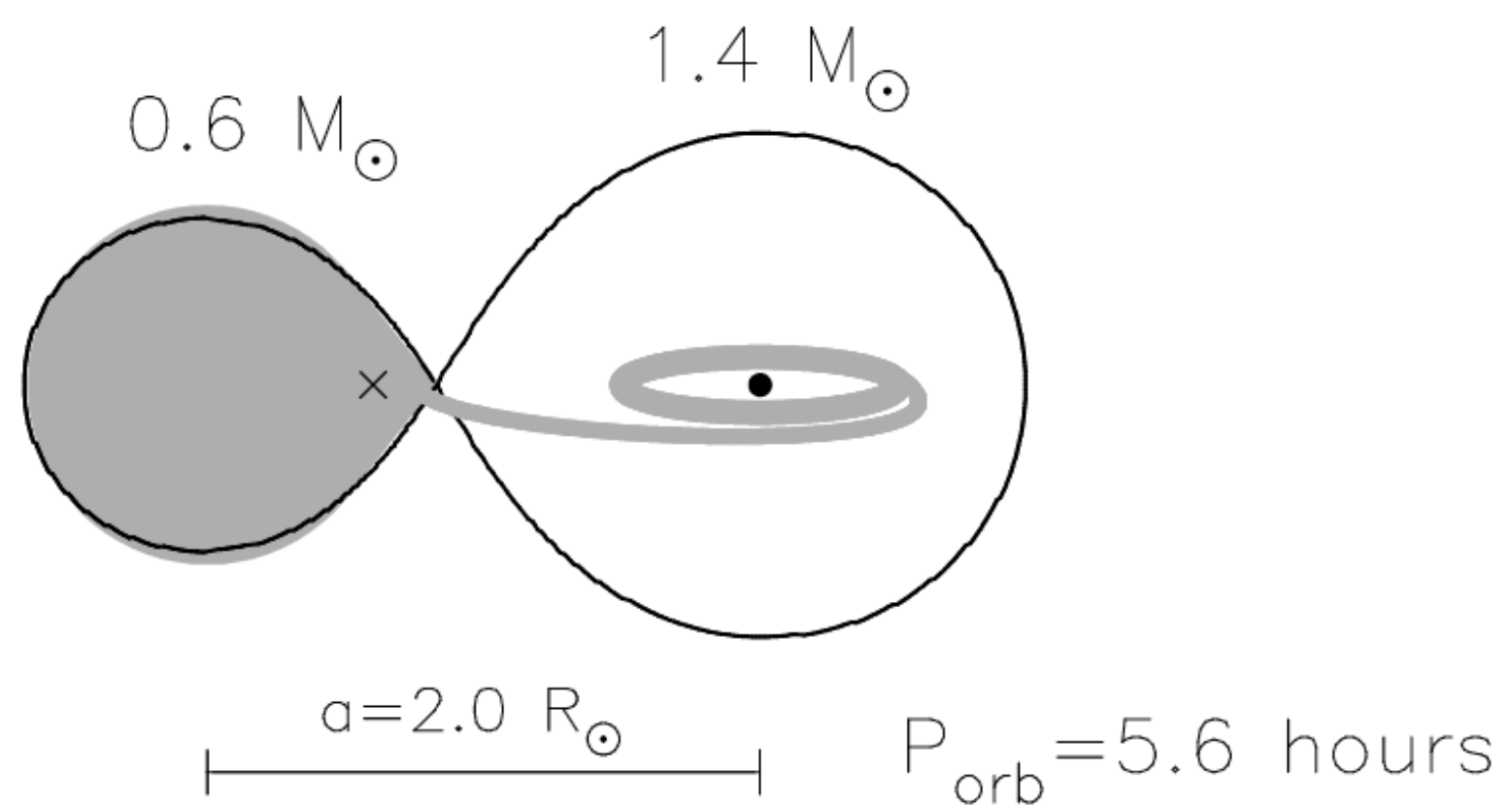
Classification of X-ray binaries

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

Classification **by an accretor**

Neutron Star  
X-ray binary  
(NSXRBs)

Black Hole  
X-ray binary  
(BHXRBS)

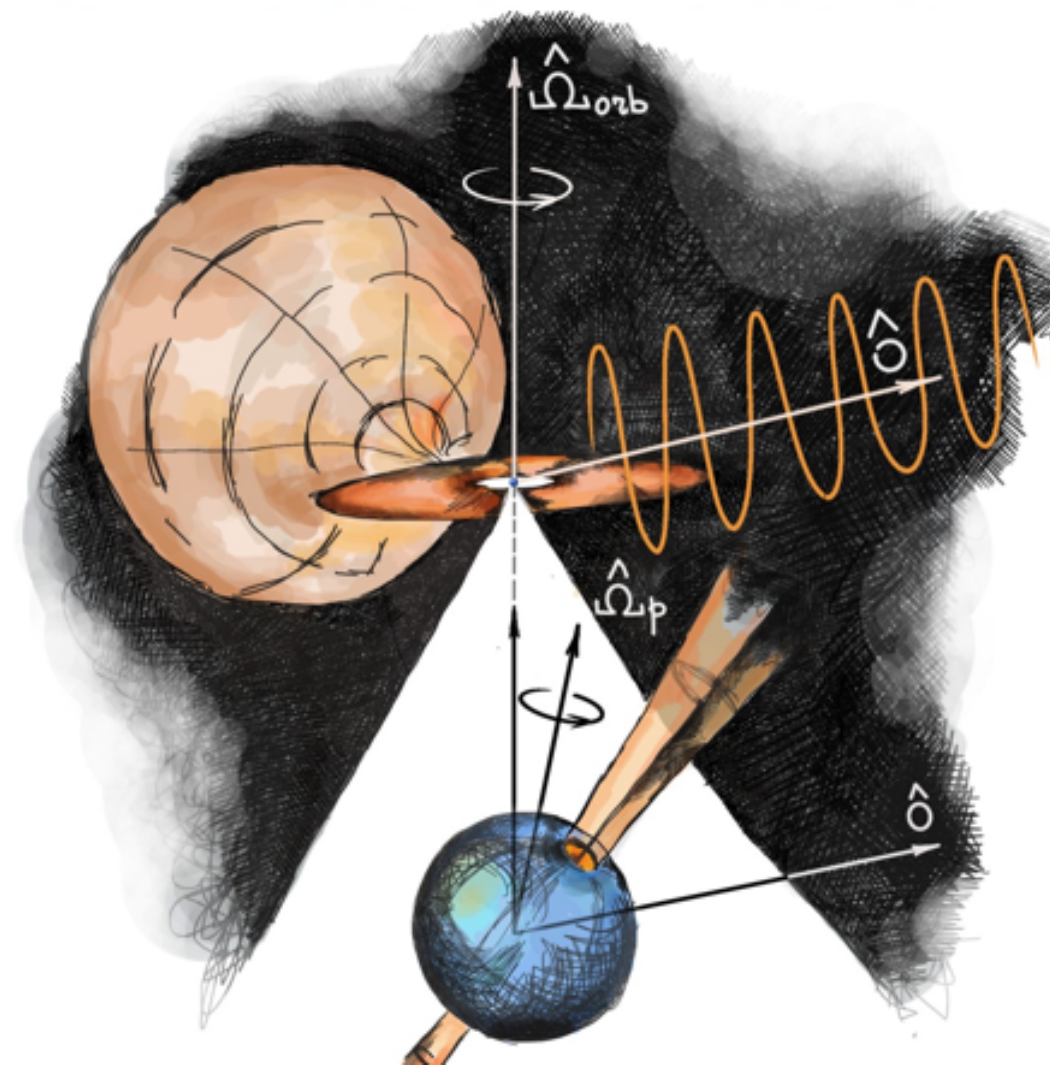


Image: Alexander Mushtukov

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Classification of X-ray binaries

Classification by an accretor

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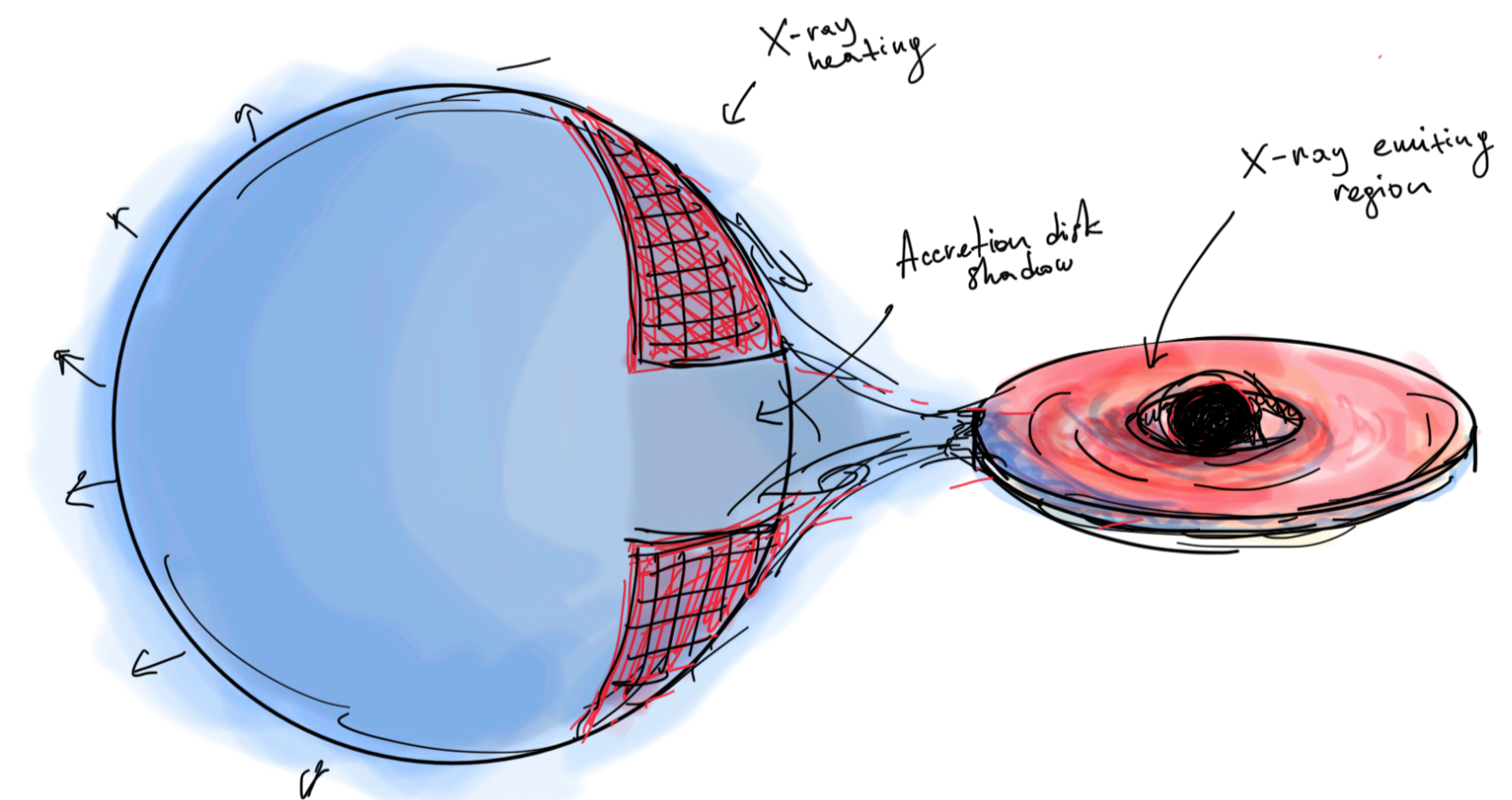
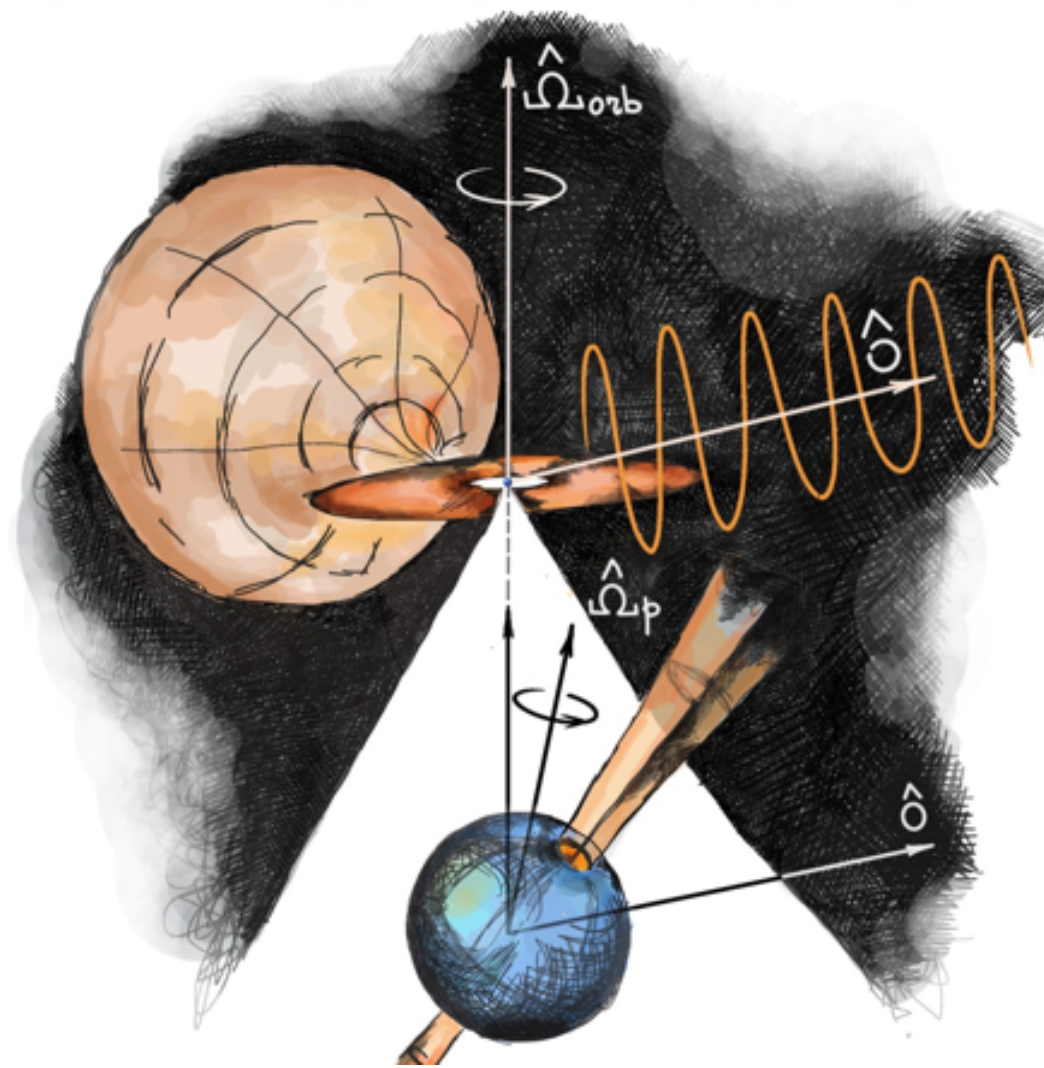
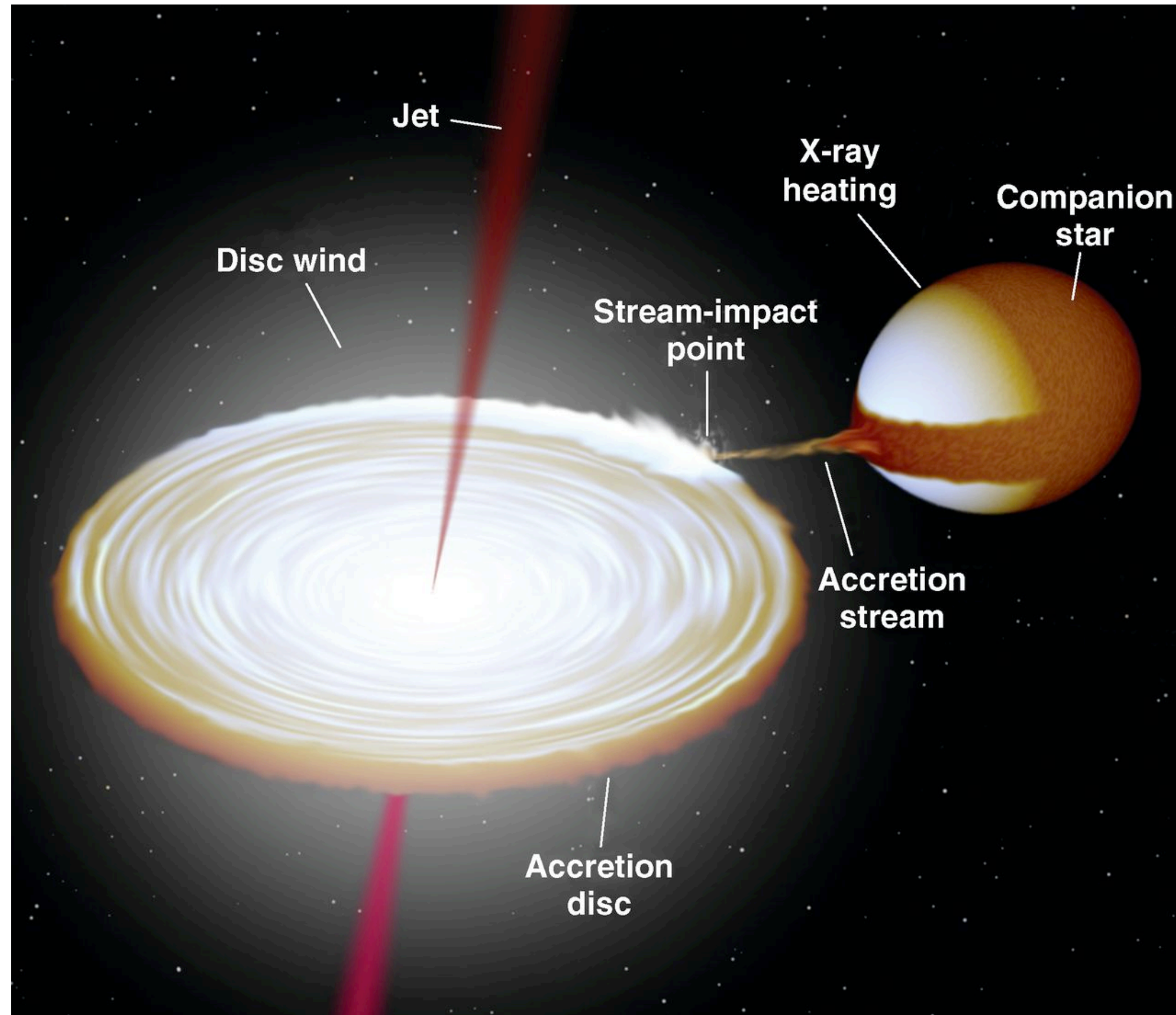


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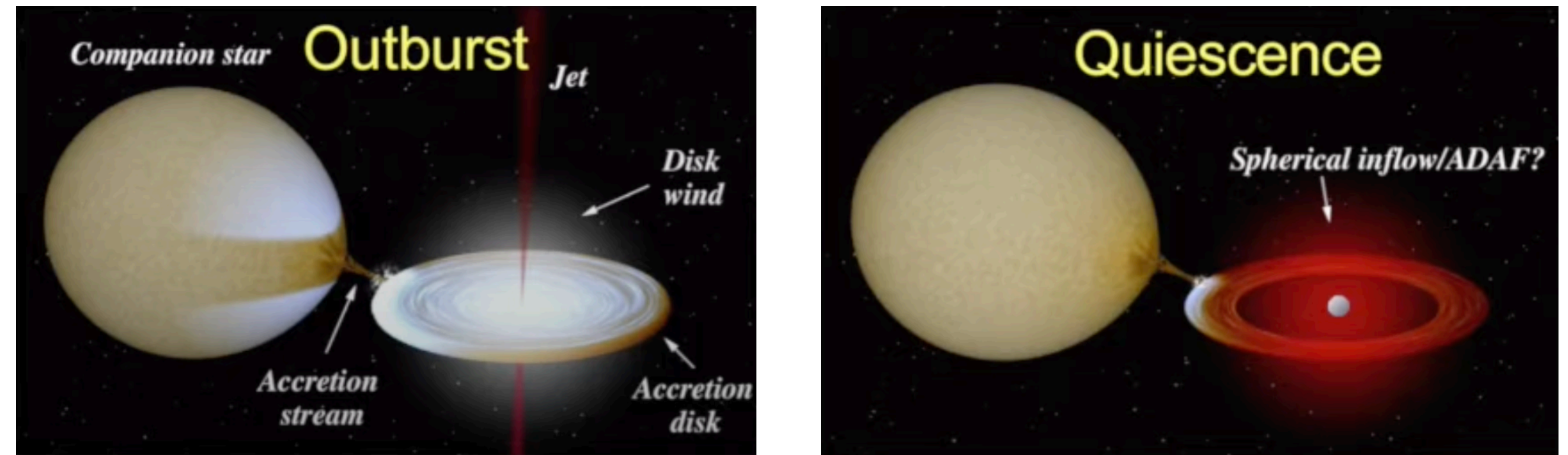
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Geometry and spectra of X-ray binaries

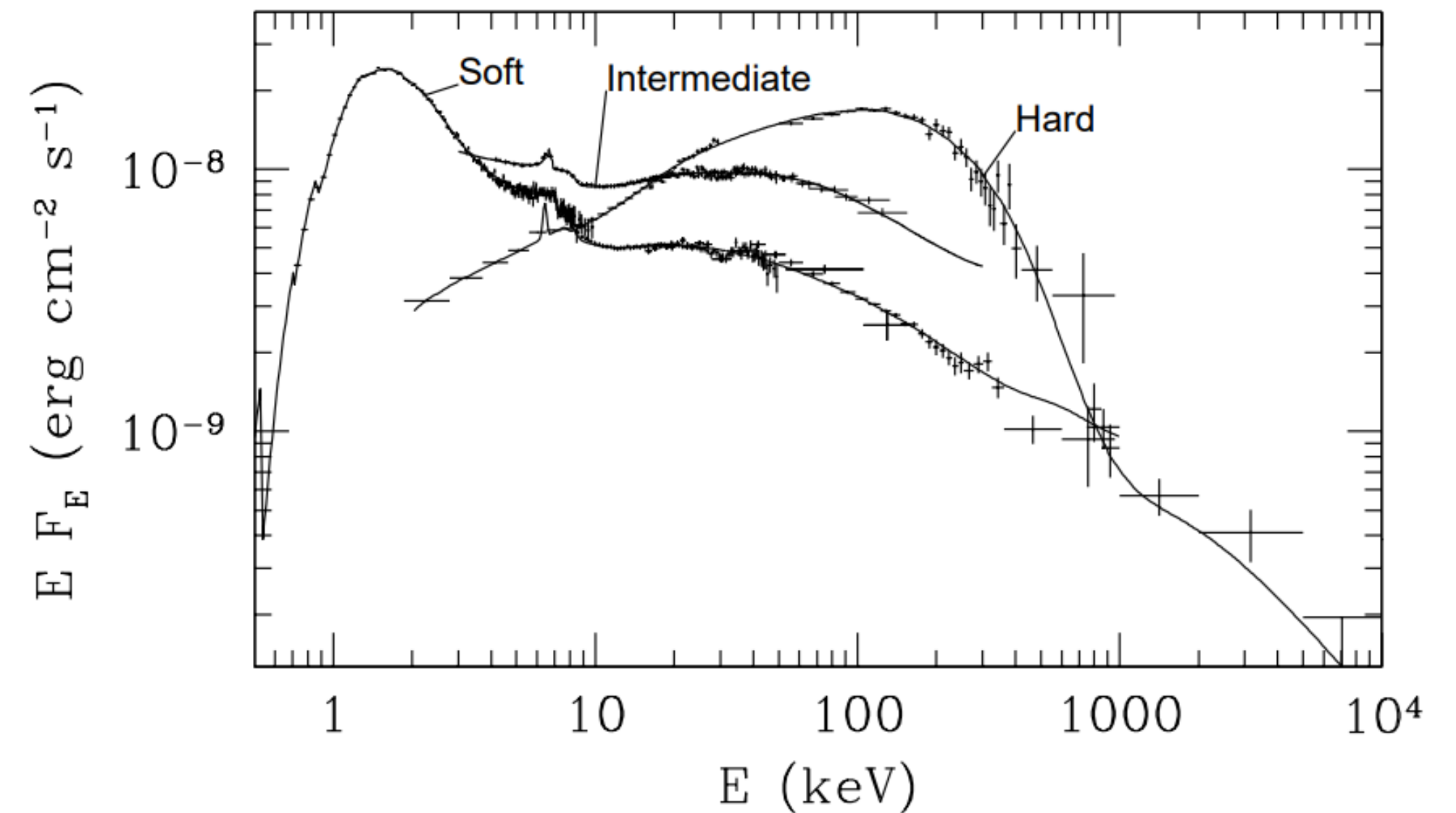


[Image produced with BinSim by Rob Hynes]

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

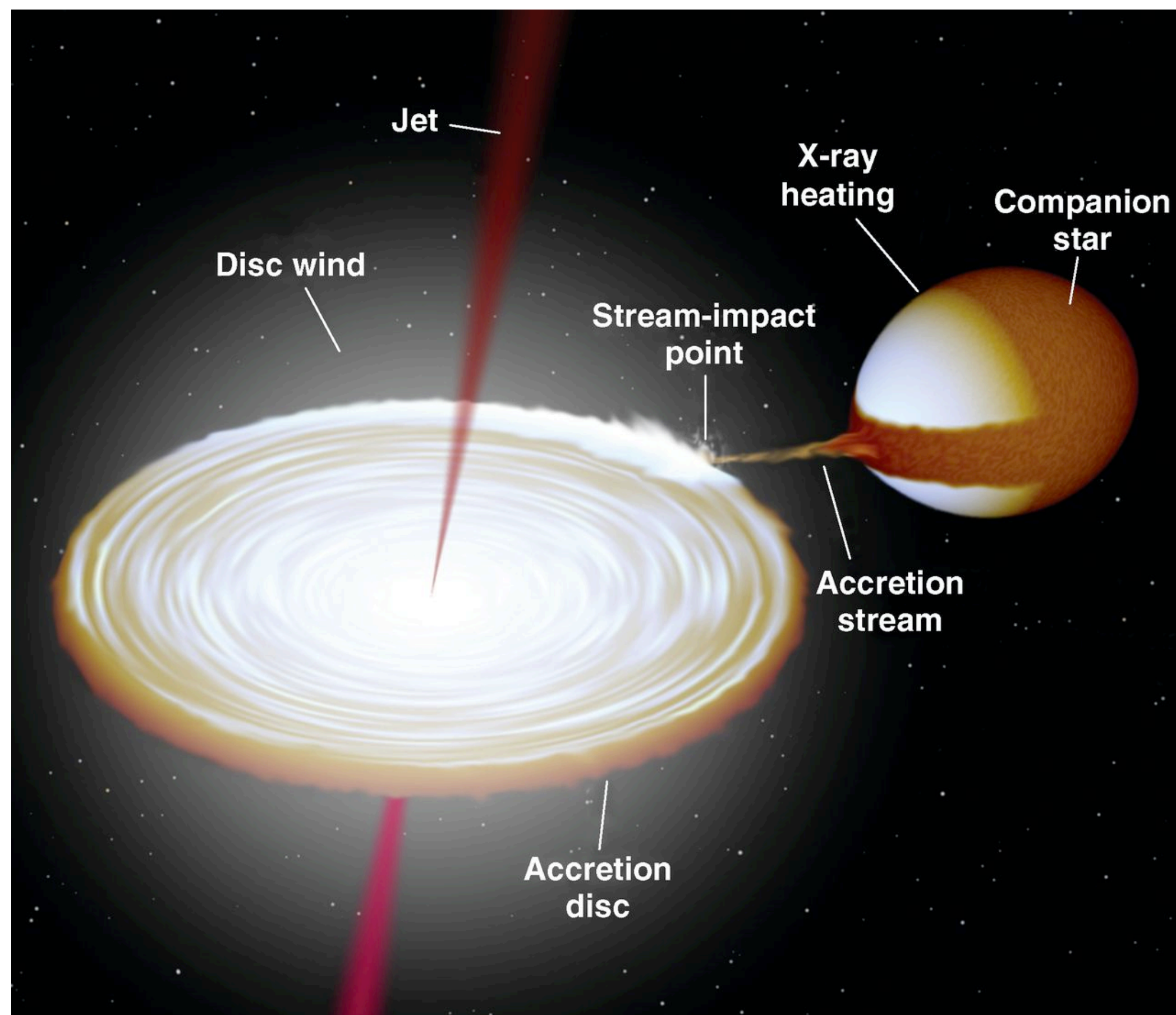


optical star + accretion disk + jet + wind + hot accretion flow + ...



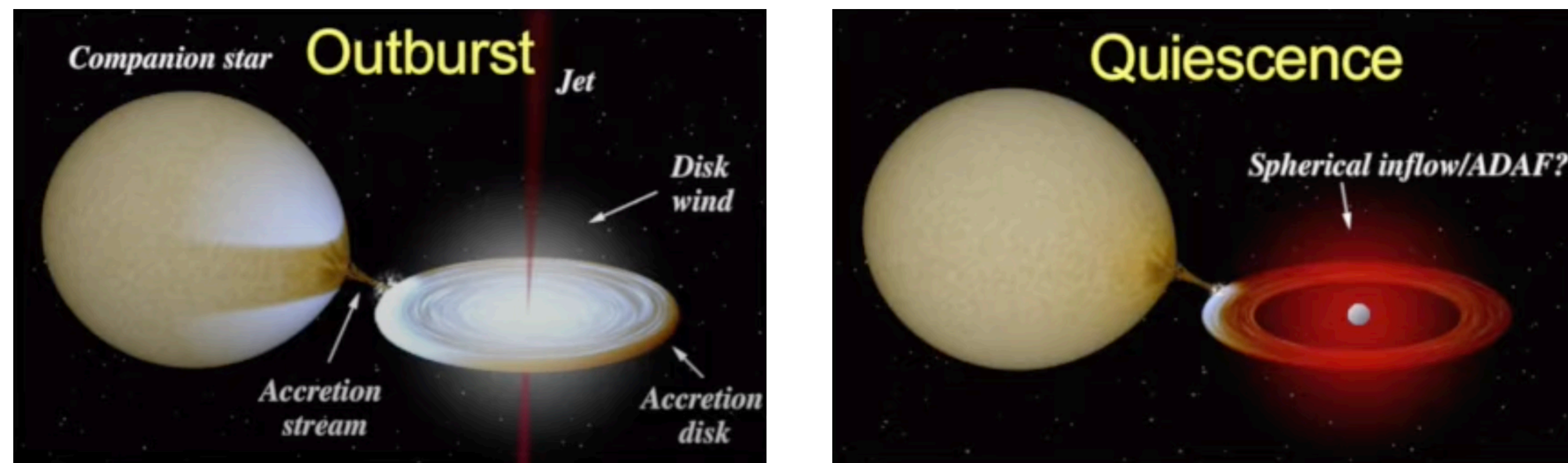
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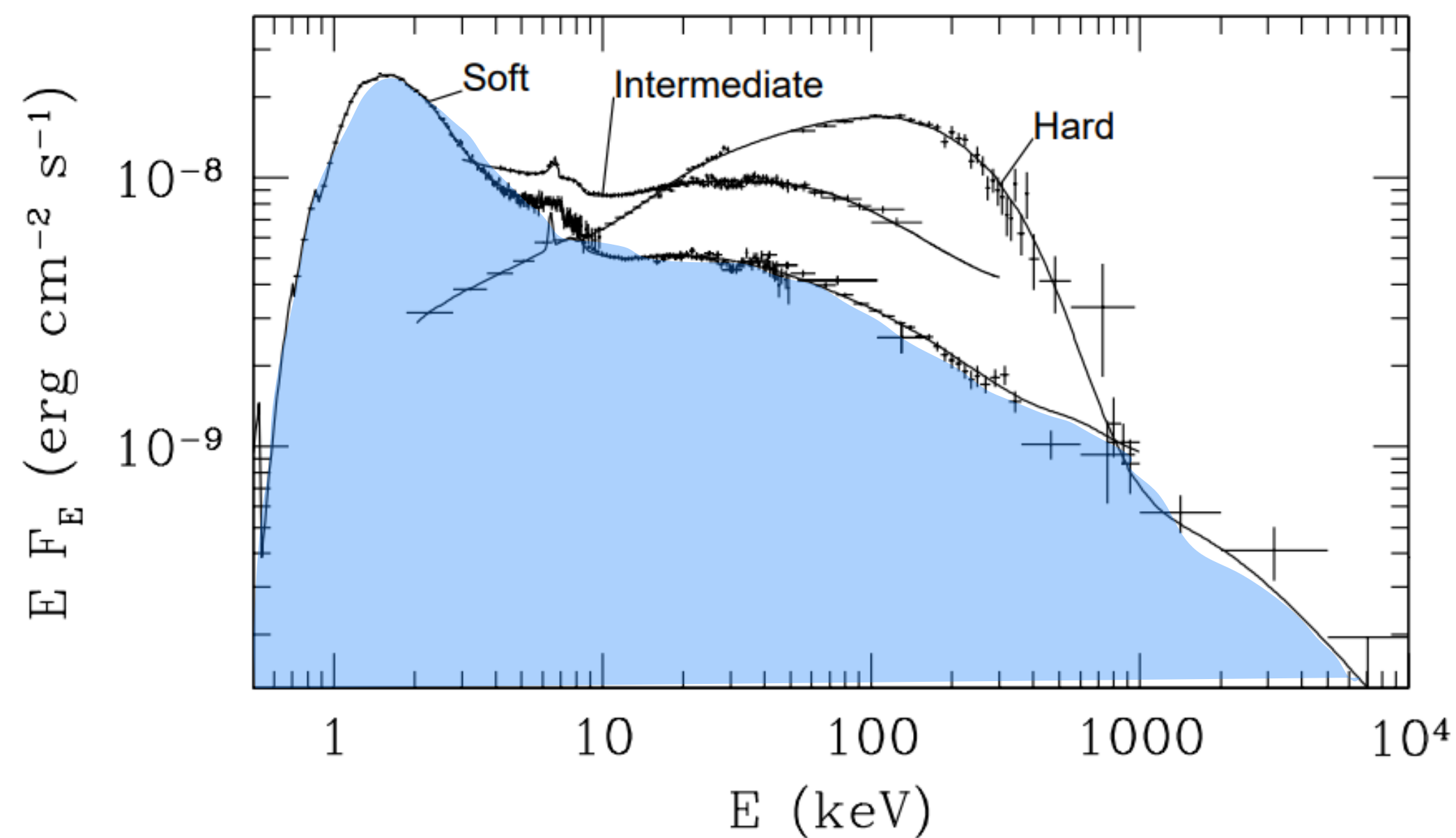


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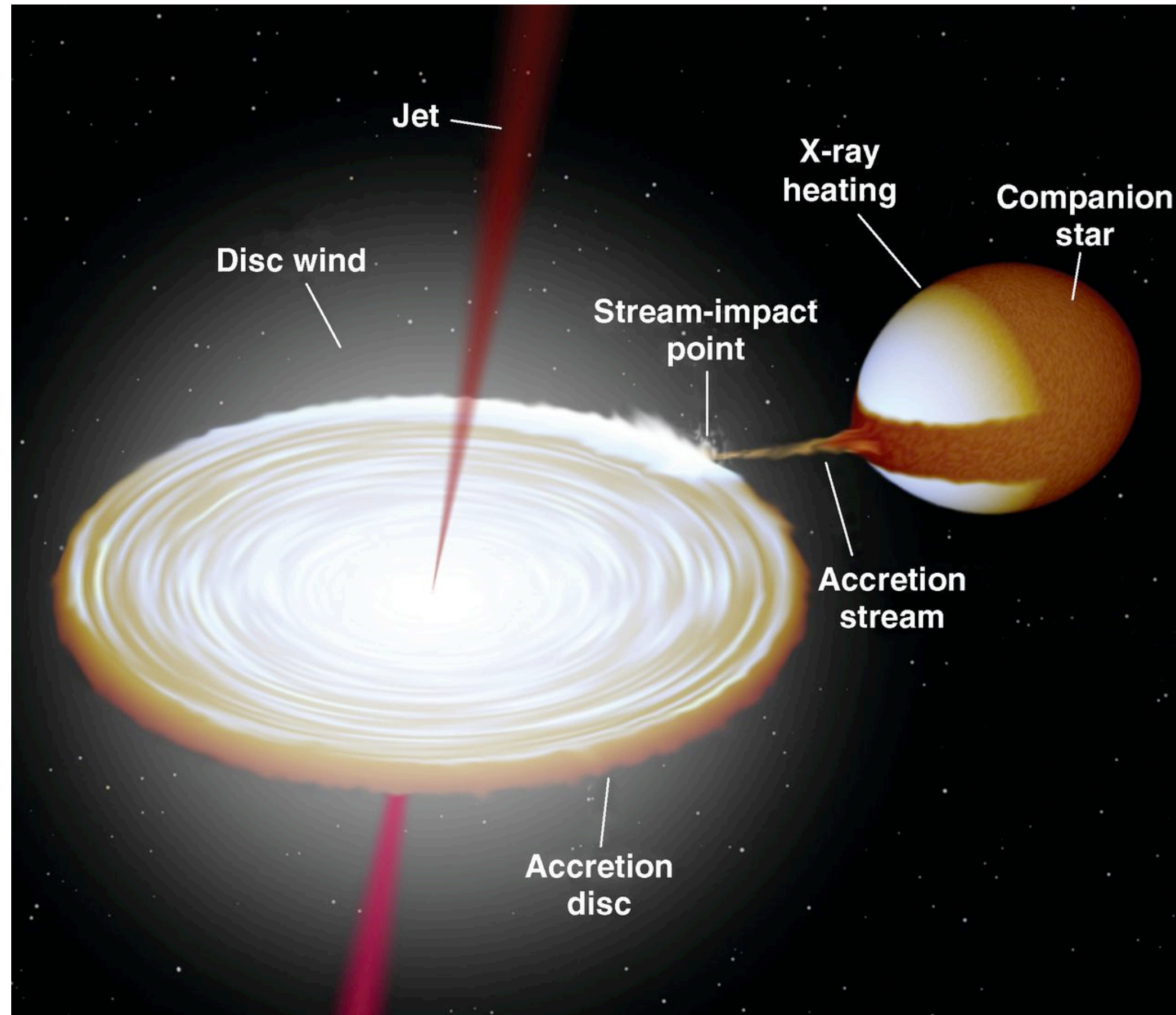


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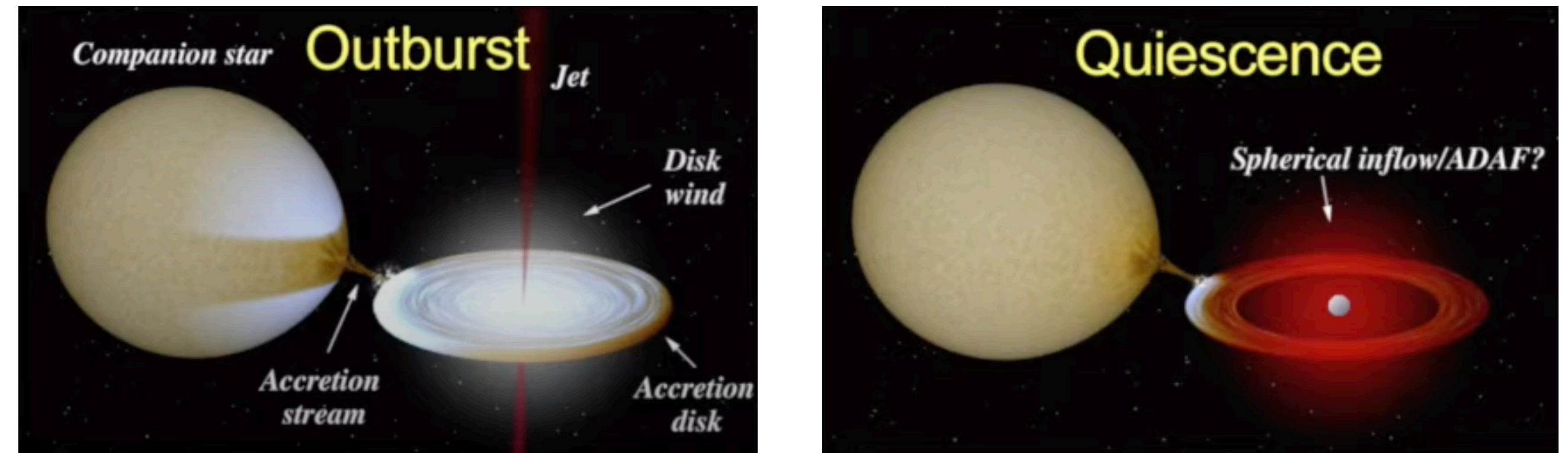
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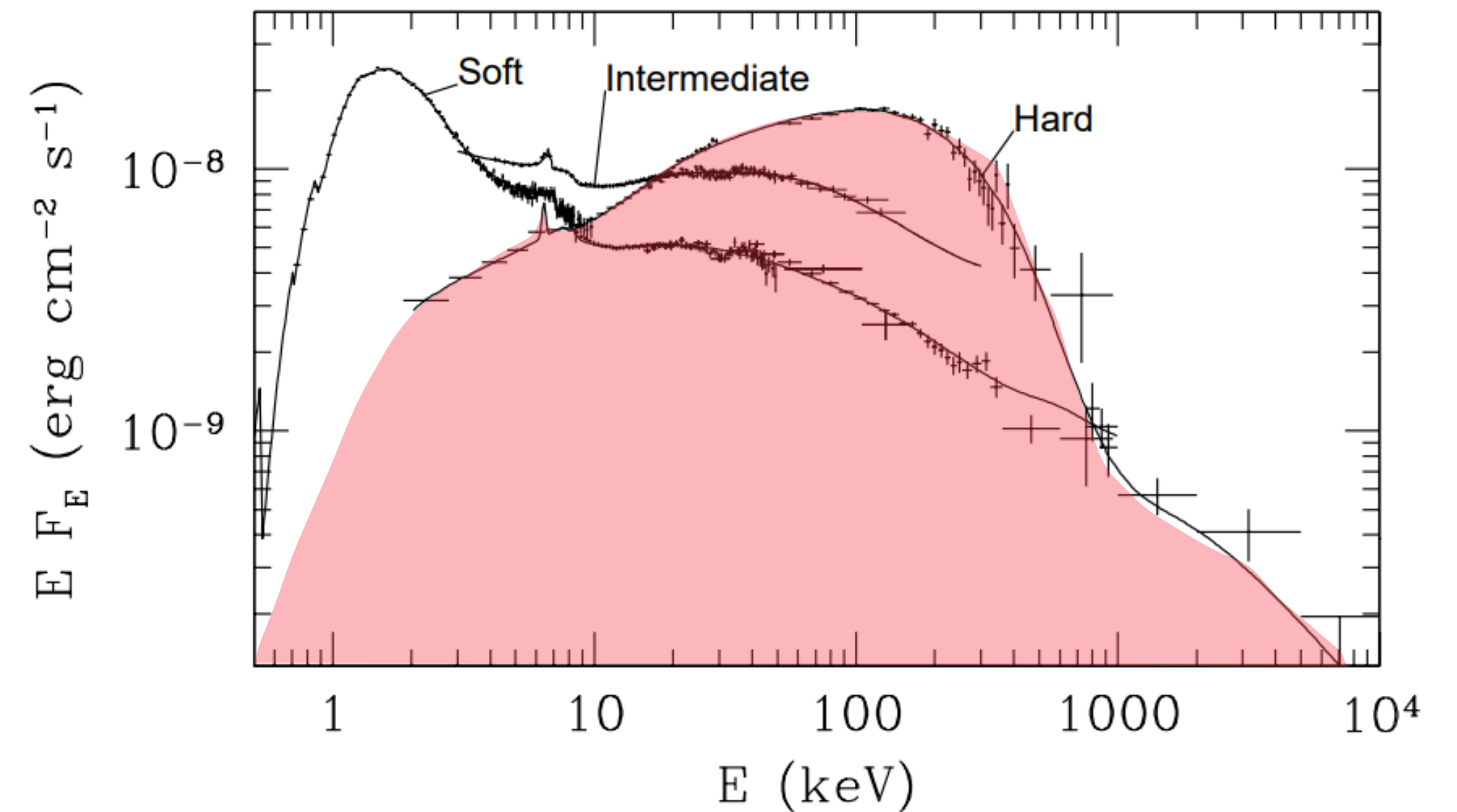


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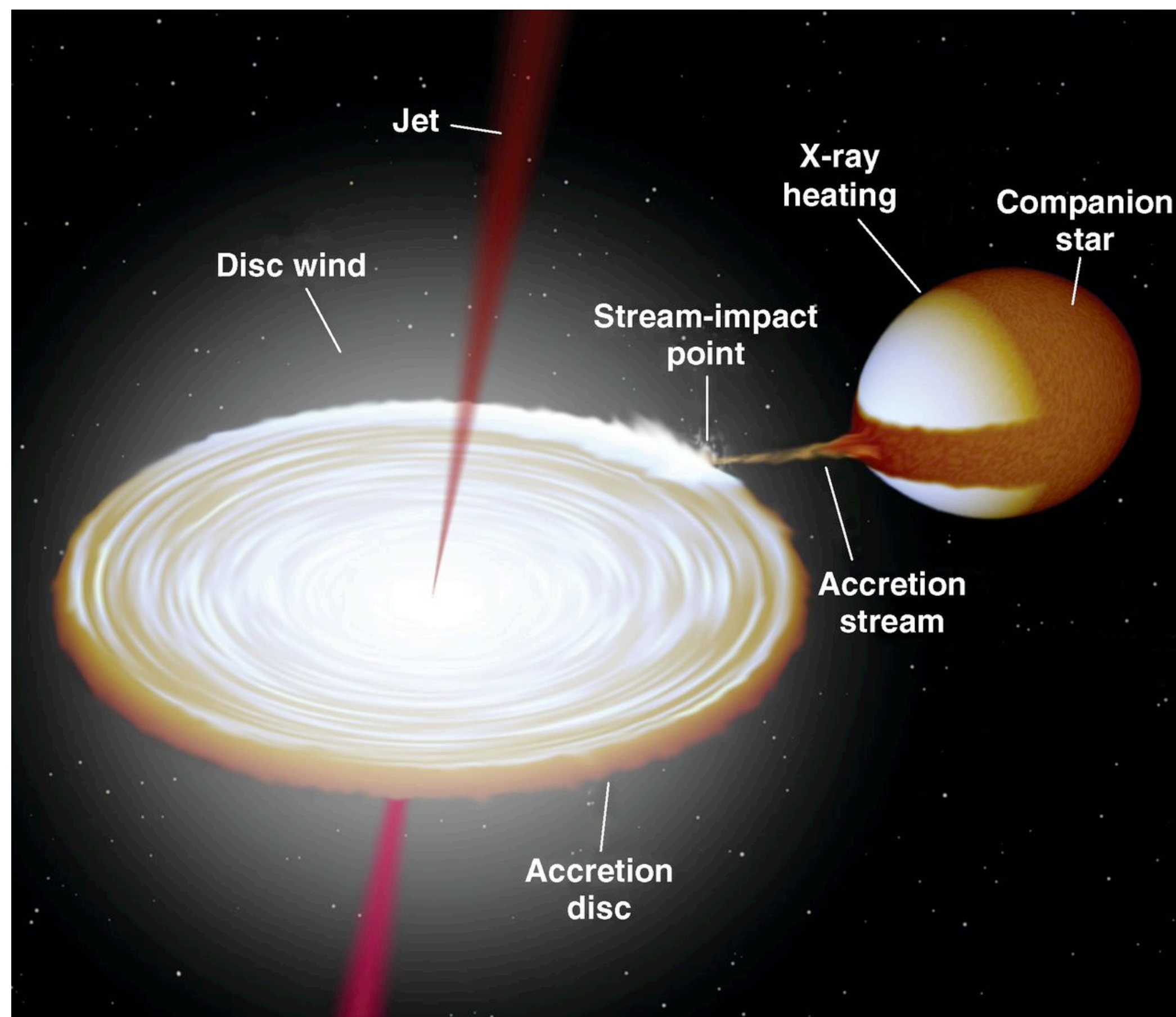


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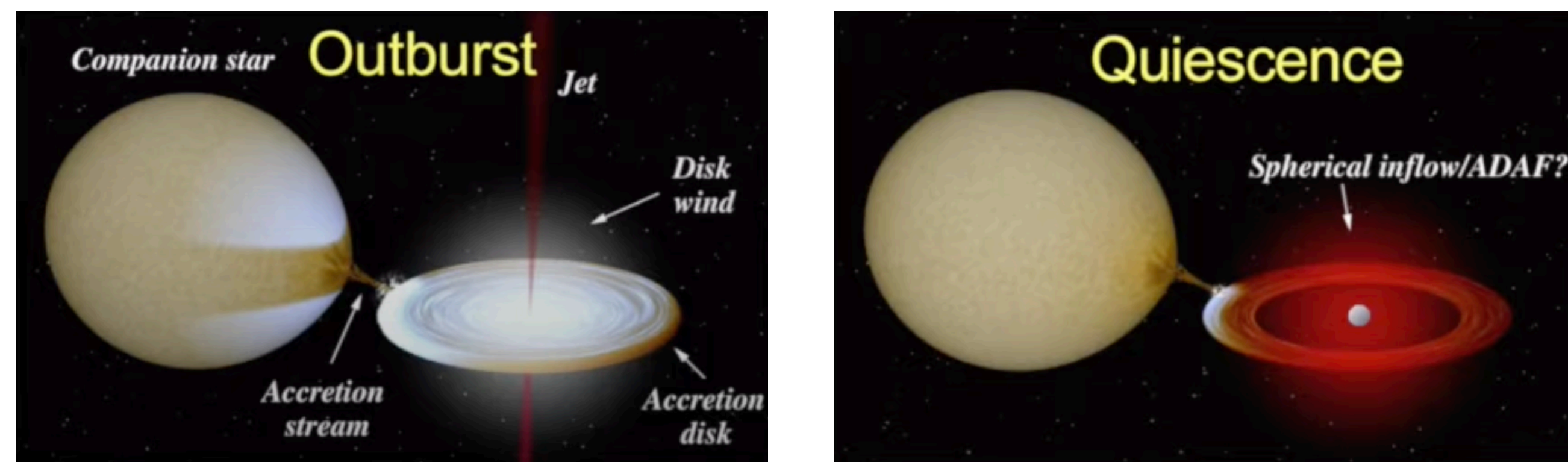
# Introduction

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 and infrared (OIR)  
emission

jet + wind + irradiated disc +  
+ hot accretion flow

optical companion + accretion  
disc/flow + hotspot/line + jet

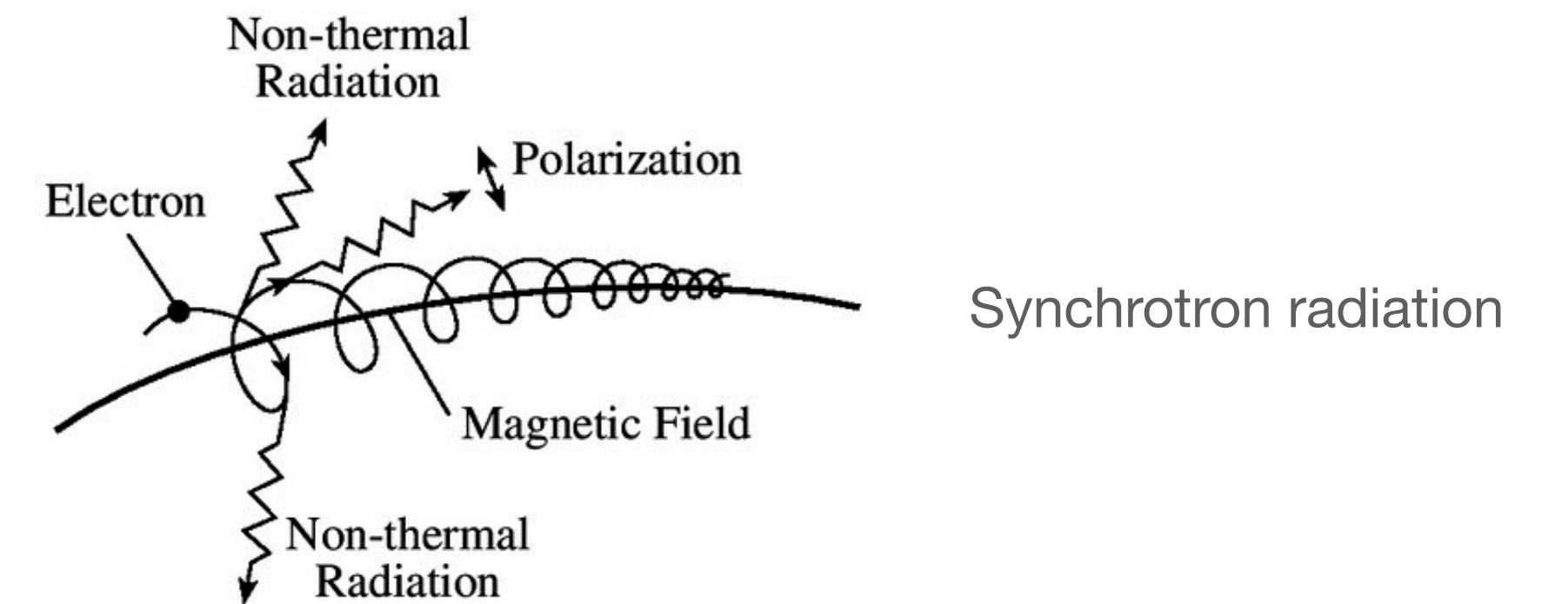
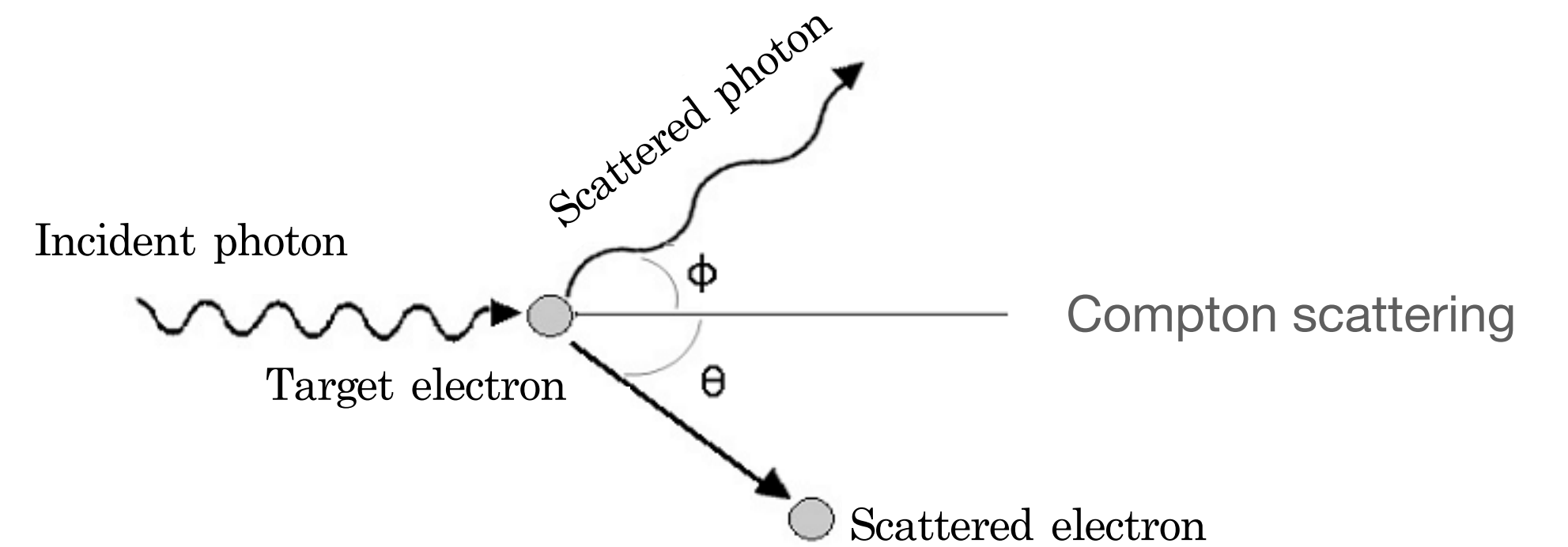
The identification of the different spectral components is essential for understanding the accretion physics in X-ray binaries.

# 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**?



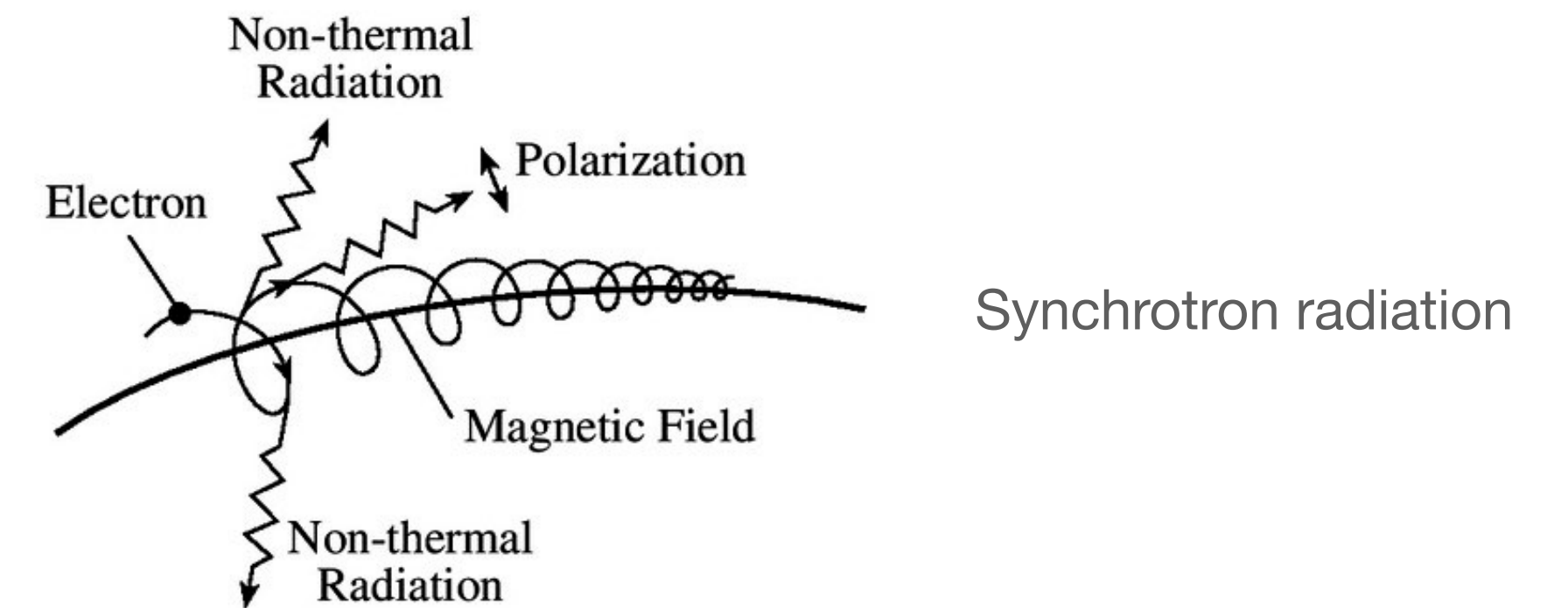
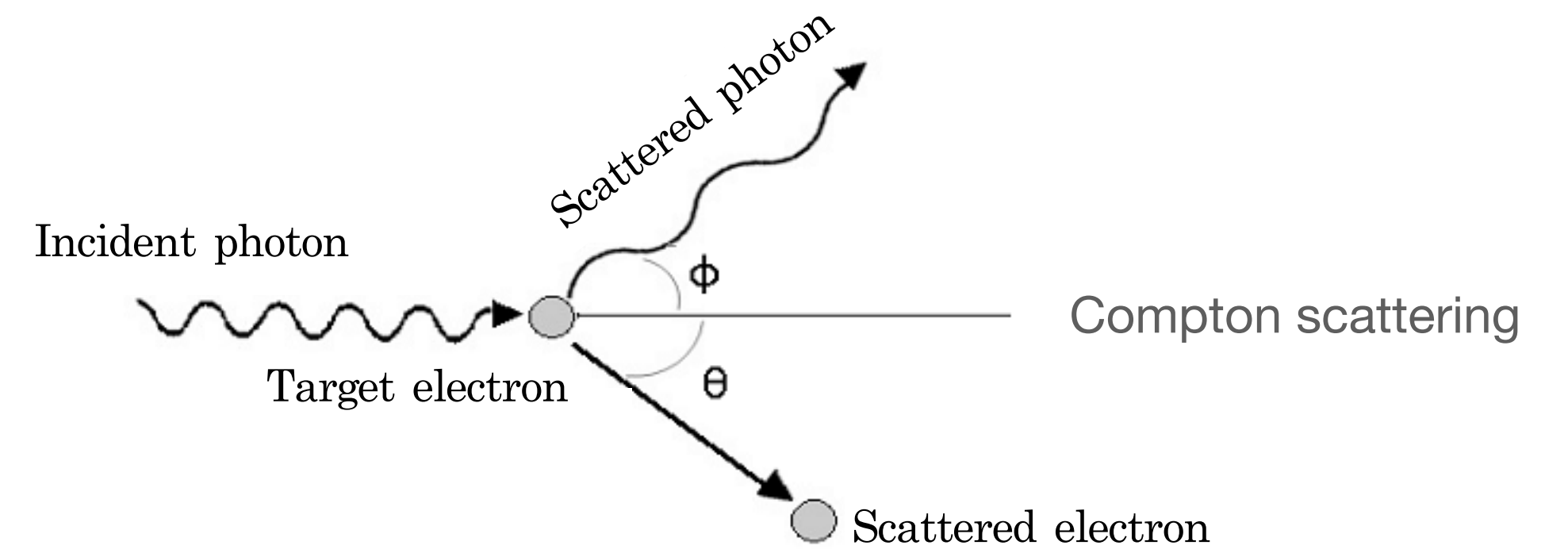
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Why **polarimetry**?

- **Polarized radiation can be produced by several** physical processes taking place in the BHXRBs, such as **synchrotron radiation** in the presence of an ordered magnetic field of the jet (hot accretion flow) or **scattering** of the accretion disk radiation **by electrons or dust**.



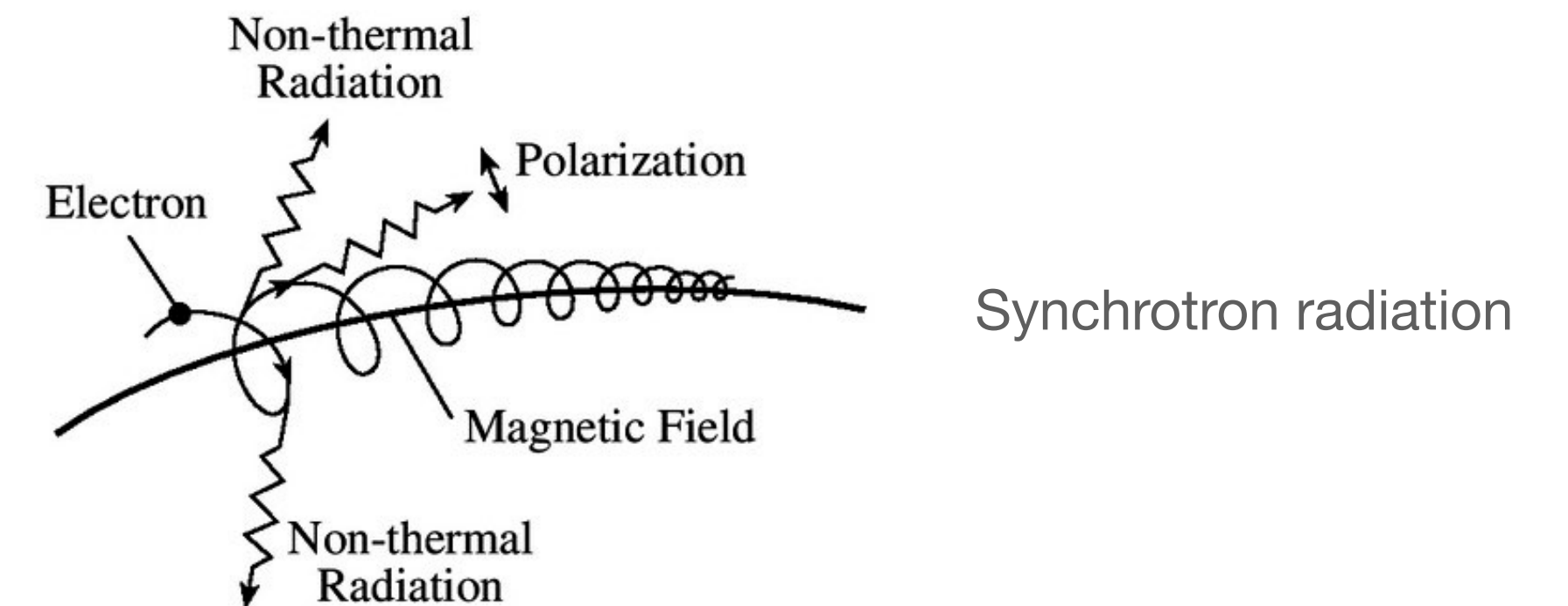
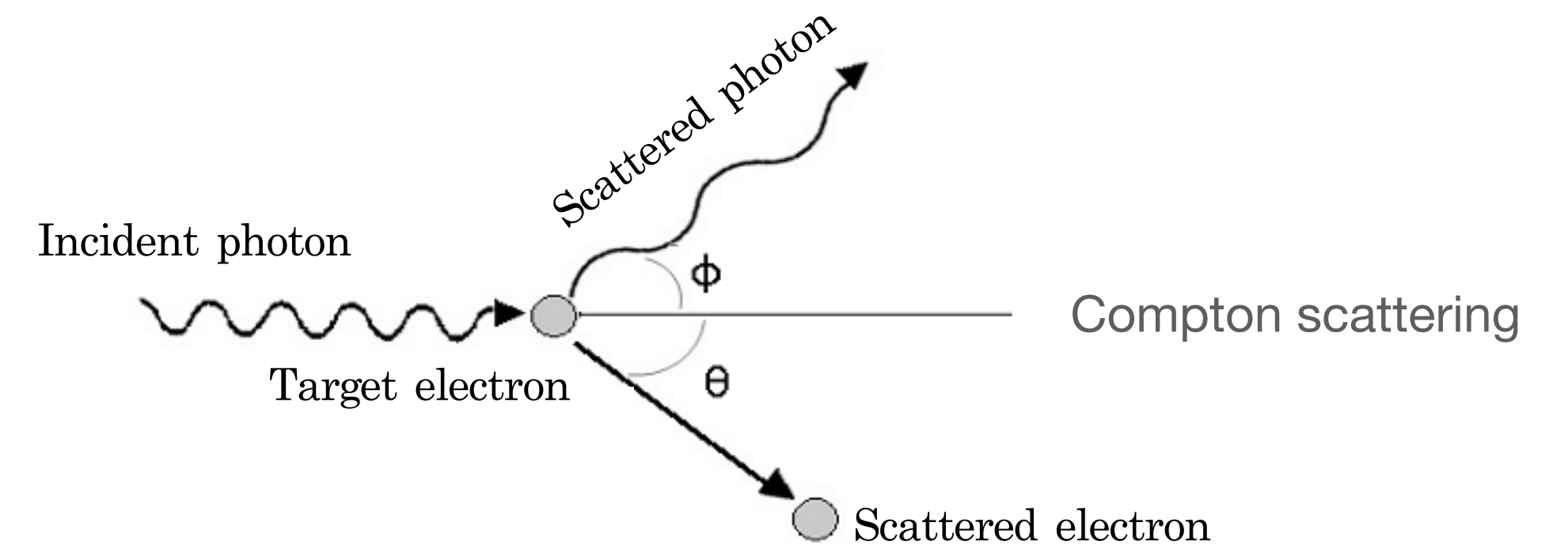
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- **Polarization carries information about the geometrical properties** of the emitting/scattering media.



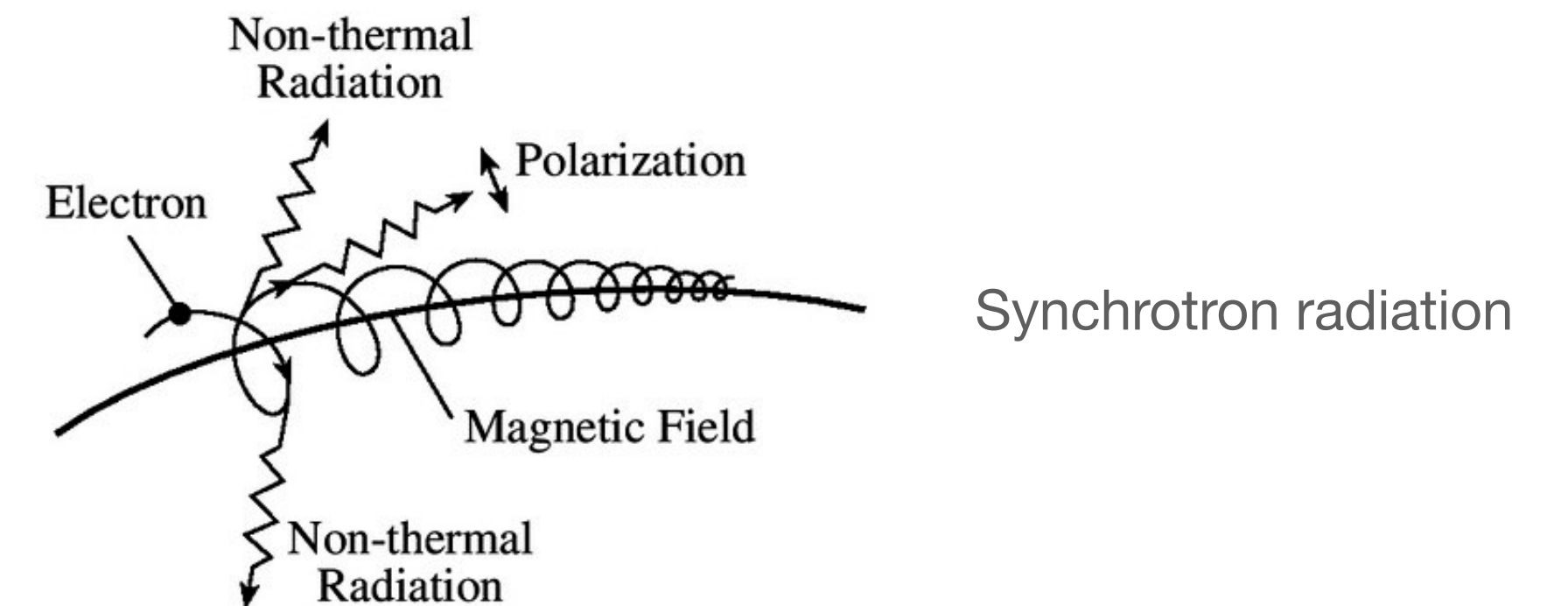
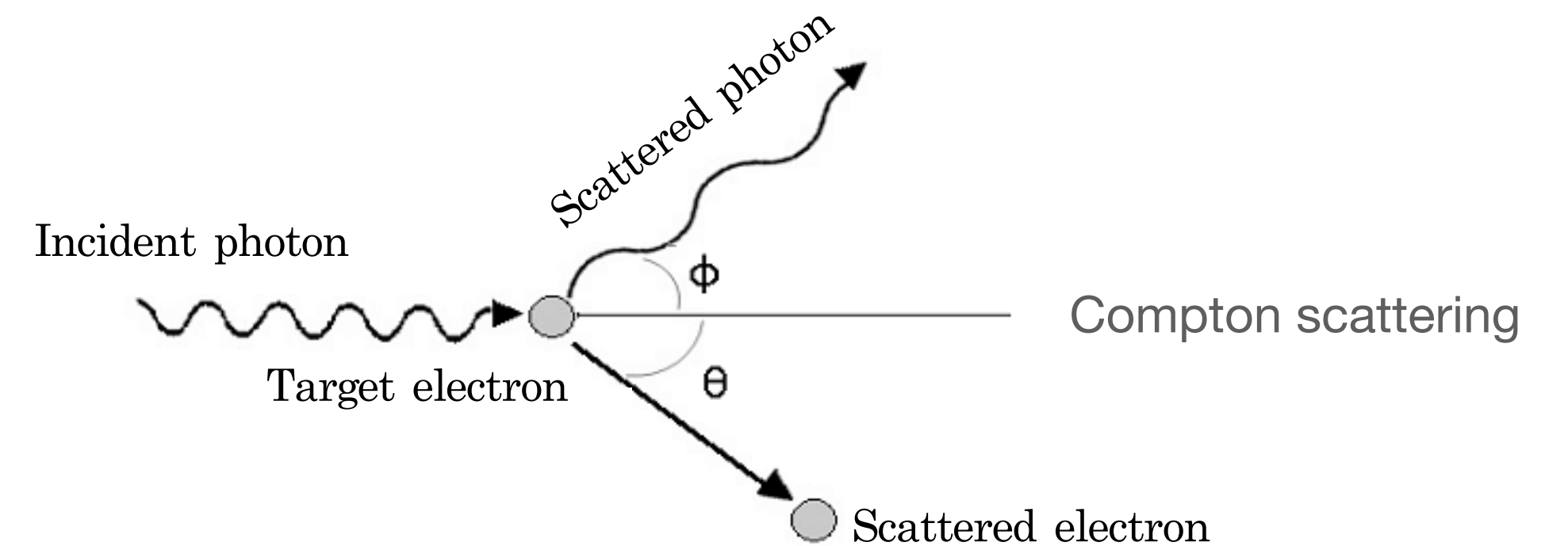
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Choice of a tool

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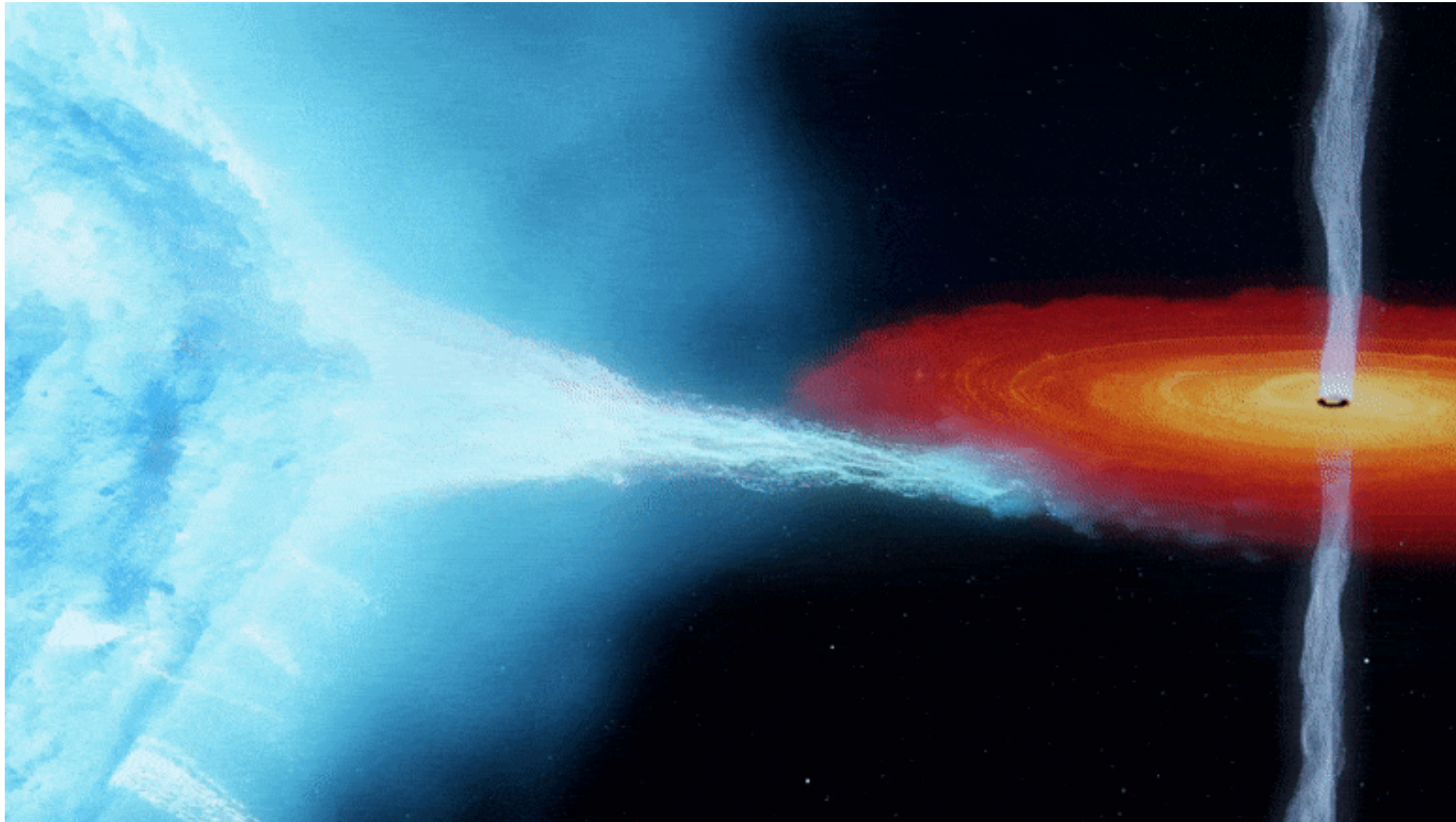
Why **polarimetry**?

- **Polarized radiation can be produced by several** physical processes taking place in the BHXRBs, such as **synchrotron radiation** in the presence of an ordered magnetic field of the jet (hot accretion flow) or **scattering** of the accretion disk radiation **by electrons or dust.**
- **Polarization carries information about the geometrical properties** of the emitting/scattering media.
- **Each component has different polarization properties** (or no polarization at all).



# Microquasar Cyg X-1

The best-studied X-ray binary to date



Basic information:

$$P_{\text{orb}} = 5.6 \text{ days}$$

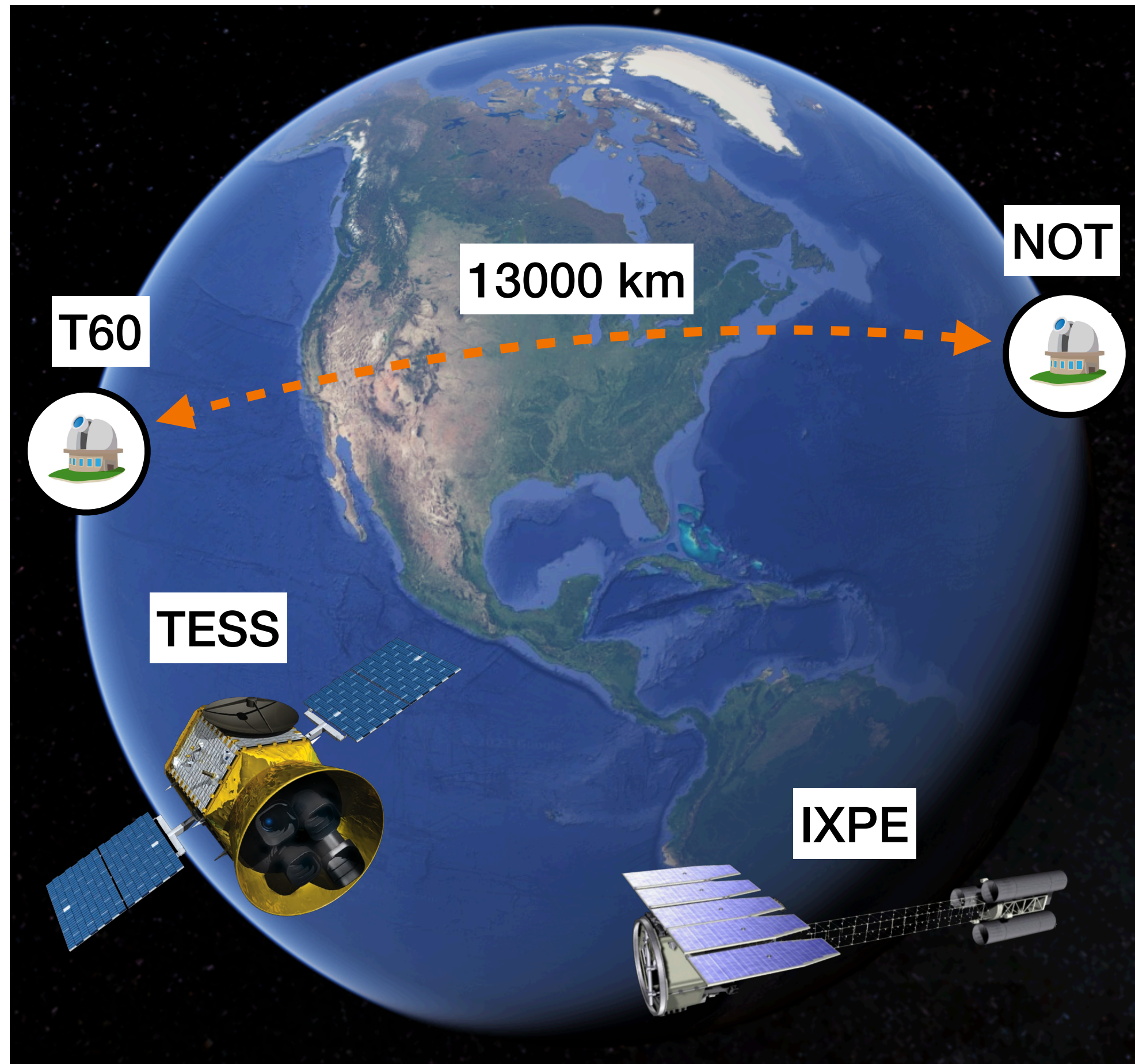
$$M_{\text{BH}} \sim 21 M_{\odot}$$

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

$$i \sim 150^{\circ}$$

# Our observations

The telescopes and instruments we used

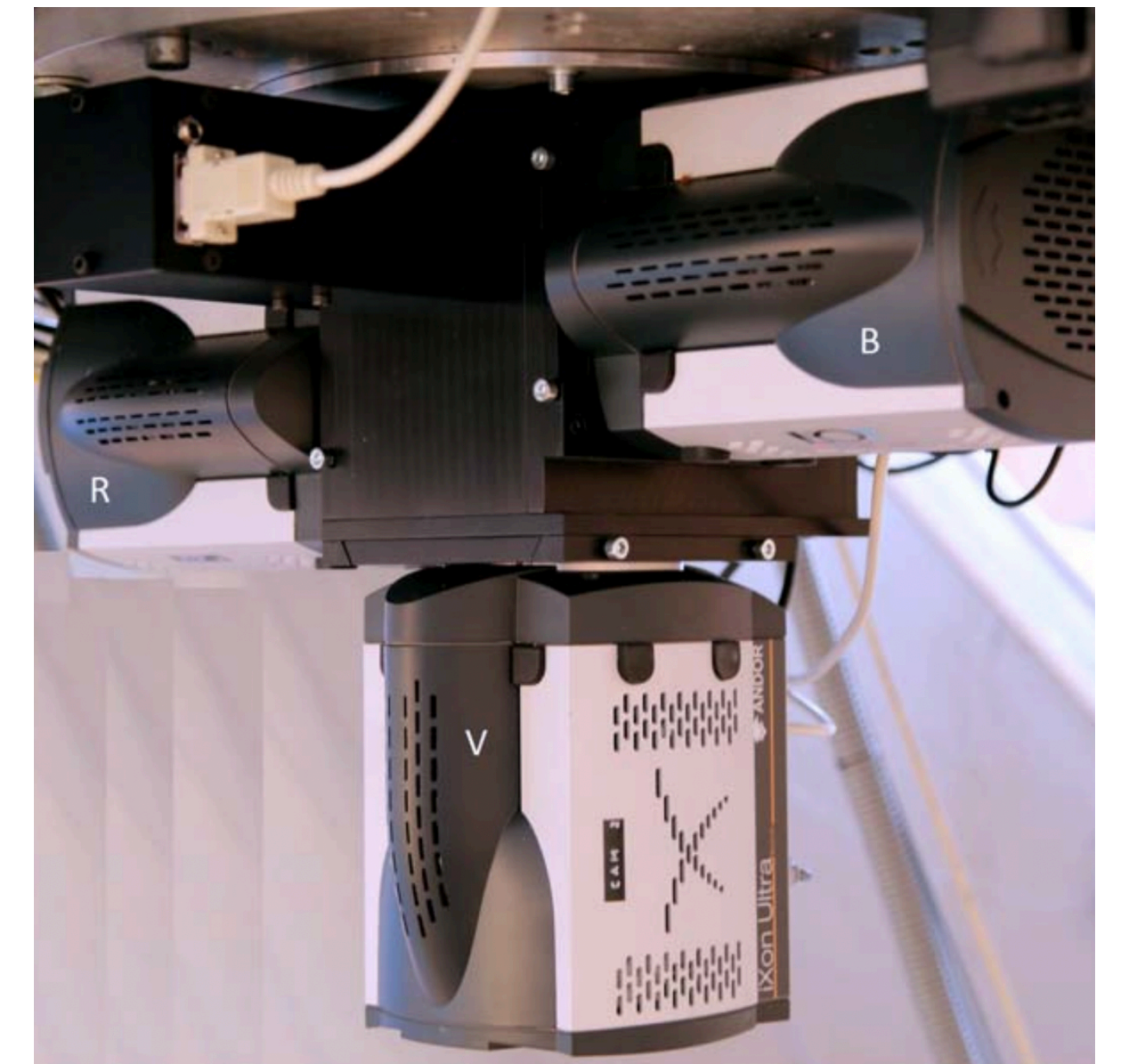


Nordic Optical Telescope (NOT)



La Palma, Canary Islands, Spain

DIPol-UF polarimeter, mounted on NOT



Simultaneous Three-color (*BVR*) polarimeter

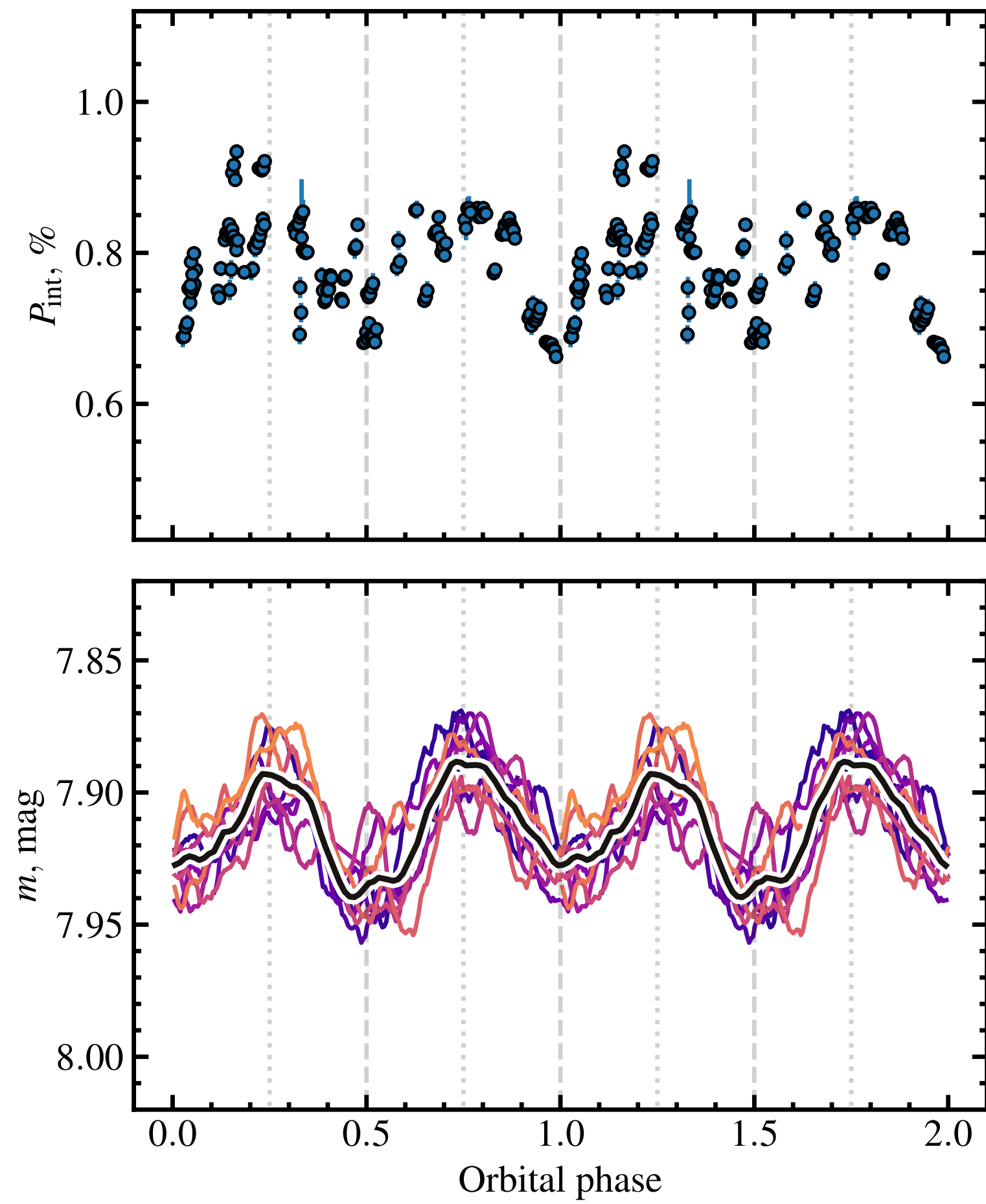
## Why DIPol-UF/2?

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

Pirola et al., 2020

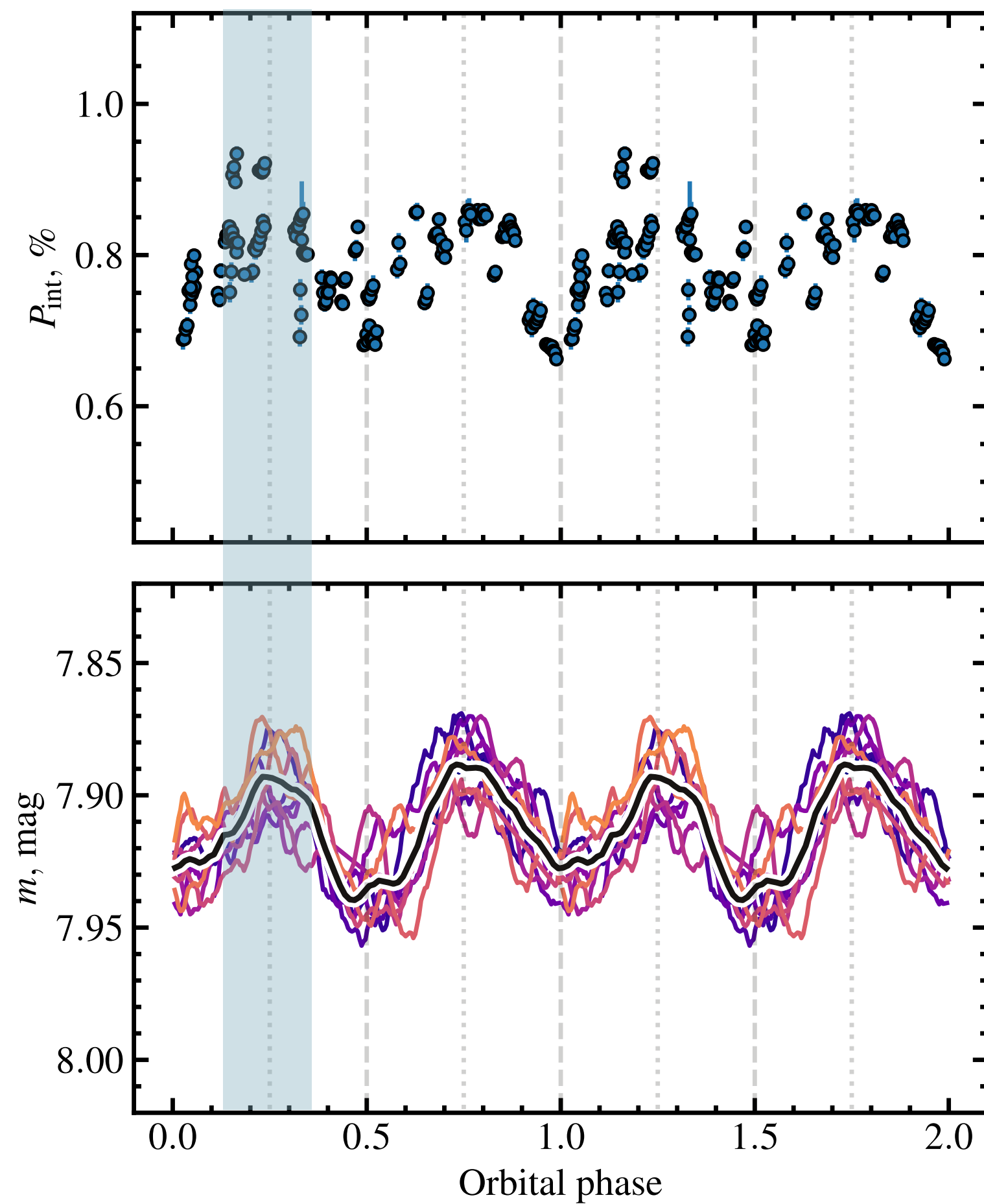
# Results

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



# Results

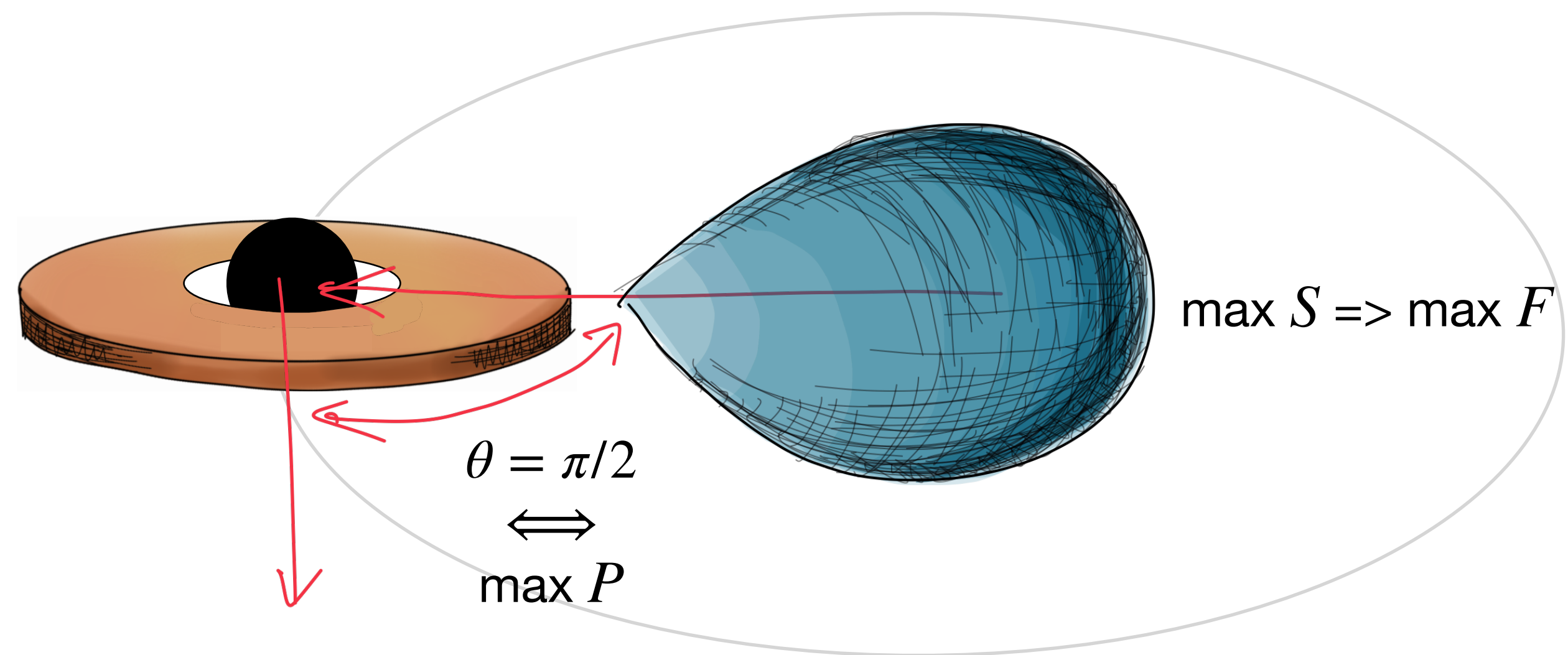
Variability of Cyg X-1 in optical part of the spectrum



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

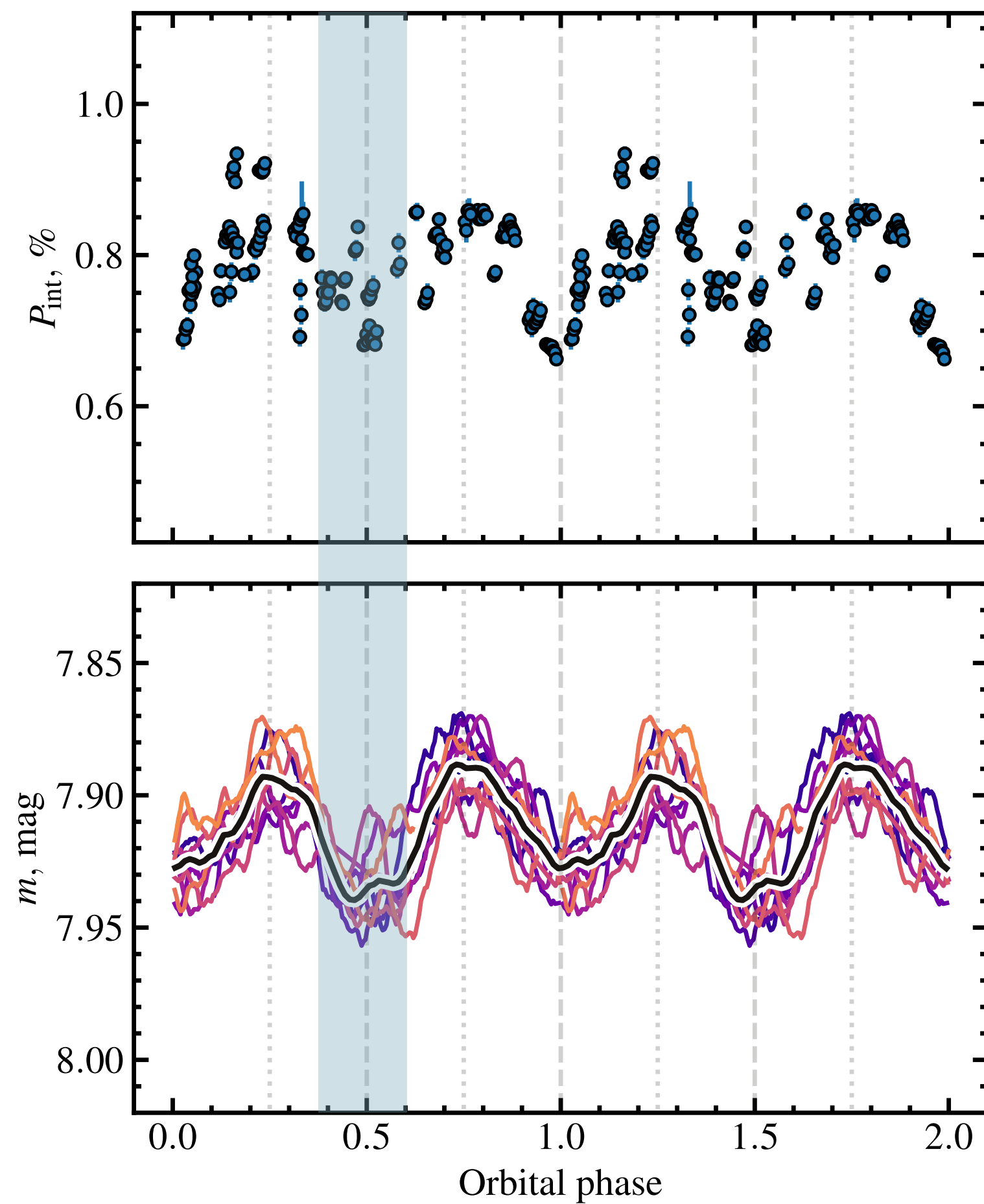
$$P = \frac{1 - \mu^2}{1 + \mu^2}, \mu = \cos \theta$$

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



# Results

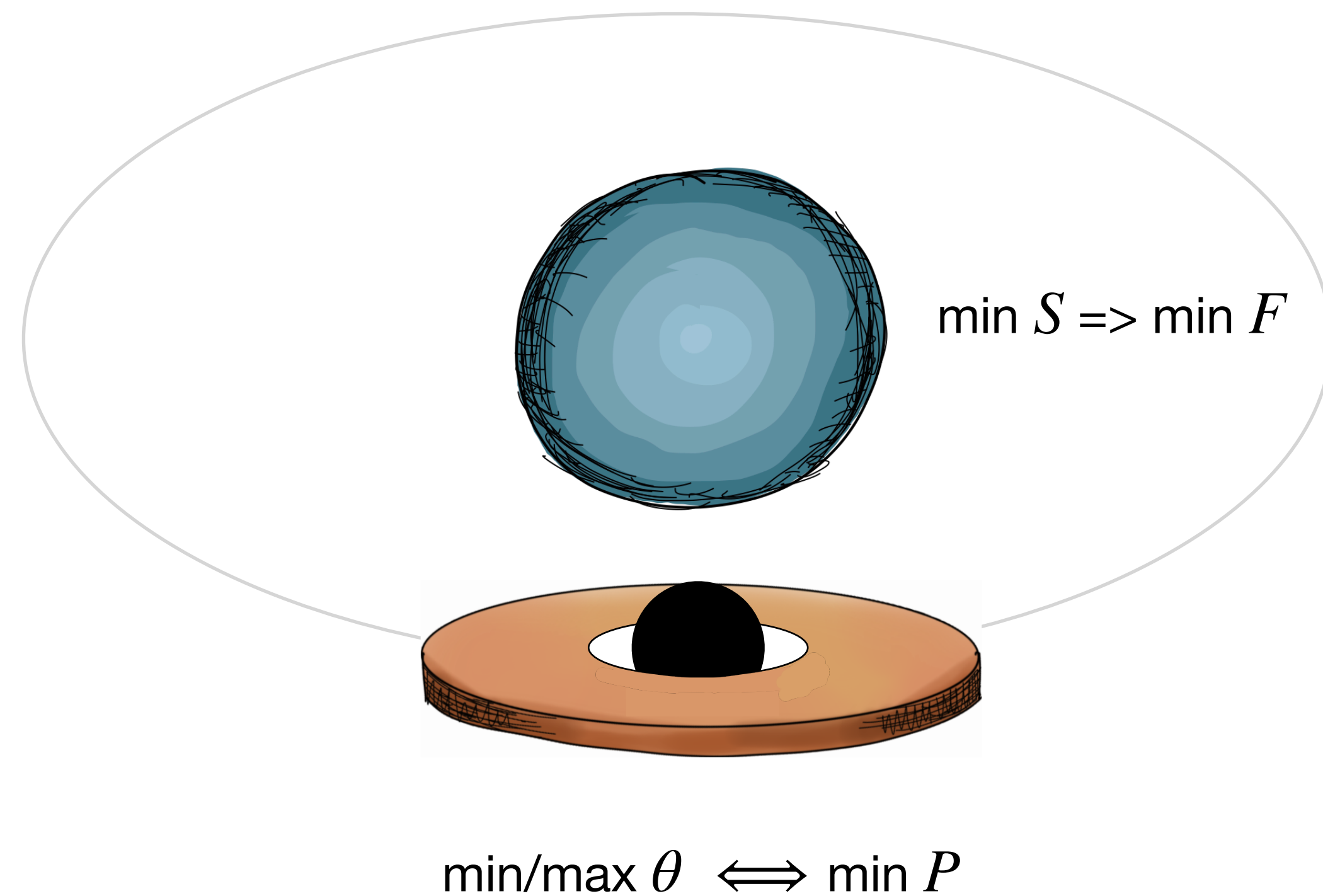
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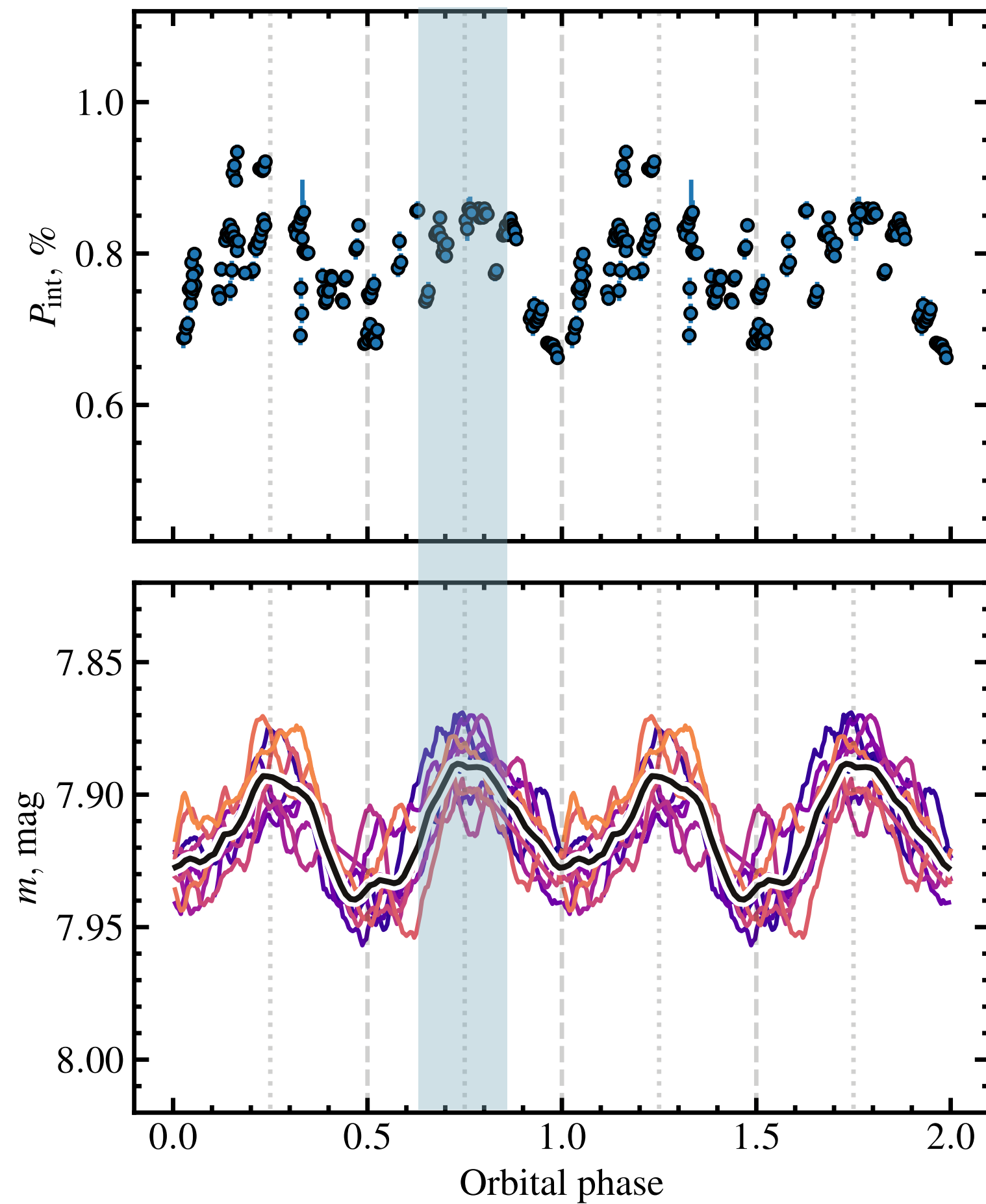
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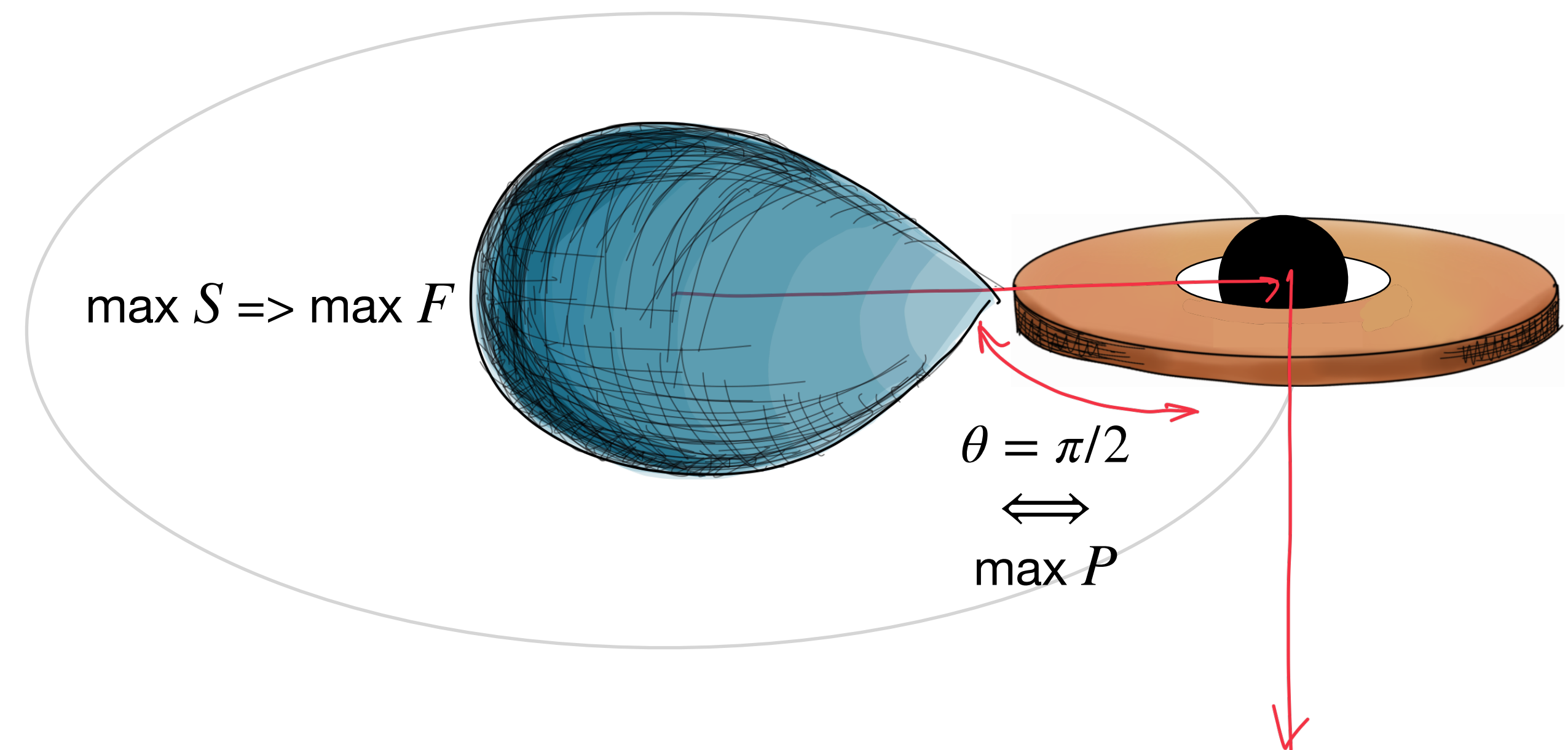
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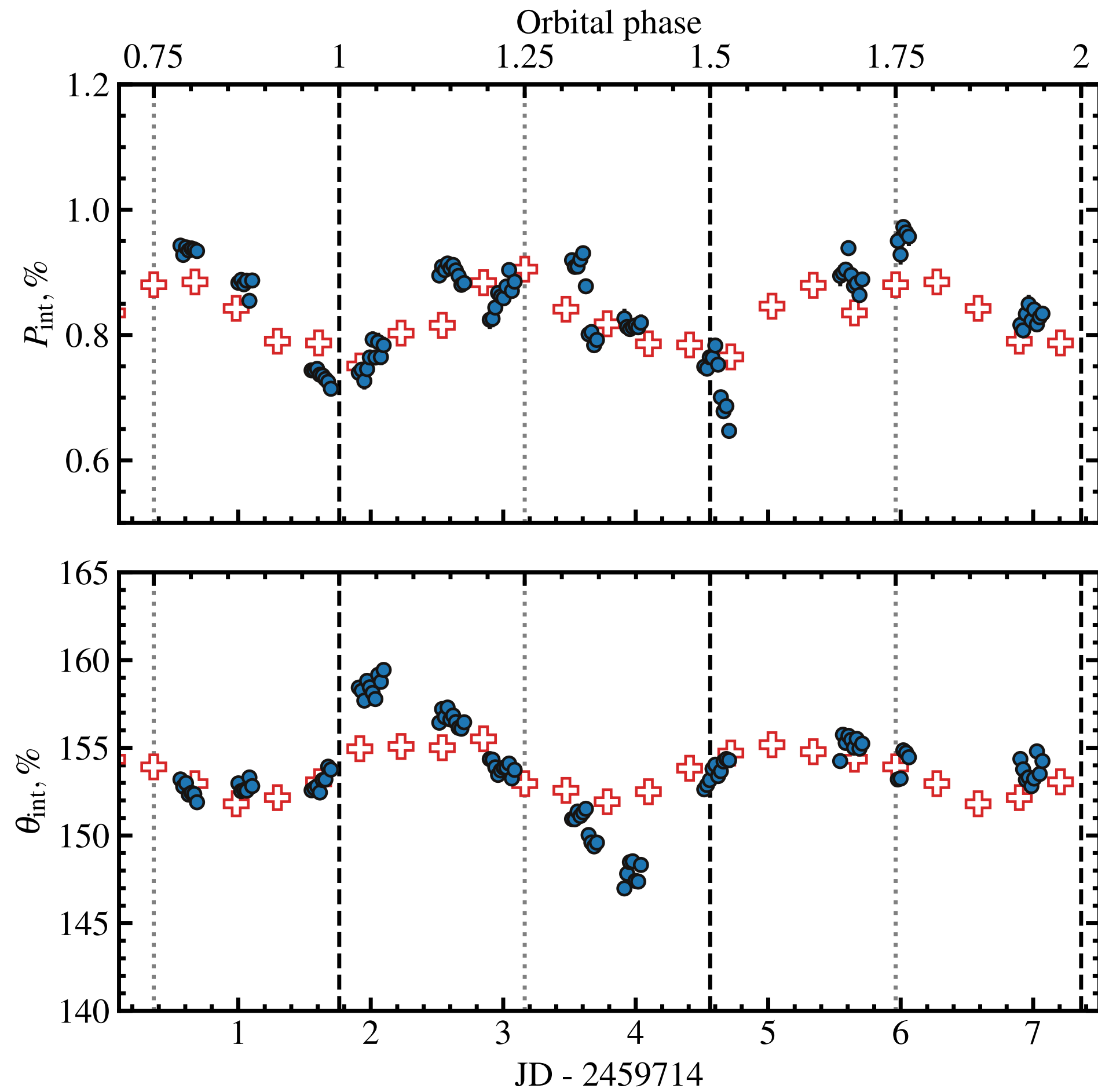
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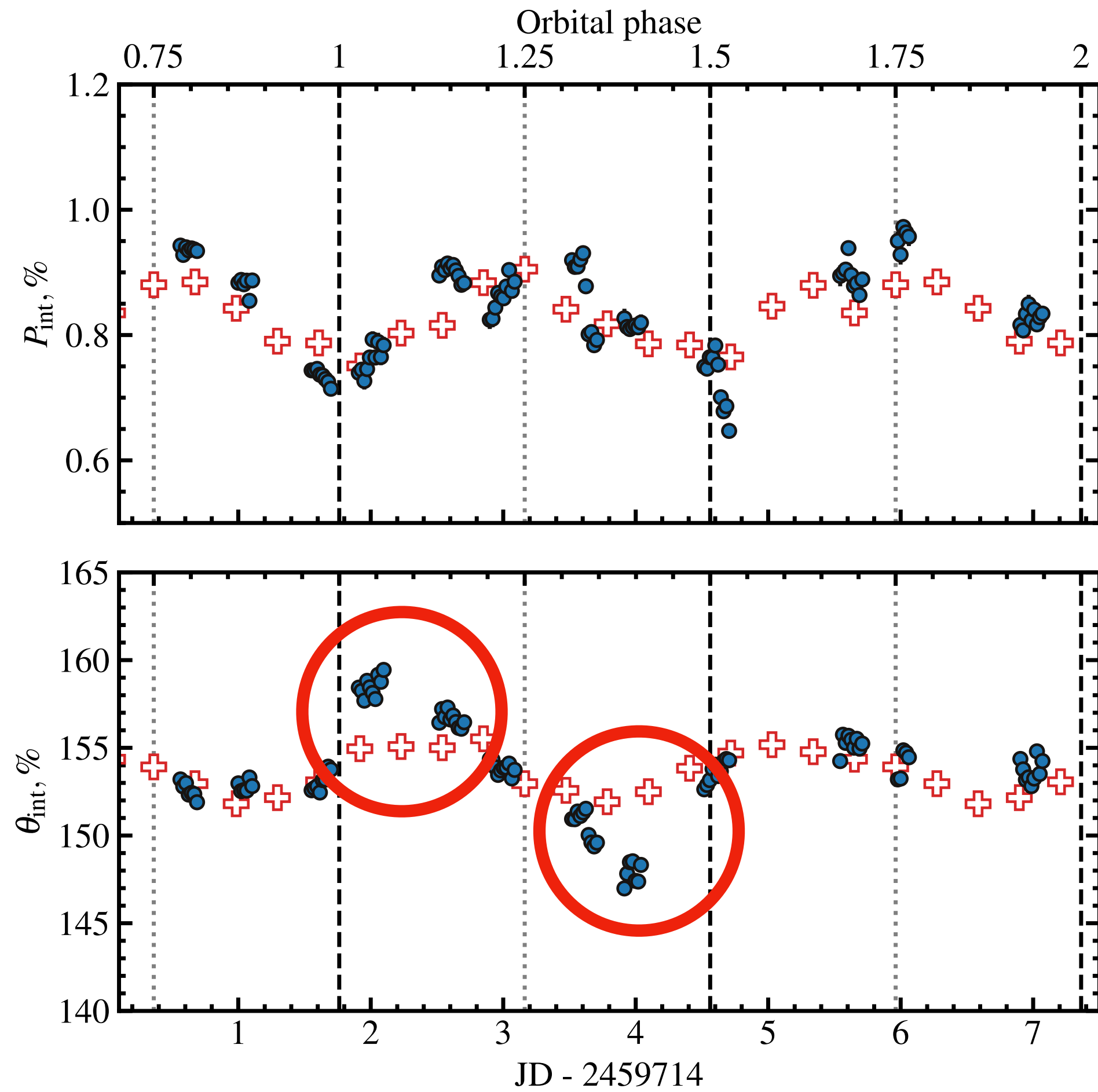
# Results

Best single orbit coverage to date



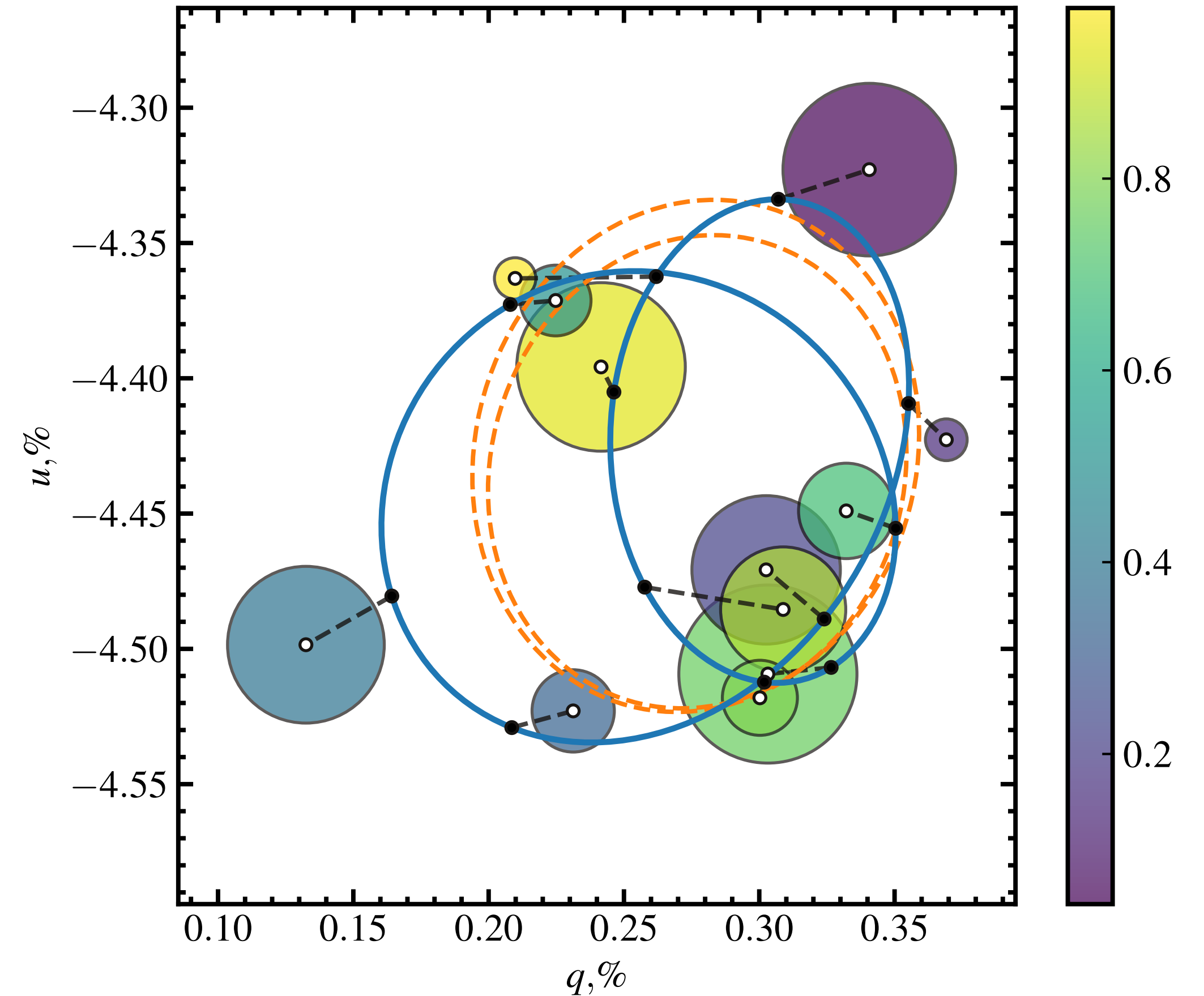
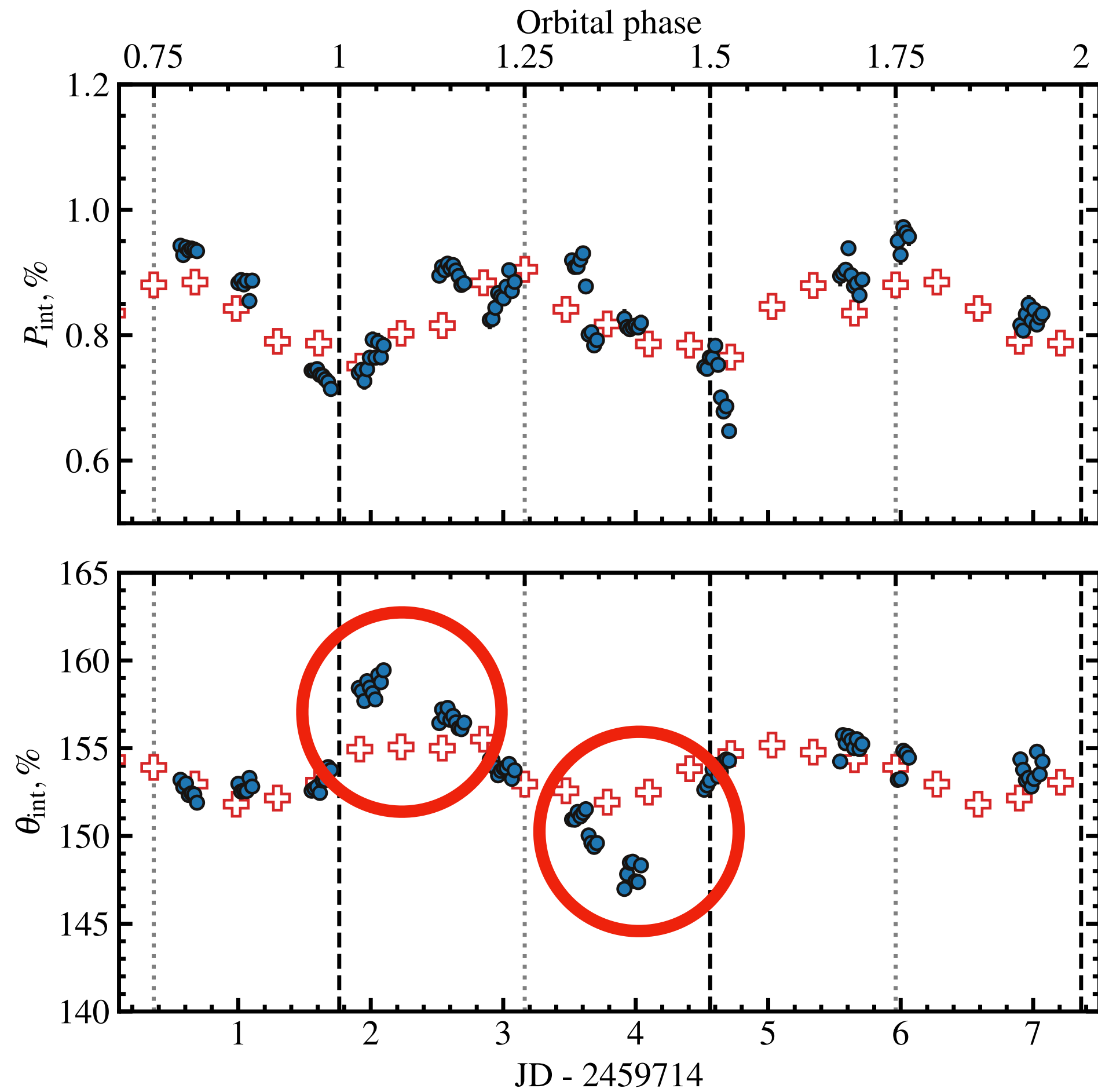
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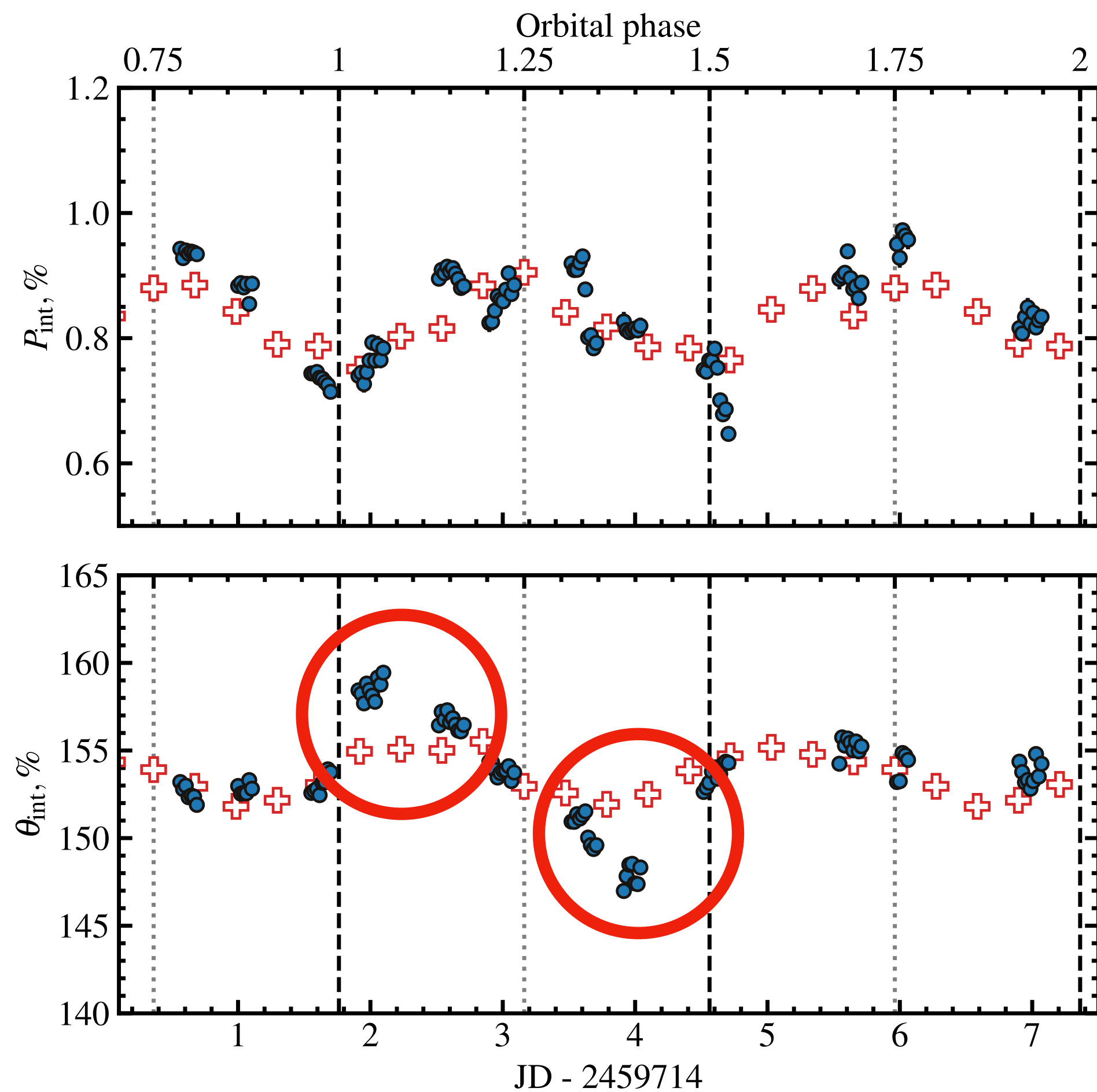
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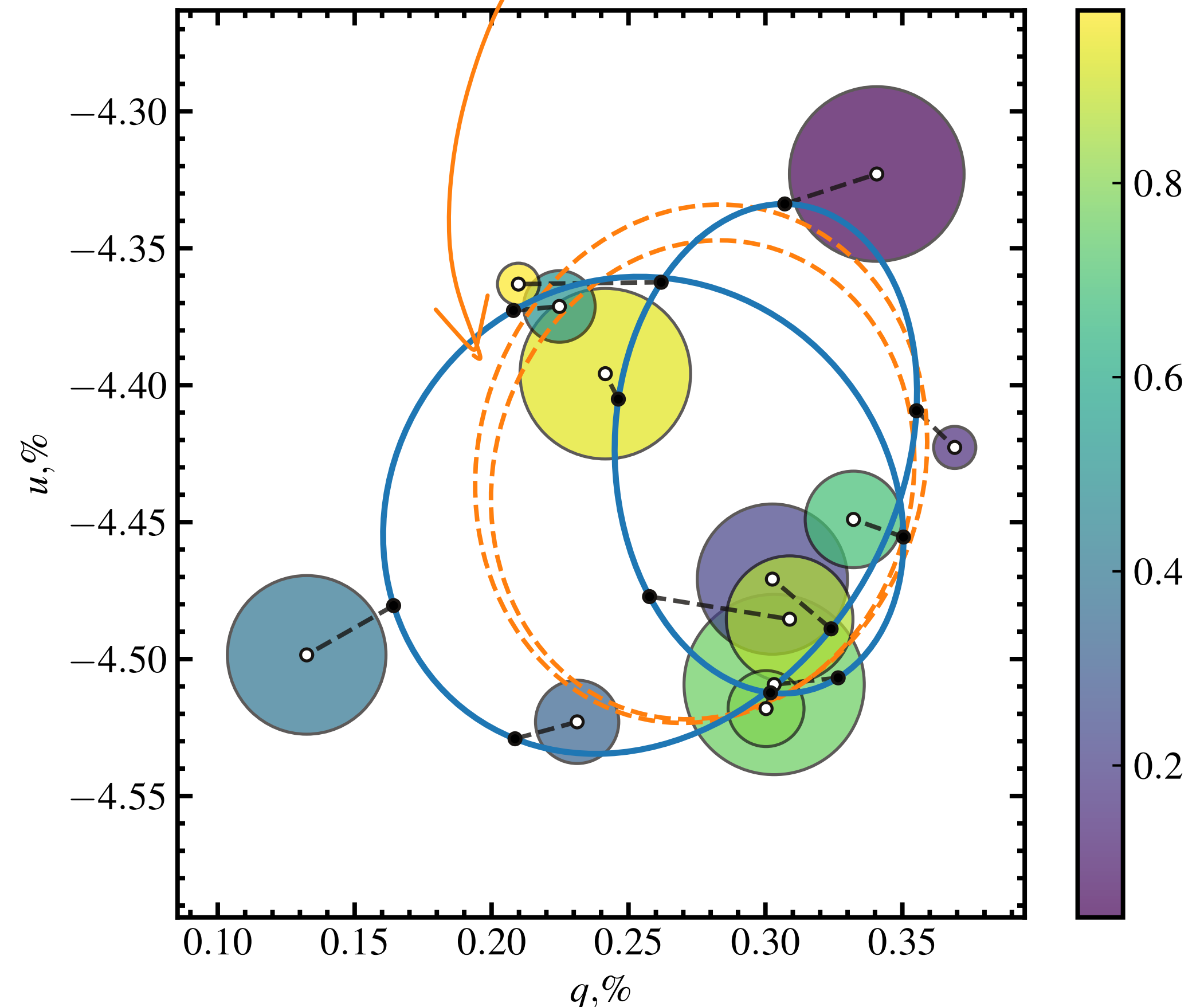


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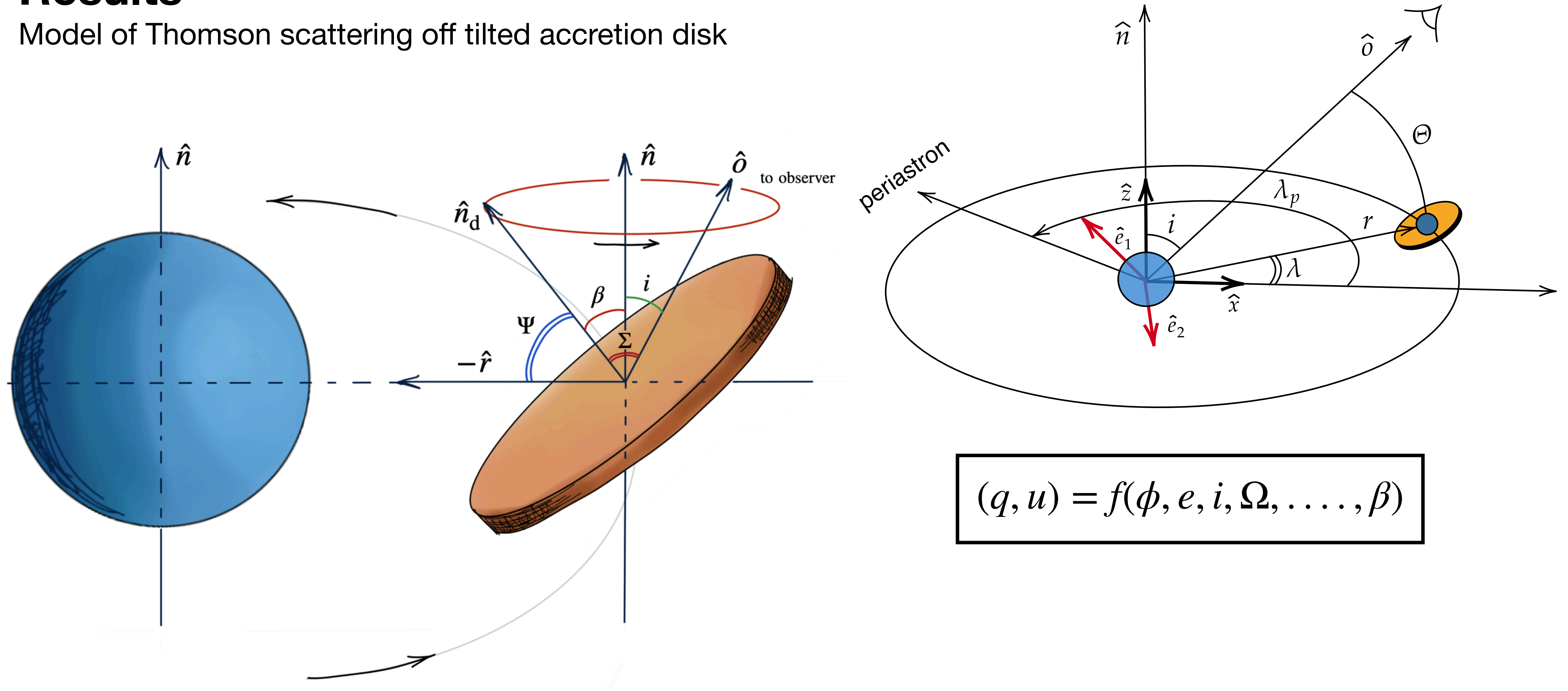


Spherical cloud on an eccentric orbit



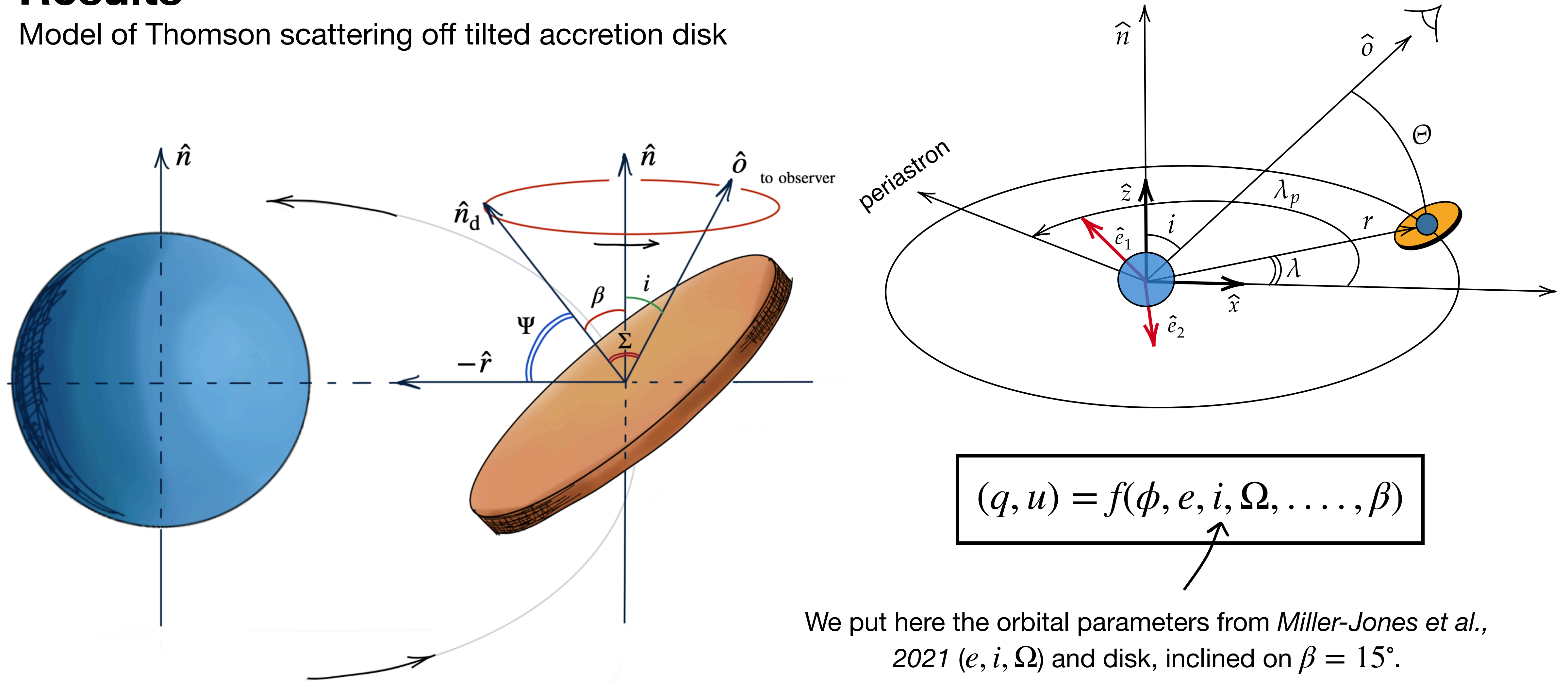
# Results

Model of Thomson scattering off tilted accretion disk



# Results

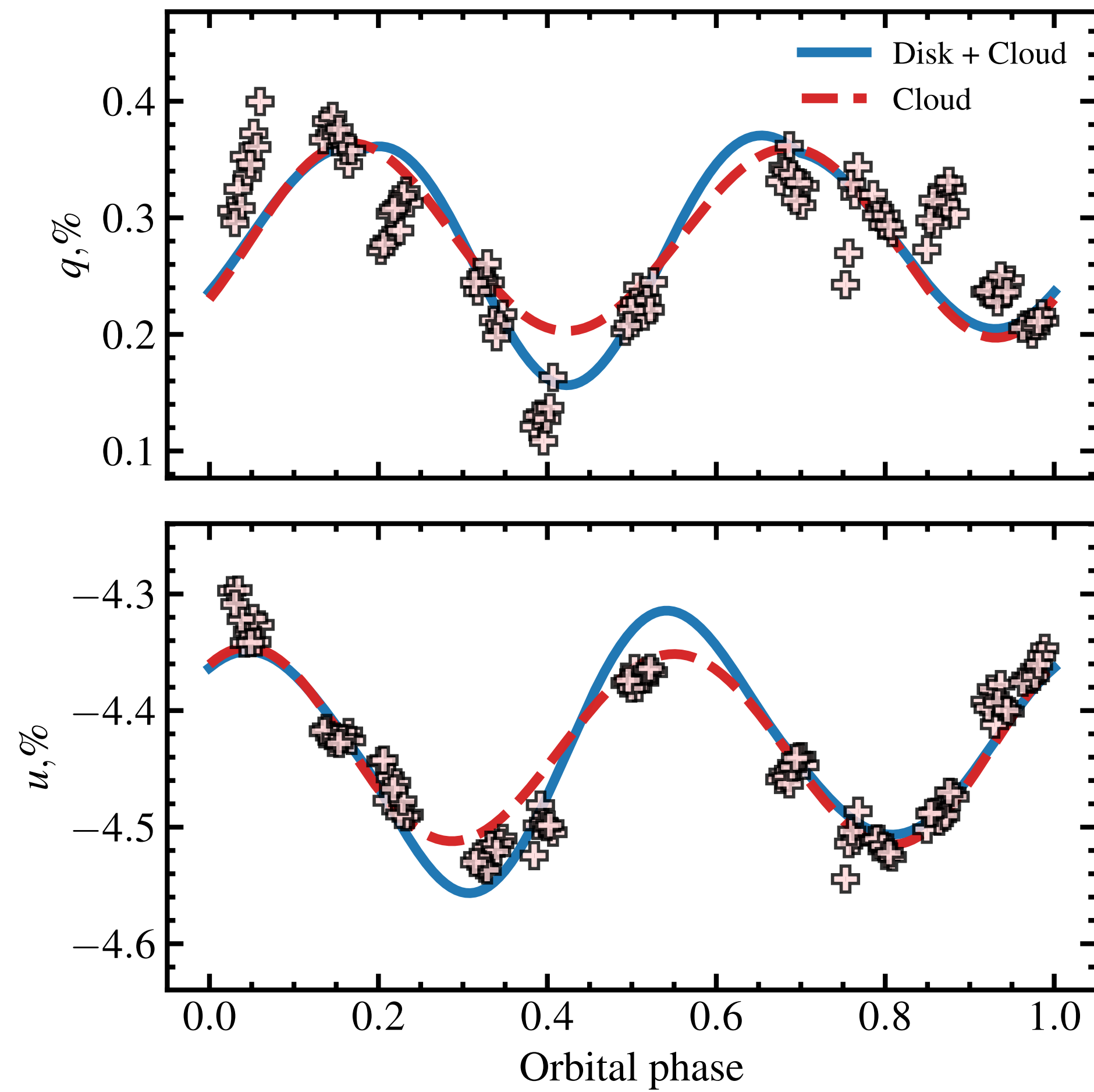
Model of Thomson scattering off tilted accretion disk



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

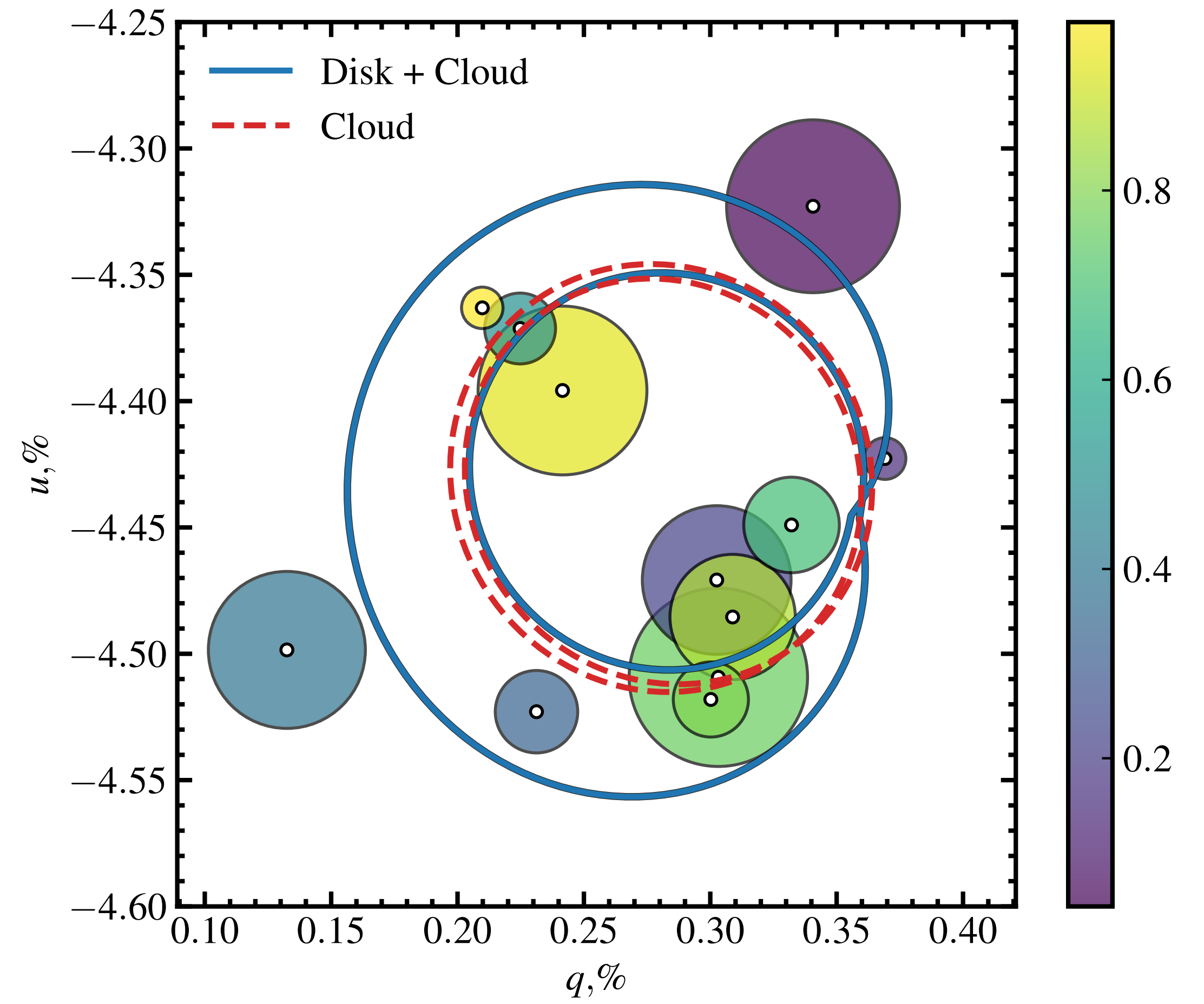
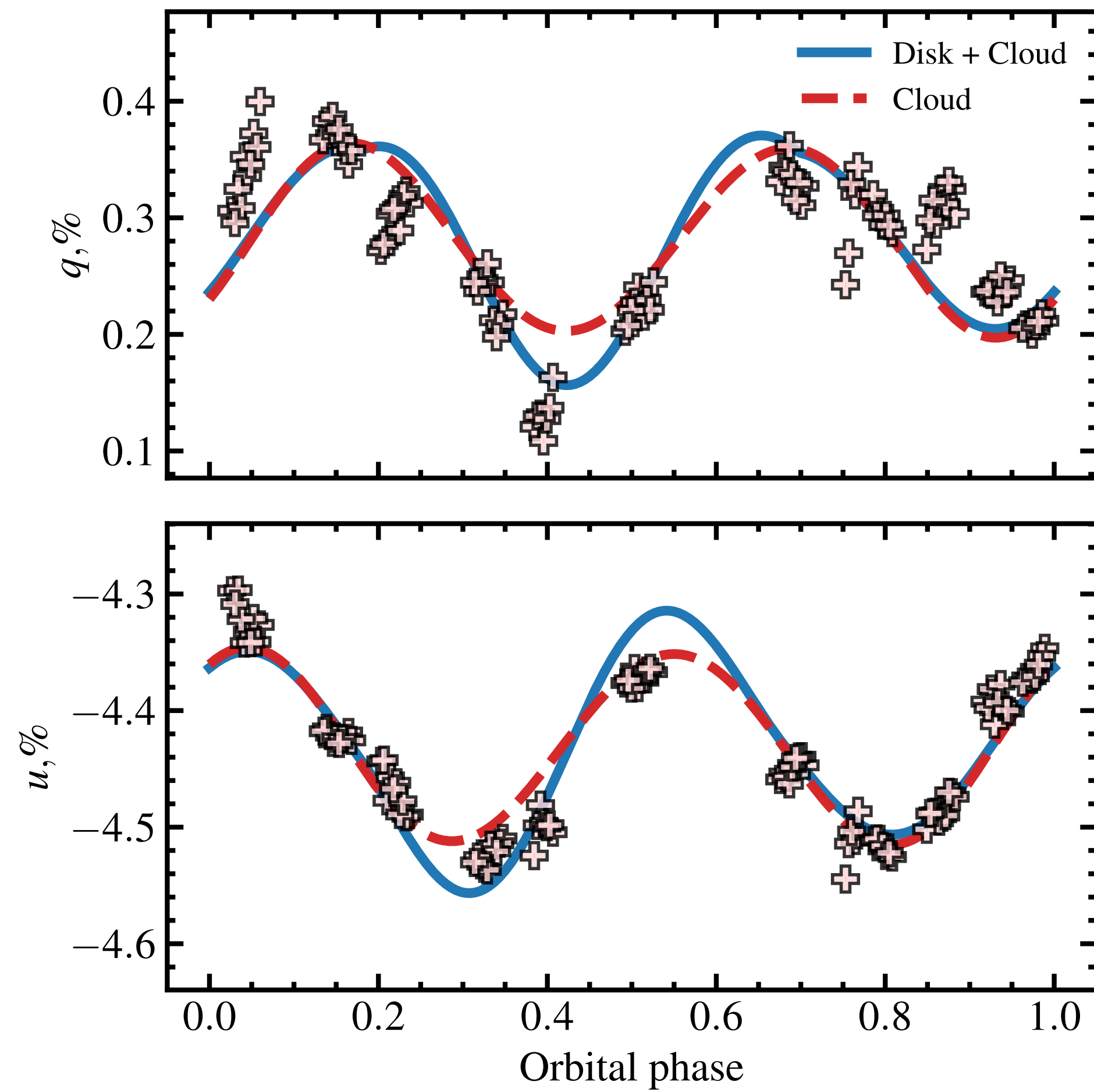
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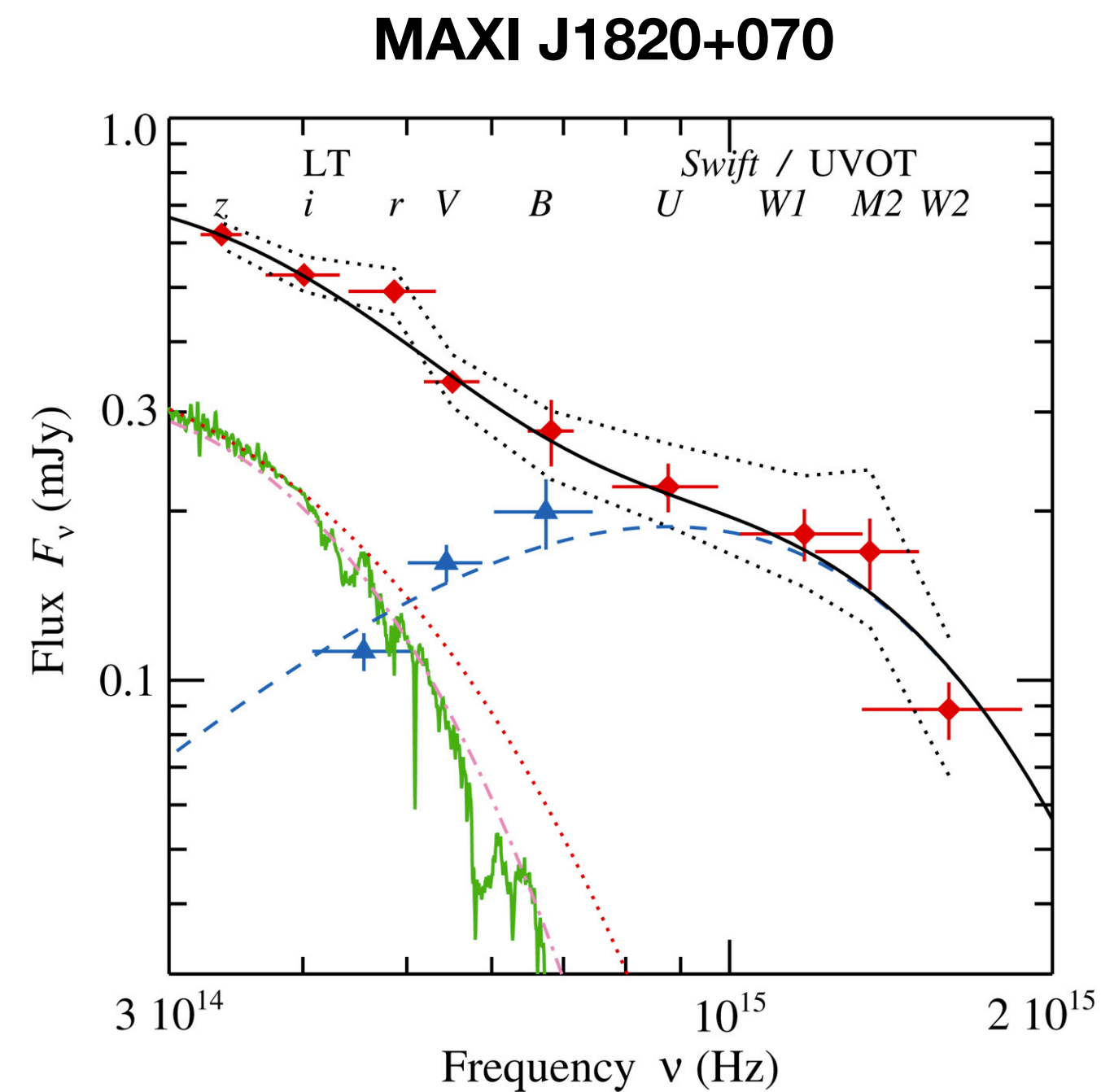
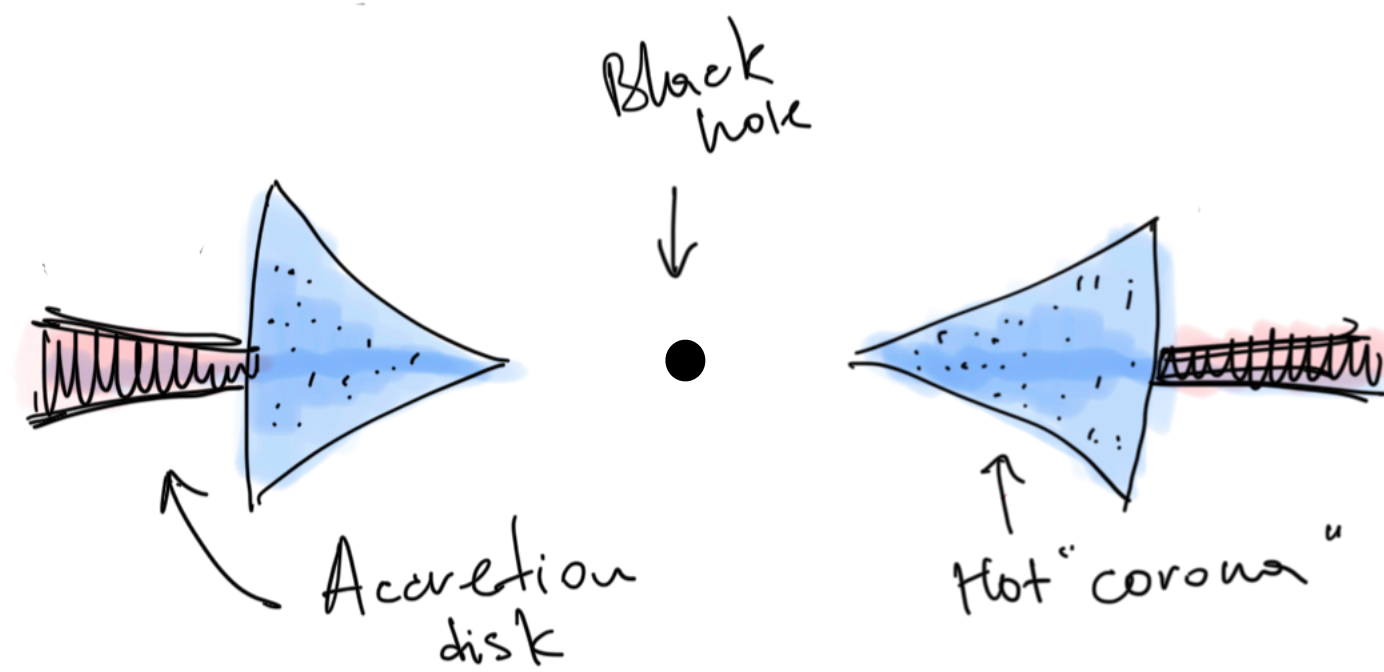
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# Exceptional sources: MAXI J1820+070

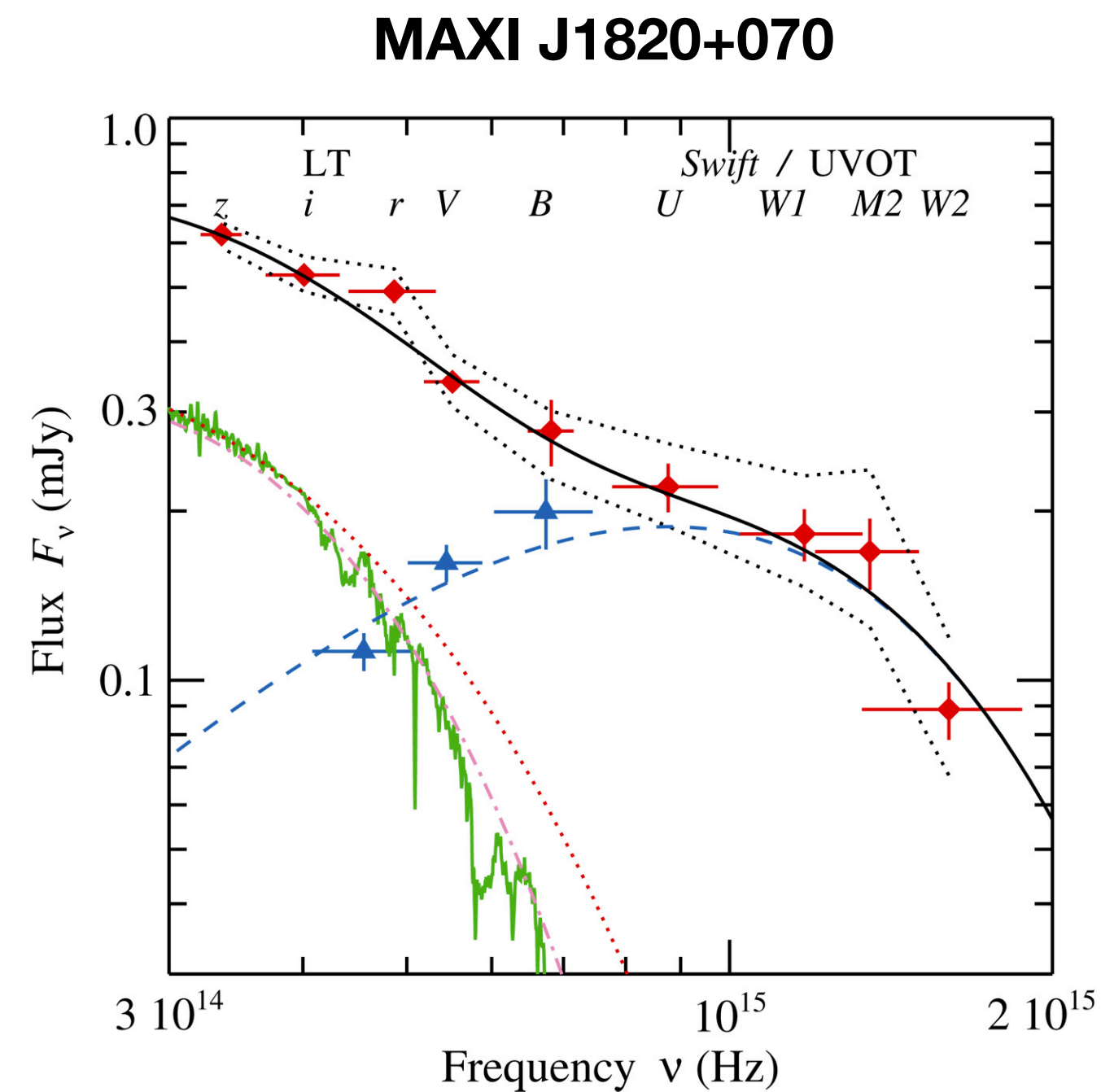
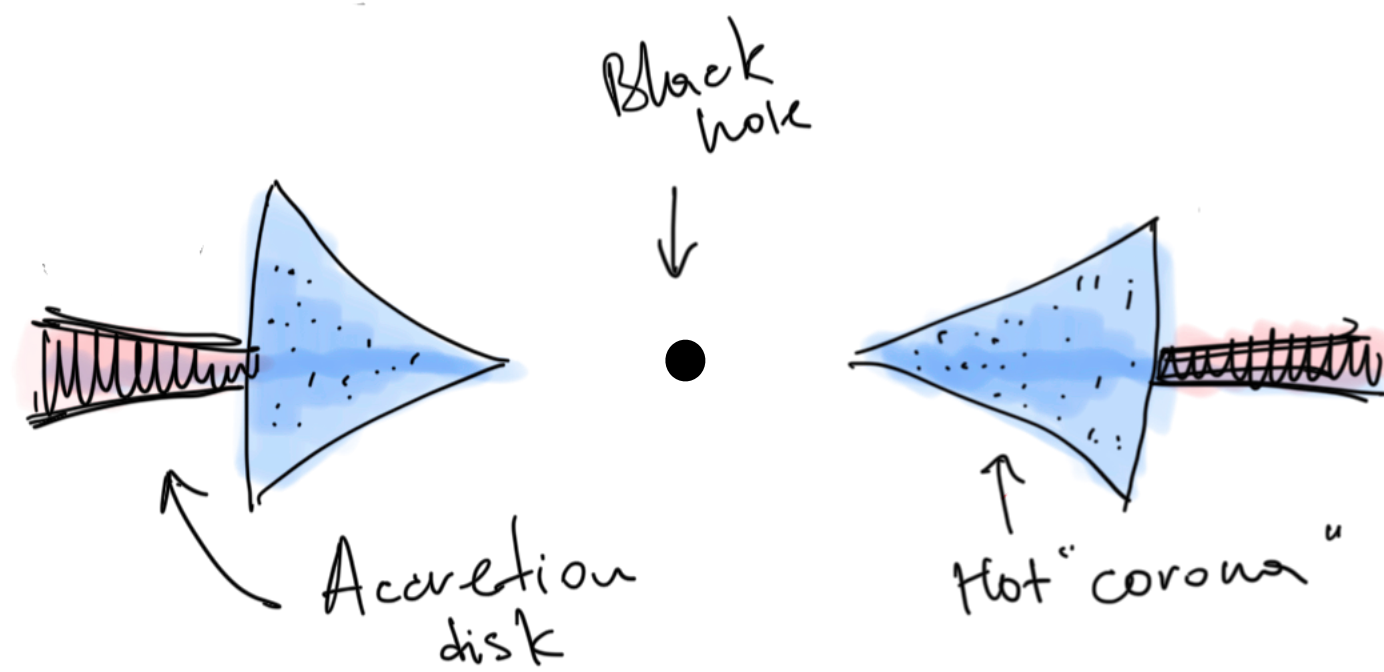
- **MAXI J1820+070:** Poutanen et al., 2022 – polarization up to  $P_{\text{int}} \sim 5\%$  with the position angle changed by  $40^\circ$  (!) relative to the value in outburst, non-synchrotron origin, jet-spin misalignment (!)



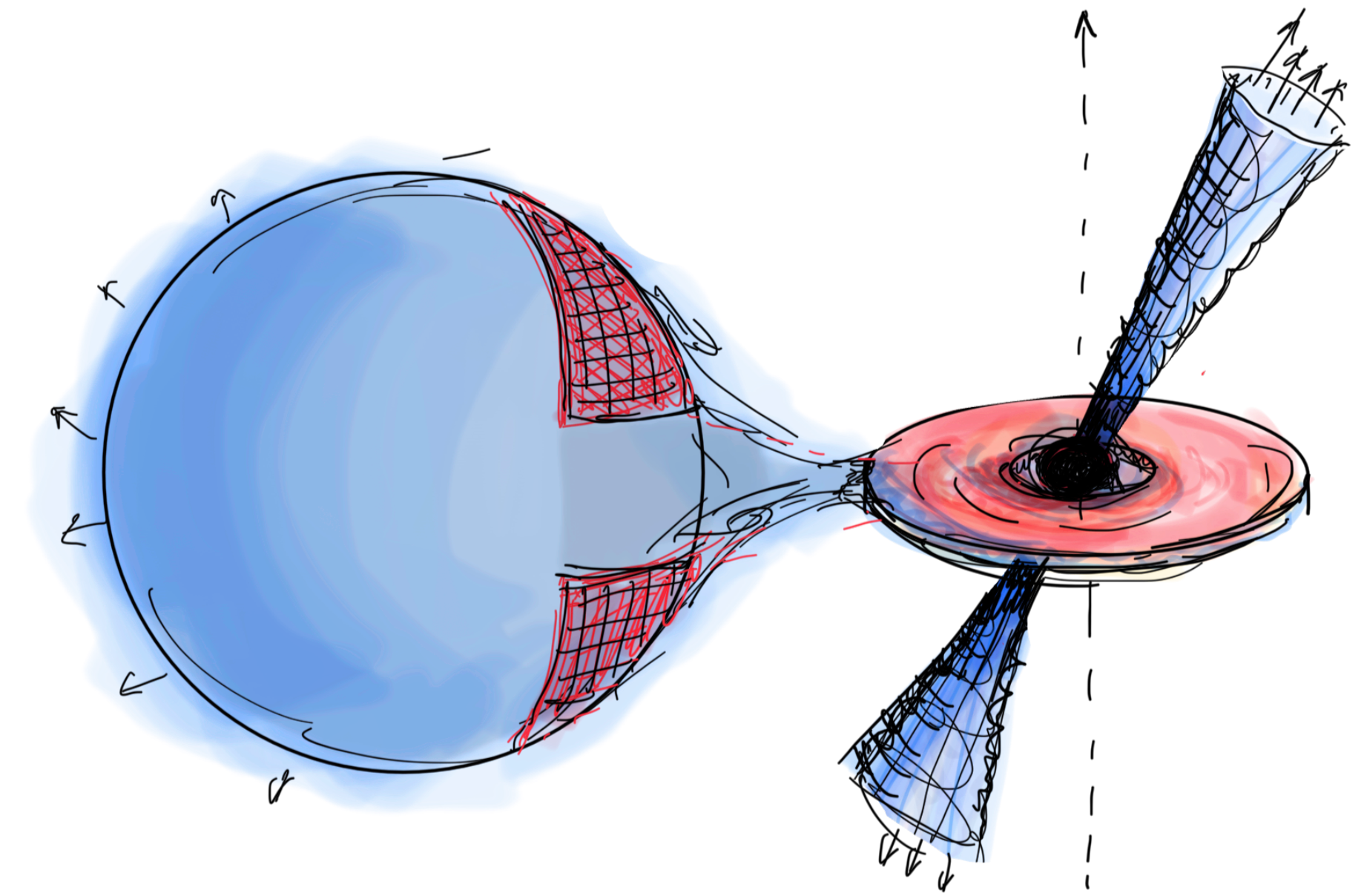
Poutanen et al., 2022, Science

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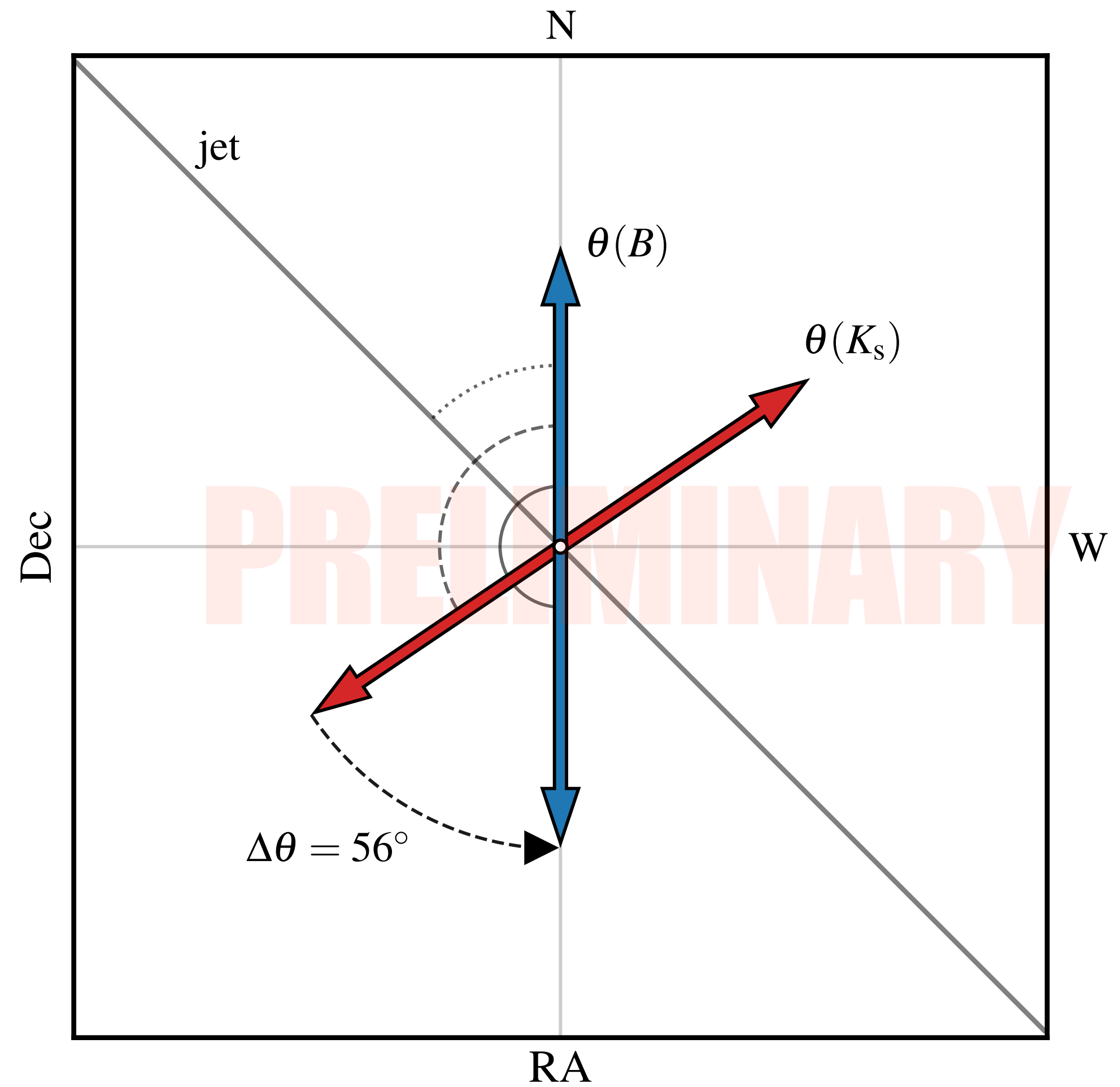
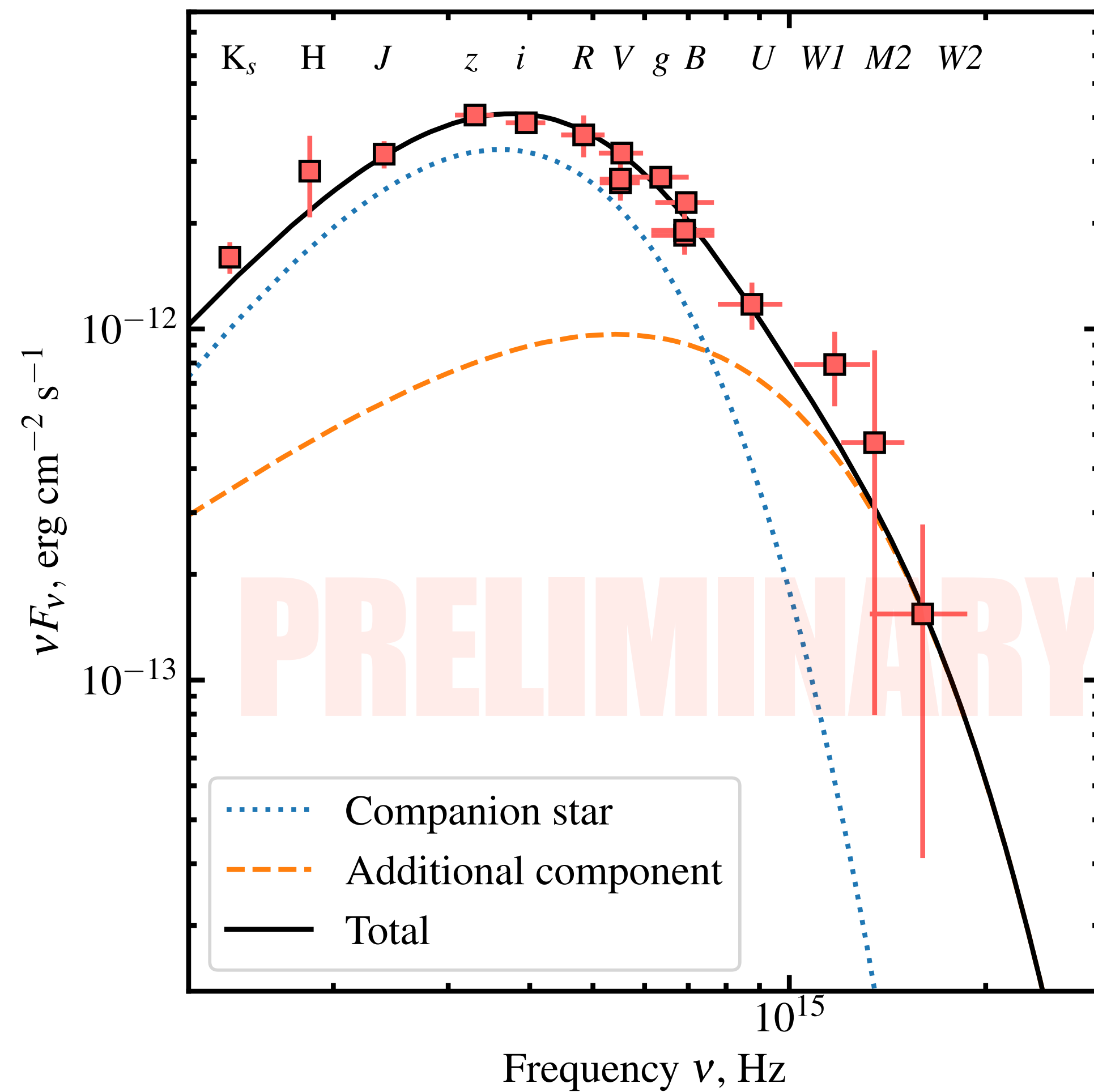
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Poutanen et al., 2022, Science



# Exceptional sources: A0620–00

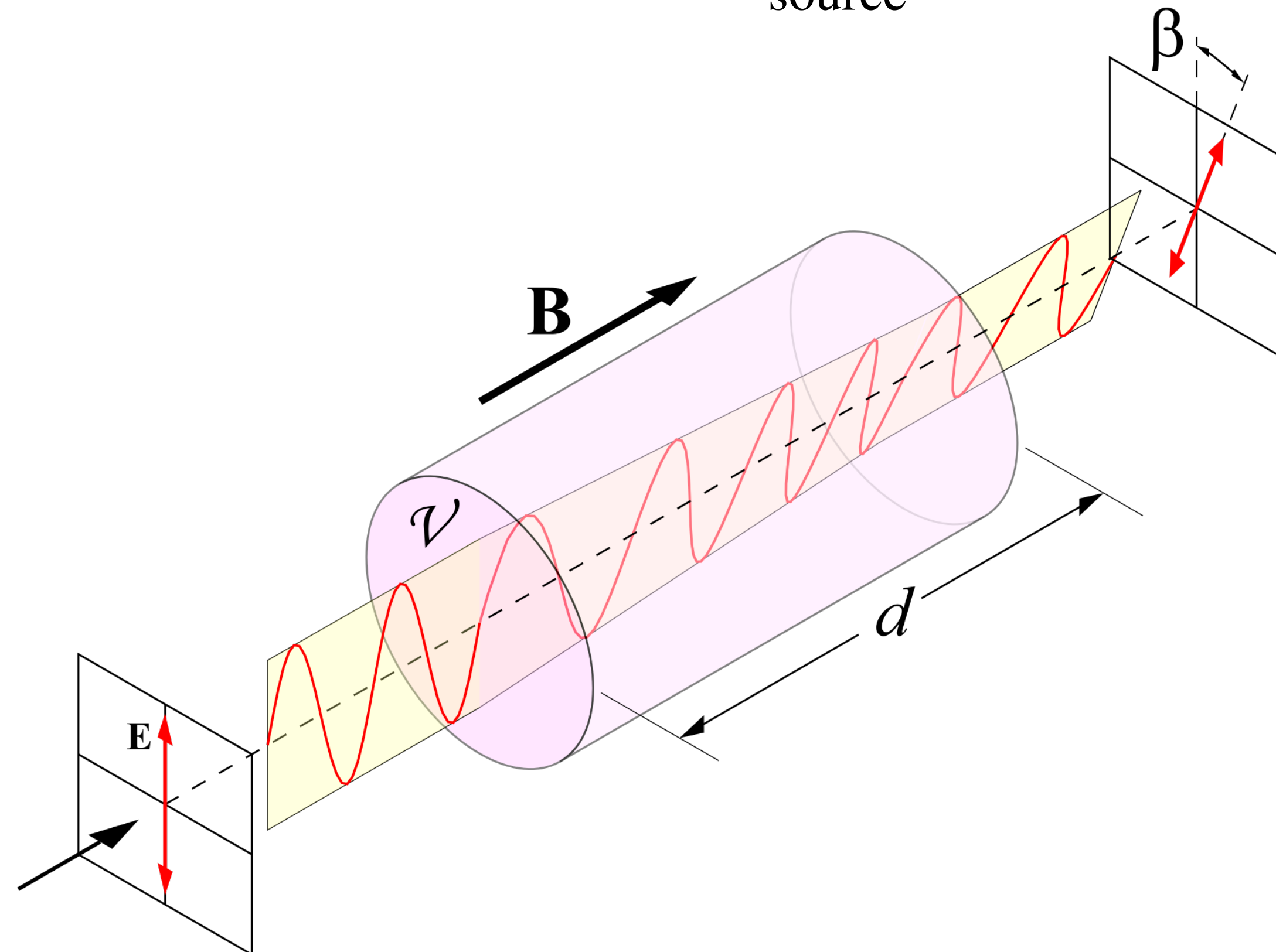


# Why angle rotates?

## Faraday rotation?

$$\Delta\theta = RM\lambda^2$$

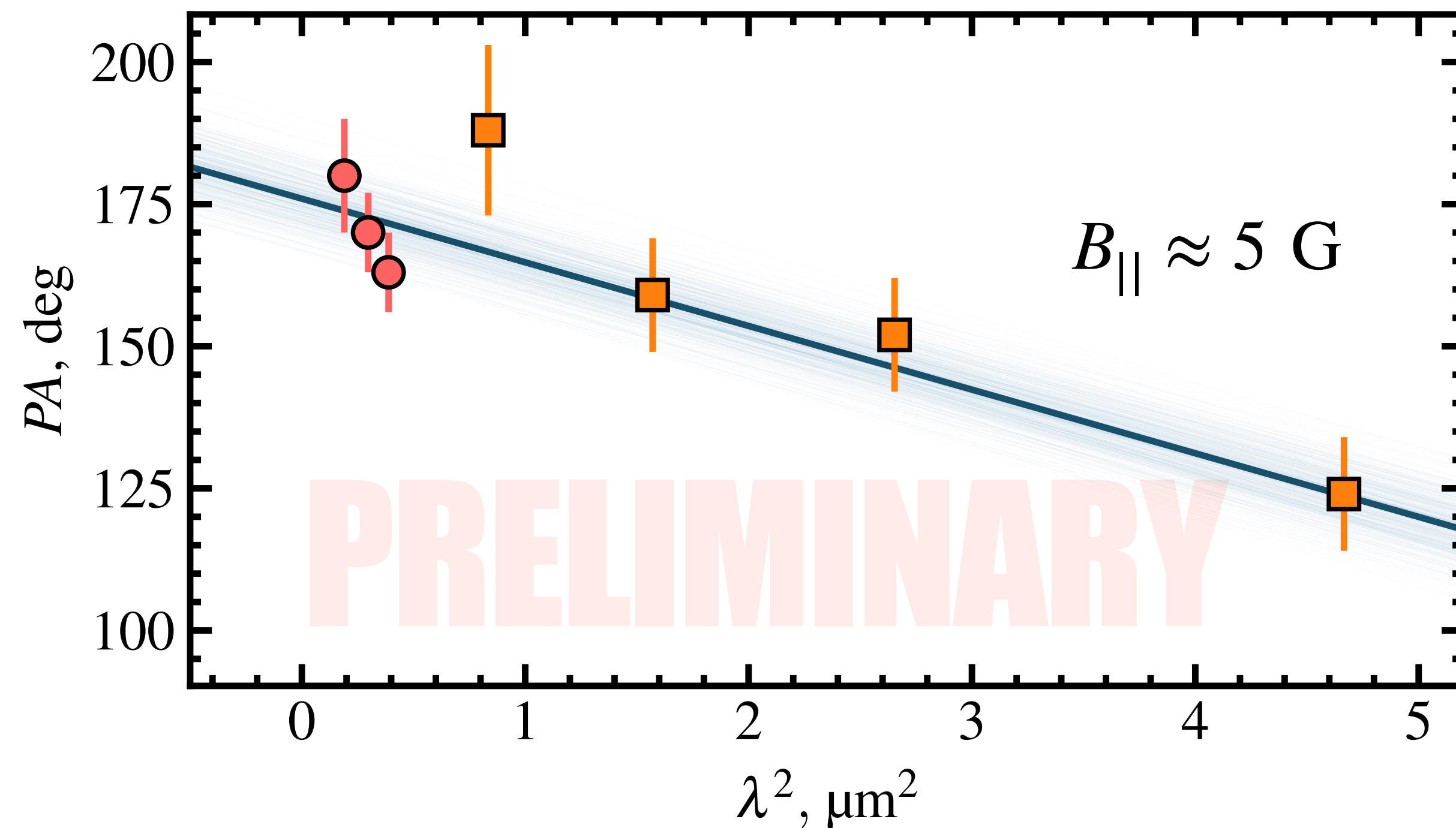
$$RM = \frac{e^3}{2\pi m^2 c^4} \int_{\text{source}}^{\text{observer}} n_e(l) B_{\parallel}(l) dl \approx 0.4\tau B_{\parallel} \text{ rad } \mu\text{m}^{-2}$$



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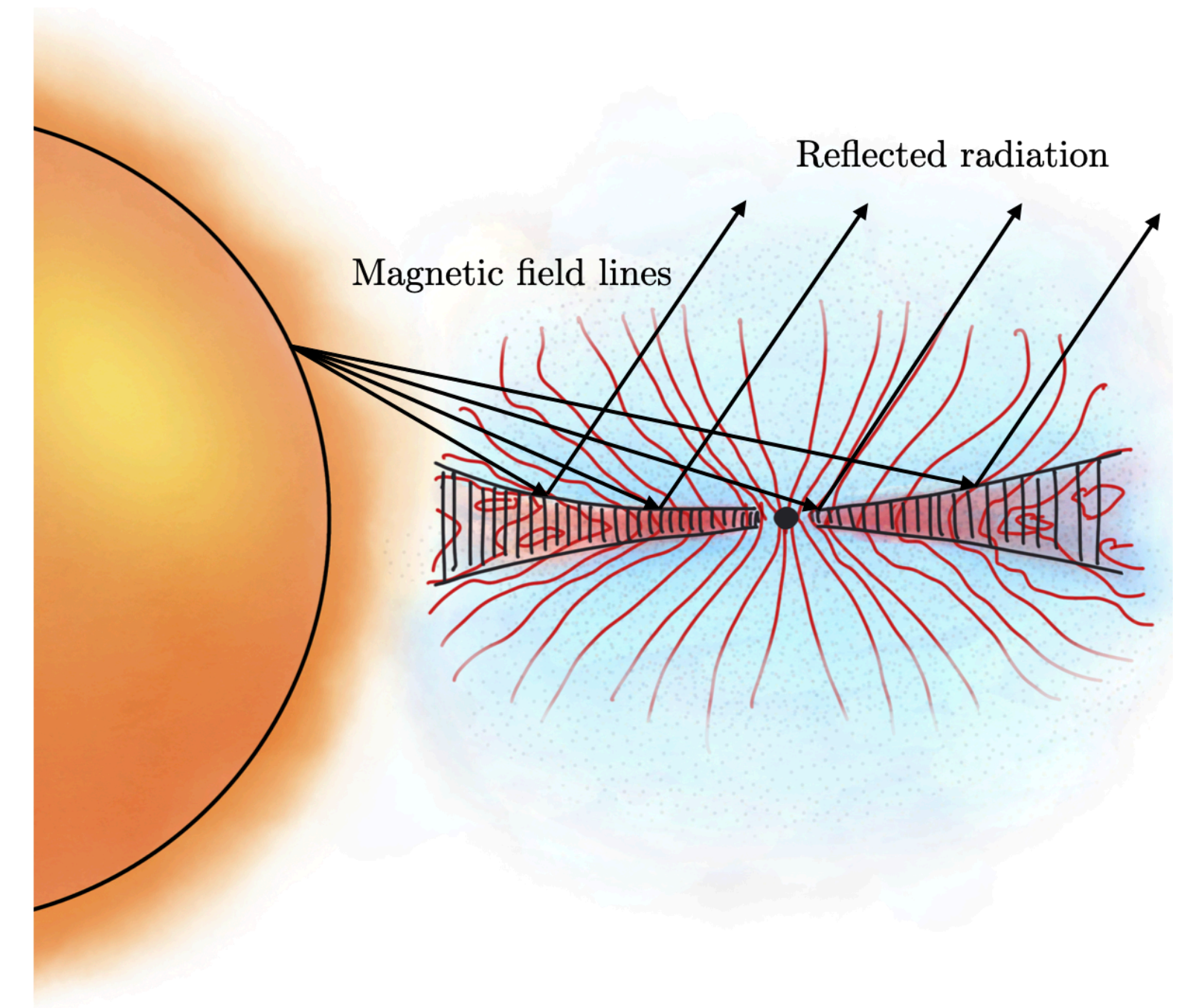
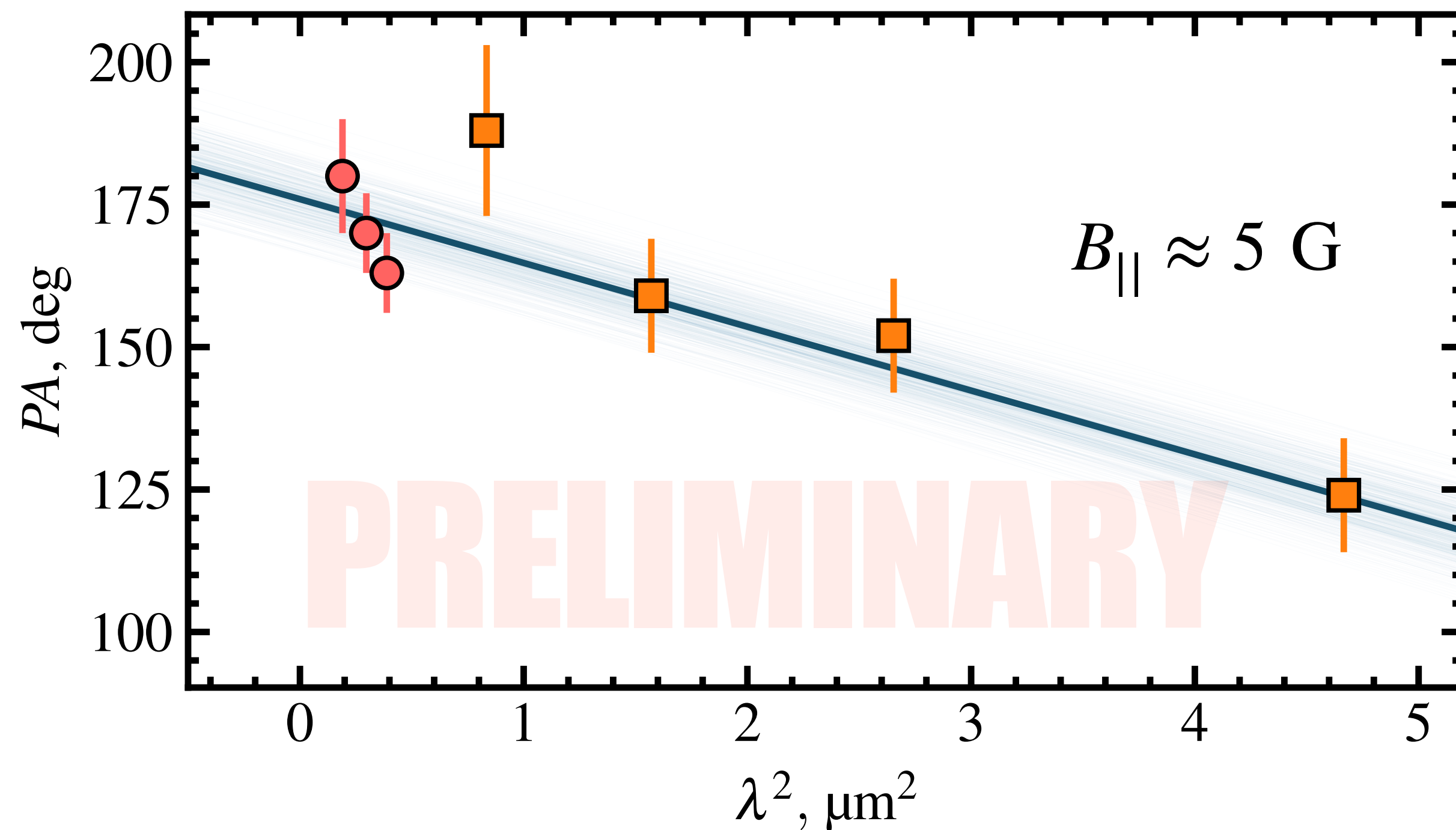
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# Conclusions

- 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