High precision optical polarimetry of black hole X-ray binaries

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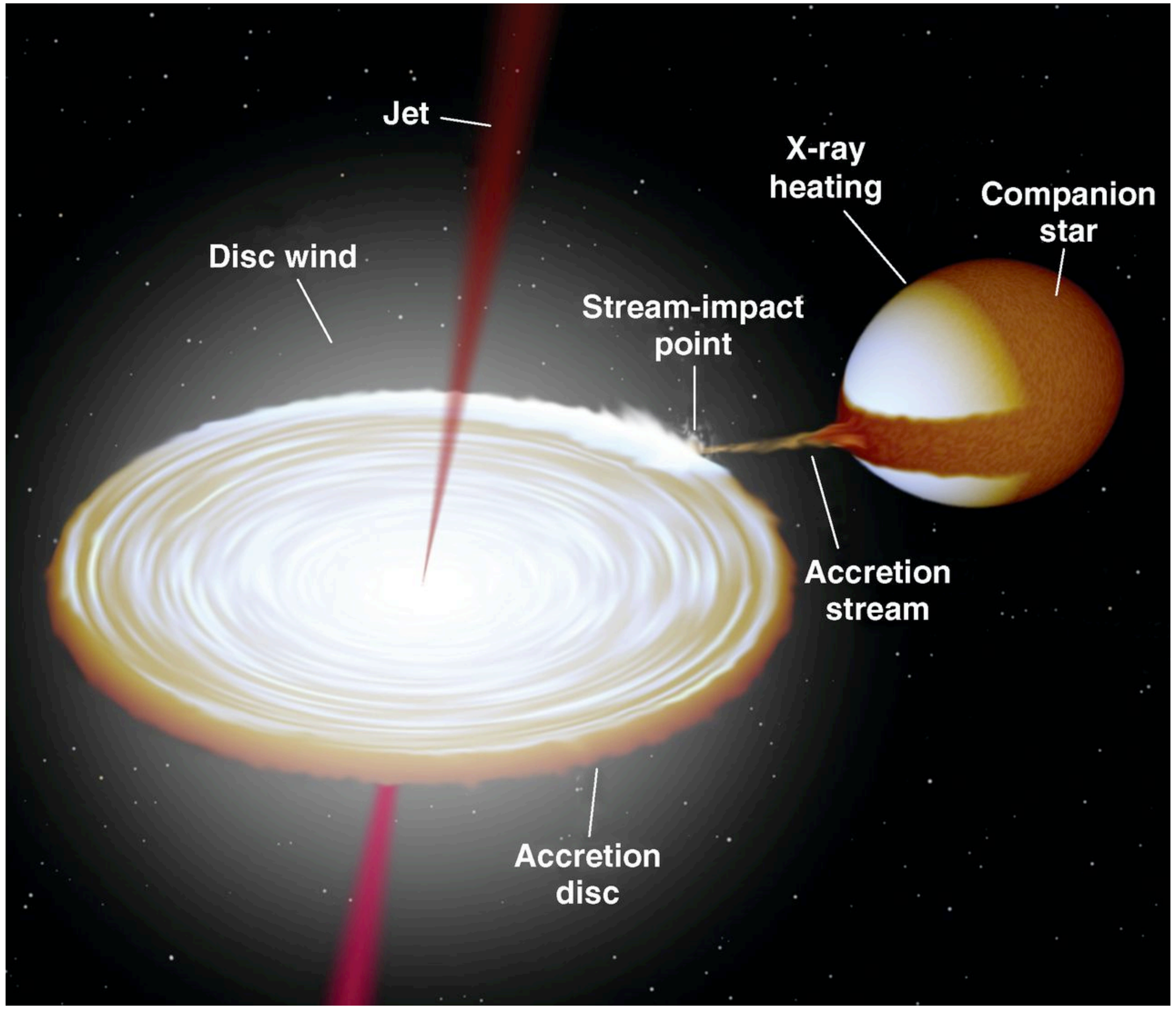
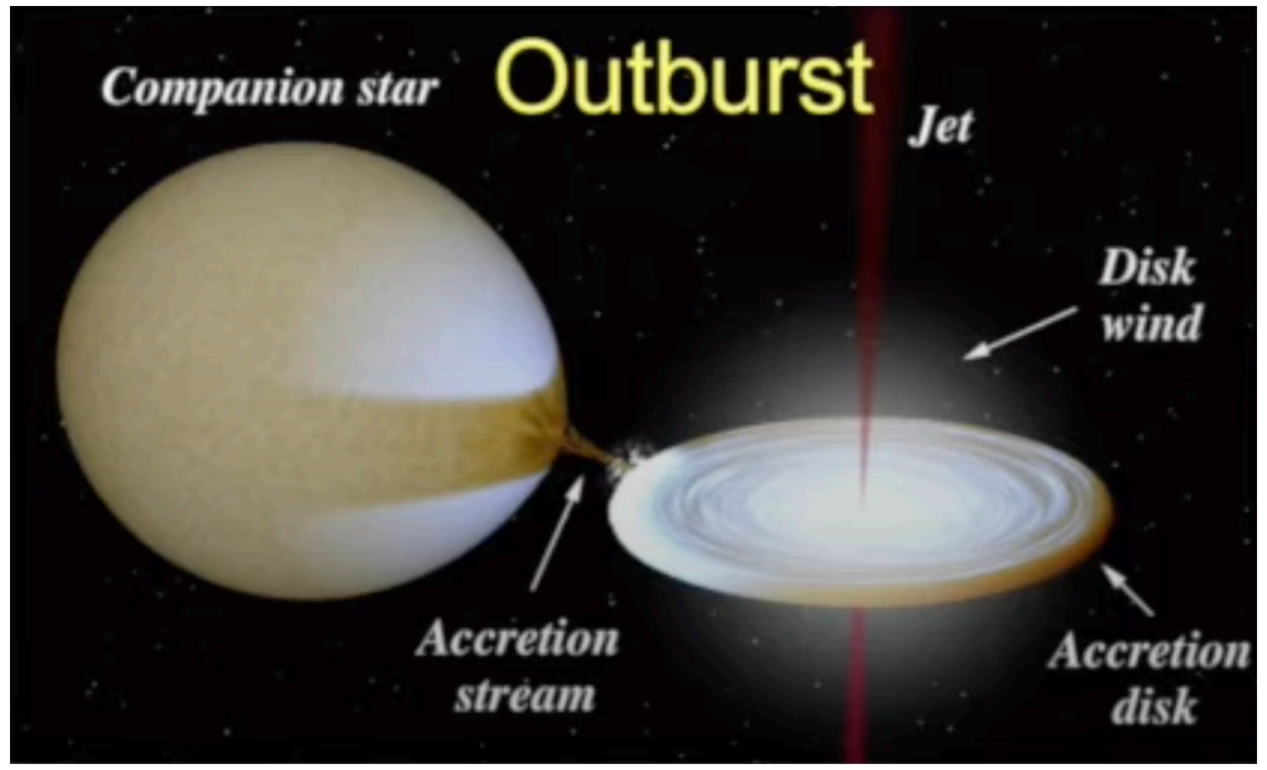
Motivation

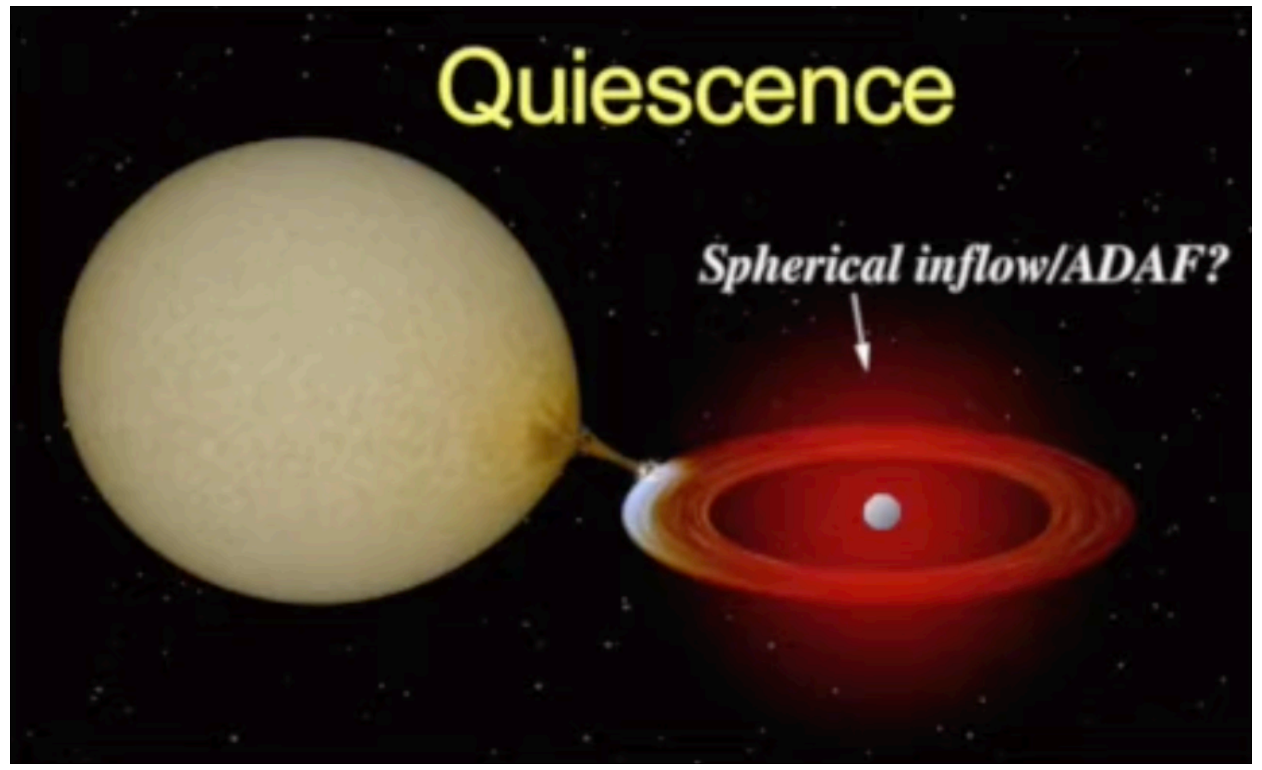
Geometry and spectral states of low-mass black hole X-ray binaries (BHXRBs)



[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

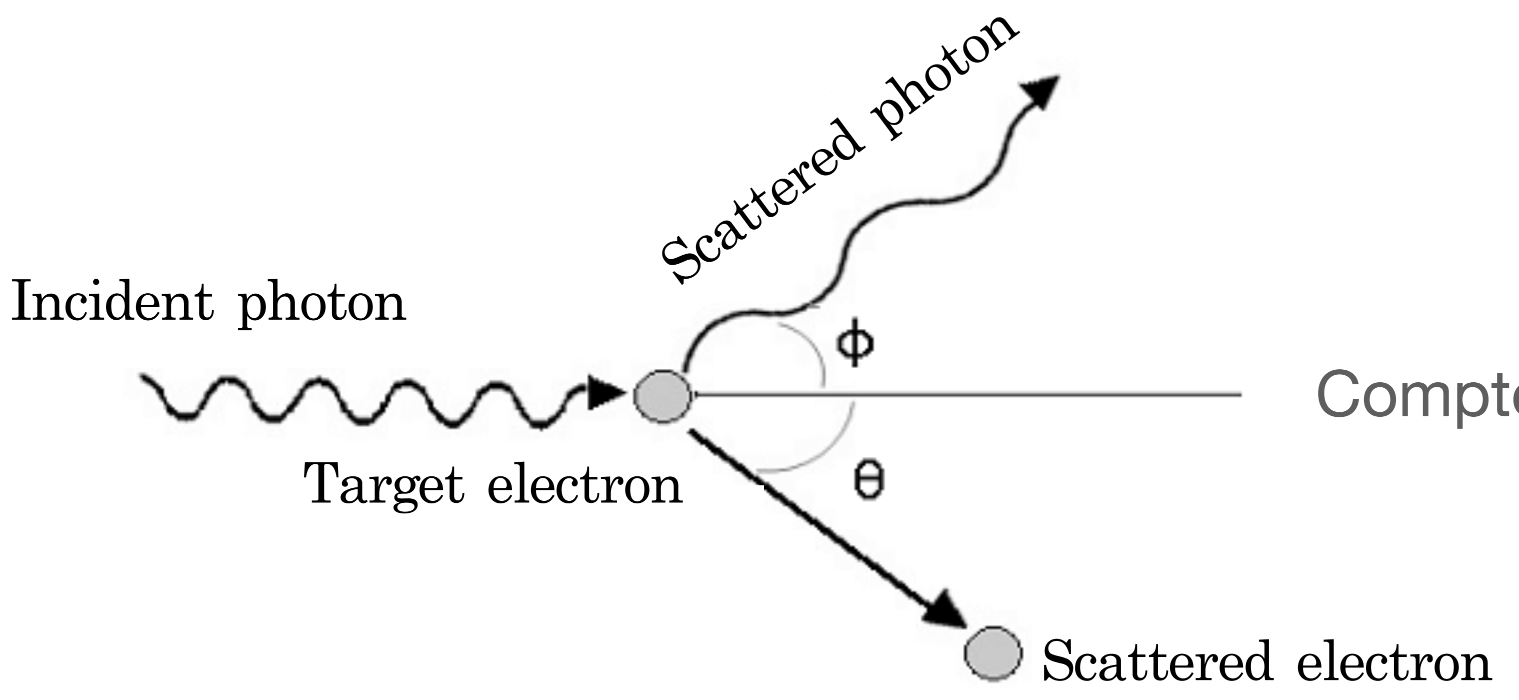
The identification of the different spectral components is essential for understanding the mechanisms that trigger the outbursts.

Motivation

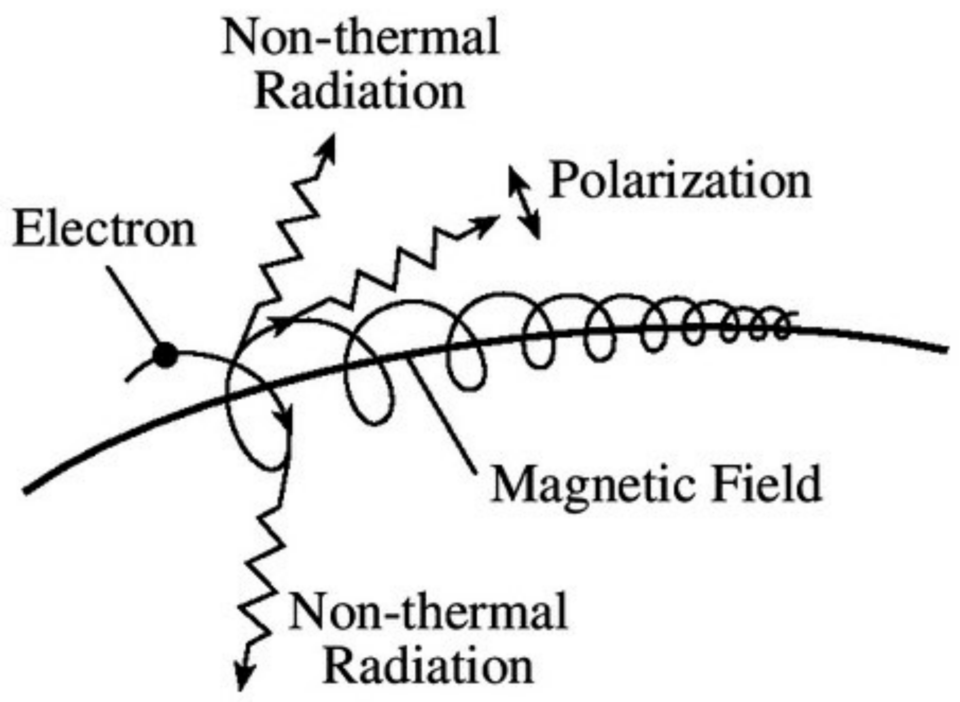
Choice of a tool

There are **several methods** that can be used to identify the **contribution of different components**: *photometry, spectroscopy, imaging, timing, and **polarimetry**.*

Why **polarimetry**?



Compton scattering



Synchrotron radiation

Motivation

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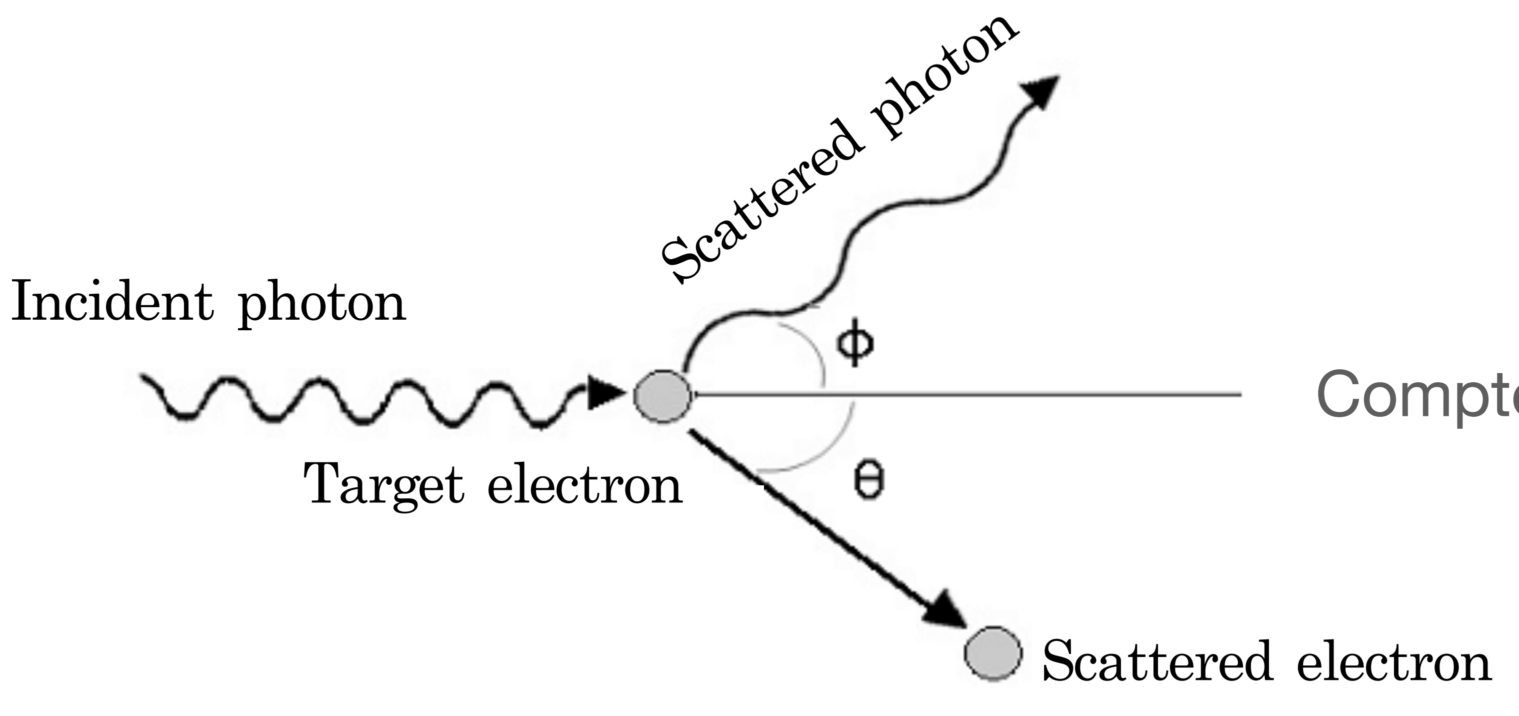
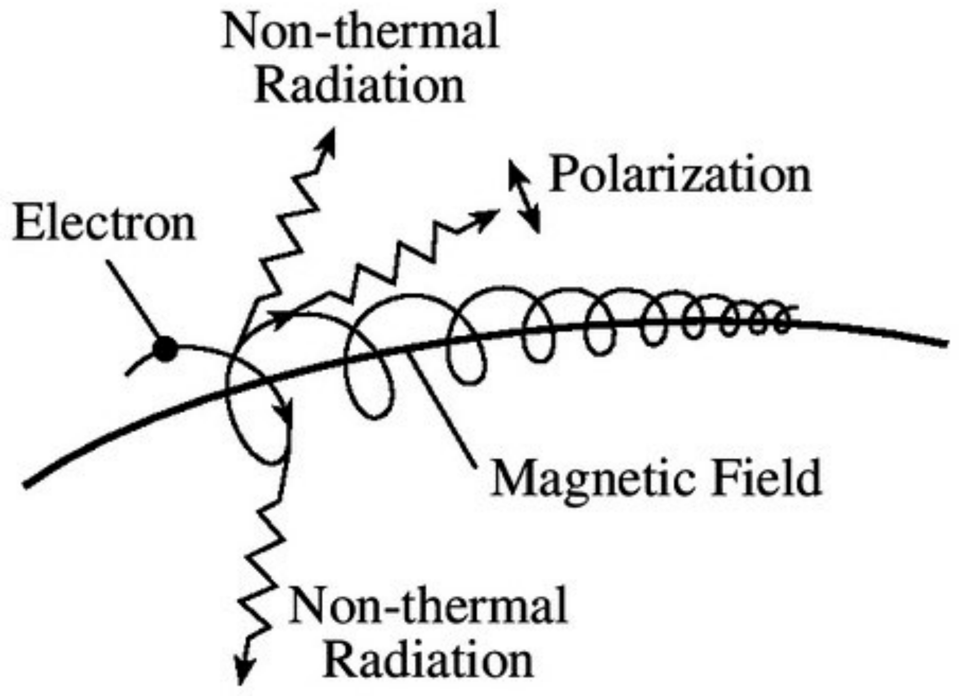
Why **polarimetry**?

- **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**.



Compton scattering



Synchrotron radiation

Vadim Kravtsov

Motivation

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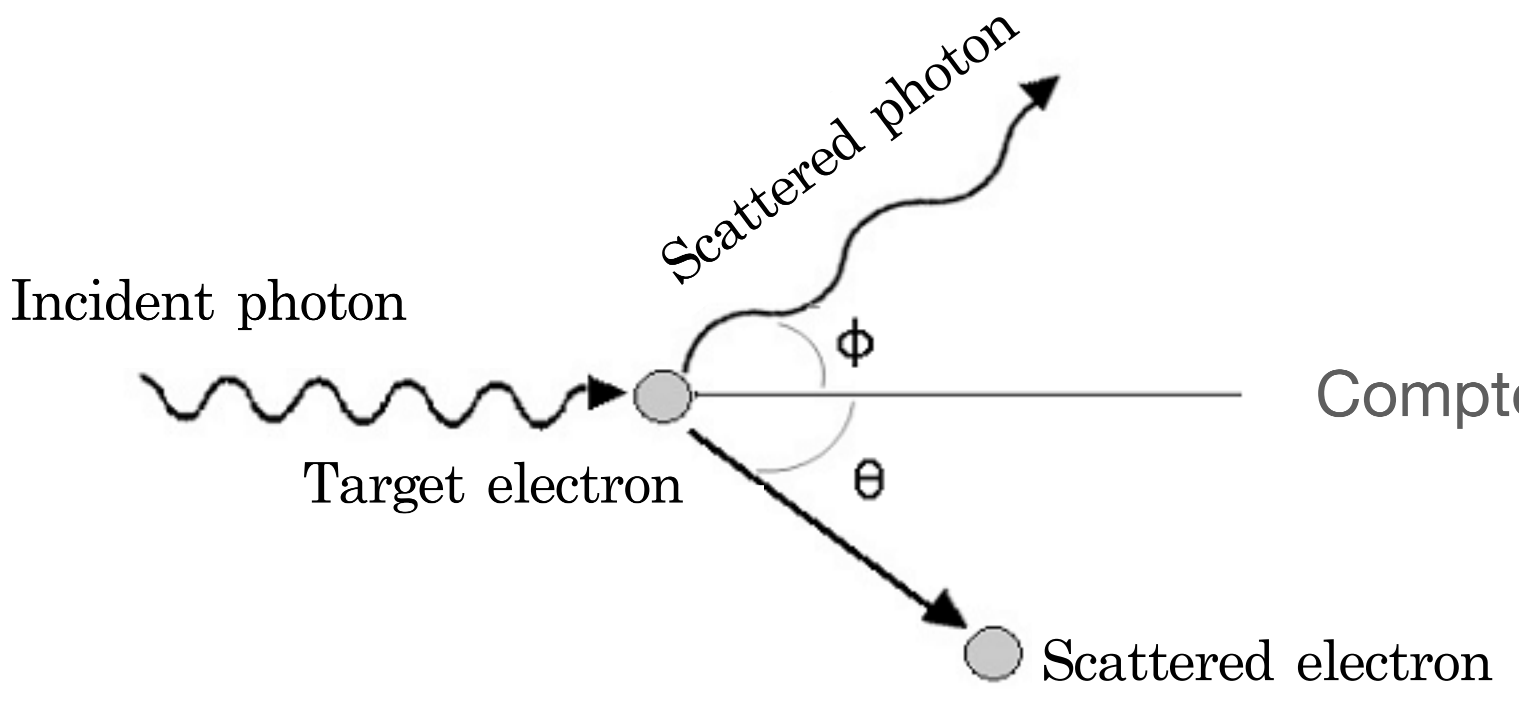
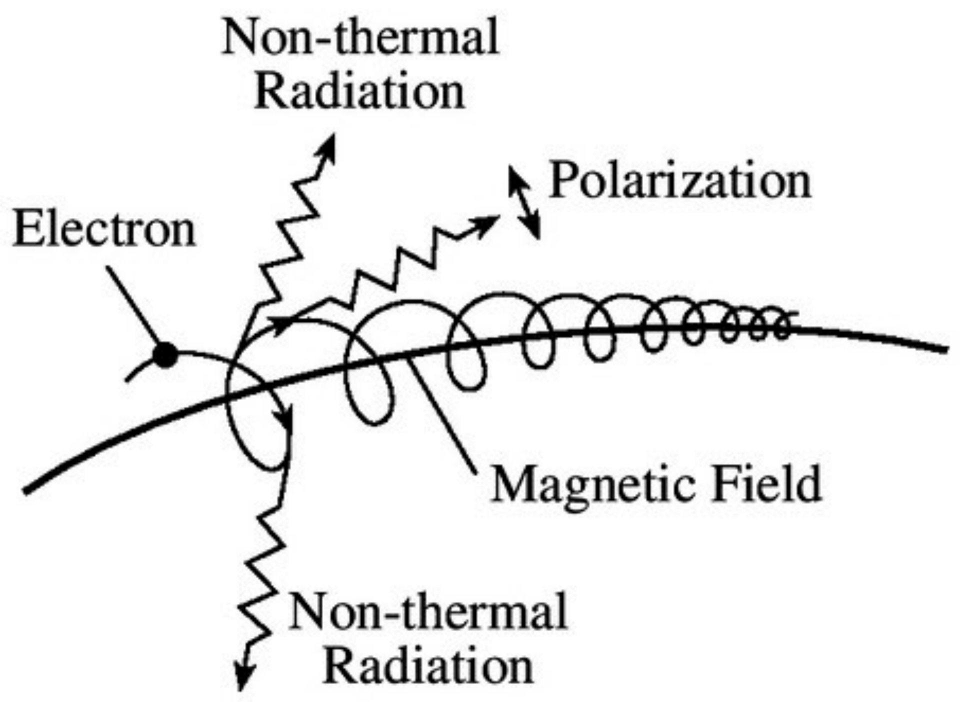
- **Polarization carries information about the geometrical properties** of the emitting/scattering media.



Compton scattering



Synchrotron radiation

Motivation

Choice of a tool

There are **several methods** that can be used to identify the **contribution of different components**: *photometry, spectroscopy, imaging, timing, and* ***polarimetry****.*

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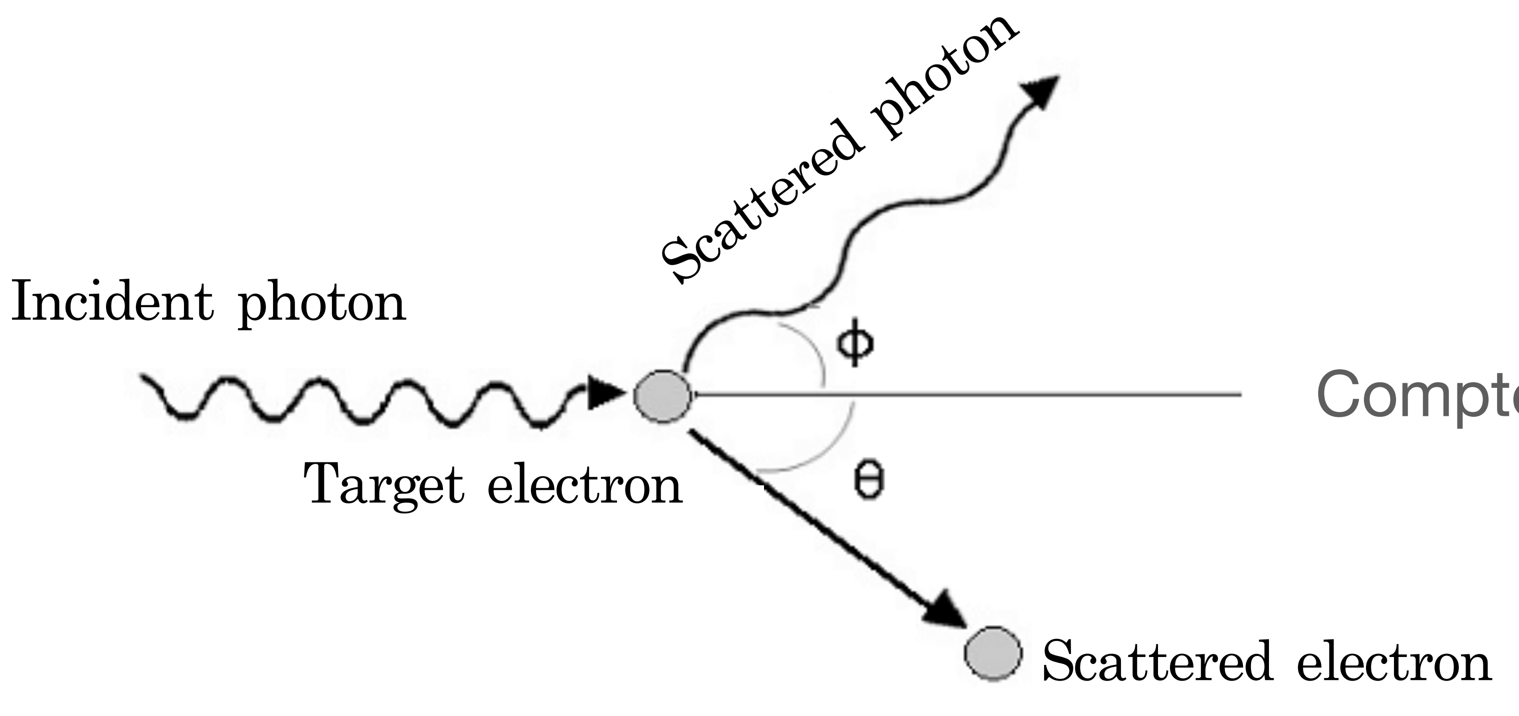
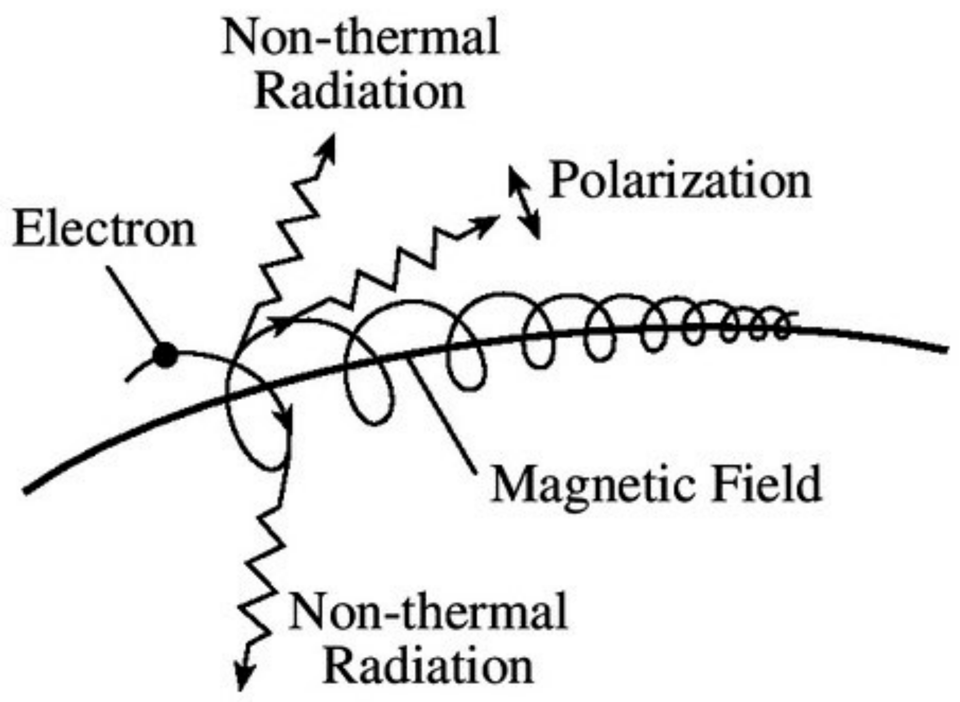
- **Polarized radiation can be produced by** several physical processes taking place in the BHXRBs, such as **synchrotron radiation** in the presence of an ordered magnetic field of the jet (hot accretion flow) or **scattering** of the accretion disk radiation **by electrons or dust**.
- **Polarization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



Compton scattering



Synchrotron radiation

BHXRBs: previous polarimetric studies

Quick review of recent results

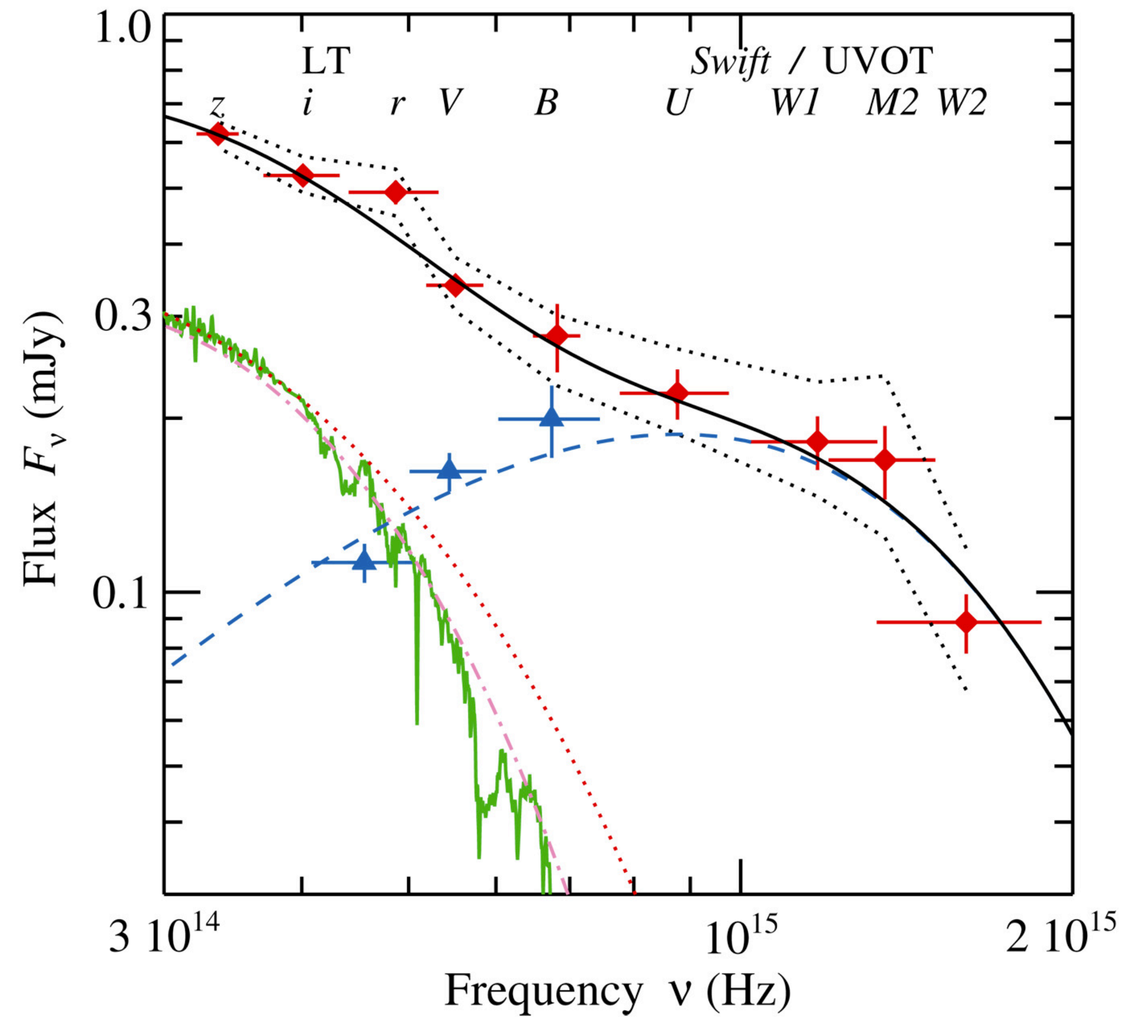
Polarization in the **outburst**:

- Shahbaz et al., 2016 – **V404 Cyg**, optical and NIR polarimetry, P_{int} ~4%, jet origin
- Tanaka et al., 2016 – **V404 Cyg**, optical and NIR polarimetry, no intrinsic polarization
- Kosenkov et al., 2017 – **V404 Cyg**, optical polarimetry, P_{int}~1%, scattering origin
- Veledina et al., 2019 – optical polarimetry of **MAXI J1820+070**, P_{int}~0.7%, scattering origin

Polarization in **quiescence**:

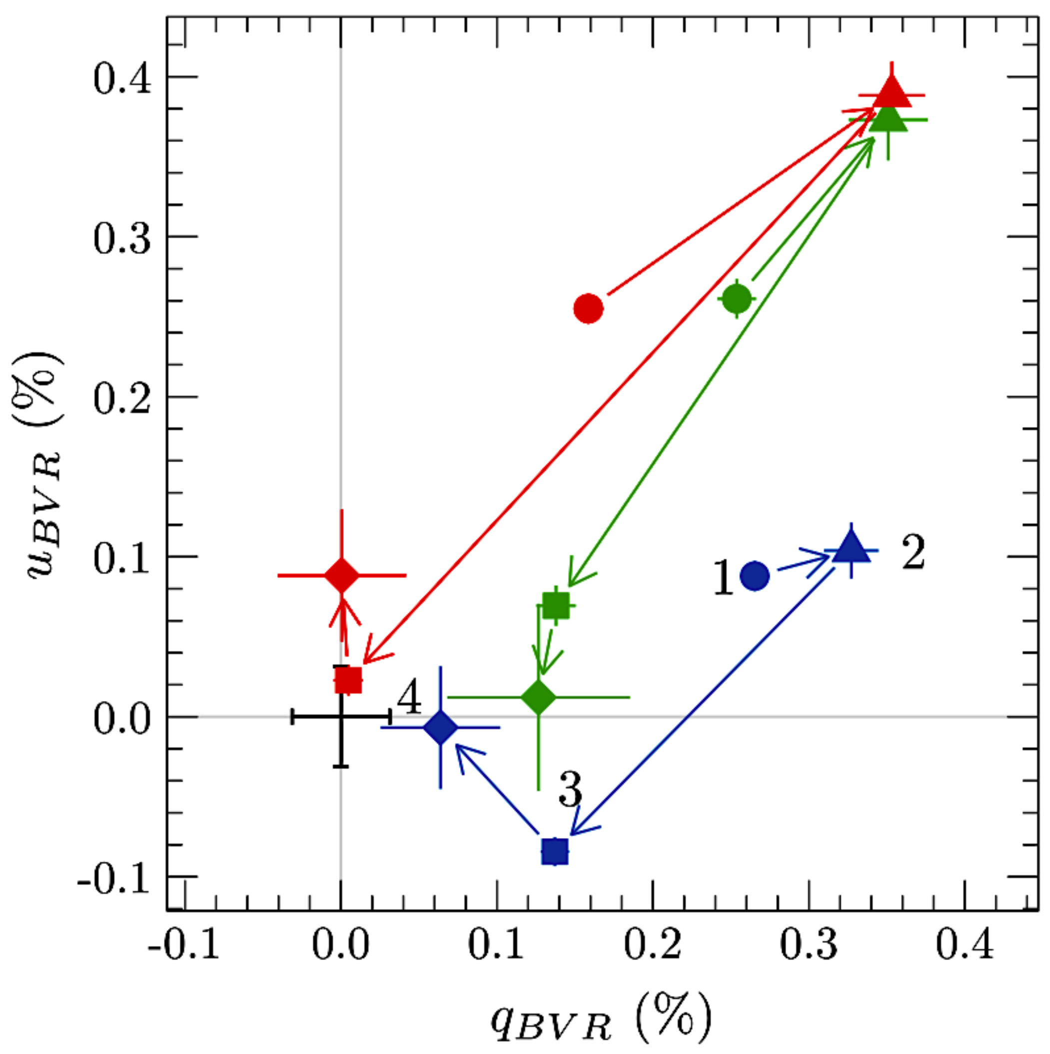
- Dolan & Tapia, 1989; Dubus et al., 2008, **1A 0620–00**, optical polarimetry, P_{int}~3%, scattering origin
- Russel et al., 2016 – **1A 0620–00, Swift J1357.2**, NIR polarimetry, P_{int}~1-8%, jet origin
- Poutanen et al., 2022 – **MAXI J1820+070**, optical polarimetry, blue polarization up to P_{int}~5%, non-synchrotron origin, jet-spin misalignment(!)

MAXI J1820+070



Poutanen et al., 2022

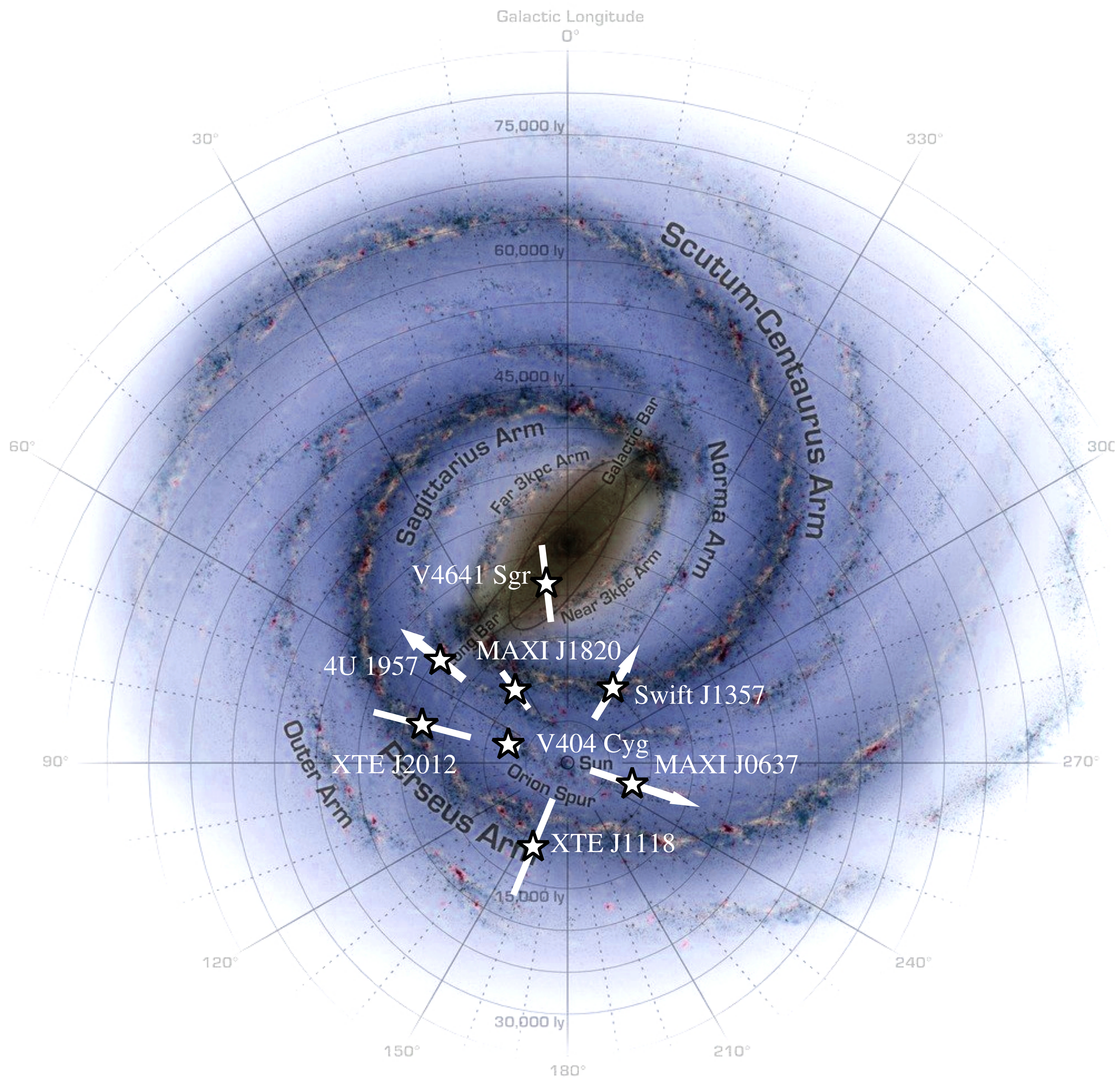
MAXI J1820+070

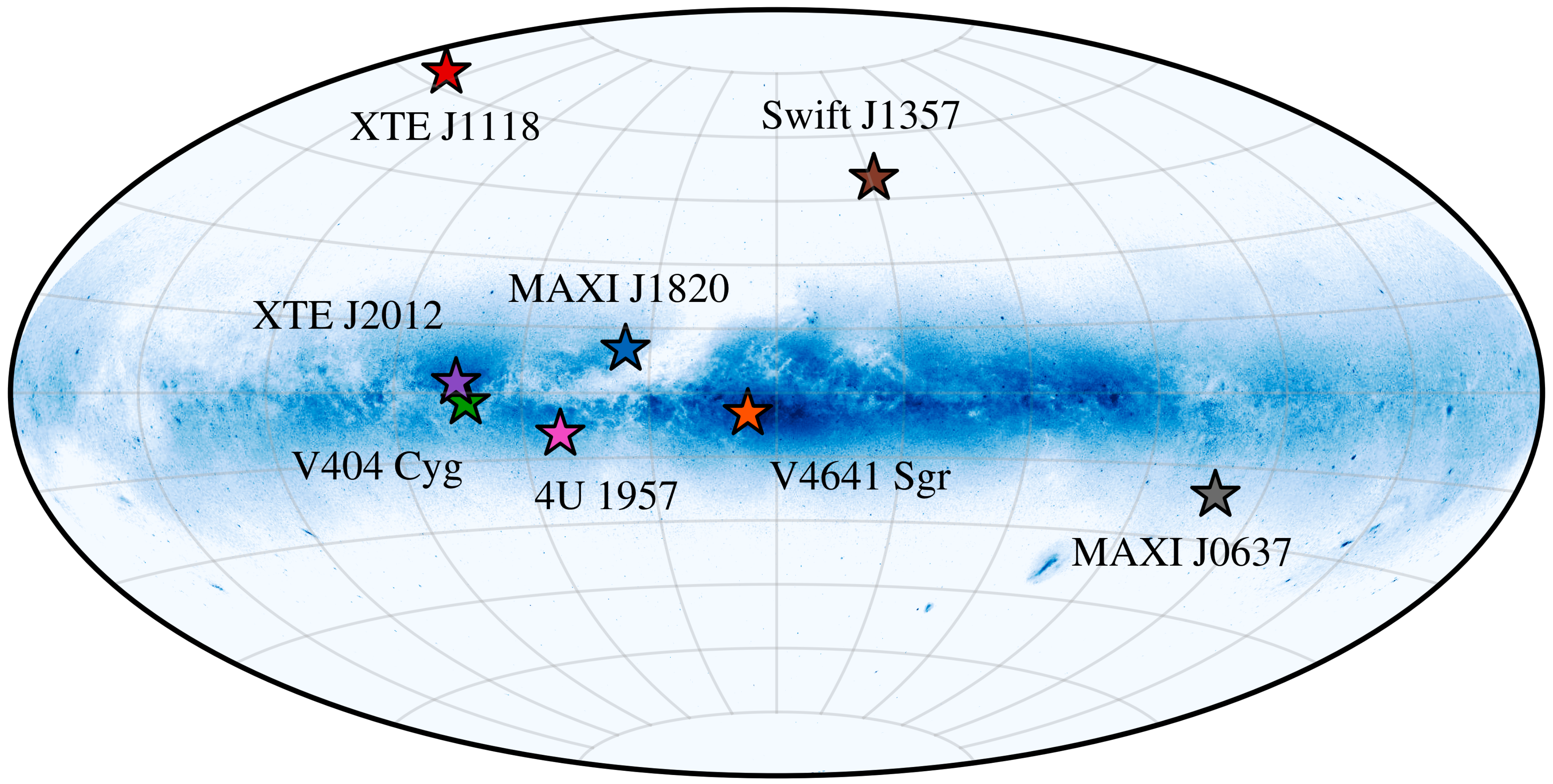


Kosenkov et al., 2020

Our sample of BHXRBs

Galactic distribution and main parameters





Object	Companion	V mag	i deg	$P_{\rm orb}$
XTE J1118+480	K7 V – M1 V	19.6 ± 0.2[1]	68 ± 2	4.07841(5) h
Swift J1357.2−0933	M5 V	17.27 ± 0.02[1]	> 70	2.8 ± 0.3 h
4U 1957+115	...	≈ 19.0[3]	20 – 70	9.33 ± 0.01 h
V404 Cyg	K3 III	≈ 18.7[2]	67 ± 3	6.473 ± 0.001 d
V4641 Sgr	B9 III	≈ 13.5[2]	72 ± 4	2.817 ± 0.001 d
XTE J2012+381	-	21.3 ± 0.1[4]	...	...
MAXI J1820+070	K4 V	-	73 ± 8	16.87 ± 0.07 h
MAXI J0637−430	...	≈ 16.5[2]	...	...

Our sample of 8 BHXRBs

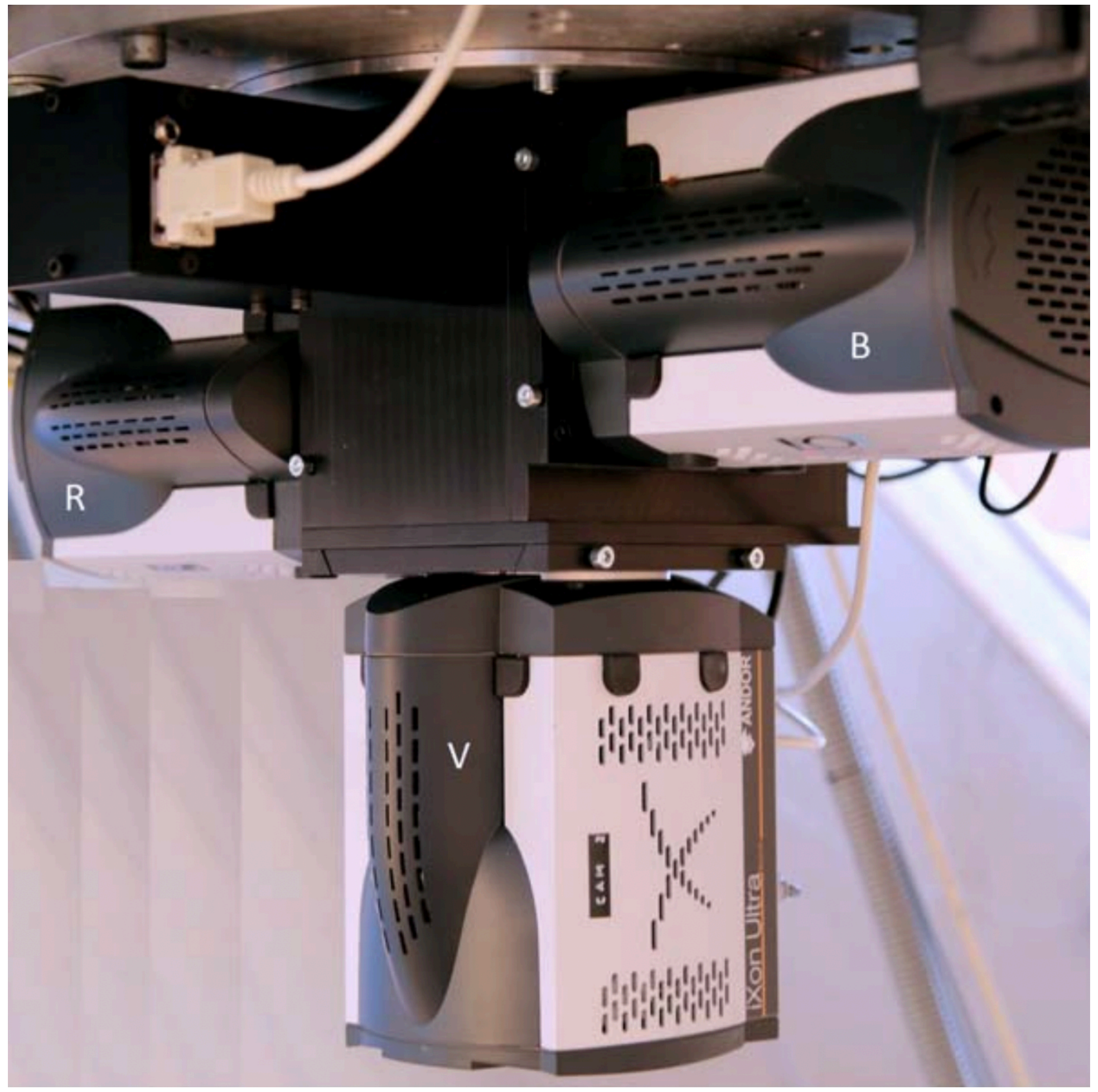
Observations

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

Observations

Detailed description

BHXRB	State	Observing nights
XTE J1118+480	**Q**	**1** (NOT)
Swift J1357.2–0933	**RH***	**1** (NOT)
4U 1957+115	**S**	**1** (NOT)
V4641 Sgr	**RH*, Q**	**11** (**5** – NOT, **6** – T60)
V404 Cyg	**RH, Q**	**2** (NOT)
MAXI J1820+070	**RH*, S, DH, Q**	**10** (T60)
MAXI J0637–430	**S**	**3** (T60)

States: Q – quiescence, RH – rising hard, S – soft, DH – decaying hard
*Failed outburst

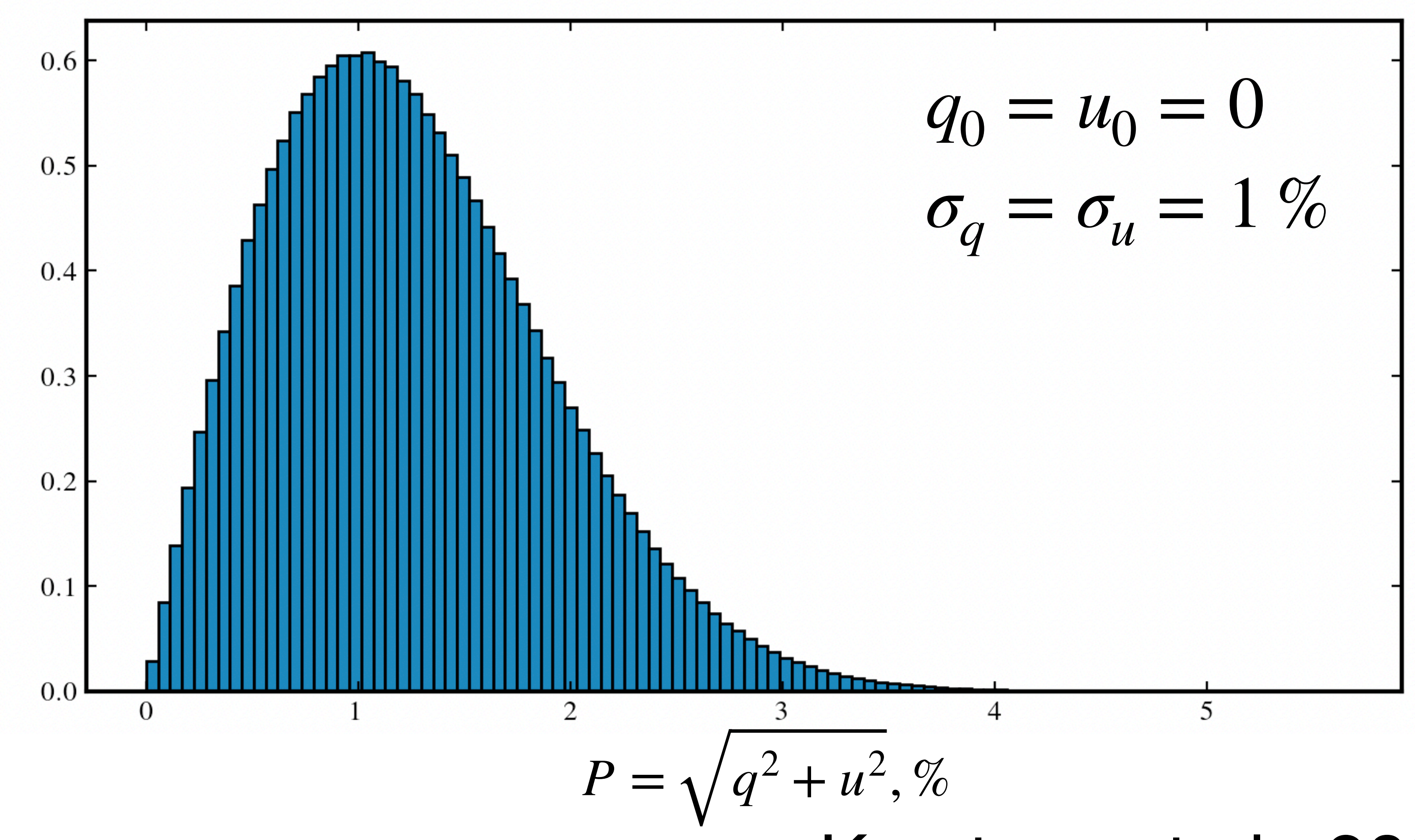
$$q_{obs} = q_{int} + q_{is} \quad u_{obs} = u_{int} + u_{is} \Rightarrow \boxed{q_{int} = q_{obs} - q_{is} \quad u_{int} = u_{obs} - u_{is}}$$

$$\boxed{P_{int} = \sqrt{q_{int}^2 + u_{int}^2} \quad \theta_{int} = \frac{1}{2} \arctan u_{int}/q_{int}}$$

When $P/\sigma < 5$, the polarization degree is biased towards higher values!

$$\boxed{P_0 = \sqrt{P^2 - 2\sigma^2}}$$, Simmons & Stewart (1985)

unbiased maximum-likelihood estimator



Results: Swift J1357.2–0933, 4U 1957+115 and XTE J1118+480

Observed and intrinsic polarization

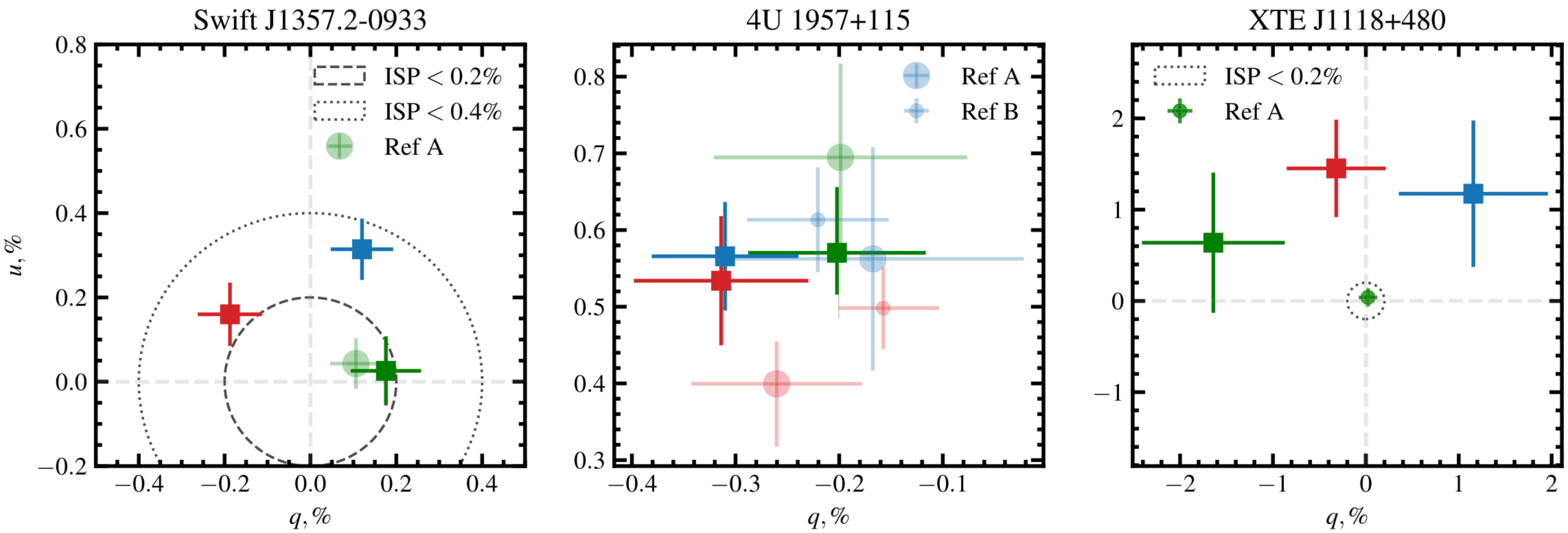


Figure 1. Normalized observed Stokes parameters (q, u) for Swift J1357.2−0933 , 4U 1957+115 , and XTE J1118+480 (from left to the right). The blue, green, and red squares with 1σ errors correspond to the B, V, and R optical polarimetric measurements of the targets and the circles correspond to nearby stars.

Results: V4641 Sgr

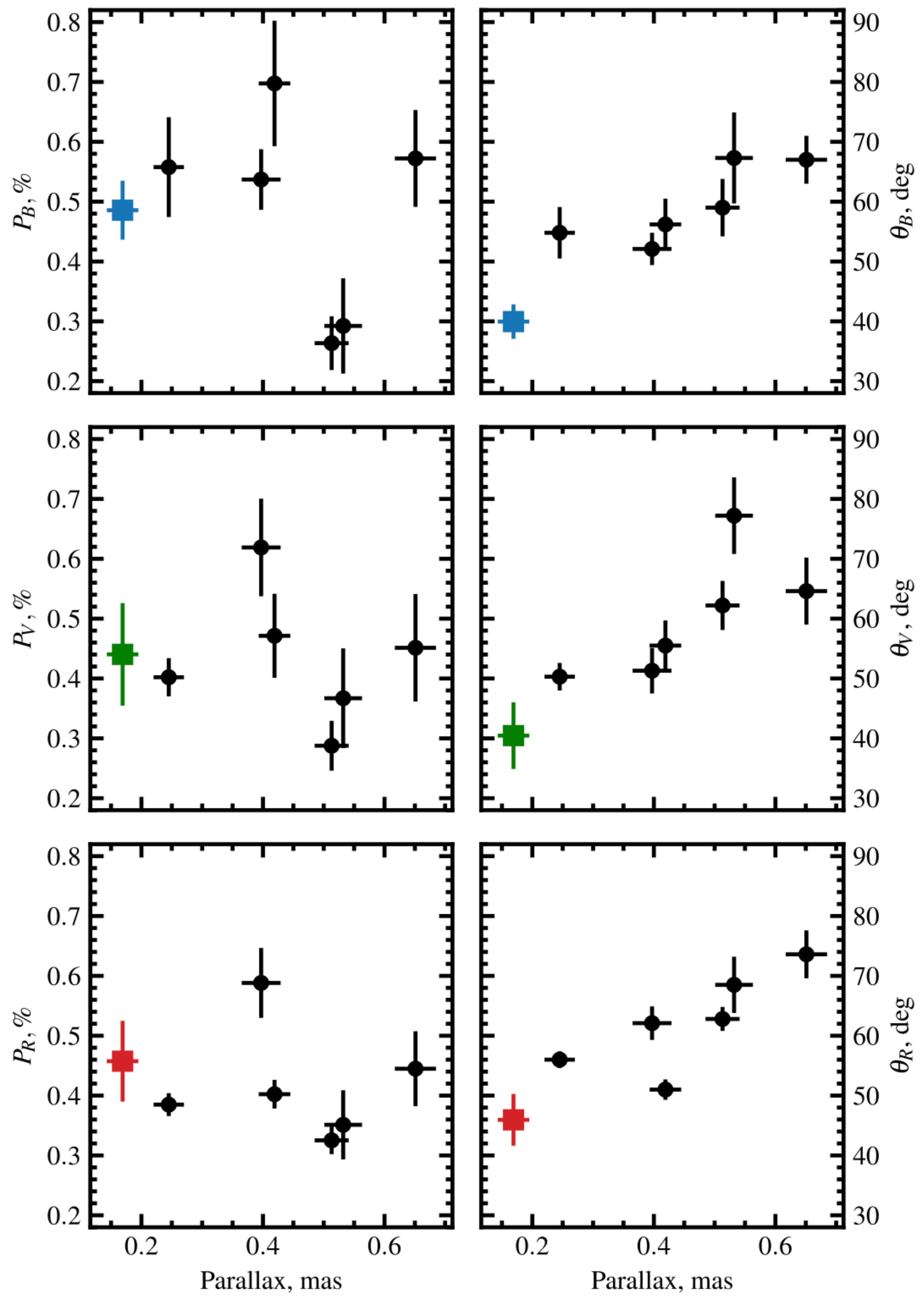
Observed and intrinsic polarization

We measured the polarization of **six** nearby field stars with similar *Gaia* parallaxes.

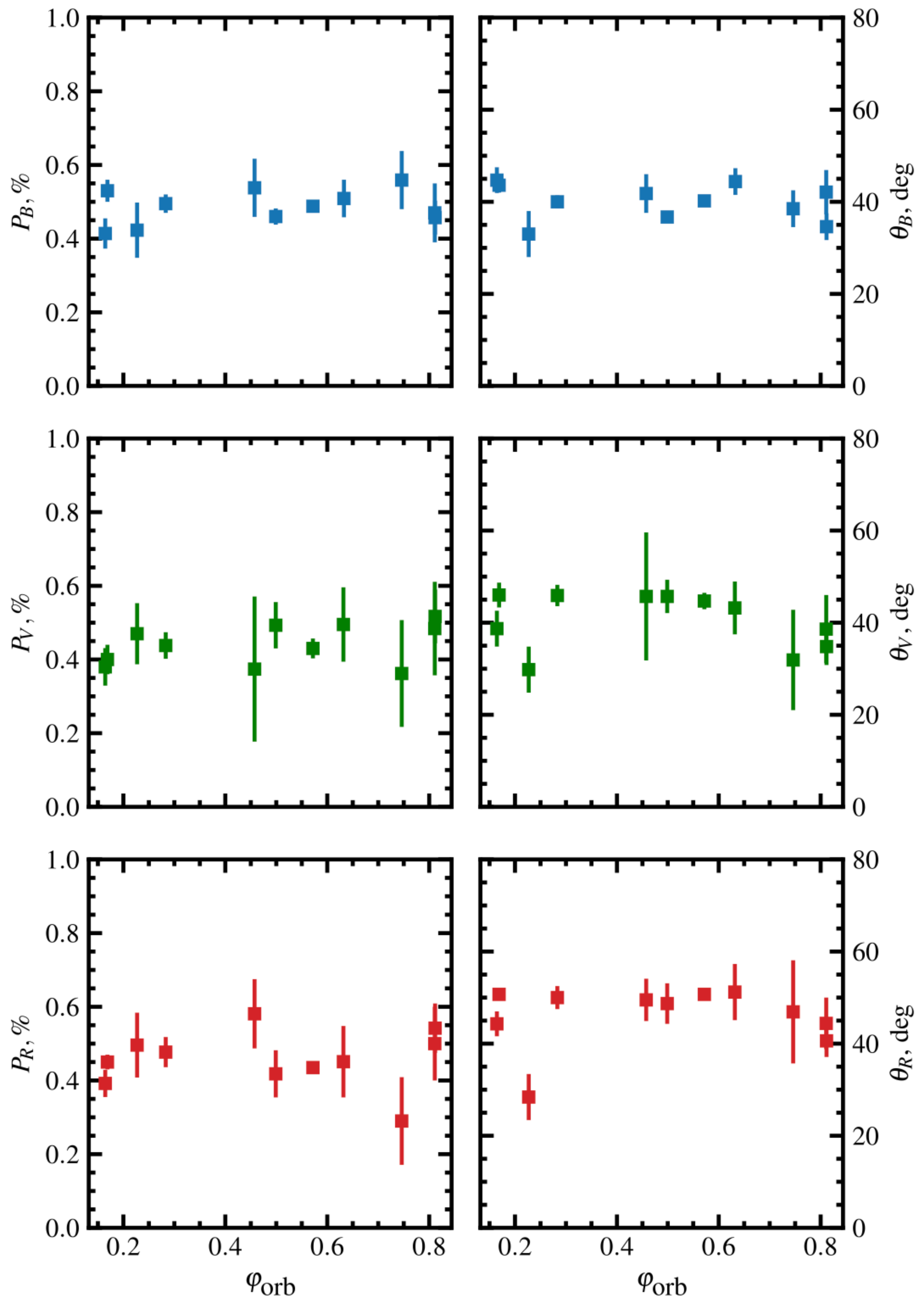
The observed polarization of **V4641 Sgr** is consistent with the polarization pattern of nearby stars and shows **no dependence on orbital phase**.

From these two facts we can conclude, that the **polarization of V4641 Sgr has an interstellar origin**.

Polarization vs *Gaia* parallax



Polarization vs Orbital phase



Results: MAXI J1820+070, V404 Cyg and MAXI J0637–430

Observed and intrinsic polarization

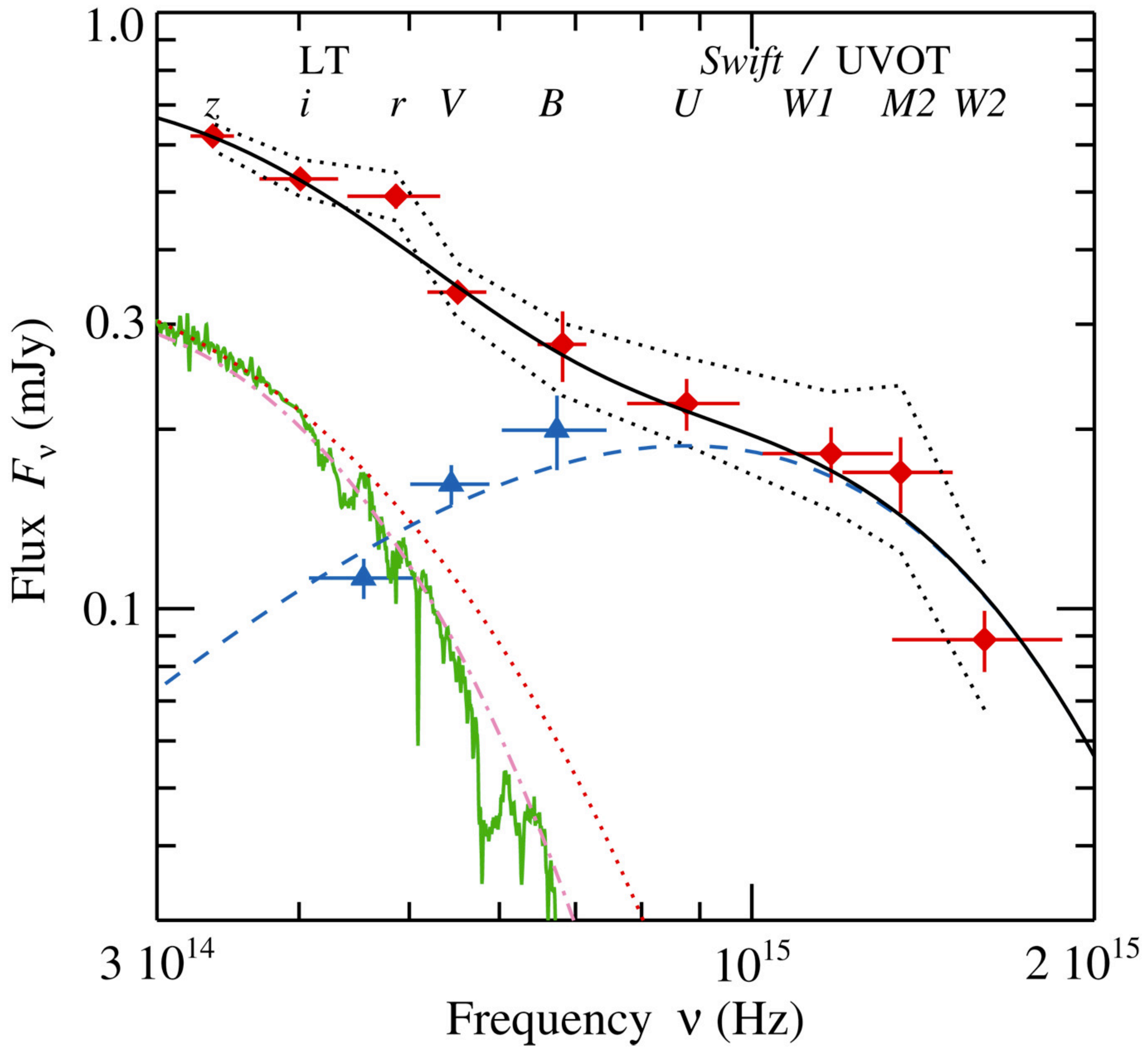
MAXI J1820+070 shows complex behaviour of intrinsic polarization:

- $P_{\rm int} \sim 0.5\,\%$ with the red spectrum in the **rising hard state**
- $P_{\rm int} \sim 0.1\,\%$ in the **soft state**
- No polarization in **decaying hard state**
- **Substantial** (up to $P_{\rm int} \sim 5\,\%$) **intrinsic polarization** with the blue spectrum in the **quiescent state** (Poutanen et al., 2022)

V404 Cyg shows small ($P_{\rm int} < 0.5\,\%$) intrinsic polarization during the **quiescent state**, consistent with the previous measurements

Unbiased maximum-likelihood estimation of **soft state** polarization of **MAXI J0637–430** is **zero** with 3σ upper limit of $P_{\rm int} < 1.1\,\%$

MAXI J1820+070



Poutanen et al., 2022

Summary

- Most of the sources show **no evidences** of significant intrinsic polarization
- The absence of intrinsic polarization at the optical wavelengths **puts constraints** on the potential contribution of non-stellar (jet, hot flow, accretion disc) components to the total spectra of black hole X-ray binaries
- High precision optical polarimetry can shed new light on the radiative mechanisms that occur in BHXRBs.

Intrinsic polarization estimates of observed sample

Source	State	P_B per cent	P_V per cent	P_R per cent
XTE J1118+480	Q	1.2 ± 0.8	1.4 ± 0.8	1.3 ± 0.5
Swift J1357.2−0933	RH[a]	≤ 0.5	≤ 0.4	≤ 0.4
4U 1957+115	S	≤ 0.2	≤ 0.3	≤ 0.3
V4641 Sgr	RH[a]	≤ 0.1	≤ 0.1	≤ 0.1
	Q	≤ 0.1	≤ 0.1	≤ 0.1
V404 Cyg	RH	0.8 ± 0.3	1.1 ± 0.1	0.5 ± 0.1
	Q	≤ 0.5	≤ 0.5	≤ 0.5
MAXI J1820+070	RH1	0.28 ± 0.01	0.36 ± 0.01	0.30 ± 0.01
	RH2	0.34 ± 0.02	0.51 ± 0.02	0.53 ± 0.02
	S	0.16 ± 0.01	0.15 ± 0.01	0.02 ± 0.01
	DH	0.06 ± 0.04	0.13 ± 0.06	0.09 ± 0.04
	RH[a]	≤ 0.3	≤ 0.4	≤ 0.3
	Q	3.2 ± 0.2	1.9 ± 0.2	0.9 ± 0.1
MAXI J0637−430	S	≤ 0.2	–	–

Notes. [a]Failed outburst. States: Q – quiescence, RH – rising hard, S – soft, DH – decaying hard

Kravtsov et al., 2022

Thank you for your attention!

LMXB State

quiescent

unpolarized

	P
XTE J1118	1.2 ± 0.8%(?)
Swift J1357	< 0.2%
V4641 Sgr	< 0.2%
V404 Cyg	< 0.5%(?)

polarized

	P
MAXI J1820	~5%
1A 0620	> 3% (?)

outburst (active)

unpolarized

	P
V4641 Sgr	< 0.2%
MAXI J0637	< 0.2%
4U 1957	< 0.2%

polarized

	P
V404 Cyg	≈ 1 %

MAXI J1820	0 – 0.7%

https://sites.google.com/view/vakrav/