Black hole spin - orbit misalignment in the black hole X-ray binary MAXI J1820+070

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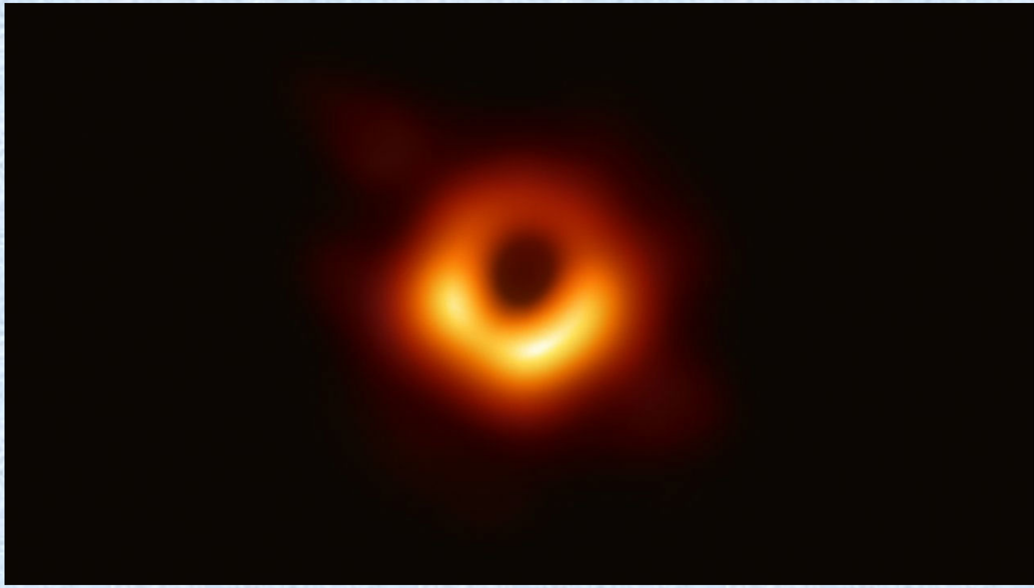
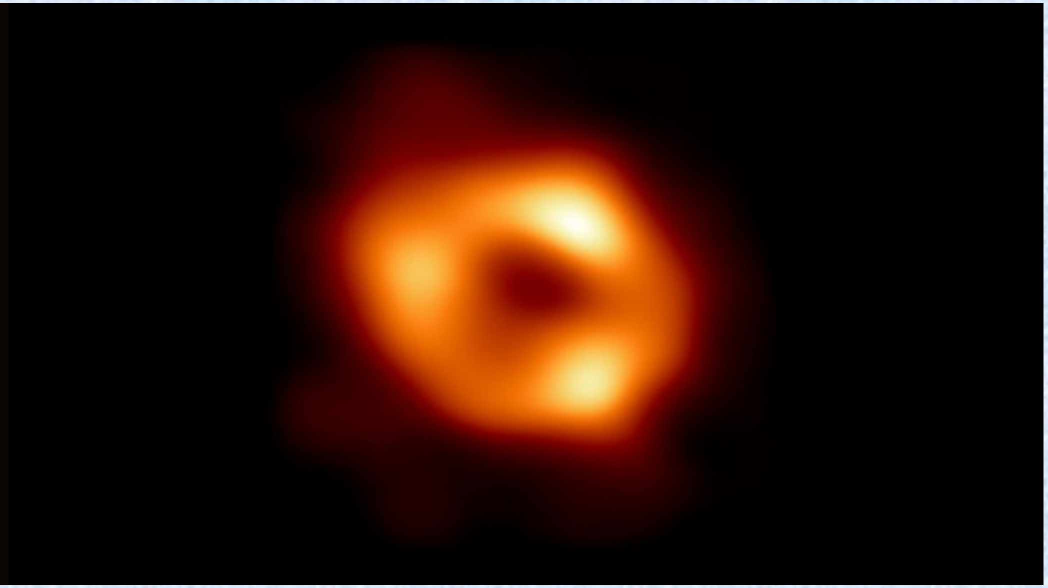
"Images" of black holes

- Event Horizon Telescope has produced "images" of gas surrounding supermassive black holes in M87 and in the Milky Way. The angular size of one Schwarzschild radius is about 8–10 μas.

- What about stellar-mass black holes?



M87 © EHT 2019



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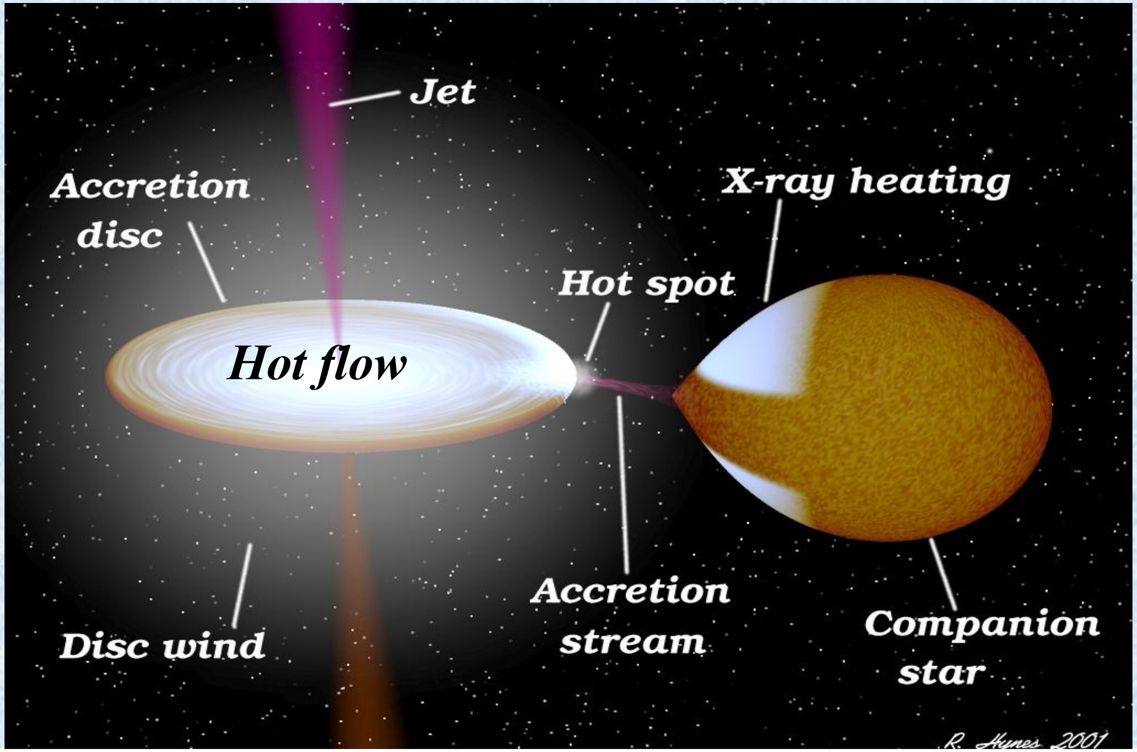
Black holes in X-ray binaries

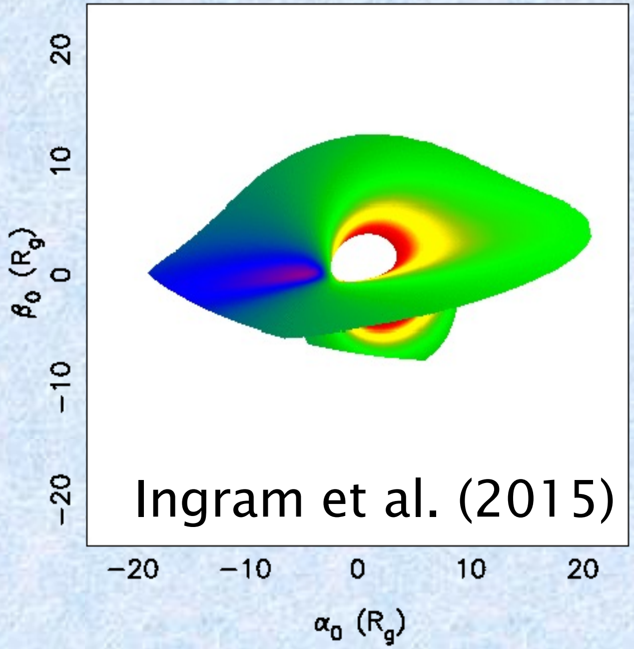
- Stellar-mass black holes have angular sizes < nano arcsec.
- If we cannot resolve it, can we learn about geometry of the source somehow?
- For example, can we learn about black hole spin relative to the orbital spin?



1. Introduction

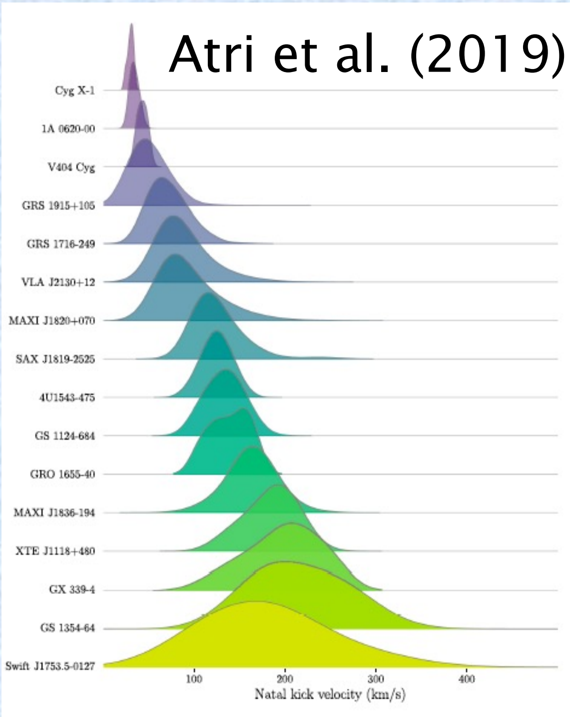
Black hole – orbit spin misalignment

Misalignment between black hole spin and orbital angular momentum is required for the model for X-ray and optical QPOs based on precession of the inner hot flow.



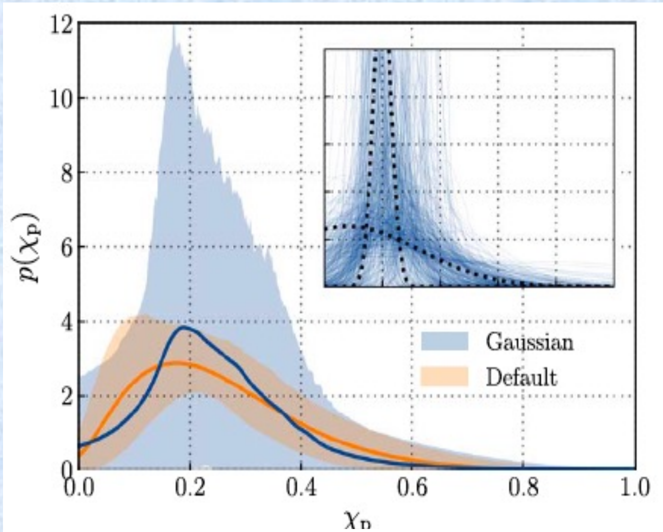
Ingram et al. (2015)

Evidence for misalignment comes from large natal kick velocities of X-ray binaries.



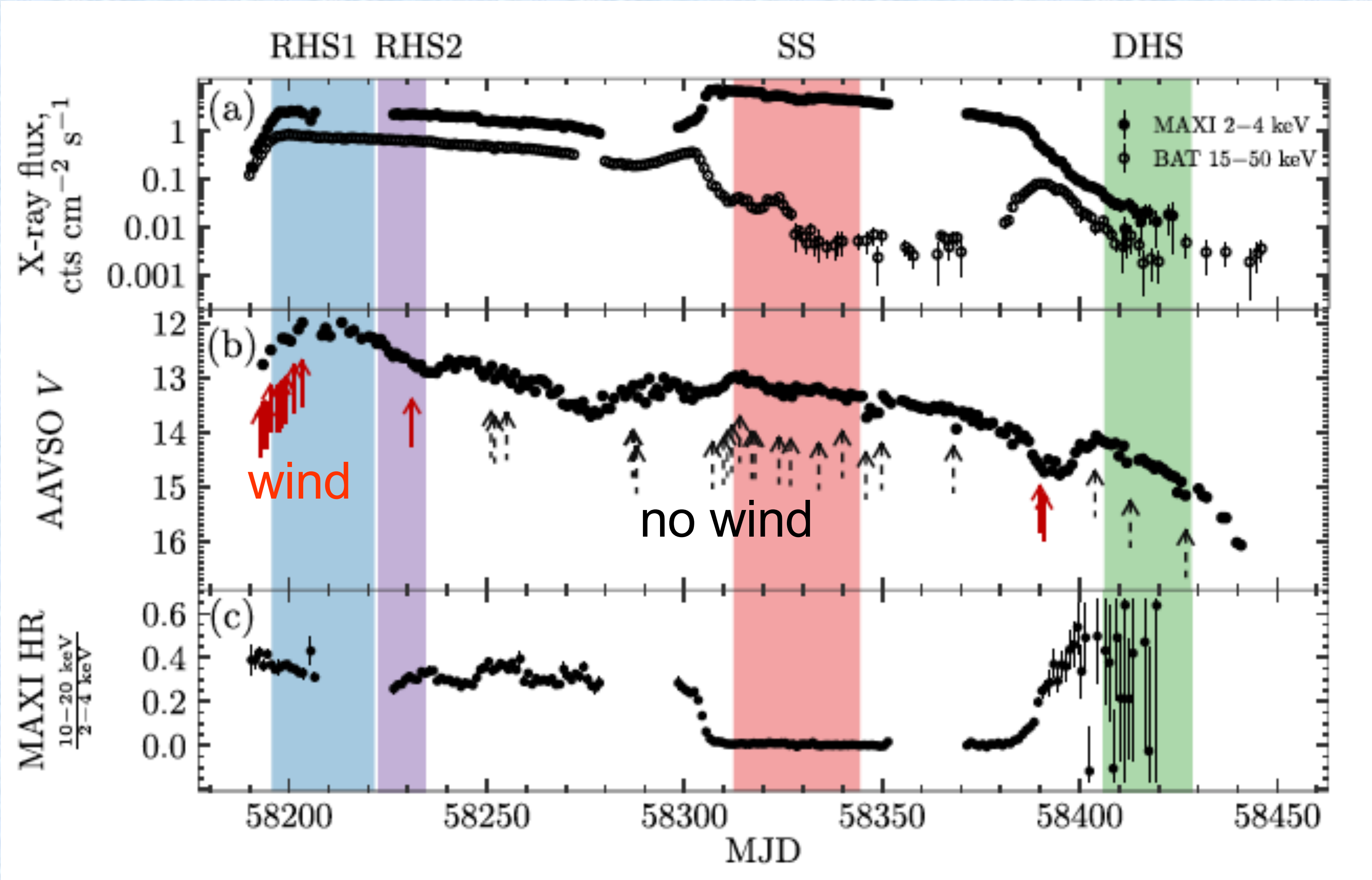
Atri et al. (2019)

LIGO finds “a fraction of merging BH systems have component spins misaligned with the orbital angular momentum, giving rise to precession of the orbital plane”.



Abbott et al. (2021)

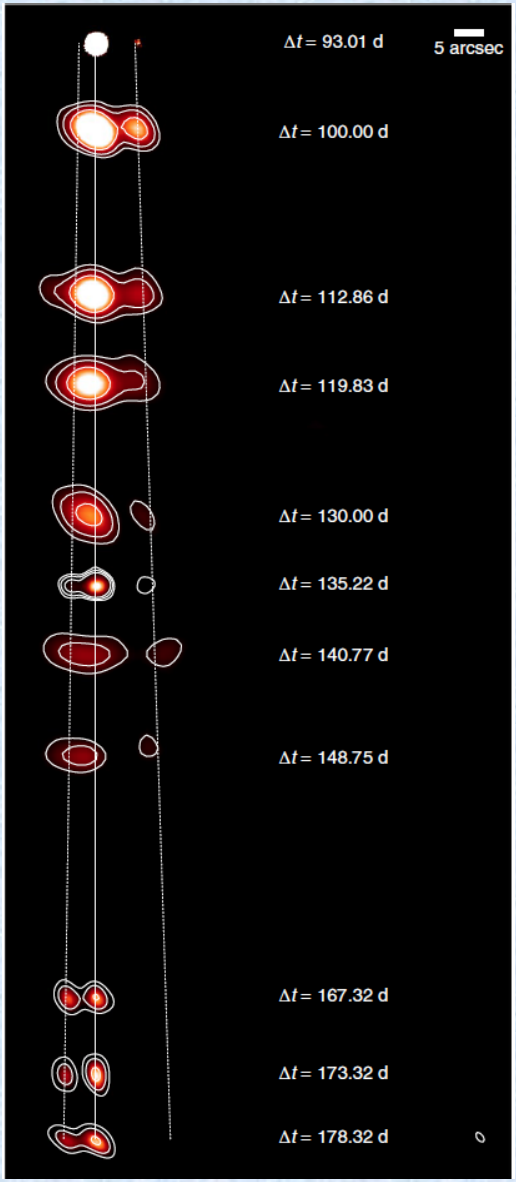
2018 outburst



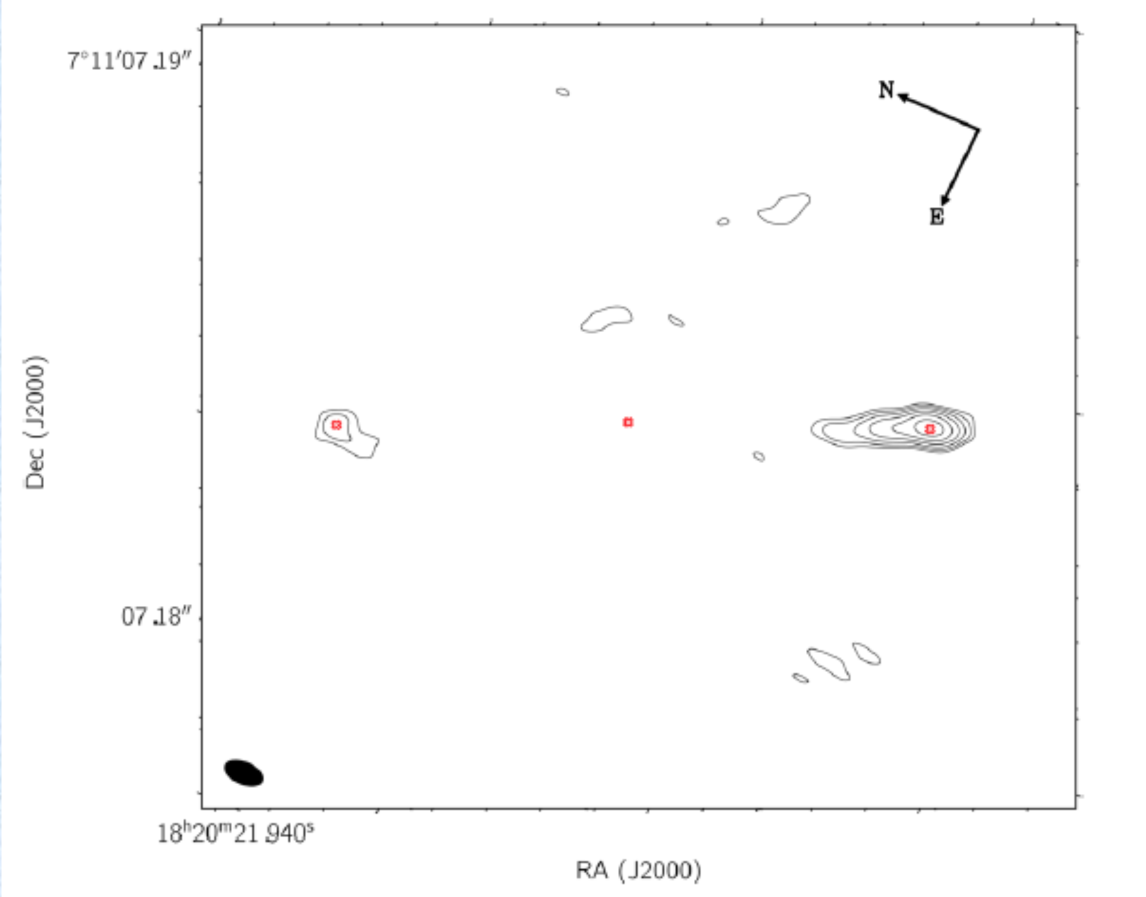
Veledina et al. (2019), Kosenkov et al. (2020)

2. MAXI J1820+070

Superluminal motion



Bright et al. (2020)



Radio jet PA = 25.8±4.4 deg
(Kosenkov et al. 2020; Bright et al. 2020)
Inclination angle 63 ± 3 deg (Atri et al. 2020)

2. MAXI J1820+070

X-ray jets from MAXI J1820+070

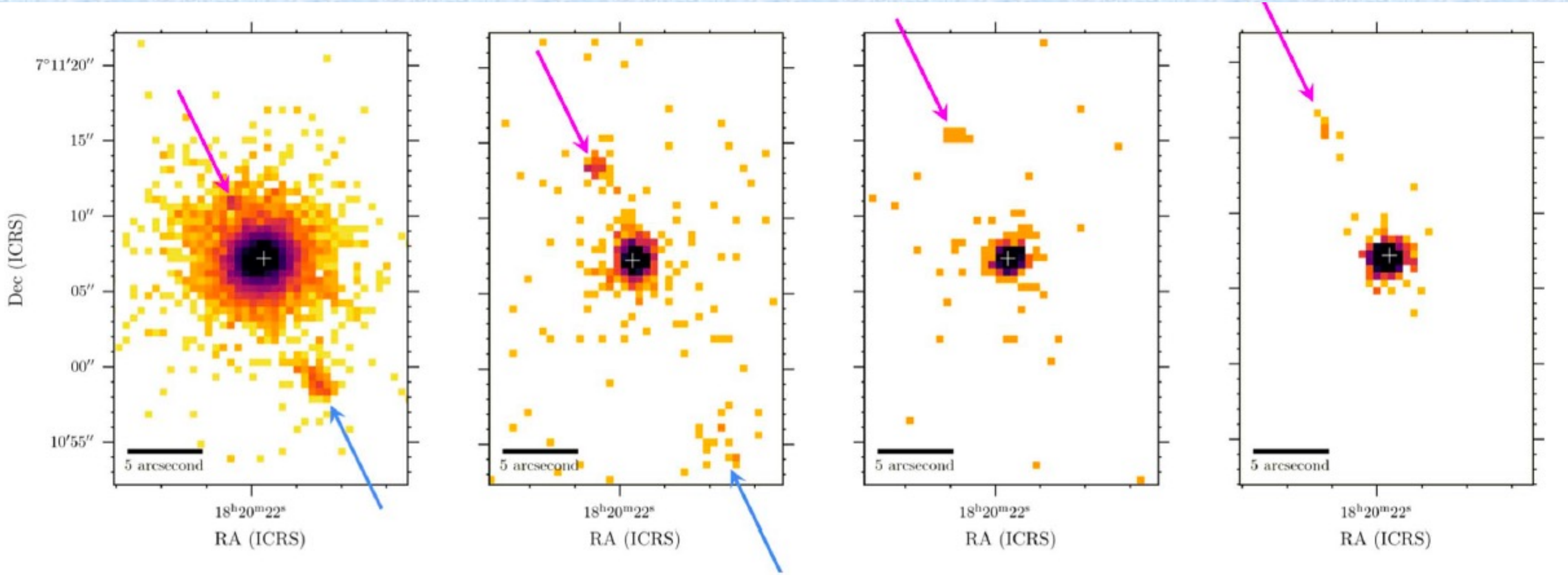


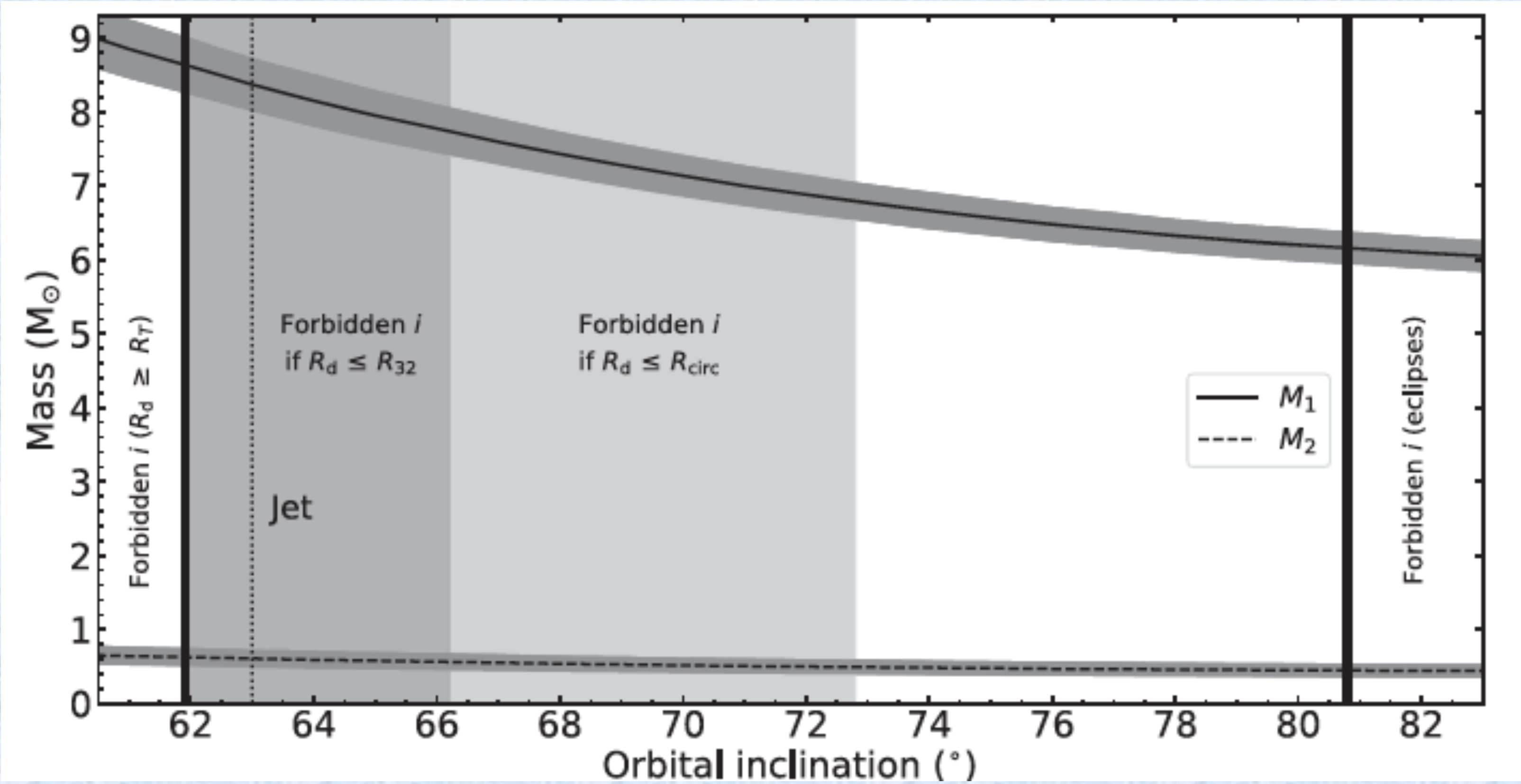
Figure 1. Images obtained from Chandra observations of MAXI J1820+070 in the 0.3–8 keV band. The observations are in chronological order: 2018 November, 2019 February, 2019 May, and 2019 June. The color scale is logarithmic and different for every image. The crosses indicate the VLBI position of MAXI J1820+070 (Atri et al. 2020). The arrows highlight the position of the north (pink) and south (blue) detected sources. The significances are, for the north and south jets, 46 and 43 (109 and 190 photons) in November and 16 and 4.2 (35 and 15 photons) in February; and for the north jet, 3.5 (6 photons) in May and 4.9 (12 photons) in June.

PA=25.1±1.4 deg (approaching jet at PA=205.1±1.4 deg)

Espinasse et al. (2020)

2. MAXI J1820+070

Orbital inclination



- Orbital period 0.685 days (Torres et al. 2019)
- Mass function 5.18±0.15 $M_\odot$ (Torres et al. 2019)
- Orbit inclination $66^o < i_{orb} < 81^o$ (Torres et al. 2020)

Geometry

- Jet
  1. We assume that the jet is aligned with the black hole spin.
  2. The jet 3D orientation can be obtained from the radio and X-ray imaging.
  3. Jet imaging – jet position angle.
  4. Superluminal motions – jet inclination

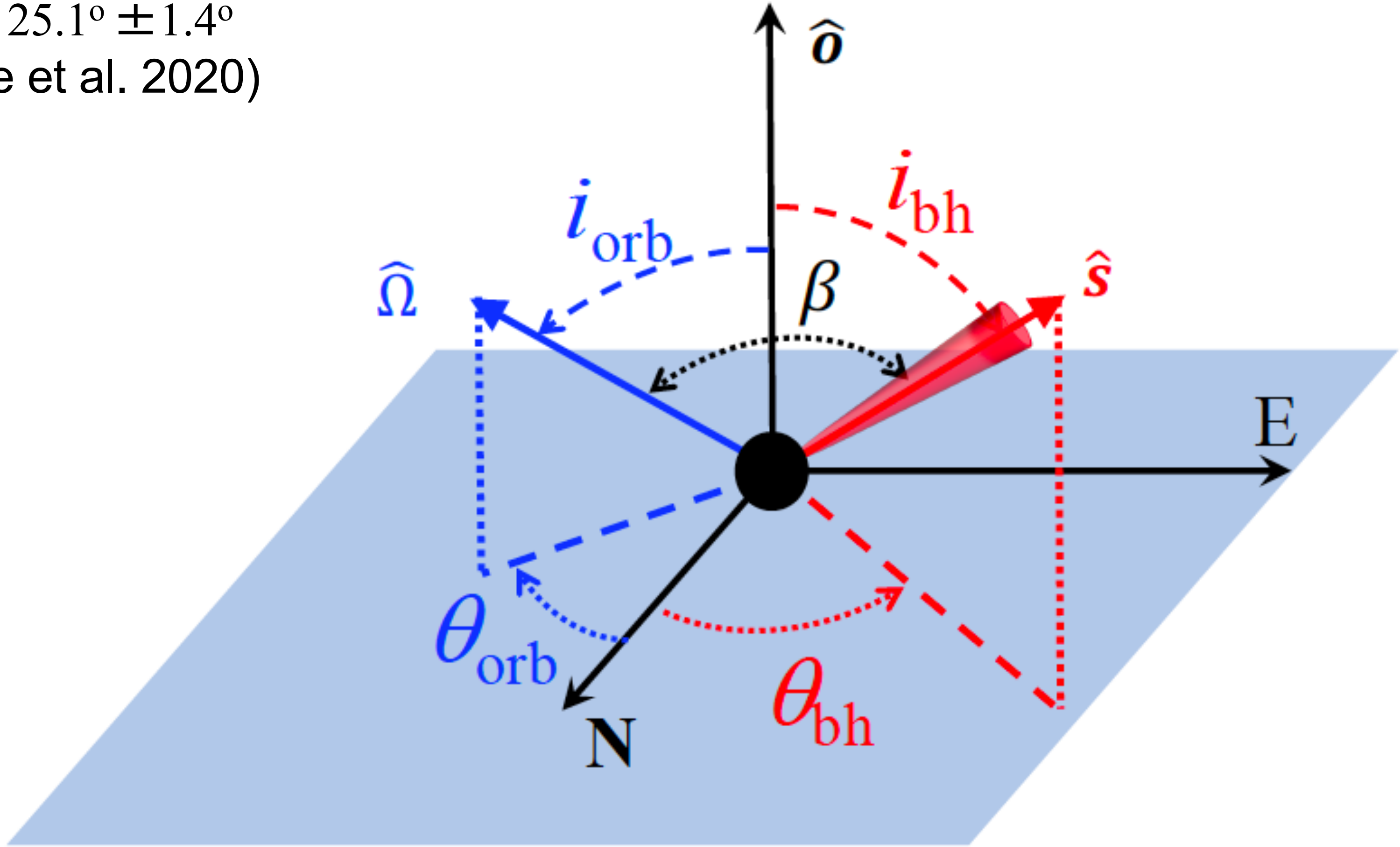
- Orbit
  1. Orbital inclination – optical photometry.
  2. We need position angle of the orbital axis.
  3. Together we then can get 3D orientation of the orbital axis.

- Polarization gives information about orientation of the orbit.
- Polarization vector is either parallel or perpendicular to the orbital angular momentum.

Geometry

Jet inclination $i_{bh} = 63^{o} \pm 3^{o}$
(Atri et al. 2020)
Disc inclination $i_{orb} = 73^{o} \pm 6^{o}, < 81^{o}$
(Torres et al. 2020)

$PA_{jet} = \theta_{bh} = 25.1^{o} \pm 1.4^{o}$
(Espinasse et al. 2020)

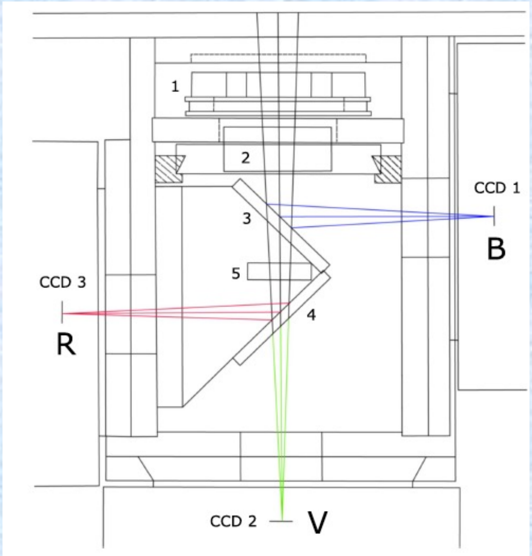


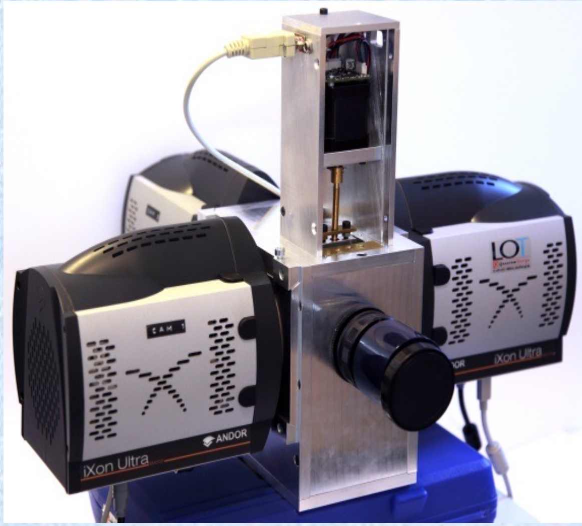
$$\cos\beta = \cos i_{orb} \cos i_{bh} + \sin i_{orb} \sin i_{bh} \cos(\theta_{orb} - \theta_{bh})$$

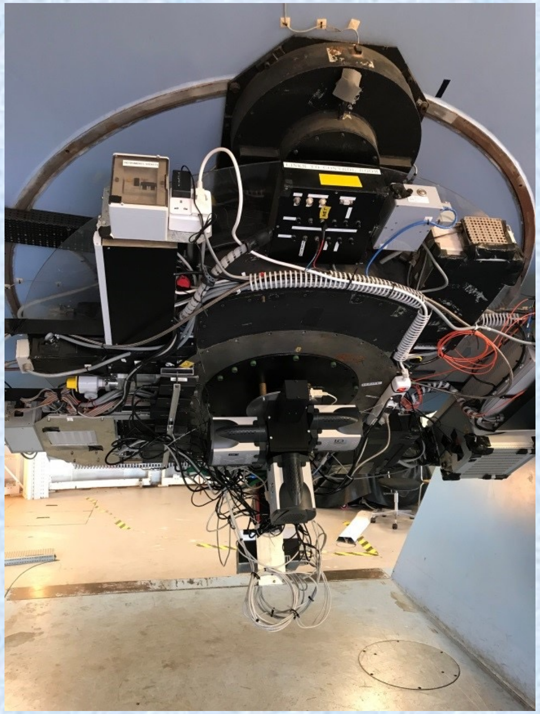
3. Polarimetry

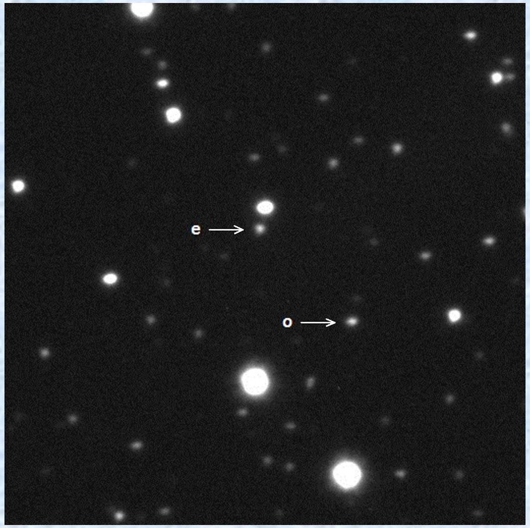
DIPol-Ultra Fast @ NOT

- Polarization unit: discretely rotated super-achromatic HWP + plane-parallel calcite
- Two dichroic mirrors for the wavelength separation (simultaneous measurements in the B_J, V_J, R_c passbands)
- Retractable polarization unit
- Two high-grade stepper motors: for HWP rotation and polarization unit retraction
- Normal and fast photometry modes
- Three ANDOR iXon Ultra 897 cameras
- Each CCD camera is controlled with separate industrial-grade mini-PCs linked together into high-speed local network
- Optimized for usage with the large-aperture telescopes
- Designed to be used remotely



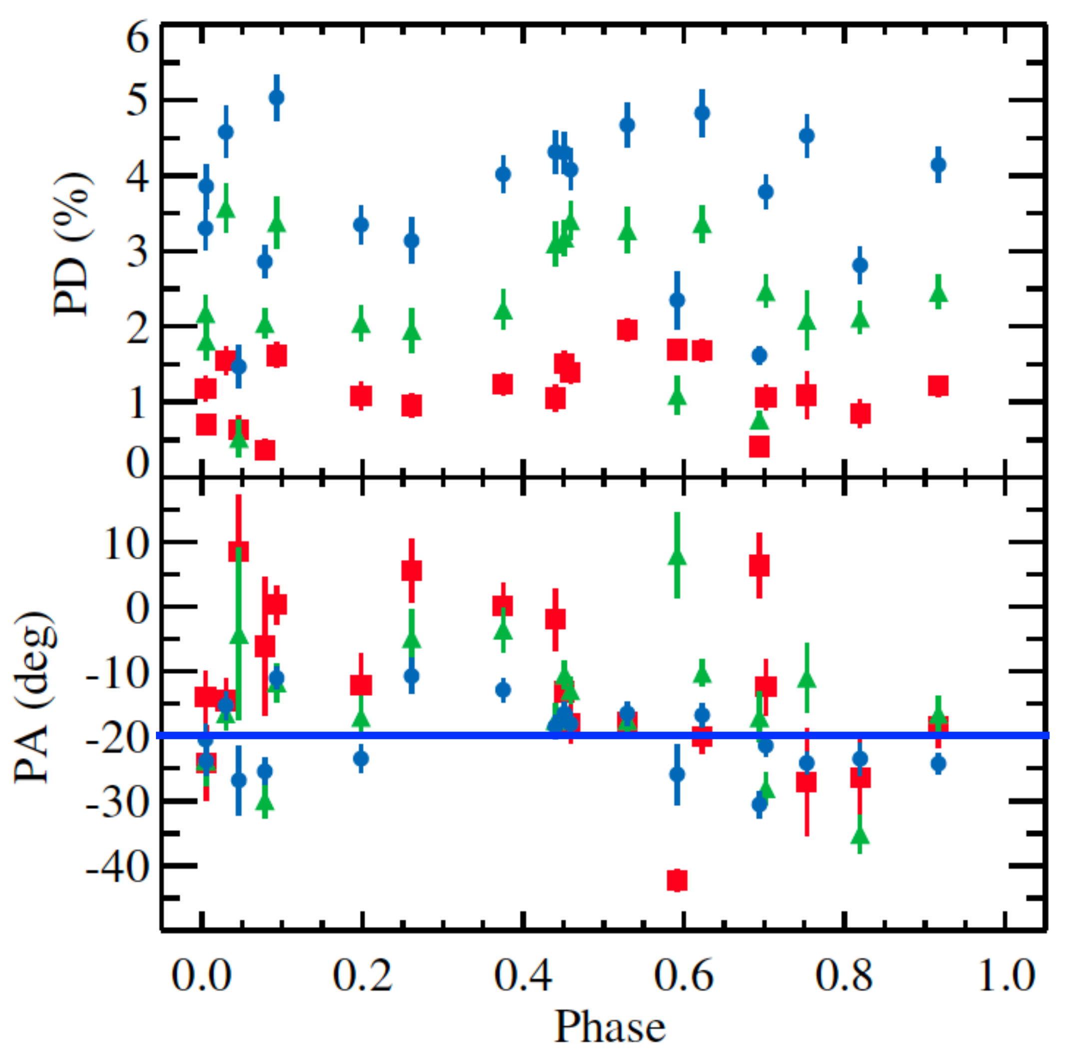






Piirola et al. 2021

MAXI J1820+070 in quiescence



was observed with DIPol-UF @ NOT in July 2019, April 2020, July 2020, and July 2021

1. PD is 1-5%, very blue
2. PD is variable, no obvious orbital dependence
3. $\langle PA_B \rangle = -19.7^o \pm 1.2^o$

Polarization is related to the orbit

Poutanen et al. (Science, 2022)

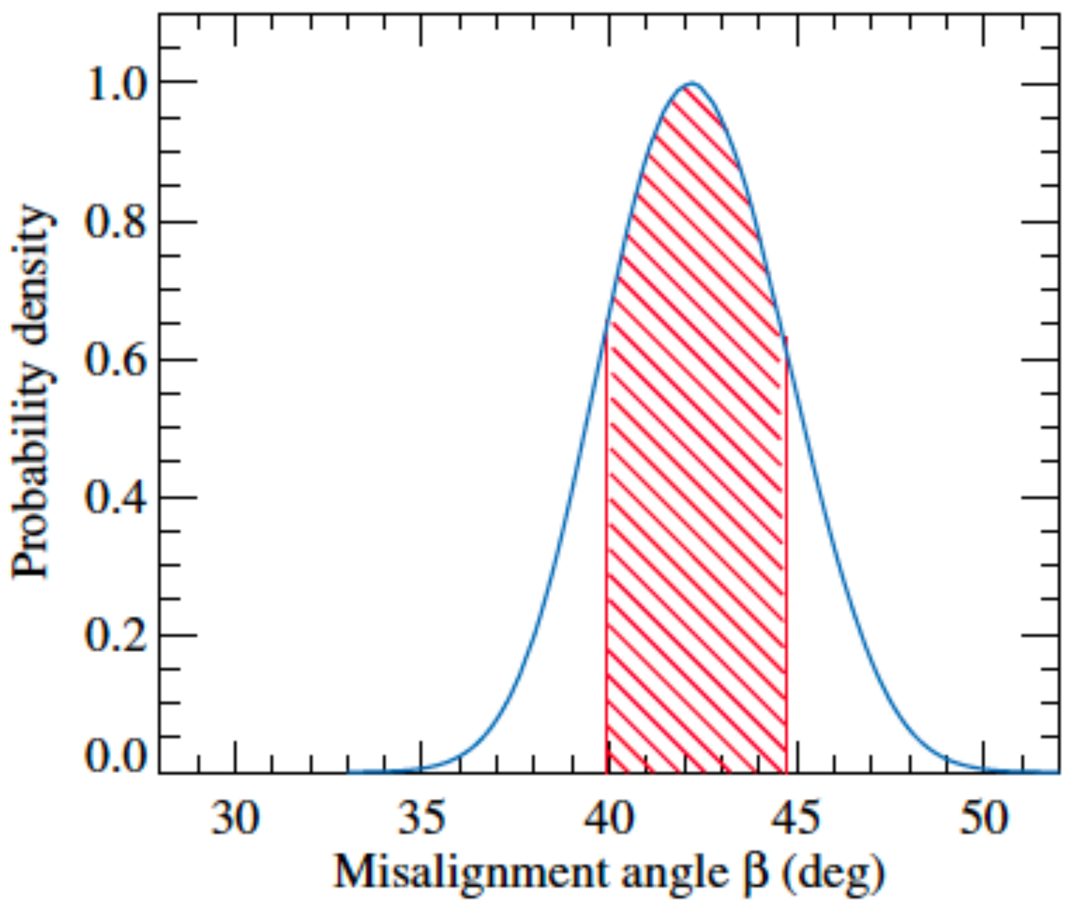
4. Geometry

BH spin – orbital spin misalignment β

Jet inclination $i_{bh} = 63^o \pm 3^o$
(Atri et al. 2020)
Disc inclination $i_{orb} = 73^o \pm 6^o, <81^o$
(Torres et al. 2020)

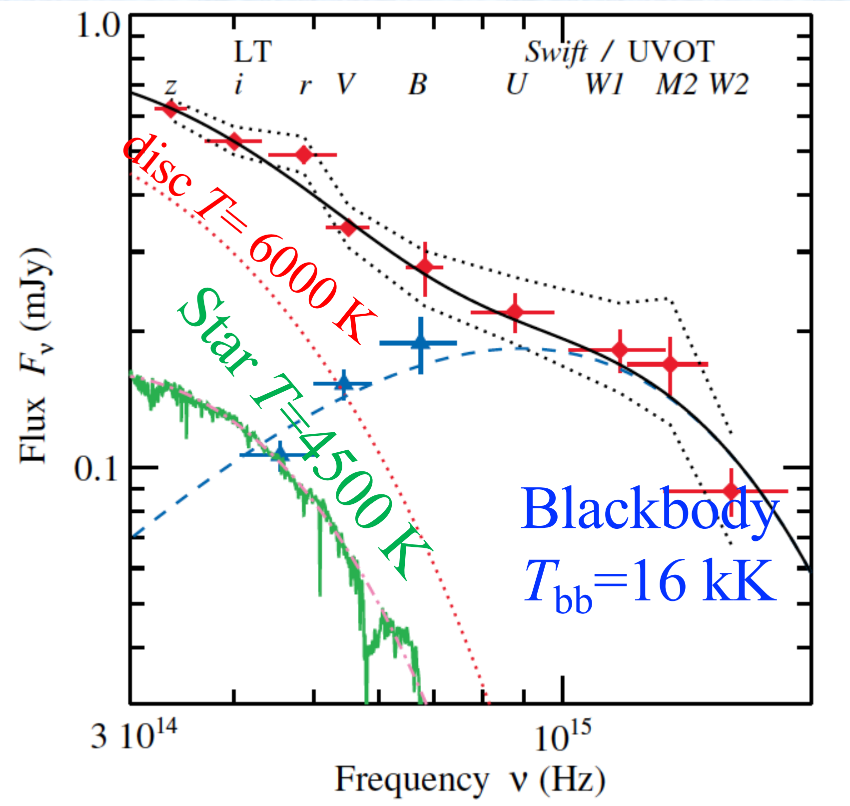
PA$_{jet}$= $\theta_{bh} = 25.1^o \pm 1.4^o$
(Espinasse et al. 2020)

Assume
θ_{orb}= PA $= -19.7^o \pm 1.2^o$



$$\cos\beta = \cos i_{orb} \cos i_{bh} + \sin i_{orb} \sin i_{bh} \cos(\theta_{orb} - \theta_{bh})$$

SED of MAXI J1820+070 in quiescence



Poutanen et al. (Science, 2022)

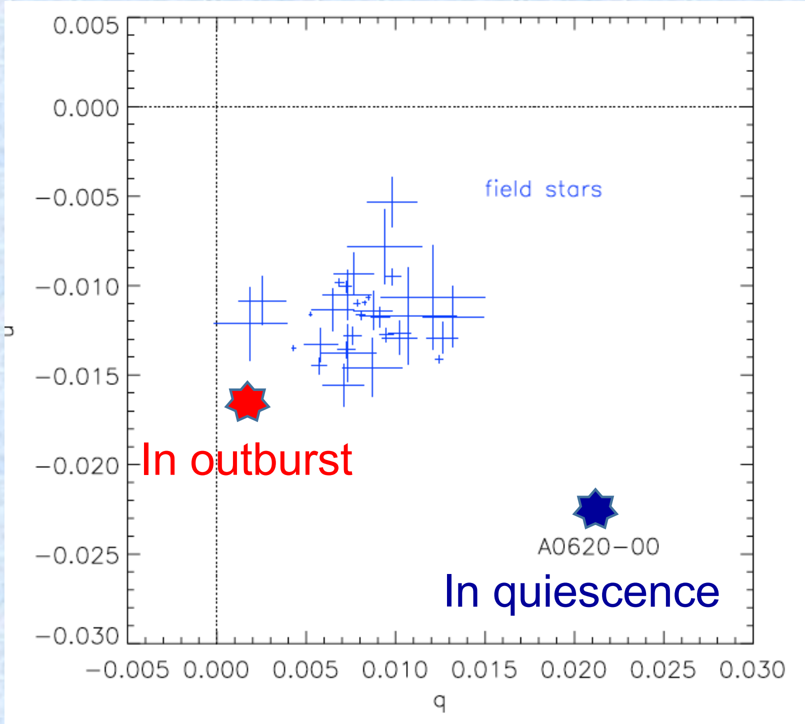
The polarized flux is consistent with the constant PD of ~6% of the UV "blackbody" component

$$PF_E = F_E \times \mathrm{PD}_E$$

$$PF_E = P \times B_E$$

Parameter	Value	Units
T_{in}	5750^{+860}_{-610}	K
R_{in}	$(8.0^{+2.0}_{-1.8}) \times 10^{10}$	cm
T_{bb}	15200^{+2300}_{-1150}	K
R_{bb}	$(8.6^{+1.8}_{-1.9}) \times 10^{9}$	cm
T_*	4500	K
R_*	5×10^{10}	cm
P_{UV}	$0.058^{+0.018}_{-0.011}$	

Polarization of in A 0620-00



In the outburst the polarization (1.7%, PA=140 deg) is close to the ISM values (Dolan & Tapia 1976).

In quiescence, polarization degree is 3%.

Intrinsic polarization is about 2%.

Nature of polarized UV excess

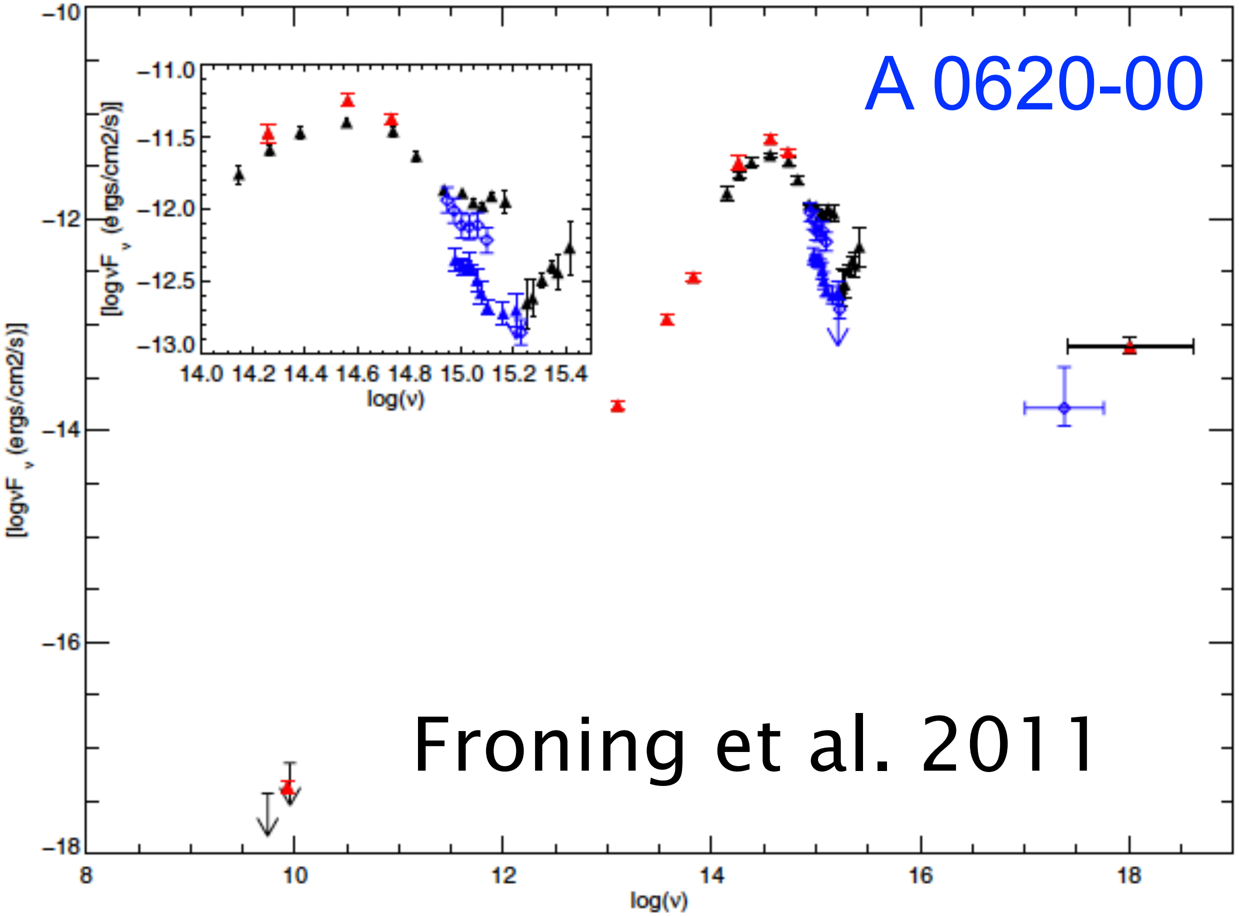


Figure 5. Broadband spectral energy distribution for A0620-00. The full SED from radio to X-rays is shown in the main window while the inset gives an expanded view of the NIR/optical/UV range. The solid black triangles are from this work. The red points show the data from Gallo et al. (2007, 2006) while the blue points are taken from Narayan et al. (1996) (FOS data; open triangles) and McClintock & Remillard (2000) (STIS data, closed triangles). Only the data >3500 Å are shown from the latter two sources because their points at longer wavelengths have had the donor star contribution removed. All the data have been dereddened using the extinction relation of Cardelli et al. (1989) assuming $E(B - V) = 0.35$. (Gallo et al. originally used a reddening of 0.39 but we have shifted their points to the common value.)

Nature of polarized UV excess

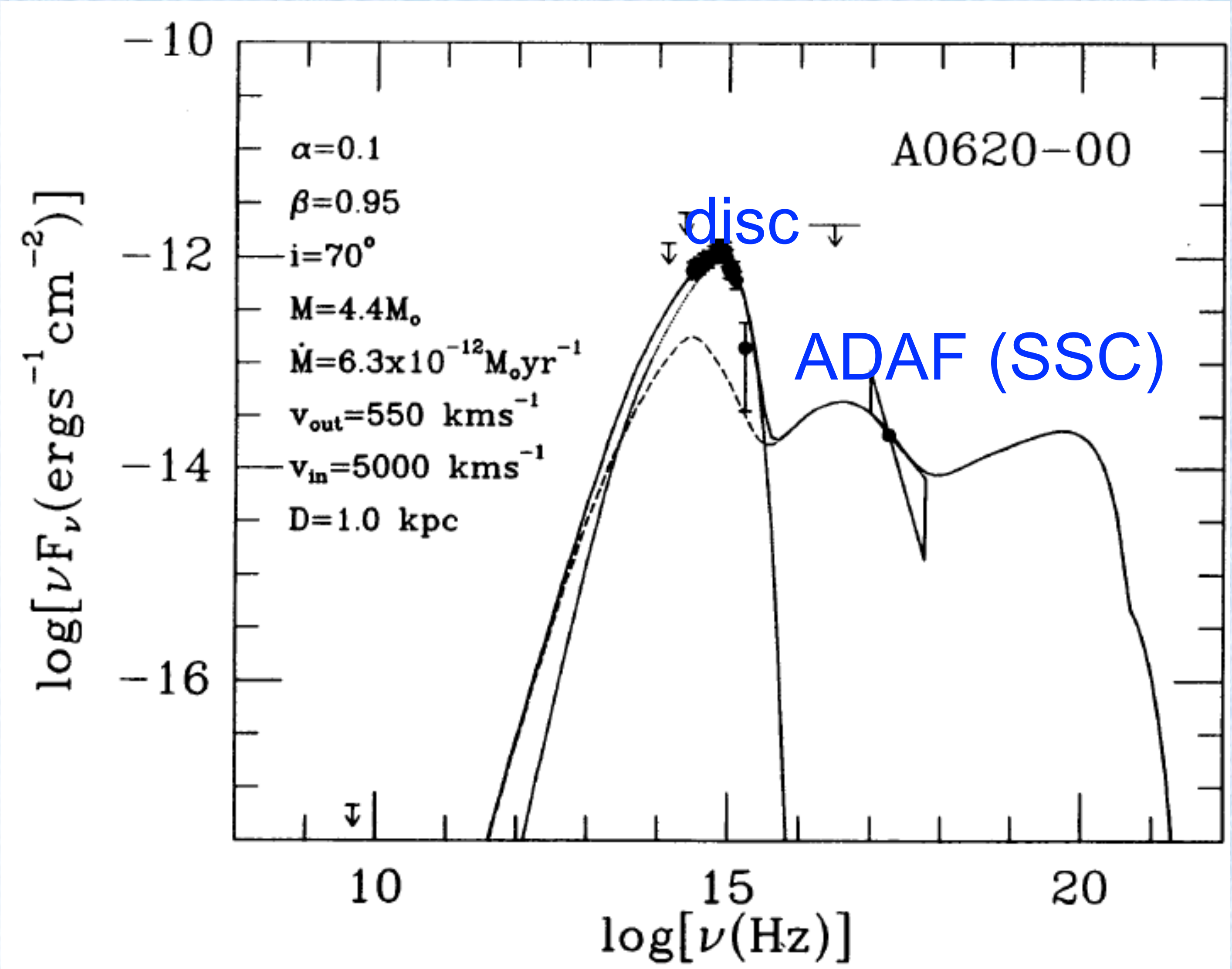
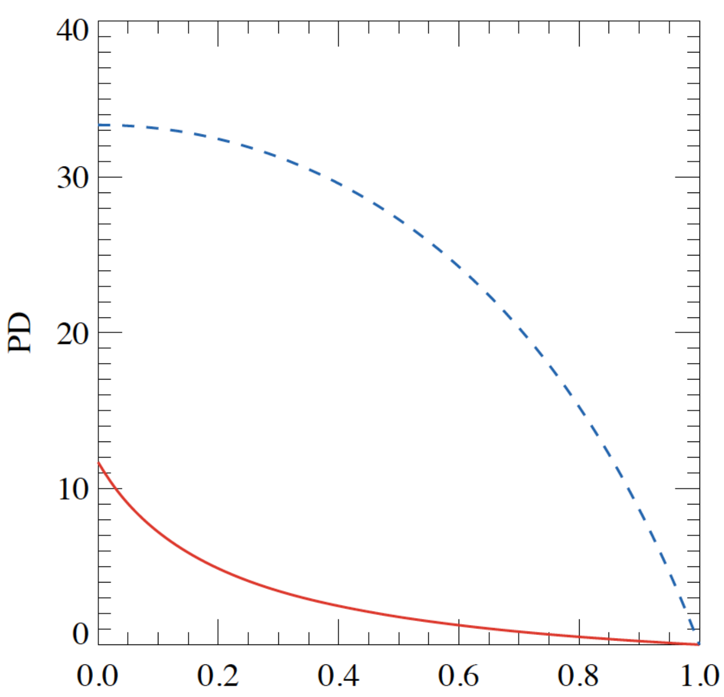


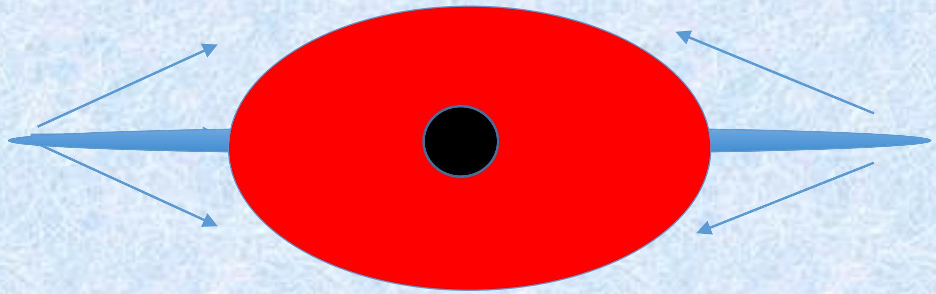
Fig. 1 from Narayan et al. 1996, ApJ, 457, 821

Nature of polarized UV excess



$\mu = \cos i_{orb}$

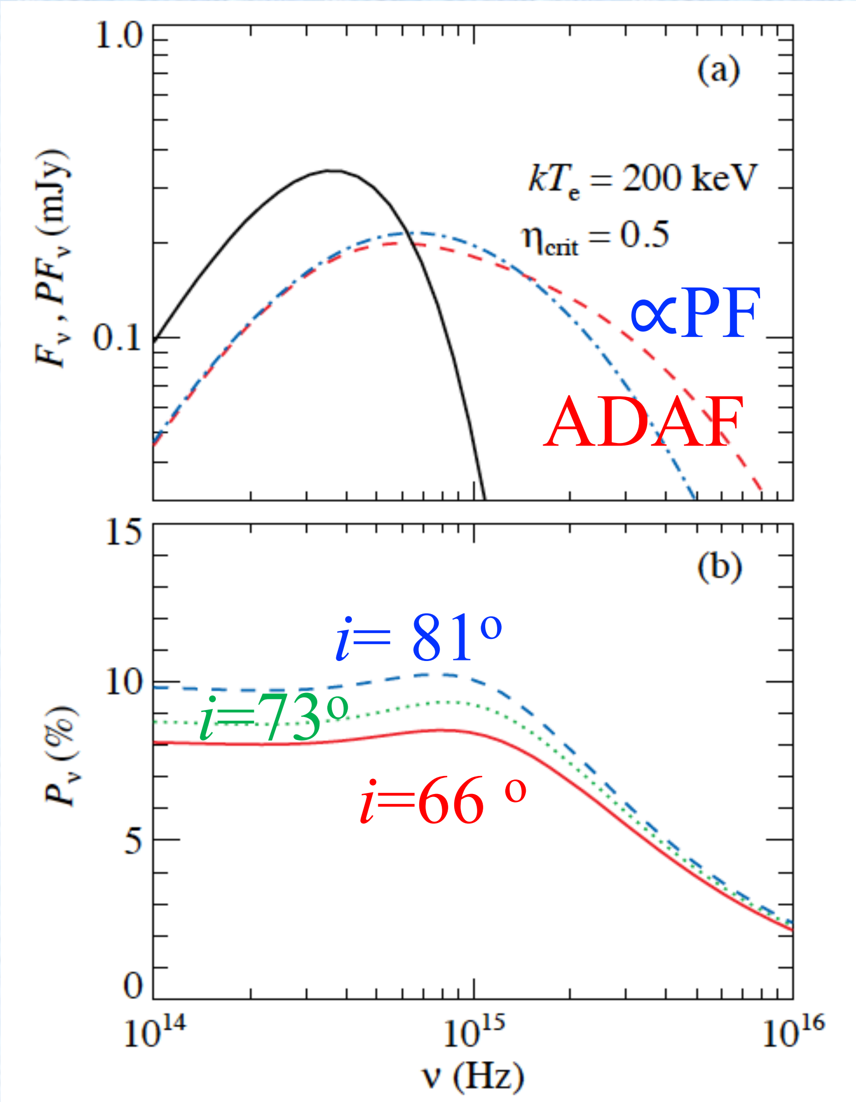
$$P = 100\% \frac{1-\mu^2}{3-\mu^2}$$ (Sunyaev & Titarchuk 1985):

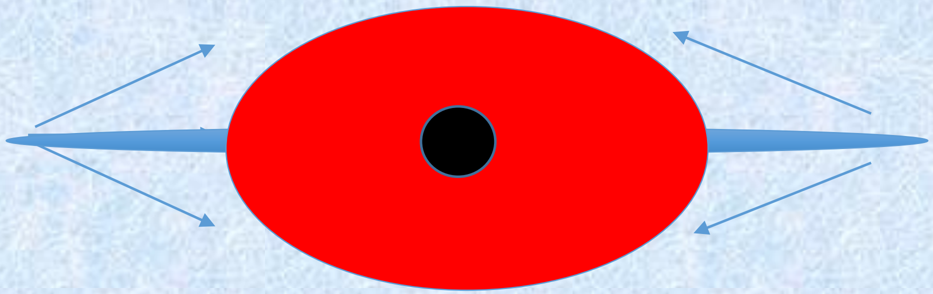


Chandrasekhar-Sobolev (optically thick electron scattering dominated) case

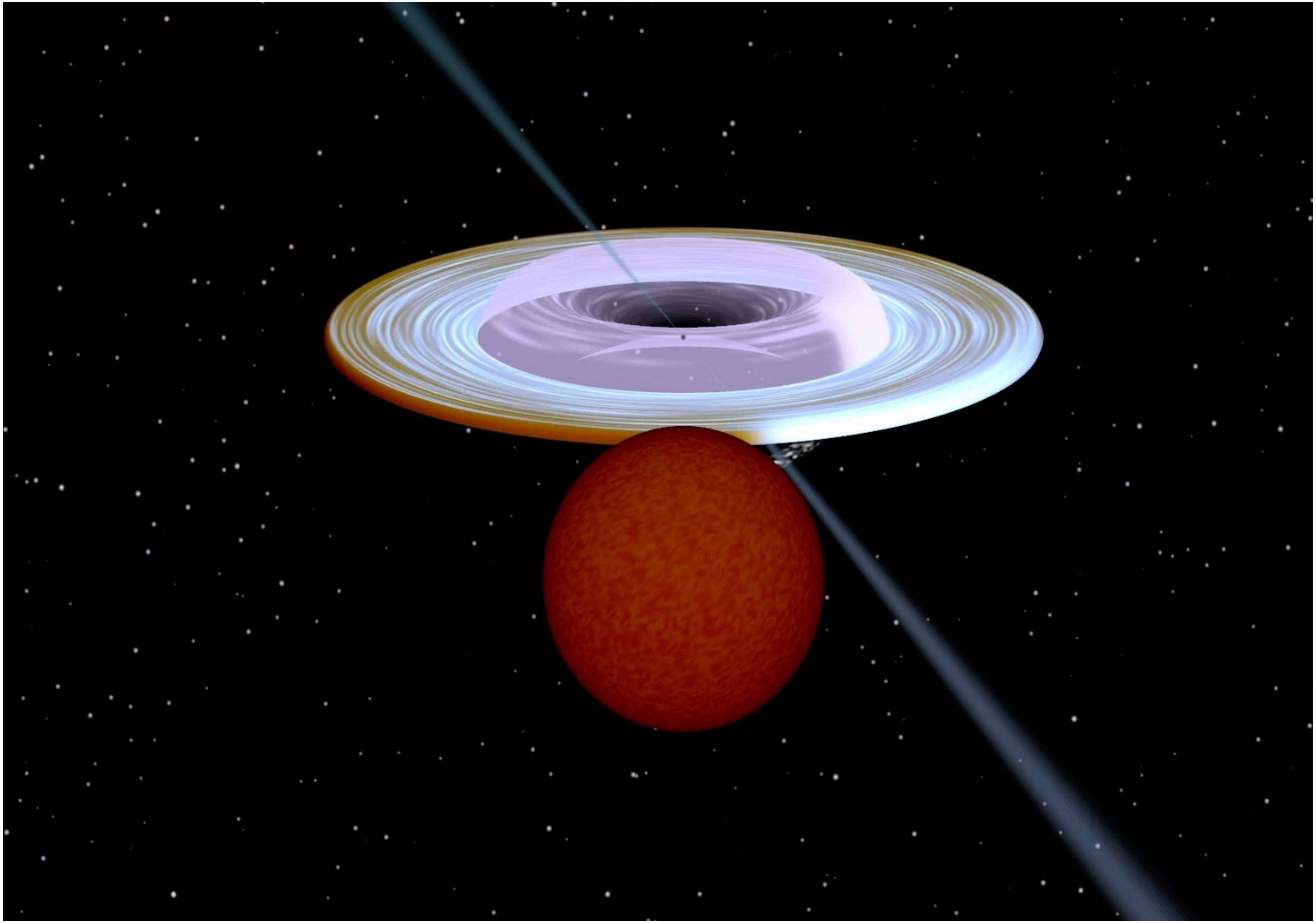
$$P = -11.7\% \frac{1-\mu}{1+3.582\mu}$$

Modelling polarized UV excess





- Higher electron temperature would reduce PD.
- Lower electron temperature would reduce disc photons energy shift.



Conclusions

- MAXI J1820+070 shows high polarization rising towards blue in its quiescent state.
- The polarized UV excess can be produced by scattering of the disc radiation in the hot inner accretion flow.
- Polarization angle is rather stable, differs from the jet position angle by about 45 deg.
- The misalignment between the jet (BH spin) and the disc is >40 deg.
- Large misalignment has profound implications for the models of black hole formation, models of X-ray and optical QPOs (Lense-Thirring precession), reliability of BH spin measurements from iron line, BH mass measurements, etc.
- X-ray polarimetric observations with IXPE can be used to test disc orientation and QPO production mechanisms.