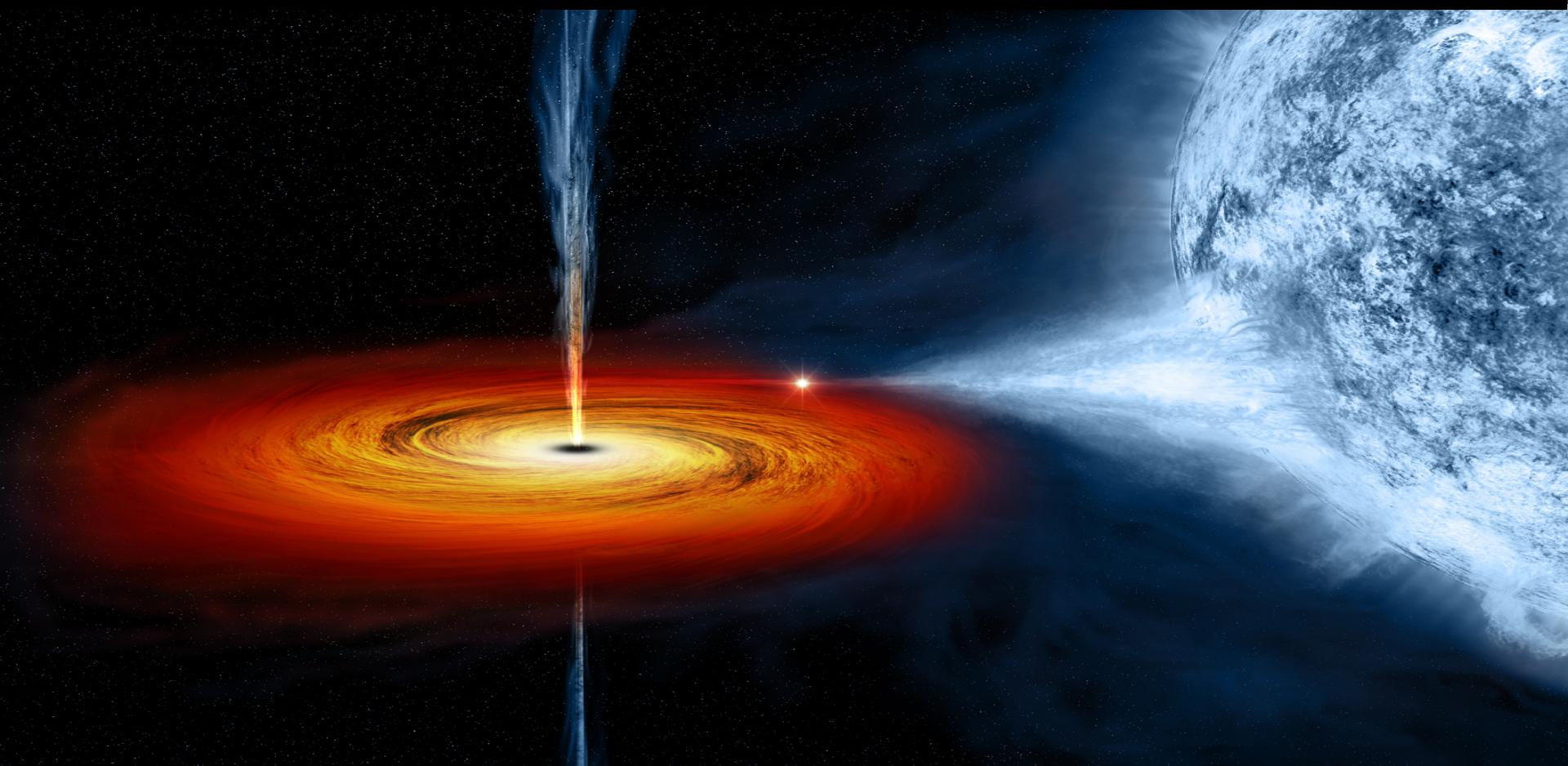


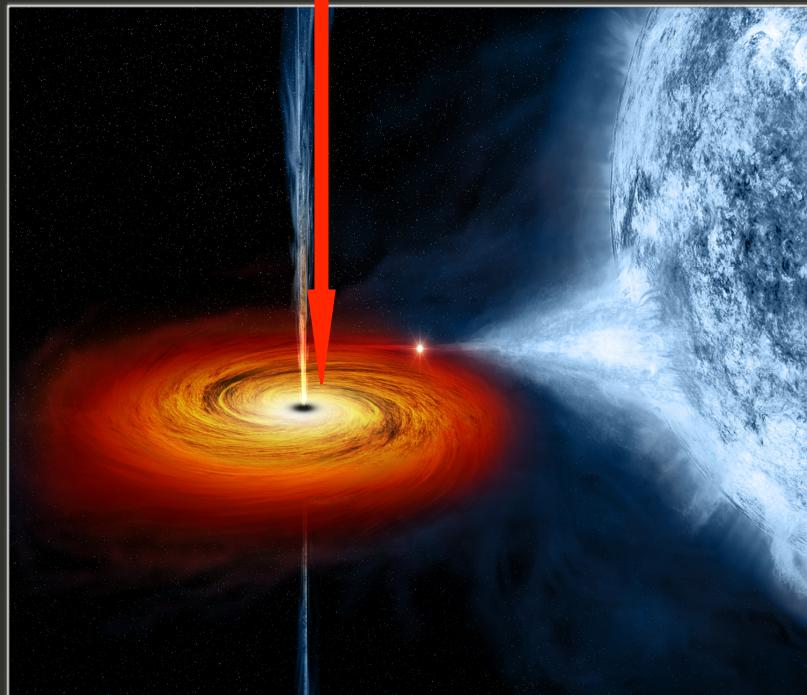
Progress and Future to Stellar BH Spin Measurement



Lijun Gou (苟利军, NAOC, Beijing)
June 15th, 2022

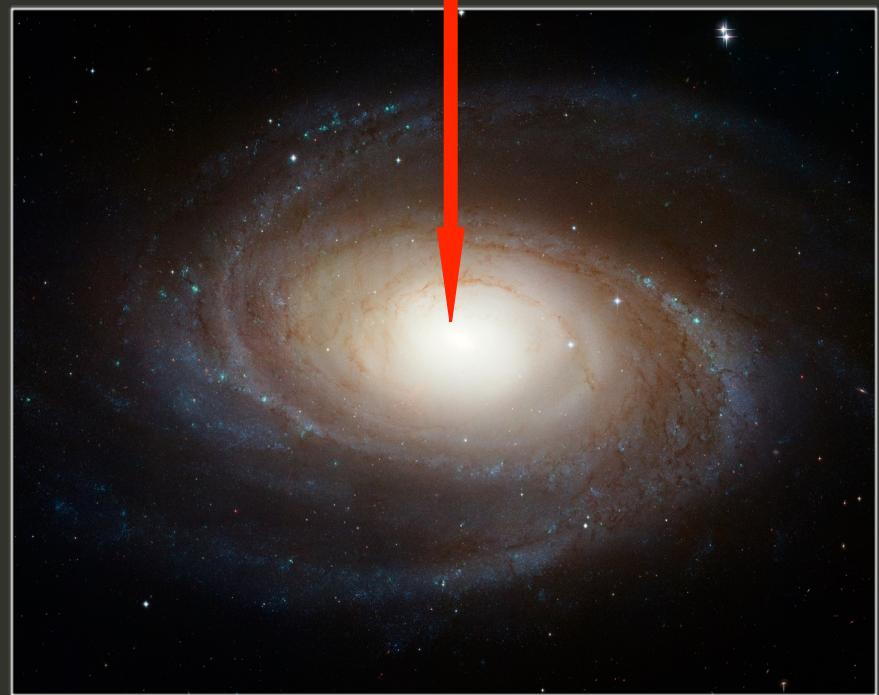
Two Classes of Black Holes

Stellar-Mass: $10 M_{\odot}$



Courtesy: NASA

Supermassive: $10^6 - 10^9 M_{\odot}$



As an extreme physical environments, it could test general relativity theory.

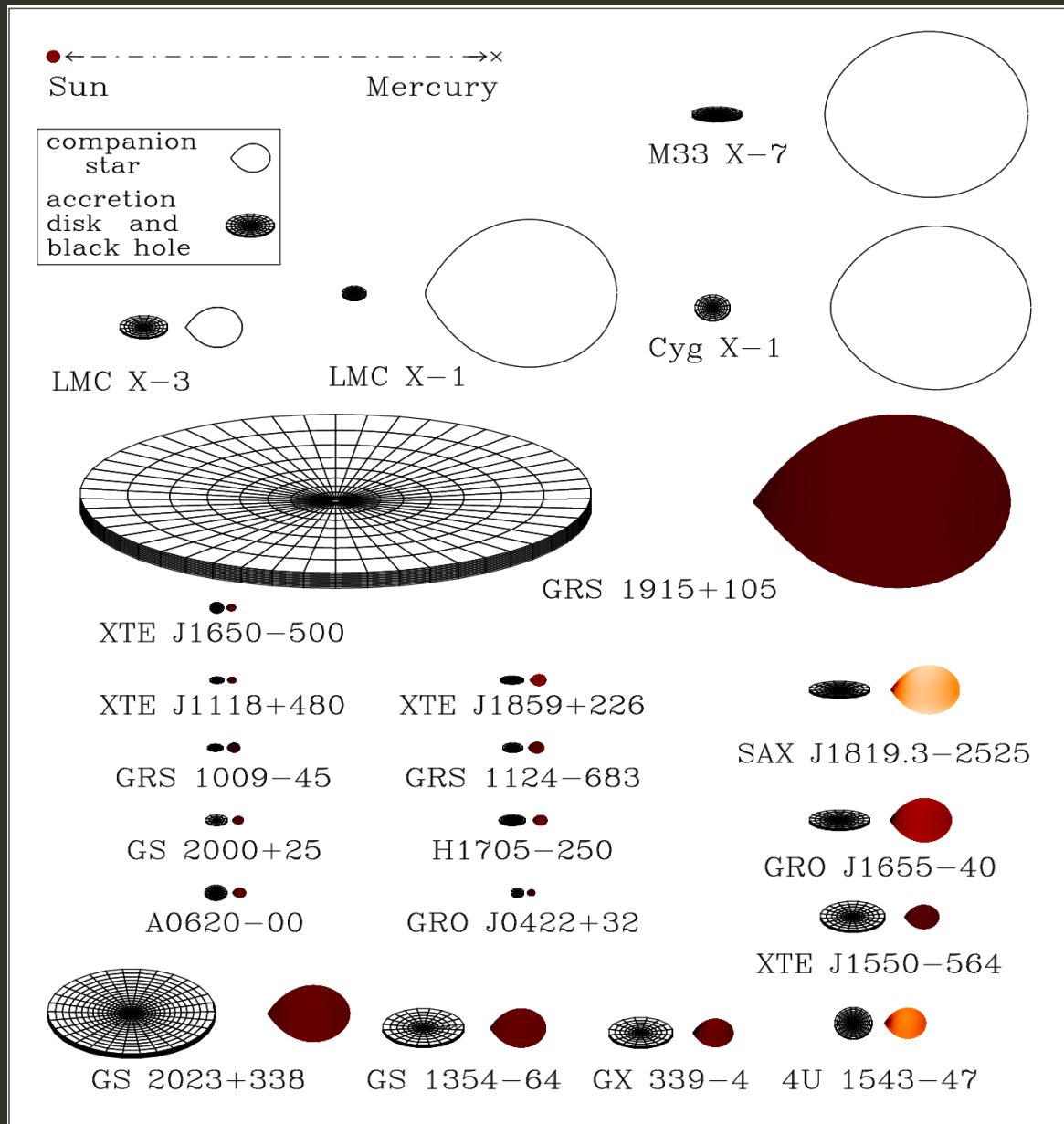
No-Hair Theorem

- Mass: M
- Spin: $a_* = ac/GM = J(c/GM^2)$ ($-1 \leq a_* \leq 1$)
 $(a_* = a/M \text{ by setting } c=G=1)$

Charge neutralized and unimportant

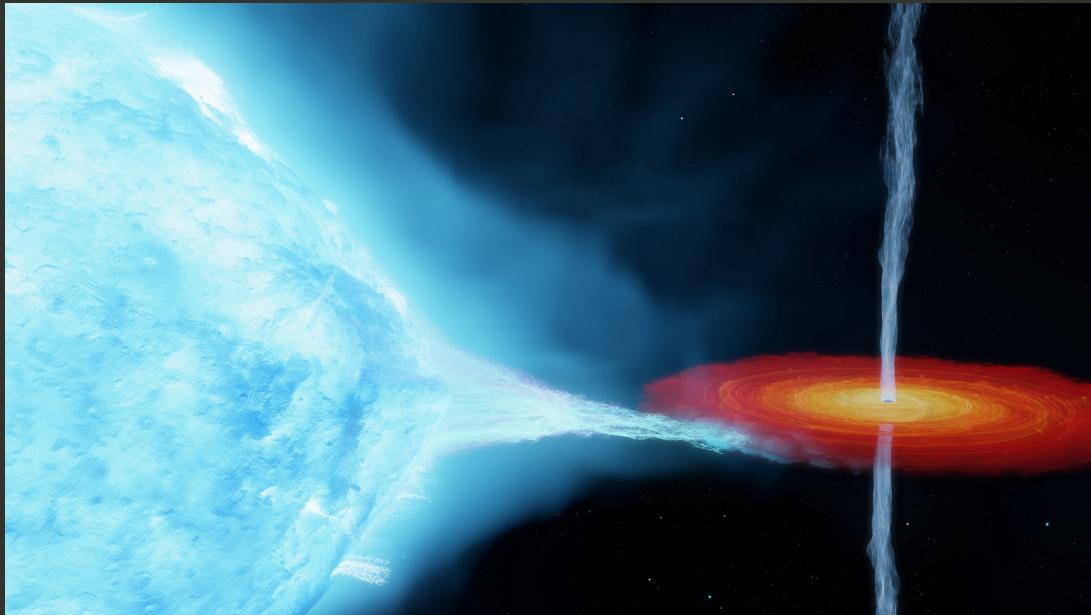
Kerr metric gives complete descriptions of astronomical BHs

Discovered Binary Systems



Precise measurement to the system parameters is essential to the better understanding of BHs, which is the ultimate goal, .

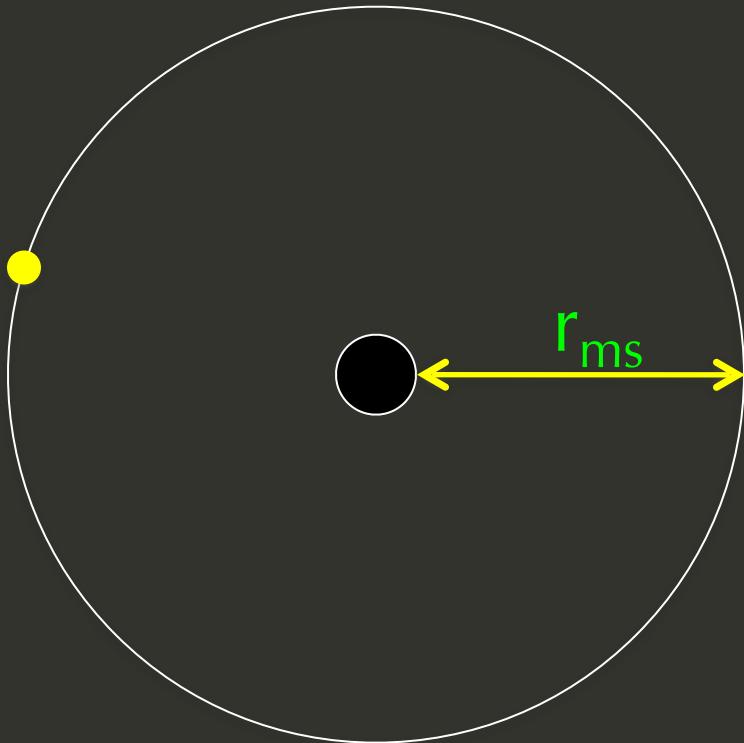
Mass Measurement



Mass can be measured through observing the motion of companion stars.

Courtesy: ICRAR

Theoretical Foundation for Measuring Spin



$R \geq R_{\text{ms}}$: Stable

$R < R_{\text{ms}}$: Unstable

$$R_{\text{ISCO}} = R_{\text{ms}}$$

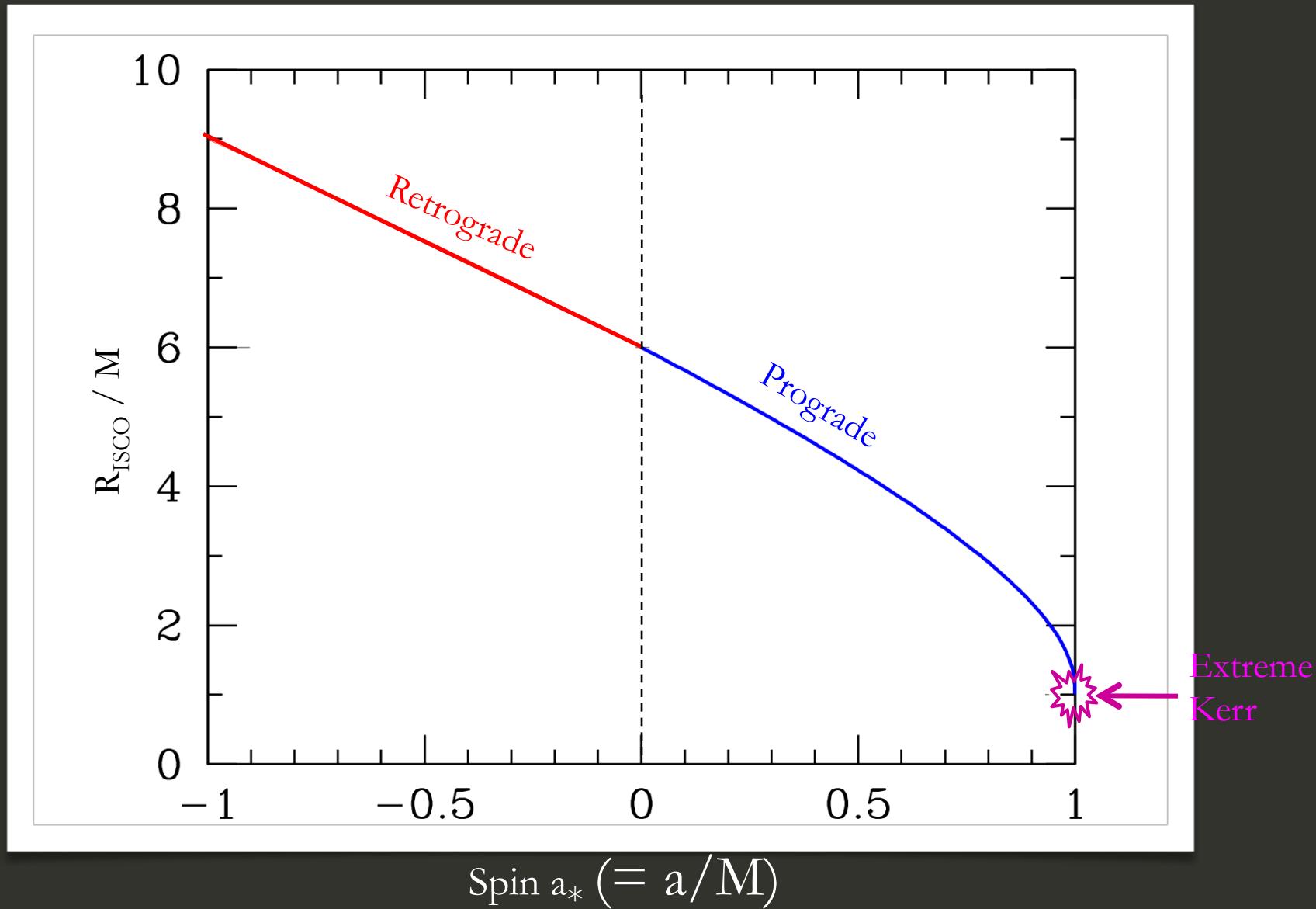
(ISCO: inner-most stable circular orbit)

Bardeen et al. 1972, ApJ, 172, 347

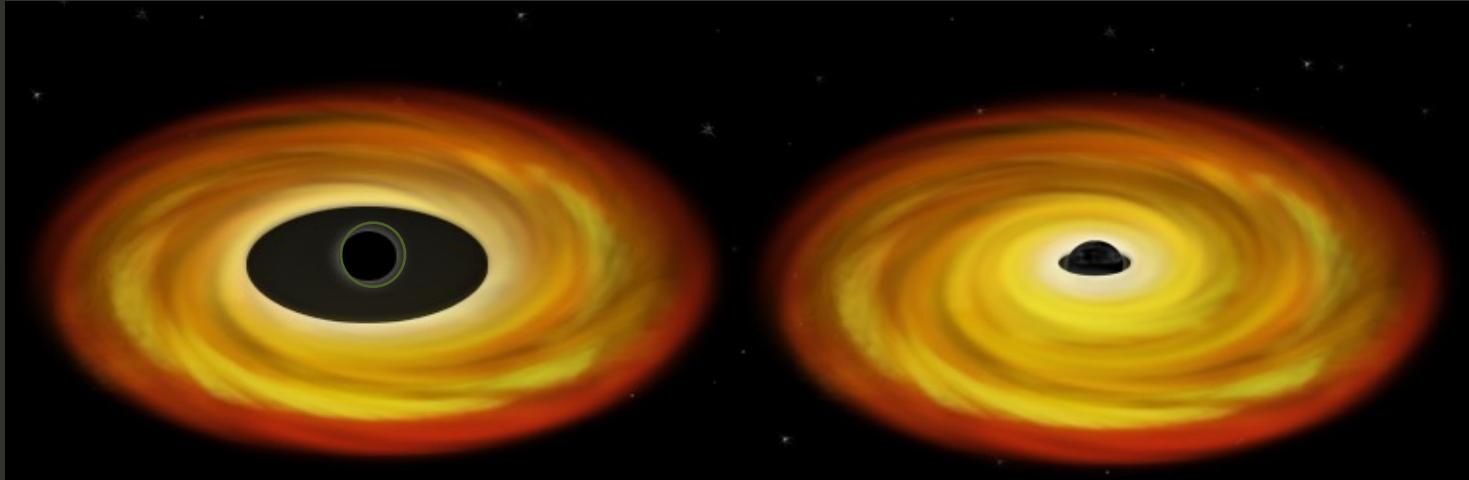
where r_{ms} is the radius of the marginally stable orbit,

$$\begin{aligned} r_{\text{ms}} &= M \{ 3 + Z_2 \mp [(3 - Z_1)(3 + Z_1 + 2Z_2)]^{1/2} \}, \\ Z_1 &\equiv 1 + (1 - a^2/M^2)^{1/3} [(1 + a/M)^{1/3} + (1 - a/M)^{1/3}], \\ Z_2 &\equiv (3a^2/M^2 + Z_1^2)^{1/2}. \end{aligned} \tag{2.21}$$

Theoretical Foundation for Measuring Spin



Innermost Stable Circular Orbit (ISCO)



$$a_* = 0$$

$$a_* = 1$$

$$R_{\text{ISCO}} = 6M = 90 \text{ km}$$

$$R_{\text{ISCO}} = 1M = 15 \text{ km}$$

Methods of Measuring Spin

Continuum Fitting (CF) Method

- Fitting the thermal 1-10 keV spectrum of the accretion disk
(Zhang, Cui & Chen 1997)

Stellar BHs only

Fe-K Method

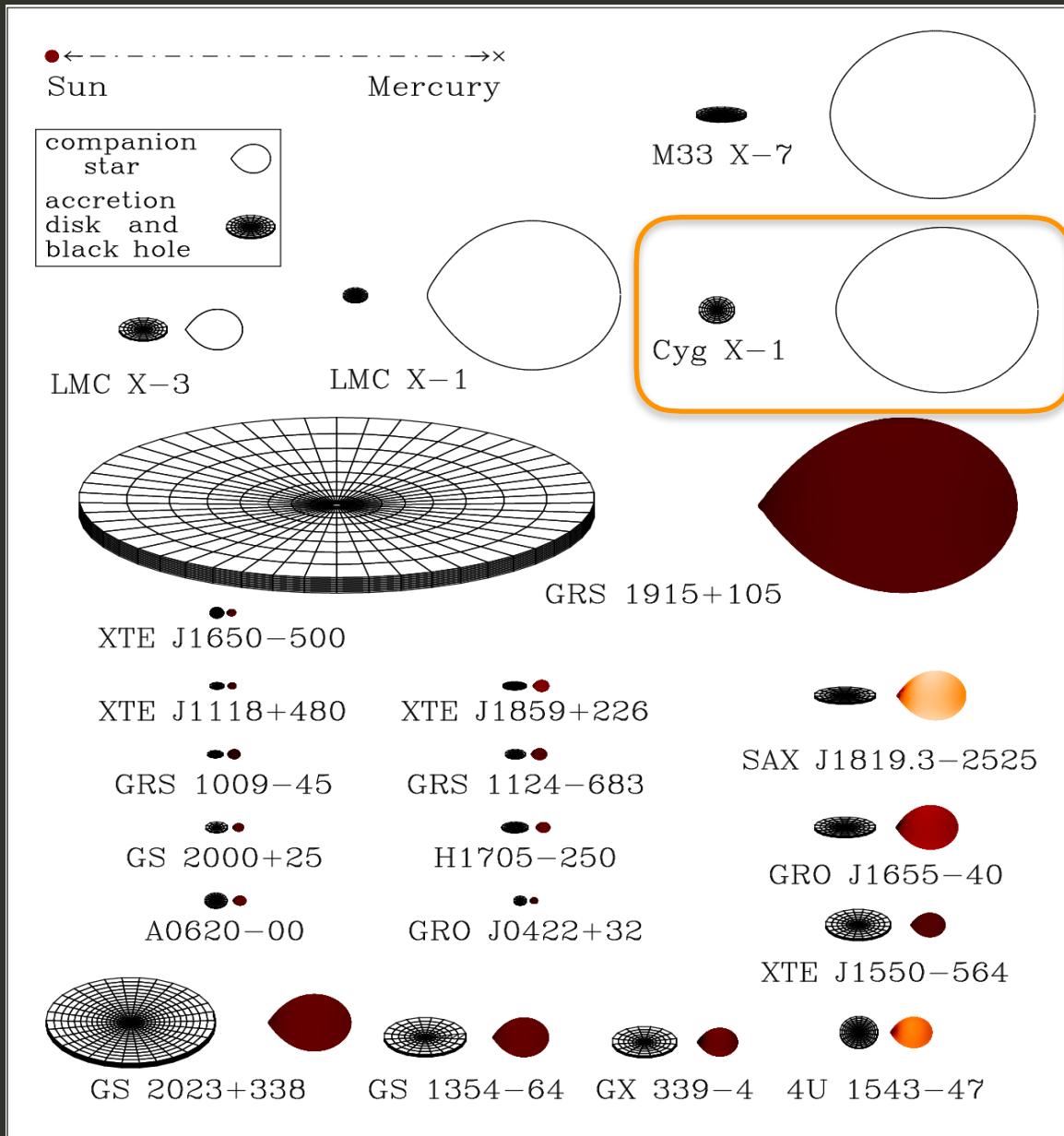
- Fitting the relativistically-broadened profile of the 6.4 keV Fe K line
(Fabian et al. 1989)

Both stellar and supermassive BHs

Promising Methods for the Future

- ✓ X-ray polarimetry
- ✓ High-frequency X-ray oscillations (100-450 Hz)
- ✓ Other (Gravitational Wave & EHT)

Discovered Binary Systems



System Parameters for Cyg X-1 Before 2010

Mass and Luminosity Versus Distance for HD 226868

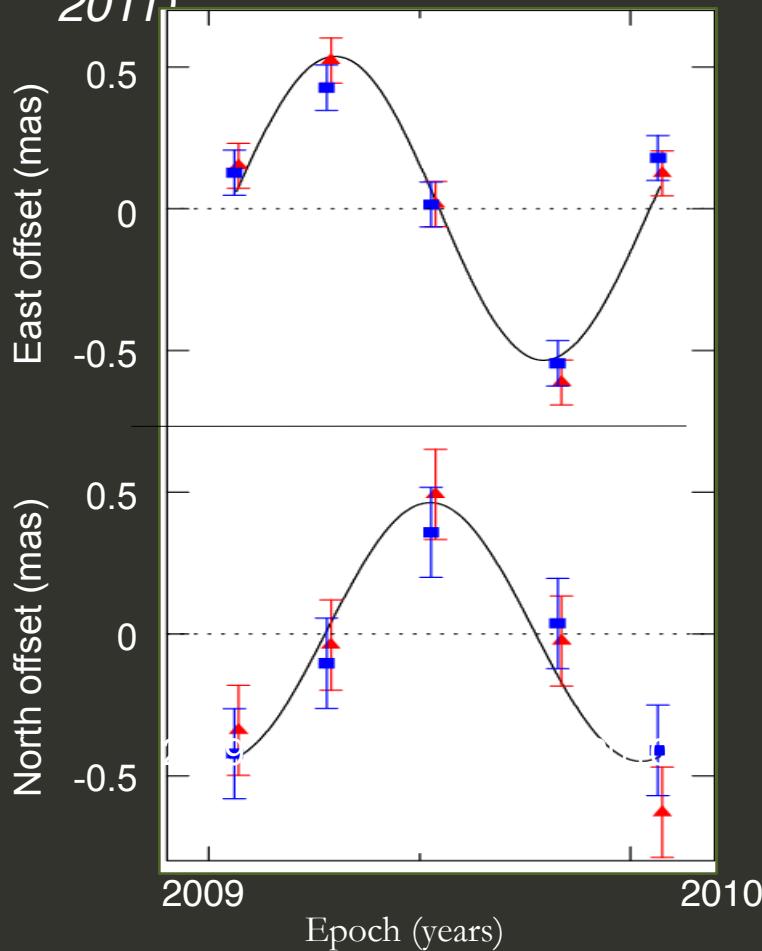
d (kpc)	i (°)	R_1 (R_\odot)	$\log L_1$ (L_\odot)	$\log L_1^*(0.9)$ (L_\odot)	$\log L_1^*(1.0)$ (L_\odot)	M_1^{\min} (M_\odot)	$M_1^{\text{sync}}(0.9)$ (M_\odot)	$M_1^{\text{sync}}(1.0)$ (M_\odot)	M_2^{\min} (M_\odot)	$M_2^{\text{sync}}(0.9)$ (M_\odot)	$M_2^{\text{sync}}(1.0)$ (M_\odot)
1.1	67.5	11.4	4.85	3.06	2.77	5.0	6.6	5.0	2.7	3.1	2.6
1.2	57.9	12.4	4.93	3.41	3.04	6.4	8.6	6.5	3.1	4.0	3.4
1.3	51.4	13.4	5.00	3.83	3.35	7.9	10.9	8.2	3.5	5.0	4.3
1.4	46.5	14.5	5.06	4.31	3.71	9.6	13.7	10.3	4.0	6.3	5.4
1.5	42.6	15.5	5.12	4.70	4.13	11.6	16.8	12.7	4.5	7.7	6.6
1.6	39.4	16.5	5.18	4.99	4.57	13.8	20.4	15.4	5.0	9.4	8.0
1.7	36.7	17.6	5.23	5.21	4.85	16.3	24.5	18.4	5.5	11.3	9.6
1.8	34.4	18.6	5.28	5.37	5.08	19.0	29.0	21.9	6.1	13.4	11.4
1.9	32.3	19.6	5.33	5.54	5.26	21.9	34.1	25.7	6.6	15.7	13.4
2.0	30.5	20.7	5.37	5.68	5.40	25.2	39.8	30.0	7.2	18.4	15.6
2.1	28.9	21.7	5.41	5.80	5.56	28.7	46.1	34.7	7.9	21.3	18.1
2.2	27.5	22.7	5.45	5.92	5.69	32.5	53.0	39.9	8.5	24.4	20.8
2.3	26.2	23.8	5.49	6.05	5.79	36.7	60.6	45.6	9.2	27.9	23.8
2.4	25.0	24.8	5.53	6.17	5.90	41.1	68.8	51.9	9.9	31.7	27.0
2.5	24.0	25.9	5.57	6.27	6.02	45.9	77.8	58.6	10.6	35.9	30.5

M2: black hole mass; Caballero-Nieves et al. (2009)

Distance and Mass for Cyg X-1 in 2010

$$D = 1.86 \pm 0.12 \text{ kpc}$$

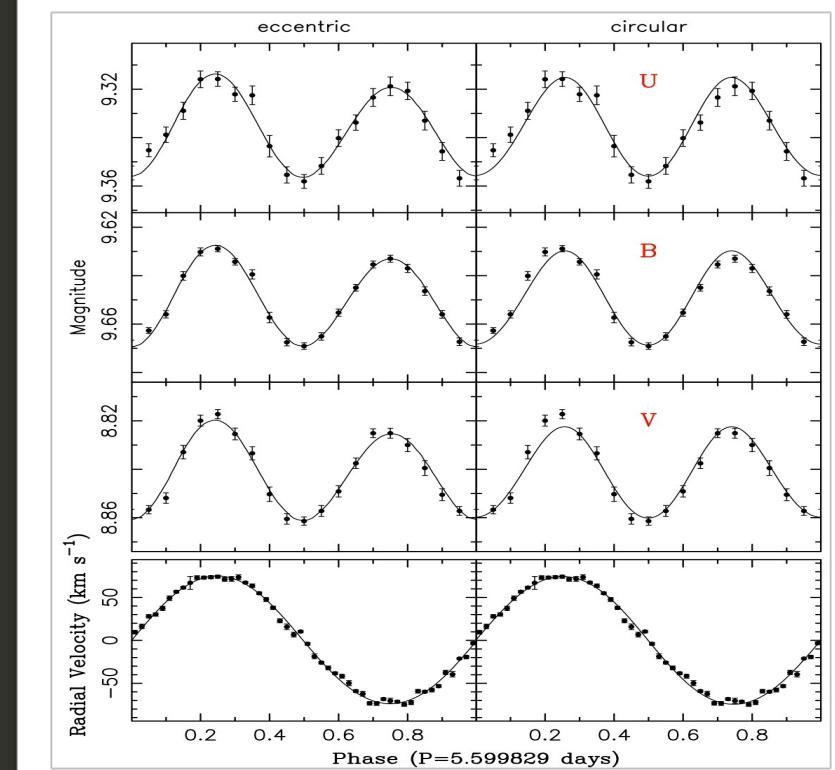
VLBA parallax (*Reid et al., ApJ, 2011*)



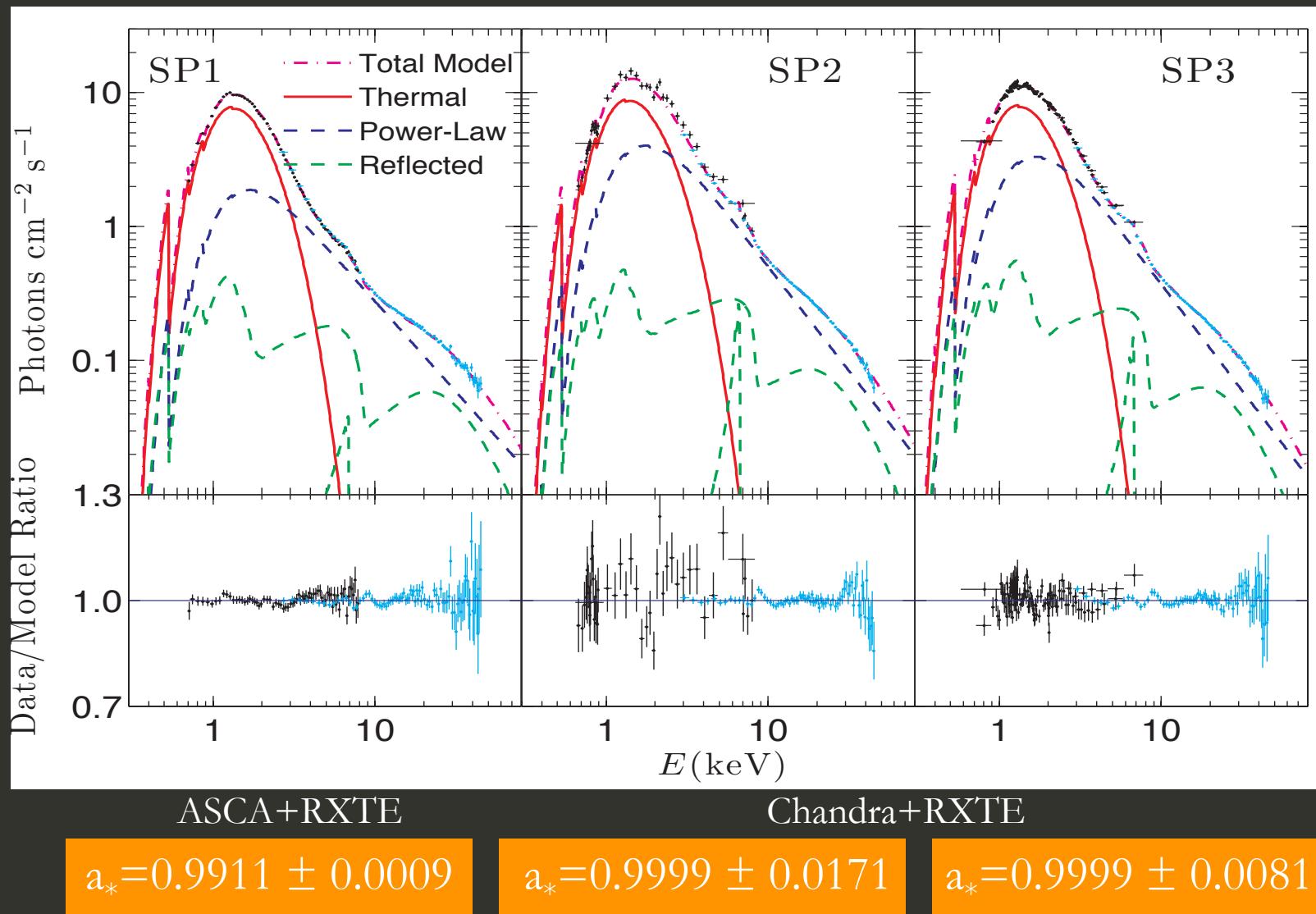
$$M = 14.8 \pm 1.0 M_{\odot}$$

$$i = 27.1 \pm 0.8 \text{ deg}$$

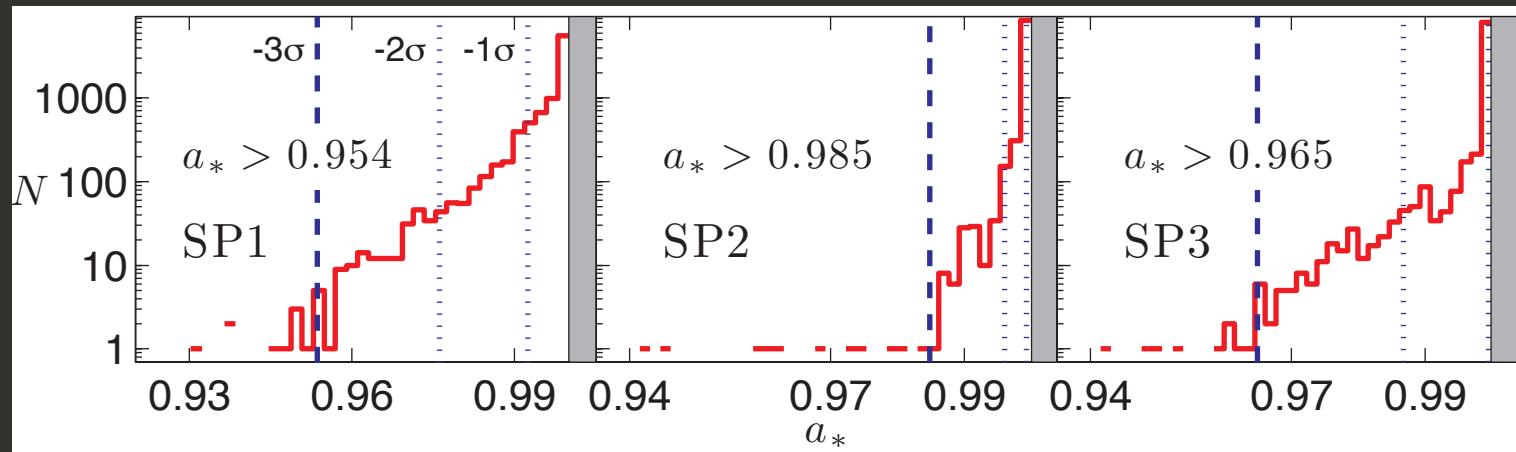
Modeling optical data (*Orosz et al., ApJ, 2011*)



Cyg X-1: Spin via CF



Error Analysis via MC Simulation



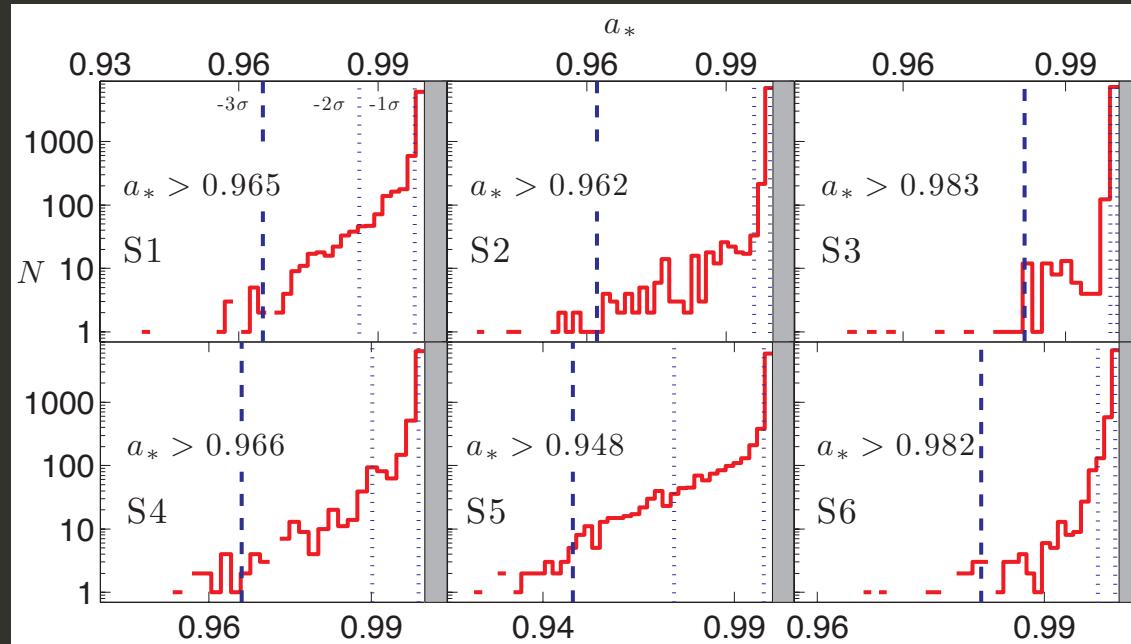
ASCA+RXTE

Chandra+RXTE

➤ $a_* > 0.95$ at 3σ ; Gou et al. (2012), ApJ

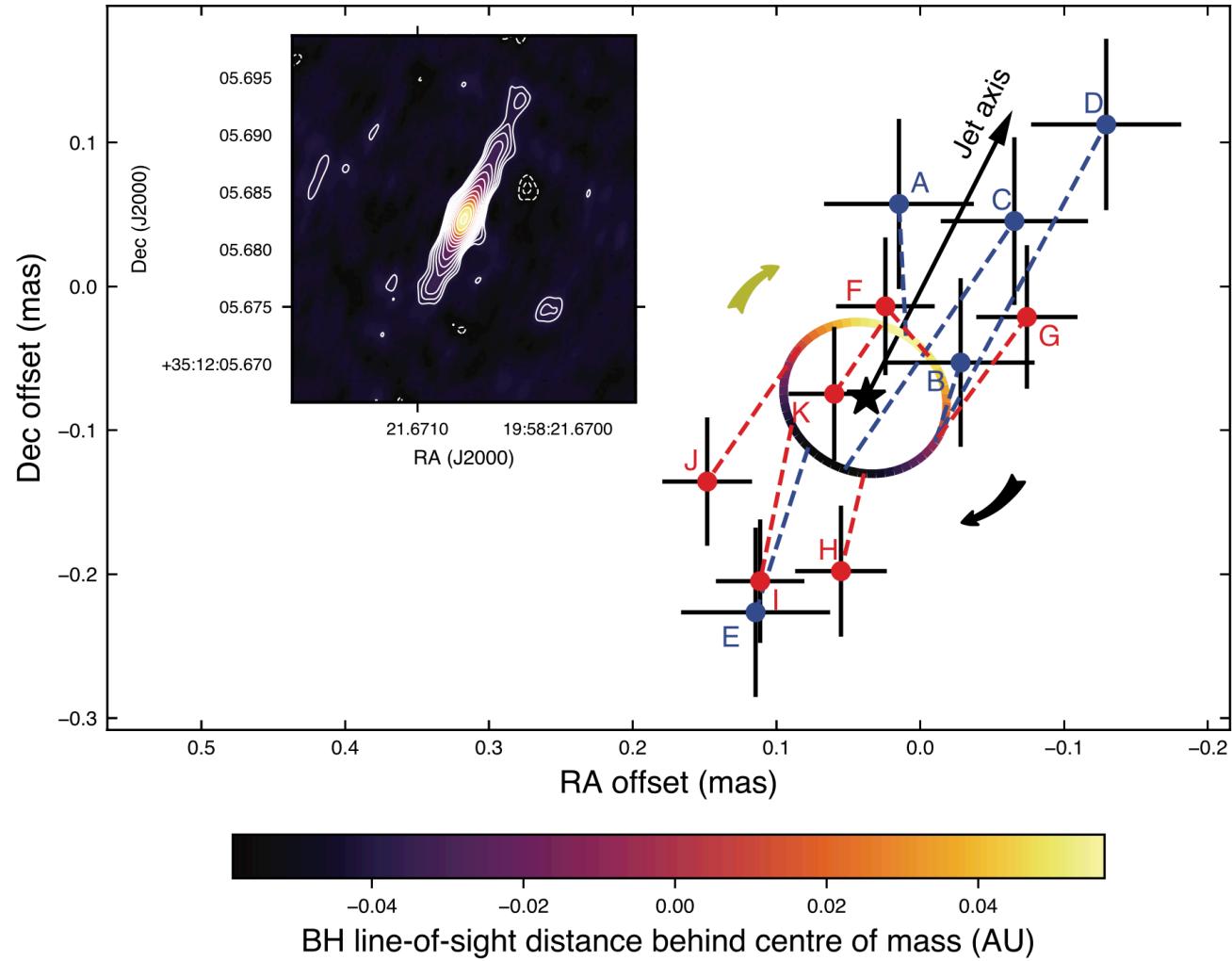
Confirmation of the Extreme Spin

- Bad quality spectra used in the previous analysis
- 5 pointings from Chandra, Suzaku, Swift, and RXTE (late 2010, and 2011).
- 11 spectra (6 suitable)



$a_* > 0.983$ at 3σ for Cyg X-1 (ApJ, 2014, 790, 29)

New Radio Observations to Cyg X-1



New Parameters to Cyg X-1



Parameter	Median	Mode	Lower bound	Upper bound
i (deg)	27.51	27.33	26.94	28.28
e	0.0189	0.0186	0.0163	0.0217
ω (deg)	306.6	306.3	300.3	313.1
$M_1 (M_\odot)$	40.6	39.8	33.5	48.3
f_1	0.960	0.999	0.930	0.988
T_{eff} (K)	31,138	31,158	30,398	31,840
$K_1 (\text{km s}^{-1})$	75.21	75.18	74.80	75.63
ϕ	0.0024	0.0023	0.0013	0.0034
Ω_{rot}	1.05	1.04	0.95	1.16
$M_{\text{BH}} (M_\odot)$	21.2	21.4	18.9	23.4
$R_1 (R_\odot)$	22.3	22.2	20.6	24.1
$\log L/L_\odot$	5.625	5.606	5.547	5.698
$\log g_1$ (cgs)	3.348	3.351	3.335	3.360
a (AU)	0.244	0.243	0.231	0.256
a_1 (AU)	0.0838	0.0840	0.0816	0.0856
a_{BH} (AU)	0.160	0.159	0.147	0.173

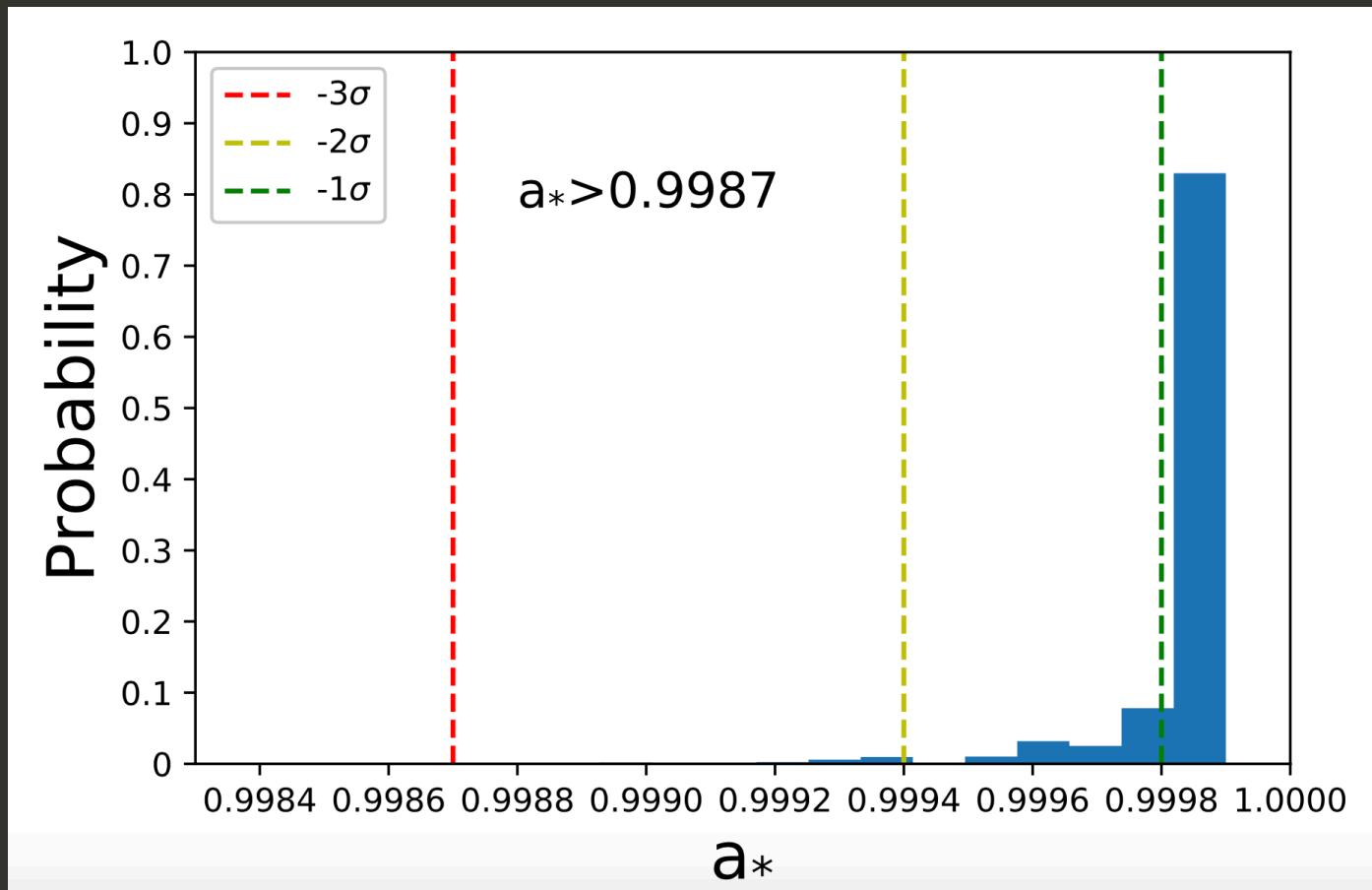
It is the most massive stellar BH among the X-ray binary systems.

Miller-Jones et al. (2021), Science

$$D = 2.22 \pm 0.12 \text{ kpc}$$
$$M = 14.8 \pm 1.0 M_\odot$$

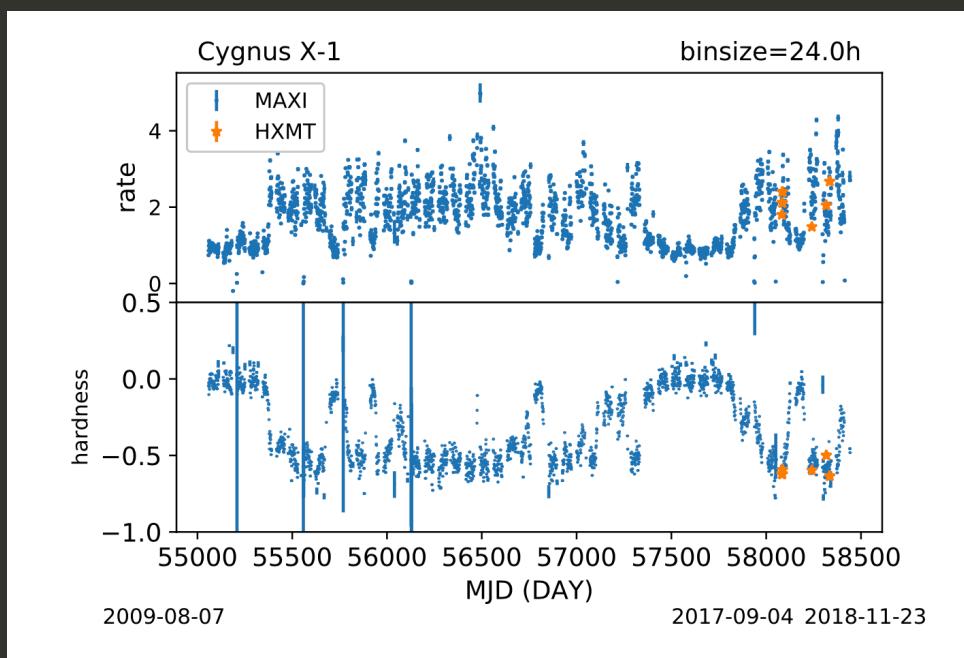
$$i = 27.1 \pm 0.8 \text{ deg}$$

New Spin to Cyg X-1

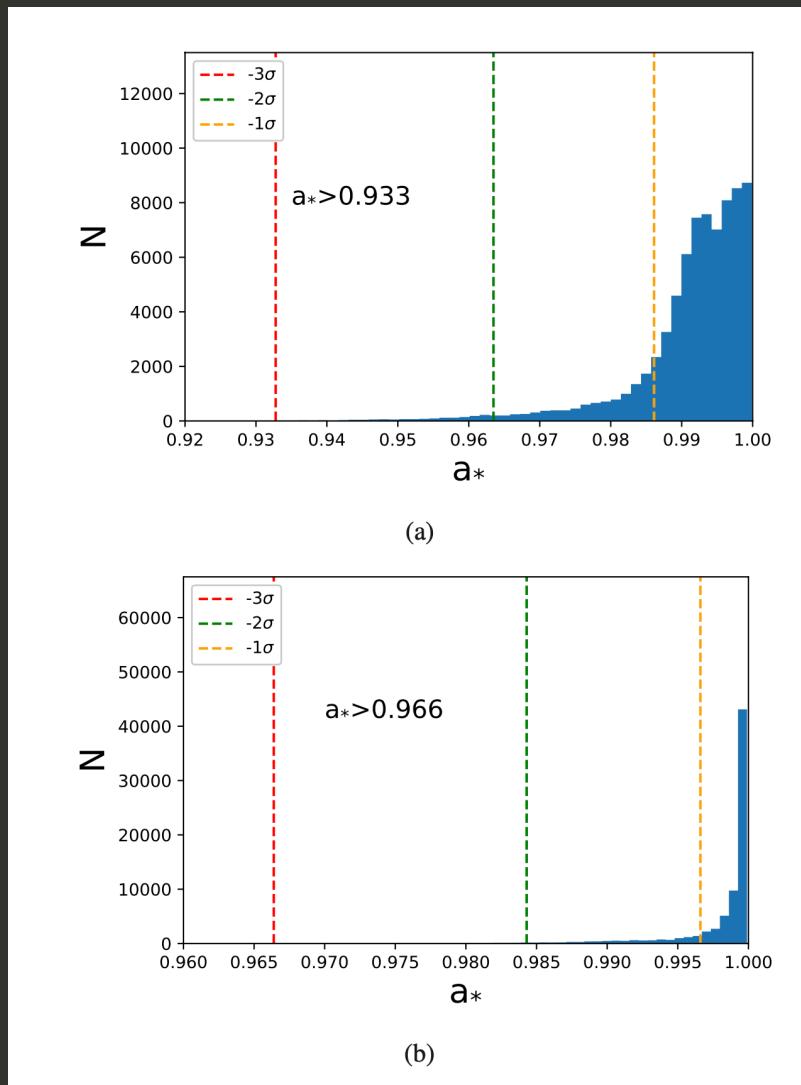


It has the highest spin among all the systems.

New Spin to Cyg X-1 with HXMT Data



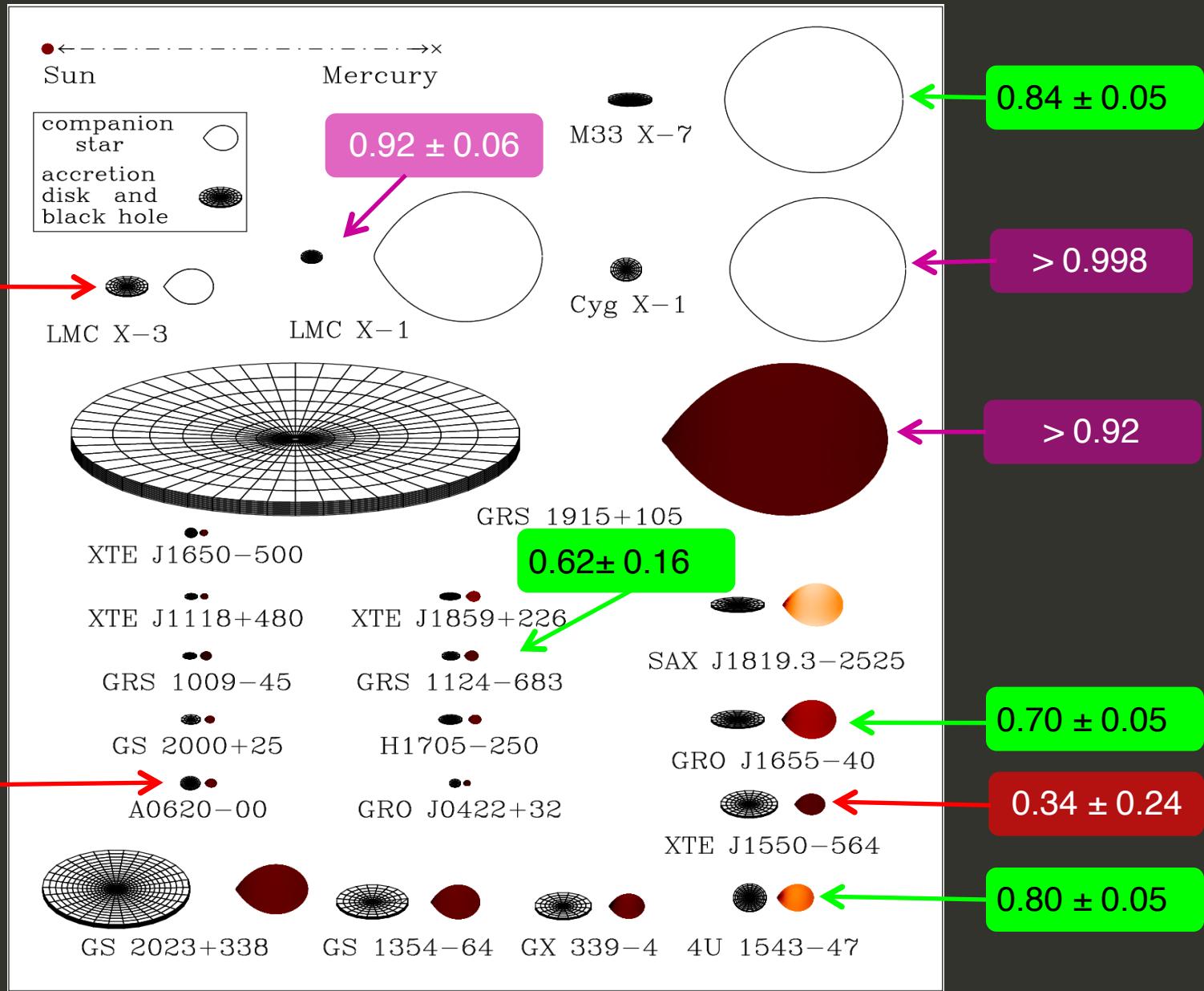
Zhao et al. (2020), IHEAP



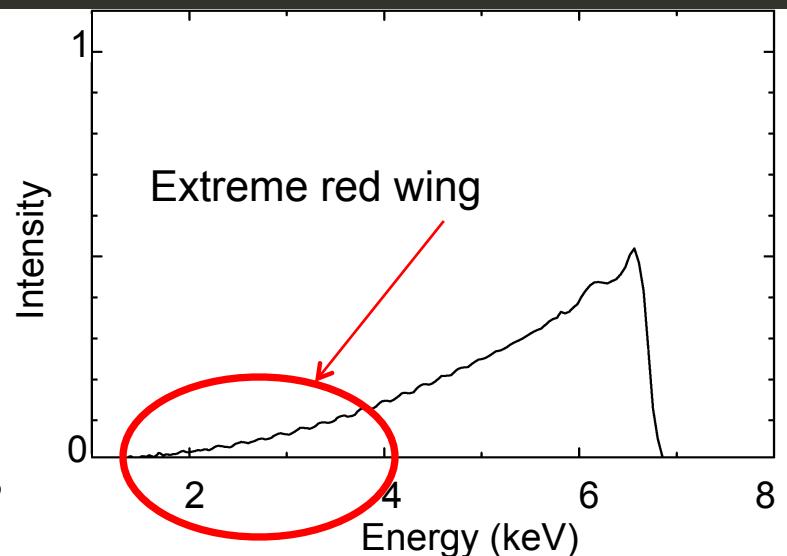
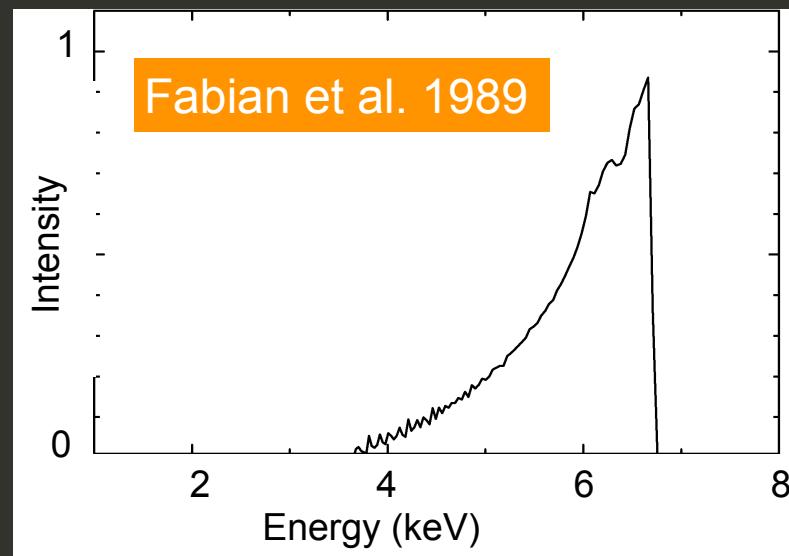
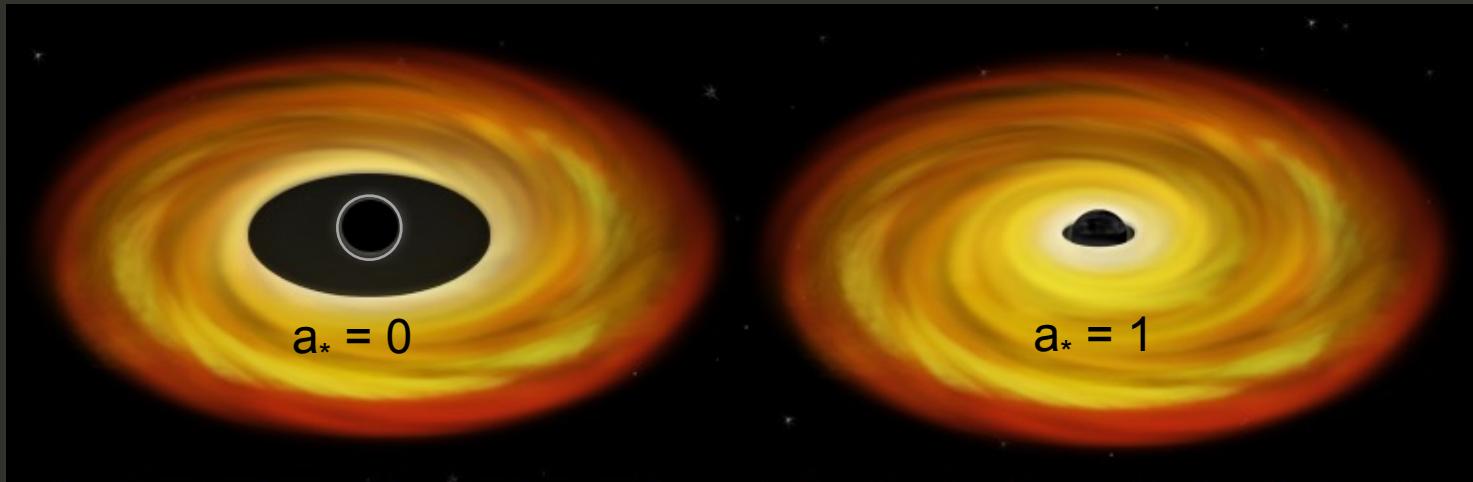
Spin Summary For 21 BH Binaries (CF)

H1743-322
:
 $a^* = 0.2 \pm$

< 0.3



Dependence of Fe K Line Profile on Spin



Models: Xillver (Garcia et al. 2010, 2013); Reflionx (Ross et al. 1999, 2005)

Fe-Line Spin Measurement for Stellar BH

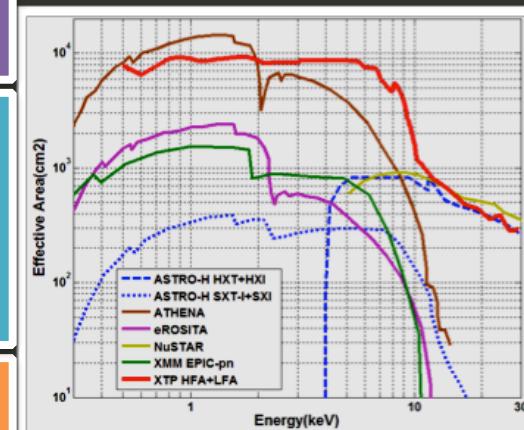
Black Hole	Spin a_* (CF)	Spin a_* (Fe K)	Principal References
Cyg X-1	> 0.9983	> 0.9	Zhao et al. 2021; Fabian ea. 2012
XTE J1550-564	0.34 ± 0.28	0.55 ± 0.1	Steiner, Reis ea. 2011
LMC X-1	0.92 ± 0.06	$0.97^{+0.02}_{-0.25}$	Gou ea. 2009; Steiner ea. 2012
4U 1543-47	$0.8 \pm 0.1^*$	0.67 ± 0.15	Shafee ea. 2006; Dong et al. 2020
GRO J1655-40	$0.7 \pm 0.1^*$	> 0.9	Shafee ea. 2006; Reis ea. 2009
GRS 1915+105	> 0.92	0.98 ± 0.01	Reid et al. 2014; Miller ea. 2014
GX 339-4	< 0.9	0.93 ± 0.05	Reis ea. 2008; Kolehmainen & Done 2010
A0620-00	0.12 ± 0.19		Gou ea. 2010
MAXI J1820+070	0.13 ± 0.10		Zhao, Gou et al. 2021
Nova Mus 1991	~ 0.62		Chen, Gou ea. 2015
MAXI J1659	$-0.67 < a^* < 0.45$		Feng, Zhao, Gou et al. 2022
M33 X-7	0.84 ± 0.05		Liu ea. 2008, 2010
LMC X-3	0.21 ± 0.12		Steiner ea. 2014
H1743-322	0.2 ± 0.3		Steiner & McClintock 2012
MAXI 1348-630		0.18 ± 0.20	Jia, Zhao, Gou et al. 2022
MAXI J1836-194		$0.88 \pm 0.05; 0.84-0.94$	Reis ea. 2012; Dong et al. 2020
Swift J1753.5		0.76 ± 0.15	Reis ea. 2009
XTE J1650-500		> 0.7	Walton ea. 2012
XTE J1752-223		0.52 ± 0.11	Reis ea. 2010
XTE J1652-453		< 0.5	Heimstra ea. 2010, Chiang ea. 2012
AT2019wey		~ 0.97	Feng et al. 2022
MAXI J1803-298		~ 0.991	Feng et al. 2022

Spin Measurement in the eXTP Era

✓ eXTP has a much larger effective area compared to the current missions over a very broad energy band, therefore it has an advantage in the spin measurement (high S/N with a shorter observation time and observe the iron line feature more easily).

✓ Due to the large effective area, it may observe more distant BHs and constrain their intrinsic parameters.

✓ It also has the polarimeter, so the polarimetry method could be advanced in the XTP/eXTP era, and it will provide independently constraints on the inclination angle and other system parameters.



eXTP provides an opportunity to check the consistency of the spin parameters with multiple methods.