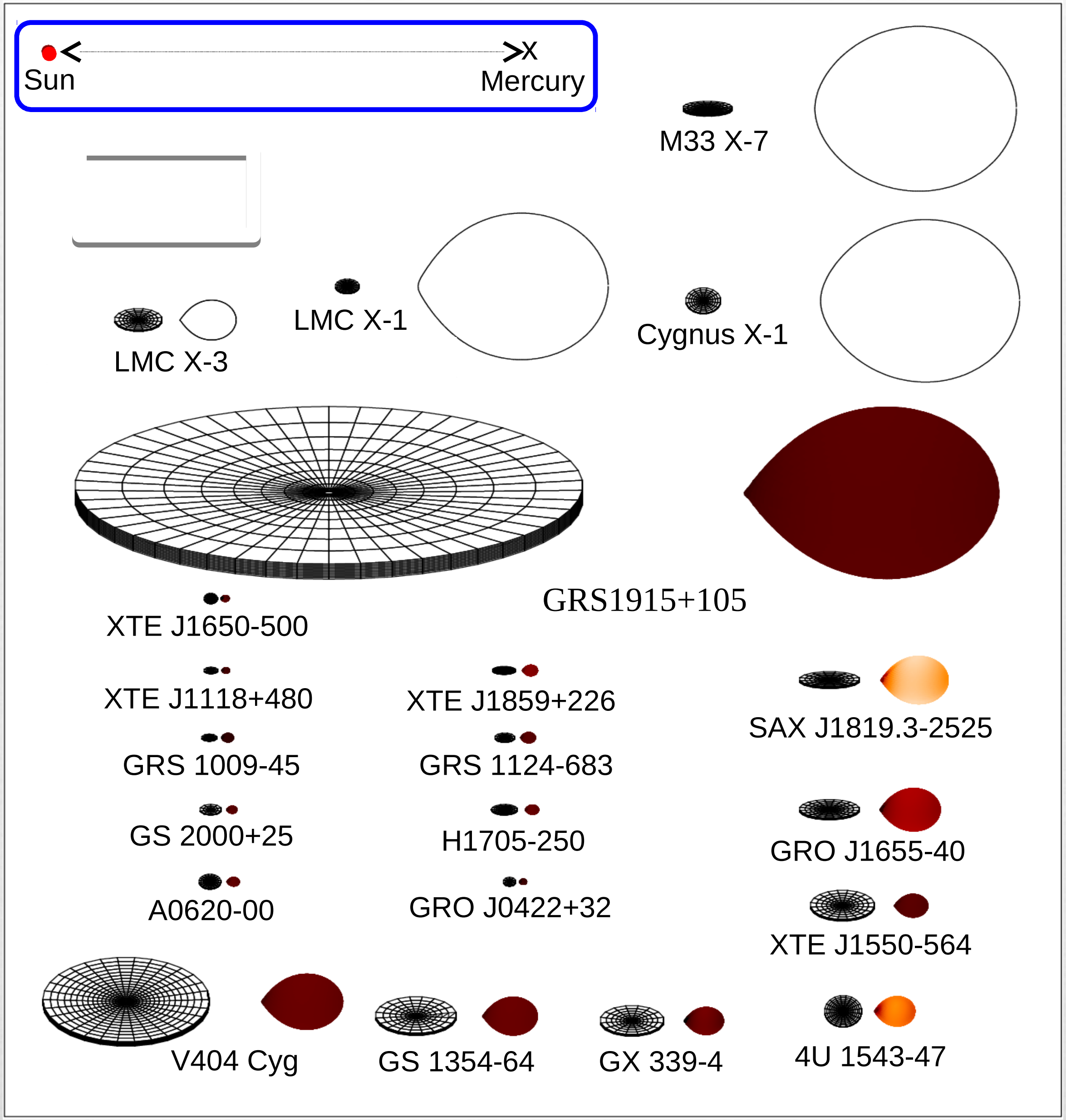
Pioneering X-ray Continuum Fitting Measurements of Black

Jeff at the Thomas Edison Museum

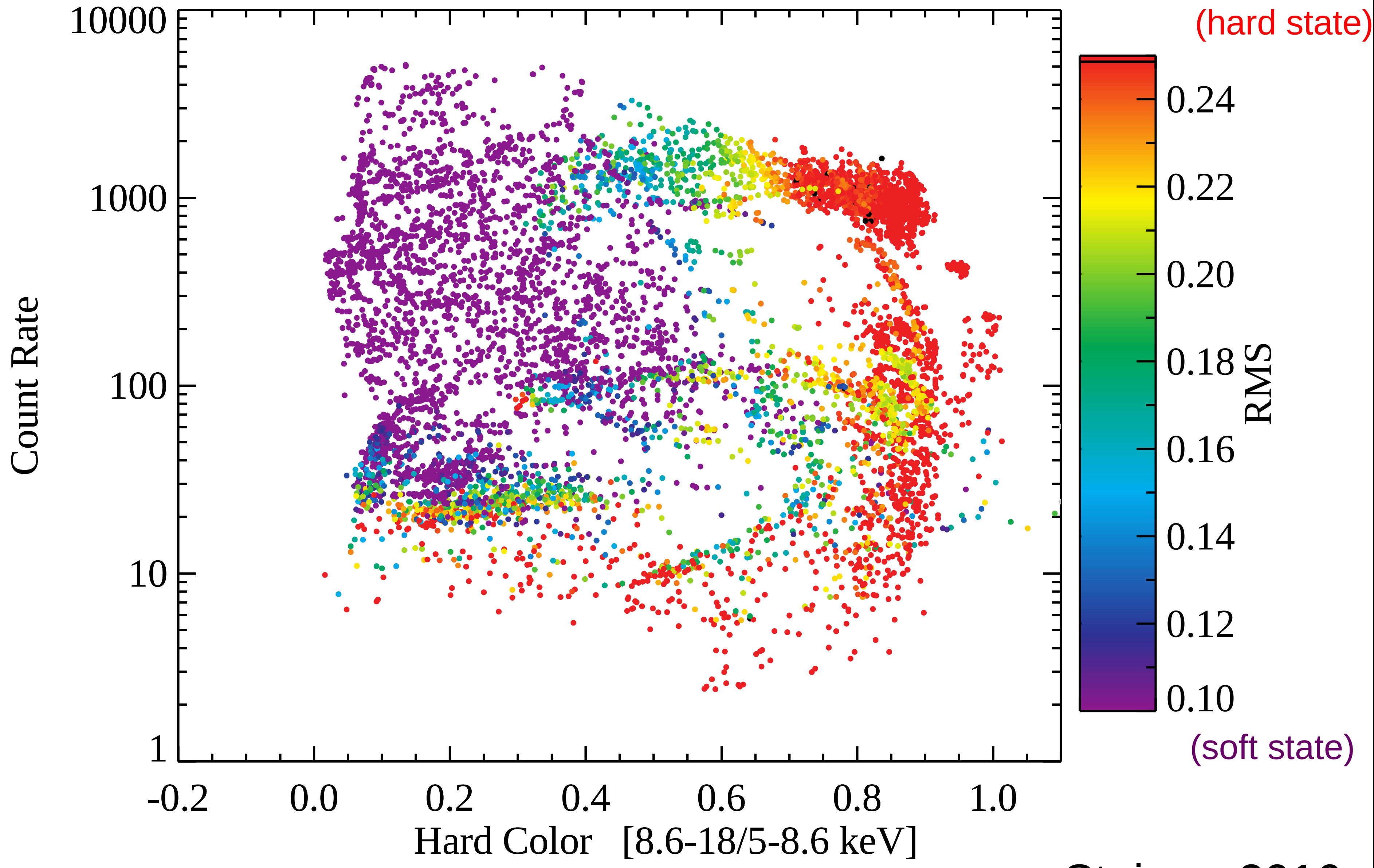
Jack Steiner
MIT Kavli Institute

The Black Hole Binary Zoo



Courtesy: J. Orosz

The RXTE Road Map



Steiner+2016

No-Hair Theorem

- Mass: M
- Spin: a_* (J= a_* GM^2/c)
- Electric Charge: Q

Charge neutralized and unimportant

The gravity of spinning BHs

"***In my entire scientific life**, **the most shattering experience has been the realization that an exact solution of Einstein's equations of general relativity, discovered by Roy Kerr, provides the absolutely exact representation of untold numbers of massive black holes that populate the universe.*** *This shuddering before the beautiful, this incredible fact that a discovery motivated by a search after the beautiful in mathematics should find its exact replica in Nature, persuades me to say that beauty is that to which the human mind responds at its deepest and most profound.*"

- Subrahmanyan Chandrasekhar

Dynamical Mass Measurements

(**Jerry Orosz's** talk)

Weighing Black Holes

"Mass function" from radial velocities

- a mass lower limit

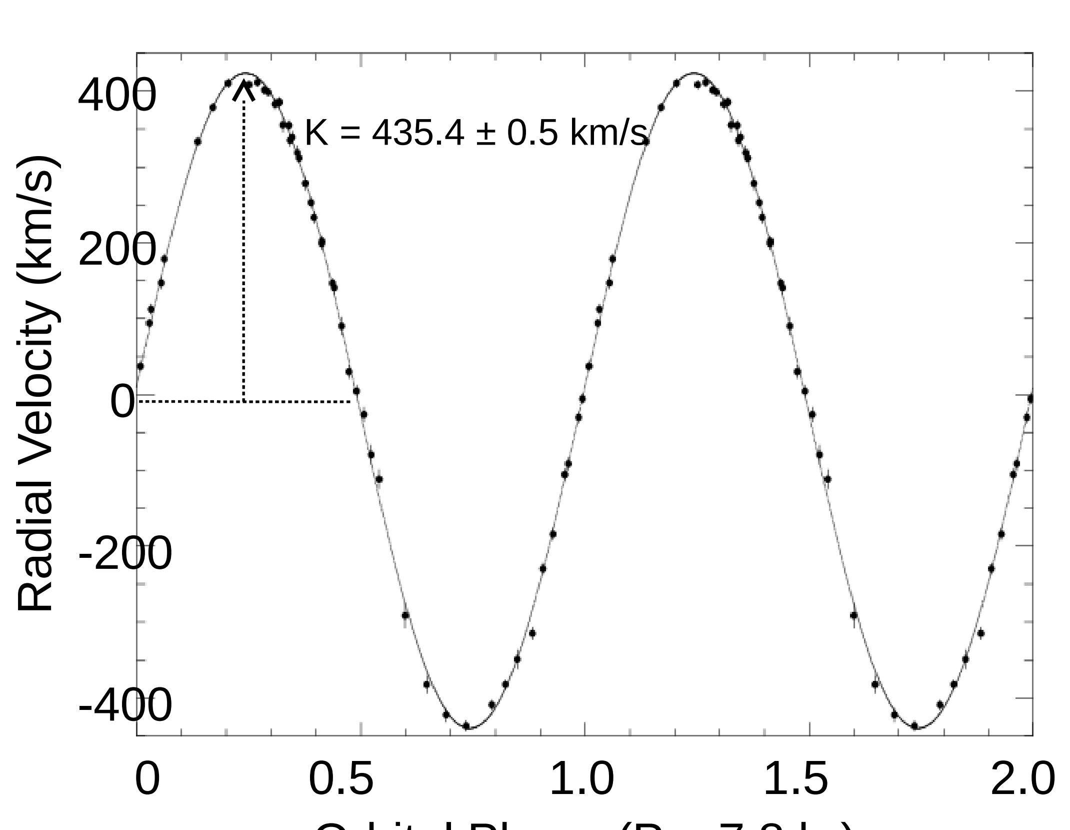
$$f(M) = \frac{P_{orb} K^3}{2\pi G} = \frac{M_X \sin^3 i}{(1+q)^2}$$

$$q = M_C / M_X$$

$M_X > f$ (M)

R=λ/Δλ≥1500 required

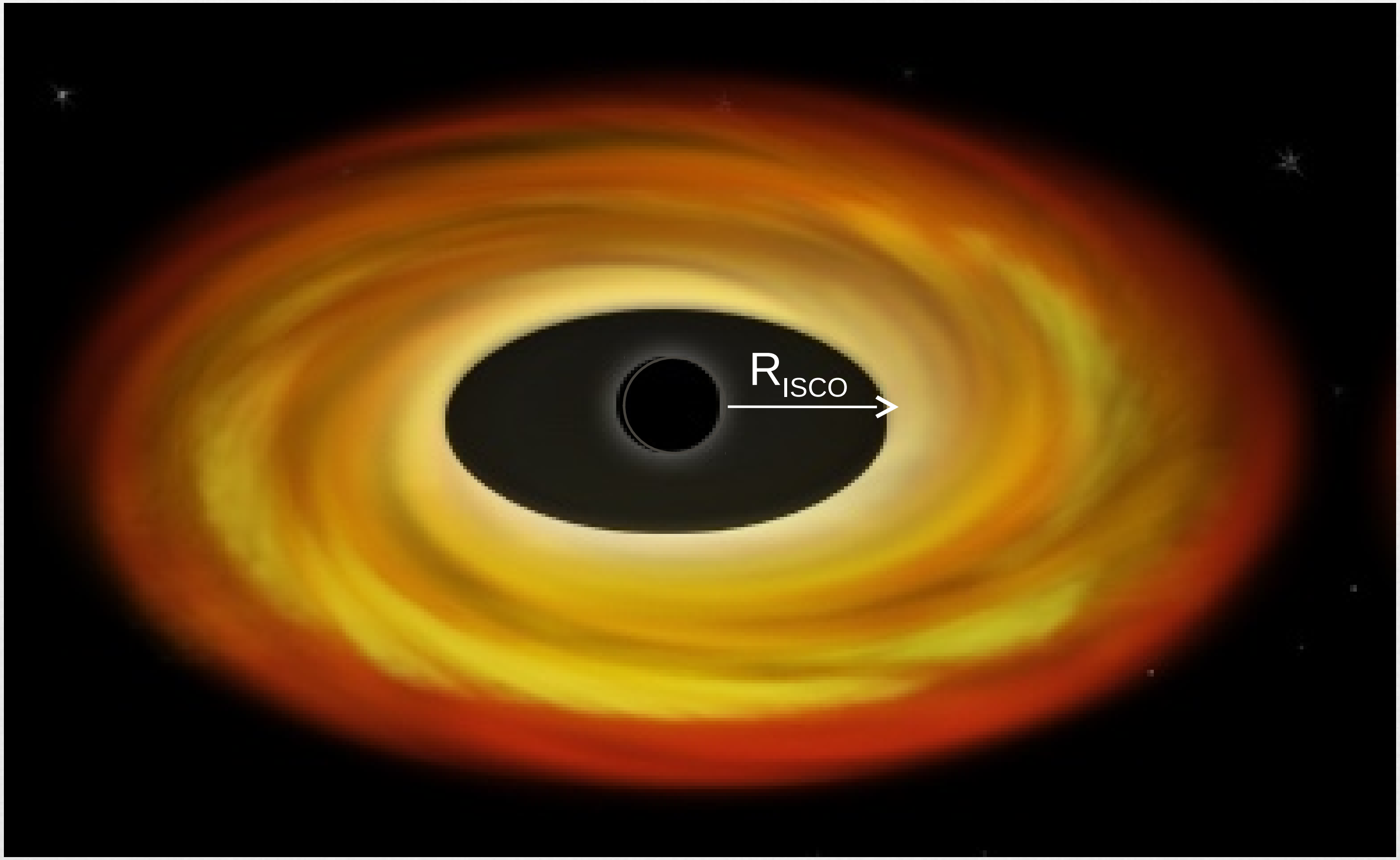
A0620-00

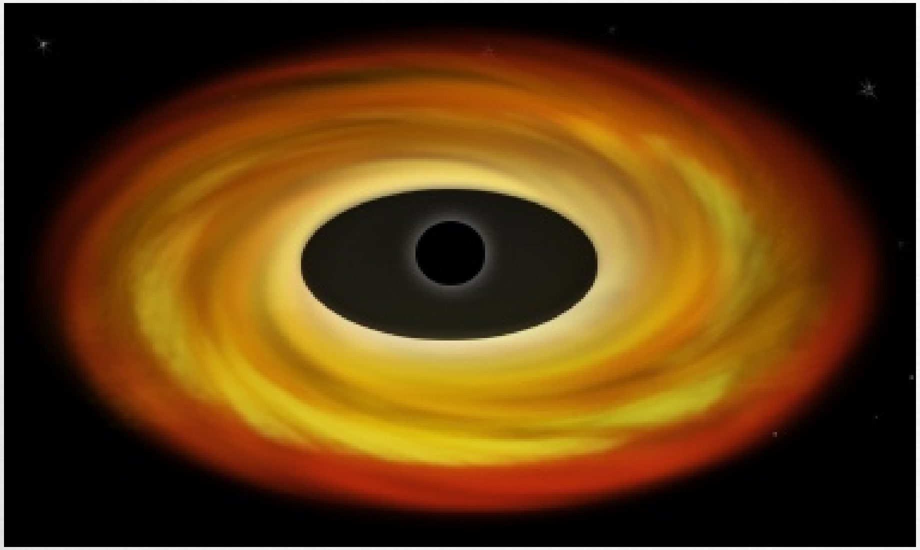


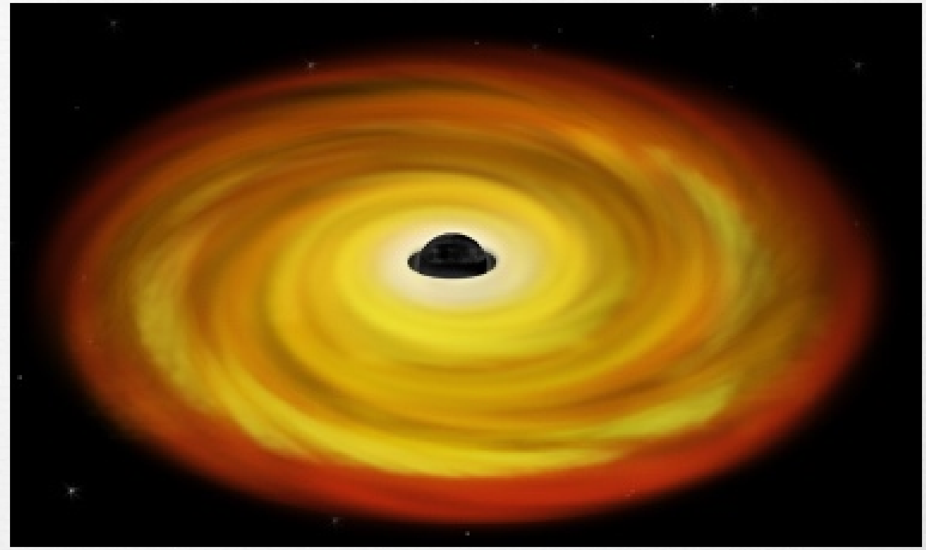
Neilsen et al. 2008

On to Spin

Measuring the Inner Disk Radius







$a_* = 0$

$R_{ISCO} = 6M\ G/c^2$

(90 km)

for $M = 10\ M_\odot$

$a_* = 1$

$R_{ISCO} = 1M\ G/c^2$

(15 km)

Two Primary Methods of Measuring Spin

- Continuum Fitting Method

  Fitting the thermal 1-10 keV spectrum of the accretion disk

- Fe Line (Reflection) Method (**Javier Garcia's** talk)

  Fitting the relativistically-broadened profile of the ~6.4 keV Fe K line

Other Methods

- Quasi-periodic X-ray oscillations (100-450 Hz)
- Gravitational Waves
- X-ray Polarimetry

Continuum Fitting

(Zhang, Cui, & Chen 1997)

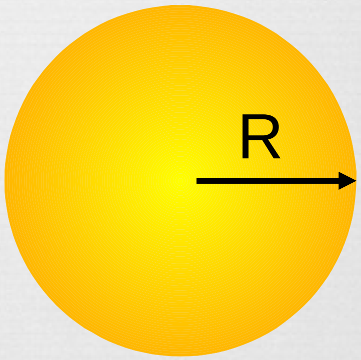
Measuring the Radius of a Star

- Measure the flux F received from the star
- Measure the temperature T_* (from spectrum)
- Independent knowledge of distance (i.e., from parallax)

$$L_* = 4\pi D^2 F = 4\pi R_*^2 \sigma T_*^4$$

$$\Delta\Omega = \frac{\pi R_*^2}{D^2} = \frac{\pi F}{\sigma T_*^4}$$

$$R_* = D\sqrt{\frac{\Delta\Omega}{\pi}} = 37.5 \frac{L_*^{1/2}}{T_*^2} (\mathrm{cgs})$$



Measuring R_{ISCO}

Radius R of a Star

$$L = 4\pi D^2 F = 4\pi R^2 \sigma T^4$$

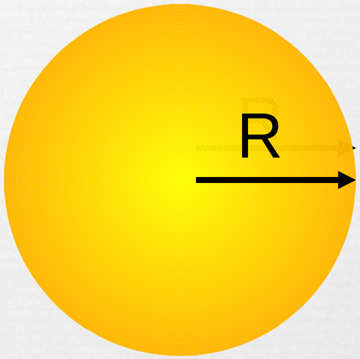
Solid angle: $(R/D)^2 = F/\sigma T^4$

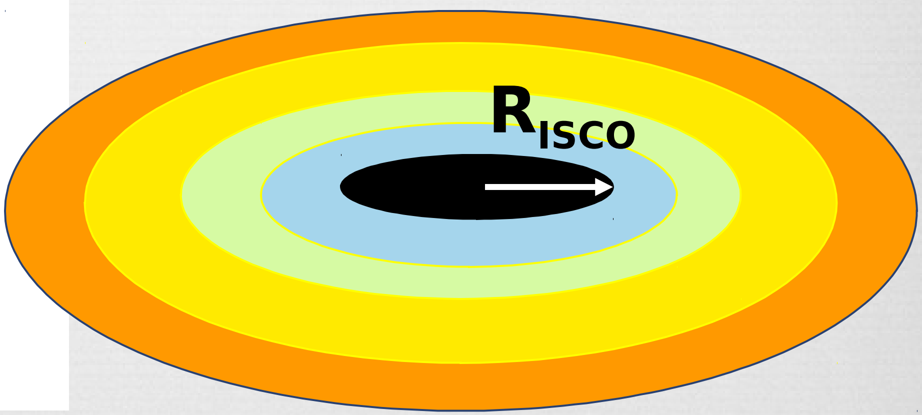
$D \rightarrow$ R

Radius R_{ISCO} of Disk Hole

F and $T \rightarrow$ solid angle

D and $i \rightarrow$ R_{ISCO}





R_{ISCO} and M $\longrightarrow$ a_*

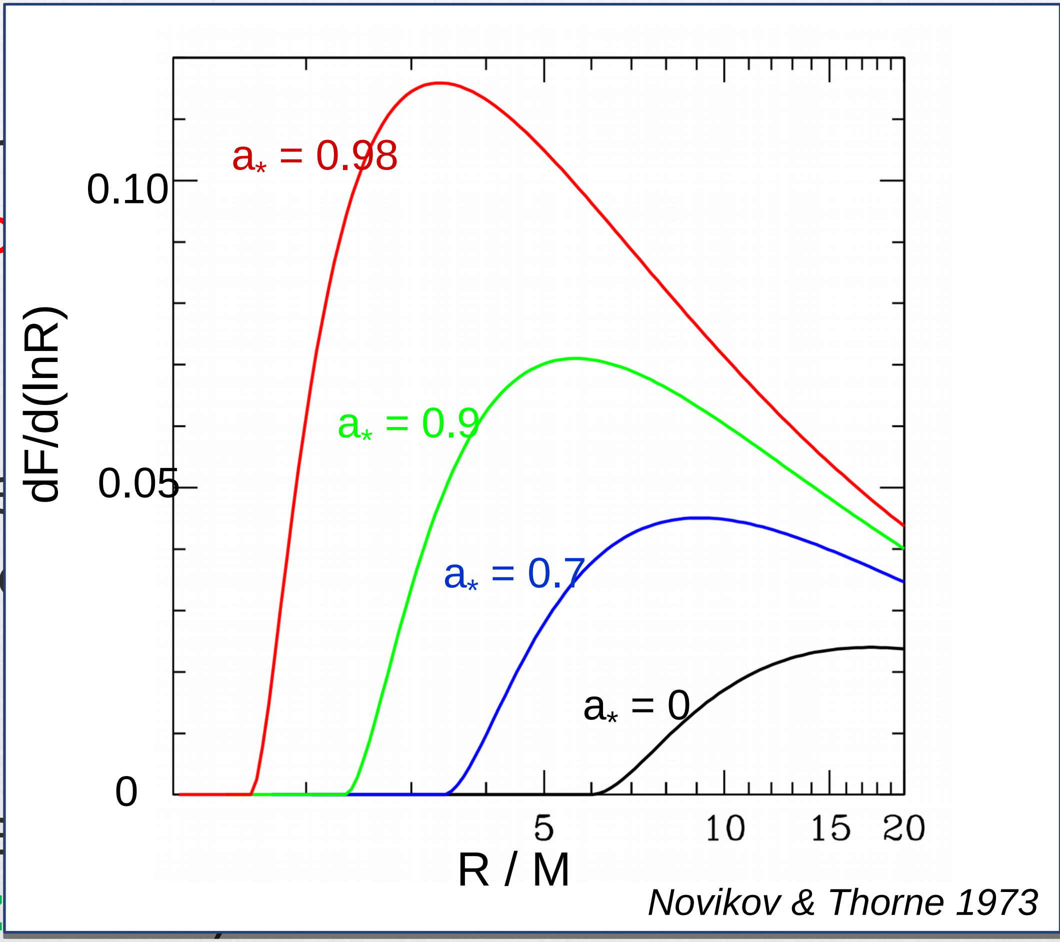
Requirements for the X-ray Continuum Fitting Method

n 1997

- Spectr
  compo

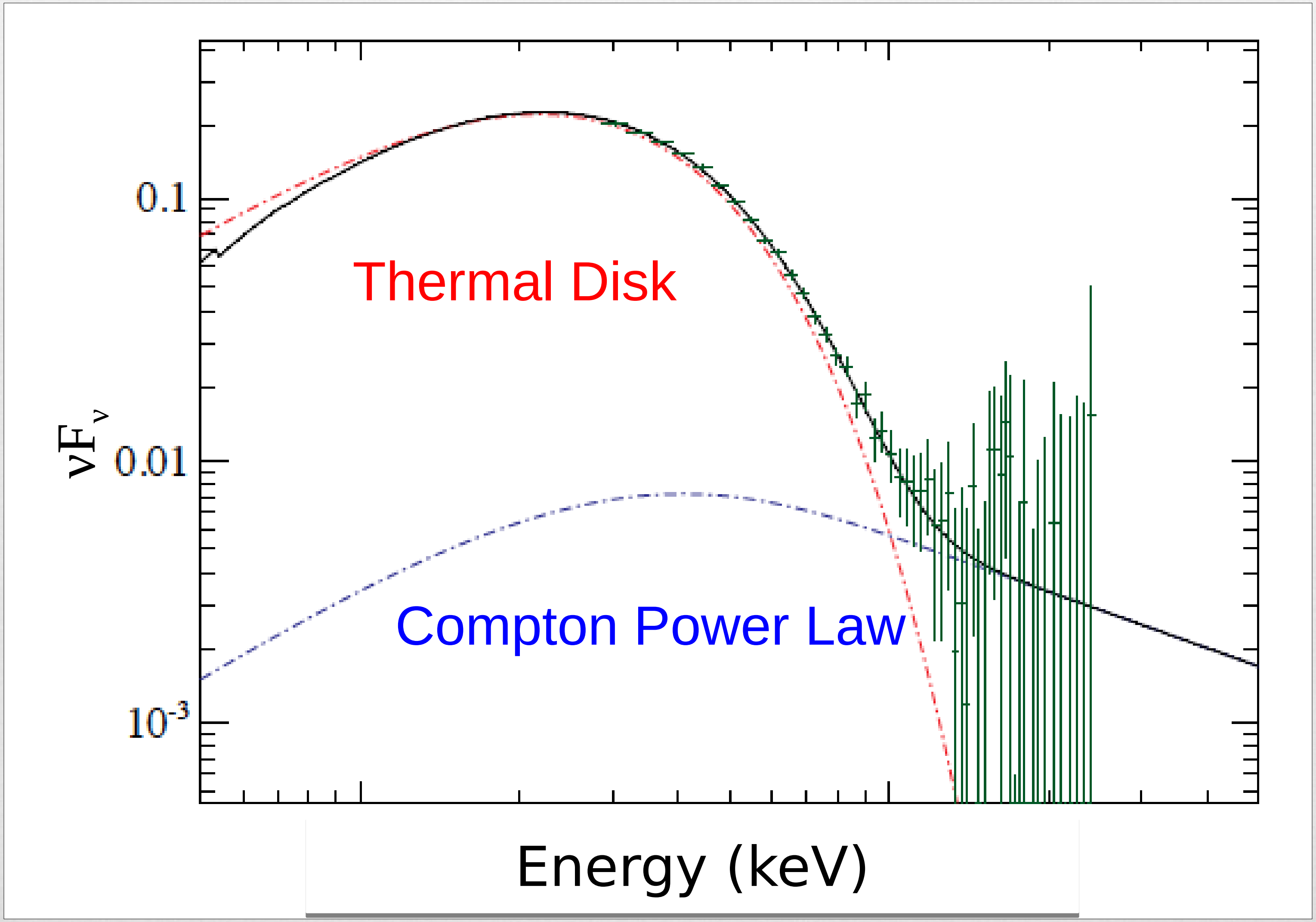
- Theore
  - Spe

- Indepe y
  Orosz

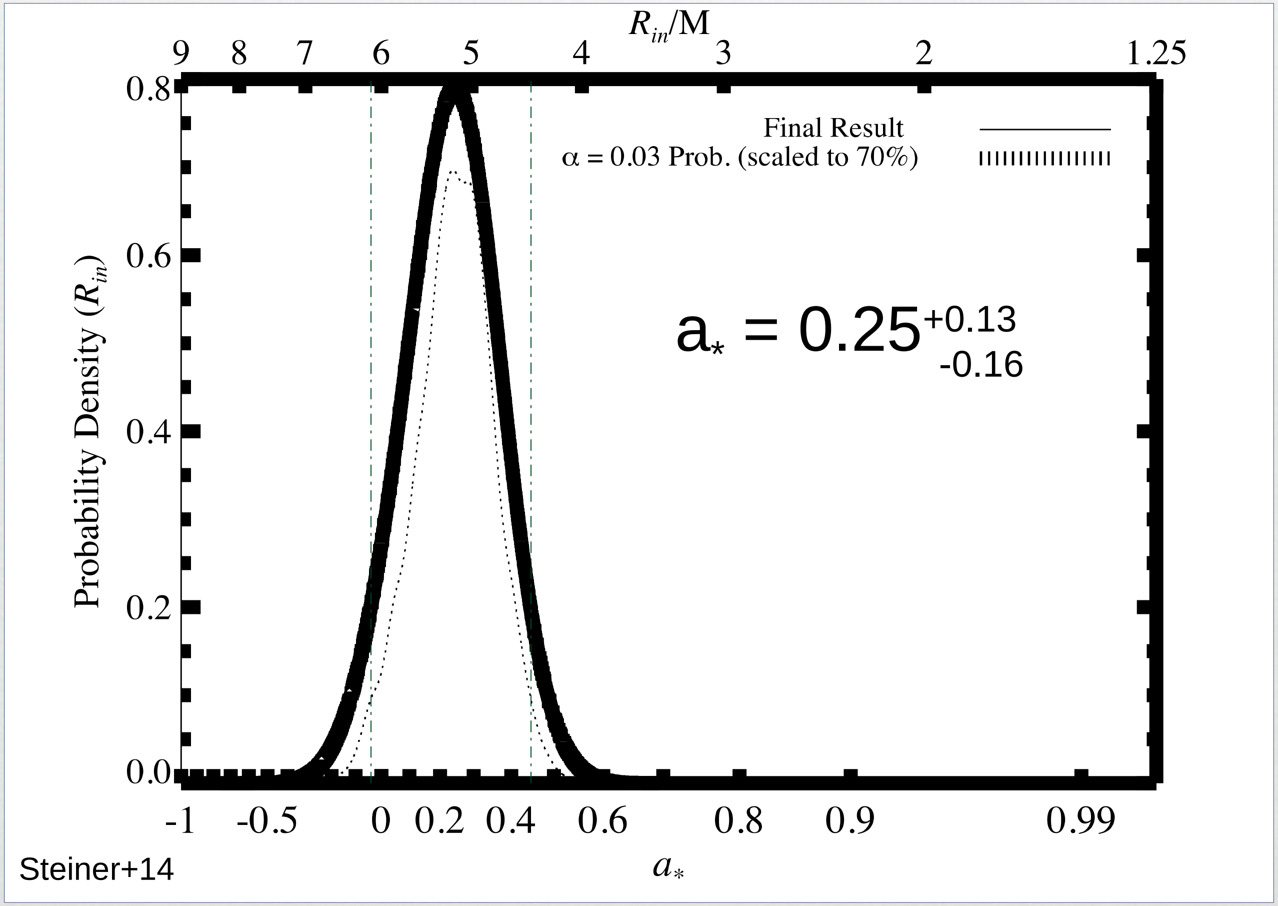


Novikov & Thorne 1973

Using many of these …



Get Spin (LMC X-3)

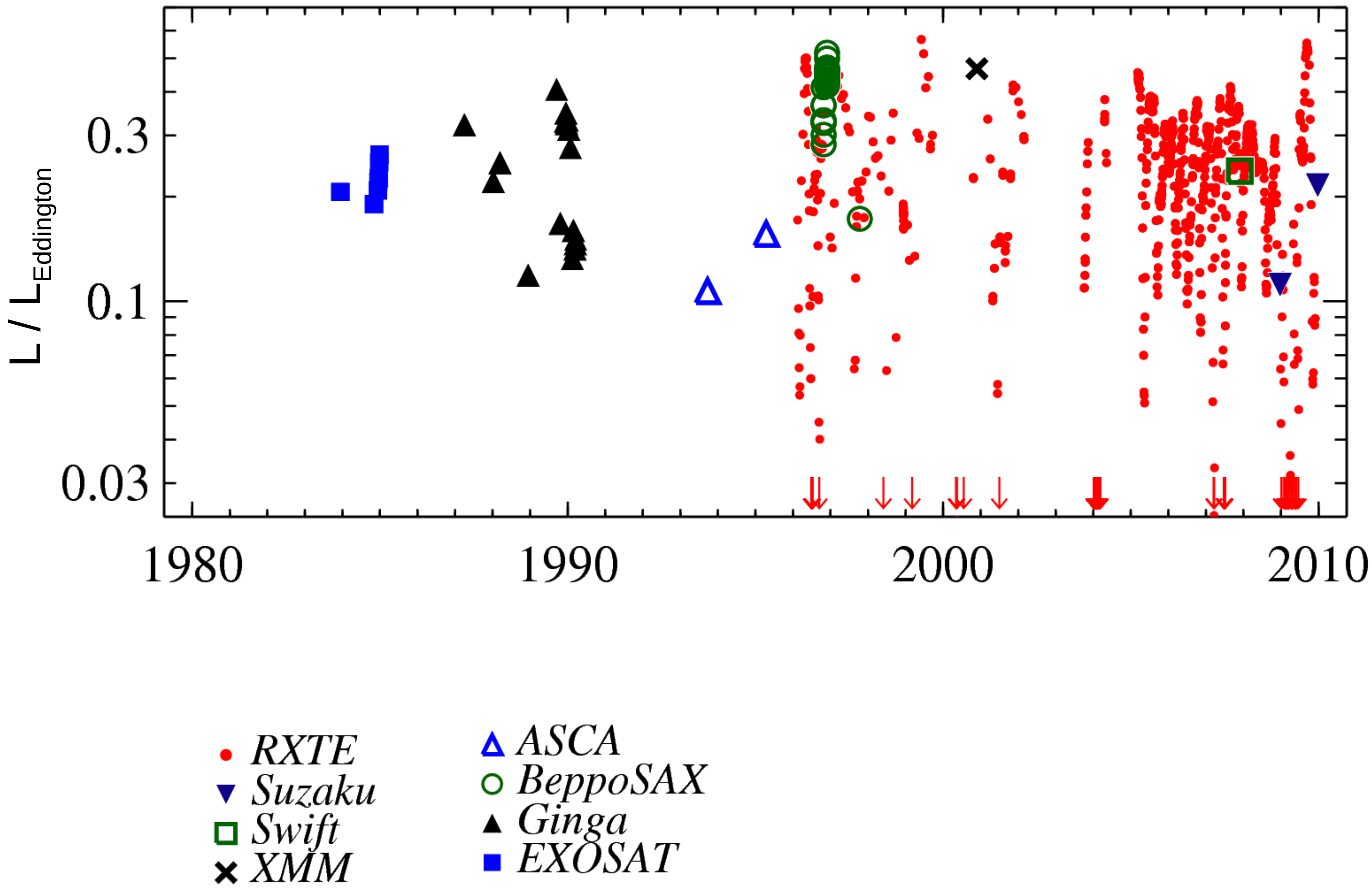


How Well Does it Work in Practice?
(Foundation 1: A constant Rin)

- Extremely well
- Multiple independent observations of the same BH
  - at different luminosities (up to 30% $L_{Eddington}$)
  - with different instruments
  - separated by many years

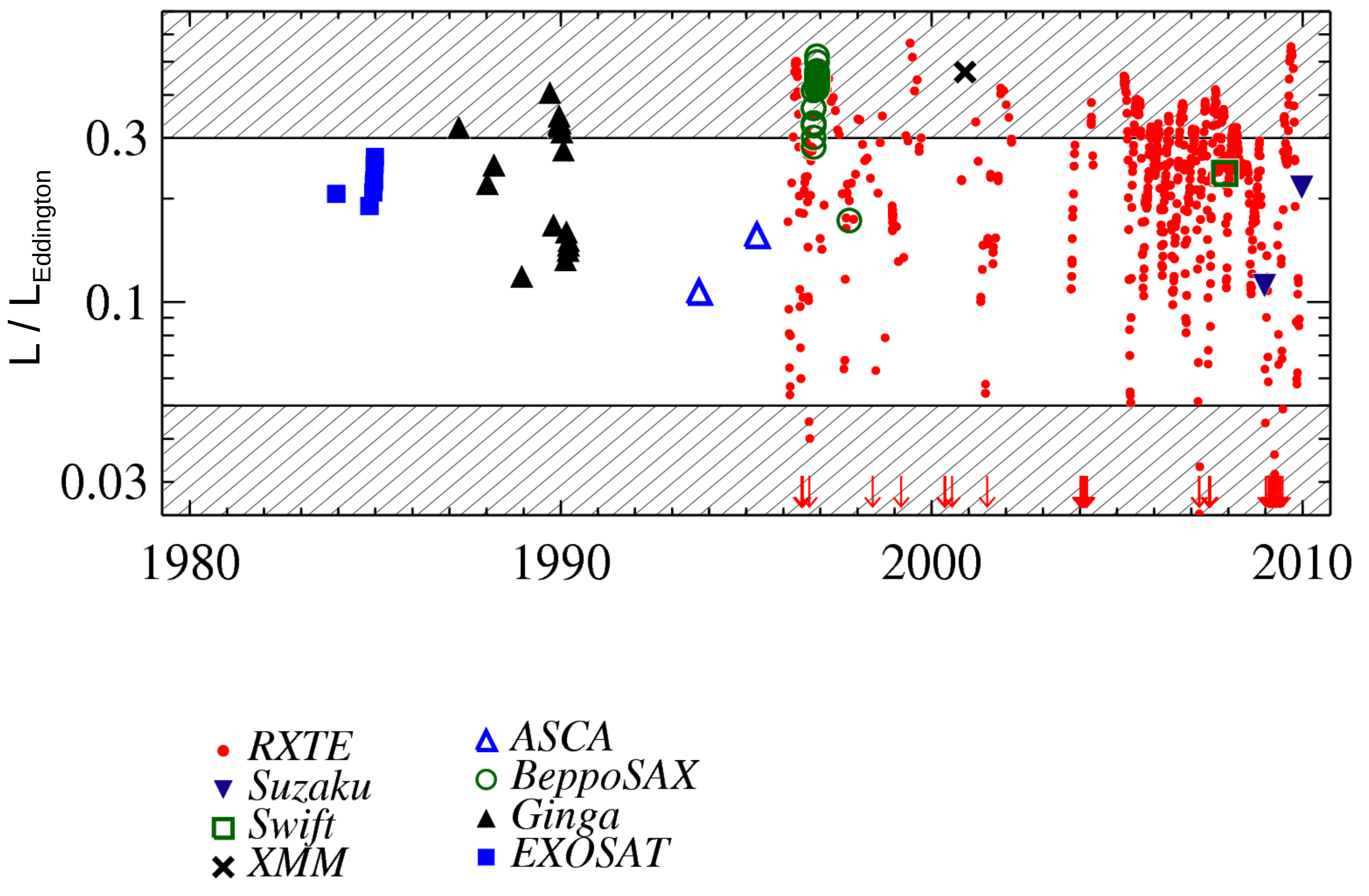
LMC X-3: 1983-2009

Steiner et al. 2010



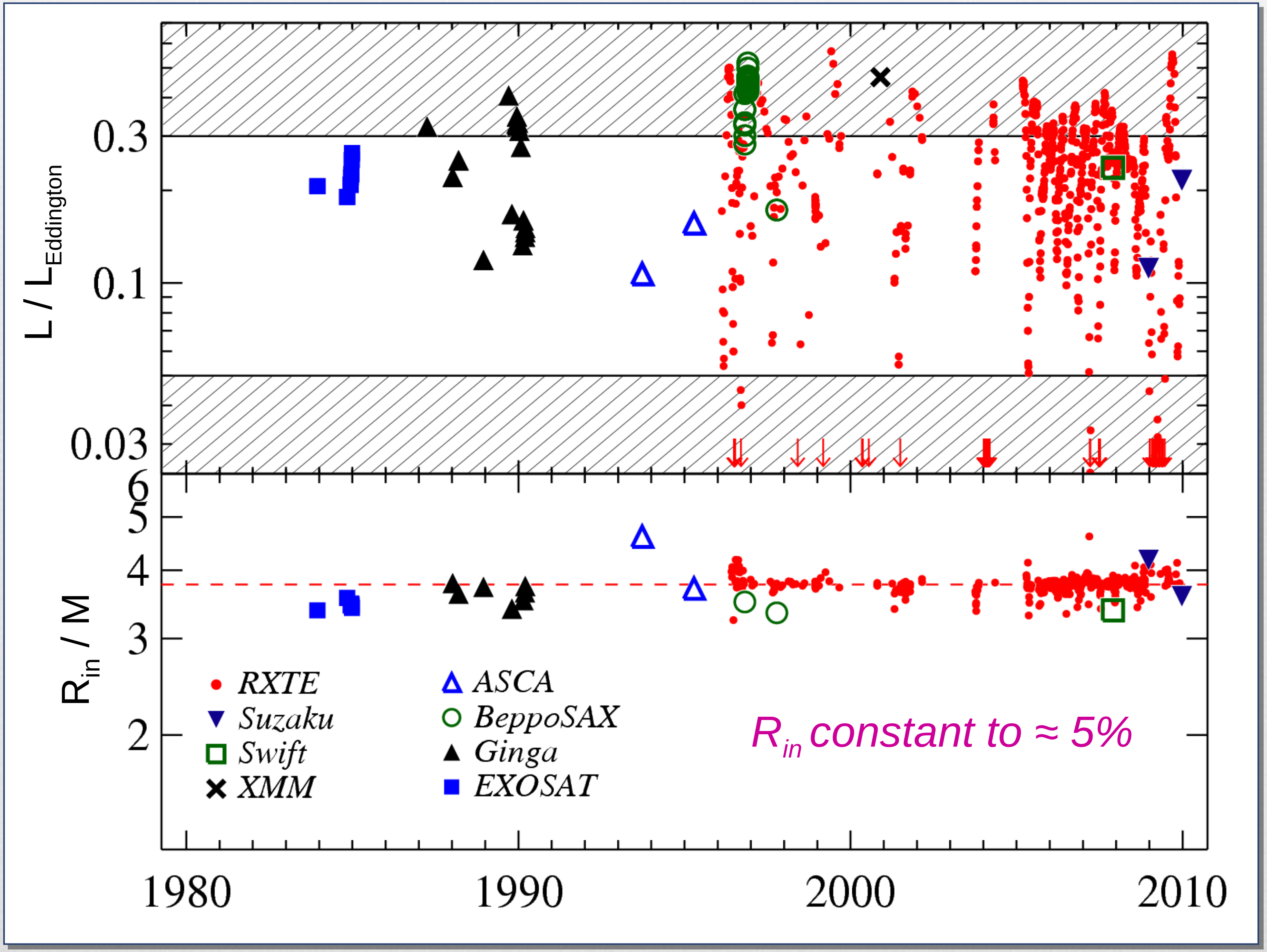
LMC X-3: 1983-2009

Steiner et al. 2010



LMC X-3: 1983-2009

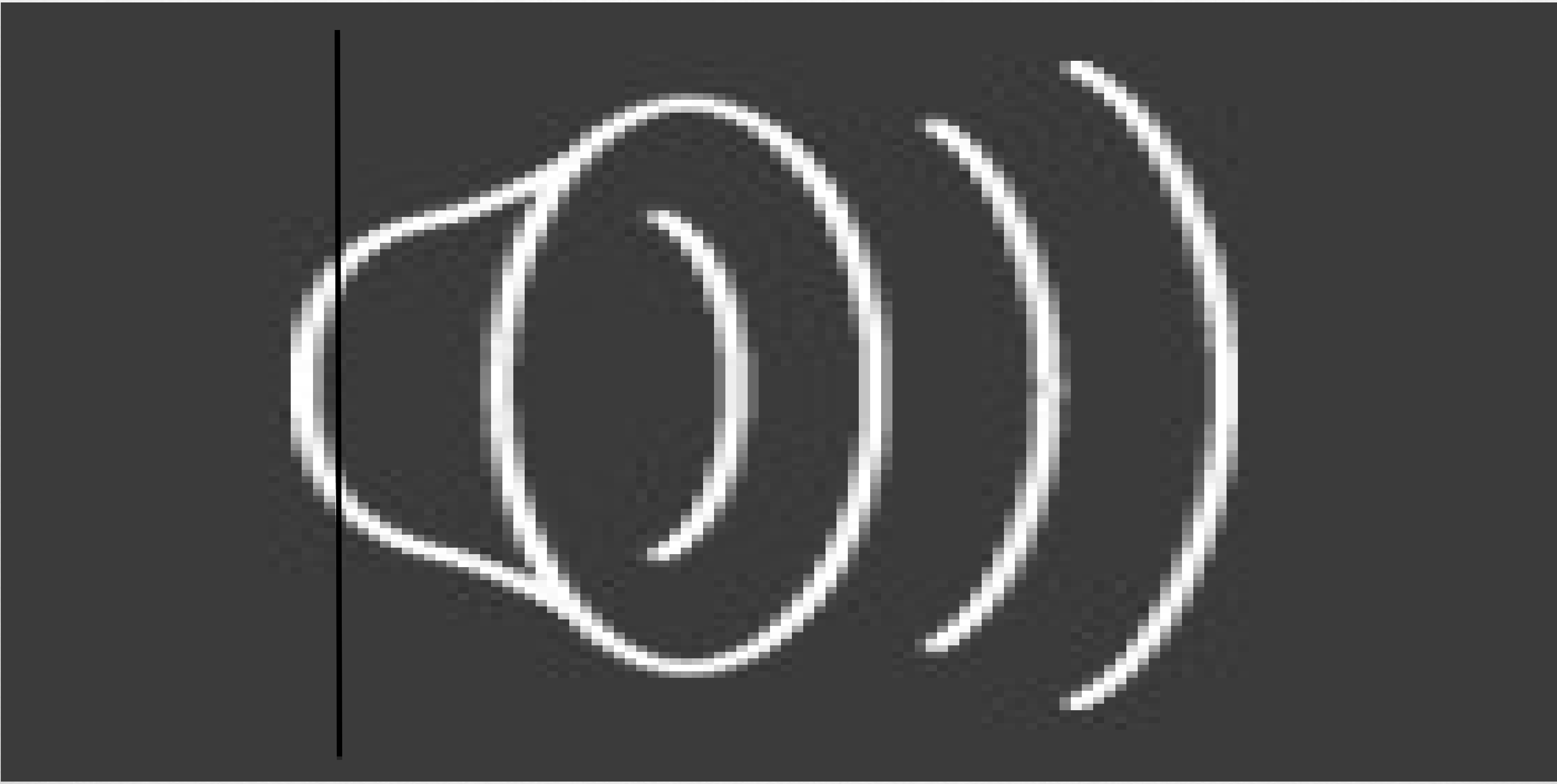
Steiner et al. 2010



Does R_{in} match R_{ISCO}?

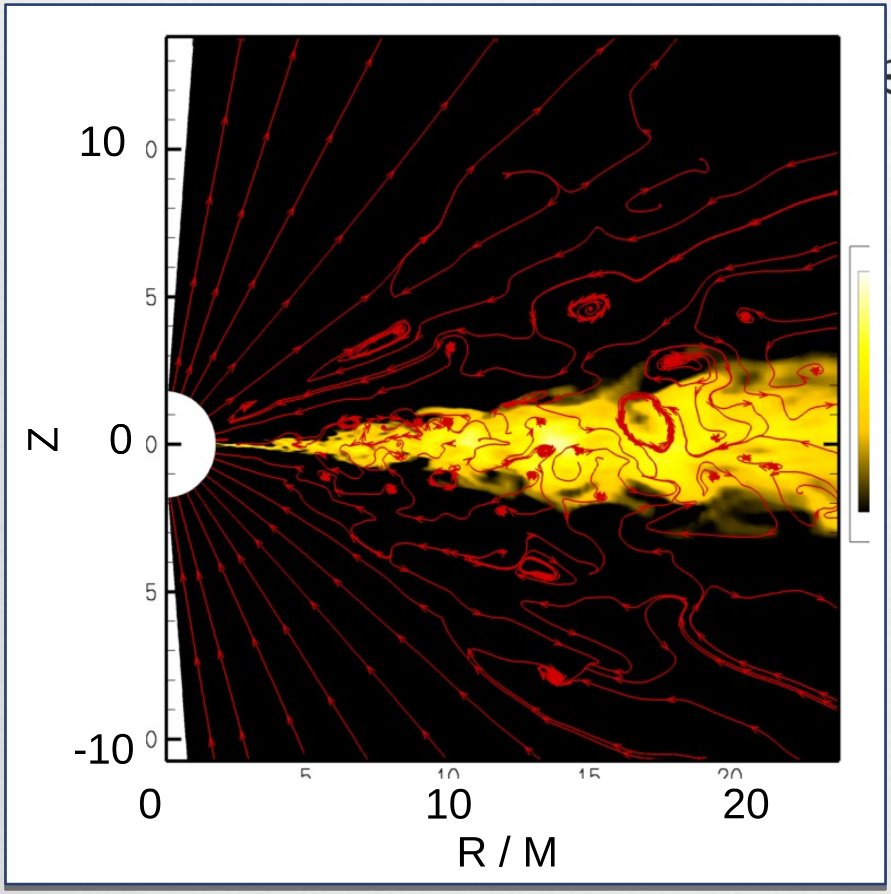
Lessons from GRMHD

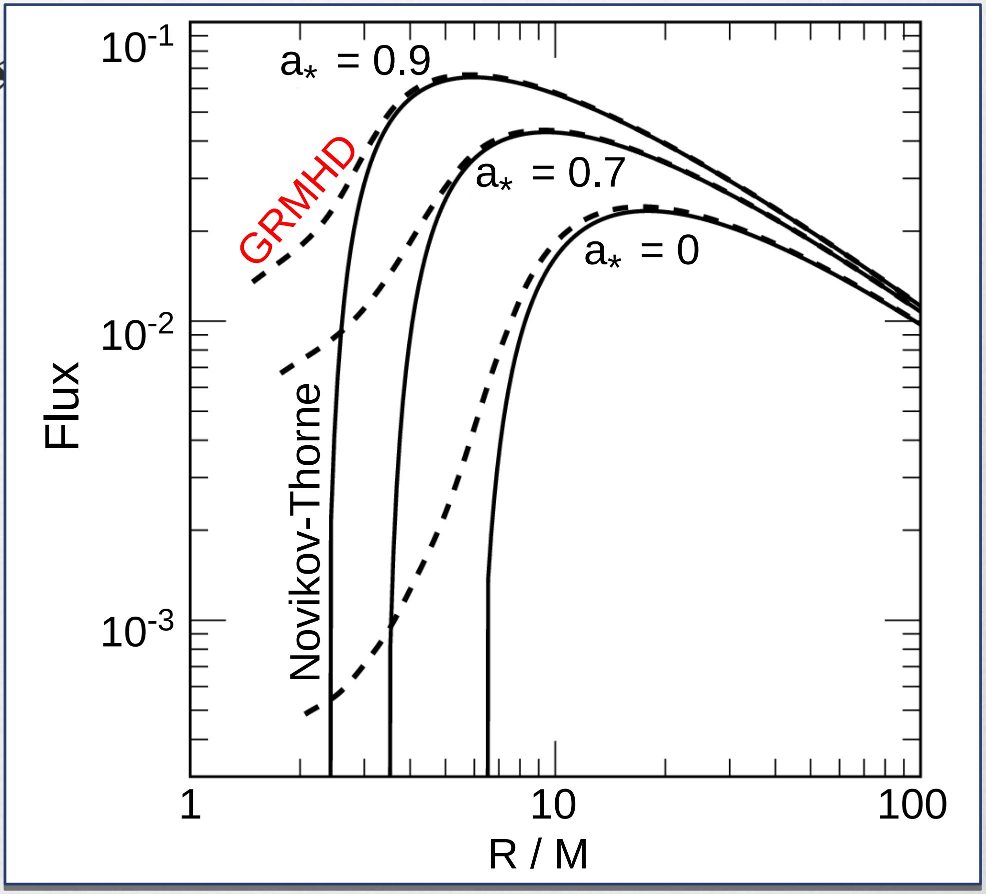
Accretion Onto a Non-Spinning BH: R_{ISCO} = 6M



Penna et al. 2010

3D GRMHD Simulation Results (for thin disks)





Shafee et al. 2008; Penna et al. 2010

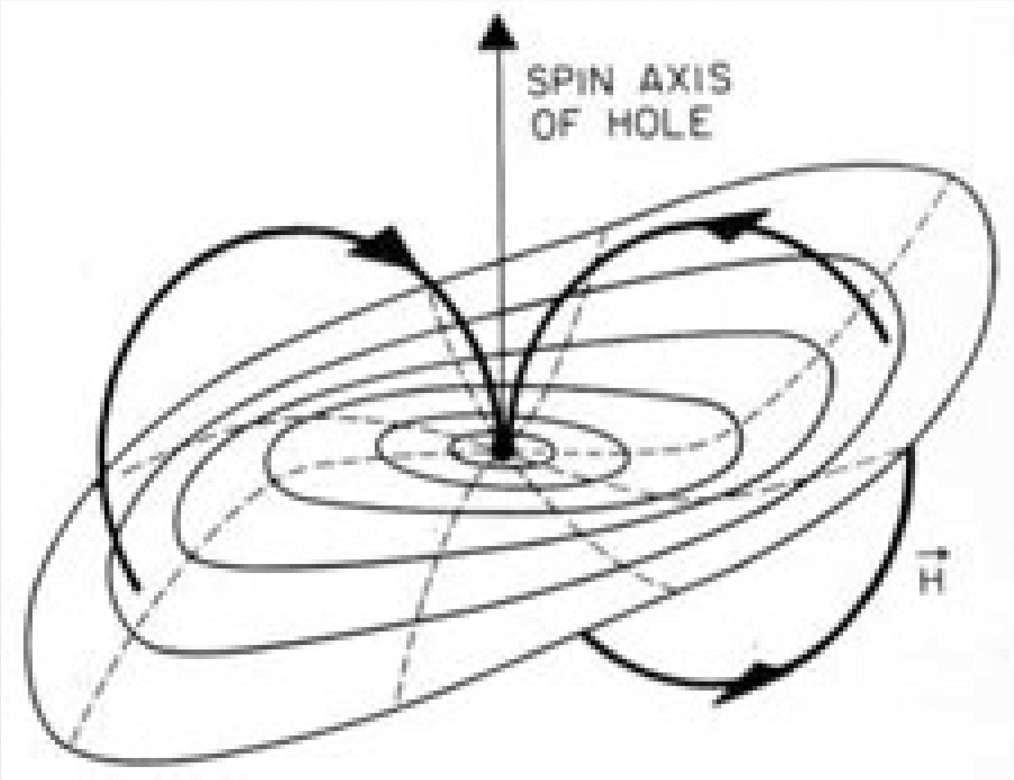
Kulkarni et al. 2011; Zhu et al. 2012

Reynolds & Fabian (2008); Noble, Krolik & Hawley (2009, 2010, 2011)

Binary Spin-Orbital Alignment

(oft-employed assumption)

BH spin and orbit align?



$$J_{orb}/J_{spin} \approx 65\, a_*^{-1} \left(\frac{M}{10\,M_\odot}\right)^{-4/3} \left(\frac{M_2}{M_\odot}\right) \left(\frac{P}{1\,\mathrm{d}}\right)^{1/3}$$

Alignment time scale < binary lifetime

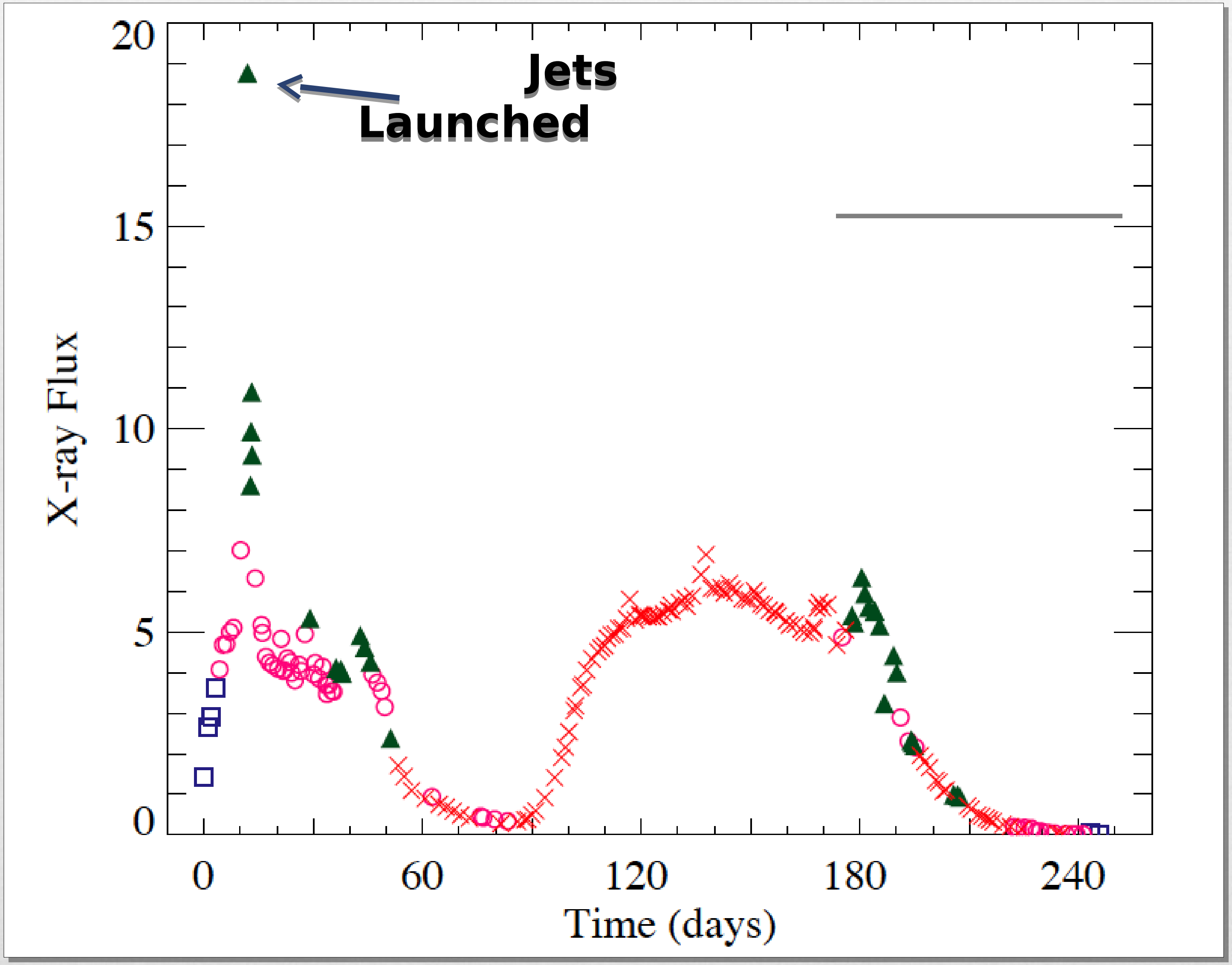
$$T_{alignment} / T_{binary} = 0.01 a^{11/16} (\alpha / 0.03)^{13/8} (L_{out} / L_{Edd})^{1/8}$$

$$\times (\varepsilon / 0.3)^{-1/8} (M_2 / M_{\odot})^{-1} \sim 0.01$$

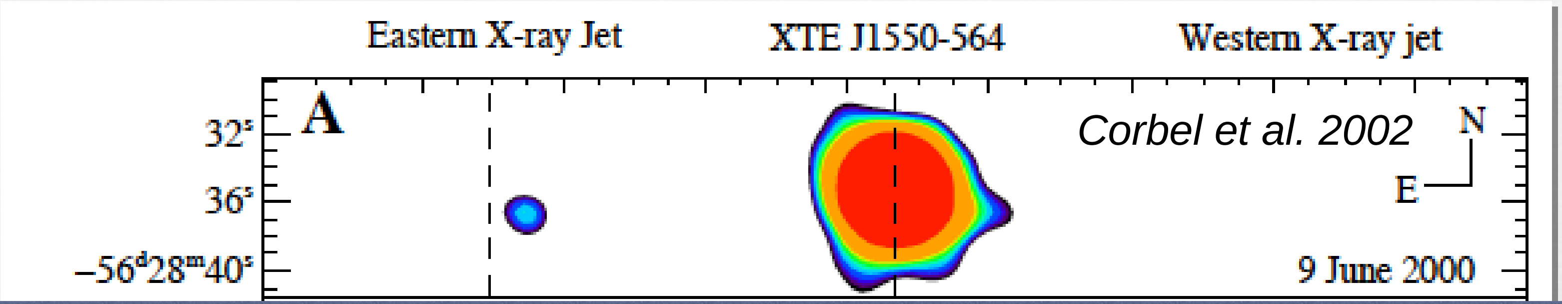
Natarajan & Pringle 1998
Maccarone 2002
Steiner & McClintock 2012

Fragos et al. (2010) very conservatively conclude that most black hole primaries will be tilted < 10 degrees.

XTE J1550-564: 1998 outburst

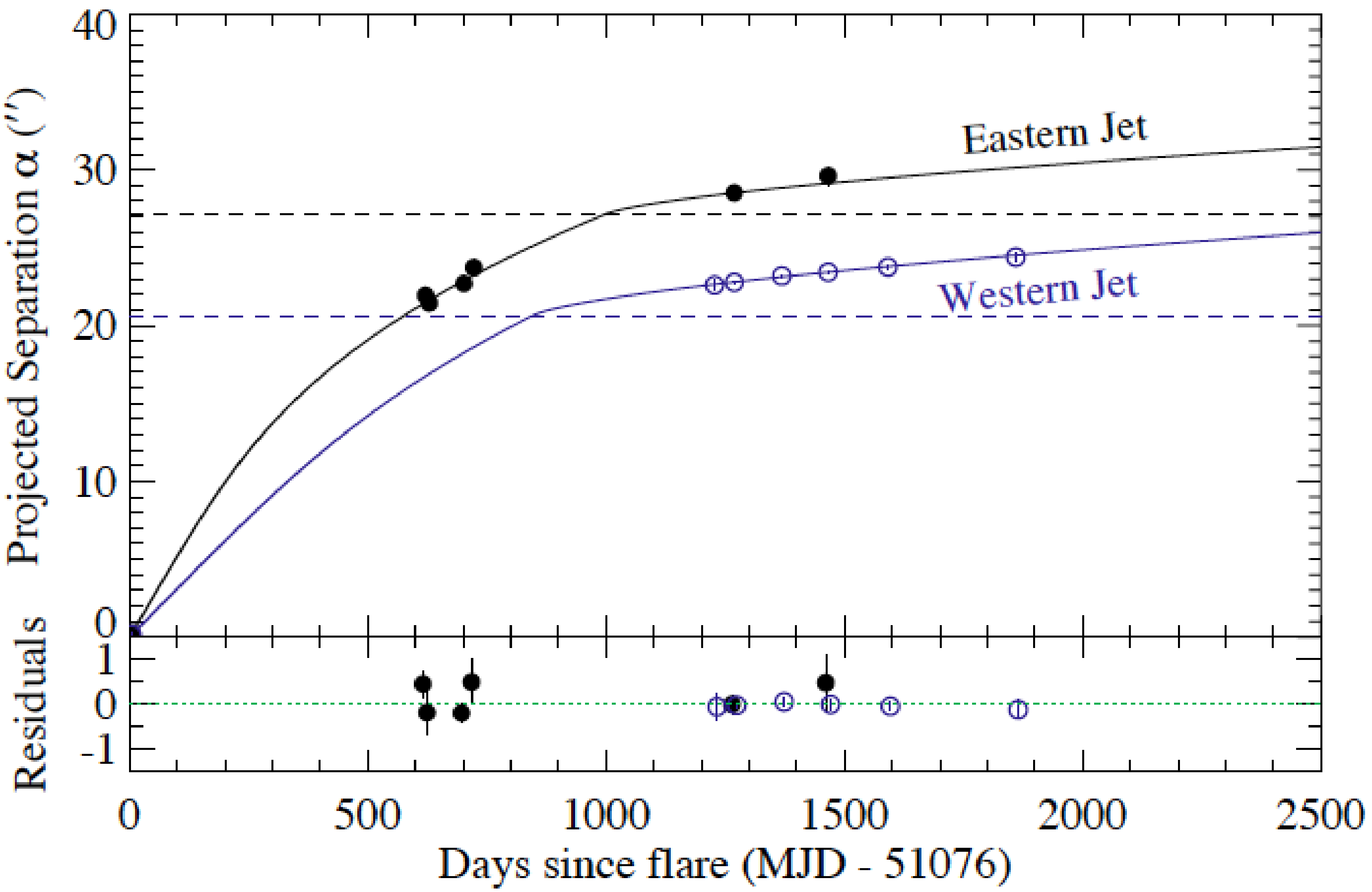


X-ray Jets



Eastern X-ray Jet
XTE J1550-564
Western X-ray jet
A
Corbel et al. 2002
N
E
32ˢ
36ˢ
−56ᵈ28ᵐ40ˢ
9 June 2000

J1550's Jet Trajectories

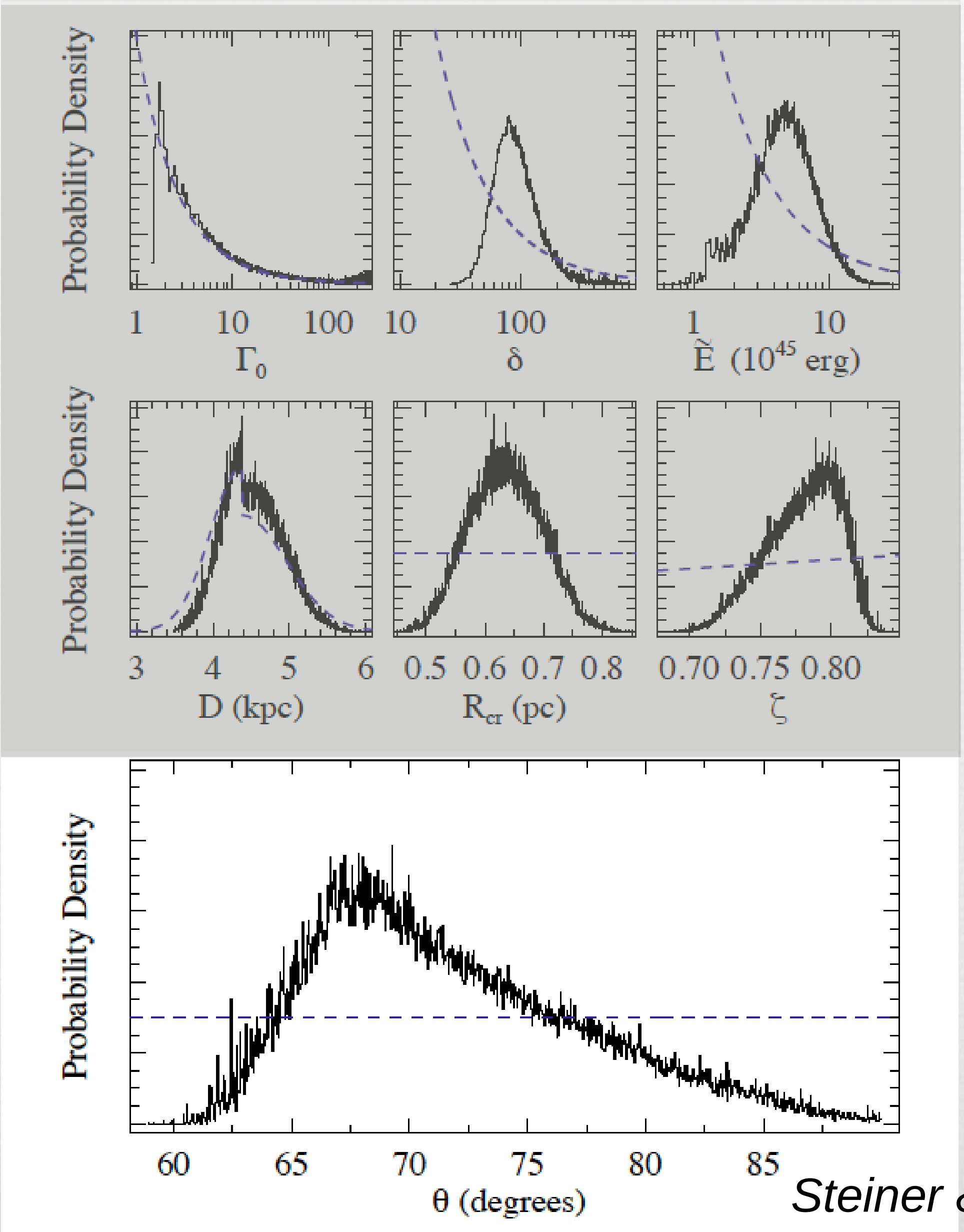


$$E_0 = (\Gamma - 1)M_0c^2 + \sigma(\Gamma_{\rm sh}^2 - 1)m_{\rm sw}c^2$$

$$m_{\rm sw} = \Theta^2 m_{\rm p} n \pi R^3/3$$

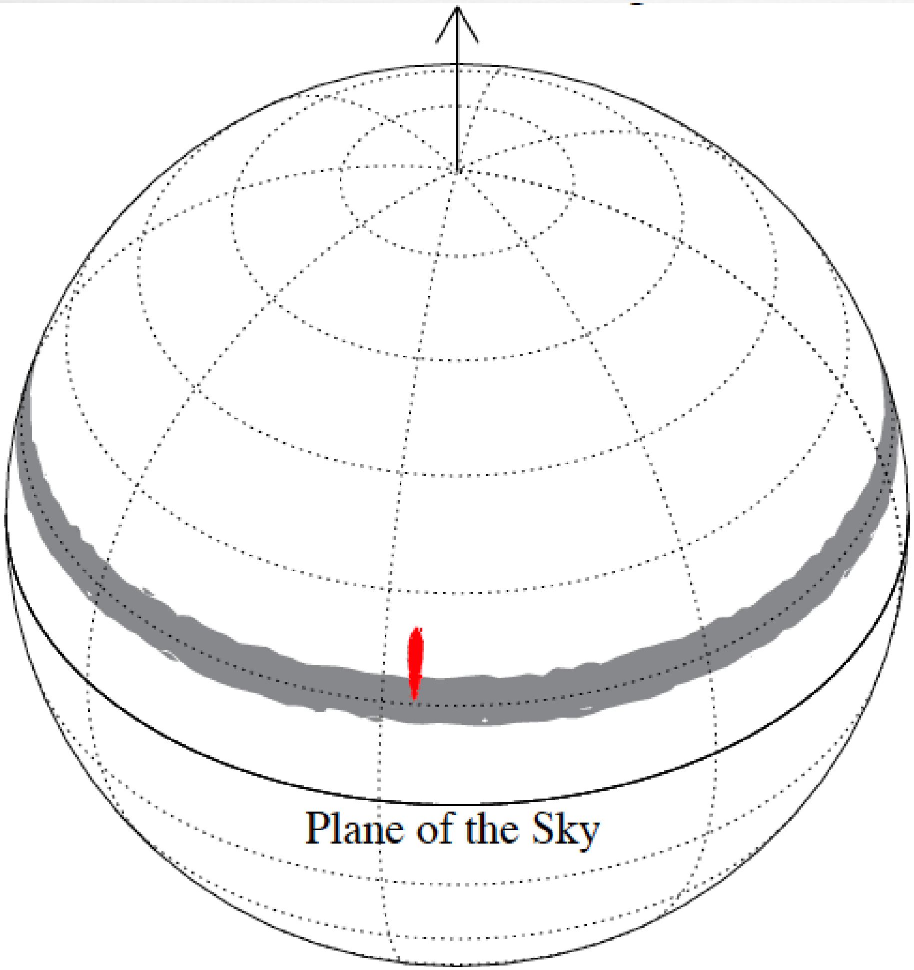
Steiner & McClintock (2012)

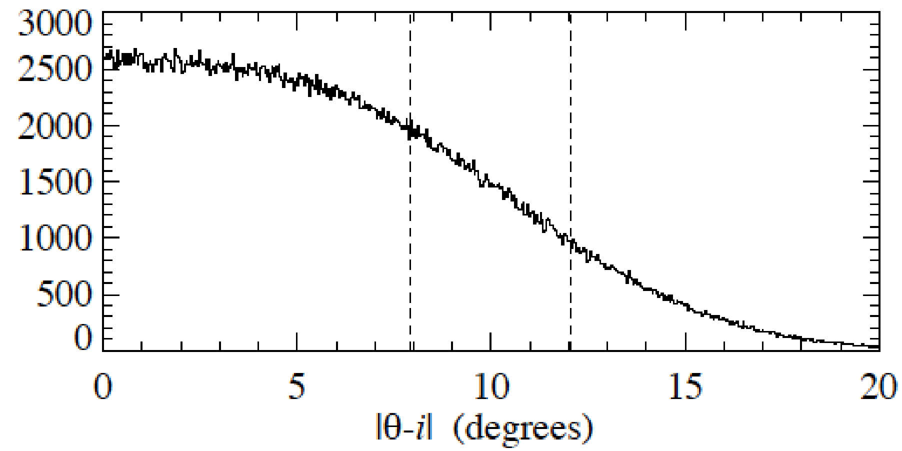
J1550's Results



Steiner & McClintock 2012)

Comparing J1550's Jet and Binary Axes Angles on the Sky





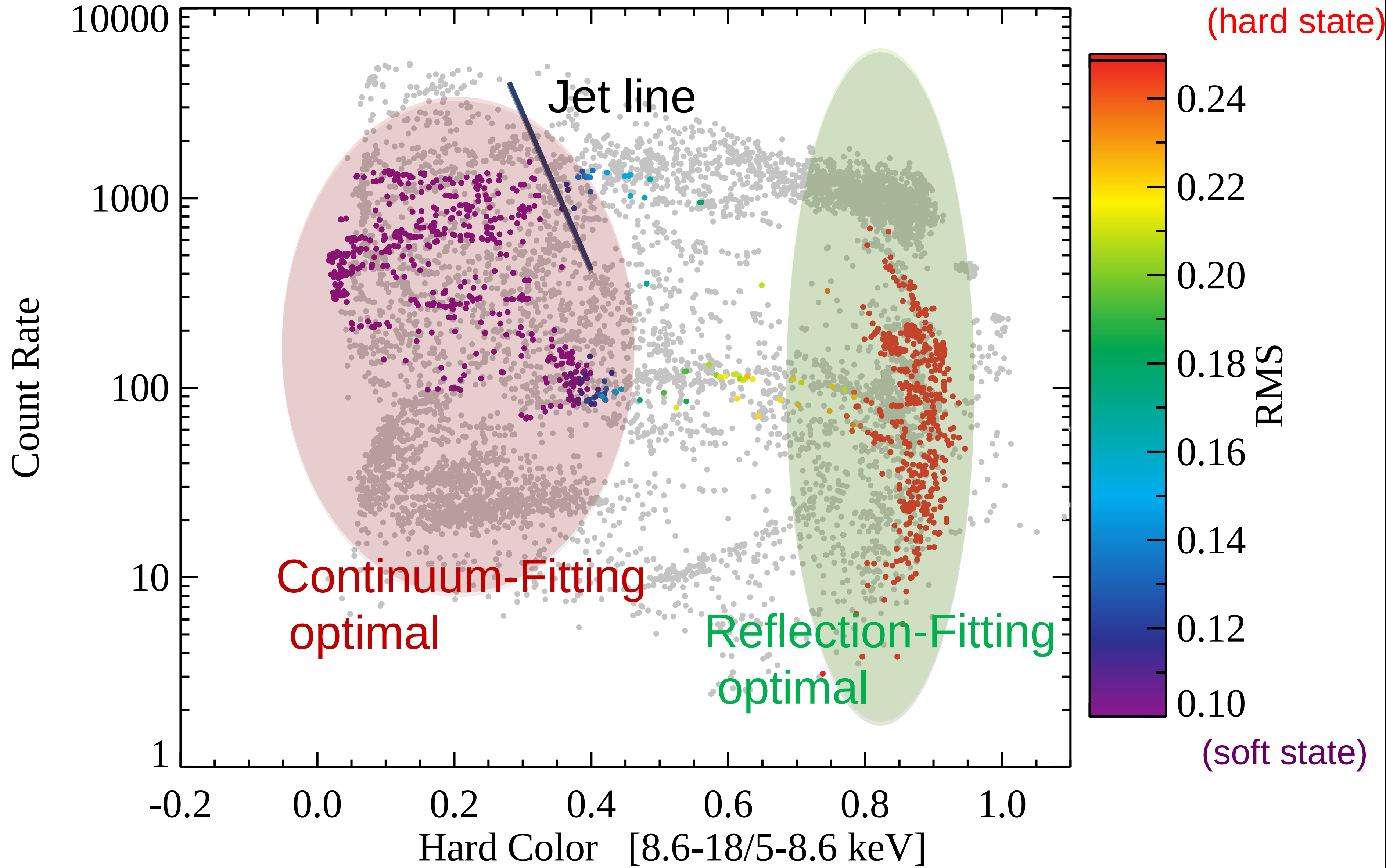
Steiner & McClintock (2012)

Jeff's BHs
A complete description of 10!

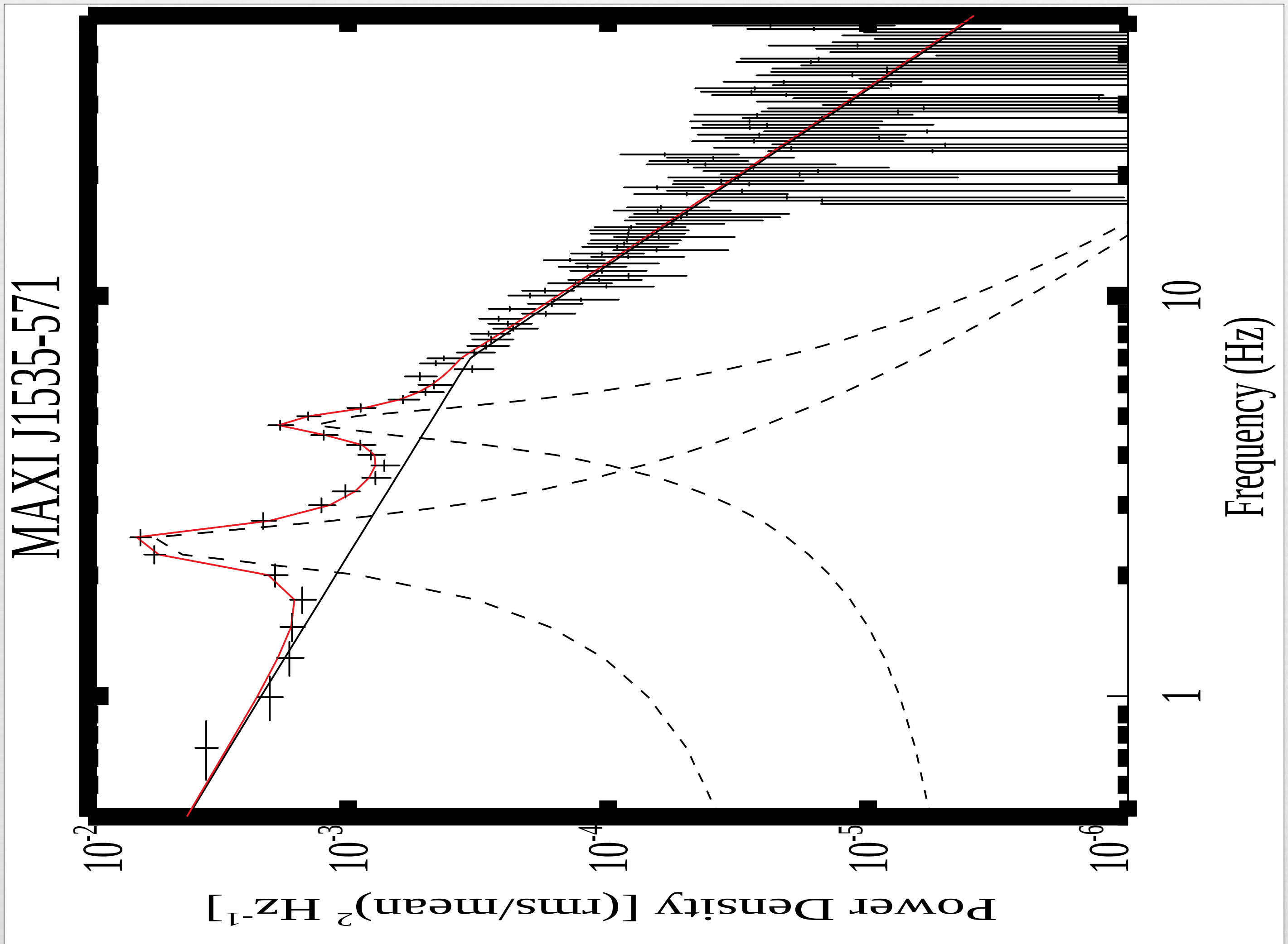
System	CF-Spin a_*	$M/M_\odot$	Reference
Wind-Fed			
Cygnus X-1	> 0.98	15.8 ± 1.0	Gou+ 2013; Orosz+ 2011
LMC X-1	0.92 ± 0.06	10.9 ± 1.4	Gou+ 2009; Orosz+ 2009
M33 X-7	0.84 ± 0.05	15.7 ± 1.5	Liu+ 2008; Orosz+ 2007
Transient			
GRS 1915+105	> 0.98	12.4 ± 1.9	McClintock+ 2006; Reid+ 2014
GRO J1655-40	0.7 ± 0.1	6.3 ± 0.5	Shafee+ 2006; Greene+ 2001
Nova Mus 1991	0.63 ± 0.18	11.0 ± 1.8	Chen+ 2016; Wu+ 2016
4U 1543-47	0.45 ± 0.25	7.5 ± 1.1	Steiner+ 2018; Orosz+ 2018
XTE J1550-564	0.34 ± 0.25	9.1 ± 0.6	Steiner+ 2011; Orosz+ 2011
LMC X-3	0.25± 0.15	7.0 ± 0.3	Steiner+ 2014; Orosz+ 2014

Prospects for Spin Measurement

Spin Measurements and State (GX 339-4)



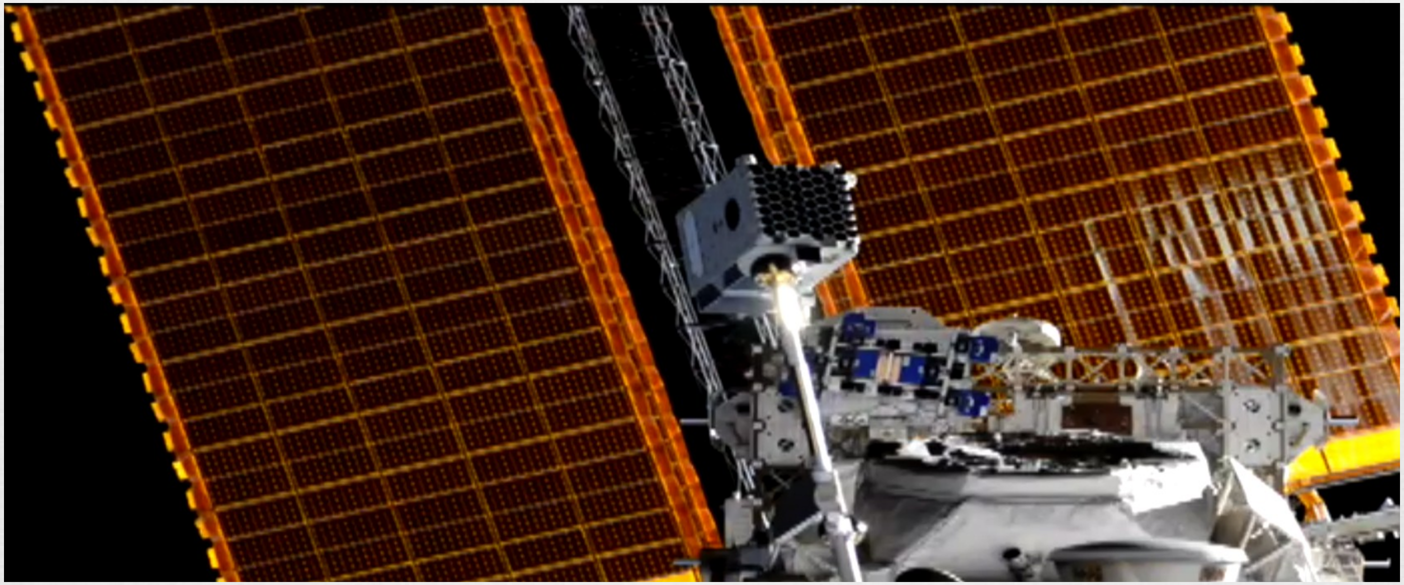
A preview - 2:1 Low-Frequency QPOs with NICER



1ks PDS
>1 Mcount

Neutron Star **I**nterior **C**omposition **E**xplore**R**

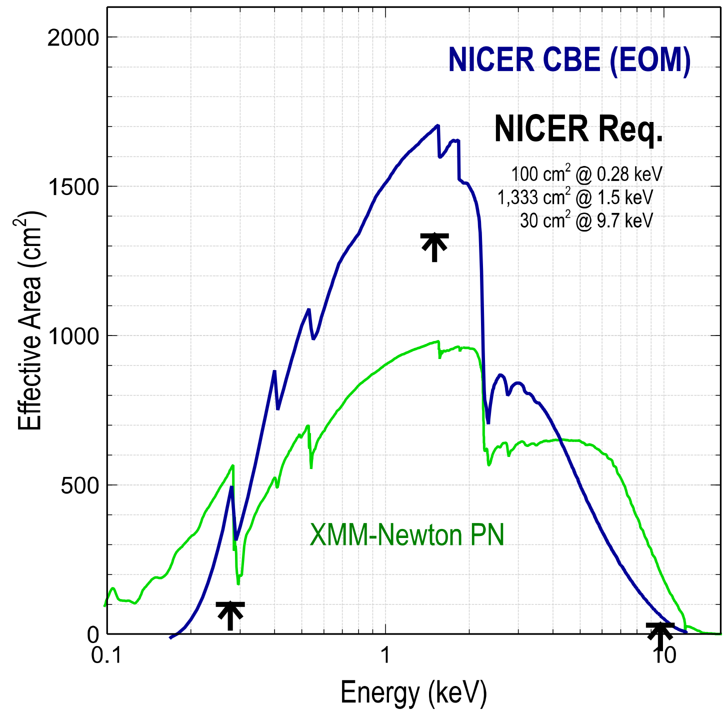
ISS external camera:



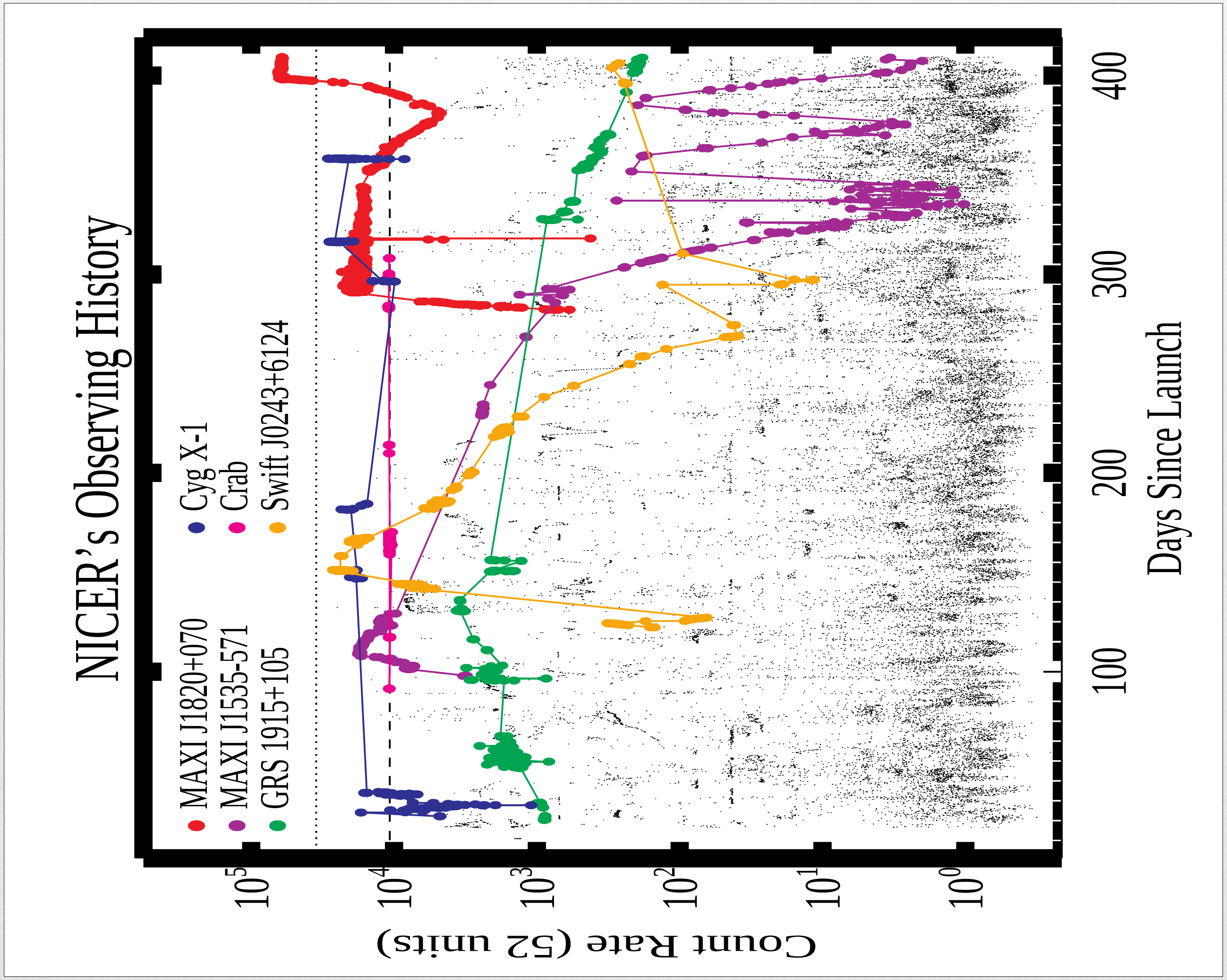
NICER’s home since June 2017

NICER specs

- Most sensitive to X-ray QPOs (2x XMM)
- Most sensitive to soft X-ray lines (better than gratings < 1 keV)
- 25x better timing than RXTE
- CCD-like energy resolution
- High sensitivity to faint sources (low bg) while handling brightest sources
- *No Pileup (!)*



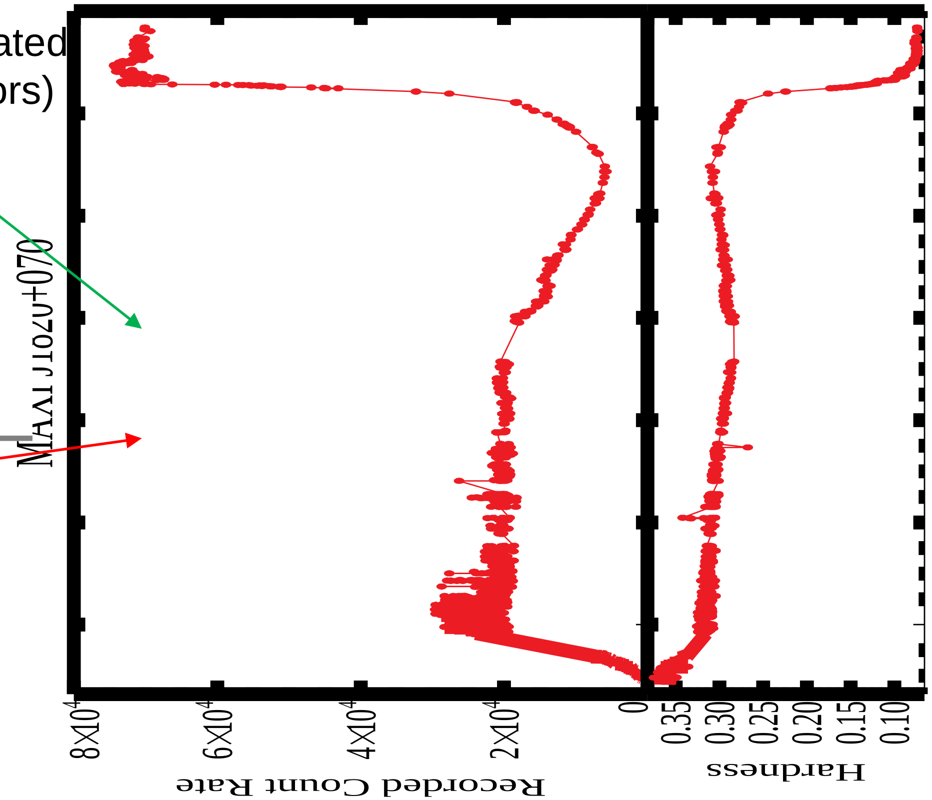
The NICER Sky

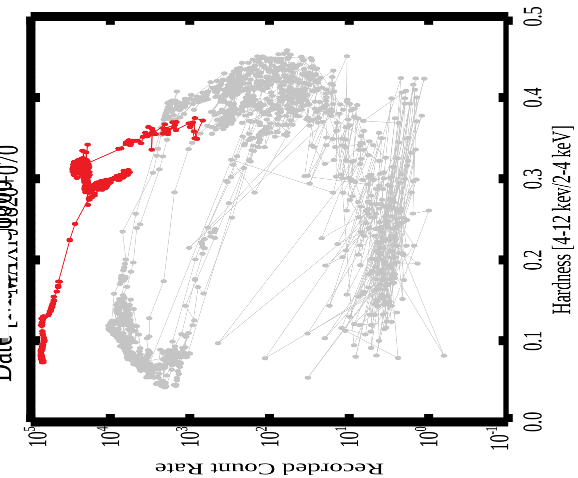


MAXI J1820+070

Telemetry saturated
(Turn off detectors)

1 Crab





The perfect BH transient
Very Bright
Low NH
Hard and soft states
(3.3 kpc distant from Gaia)

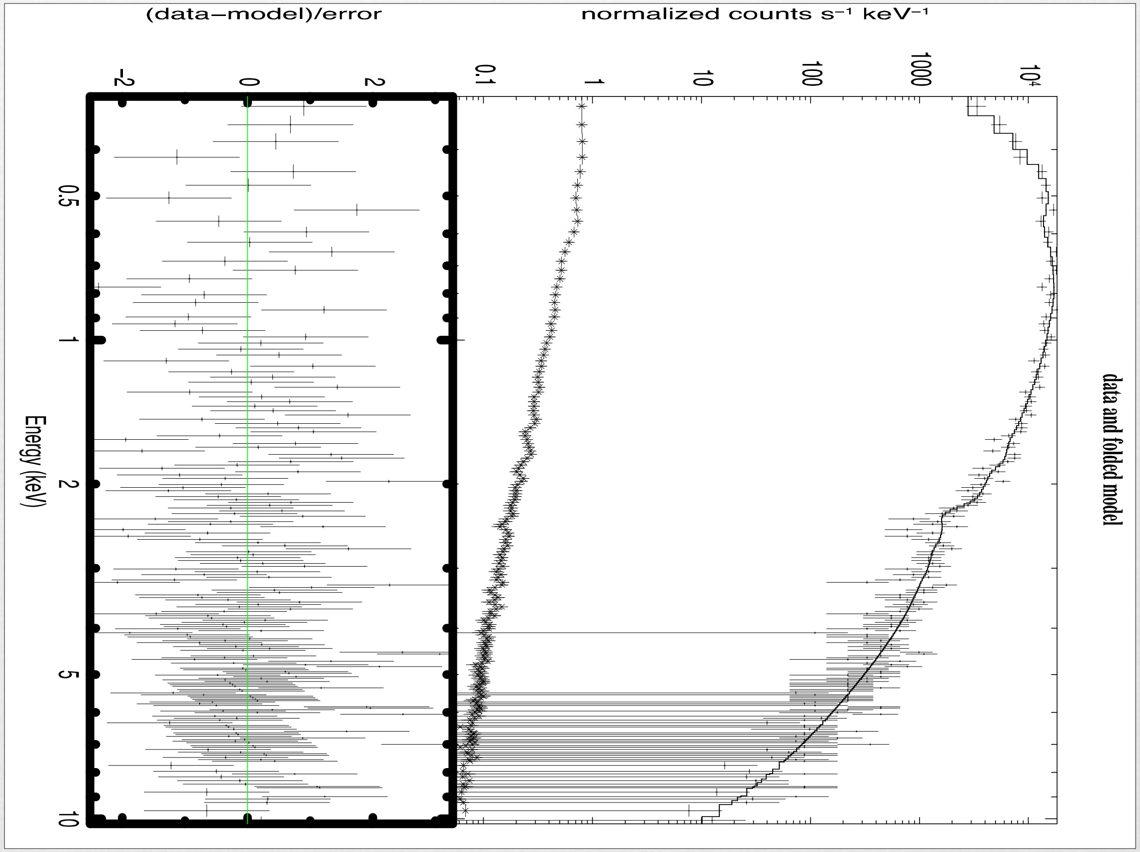
Fast Spectroscopy

- Break the MAXI 1820 data into segments of 5,000 counts **(~0.2s)** at peak**.**
- **The viscous timescale for the inner disk of a stellar BH is ~1s.**
- Adopt simplistic spectral fitting: thermal component (ezdiskbb), nonthermal component (simpl), and absorption (tbabs)
- **> 1.5 million spectral fits required**

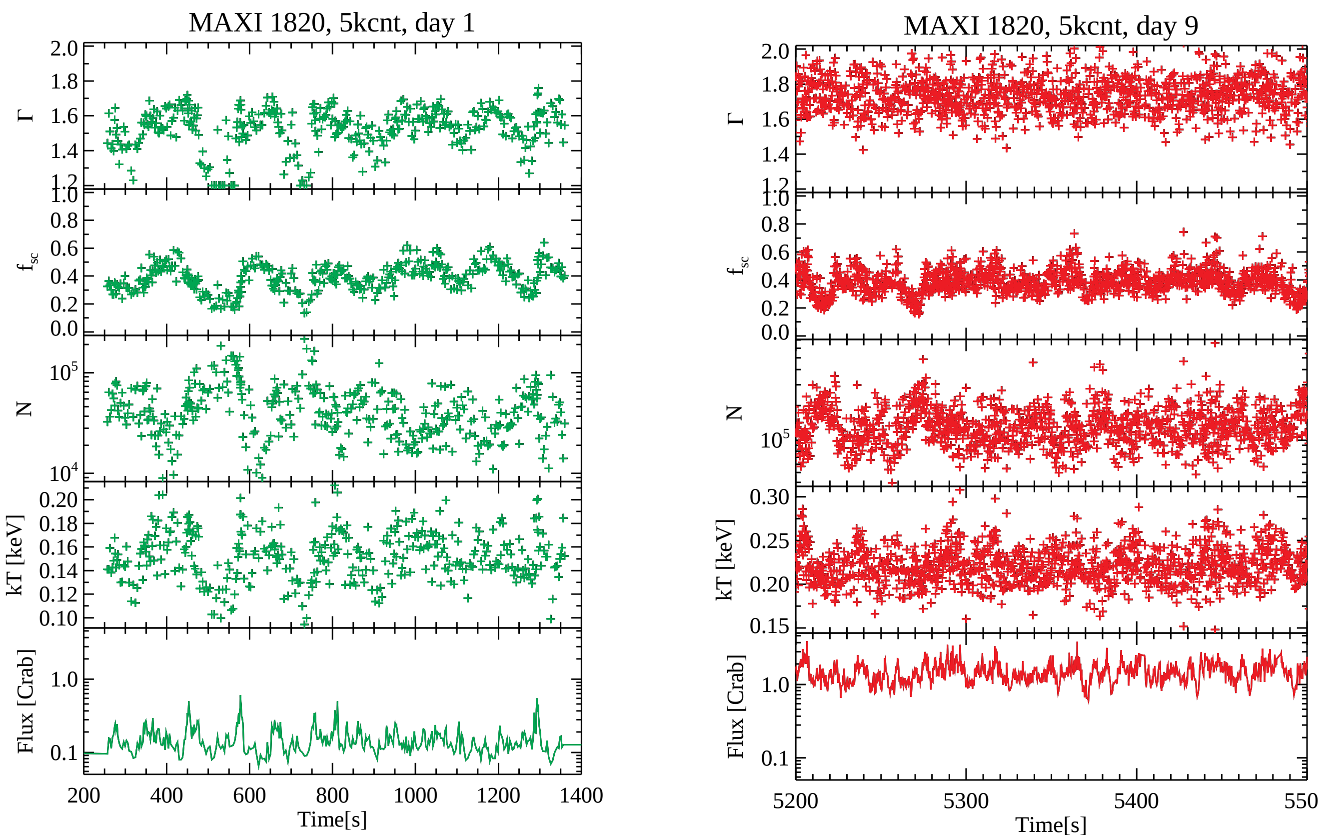
One example

4 free parameters; 200 bins

Disk: kT, N
Nontherm: Gamma, fsc



Fast spectral modeling



A legacy - spin measurements applied

- First gravitational waveform computations with spin: (Campanelli+2006, Ajith 2011), and later GW limits: (Abbot+2016)
- How BHs are formed: (e.g., Woosley+2006, Fragos+2015)
- Tests of the no-hair theorem and GR: (e.g., Barausse+2011, Bambi+2012, 2015, Johannsen 2013,2016)
- Searching for string axions: (e.g., Arvanitaki+2015)
- Investigating how jets are powered: (e.g., Narayan & McClintock 2012, Fender+2010)

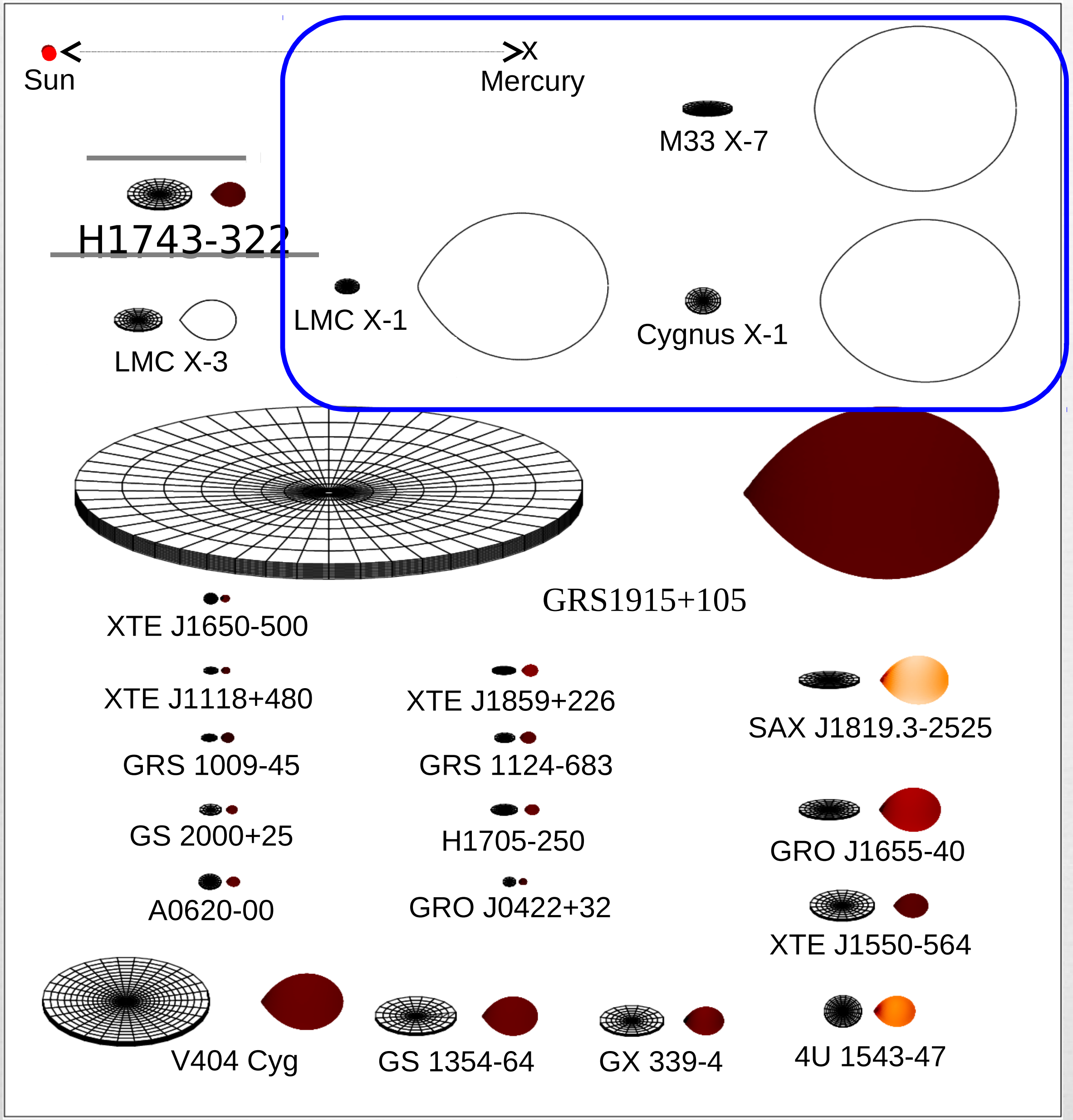
Jeff's BHs
A complete description of 10!

System	CF-Spin a_*	$M/M_\odot$	Reference
Wind-Fed			
Cygnus X-1	> 0.98	15.8 ± 1.0	Gou+ 2013; Orosz+ 2011
LMC X-1	0.92 ± 0.06	10.9 ± 1.4	Gou+ 2009; Orosz+ 2009
M33 X-7	0.84 ± 0.05	15.7 ± 1.5	Liu+ 2008; Orosz+ 2007
Transient			
GRS 1915+105	> 0.98	12.4 ± 1.9	McClintock+ 2006; Reid+ 2014
GRO J1655-40	0.7 ± 0.1	6.3 ± 0.5	Shafee+ 2006; Greene+ 2001
Nova Mus 1991	0.63 ± 0.18	11.0 ± 1.8	Chen+ 2016; Wu+ 2016
4U 1543-47	0.45 ± 0.25	7.5 ± 1.1	Steiner+ 2018; Orosz+ 2018
XTE J1550-564	0.34 ± 0.25	9.1 ± 0.6	Steiner+ 2011; Orosz+ 2011
LMC X-3	0.25± 0.15	7.0 ± 0.3	Steiner+ 2014; Orosz+ 2014



fin

Are “Massive” BHs a Distinct Class?



Courtesy: J. Orosz

Wind fed systems:

- young (<Myr)
- highest mass BHs (>10)
- high spin (a* > 0.8)

Is this significant?

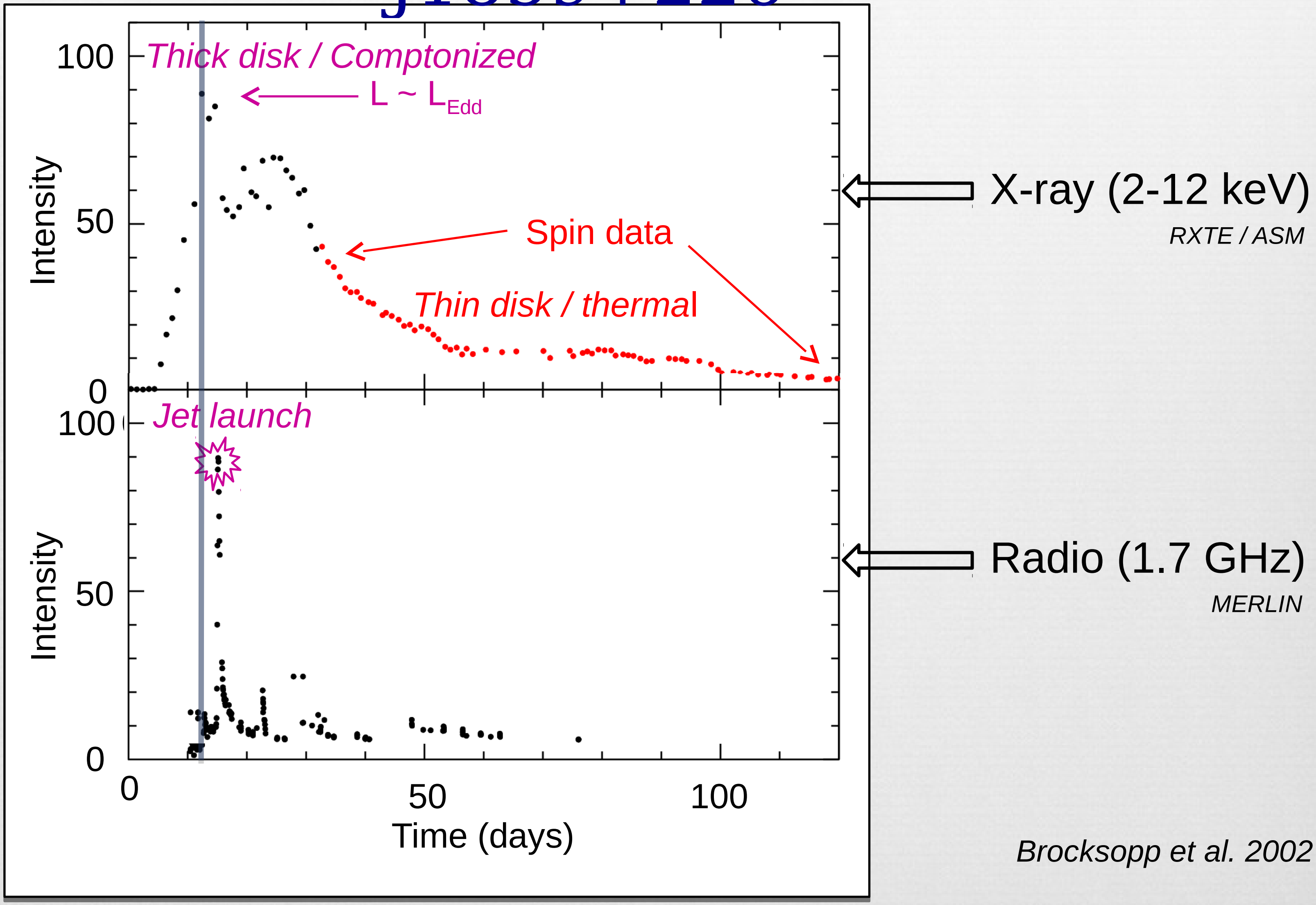
Black Hole	Spin a_* (CF)	Spin a_* (Fe K)	Principal References
Cyg X-1	> 0.98	> 0.9	Gou ea. 14; Tomsick ea. 14, Fabian ea. 12
GRS 1915+105	> 0.98	0.98 ± 0.01	McClintock ea. 2006; Miller ea. 2014
4U 1630-47		> 0.95	King ea. 2014
LMC X-1	0.92 ± 0.06	$0.97^{+0.02}_{-0.25}$	Gou ea. 2009; Steiner ea. 2012
GX 339-4	< 0.9	0.93 ± 0.05	Reis ea. 2008; Kolehmainen & Done 2010
MAXI J1836-194		0.88 ± 0.05	Reis ea. 2012
M33 X-7	0.84 ± 0.05		Liu ea. 2008, 2010
4U 1543-47	0.8 ± 0.1*		Shafee ea. 2006 (also Morningstar ea. 14)
Swift J1753.5		0.76 ± 0.15	Reis ea. 2009
IC 10 X-1	>0.7		Steiner et al. 2016
XTE J1650-500		> 0.7	Walton ea. 2012
GRO J1655-40	0.7 ± 0.1*	> 0.9	Shafee ea. 2006; Reis ea. 2009
Nova Mus	~0.6 ± 0.2		Chen ea. 2015
XTE J1752-223		0.52 ± 0.11	Reis ea. 2010
XTE J1652-453		< 0.5	Heimstra ea. 2010, Chiang ea. 2012
XTE J1550-564	0.34 ± 0.28	0.55 ± 0.1	Steiner, Reis ea. 2011
LMC X-3	0.25± 0.15		Steiner ea. 2014
H1743-322	0.2 ± 0.3		Steiner & McClintock 2012
A0620-00	0.12 ± 0.19		Gou ea. 2010
M31 uQ	< -0.2		Middleton ea. 2014

Spin and

(Ballistic) Jets

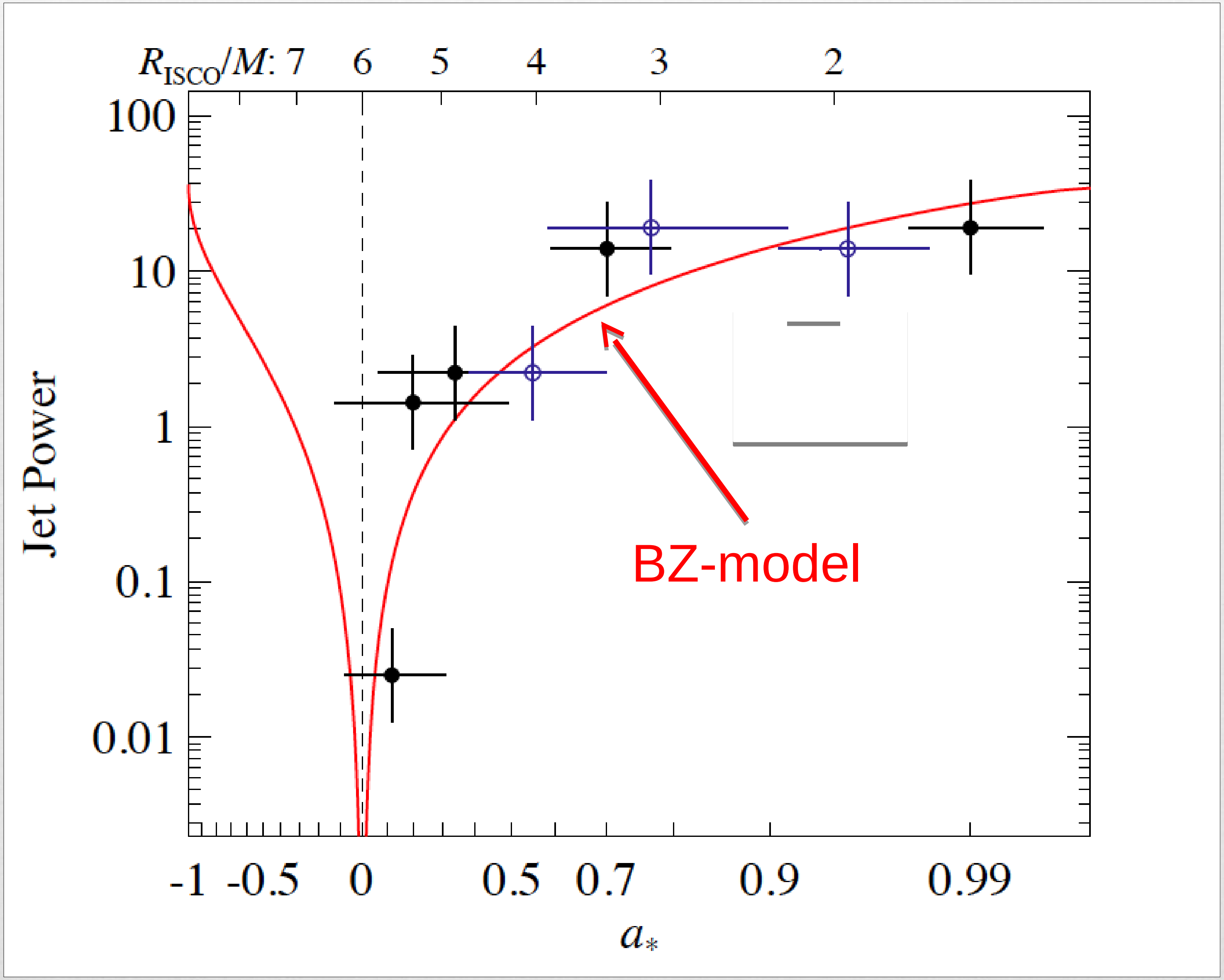
Black Hole	Spin a_* (CF)	Spin a_* (Fe K)	Principal References
Cyg X-1	> 0.98	> 0.9	Gou ea. 14; Tomsick ea. 14, Fabian ea. 12
GRS 1915+105	> 0.98	0.98 ± 0.01	McClintock ea. 2006; Miller ea. 2014
4U 1630-47		> 0.95	King ea. 2014
LMC X-1	0.92 ± 0.06	$0.97^{+0.02}_{-0.25}$	Gou ea. 2009; Steiner ea. 2012
GX 339-4	< 0.9	0.93 ± 0.05	Reis ea. 2008; Kolehmainen & Done 2010
MAXI J1836-194		0.88 ± 0.05	Reis ea. 2012
M33 X-7	0.84 ± 0.05		Liu ea. 2008, 2010
4U 1543-47	0.8 ± 0.1*		Shafee ea. 2006 (also Morningstar ea. 14)
Swift J1753.5		0.76 ± 0.15	Reis ea. 2009
IC 10 X-1	>0.7		Steiner et al. 2016
XTE J1650-500		> 0.7	Walton ea. 2012
GRO J1655-40	0.7 ± 0.1*	> 0.9	Shafee ea. 2006; Reis ea. 2009
Nova Mus	~0.6 ± 0.2		Chen ea. 2015
XTE J1752-223		0.52 ± 0.11	Reis ea. 2010
XTE J1652-453		< 0.5	Heimstra ea. 2010, Chiang ea. 2012
XTE J1550-564	0.34 ± 0.28	0.55 ± 0.1	Steiner, Reis ea. 2011
LMC X-3	0.25± 0.15		Steiner ea. 2014
H1743-322	0.2 ± 0.3		Steiner & McClintock 2012
A0620-00	0.12 ± 0.19		Gou ea. 2010
M31 uQ	< -0.2		Middleton ea. 2014

X-ray/radio outburst of XTE J1859+226



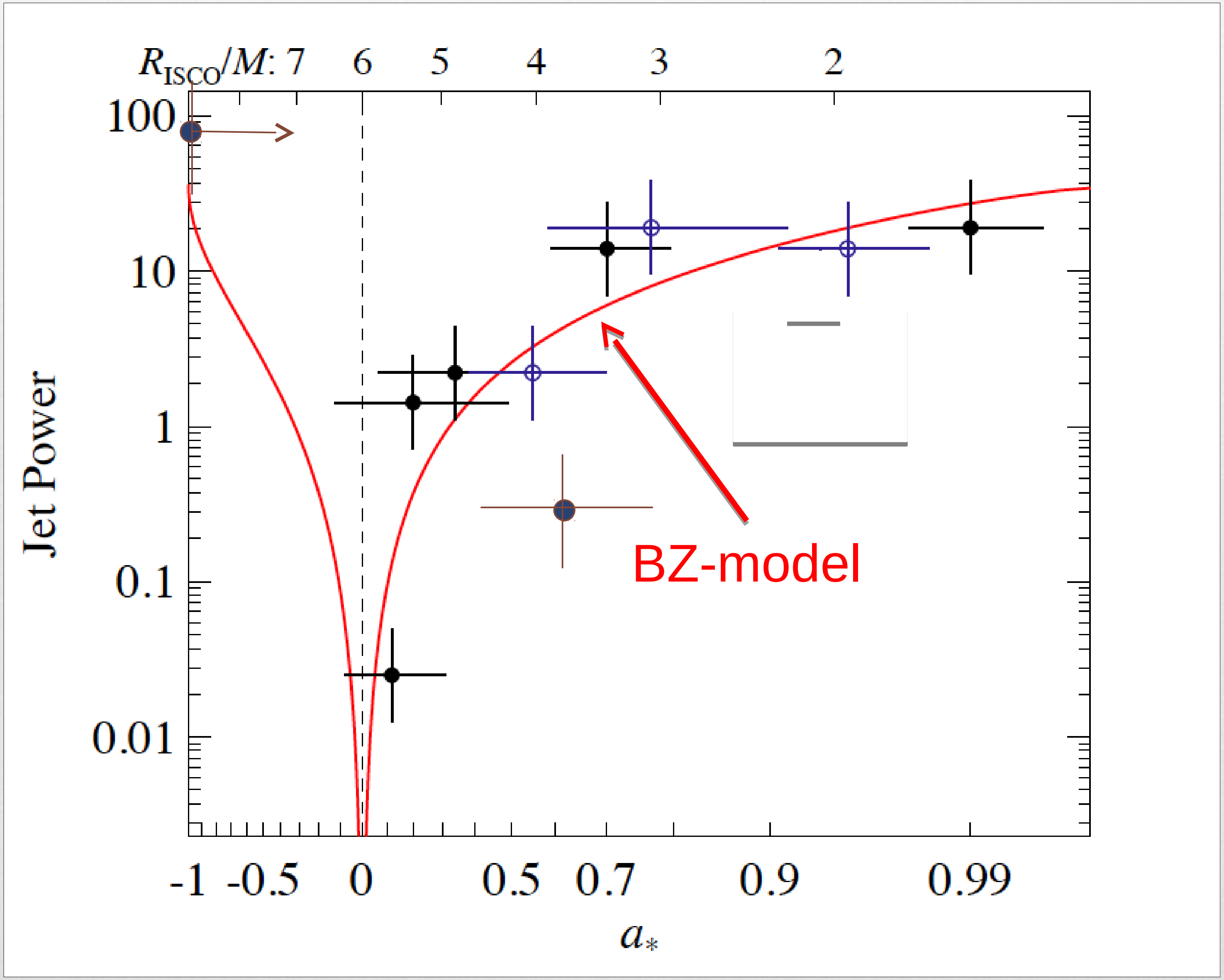
Brocksopp et al. 2002

A link between spin and jets



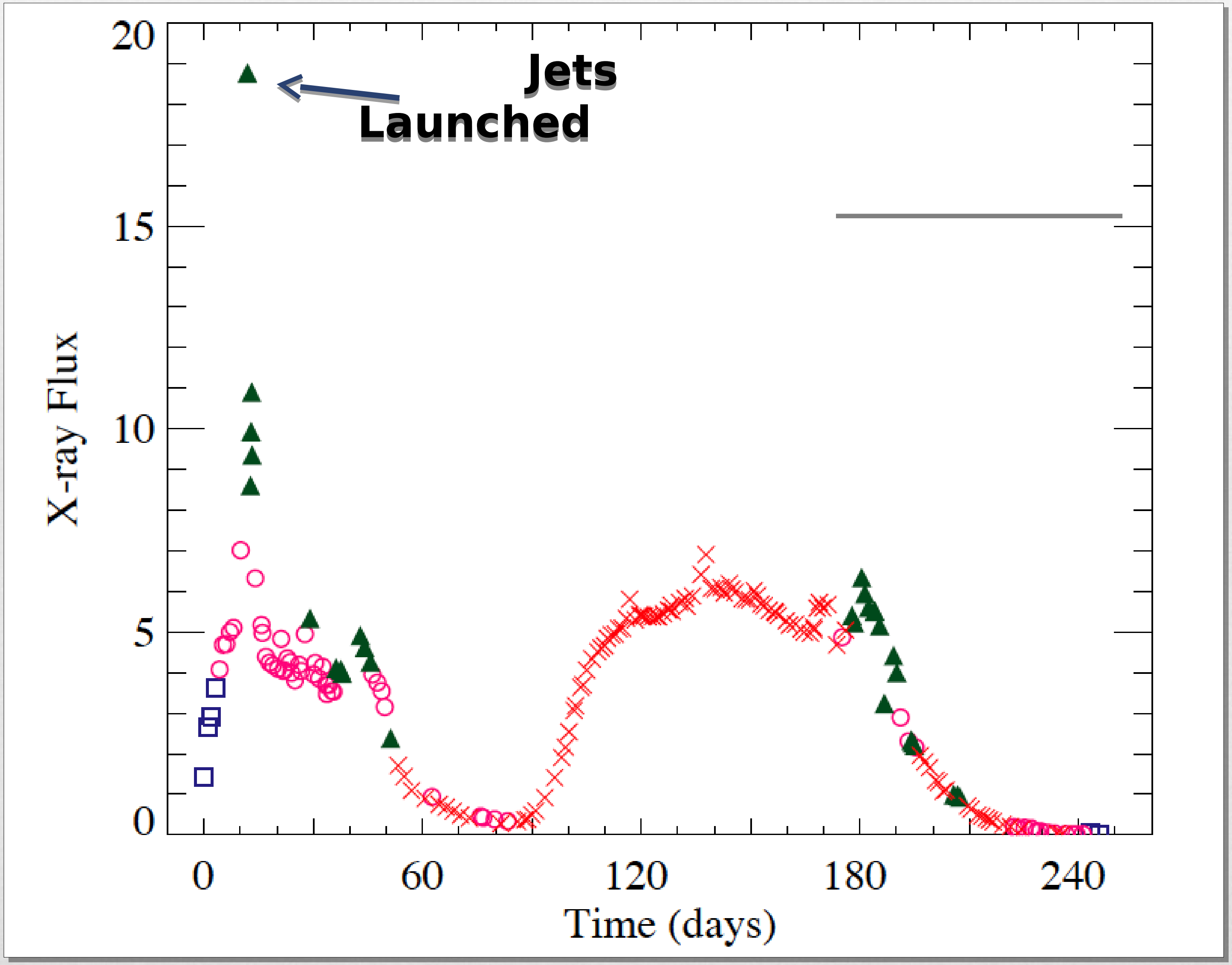
Steiner, McClintock, & Narayan 2013, Narayan & McClintock 2012

A link between spin and jets

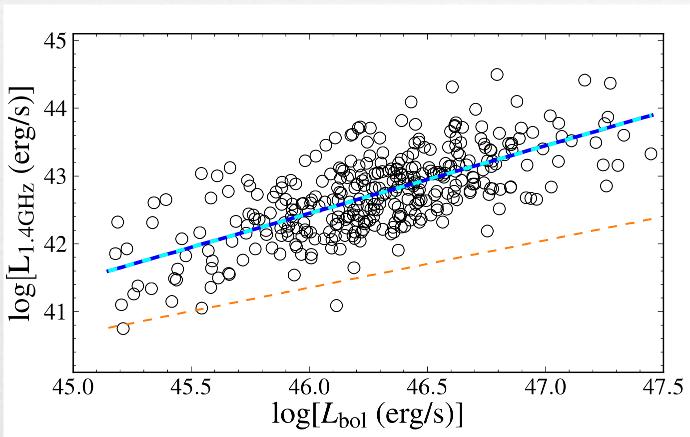


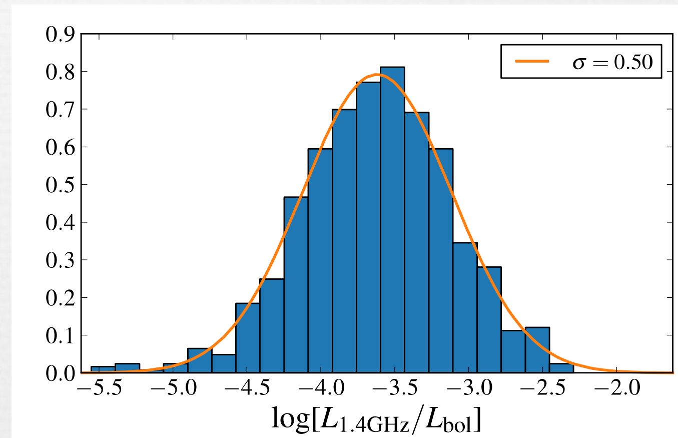
Steiner, McClintock, & Narayan 2013, Narayan & McClintock 2012

XTE J1550-564: 1998 outburst



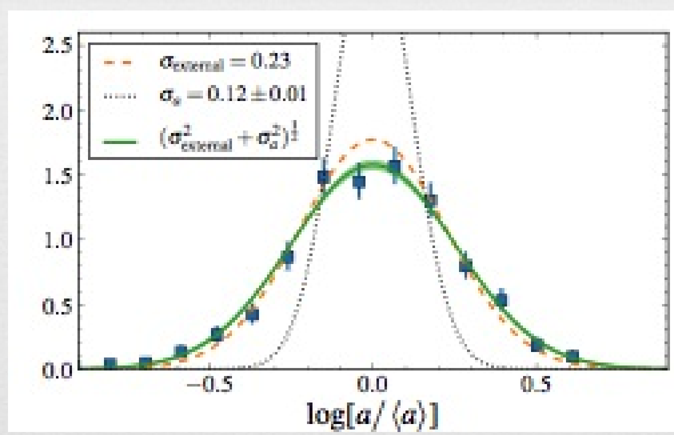
Supermassive BH analog



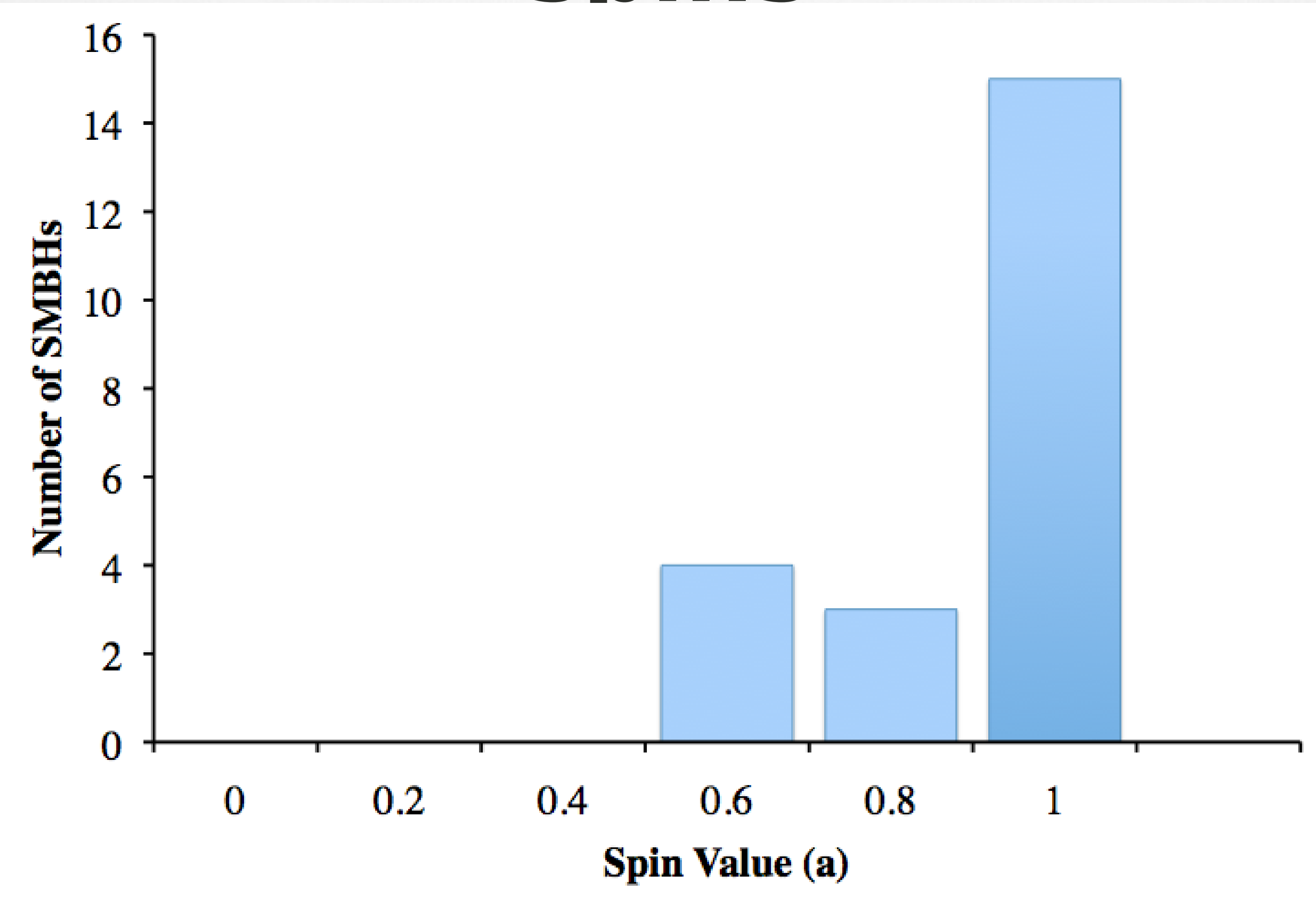


van Velzen & Falcke 2013

A sampling of FR IIs



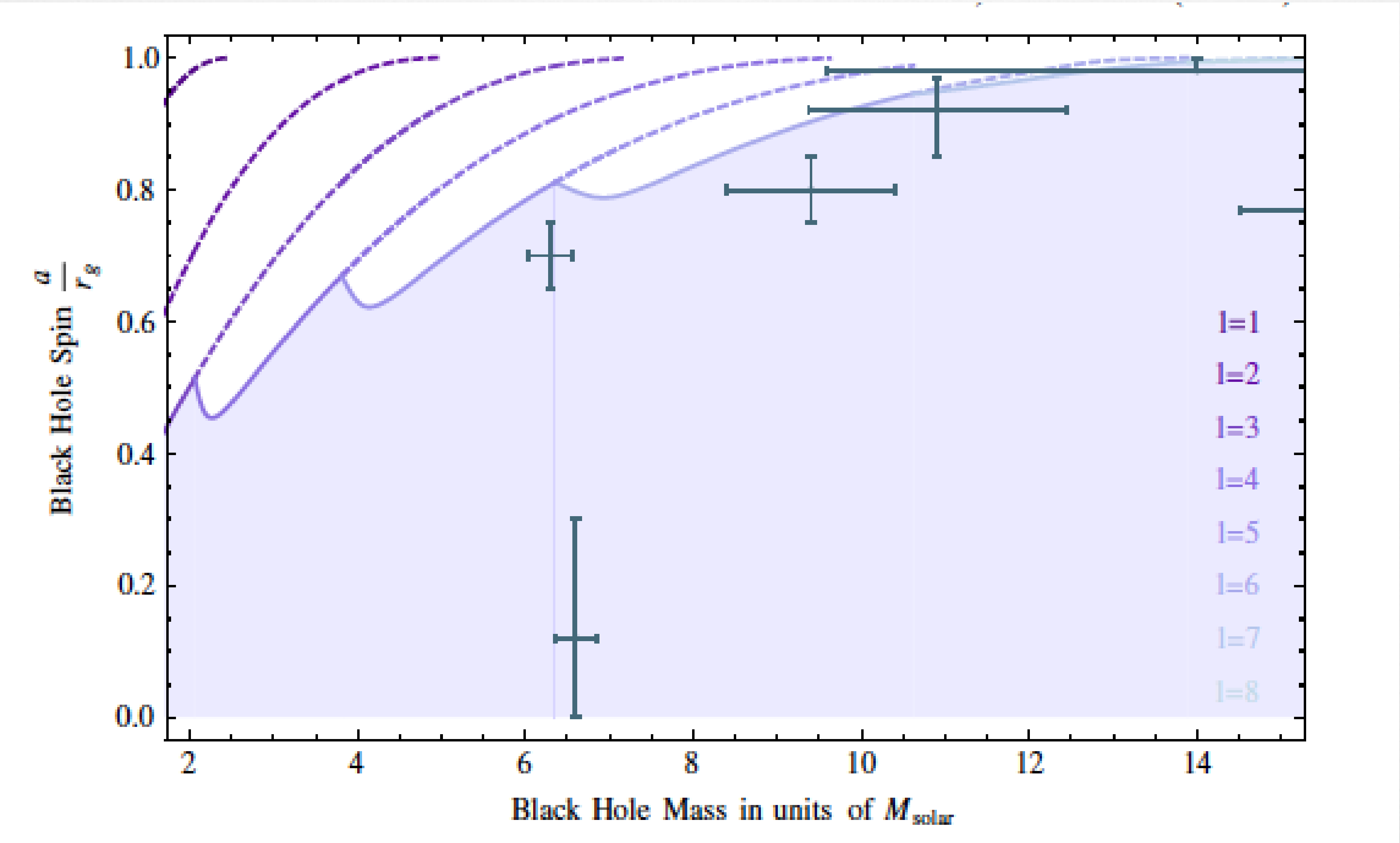
The Distribution of SMBH spins



Brenneman (*SpringerBrief*, 2013)

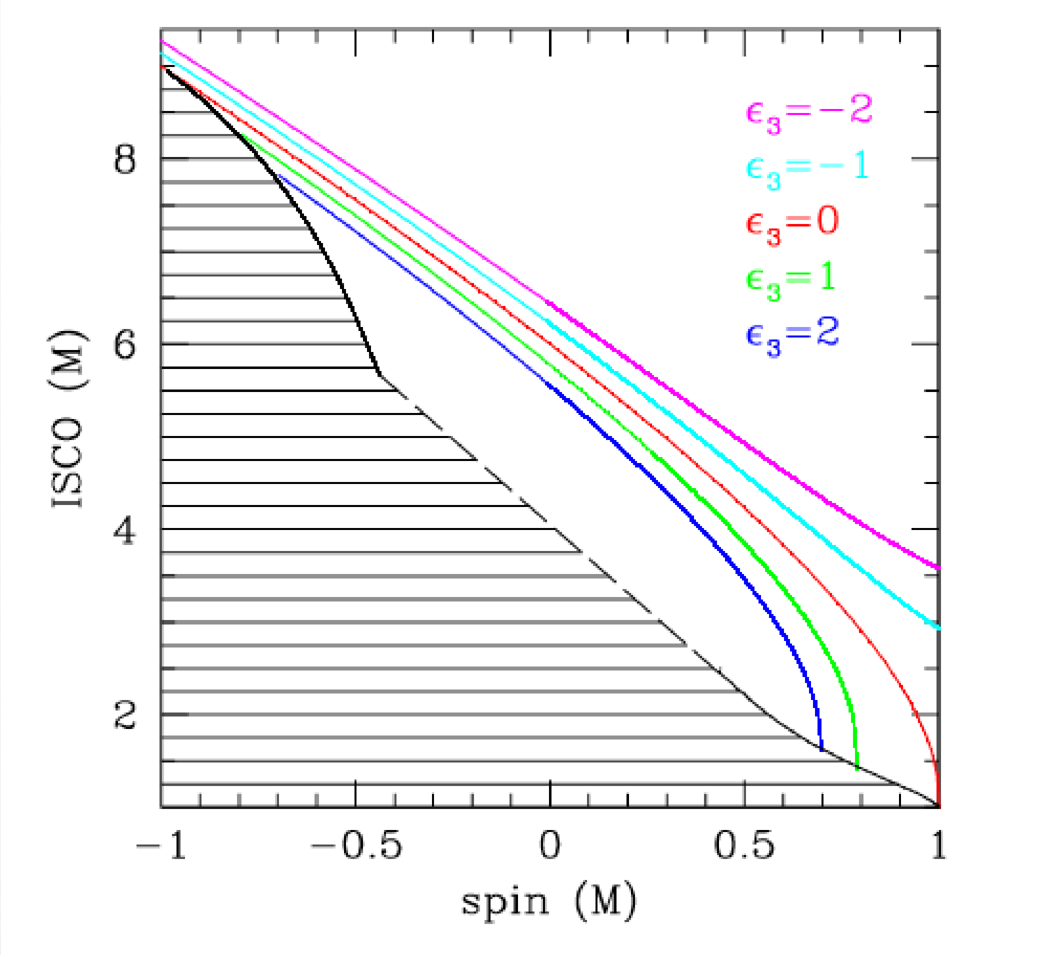
Fundamental Physics

Steady-state spins in a string axiverse



Arvanitaki et al. 2011

Testing GR via the no-hair theorem

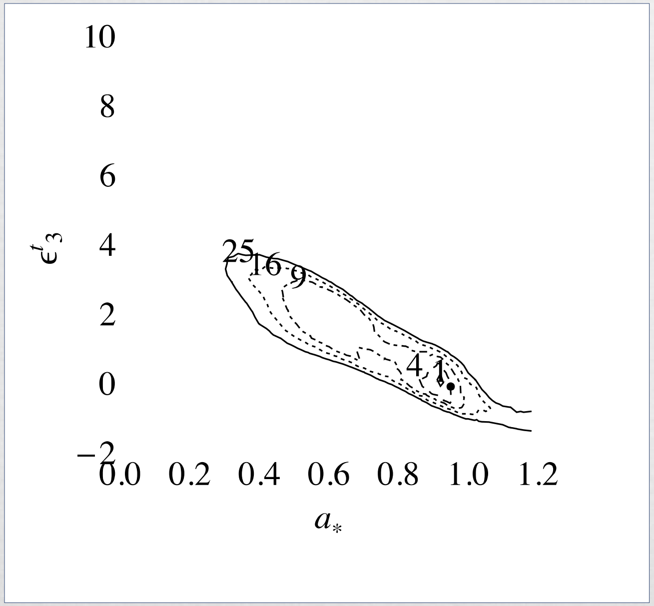


Johannsen & Psaltis 2011

(also, see related work by Nicolas Yunes, Clifford Will, Cosimo Bambi, Sarah Vigeland, and Scott Hughes)

Fe Lines in CPR

Simulations with 10^6 counts (10^4 in the line)



Jiang+2015