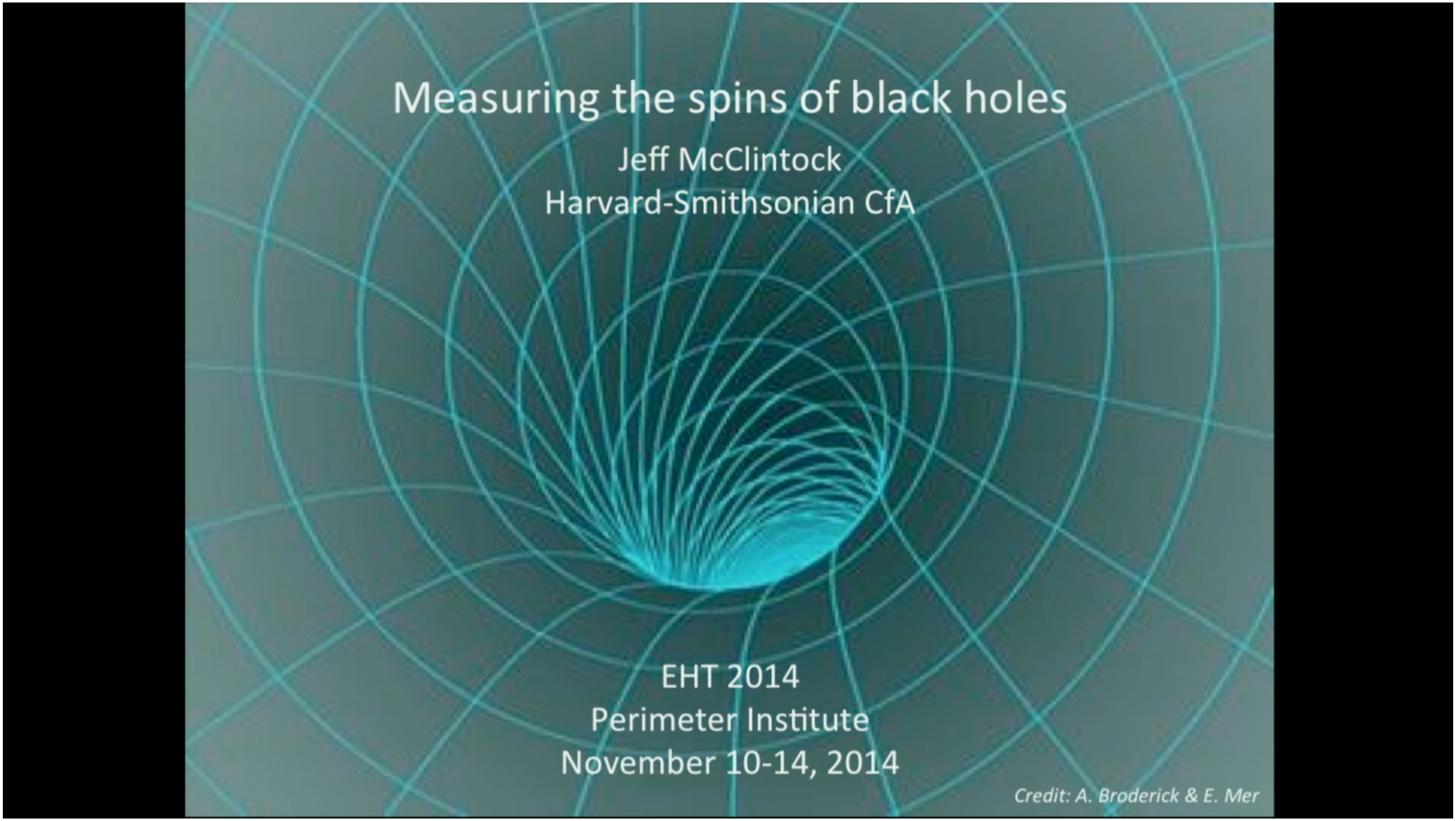
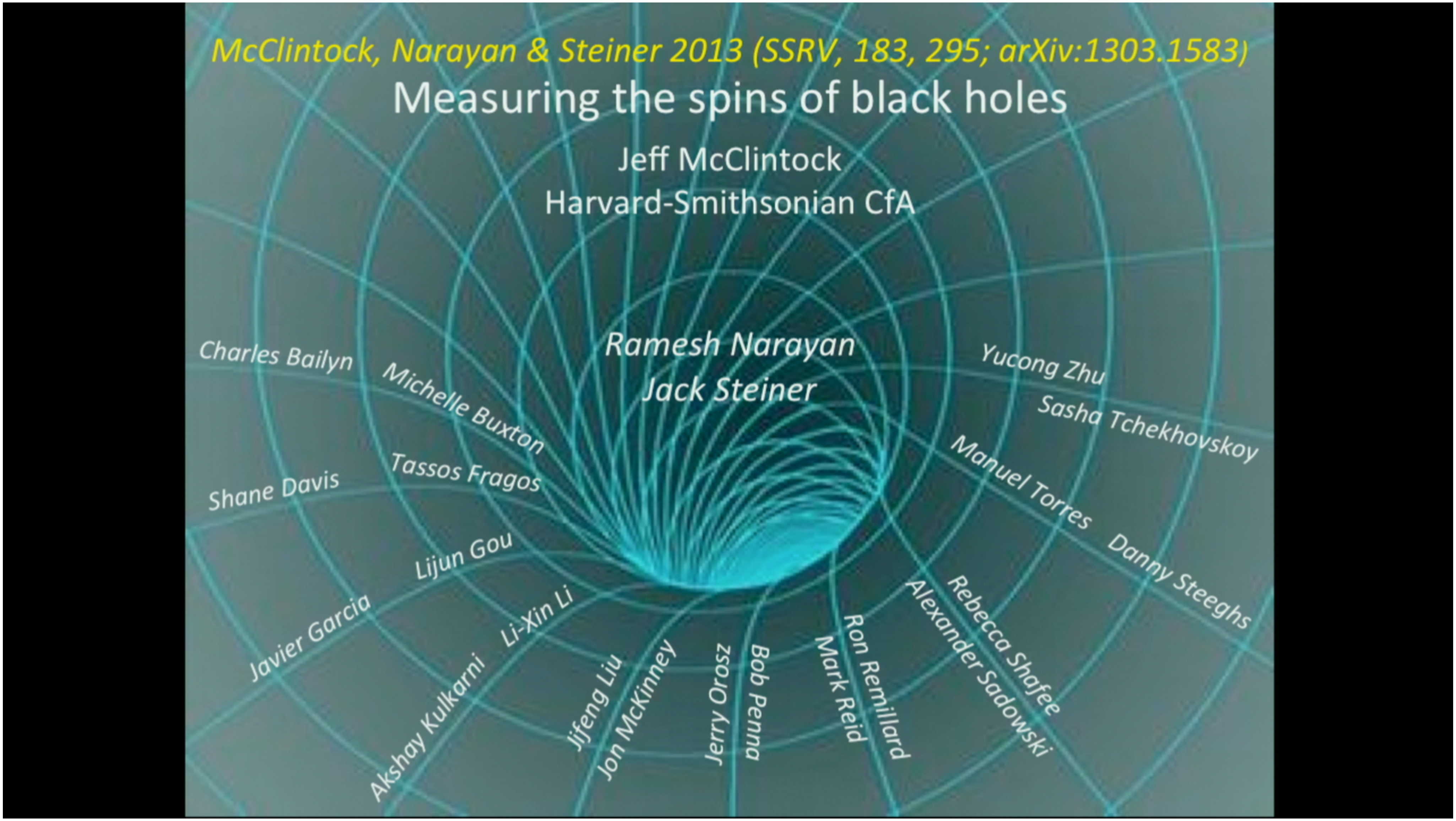
Title: Measuring the Spins of Black Holes

Date: Nov 11, 2014 09:50 AM

URL: http://pirsa.org/14110063

Abstract: Both the continuum-fitting and Fe-line methods of measuring black hole spin will be discussed and compared, with attention to sources of systematic error. Both methods rely on estimating the inner radius of the black hole's accretion disk and identifying it with the radius of the ISCO. The Fe-line method is extremely important because of its dominant role in measuring the spins of supermassive black holes, which is problematic for the continuum-fitting method. Meantime, both methods are applicable to stellar-mass black holes, and we will discuss current efforts to cross-check the spins of individual black holes. Finally, a comprehensive summary of spin results for both stellar-mass and supermassive black holes will be presented.


Measuring the spins of black holes
Jeff McClintock
Harvard-Smithsonian CfA
EHT 2014
Perimeter Institute
November 10-14, 2014
Credit: A. Broderick & E. Mer

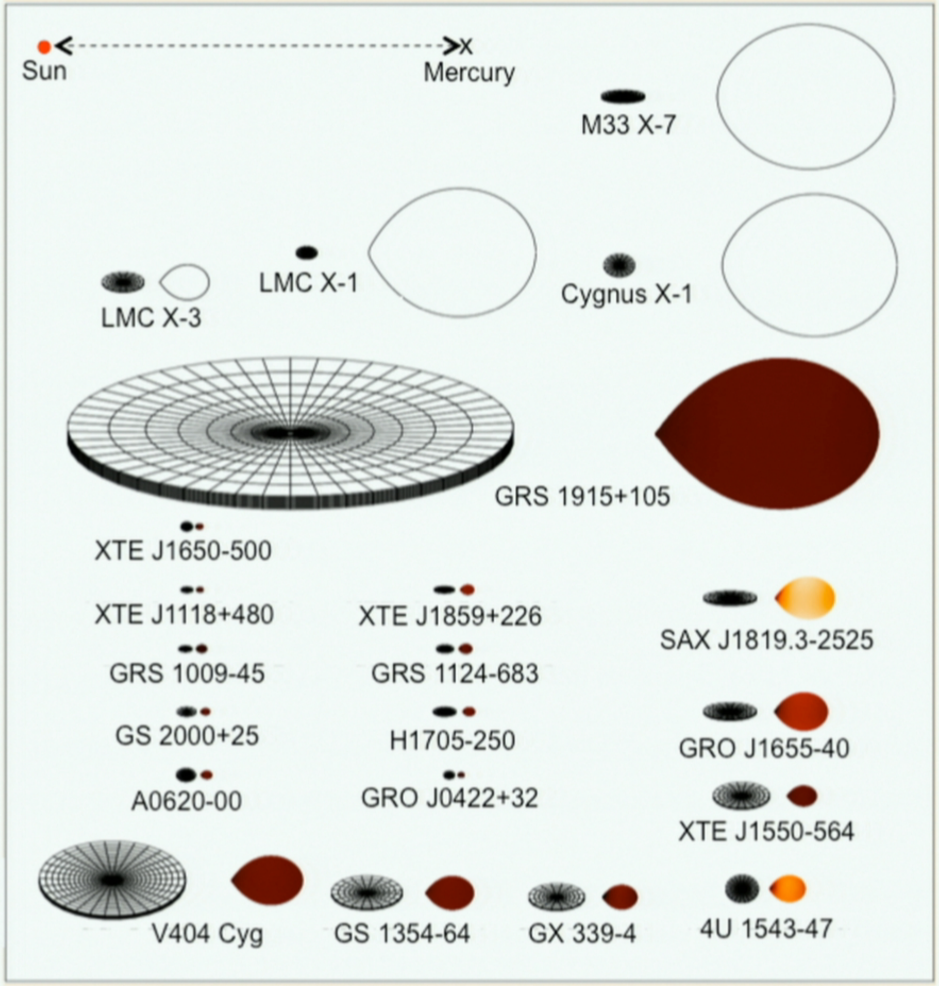

McClintock, Narayan & Steiner 2013 (SSRV, 183, 295; arXiv:1303.1583)
Measuring the spins of black holes
Jeff McClintock
Harvard-Smithsonian CfA
Ramesh Narayan
Jack Steiner
Charles Bailyn
Michelle Buxton
Tassos Fragos
Shane Davis
Lijun Gou
Javier Garcia
Li-Xin Li
Akshay Kulkarni
Jifeng Liu
Jon McKinney
Jerry Orosz
Bob Penna
Mark Reid
Ron Remillard
Alexander Sadowski
Rebecca Shafee
Yucong Zhu
Sasha Tchekhovskoy
Manuel Torres
Danny Steeghs

Outline

- Introduction
- The continuum-fitting (CF) method
- Two applications of CF
- The Fe-line method
- Comparison of Fe-line and CF spins
- Conclusions

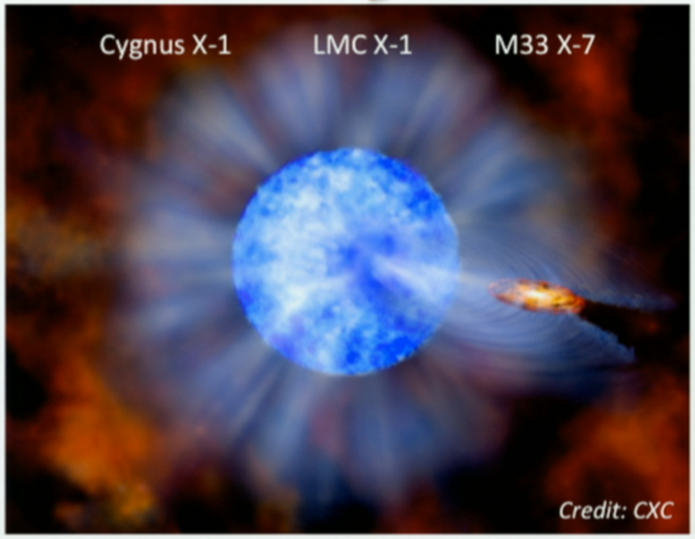
McClintock, Narayan & Steiner 2013 SSRV, 183, 295

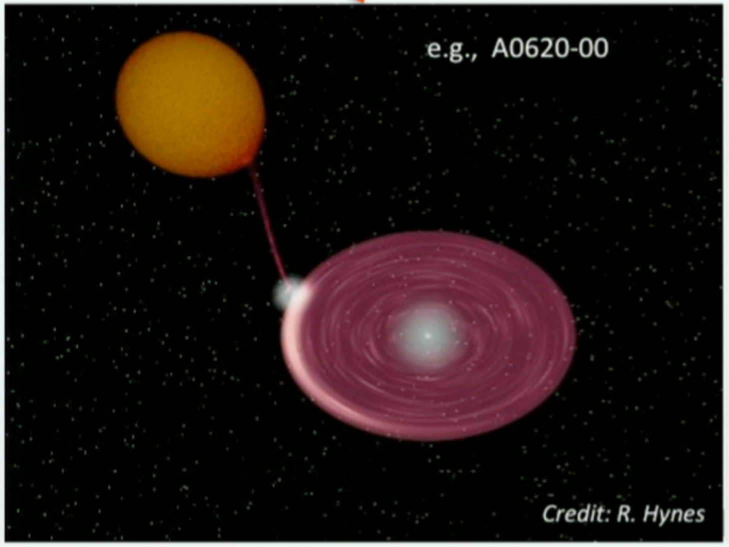
Black hole binaries



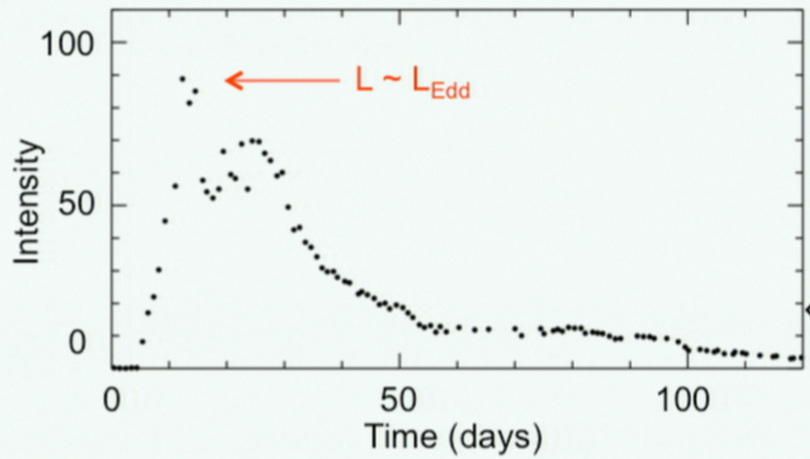
Courtesy: J. Orosz

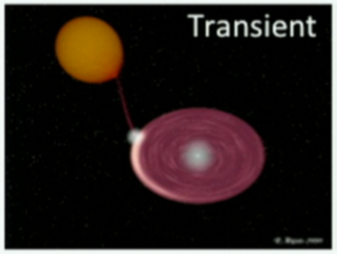
Comparison of persistent and transient BH binaries





X-ray/radio outburst of XTE J1859+226

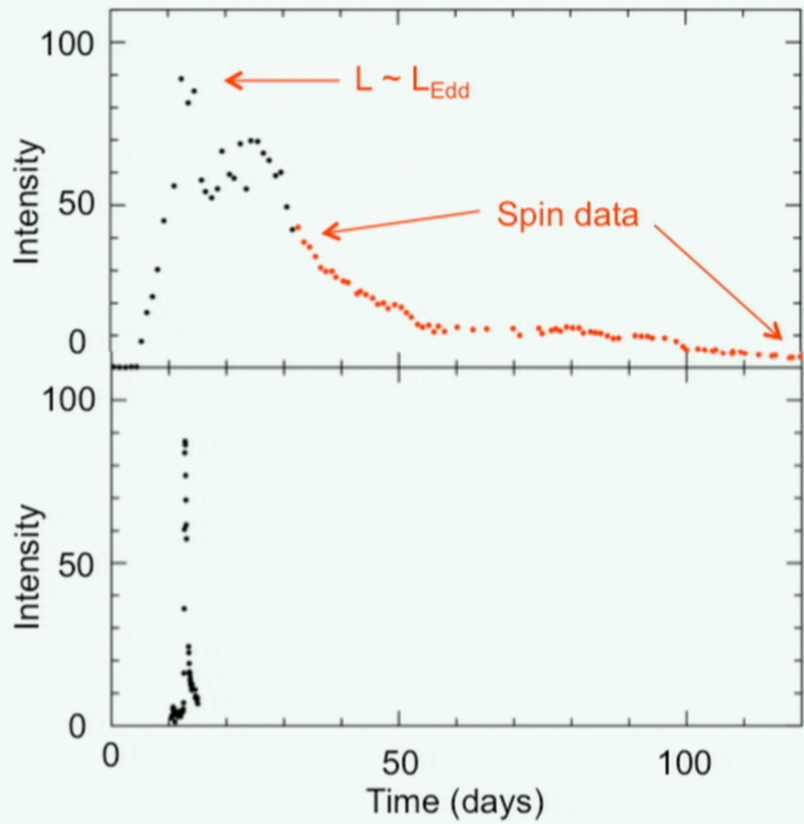


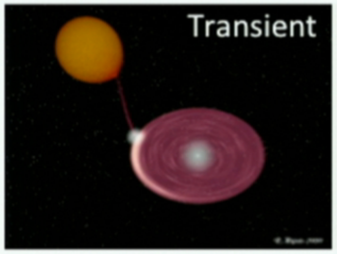


X-ray (2-12 keV)

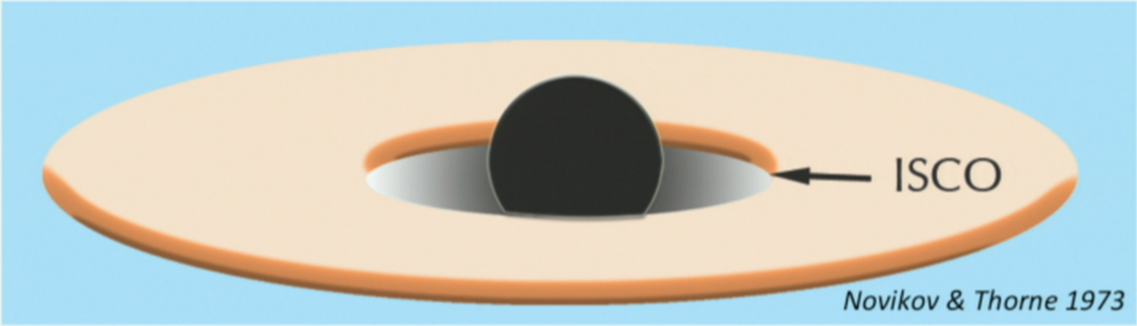
RXTE / ASM

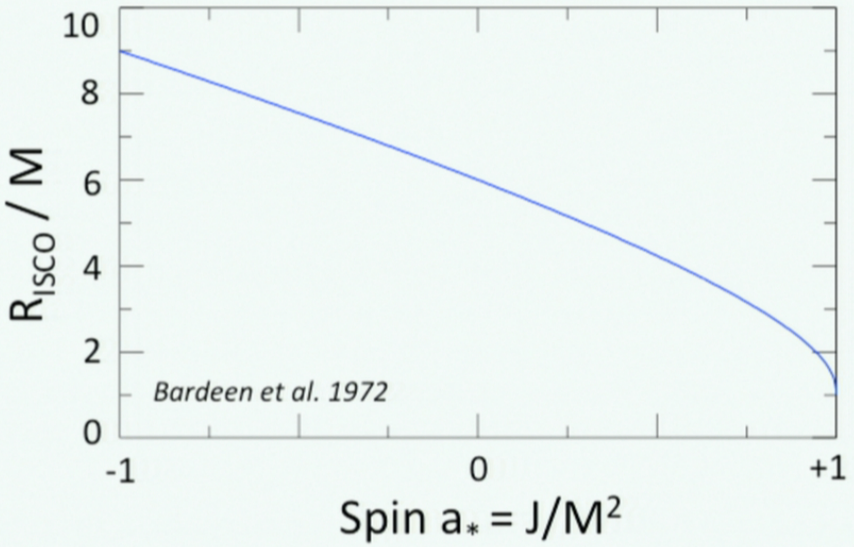
X-ray/radio outburst of XTE J1859+226





Continuum-Fitting: Measuring R_{ISCO} & inferring a_*





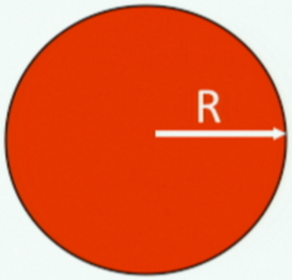
Measuring R_{ISCO} is Analogous to Measuring the Radius of a Star

Radius R of a Star

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

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

$D \rightarrow R$



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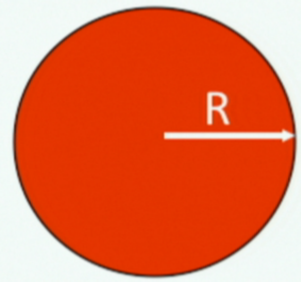
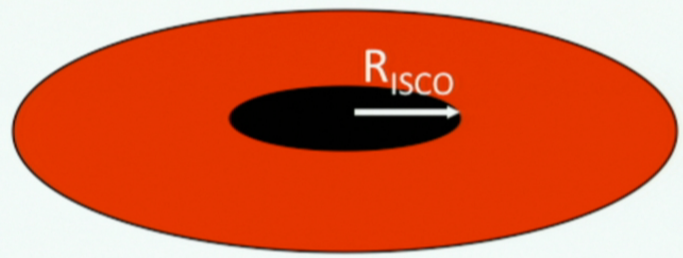


Radius R_{ISCO} of Disk Hole

F and $T \rightarrow$ solid angle

D and $i \rightarrow R_{ISCO}$



Bottom Line: R_{ISCO} & M ➔ a_*

Measuring R_{ISCO} is Analogous to Measuring the Radius of a Star

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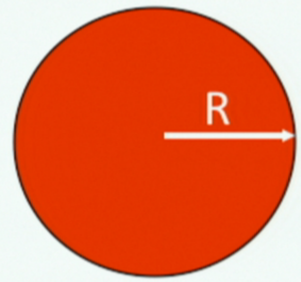
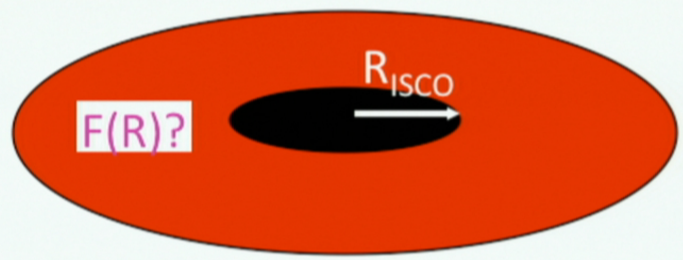


Require accurate values of M, i, D

Radius $R_{\rm ISCO}$ of Disk Hole

F and T $\rightarrow$ solid angle

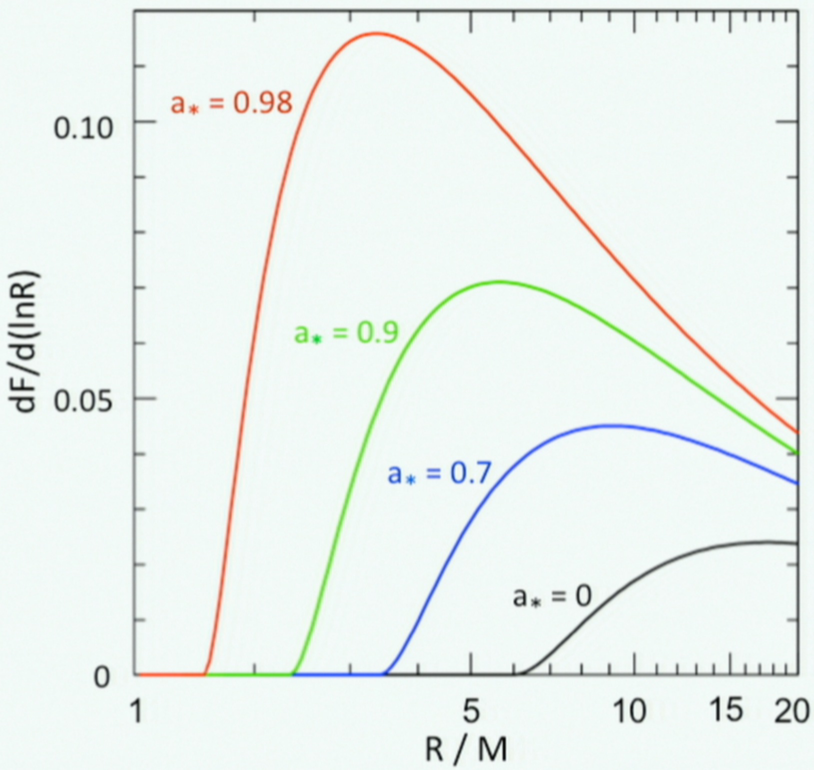
D and i $\rightarrow$ R_{ISCO}



Bottom Line: R_{ISCO} & M $\rightarrow$ a_*

Novikov & Thorne *Thin-Disk* Model: F(R)

Four Identical Black Holes Differing Only in Spin



Novikov & Thorne 1973

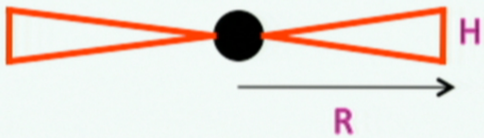
Requirements for the Continuum Fitting Method

See McClintock, Narayan & Steiner 2013 (SSRV, 183, 295)

- Disk atmosphere model of **spectral hardening**

  Davis et al. 2005, 2006, 2009; Davis & Hubeny 2006; Blaes et al. 2006

- Thin disk: **$H/R < 0.05$** equivalent to **$L/L_{Eddington} < 0.3$**

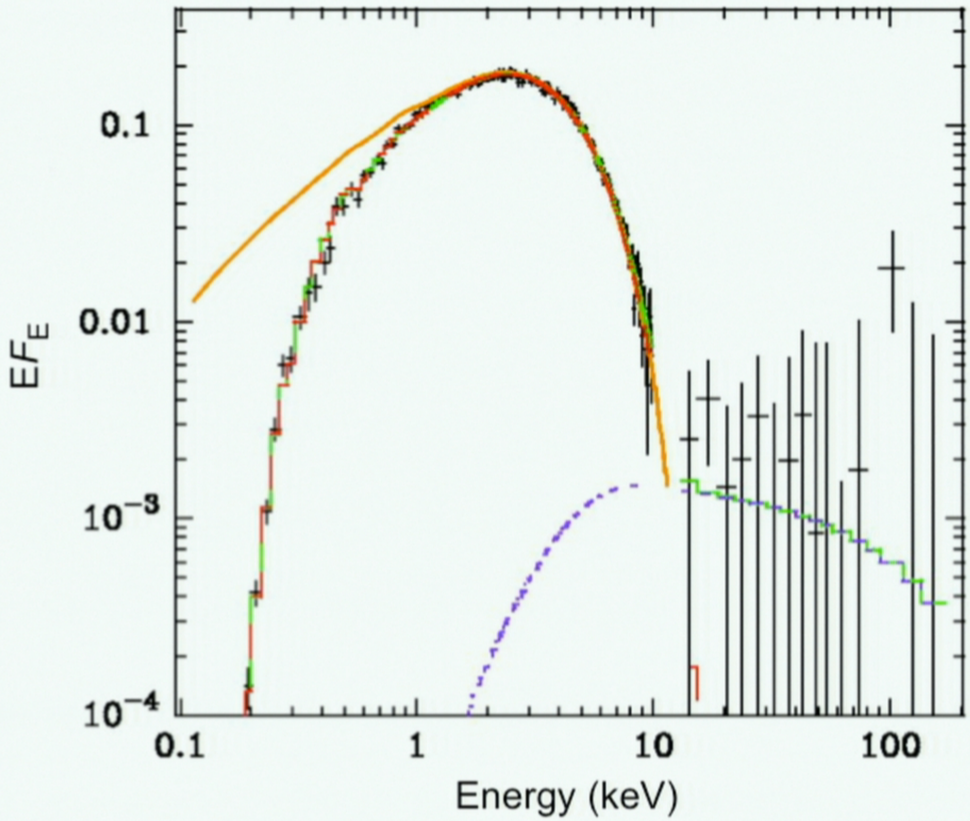


- Assume BH spin aligned with orbital angular momentum

  Tassos et al. 2010; Steiner et al. 2012

- Spectrum dominated by accretion disk

Continuum fitting in practice



LMC X-3: Beppo-SAX

Davis, Done & Blaes 2006

Complete descriptions of 10 black holes

System	Spin a_*	$M/M_\odot$	References
Persistent			
Cygnus X-1	> 0.983	15.8 ± 1.0	Gou+ 2011, 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	> 0.95	10.1 ± 0.6	McClintock+ 2006; Steeghs+ 2013
4U 1543-47	0.8 ± 0.1	9.4 ± 1.0	Shafee+ 2006; Orosz+ 2003
GRO J1655-40	0.7 ± 0.1	6.3 ± 0.5	Shafee+ 2006; Greene+ 2001
XTE J1550-564	0.34 ± 0.24	9.1 ± 0.6	Steiner+ 2011; Orosz+ 2011
LMC X-3	0.21 ± 0.12	7.0 ± 0.5	Steiner+ 2013; Orosz+ 2013
H1743-322	0.2 ± 0.3	≈ 8	Steiner+ 2012; Ozel+ 2010
A0620-00	0.12 ± 0.19	6.6 ± 0.3	Gou+ 2010; Cantrell+ 2010

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M33 X-7	0.84 ± 0.05	15.7 ± 1.5	Liu+ 2008; Orosz+ 2007
Transient			
GRS 1915+105	> 0.95	10.1 ± 0.6	McClintock+ 2006; Steeghs+ 2013
4U 1543-47	0.8 ± 0.1	9.4 ± 1.0	Shafee+ 2006; Orosz+ 2003
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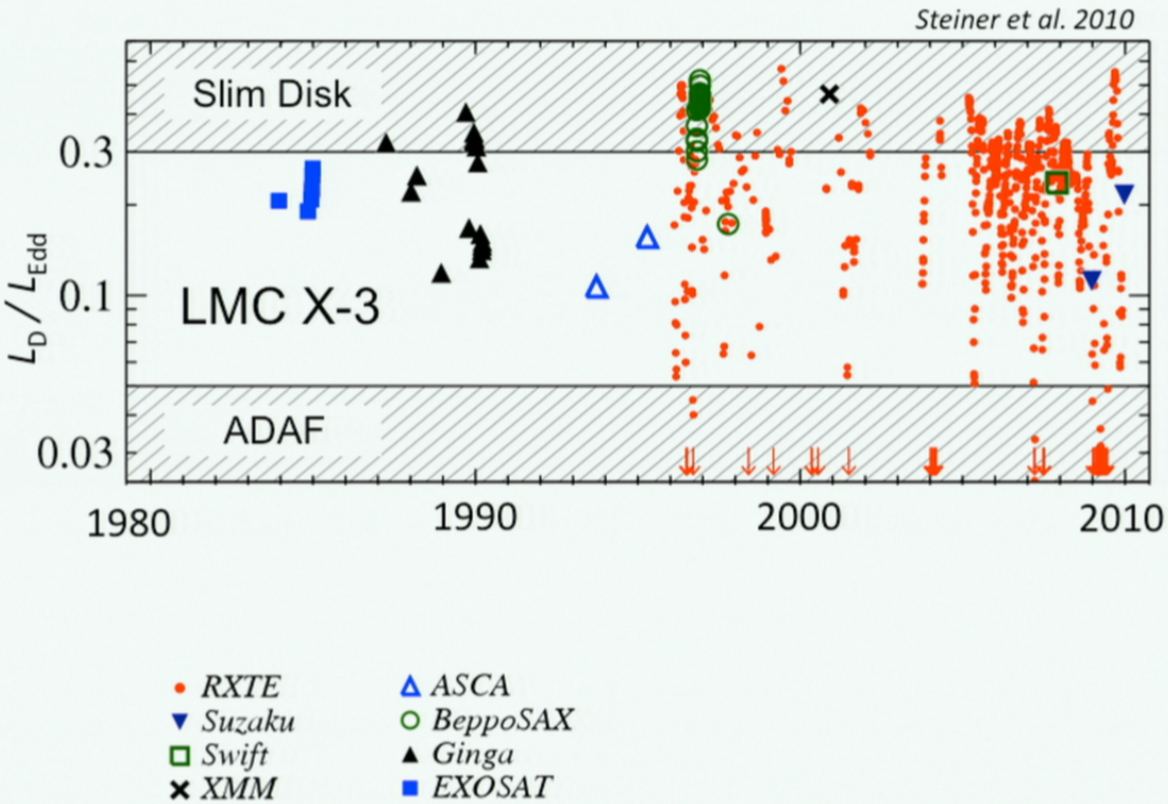
A0620-00	0.12 ± 0.19	6.6 ± 0.3	Gou+ 2010; Cantrell+ 2010

Also, two provisional claims for retrograde spin { Nova Mus 1991 (*Morningstar et al. 2013*)
M31 microquasar (*Middleton et al. 2014*)

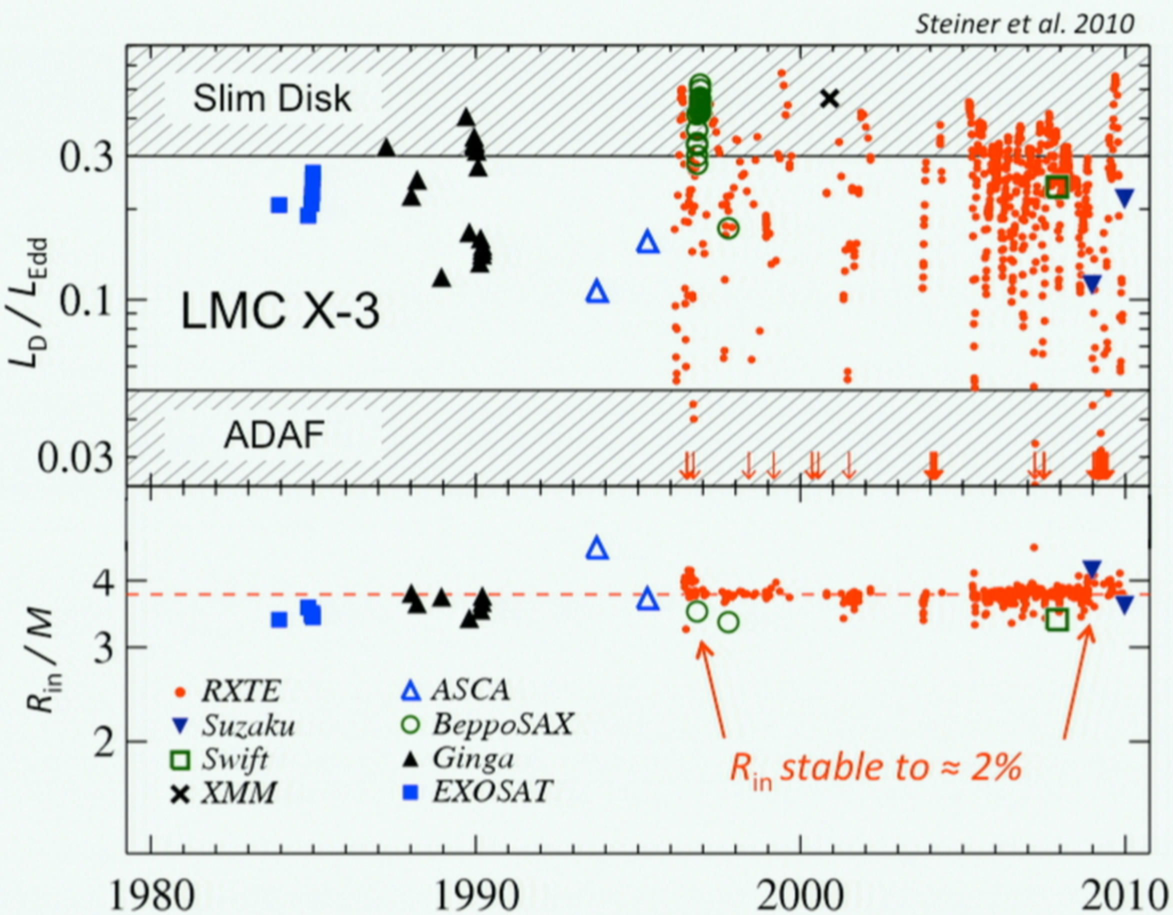
No. of independent CF measurements of spin

System	Spin a_*	Number
Persistent		
Cygnus X-1	> 0.983	9
LMC X-1	0.92 ± 0.06	19
M33 X-7	0.84 ± 0.05	15
Transient		
GRS 1915+105	> 0.95	6
4U 1543-47	0.8 ± 0.1	34
GRO J1655-40	0.7 ± 0.1	33
XTE J1550-564	0.34 ± 0.24	60
LMC X-3	0.21 ± 0.12	390
H1743-322	0.2 ± 0.3	32
A0620-00	0.12 ± 0.19	1

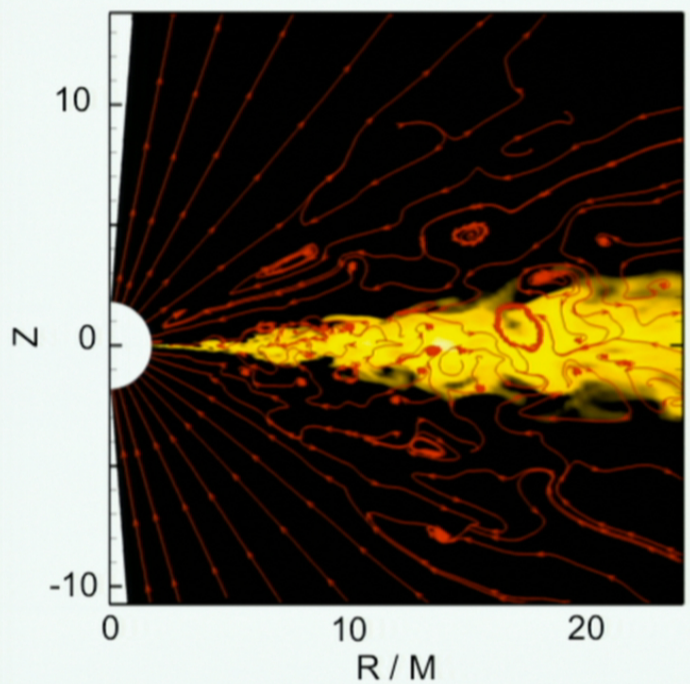
Observational foundation for CF method



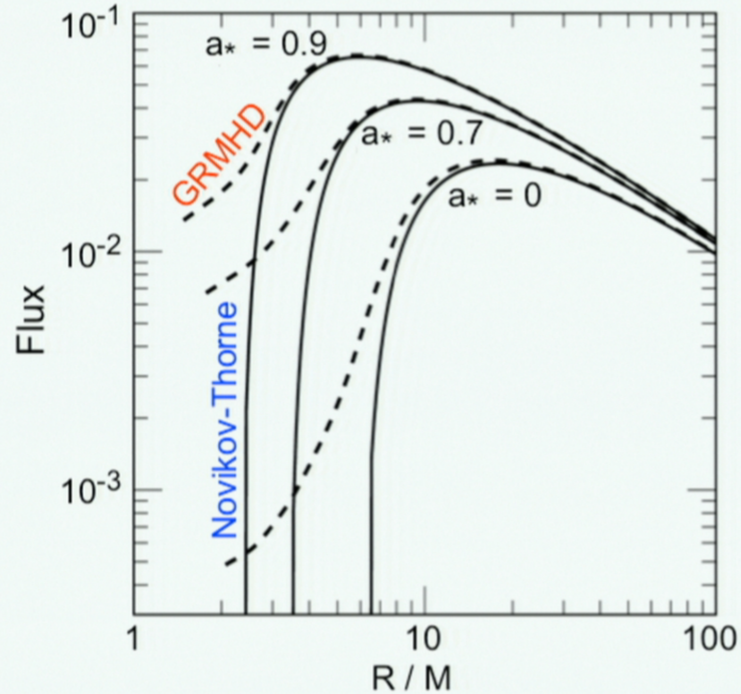
Observational foundation for CF method



Theoretical foundation for CF method



Shafee et al. 2008; Penna et al. 2010



Kulkarni et al. 2011; Zhu et al. 2012

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

Persistent BHs vs. Transient BHs

System	Spin a_*	$M/M_\odot$
Persistent	> 0.8	11-16
Cygnus X-1	> 0.983	15.8 ± 1.0
LMC X-1	0.92 ± 0.06	10.9 ± 1.4
M33 X-7	0.84 ± 0.05	15.7 ± 1.5
Transient	0 ↔ 1	7.8 ± 1.2
GRS 1915+105	> 0.95	10.1 ± 0.6
4U 1543-47	0.8 ± 0.1	9.4 ± 1.0
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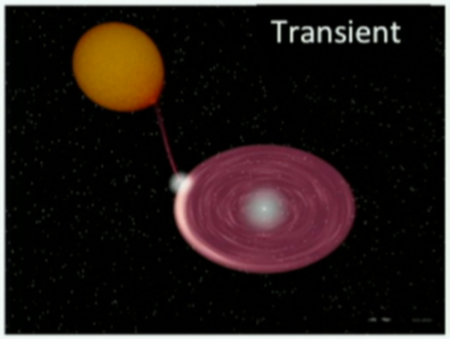
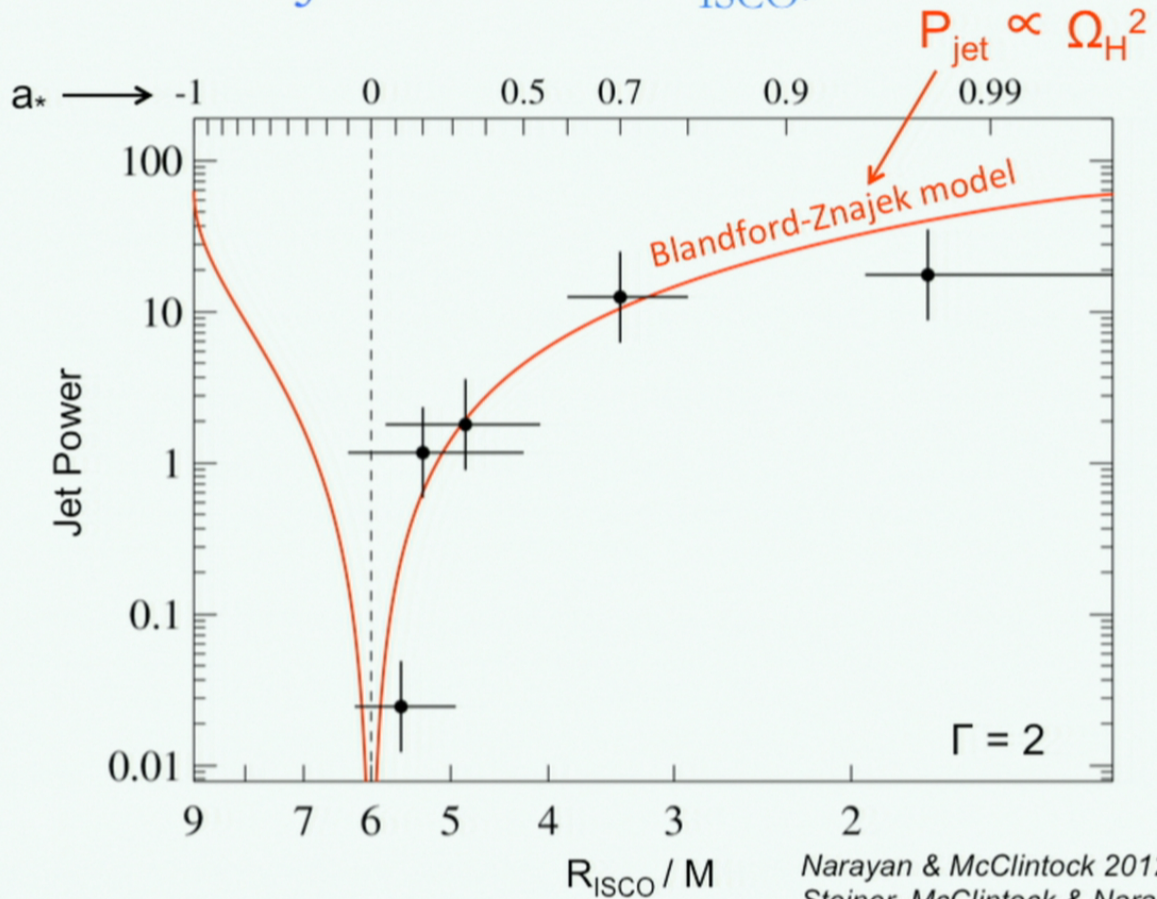


Two Applications of CF Spins

- Origin of spin
- Jet power and black hole spin

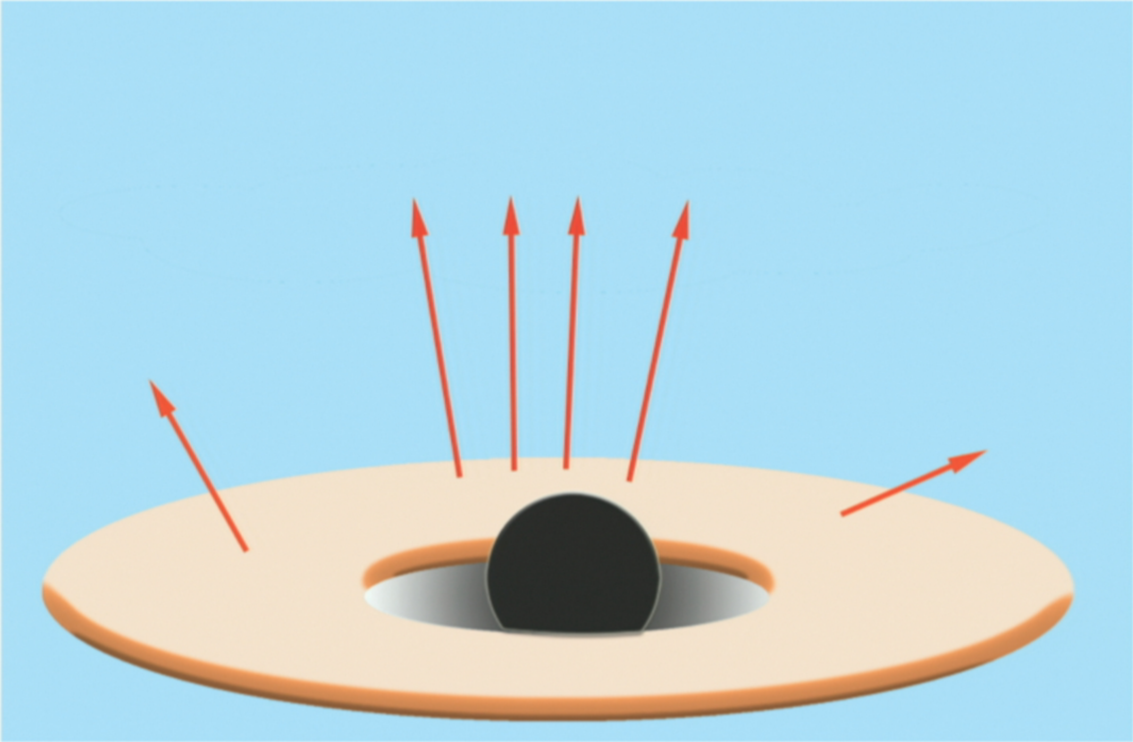
Jet Power vs. R_{ISCO}/M



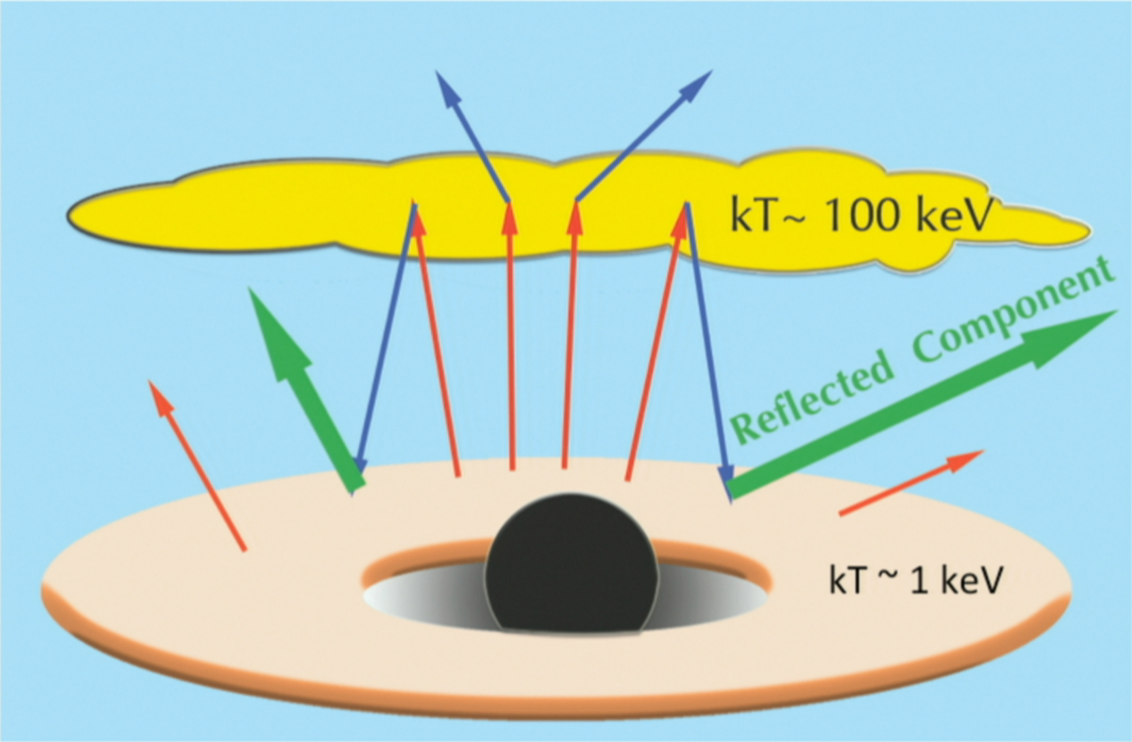
Narayan & McClintock 2012
Steiner, McClintock & Narayan 2012
(but, see Russell et al. 2013)

Fe-Line Method
(X-ray “reflection” spectroscopy)

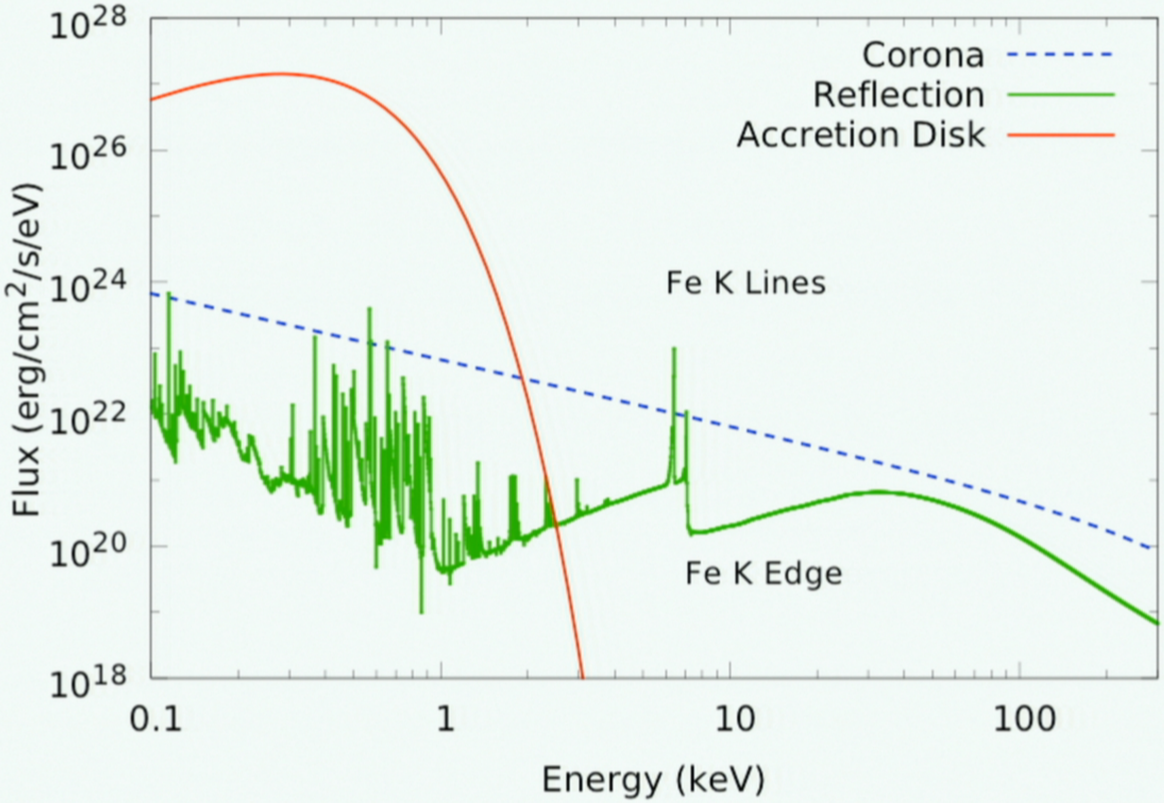
Continuum-fitting method



Fe-line method

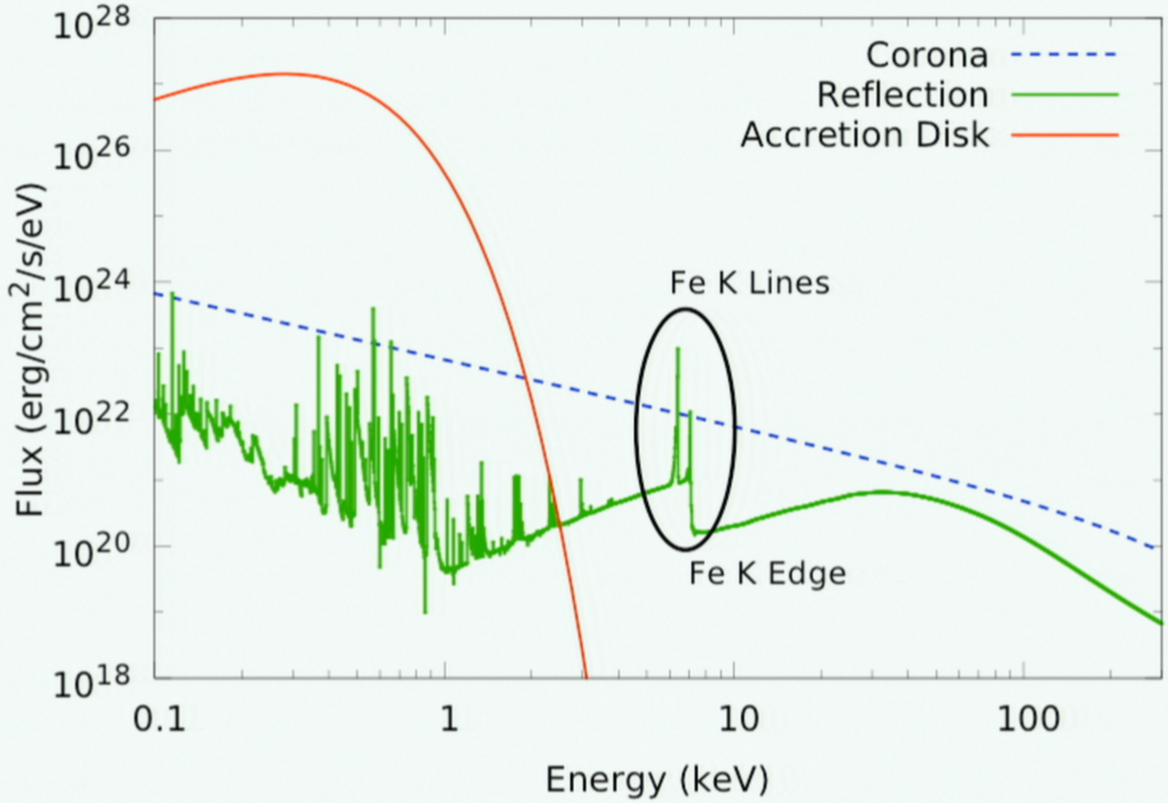


Three key spectral components



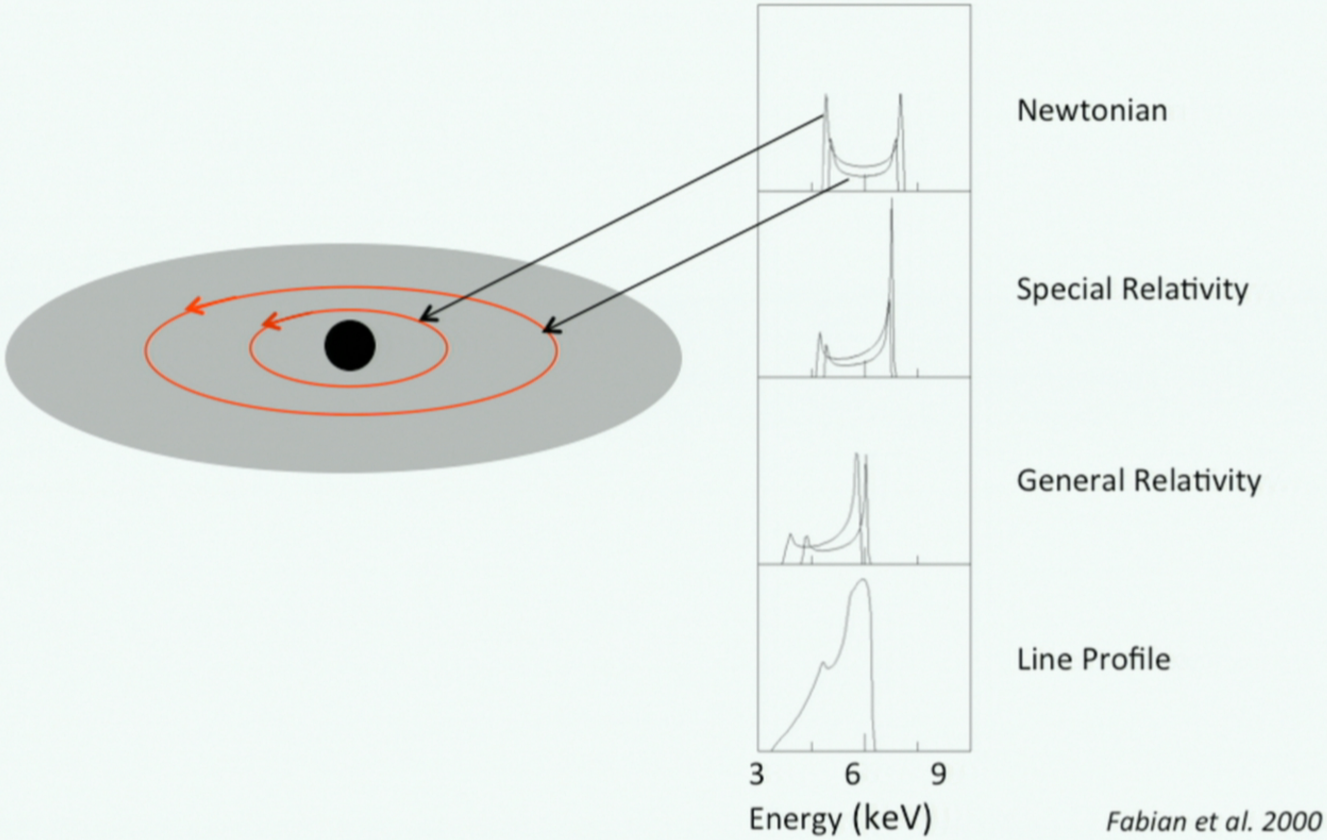
Garcia et al. 2011, 2012, 2014

Three key spectral components

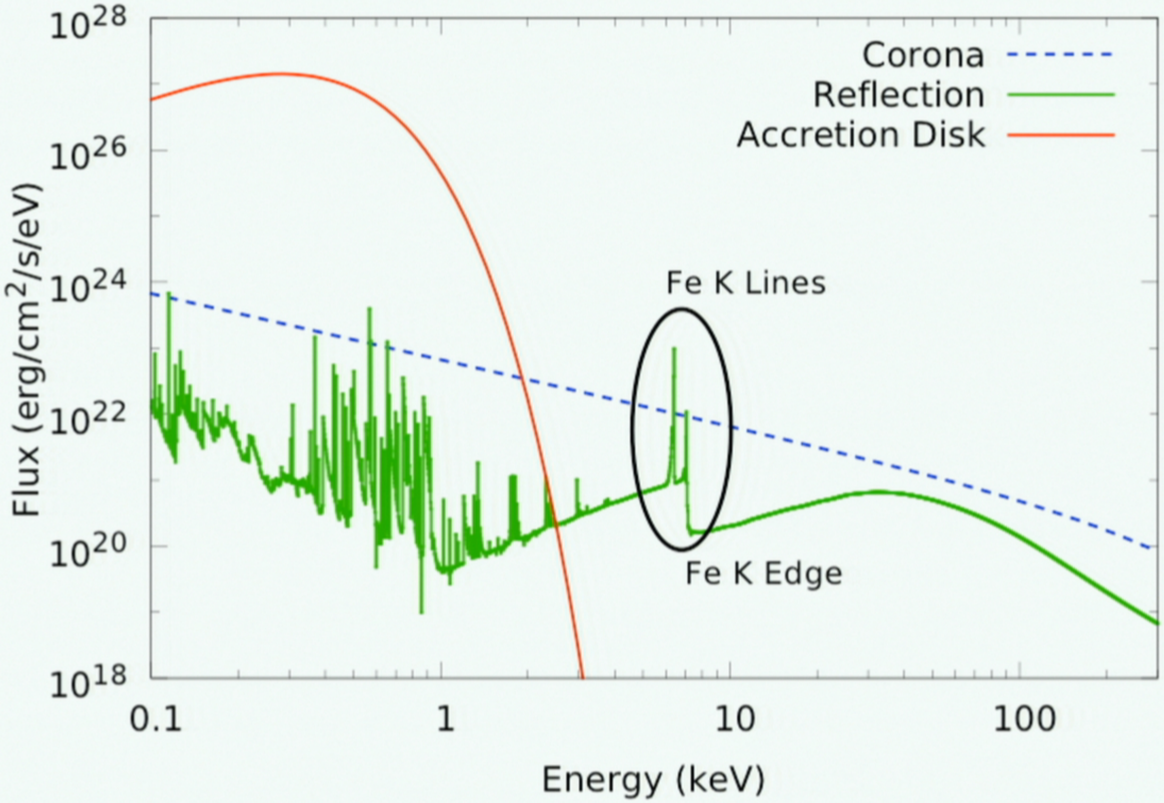


Garcia et al. 2011, 2012, 2014

Formation of Broad Fe K Emission Line

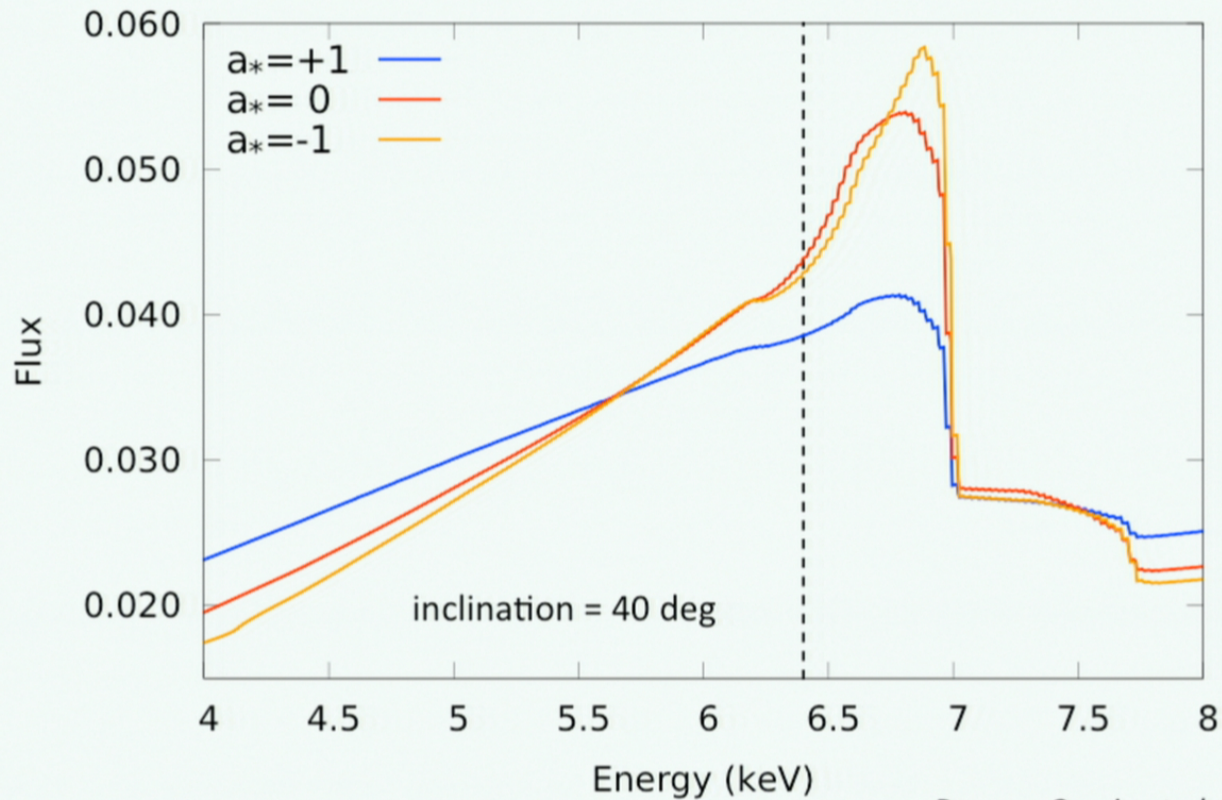


Three key spectral components



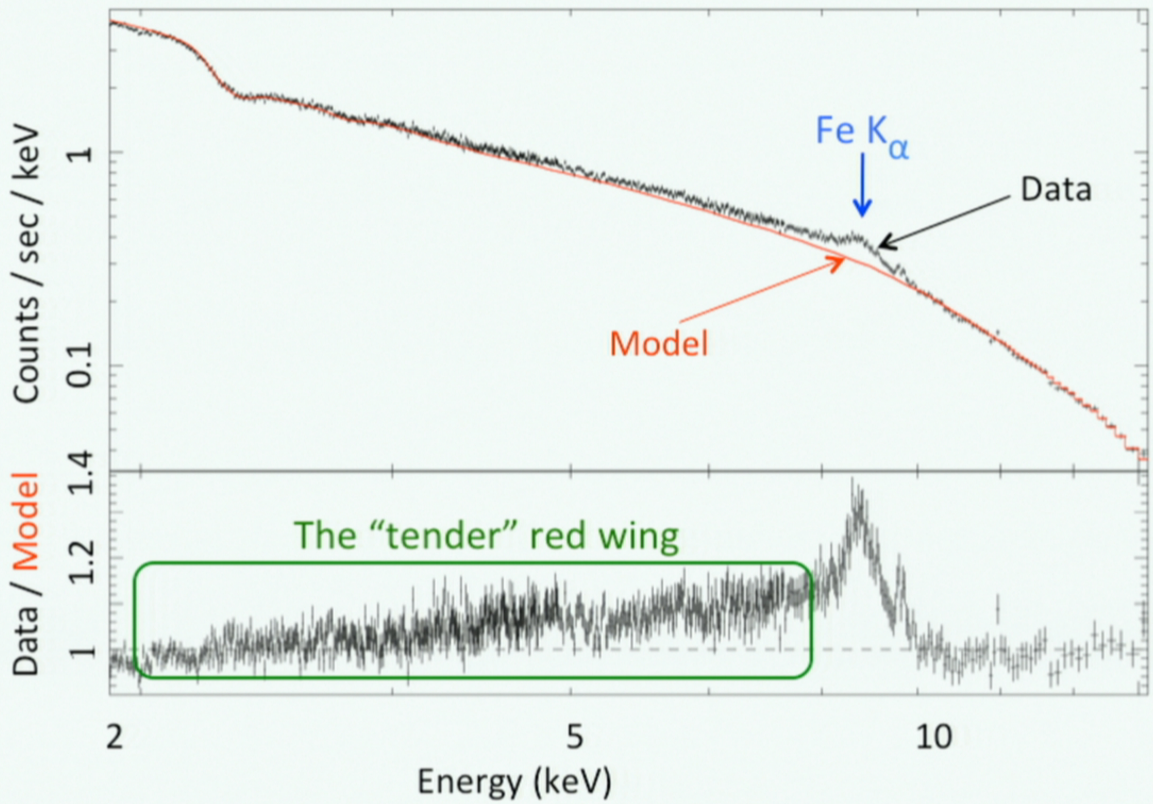
Garcia et al. 2011, 2012, 2014

Relativistically-broadened Fe line profile



Dauser, Garcia et al. 2013
Garcia, Dauser et al. 2014

The Seyfert galaxy MCG-6-30-15



Brenneman & Reynolds 2006

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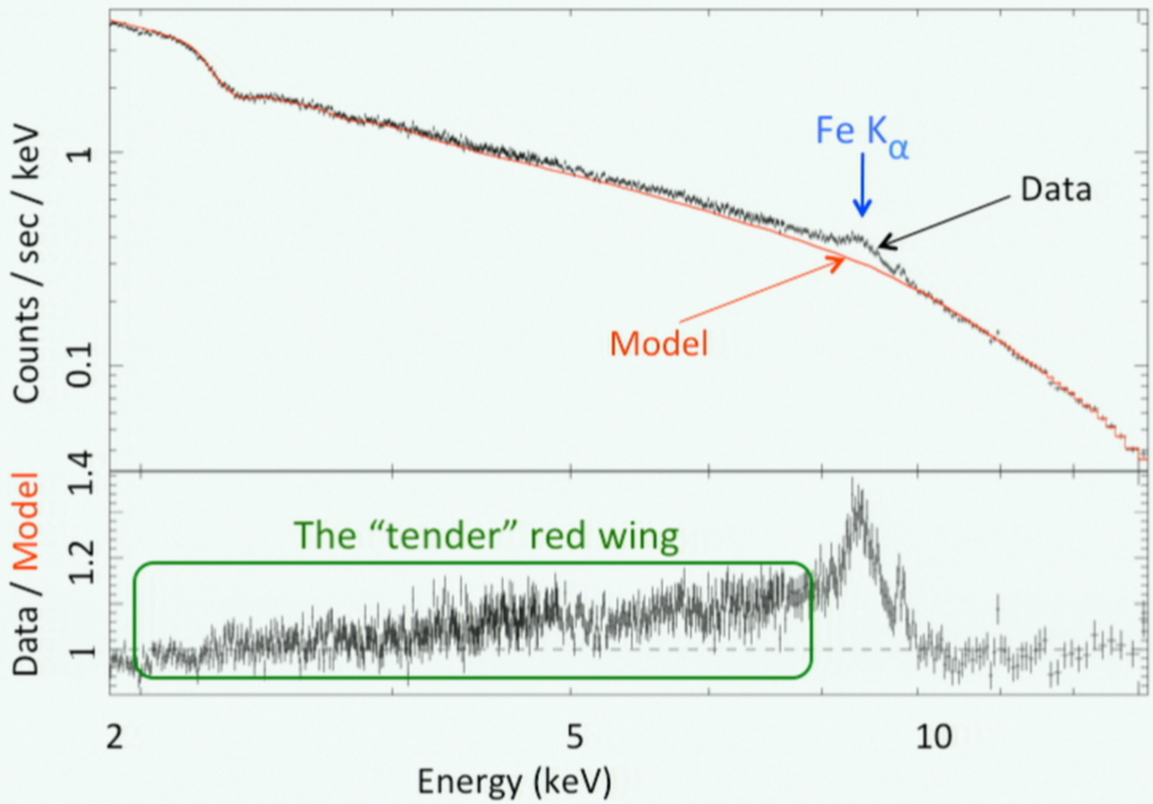

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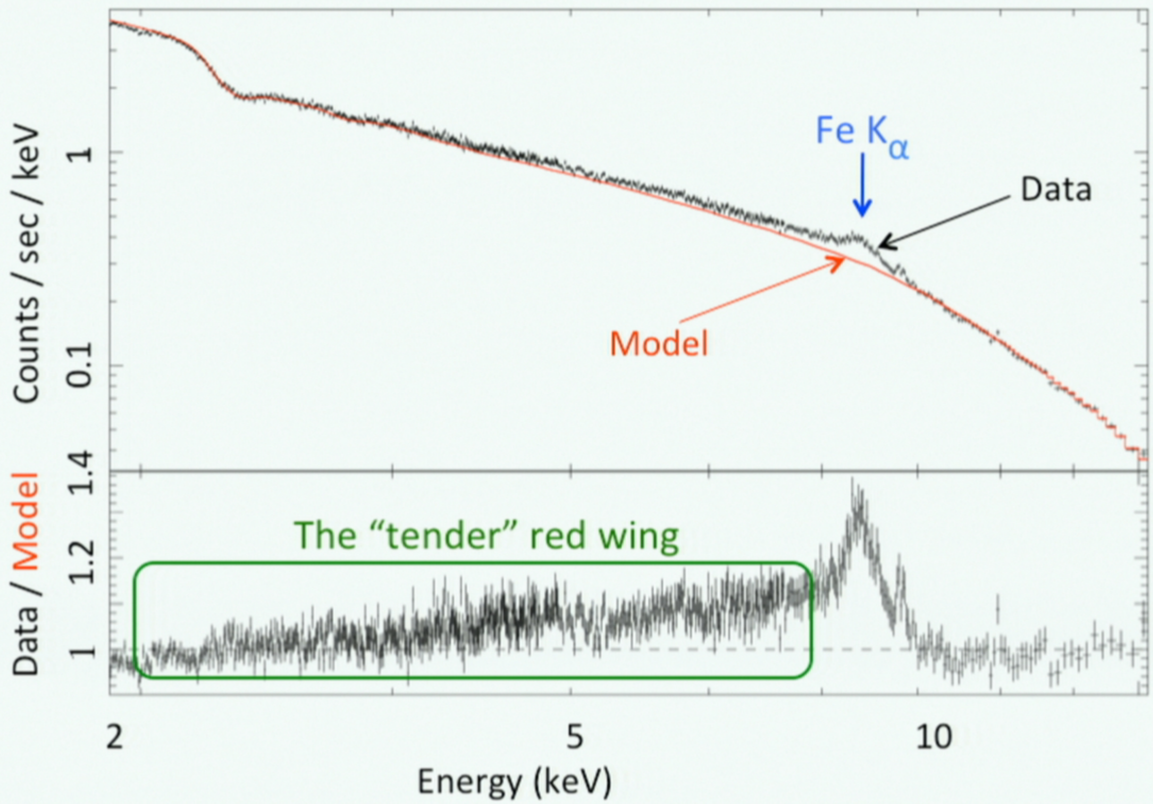

Brenneman & Reynolds 2006

Spins of *supermassive* BHs in AGN

	AGN	Spin a_*
1	IRAS 13224-3809	≥ 0.995
2	Mrk 110	≥ 0.99
3	NGC 4051	≥ 0.99
4	MCG-6-30-15	≥ 0.98
5	NGC 3783	≥ 0.98
6	RBS 1124	≥ 0.98
7	1 H0707-495	≥ 0.98
8	NGC 1365	0.97 (+0.01,-0.04)
9	Ark 564	0.96 (+0.01,-0.06)
10	Swift J0501.9-32	≥ 0.96
11	3C120	≥ 0.95
12	Ark 120	0.94 (+0.1,-0.01)
13	Ton S180	0.91 (+0.02,-0.09)

Brenneman 2013 (arXiv: 1309.6334)

Spins of *supermassive* BHs in AGN

	AGN	Spin a_*		AGN	Spin a_*
1	IRAS 13224-3809	≥ 0.995	14	1H0419-577	0.88 (+0.12,-0.12)
2	Mrk 110	≥ 0.99	15	IRAS 00521-7054	≥ 0.84
3	NGC 4051	≥ 0.99	16	Mrk 335	0.70 (+0.12,-0.01)
4	MCG-6-30-15	≥ 0.98	17	Mrk 79	0.7 (+0.1,-0.1)
5	NGC 3783	≥ 0.98	18	Swift J2127+56	0.7 (+0.2,-0.2)
6	RBS 1124	≥ 0.98	19	Mrk 359	0.66 (+0.30,-0.54)
7	1 H0707-495	≥ 0.98	20	Mrk 1018	0.58 (+0.36,-0.74)
8	NGC 1365	0.97 (+0.01,-0.04)	21	Mrk 841	≥ 0.52
9	Ark 564	0.96 (+0.01,-0.06)	22	Fairall 9	0.52 (+0.19,-0.15)
10	Swift J0501.9-32	≥ 0.96			
11	3C120	≥ 0.95			
12	Ark 120	0.94 (+0.1,-0.01)			
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Comparison of Fe-line and CF results

Continuum-fitting and Fe-line spin results

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Cygnus X-1	> 0.983	0.97 ± 0.02	9 / 1	Gou+ 2011, 2014 Fabian+ 2012
LMC X-1	0.92 ± 0.06	0.72 – 0.99	19 / 1	Gou+ 2009 Steiner+ 2012
GRS 1915+105	> 0.95	0.98 ± 0.01	6 / 1	McClintock +2006 Miller +2013
XTE J1550-564	0.34 ± 0.24	0.55 ± 0.20	60 / 2	Steiner, Reis+ 2011
GRO J1655-40	0.8 ± 0.1	> 0.9	33 / 2	Shafee+ 2006 Reis+ 2009
4U 1543-47	0.7 ± 0.1	0.3 ± 0.1	34 / 1	Shafee+ 2006 Miller+ 2009

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4U 1543-47	0.7 ± 0.1	0.3 ± 0.1	34 / 1	Shafee+ 2006 Miller+ 2009	✕

The case of Cyg X-1

Fe line	$a_* = 0.05 \pm 0.01$	Miller, Reynolds, Fabian+2 (2009)
CF	$a_* > 0.95$ (3 σ)	Gou, McClintock+8 (2011)
Fe line	$a_* = 0.97 \pm 0.02$	Fabian, Wilkins, Miller+9 (2012)

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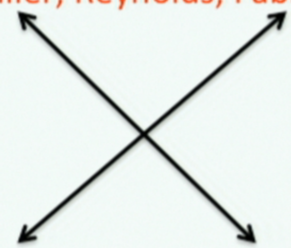
?



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Systematic errors: The case of Cyg X-1

Confirmation via the Continuum-Fitting Method that the Spin of the Black Hole in Cygnus X-1 is Extreme ($a_* > 0.983$ @ 3σ)

L. Gou, J. McClintock, R. Remillard, J. Steiner, M. Reid, et al. 2014, ApJ, 790, 29

Section 5: ROBUSTNESS OF SPIN ESTIMATES

5.1 Errors from the Novikov-Thorne model
5.2 Effects of pileup
- 5.2.1 Chandra CC mode
- 5.2.2 Chandra TE mode
- 5.2.3 Swift

5.3 Effect of iron line and edges
5.4 Effect of extending the bandwidth from 45 keV to 150 keV
5.5 Effect of using a different reflection model
5.6 On the accuracy of our adopted reflection model
5.7 Effect of varying the viscosity parameter and metallicity
5.8 Effect of a warm absorber
5.9 Effect of dust scattering
5.10 Effect of a possible spin-orbit misalignment

Summary

- Ten continuum-fitting measurements of spin
  - ✓ Simplest BH state, simplest BH model, abundant data
  - ✓ Method is demonstrably robust
- Two applications of continuum-fitting spin data
  - ✓ [Spins of persistent sources are natal
    Spins of transients acquired via accretion torques
  - ✓ First evidence that some jets are powered by BH spin energy
- Continuum-fitting & Fe-line spins for 6 BHs
  - ✓ Four in reasonable agreement
  - ✓ Two disagree & need rework
  - ✓ Fe-line method problematic for BH binaries – but important!

McClintock, Narayan & Steiner 2014 Space Sci. Rev. 183, 295 (arXiv:1303.1583)

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