# Measuring Spin for Stellar-Mass Black Holes

Jack Steiner
MIT

# No-Hair Theorem

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

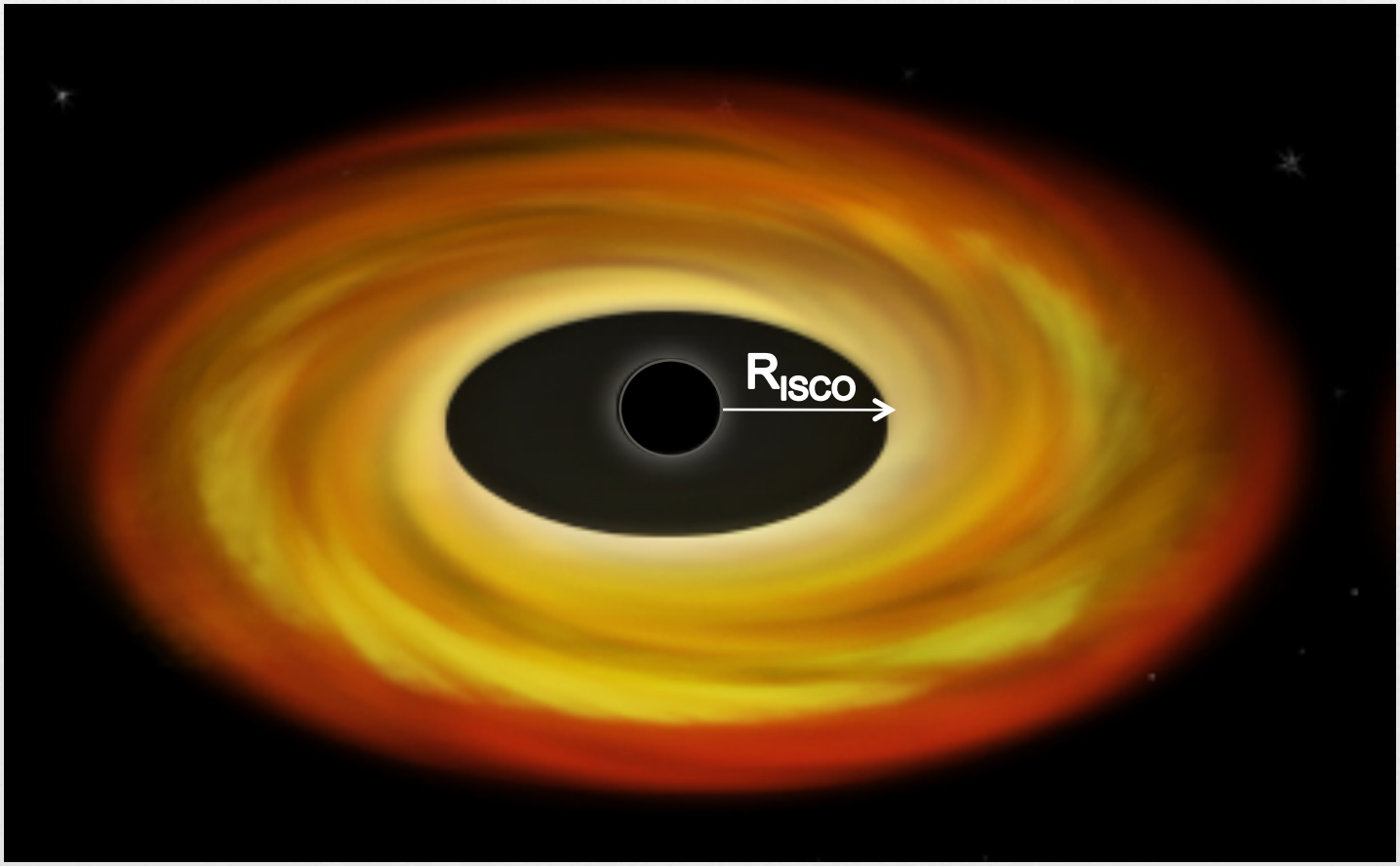
Charge neutralized and unimportant

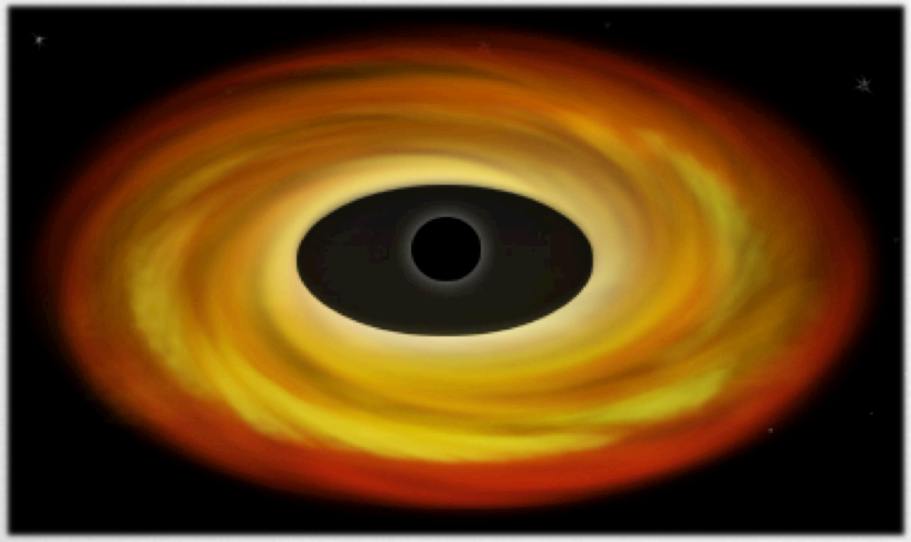
# The gravity of spin

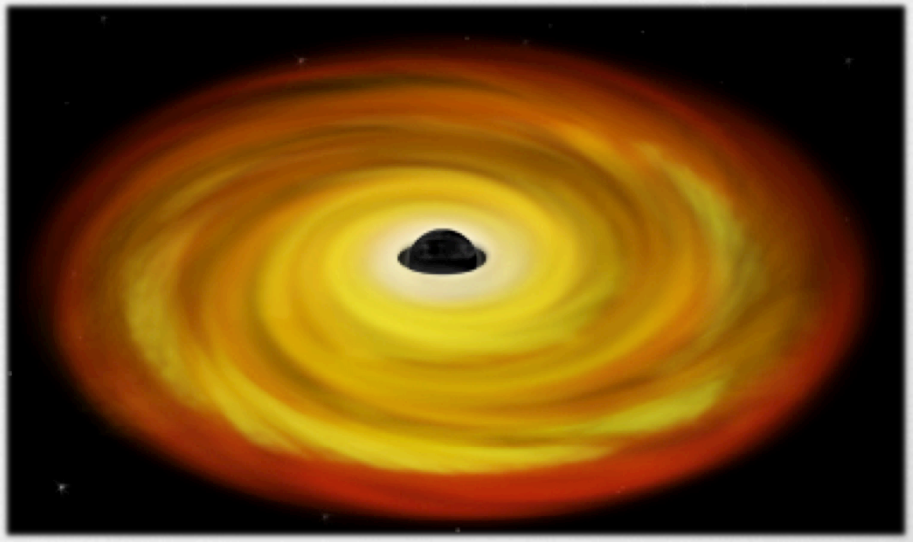
*"In my entire scientific life, extending over forty-five years, the most shattering experience has been the realization that an exact solution of Einstein's equations of general relativity, discovered by the New Zealand mathematician, Roy Kerr, provides the absolutely exact representation of untold 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

# Measuring the Inner Disk Radius







$a_* = 0$

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

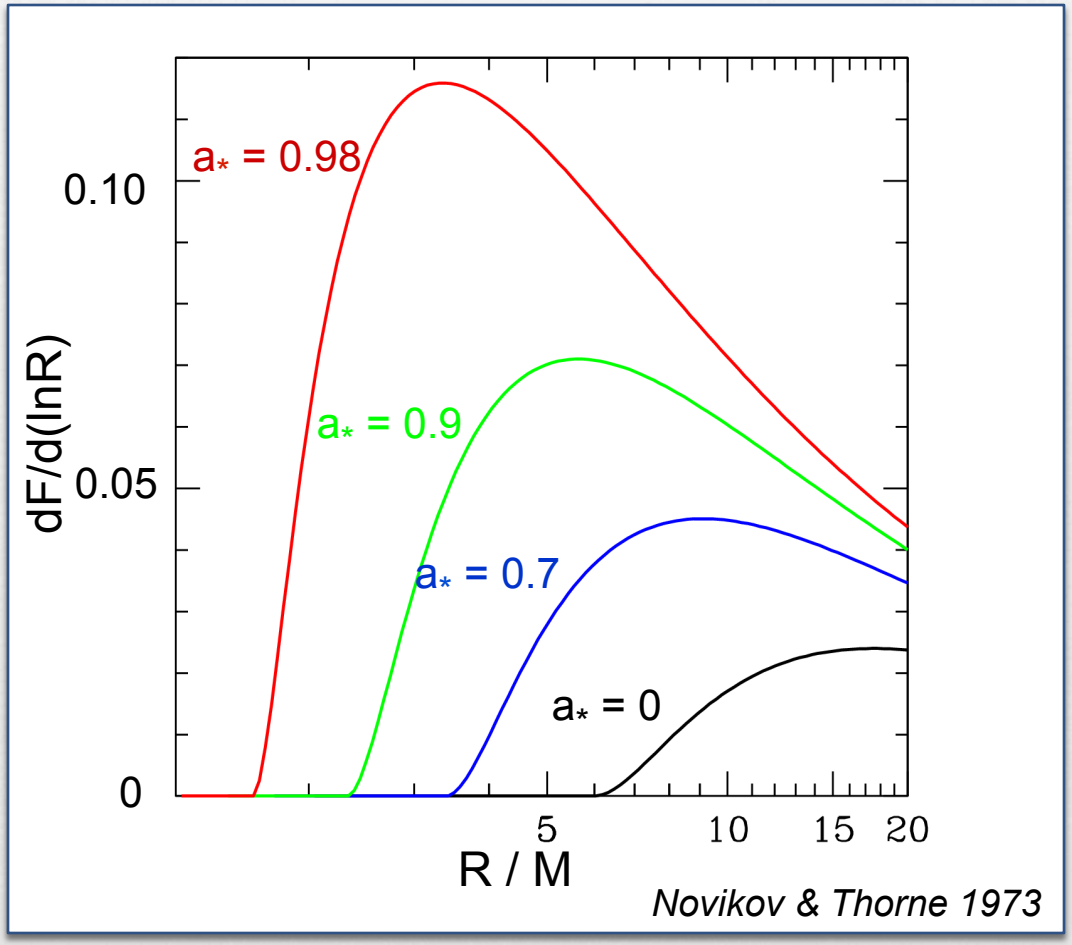
(90 km)

for $M = 10\ M_\odot$

$a_* = 1$

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

(15 km)


a* = 0.98
a* = 0.9
a* = 0.7
a* = 0
0.10
0.05
0
dF/d(lnR)
5
10
15
20
R / M
Novikov & Thorne 1973

# Two Primary Methods of Measuring Spin

- Continuum Fitting Method

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

- Fe Line (Reflection) Method

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

# Continuum Fitting

(Zhang, Cui, & Chen 1997)

# Measuring $R_{ISCO}$

**Radius $R$ of a Star**

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

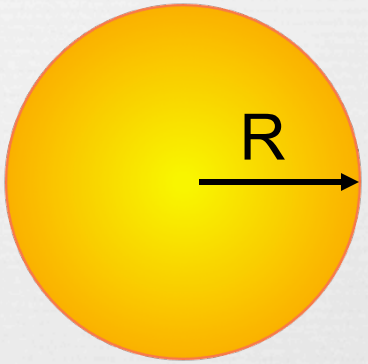
Solid angle: $(R/D)^2 = F/\sigma T^4$

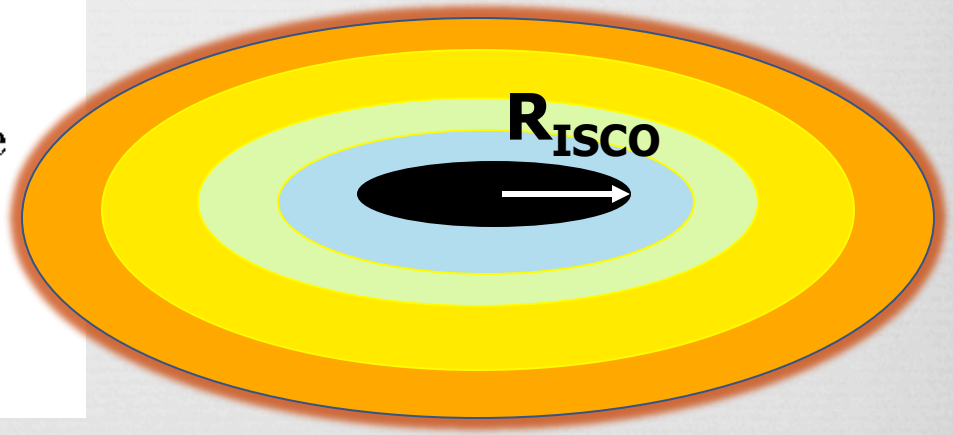
$D \rightarrow$ R

**Radius $R_{ISCO}$ of Disk Hole**

F and $T \rightarrow$ solid angle

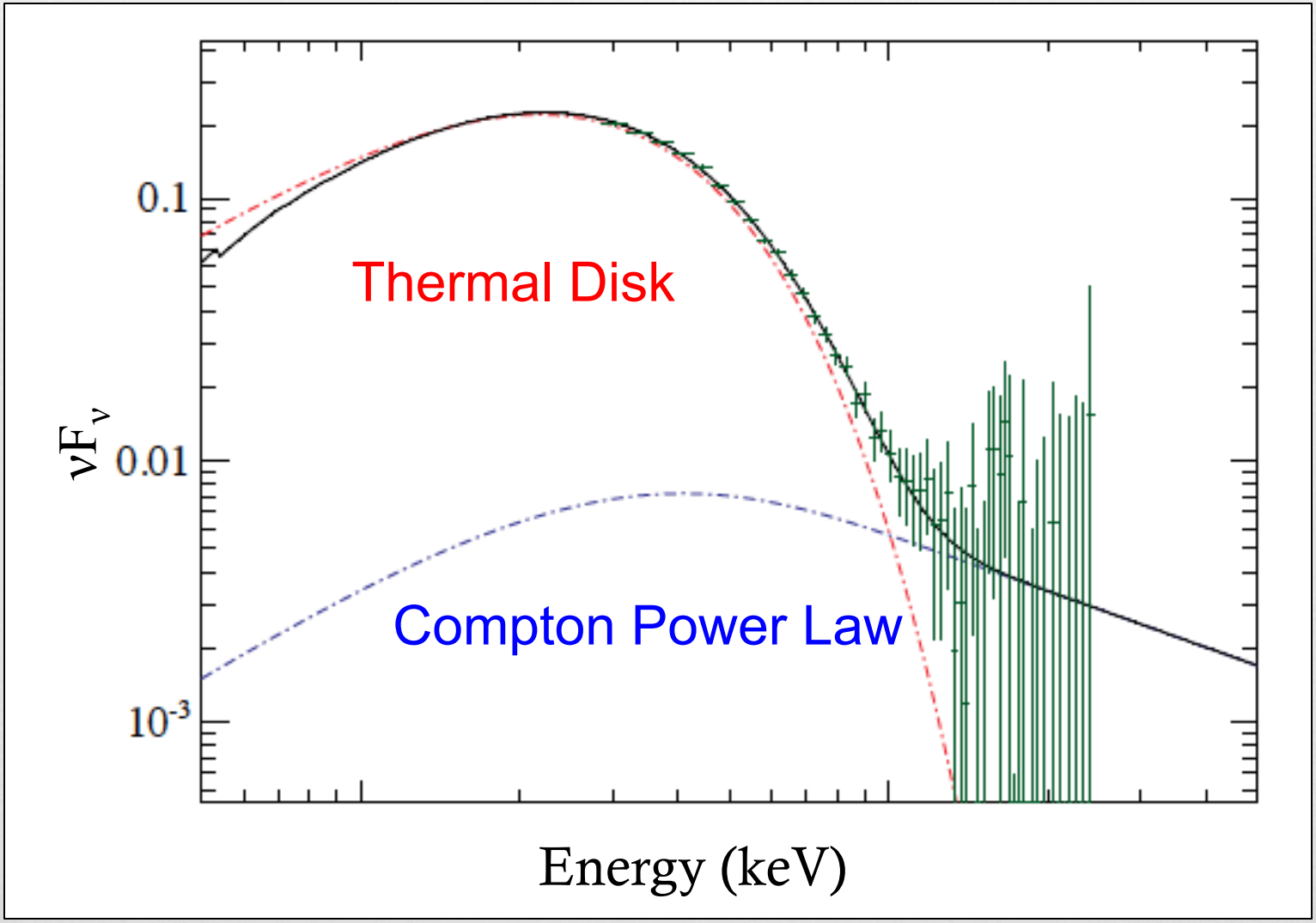
$D$ and $i \rightarrow R_{ISCO}$



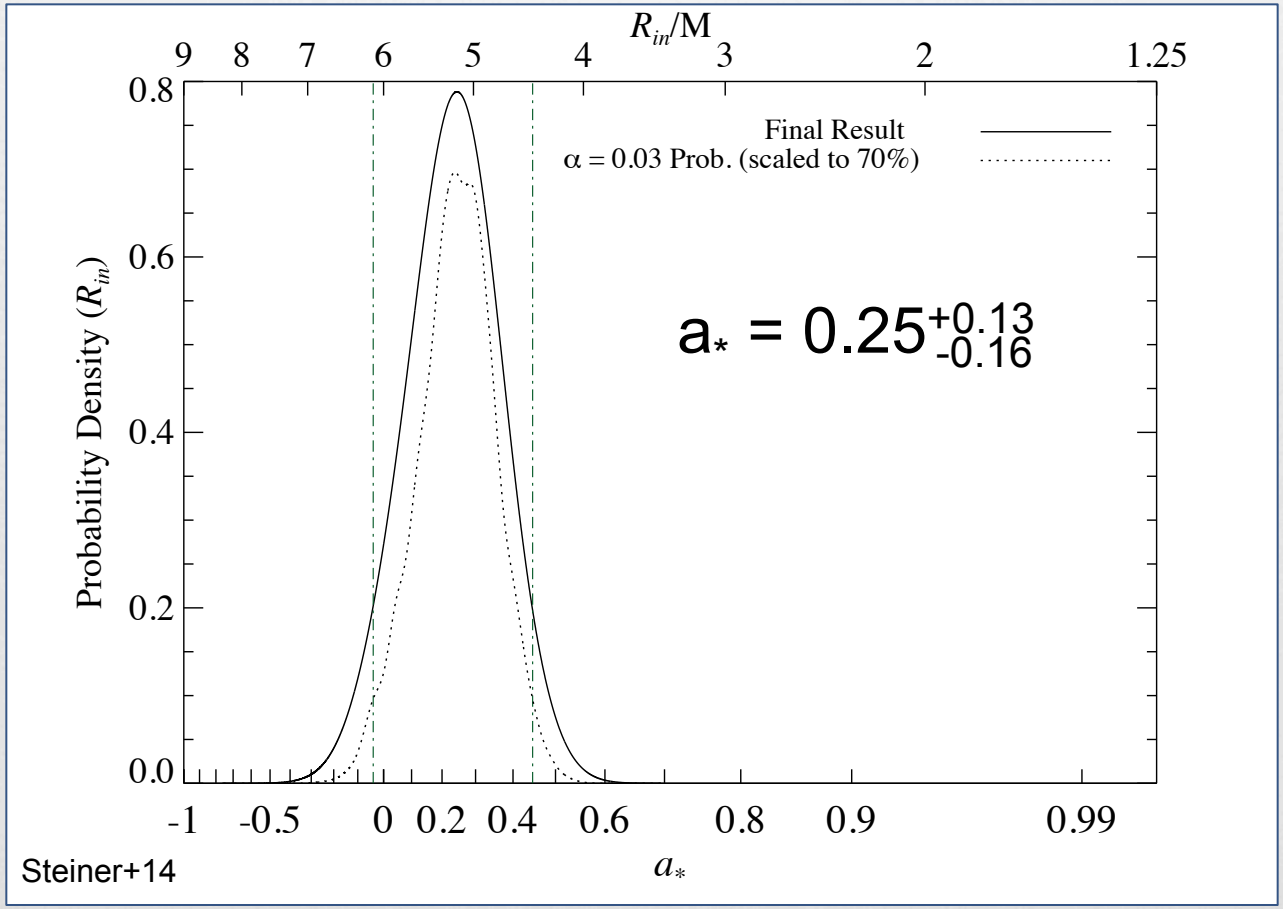




$R_{ISCO}$ and M ⟶ $a_*$

# Using many of these …



# Get Spin (LMC X-3)

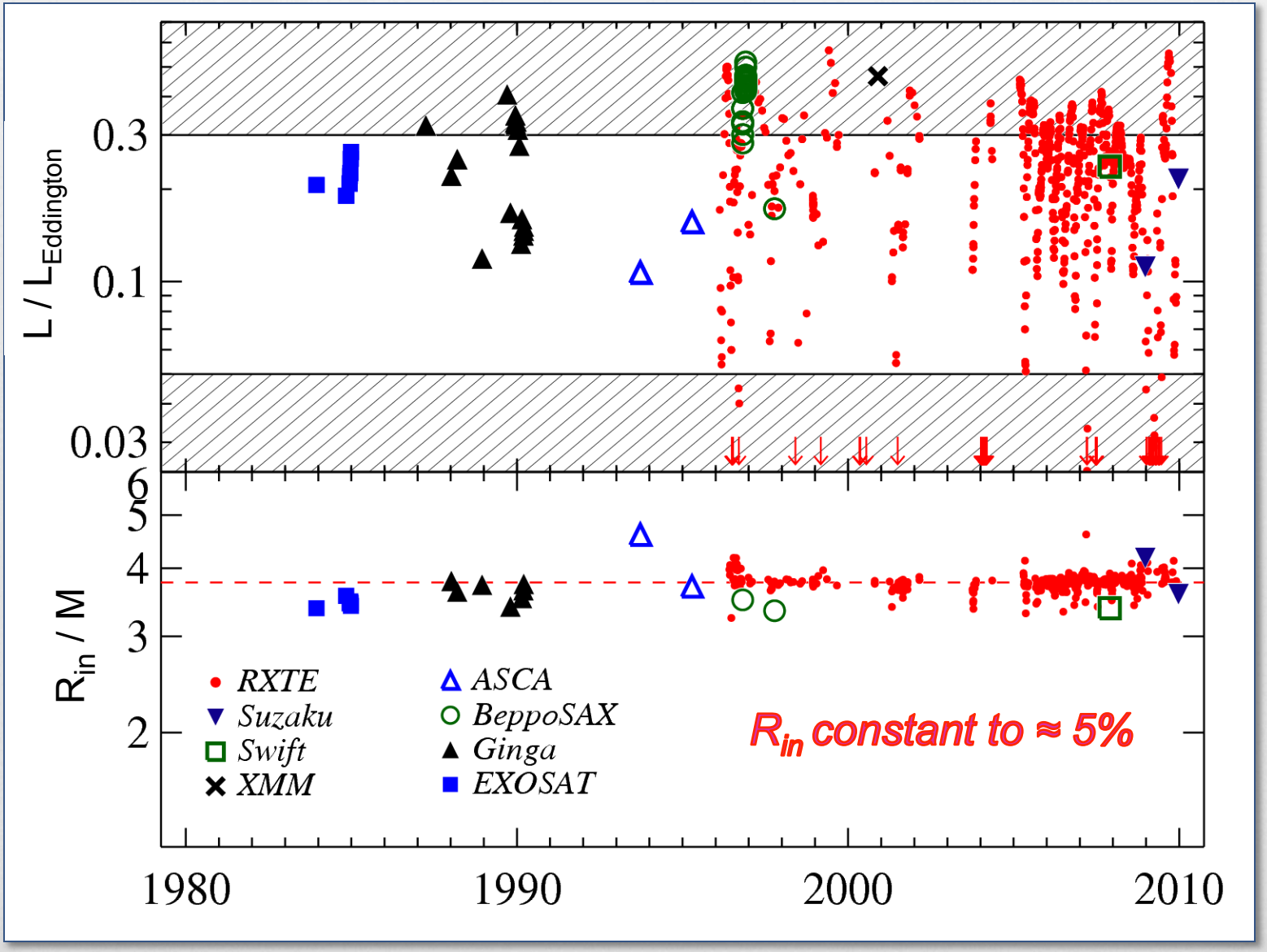


# How Well Does it Work in Practice?

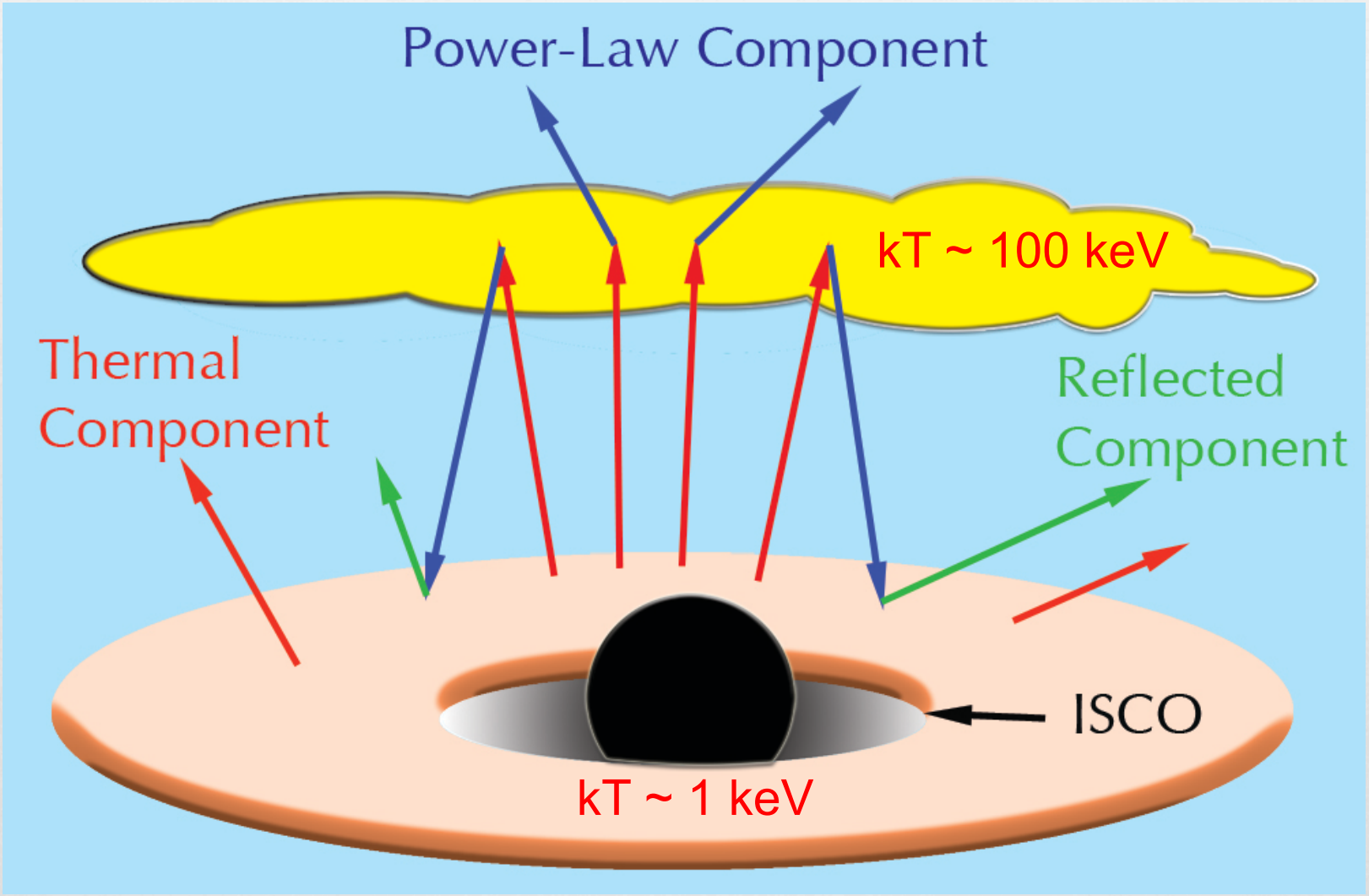
- Extremely well
- Multiple independent observations of the same BH
  - at different luminosities (up to 30% $L_{Eddington}$)
  - with different instruments
  - separated by many years

# LMC X-3: 1983-2009

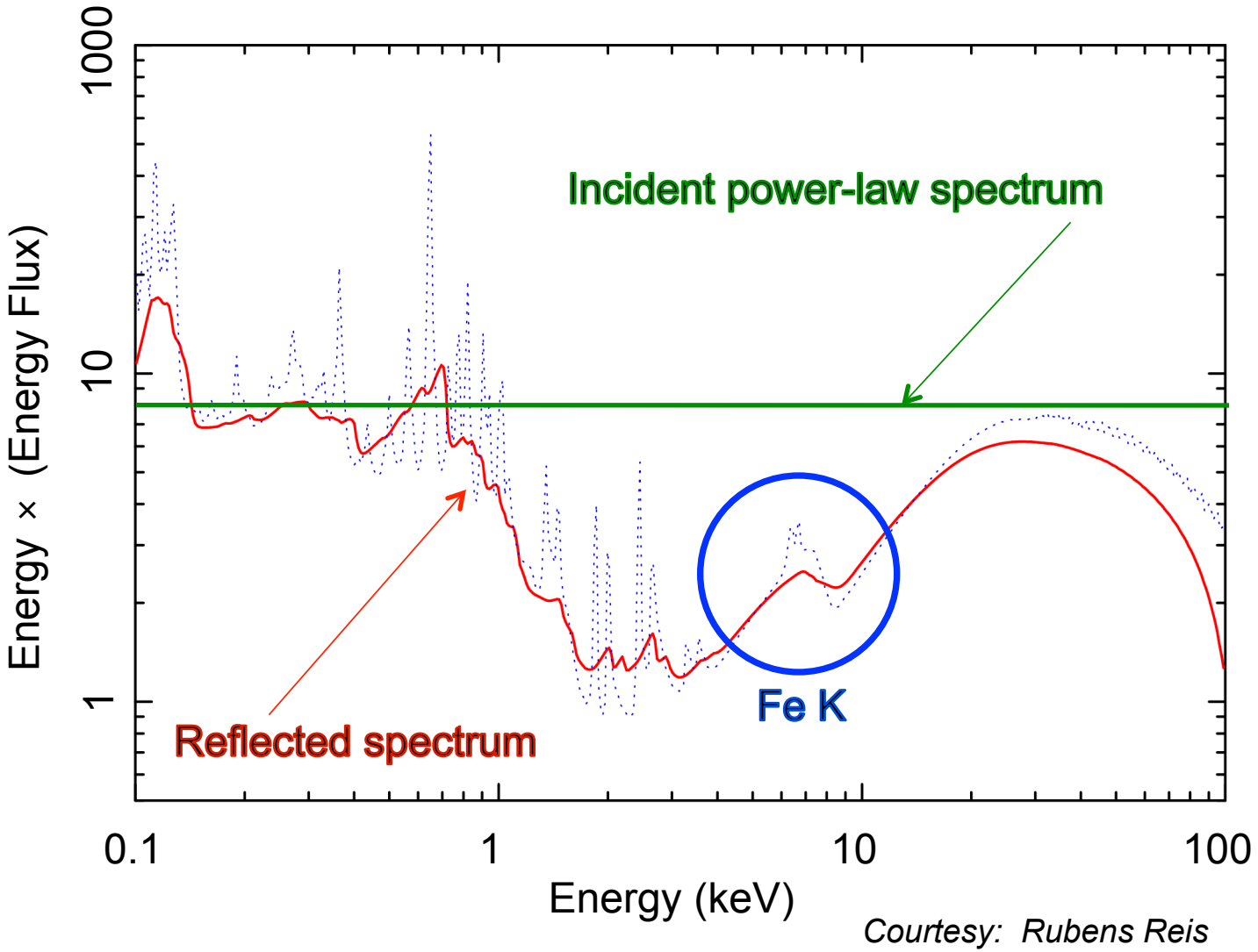
Steiner et al. 2010



# Reflection / Iron Line Method

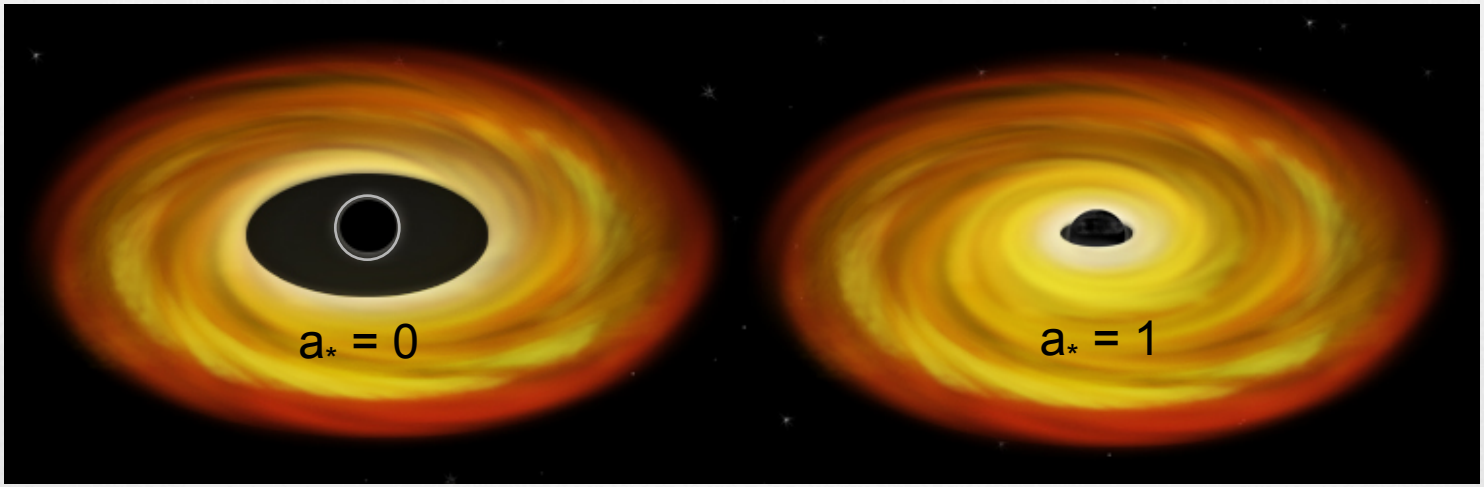

Power-Law Component
kT ~ 100 keV
Thermal
Component
Reflected
Component
ISCO
kT ~ 1 keV

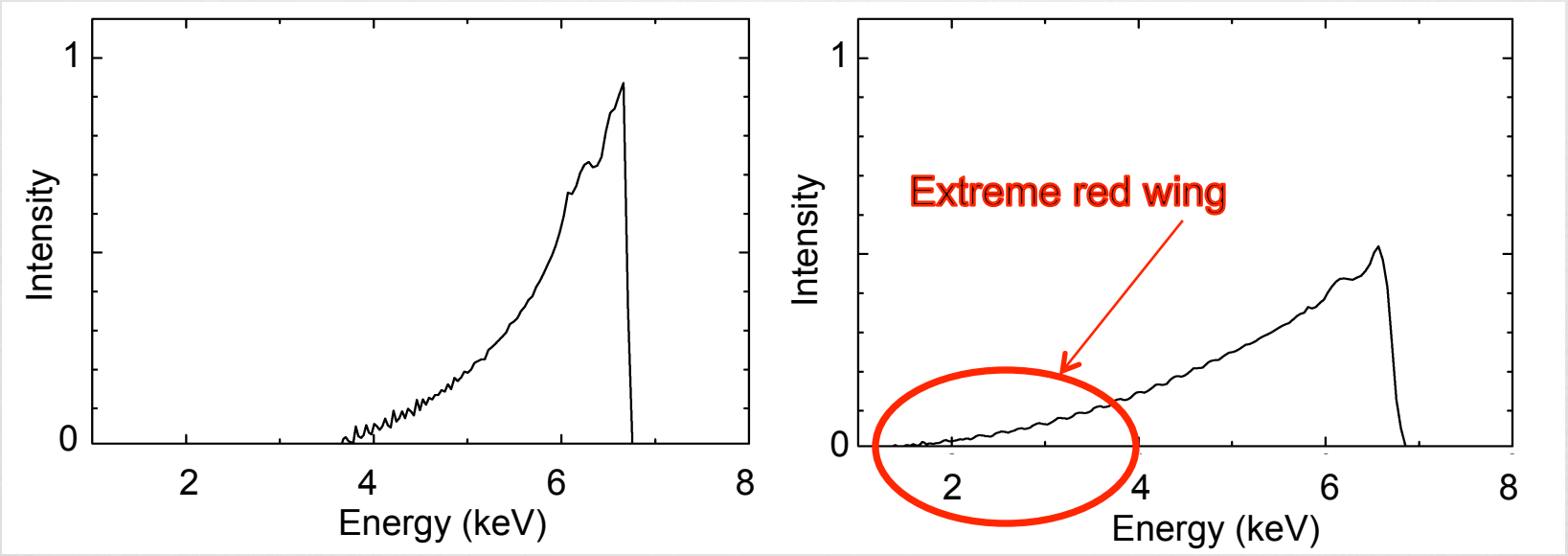
# Coronal X-ray Spectrum "Reflected" by the Disk

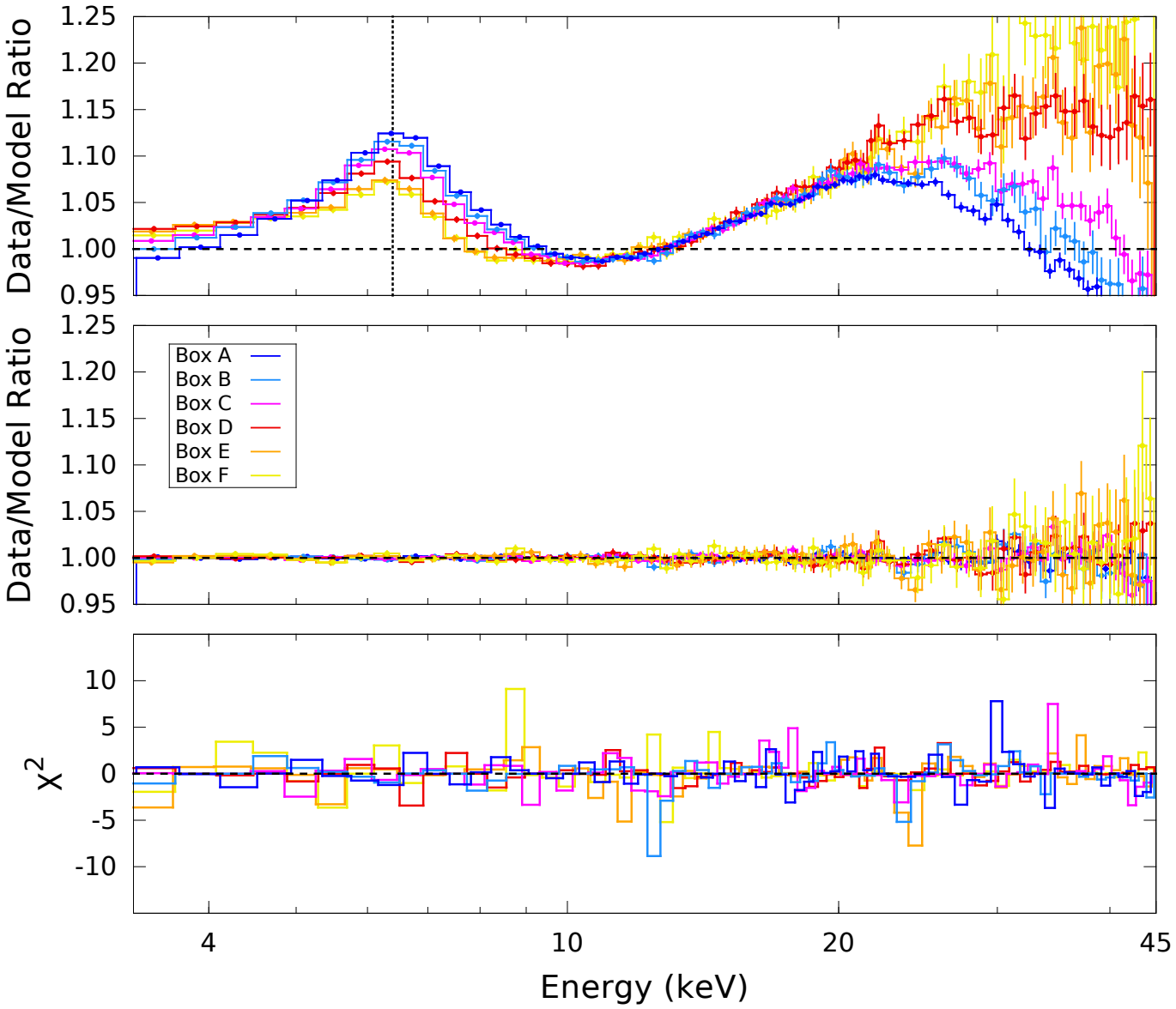



*Courtesy: Rubens Reis*

# Dependence of Fe K Line Profile on Spin






Garcia et al. 2015

# spin results from the last decade

| 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 |
| 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 |

# What comes next?

# Burning Questions

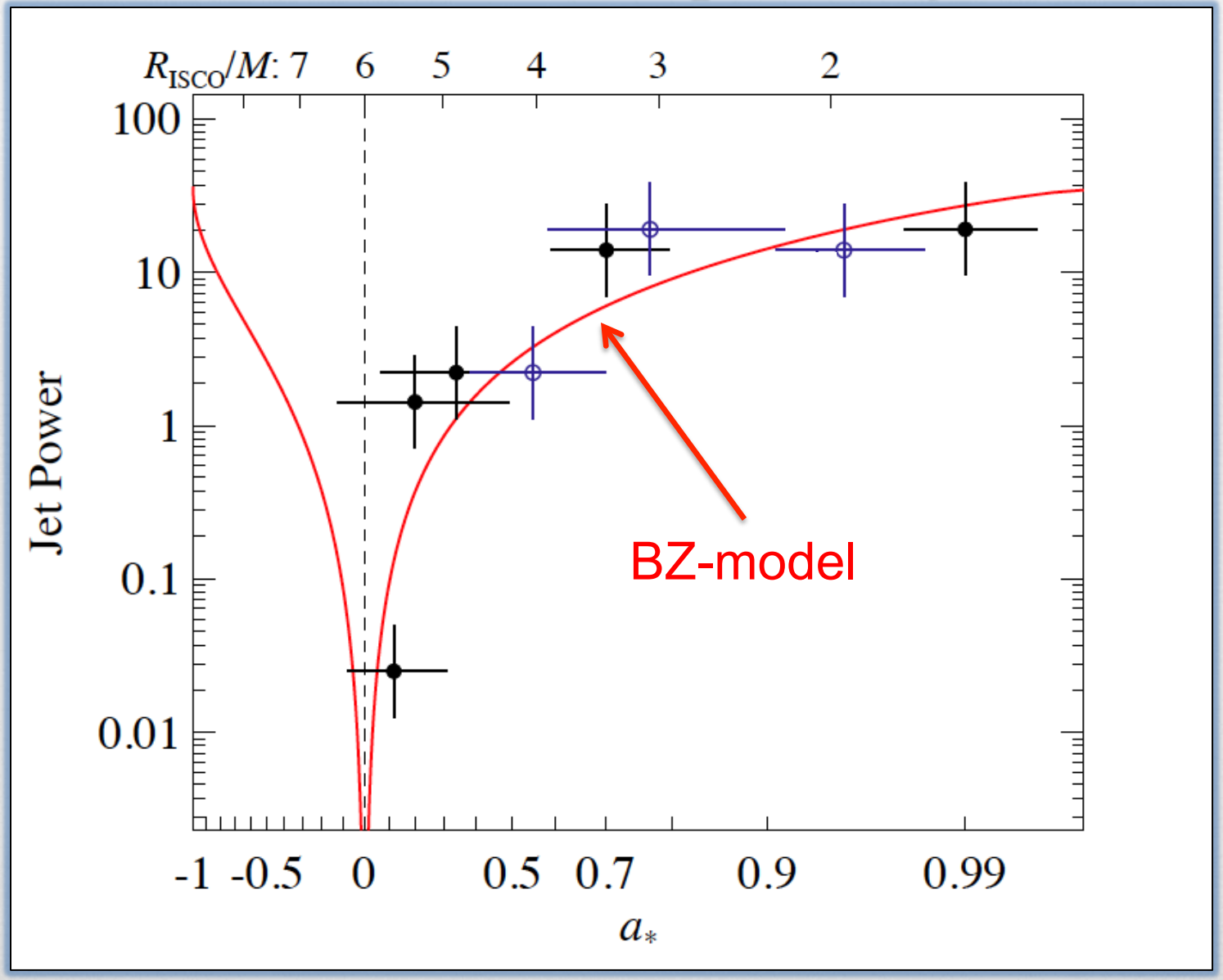
- How well do the two methods agree?
- What produces the spin distribution?
- Is there a link between spin and jets?

**Challenges**

- Next gen, fully consistent Comptonized disk & reflection models
- Can we use this approach to test GR?

| 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 |
| 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 |

# A link between spin and jets




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

# Summary

- Groups are employing and comparing two major methods currently used for measuring stellar-mass BH spins
  - Continuum fitting & reflection modeling
  - consistent within ~2 sigma

- The foundation for both methods is empirically supported by the existence of a constant $R_{in}$.
  - Stability of $R_{in}$ for LMC X-3

- About 20 stellar BH spins measured so far. Can hope to double the sample.

- Controversial evidence that jets are powered by BH spin

- More to come!