Title: Measuring Black Hole Spin

Date: Feb 19, 2009 11:00 AM

URL: http://pirsa.org/09020045

Abstract: An astrophysical black hole is completely described with just two parameters: its mass and its dimensionless spin. A few dozen black holes have mass estimates, but until recently none had a reliable spin estimate. The first spins have now been measured for black holes in X-ray binaries.

MEASURING BLACK HOLE SPIN

Ramesh Narayan

MEASURING BLACK HOLE SPIN

Ramesh Narayan

A Black Hole is Extremely Simple

- Mass: M
- Spin: a_* $(J=a_*GM^2/c)$
- Charge: Q (~ 0)

We would like to measure these parameters

X-ray Binaries

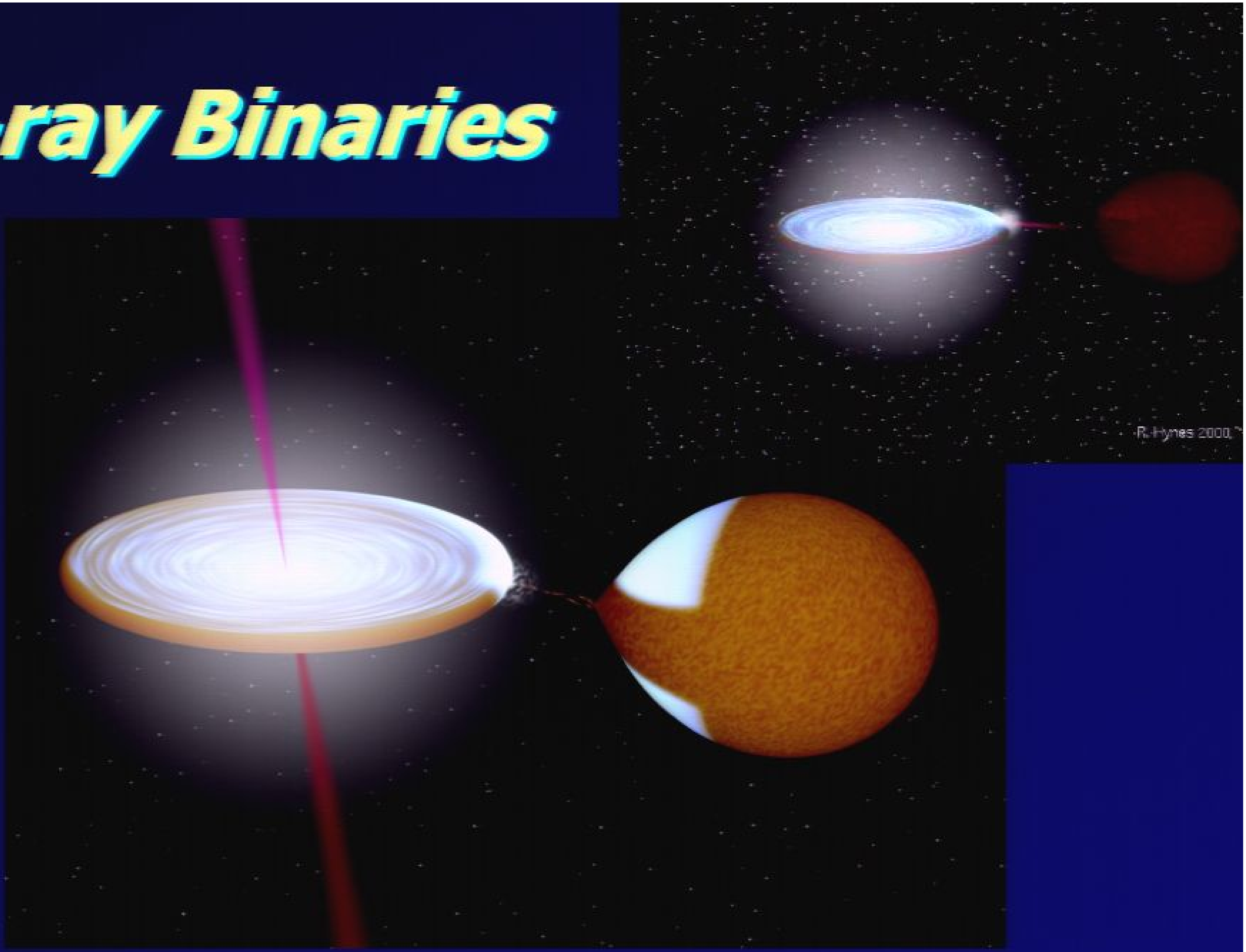


Image credit: Robert Hynes

X-ray Binaries

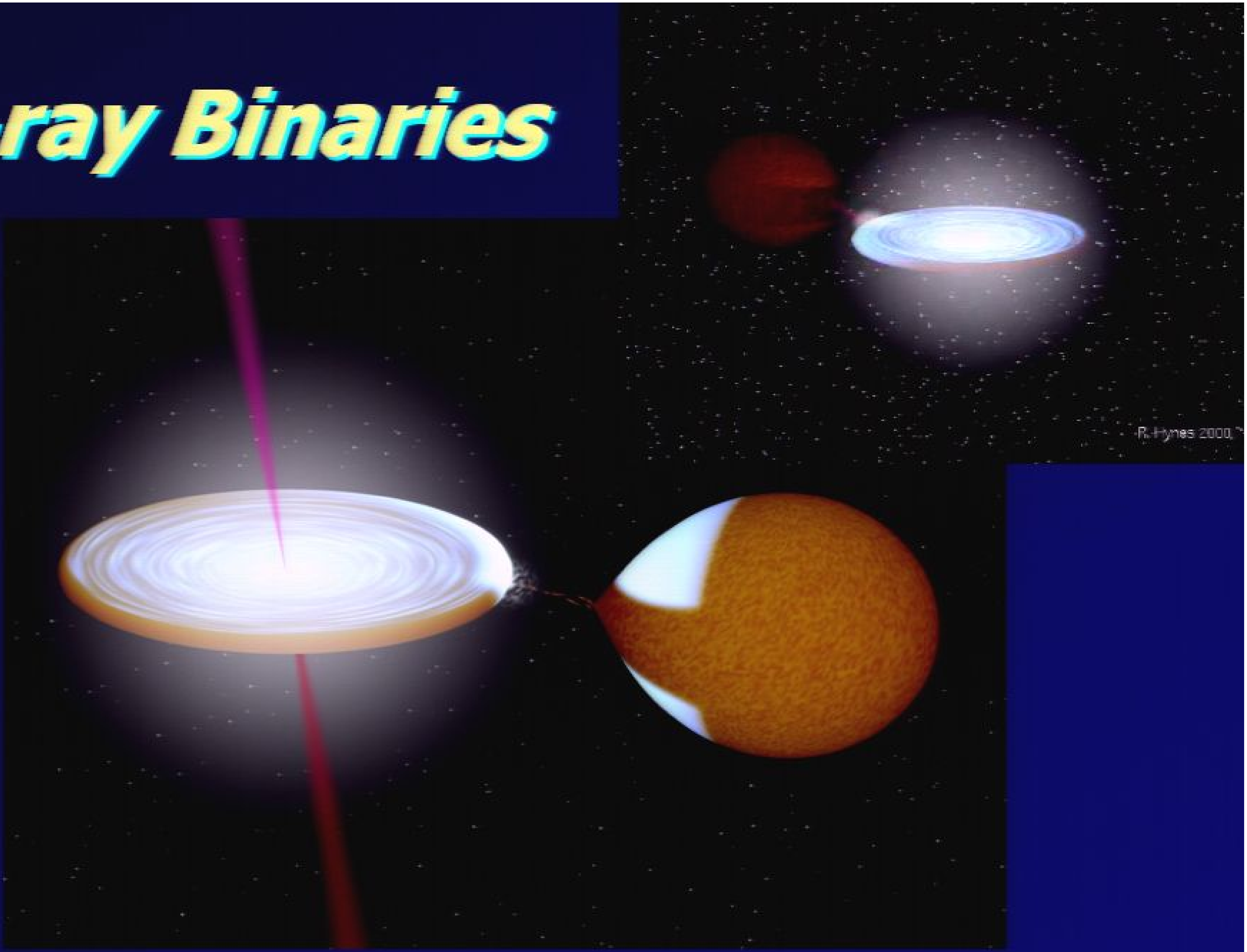


Image credit: Robert Hynes

X-ray Binaries

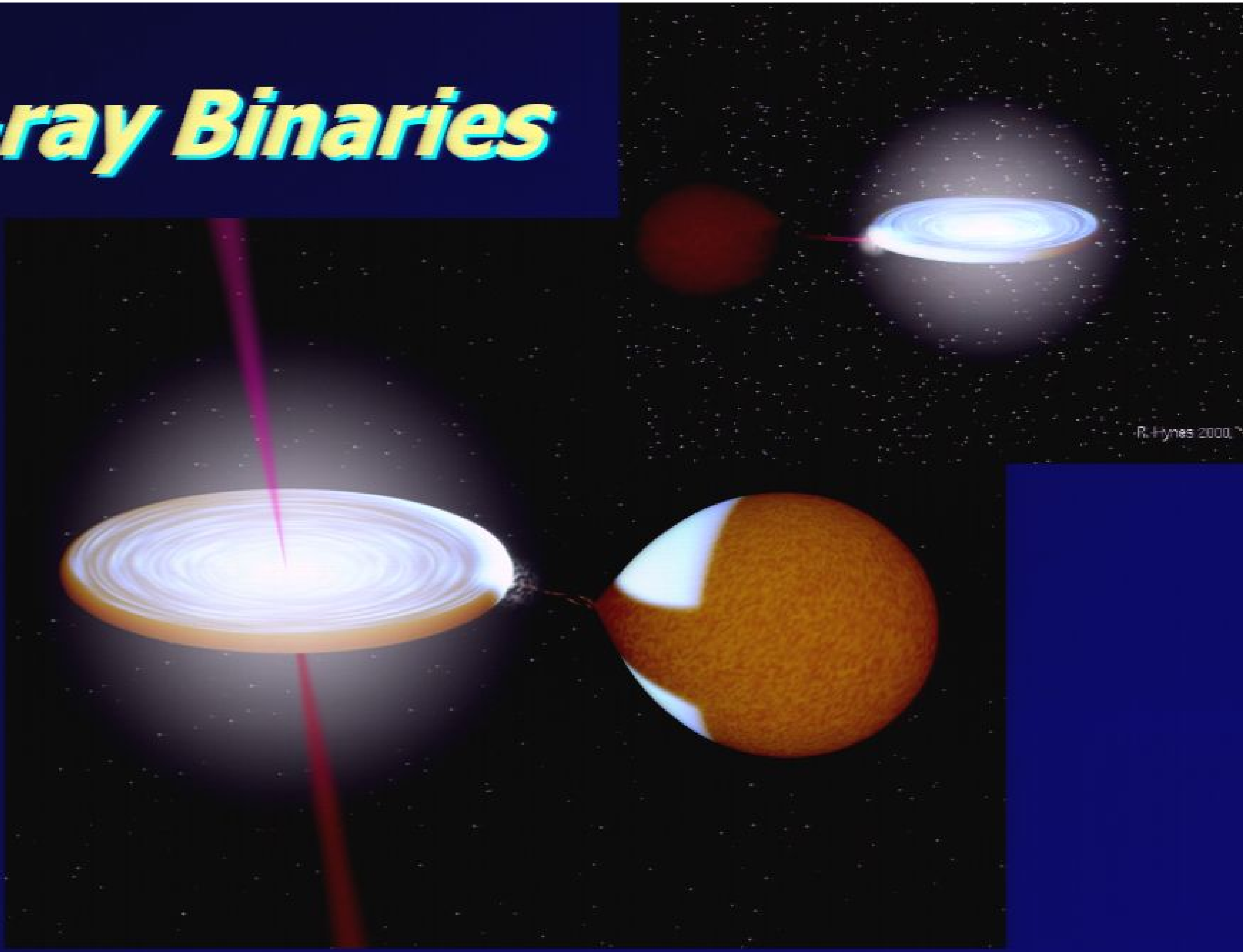


Image credit: Robert Hynes

X-ray Binaries

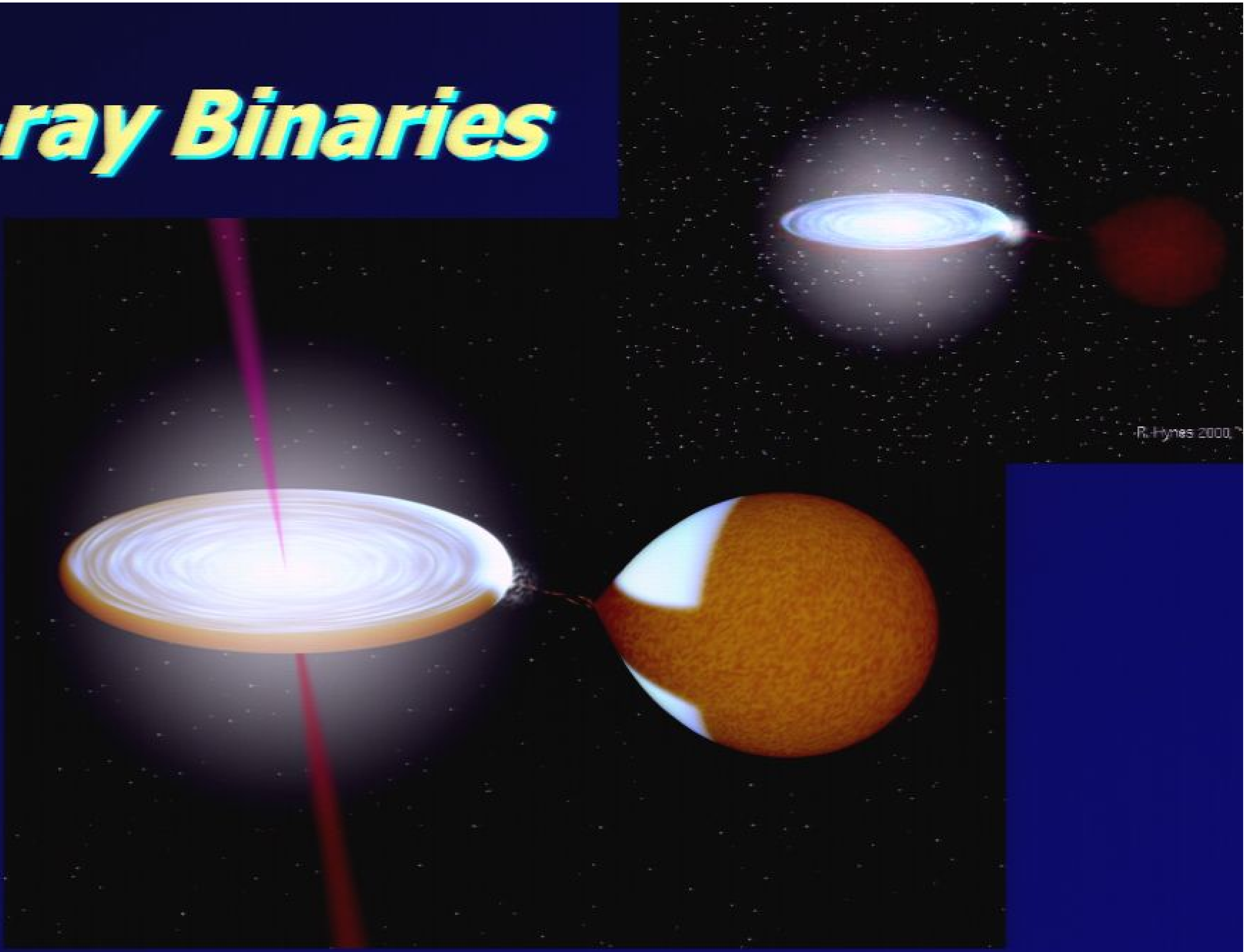


Image credit: Robert Hynes

X-ray Binaries

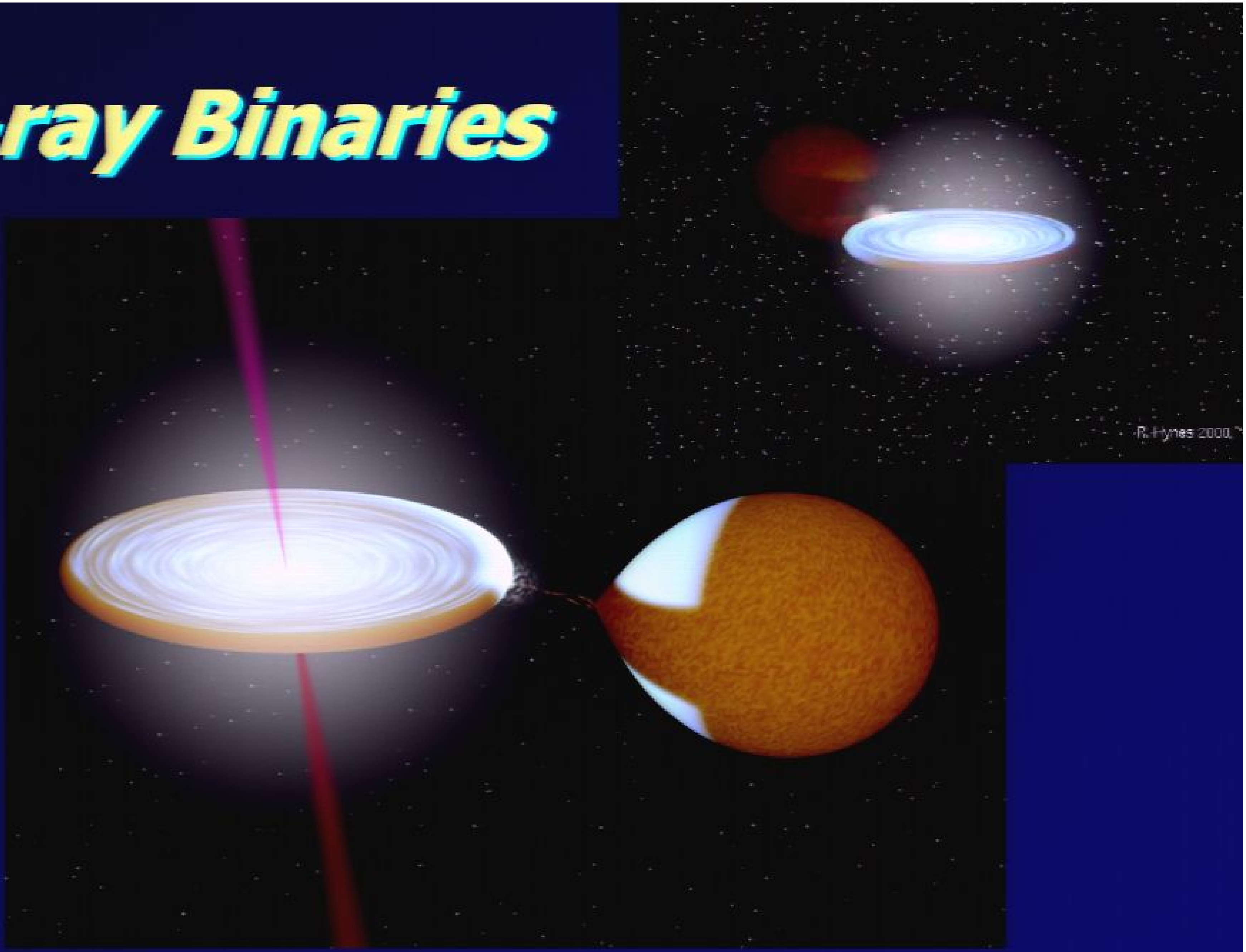


Image credit: Robert Hynes

X-ray Binaries

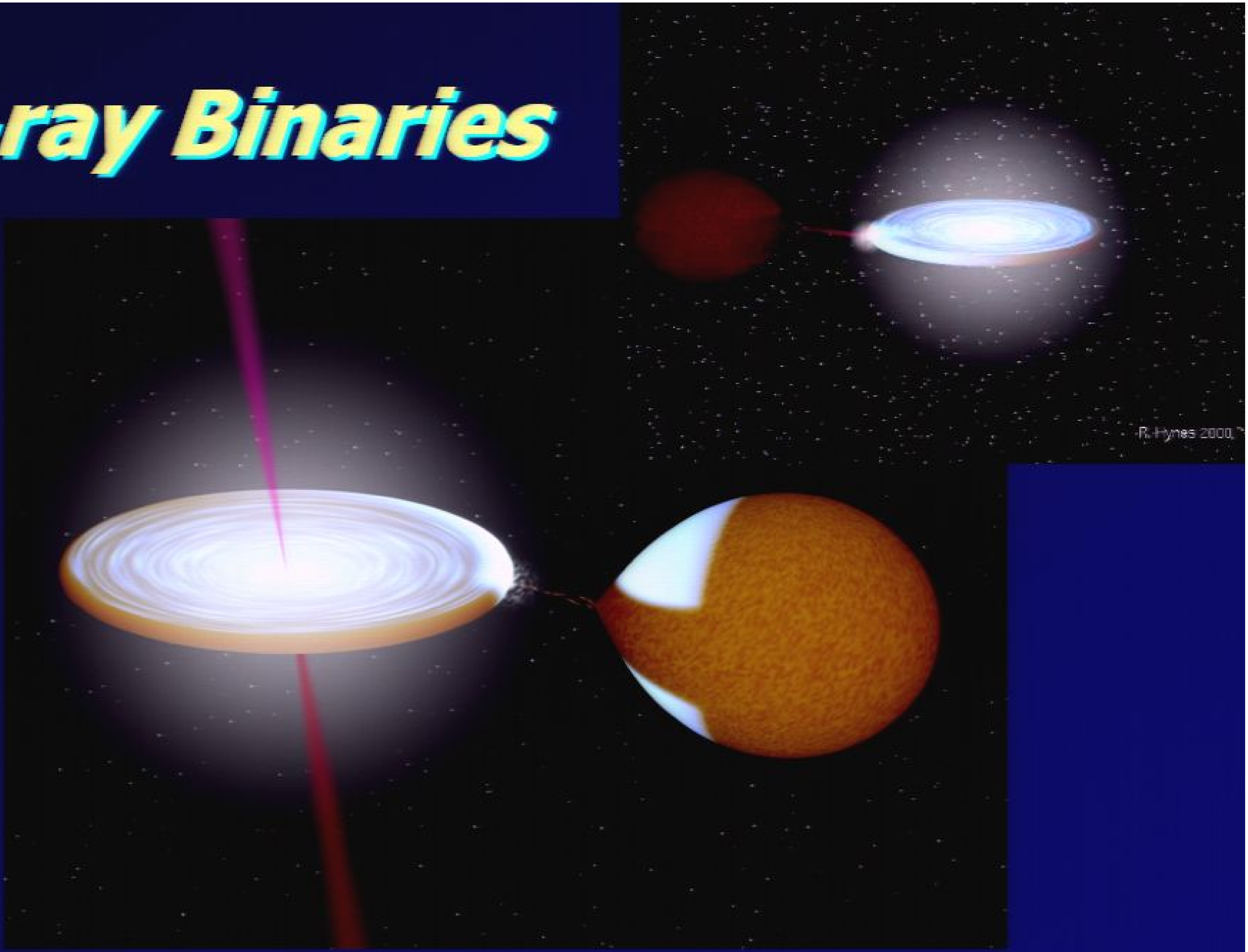


Image credit: Robert Hynes

X-ray Binaries

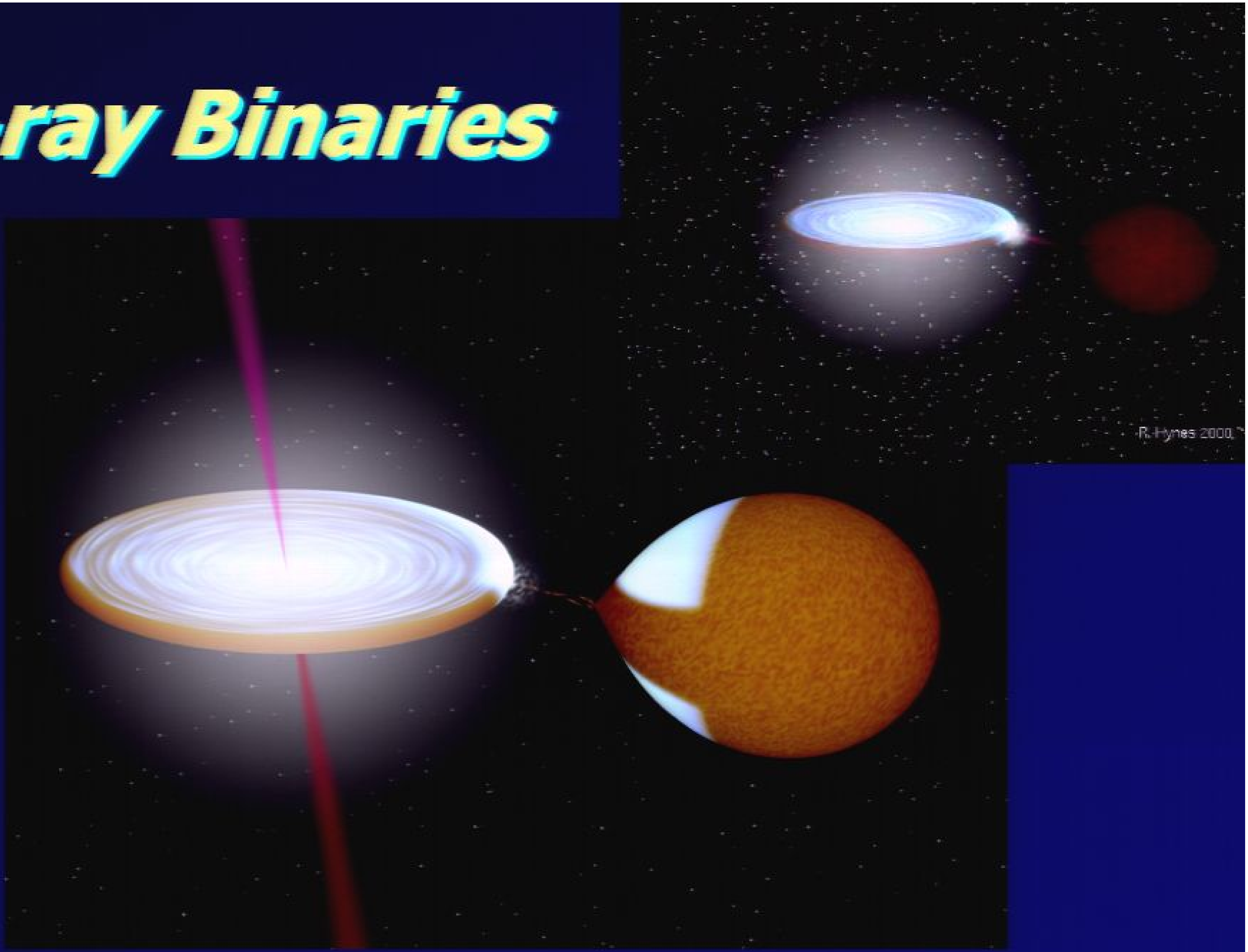


Image credit: Robert Hynes

Binary	Likely $M_X(M_\odot)$	$f(M)=M_{X,min}(M_\odot)$
LMC X-1	4.0—10.0	0.13±0.05
Cyg X-1	6.8—13.3	0.244 ±0.005
4U1543-47	7.4—11.4	0.25 ± 0.01
M33 X-7	14.2—17.1	0.46 ± 0.08
GRO J0422+32	3.2—13.2	1.19 ± 0.02
LMC X-3	5.9—9.2	2.3 ± 0.3
A0620-00	3.3—12.9	2.72 ± 0.06
GRO J1655-40	6.0—6.6	2.73 ± 0.09
XTE J1650-500	>2.2	2.73±0.56
GRS 1124-683	6.5—8.2	3.01 ± 0.15
SAX J1819.3-2525	6.8—7.4	3.13 ± 0.13
GRS 1009-45	6.3—8.0	3.17 ± 0.12
H1705-250	5.6—8.3	4.86 ± 0.13
GS 2000+250	7.1—7.8	5.01± 0.12
GS 1354-64	>5.4	5.75±0.30
GX 339-4	>5.3	5.8±0.5
GS 2023+338	10.1—13.4	6.08 ± 0.06
XTE J1118+480	6.5—7.2	6.1 ± 0.3
XTE J1550-564	8.4—10.8	6.86 ± 0.71
XTE J1859+226	7.6—12.0	7.4 ± 1.1
GRS 1915+105	10--18	9.5 ± 3.0

Binary	Likely $M_X(M_\odot)$	$f(M)=M_{X,min}(M_\odot)$
LMC X-1	4.0—10.0	0.13 ± 0.05
Cyg X-1	6.8—13.3	0.244 ± 0.005
4U1543-47	7.4—11.4	0.25 ± 0.01
M33 X-7	14.2—17.1	0.46 ± 0.08
GRO J0422+32	3.2—13.2	1.19 ± 0.02
LMC X-3	5.9—9.2	2.3 ± 0.3
A0620-00	3.3—12.9	2.72 ± 0.06
GRO J1655-40	6.0—6.6	2.73 ± 0.09
XTE J1650-500	>2.2	2.73 ± 0.56
GRS 1124-683	6.5—8.2	3.01 ± 0.15
SAX J1819.3-2525	6.8—7.4	3.13 ± 0.13
GRS 1009-45	6.3—8.0	3.17 ± 0.12
H1705-250	5.6—8.3	4.86 ± 0.13
GS 2000+250	7.1—7.8	5.01 ± 0.12
GS 1354-64	>5.4	5.75 ± 0.30
GX 339-4	>5.3	5.8 ± 0.5
GS 2023+338	10.1—13.4	6.08 ± 0.06
XTE J1118+480	6.5—7.2	6.1 ± 0.3
XTE J1550-564	8.4—10.8	6.86 ± 0.71
XTE J1859+226	7.6—12.0	7.4 ± 1.1
GRS 1915+105	10--18	9.5 ± 3.0

X-ray Binaries

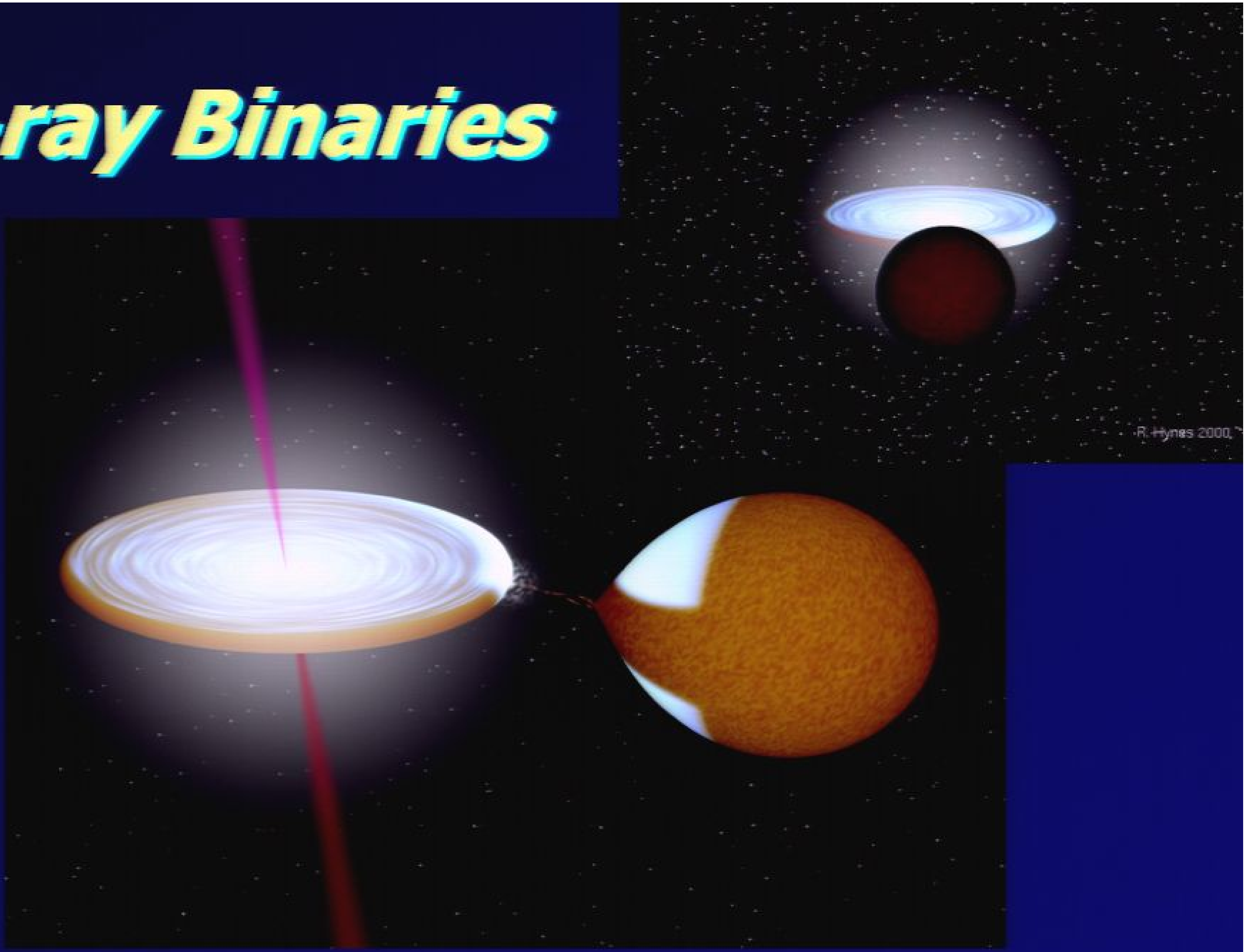
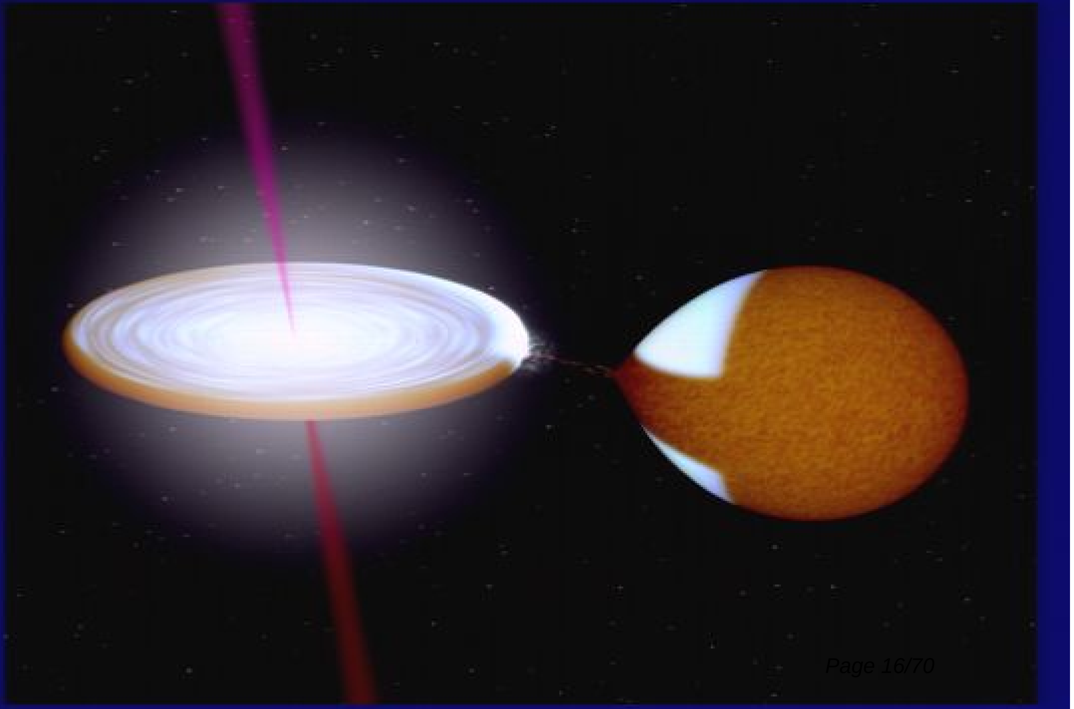


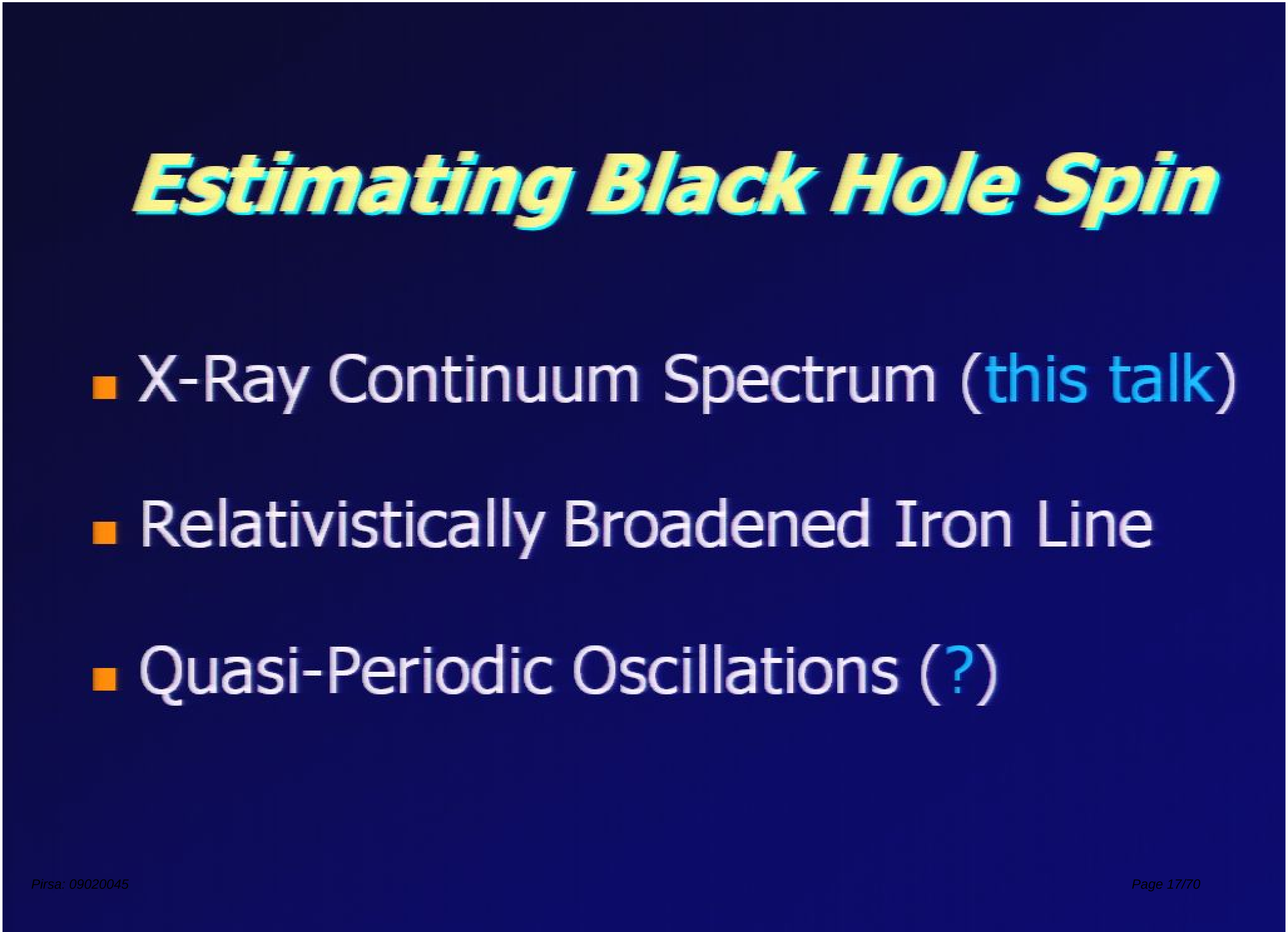
Image credit: Robert Hynes

Binary	Likely $M_X(M_\odot)$	$f(M)=M_{X,min}(M_\odot)$
LMC X-1	4.0—10.0	0.13±0.05
Cyg X-1	6.8—13.3	0.244 ±0.005
4U1543-47	7.4—11.4	0.25 ± 0.01
M33 X-7	14.2—17.1	0.46 ± 0.08
GRO J0422+32	3.2—13.2	1.19 ± 0.02
LMC X-3	5.9—9.2	2.3 ± 0.3
A0620-00	3.3—12.9	2.72 ± 0.06
GRO J1655-40	6.0—6.6	2.73 ± 0.09
XTE J1650-500	>2.2	2.73±0.56
GRS 1124-683	6.5—8.2	3.01 ± 0.15
SAX J1819.3-2525	6.8—7.4	3.13 ± 0.13
GRS 1009-45	6.3—8.0	3.17 ± 0.12
H1705-250	5.6—8.3	4.86 ± 0.13
GS 2000+250	7.1—7.8	5.01± 0.12
GS 1354-64	>5.4	5.75±0.30
GX 339-4	>5.3	5.8±0.5
GS 2023+338	10.1—13.4	6.08 ± 0.06
XTE J1118+480	6.5—7.2	6.1 ± 0.3
XTE J1550-564	8.4—10.8	6.86 ± 0.71
XTE J1859+226	7.6—12.0	7.4 ± 1.1
GRS 1915+105	10--18	9.5 ± 3.0

Measuring Mass is Easy Spin is Hard

- Mass can be measured in the Newtonian limit using test particles (e.g., stellar companion) at large radii
- Spin has no Newtonian effect
- To measure spin we must be in the regime of strong gravity, where **General Relativity** operates
- Need test particles at small radii
- Fortunately, we have the gas in the accretion disk…





Estimating Black Hole Spin

- X-Ray Continuum Spectrum (this talk)
- Relativistically Broadened Iron Line
- Quasi-Periodic Oscillations (?)

Our Team

Jeff McClintock **Ramesh Narayan**

Shane Davis, Lijun Gou, Li-Xin Li,

Jifeng Liu, Jon McKinney,

Jerry Orosz, Mark Reid, Ron Remillard,

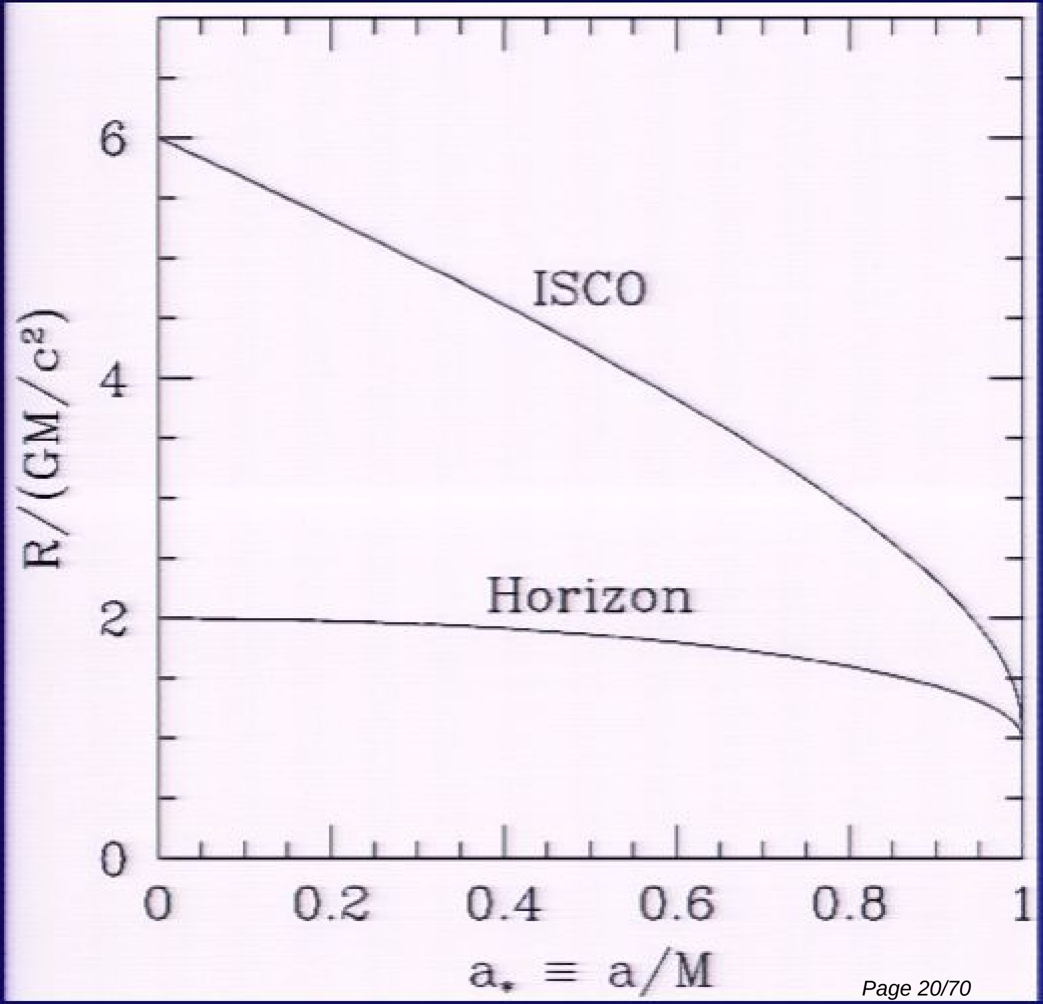
Rebecca Shafee, Jack Steiner

Circular Orbits

- In Newtonian gravity, stable circular orbits are available around a point mass at all R
- This is no longer true in General Relativity
- For a non-spinning BH (Schwarzschild metric), stable orbits allowed only down to $R=6M$
- This is the innermost stable circular orbit, or **ISCO**
- The radius of the ISCO (R_{ISCO}) depends on the BH spin

Innermost Stable Circular Orbit (ISCO)

- R_{ISCO}/M depends on the value of a_*
- If we can measure R_{ISCO}, we will obtain a_*
- Note factor of 6 variation in R_{ISCO}



Continuum Method: Basic Idea

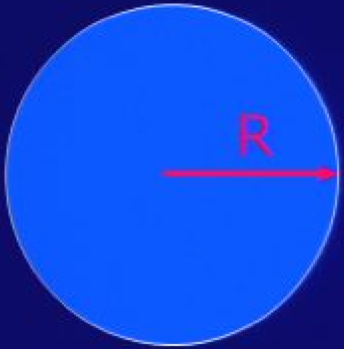
Measure Radius of the Hole by estimating the area of the bright inner disk

Zhang et al. (1997); Shafee et al. (2006); Davis et al. (2006); McClintock et al. (2006); Middleton et al. 2006; Liu et al. (2008);...

Measuring the Radius of a Star

- Measure the flux F received from the star
- Measure the temperature T (from spectrum)
- Then, using blackbody radiation theory:

$$\boxed{\begin{gathered} L = 4\pi D^2 F = 4\pi R^2 \sigma T^4 \\ R = \sqrt{\frac{F}{\sigma}}\frac{D}{T^2} \end{gathered}}$$



- If we know F, T and D, we directly obtain R

Measuring the Radius of the Disk Inner Edge

- Here we want the radius of the 'hole' in the disk emission
- Same principle as before
- From F_X, T_X and D, we get R_{ISCO} (some geometrical factors: inclination i)
- From R_{ISCO}/M get a_*
- This is the idea, but in practice need to include many relativistic effects, spectral hardening, etc.

Zhang et al. (1997); Li et al. (2005); Shafee et al. (2006); McClintock et al. (2006); Davis et al. (2006); Liu et al. (2007); ...

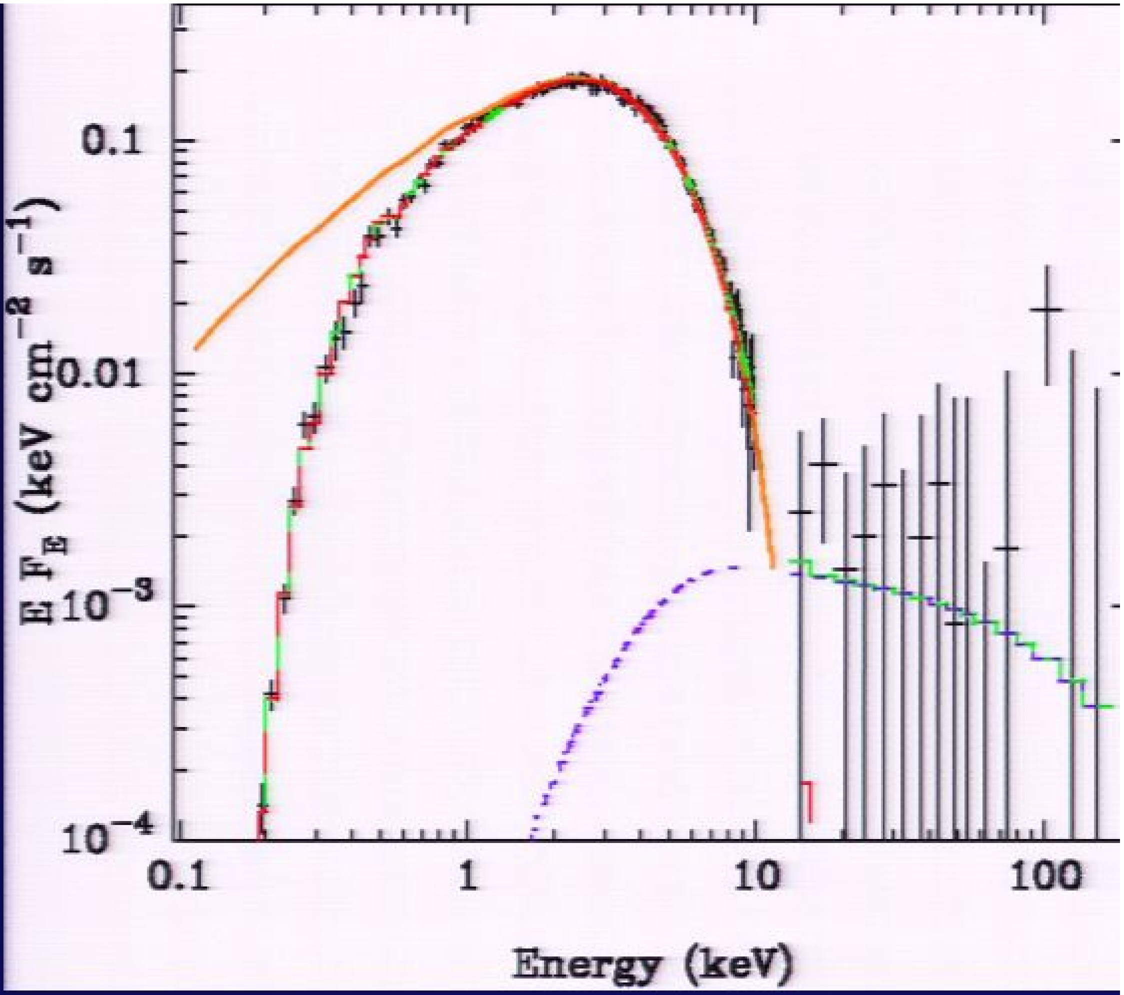
Blackbody-Like Thermal Spectral State

- BH XRBs are sometimes found in the Thermal State (or High Soft State)
- Soft blackbody-like spectrum, which is consistent with thin disk model
- Only a weak power-law tail
- Perfect for quantitative modeling
- **XSPEC**: diskbb, ezdiskbb, diskpn, **KERRBB**, **BHSPEC**

Blackbody-Like Spectral State in BH Accretion Disk

LMC X-3: Beppo-SAX
(Davis, Done & Blaes 2006)

Up to 10 keV, the only component seen is the disk
Beyond that, a weak PL tail



- Perfect for estimating inner radius of accretion disk → BH spin
- Just need to estimate L_X, T_X (and N_H) from X-ray continuum
- Use full relativistic model (Novikov-Thorne 1973; KERRBB, Li et al. 2005)

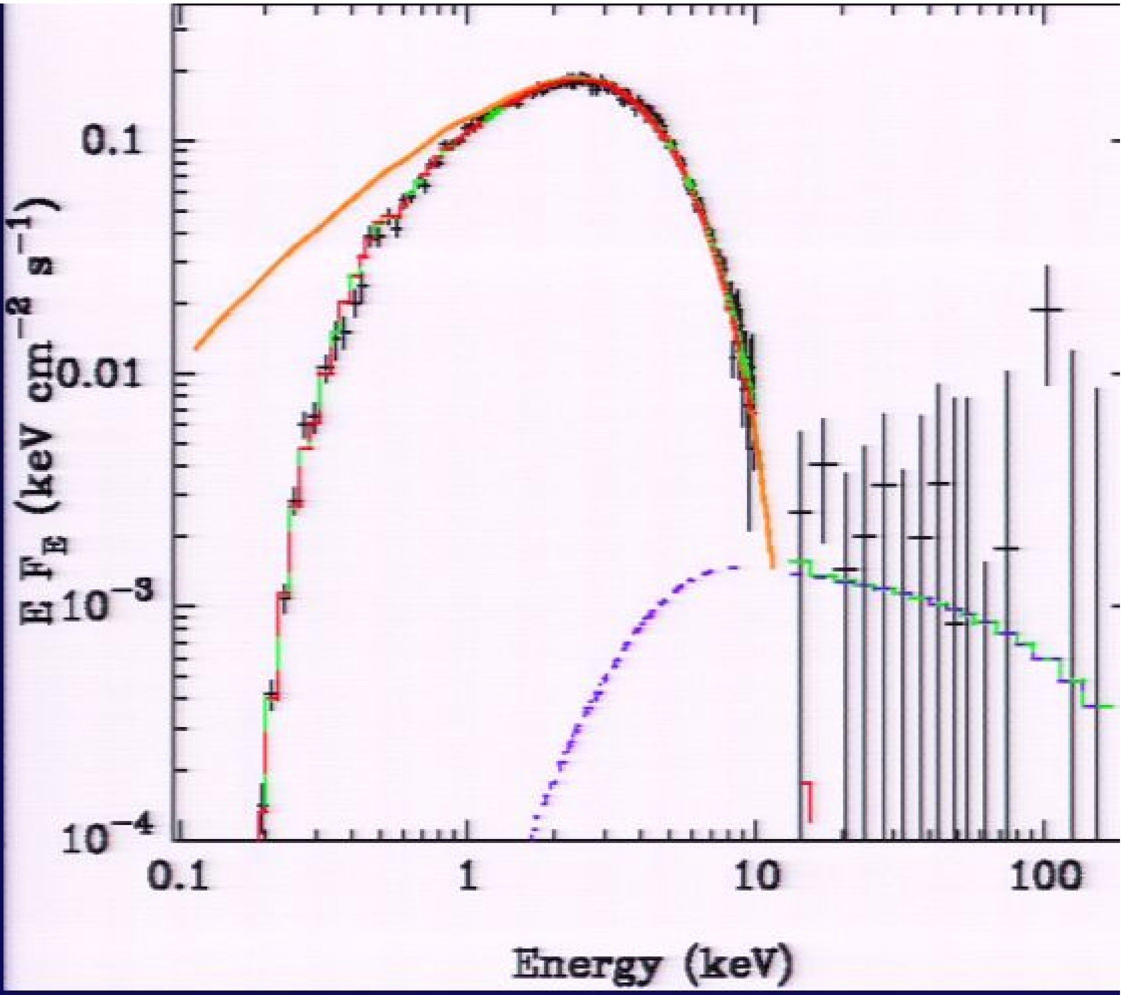
Blackbody-Like Thermal Spectral State

- BH XRBs are sometimes found in the Thermal State (or High Soft State)
- Soft blackbody-like spectrum, which is consistent with thin disk model
- Only a weak power-law tail
- Perfect for quantitative modeling
- **XSPEC**: diskbb, ezdiskbb, diskpn, **KERRBB**, **BHSPEC**

Blackbody-Like Spectral State in BH Accretion Disk

LMC X-3: Beppo-SAX
(Davis, Done & Blaes 2006)

Up to 10 keV, the only component seen is the disk
Beyond that, a weak PL tail

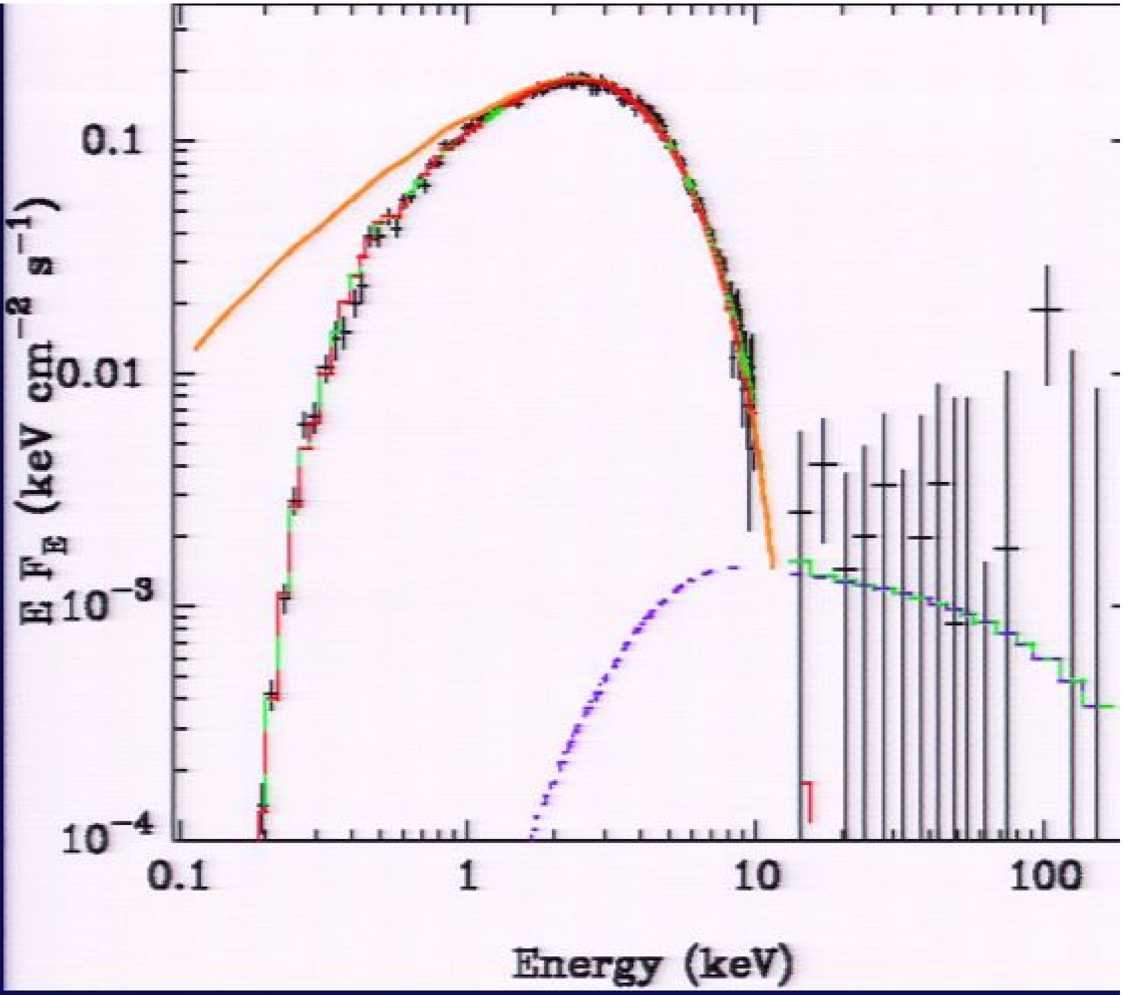


- Perfect for estimating inner radius of accretion disk → BH spin
- Just need to estimate L_X, T_X (and N_H) from X-ray continuum
- Use full relativistic model (Novikov-Thorne 1973; KERRBB, Li et al. 2005)

Blackbody-Like Spectral State in BH Accretion Disk

LMC X-3: Beppo-SAX
(Davis, Done & Blaes 2006)

Up to 10 keV, the only component seen is the disk
Beyond that, a weak PL tail



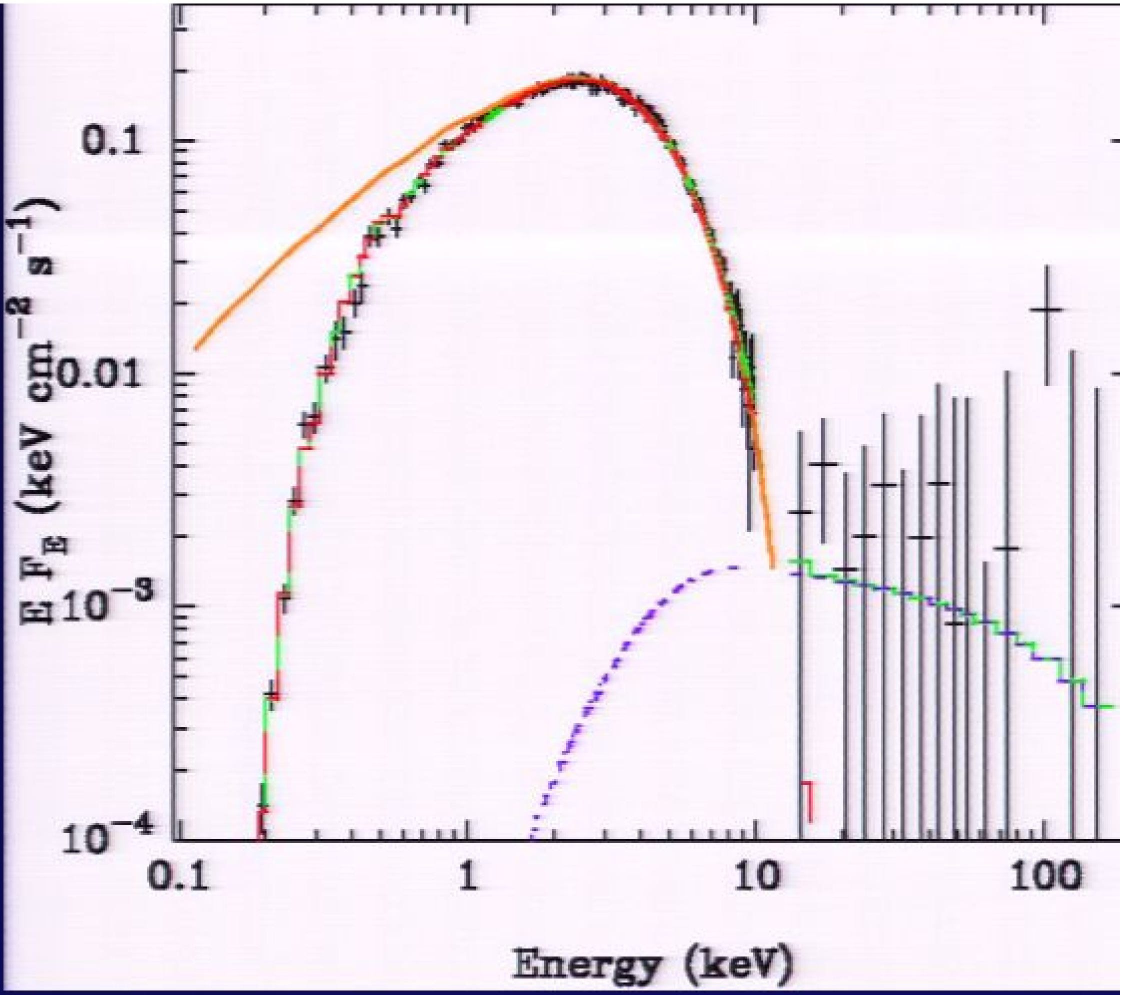
- Perfect for estimating inner radius of accretion disk → BH spin
- Just need to estimate L_X, T_X (and N_H) from X-ray continuum
- Use full relativistic model (Novikov-Thorne 1973; KERRBB, Li et al. 2005)

50

Blackbody-Like Spectral State in BH Accretion Disk

LMC X-3: Beppo-SAX
(Davis, Done & Blaes 2006)

Up to 10 keV, the only component seen is the disk
Beyond that, a weak PL tail



- Perfect for estimating inner radius of accretion disk → BH spin
- Just need to estimate L_X, T_X (and N_H) from X-ray continuum
- Use full relativistic model (Novikov-Thorne 1973; KERRBB, Li et al. 2005)

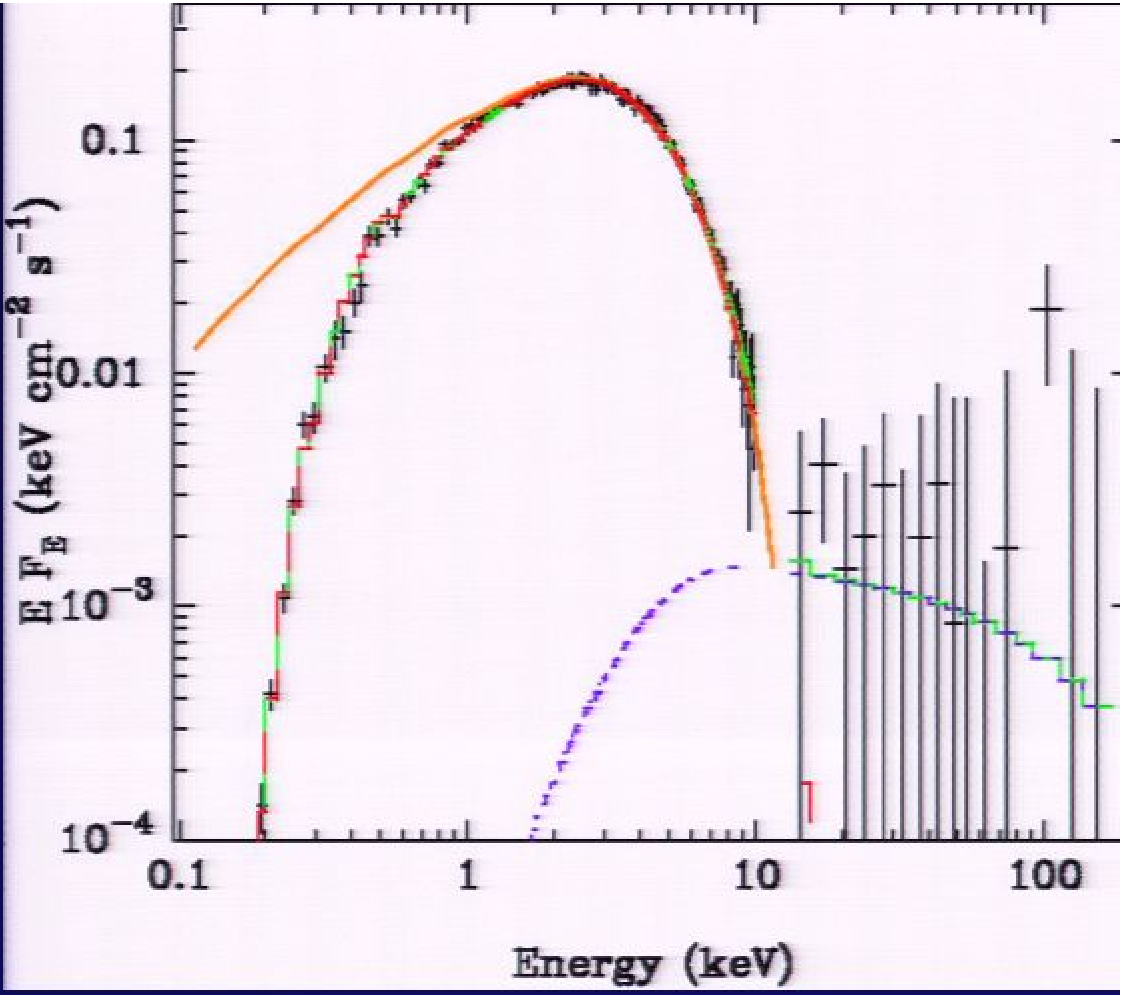
Blackbody-Like Thermal Spectral State

- BH XRBs are sometimes found in the Thermal State (or High Soft State)
- Soft blackbody-like spectrum, which is consistent with thin disk model
- Only a weak power-law tail
- Perfect for quantitative modeling
- **XSPEC**: diskbb, ezdiskbb, diskpn, **KERRBB**, **BHSPEC**

Blackbody-Like Spectral State in BH Accretion Disk

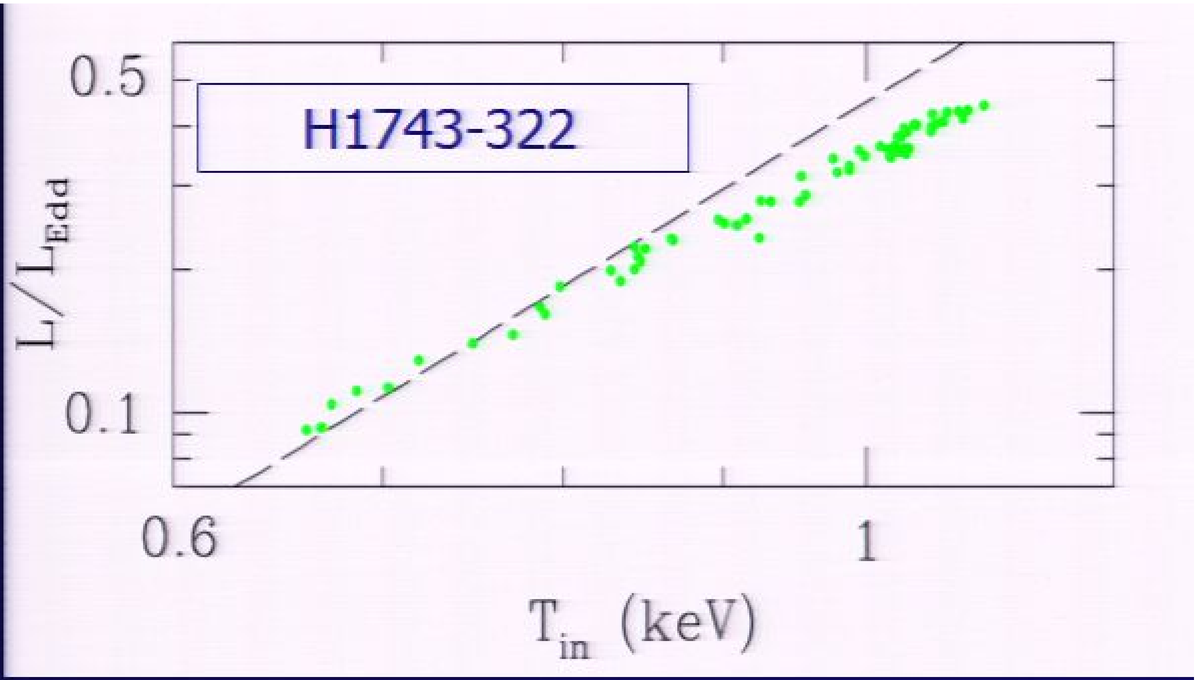
LMC X-3: Beppo-SAX
(Davis, Done & Blaes 2006)

Up to 10 keV, the only component seen is the disk
Beyond that, a weak PL tail



- Perfect for estimating inner radius of accretion disk → BH spin
- Just need to estimate L_X, T_X (and N_H) from X-ray continuum
- Use full relativistic model (Novikov-Thorne 1973; KERRBB, Li et al. 2005)

A Test of the Blackbody Assumption



Kubota et al. (2002)

McClintock et al. (2008)

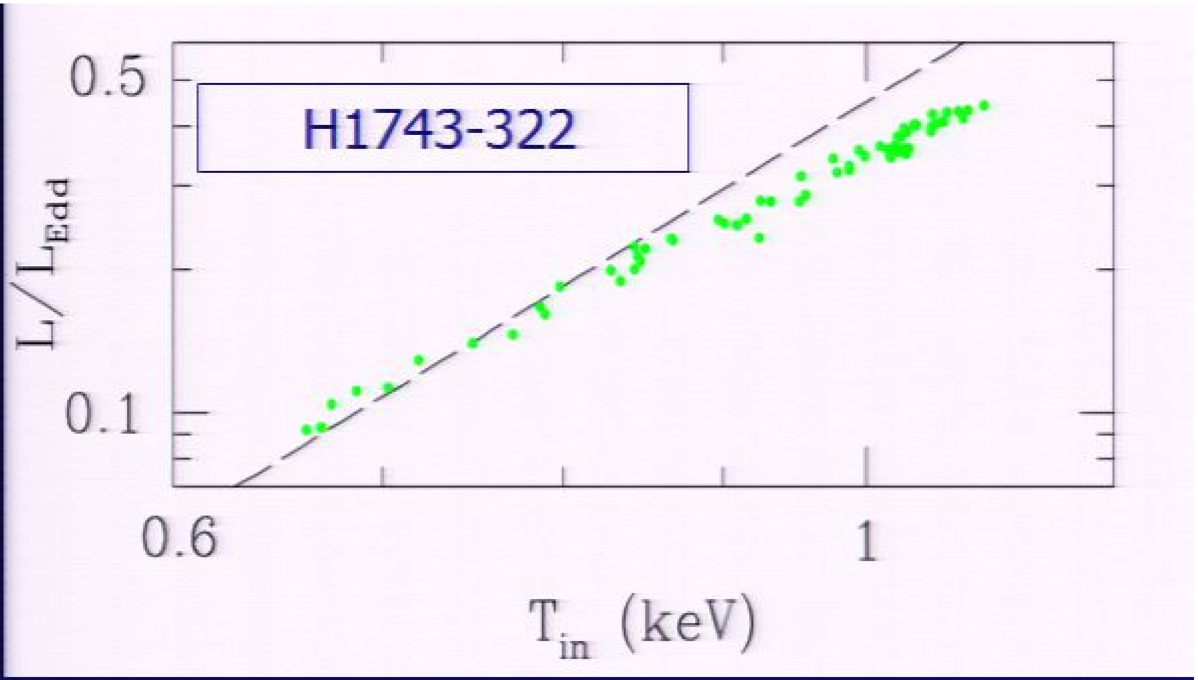
- For a blackbody, L scales as T^4 (Stefan-Boltzmann Law)
- BH accretion disks vary a lot in their luminosity
- If a disk is a good blackbody, L should vary as T^4
- **Looks reasonable**

$$\boxed{L = A\sigma T^4}$$

Spectral Hardening Factor

- Disk emission is not a perfect blackbody
- Need to calculate non-blackbody effects through detailed atmosphere model
- True also for measuring radii of stars
- Davis, Blaes, Hubeny et al. have developed state-of-the-art models

A Test of the Blackbody Assumption



- For a blackbody, L scales as T^4 (Stefan-Boltzmann Law)
- BH accretion disks vary a lot in their luminosity
- If a disk is a good blackbody, L should vary as T^4
- **Looks reasonable**

Kubota et al. (2002)

McClintock et al. (2008)

$$\boxed{L = A\sigma T^4}$$

Spectral Hardening Factor

- Disk emission is not a perfect blackbody
- Need to calculate non-blackbody effects through detailed atmosphere model
- True also for measuring radii of stars
- Davis, Blaes, Hubeny et al. have developed state-of-the-art models

$f = T_{col}/T_{eff}$

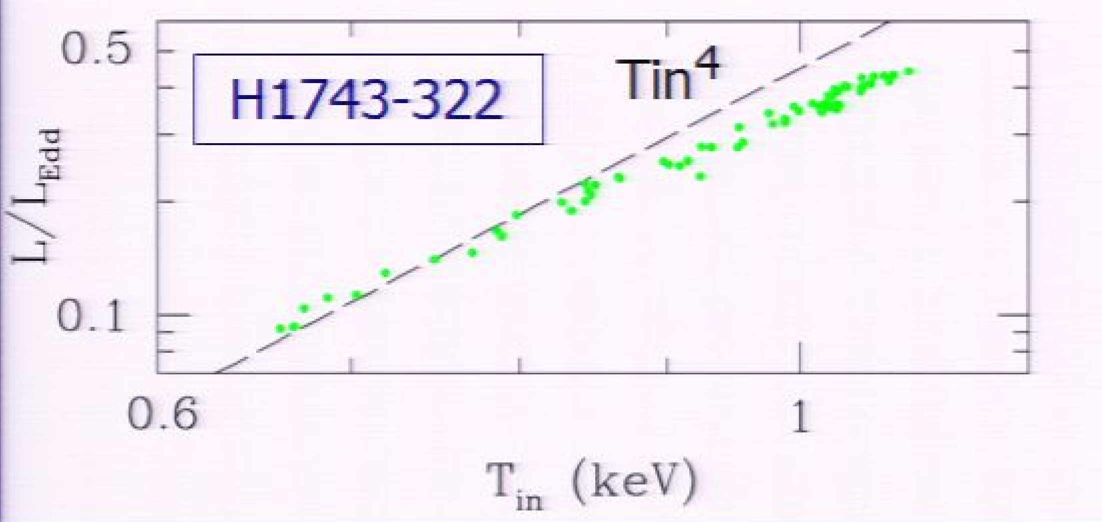
Davis et al. (2005, 2006)

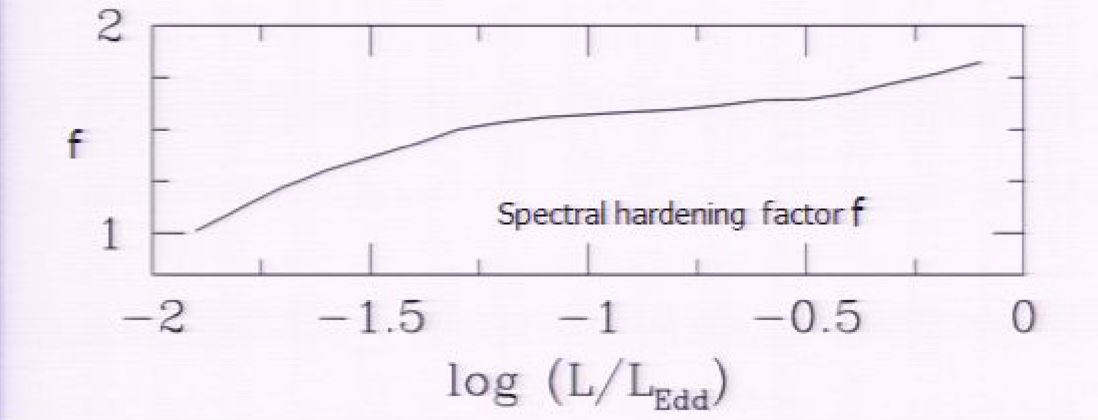
With color correction (from Shane Davis), get an excellent L-T^4 trend

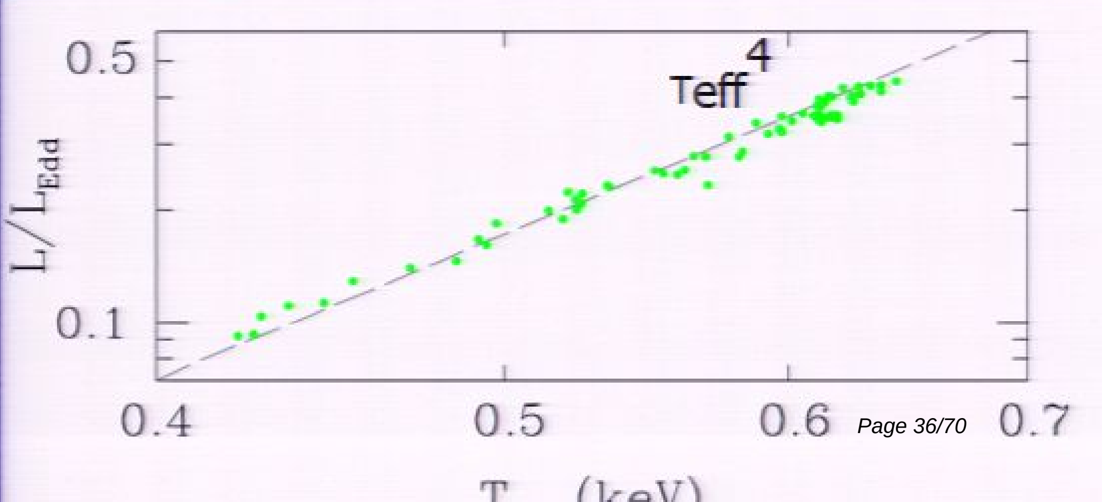
Conclusion:

Thermal State is very good for quantitative modeling

→ **ISCO**





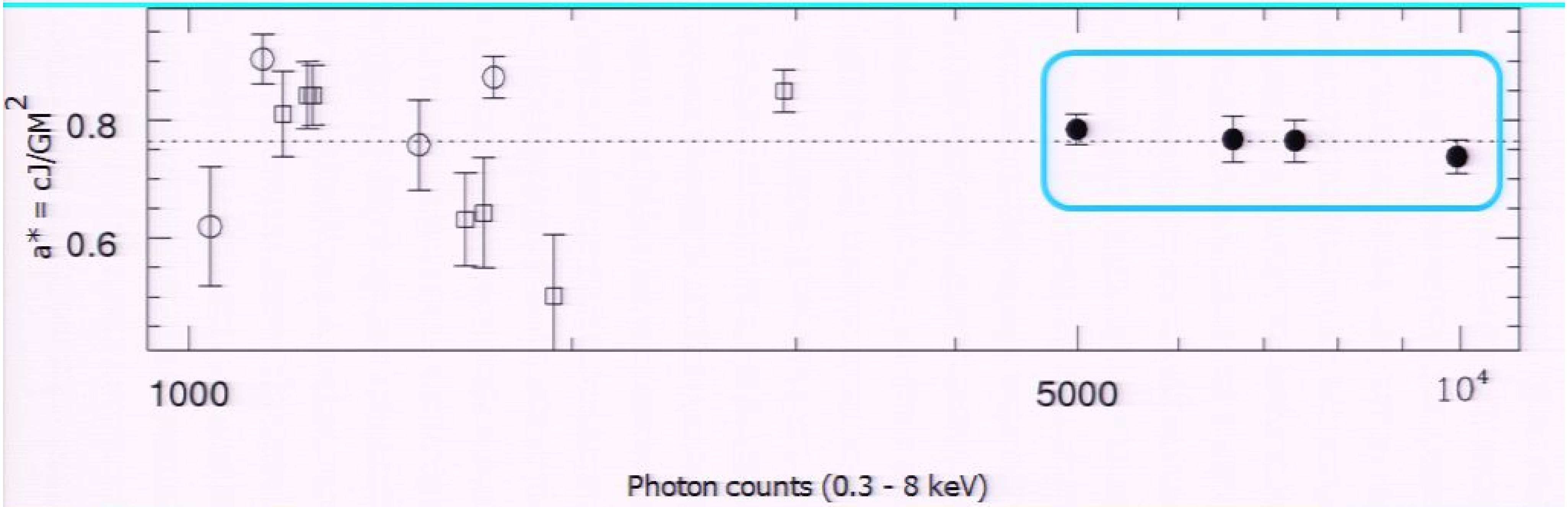


BH XRBs With Spin Estimates

- GRO J1655-40
- 4U 1543-47
- GRS 1915+105
- M33 X-7
- LMC X-1
- LMC X-3
- (XTE J1550-564)

M33 X-7: Spin

15 total spectra: 4 "gold" + 11 "silver"



Chandra & XMM-Newton
Liu et al. (2008)

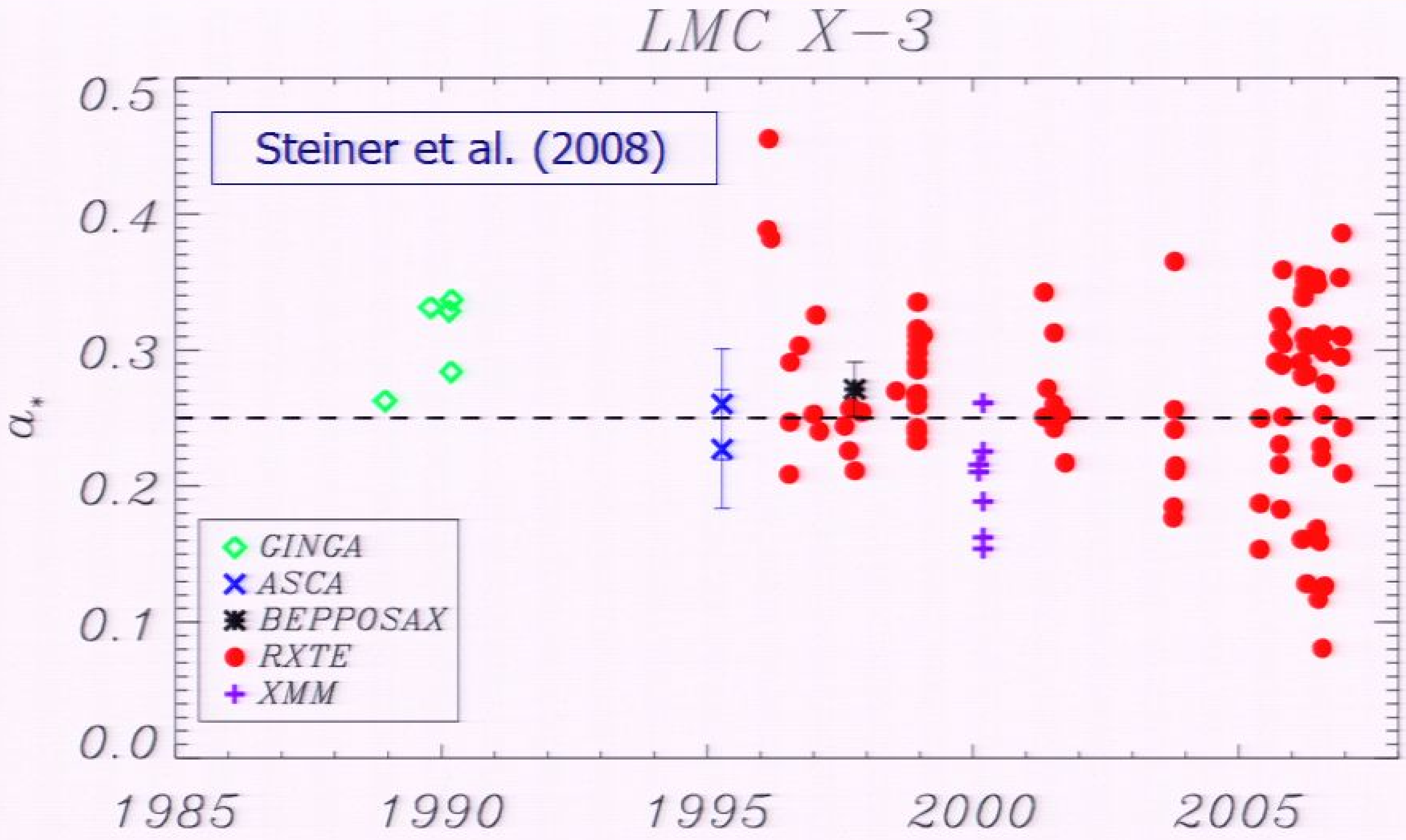
4 **gold** Chandra spectra

$a_* = 0.77 \pm 0.02$

Including uncertainties in D, **i** & M

$a_* = 0.77 \pm 0.05$

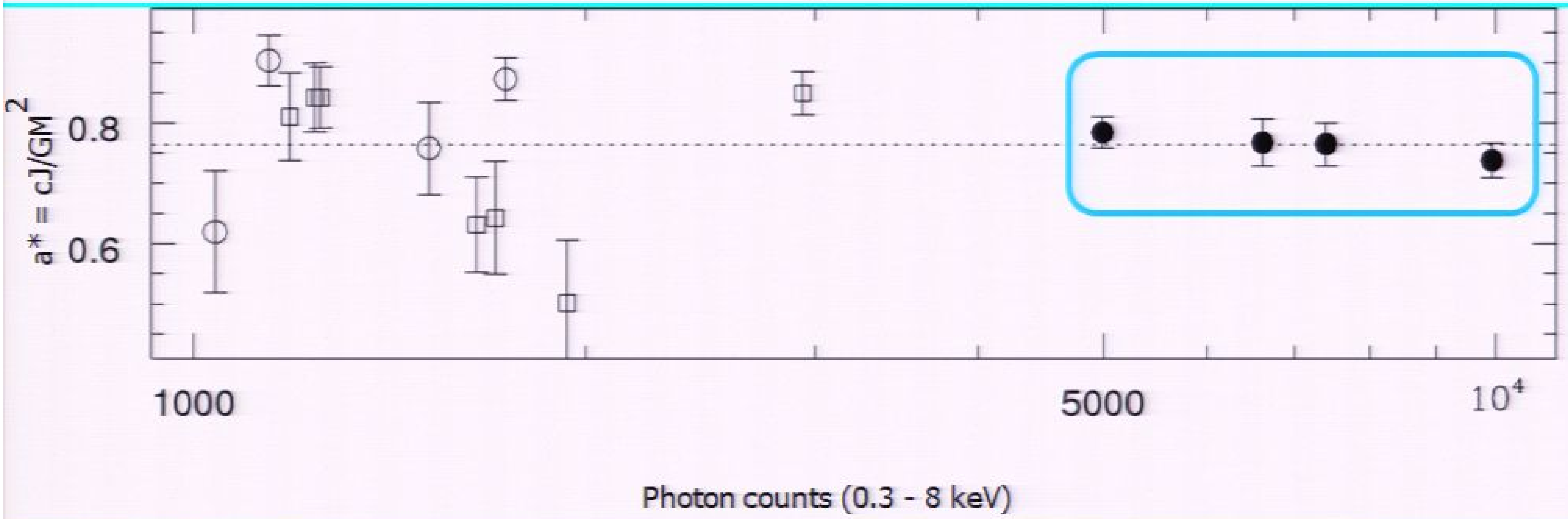
LMC X-3: Five missions agree!



Further strong evidence for existence of a constant radius!

M33 X-7: Spin

15 total spectra: 4 "gold" + 11 "silver"



Chandra & XMM-Newton
Liu et al. (2008)

4 gold Chandra spectra

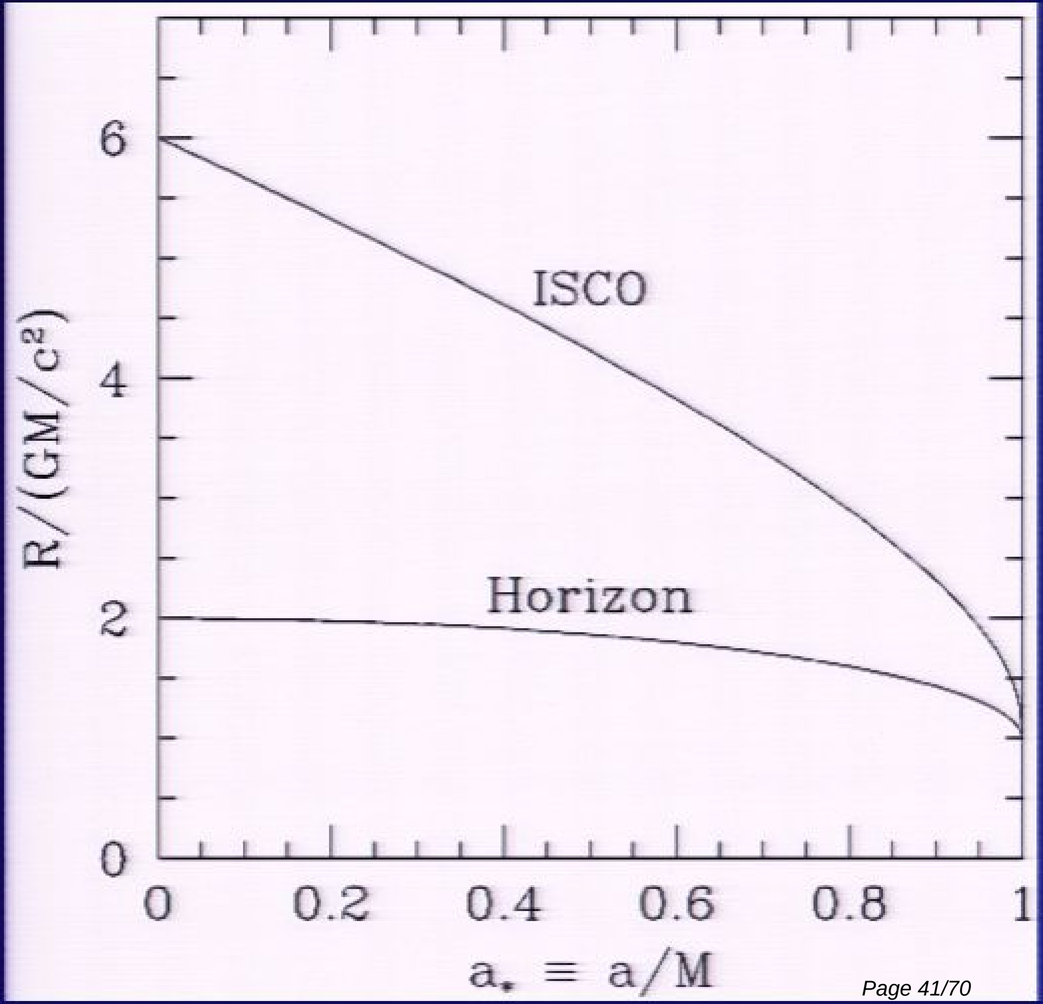
$a_* = 0.77 \pm 0.02$

Including uncertainties in D, **i** & M

$a_* = 0.77 \pm 0.05$

Innermost Stable Circular Orbit (ISCO)

- R_{ISCO}/M depends on the value of a_*
- If we can measure R_{ISCO}, we will obtain a_*
- Note factor of 6 variation in R_{ISCO}

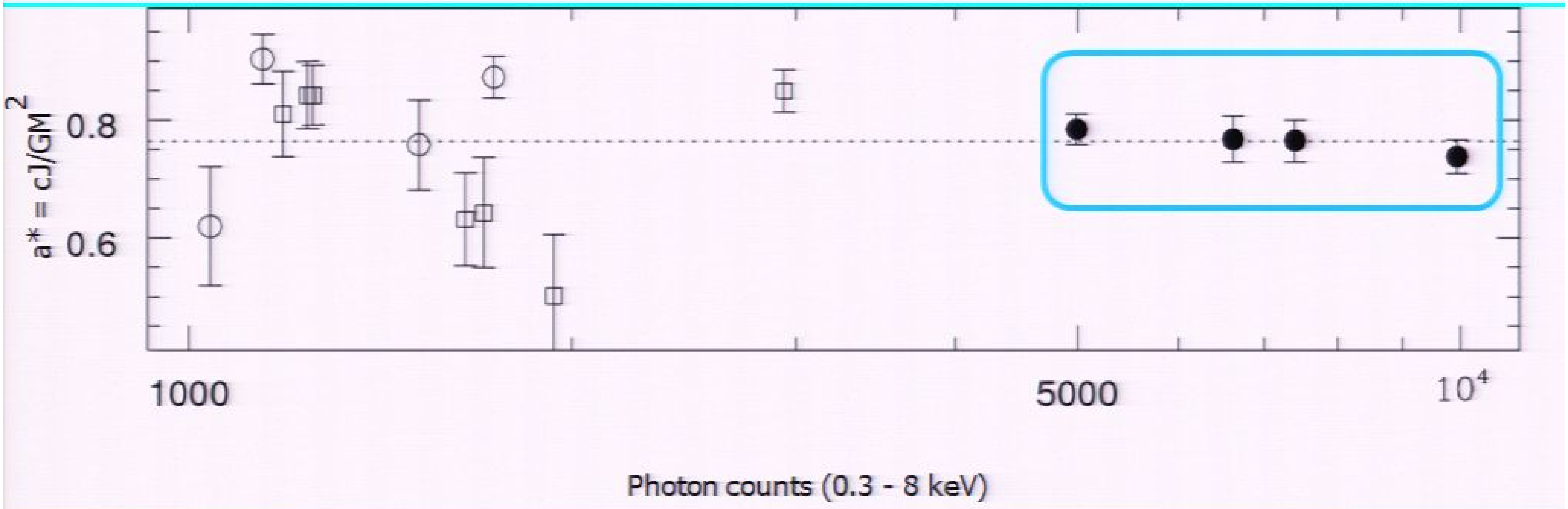


Summary

- BH mass measurements are routine these days, and they are reliable
- BH spin measurements have finally become feasible, at least for BH XRBs, via the continuum-fitting method
- Reliability of results unclear, but the method generally looks promising
- We may soon be able to study the role of BH spin in generating relativistic jets and other astrophysical phenomena

M33 X-7: Spin

15 total spectra: 4 "gold" + 11 "silver"



Chandra & XMM-Newton
Liu et al. (2008)

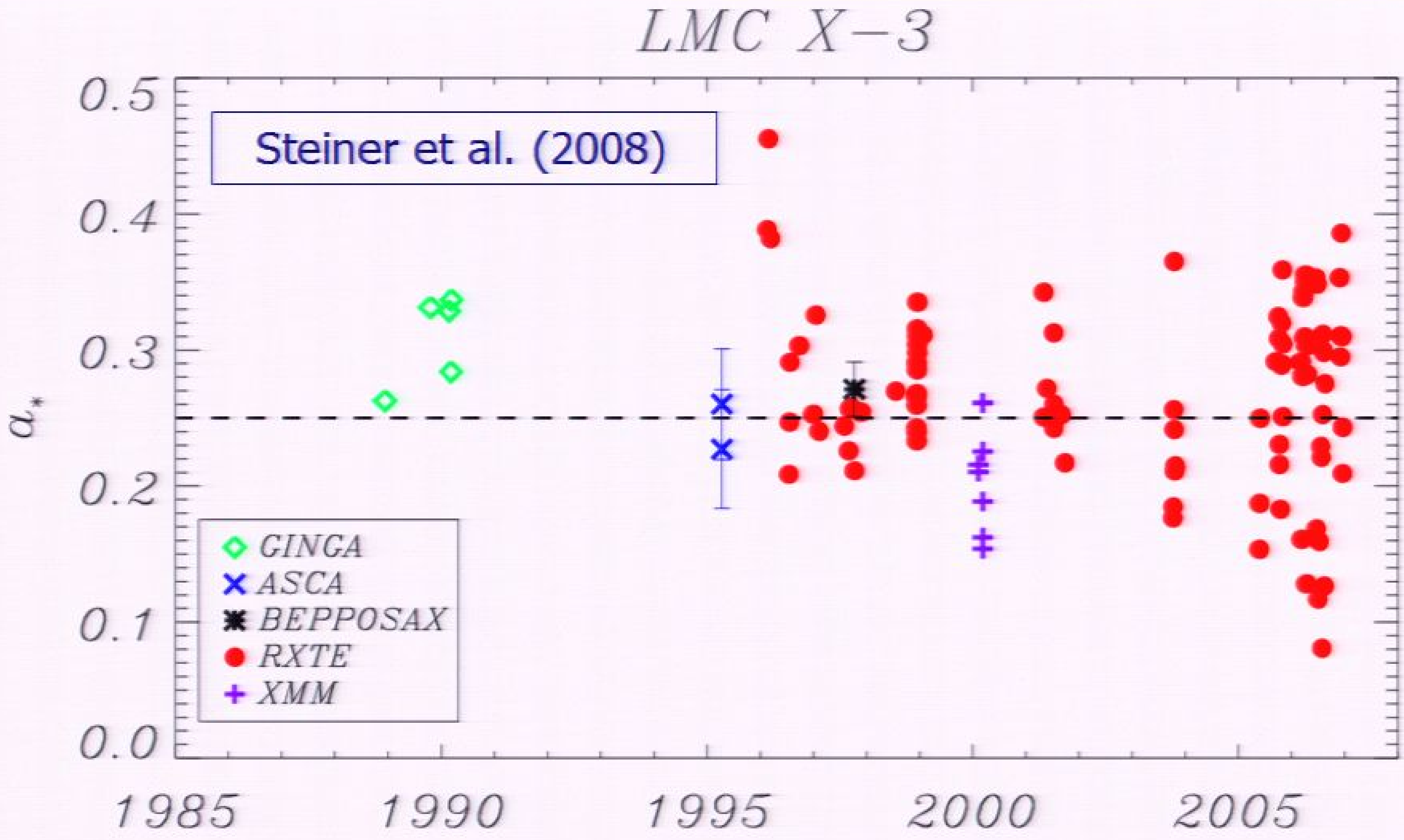
4 gold Chandra spectra

$a_* = 0.77 \pm 0.02$

Including uncertainties in D, **i** & M

$a_* = 0.77 \pm 0.05$

LMC X-3: Five missions agree!



Further strong evidence for existence of a constant radius!

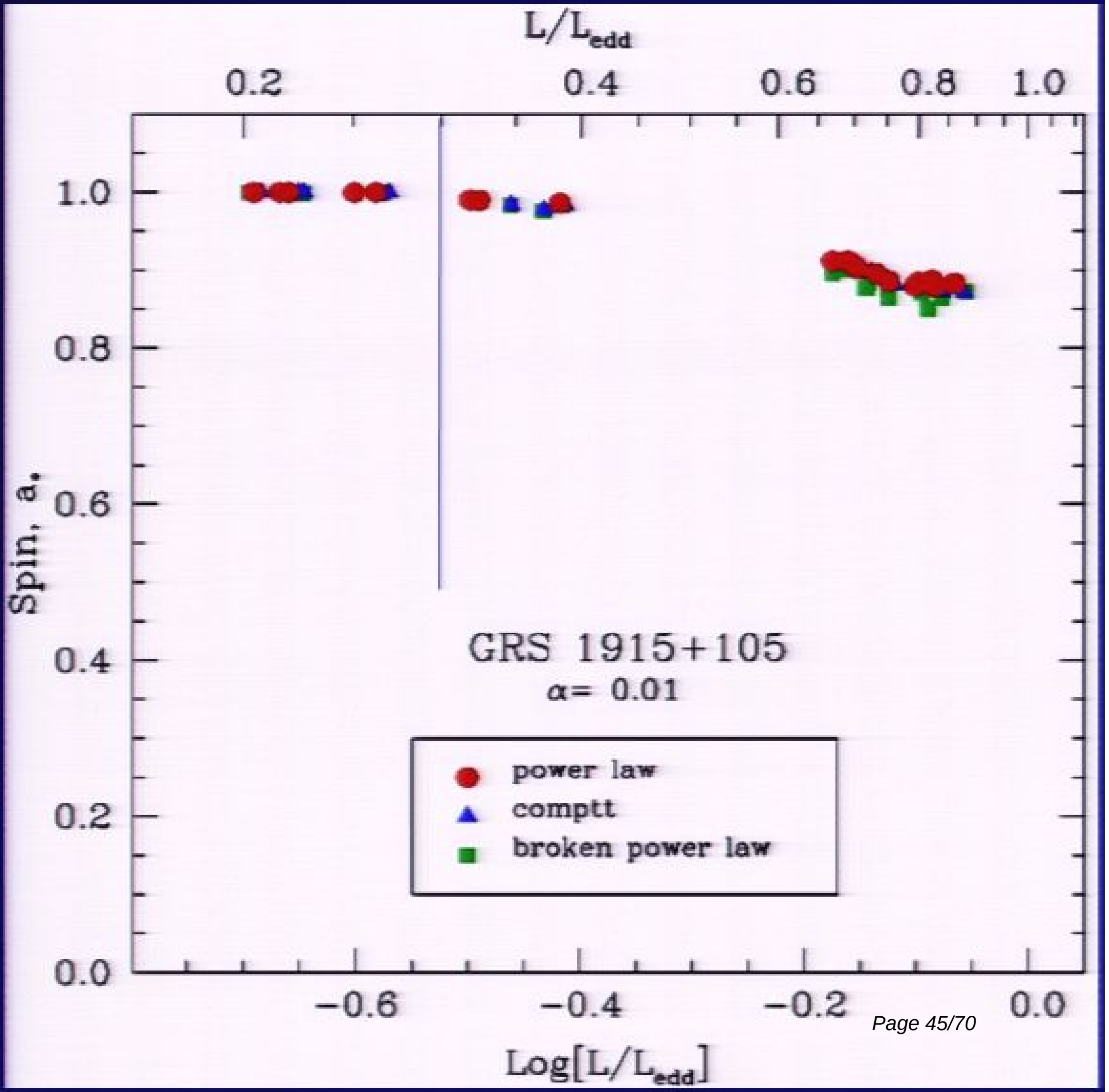
GRS 1915+105

Estimated spin of

GRS 1915+105:

a* ~ 0.98—1.0

(McClintock et al. 2006)



BH Masses and Spins

Source Name	BH Mass ($M_\odot$)	BH Spin (a_*)
LMC X-3	5.9—9.2	~0.25
XTE J1550-564	8.4—10.8	(~0.5)
GRO J1655-40	6.0—6.6	0.65—0.80
M33 X-7	14.2—17.1	0.77 ± 0.05
4U1543-47	7.4—11.4	0.7—0.85
LMC X-1	9.0—11.6	0.81—0.94
GRS 1915+105	10—18	0.98—1

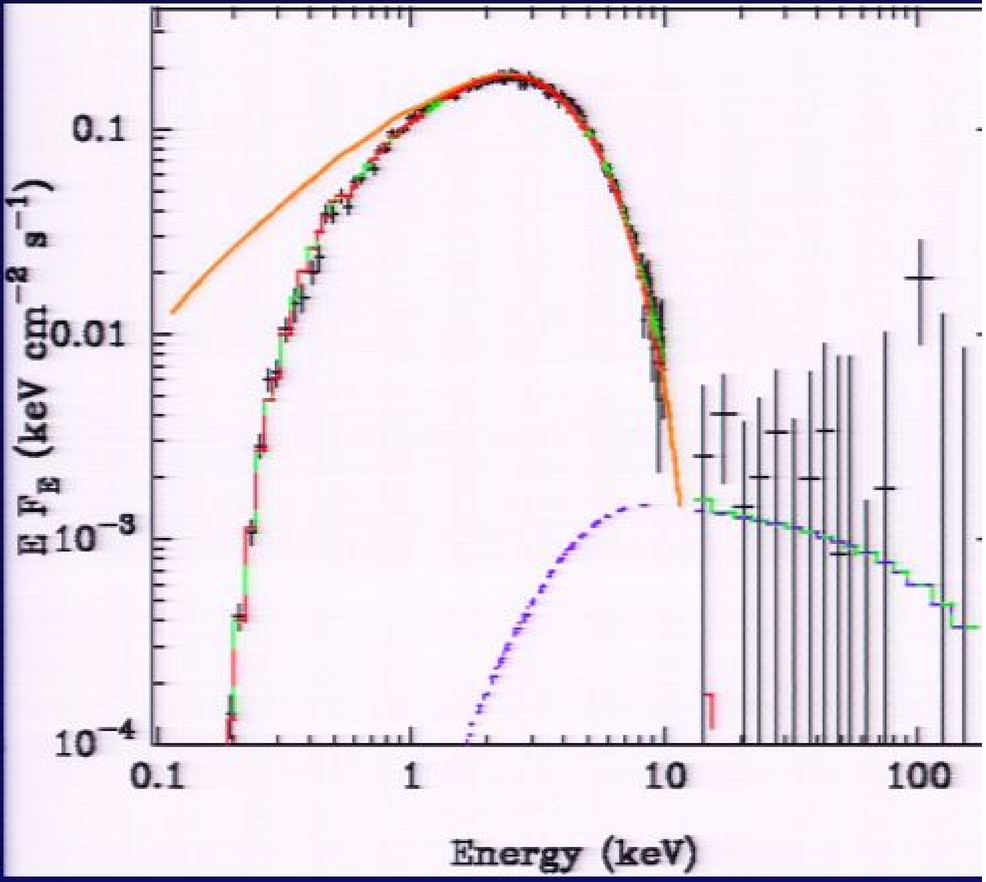
Shafee et al. (2006); McClintock et al. (2006); Davis et al. (2006); Liu et al. (2007); Gou et al. (2009) ; Steiner et al. (unpublished)

Good News/Bad News

- Good news:
  - Only need F_X, T_X from X-ray data
  - Theoretical model is conceptually simple and reliable (just energy conservation, no α)
  - Disk atmosphere fairly well understood
- Bad news:
  - Need accurate M, D, i: requires a lot of supporting optical/IR/radio observations
  - MHD effects in the disk unclear/under study
  - Disk inclination not directly measured

Robust X-ray Analysis

- We fit only two parameters – a_* and Mdot – from the X-ray data (plus the usual N_H)
- Obtain these from X-ray flux and temperature
- X-ray analysis is thus straightforward & robust
- Significant advantage over other methods

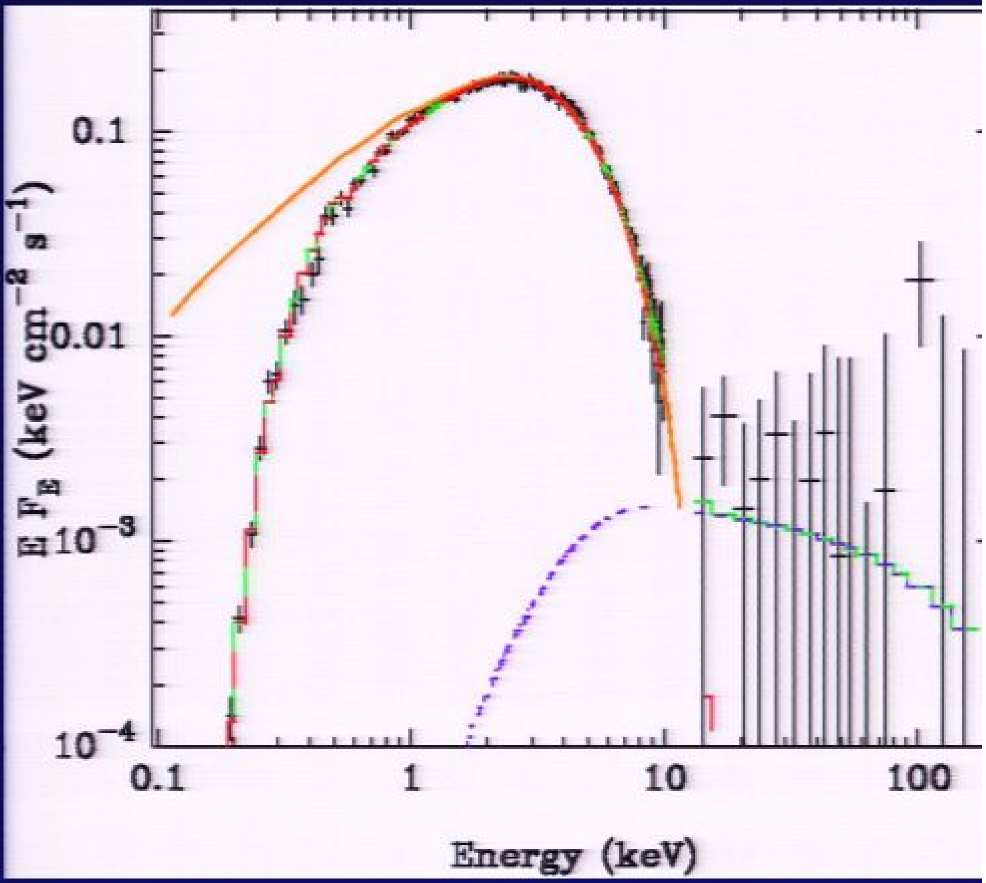


Good News/Bad News

- Good news:
  - Only need F_X, T_X from X-ray data
  - Theoretical model is conceptually simple and reliable (just energy conservation, no α)
  - Disk atmosphere fairly well understood
- Bad news:
  - Need accurate M, D, i: requires a lot of supporting optical/IR/radio observations
  - MHD effects in the disk unclear/under study
  - Disk inclination not directly measured

Robust X-ray Analysis

- We fit only two parameters – a_* and Mdot – from the X-ray data (plus the usual N_H)
- Obtain these from X-ray flux and temperature
- X-ray analysis is thus straightforward & robust
- Significant advantage over other methods



Good News/Bad News

- Good news:
  - Only need F_X, T_X from X-ray data
  - Theoretical model is conceptually simple and reliable (just energy conservation, no α)
  - Disk atmosphere fairly well understood
- Bad news:
  - Need accurate M, D, **i**: requires a lot of supporting optical/IR/radio observations
  - MHD effects in the disk unclear/under study
  - Disk inclination not directly measured

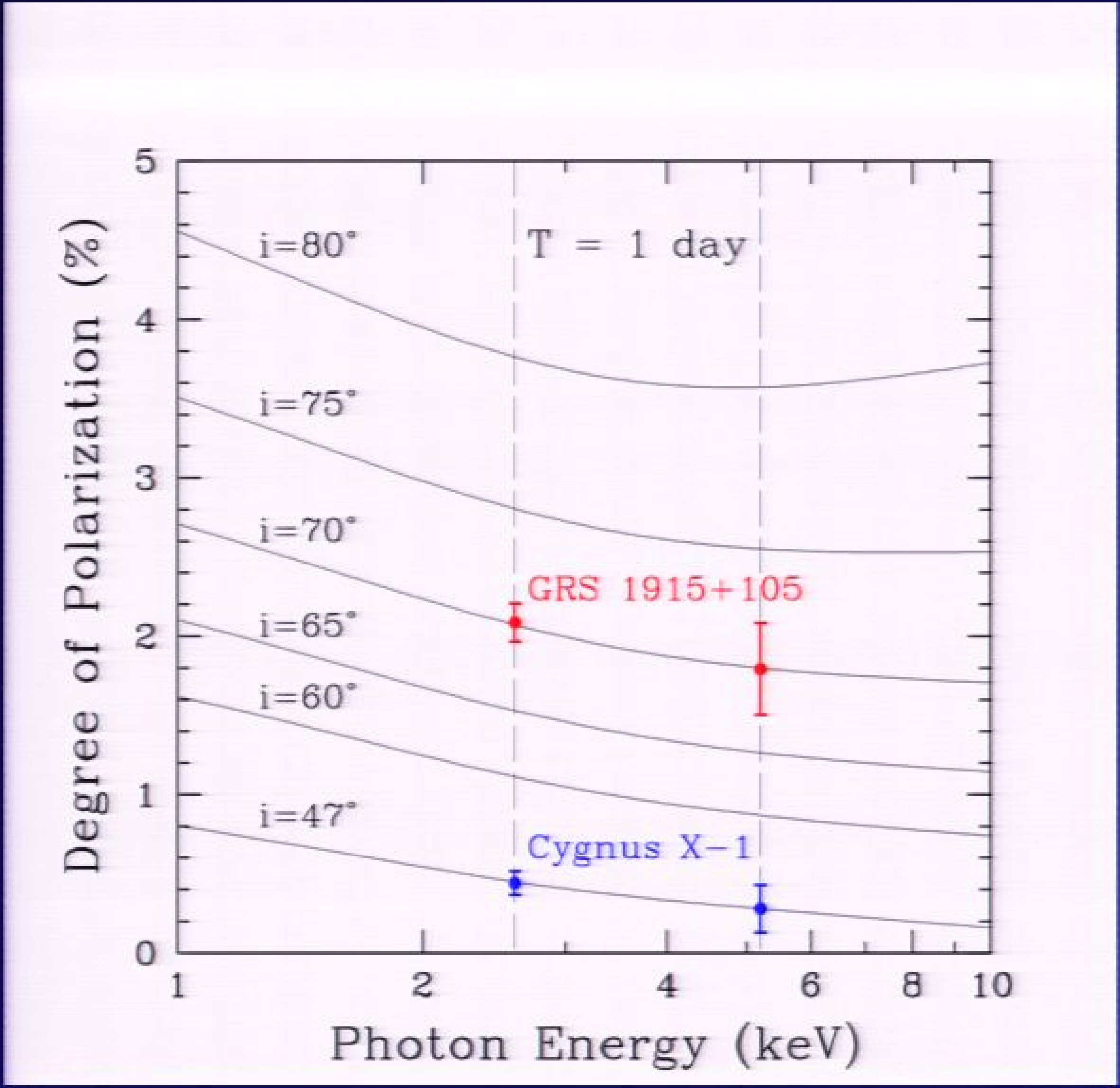
Disk Inclination

Is BH spin aligned with orbit vector?

Are disks warped?

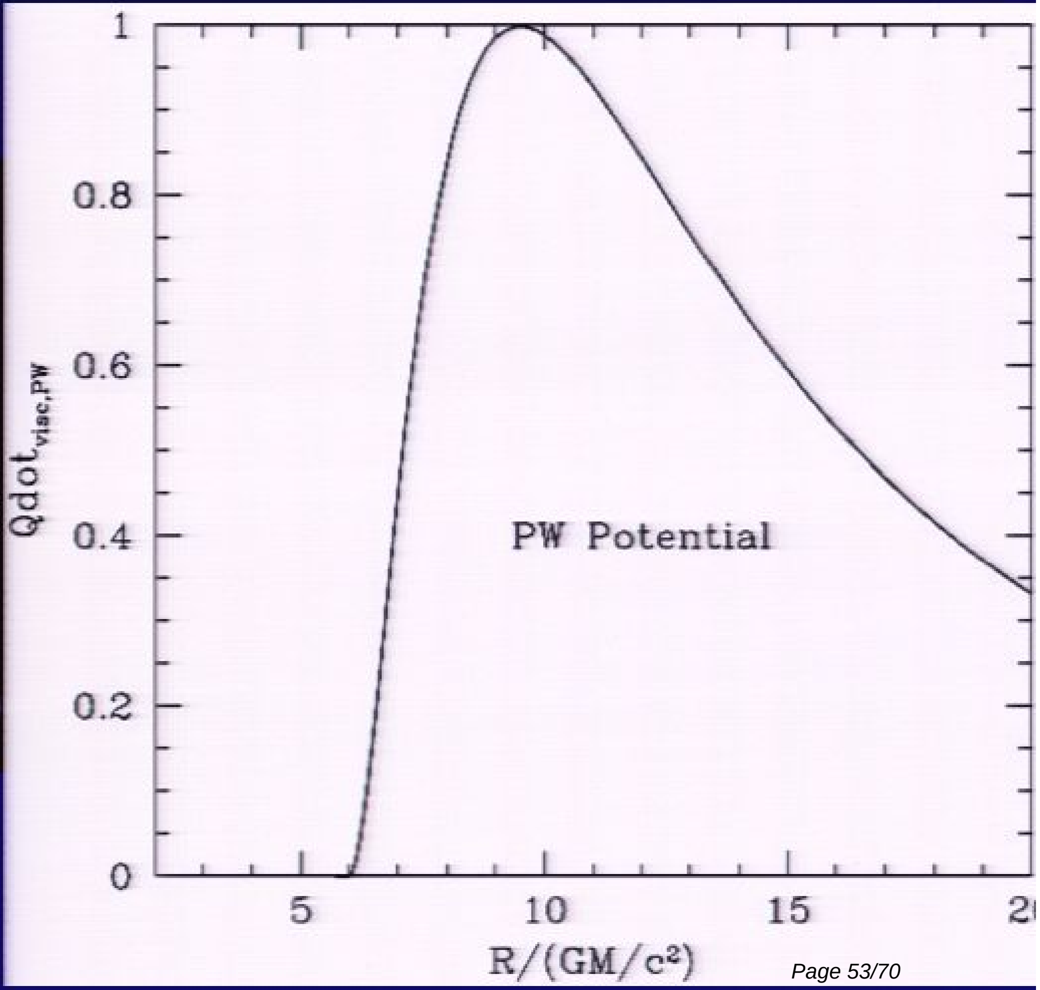
X-ray polarimetry can decide

A SMEX polarimeter can achieve ±0.1%



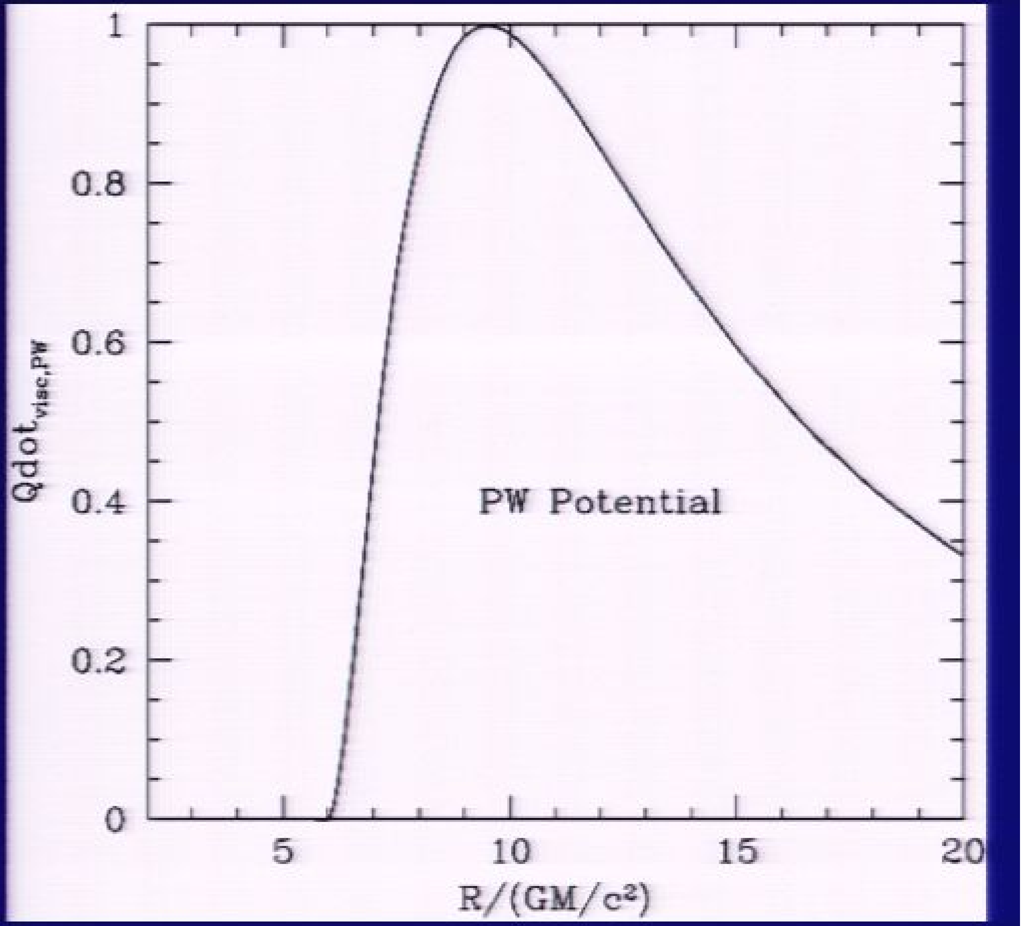
Li, Narayan & McClintock (2009)

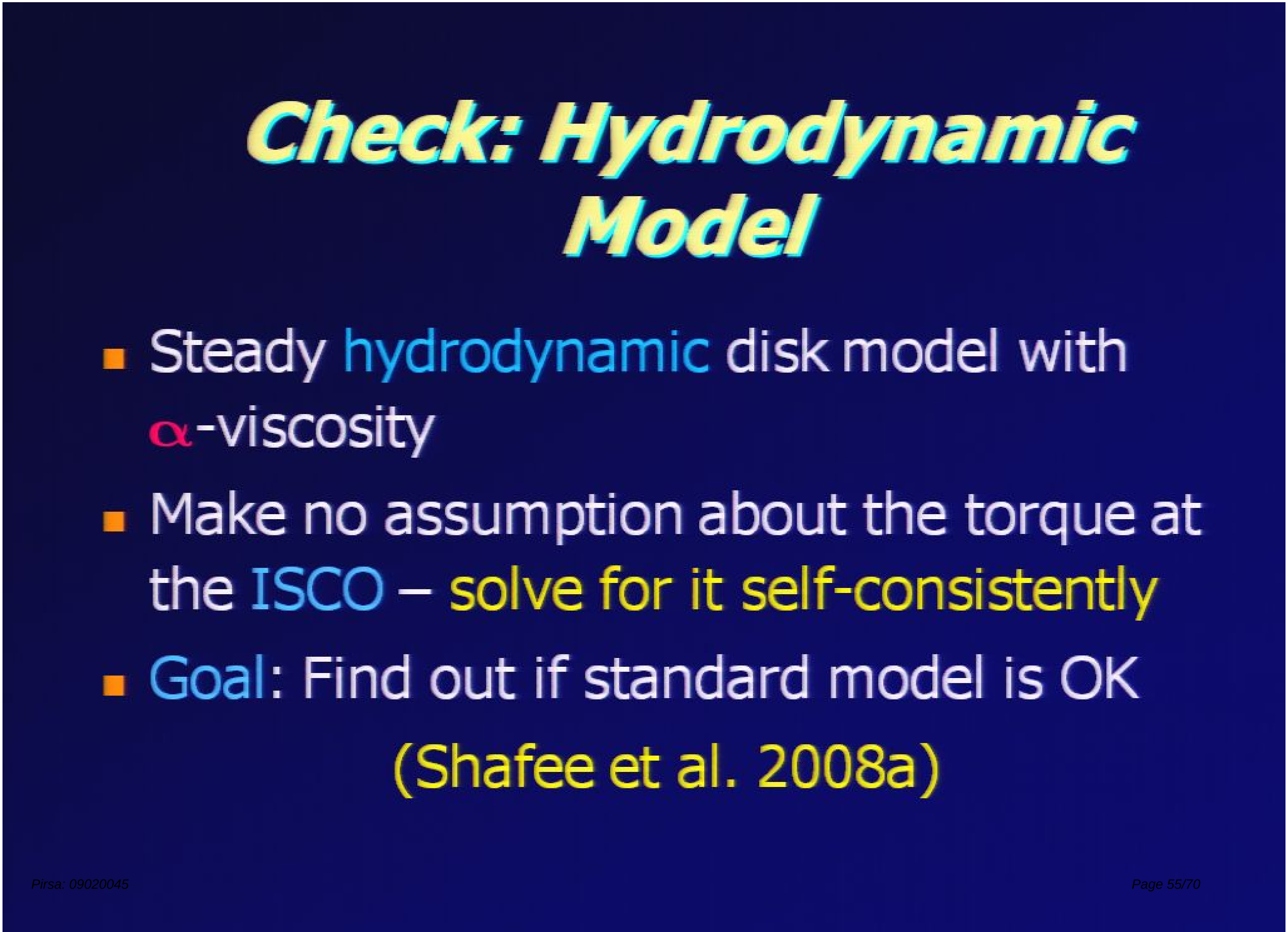
How Reliable is the Theoretical Disk Flux Profile?



A Major Issue

- The theoretical model assumes that the torque vanishes at the inner edge (ISCO) of the disk (Shakura & Sunyaev 1973)
- But magnetic fields could produce significant torque at and inside the ISCO (Krolik 1999; Gammie 1999)
- Afshordi & Paczynski (2003) say this effect is not important for a thin disk
- **Is this really true?**



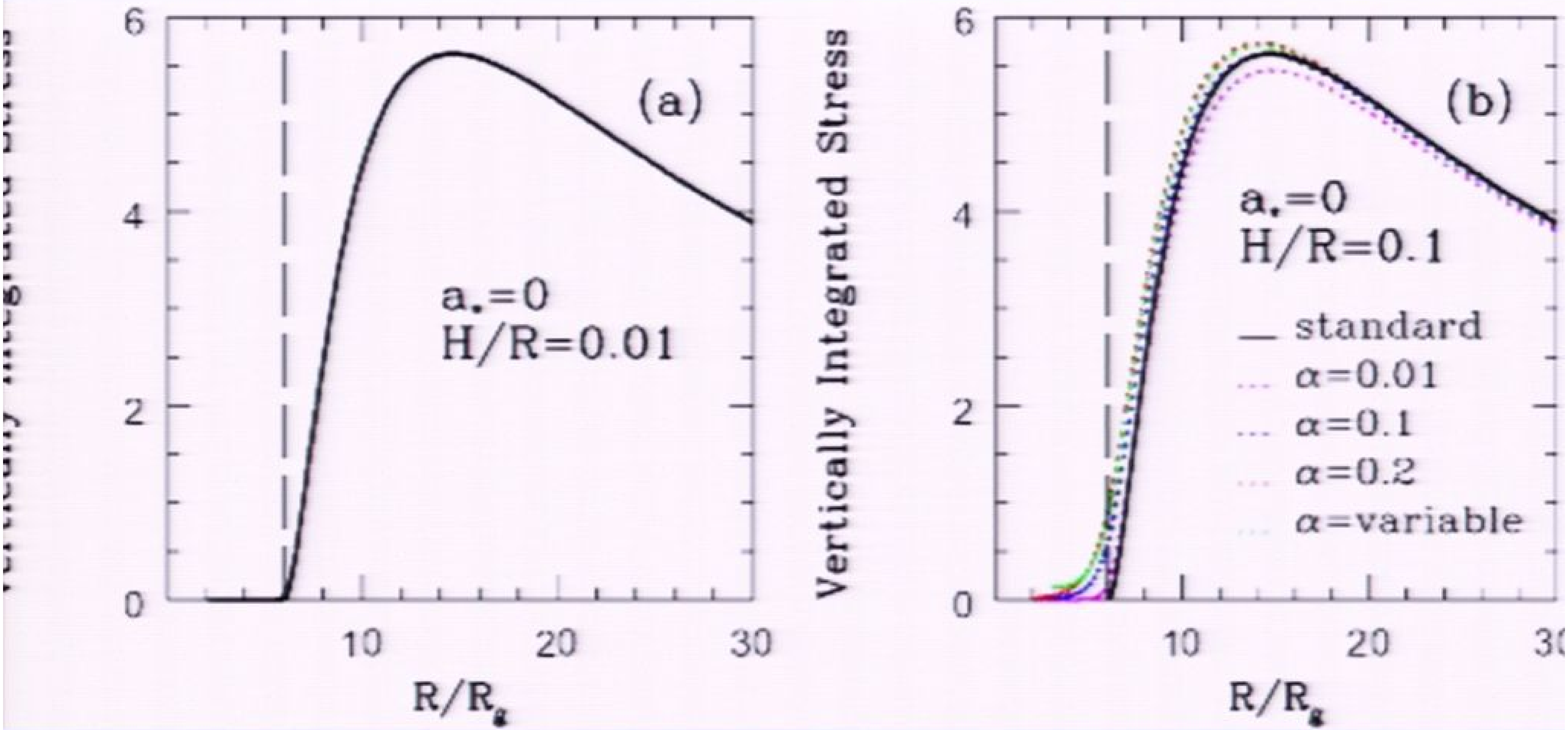


Check: Hydrodynamic Model

- Steady hydrodynamic disk model with α-viscosity
- Make no assumption about the torque at the ISCO – solve for it self-consistently
- Goal: Find out if standard model is OK

(Shafee et al. 2008a)

Torque vs Disk Thickness



- For H/R < 0.1, good agreement with idealized thin disk model (i.e., we confirm results of Afshordi & Paczynski 2003)
- Result is insensitive to the value of α

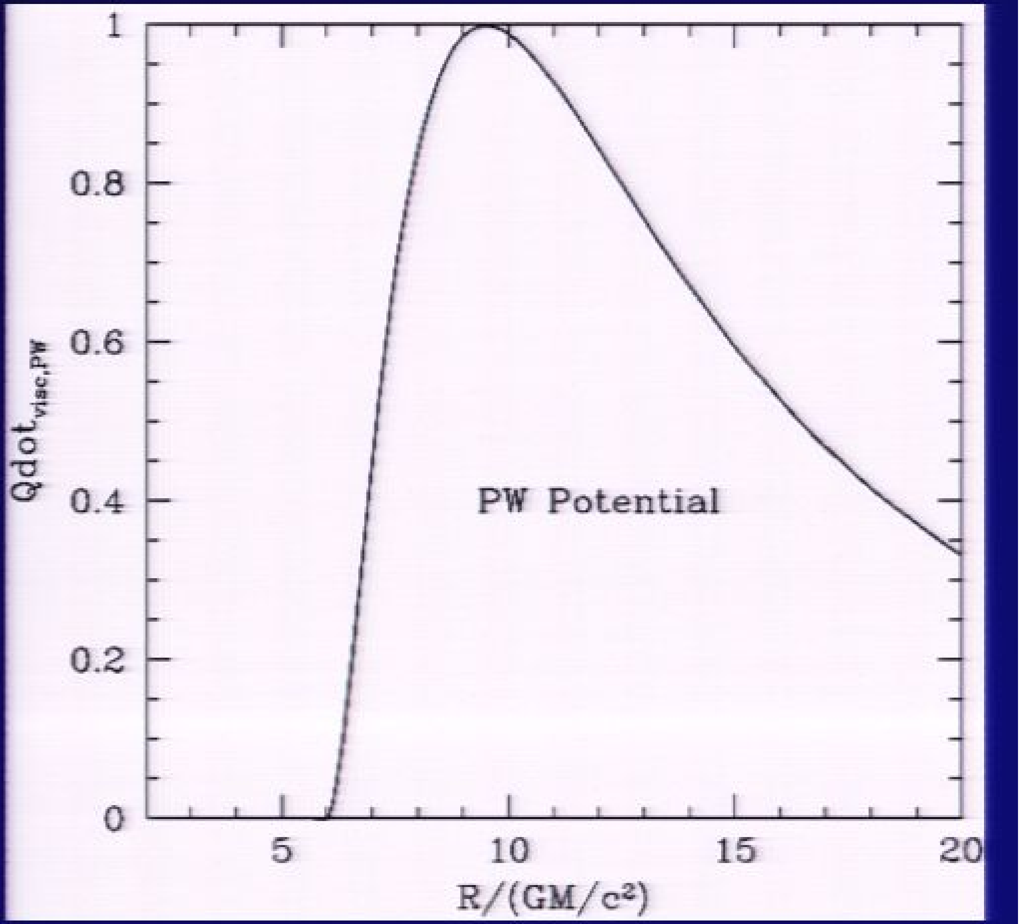
Check: Hydrodynamic Model

- Steady hydrodynamic disk model with α-viscosity
- Make no assumption about the torque at the ISCO – solve for it self-consistently
- Goal: Find out if standard model is OK

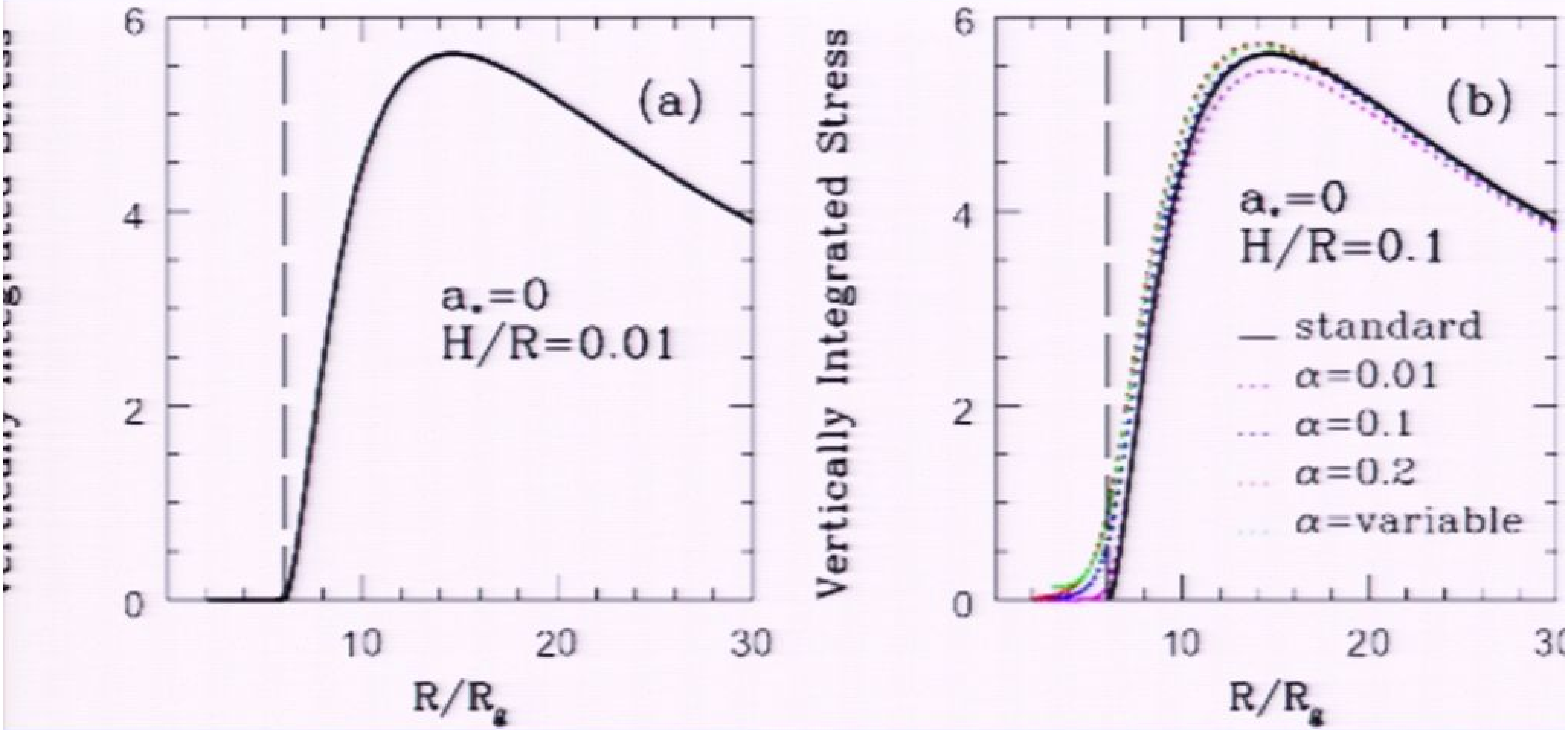
(Shafee et al. 2008a)

A Major Issue

- The theoretical model assumes that the torque vanishes at the inner edge (ISCO) of the disk (Shakura & Sunyaev 1973)
- But magnetic fields could produce significant torque at and inside the ISCO (Krolik 1999; Gammie 1999)
- Afshordi & Paczynski (2003) say this effect is not important for a thin disk
- **Is this really true?**



Torque vs Disk Thickness



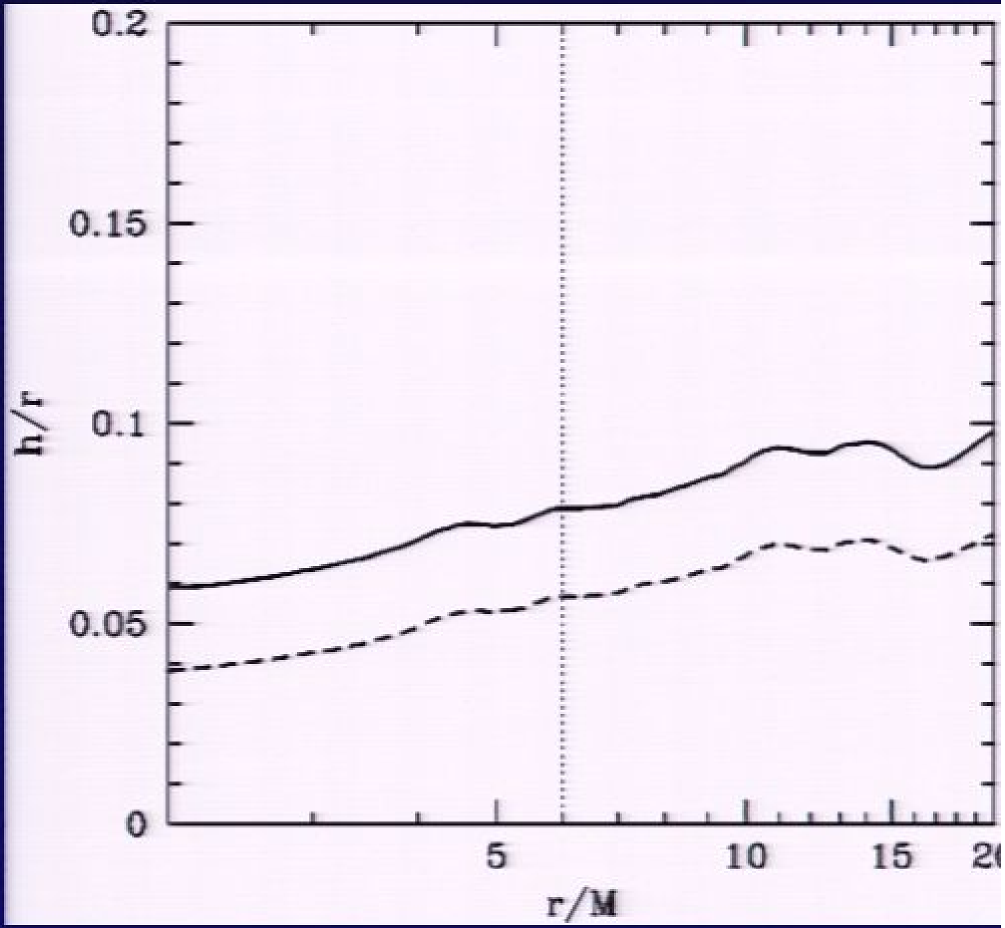
- For $H/R < 0.1$, good agreement with idealized thin disk model (i.e., we confirm results of Afshordi & Paczynski 2003)
- Result is insensitive to the value of α

Caveat

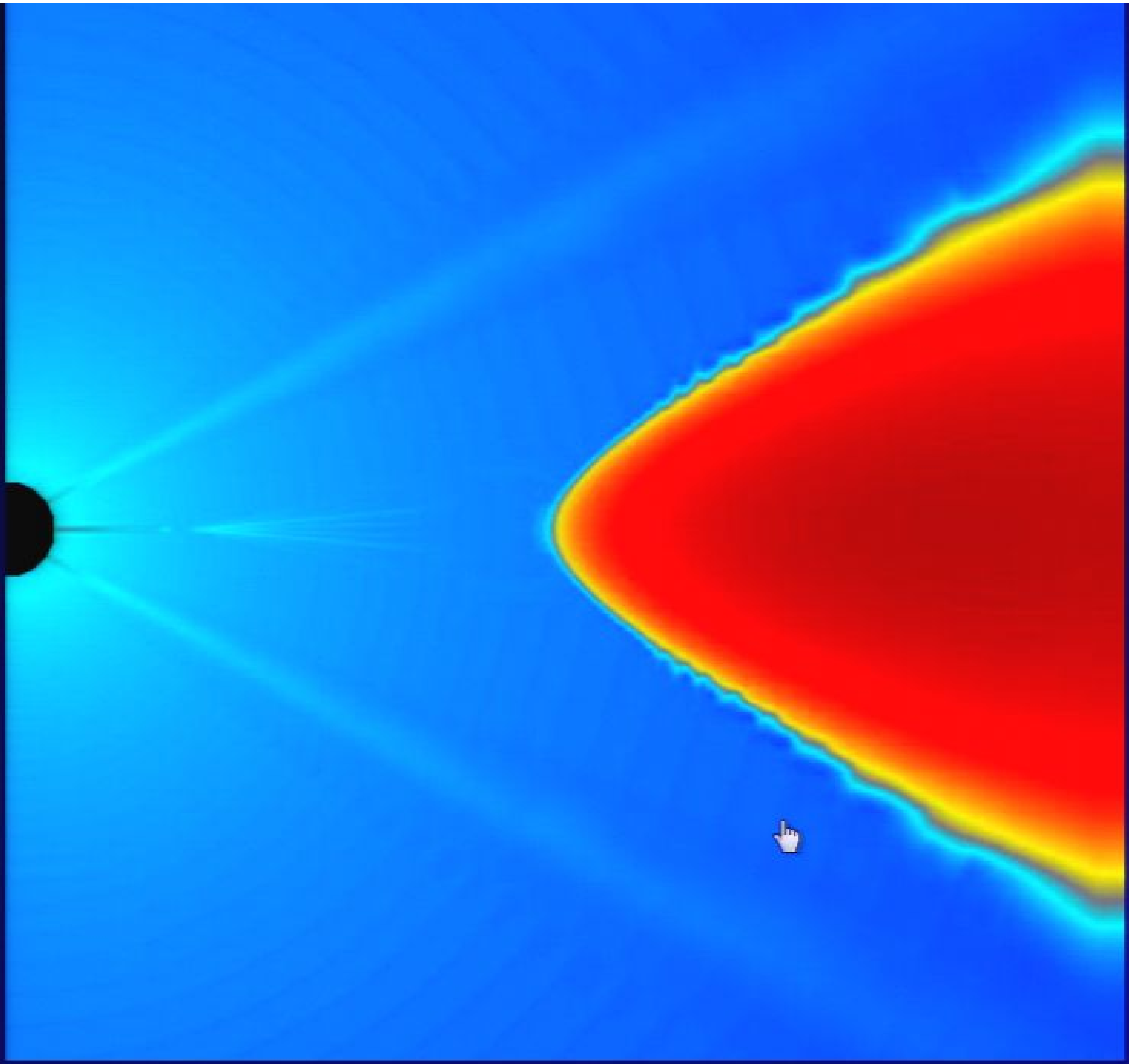
- The results just described are based on a hydrodynamic disk model with α-viscosity
- But 'viscosity' in an accretion disk is from magnetic fields via the MRI
- Therefore, we should do multi-dimensional MHD simulations, and
    - Directly check magnetic stress profile
    - Check viscous energy dissipation profile

3D GRMHD Simulation of a Thin Accretion Disk

- Shafee et al. (2008b)
- 512 x 128 x 32 grid
- Self-consistent MHD simulation
- All GR effects included
- h/r ~ 0.05 — 0.1 (thin!!)
- Very few other thin disk simulations: Reynolds & Fabian (2008); Noble, Krolik & Hawley (2009)

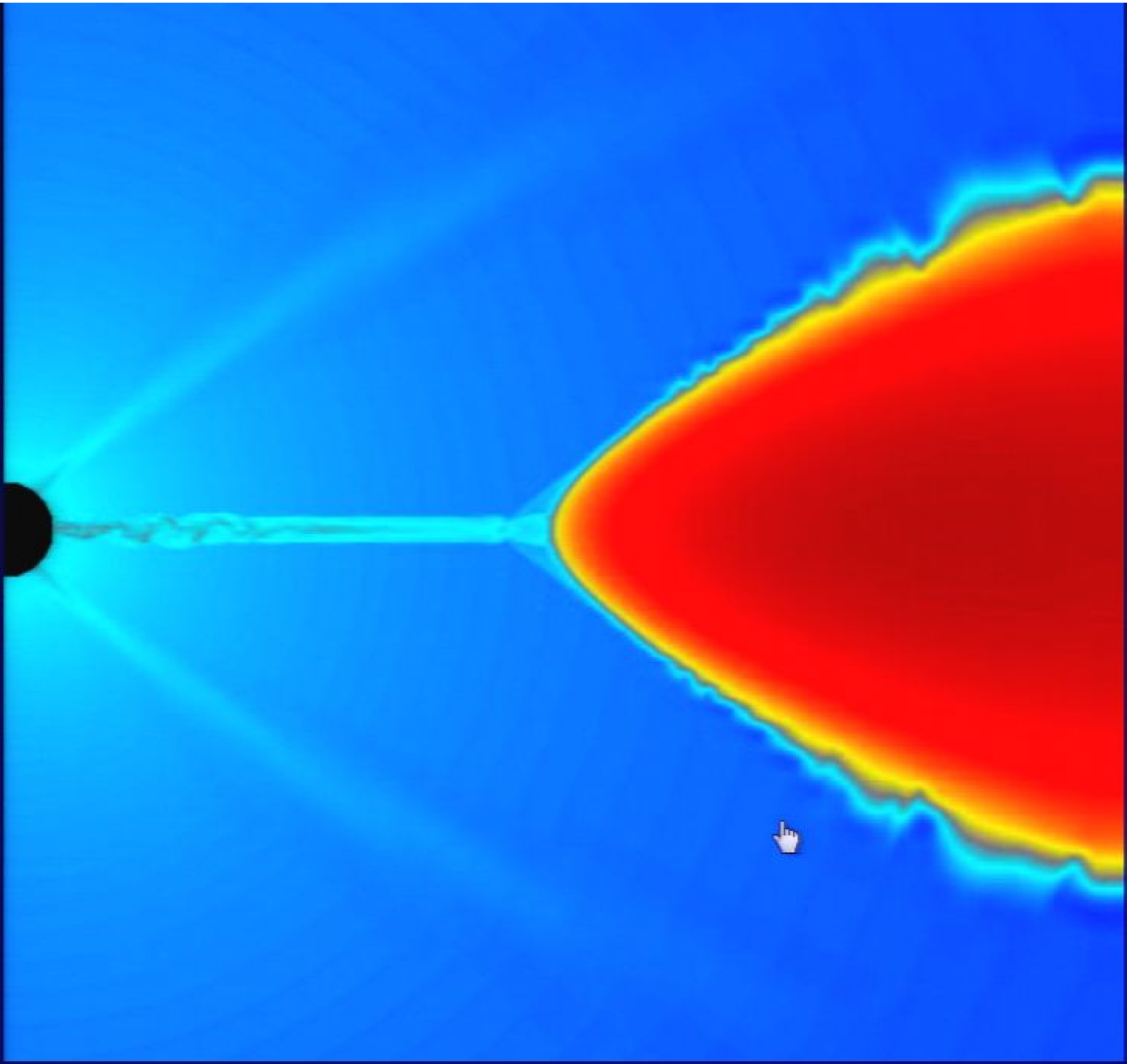


512x128x32



Shafee et al. (2008b)

512x128x32



Shafee et al. (2008b)

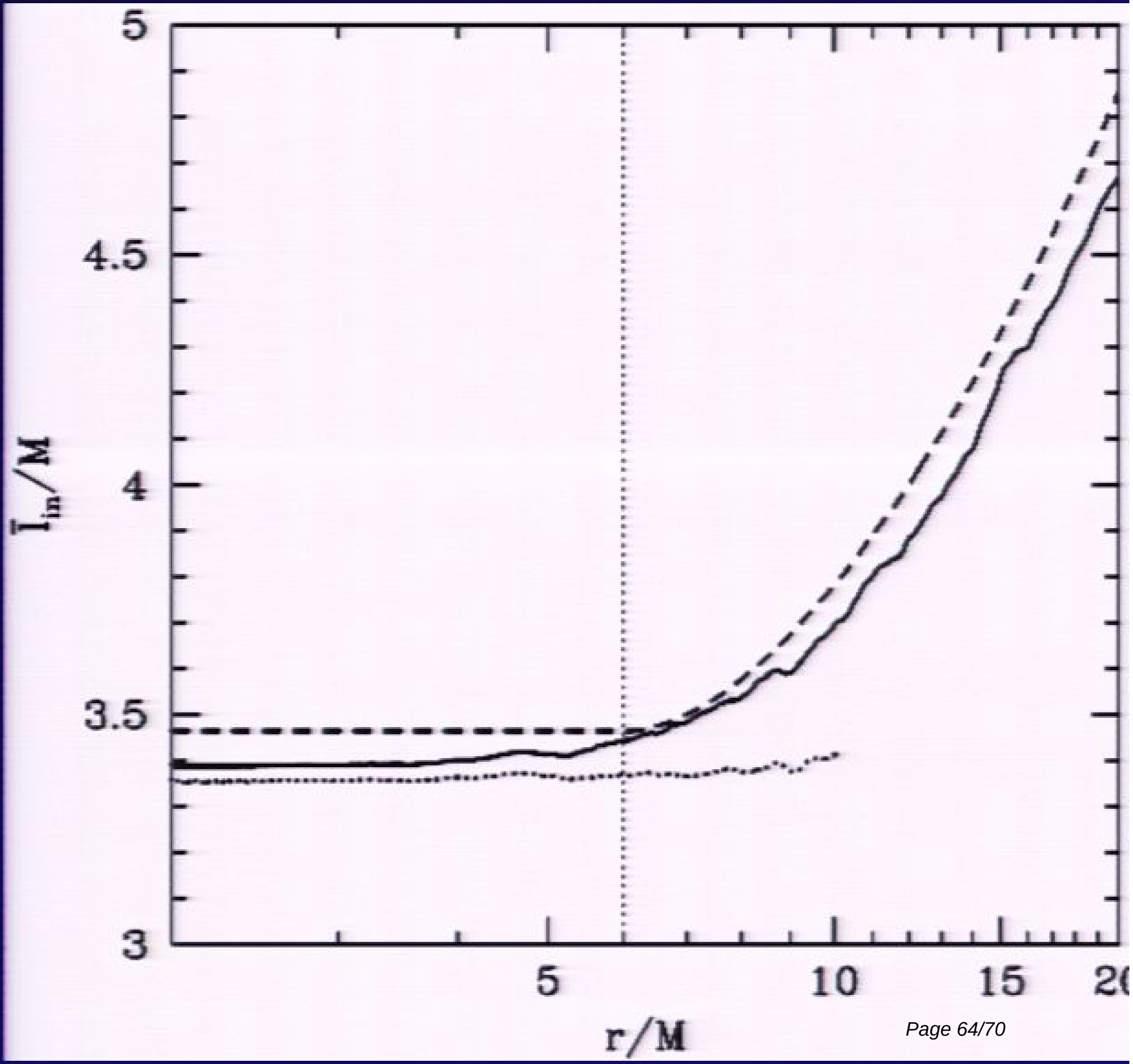
3D GRMHD Simulation Results

Angular mmtm profile from the 3D simulations is very close to that of the idealized Novikov-Thorne model (within 2%)

Very little torque at the ISCO (~2%)

Dissipation profile F(r) is still uncertain, but probably ~5% error in a_*

(Shafee et al. 2008b)



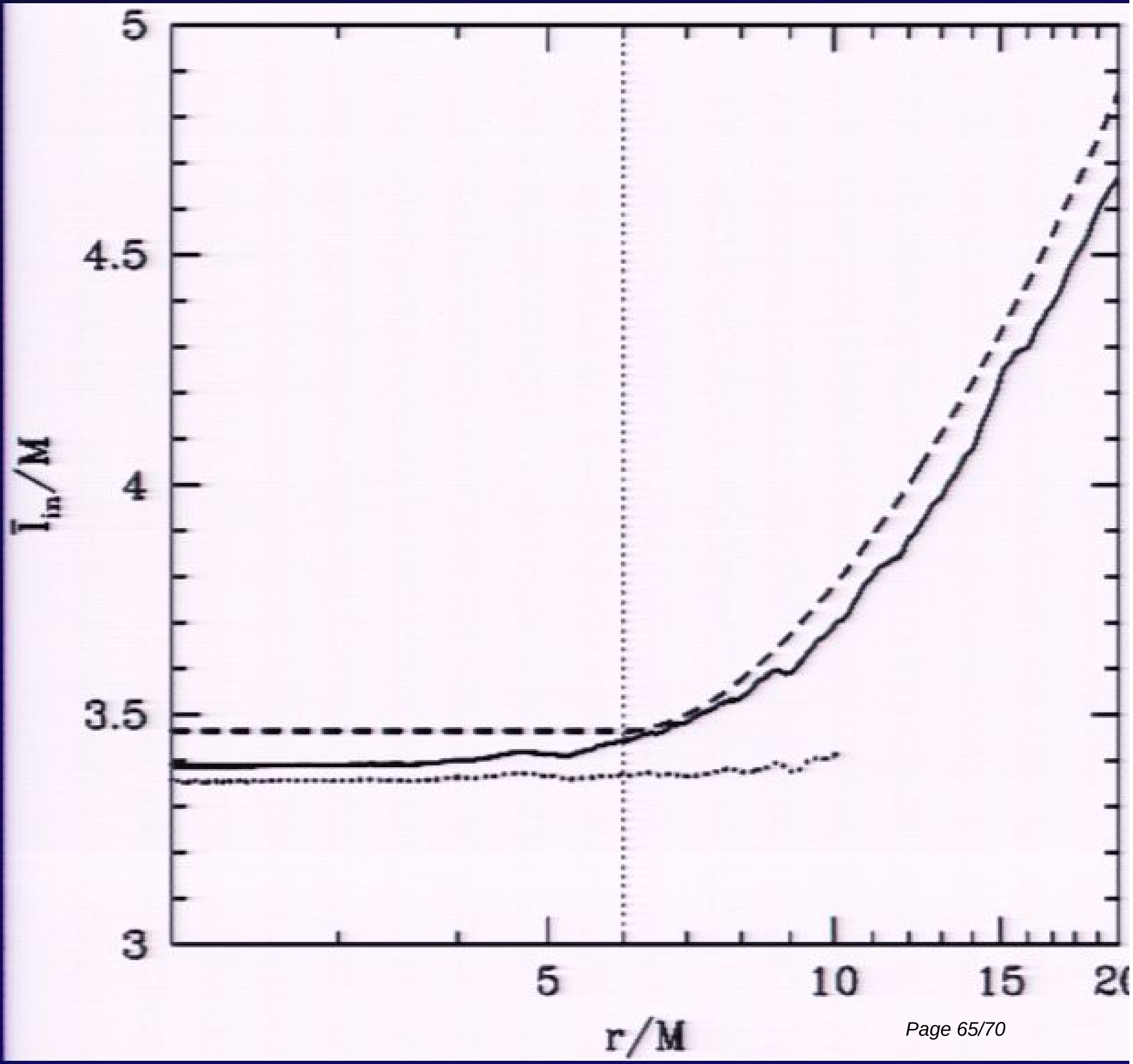
3D GRMHD Simulation Results

Angular mmtm profile from the 3D simulations is very close to that of the idealized Novikov-Thorne model (within 2%)

Very little torque at the ISCO (~2%)

Dissipation profile F(r) is still uncertain, but probably ~5% error in a_*

(Shafee et al. 2008b)

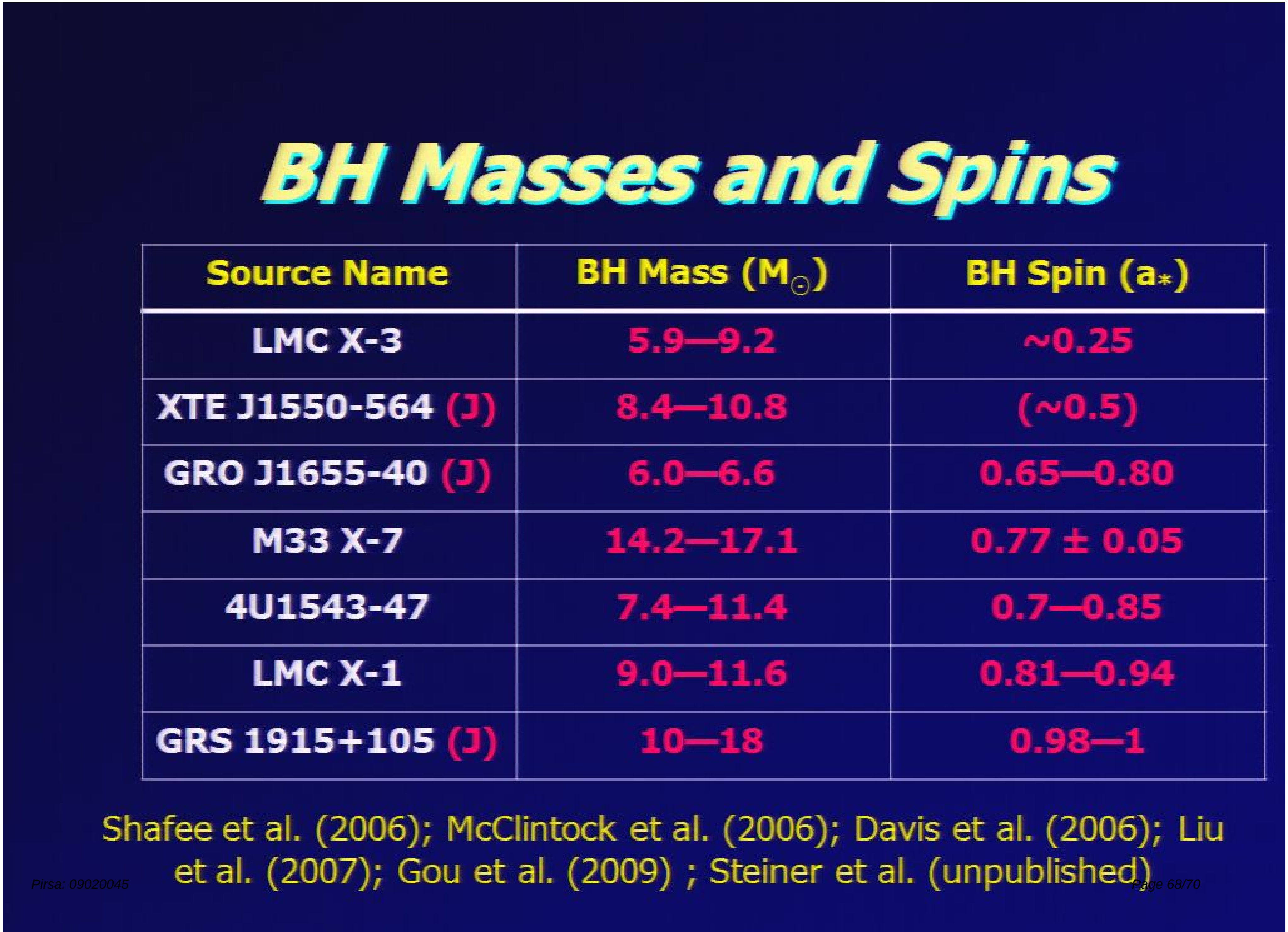


Bottom Line

- We are reasonably optimistic that the spin estimates obtained from fitting continuum X-ray spectra of BH XRBs are believable, provided disk is thin
- Of course, much more MHD simulation work is needed
- Plus plenty of hard Observational work

Spinning Black Hole as an Energy Source

- A spinning BH has free energy -- behaves like a flywheel
- Can we "grip" the BH and access the free energy?!
- Can be done with specially designed particles (Penrose 1969), but this scenario is unlikely to take place naturally
- Magnetic fields are more promising: Magnetic Penrose Process
- Are relativistic jets related to BH spin?



BH Masses and Spins

Source Name	BH Mass ($M_\odot$)	BH Spin (a_*)
LMC X-3	5.9—9.2	~0.25
XTE J1550-564 (J)	8.4—10.8	(~0.5)
GRO J1655-40 (J)	6.0—6.6	0.65—0.80
M33 X-7	14.2—17.1	0.77 ± 0.05
4U1543-47	7.4—11.4	0.7—0.85
LMC X-1	9.0—11.6	0.81—0.94
GRS 1915+105 (J)	10—18	0.98—1

Shafee et al. (2006); McClintock et al. (2006); Davis et al. (2006); Liu et al. (2007); Gou et al. (2009) ; Steiner et al. (unpublished)

Other Methods

- The iron line method is being applied to a few BH XRBs
- It is important to check and compare the two methods on the same BH XRBs
- Vital if we wish to measure spins of supermassives BHs, where only the iron line method is feasible

Summary

- BH mass measurements are routine these days, and they are reliable
- BH spin measurements have finally become feasible, at least for BH XRBs, via the continuum-fitting method
- Reliability of results unclear, but the method generally looks promising
- We may soon be able to study the role of BH spin in generating relativistic jets and other astrophysical phenomena