MEASURING BLACK HOLE SPIN VIA CONTINUUM SPECTROSCOPY

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Spin: A Fundamental Property of a Black Hole

- No-Hair Theorem: A BH is completely described with only two parameters: M, a_* (=J/(GM^2/c)
- BH spin a_* very likely plays a role in, or at least provides information on, many astrophysical phenomena:
  - Relativistic jets
  - GRBs
  - Angular momenta of progenitor stars
  - Galaxy merger history (SMBH BH spins)

Estimating Black Hole Spin

- X-Ray Continuum Spectrum √
- Relativistically Broadened Iron Line √
- Quasi-Periodic Oscillations **?**

Our Team

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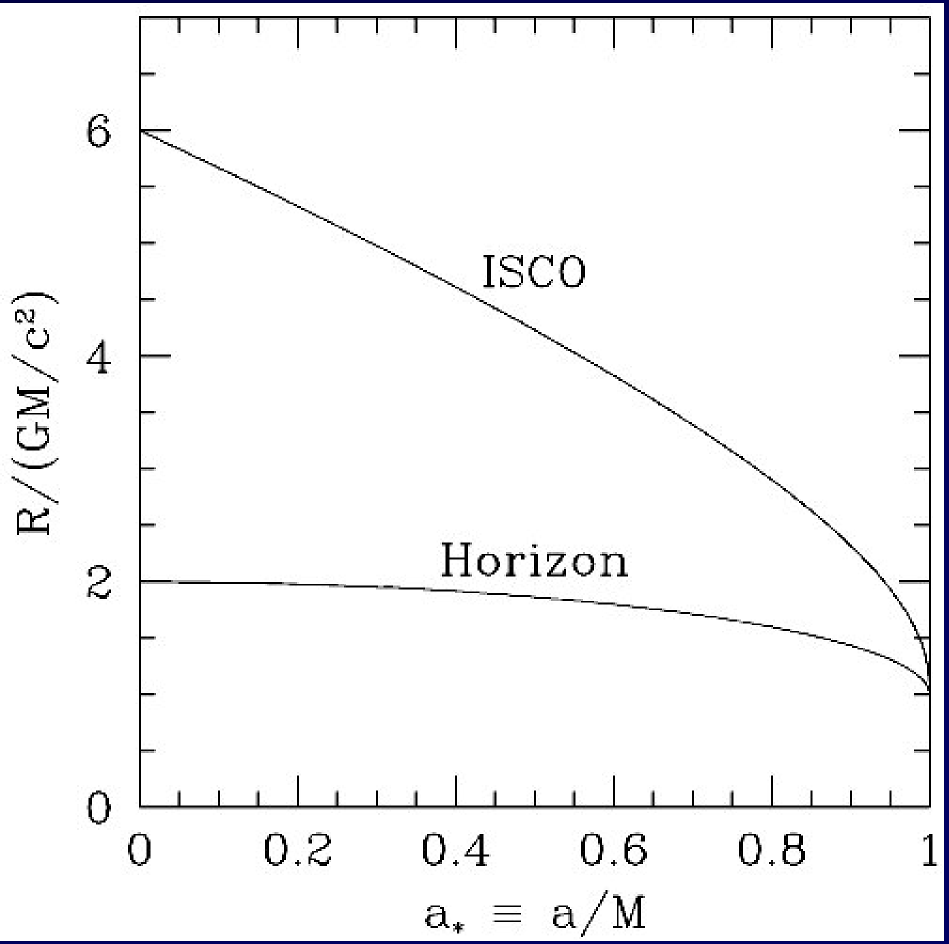
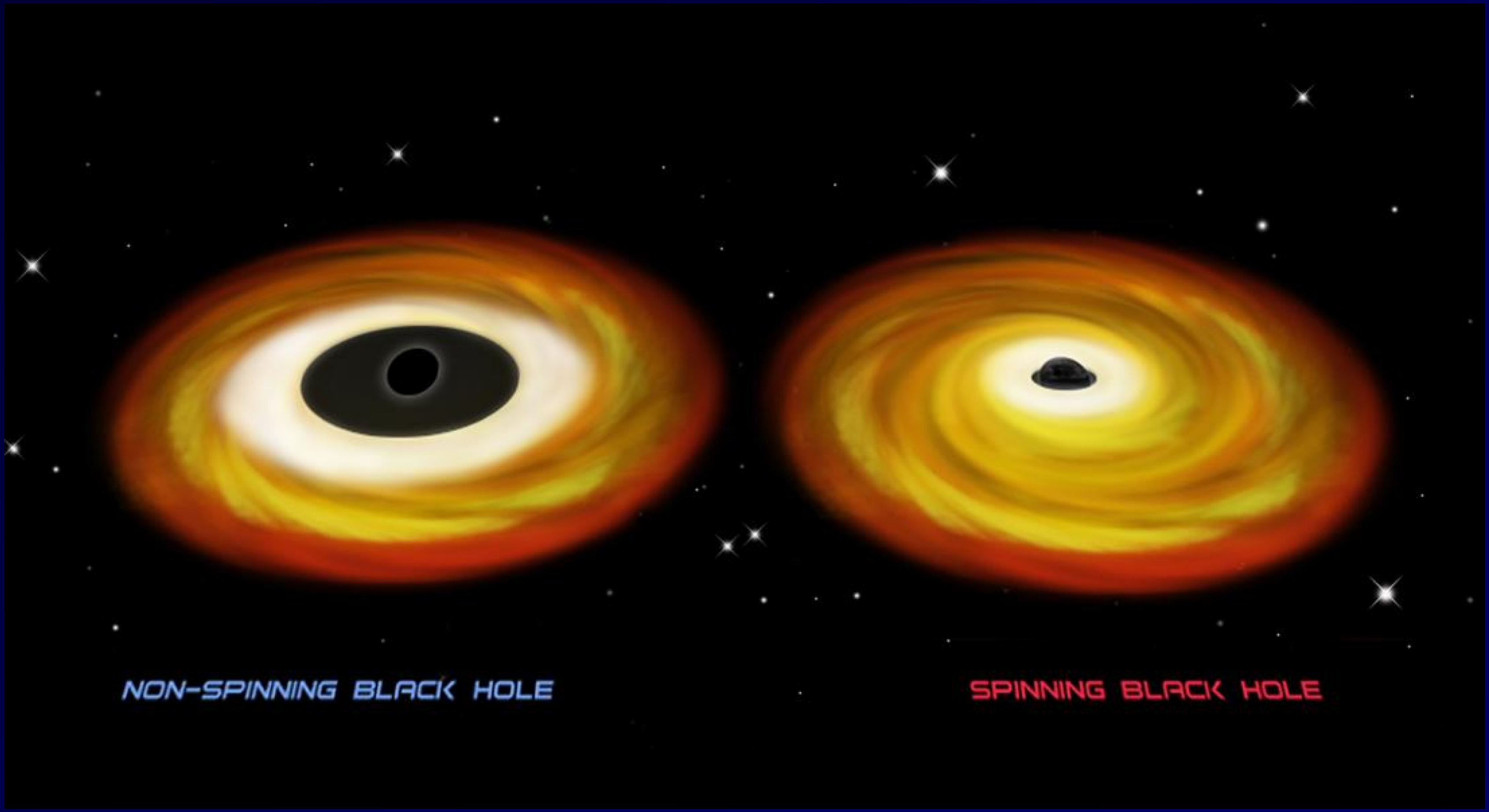
Innermost Stable Circular Orbit (ISCO)

- 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}
- Especially sensitive as $a_* \rightarrow 1$



The Basic Idea



Accretion disk has a dark central "hole" with no radiation

Measure radius of hole by estimating area of the bright inner disk

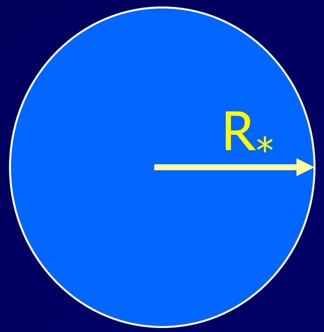
Measuring the Radius of a Star

- Measure the flux F received from the star
- Measure the temperature T_* (from spectrum)

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

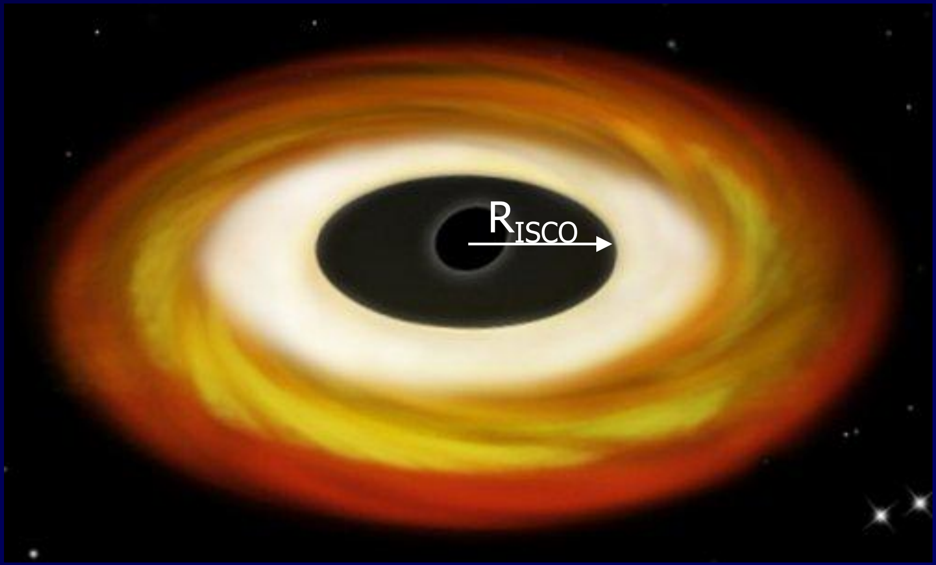
$$\Delta\Omega = \frac{\pi R_*^2}{D^2} = \frac{\pi F}{\sigma T_*^4}$$

$$R_* = D\sqrt{\frac{F}{\sigma T_*^4}} = 37.5\frac{L_*^{1/2}}{T_*^2} \quad (\mathrm{cgs})$$



Measuring the Radius of the Disk Inner Edge

- We want the radius of the "hole" in the disk emission
- Same principle as for a star
- From X-ray data we obtain F_X and T_X → $\Delta\Omega$ (bright)
- Knowing distance **D** and inclination *i* we get R_{ISCO} (geometrical factors)



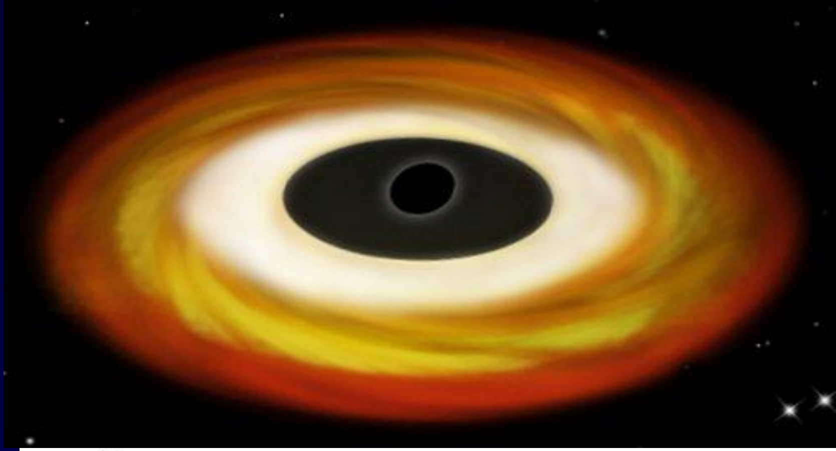
- From R_{ISCO}/M we get a_*
- Need to be careful: focus on Thermal Dominant (TD) data

Zhang et al. (1997); Li et al. (2005); Shafee et al. (2006); McClintock et al. (2006); Davis et al. (2006); Liu et al. (2007); Gou et al. (2009,2010); Steiner et al. (2010)…

Can We Achieve Necessary Accuracy to Measure a_*?

- **YES**
- The disk model is quantitatively robust – very few uncertainties (no α)
- Accreting BHs sometimes switch to a Thermal Dominant (TD) spectral state where radiation processes are simple and spectral models are reliable
- Spectral hardening is under control

$$L_{\rm disk} = \frac{GM\dot{M}}{2R_{\rm in}}$$

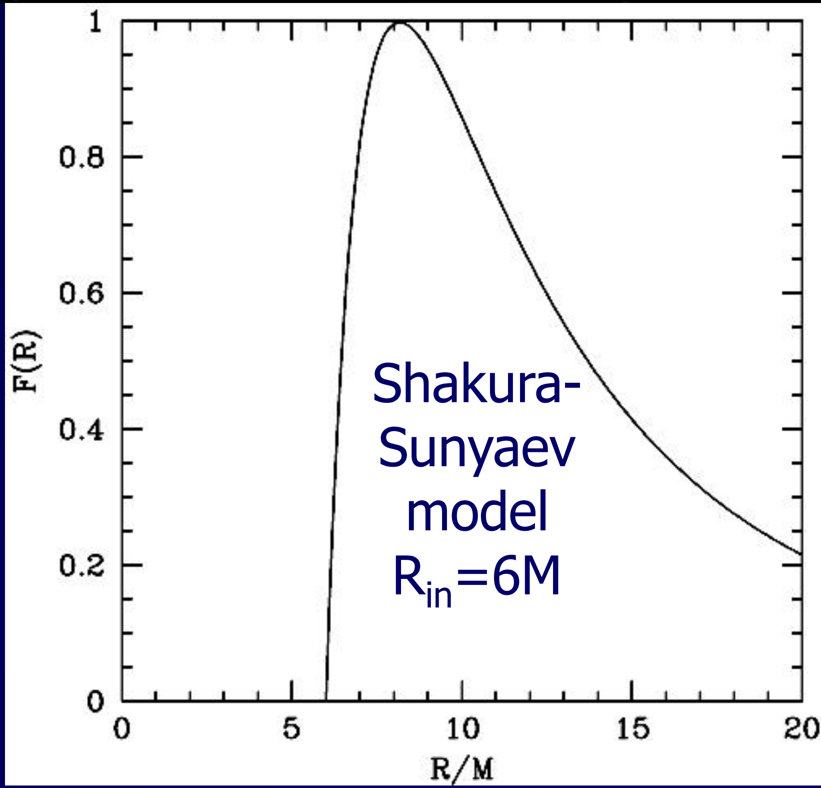


$$F(R) = \frac{3GM\dot{M}}{8\pi R^3}\left(1-\sqrt{\frac{R_{\rm in}}{R}}\right) = \sigma T_{\rm eff}^4(R)$$

$$T_{\rm eff}(R) = T_*\left(\frac{R_{\rm in}}{R}\right)^{3/4}\left(1-\sqrt{\frac{R_{\rm in}}{R}}\right)^{1/4}$$

$$T_* = \left(\frac{3GM\dot{M}}{8\pi\sigma R_{\rm in}^3}\right)^{1/4}, \quad T_{\rm eff,max} = 0.4879 T_*$$

$$R_{\rm in} = 15.4\frac{L_{\rm disk}^{1/2}}{T_{\rm eff,max}^2} \quad ({\rm cgs})$$



Note that the result does not depend on the details of the 'viscous' stress (α parameter)

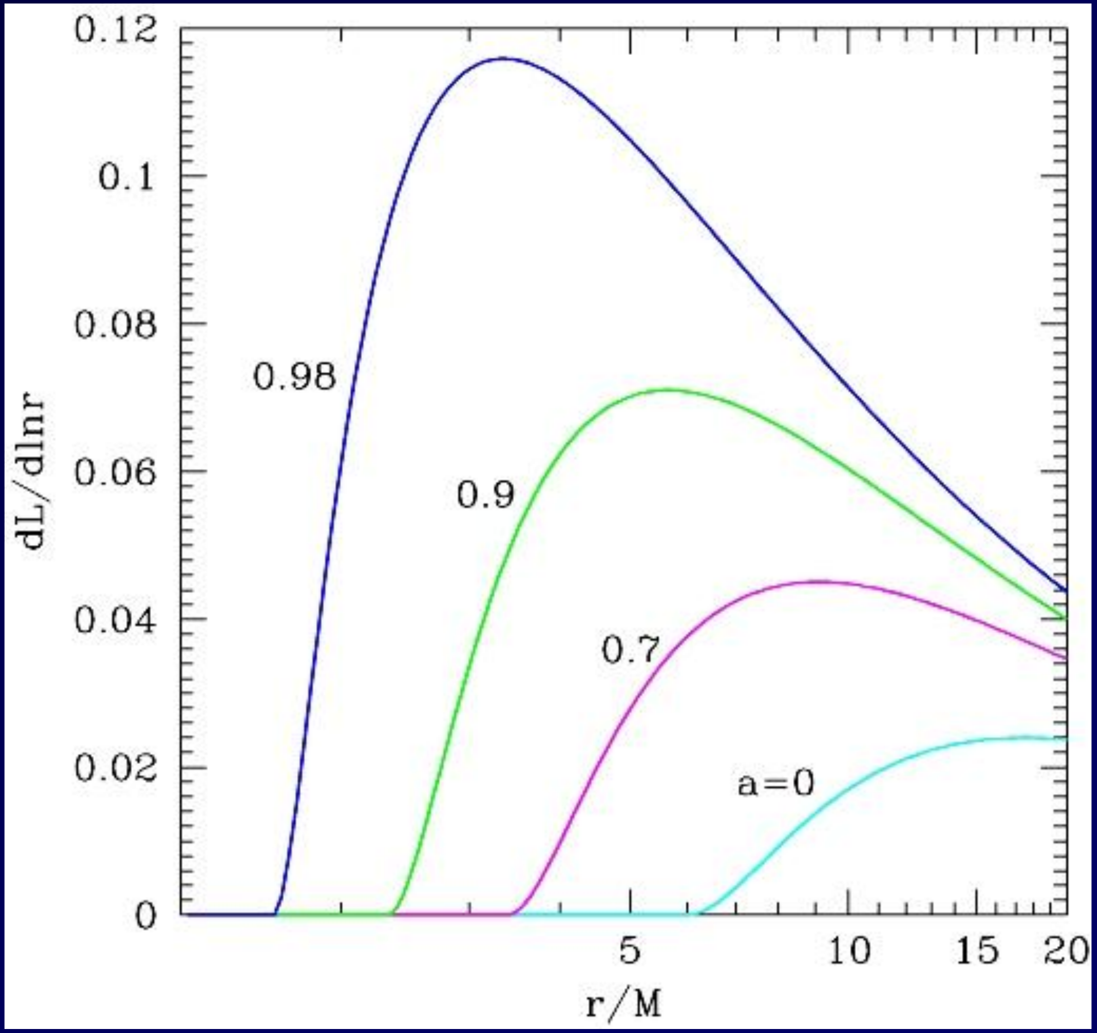
General Relativistic Disk Model: Novikov & Thorne (1973)

L(r) peaks at a different radius for each value of a_*

Therefore, the observed spectrum depends on a_*

We can use this to estimate a_* from observations

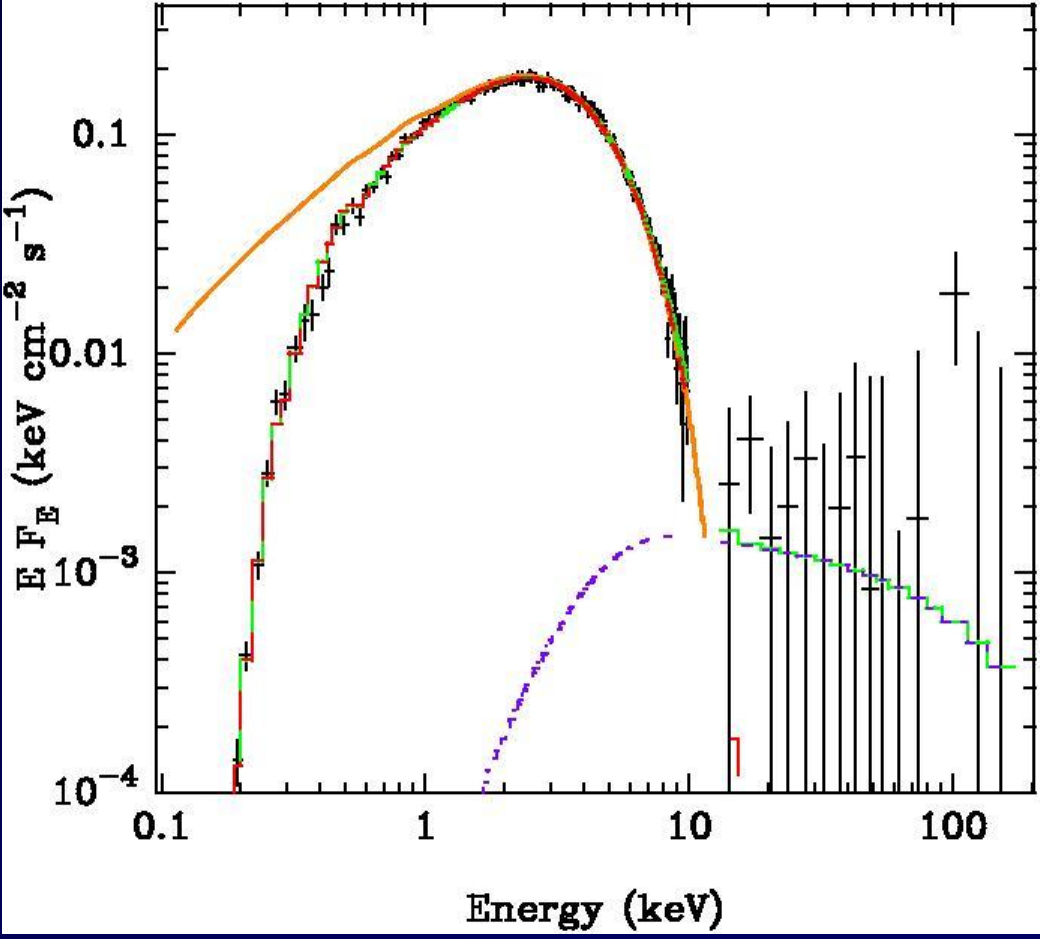
No α dependence



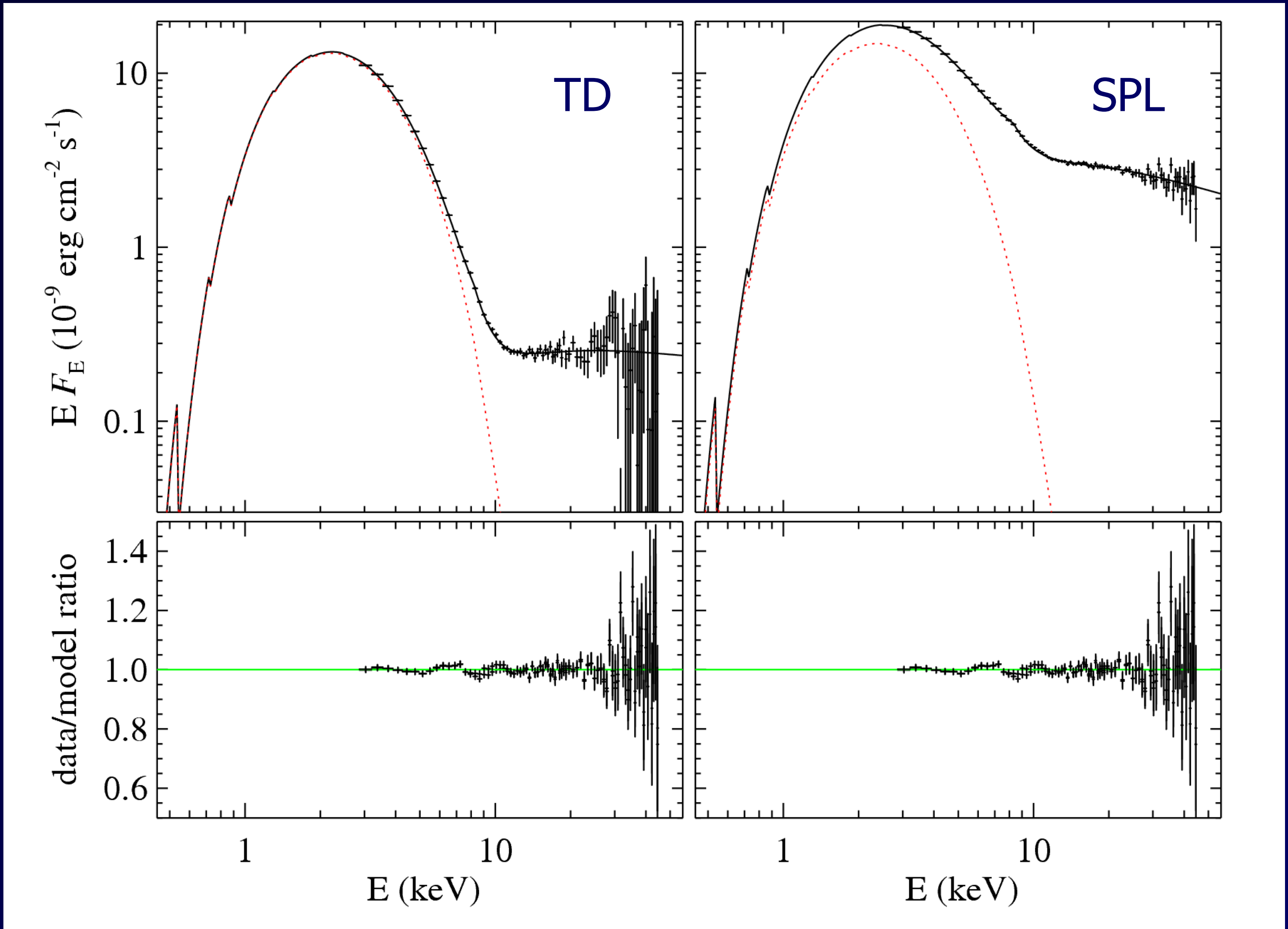
Blackbody-Like Spectral State in BH Accretion Disk

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



- BH XRBs in the "Thermal-Dominant (TD) state" are very well-behaved
- Perfect for estimating inner radius of accretion disk → BH spin
- Just need to estimate F_X, T_X (and N_H) from X-ray continuum spectrum
- Use full relativistic model (Novikov-Thorne 1973; KERRBB, Li et al. 2005)



X-ray continuum spectral fits and residuals for a TD and an SPL observation of XTE J1550-564 (Steiner et al. 2010)

Test: $L = A\sigma T^4$

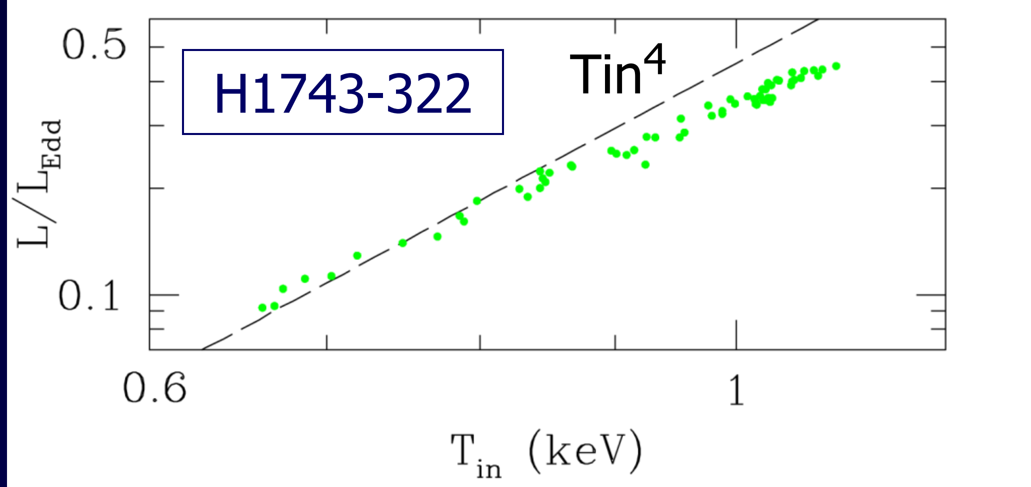
$f = T_{col}/T_{eff}$

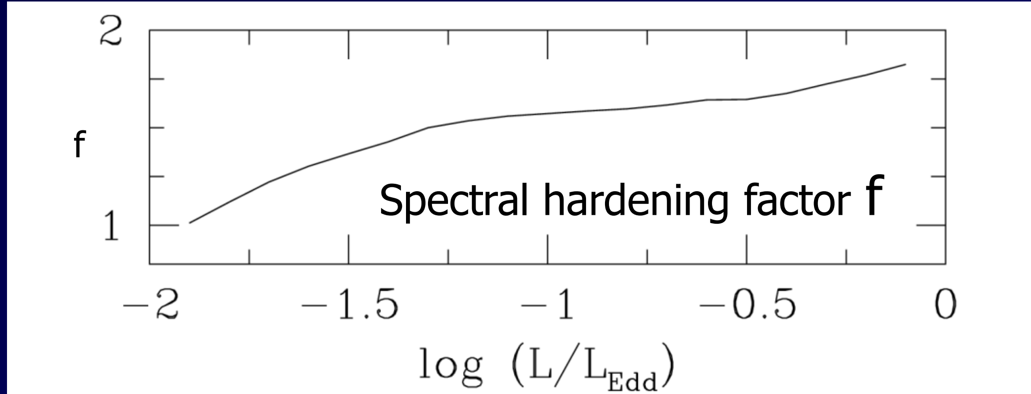
Davis et al. (2005, 2006)

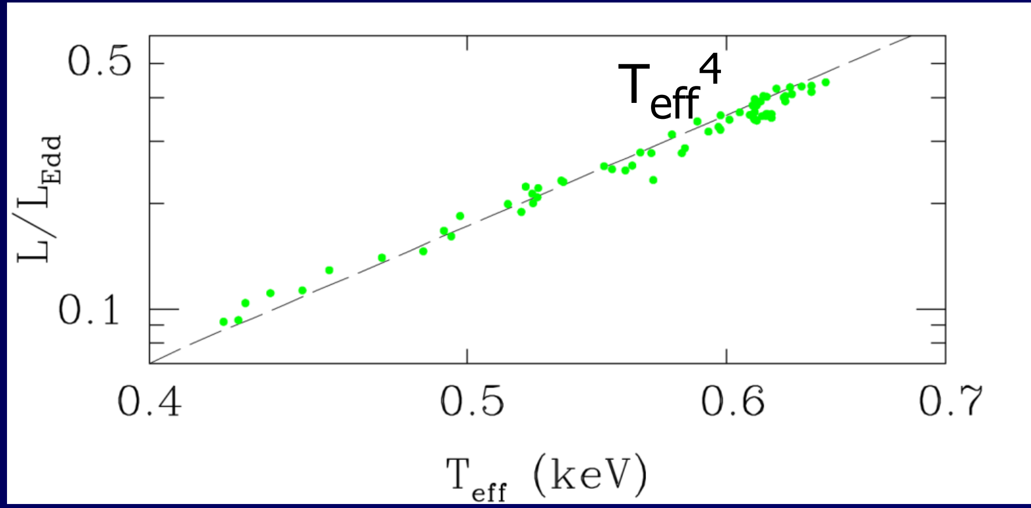
After including the color correction, we get an excellent L-T^4 trend

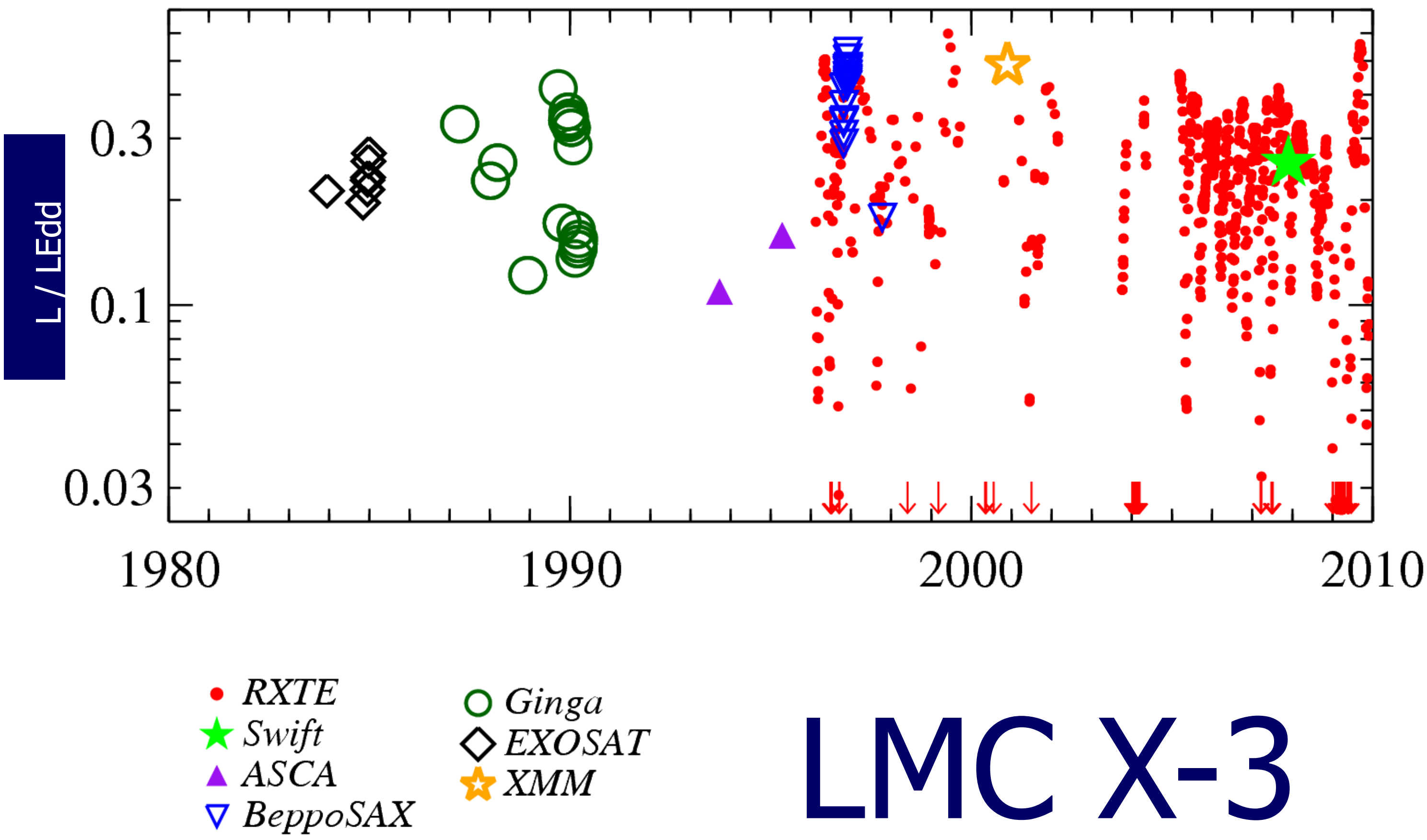
Conclusion:

Thermal State is very good for quantitative modeling



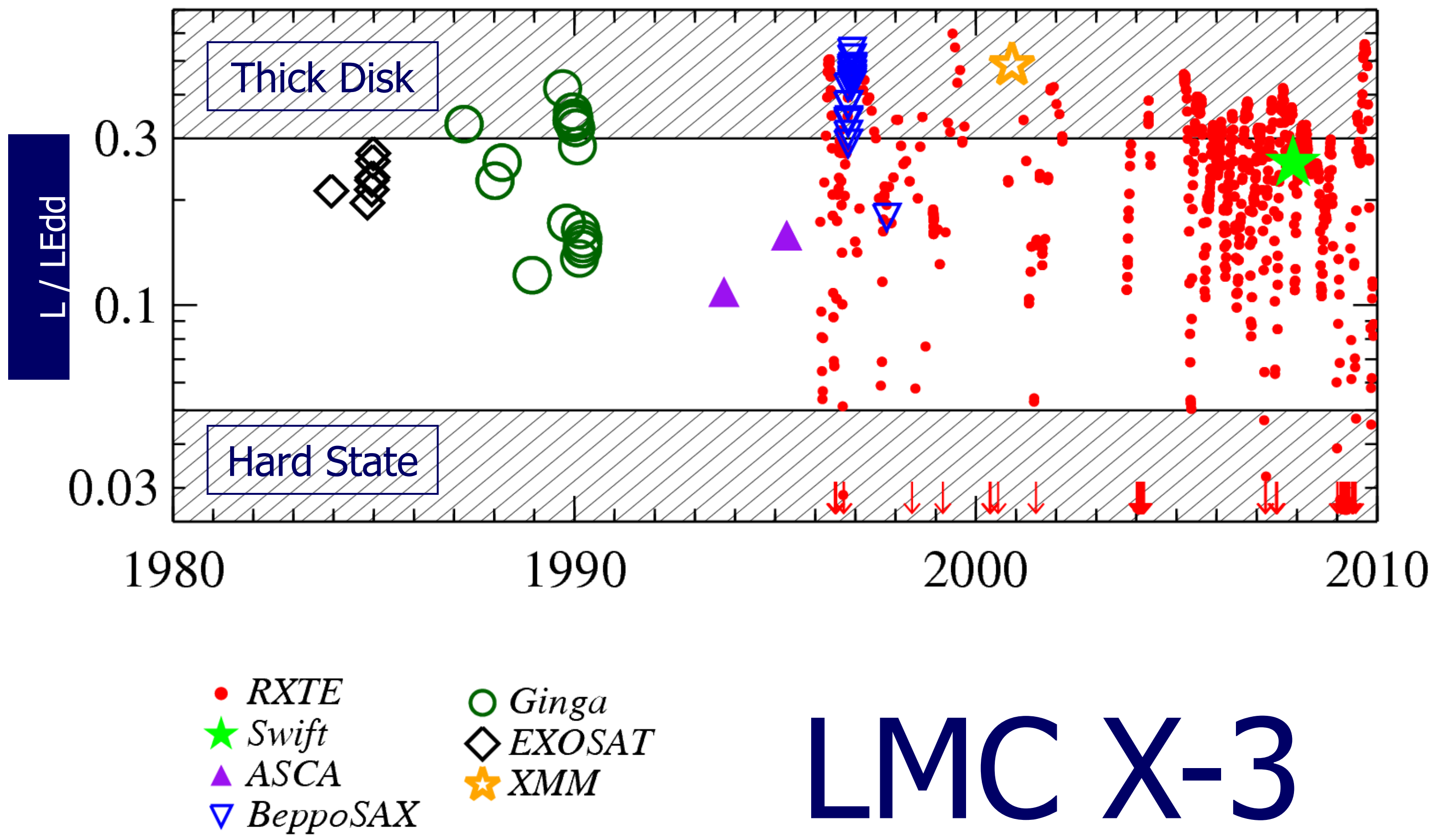




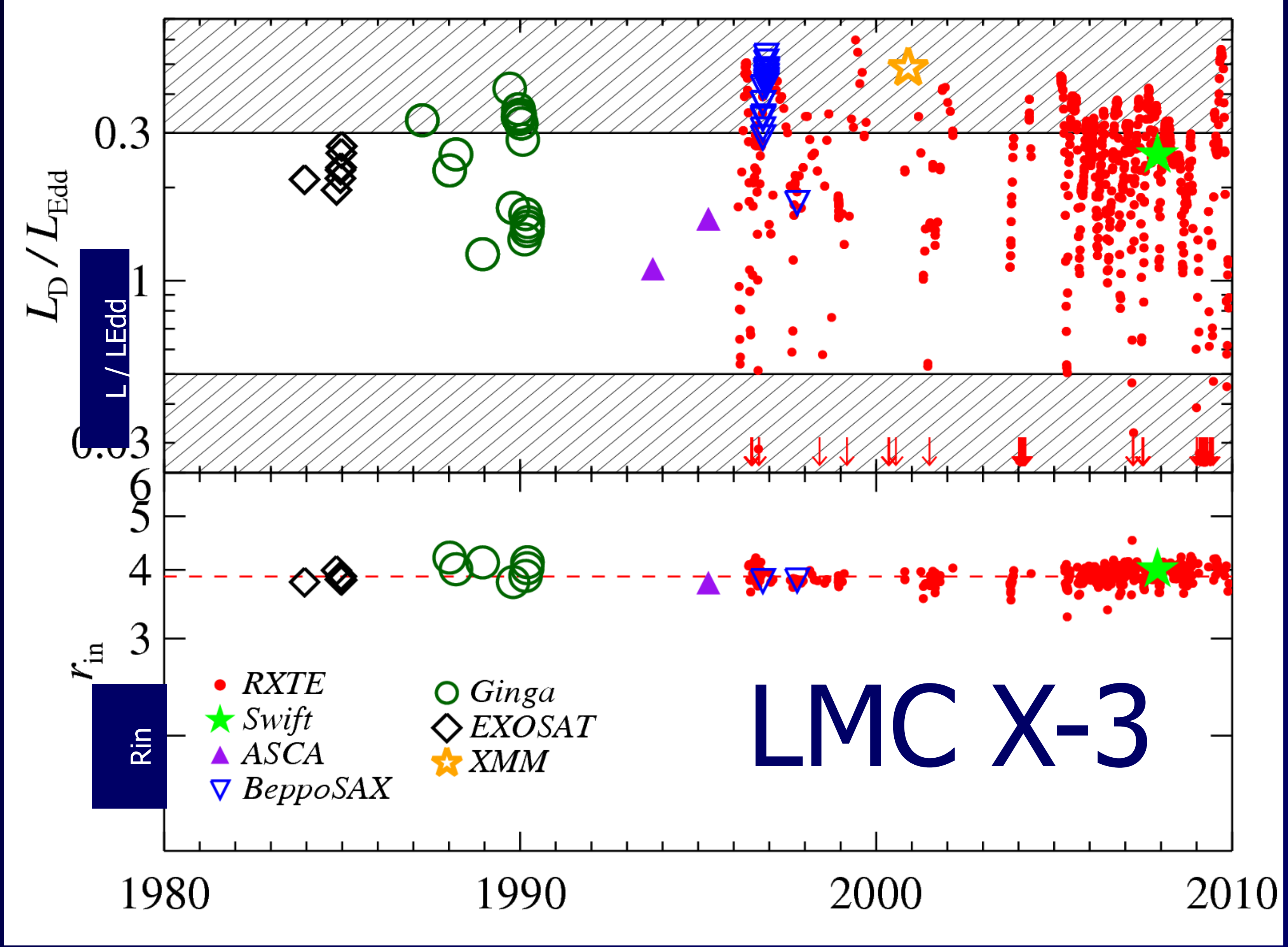


L / LEdd
0.3
0.1
0.03
1980
1990
2000
2010
RXTE
Swift
ASCA
BeppoSAX
Ginga
EXOSAT
XMM

LMC X-3

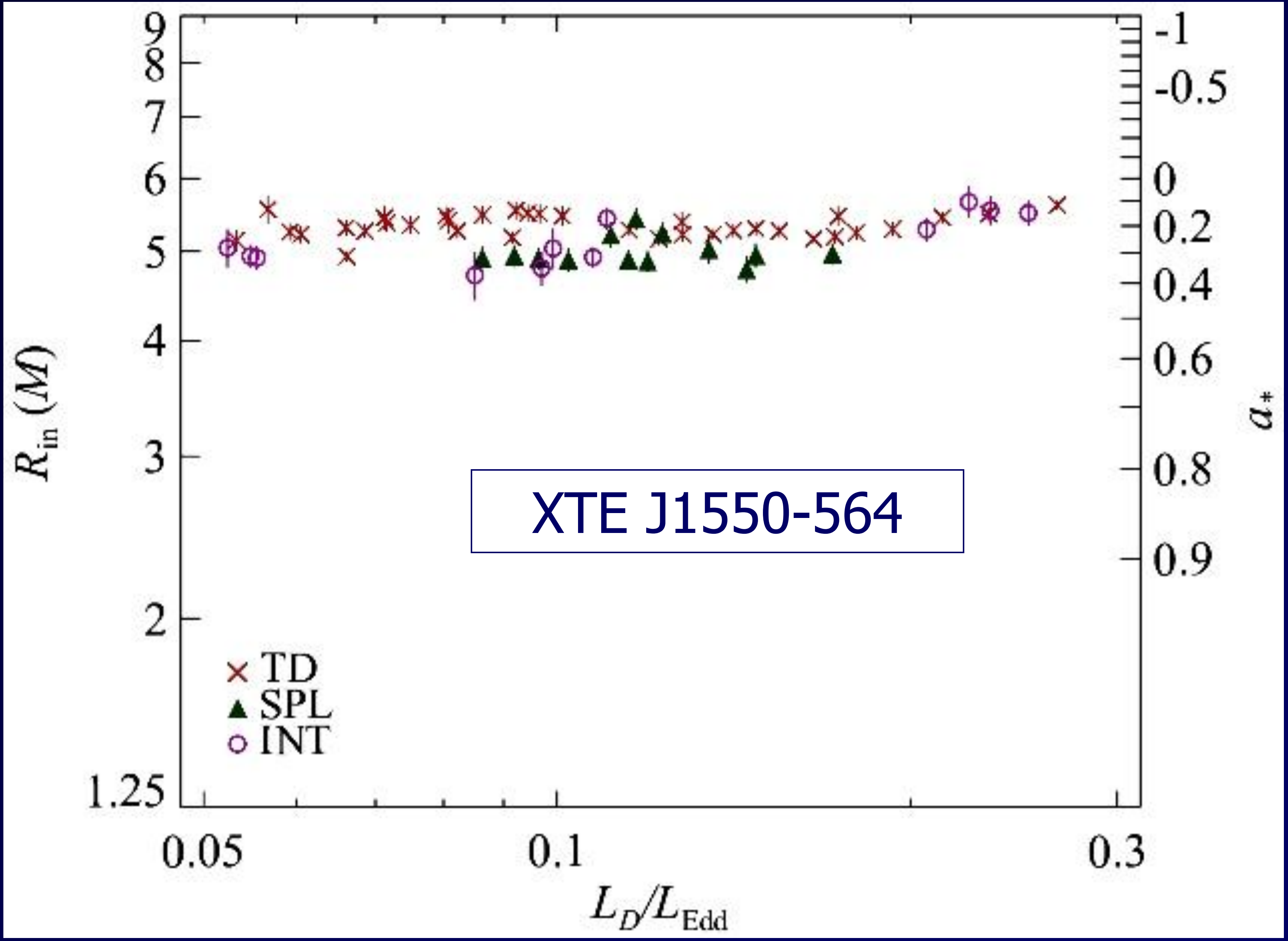

Thick Disk
Hard State
L / LEdd
0.3
0.1
0.03
1980
1990
2000
2010
RXTE
Swift
ASCA
BeppoSAX
Ginga
EXOSAT
XMM

LMC X-3



Steiner et al. (2010)

403 spectra (assuming $M=10M_{\odot}$, $i=67^{o}$)



Estimates of disk inner edge R_{in} and BH spin parameter a_* from all suitable TD ("gold") and SPL/Intermediate ("silver") observations

XTE J1550-564: Consistency! (Steiner, Reis et al. 2010)

- $M=9.10\pm0.61$, $D=4.38\pm0.5$, $i=74.7\pm3.8$ (Orosz et al. 2010)
- Spin estimate from continuum fitting: $a_* \sim 0.34$ (1σ limits: 0.08, 0.54)
- Spin estimate from iron line fitting: $a_* \sim 0.55$ (1σ limits: 0.33, 0.70)
- Combined spin estimate: $a^* = 0.49$ (1σ limits: 0.29, 0.62)

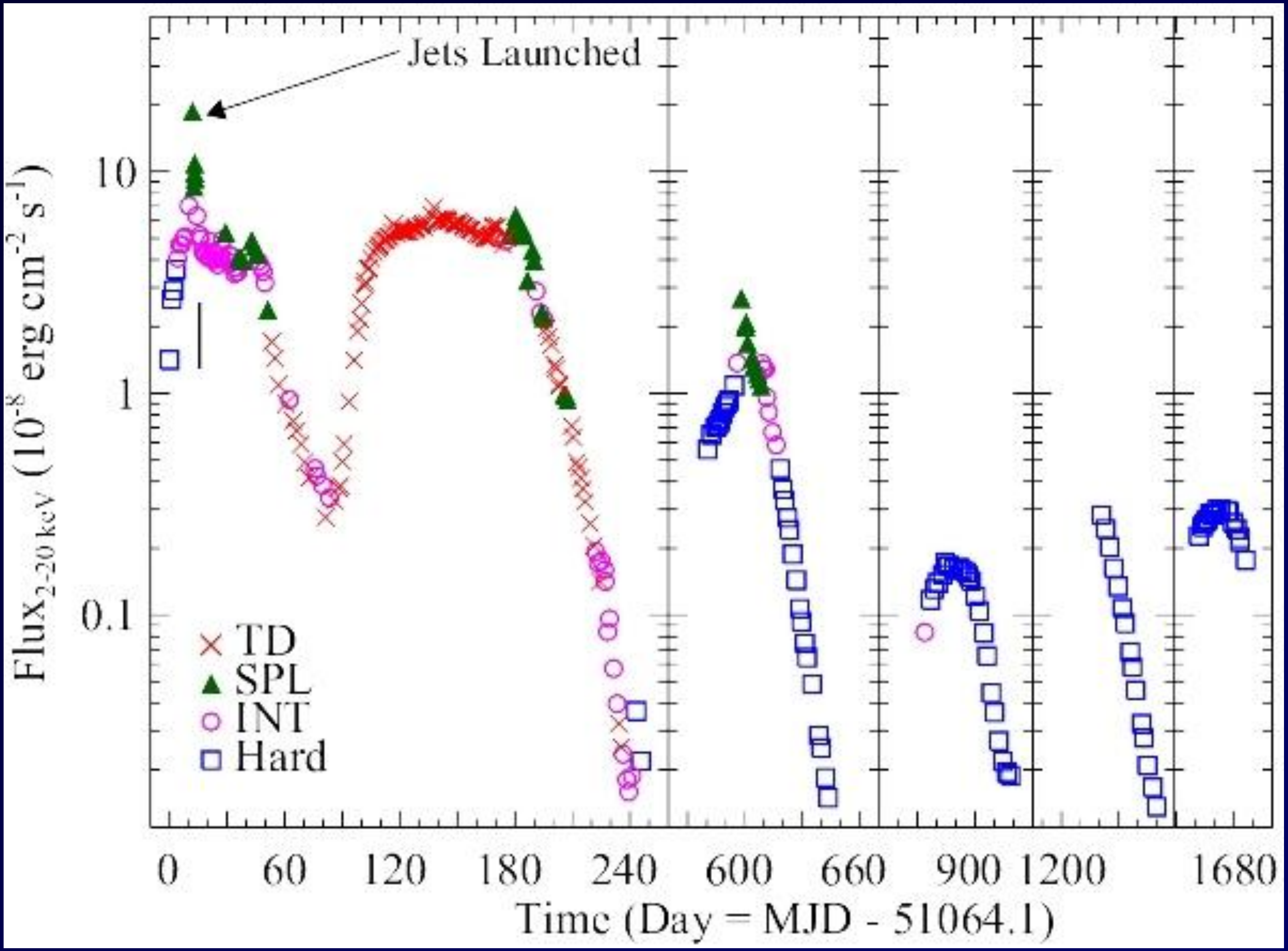
BH Spin Results via Continuum-Fitting

Source Name	BH Mass ($M_\odot$)	BH Spin (a_*)
A0620-00	6.3—6.9	0.12 ± 0.19
LMC X-3	5.9—9.2	~0.25
XTE J1550-564	8.5—9.7	0.34±0.24
GRO J1655-40	6.0—6.6	0.70 ± 0.05
4U1543-47	8.4—10.4	0.80 ± 0.05
M33 X-7	14.2—17.1	0.84 ± 0.05
LMC X-1	9.4—12.4	0.92 ± 0.06
Cyg X-1	13.8—15.8	> 0.97
GRS 1915+105	10—18	> 0.98

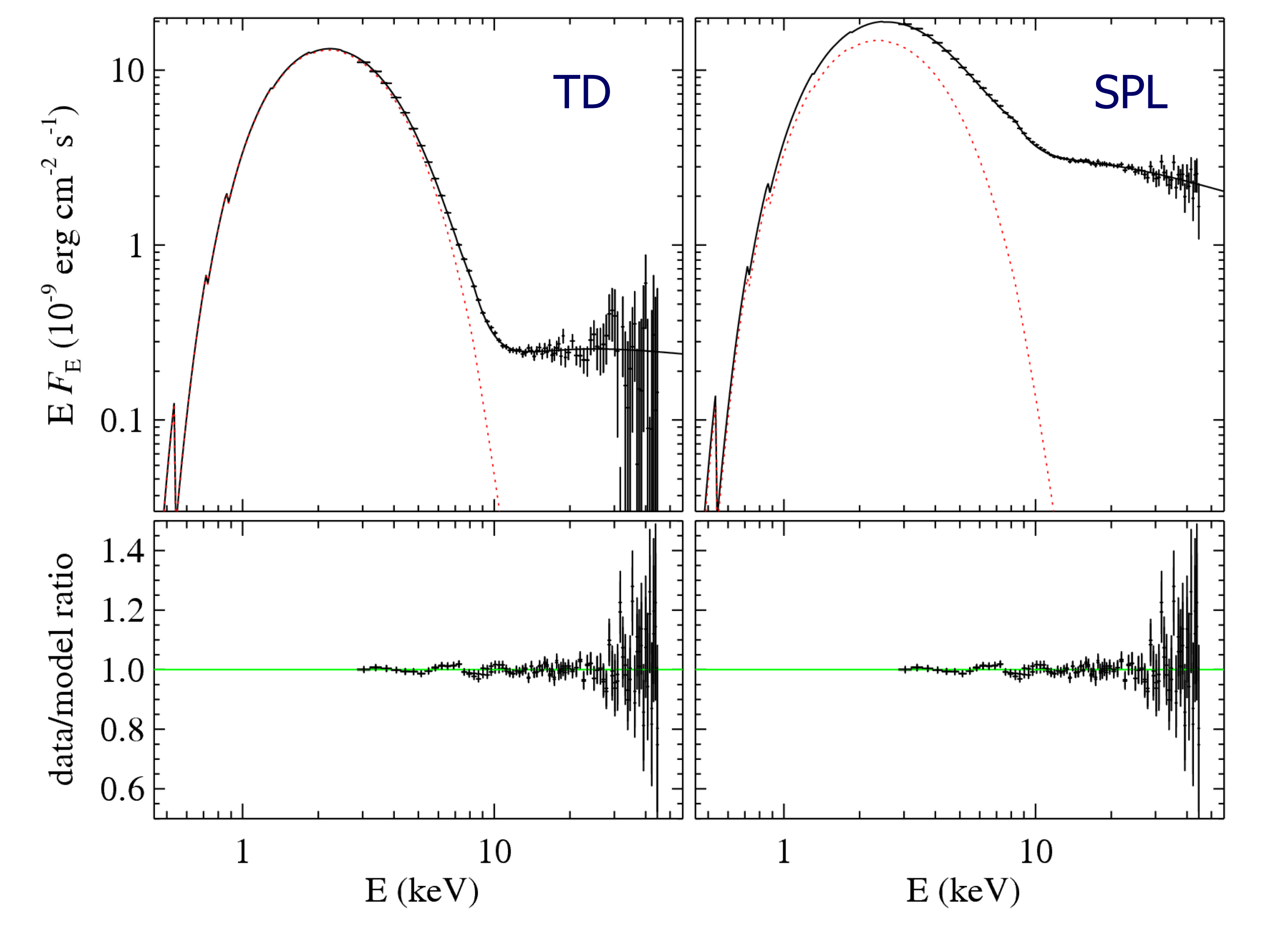
Shafee et al. (2006); McClintock et al. (2006); Davis et al. (2006); Liu et al. (2007,2009); Gou et al. (2009,2010, 2011); Steiner et al. (2011)

ASTROSAT Could Make a Major Contribution

- The SSM will be a powerful discovery machine for finding new BH transients
- Prompt spectral follow-up with good time sampling will provide a great database for measuring a_*
- Wide energy coverage (0.5 – 100 keV) will provide improved constraints on
  - Hard power-law tail (Comptonizing corona)
  - Soft energy spectrum (self-irradiation)



XTE J1550-564: Outburst Light Curve 1998-1999 (RXTE)



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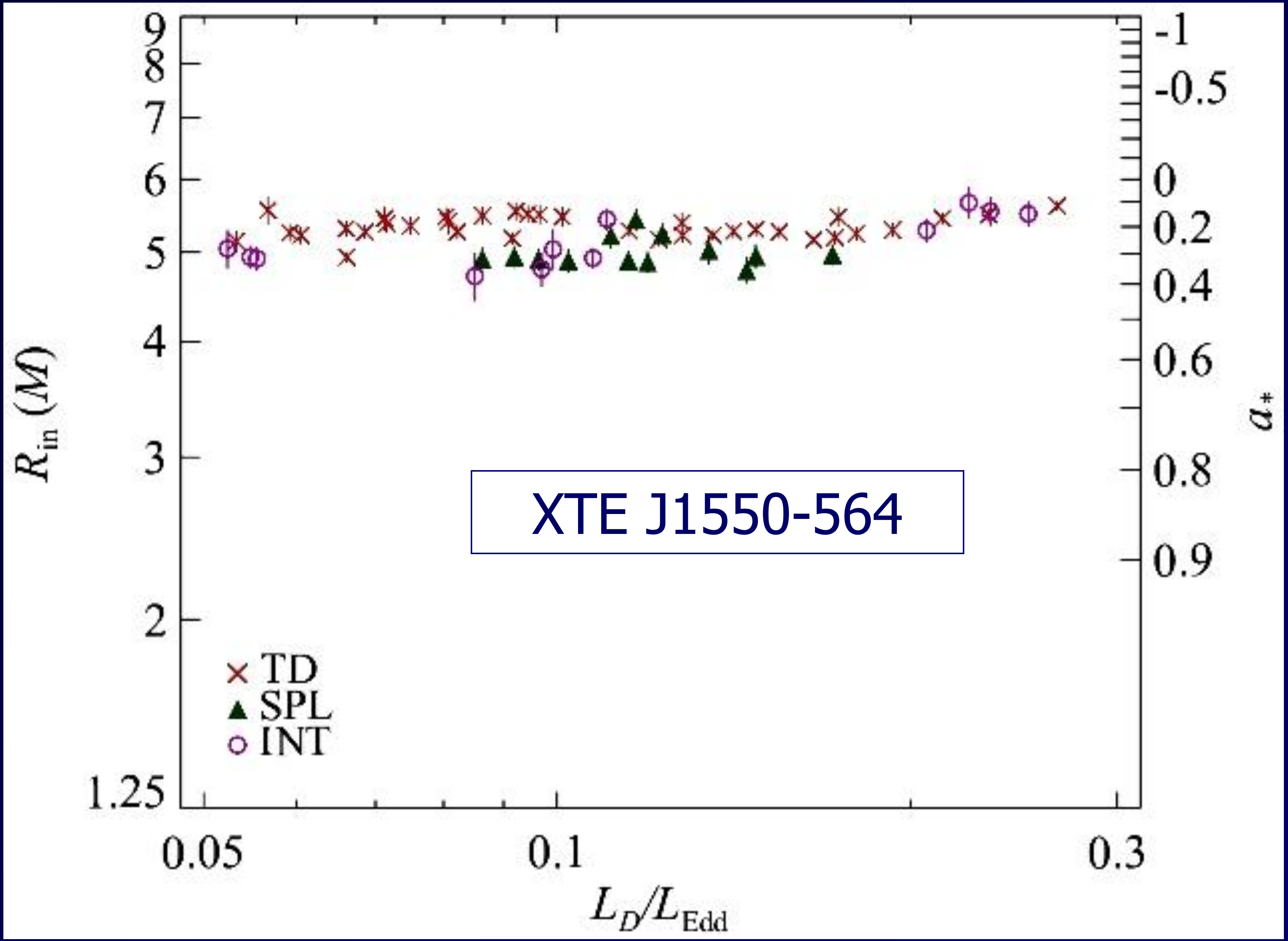

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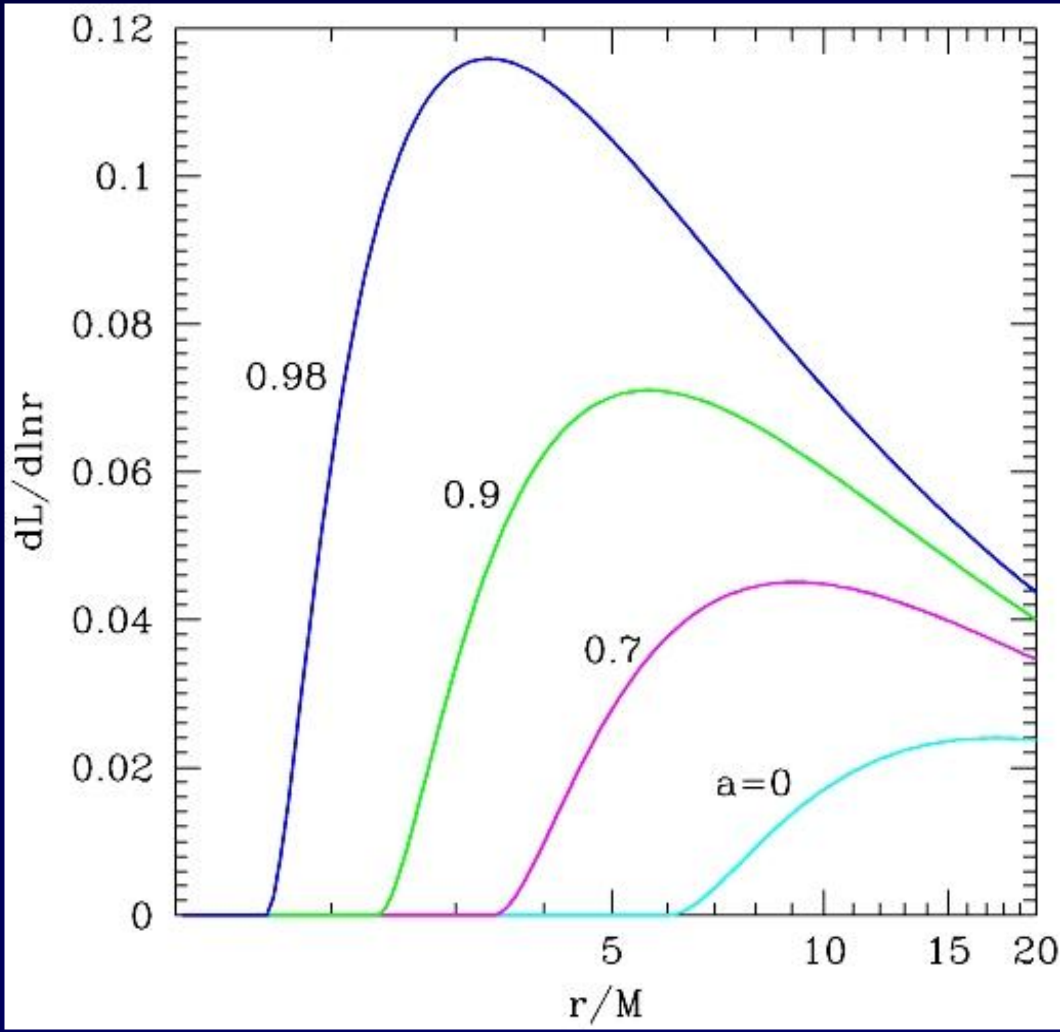
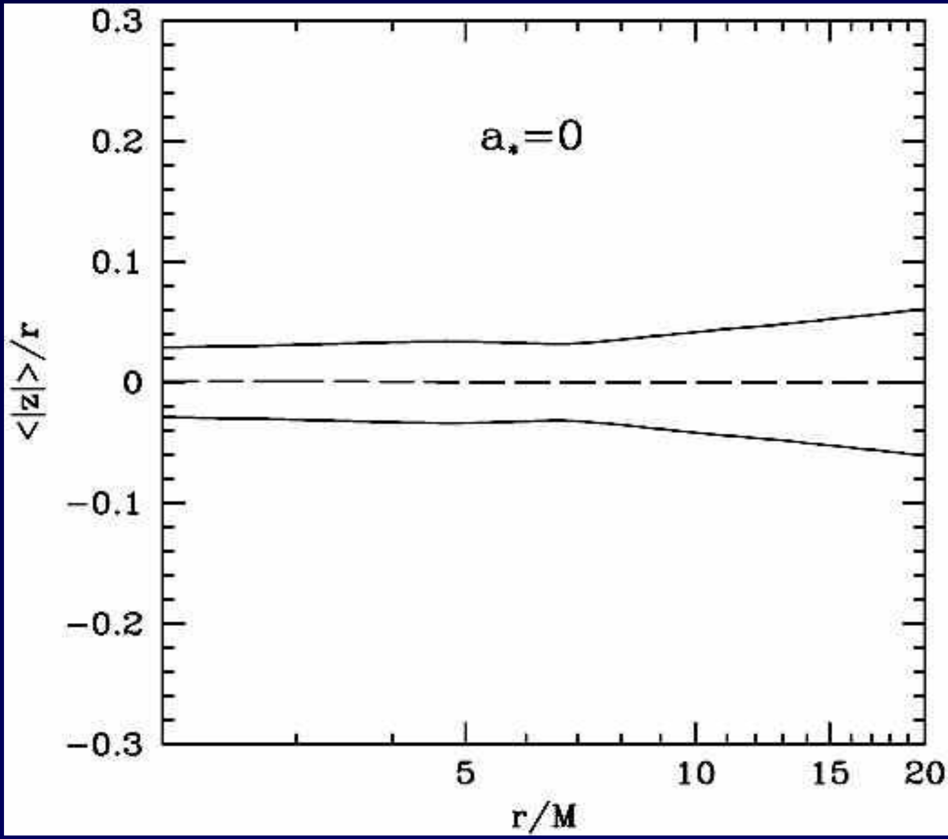
A Theoretical Issue

- NT model assumes that the torque vanishes at the ISCO (Shakura & Sunyaev 1973)
- But magnetic fields could produce significant torque at and inside the ISCO (Krolik 1999; Gammie 1999)
- Afshordi & Paczynski (2003), Shafee et al. (2008) showed that the effect is not important for a **THIN** hydrodynamic disk
- What about an MHD disk?

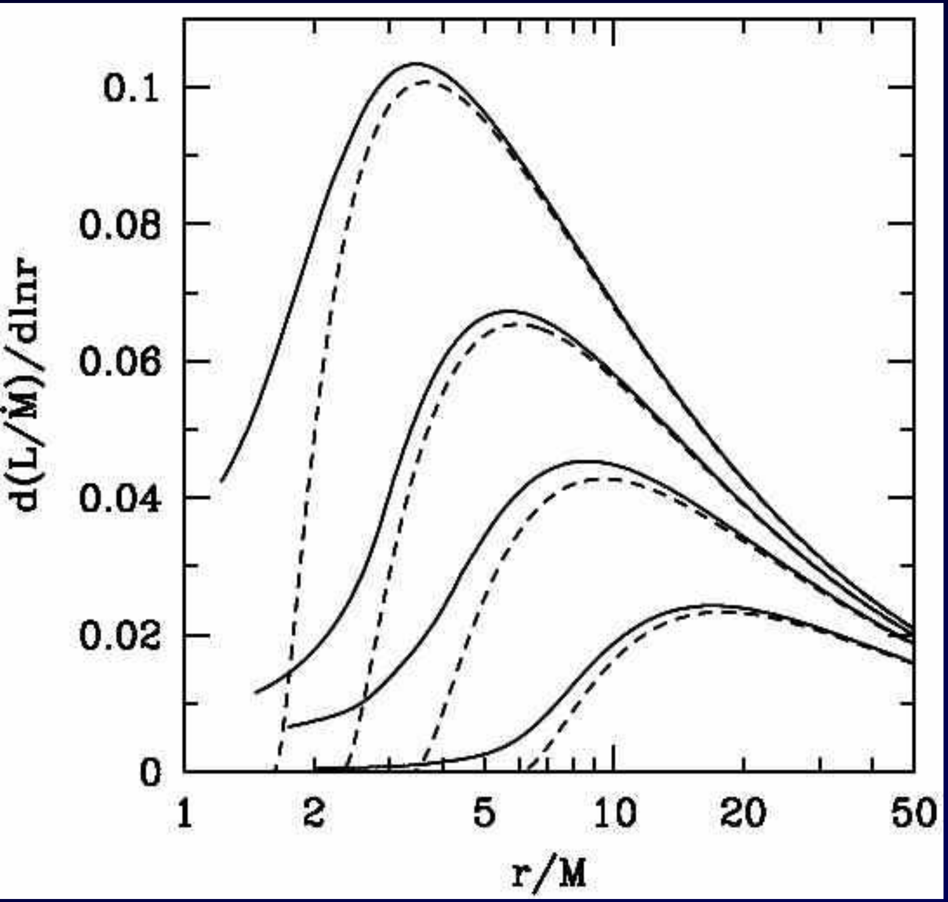


3D GRMHD Simulations of Thin Accretion Disks

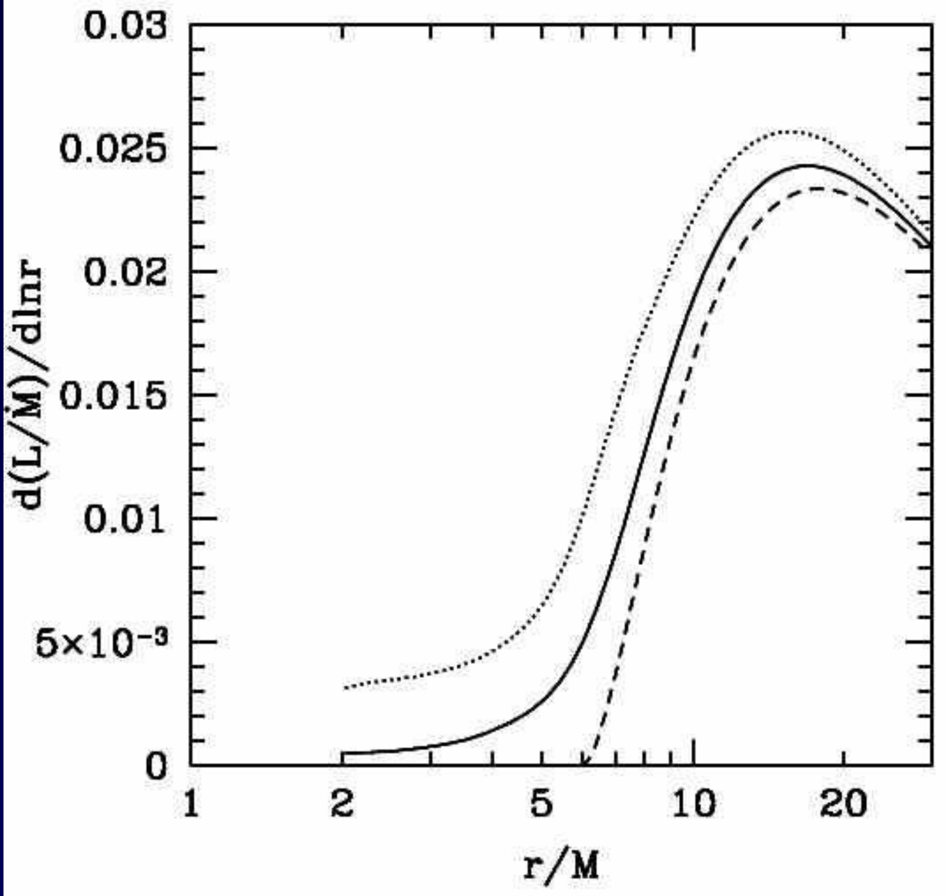
- Shafee et al. (2008), Penna et al. (2010)
- Self-consistent MHD simulations (HARM: Gammie, McKinney & Toth 2003)
- All GR effects included
- h/r ~ 0.05 (thin!!)
- Very few other thin disk simulations: Reynolds & Fabian (2008); Noble, Krolik & Hawley (2009, 2010)



Disk thickness profile (**a_*=0**)
Penna et al. (2010)



Luminosity profile
Simulation vs NT model
$a_* = 0, 0.7, 0.9, 0.98$
Kulkarni et al. (2011)



Luminosity profile
Thin disk vs Thicker disk
$a_* = 0$
Kulkarni et al. (2011)

Modeling Error Due to Deviations From the Novikov-Thorne Model

	$a_*=0$	$a_*=0.7$	$a_*=0.9$	$a*=0.98$
$i=15^o$	0.09	0.75	0.91	0.985
$i=45^o$	0.11	0.77	0.92	0.986
$i=75^o$	0.17	0.83	0.93	0.991

Kulkarni et al. (2010)

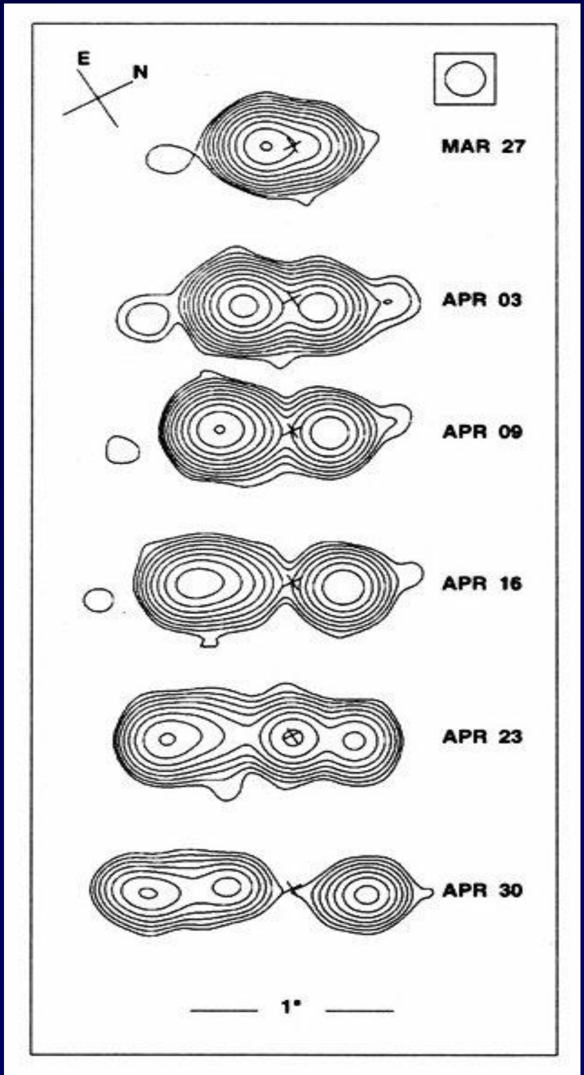
- The systematic error due to assuming the NT model is $\lesssim$ the statistical error due to measurement uncertainties
- The simulated disks correspond to $L \sim 0.4\ L_{Edd}$
- Measurements are, however, made using data at $L \lesssim 0.3\ L_{Edd}$
- $\Rightarrow$ **True systematic errors will be less than the above values**

BH Spin vs Relativistic Jets

GRS 1915+105 has an extreme value of spin: a*=0.98–1

Also spectacular relativistic jets

Could the relativistic ejections be connected to the BH spin?



GRS 1915+105

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Summary

- BH spin measurement by continuum fitting is now a well-developed technique
- Measurement errors are quantifiable (except for disk inclination)
- Systematic model errors (e.g., theoretical model) are mostly under control
- XTE J1550-564: Consistent spin estimates from continuum-fitting & Fe-line methods
- BH spin vs relativistic jets…

Relevance for ASTROSAT

- Measuring reliable BH spins in BH XRBs by continuum-fitting is highly desirable
  - Many applications related to XRBs
  - Check/calibrate other methods: Fe, QPO
  - Will enable SMBH spin measurements
  - Enormous applications in galaxy evolution
- ASTROSAT could play a dominant role
- But it requires a **Local Enthusiast** and a flexible observing plan **(TOO)**