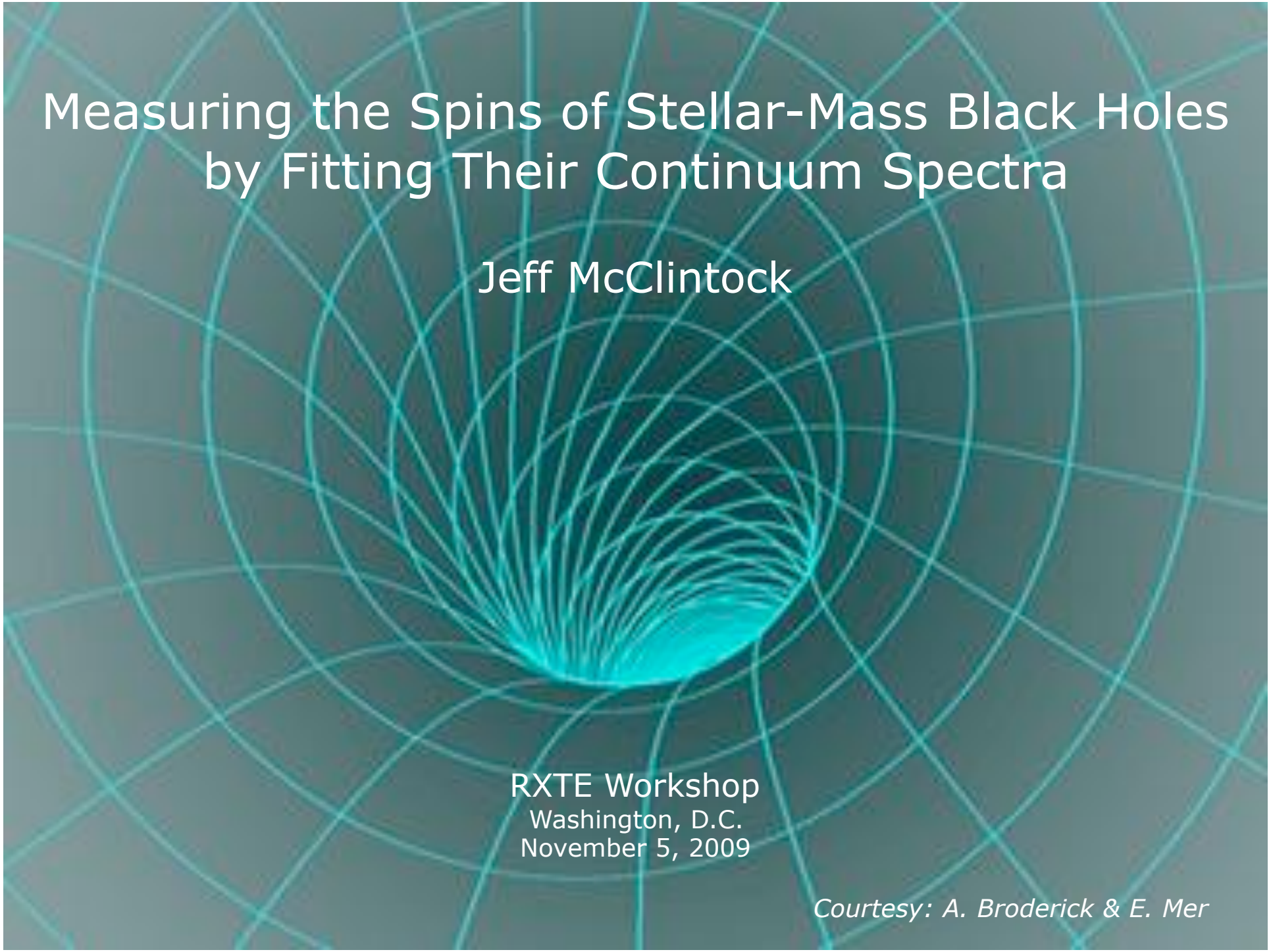
Measuring the Spins of Stellar-Mass Black Holes by Fitting Their Continuum Spectra

Jeff McClintock



RXTE Workshop
Washington, D.C.
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Courtesy: A. Broderick & E. Mer

Our Team

Jeff McClintock Ramesh Narayan

Charles Bailyn Shane Davis Vivek Dhawan

Ken Ebisawa Lijun Gou Li-Xin Li Jifeng Liu

Jon McKinney Jerry Orosz Bob Penna

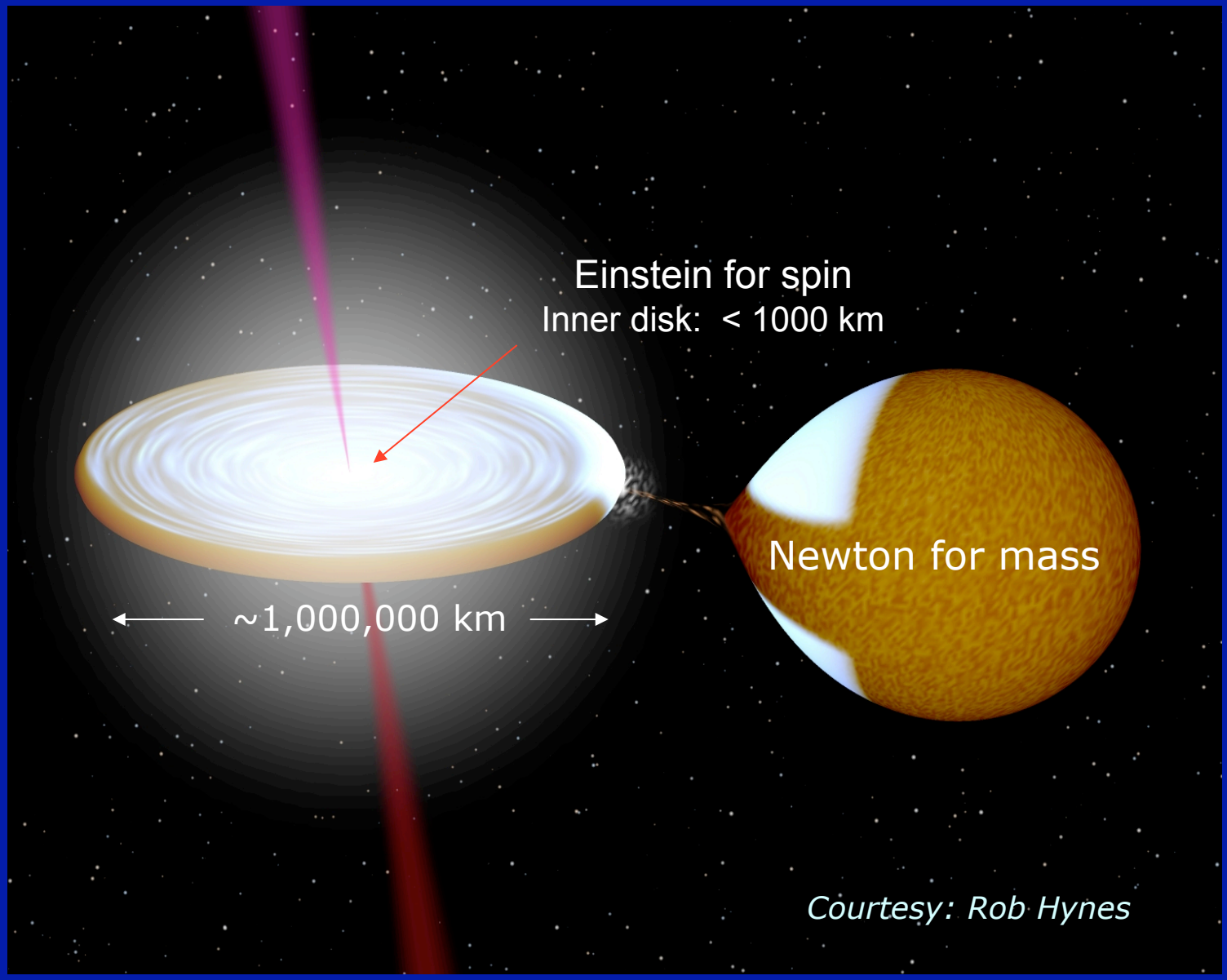
Mark Reid Ron Remillard Rebecca Shafee

Jack Steiner Danny Steeghs Manuel Torres

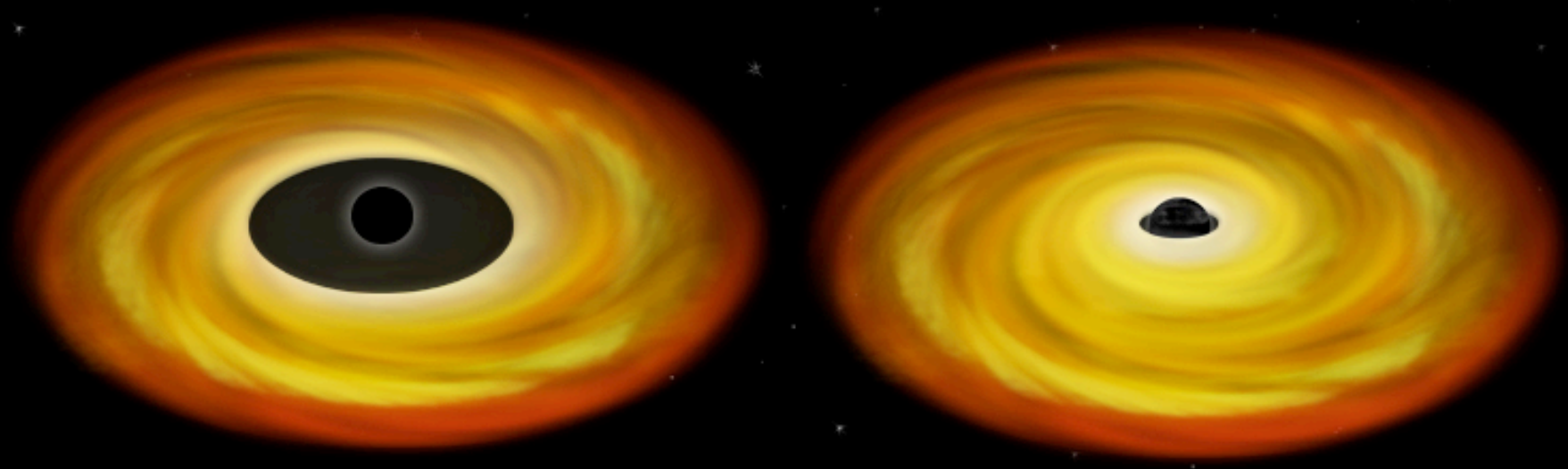
Black Holes are Extremely Simple

- Mass: M
- Spin: $a_* = cJ/GM^2$ $(-1 \leq a_* \leq 1)$
- (Electric Charge: Q)

Black Hole X-ray Binary



Innermost Stable Circular Orbit (ISCO) Dependence on Spin Parameter a*



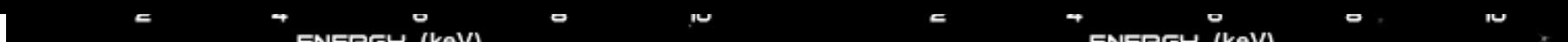
$a_* = 0$

$R_{ISCO} = 6MG/c^2 = 90$ km

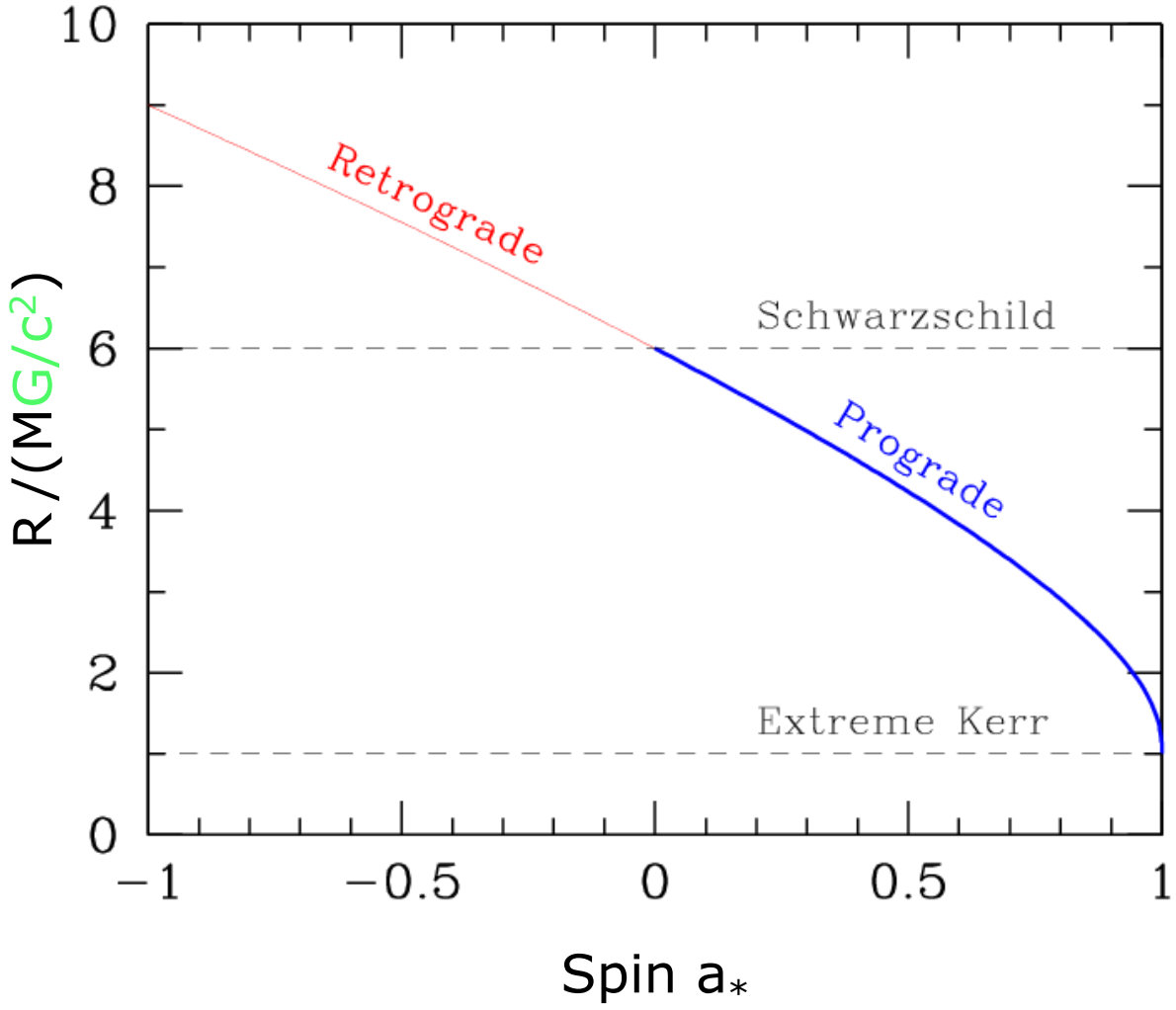
$a_* = 1$

$R_{ISCO} = MG/c^2 = 15$ km

(for $M = 10\ M_\odot$)



Radius of ISCO vs. Spin



90 km

for 10 $M_\odot$

15 km

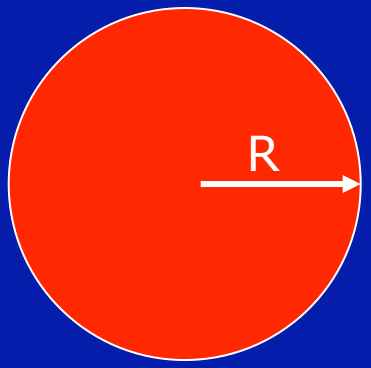
Measuring the Radius of a Star

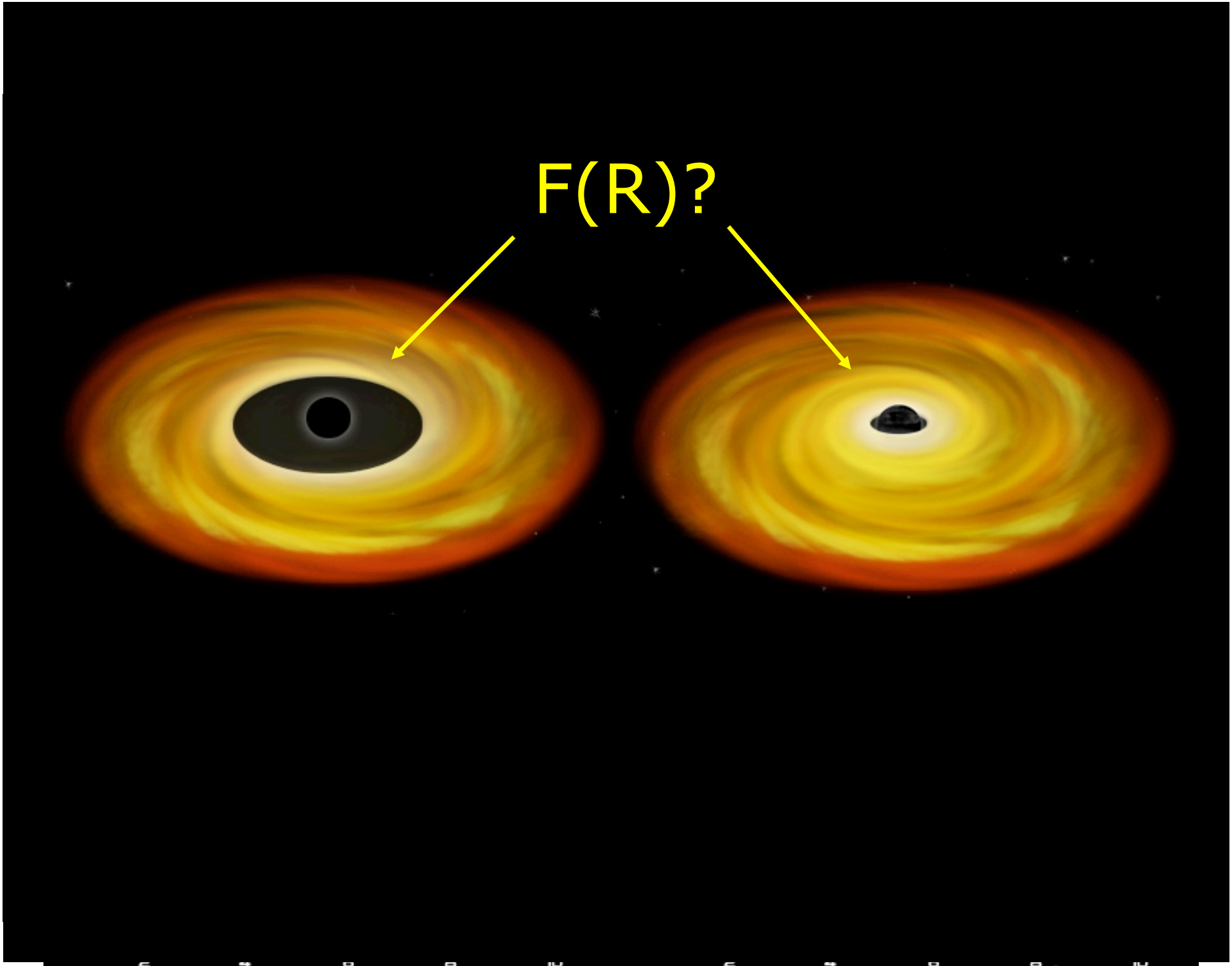
Radius R of a Star

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

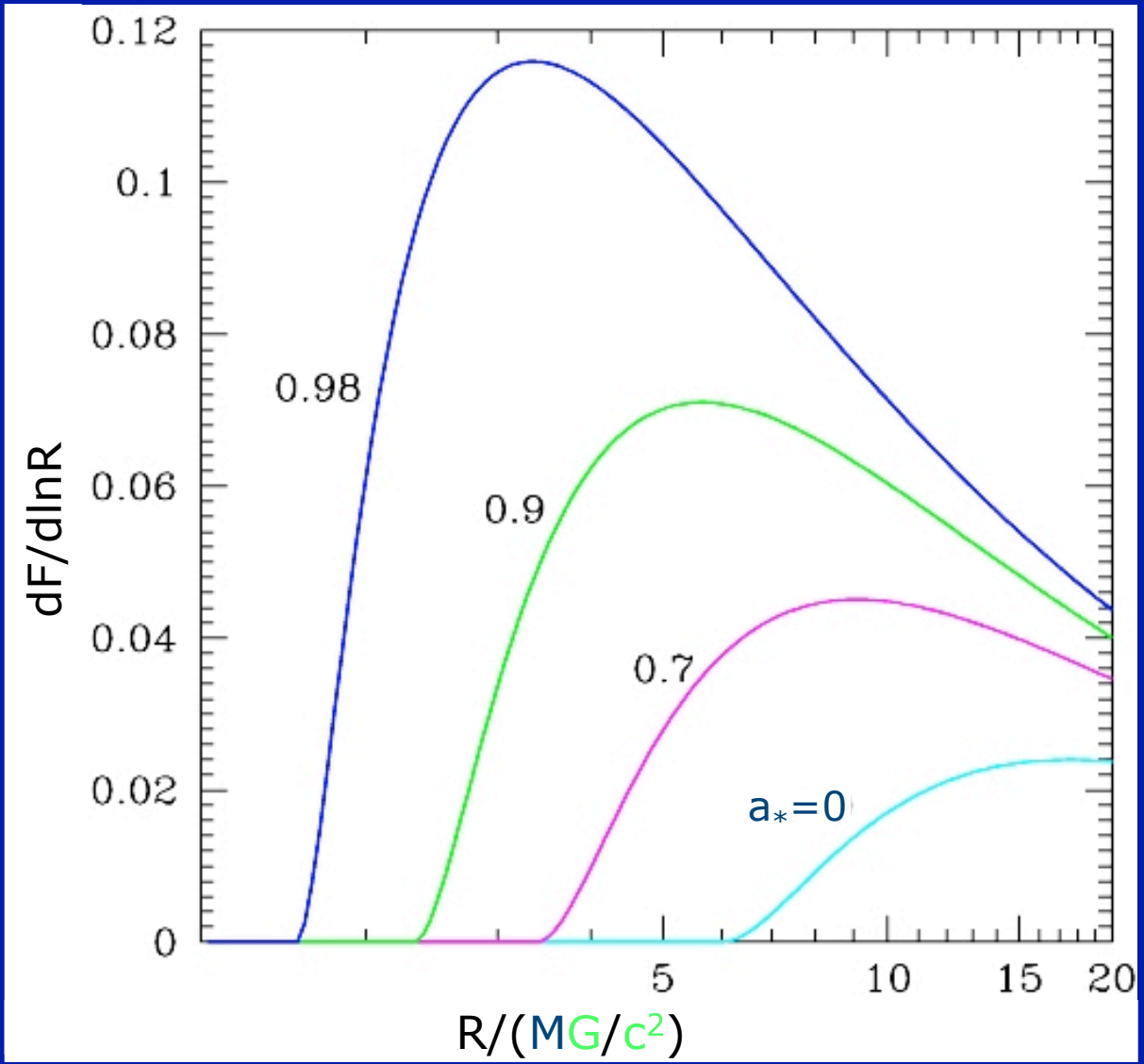
Solid angle: $(R/D)^2 = F/\sigma T^4$

$D \rightarrow$ R




F(R)?

Novikov & Thorne F(R)



Novikov & Thorne 1973

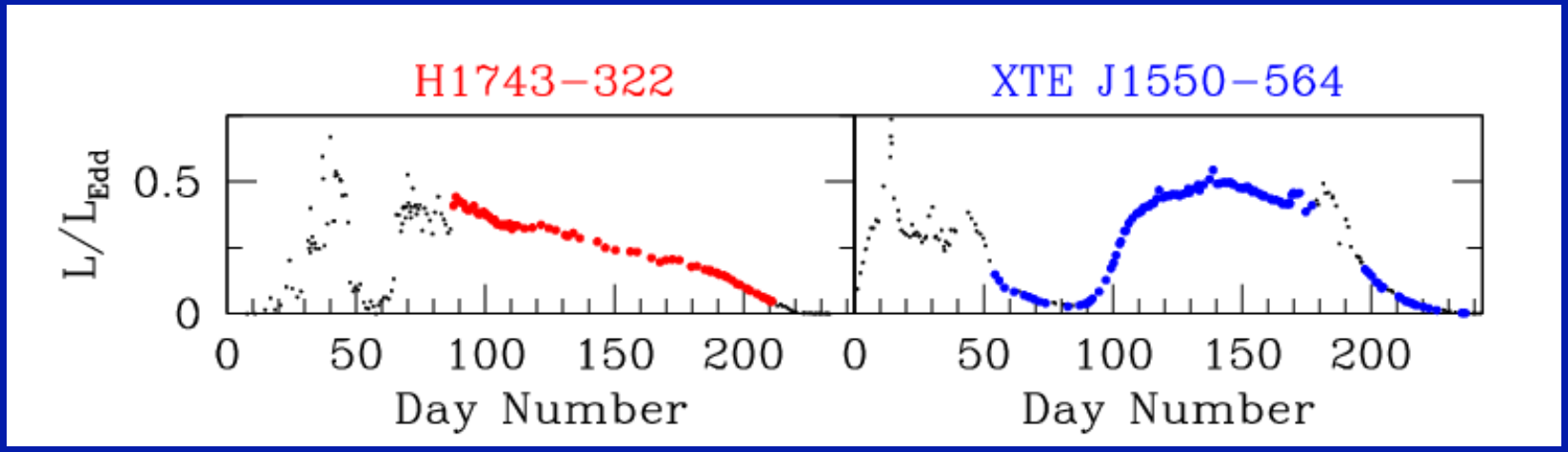
Li et al. 2005 (KERRBB)

GRMHD: Shafee et al. 2008

GRMHD: Penna et al.

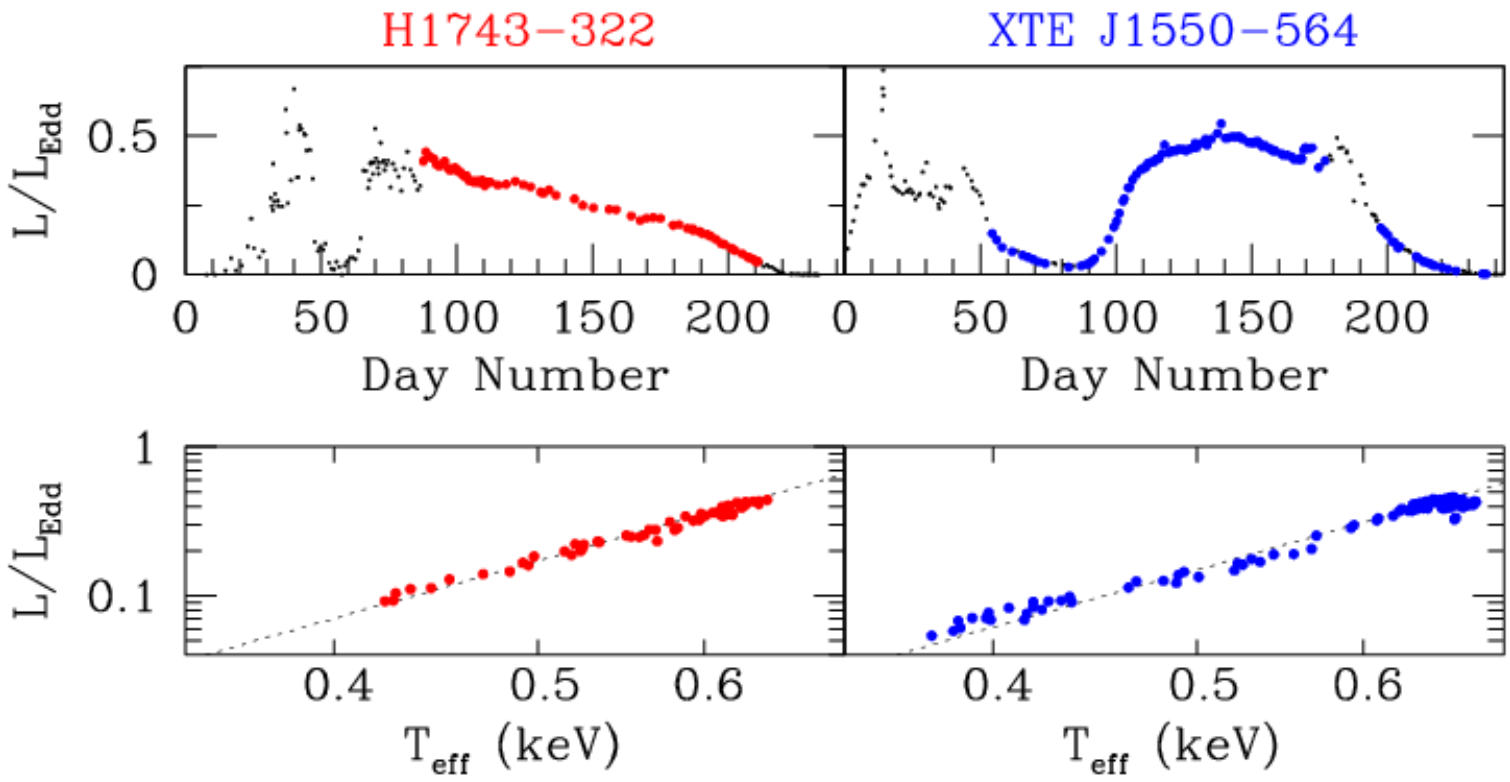
RXTE

There Exists a Constant Inner Disk Radius (1 of 2)



RXTE

There Exists a Constant Inner Disk Radius (2 of 2)



Mitsuda et al. 1984; Makishima et al. 1986; Tanaka & Lewin 1995; Kubota et al. 2001; Kubota & Makishima 2004; Gierlinski & Done 2004; Abe et al. 2005; Davis, Done & Blaes 2006; McClintock et al. 2009

Requirements for Continuum-Fitting Method

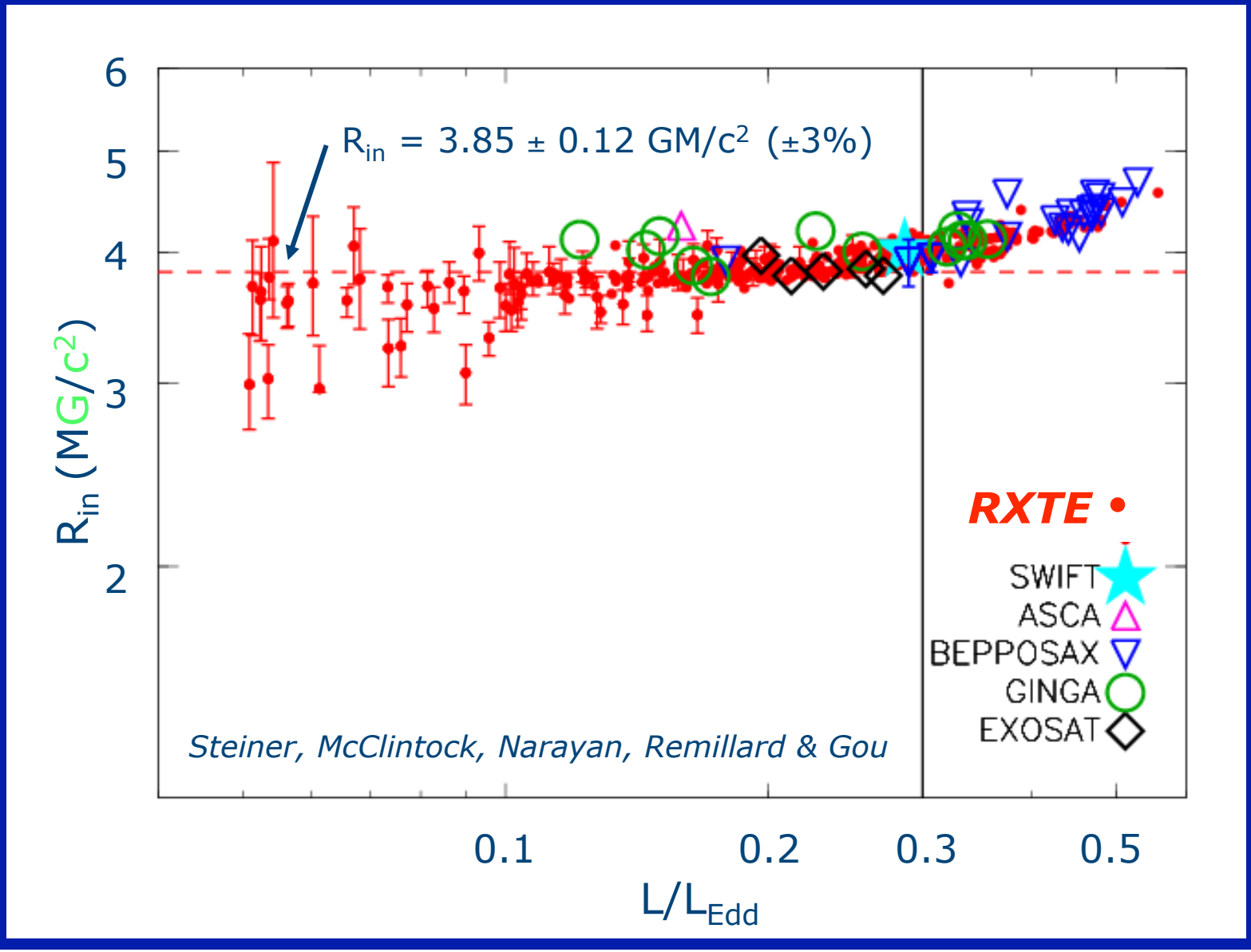
(Zhang, Cui & Chen 1997)

- Theoretical profile of disk flux F(R) ✔
- Strong thermal component of emission ✔
- Thin disk: H/R < 0.1 $\longleftrightarrow$ $L/L_{Edd} < 0.3$ ✔
- Response at E > 10 keV to constrain PL component ✔
- Accurate estimates of M, D, i ✔

Spins: Published and in the Works

System	a_*	Reference
GRO J1655-40	0.65 - 0.75	Shafee et al. 2006
4U 1543-47	0.75 - 0.85	Shafee et al. 2006
LMC X-3	< 0.26	Davis et al. 2006
GRS 1915+105	0.98 - 1	McClintock et al. 2006
M33 X-7	0.77 ± 0.05	Liu et al. 2007
LMC X-1	0.92 (+0.05, -0.07)	Gou et al. 2009
XTE J1550-564	TBD	Steiner et al.
A0620-00	TBD	Gou et al.
Cygnus X-1	TBD	Gou et al.
LMC X-3 (redo)	TBD	Steiner et al.

LMC X-3: 1983 - 2007



Numbers of Observations for 9 Sources and 9 X-ray Missions

System / Mission	RXTE	ASCA	Ginga	Chandra	XMM	BSAX	EXOSAT	Swift	OSO-8
GRO J1655-40	31	2							
4U1543-47	34								
LMC X-3	360	1	12		1	22	5	1	
GRS 1915+105	20	2							
M33 X-7				8	7				
LMC X-1	53								
XTE J 1550-564	136								
A0620-00									1
Cygnus X-1	1	1							
Total	635	6	12	8	8	22	5	1	1

a_* and M *Completely* Define a BH

Goal: With a secure sample of a dozen measurements of a_* & M in hand:

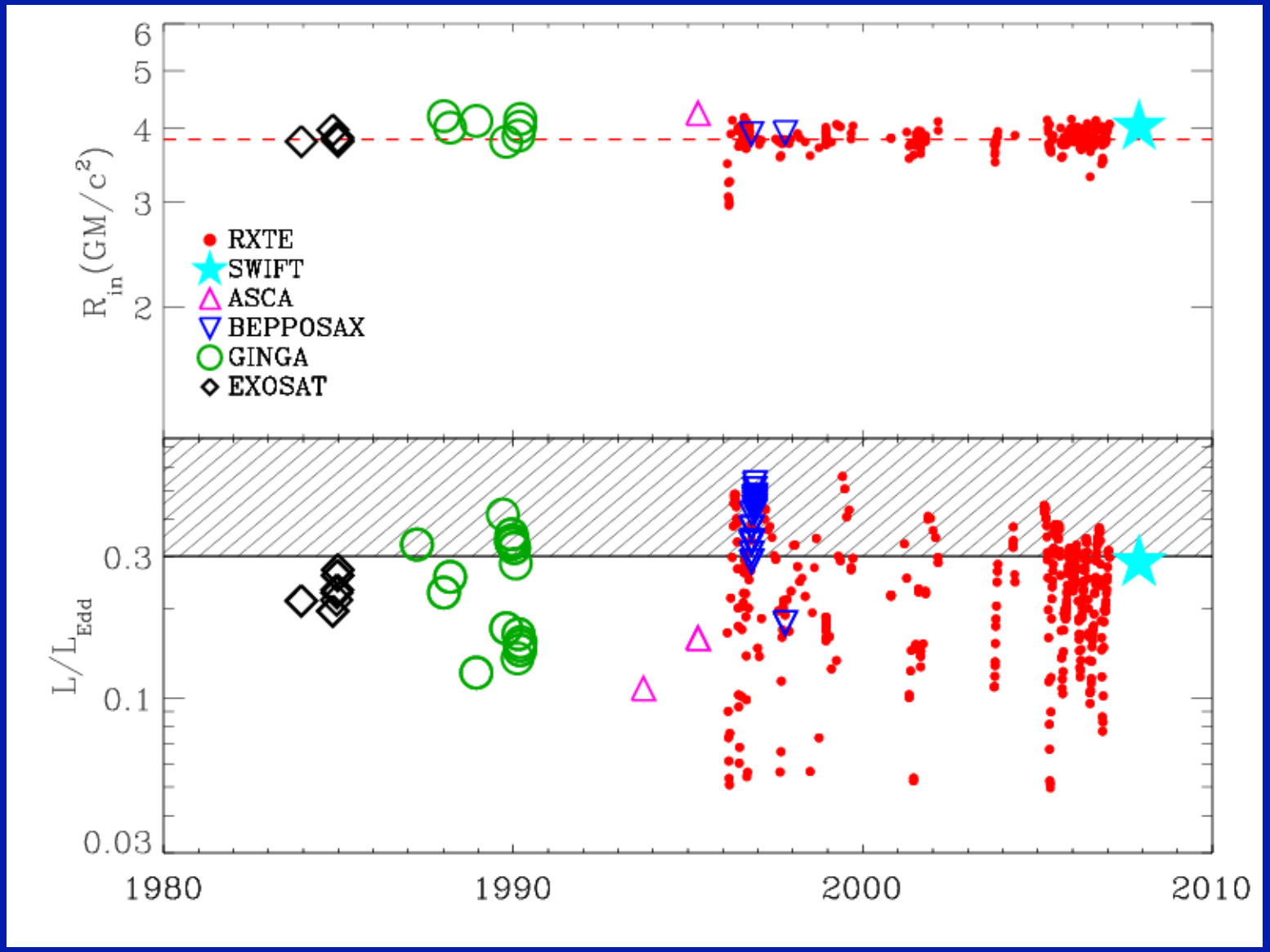
- Test models of jets
- Test models of GRBs
- Test models of BH formation
- Test models of BH binary evolution
- Validate Fe line and other spin methods
- Inform gravitational waveform modelers
- Etc.

Conclusion and Acknowledgments

- RXTE has played the central role in measuring BH spin via the continuum fitting method because of
  - the sheer abundance of data provided, and
  - the PCA's good response above 10 keV.

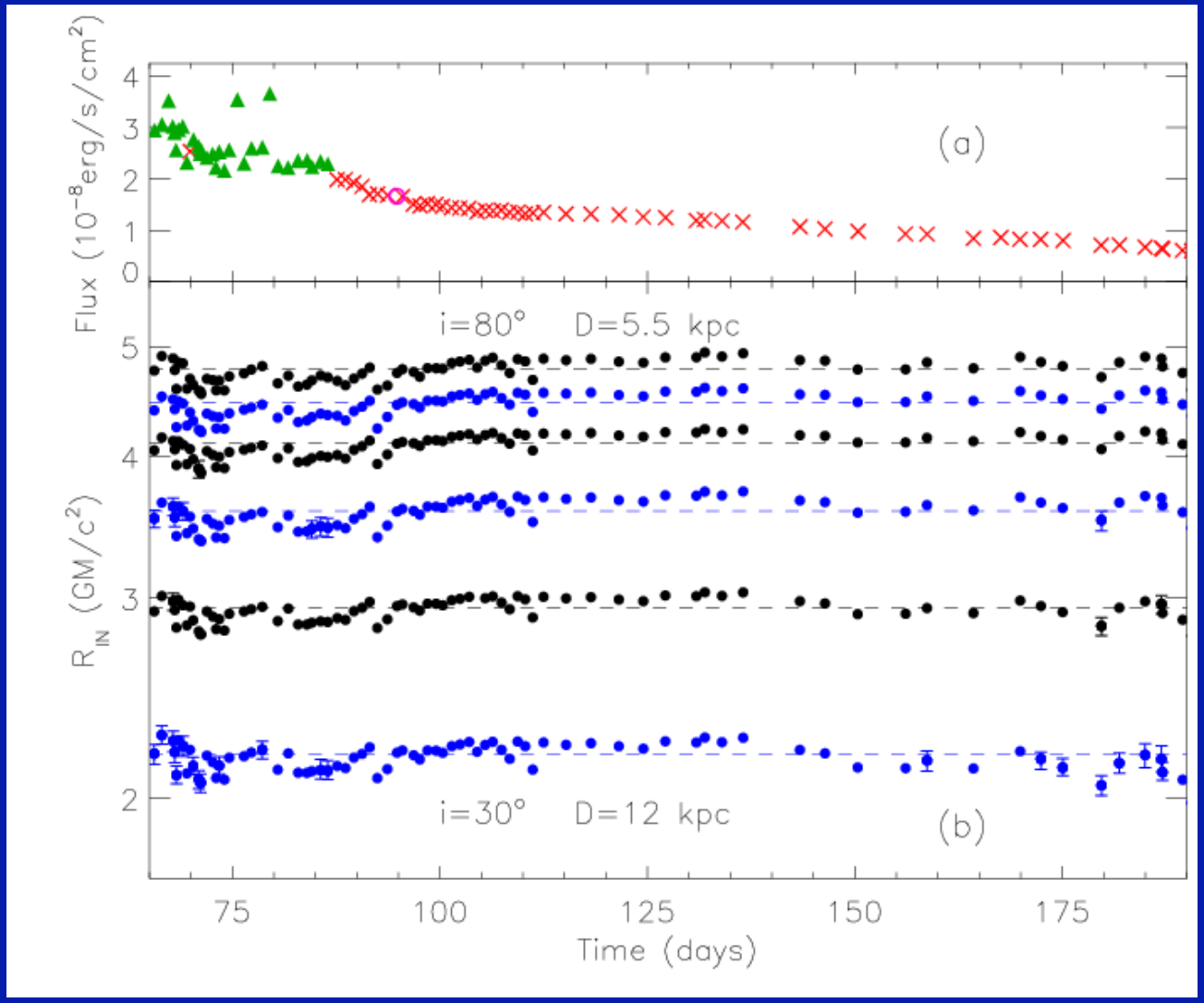
- Our team gratefully acknowledges the crucial contributions of those who have dedicated their careers to the RXTE mission and to the establishment and operation of the HEASARC.

LMC X-3: 1983-2007



H1743-322 Light Curve

Six Dynamical Models ⟶ Six Values of R_{in}



Beyond the Thermal Dominant State

Steiner, McClintock, Remillard, Narayan & Gou 2009

RXTE

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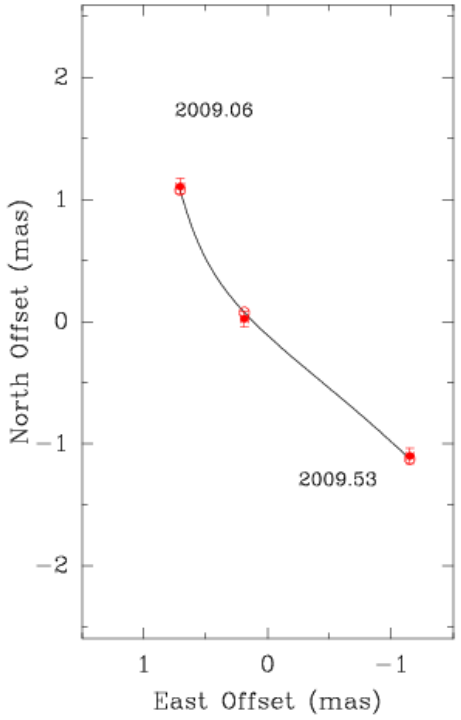
LMC X-3 (redo)	TBD	Steiner et al.

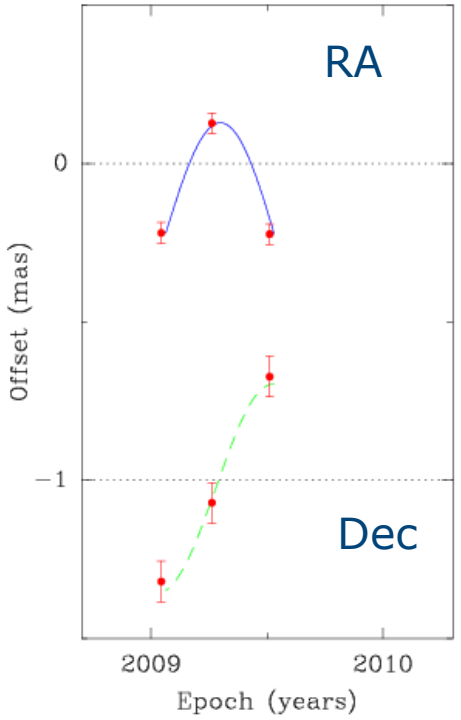
M33 X-7: 70 $M_\odot$ secondary ➔ 3 Myr age, but 140 Myr to spin BH to a_*=0.77 ➔ SPIN IS NATAL

Cyg X-1 VLBA Parallax (2 of 2)

Parallax + Proper Motion

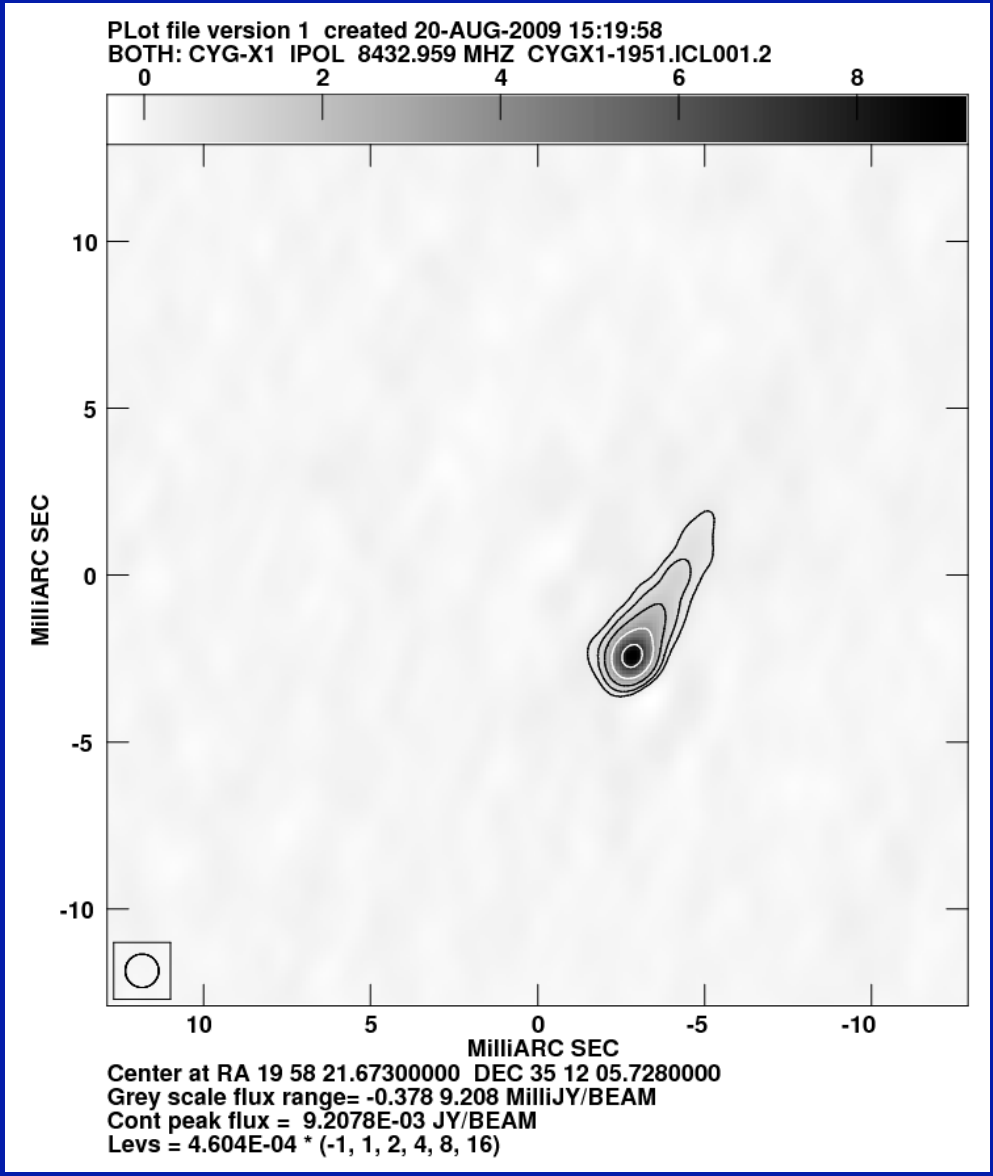


Parallax



Reid, McClintock, Gou, Remillard & Narayan

Cyg X-1 Parallax (1 of 2)



In progress:
3 of 5 epochs completed
6 months to go

Reid, McClintock, Gou, Remillard & Narayan

Thin Disks (H/R < 0.1): GRMHD vs. Novikov & Thorne

Specific angular momentum of the inflowing gas

$a_* = 0$: Shafee, McKinney, Narayan, Tchekhovskoy, Gammie & McClintock 2008

$a_* > 0$: Penna, McKinney, Narayan & Gammie