Measuring Black Hole Spin

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Astrostatistics Forum
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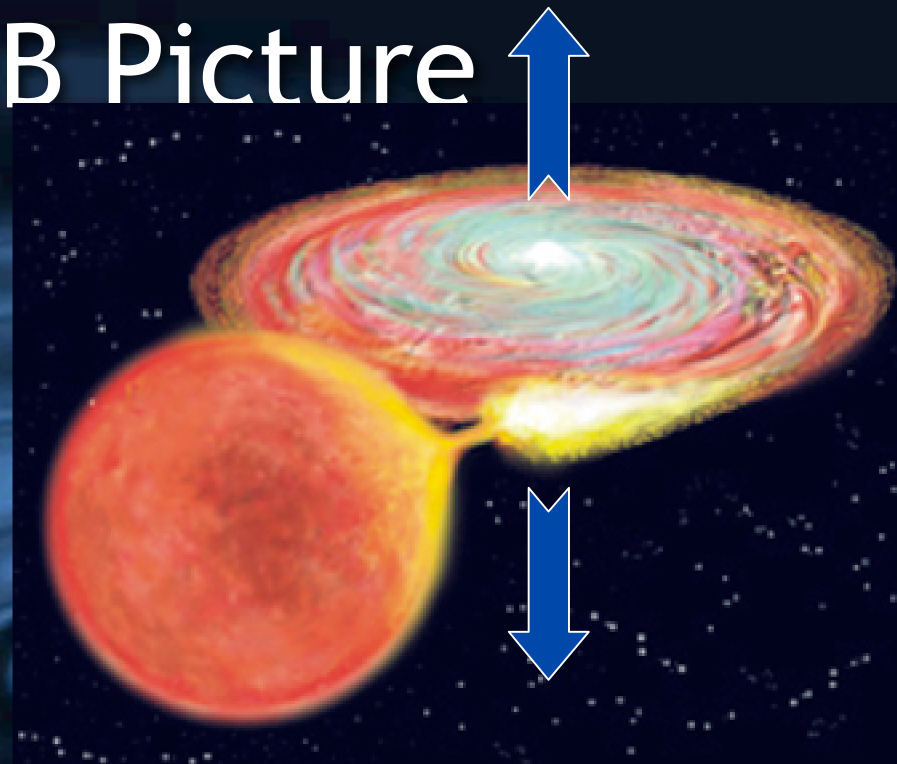
Overview

- ✧ Objects: Stellar-mass BHs in X-ray binaries
- ✧ Method: Spin via fitting the X-ray continuum
- ▪ Statistical Questions:

(digression : MCMC in XSPEC)

BH -XRB Picture

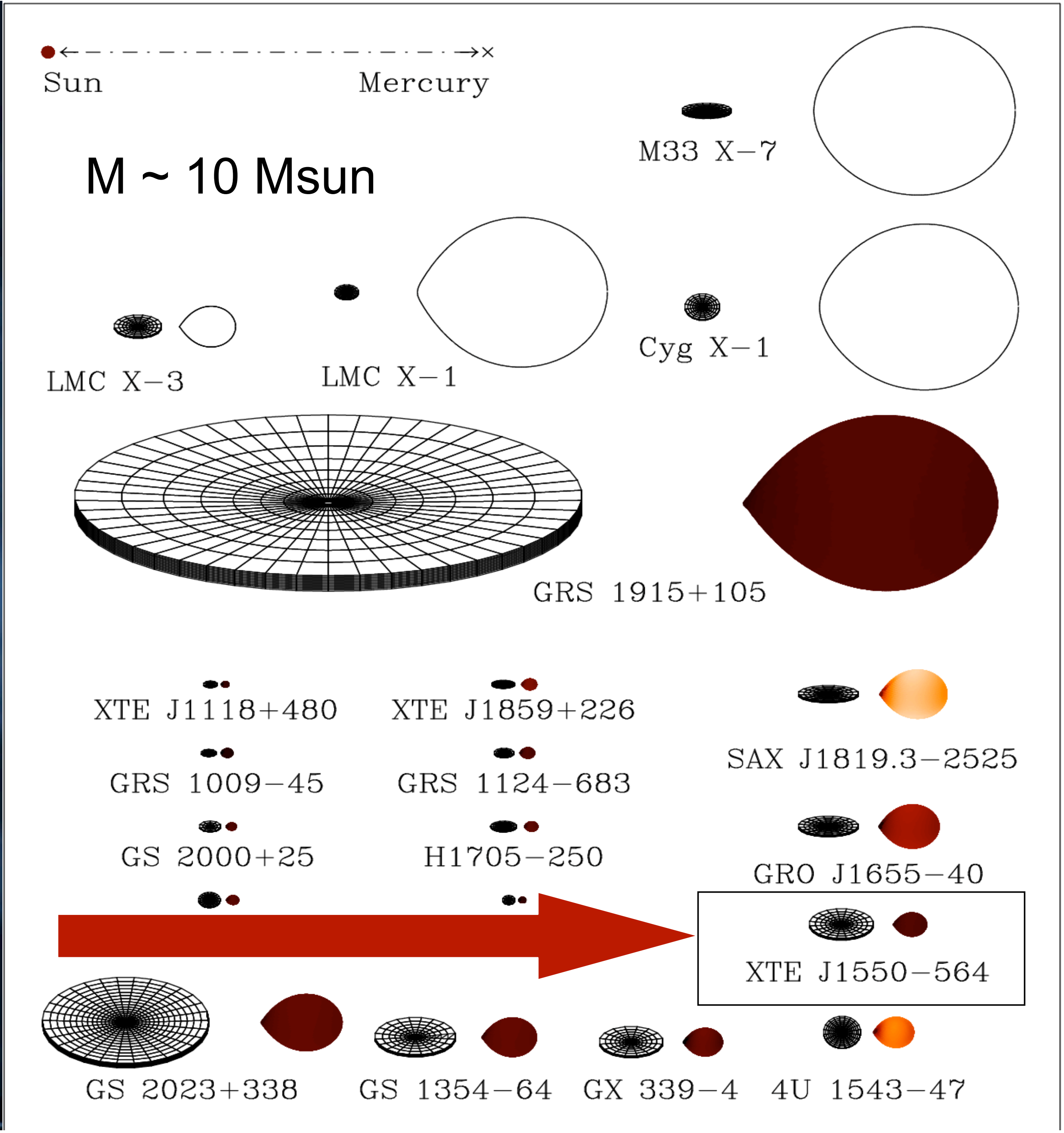


nasa.gov

- BH
  - 5-15 M_0
- Companion Star
  - Tidally distorted
- Accretion Disk
  - Most efficient engine in the universe!
    - 5%-40% compared to 0.7%
- Corona
  - Hot ions in a cloud, surrounding the disk
- (Jets - Microquasars)
  - Beamed highly relativistic ejections (along the BH spin axis)

Number of BH binaries known = 21

Courtesy J. Orosz



Measuring Properties

- Optical Spectra
  - Radial Velocities
  - Mass Function
  - Spectral Type of Companion Star ⇔ Temp
- Imaging
  - Ellipsoidal Light Curves
  - Genetic Fitting
    - (ELC = pikaia + black sheep)
- X-ray Spectra
  - Accretion Disk Physics

Black Holes are Extremely Simple

- Mass: M
- Spin: $J = a_* GM^2/c$ $(0 < a_* < 1)$
- (Electric Charge)
  - Astrophysically, has no importance

21 BH masses have been measured

Obvious next frontier: Measure BH spin a_*

Uses of Spin Data

- Test Jet Models
- Validate core-collapse GRB models
  - Collapsar: Enough J to form disk?
- Inform models of GR waveforms
  - Shafee et al. motivated first waveform work to include spin
- Test evolutionary model of binary black-hole formation
  - Were GRS 1915+105, GRO J1655-40?, etc. GRB sources?
- Understand disk QPOs
  - Both HF/LF in several systems, 2:1
- Modeling the growth of SMBH

Physics of Spin
(in brief)

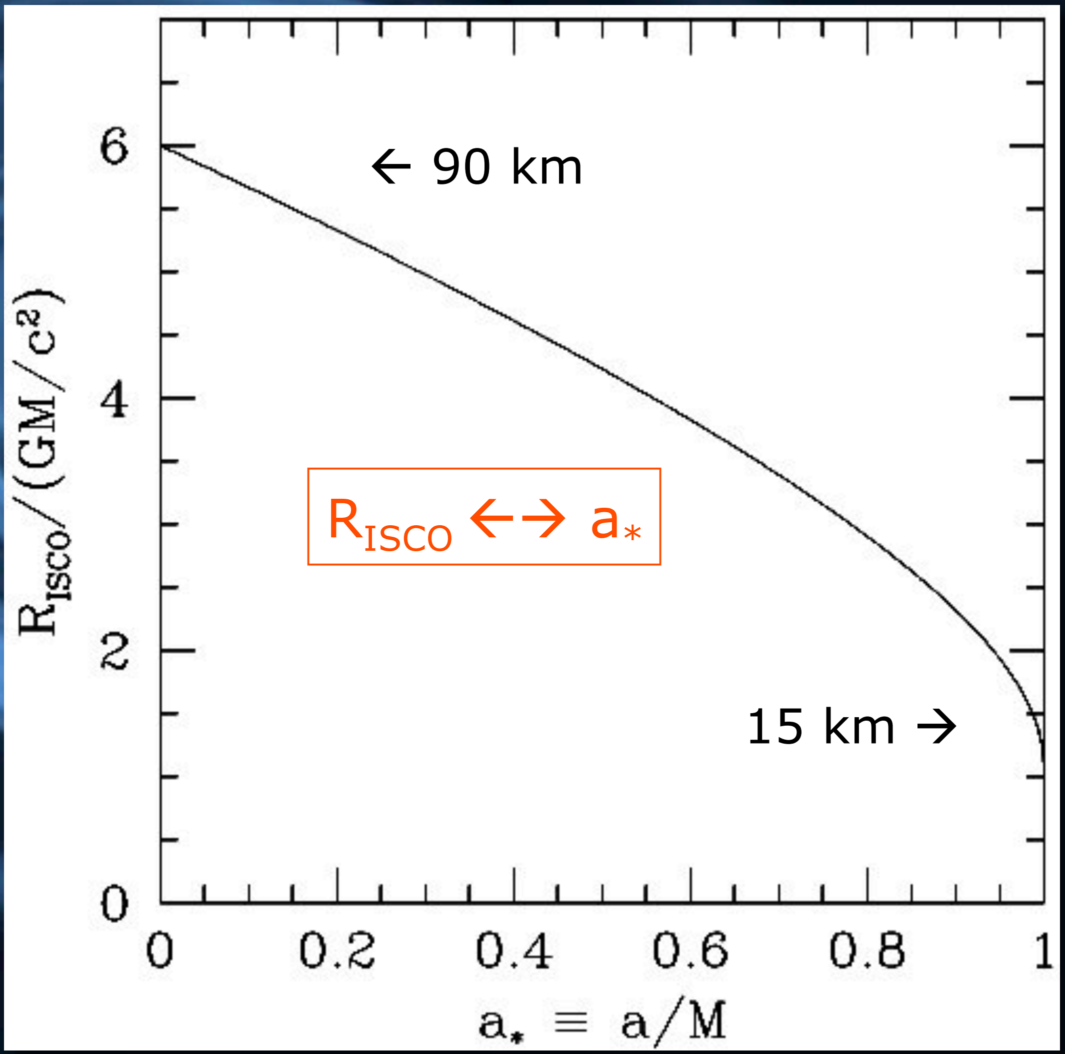
Two Foundations

- 1. ISCO (Innermost Stable Circular Orbit)
  - From General Relativity
- 2. Thermal Dominant State

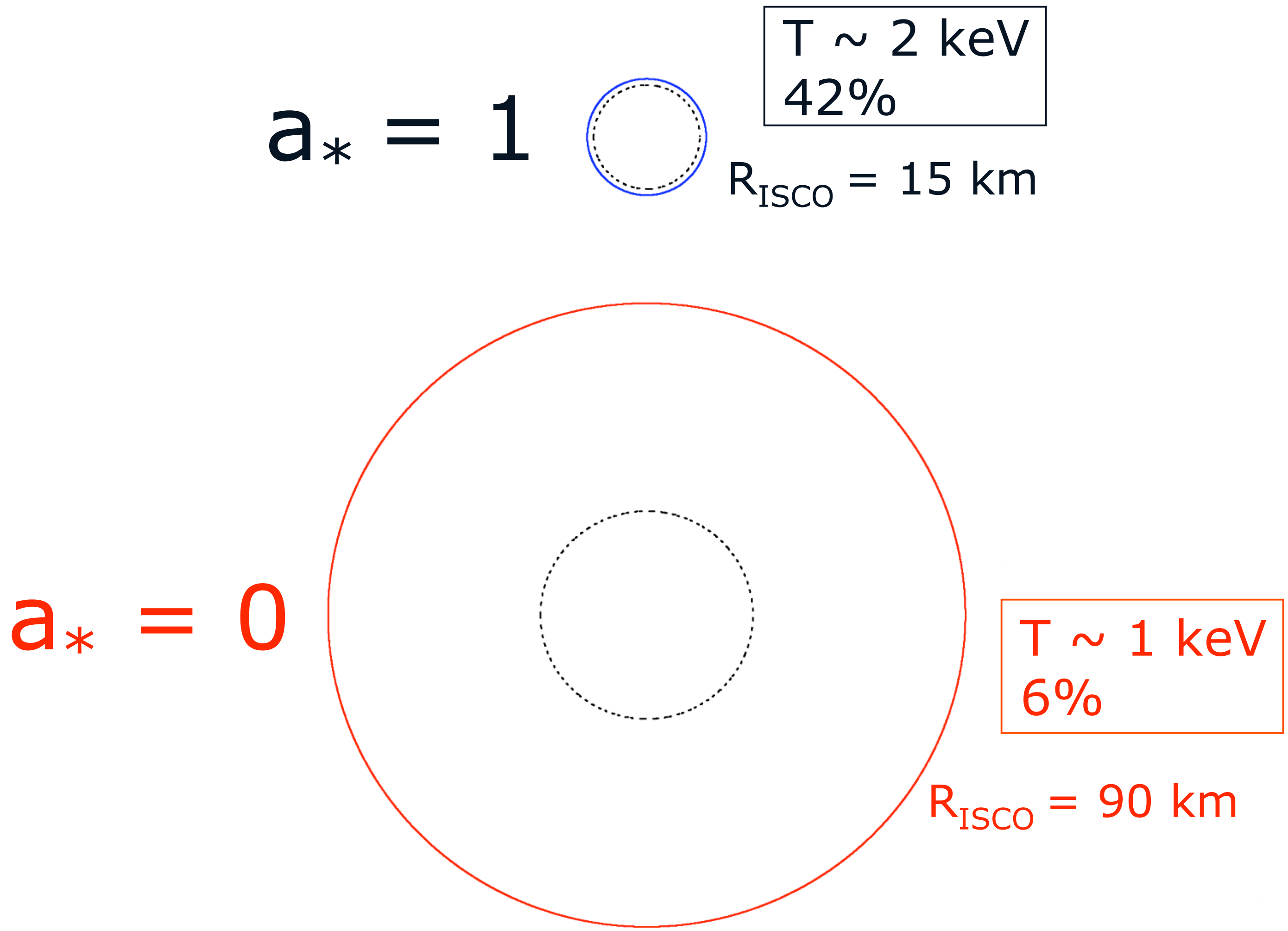
First Foundation

Innermost Stable Circular Orbit (ISCO)

- A disk terminates at R_{ISCO} and gas falls freely onto the BH inside this radius.
- Thus, disk emission has a "hole" of radius R_{ISCO} at center.
- If we measure the size of the hole, we will obtain a_*



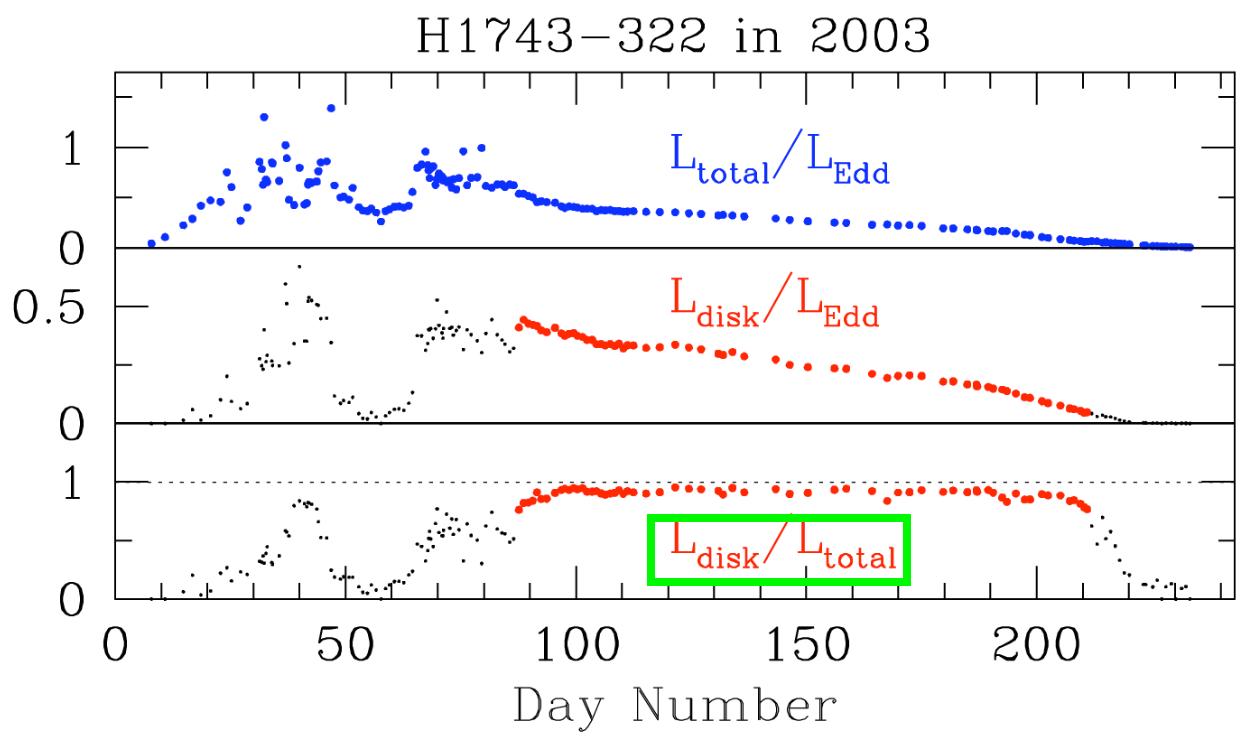
R_{ISCO}: Extreme-Kerr vs. Schwarzschild



Second Foundation

- The Thermal State :
- Thermal Disk Model
  - Describes a physical limit in which:
    - The accretion disk is thin ($H/R \ll 1$)
    - **The emission is dominated by a thermal component (set by a characteristic temperature)
    - (Shakura & Sunyaev alpha-disk prescription)

Second Foundation (cont.)

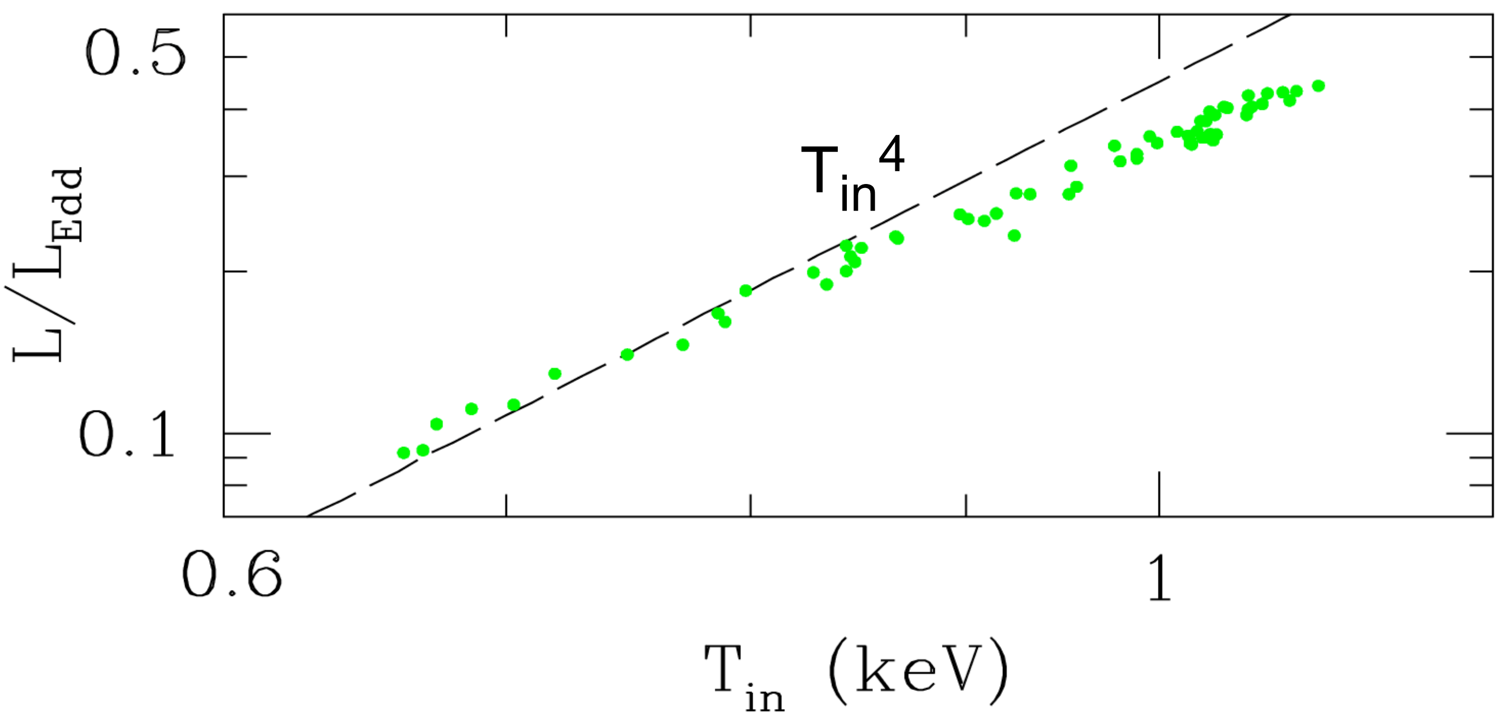


Thermal Dominant State

- L_{disk} / L_{total} > 75% (2-20 keV)
- No QPOs
- Power-law/Comptonization minimal

Remillard & McClintock 2006, ARAA, 44,49

Second Foundation (cont.)



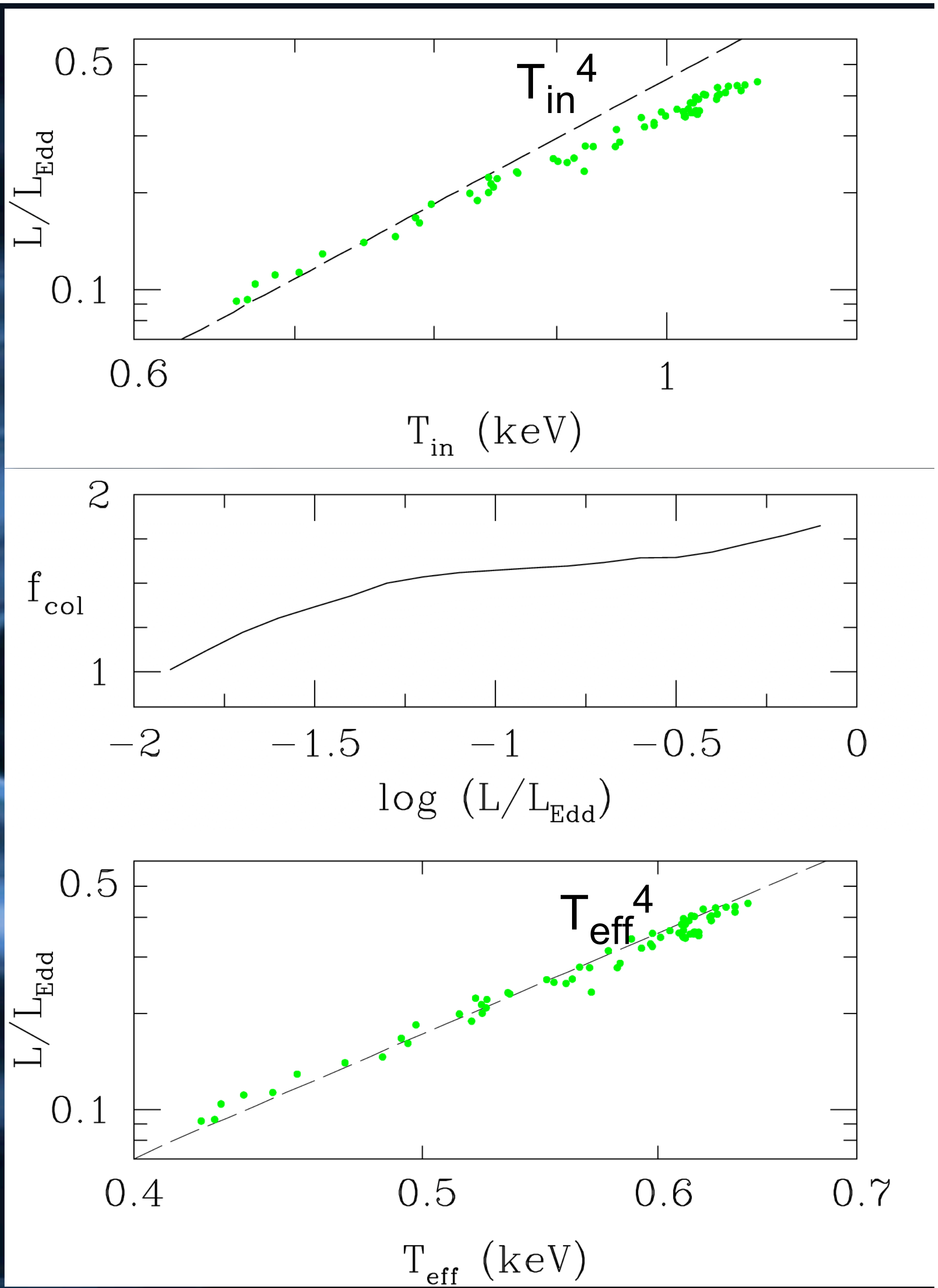
Kubota et al. 2001
Kubota & Makishima 2004
Kubota & Done 2004
Gierlinski & Done 2004

Second Foundation

Improvement from theory:

$$f_{col} = T_{in}/T_{eff}$$

Davis et al. 2005, 2006



Conclusion:

There exists a constant radius

Estimating Spin: Our approach

→ Fitting the X-ray continuum ←

Measuring the Radius of the Disk Inner Edge

- We want to measure the radius of the 'hole' in the disk emission
- Same principle as measuring stellar radius
- From F and T get angle of hole
- Knowing D and i R_{ISCO}
- From R_{ISCO} and M get a_*

Zhang et al. (1997) Gierlinski et al. 2001; Li et al. (2005);
Shafee et al. (2006); McClintock et al. (2006); Davis et al. (2006);...

Underlying Theory

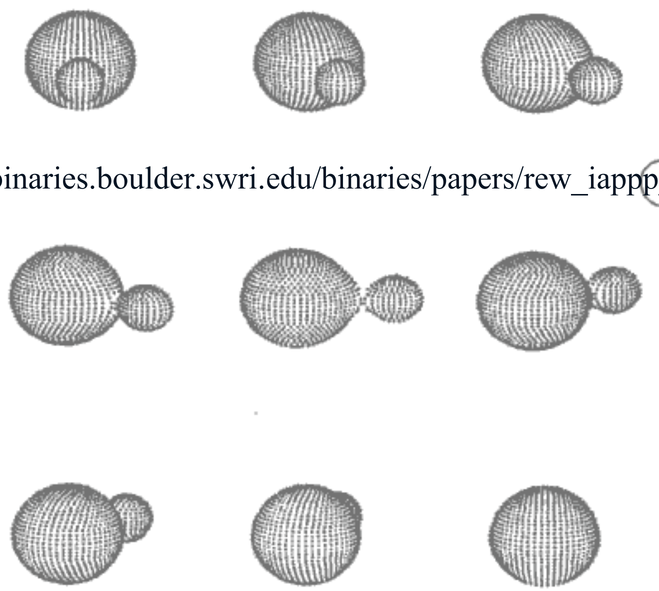
- Need accurate theoretical profiles of disk flux F(R) and temperature T(R)
- Answer: KerrBB - a fully relativistic accretion disk model

Only a_* and Mdot Determined from X-ray Spectrum

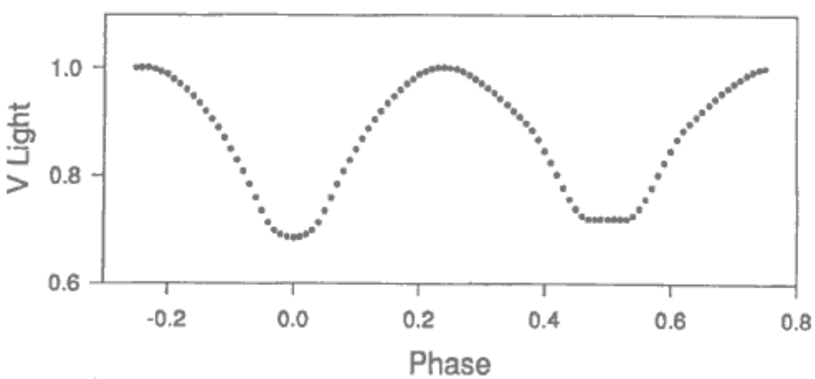
- M,D,i from ground-based observations
- f_{col} from disk atmosphere model
- Zero torque condition satisfied at ISCO for $L/L_{edd} < 0.3$
- Fit for a_* and Mdot (Mdot ⇔ L/L_{edd}) only

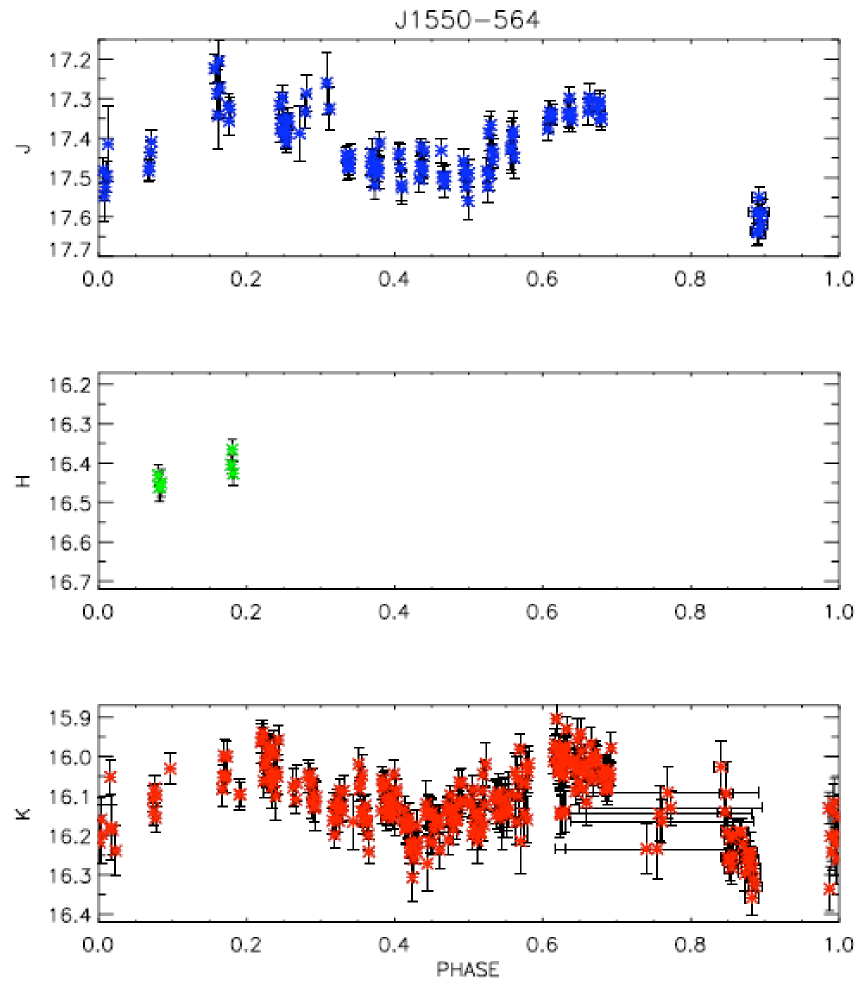
  T & flux → a_* & Mdot

Ellipsoidal Light Curves



http://binaries.boulder.swri.edu/binaries/papers/rew_iappp_94

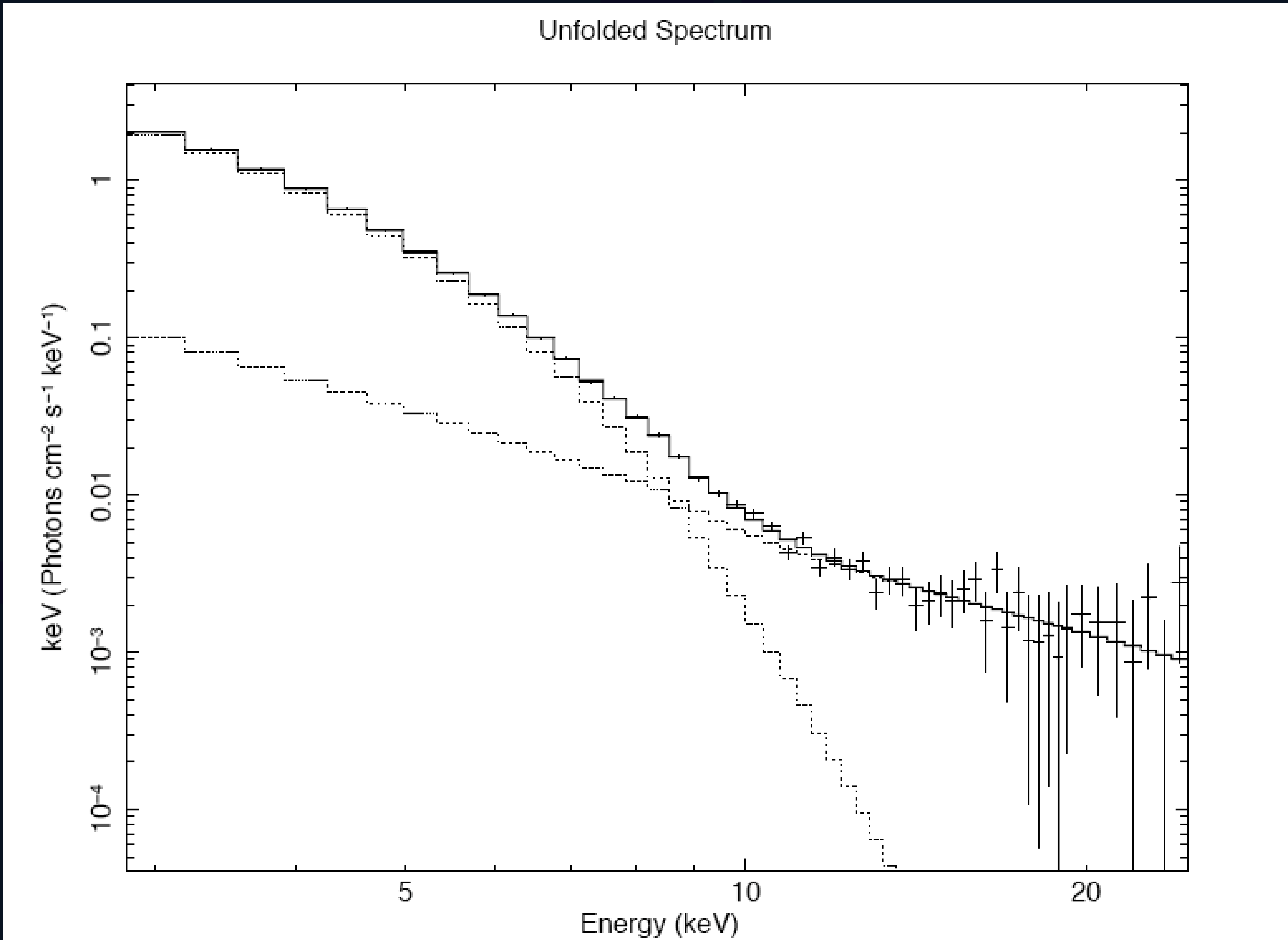




Statistics

Spectral Fitting

- ~130 RXTE X-ray spectra fit with XSPEC
  - Fitting absorption on top of a thermal disk component (to derive spin) and a power law
  - Free parameters:
    - kerrbb: a_*, Mdot
    - smedge: energy, optical depth
    - powerlaw: normalization, slope
  - Fixed parameters:
    - kerrbb: M, i, D, boundary torque, normalization, and flags for returning radiation & limb darkening
    - smedge: energy width, spectral index
    - phabs: N_H (derived from Chandra spectra)



Unfolded Spectrum
keV (Photons cm⁻² s⁻¹ keV⁻¹)
1
0.1
0.01
10⁻³
10⁻⁴
5
10
20
Energy (keV)

Spectral Fitting - (ctd)

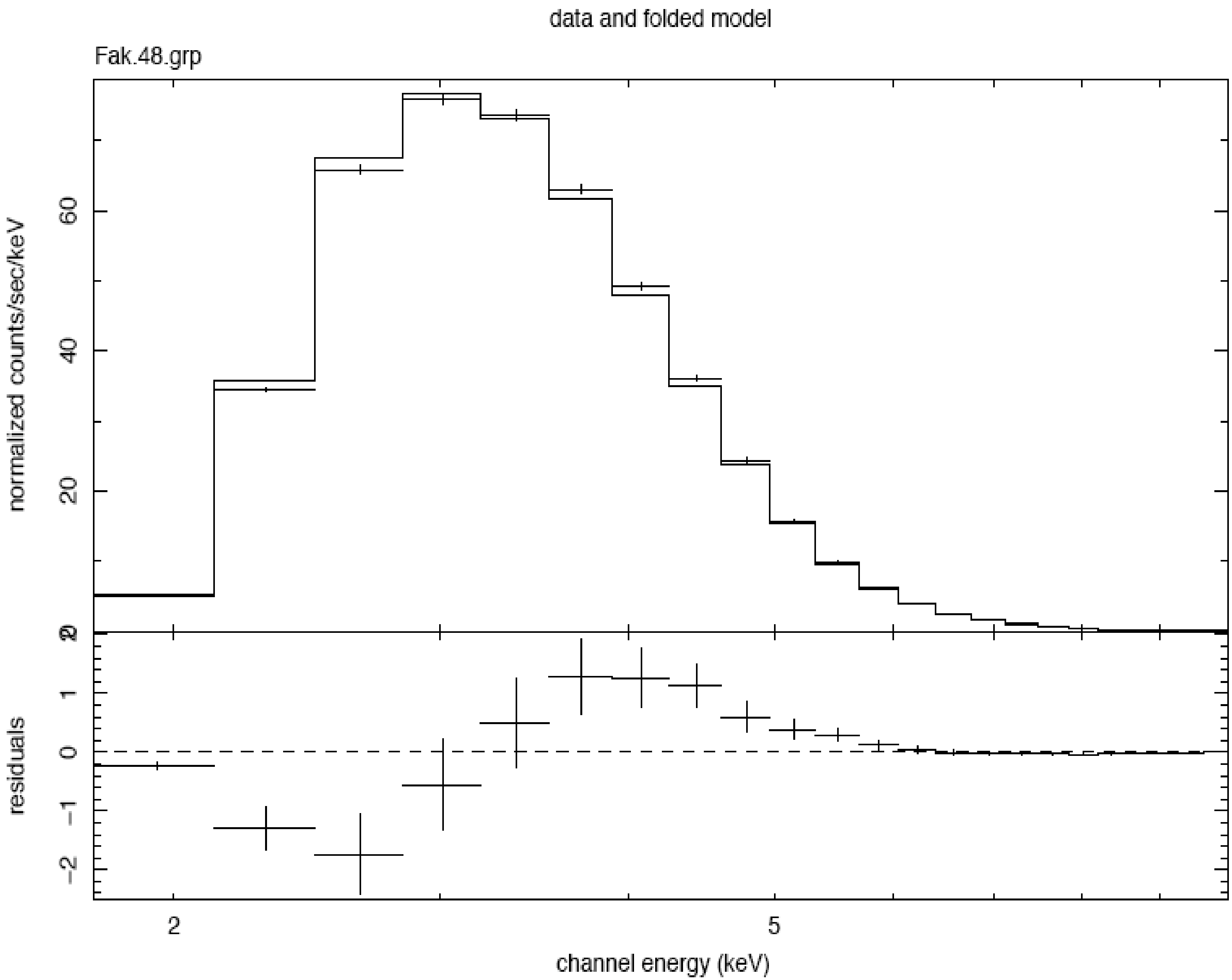
- Questions:
  - To MCMC or not to MCMC?
    - Only fitting for two primary parameters and ~4-6 secondary parameters giving 40-50 d.o.f.
    - Is it worth the computational expense to find the global minimum if good fits are obtained?
  - A Common Complaint
    - Interpretation of Cash statistic
    - **ONLY for Poisson errors?
    - The idea of $\chi_\nu^2=1$ being preferred is intuitive (as opposed to 0). Does Cash have a similarly immediate interpretation?

Comparing Distinct Models

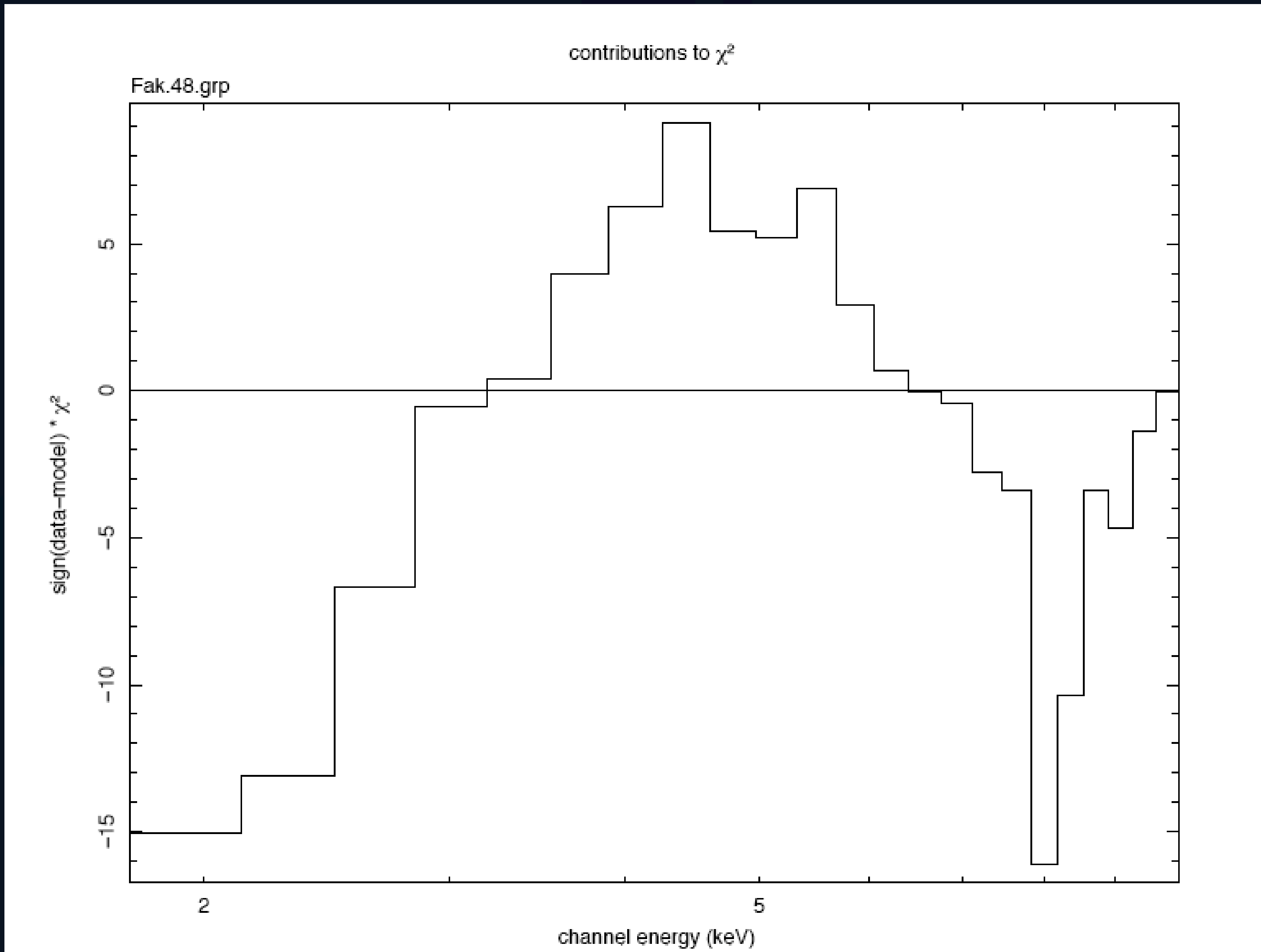
- To compute the hardening factor, f, we have to compare our fully relativistic model of a multi-color disk to a partially-relativistic model that includes the relevant atomic physics
- These models are fundamentally different
- What is the best way to do this?

BHSPEC vs. KERRBB

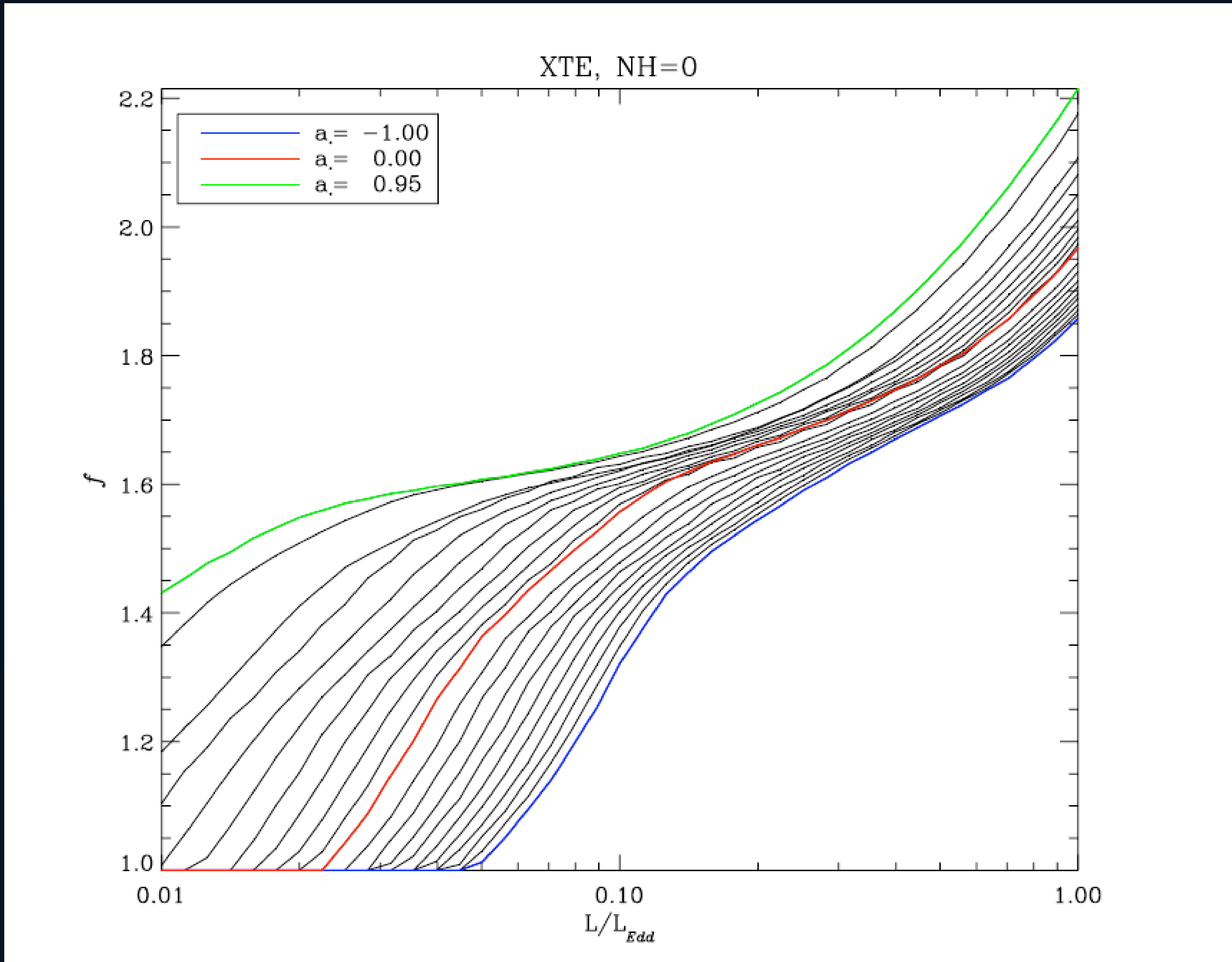
- KerrBB
  - Assumes blackbody rings, no radiative transfer
    - (no electron scattering or atomic absorption)
  - Includes gravitational redshift, doppler boosting, limb darkening, returning radiation, Lense-Thirring frame dragging, can account for non-zero torque boundary condition
- BHSPEC
  - Similar to stellar atmosphere calculations
    - Uses radiative transfer to calculate disk vertical structure
    - Takes into non LTE account electron scattering and atomic opacities
  - Includes limb darkening and gravitational redshift ONLY



data and folded model
Fak.48.grp
normalized counts/sec/keV
60
40
20
0
residuals
2
1
0
−1
−2
2
5
channel energy (keV)



contributions to χ²
Fak.48.grp
sign(data-model) * χ²
channel energy (keV)
2
5
5
0
−5
−10
−15


XTE, NH=0
a. = −1.00
a. = 0.00
a. = 0.95
f
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.01
0.10
1.00
L/L_Edd

Apples to Apples

- Current approach :
- Simulated data of an accretion disk are produced by "observing" the BHSPEC model with an RXTE instrumental response matrix.
- The fake data are assigned Poisson errors and fitted with KerrBB over the same energy range as the data, fitting for 'f'
- Question: Should we consider an alternative method of comparison?
  - e.g. use a uniform response matrix with uniform error bars, fitting over the entire thermal range?

Data Classification

- Currently, we are using two selection criteria to determine which data are considered.
- I'd like to consider blurring these sharp boundaries
  - Is there a preferred way to introduce this?
    - e.g. sigmoid

"Thermal-Dominant": $L_{disk} > 75\% \ L_{tot}$ thermal disk flux
Zero Torque, Thin Disk: $L_{disk} < 30\% \ L_{edd}$

MC Sampling

- Genetic fitting produces a high dimensional (D>10) hypersurface.
- Collapse this into a 4-D topology of M,i,D vs. χ^2
- We will need to run an iteration of our analysis at each point in a large sample of M,i,D.
- Since these uncertainties dominate our error in a*, representative sampling from this space is crucial for determining spin.
- Challenge: how to sample from a sparsely, and nonrandom space
- Our Answer: try to grid-sample near the best fit
- The plan is to shoot for a few thousand points and compare 2 runs as a convergence check.

Uniform Weight Resampling

- The current plan:
  - N iterations (~5000)
  - Each iteration will produce 'm' spin estimates (~100)
  - Selection function y
- Randomly select a group of "n" results from each of the N iterations such that $y(x_{ik}) \mid i \in 1 \ldots m$ and $k \in 1 \ldots N$ gives the probability of selecting x_{ik}.
- Use this to construct the spin PDF

Summary

- By using the constant inner radius (ISCO) of accretion disks, we are able to determine black hole spin via X-ray continuum fitting
- Spin is a very new field with promise to test and motivate fundamental theory
- We are now working to perfect our methodology, and to bring in modern statistical techniques

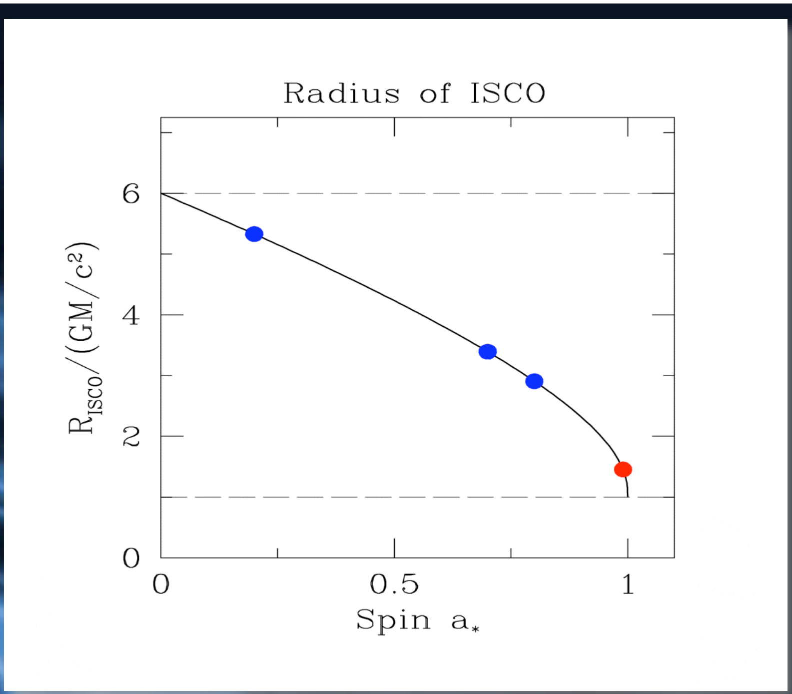

Fin.

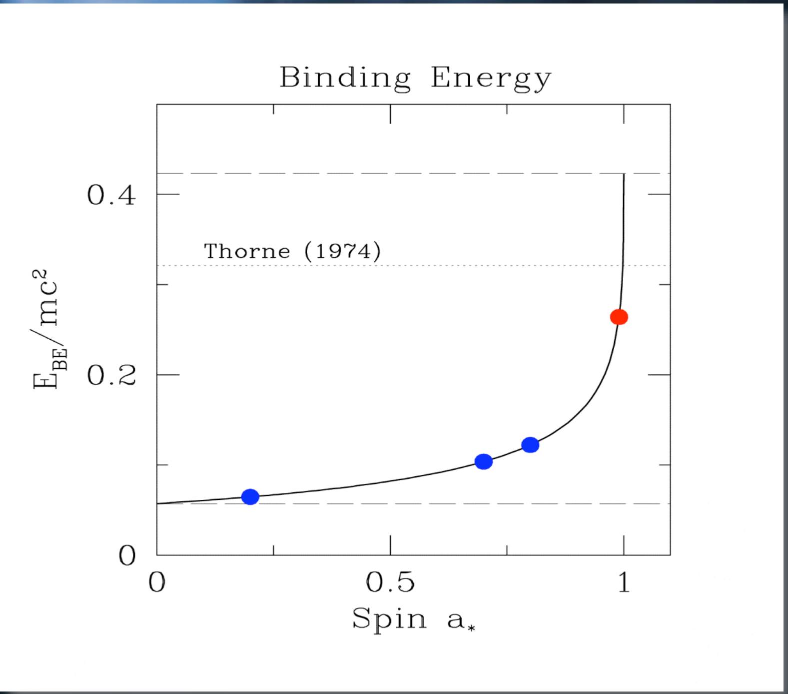
Nominal Spins of 4 BHs

LMC X-3: $a_* = 0.2$
GRO J1655-40: $a_* = 0.7$
4U 1543-47: $a_* = 0.8$

GRS 1915+105: $a_* = 0.99$

McClintock, Shafee, Narayan, et al.





Tempus Fugit

- Despite all our best intentions, we need to weigh in the computer-time required to run through our analysis
- 3000 iterations (with no MCMC) ⇔ 1 month
- Want to optimize the tradeoff between quality of our result and time

3 Other Avenues to Spin

Remillard & McClintock 2006, ARAA 44, 49

- Fe line profile

  Fabian et al. 1989
  Reynolds & Nowak 2003

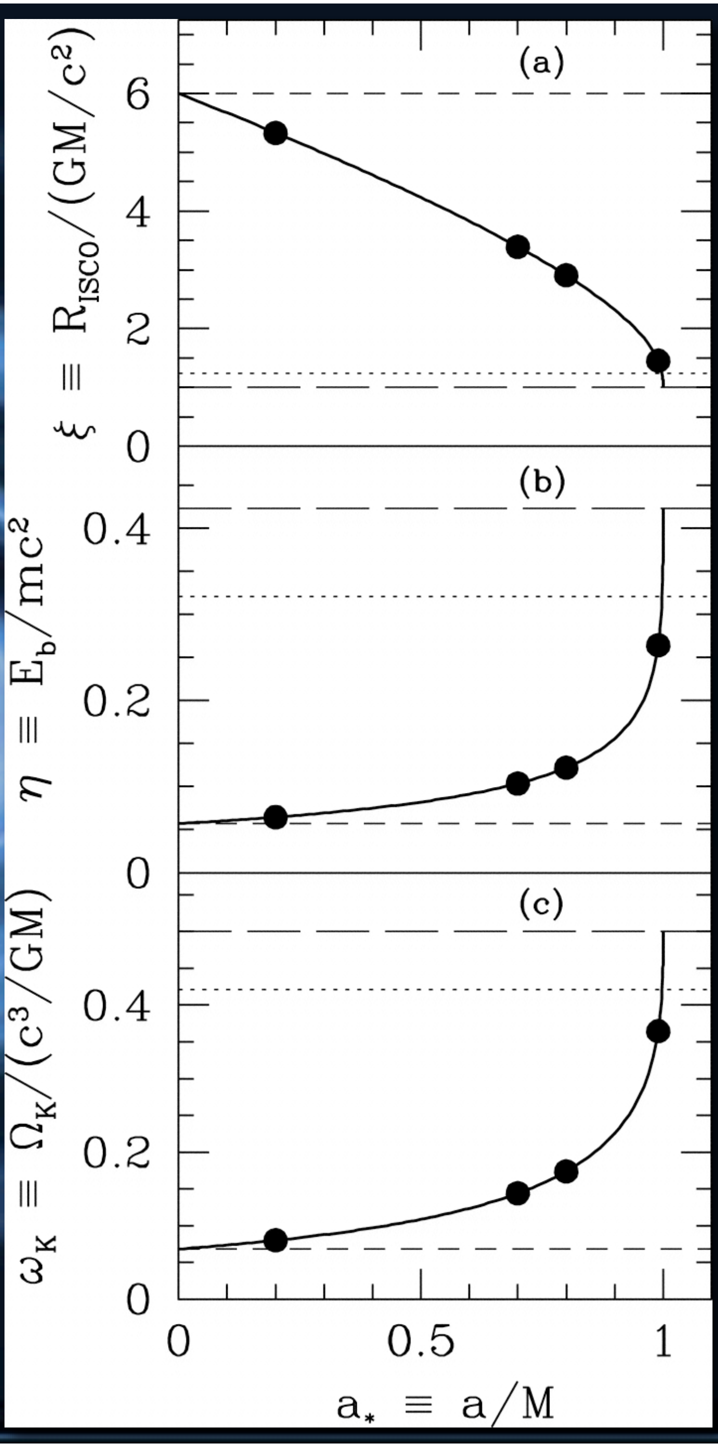
- High-frequency X-ray QPOs (100-450 Hz)

  Abramowicz & Kluzniak 2001
  Torok et al. 2005

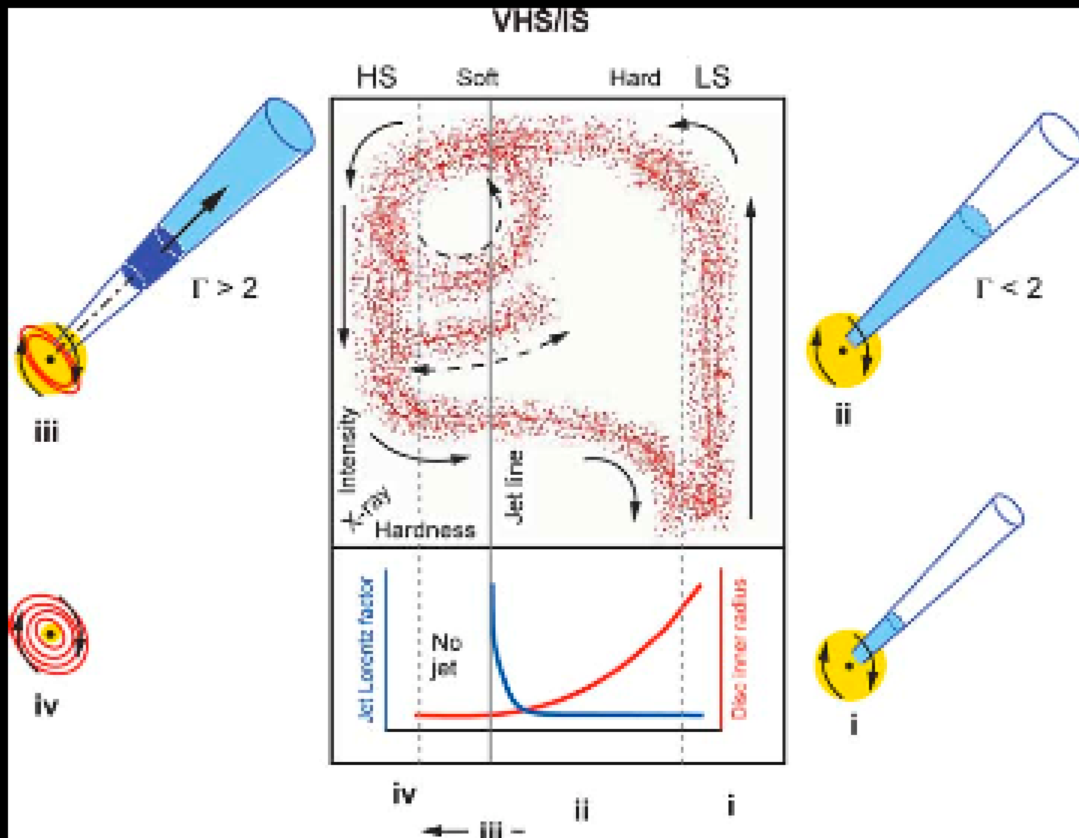
- X-ray polarimetry

  Lightman & Shapiro 1975
  Connors, Piran & Stark 1980

- Properties of the ISCO as a function of spin.
- Note the nonlinearity at high spin.
- (Shafee et al, 2006)



Spectral States



Fender et al. (2004)