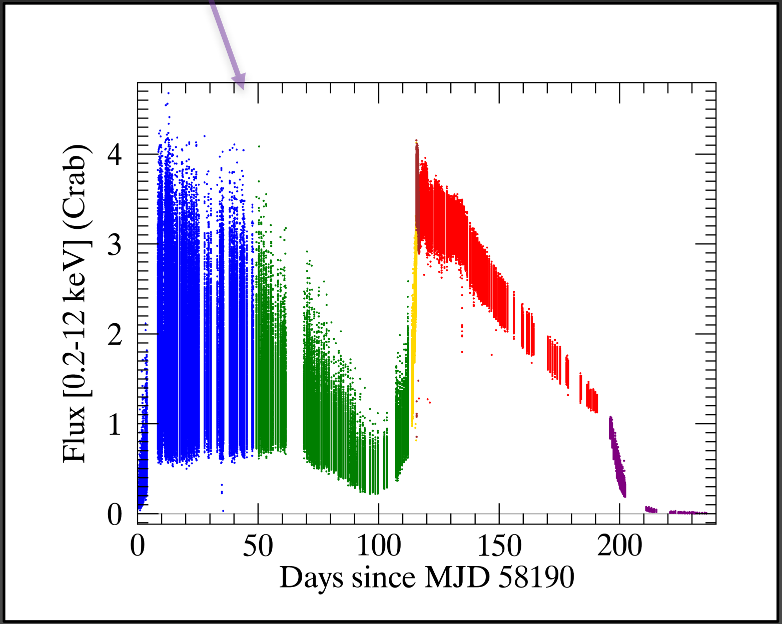
Galactic Black Hole and Neutron Star Systems Part 2

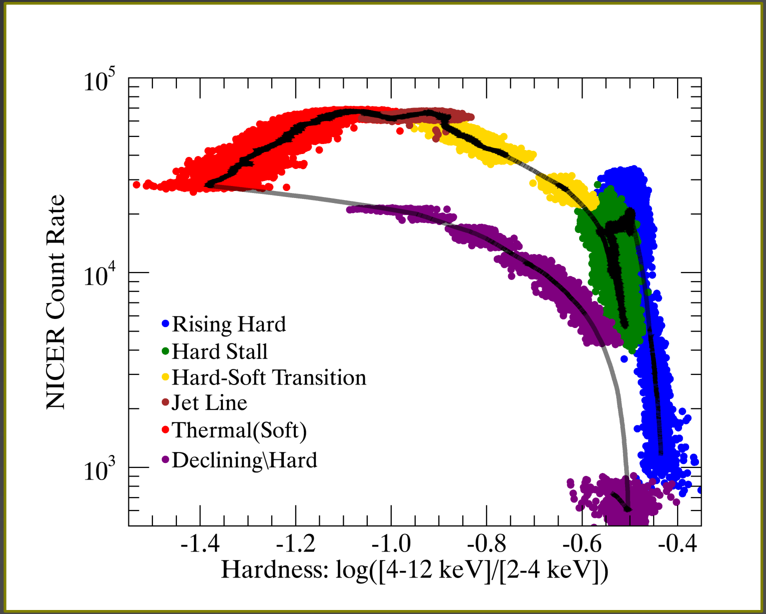
Jack Steiner

Harvard-Smithsonian Center for Astrophysics

RMS "flicker-noise" illustrated with MAXI J1820+070 in 2 million 5kcnt segments

Times as short as ~0.2s

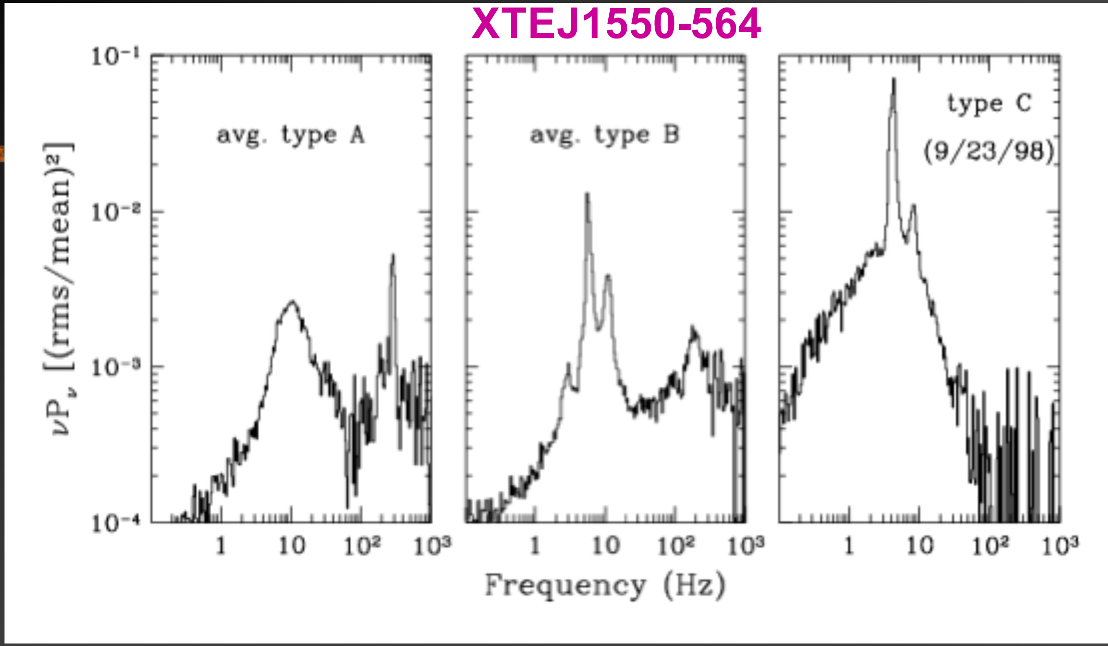




Overview

- Black Holes
  - QPOs
  - BH Spin
- Neutron Stars
  - Classes, energy spectra, and PDS
  - NS equation of state
- Practical Advice on XRB Spectral Modeling

BH Low-Frequency QPOs



Wijnands et al. 1999

Cui et al. 1999

Remillard et al. 2002

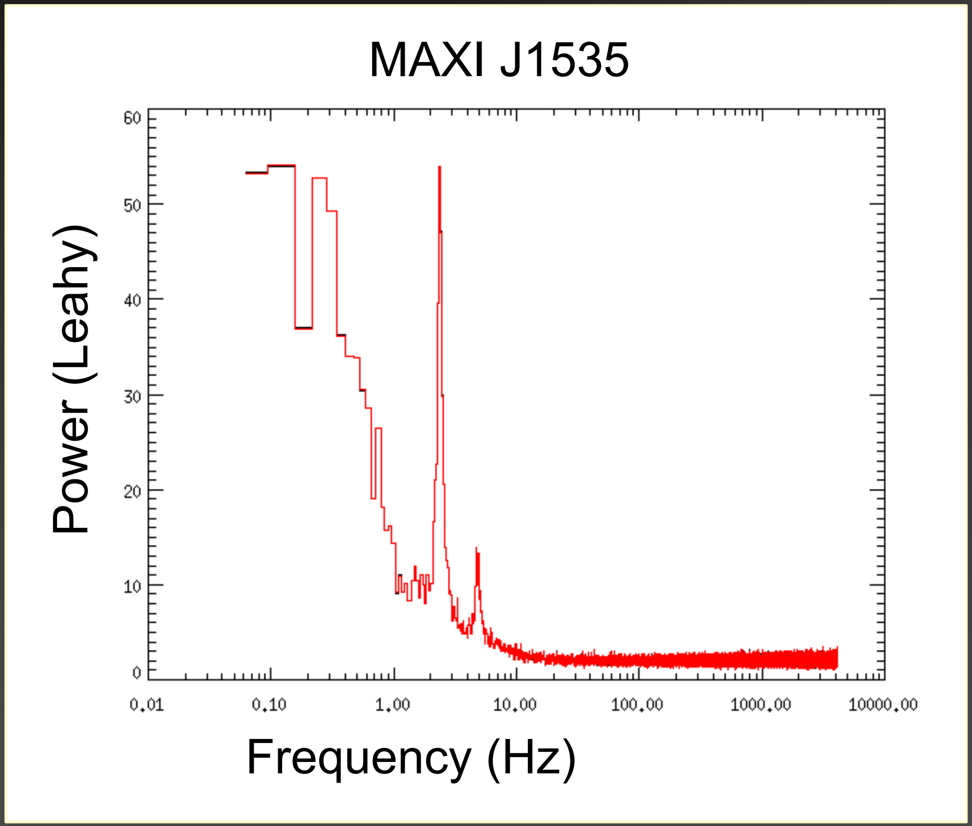
Rodriguez et al. 2004

Casella et al. 2005

Type:	A	B	C
$\nu 0$ (Hz):	~8	~6	~0.1 – 15
a (rms %):	few	few	5 – 20
Q :	2 – 3	~10	~10
State:	Int.(jetline)	Int.(jetline)	Hard/Int.
Commonality:	rare	common	very common

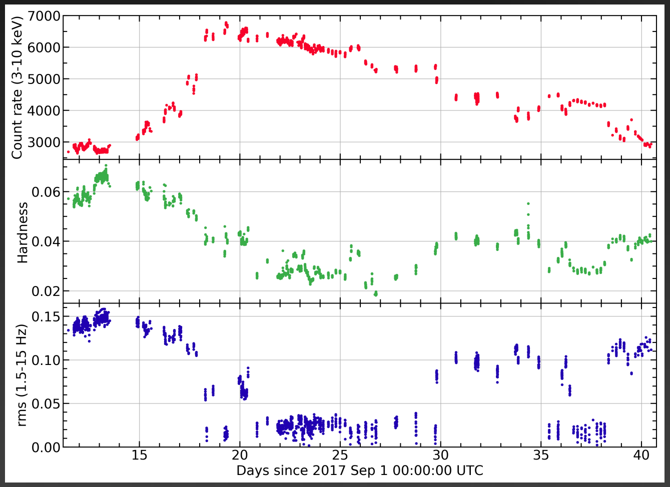
Credit: R. Remillard

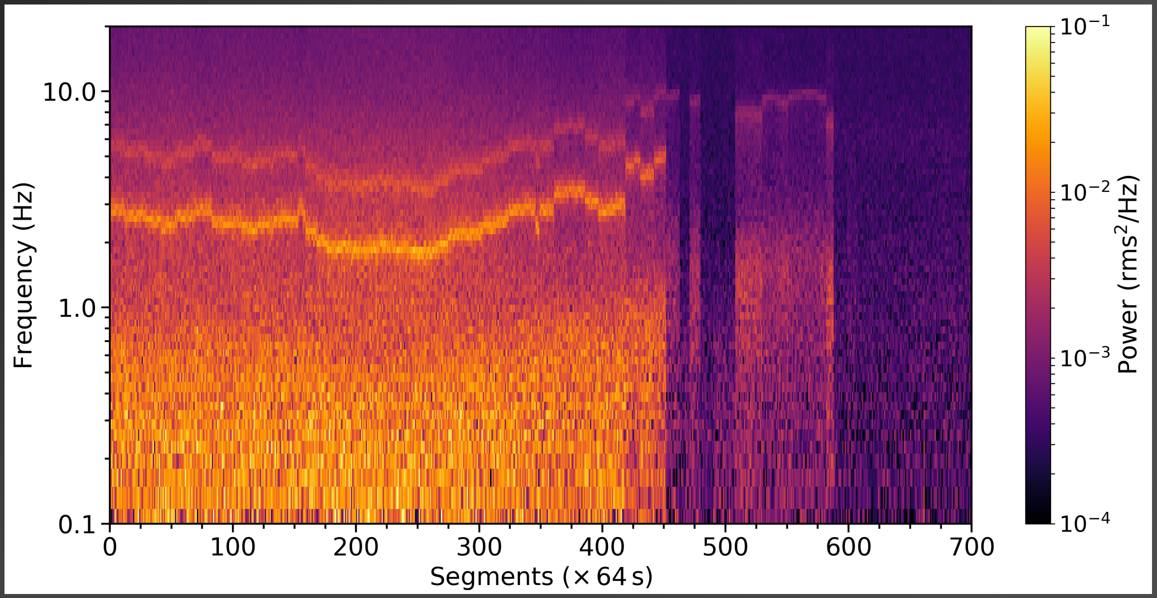
MAXI J1535-571

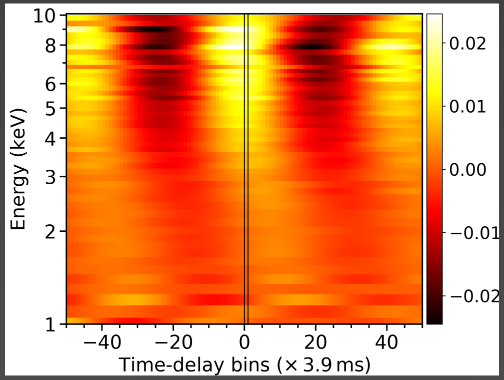


- Likely the very strongest BH QPO (by raw signal, not by rms)
- Twin ~2.5, 5 Hz type-C low-frequency QPOs

MAXI J1535-571 – dynamic QPOs



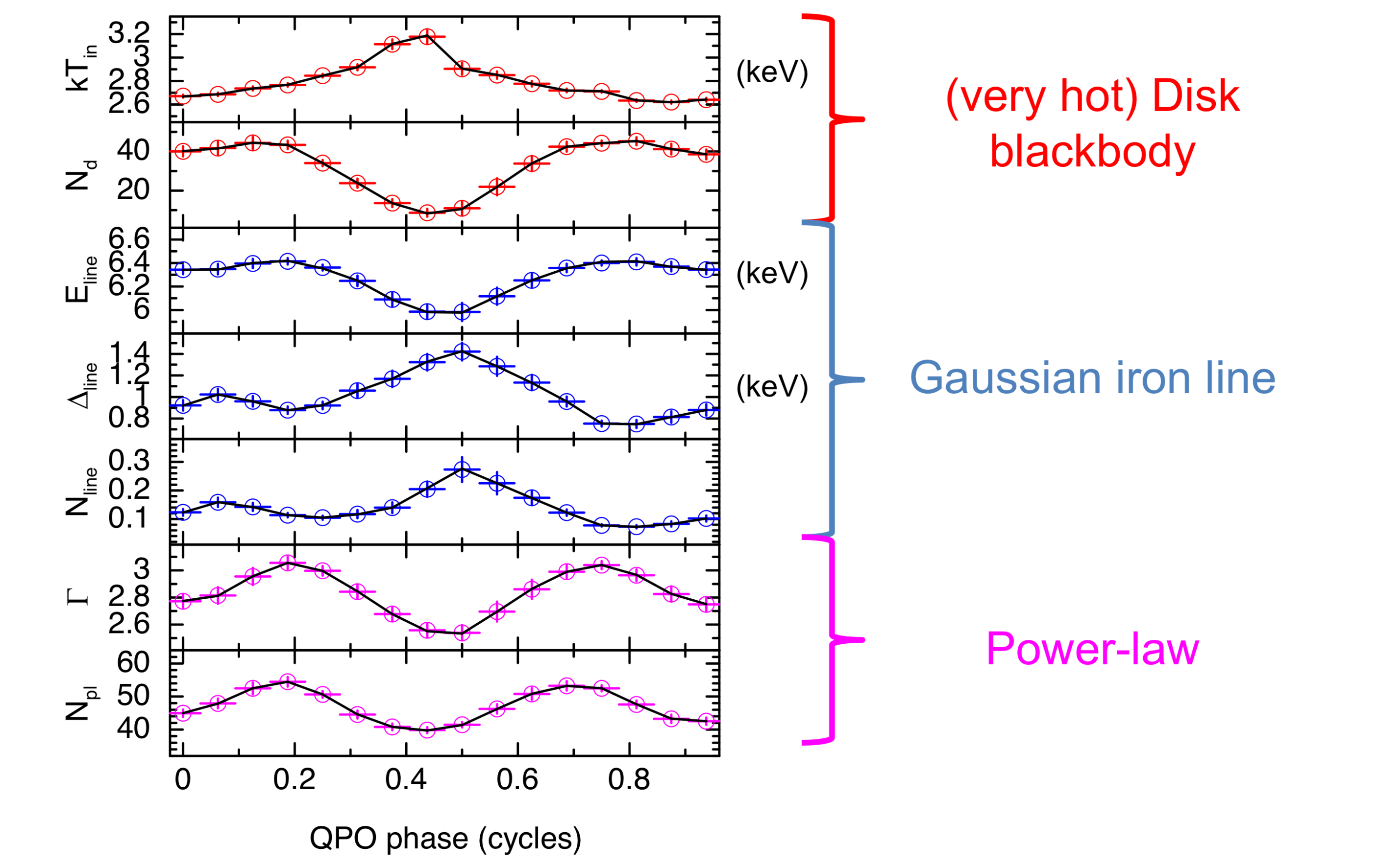




Stevens et al.

MAXI J1535-571 – phased spectroscopy

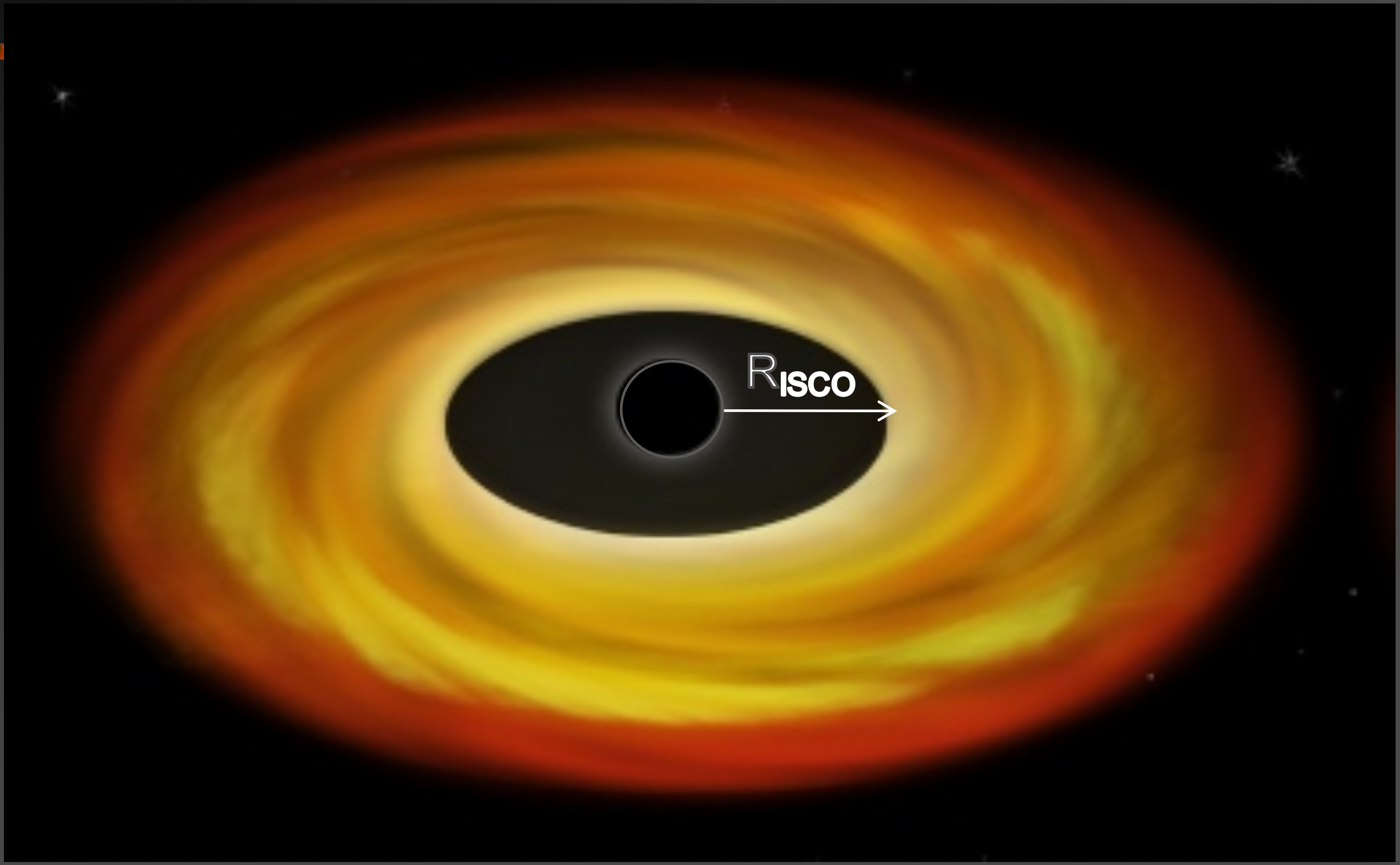
Phase-folded on QPO frequency

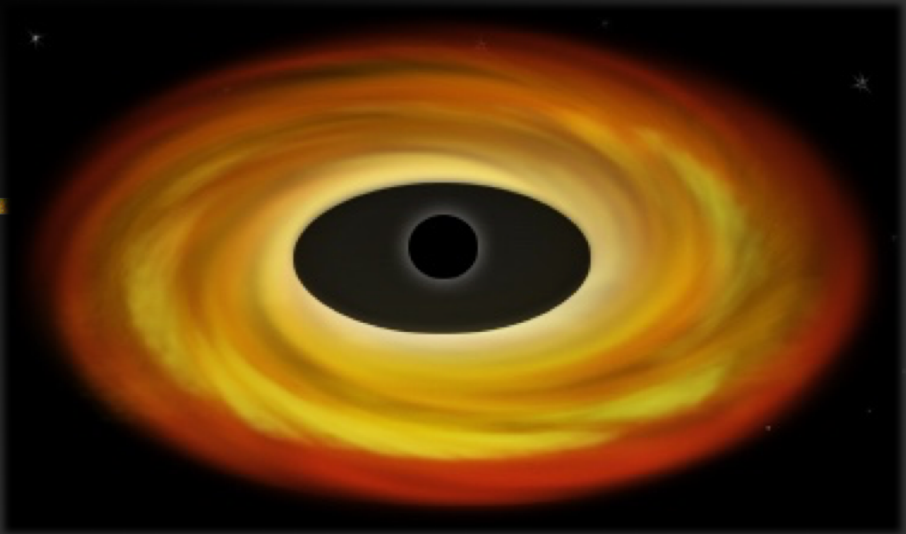


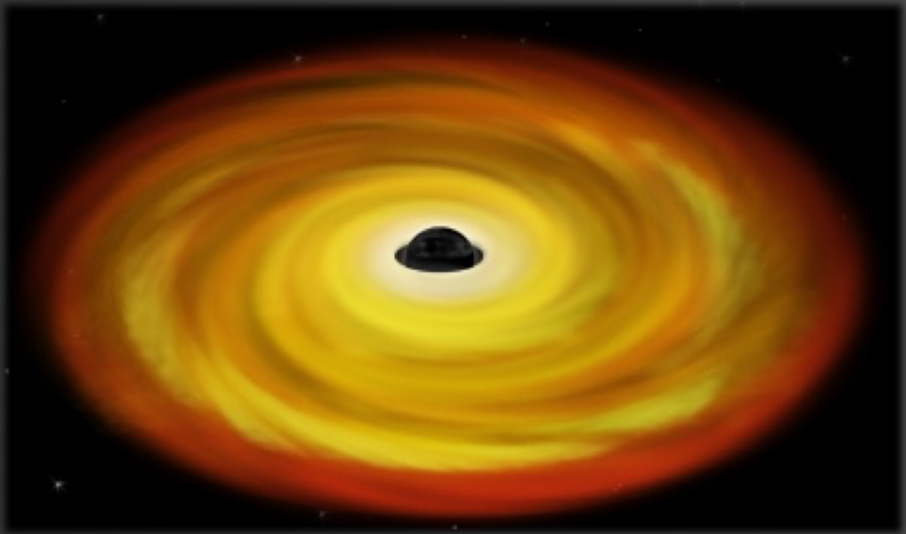
Ingram et al.

Black-Hole Spin:
X-ray Continuum Fitting

Goal: Measure 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)

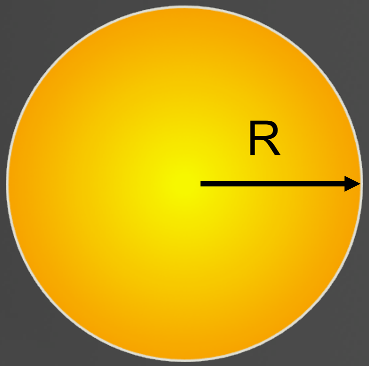
Measuring the Radius of a Star

- Measure the flux F received from the star
- Measure the temperature T_* (from spectrum)
- Independent knowledge of distance (i.e., from parallax)

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

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

$$R_* = D\sqrt{\frac{\Delta\Omega}{\pi}} = 37.5\frac{L_*^{1/2}}{T_*^2}(\text{cgs})$$



Measuring R_{ISCO}

Radius R of a Star

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

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

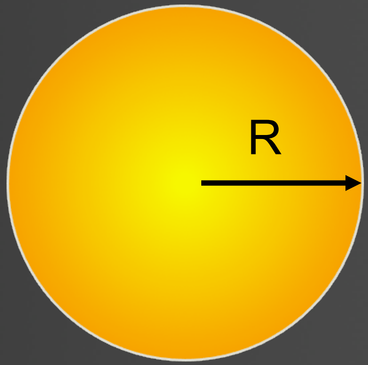
$D \rightarrow$ R

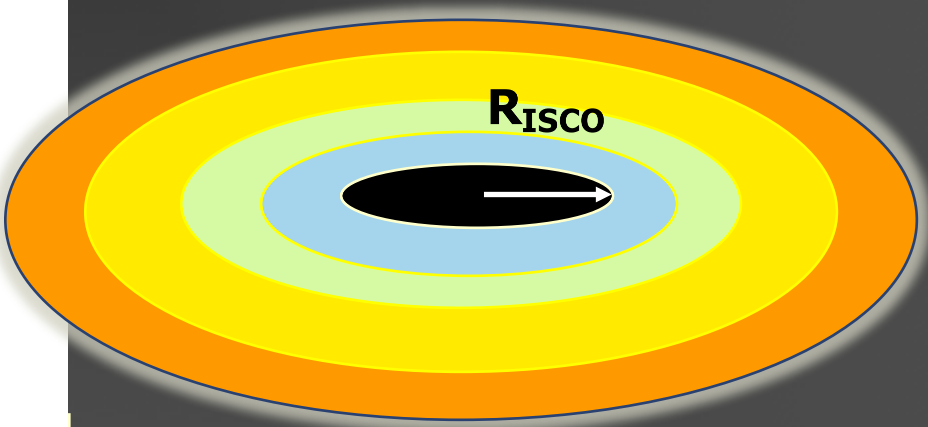
Radius $R_{\rm ISCO}$ of Disk Hole

F and $T \rightarrow$ solid angle

D and $i \rightarrow R_{ISCO}$

R_{ISCO} and **M** ⟶ **a_***



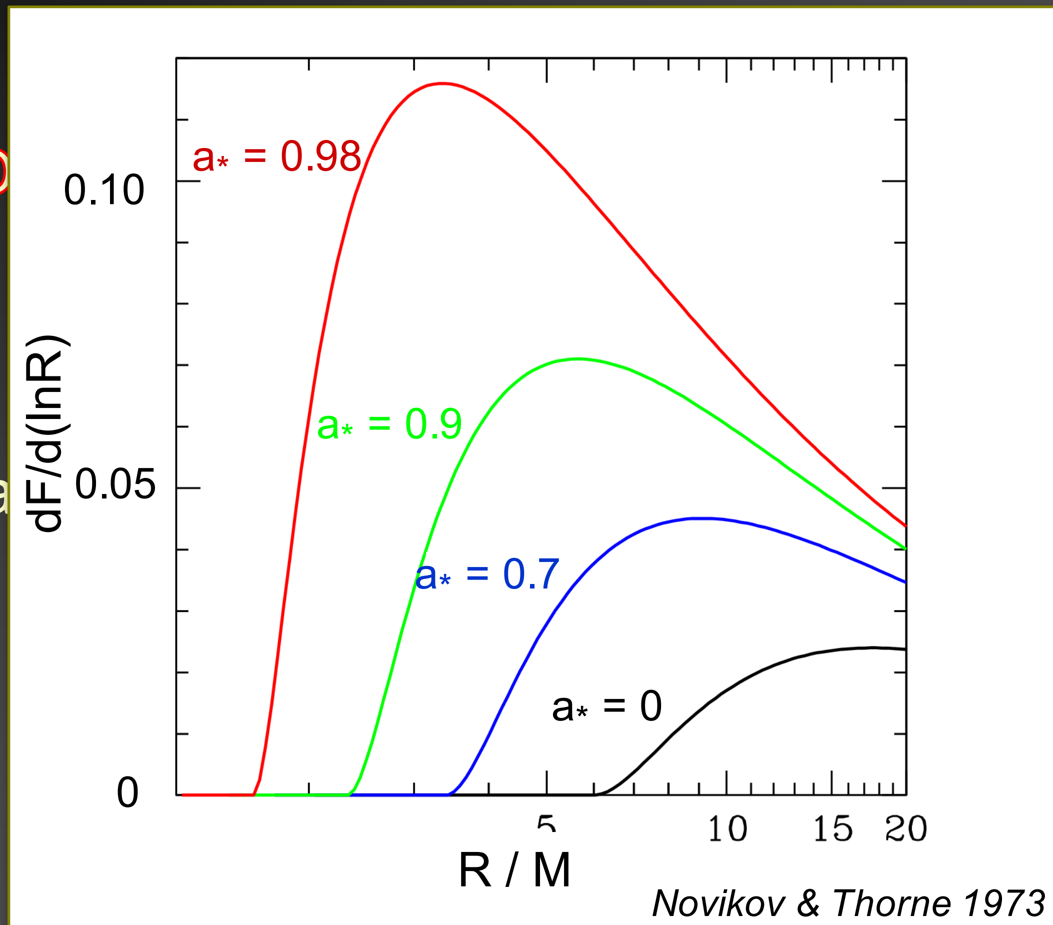


The X-ray Continuum Fitting Method

Zhang, Cui & Chen 1997

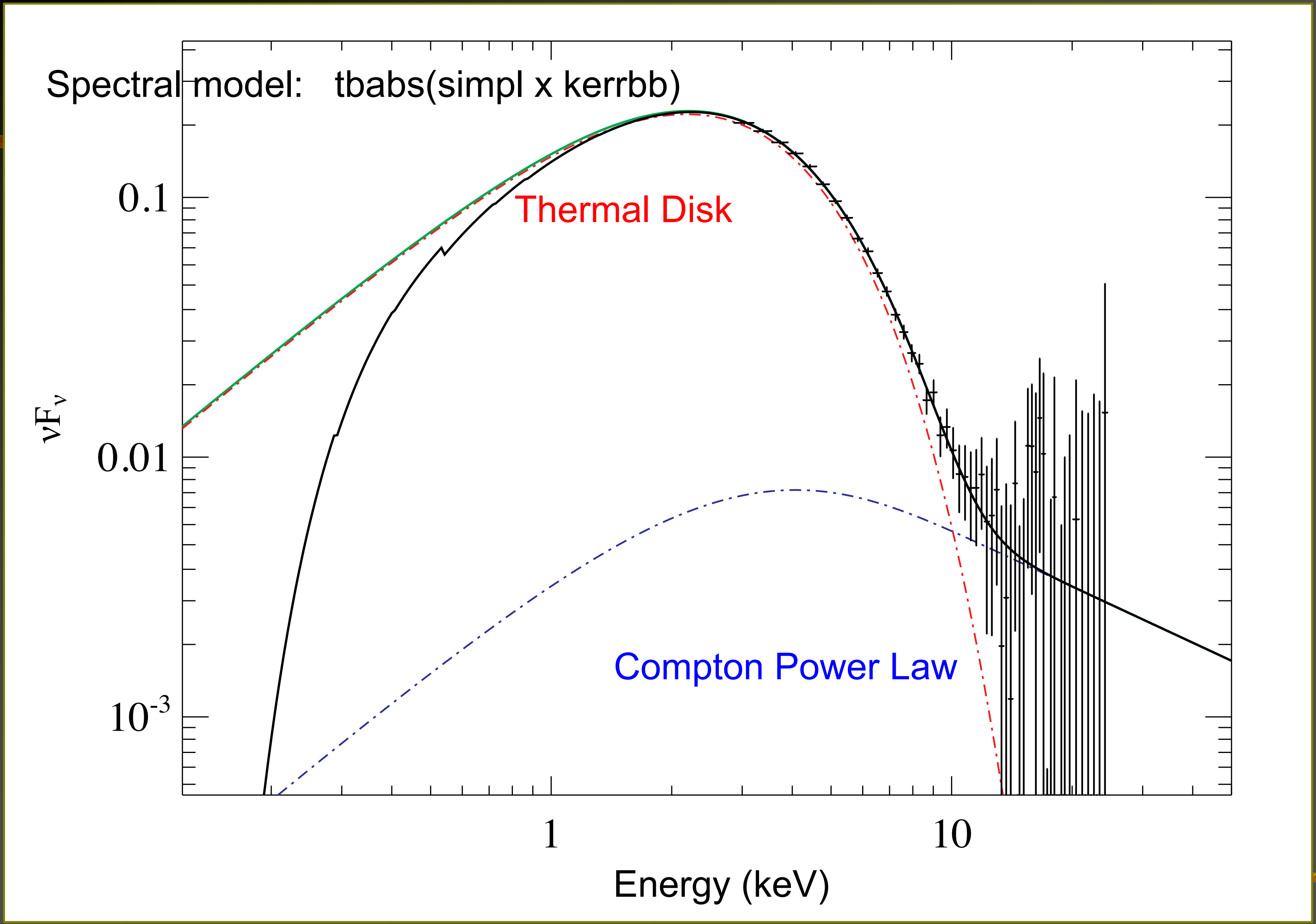
- Applied ... by accretio ... mal state)

- Theoretica ...



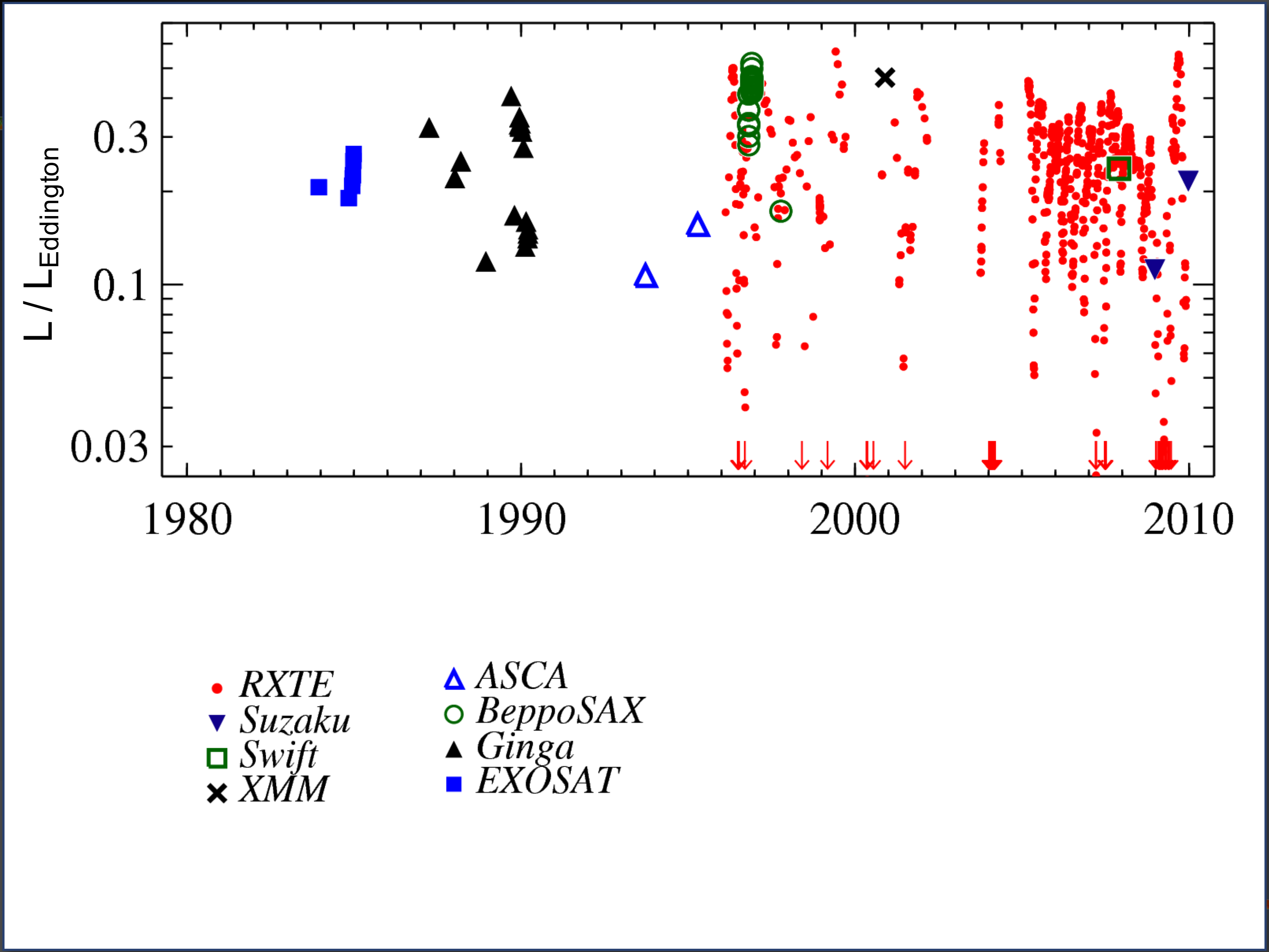
Novikov & Thorne 1973

A soft/thermal state spectrum



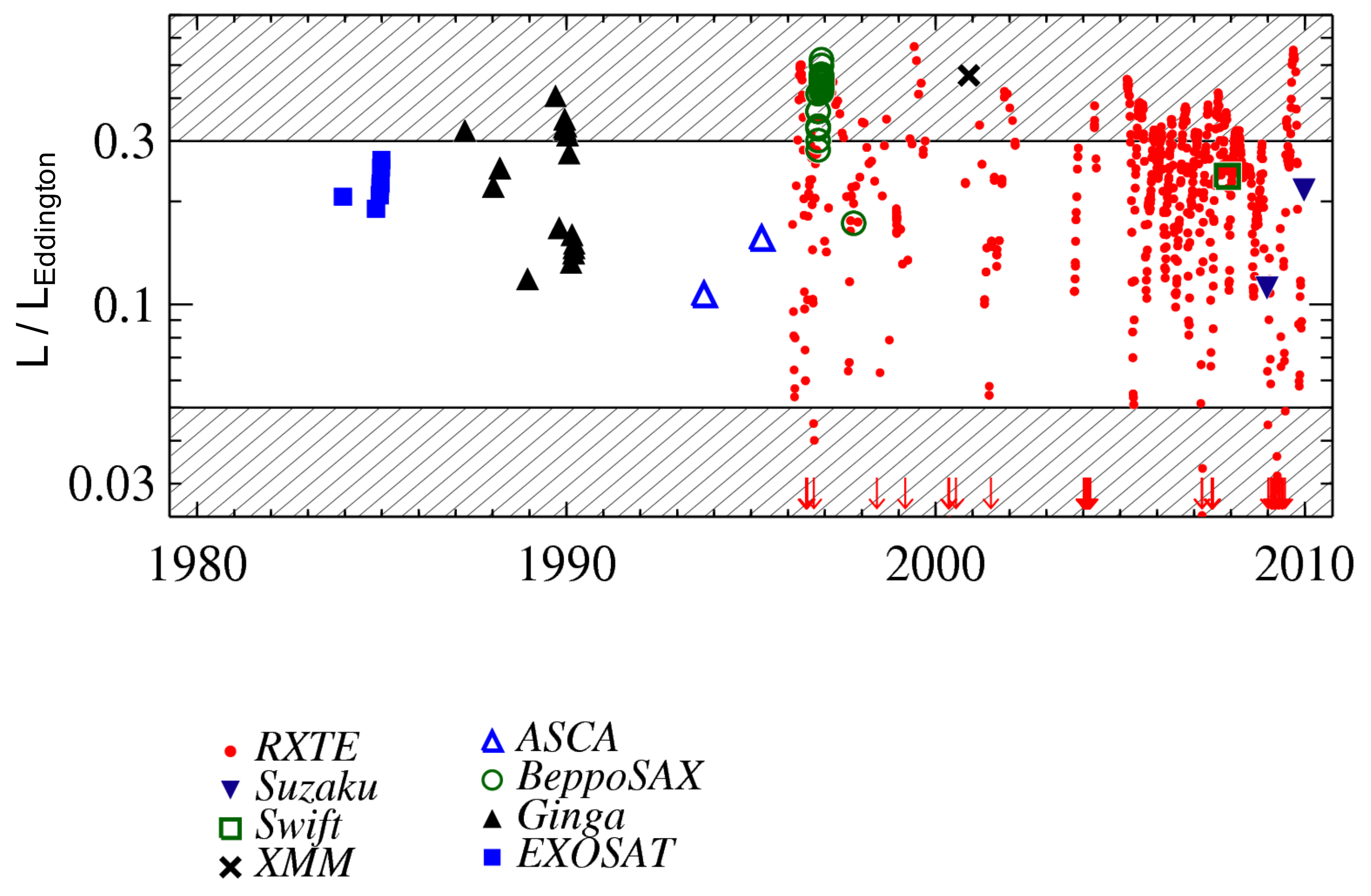
Test-Case- LMC X-3: 1983-2009

Steiner et al. 2010



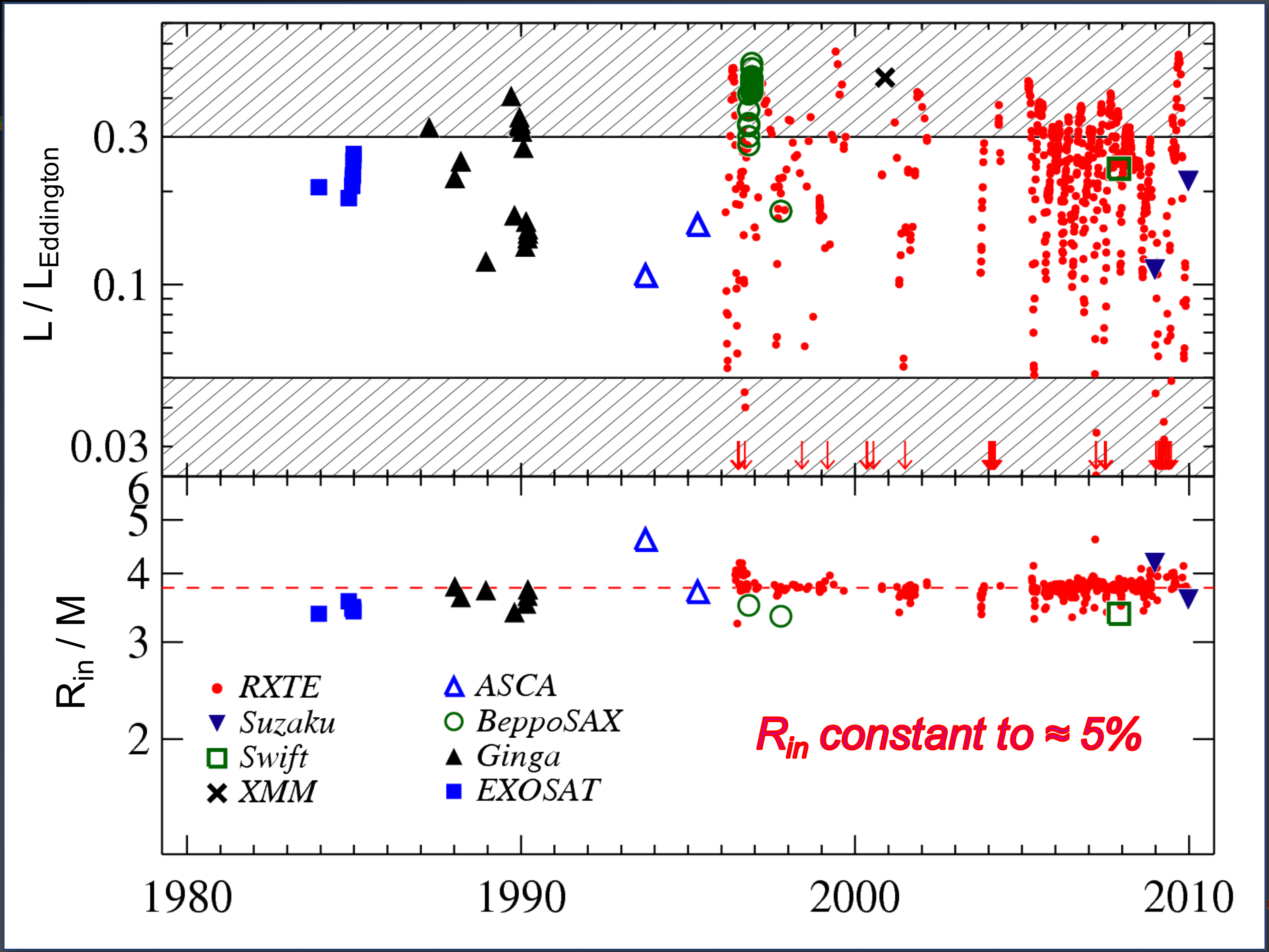
LMC X-3: 1983-2009

Steiner et al. 2010



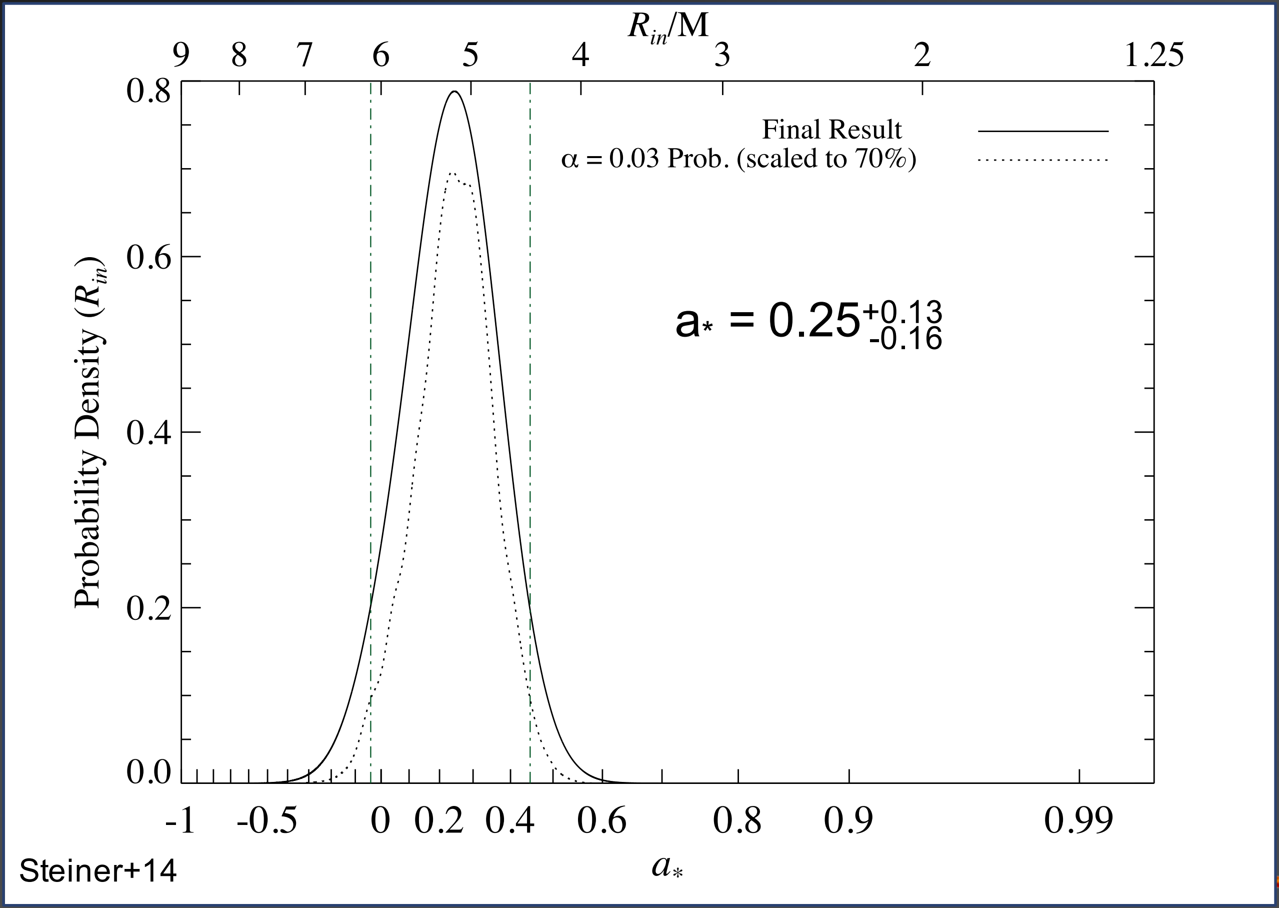
LMC X-3: 1983-2009

Steiner et al. 2010



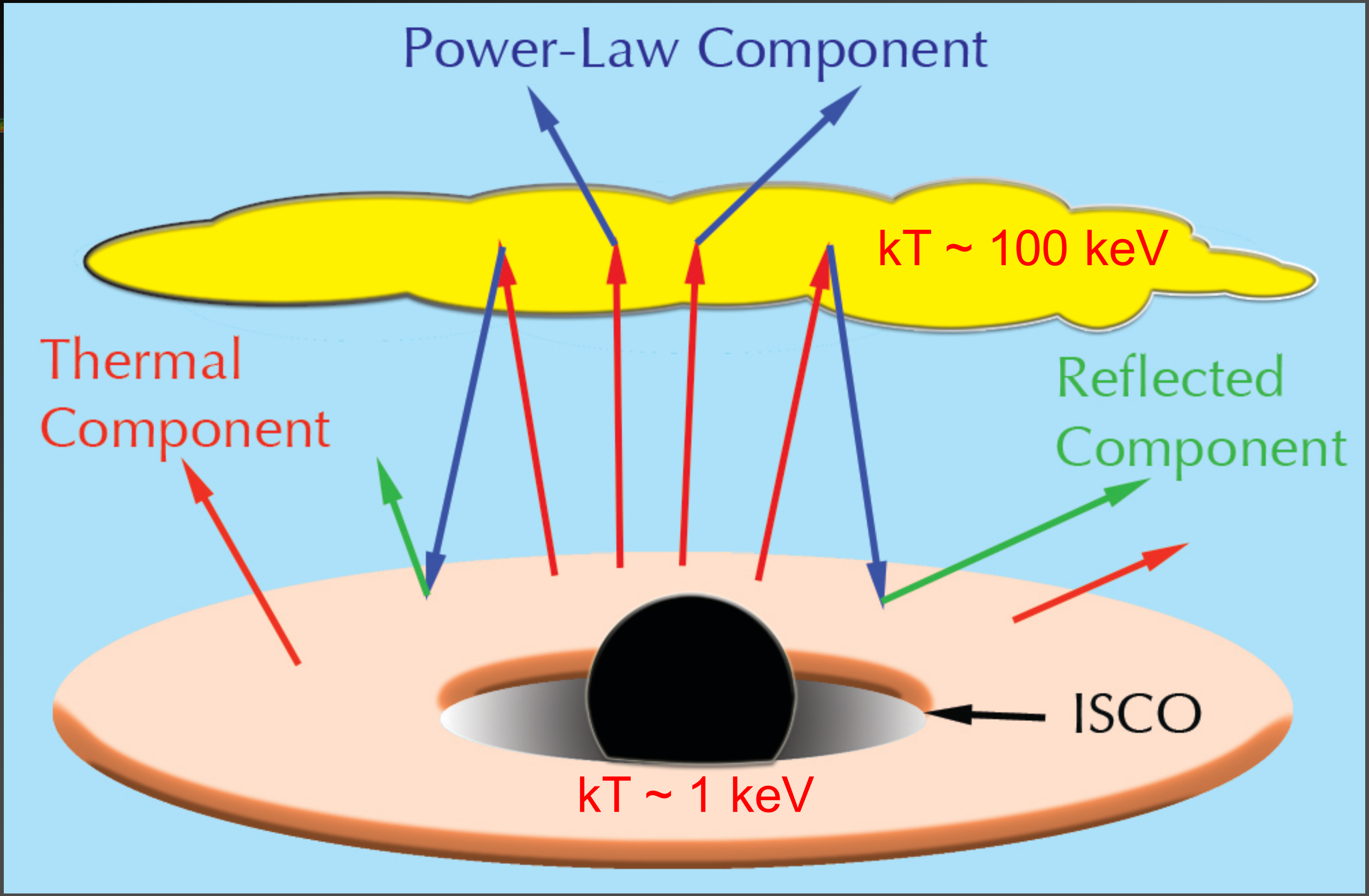
LMC X-3: Final Spin

Obtained using hundreds of kerrbb(2) fits with error dominated by uncertainty in M, i, D.

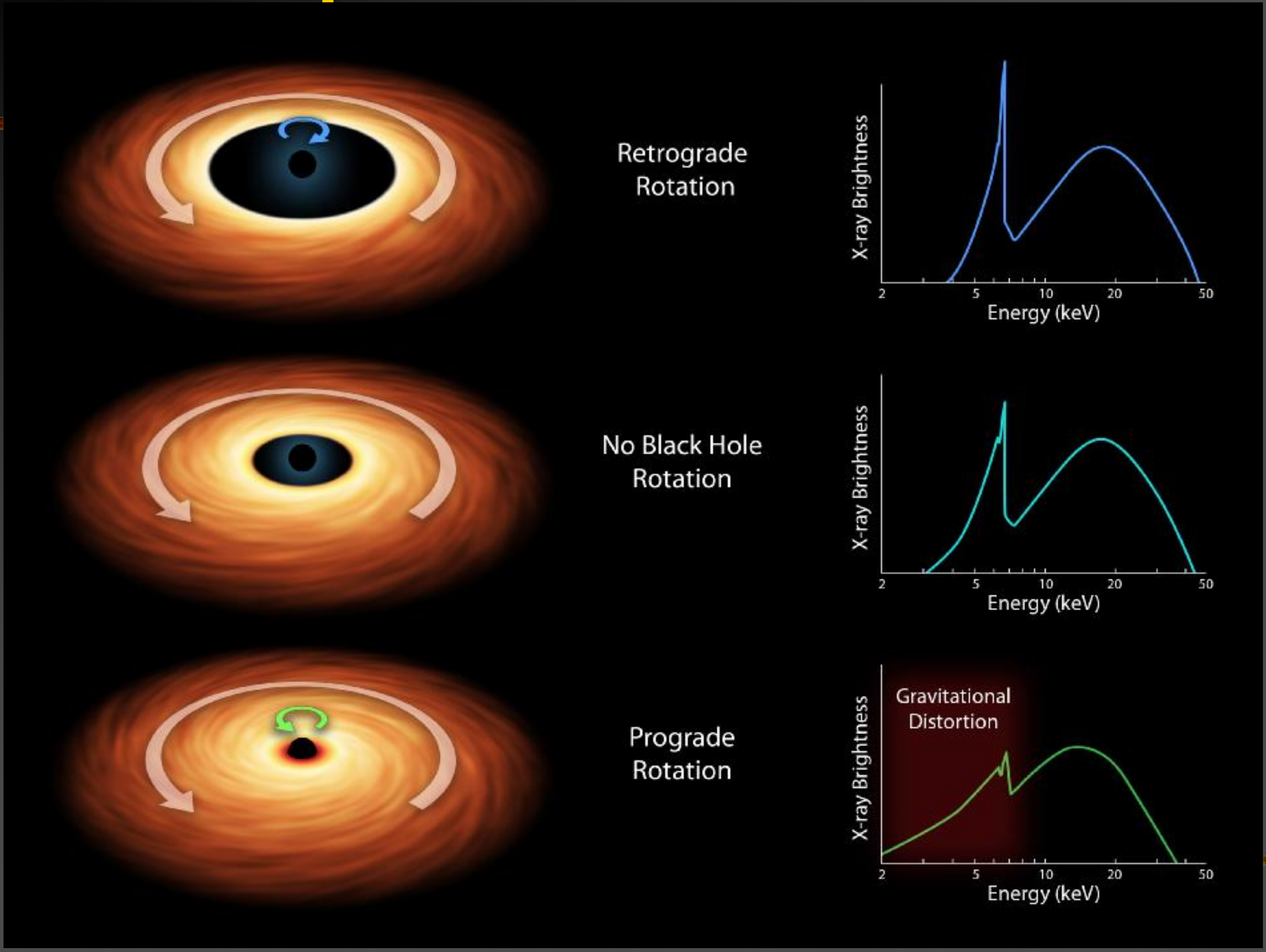


Black-Hole Spin:
X-ray Reflection

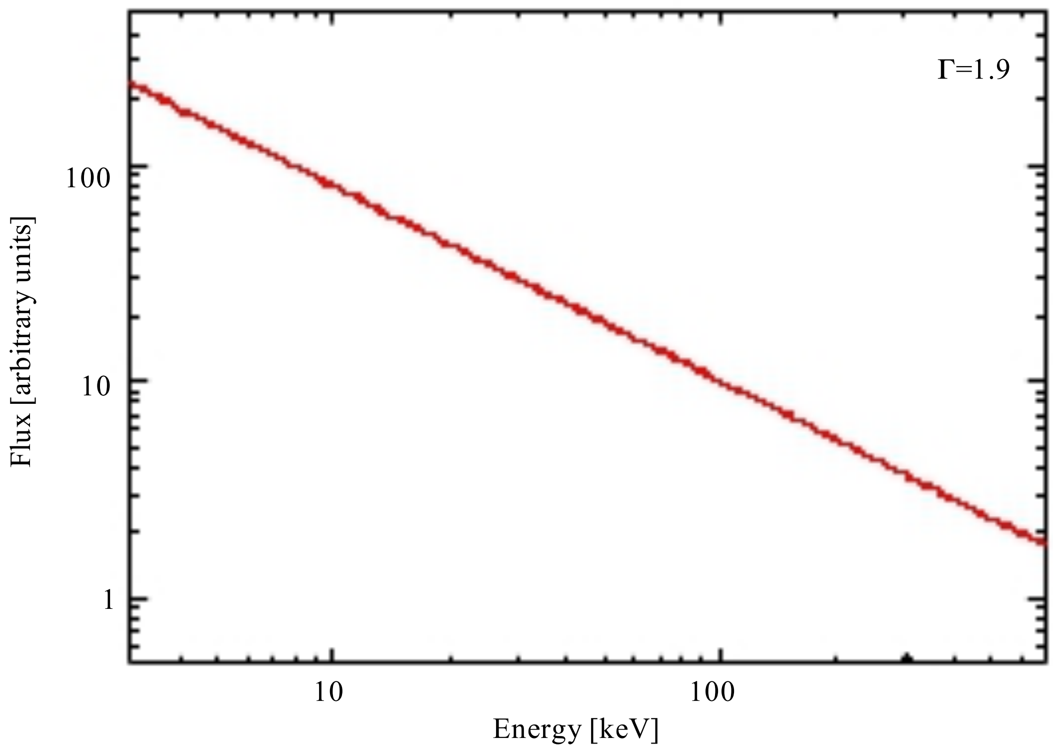
Hot X-ray Corona Illuminating Cold Accretion Disk



Effect of Spin on Reflection Features



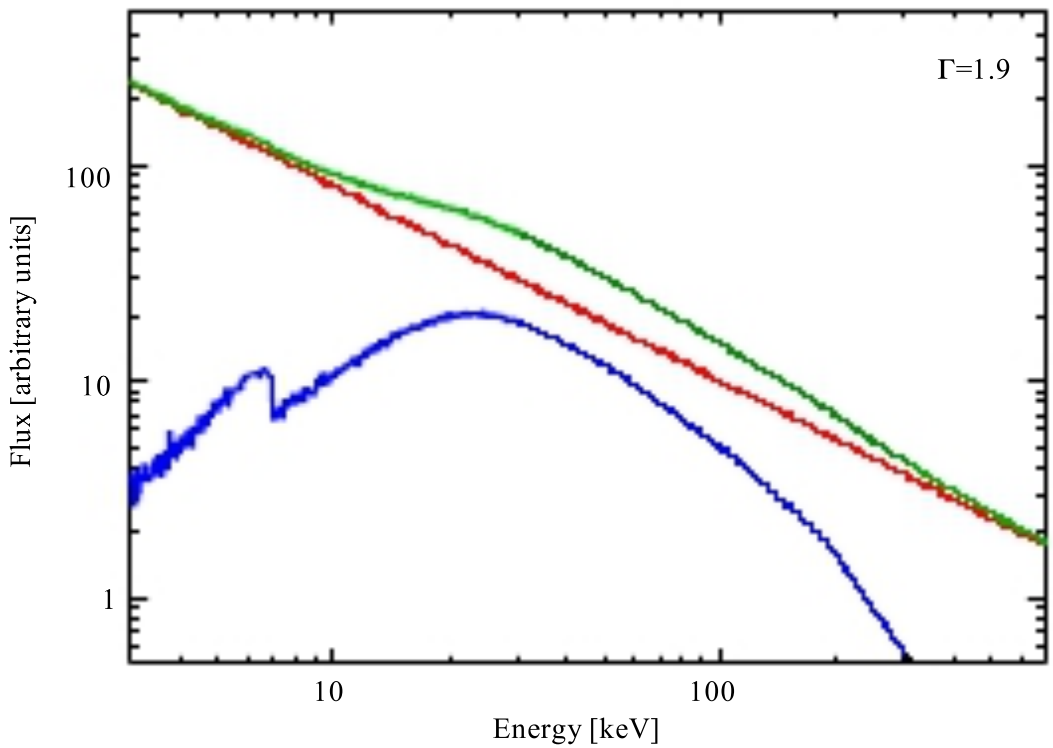
GBH/AGN X-Ray Spectrum



Comptonization of soft X-rays from accretion disk in hot corona (T ~ 10^8 K) or from a Jet: power law continuum.

credit: J. Garcia

GBH/AGN X-Ray Spectrum

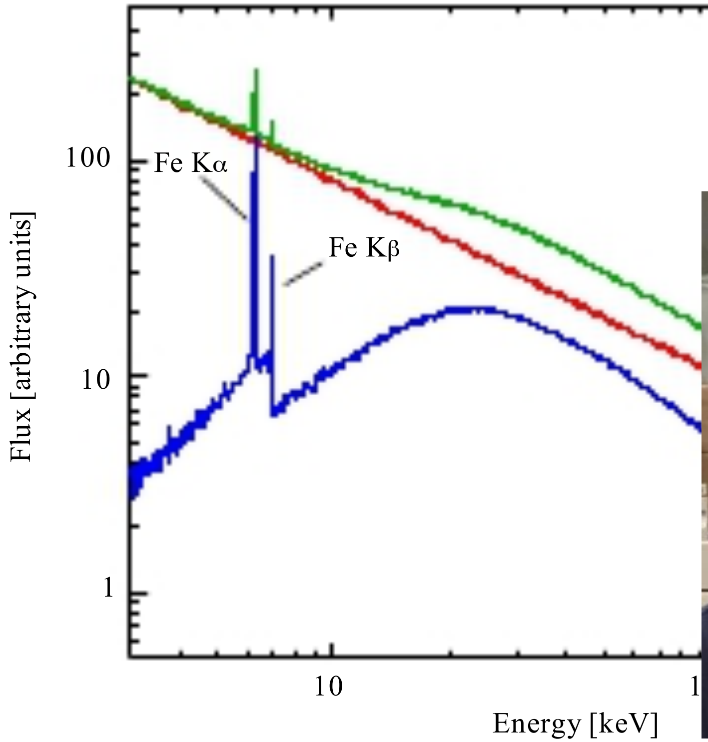


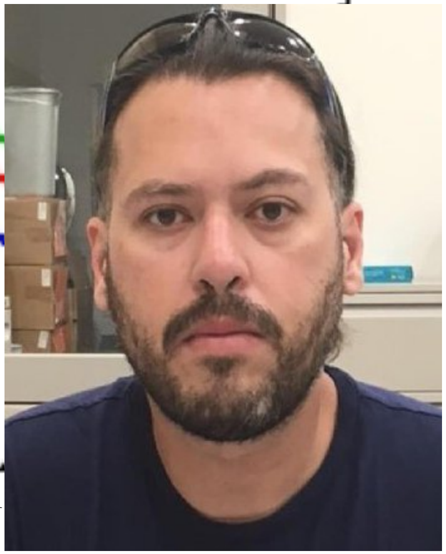
Comptonization of soft X-rays from accretion disk in hot corona ($T \sim 10^8$ K) or from a Jet: power law continuum.

Thomson scattering of power law photons in disk: Compton Reflection Hump

credit: J. Garcia

GBH/AGN X-Ray Spectrum



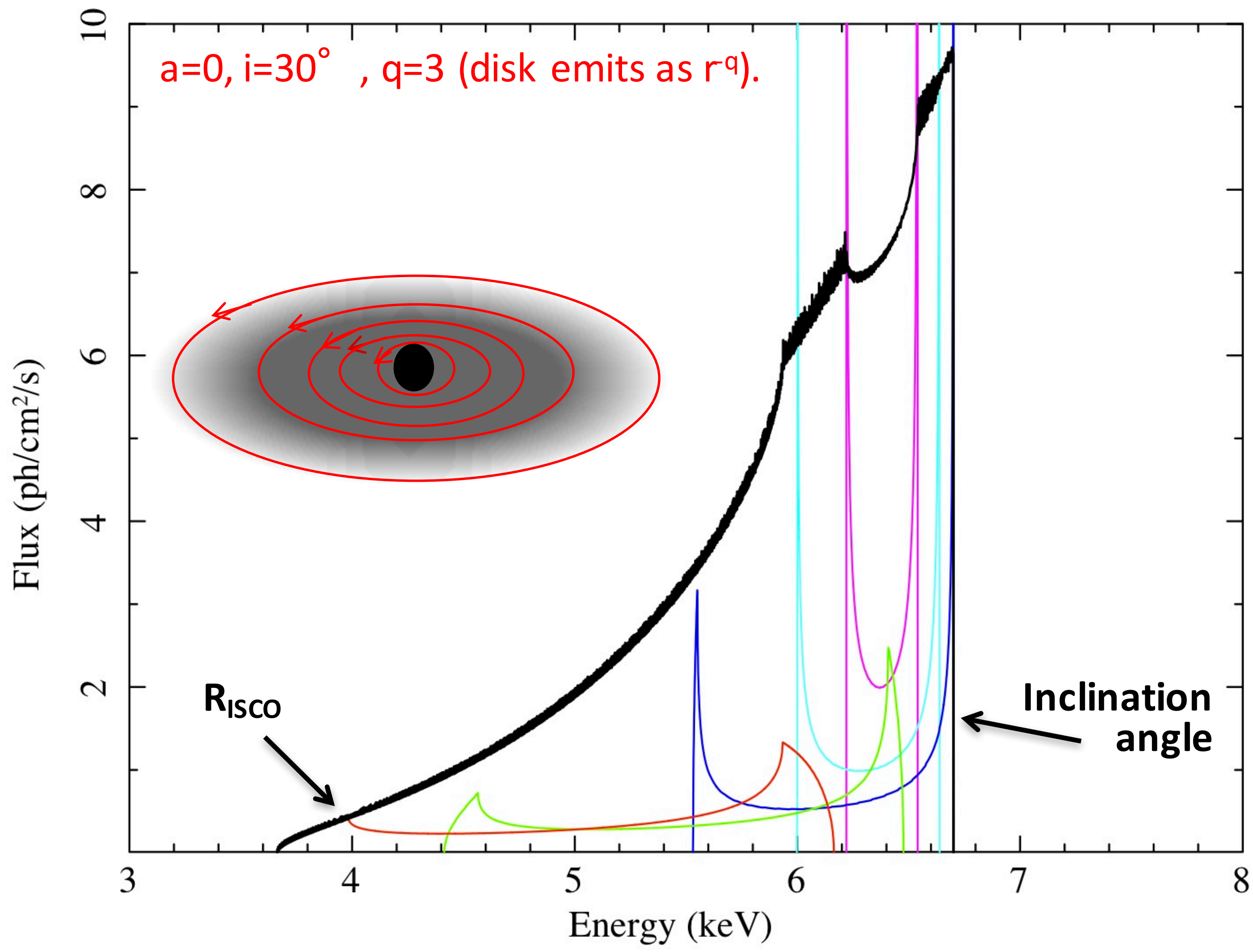


Comptonization of soft X-rays from accretion disk in hot corona ($T \sim 10^8$ K) or from a Jet: power law continuum.
Thomson scattering of power law photons in disk: Compton Reflection Hump
Photoabsorption of power law photons in disk: fluorescent Fe Kα Line at ~6.4keV

Leading reflection model is *relxill*
Javier, one of its two authors, will be here next week.

credit: J. Garcia

Fe Kα emission line from different disk annuli



KERRDISK or RELLINE model (Brenneman & Reynolds 2006; Dauser+ 2010)

Spin Method Comparison

	Continuum Fitting	**Fe Line / Reflection**
Approach	Measure R_{ISCO}	Measure R_{ISCO}
Signal being fitted	Thermal disk continuum	Broadened line features
Spectral state	Thermal / soft (best), intermediate can be okay	bright hard state (best), intermediate can be okay
Suitable for	Mostly stellar-mass	**AGN and stellar-mass**
Model Complexity	**Low (though alignment question)**	High
Independent inputs and dependencies	M, i, D, thin-disk regime (L/L_{Edd} cut)	A prescription for coronal geometry, assumption of disk ionization and density profiles
Systematics	Well-explored (~0.1)	Less constrained (~0.1 ?)

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
MAXI J1535-571		>0.94	Xu ea. 2018
XTE J1752-223		0.92 ± 0.06	Garcia ea. 2018
V404 Cyg		>0.92	Walton ea. 2017
GX 339-4	< 0.9	~0.3 OR >0.9	Garcia ea. 2015, Steiner ea. 2017, Kolehmainen ea. 2010
GS 1354-645		>0.9	El Batal ea. 2016
MAXI J1836-194		0.88 ± 0.05	Reis ea. 2012
M33 X-7	0.84 ± 0.05		Liu ea. 2008, 2010
GRS 1739-278		0.8± 0.2	Miller ea. 2015
Swift J1753.5		0.76 ± 0.15	Reis ea. 2009
IC 10 X-1	>0.7		Steiner et al. 2016
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
4U 1543-47	0.5 ± 0.2		Steiner ea. (also Morningstar ea. 14)
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

Overview

- Black Holes
  - QPOs
  - BH Spin
- Neutron Stars
  - Classes, energy spectra, and PDS
  - NS equation of state
- Practical Advice on XRB Spectral Modeling

Neutron Star LMXB Systems

- 2 main types
  - Z- vs Atoll
- Distinguished by color-color patterns at short-timescales

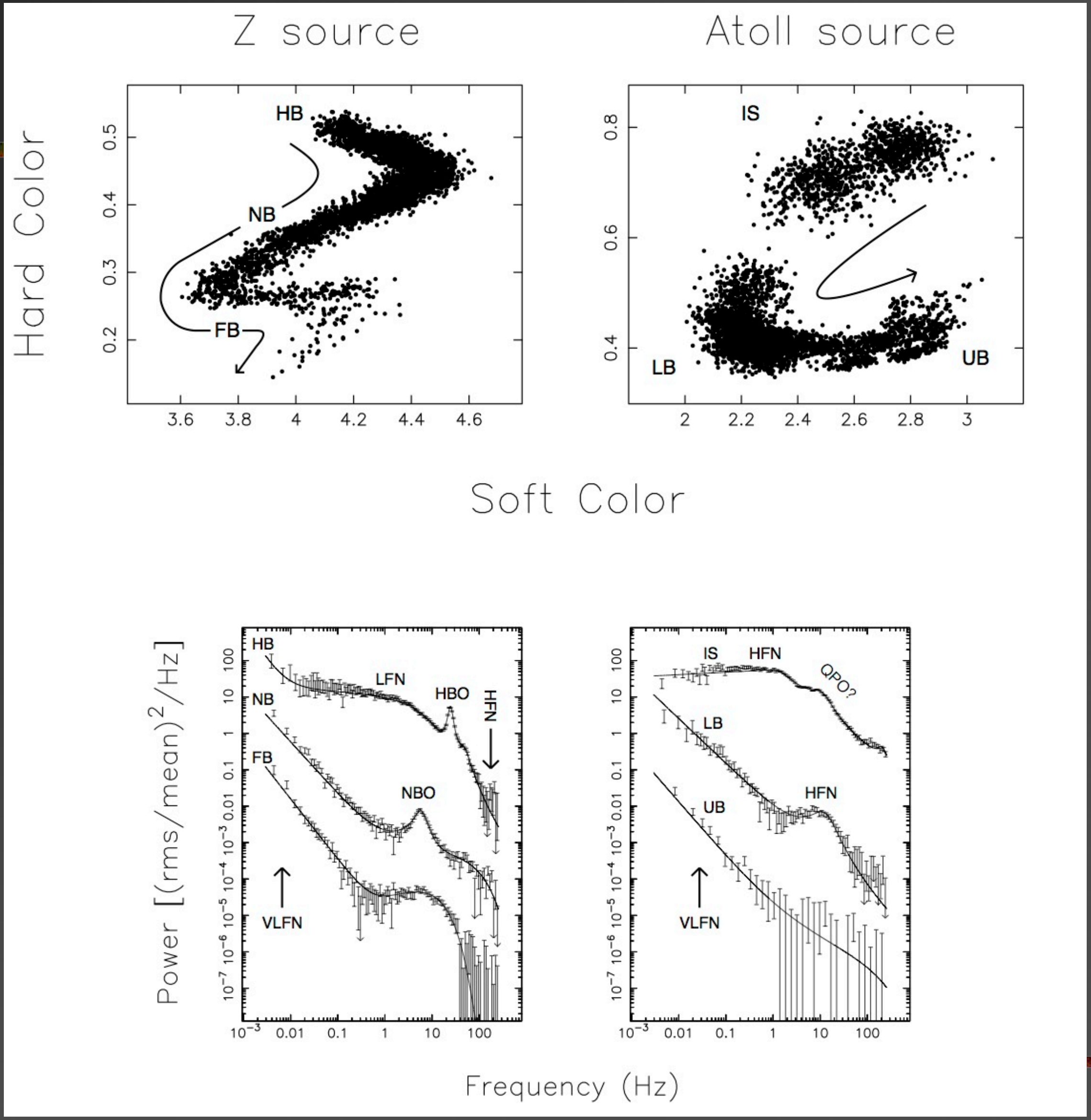
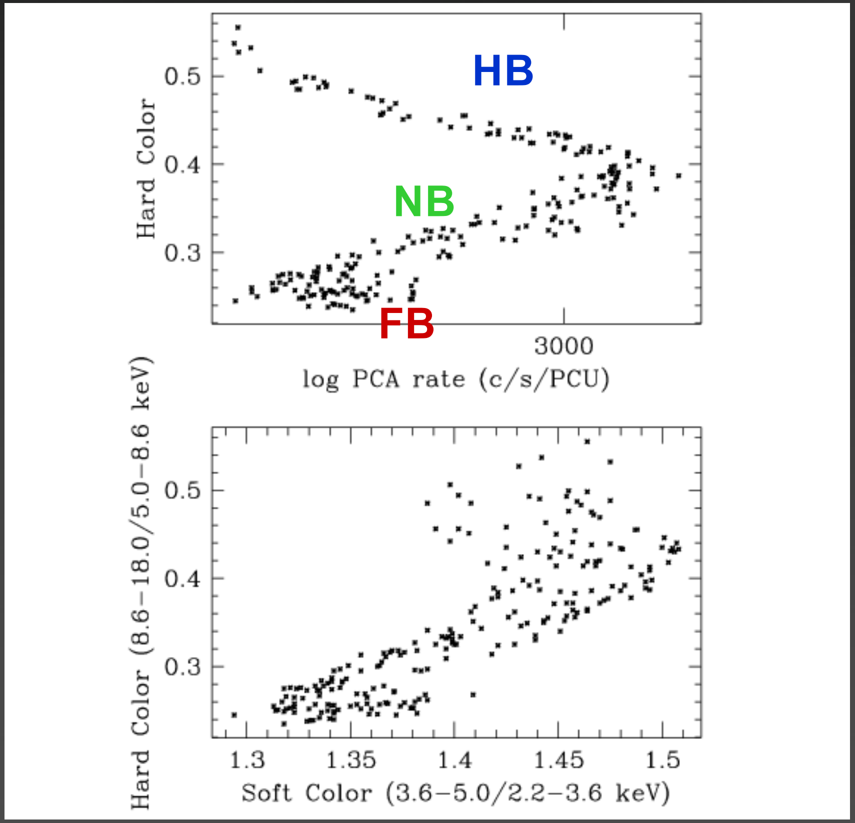


figure: R. Wijnands

Z Sources - 2 sub-types

"Cyg X-2 –like"

GX5-1



"Sco X-1 –like"

GX17+2

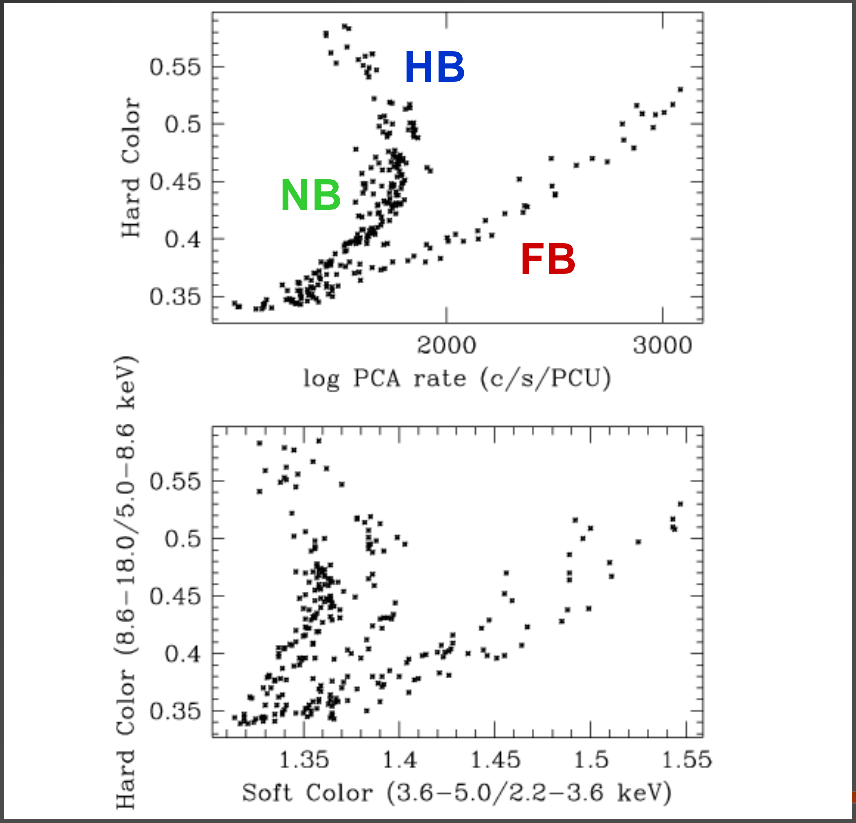
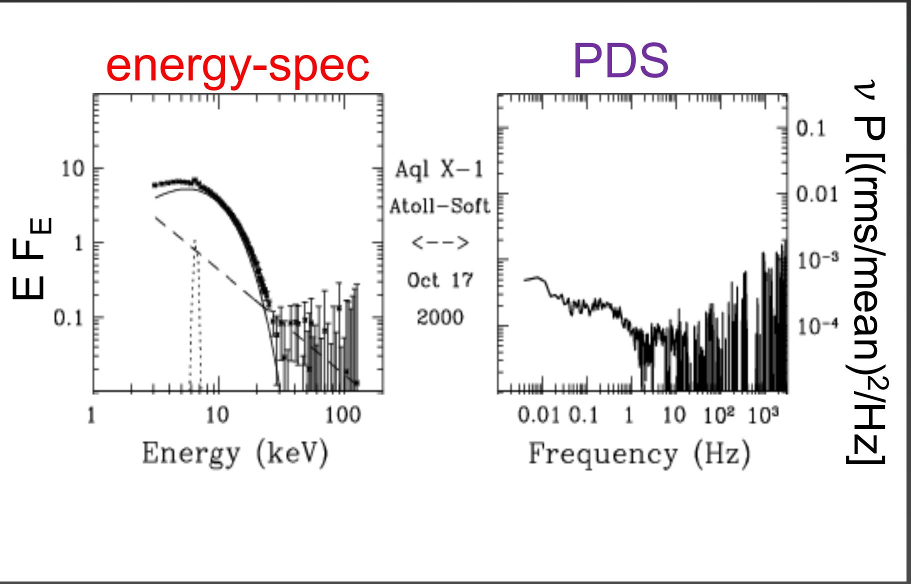


Fig: R. Remillard

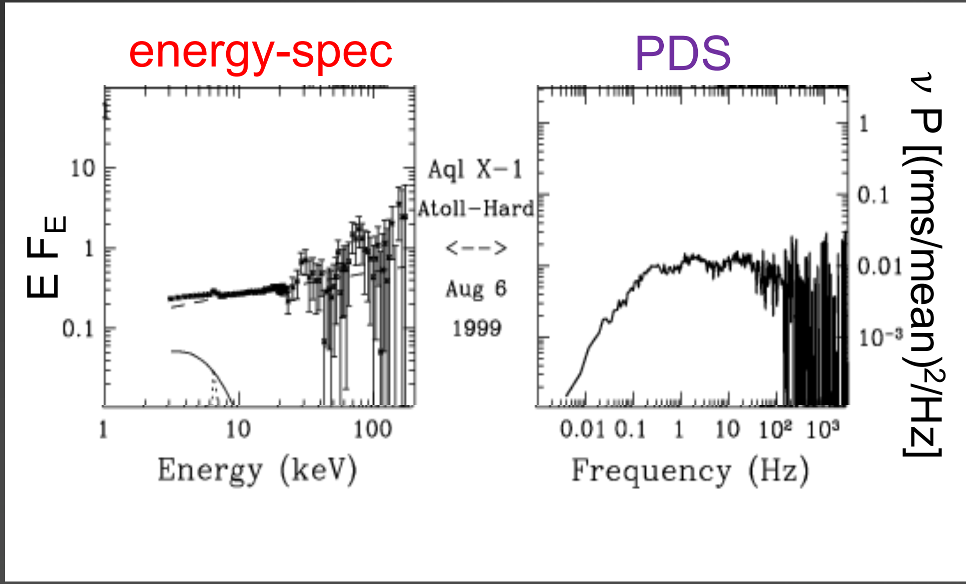
Atoll Energy and Power- Spectra

- Generally very similar in appearance to BH soft and hard states.
- Commonly fitted with a combination of a blackbody, disk-blackbody, and a Compton / power-law component

Soft state

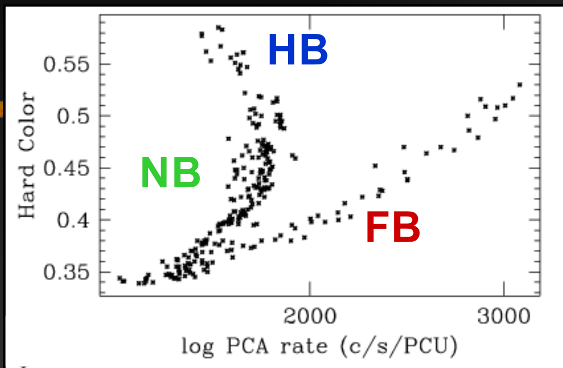


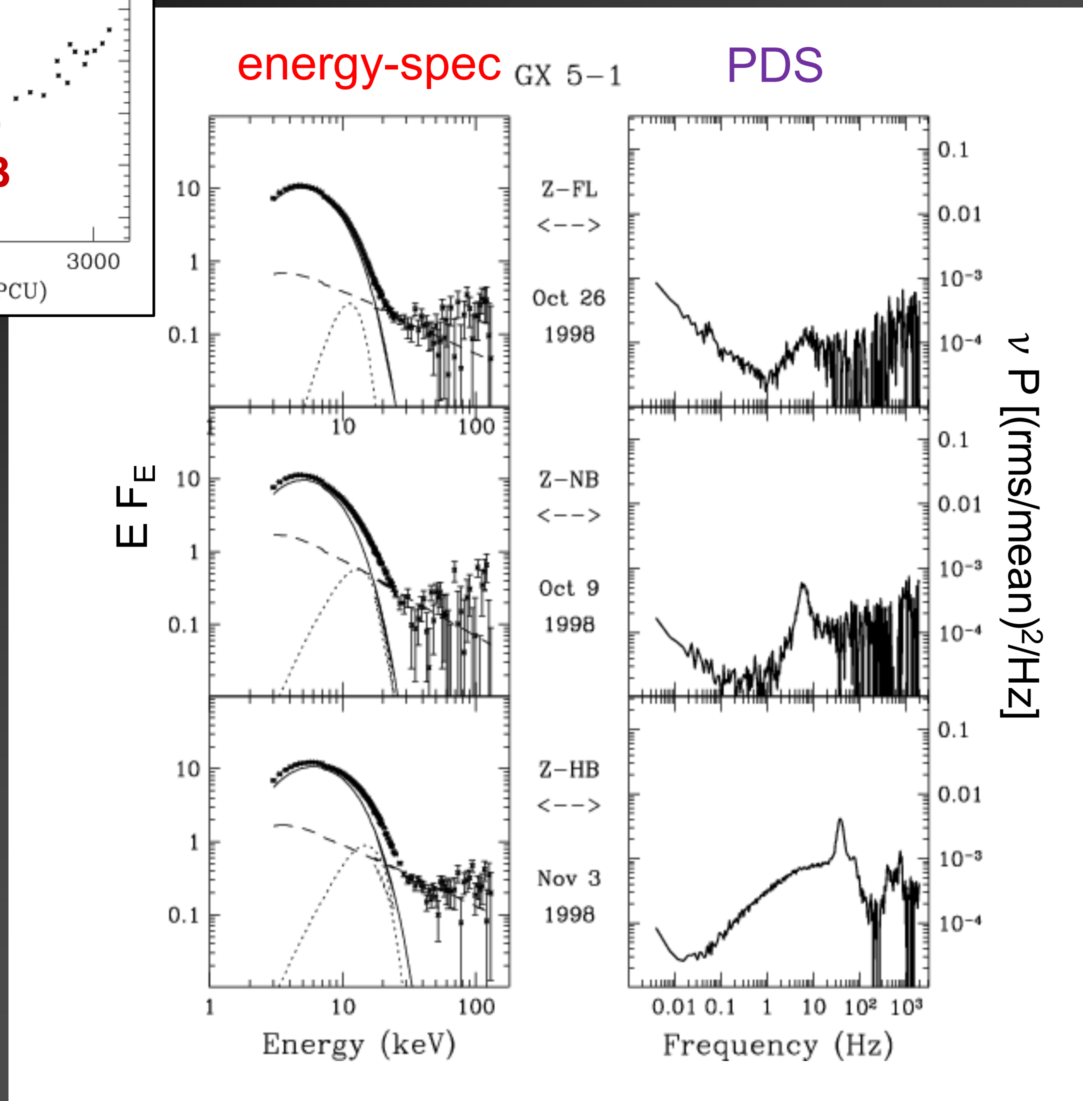
Hard state



Figs: R. Remillard

Z-source Energy and Power- Spectra





Flaring Branch

Normal Branch

Horizontal Branch

Fig: R. Remillard

Rosetta Stone NS Transient XTE J1701-462 Decodes the Different Classes

2006 outburst

RXTE: 866 obs.

3 Ms archive

Horizontal (HB)

Normal (NB)

Flaring (FB)

Homan et al. 2007

Lin, Remillard & Homan 2008

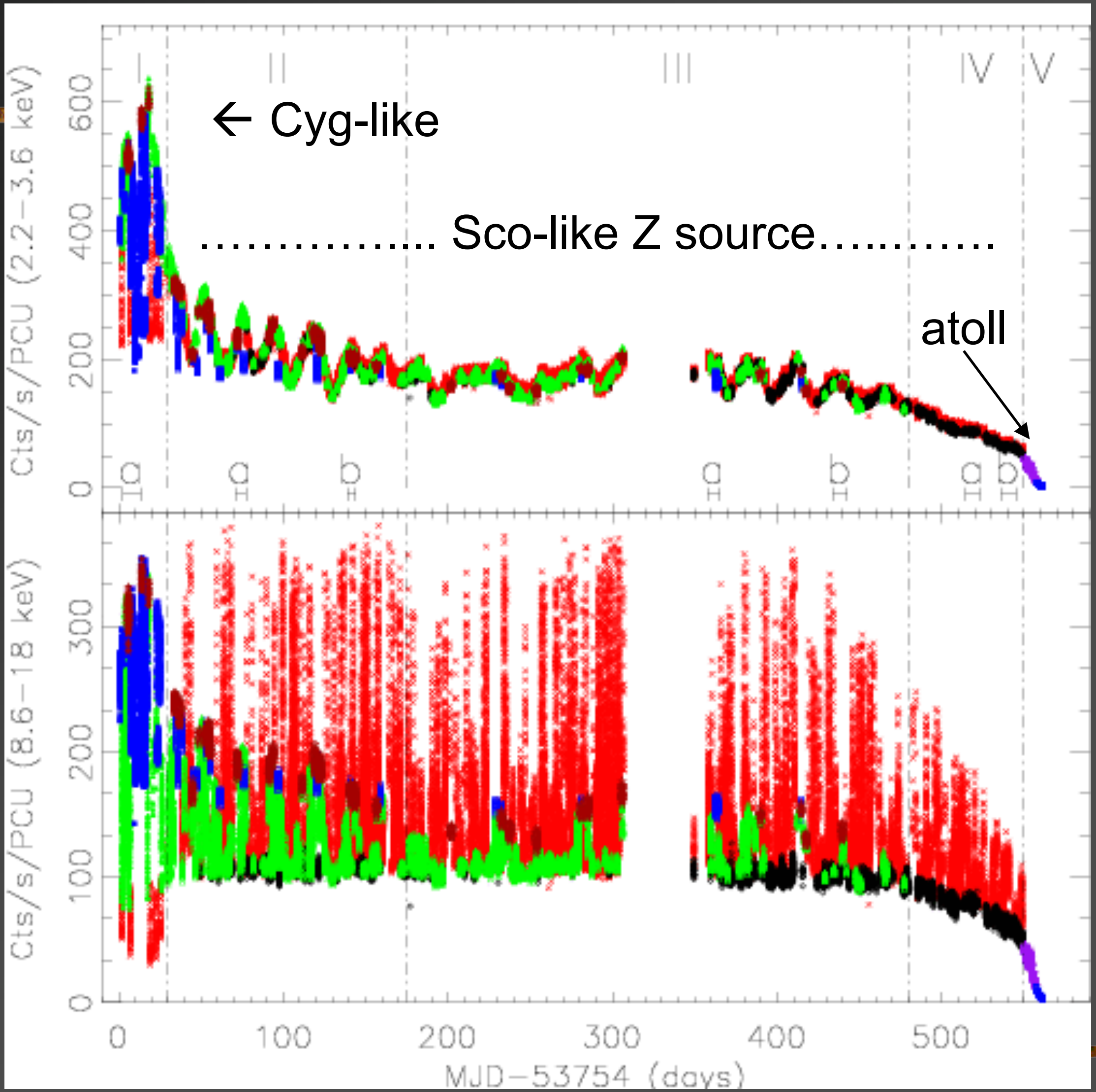
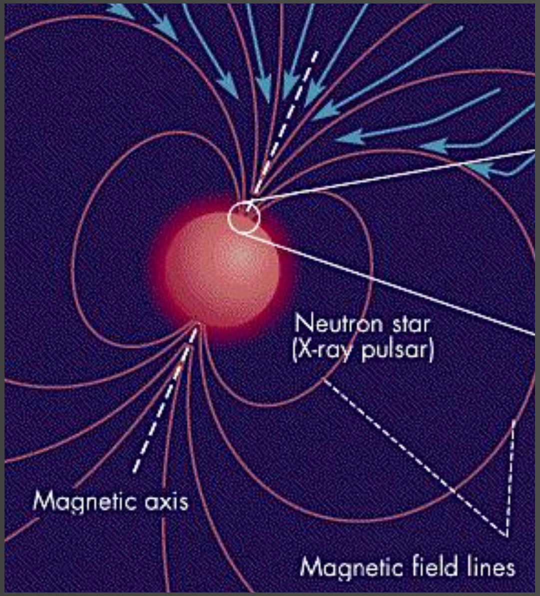


Fig: R. Remillard

Accreting X-ray Pulsars



- >100 in the Galaxy and LMC/SMC
- Pulse-periods milliseconds to hours
- Generally not radio pulsars
  - "Transitional" subset switch between radio and X-ray activity
- Typically wind-fed HMXBs
- Most are Be X-ray Binaries
  - Be-systems are rapidly rotating B-stars which expel a disk of gas
  - Usually very young, orbiting with high eccentricity.

Accreting X-ray Pulsar Energy & Power- Spectra

Spectra can be highly structured; note cyclotron absorption below: E_c [keV] ~10 B_{12}
Note the appearance of *pulsations* and their distinct sharpness vs QPOs

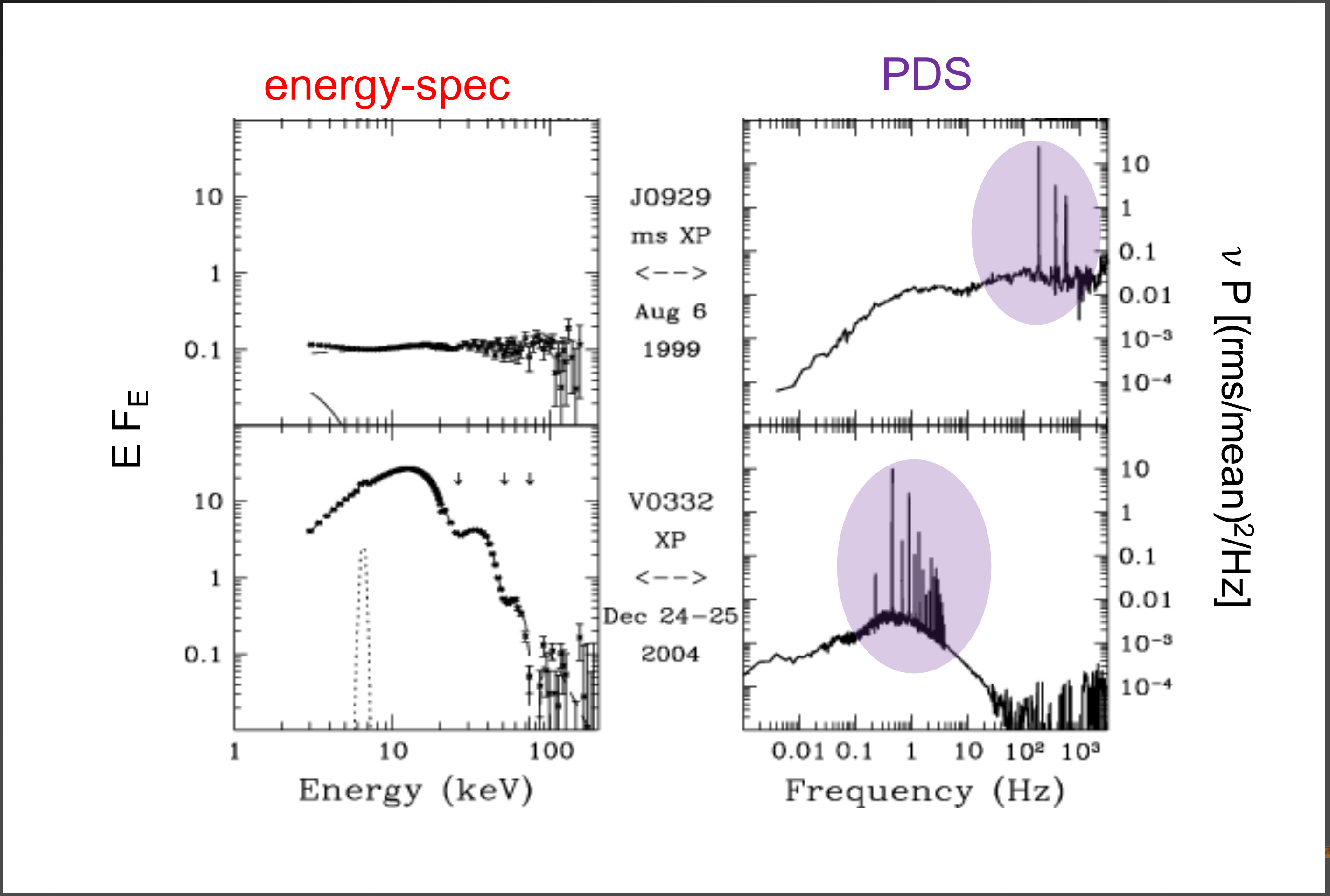
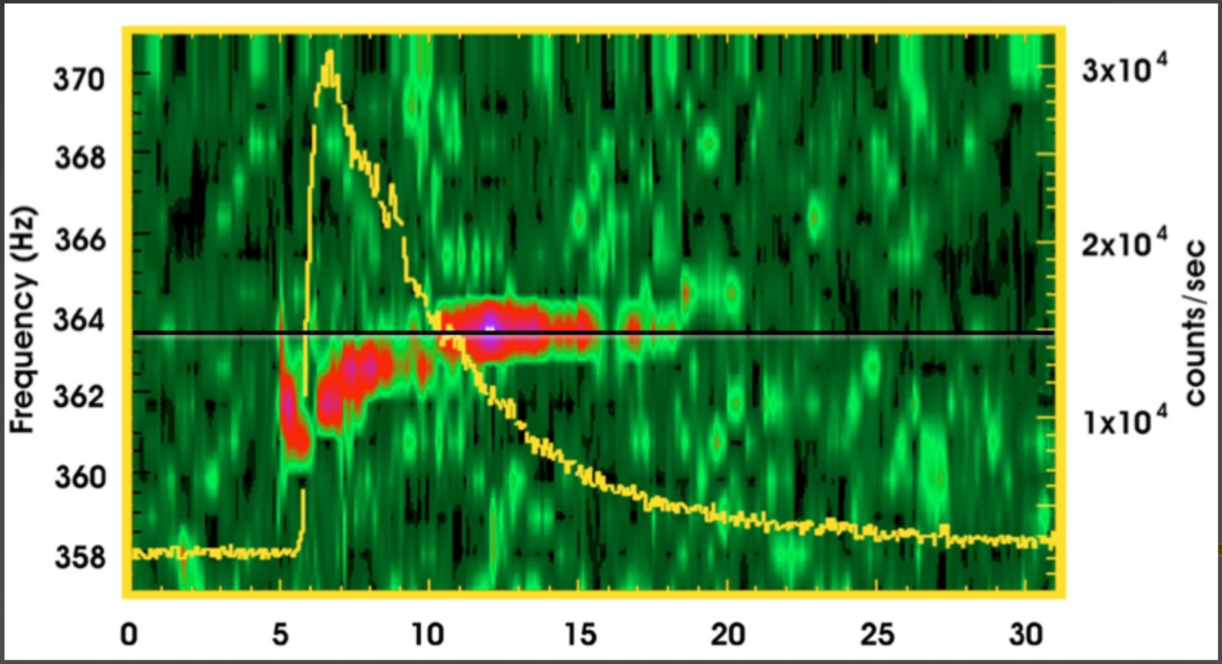


Fig: R. Remillard

A note on NS spins

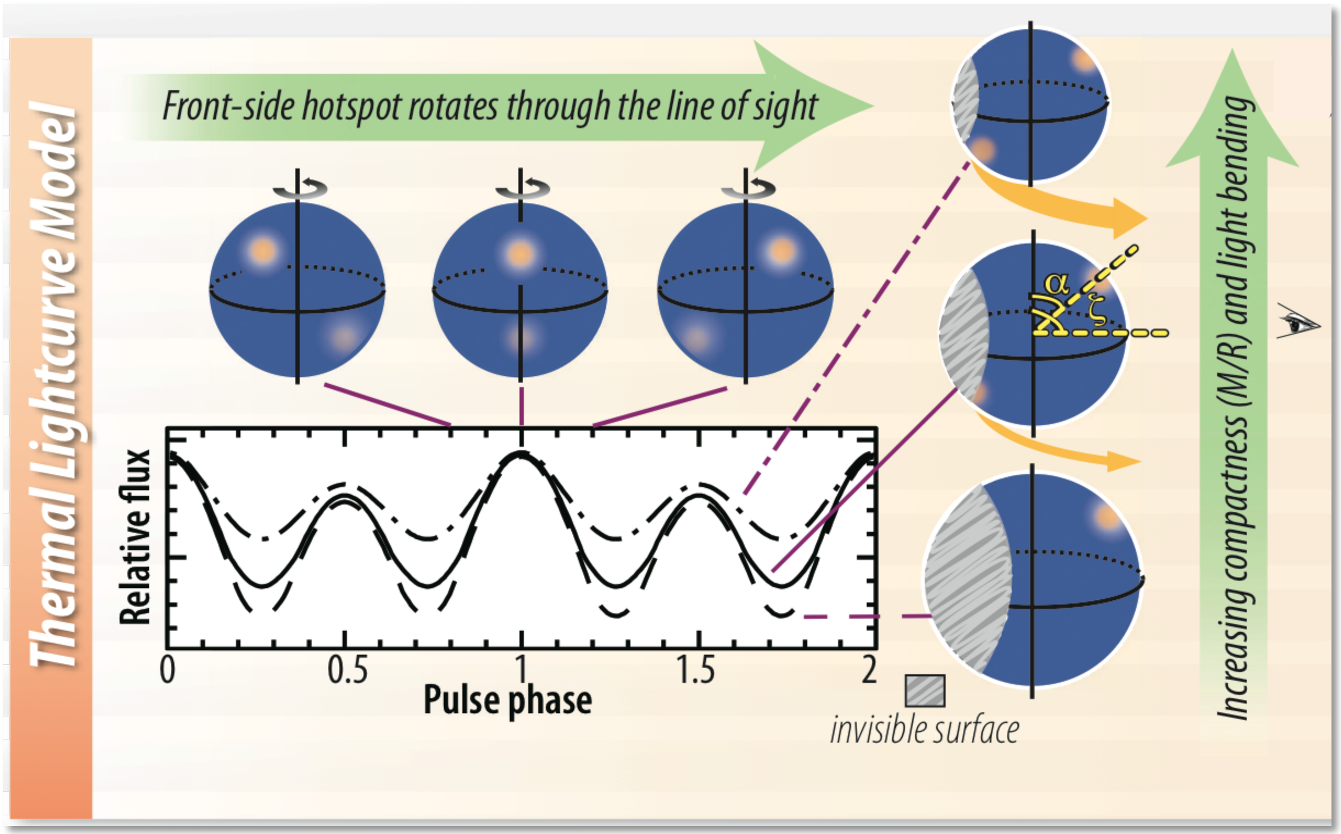
- Can be determined from non-pulsing systems which produce X-ray bursts. A high-frequency coherent signal during X-ray bursts
  - “burst oscillations”



Strohmayer & Markquardt 99

NICER: Finding Neutron Star M/R via Pulsar Light Curves

Non-accreting msec Pulsars



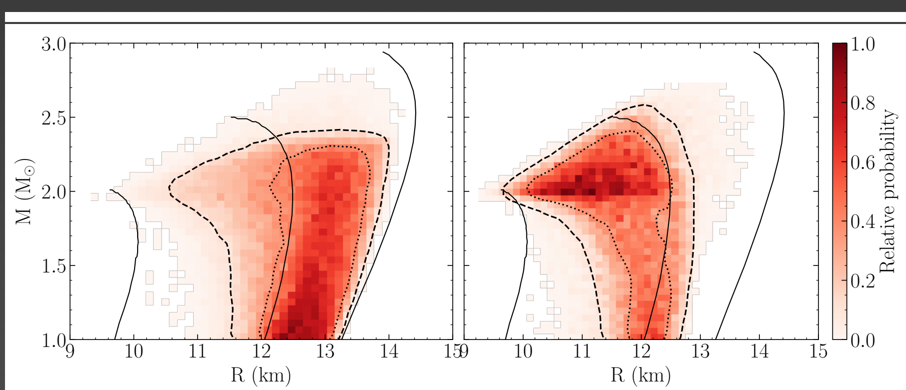
Lightcurve modeling constrains the compactness (*M/R*) and viewing geometry of a non-accreting millisecond pulsar through the depth of modulation and harmonic content of emission from rotating hot-spots, thanks to gravitational light-bending…

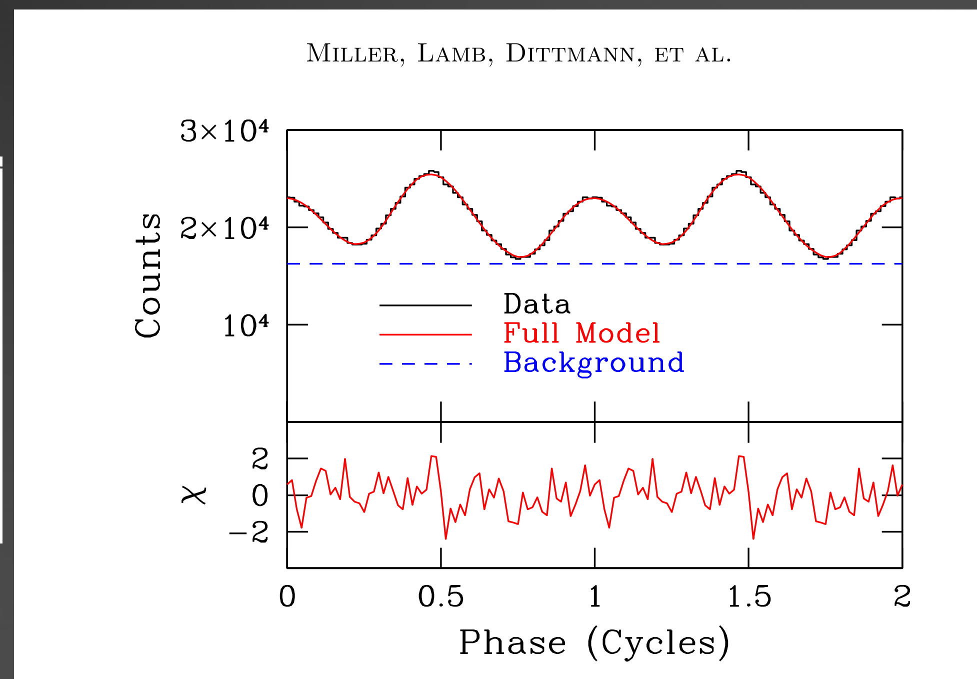
NICER's First Milestone EoS Results in 2019

EoS papers on PSR J0030+0451

Bogdanov et al. 2019
Miller et al. 2019
Raaijmakers et al. 2019
Riley et al. 2019

Raaijmakers et al. 2019





Overview

- Black Holes
  - QPOs
  - BH Spin
- Neutron Stars
  - Classes, energy spectra, and PDS
  - NS equation of state
- Practical Advice on XRB spectral modeling

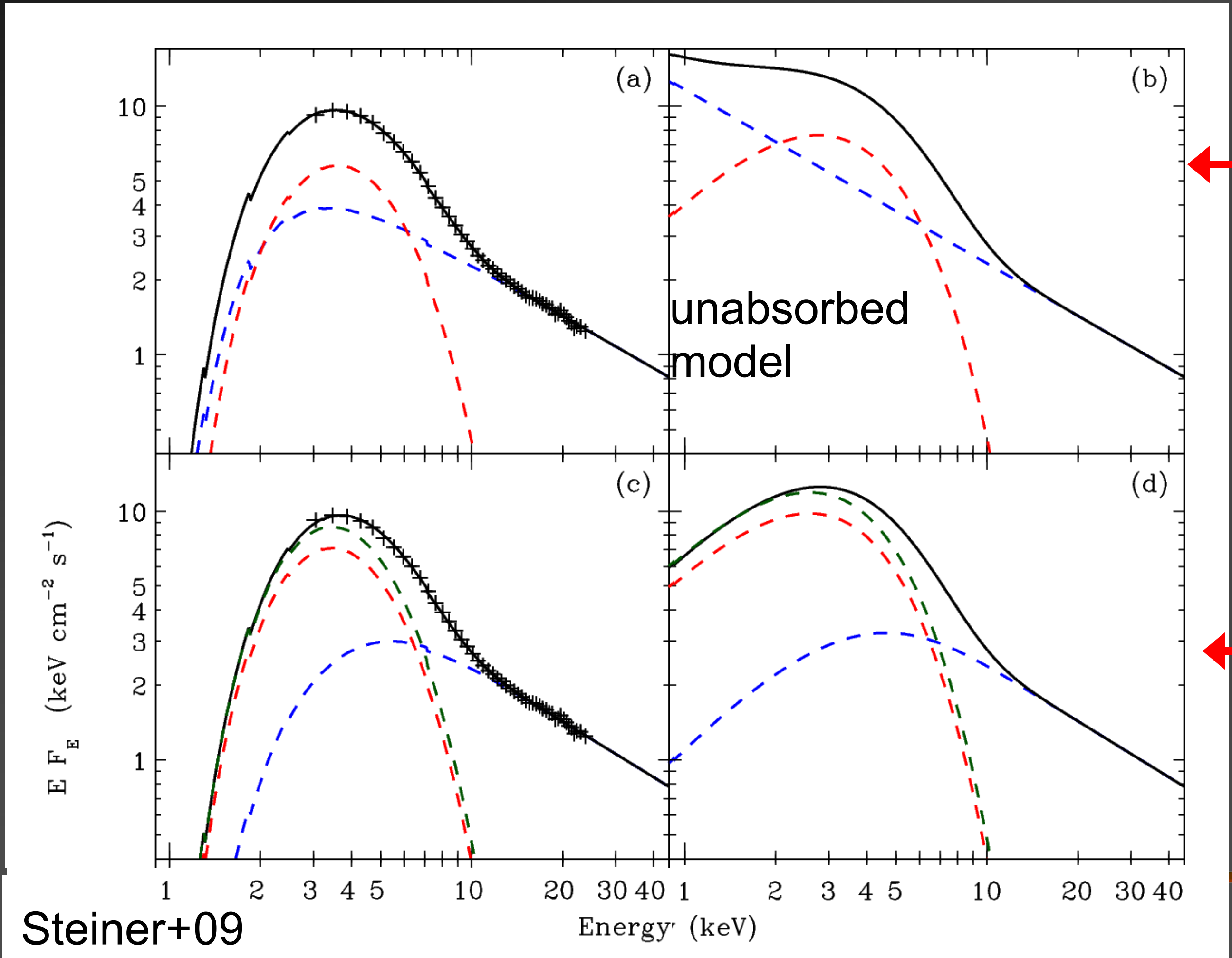
XRB Data Analysis Roadmap (here be dragons!)

- New data in hand
- Fit with powerlaw
  - (not good enough…)
- Fit with diskbb+powerlaw
  - (reflection residuals!)
- Fit with diskbb+relxill
  - (Pretty good fit, let's use this.)

XRB Data Analysis Roadmap (here be dragons!)

- New data in hand
- Fit with powerlaw
  - (not good enough…)
- **Fit with diskbb+powerlaw**
  - (reflection residuals!)
- Fit with diskbb+relxill
  - (Pretty good fit, let's use this.)

The problem with diskbb+powerlaw



powerlaw

simpl

Steiner+09

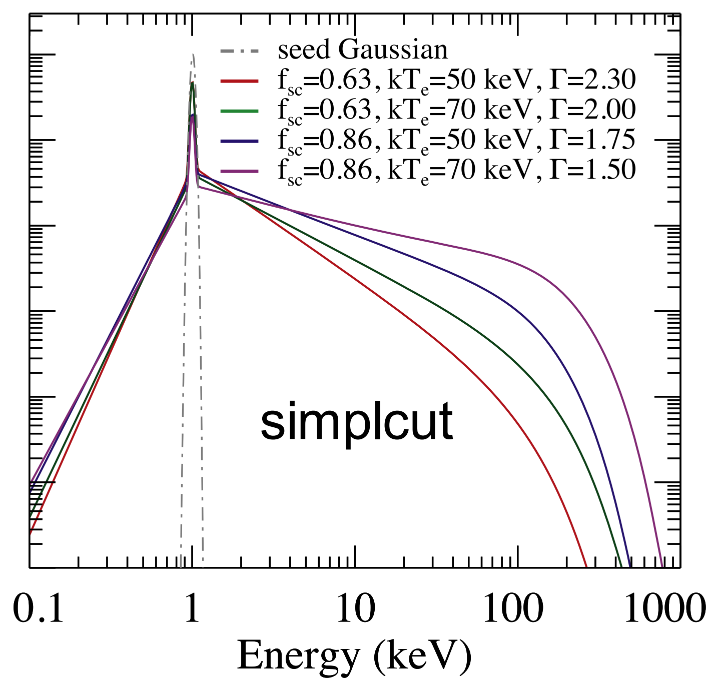
The problem with diskbb+powerlaw

- It’s adding unphysical nonsense at energies <~kT and > kTe
- Structurally incorrectly applies assumption that two entities are *directly and <u>separately</u>* emitting photons: a disk and a corona.
- Causes NH to be systematically overestimated, kT to be overestimated, and N_disk to be underestimated.
  - NH is often reported as varying *artificially* with state from this (since Gamma dependent).
- Solved when using models like compTT, nthcomp
  - However, N_disk will still be underestimated (Compton photons *originated* as seed thermal emission).
- Solved and made self-consistent when using convolution models like simpl/cut or thcomp.

simpl/cut and thcomp as alternatives

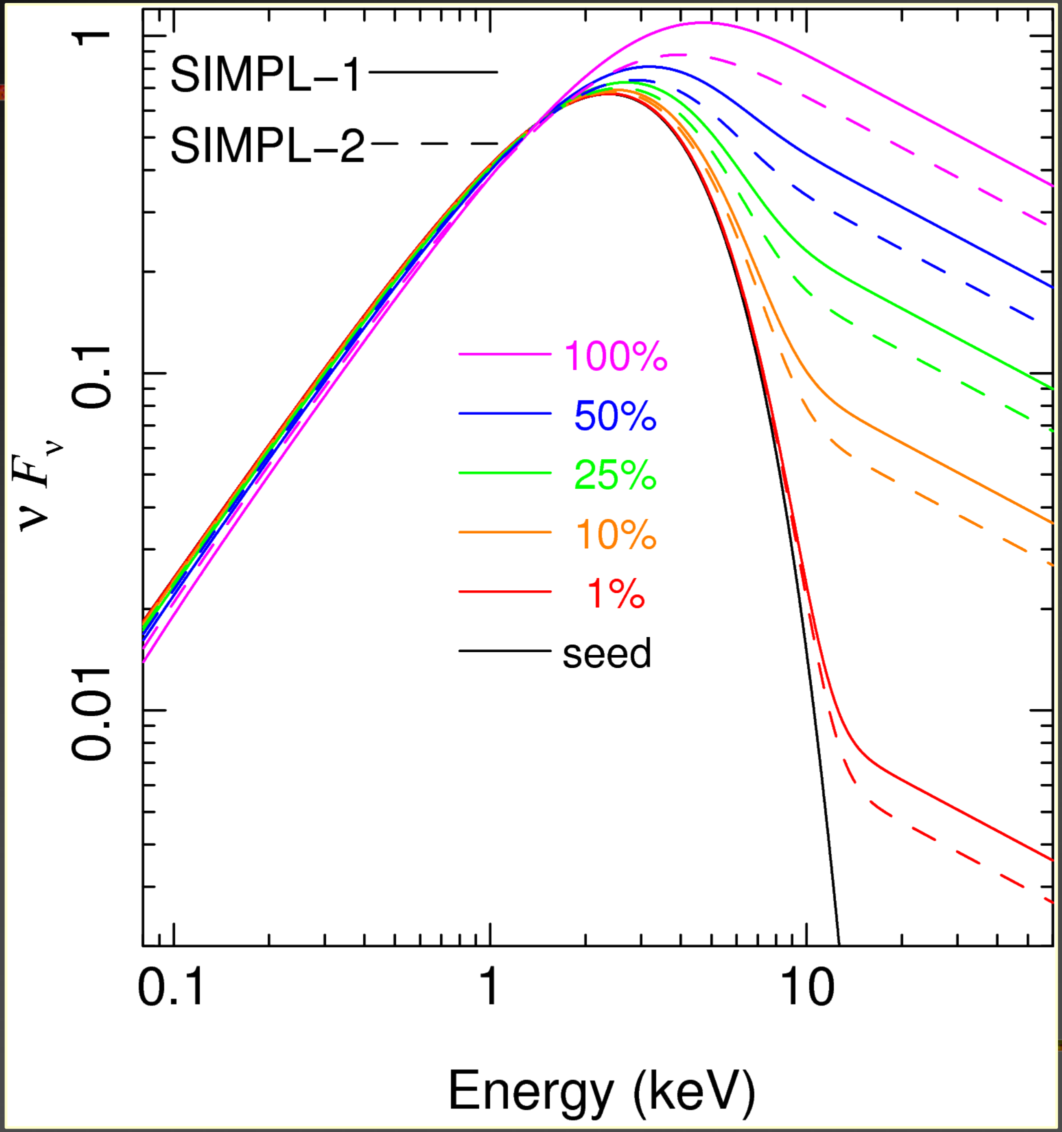
- Convolutional scattering models which are structurally matched to the action of the corona.
- They scatter seed (thermal disk) photons into a Compton power law.
- Photons are conserved.

Caution: when using simpl or simplcut, you must define a new, broad energy grid for xspec: (e.g., “energies 0.005 1000. 1000 log”)



Steiner+17

Scattering a disk spectrum

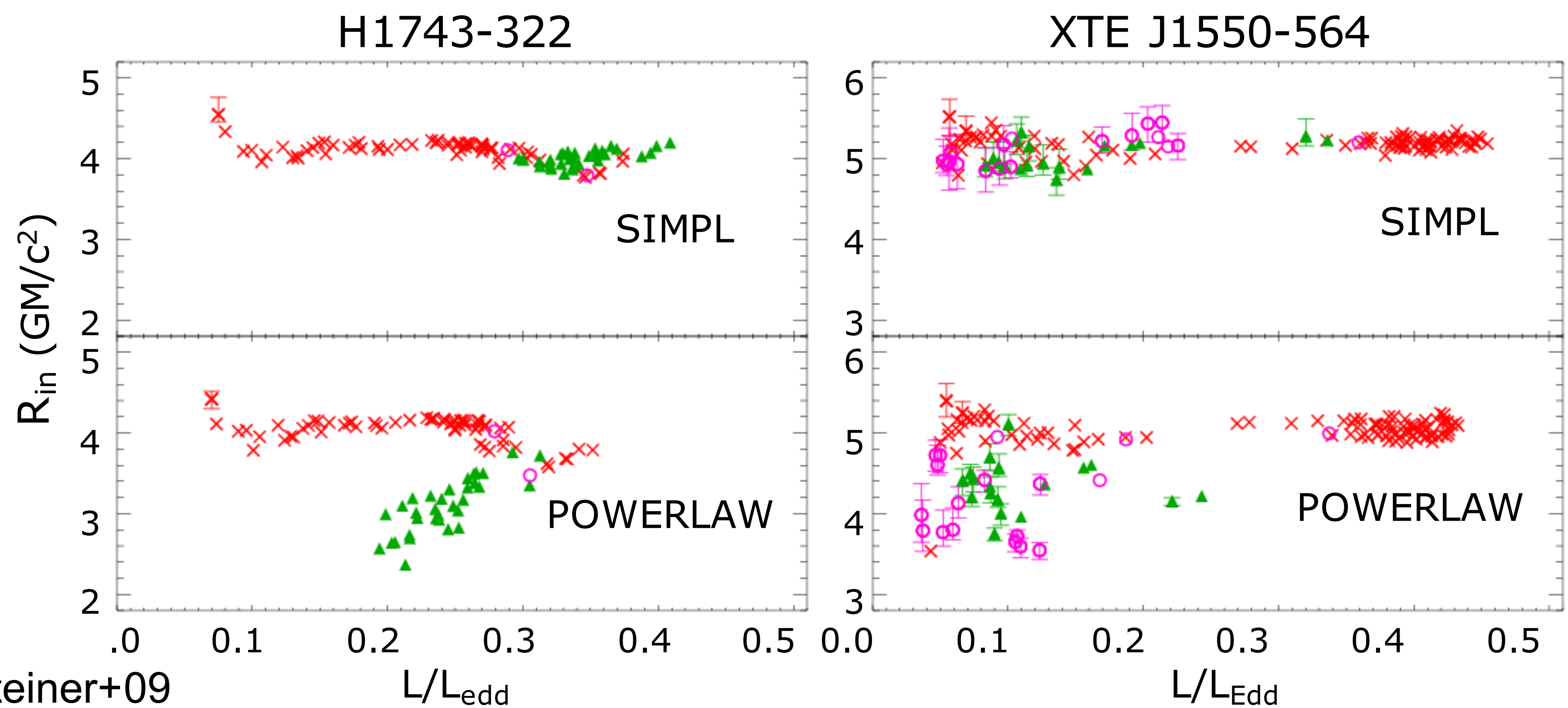


Steiner+09

Is the “photon accounting” useful?

Yes, necessary for robust CF spin

- Thermal emission in soft through SPL and intermediate states yield remarkable consistency:



Steiner+09

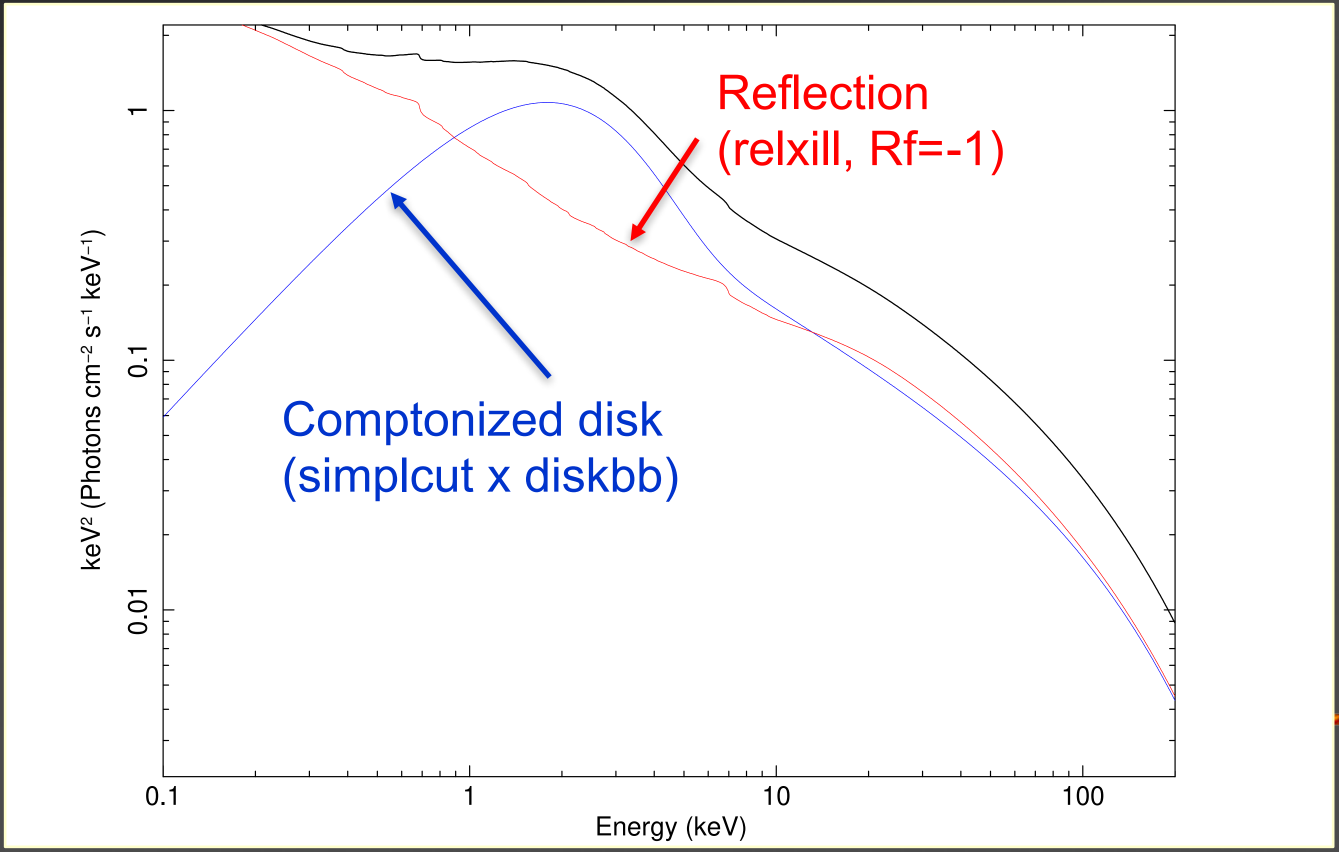
How about Reflection?

XRB Data Analysis Roadmap (here be dragons!)

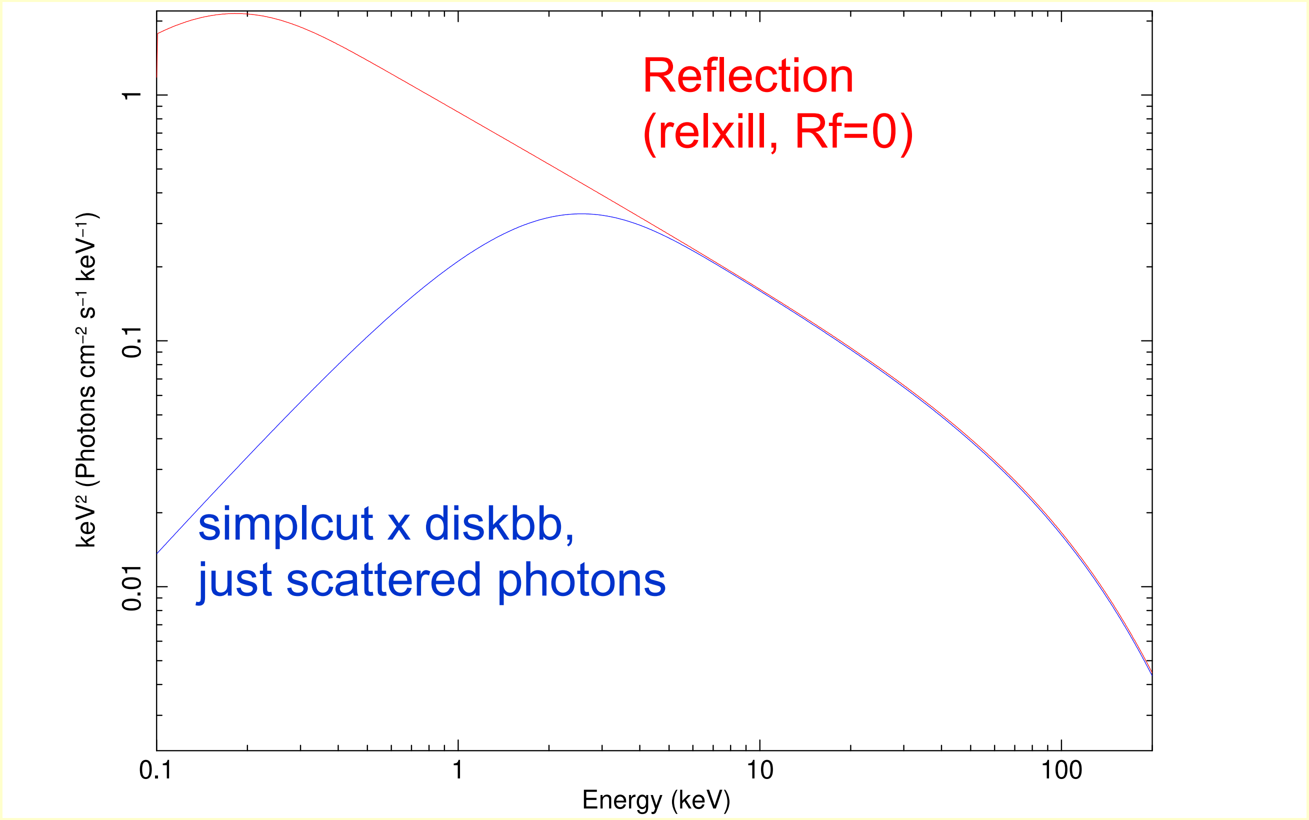
- New data in hand
- Fit with powerlaw
  - (not good enough…)
- Fit with diskbb+powerlaw
  - (reflection residuals!)
- **Fit with diskbb+relxill**
  - **(Pretty good fit, let's use this.)**

Reflection from a BH XRB

- Analogous issues with relxill *for XRBs only*, most problematic when disk is hot and/or power-law is steep.

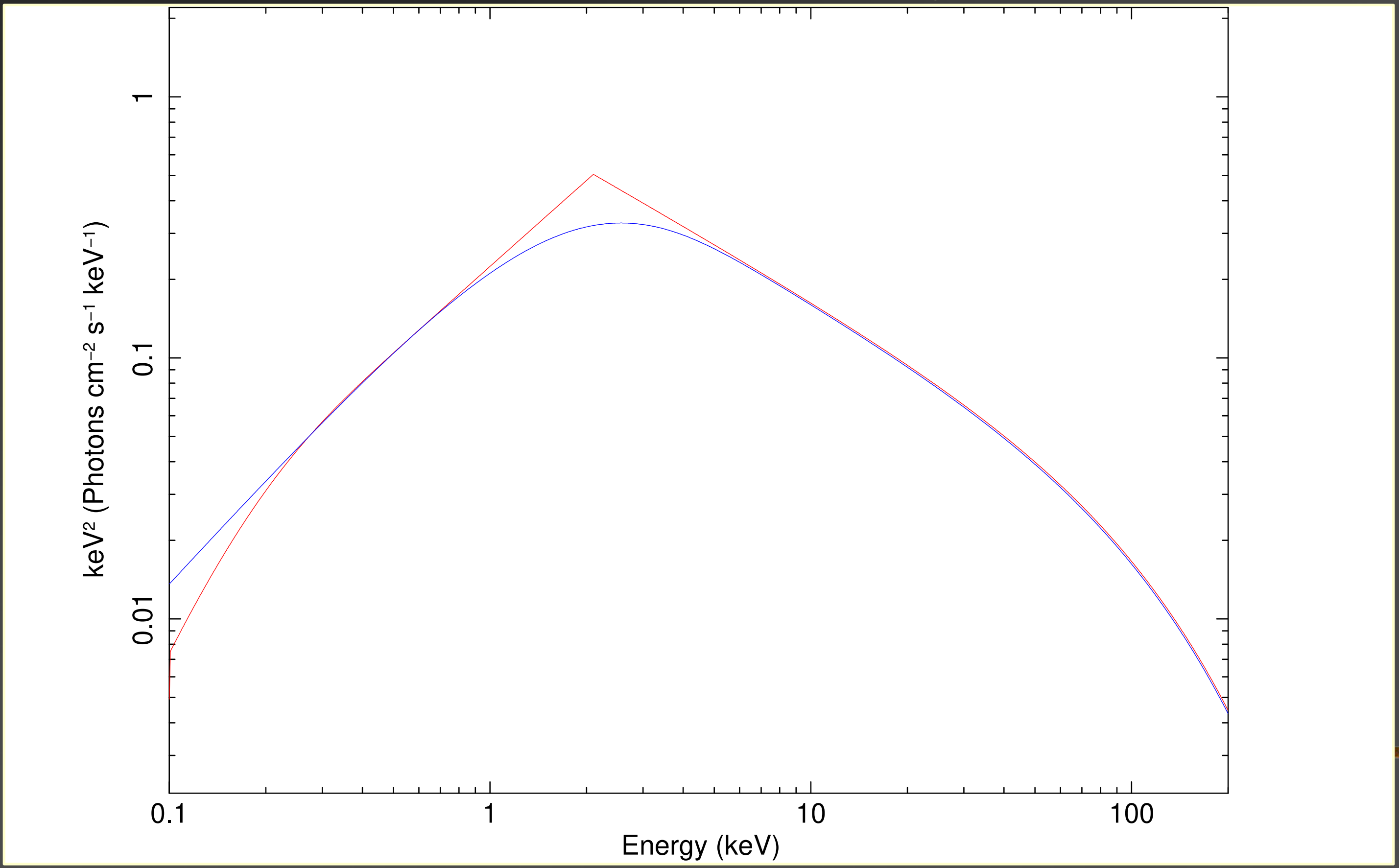


Assumed vs Actual Coronal Illumination of the Disk



What to do about this?

- ~~Produce a new code with thermal photons from beneath and self-consistently figure out the thermal, Compton, reflection pieces.~~
- Practical fix - chop off the reflection excess, thusly:



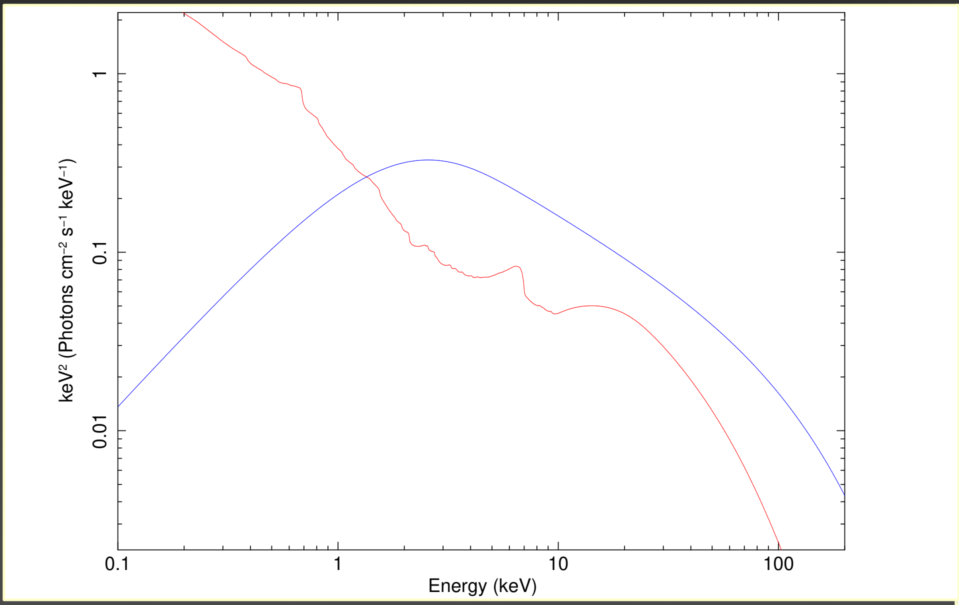
A practical hack

- **`Xspec command`**: `mdef mbknpo (max(E,B)-B)/abs(E-B+0.0000001)+(1-(max(E,B)-B)/abs(E-B+0.0000001))*(E/B)^I : mul`
- This multiplicative broken power-law reshapes the continuum between a break energy ”B” by index I.
  - In practice, can either fix B to be ~2.5 kT or potentially fit it in a range ~1.5-5 kT.
    - Precise value appears to differ a bit between diskbb and kerrbb (different continuum shapes after all…), and a bit with Gamma
  - Best value for I seems to be Gamma-0.8
    - I would freeze this parameter – not fit it!
  - (Easy to check with plots like on the last page that index and peak are reasonably matched)
- Punchline: Adds one or zero more free parameters, but makes the continuum match reality a hell of a lot better

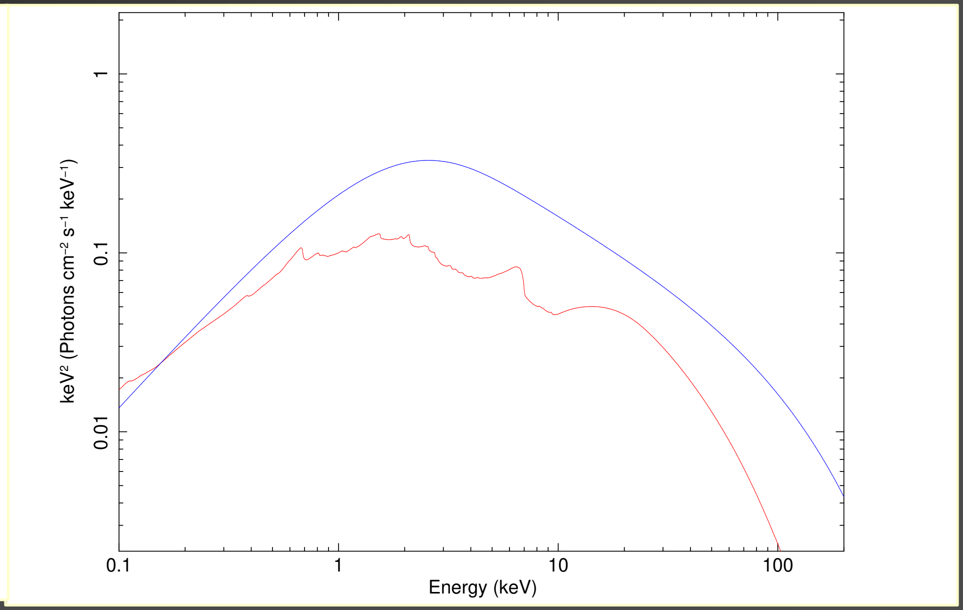
- **Federico Garcia was exploring the same issue and came up with a similar approach to this; his method is a bit more sophisticated than mine.**

The (unscattered) reflection prediction compared to the Compton continuum

Before: simplcutx(diskbb) + relxillCp

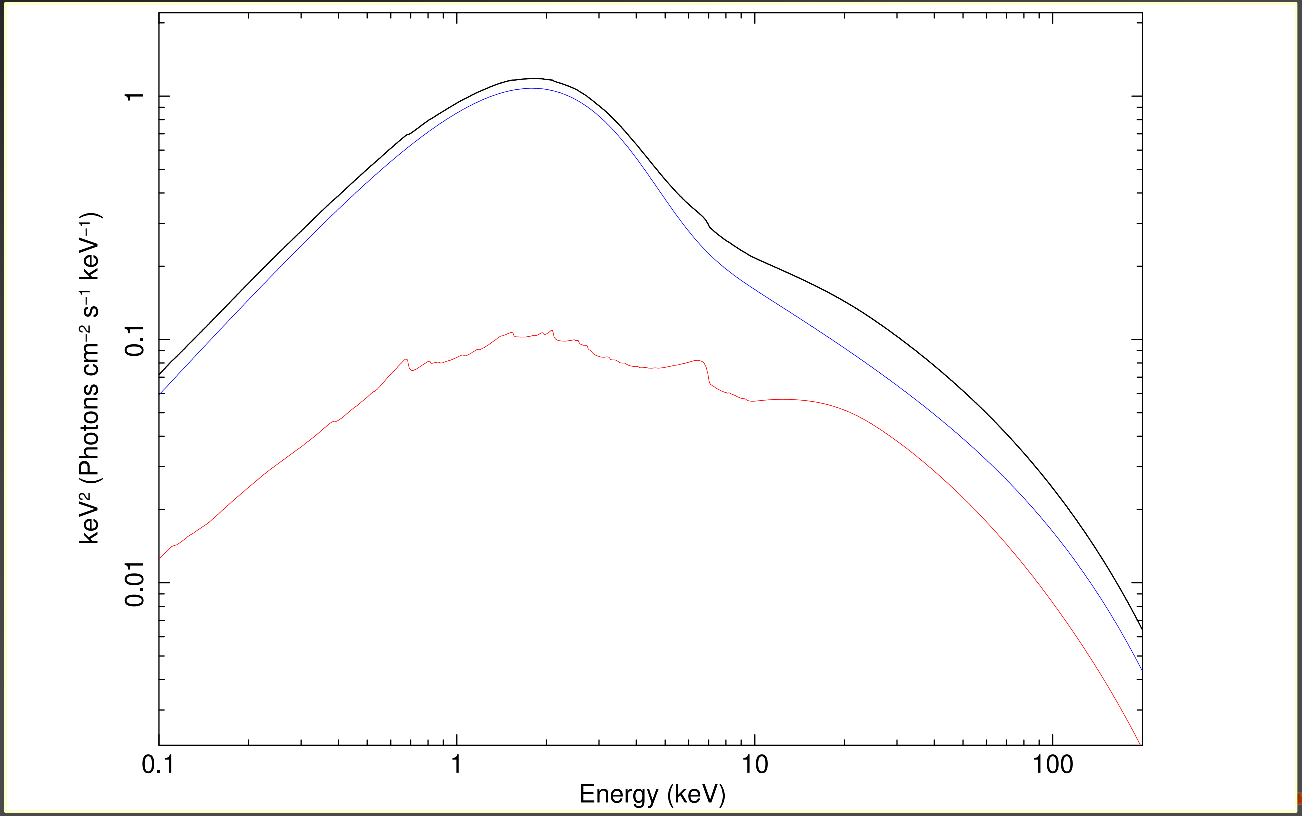


After: simplcutx(diskbb) + mbknpo*relxillCp



The net result:

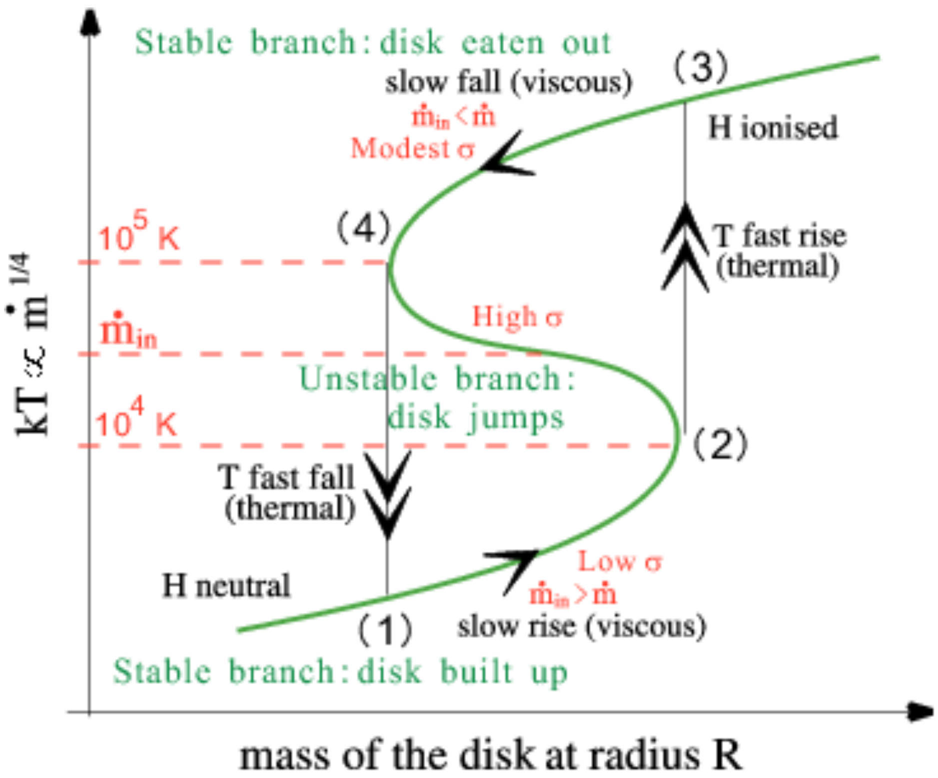
- simplcut (diskbb + mbknpo*relxillCp)



Part 2 Takeaway

- Basics of LF QPOs in BHs
- Familiarity with how BH spins are measured
  - Nature produces stellar-BHs with spins from 0 to 1
- Familiarity with some of the zoo of NS sources
- Spectral fitting suggestion
  - Watch out for runaway or unphysical model behavior
  - Opt for self-consistent models when its easy to do so.
  - Important to curtail powerlaw runaway below kT_{seed} for Comptonization.

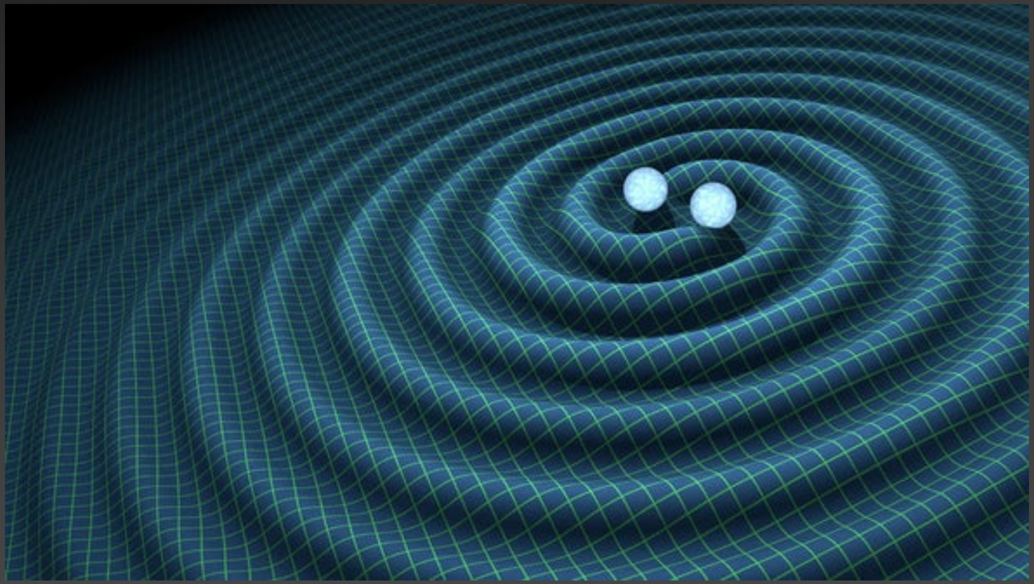
Extra Slides

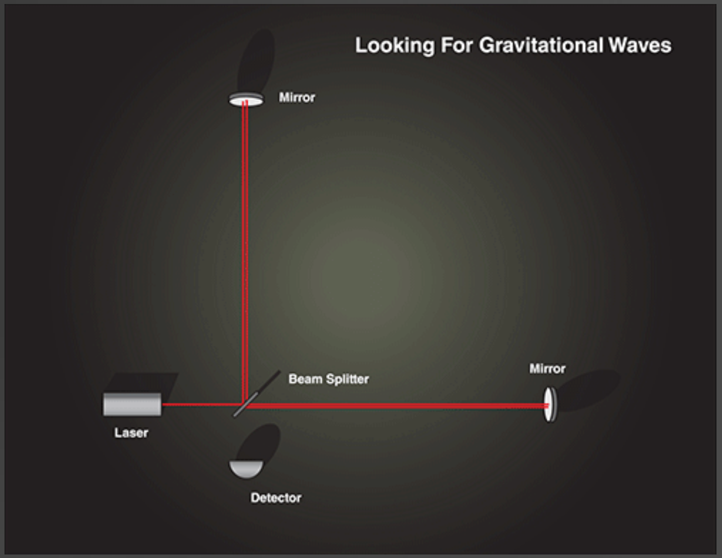


Zhang 2013 review article; idea due to Meyer & Meyer-Hofmeister 1981, transition from convective at low mdot to radiative at high mdot

∝

Gravitational Waves – LIGO & VIRGO





"Equivalent to measuring the distance to the nearest star (some 4.2 light years away) to an accuracy smaller than the width of a human hair!"

LIGO / GW BHs


Masses in the Stellar Graveyard
in Solar Masses
160
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
LIGO-Virgo Neutron Stars