Continuum-Fitting of Spinning (Stellar-Mass) Black Holes with STROBE-X

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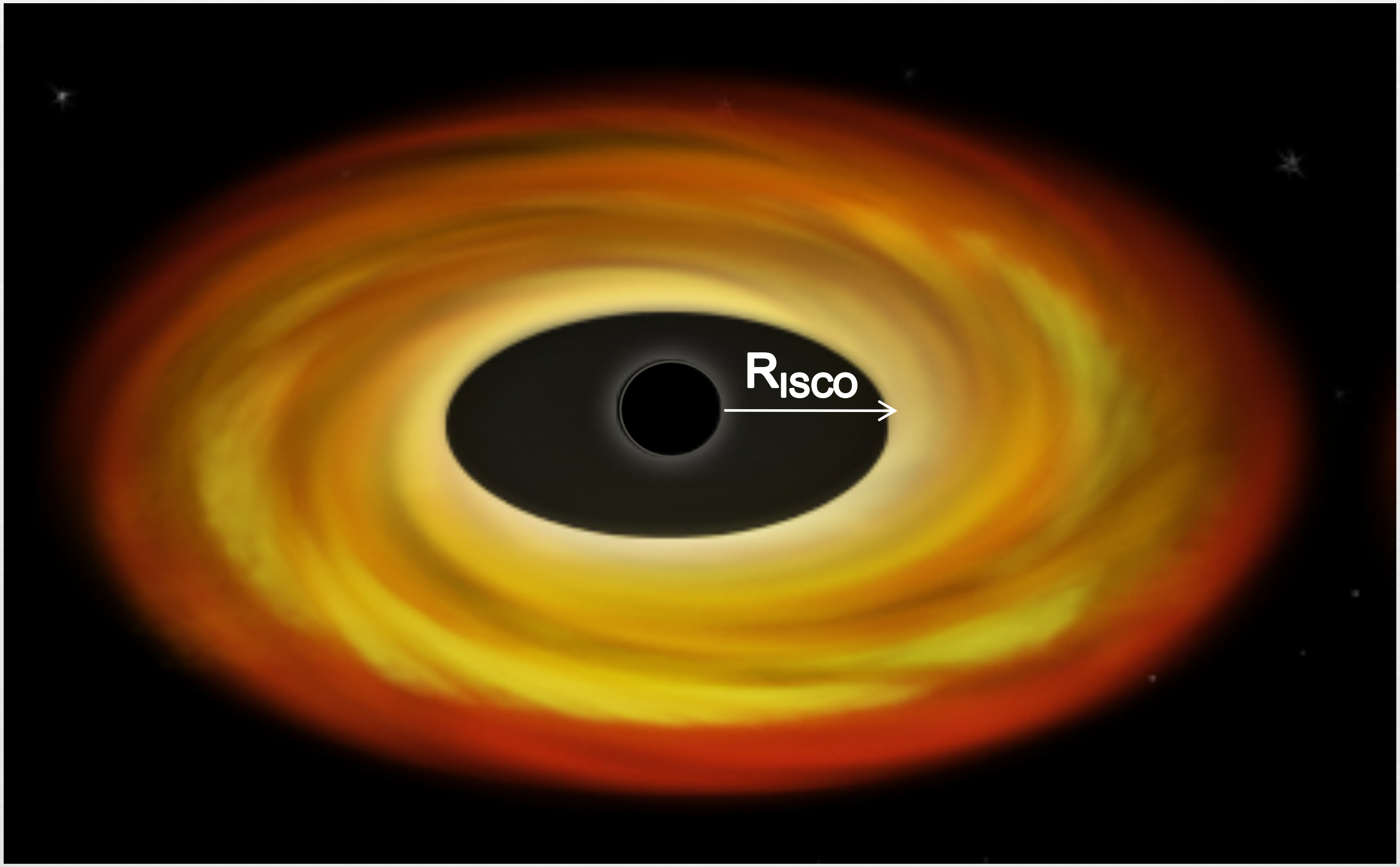
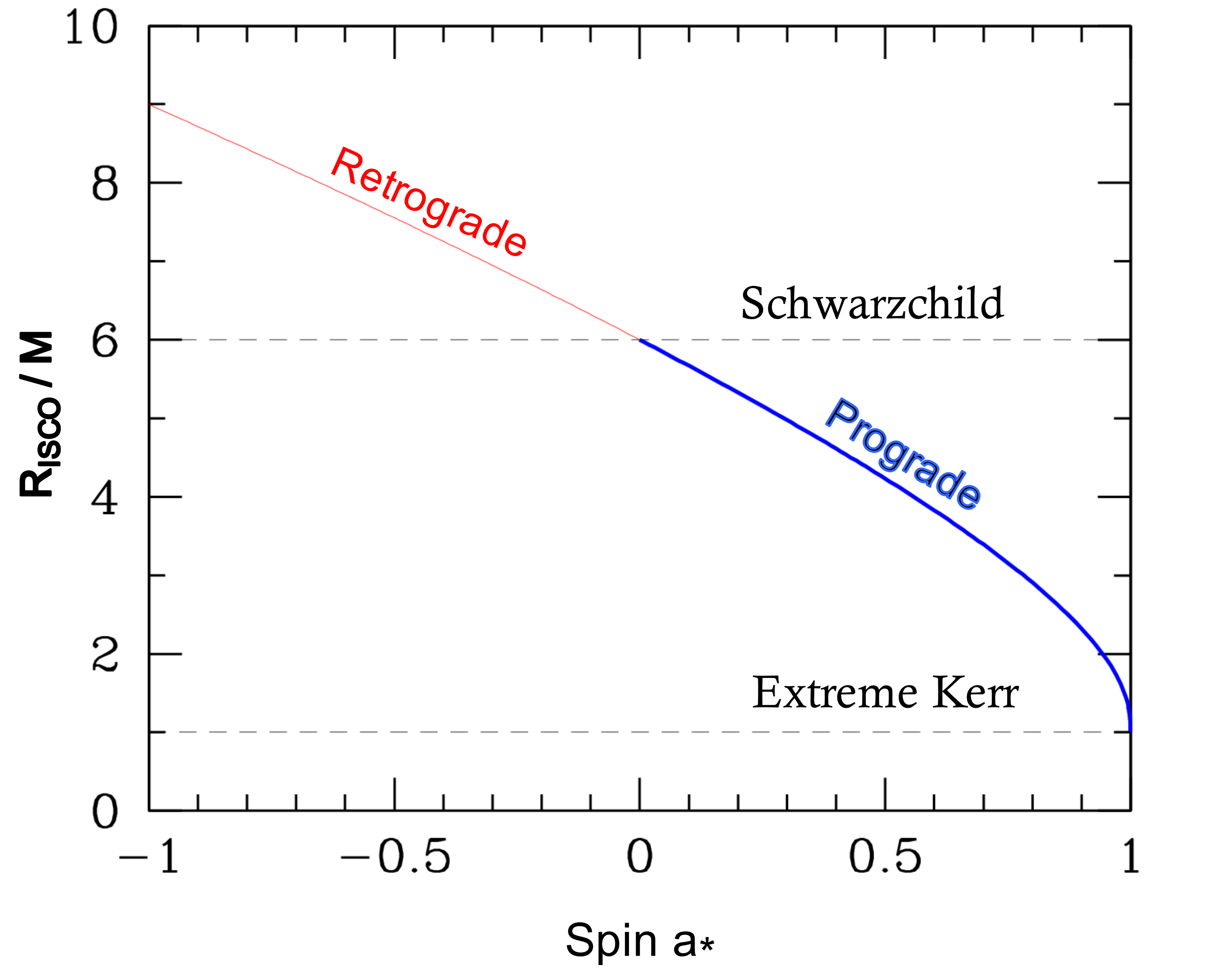
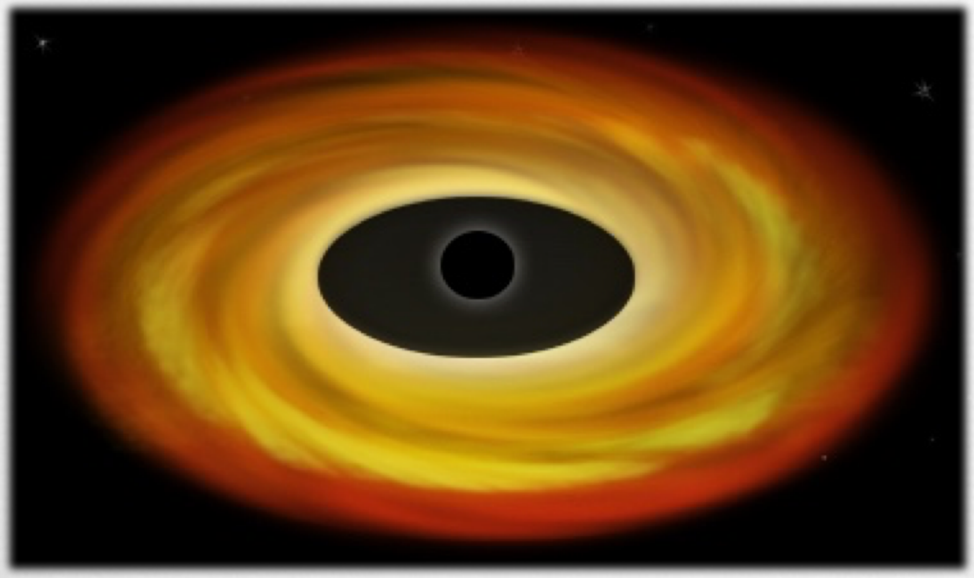
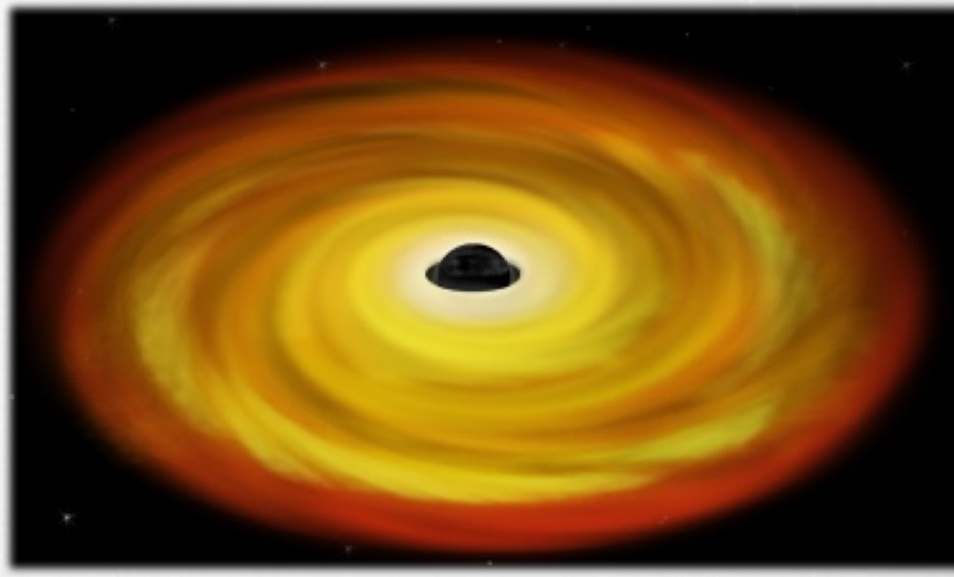
Measuring the Inner Disk Radius



Radius of ISCO versus Spin







$a_* = 0$

$R_{ISCO} = 6M\ G/c^2$

(90 km)

for $M = 10\ M_\odot$

$a_* = 1$

$R_{ISCO} = 1M\ G/c^2$

(15 km)

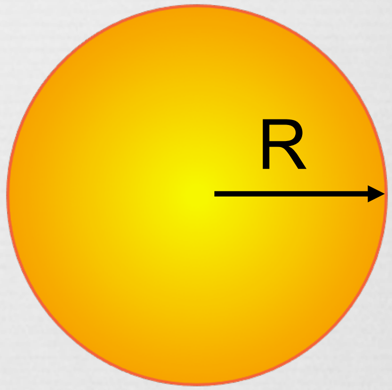
Continuum Fitting

(Zhang, Cui, & Chen 1997)

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)

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



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

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

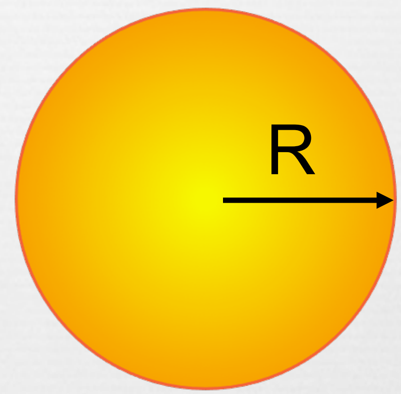
Measuring R_{ISCO}

Radius R of a Star

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

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

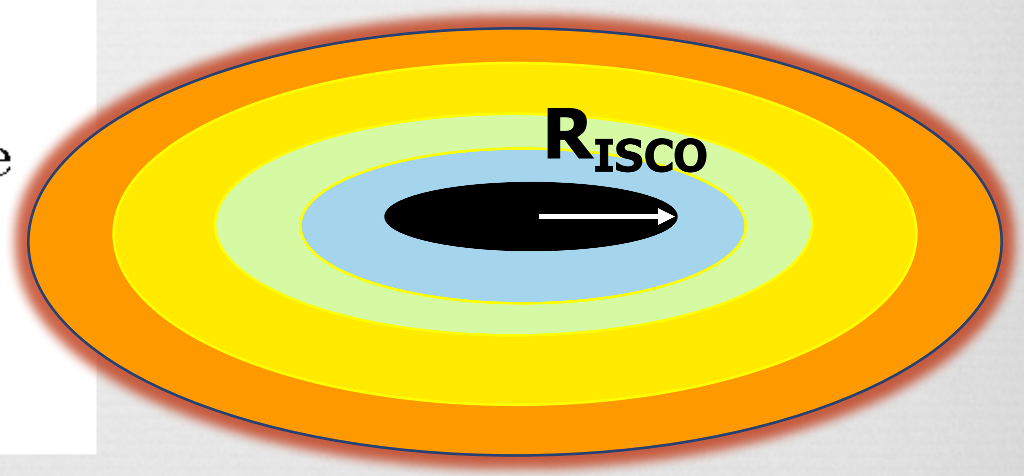
$D \rightarrow$ R



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

F and $T \rightarrow$ solid angle

D and $i \rightarrow R_{ISCO}$



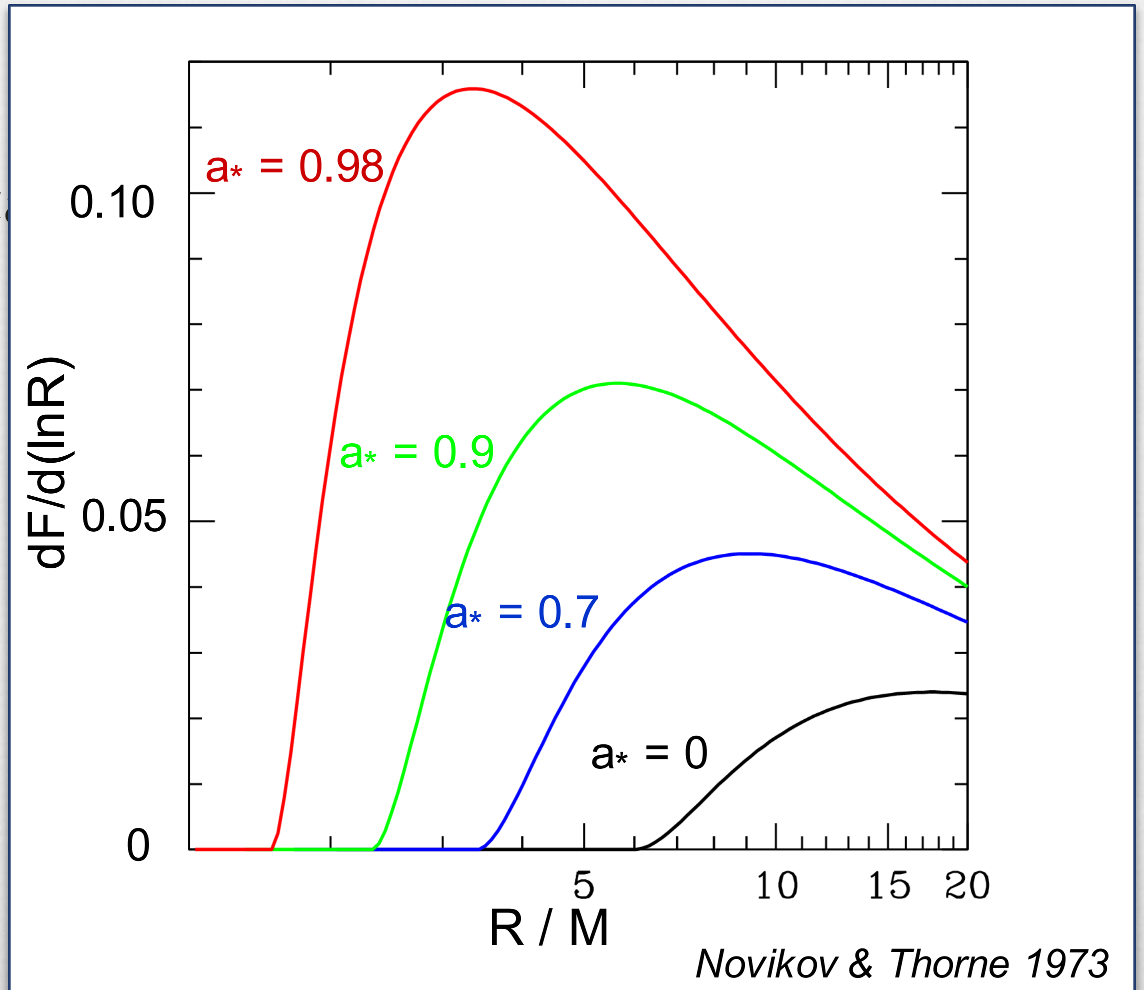
R_{ISCO} and **M** $\longrightarrow$ a_*

Requirements for the X-ray Continuum Fitting Method

Zhang, Cui & Chen 1997

- Spectrum dominated by **accretion disk component**

- Theoretic

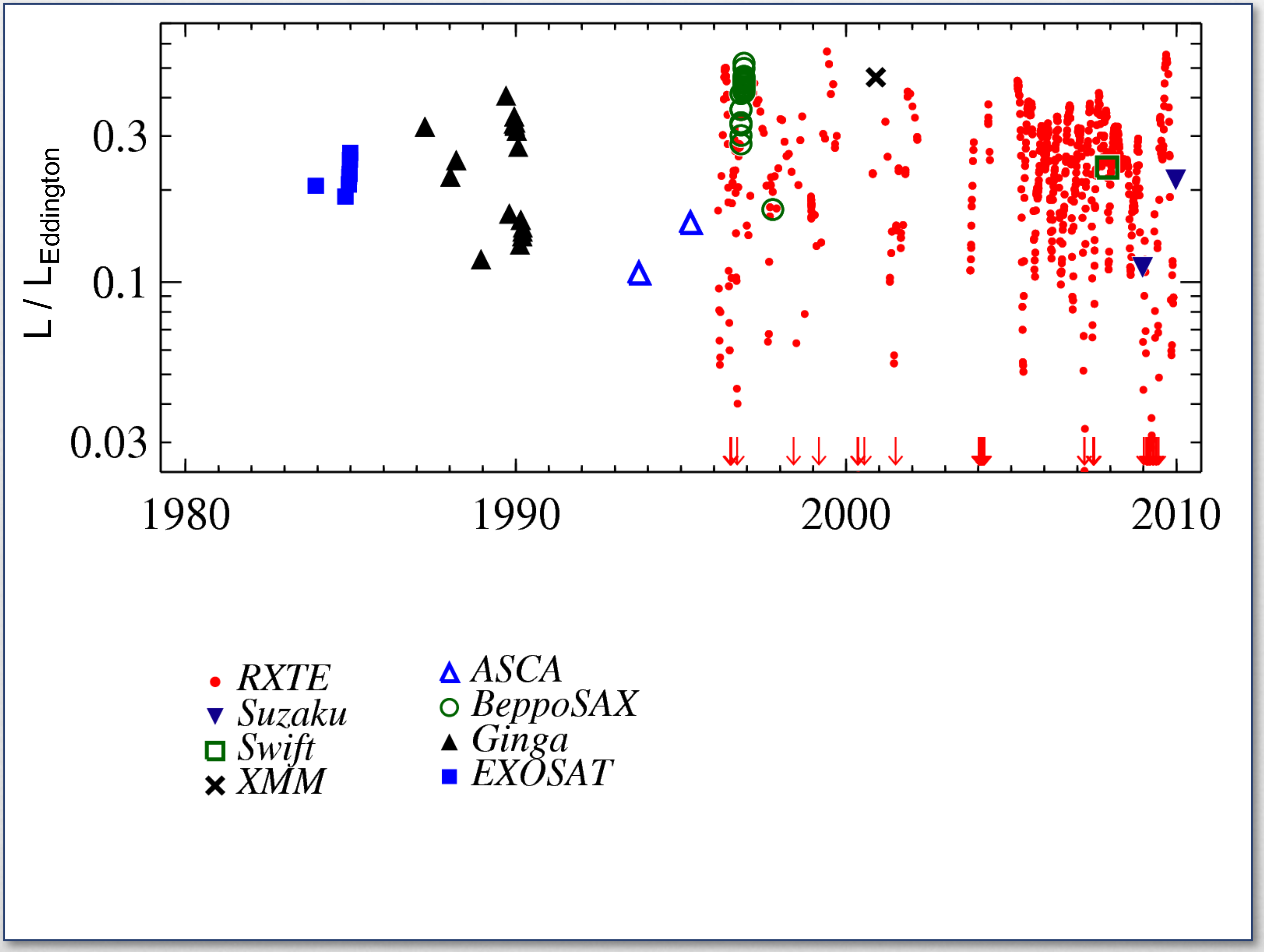


How Well Does it Work in Practice?

- Extremely well
- Multiple independent observations of the same BH
  - at different luminosities (up to 30% $L_{Eddington}$)
  - with different instruments
  - separated by many years

LMC X-3: 1983-2009

Steiner et al. 2010



LMC X-3: 1983-2009

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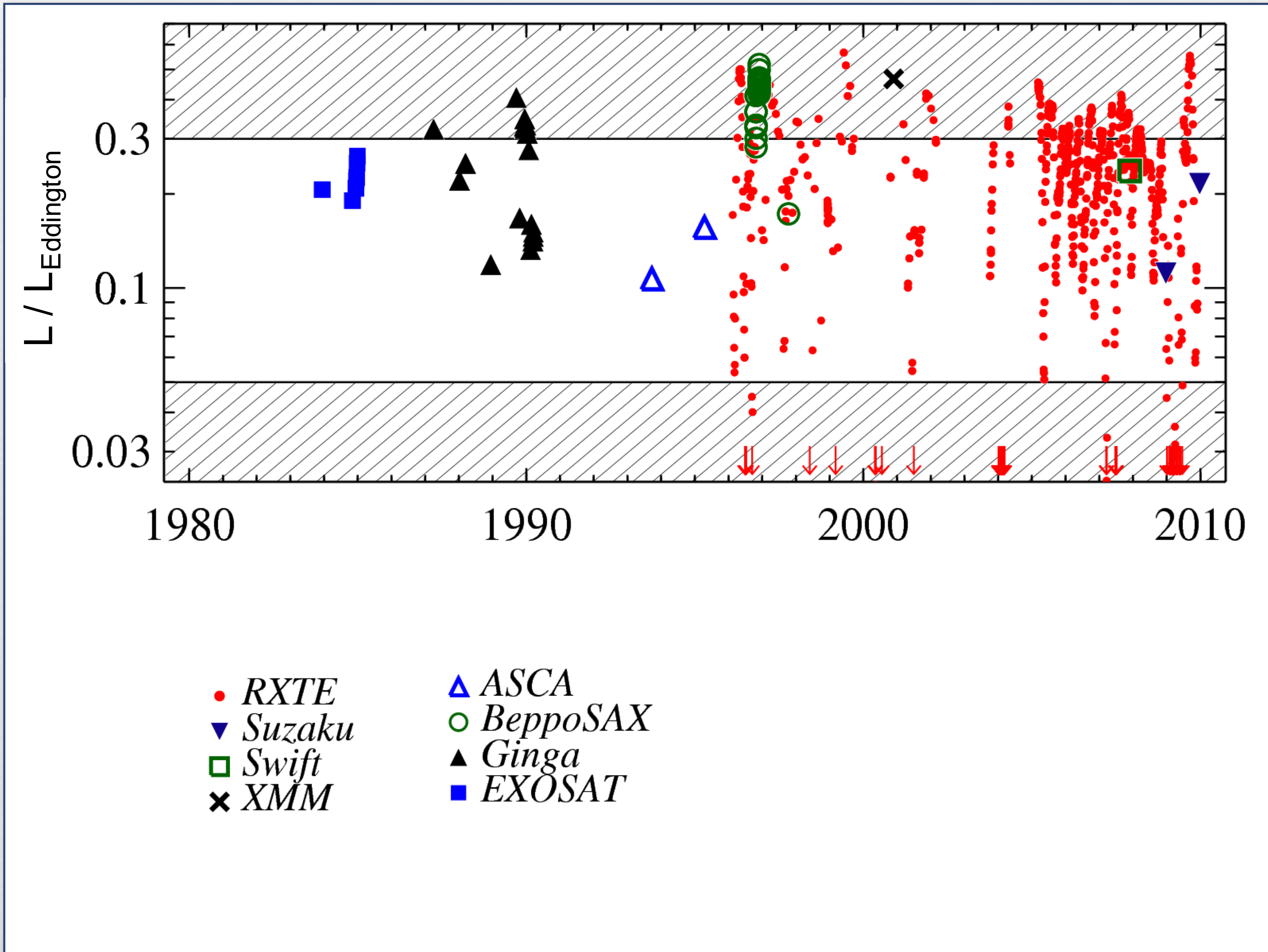

LMC X-3: 1983-2009

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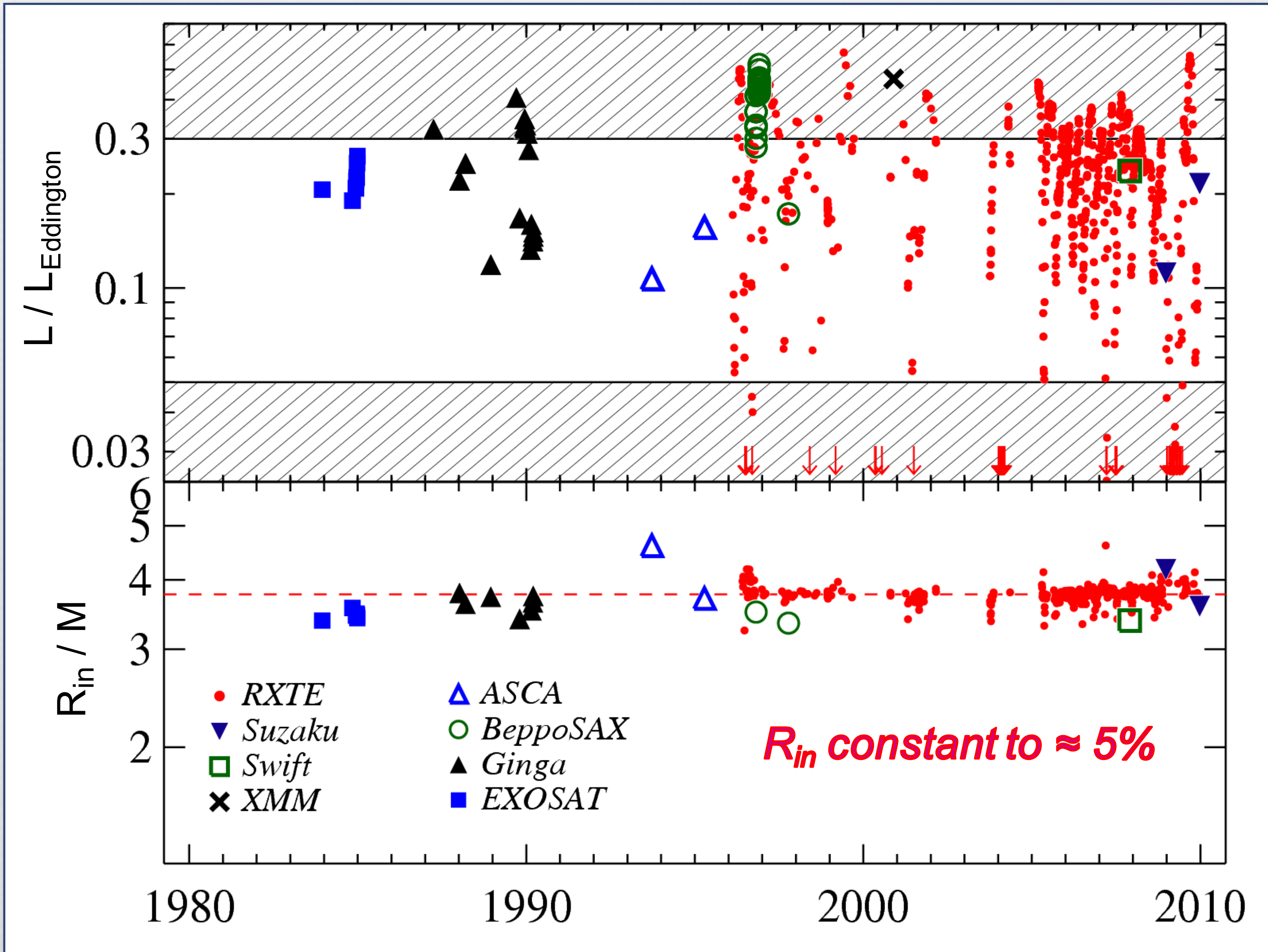
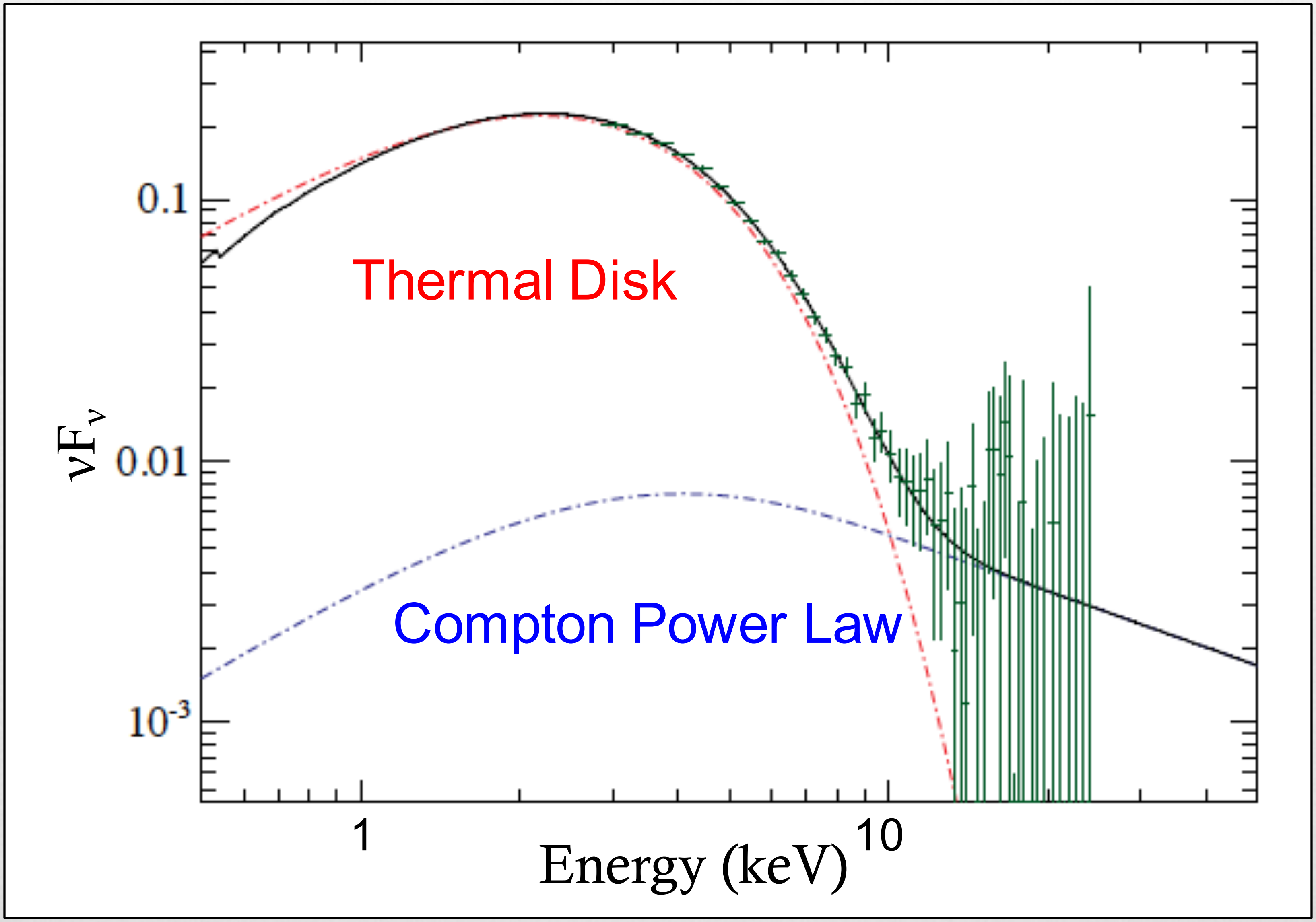
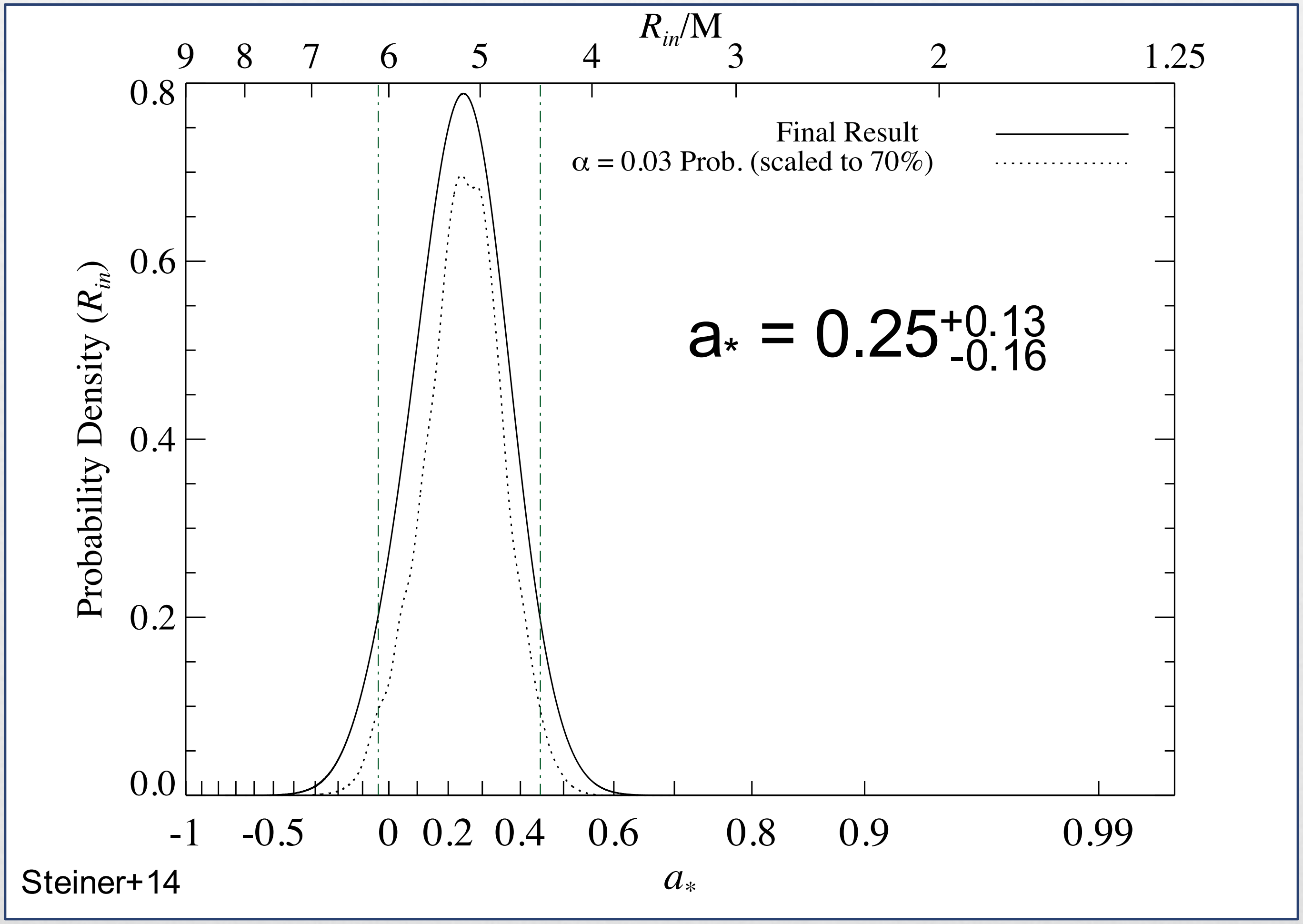


Using many *spectra* like this:

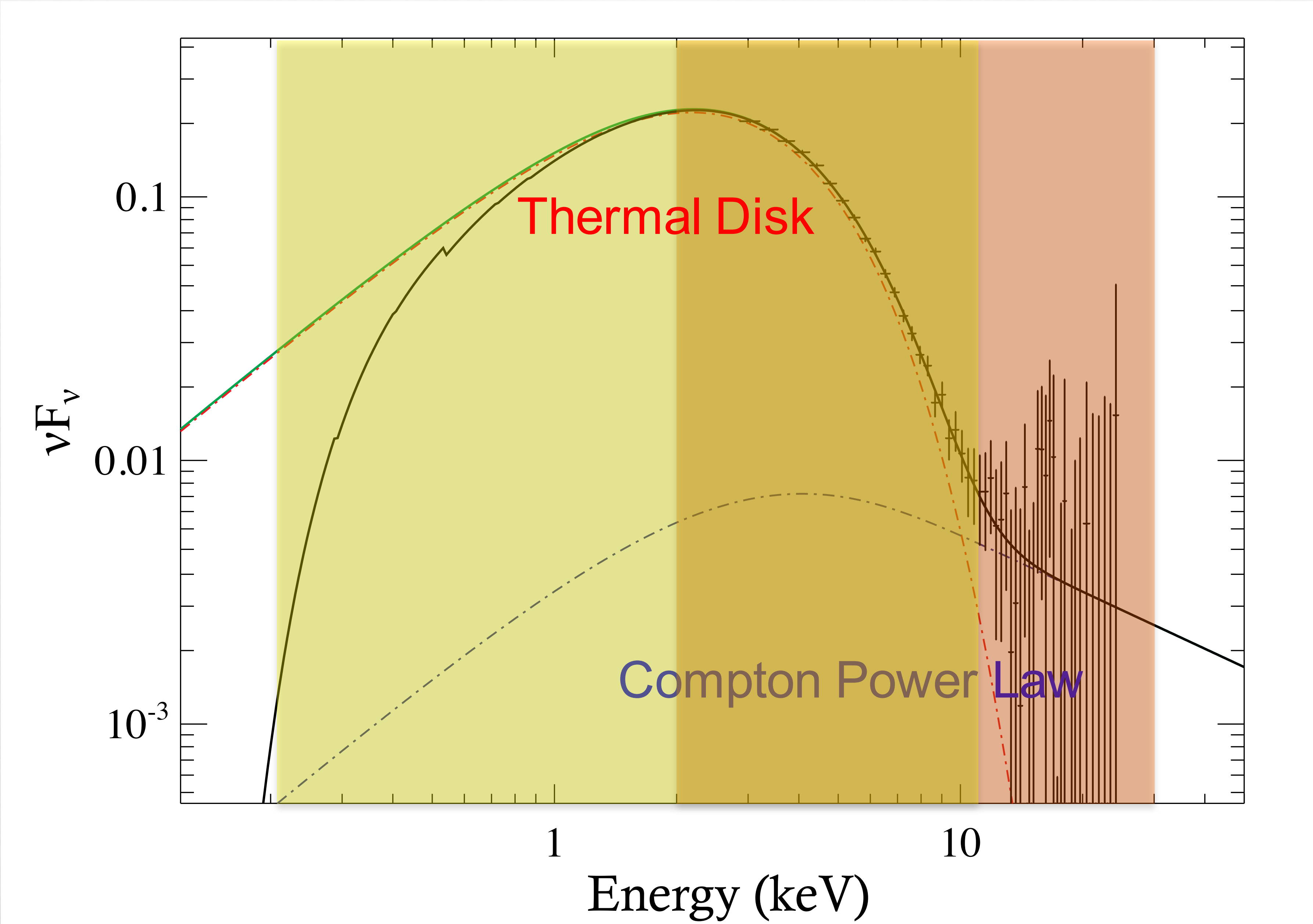


Get Spin (LMC X-3)

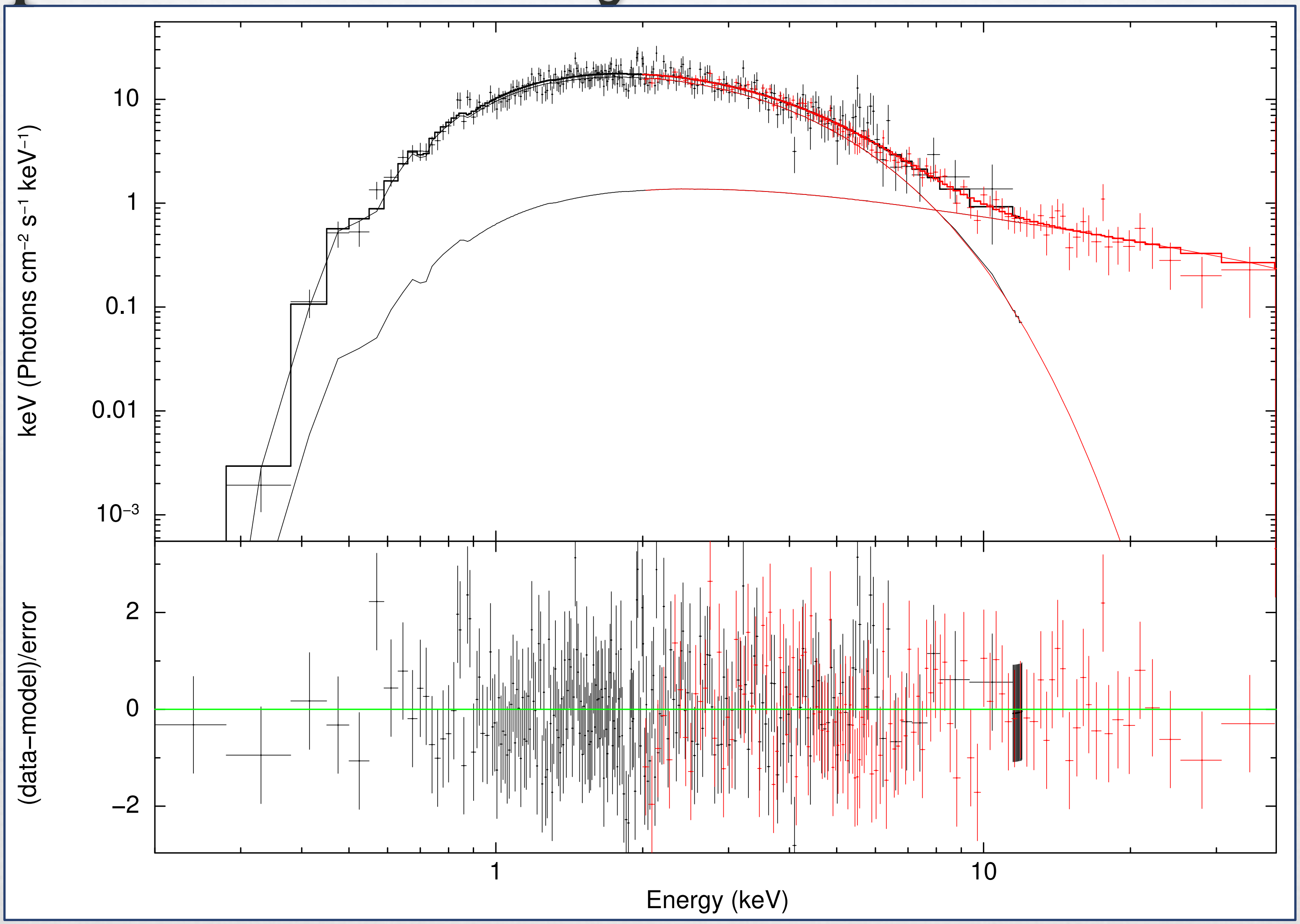


A STROBE-X Perspective

STROBE-X's view of the thermal state



STROBE-X
spectra on a dynamical timescale!

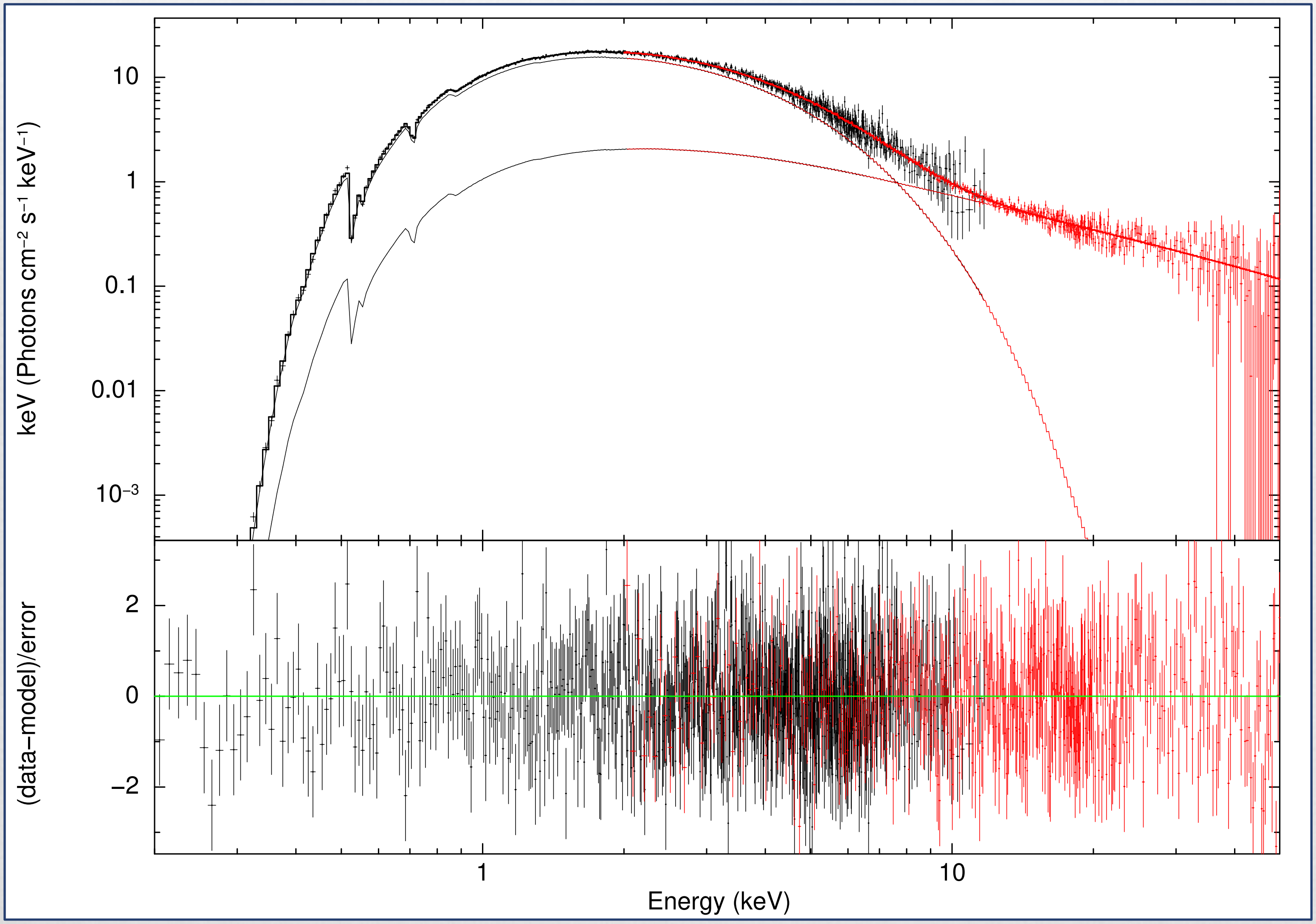


3 Crab
15kCnt
0.01s(!)

Reaching Fundamental Timescales

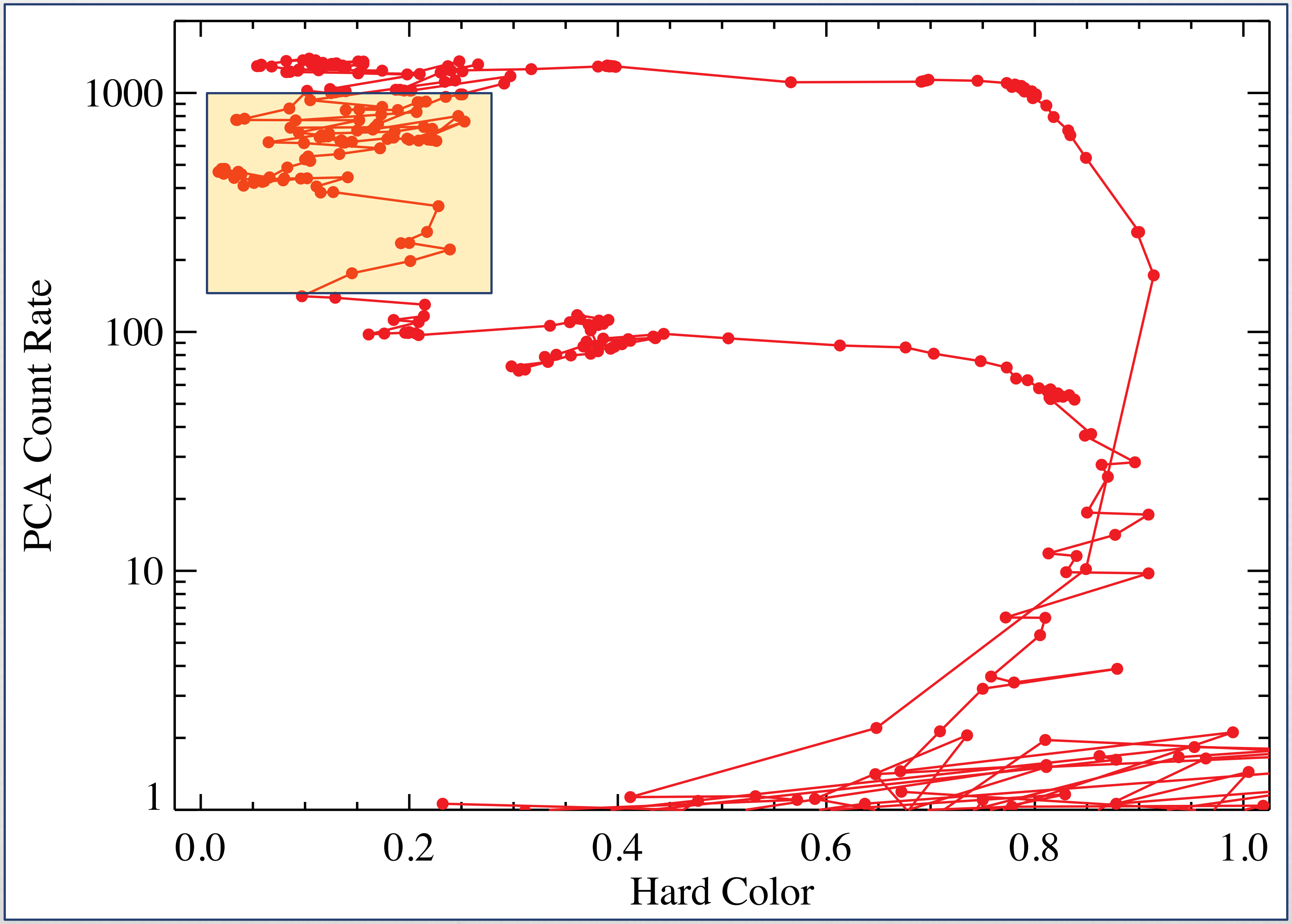
- NICER gets a ~10% disk radius each second (the viscous timescale)
- **STROBE-X obtains a ~10% disk radius each 10^{-2}s for a bright BH (orbital timescale at 10 Rg).**
- Enables phase-resolved spectroscopy of a HFQPO
- Can map disk structure at the viscous timescale

Viscous timescale (peeking under the hood of CF)

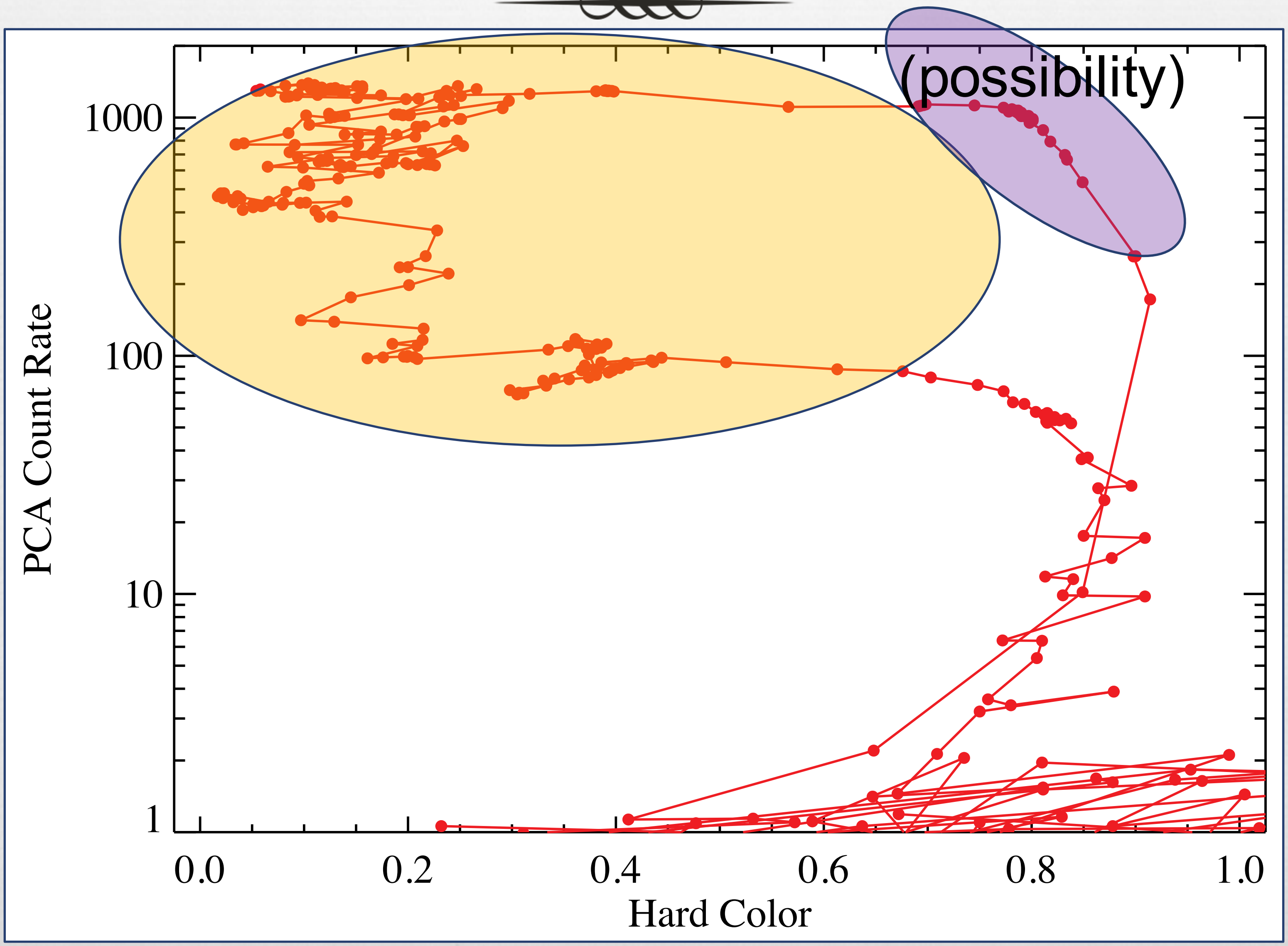


3 Crab
1.5MCnt
1s

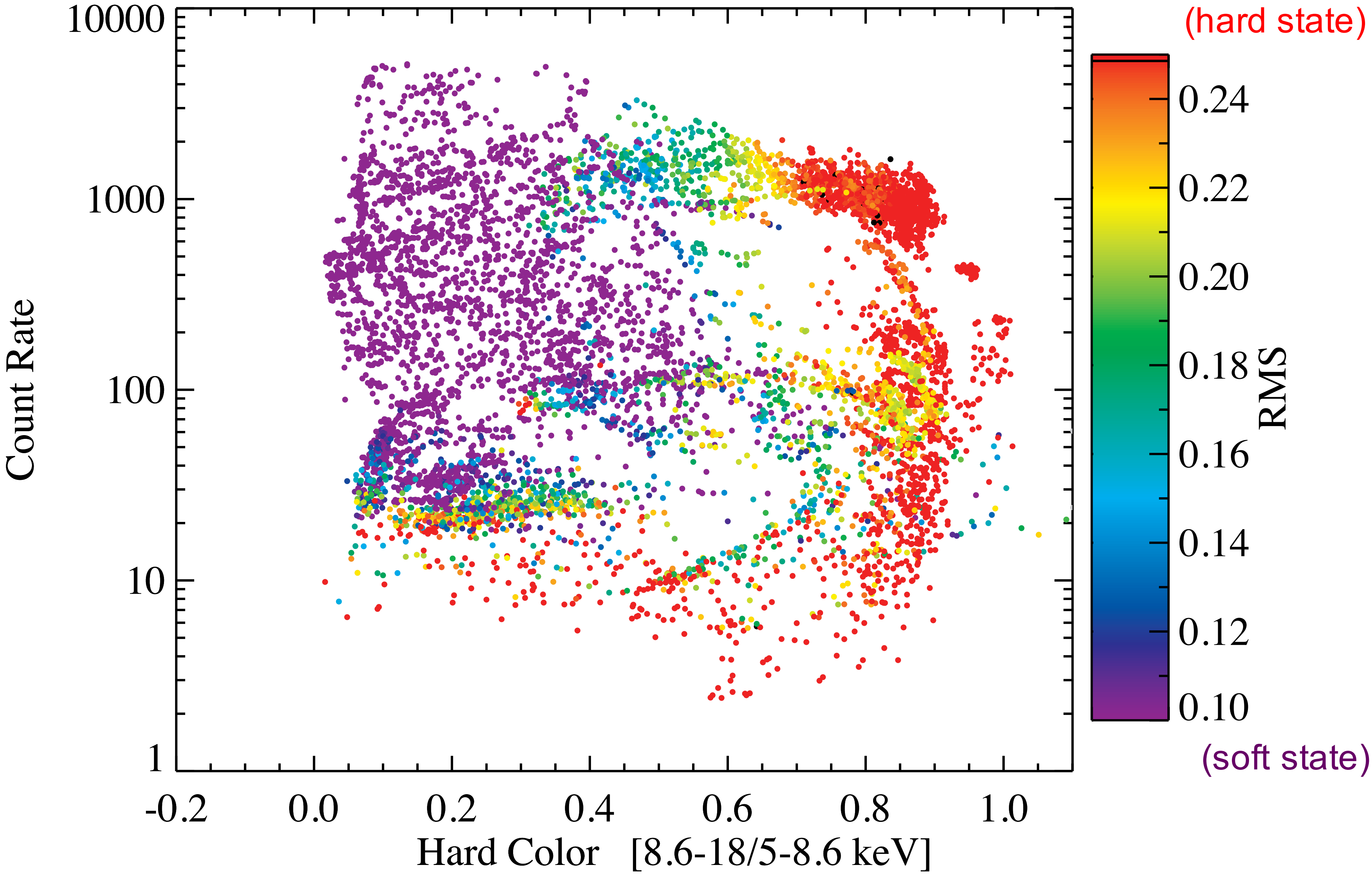
Continuum Fitting in Practice



Continuum Fitting++ with STROBE-X



The RXTE Road Map

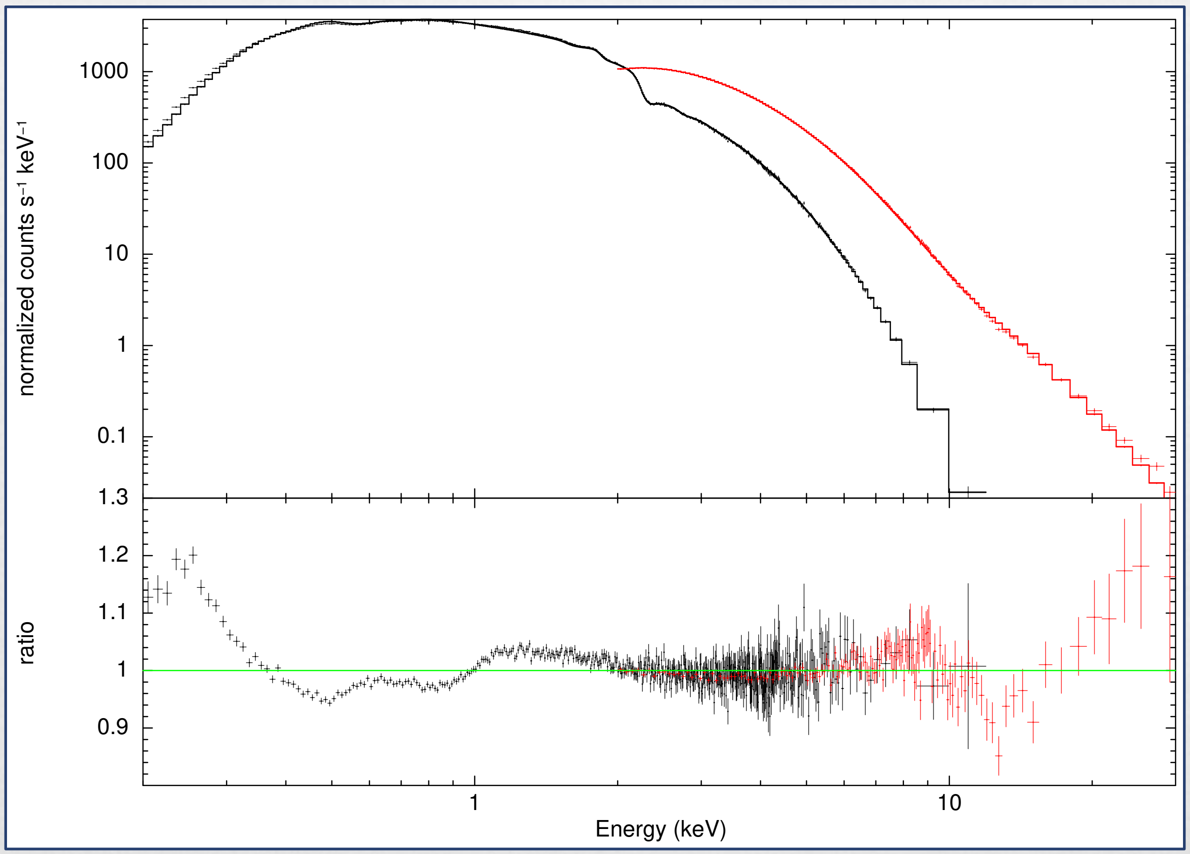


How to get there? (in outline)

- Empirical tests of disk spectrum
- Establishing disk evolution beyond ”thin” limit
- Bright-hard state: Truncation? Variability confounding? Extending self-consistent modeling?

Testing Disk Structure

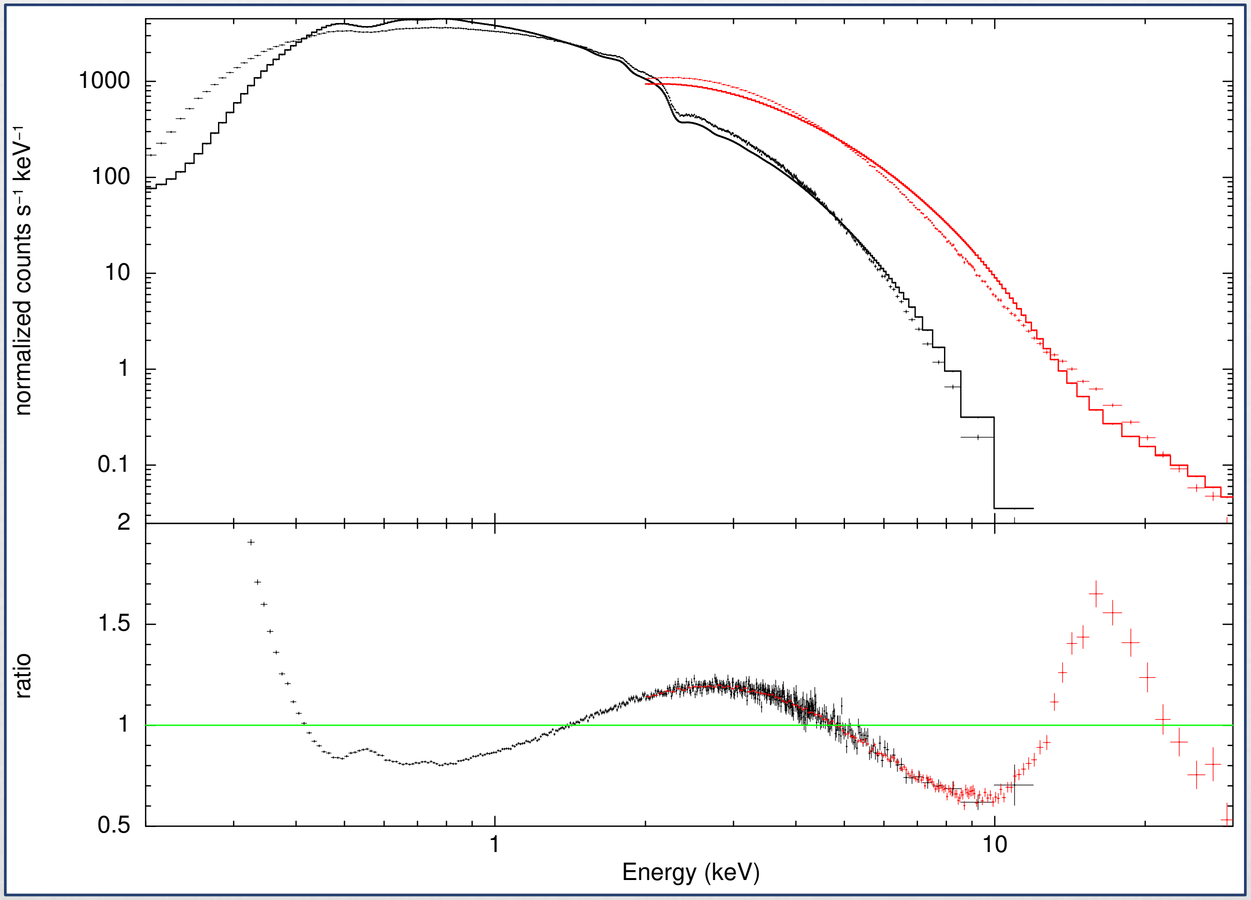
- NonLTE effects (atomic edges, electron scattering, etc.)



LMC X-3
(10 mCrab)
8 MCnt
1ks

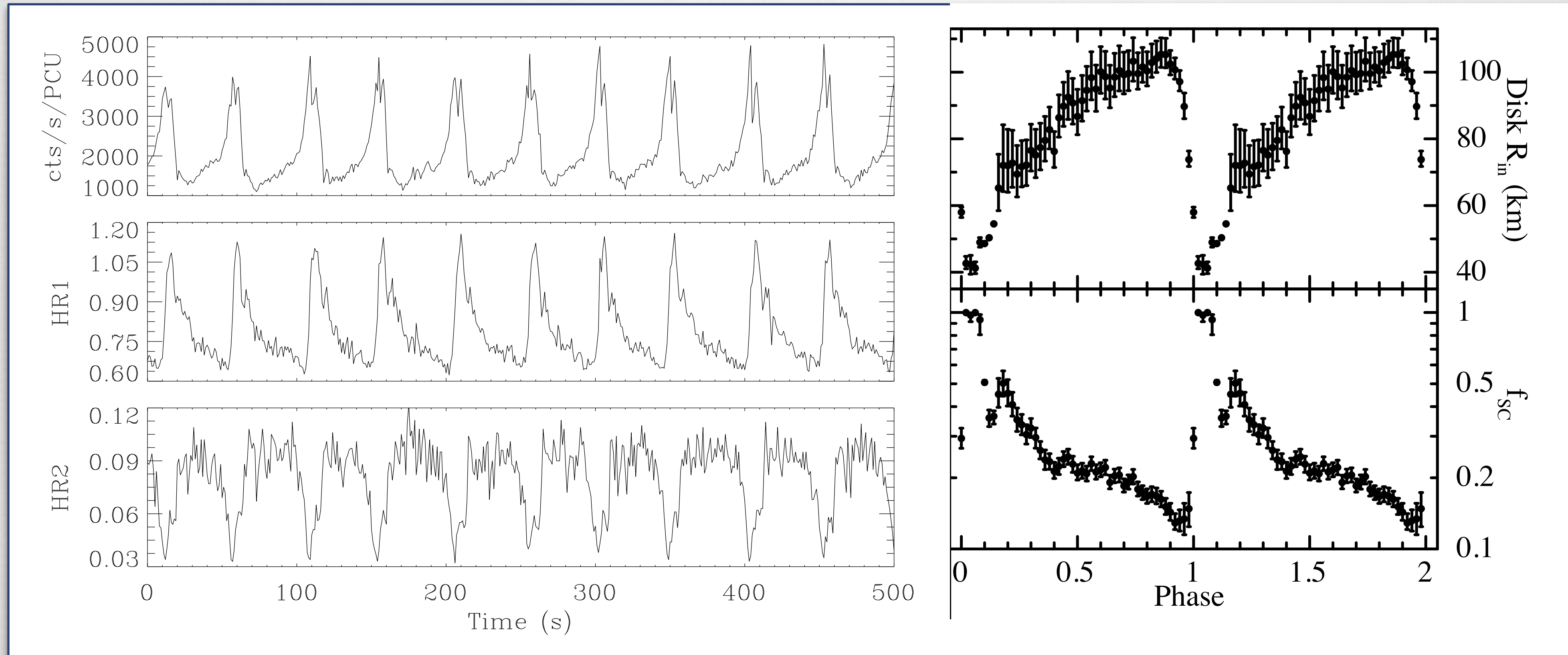
Testing Disk Structure

- Can directly test for slim disk departure from thin-disk models with growing luminosity



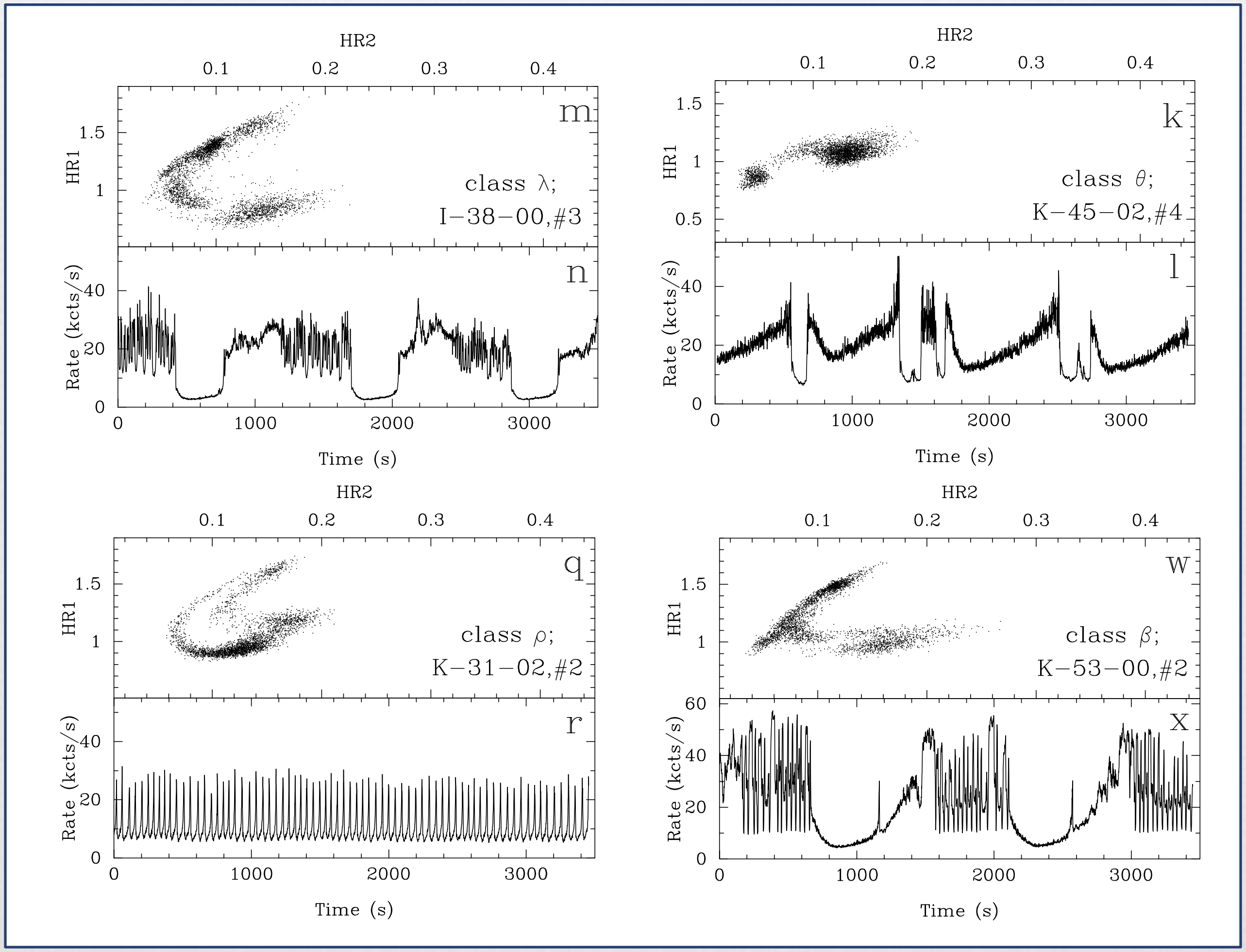
LMC X-3
(10 mCrab)
8 MCnt
1ks

Examining Accretion Instabilities



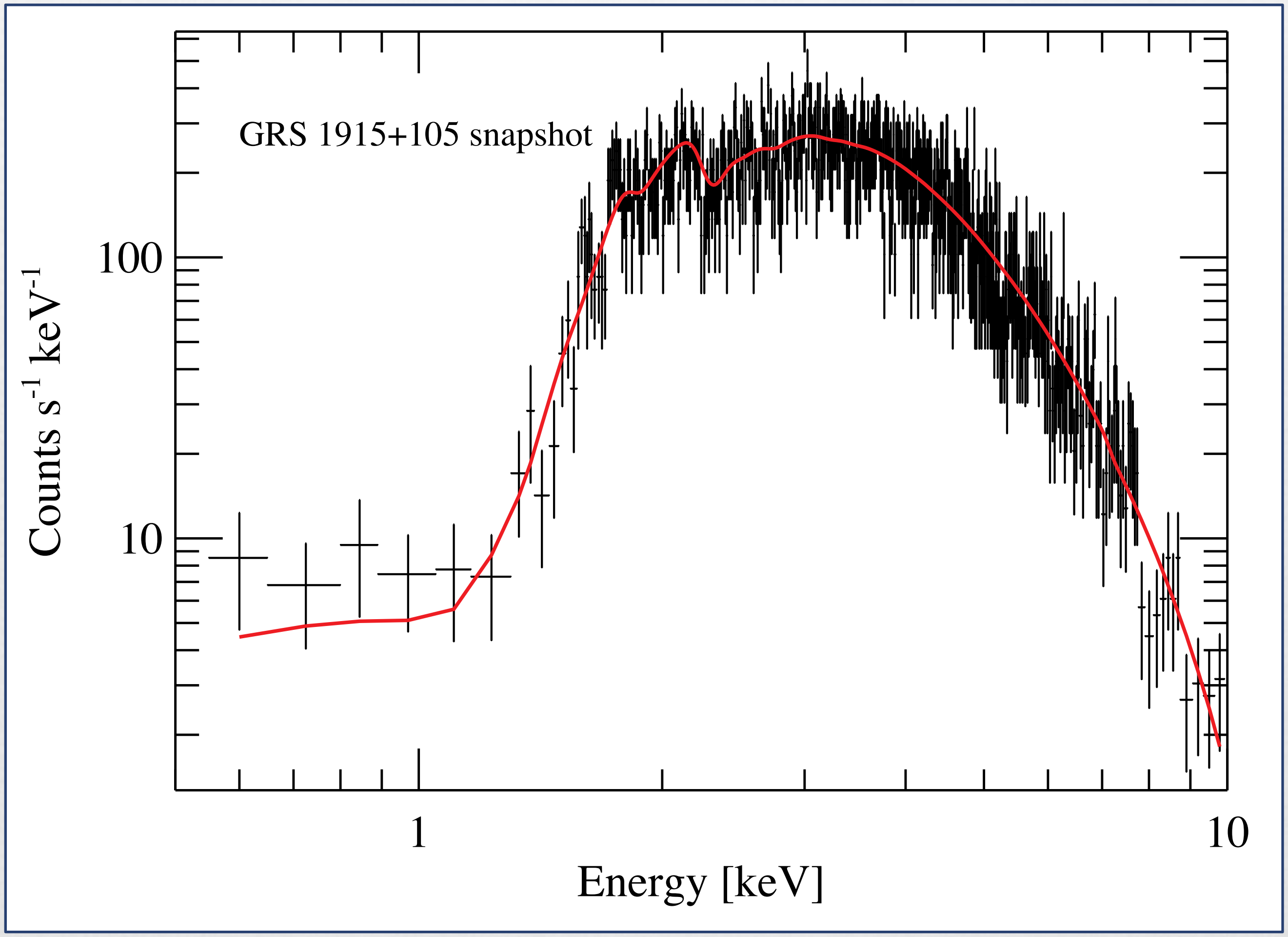
GRS 1915+105 Heartbeats (Neilsen+2011)

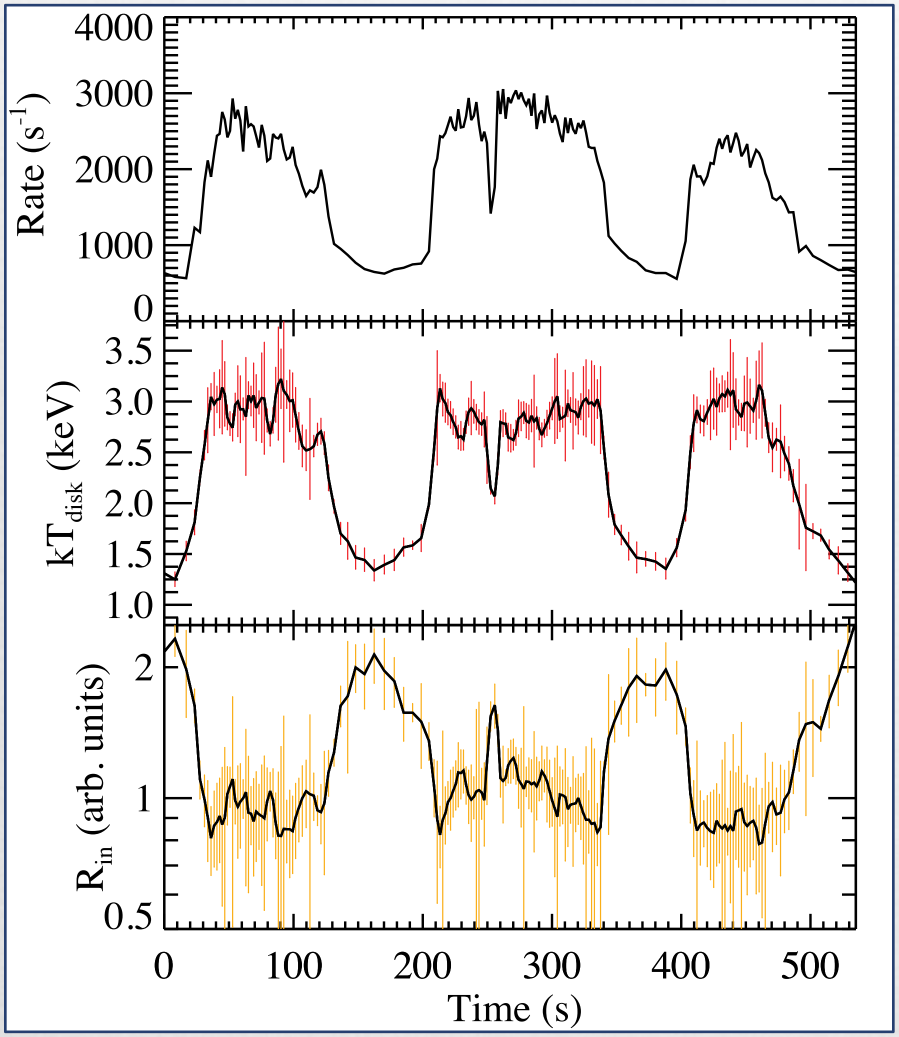
GRS 1915+105 variable modes



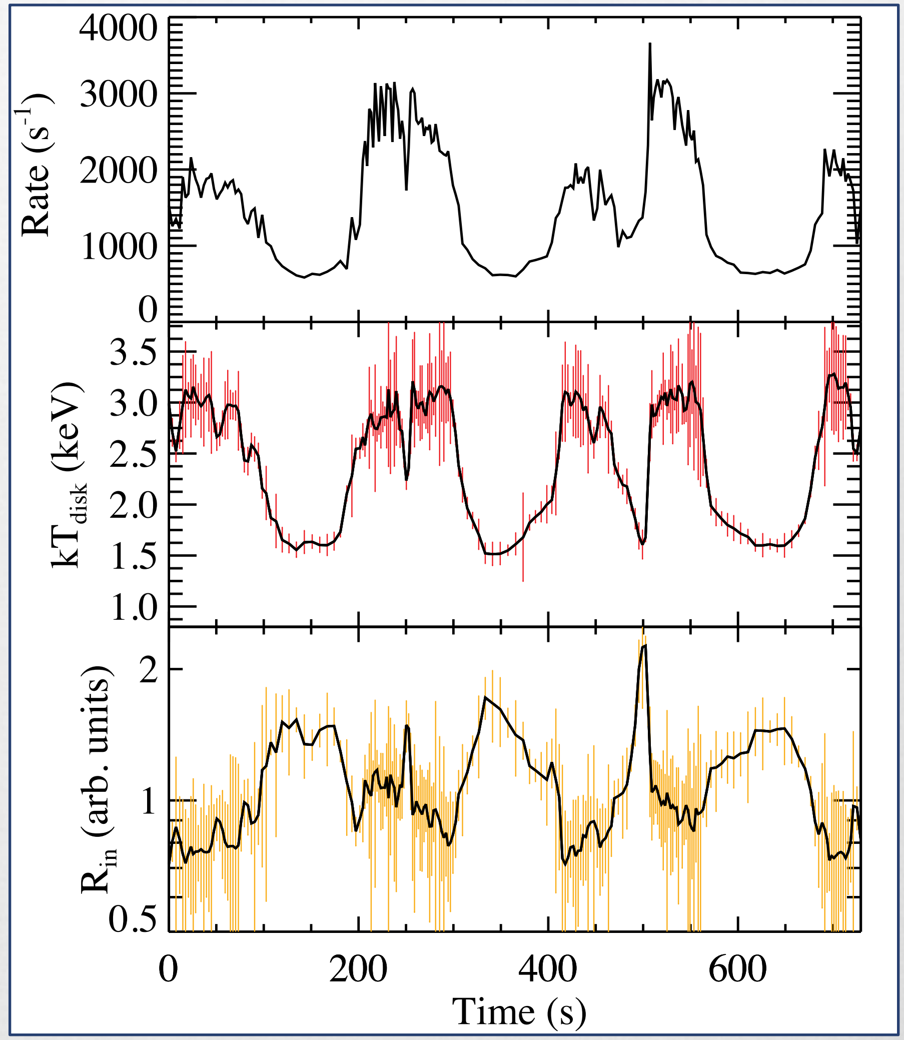
Belloni+2000

GRS 1915+105 in 3s with NICER (5000 cts)



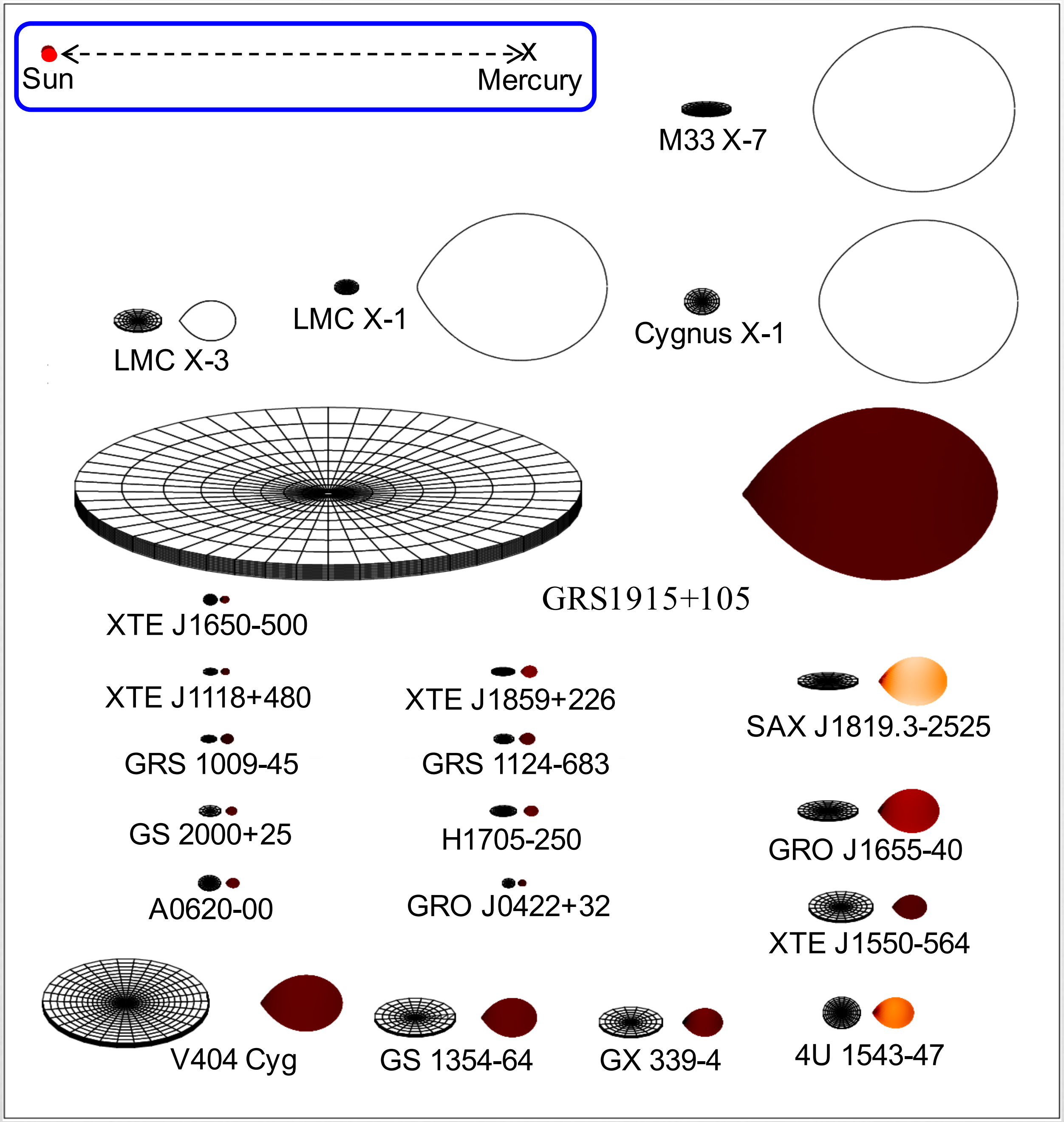


Rate (s^-1)
kT_disk (keV)
R_in (arb. units)
Time (s)



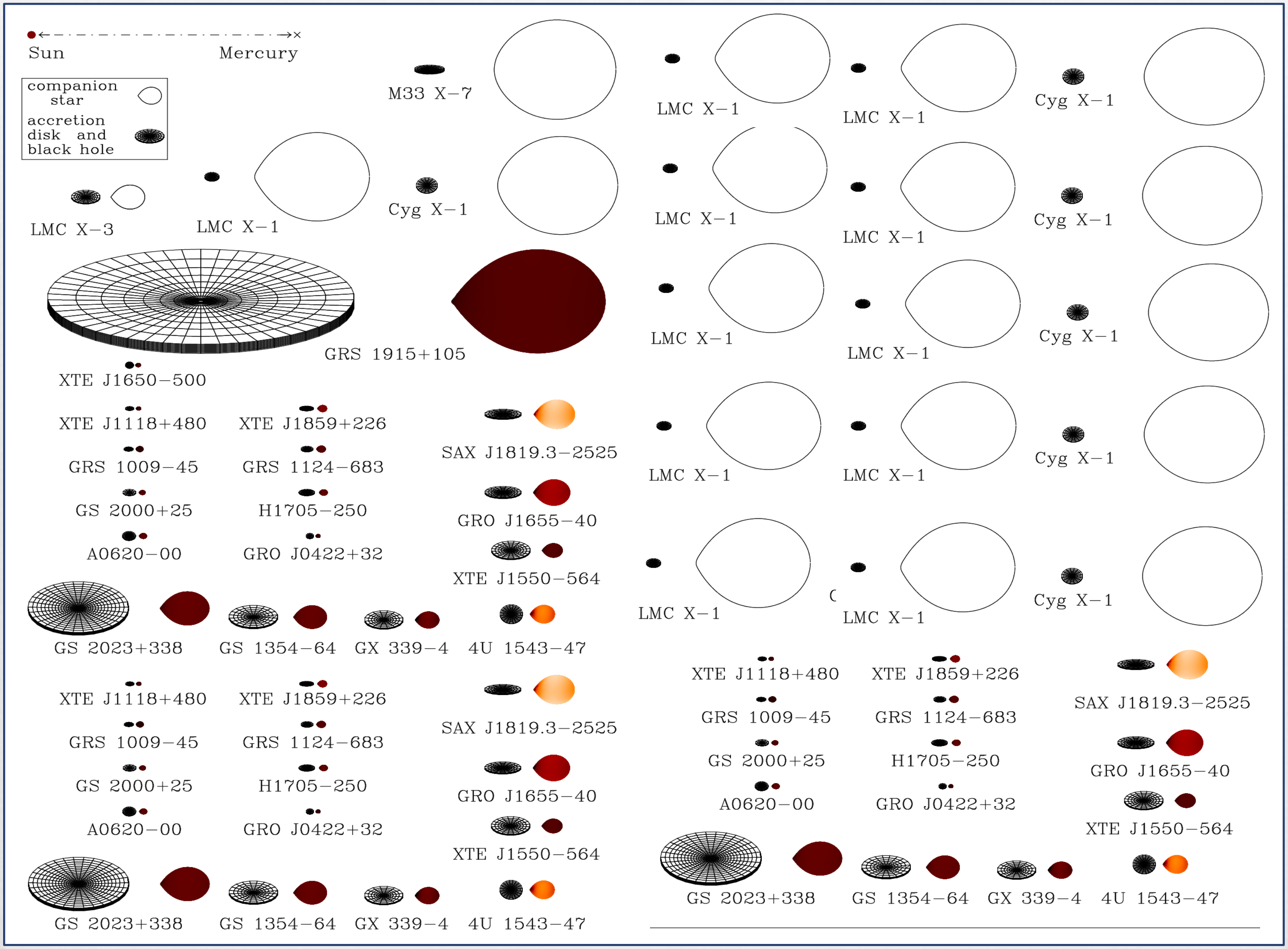
Rate (s^-1)
kT_disk (keV)
R_in (arb. units)
Time (s)

The Current Black Hole Binary Zoo



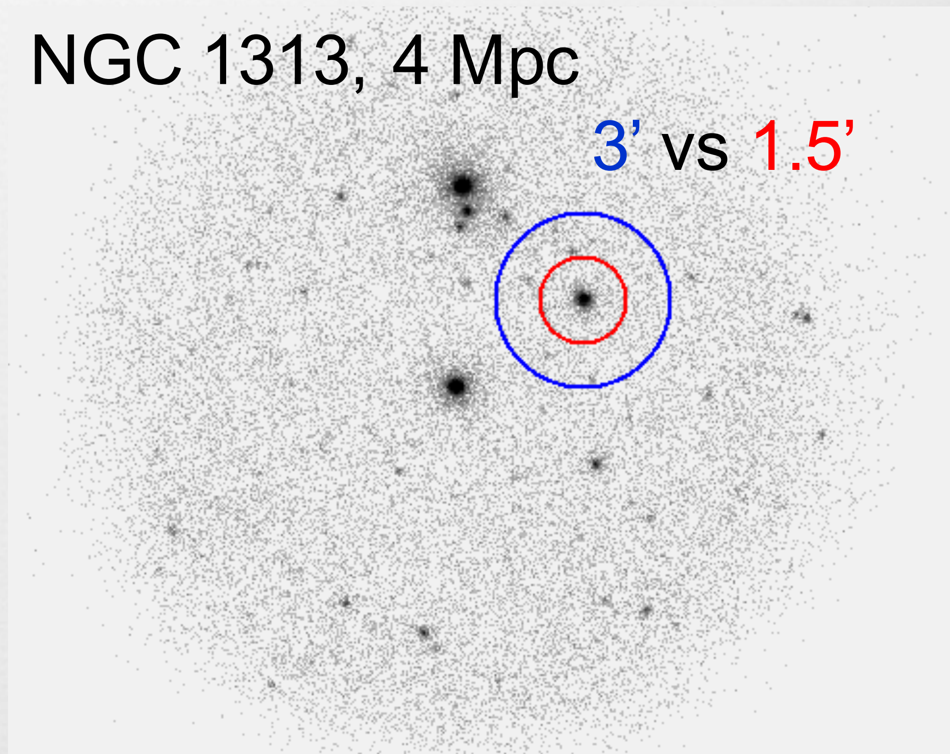
Courtesy: J. Orosz

A Local Group View?



Extragalactic Stellar BHs

- Competing with Athena in Athena's wheelhouse
- LAD is not helpful here
- Puts demands on XRCA FoV
  - (push to 1.5' radius?)



- Need an X-ray imager to inform our program

Cause for Excitement

- Have access to the outskirts of all Local Group members
  - Low N_H, less crowded
  - Many low-mass LG members
  - Can sweep up radius estimates for a dozen proximate sources in 10 ks. (~100s-1ks apiece for ~5000 ct benchmark)
  - Distance known precisely
- Establish as THE black hole monitor? ~Weekly measurements of target LG members
- Establish a critical-mass population of 50-100 stellar BH spins (and masses)
- Age of big glass on the ground: can get masses for stellar BHs in the Local Group (R~26+) with AO.

Operational and Instrumentation Tradeoffs

- Extragalactic a priority? : Pushing the optics – benefits from ground-based and space X–ray imaging partnerships
- Energy Resolution: Not critical for continuum fitting.
- Effective Area: Area and brightness trade off against the crucial timescales we can probe; bigger is better, but cuts will not hamstring science.
- **Throughput: Up to million(s) of events per second, please!**
- **Energy range:** Most important for the science grasp is to anchor the high-energy tail; best achieved by extending the reach on the LAD: *Can we push to 50+ keV?* This affects downscattering as well as upscattering. (Also important for AGN and ULX science.)

Continuum-Fitting Discussion Prompts

- “Hotspot” / waterfall-analog for Galactic systems – mass and spin from joint spectral/timing continuum data.
- Dust-scattering halos – probe dust structures near and far (different scales accessed with LAD and XRCA)
- Extragalactic merits?
- Truncation in continuum

STROBE-X and BH Spin

- Spins can be measured with three techniques: continuum-spectroscopy, reflection spectroscopy, and QPO timing
- STROBE-X offers groundbreaking capabilities for each method
- A simultaneous constraint with all three would (in principle) be possible