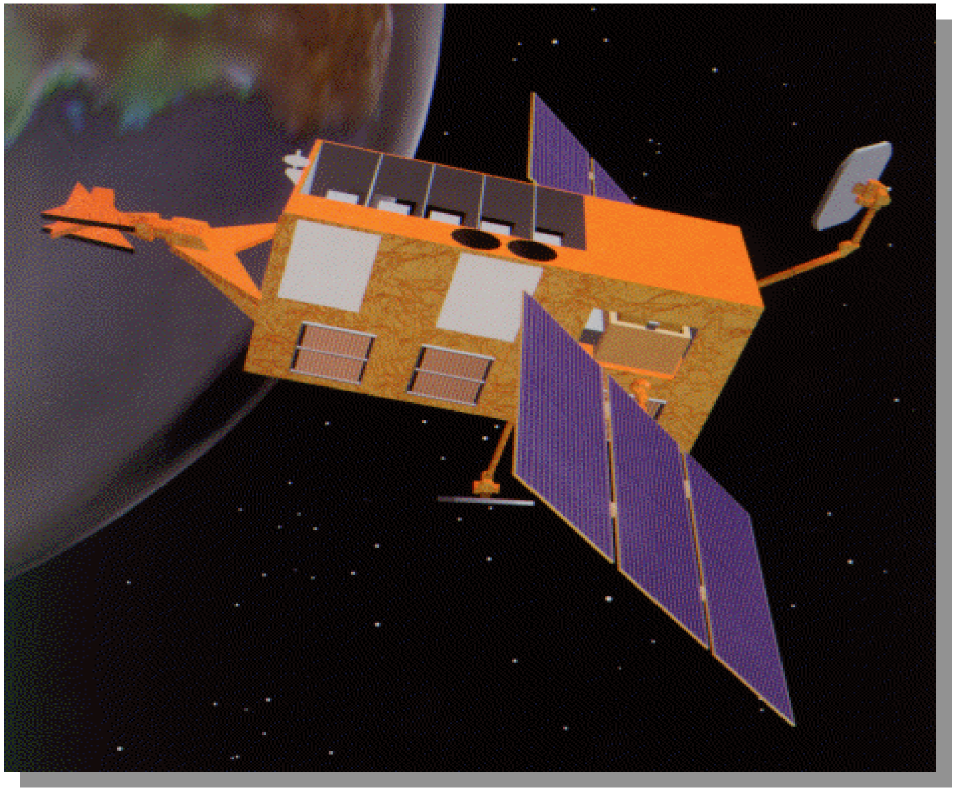
RXTE Presentation to the 2004 Senior Review of Mission Operations and Data Analysis

Frederick K. Lamb
University of Illinois
Chairman, RXTE Users Group



The Rossi X-Ray Timing Explorer

RXTE

Addresses Fundamental Astrophysics Questions with Unique Capabilities

RXTE addresses many fundamental questions, including —

- Gravitational physics in the strong-field regime
  - » Pulsar and burst oscillation frequencies determine precisely the spins of neutron stars needed to compute their external spacetimes
  - » Kilohertz orbital frequencies probe the properties of spacetime near neutron stars and black holes
  - » Relativistically-broadened iron lines from near black hole event horizons probe black hole properties such as spin
- Physics of ultradense matter and ultrastrong magnetic fields
  - » Spin frequencies ~ 600 Hz exclude stiff neutron star equations of state
  - » Burst oscillation and kilohertz orbital frequencies constrain the masses, radii, and equations of state of neutron stars
  - » X-ray spectra and the waveforms of accreting pulsars provide data on the structure of their magnetic fields and on quantum electrodynamic effects
- Mass inflows and outflows in accretion-powered systems
  - » Broad-band X-ray spectra probe the physics of disks and coronae; multiwavelength coordinated observations study the formation of relativistic jets

RXTE Unique Astrophysics Capabilities

- Fast timing — no comparable capabilities for at least a decade
- PCA scans yield sensitive triggers of galactic-plane transients — important sources are transient or highly variable
- Large dynamic range in X-ray flux – can handle bright and faint sources
- Provides the most sensitive measurements of spectra over the 2–200 keV energy band
- Continuous monitoring of almost the entire sky in soft X-rays
  - Spectral states, flux, and long-term variability for 300+ sources
  - Provides context for ground- and other space-based observations
  - Provides triggers of RXTE, Chandra, XMM-Newton, INTEGRAL, VLA, HST, VLT
- Extremely flexible observing program — access to most of the sky at all times and frequent short-notice re-scheduling in response to events

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Important New Results on Neutron Stars and Black Holes

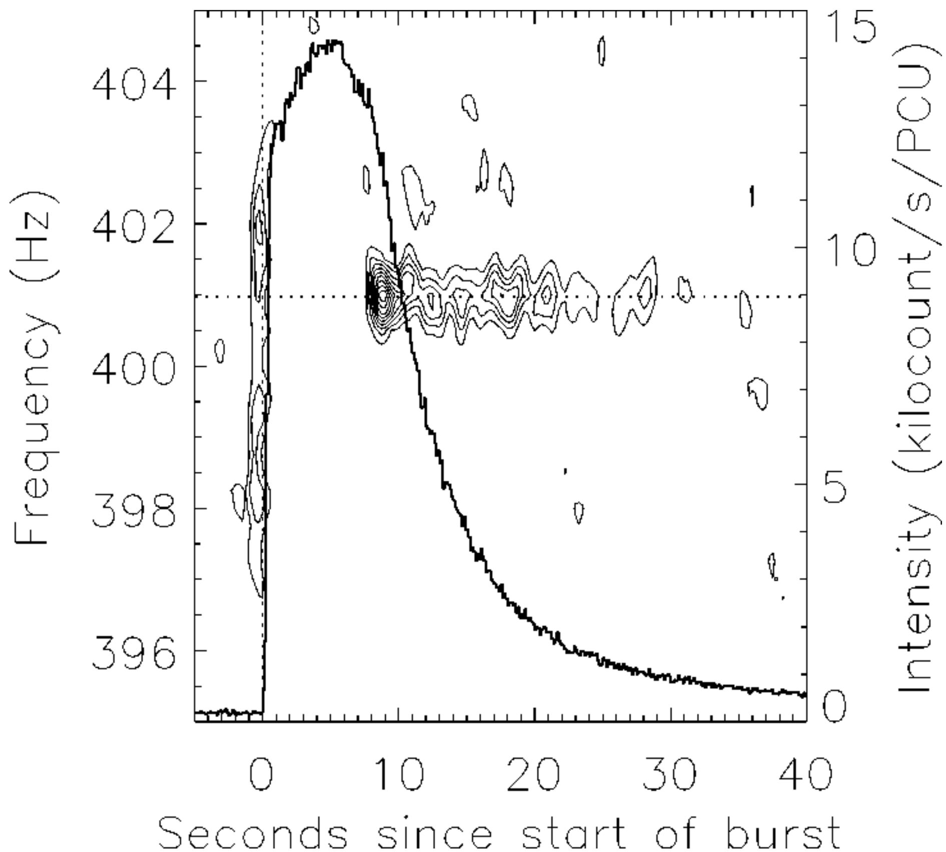
- During the past 18 months we have made major discoveries and advances in understanding high-frequency X-ray oscillations in neutron stars and black holes and the physics using Rossi XTE

The answers are simple!

- Recent discoveries have established beyond any doubt that the burst oscillations are produced by the spin of the neutron star, which appears to have an upper limit
- Recent discoveries have shown conclusively that the spin of the neutron star plays a central role in generating its kilohertz QPOs
- The new results support the original idea that the upper kilohertz QPO is generated by orbital motion while the lower kilohertz QPO is generated by interaction of the star’s spin with this orbital motion, but…
- They also show that our original idea about the mechanism involved is incorrect or at least incomplete, forcing revision of our ideas about the specific mechanism involved
- Observations using Rossi XTE have sharpened basic questions about the origins of high-frequency QPOs of black-hole candidates

RXTE Burst Oscillations in SAX J1808.–3658

$\nu_{burst} = \nu_{spin}$



Chakrabarty et al. 2003

- Four bursts were observed; all show 3–5% oscillations in the burst rise and the burst tail
- During the rise of the burst, ν_{burst} increases quickly, 10X faster than in any other X-ray burst source, and overshoots the spin frequency
- The oscillation disappears during the radius expansion that occurs at the peak of the burst
- The oscillation reappears in the tail of the burst, with a frequency $\nu_{burst} = \nu_{spin}$ + 6 mHz
- The oscillation in the tail *begins in phase* with the magnetic pole, but *then drifts* by 0.1 in phase

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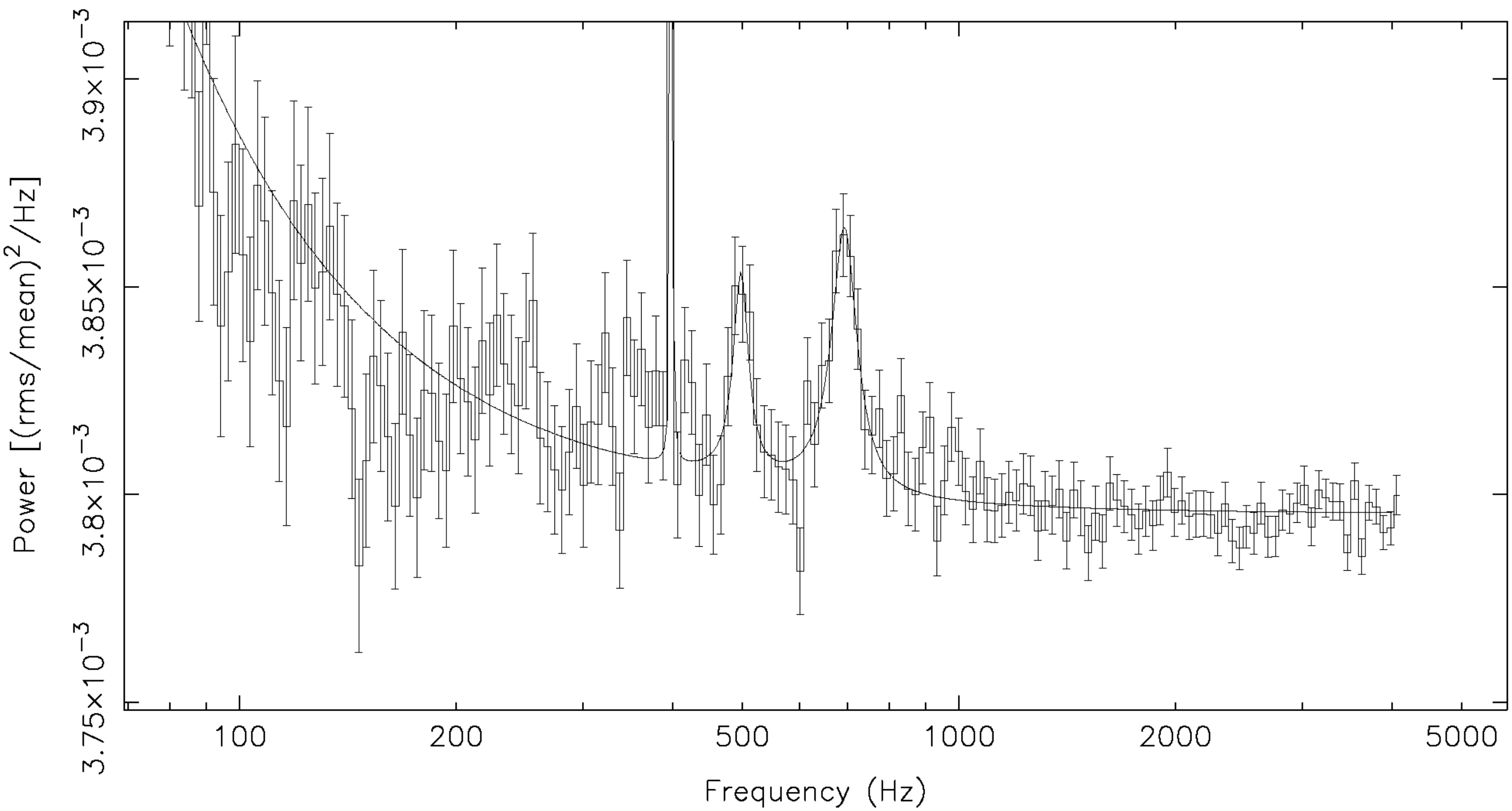
Kilohertz QPOs in a Millisecond Accretion-Powered Pulsar

$\Delta\nu_{QPO} = \nu_{spin}/2$ in the accreting X-ray pulsar SAX J1808.4–3658:



ν_{spin} = 401 Hz, $\nu_{QPO1} \approx$ 500 Hz, $\nu_{QPO2} \approx$ 700 Hz, $\Delta\nu_{QPO} \approx$ 200 Hz

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High-Frequency QPOs in Accreting Neutron Stars

3 Basic Types

- Persistent oscillations at the neutron star's spin frequency ("X-ray pulsations"); 5 accretion-powered millisecond X-ray pulsars are now known, with frequencies ranging from 185 Hz to 435 Hz

- Oscillations during X-ray bursts ("burst oscillations") generated by the spin of the neutron star; 16 such "nuclear-powered pulsars" are known

- 2 strong kilohertz quasi-periodic oscillations (kilohertz QPOs) that vary in frequency by factors ~ 3 but maintain a nearly constant frequency separation $\Delta\nu \approx 1.0$ or $0.5\ \nu_{spin}$; clearly, the spin of the star plays a fundamental role. Some 25 neutron stars are currently known to produce kilohertz QPOs.

  The fact that there are only *2* strong kHz QPOs indicates they are a single-sideband ("beat-frequency") phenomenon. The fact that the spin is involved indicates that the main frequency is also a rotation, i.e., orbital motion.

  $\Delta\nu = 0.5\ \nu_{spin}$ is inconsistent with the original beat-frequency model but not with all beat-frequency models (see Lamb & Miller 2003, astro-ph/0308179)

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kHz QPOs and Burst Oscillations in Neutron Stars with Known Spins

Spin Rate (Hz)	Object	Millisecond Pulsar References
185	XTE J0929–314	Galloway et al. 2002
191 •	XTE J1807–294	Markwardt et al. 2003a
270	4U 1916–05	
314	XTE J1814–338	Markwardt et al. 2003b
330	4U 1702–429	
363	4U 1728–34	
401 •	SAX J1808.4–3658	Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998
410	SAX J1748.9–2021	
435	XTE J1751–305	Markwardt et al. 2002
524	KS 1731–260	
549	Aql X-1	
567	X 1658–298	
581	4U 1636–53	
589	X 1743–29	
601	SAX J1750.8–2900	
619	4U 1608–52	

Boldface : known pulsars; • : pulsars with known kHz QPOs;
italics : neutron stars without known burst oscillations

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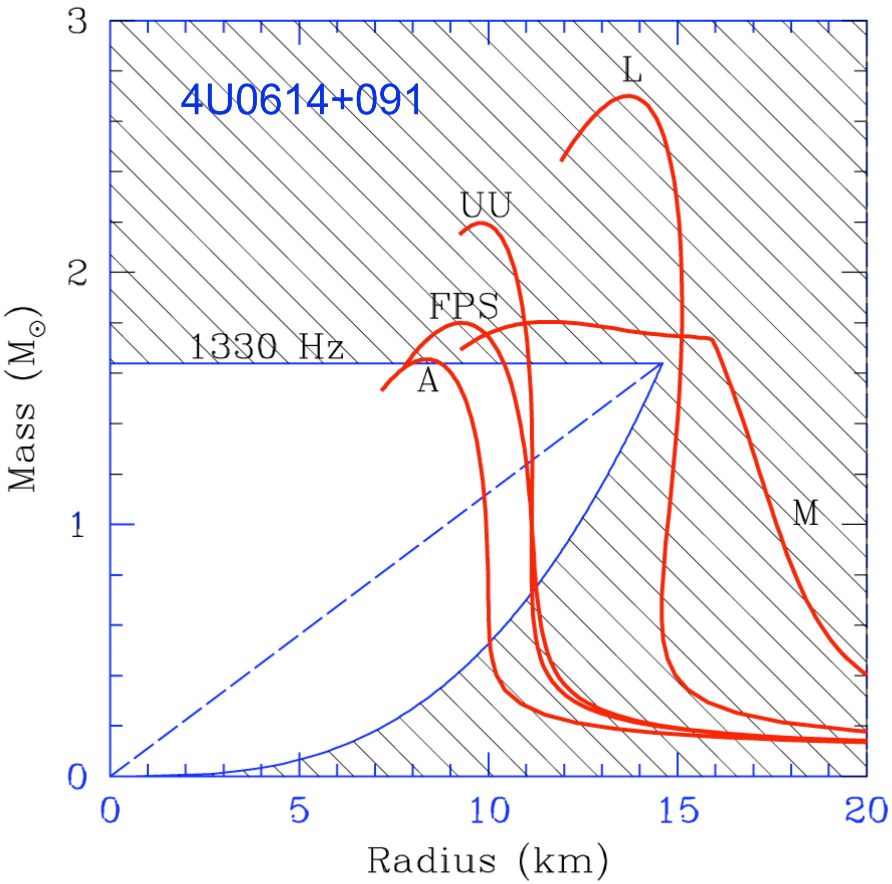
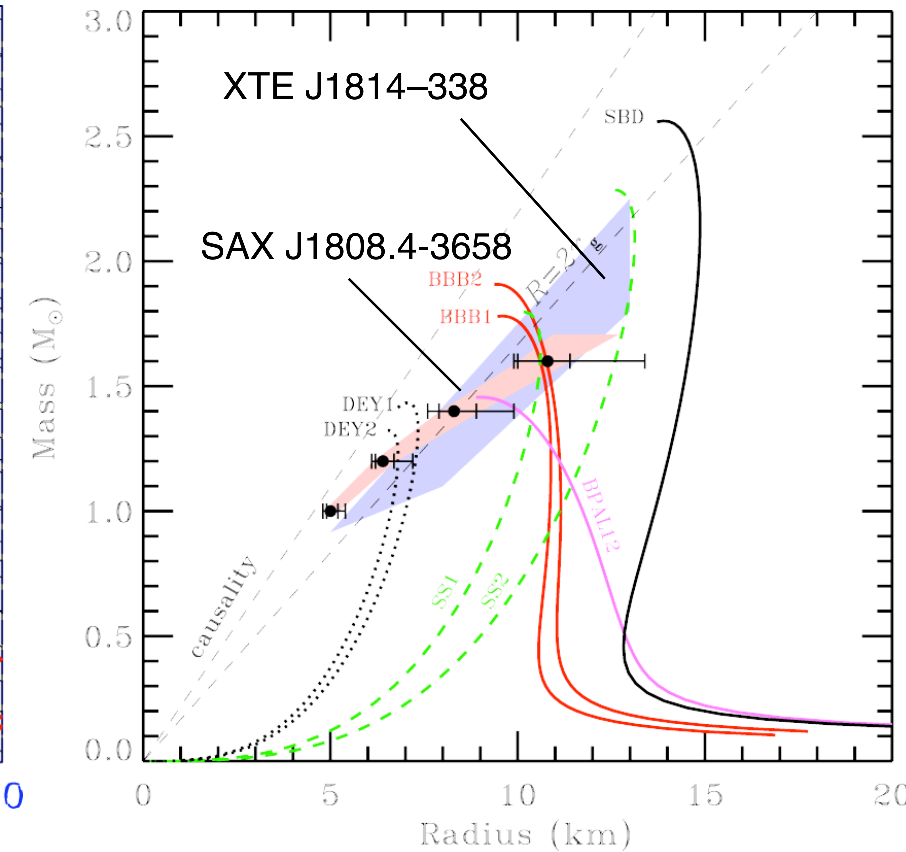
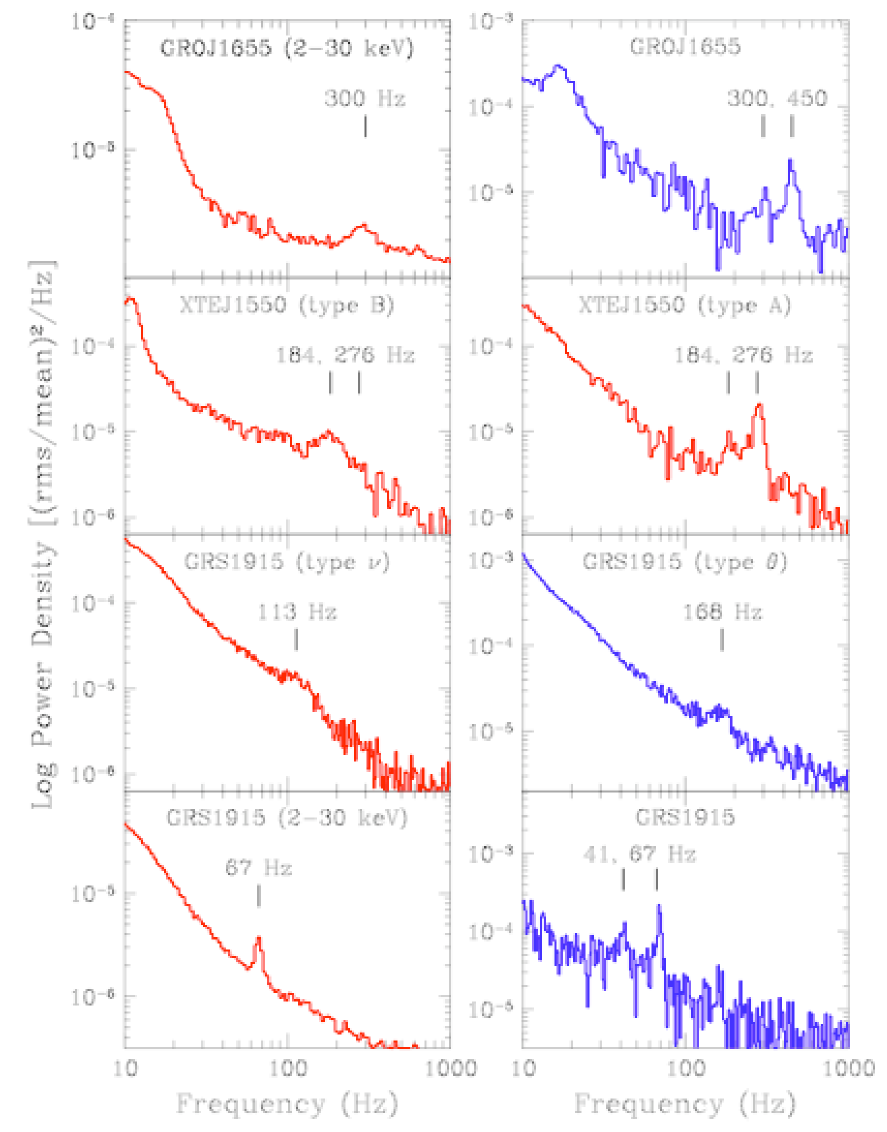
Properties of Dense Matter and General Relativistic Effects





Left: Comparison of upper kilohertz QPO frequency with NS EOS
Right: Comparison of illustrative burst oscillation data with NS EOS

RXTE High-Frequency QPOs in Black Holes



- The frequencies are stable, with evidence for ~ 3:2 ratios in some, sometimes
- QPOs are strongest at photon energies greater than 10 keV
- QPO amplitude ratios change systematically with the X-ray spectral state

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High-Frequency QPOs in Accreting Black Holes

Are fundamentally different from kilohertz QPOs in neutron stars —

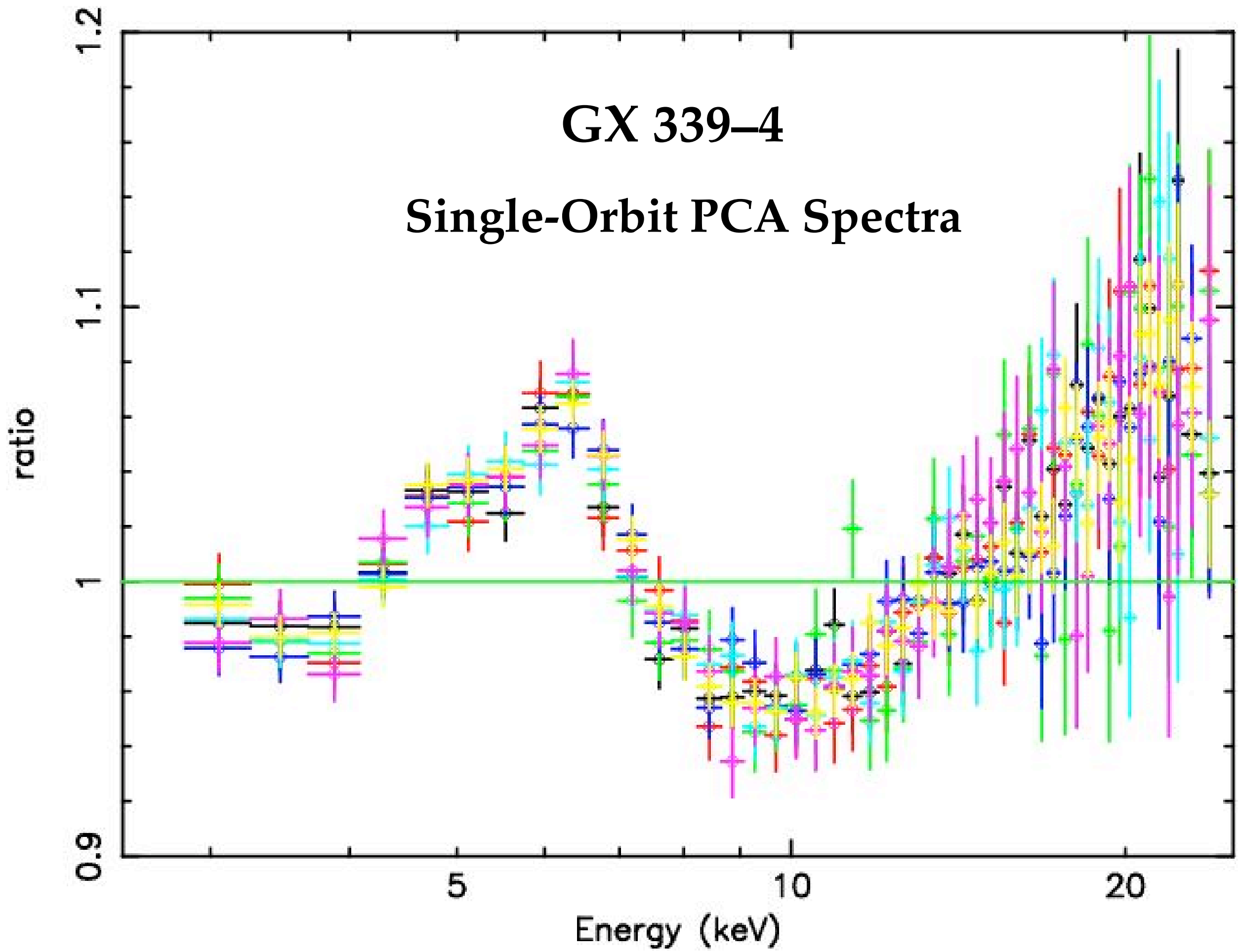
- The frequencies of most high-frequency QPOs in BHCs *do not vary* (there is no detectable variation as the X-ray flux varies by > 2X)
- The spin of the black hole plays no direct role in generating the oscillation (frame dragging can affect orbital and pattern frequencies)
- The high-frequency QPOs of BHCs have much lower amplitudes than the kilohertz QPOs of neutron stars

The high-frequency QPOs of BHCs probably originate in the disk, but the physical mechanism that produces them is not yet known —

- Some show frequency ratios that are approximately 3:2 or 5:6, but . . .
- The mechanism cannot be a simple nonlinear resonance in the disk, because different frequency pairs are seen GRS 1915, *apparently sometimes simultaneously*, which implies different frequency ratios

RXTE Black Hole Reflection Component

Improved PCA Calibration Allows More Detailed Spectroscopy



RXTE Coordinated Observations

X-ray —
- Chandra
- XMM-Newton
- INTEGRAL
- (Astro-E2)

Optical/IR —
- Yalo
- VLT
- Magellan
- (SIRTF)

γ-ray —
- Whipple/Veritas
- MAGIC
- Hegra/HESS
- (Swift)

Radio —
- VLA
- VLBI
- Merlin
- Molonglo
- ATCA

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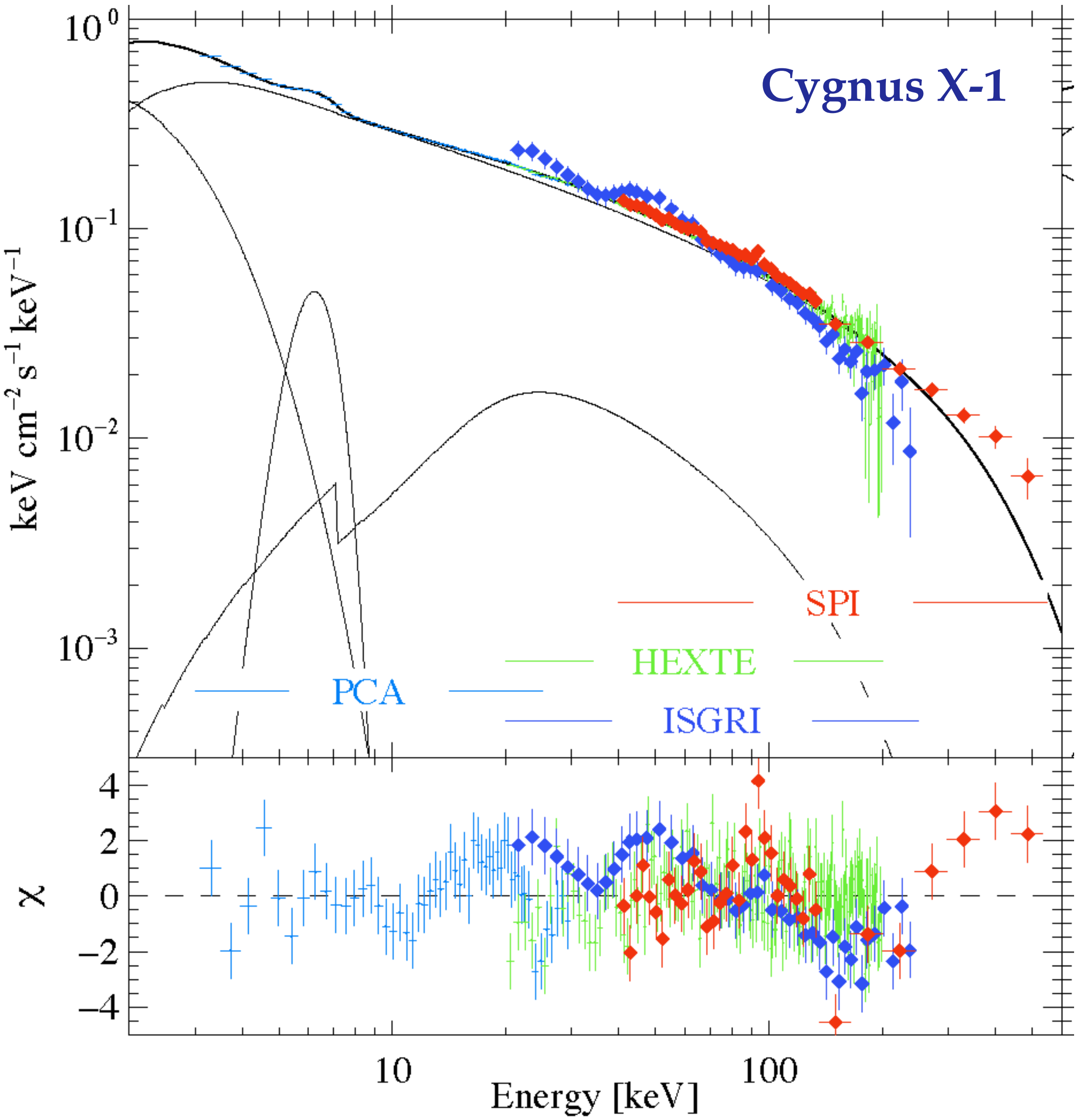
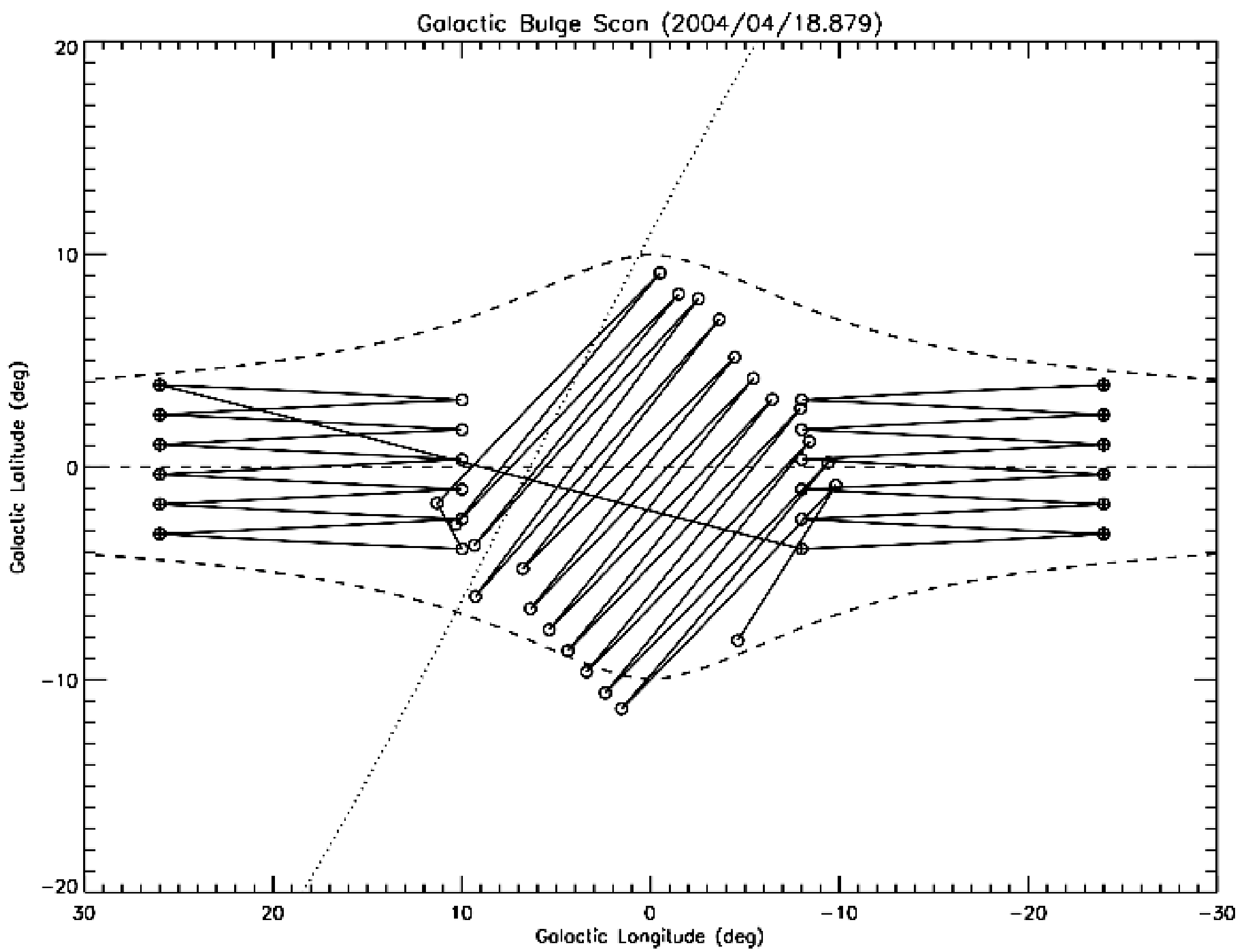
Simultaneous RXTE/Integral Observation



RXTE Evolving Observing Strategies

- A larger proportion of observations are TOOs
- Long (up to 6- week), almost uninterrupted observations of critical transient sources, such as accretion-powered ms pulsars
- Longer observations of interesting persistent sources
- Improved strategies for discovering uncataloged sources in All Sky Monitor data
- Automated searches of slew data for serendipitous sources
- Focused searches for important transients, such as millisecond accretion-powered pulsars
- Regular (twice per week) scans of the galactic bulge; scanned region is being expanded
- Multiwavelength observations are now routine

RXTE Expanded Galactic Bulge Scans



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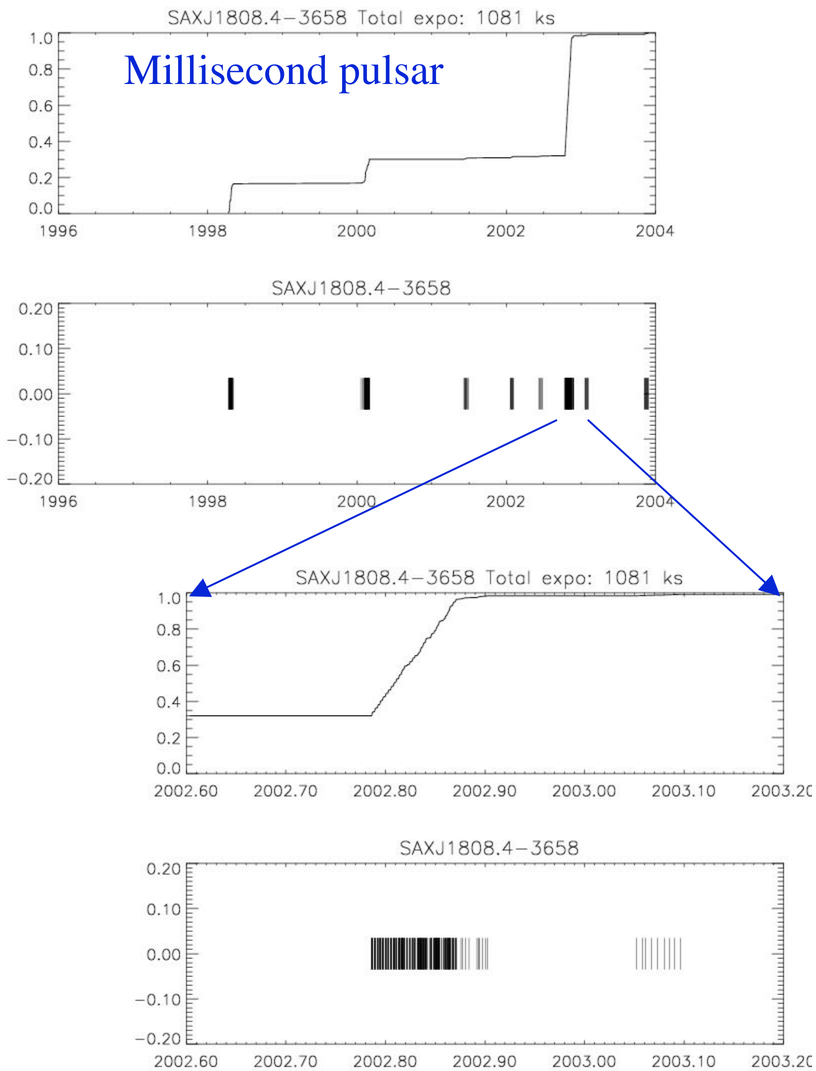
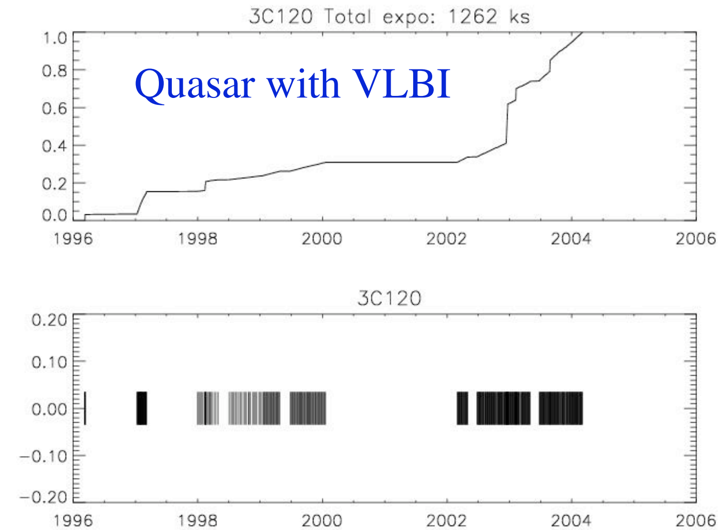
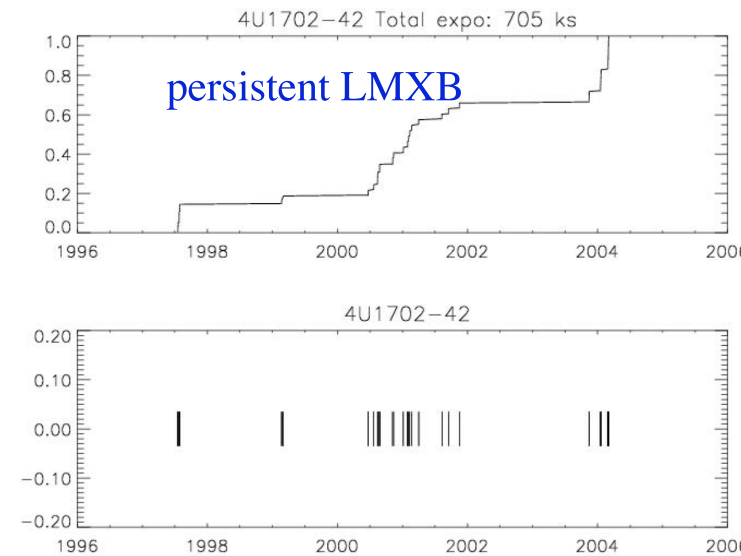
New Tool for Managing Observations

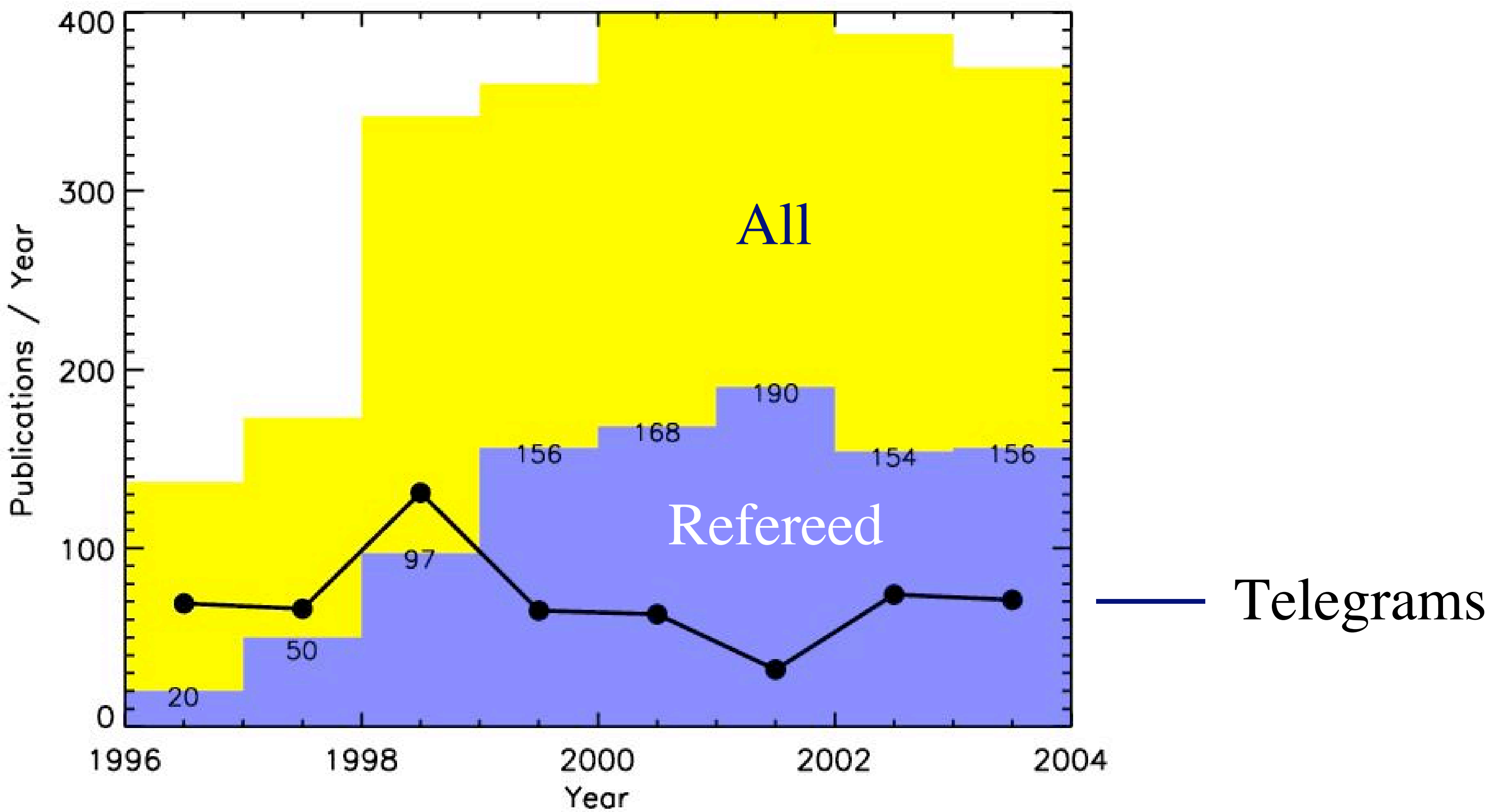






Publications Per Year Since Launch

RXTE



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Guest Observer Program

	Cycle 9	Cycle 8
Submitted	168	188
Accepted	108	114
U.S.	69	70
Foreign	39	43
U.S. PIs	46	46
Foreign PIs	28	30
Proposals funded	68	63
Average award	$12,700	$14,000

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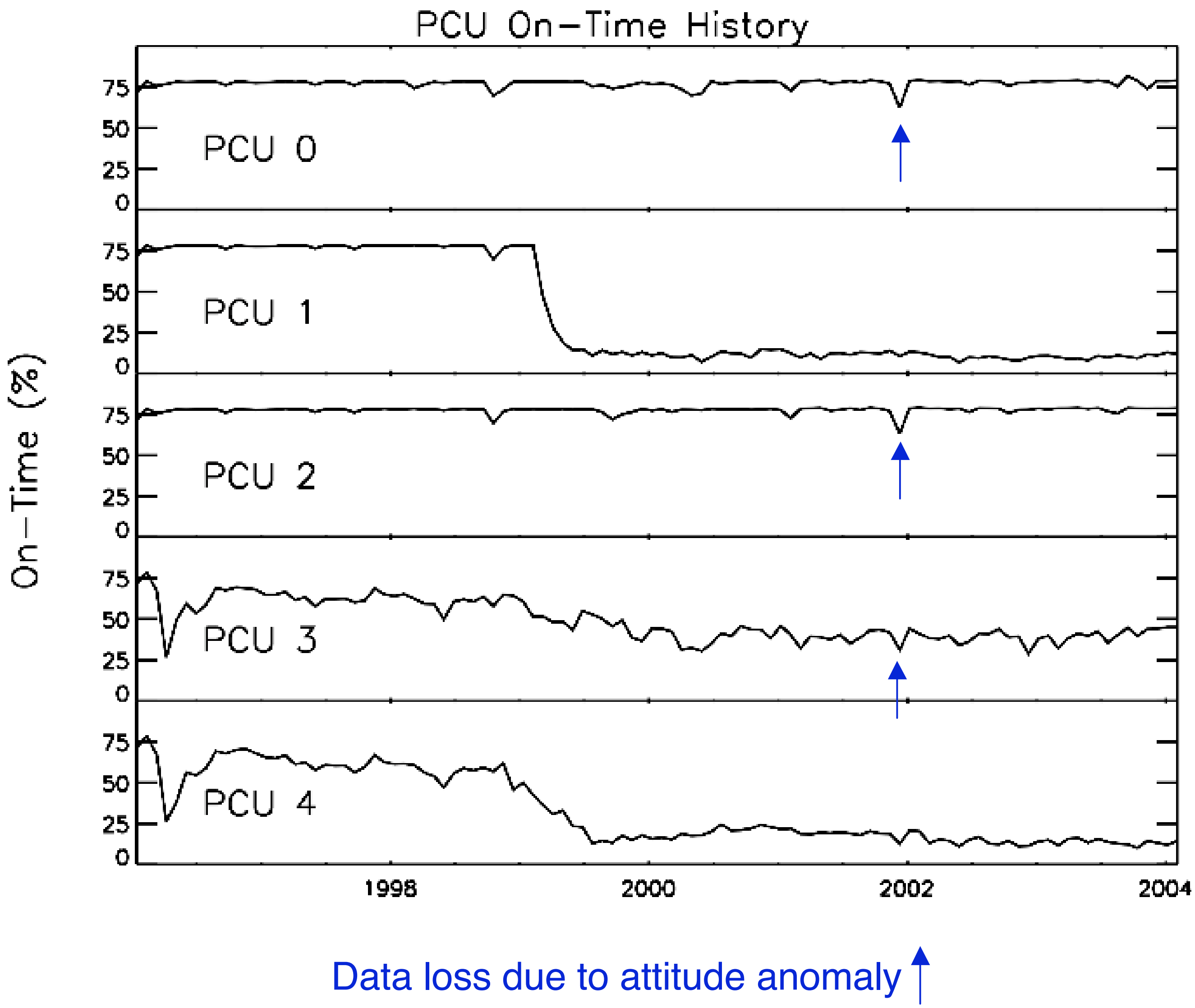
PCA Detector Health



RXTE Detector Area for Observations