# NS LMXBs and isolated NSs with ASTROSAT

## A few points

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1. Two types of baseline sciences
2. Burst reprocessing from accretion disk, companion star
3. Kilo-Hertz Quasi-Periodic Oscillations (KHz QPO)
4. Multi-wavelength studies of NS LMXBs
5. Relativistic disk lines
6. Galactic bulge scan
7. NS LMXBs: other science goals
8. Isolated NSs

# 1. Two types of baseline sciences

1. **Detailed study of a source to understand the physics of some processes or phenomena.**

   **Plan:** Pick up a few well-known (may be somewhat well-studied) sources, and have long well-planned observations of them to take advantage of ASTROSAT's unique capabilities.

   **Example:** Choose one or two kilo-Hertz (kHz) QPO sources and study the kHz QPO feature in detail.

2. **Discovery of new types of sources or phenomena.**

   **Plan:**

   (a) Study the existing catalogues of X-rays and other wavelengths in detail, and identify peculiar sources. Observe them with ASTROSAT (at first for short time, and later, if required, for long time). This requires huge effort and data mining. (b) Have at least short observations with ASTROSAT of as many first-known outbursts of transients as possible.

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   **Plan:** Pick up a few well-known (may b[illegible]at well-studied) sources, and hav[illegible]planned observations of them to take advantage of ASTROSAT's unique capabilities.

   **Kill many birds with one stone.**

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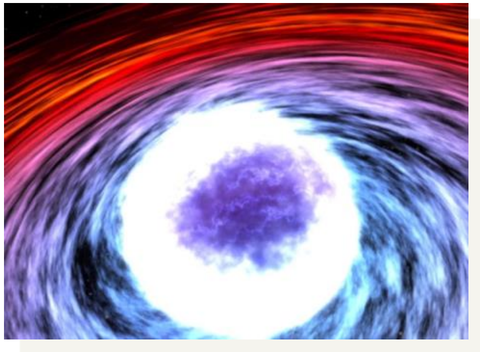
# 2. Burst reprocessing from accretion disk, companion star

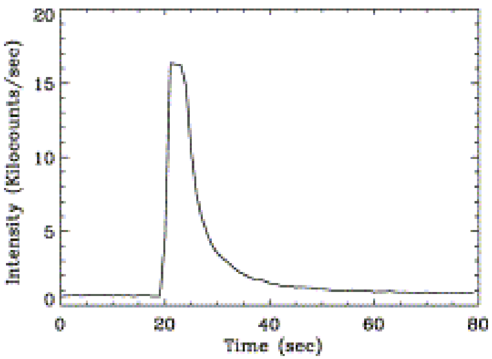


Accretion on neutron star

What is a thermonuclear X-ray burst?

Unstable nuclear burning of accreted matter on the neutron star surface causes type I (thermonuclear) X-ray bursts.

Burst light curve




Rise time ≈ 0.5 - 5 seconds
Decay time ≈ 10 - 100 seconds
Recurrence time ≈ hours to day
Energy release in 10 seconds
≈ $10^{39}$ ergs
↓

Sun takes more than a week to release this energy.

Why is *unstable* burning needed?

Energy release:
Gravitational ≈ 200 MeV / nucleon
Nuclear ≈ 5 MeV / nucleon

**Accumulation of accreted matter for hours → Unstable nuclear burning for seconds ⇒ Thermonuclear X-ray burst.**

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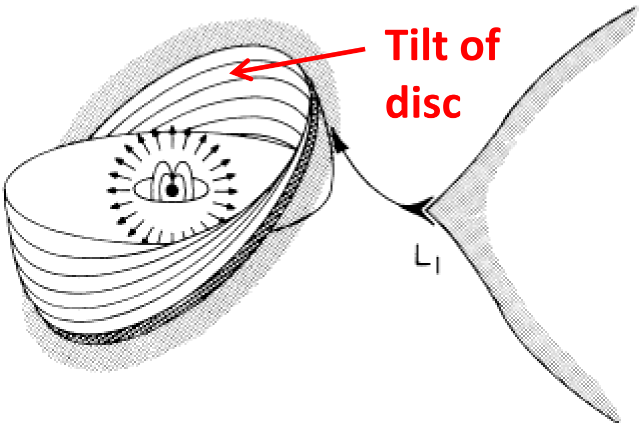
# 2. Burst reprocessing from accretion disk, companion star

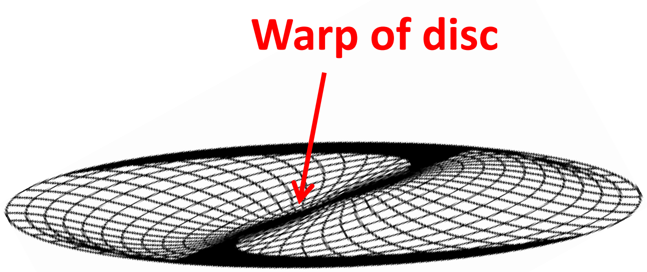
Thermonuclear X-ray bursts illuminate the accretion disk and the companion star like a lighthouse.

The known origin (location), high S/N, high fraction of total X-ray luminosity and relatively short lifetime make them a unique tool to study size, structure and other properties of the accretion disk, the size of the binary system, etc.

For this, one needs to observe the bursts simultaneously in X-ray/UV/optical, and model the observed time lag, spectrum, etc.




Petterson (1975)




Ogilvie & Dubus (2001)

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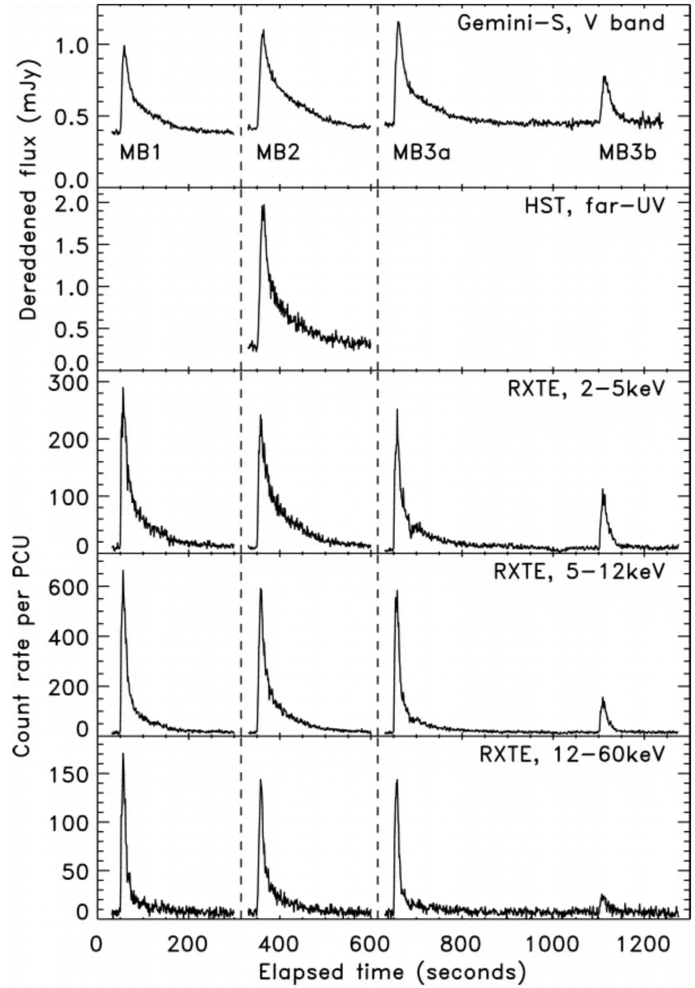
# 2. Burst reprocessing from accretion disk, companion star

Simultaneous observations in several X-ray/UV/optical bands are very difficult both for planning (bursts are usually unpredictable) and for convincing the reviewers of a proposal (bursts are short-lived).

ASTROSAT will always simultaneously observe bursts in **3-4 X-ray/UV/optical bands**, and should cause a very significant progress in this field. There are more than a dozen good sources.

**How to plan?** Bursts are unpredictable, but we have an idea about their average recurrence times for many sources. In some cases, we also have some idea about the correct persistent spectral states.

The clock burster GS 1826-24 is the only persistent source, which shows almost periodic bursts (period changes slowly over the years). So we can plan to observe this source only during the bursts.




Hynes et al. (2006)

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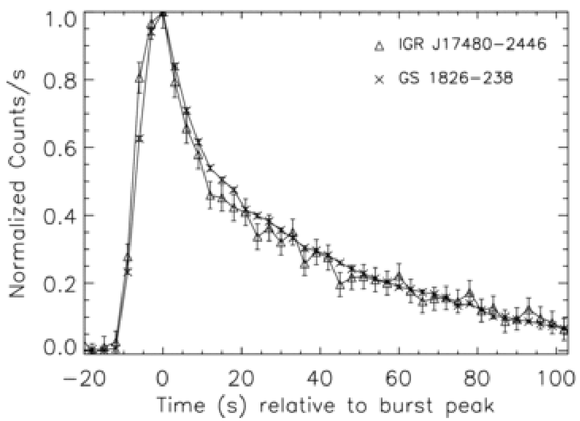
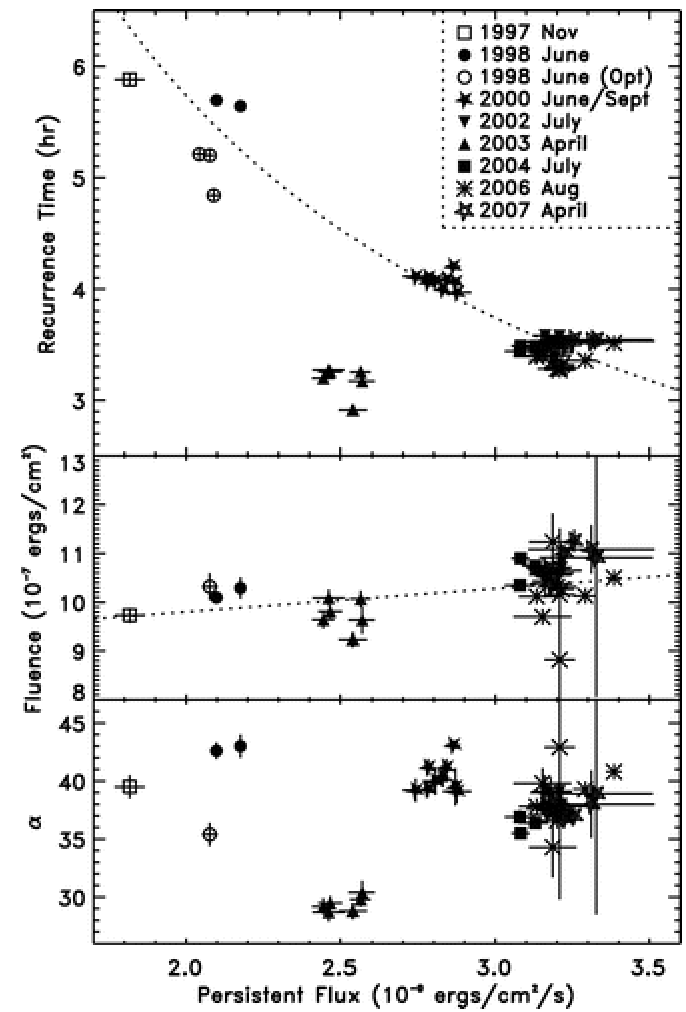
# 2. Burst reprocessing from accretion disk, companion star

## Observation of the clock burster (GS 1826-24) with ASTROSAT: A baseline science




Chakraborty and SB (2011)




Thompson et al. (2008)

Advantages: (1) Almost periodic bursts.
(2) All bursts have similar shape.

Previous results: 3 sec lag between X-ray and optical bursts observed from one burst (Kong et al. 2001).

Plan: Repeated observations with ASTROSAT, each for 300 sec only during a burst, with an interval of n*P (P = burst recurrence period, n = 1, 2, 3, …).

Main instruments: LAXPC and UVIT. However, all X-ray instruments are required to estimate the persistent emission during bursts.

Preparation: (1) Decide on UVIT modes, filters, etc.
(2) Theoretical modelling.

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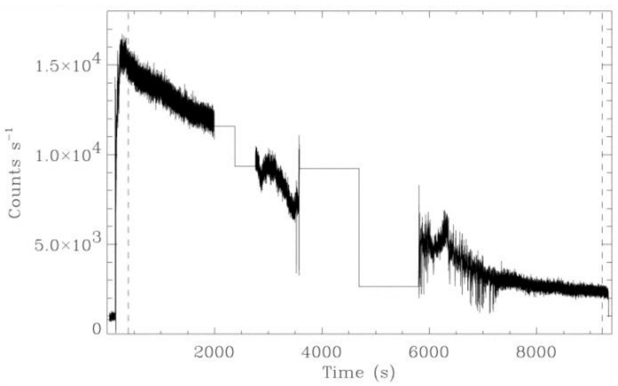
# 2. Burst reprocessing from accretion disk, companion star

**Superbursts:** 1. A challenge for nuclear physicists!

2. The long duration can be useful to study burst oscillations and burst spectrum.
3. **The effects on accretion disk, corona, etc. can be studied in broadband.**
4. **Study of superburst reprocessing observed in several X-ray/UV/optical bands will very important.**



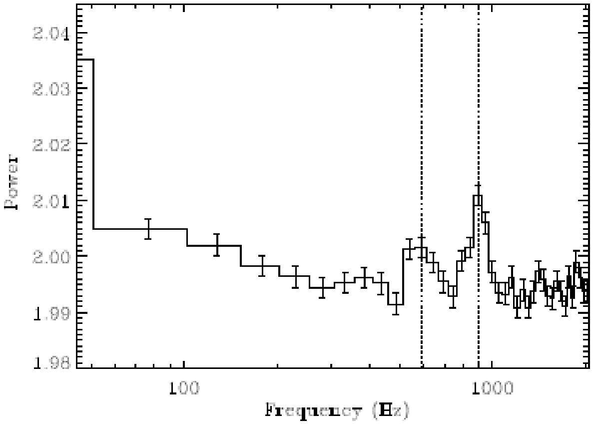

Strohmayer and Brown (2001)

Released energy ~ $10^{42}$ ergs
Recurrence time ~ years
Decay time ~ 3 hours
Usually believed to be caused by $^{12}C$ fusion at a column depth of ~$10^{12}$ g cm$^{-2}$

So far only about 20-25 superbursts (not all confirmed) have been observed from about 15 sources. No multiwavelength study has been done so far. **Observations with ASTROSAT will be useful for 1-4 above.**

**A baseline science : Very fast 'planned ToO observations' of superbursts, identified based on ASTROSAT/SSM count rate, its rate of change and duration of higher values (automatically and immediately estimated on ground), of specified sources (e.g., 4U 1636-536, 4U 1608-522). A special ToO: response time < 1 hr.**

# 3. Kilo-Hertz Quasi-Periodic Oscillations (KHz QPO)




KHz QPOs often appear in a pair in the power spectrum, in the 200-1200 Hz frequency range.

**This observationally robust timing feature have been detected from many neutron star LMXBs.**
**The high frequency suggests that this feature originates from within a few Schwarzschild radii of the neutron star.**
**In fact, according to almost all the models, the uniquely high kHz QPO frequencies are either the various relativistic frequencies of the accretion disk, or the beating or resonances among them, or with the neutron star spin frequency.**

**Therefore, kHz QPO can be a useful tool to measure neutron star parameters, to probe the strong gravity region and to test a law of gravitation.**

**But the correct model of kHz QPO is not yet known, and hence it cannot be used as a reliable tool yet.**

**Study of energy-dependent properties (e.g., fractional amplitude, phase-lag) can be useful to understand the origin of kHz QPO.**

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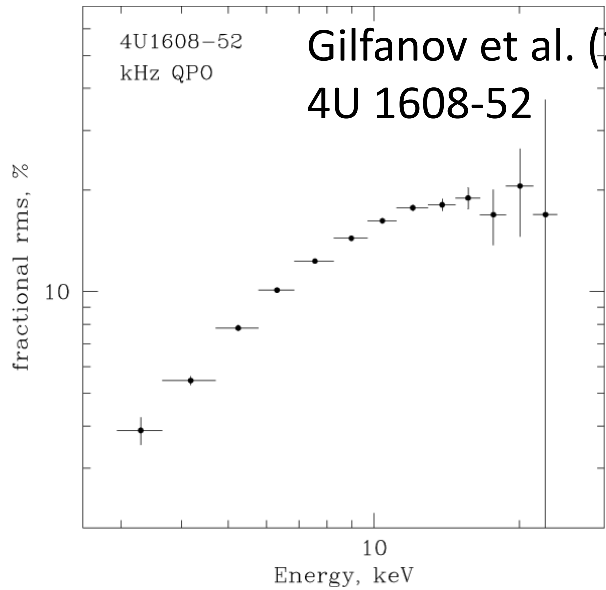
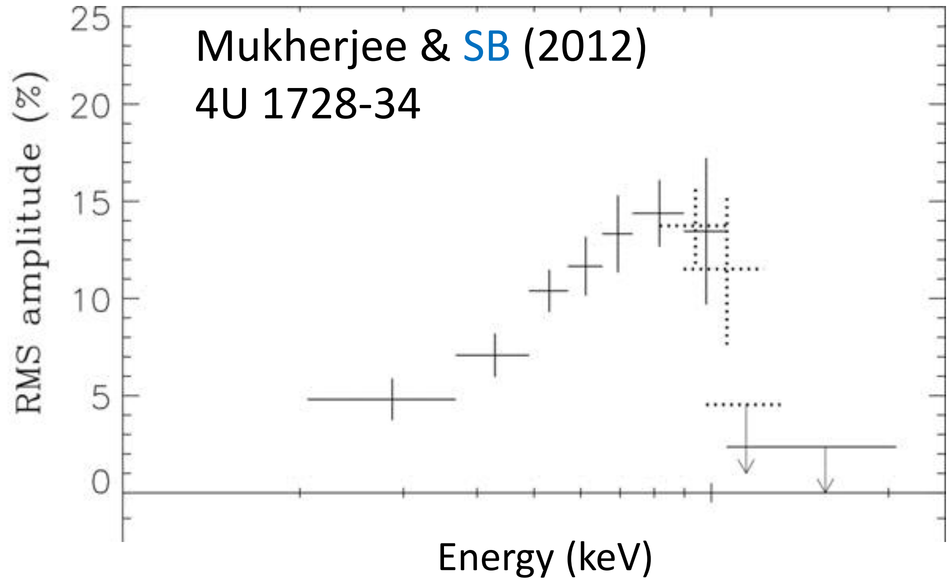


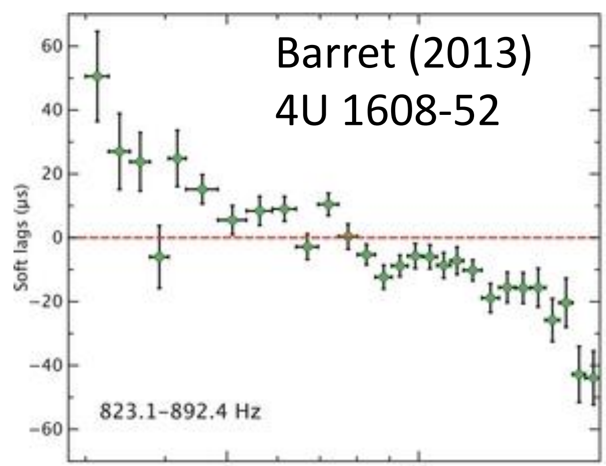

**A baseline science :**

Advantage: Much larger area of LAXPC (relative to that of RXTE PCA) at hard X-rays.

Plan: Repeated observations of a suitable source (say, 4U 1608-52 / 4U 1636-536) with ASTROSAT.

Main instruments: LAXPC. However, all X-ray instruments are required to estimate the energy spectrum, which is essential for modelling of kHz QPO properties.

Preparation: (1) Simulation with LAXPC response .
(2) Modelling of kHz QPO properties.



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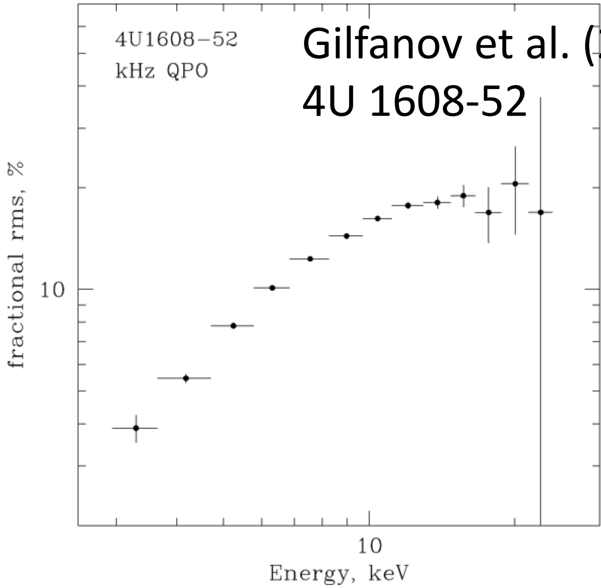


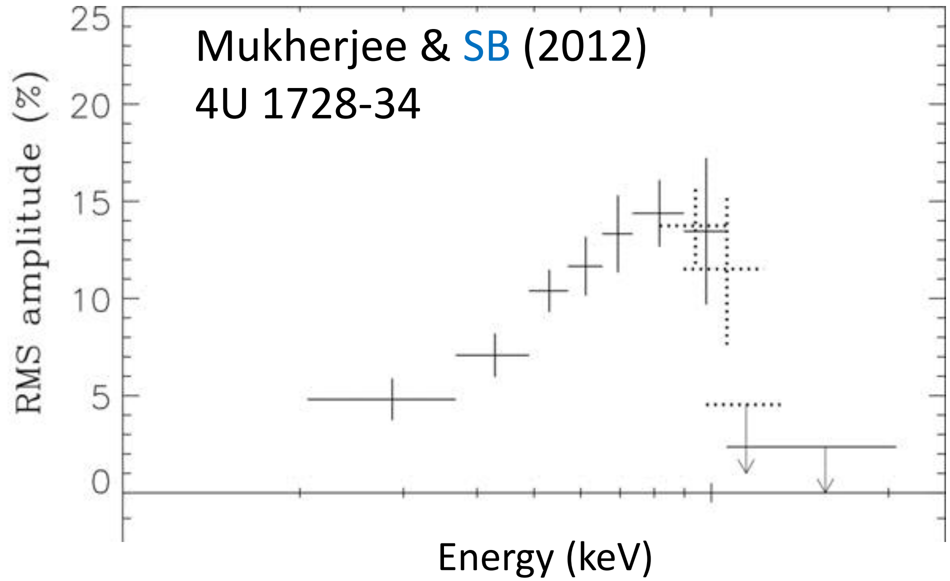


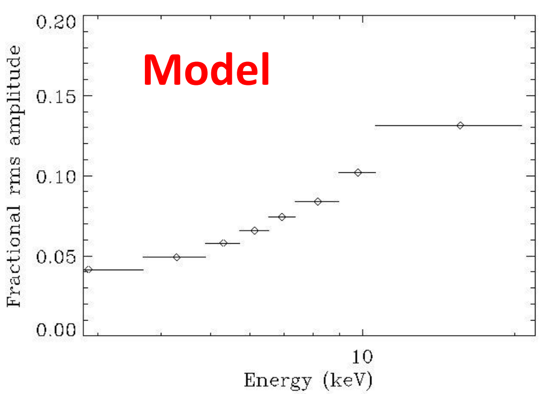


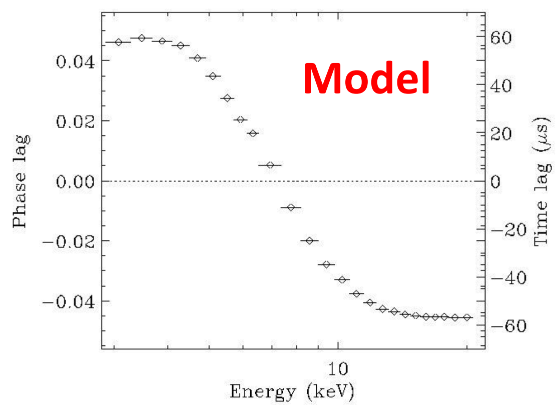


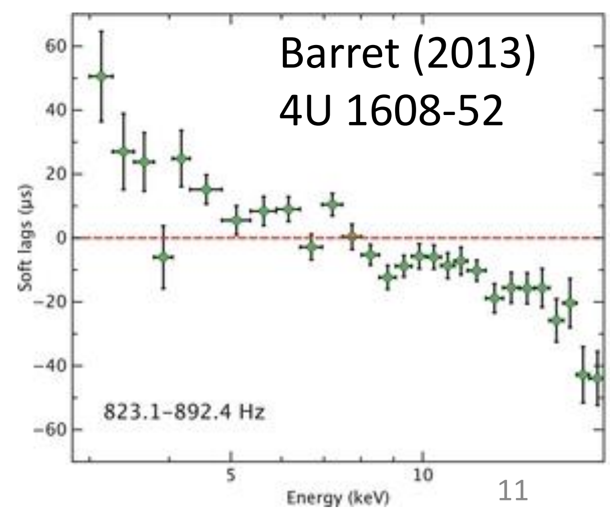


Models combined with RXTE PCA response. Models will be improved and can easily be combined with LAXPC response.

# 4. Multi-wavelength studies of NS LMXBs

**Problems:** There are some basic problems in understanding the X-ray emissions of NS LMXBs.

**1. What are the various spectral components in various states?**
**(Many models fit the data). General idea: disk, NS surface, corona, jet.**

**2. What is the location, size and structure of each component?**

NS LBXB XB 1254-690: an example with RXTE PCA data

| Model | $\chi_\nu^2$(dof) | Model | $\chi_\nu^2$(dof) |
|---|---|---|---|
| diskbb+comptt | 1.95(30) | diskbb+powerlaw | 1.95(32) |
| diskbb+cutoffpl | 1.97(31) | **diskbb+bknpower** | **0.52(30)** |
| comptt+bbody | 1.50(30) | powerlaw+bbody | 2.24(32) |
| cutoffpl+bbody | 1.65(31) | bknpower+bbody | 2.39(30) |
| diskbb+bbody | 2.75(32) | **comptt+comptt** | **0.91(28)** |
| **powerlaw+comptt** | **0.95(30)** | **cutoffpl+comptt** | **0.91(29)** |
| **bknpower+comptt** | **0.54(28)** | powerlaw+powerlaw | 32.31(32) |
| cutoffpl+powerlaw | 2.33(31) | bknpower+powerlaw | 3.47(30) |
| cutoffpl+cutoffpl | 1.54(30) | **bknpower+cutoffpl** | **0.53(29)** |
| bknpower+bknpower | 3.73(28) | | |



Mukherjee and SB (2011)

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# 4. Multi-wavelength studies of NS LMXBs

**Problems:** **There are some basic problems in understanding the X-ray emissions of NS LMXBs.**

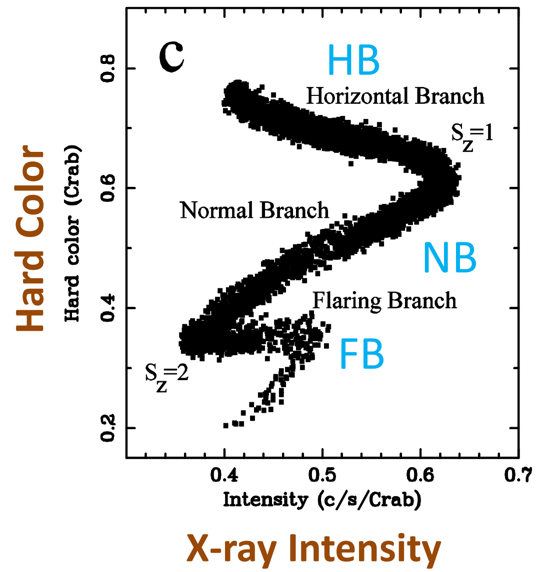
## 3. How does accretion rate change during state evolution?

One usually tries to understand the Z-curves based on accretion rate increase from HB to NB to FB; and similarly  the atoll curves based on accretion rate increase from island state to banana state.

But clearly such monotonic increase cannot always be inferred from the X-ray intensity evolution (see the figures to the right).

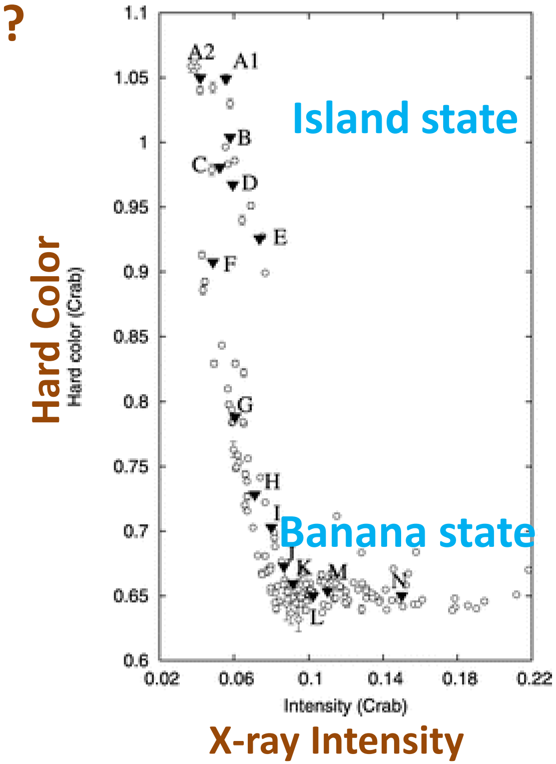
The monotonic accretion rate increase was inferred from some old coordinated X-ray/UV observations and their interpretations based on UV originated from X-ray heated disk (e.g., Vrtilek et al. (1990)). But this field is poorly studied, and later studies showed that direct emissions from disk and jet could also give rise to UV.

Z source




Van der Klis (2006)

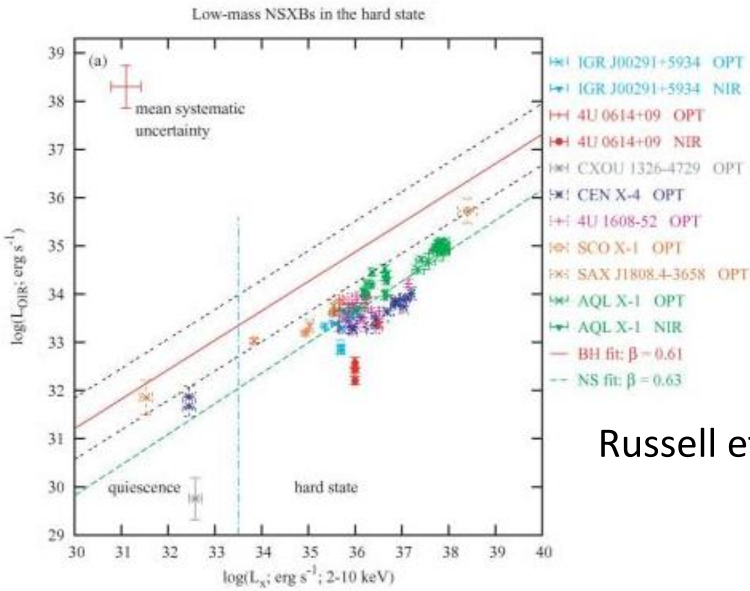
Atoll source




Altamirano et al. (2008)

**This shows the importance of simultaneous X-ray/UV observations in detail.**

# 4. Multi-wavelength studies of NS LMXBs

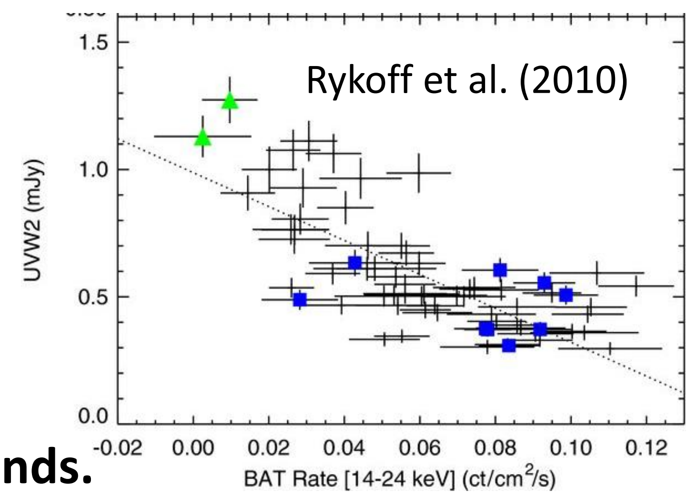



Russell et al. (2006)

**Table 6.** The OIR emission processes that can describe the empirical OIR–X-ray relations and SEDs.

| Sample | X-ray state | X-ray repro-cessing | Jet emis-sion | Viscous disc | Intrinsic com panion |
|---|---|---|---|---|---|
| NSXBs; OPT | Hard | √ | × | √ | × |
| NSXBs; NIR | Hard | √ | √ | × | × |

SWIFT data of Cyg X-2




## A baseline science:

**What do we need to do?**

**(1) SED (optical to 100 keV).**

**(2) Correlation among X-ray, UV and optical bands.**

**(3) Time lag among various X-ray, UV and optical bands.**

**Suggested sources:**

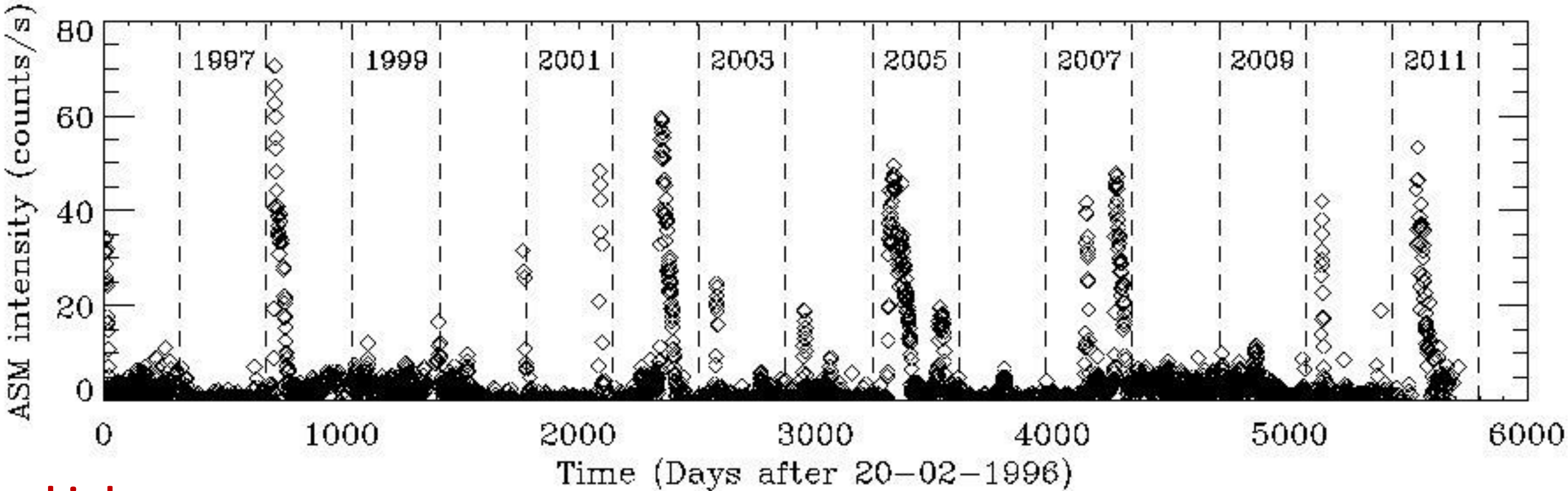
**Sco X-1 (Sco-like Z source); Cyg X-2 (Cyg-like Z source); 4U 1608-522/Aql X-1 (transient atoll source); 4U 1636-536 (persistent atoll source).**

**Instruments: All**

**Preparation: Analysis of existing data and simulation.**

# 4. Multi-wavelength studies of NS LMXBs

## 4U 1608-522




**Many birds:**

1. **Thermonuclear bursts**
2. **Burst oscillations**
3. **mHz QPO**
4. **KHz QPO**
5. **Low-frequency QPOs**
6. **Optical/UV observation possible**
7. **Burst reprocessing:**
   (a) **Superbursts**

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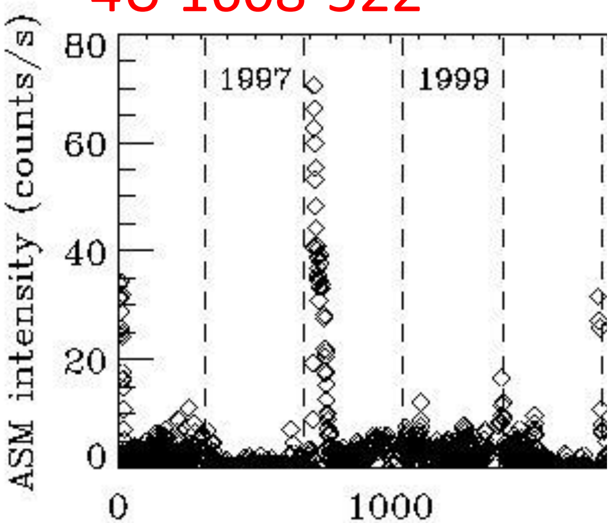
# 4. Multi-wa

## 4U 1608-522

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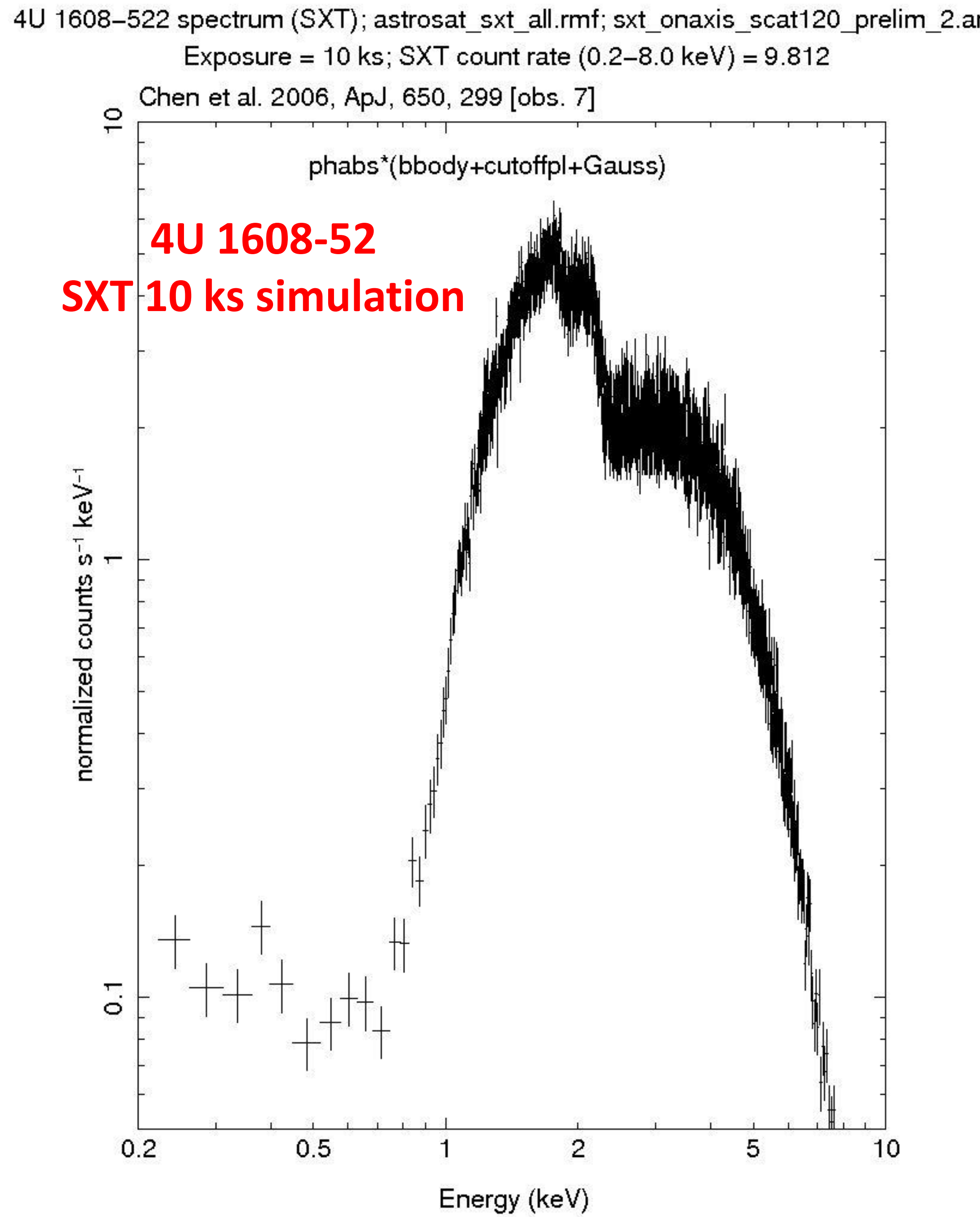
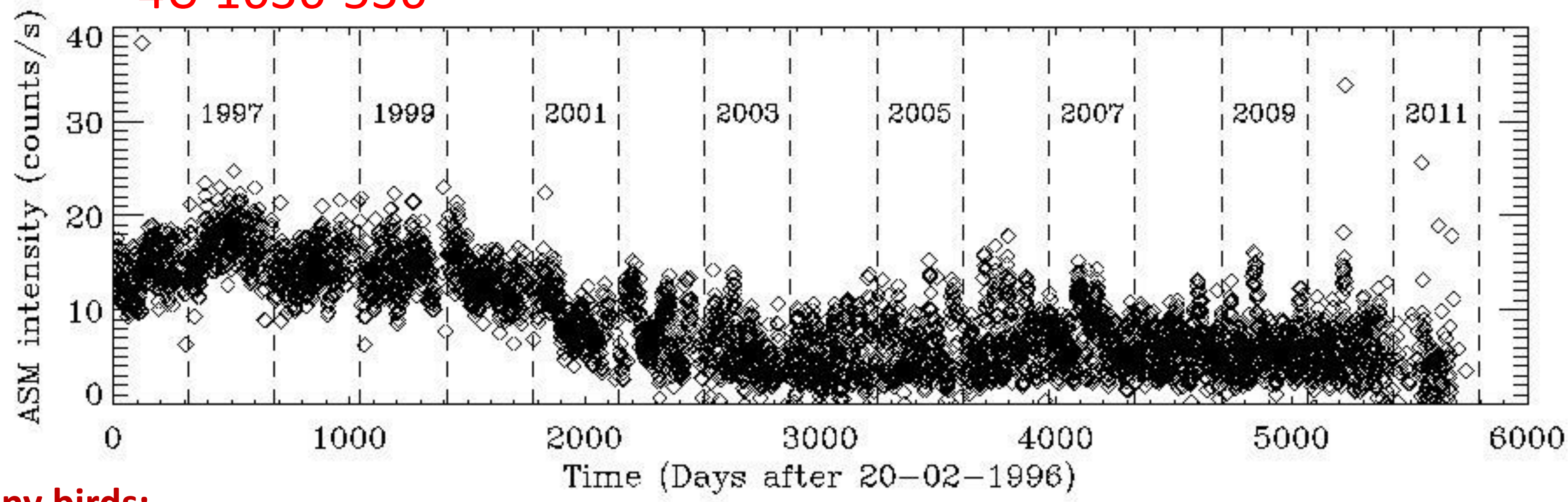


# 4. Multi-wavelength studies of NS LMXBs

## 4U 1636-536



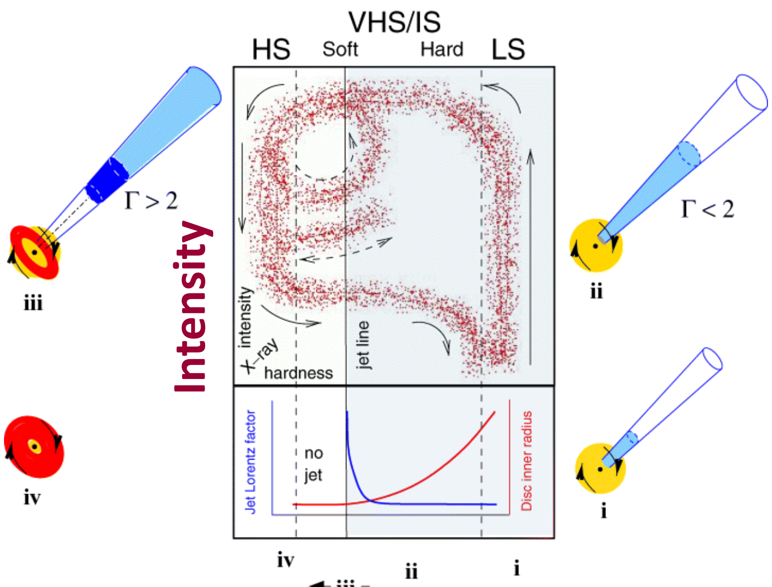

**Many birds:**

1. Thermonuclear bursts
2. Burst oscillations
3. mHz QPO
4. KHz QPO
5. Low-frequency QPOs
6. Relativistic disk line
7. Optical/UV observation possible
8. Burst reprocessing:
   (a) Superbursts
   (b) Known super-orbital period
   (c) Known orbital period

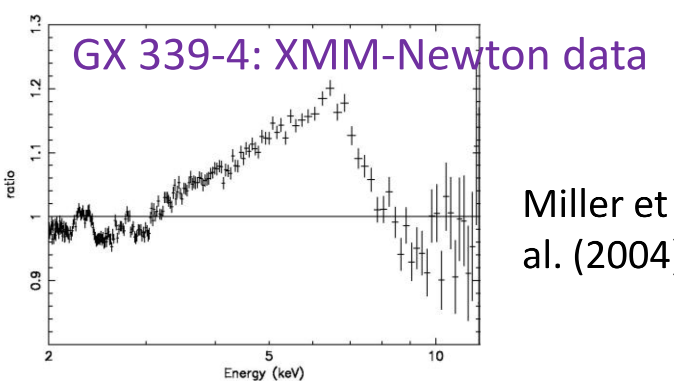
# 5. Relativistic disk lines

**A baseline science :** Observation of BHXB sources along the outbursts with high time resolution (e.g., 1-3 days), especially where the source moves fast. Study of relativistic disk line evolution. GX 339-4 is a suitable source with relatively frequent outbursts.

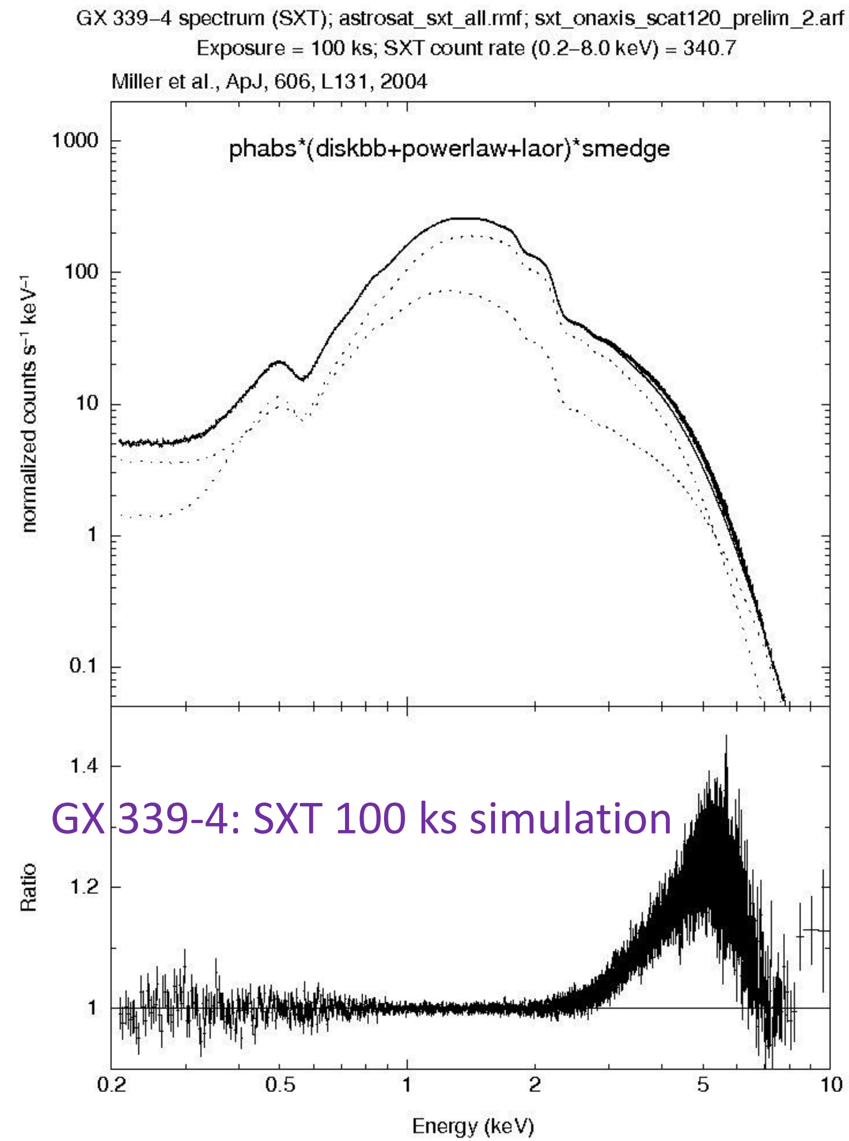
**Spectral state**




Fender et al. (2004)




Miller et al. (2004)



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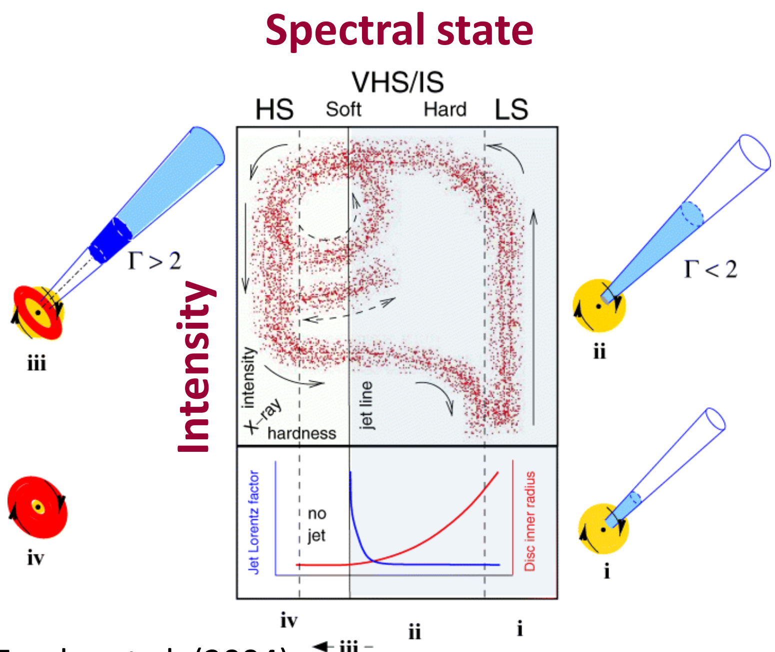
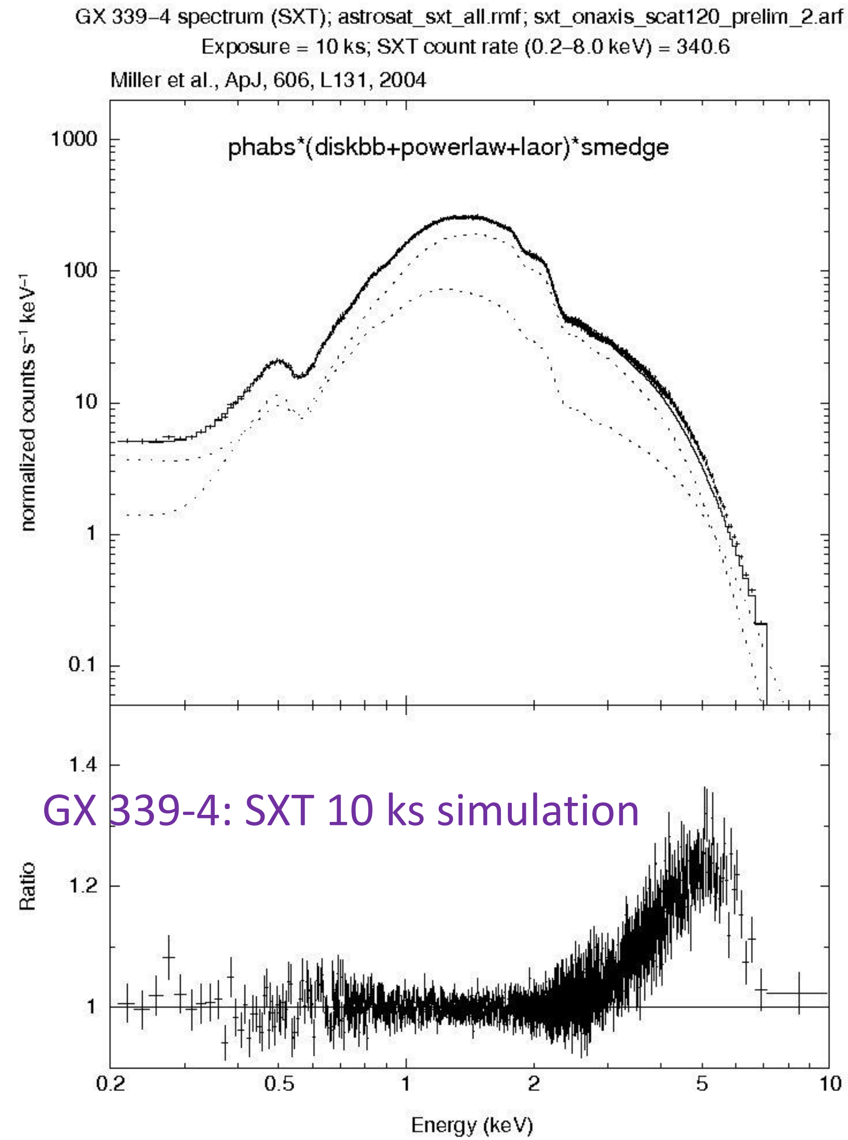
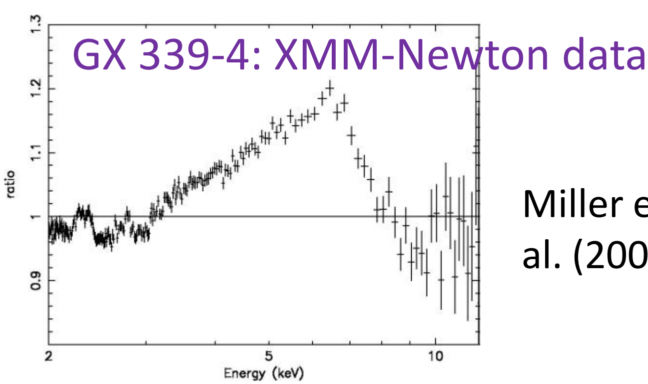



Fender et al. (2004)




Miller et al. (2004)

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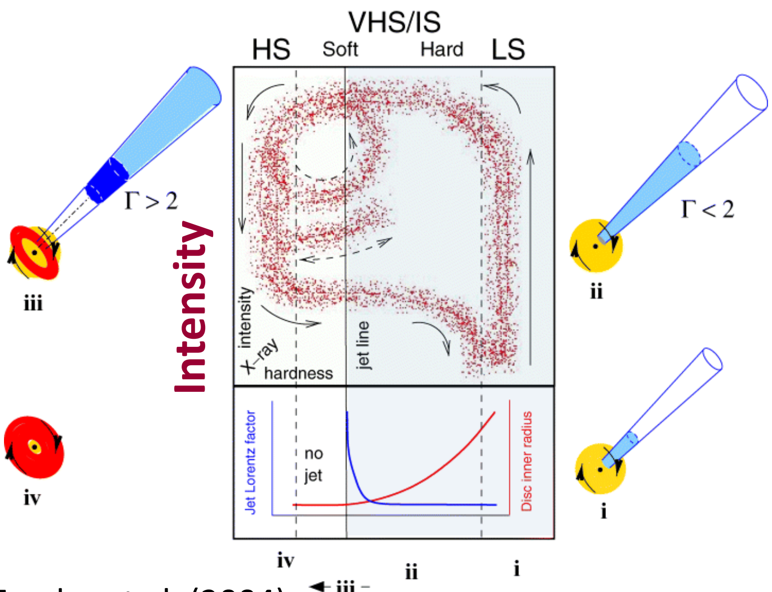
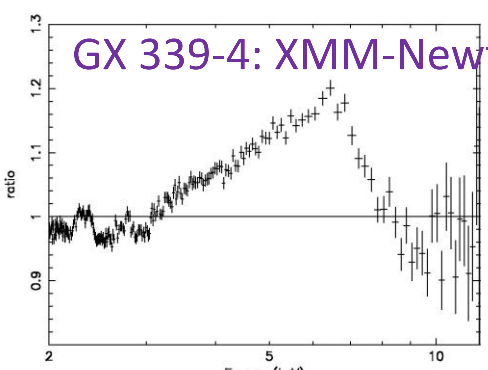
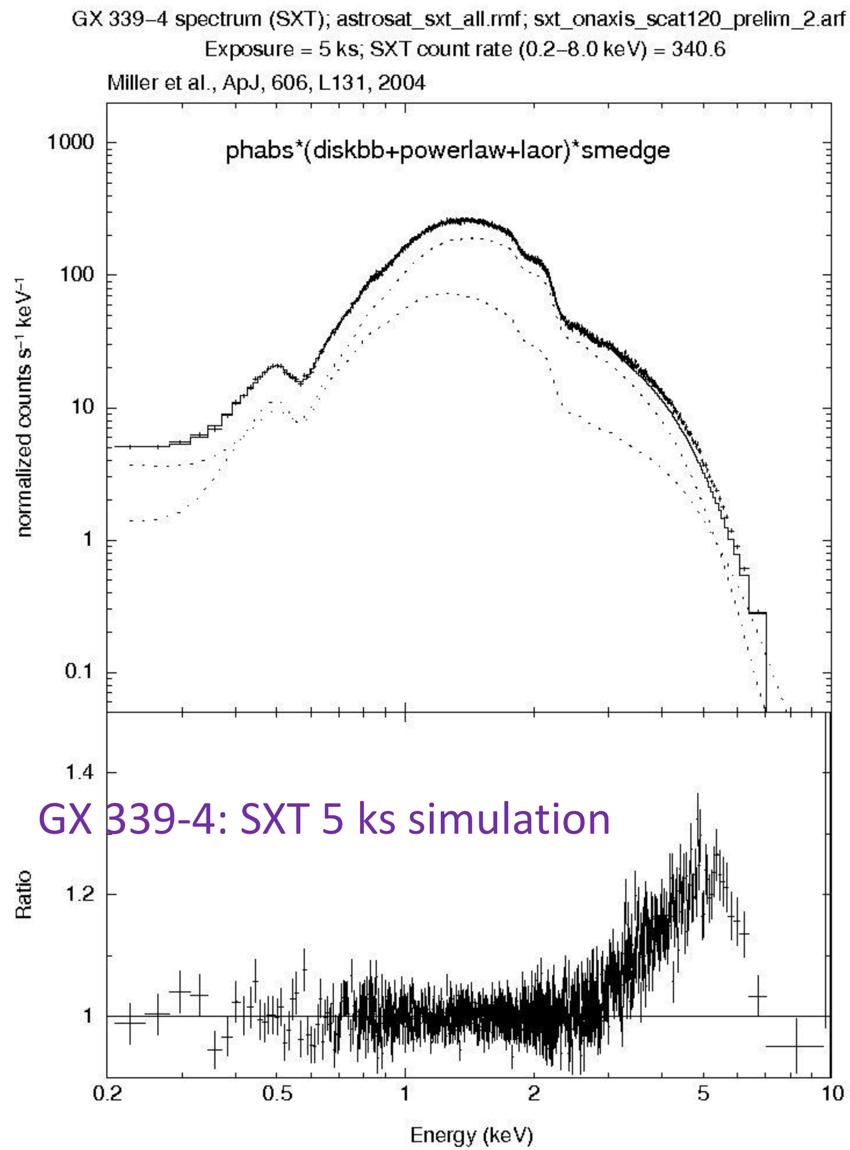



Fender et al. (2004)




GX 339-4: XMM-Newton data

Miller et al. (2004)




GX 339-4: SXT 5 ks simulation

# 6. Galactic bulge scan

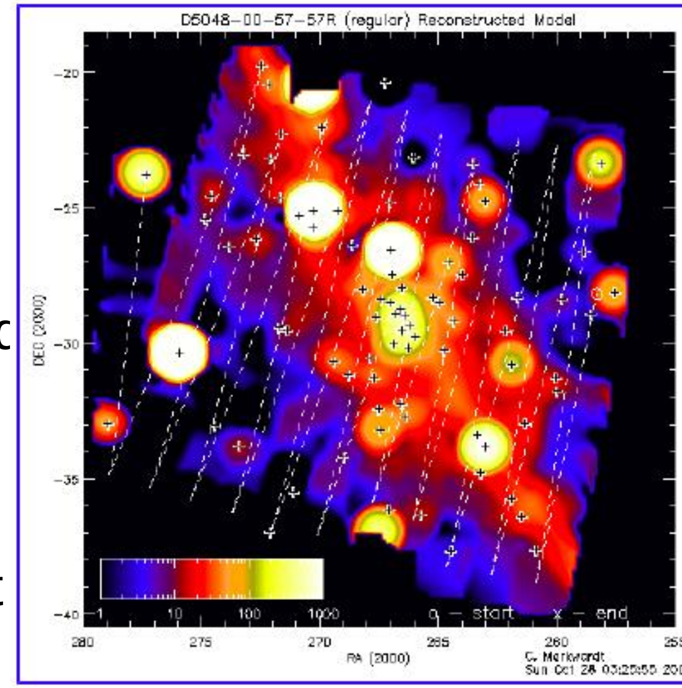
## With RXTE PCA

### What?

RXTE PCA scanned Galactic bulge + up to 26$^{o}$ along Galactic longitude on each side (total ~500 sq. degrees) twice a week; each time 4 orbits were used. Continuous slew of 11$^{o}$ (at 6$^{o}$ per minute), settling for 110 sec, then again slew for 11$^{o}$ and so on.

### Why?

1. Most of the X-ray transients are expected to be in the Galactic bulge and plane.
2. ASM could not detect smaller outbursts and early phases of outbursts. In the crowded bulge region, PCA could detect up to 1 mCrab (depending on location, known vs. unknown source, etc.), while ASM was confusion limited at about 50 mCrab.
3. With PCA observations, more informed decision could be made about a possible pointed observation.




RXTE PCA Galactic bulge scan: constructed image.

Courtesy:http://asd.gsfc.nasa.gov/Craig.Markwardt/galscan/

# 6. Galactic bulge scan

## With RXTE PCA

**Results:**

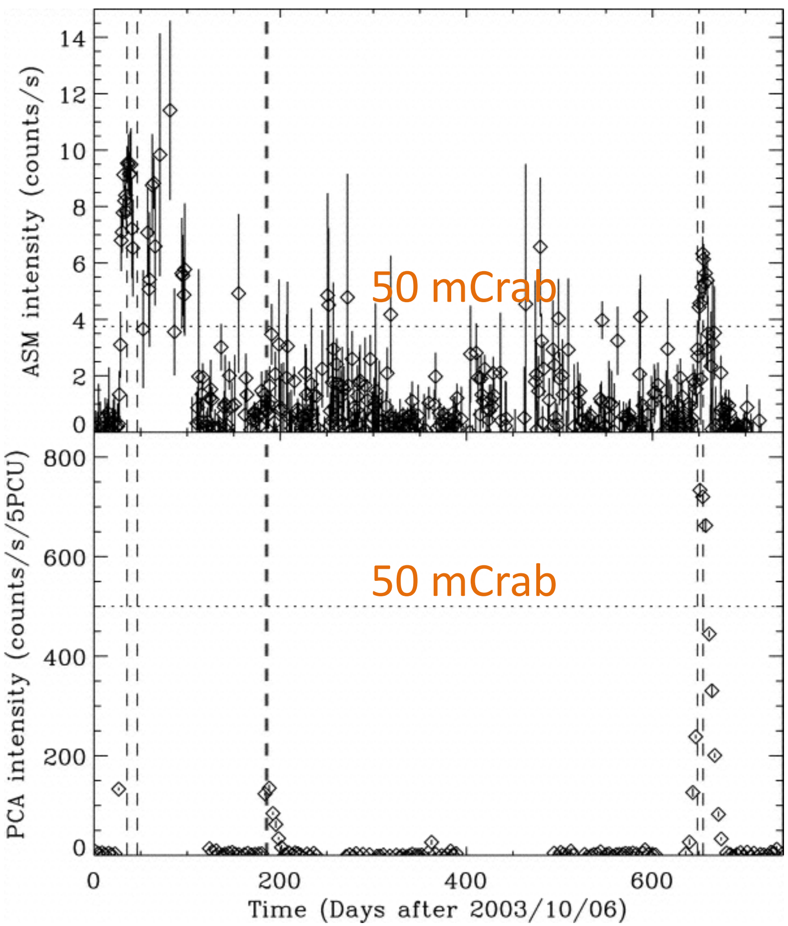
Galactic bulge scan with RXTE PCA and the corresponding follow-up observations led to important discoveries.

Examples:

1. Detected about 150 sources, of which about 33 were newly discovered (or co-discovered) [up to ~2007].
2. Discovered 3 new accreting ms pulsars [up to ~2007].
3. The early PCA detection of the October 2002 outburst of SAX J1808.4--3658 enabled pointed observations to catch four X-ray bursts that contained oscillations at the spin frequency, a long sought after goal.

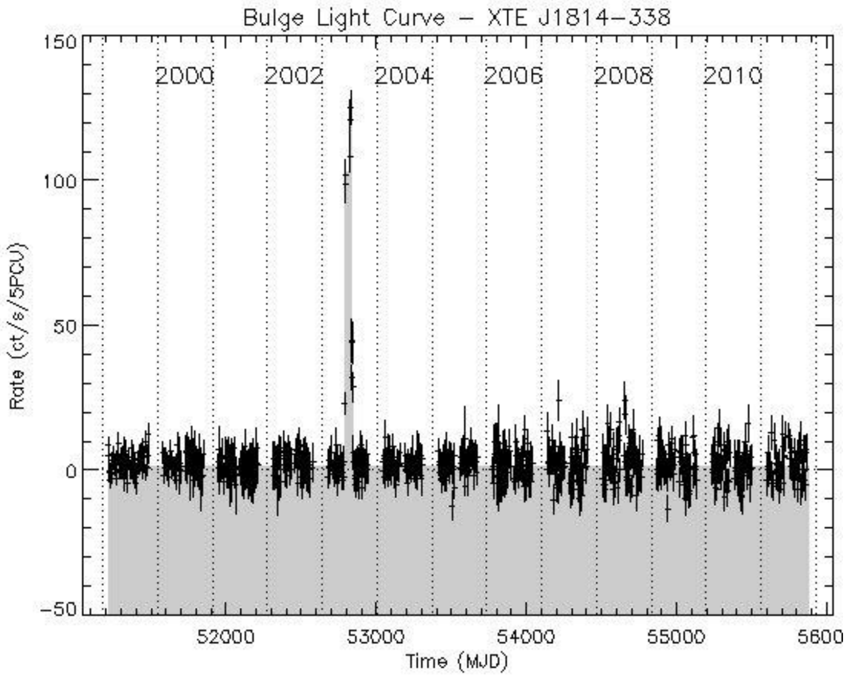
**Example**: For 1A 1744-361, ASM could not detect the second outburst. But the first discovery of QPOs from this source was made during *this* outburst.

1A 1744-361




SB et al. (2006)

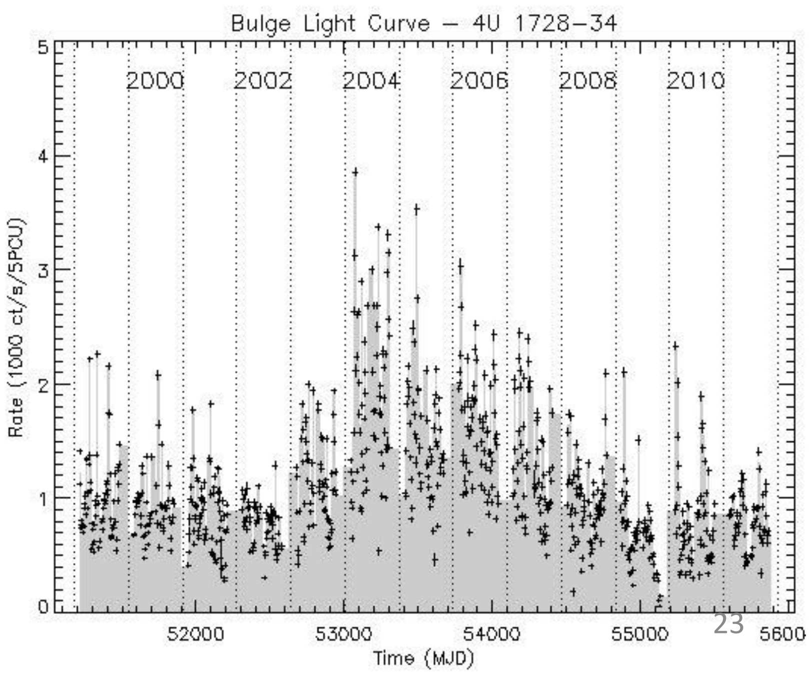
# 6. Galactic bulge scan
## With RXTE PCA




RXTE PCA Galactic bulge scan of the accreting ms pulsar XTE J1814-338

The outbursts of accreting ms pulsars are usually small.
(Should be kept in mind when planning for selection of outbursts for pointed observation).

RXTE PCA Galactic bulge scan of 4U 1728-34




Courtesy:
http://asd.gsfc.nasa.gov/Craig.Markwardt/galscan/

# 6. Galactic bulge scan
## With LAXPC

**Why will ASTROSAT do better than RXTE?**

1. SXT and CZT will identify the sources during follow-up observations. RXTE did not have such imaging instruments.
2. Unlike RXTE PCA, LAXPC will detect outbursts from hard X-ray transients.

**What we may expect from LAXPC Galactic bulge scan:**

1. Detection of new sources (including accreting ms pulsars and black holes) and new features from known sources.
2. Unexpected discovery of new kinds of sources, and new kinds of timing and spectral features.
3. Finding parameter values of sources in new (or, unexpected) range. For example, a neutron star with spin frequency greater than 1000 Hz will address problems of fundamental physics.
4. Long term light curves will make the periodicity search possible.
5. **Sensitive detection of outbursts will spur national and international collaborations, and the follow-up observations of both soft and hard X-ray transients will address important scientific problems**.

**Plan: Scanning only the Galactic bulge once in a week may require 2% of the total observation time. This might partially be provided from the ToO time.**

# 7. NS LMXBs: other science goals

1. **Burst continuum spectrum:** NS radius measurement, etc., and study of systematics due to non-burst emission evolution during bursts.

   Advantages:

   (a) Burst spectrum (LAXPC) and non-burst spectrum (all X-ray instruments)

   (b) Full LAXPC area (RXTE collected most bursts with reduced area)

   (c) Known best sources from RXTE observations

2. **Burst oscillations:** (a) Measurement of new neutron star spin frequencies (Important to understand binary evolution, gravitational radiation, disk-magnetosphere interaction, etc.)

   (b) Flame spreading, NS parameter measurement (Full LAXPC area)

3. **Discovery of interesting burst behavior from transients:** Unique bursts were discovered from IGR J17480-2446 in the 15th year of RXTE.

# 7. NS LMXBs: other science goals

4. Accreting (ms) pulsars: (a) Target faint outbursts of new transients with ToO to increase the sample size
   (b) Possible discovery of sub-ms pulsars (impact on NS EoS models, binary evolution, gravitational radiation, disk-magnetosphere interaction)
   (c) Broadband spectral and timing studies of pulsars to understand them better. Especially target burst oscillation sources
   (d) Model fitting to constrain neutron star properties
   Advantages: Access to higher energies (LAXPC, CZT; best sources are known from RXTE observations)

5. CD and HID for higher energies to find new trends (LAXPC).

6. Broadband study of low-frequency features.

# 8. Isolated NSs

1. **Rotation Powered Pulsars (RPP)**

   **[total ~ 2000; ~100 in X-rays; ~10 in NIR/optical/UV]**

   **[Non-thermal: from magnetosphere (radio to Gamma-ray); Thermal: from NS surface and polar cap (UV to soft X-rays)]**

   **including Rotating Radio Transients (RRAT)**

   **[~70; only PSR J1819-1458 in X-rays]**

2. **Compact Central Objects (CCOs) in SNRs**

   **[~10; observed only in (soft) X-rays]**

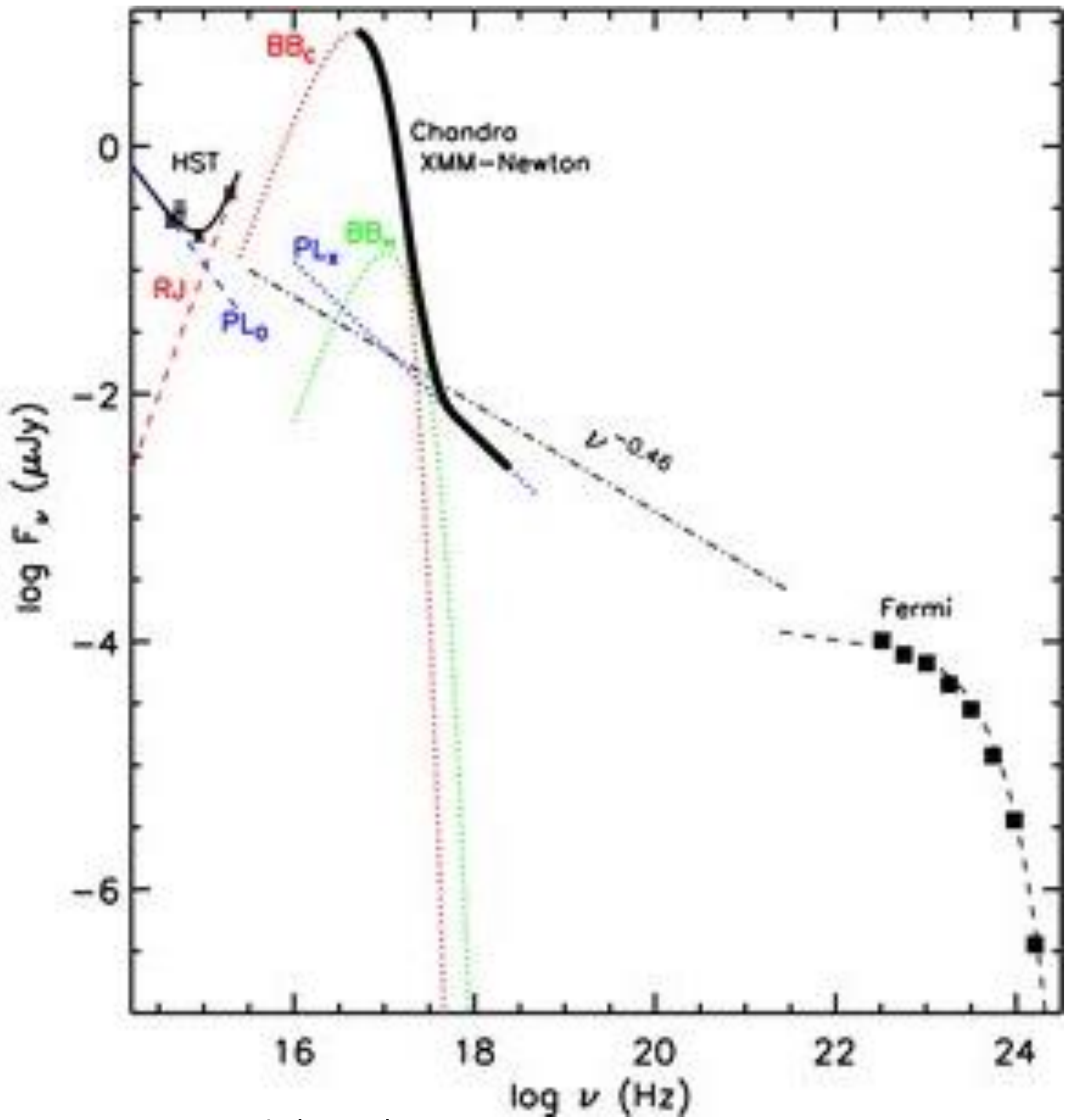
3. **Thermally Emitting NSs (TENSs/XDINSs/M7)**

   **[total 7; observed only in X-rays + faint optical/UV]**

4. **Magnetars**

   **Anomalous X-ray Pulsars (AXPs) and Soft Gamma-Ray Repeaters (SGRs)**

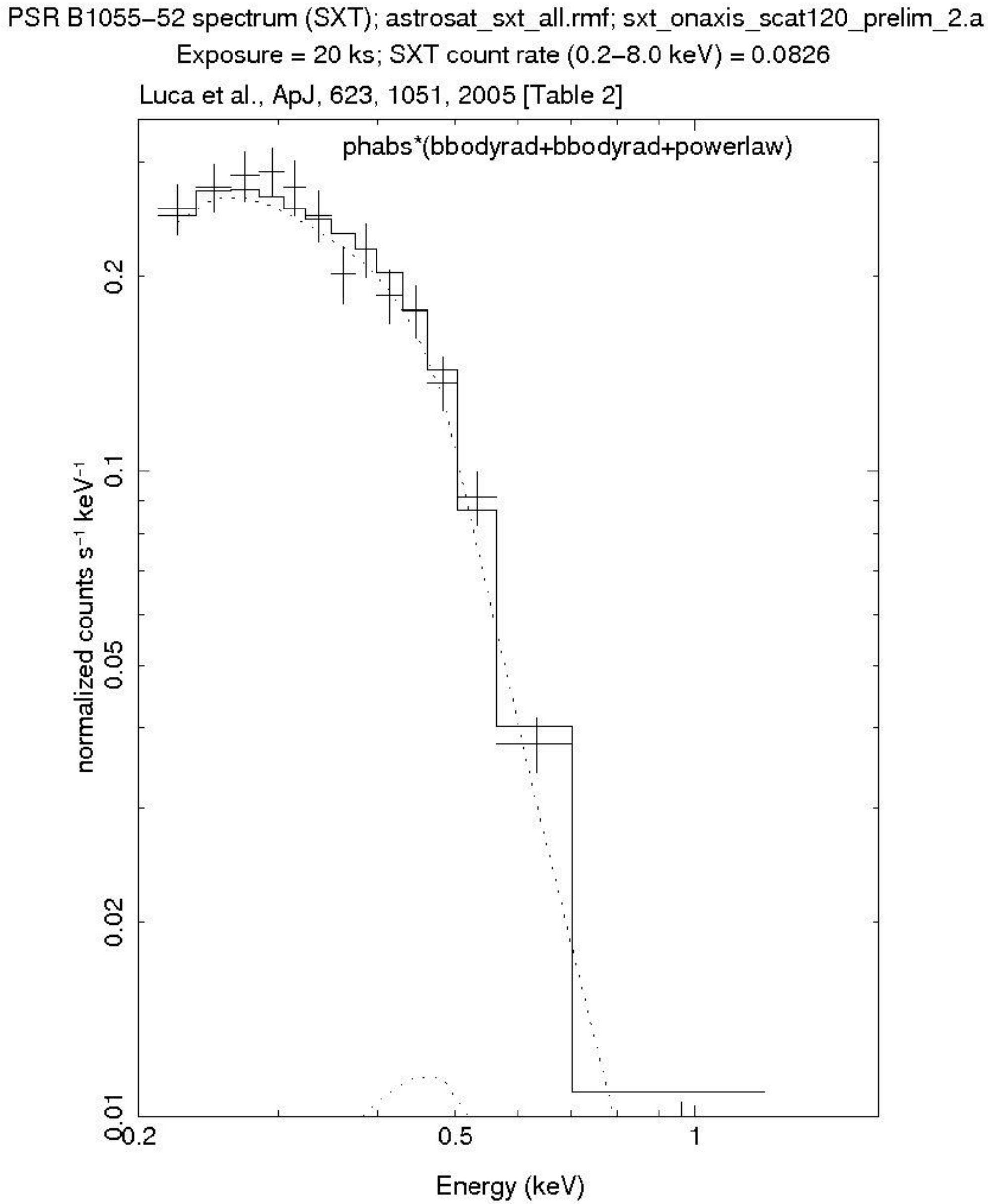
# 8. Isolated NSs




Mignani et al. (2010)

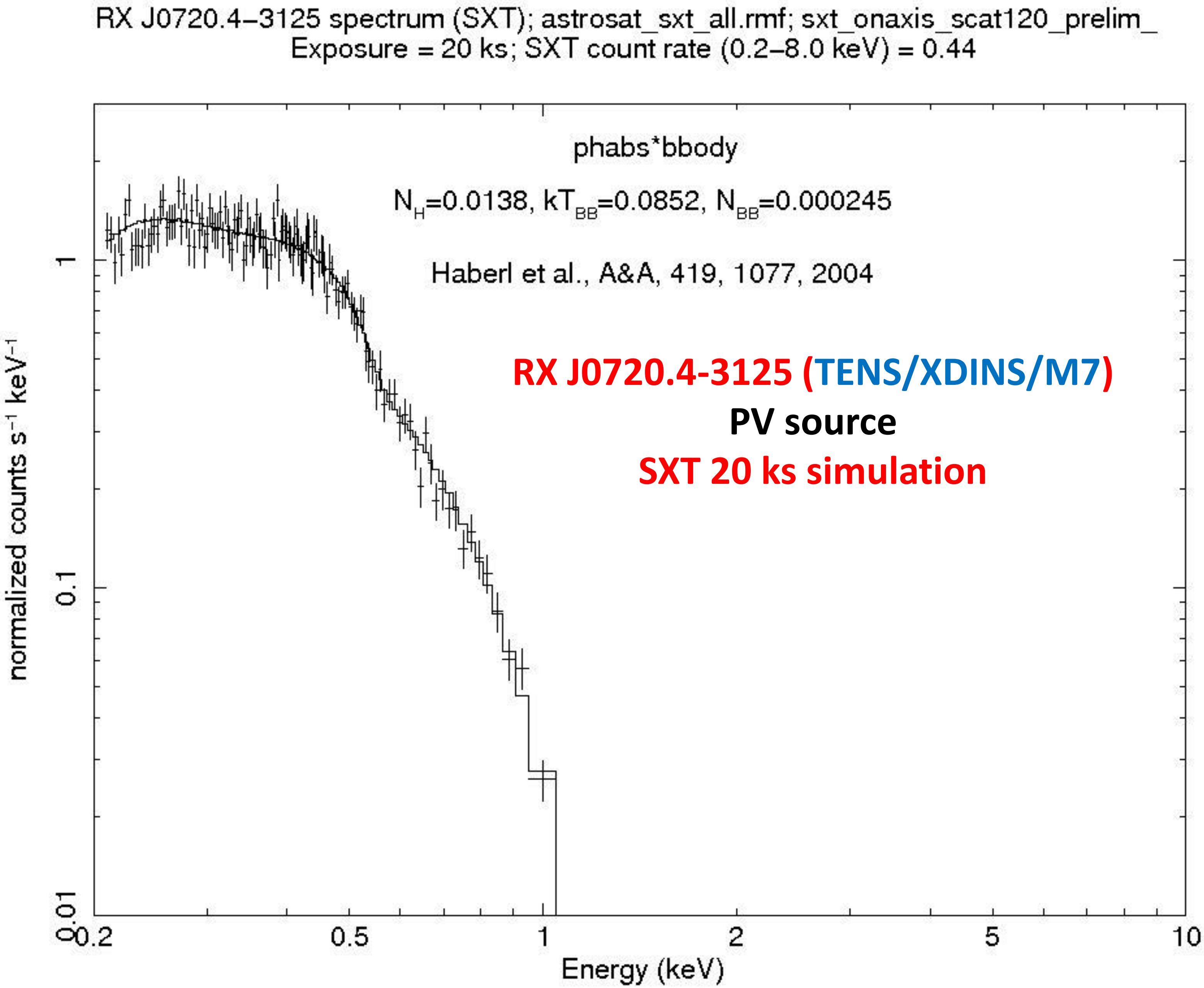
**Multi-wavelength spectrum of PSR B1055-52 (RPP)**

# 8. Isolated NSs

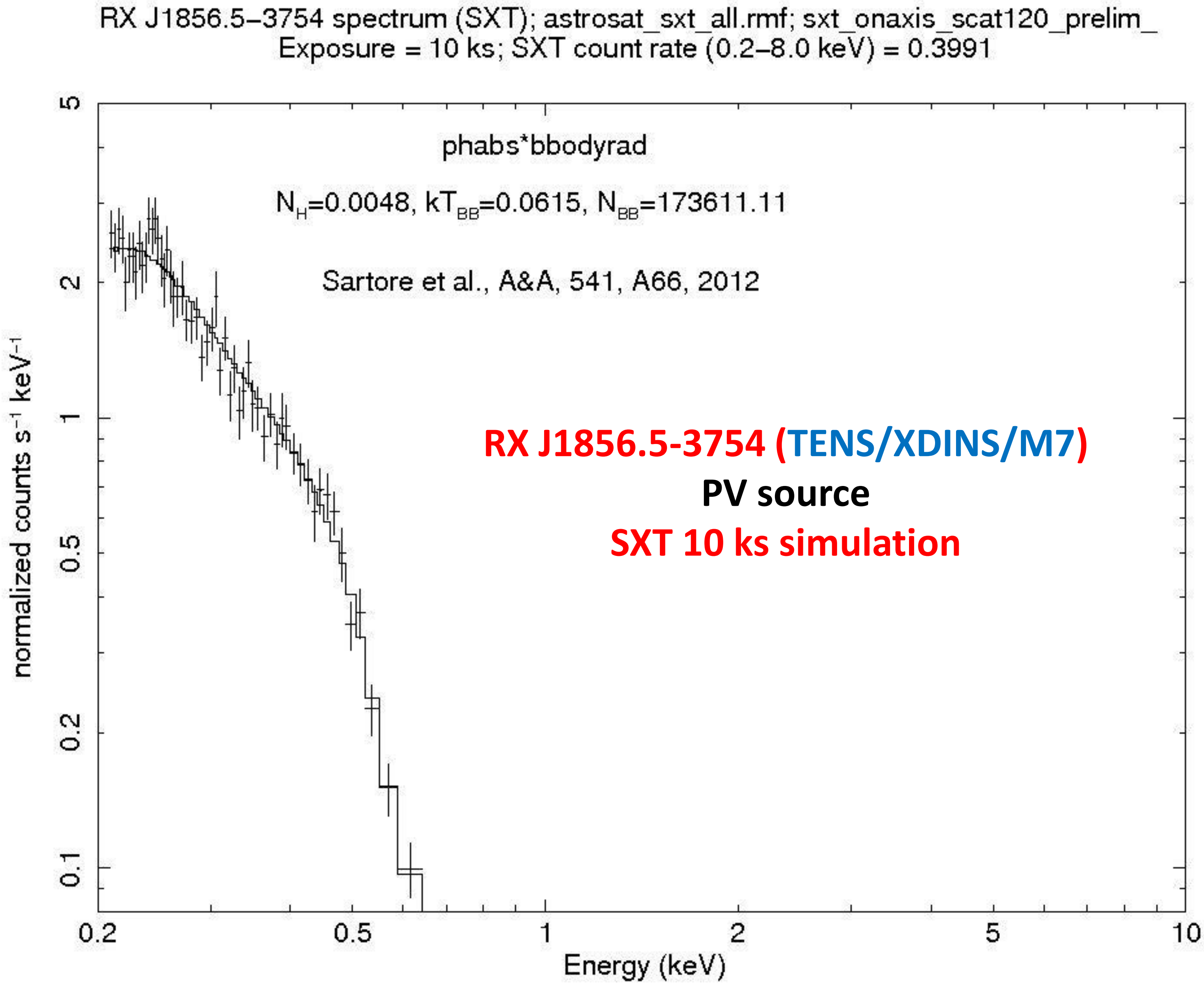



**PSR B1055-52 (RPP)**
**SXT 20 ks simulation**

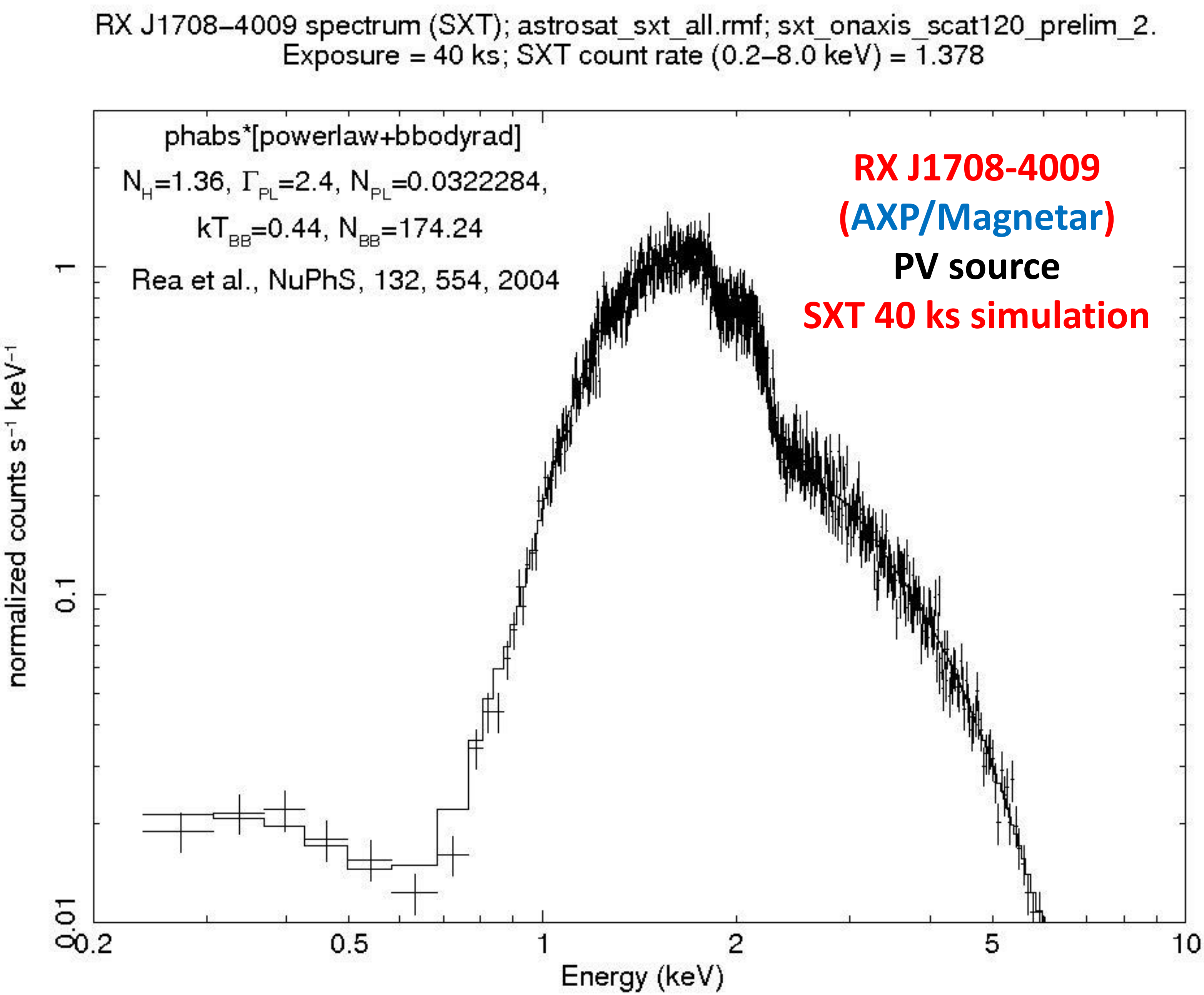
# 8. Isolated NSs



# 8. Isolated NSs



# 8. Isolated NSs



**For good planning of simultaneous X-ray/UV/optical observations, X-ray astronomers (team members and all other users) need to know:**

1. how to create an SED from UVIT and X-ray instruments and how to fit a model to it; how to calculate time-lag, cross-correlation, etc. using the data from UVIT and X-ray instruments ;

2. how to create simulated UVIT data;

3. how to decide on the best filter/instrument/mode combination for UVIT for a given science.

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**Thank you!**