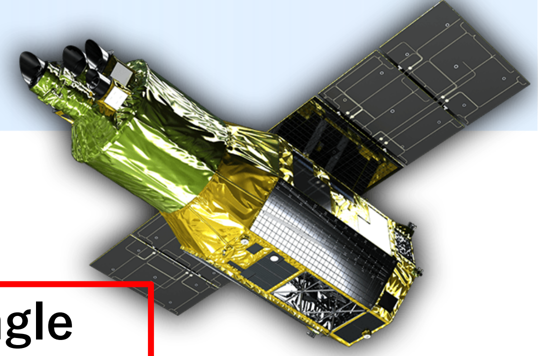
超小型X線衛星NinjaSatが目指すサイエンス
Science for the micro X-ray satellite, NinjaSat

W.Iwakiri (Chuo Univ.), T. Enoto, T.Tamagawa, T.Kitaguchi, Y.Kato, M.Numazawa, T.Mihara(RIKEN), T.Takeda, Y.Yoshida, N.Ota, S.Hayashi, K.Uchiyama (Tokyo Univ. of Sci), H.Sato(Shibaura Inst. of Tech), H.Takahashi (Hiroshima Univ.), H.Odaka, T.Tamba (The Univ. of Tokyo), Chin-Ping Hu (National Changhua University of Education), K.Taniguchi(Waseda Univ/RIKEN)

X-ray astronomy : recent problems



https://xrism.isas.jaxa.jp/

X-ray observation needs to be performed outside the atmosphere.

Problem 1

Difficult to observe a single object for a long time because X-ray satellite is a public observatory

How many X-ray sources are known currently?

Year	No. Unique X-ray Sources known	Based on
1960	0	(excluding the Sun)
1962	1	Rocket experiments
1965	10	Rocket experiments
1970	60	Rocket & balloon experiments
1974	160	3rd Uhuru Catalog
1980	680	Amnuel et al. (1982) Catalog
1984	840	HEAO A-1 Catalog
1990	8,000	Einstein & EXOSAT source catalogs
2000	340,000	ROSAT source catalogs
2010	780,000	above + XMM-Newton & Chandra detected sources
2017	1,250,000	above + XMM-Newton, Swift & Chandra detected sources

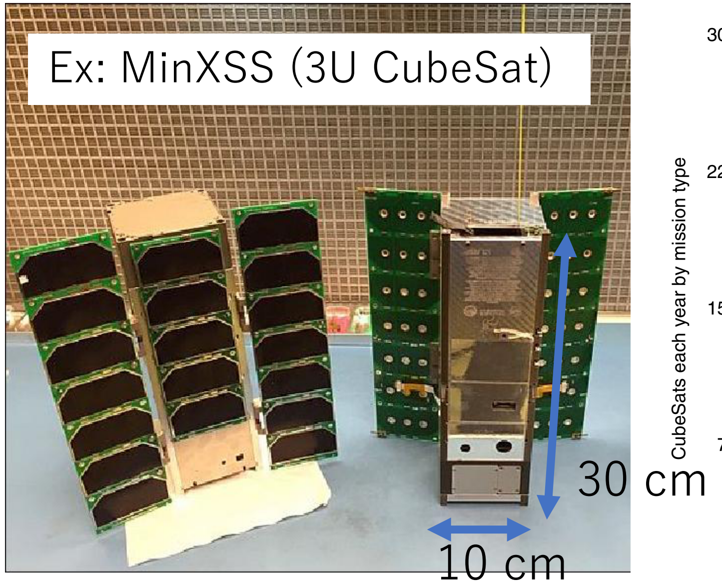
https://heasarc.gsfc.nasa.gov/docs/heasarc/headates/how_many_xray.html

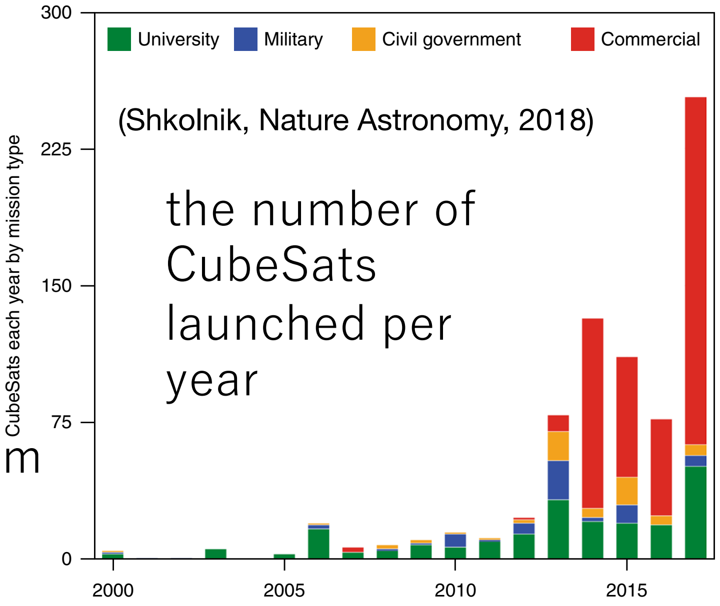
Problem 2

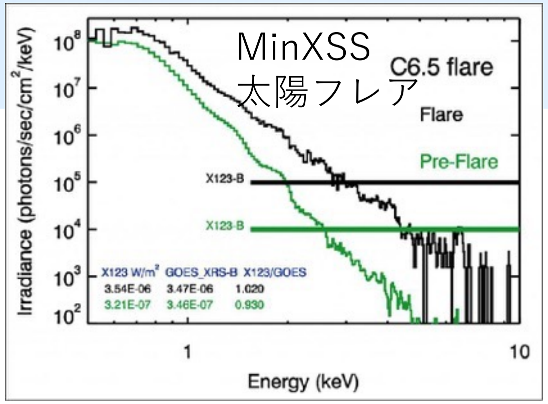
Difficult to design an observation instrument that can cover all the objects.
As a result, bright objects are out of the target because they are few in number.

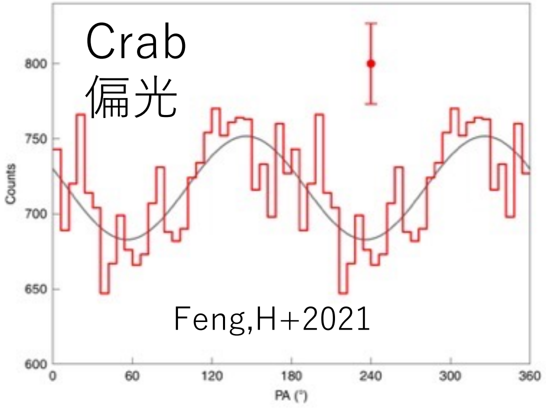
Recently, it is not possible to make long-term observations of bright X-ray sources

CubeSat



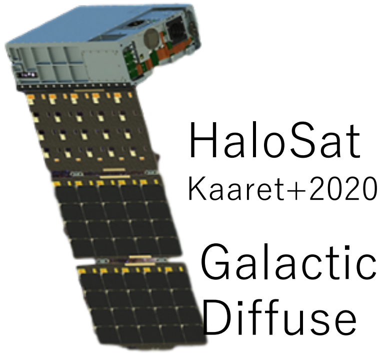






CubeSat : made up of multiples of 10 cm³ cubic units called 1U

The commercial use of CubeSats has expanded rapidly in the 2010s, and their use as X-ray astronomy satellites has been increasing.



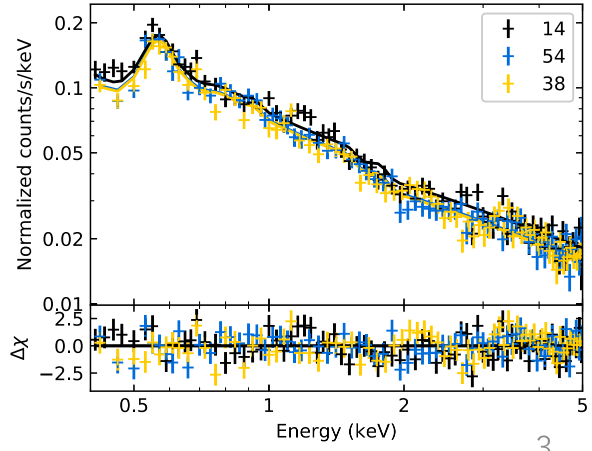
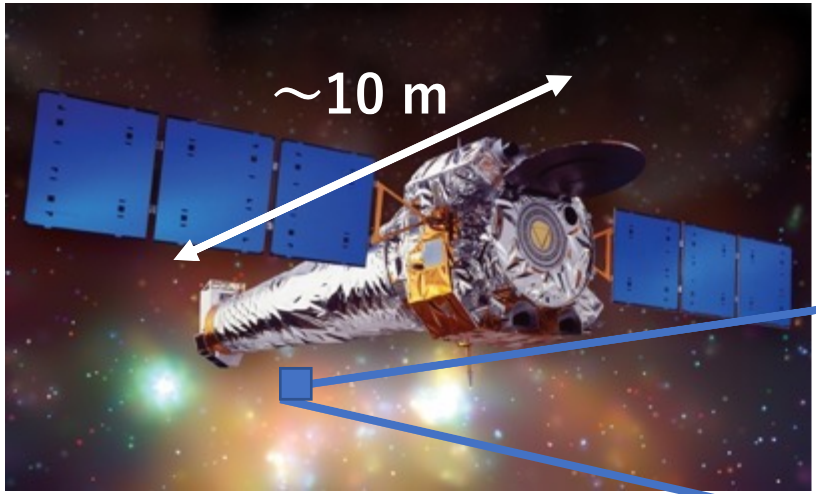
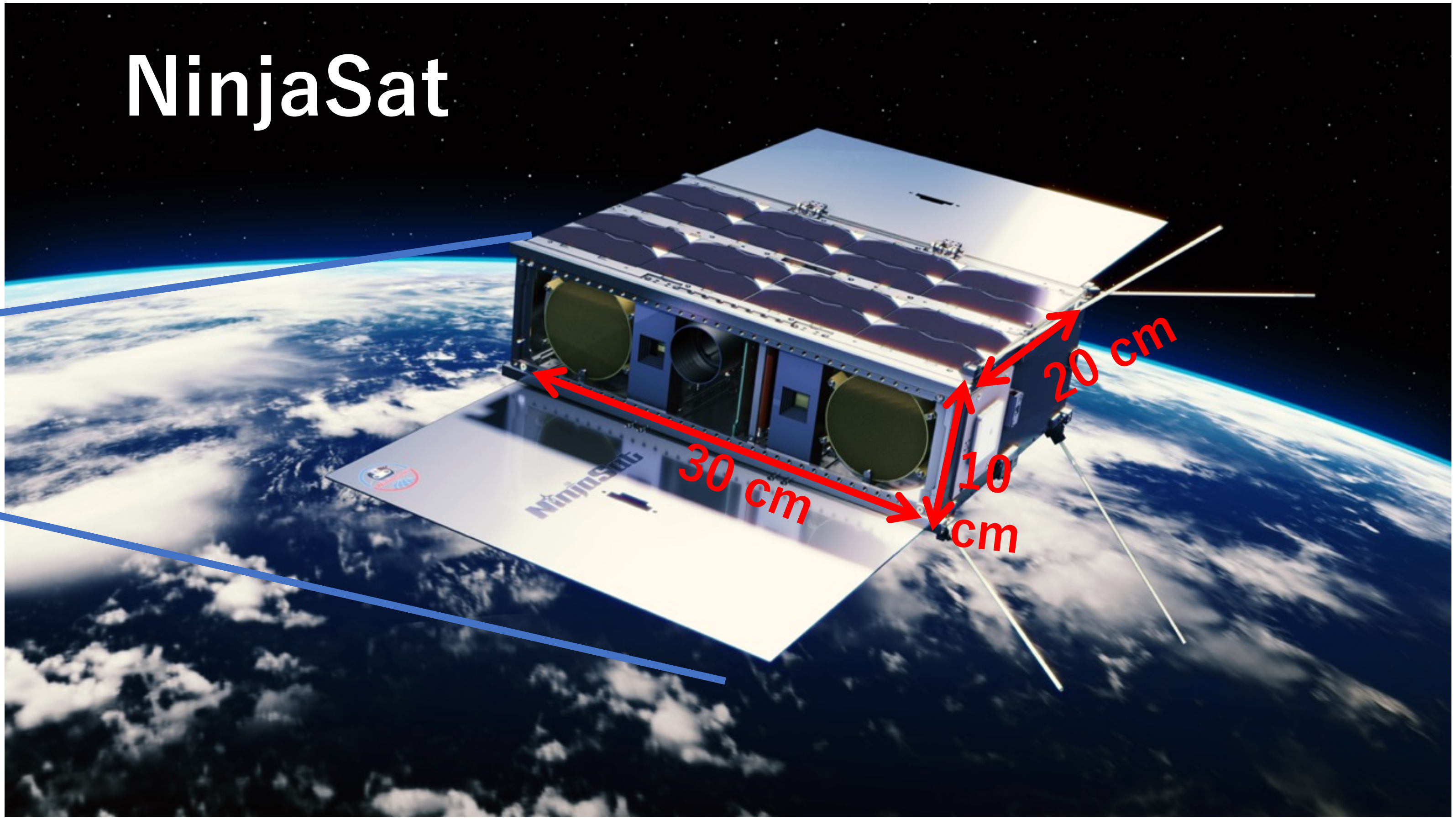


Figure 9. X-ray spectra of a halo field. Data from all three detectors are shown as indicated by the legend.

NinjaSat, small satellite for observing bright X-ray sources



Need a small satellite which acts behind huge X-ray satellite like a "Ninja"

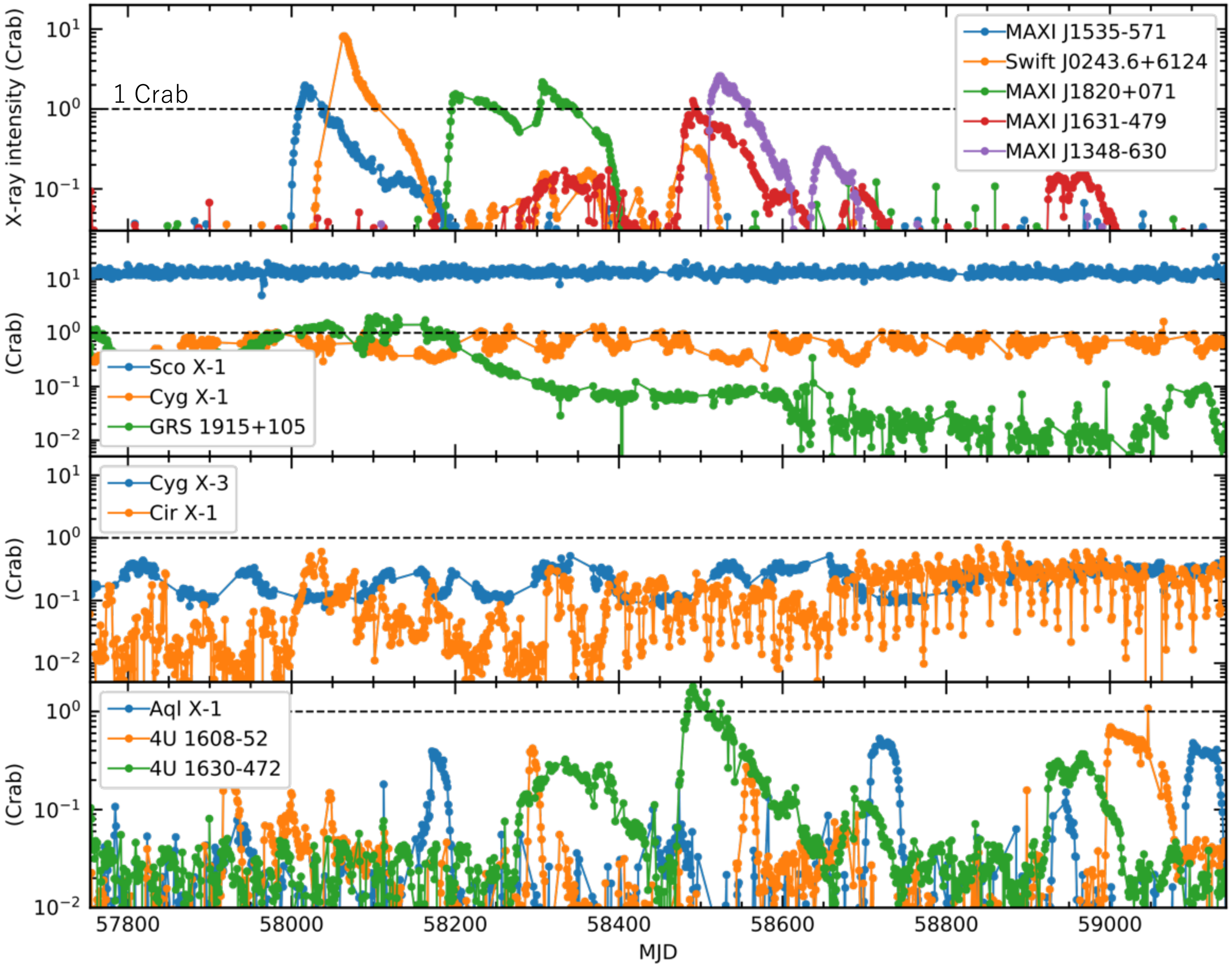


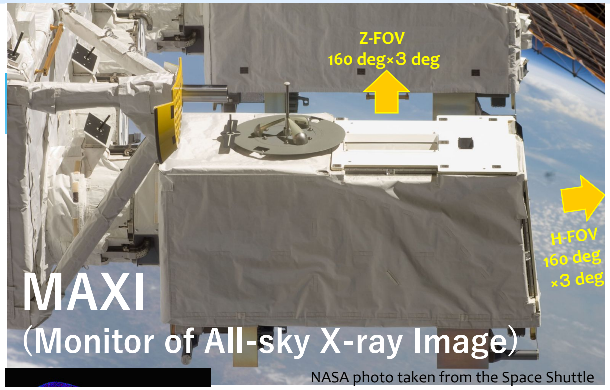
We proposed "NinjaSat", small satellite for observing bright X-ray sources

Purpose:
1. Long-term (several months) monitoring of bright objects
2. Flexible ToO and simultaneous multi-wavelength observation arrangements

What kind of sources are the targets of NinjaSat?

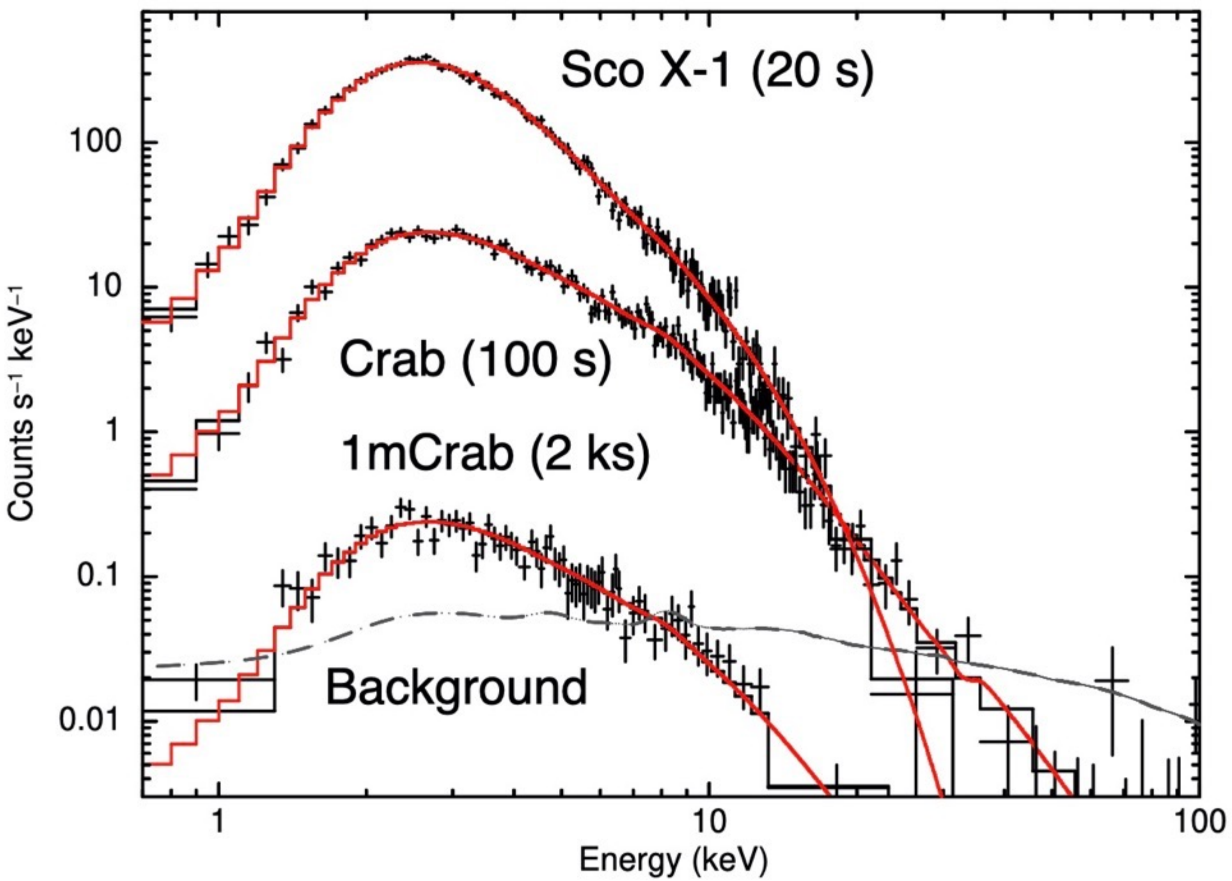
MAXI lightucurves (2-20 keV) of bright X-ray sources

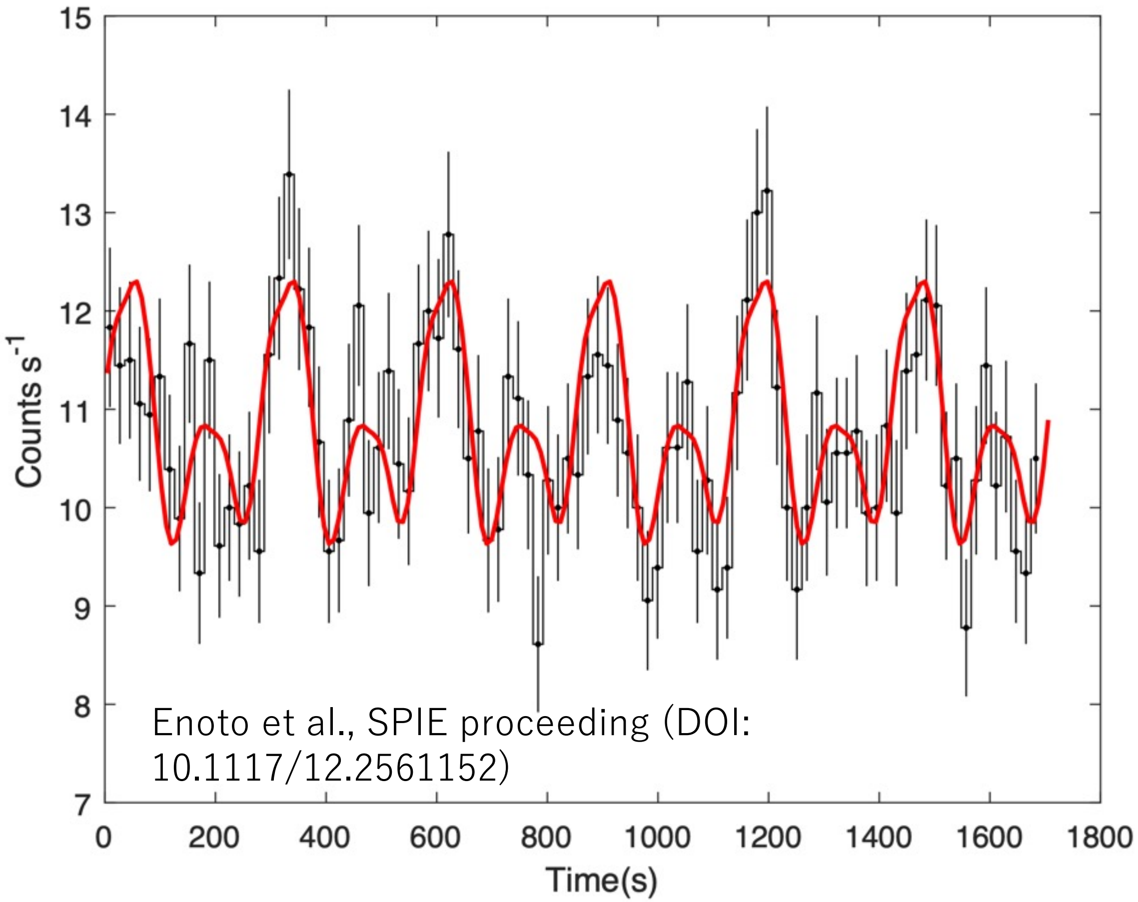




- Bright X-ray Nova (BH)
- Giant outburst of Be X-ray pulsar (as for ULX pulsars, see Karino-san's talk)
- Long-term observation of most bright X-ray source Sco X-1 → important to detect Continuous Gravitational Waves (see Ito-san's talk)
- Long-term monitoring of soft X-ray transients → Recurrence time, persistent flux, and burst profile of X-ray bursts (see Dohi-san's talk)

Spectroscopy & Photometry — Simulations

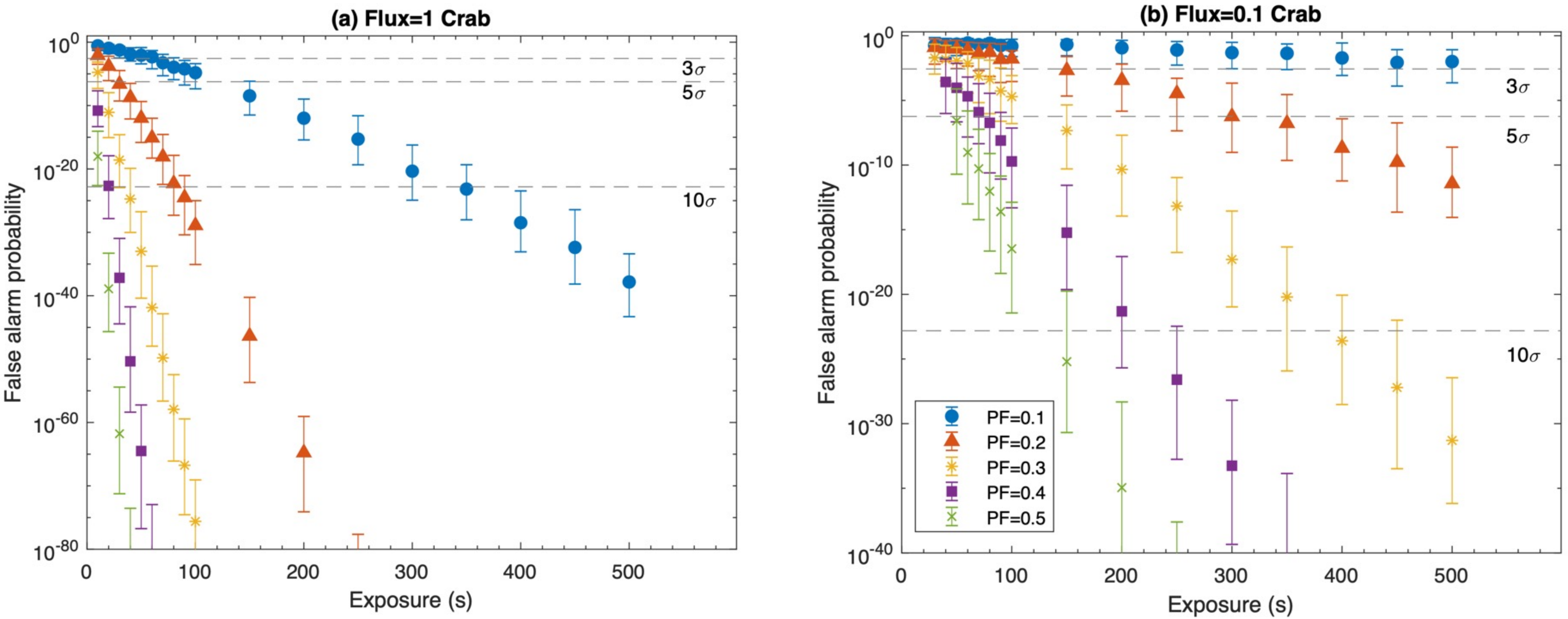




Enoto et al., SPIE proceeding (DOI: 10.1117/12.2561152)

- Expected 2-20 keV rates: 94 cps for Crab, 910 cps for Sco X-1 at a normal branch, 10 cps for Vela X-1, 0.8 cps for backgrounds (NXB+CXB)
- Sensitivity (2-20 keV): 1.5×10^{-11} ergs s^{-1} cm^{-2} (~0.5 mCrab) in 10 ks

Timing analyses — Pulsation search sensitivity



- Required exposure for 5σ detections of pulsations
  - ~100 sec required (10% pulsed fraction, 1 Crab source)
  - ~200 sec required (40% pulsed fraction, 100 mCrab source)

Enoto et al., SPIE proceeding
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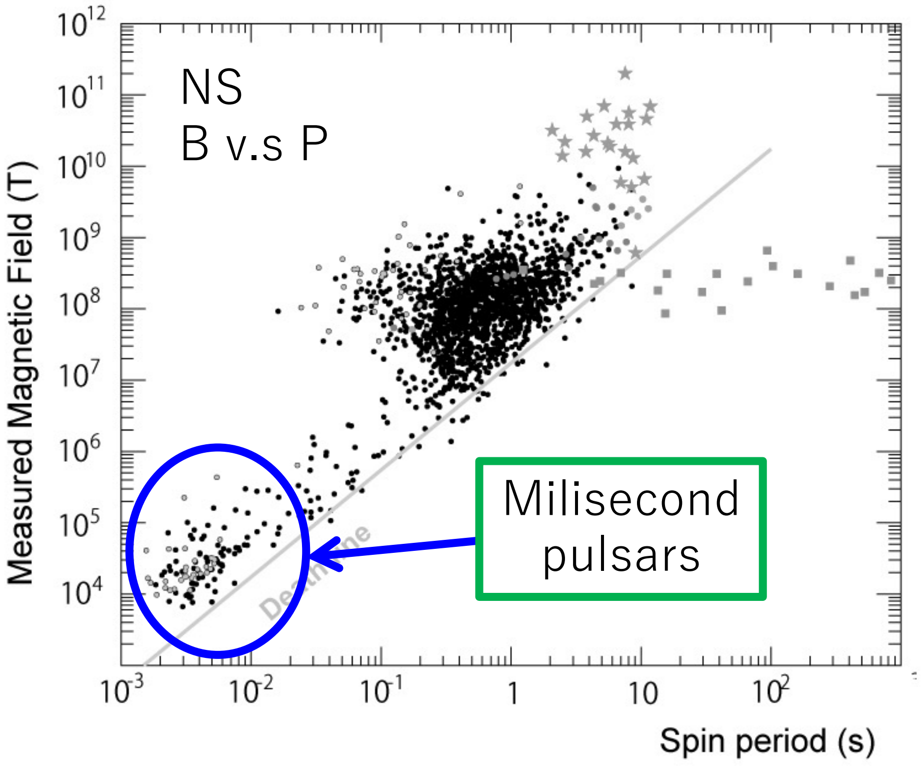
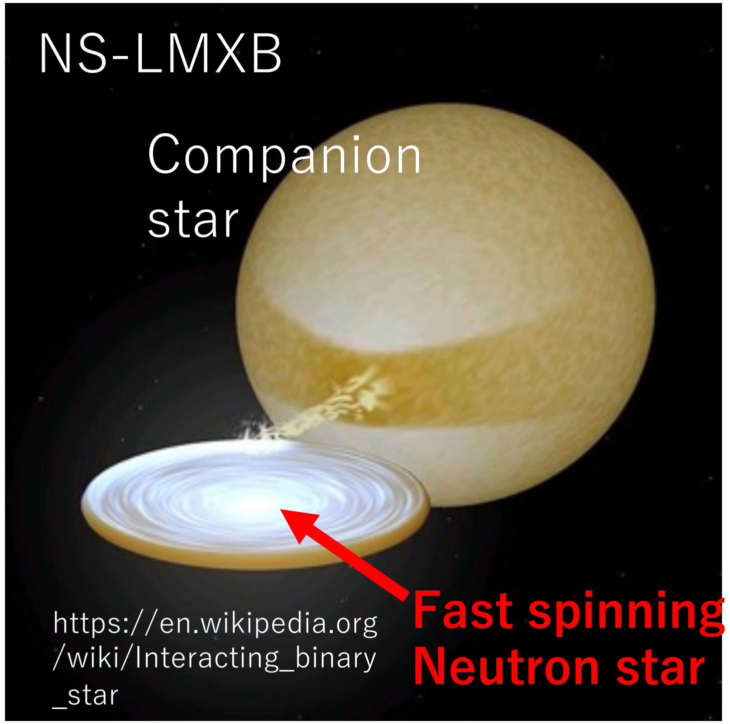
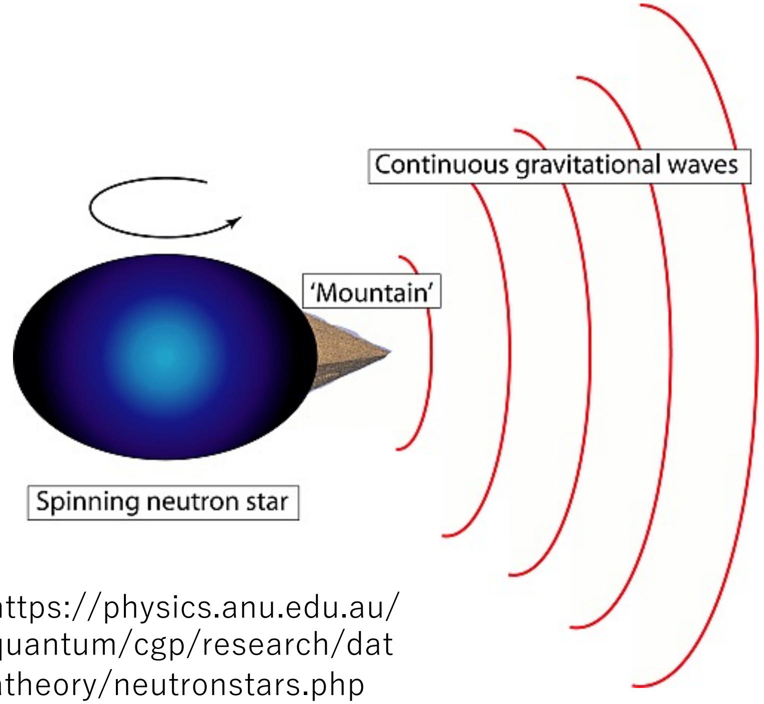
NS-LMXBs: CGW candidate



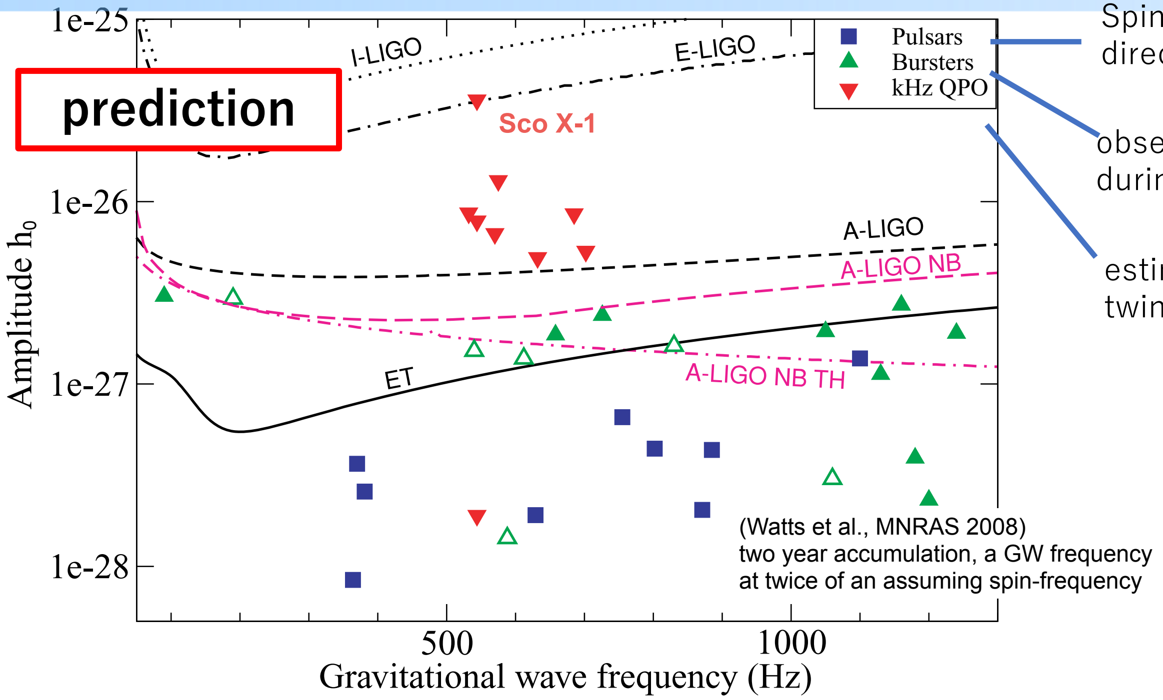




https://physics.anu.edu.au/quantum/cgp/research/datatheory/neutronstars.php

- NS Low Mass X-ray binary: NS-LMXB is a binary system of NS and normal star
- In such a system, the matter of the companion accretes to NS
- NS has been spun-up due to angular momentum of the accretion matter
- The critical spin-frequency of collapse of NS by centrifugal force is estimated ～1 kHz
  →However, observed spin frequencies of NS-LMXB is distributed in ～200 – 600 Hz
  →CGW pulls out the angular momentum? non-axisymmetry due to mountains?

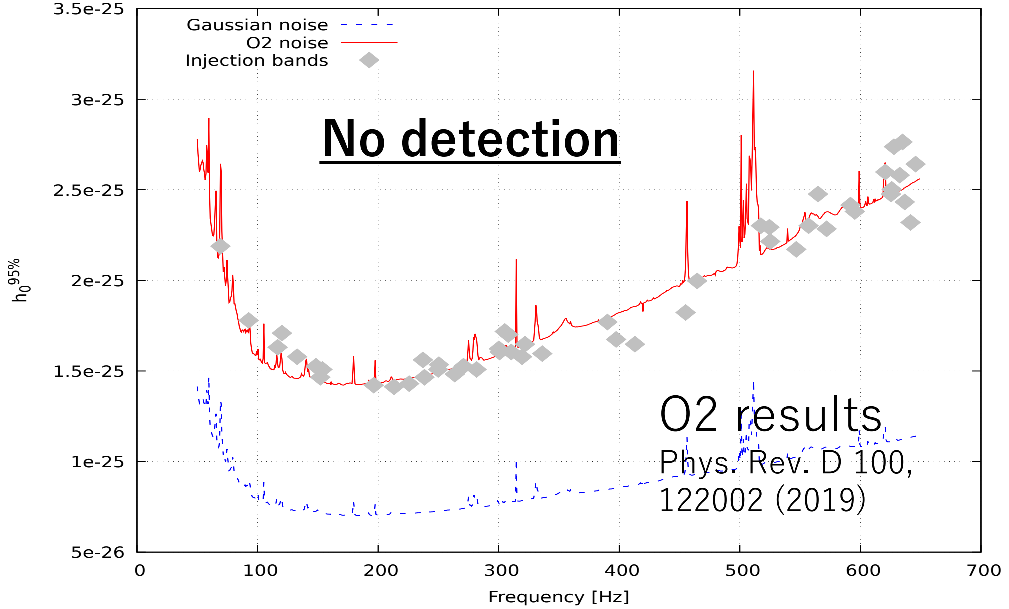
Theoretical prediction of CGWs from NSs and problems with their detection



Spin measured directly

observed only during X-ray burst

estimated from twin-kHz QPO



Expected CGW amplitude:

$$h_0 = 3 \times 10^{-27} \left(\frac{F}{10^{-8}\,\mathrm{erg\,cm^{-2}\,s^{-1}}} \right)^{1/2} \left(\frac{1\,\mathrm{kHz}}{\nu_s} \right)^{1/2}$$

Assuming the accretion torque is balanced by the GW torque

F is the bolometric X-ray flux, ν_s is the spin frequency

X-ray bright source, such as Scorpius X-1, is expected to detect a CGW

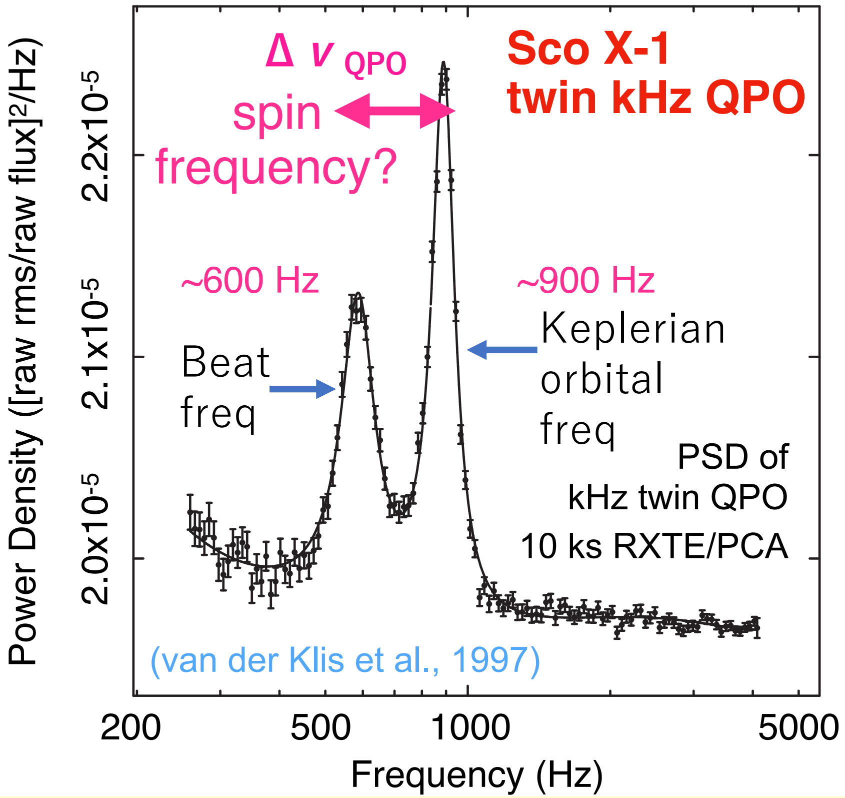
has not yet been detected in LIGO data

Major problem: the ν_s of Sco X-1 is unknown

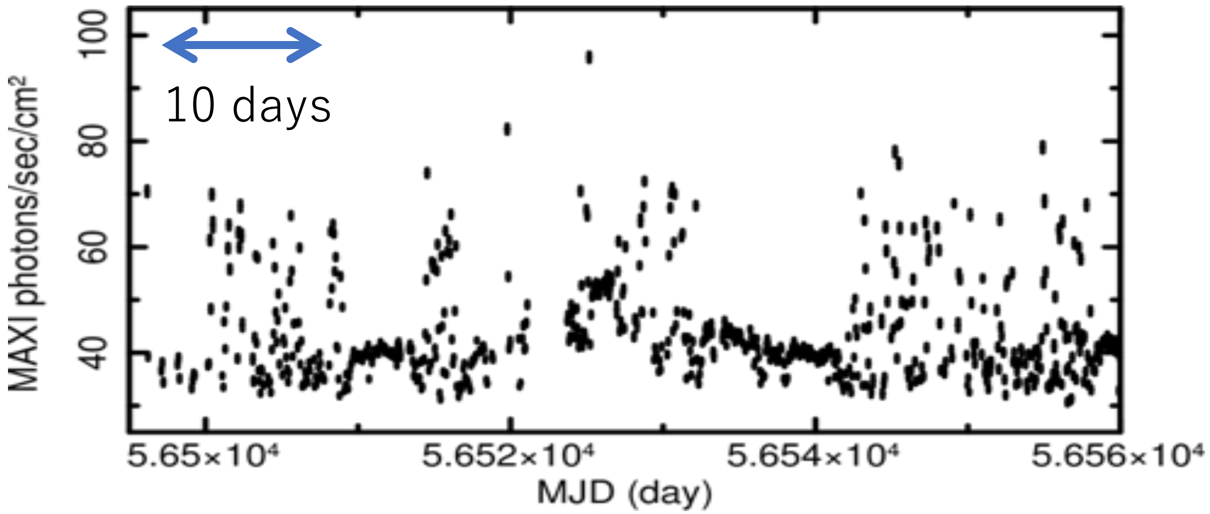
- For signal search, wide parameter space to search for ν_s and binary orbital parameters is a major barrier to computation.

X-ray properties of Sco X-1

Short X-ray variability (RXTE/PCA : 3 – 20 keV)



Long X-ray flux variability (MAXI : 2 – 20 keV)



- **The origin of the twin QPO is thought to be a beat frequency between the NS spin and Keplerian orbital frequency at the inner radius of the accretion disk (BFK model).**
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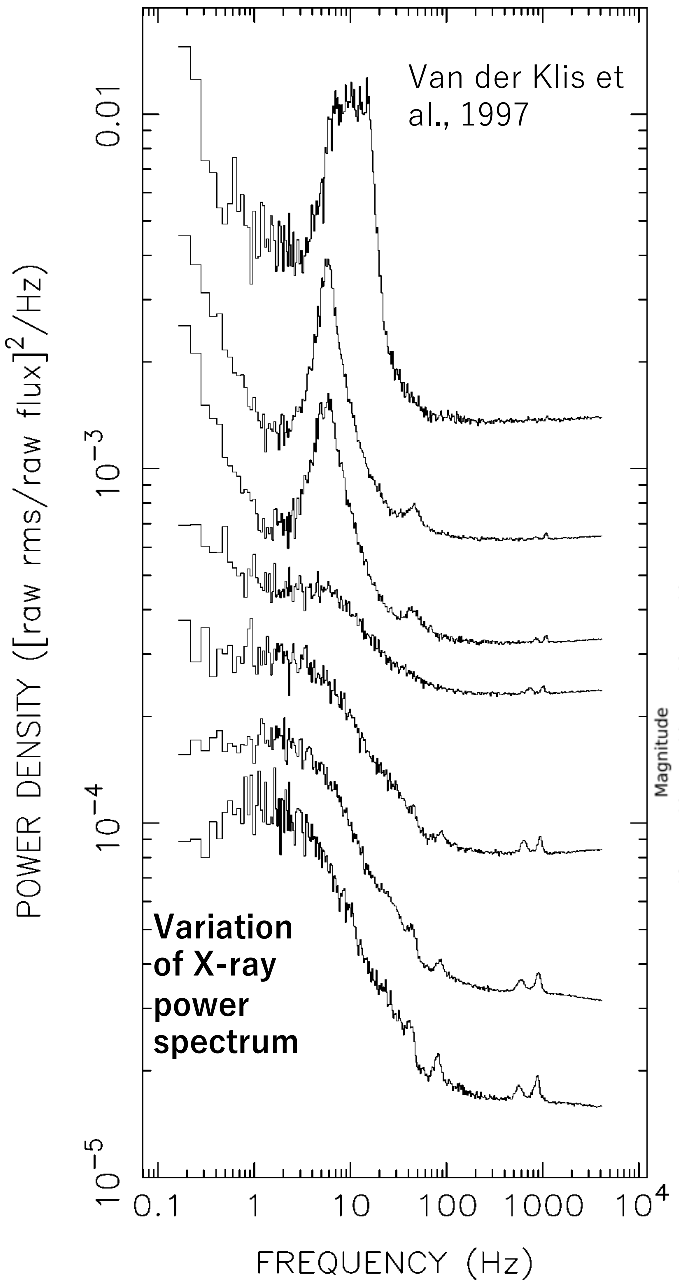
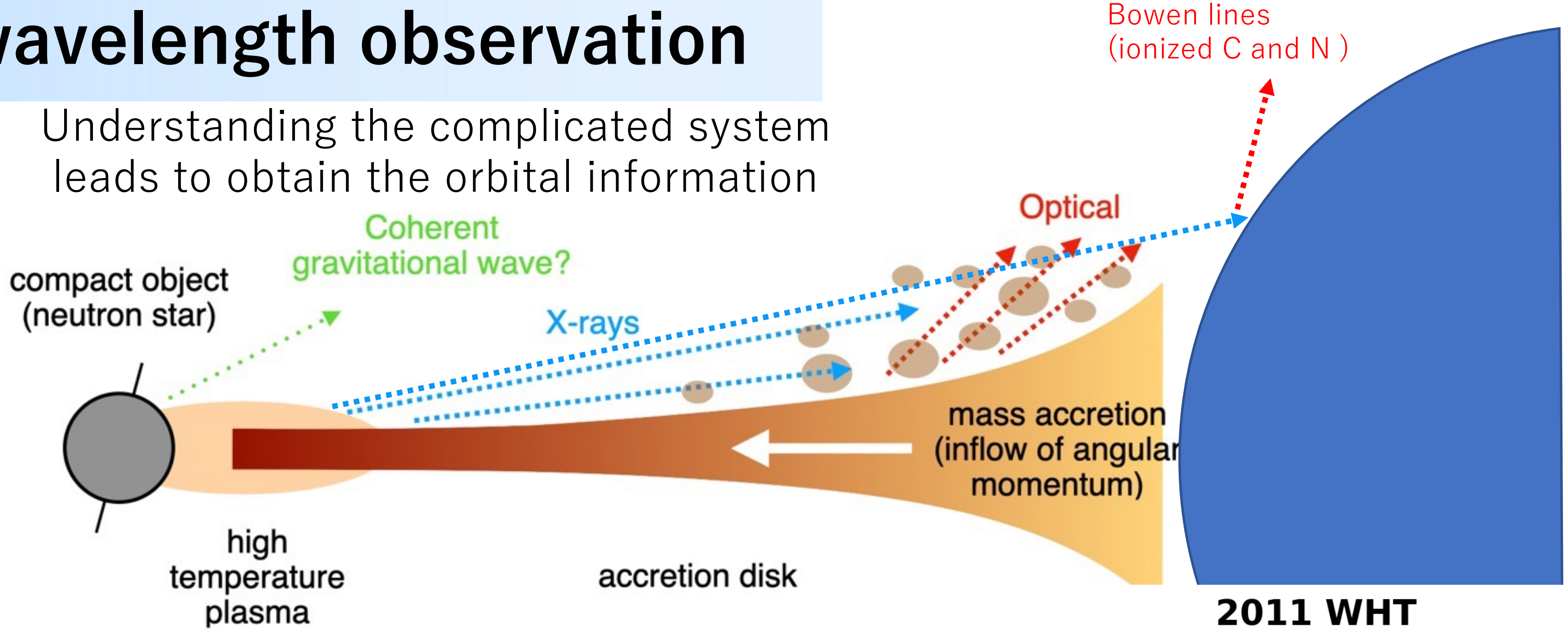
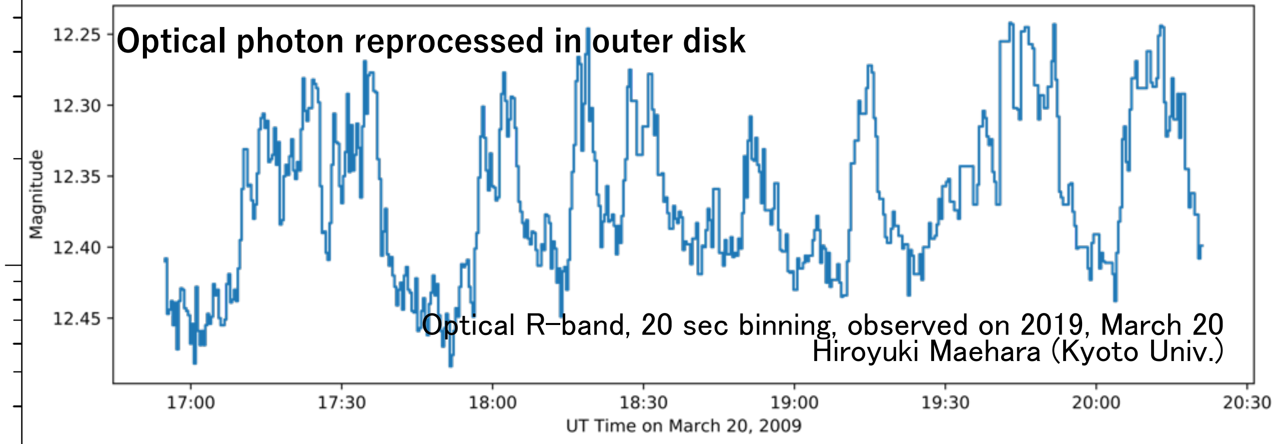
- **However, $\Delta \nu_{QPO}$ has not been well monitored since 1999. Spin will be "wandering" caused by accretion → Frequency monitor by long-term X-ray observation is important to search CGWs by integration over year long data**

Simultaneous multi-wavelength observation

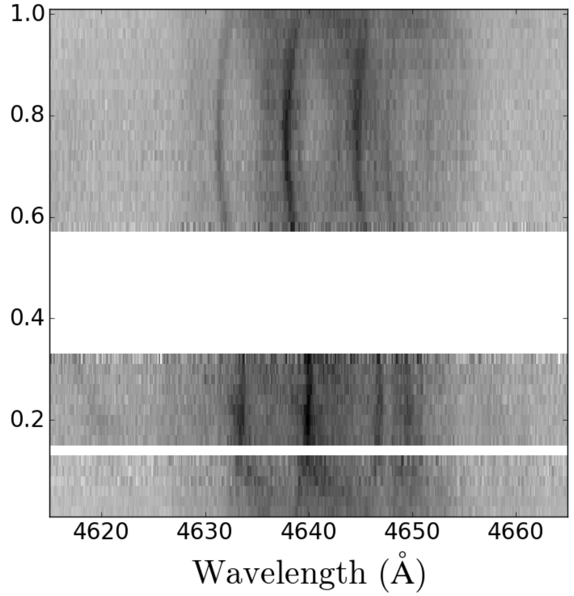


Understanding the complicated system leads to obtain the orbital information





2011 WHT



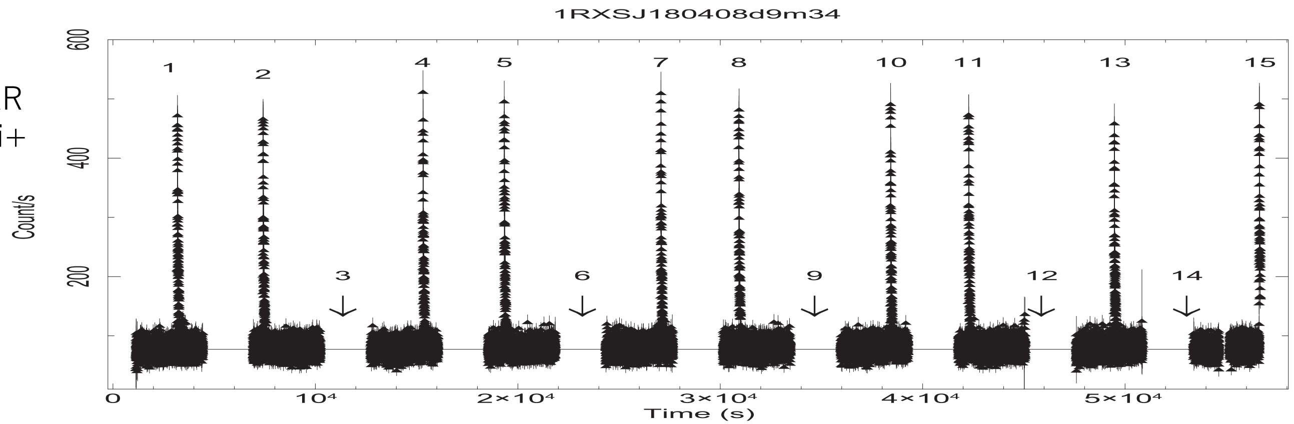
Bowen lines
Wang+2018

To understand the complex binary star system of Sco X-1, long term simultaneous observations at various wavelengths are important

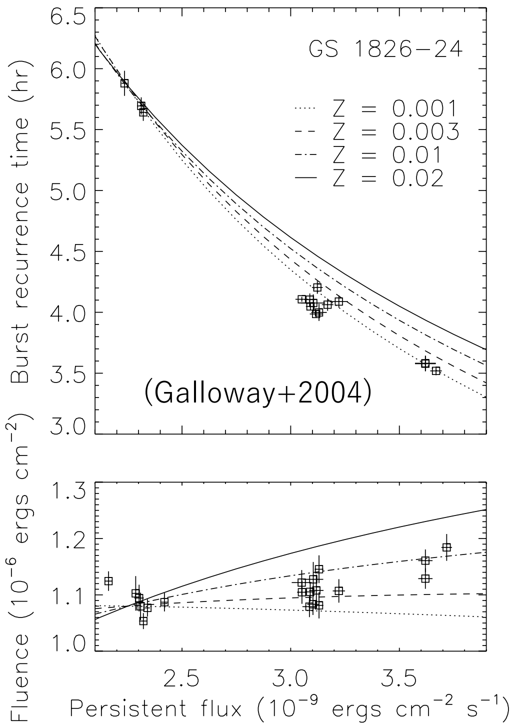
X-ray burst

Measuring recurrence time and persistent flux (Mdot)
- **Constraints EOS (see Dohi-san's talk)**

NuSTAR
Fiocchi+
2019



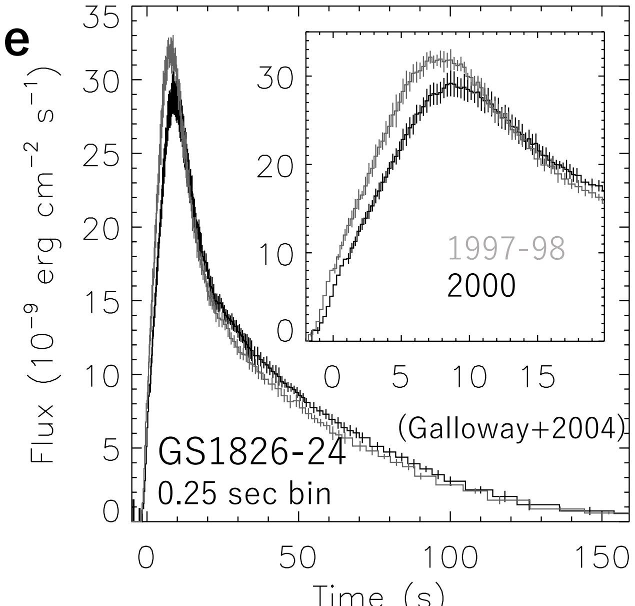
<u>can be observable by NinjaSat</u>

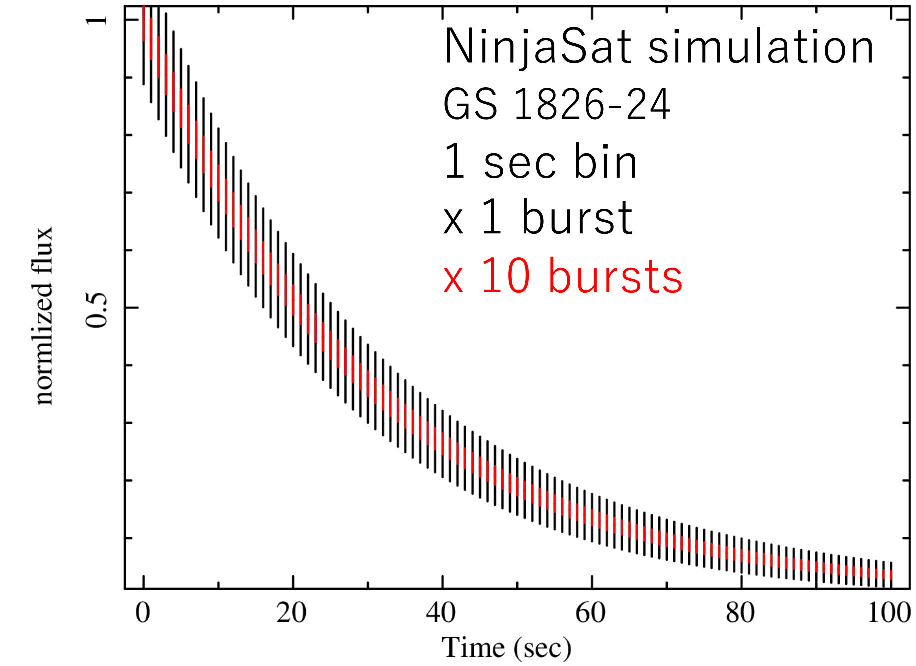


Not many other objects have been studied it. What is the uniqueness of each source?

Measuring the accurate burst profile (from summing up burstrs)
- **fuel composition**
- **rp-process**

RXTE results





Summing up ~10 bursts by the NinjaSat data, can we get data with meaningful accuracy to compare with theoretical calculations?

Crab

田中周太さんの第1回NSワークショップ2015のスライド

Discussion

- 理論はまだ**One-zone, 1D**で理解を深める段階を終えていない。
- **2D, 3D**の計算が行われるようになってきたが、観測との定量的な比較は困難。　←どっちもぐちゃぐちゃ
- 最新の観測は基本的なデータが出なくなった。 **(Total flux**が過去の観測と合うか**?)**　←**Crab**の変動
- 理論屋が計算できる量をうまく数値化して欲しい。

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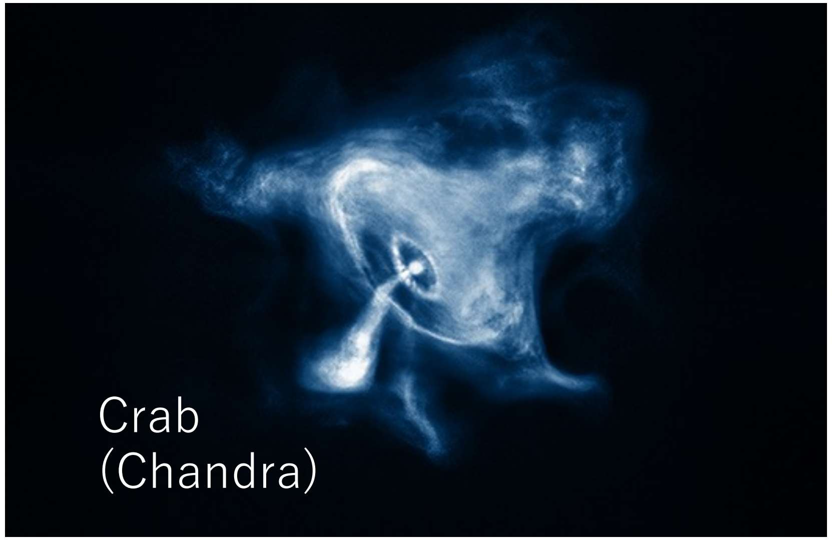
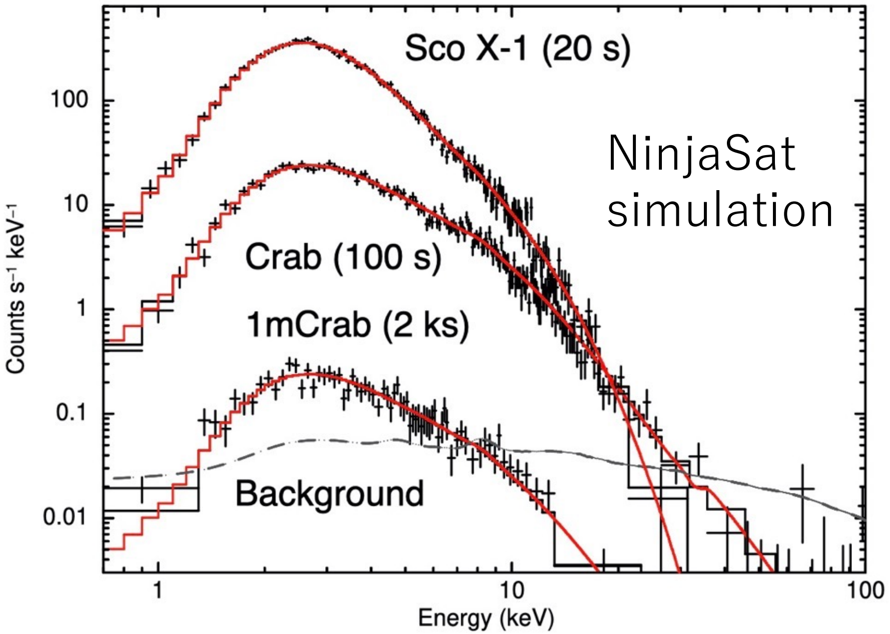
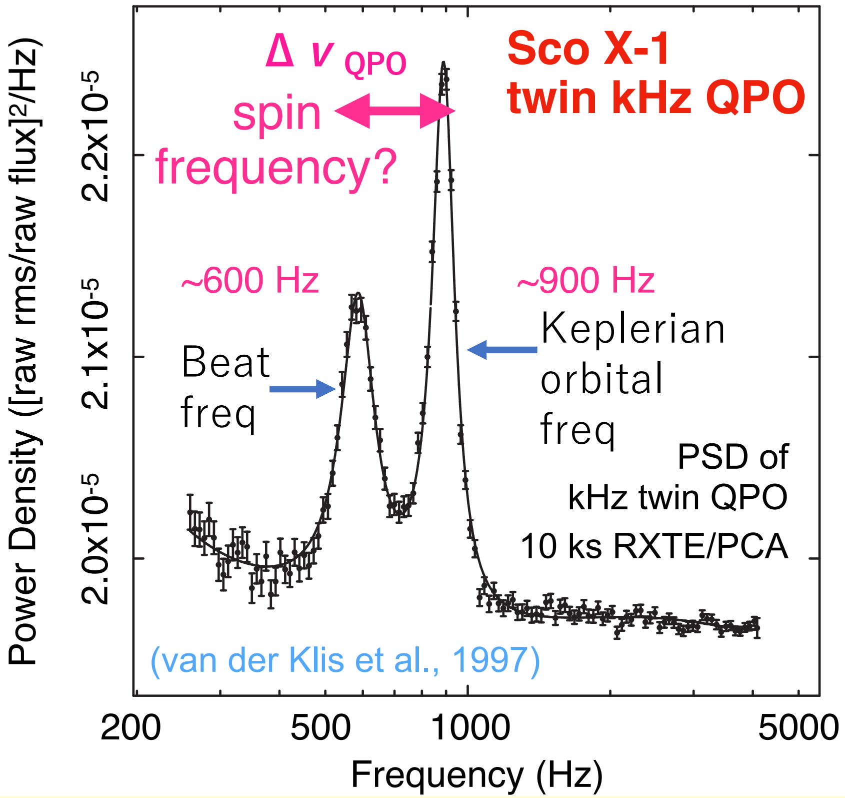


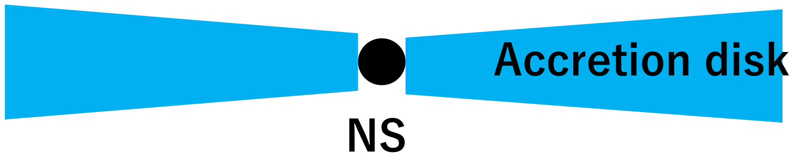


Let‘s discuss later!

X-ray properties of Sco X-1

Short X-ray variability (RXTE/PCA : 3 – 20 keV)





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Evidence of BFM seen in other LMXB

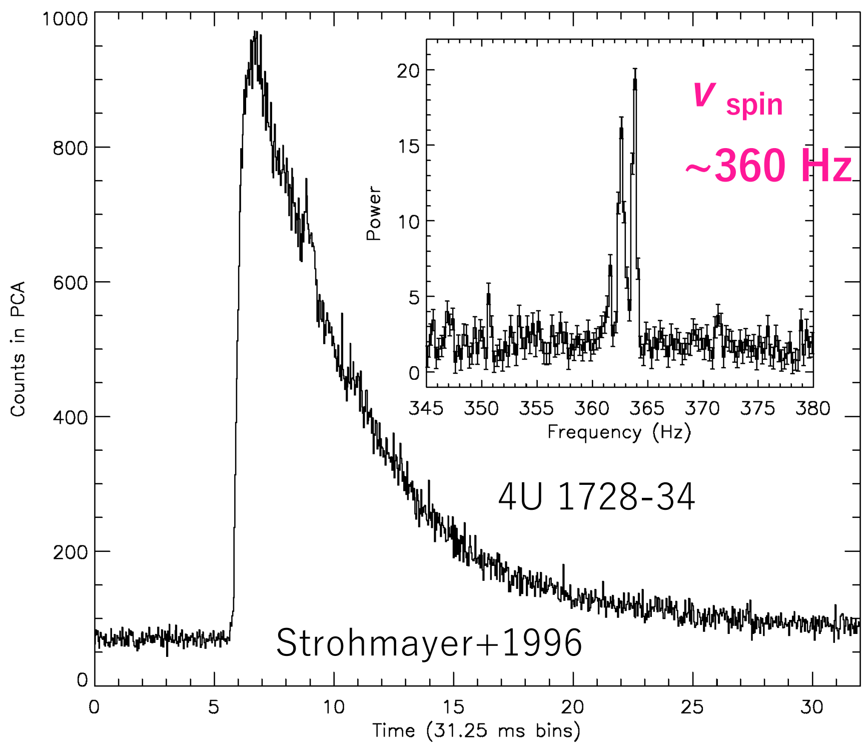

FIG. 1.—Light curve of the burst that occurred at 10:00:45 UTC on 1996 February 16. The main panel shows the total PCA counts in 31.25 ms bins. The inset panel shows a portion of the power spectrum computed from 32 s of 122 μs data. Each bin is 0.25 Hz wide and represents the average of eight original power spectral bins. The error bars include only the uncertainties due to Poisson counting statistics.

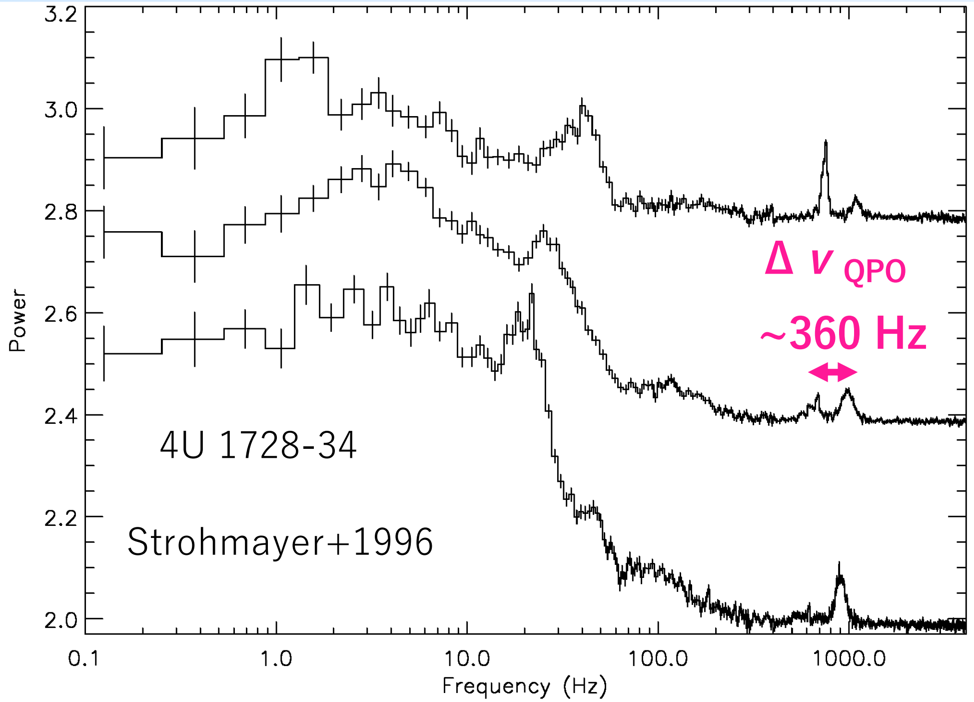

FIG. 3.—Average power spectra computed from 1996 February 15 at 11:50:22 to February 16 at 10:13:01 UTC showing the evolution of the two kilohertz QPOs. The source count rate was increasing from figure bottom to top. Also note the QPO between 20 and 40 Hz and the broadband noise component between 0.1 and 10 Hz that decreases in strength as the source intensity increases. The Nyquist frequency is 4096 Hz in each panel, and the small dead-time correction to the Poisson level has not been subtracted. For clarity, the two upper curves have been displaced by 0.4 and 0.8, respectively

Almost LMXBs are non-pulsating pulsars. However, during type-I X-ray bursts (unstable thermonuclear flush onto the NS surface), sometimes coherent pulsations corresponding to their spin frequency have been seen.

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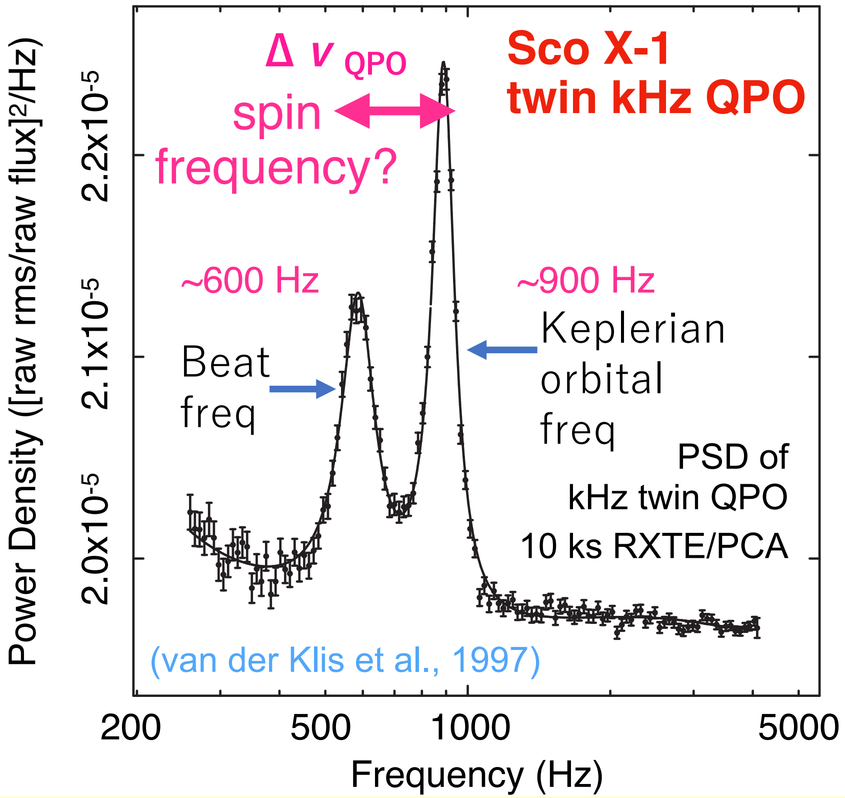
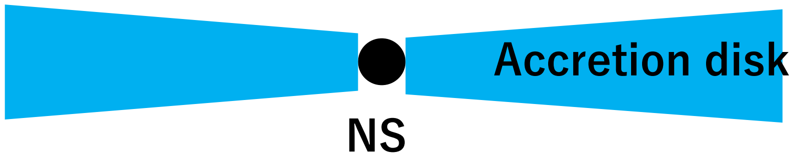
Short X-ray variability (RXTE/PCA : 3 – 20 keV)





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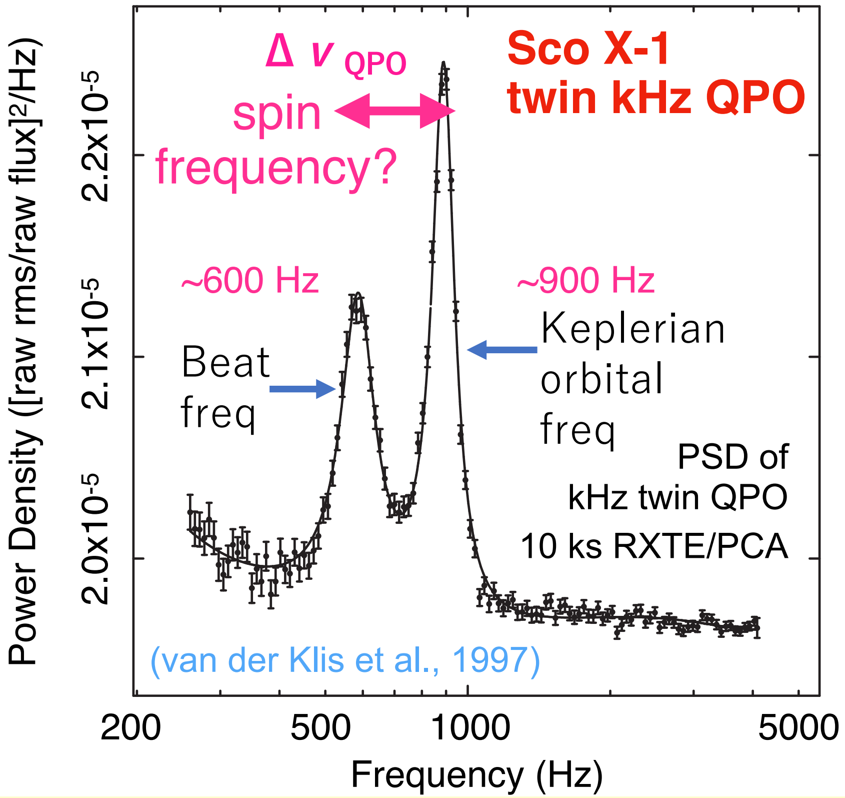

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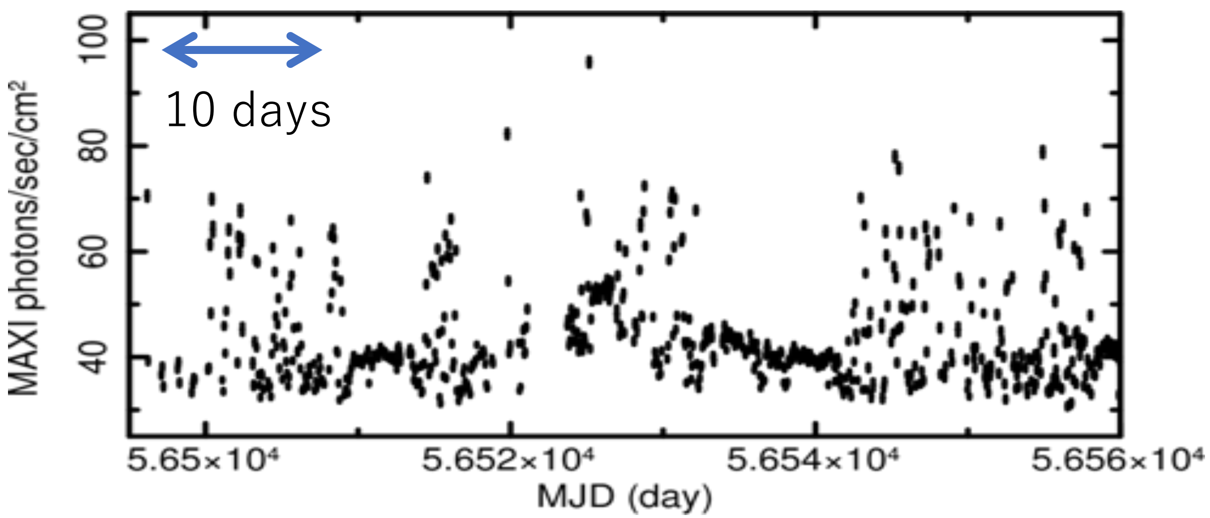

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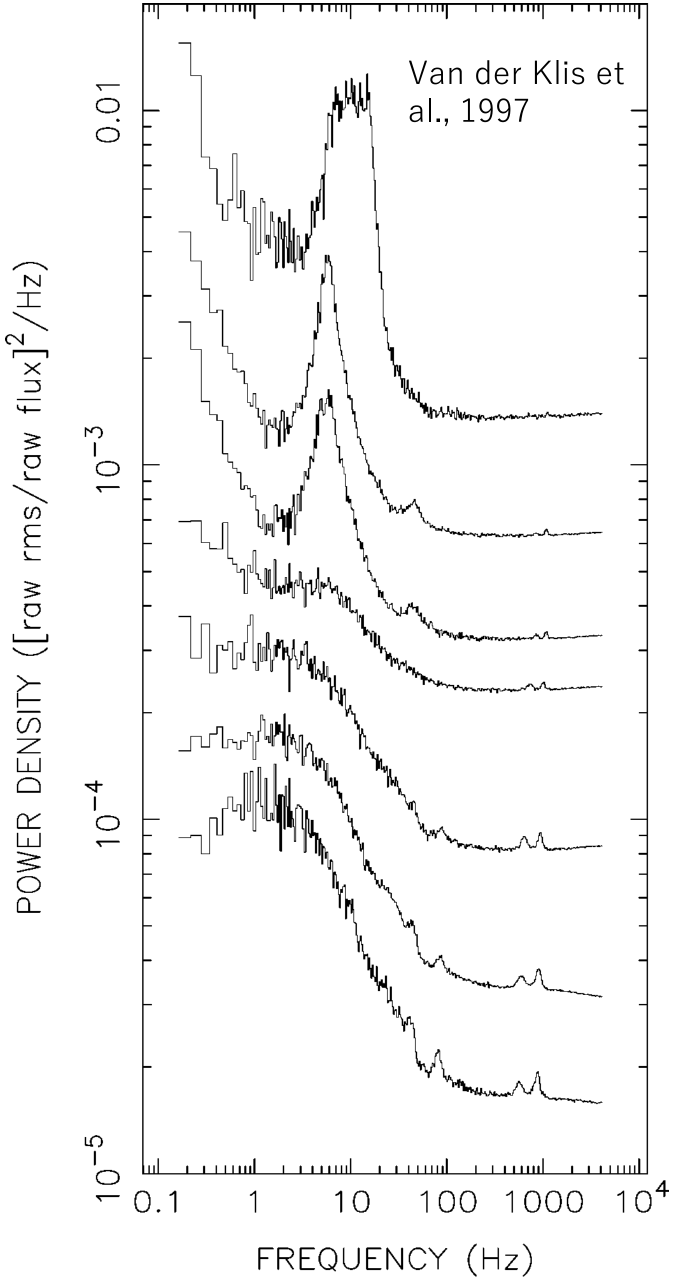
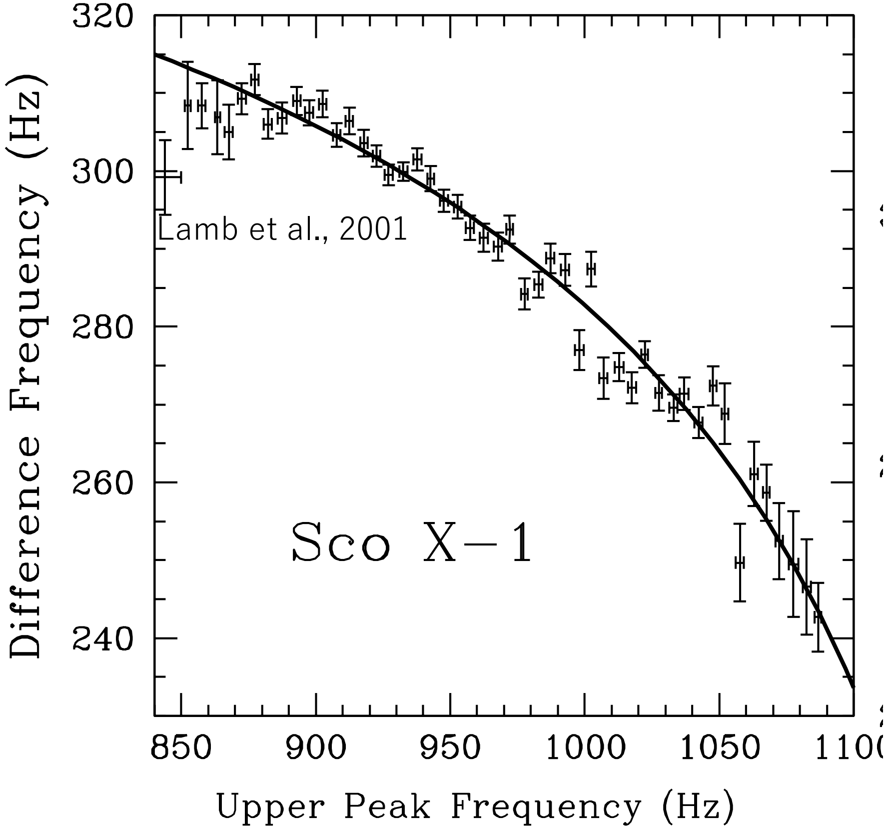


Sonic Point Beat Frequency Model



http://research.physics.illinois.edu/cta/movies/sp2/