Monitoring SMC X-1's Spin and Superorbital Modulation using MAXI and NinjaSat

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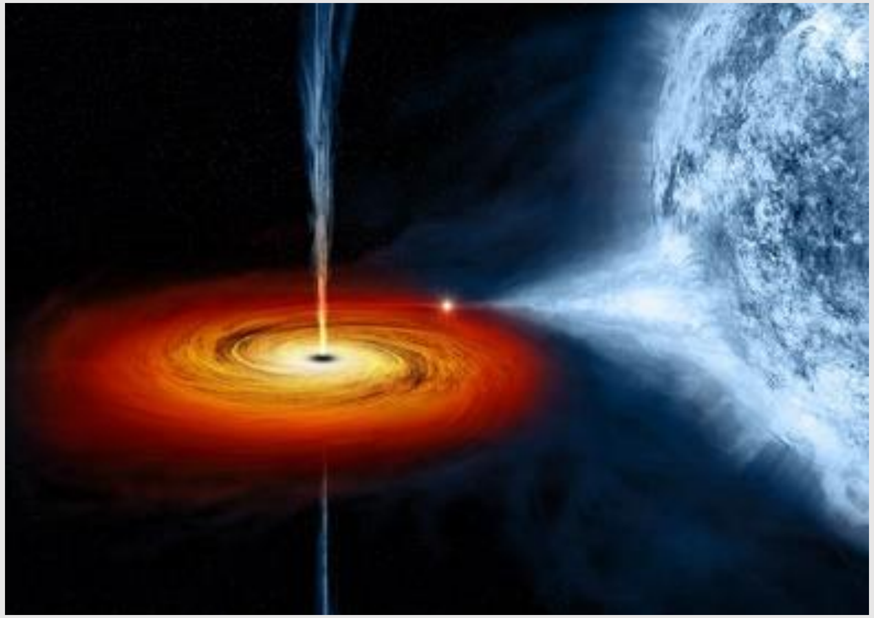

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References:

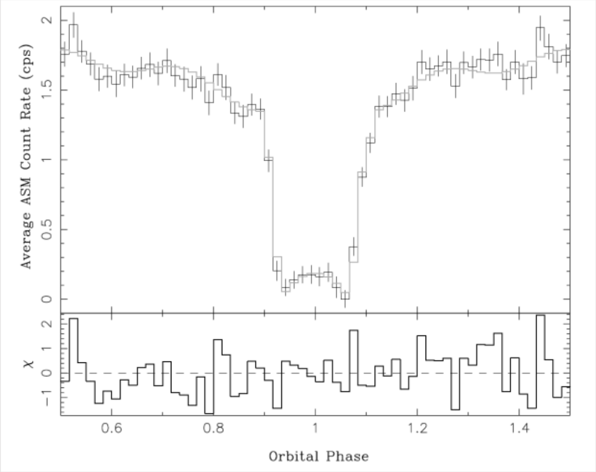
Hu et al., MNRAS, 520, 3436 (2023)

Hu et al., ApJ, 885, 123 (2019)

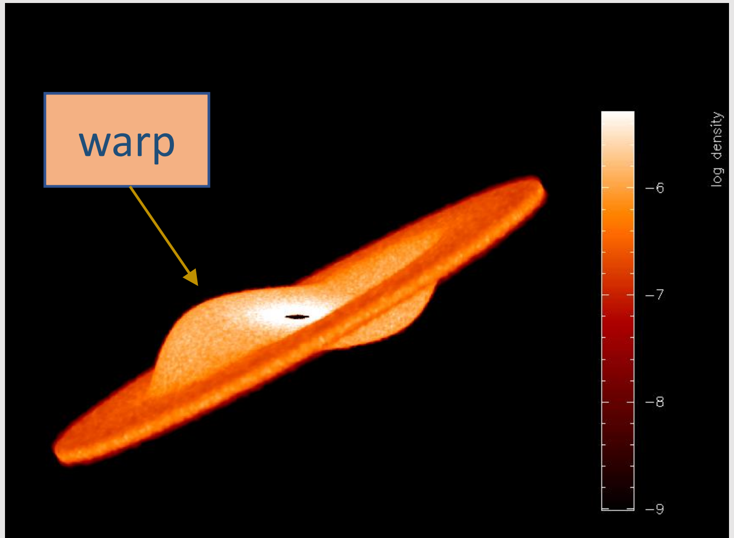
Dec. 11, 2024, MAXI 15 Year Workshop @ Nihon University

SMC X-1

- High-mass X-ray Binary
- Spin period = 0.7 s
  - $\frac{\dot{P}_{spin}}{P_{spin}} = -4.52 \times 10^{-4}\ yr^{-1}$
- Orbital Period = 3.9 days
  - Eclipsing binary
  - $\frac{\dot{P}_{orb}}{P_{orb}} = -3.35 \times 10^{-6}\ yr^{-1}$
- Superorbital modulation period = 40 ~ 65 days
- Luminosity ~ 5×10^{38} erg/s
  - Super-Eddington luminosity
  - Local analogue of ULX pulsars?



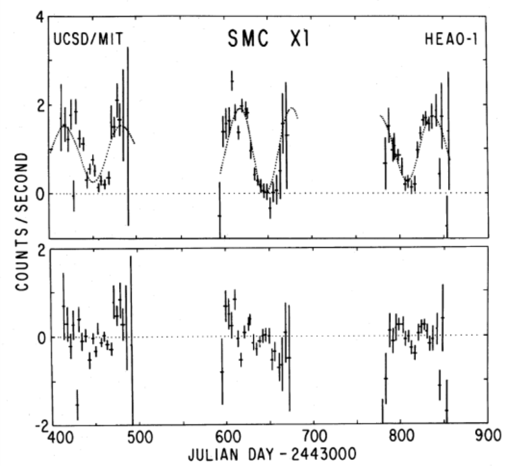
Trowbridge et al. (2007)



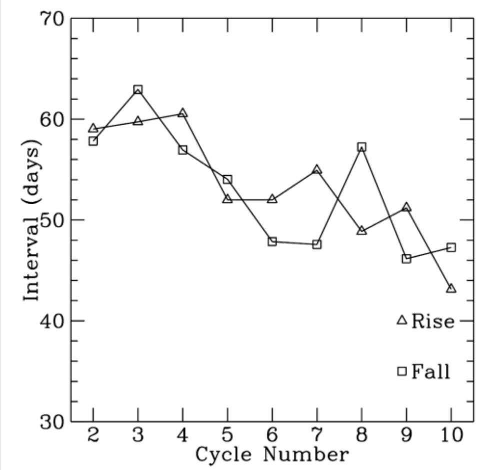
Credit: Dr. Lodato

Superorbital Modulation

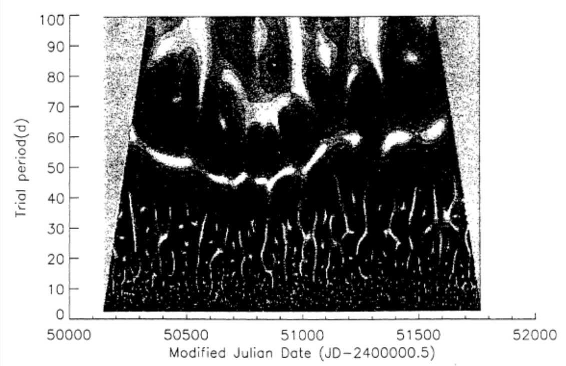
- Roughly 60 days (Gruber et al. 1984)
- Decay from 60 days to 40 days (Wojdowski et al. 1998)
    - Quasi-periodic occultation
- Decrease from 60 to 45 day and increase back (Ribó et al. 2001)
- Varies between 60 and 40 days (Clarkson et al. 2003)
- Obscured by warped accretion disk
    - Similar to LMC X-4 and Her X-1
    - Non-linear and non-stationary



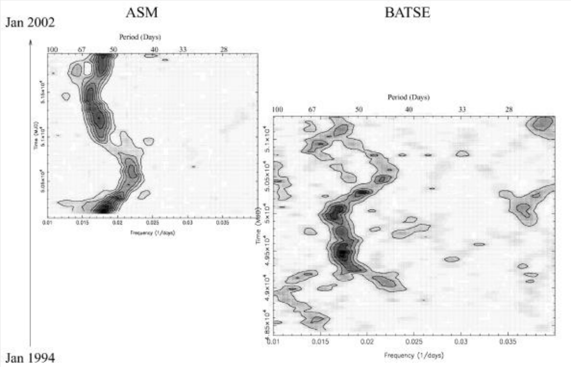
(Gruber et al. 1984)



(Wojdowski et al. 1998)



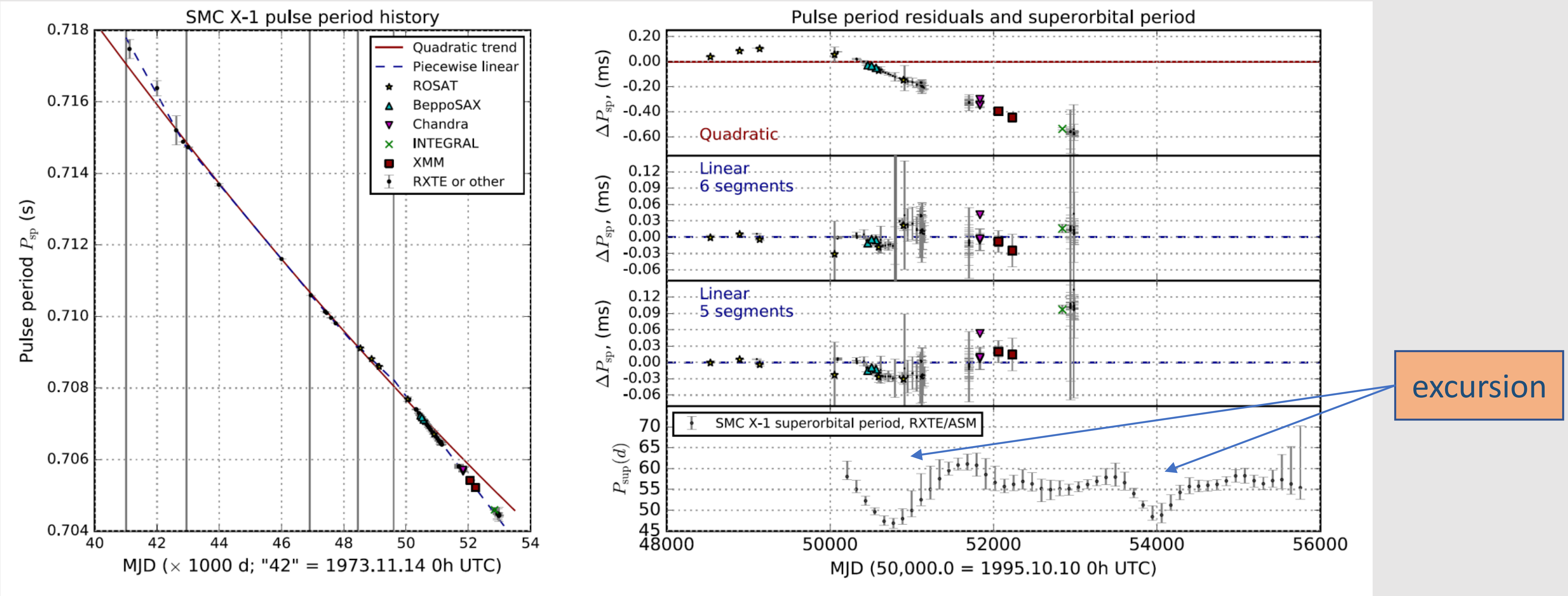
(Ribó et al. 2001)



(Clarkson et al. 2003)

Spin-Superorbital Connection?

- Highly depends on the definition of the epochs
- The spin and superorbital modulations after MJD 56000 are not investigated

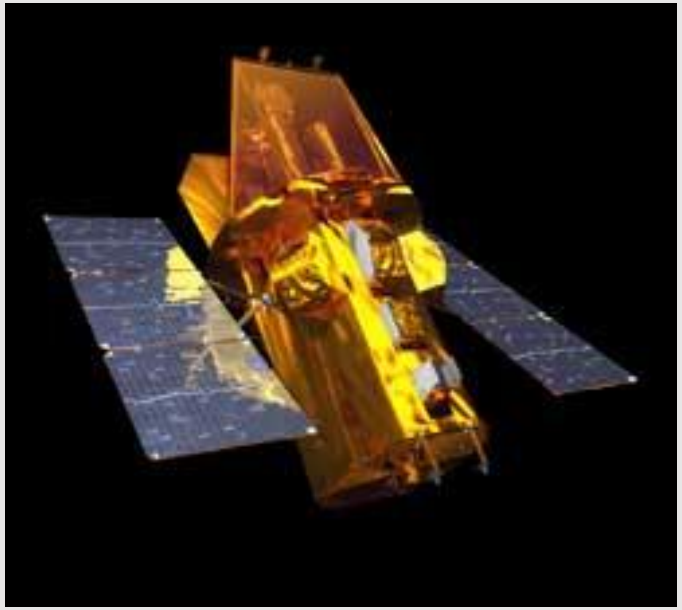


Dage et al. 2019

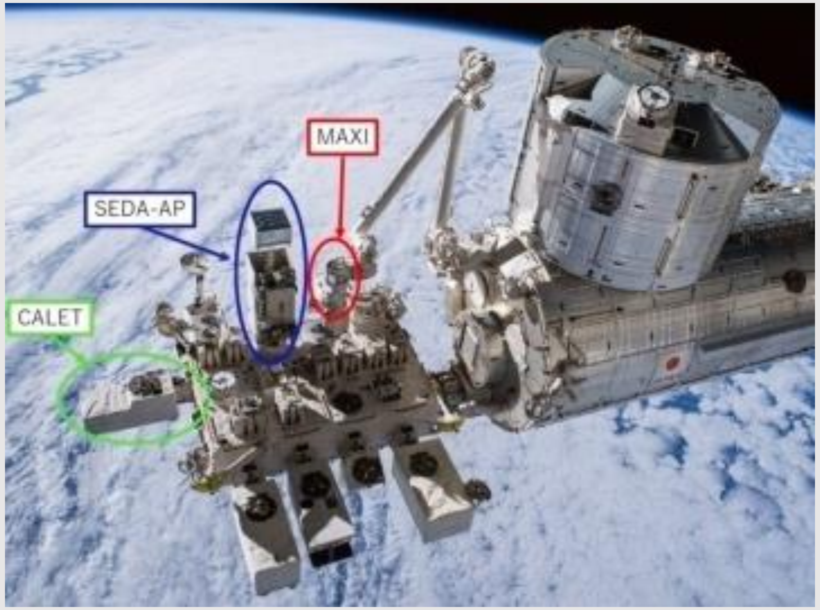
SMC X-1: 28 years of observation

- RXTE ASM (1996 – 2012), Swift BAT (since 2004), MAXI GSC (since 2008)
  - Light curves from RXTE ASM and Swift BAT are used to trace the evolution of superorbital frequency and high/low state fluxes
  - Photon events collected with MAXI GSC are used to search for pulsation

RXTE ©NASA



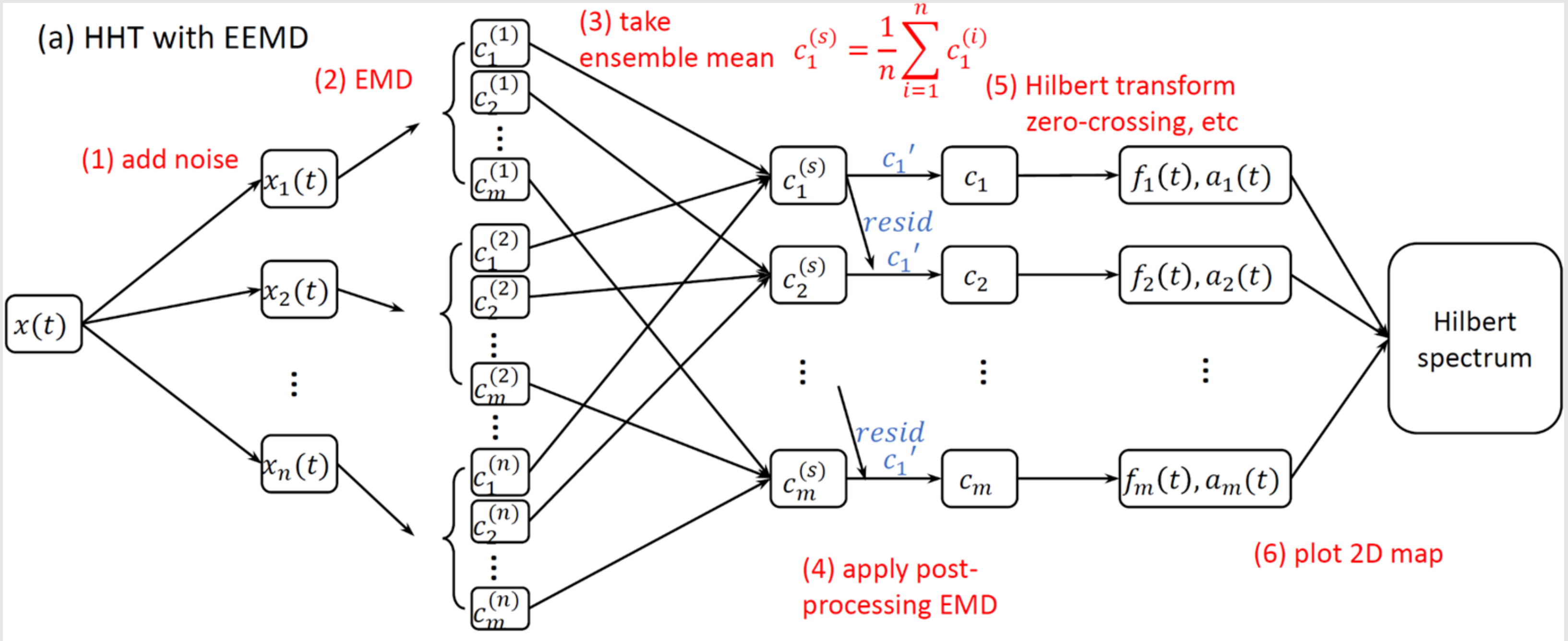
Swift ©NASA

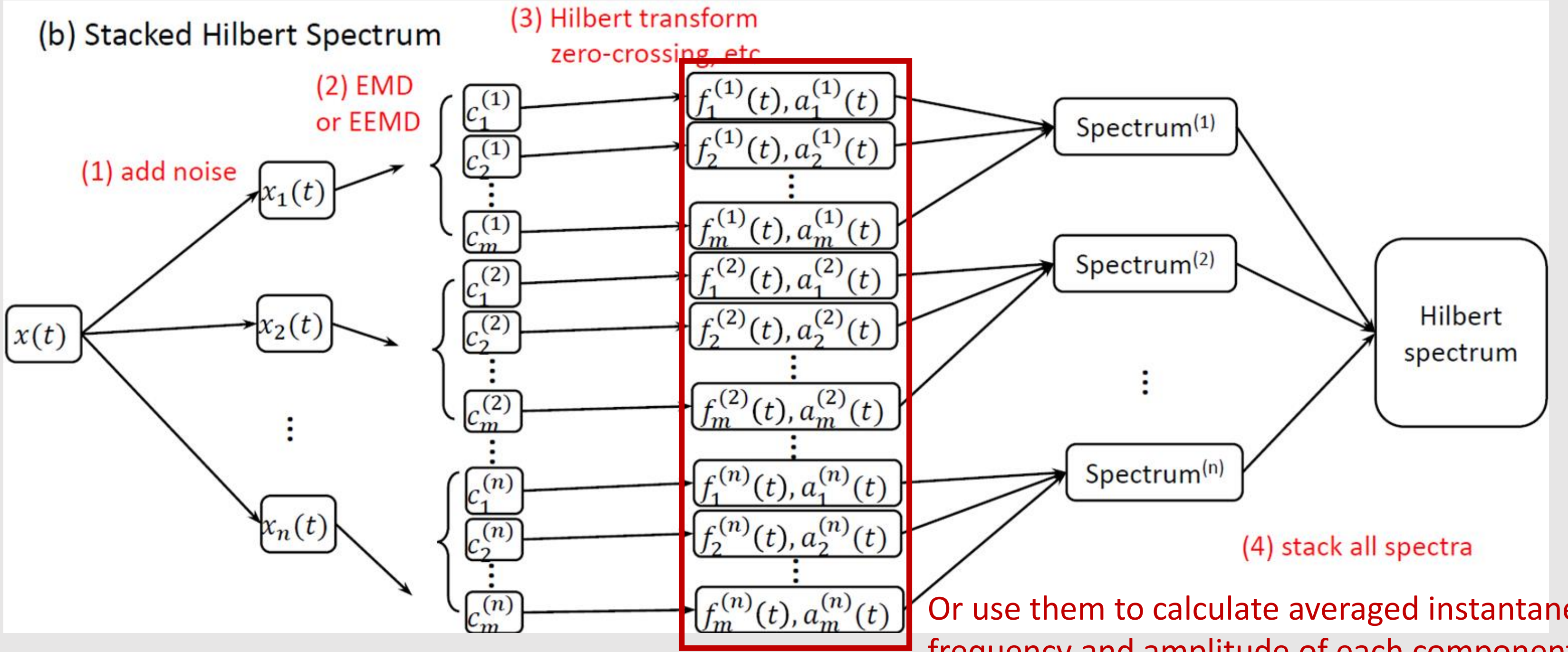


ISS and MAXI ©JAXA/NASA

Stacked Algorithm of Hilbert-Huang Transform

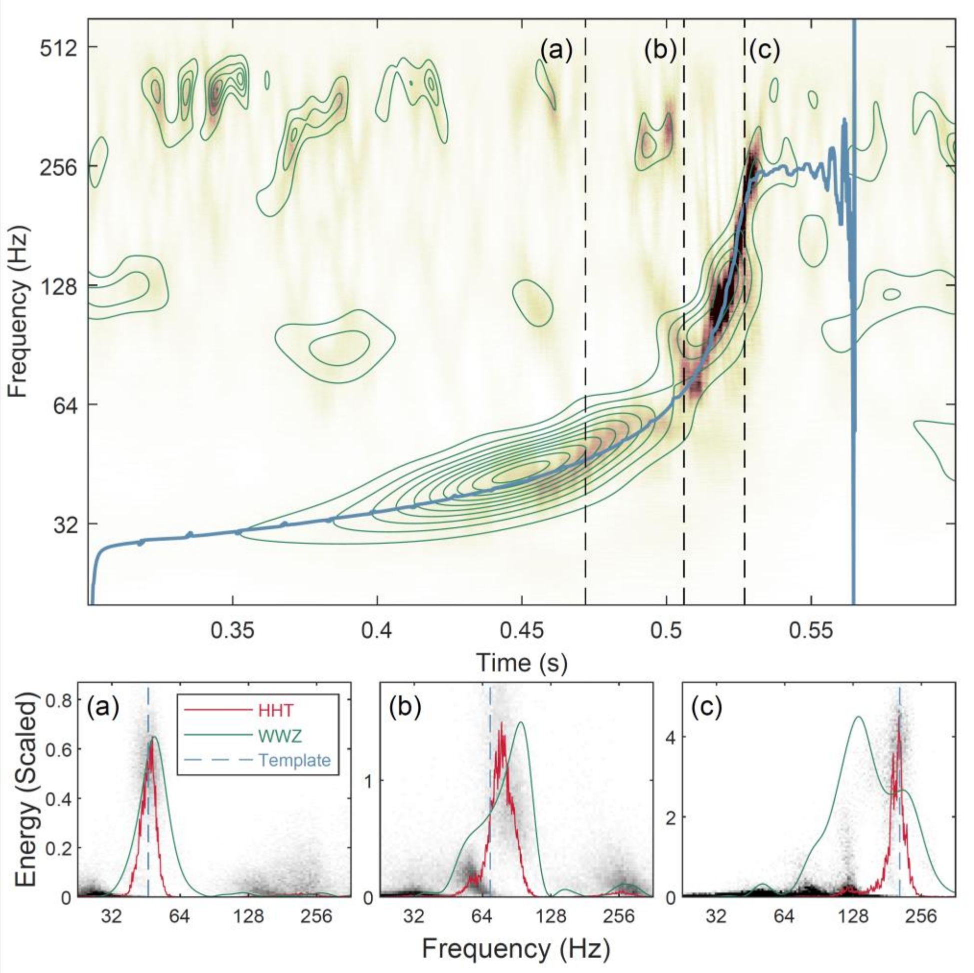
- Hilbert-Huang Transform = decomposition (EMD, EEMD) + instantaneous frequency calculation (Hilbert transform, quadrature, zero-crossing…)
  - Empirical Mode Decomposition: mode-mixing problem
  - Ensemble EMD (EEMD): proposed to solve the mode-mixing problem
  - However, if the frequency range of a signal is larger than a factor of ~2, mode-mixing is unavoidable.
- Stack-spectrum algorithm: Stacking the time-frequency map instead of taking the ensemble mean of decomposed components.



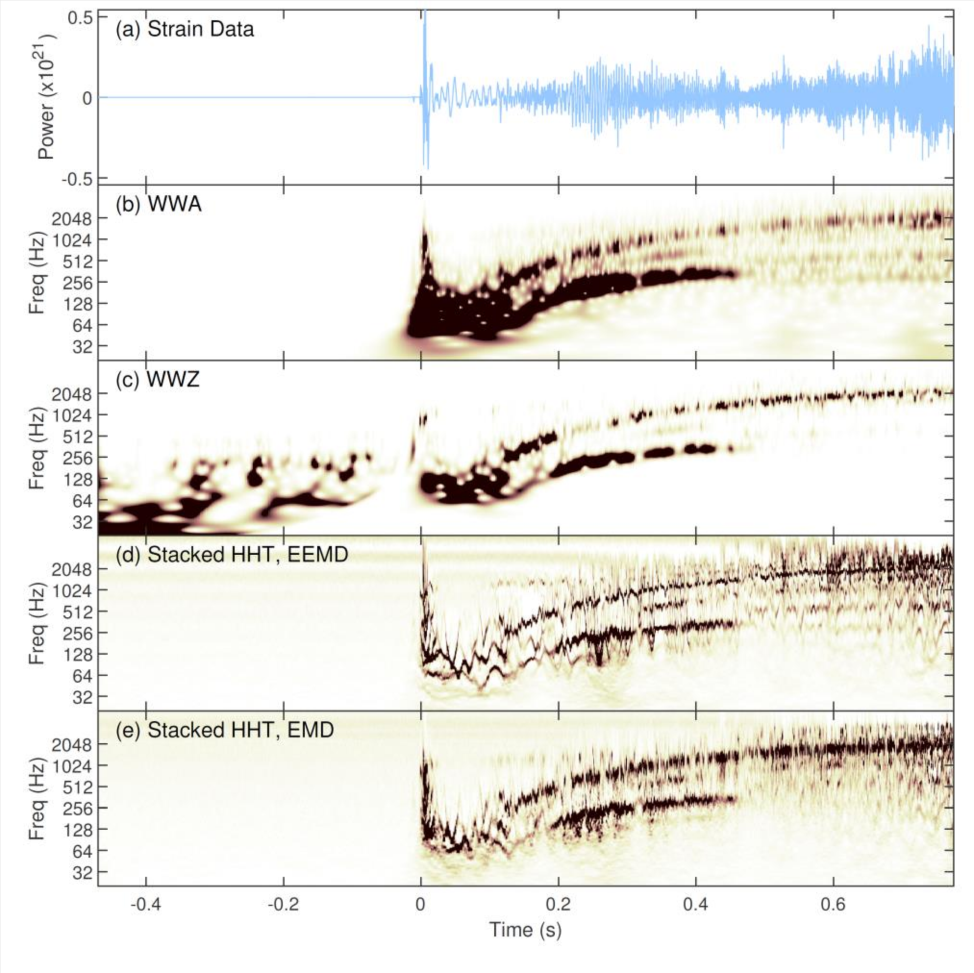


Or use them to calculate averaged instantaneous frequency and amplitude of each component

Successful Application in GW!



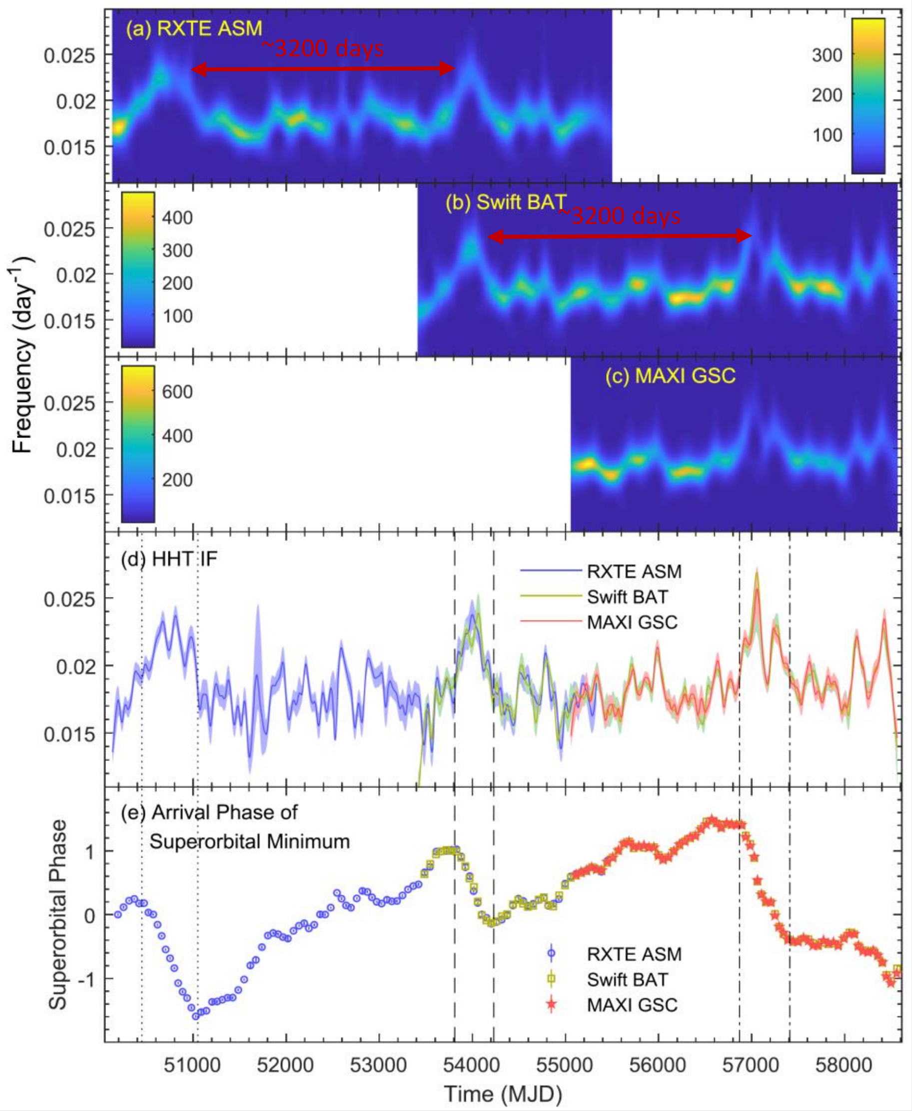
GW 150914: sHHT vs wavelet

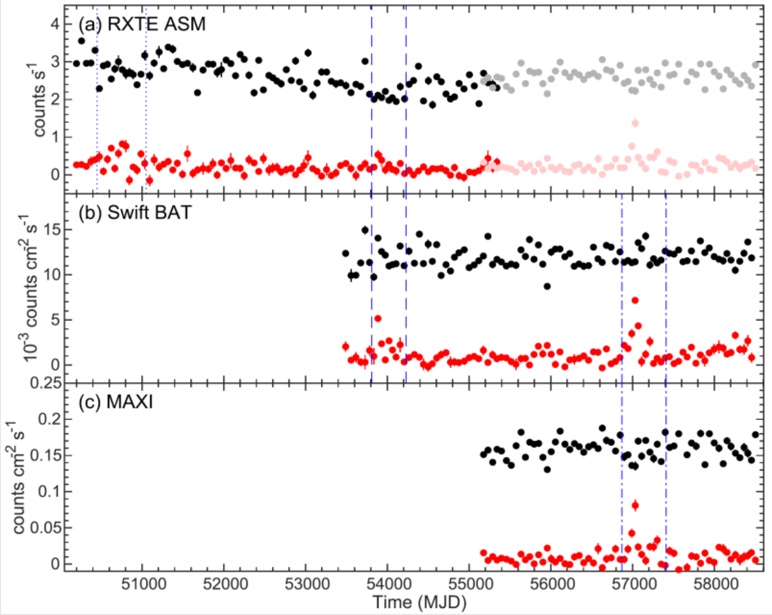


Core-collapse supernova (simulated)

Hu et al. (2022)

2019 Results

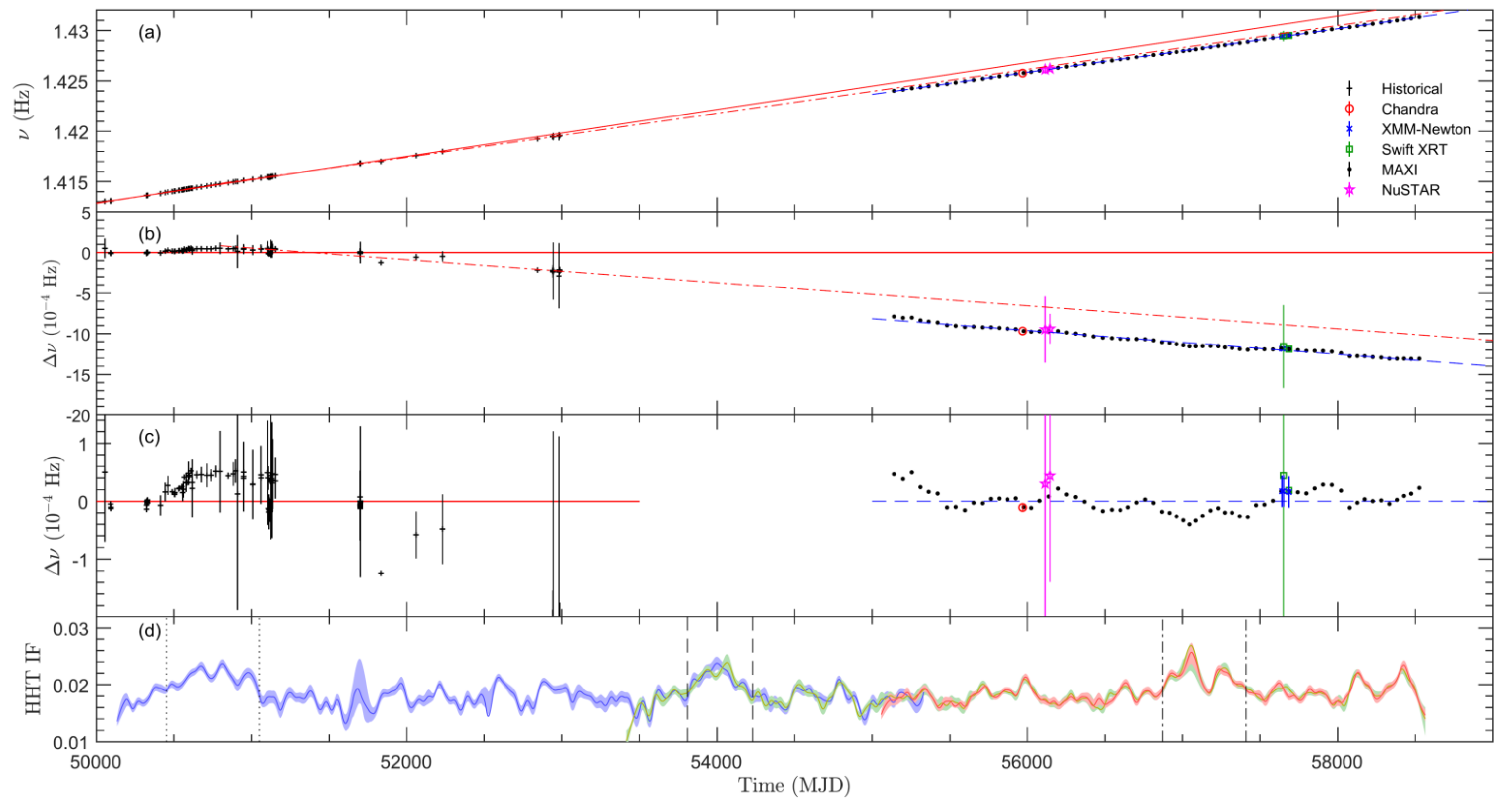


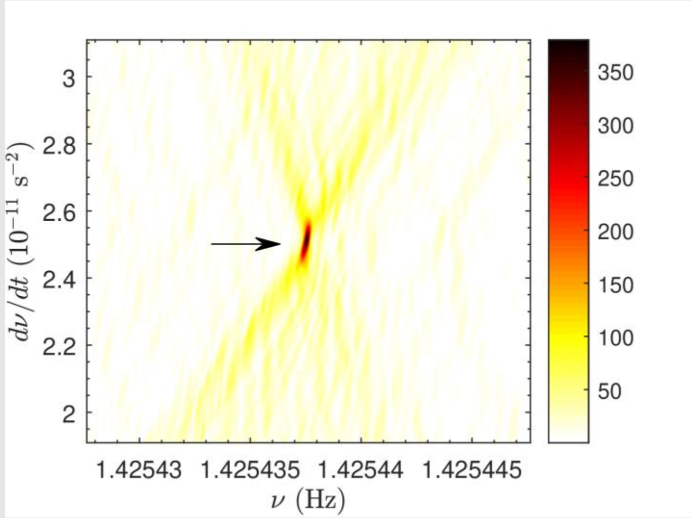


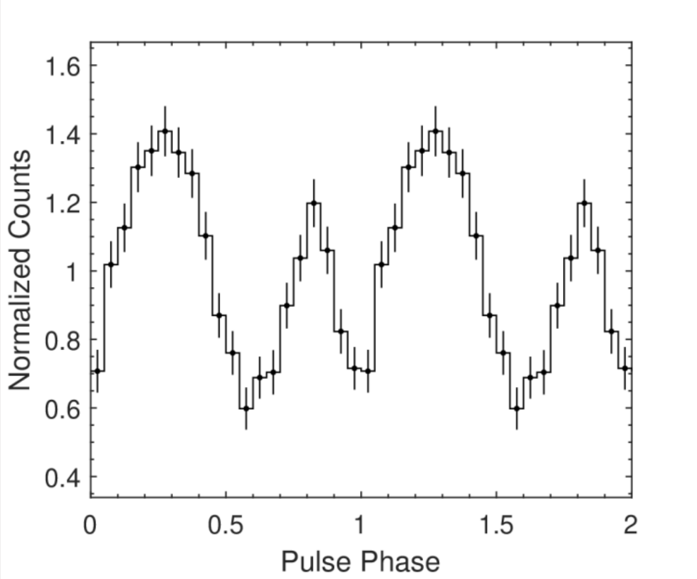
- The third “excursion” event occurred around 2015
- During excursions, high-state flux remains stable while low-state count rates increase.
  - Radiation driven disk warp (?)
  - Change in inclination angle (?)

Hu et al. (2019)

Spin Period Evolution





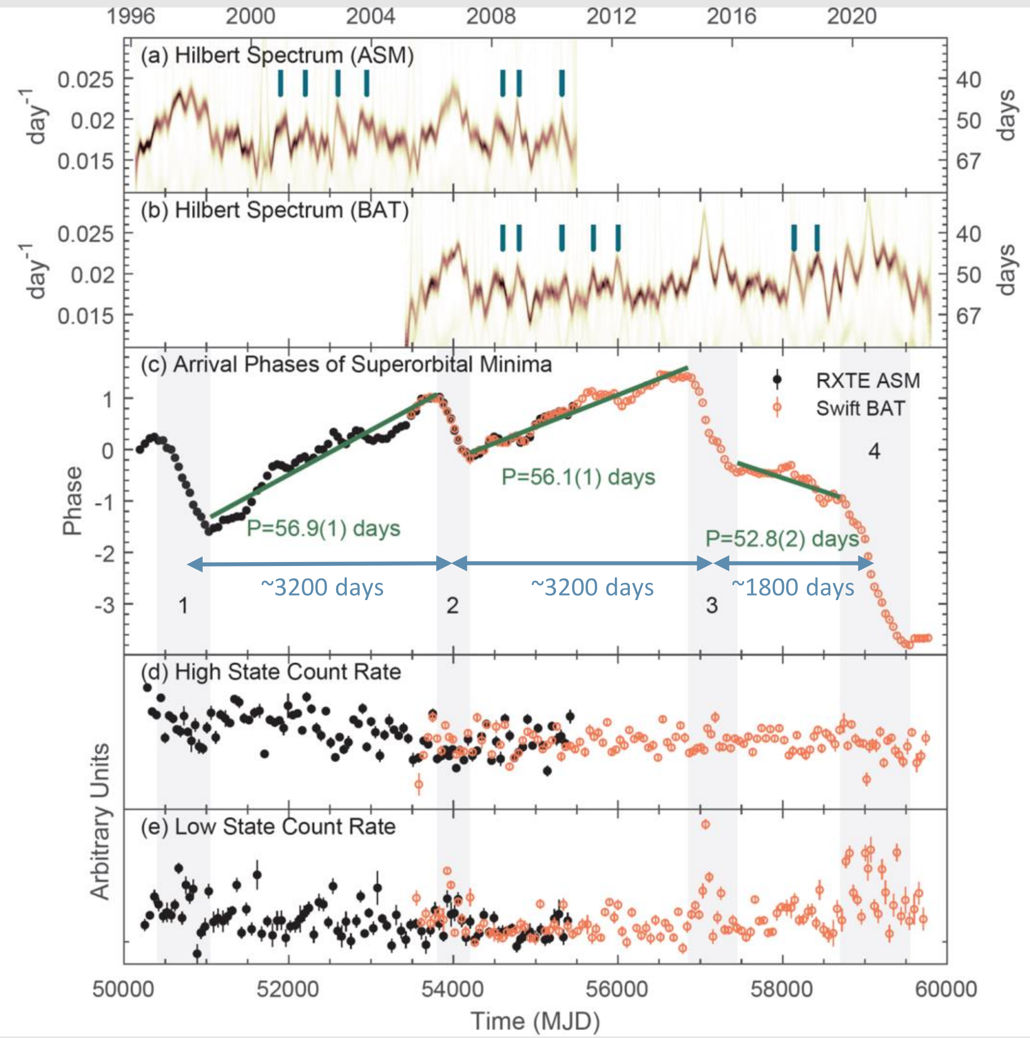


- The spin period can be traced with MAXI
- No change in spin-up rate is seen during the 2015 excursion.

Hu et al. (2019)

New Excursion Event

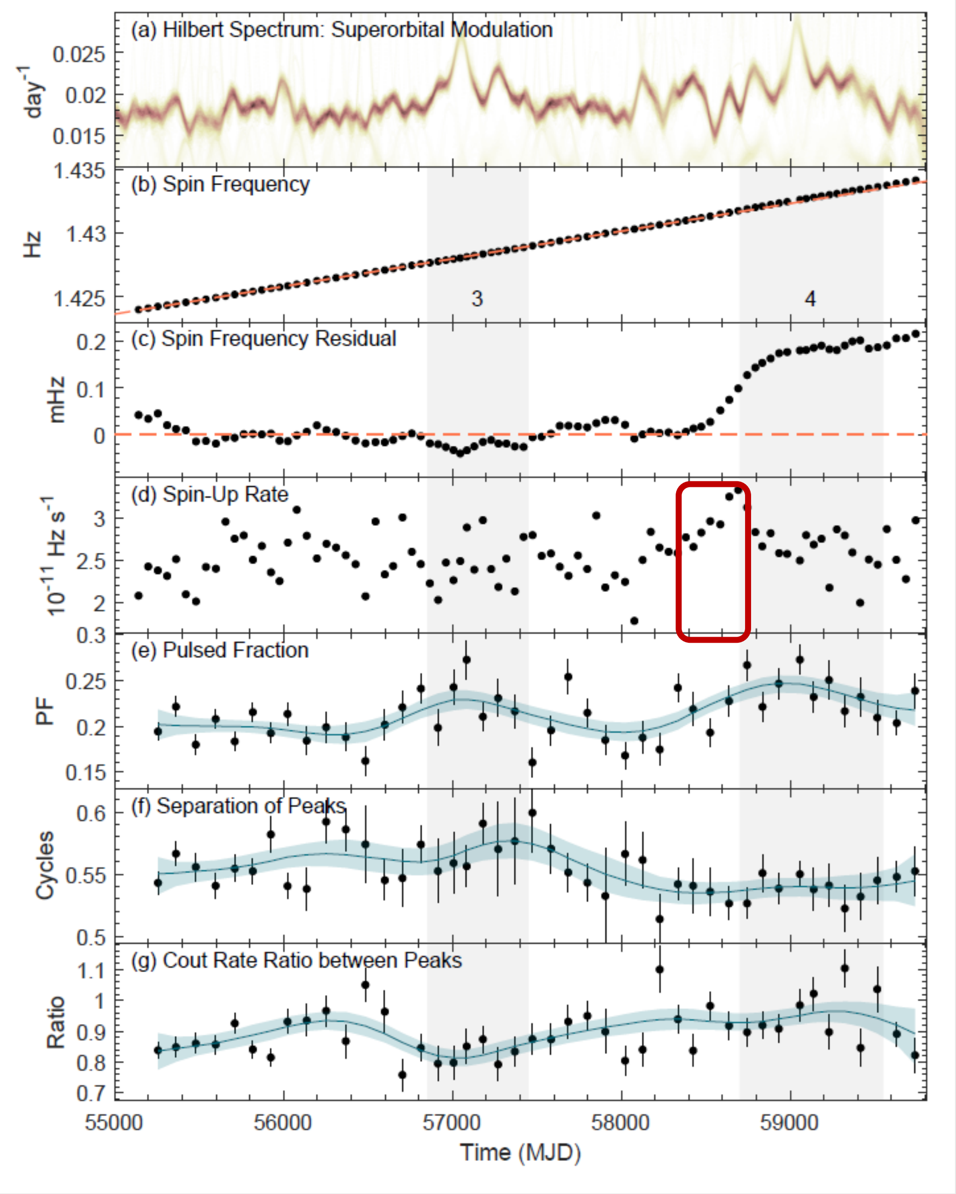
- In 2020, a new excursion occurred unexpectedly, approximately 1800 days after the third one.
  - The intervals between excursions are not (quasi-)periodic.
  - A few “mini excursions” can be observed
- High-state count rate remains stable during excursions
- Low-state count rate increases during excursion.
  - Radiation-driven warp?



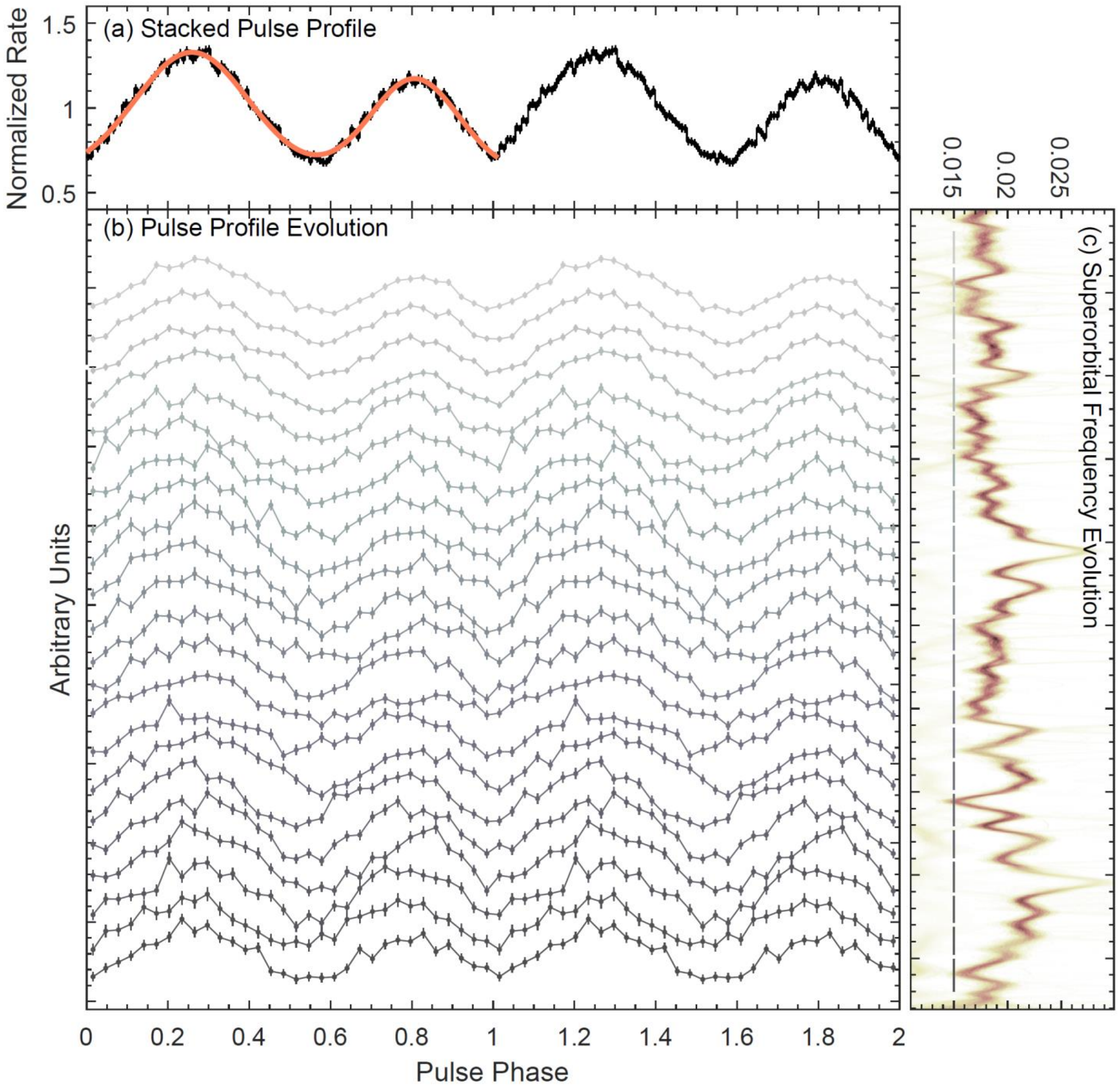
Hu et al. (2022)

Spin-Up Acceleration

- The spin-up accelerates monotonically 2 year before the onset of the 4th excursion, and decay back in ~1 year
  - A significant increase in the residual
  - An inside-out process connecting spin-up rate change and superorbital excursion?
  - Similar event is NOT seen in the 3rd excursion
  - A threshold? A coincidence?
  - The pulsed fraction seems increase during the superorbital excursion
  - Future detailed observations with phase-coherent analysis are essential



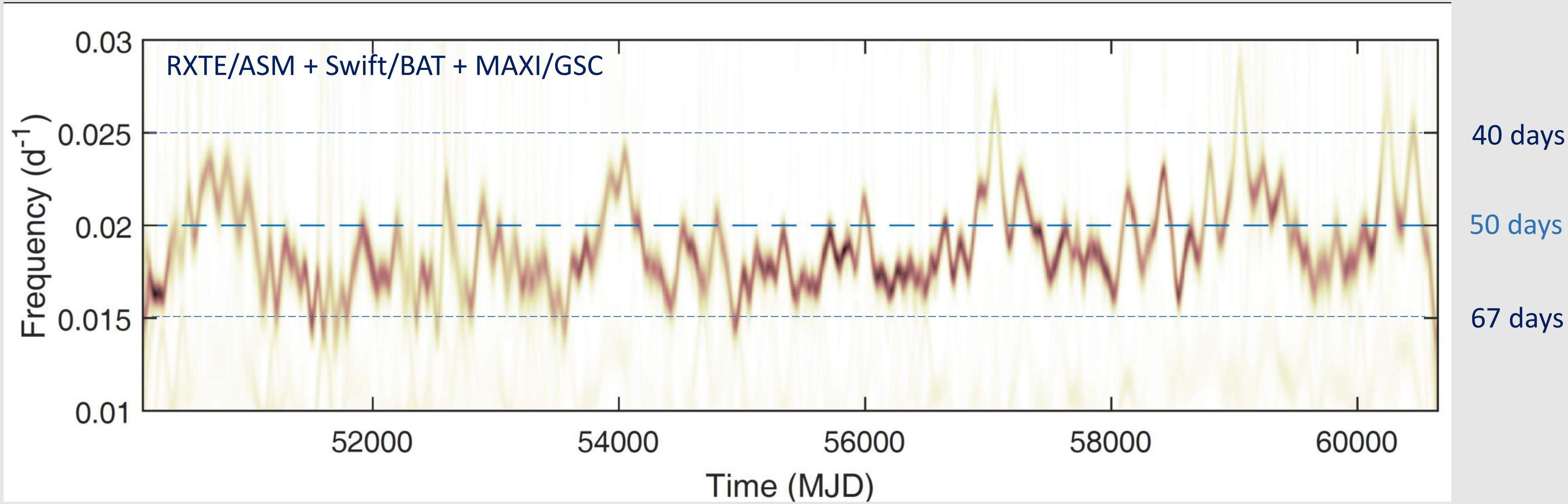
Hu et al. (2023)



(a) Stacked Pulse Profile
Normalized Rate
1.5
1
0.5
(b) Pulse Profile Evolution
Arbitrary Units
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Pulse Phase
0.015
0.02
0.025
(c) Superorbital Frequency Evolution

Hu et al. (2023)

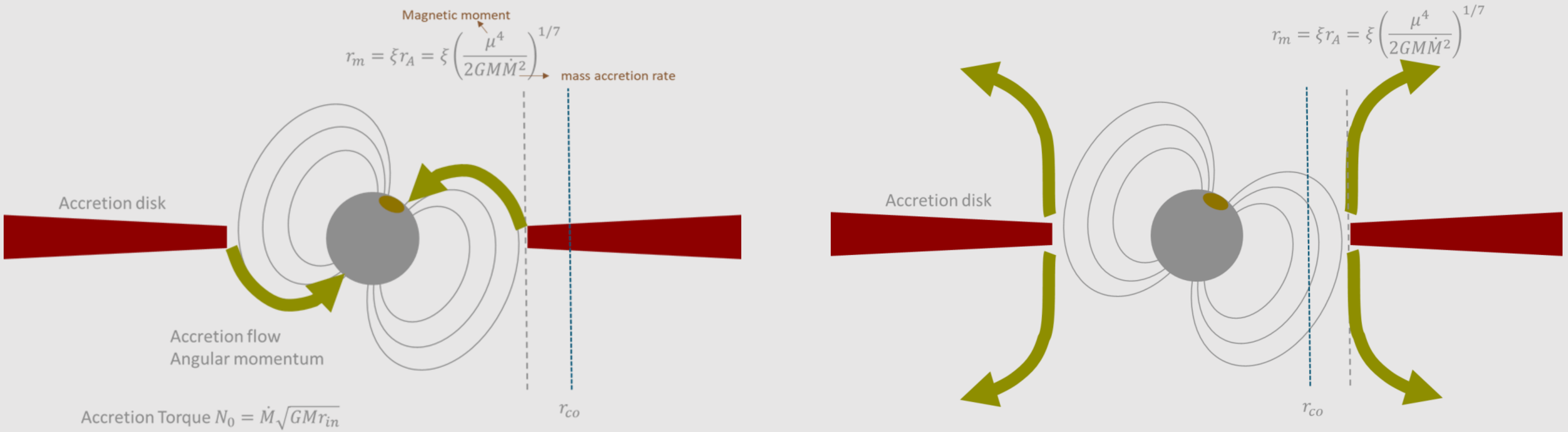
Recent Update



- The superorbital modulation period of SMC X-1 seems to decrease over time.
  - After MJD 57,000, the superorbital period is frequently shorter than 50 days.

Hu et al. (in prep)

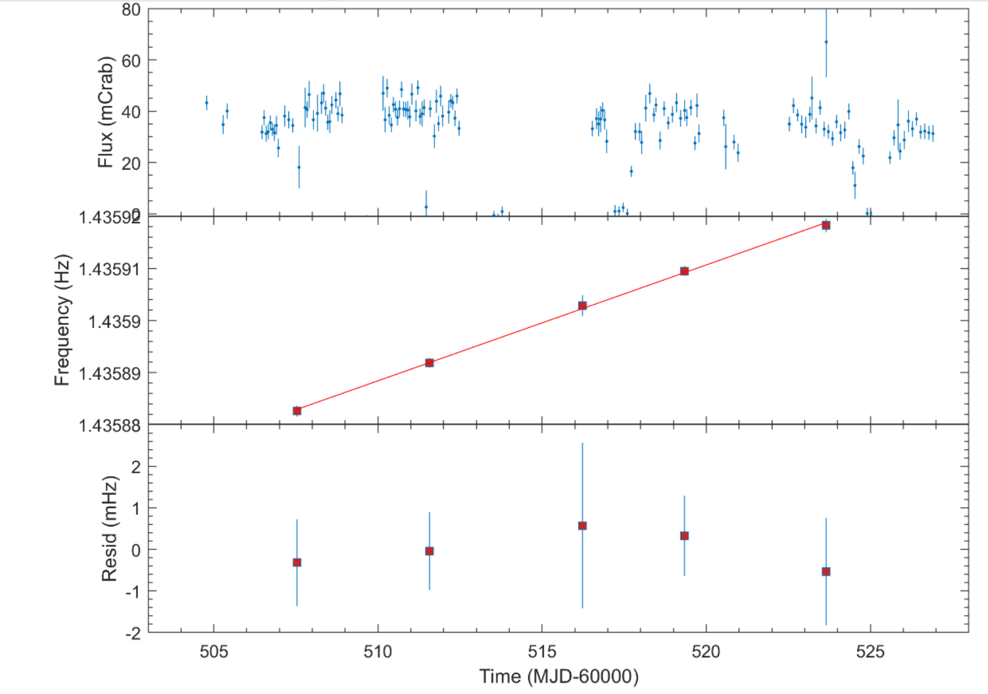
Disk Precession vs Propeller



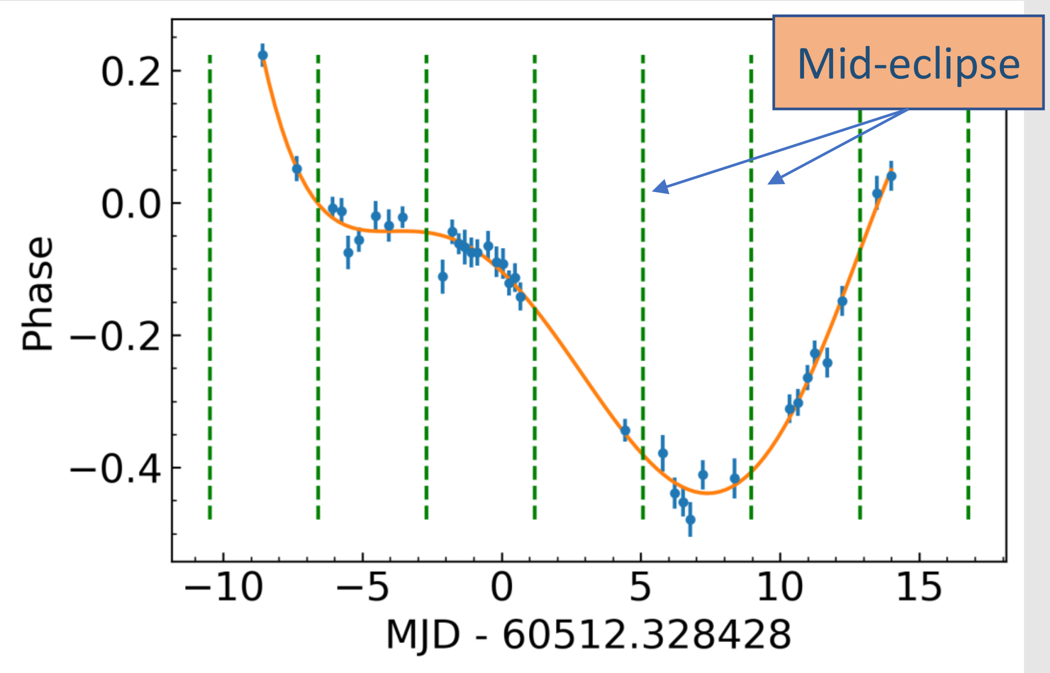
- Some evidence against the radiation driven warp model
  - NuSTAR observations detected pulsations in the low state, making simple obscuration unlikely (Pradhan et al. 2020).
- Many ULX pulsars show long-term variability with bimodal flux distributions.
  - Propeller effect? (change in mass accretion rate)
  - If the propeller effect were involved, the spin-up rate should change dramatically during the propeller phase!

High-Cadence Monitoring: NinjaSat

Z_2^2-search result



Phase-coherent analysis



- NinjaSat: a 6U CubeSAT (PI: Toru Tamagawa, Teruaki Enoto)
- First trial run: 2024 July – Phase coherent analysis is available
- We plan to monitor SMC X-1 for nearly a complete superorbital cycle since Dec. 13.

Hu et al. (in prep)

Summary and Future Work

- Stack Spectrum HHT is a powerful tool for tracing non-stationary signals with frequency changes greater than a factor of ~2.
- The processes behind superorbital modulation and superorbital excursions are still not fully understood.
  - During excursions, high-state flux remains stable while low-state count rates increase.
  - The most recent excursion shows a possible connection between changes in the spin-up rate and the superorbital excursion.
  - A noticeable change in the pulsed fraction has also been observed
  - Obscuring? Accretion rate variability?
- Monitoring spin period evolution is needed to test the propeller scenario.
  - A small CubeSat like NinjaSat can facilitate long-term, phase-connected observations, providing valuable data to unveil these mysteries.