Detection of hard X-ray pulsation from LS 5039 using Suzaku and NuSTAR

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Variable Galactic Gamma-Ray Sources (V)
@Barcelona University
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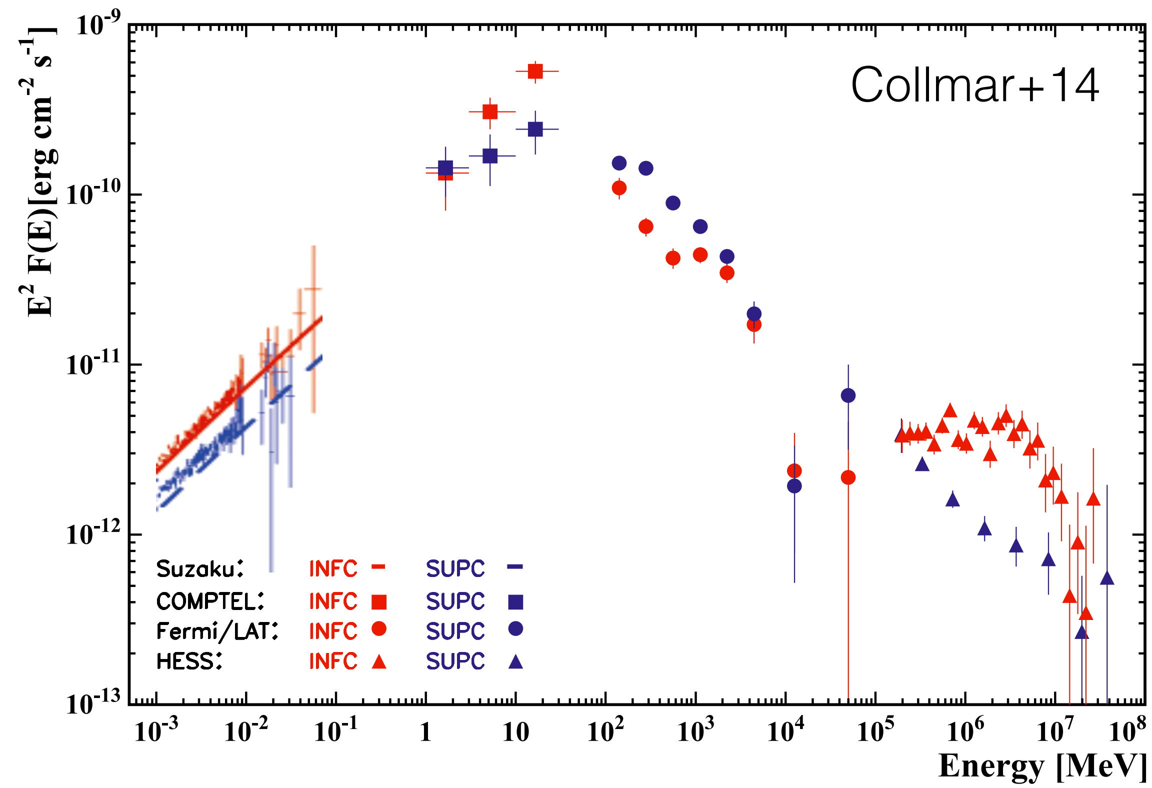
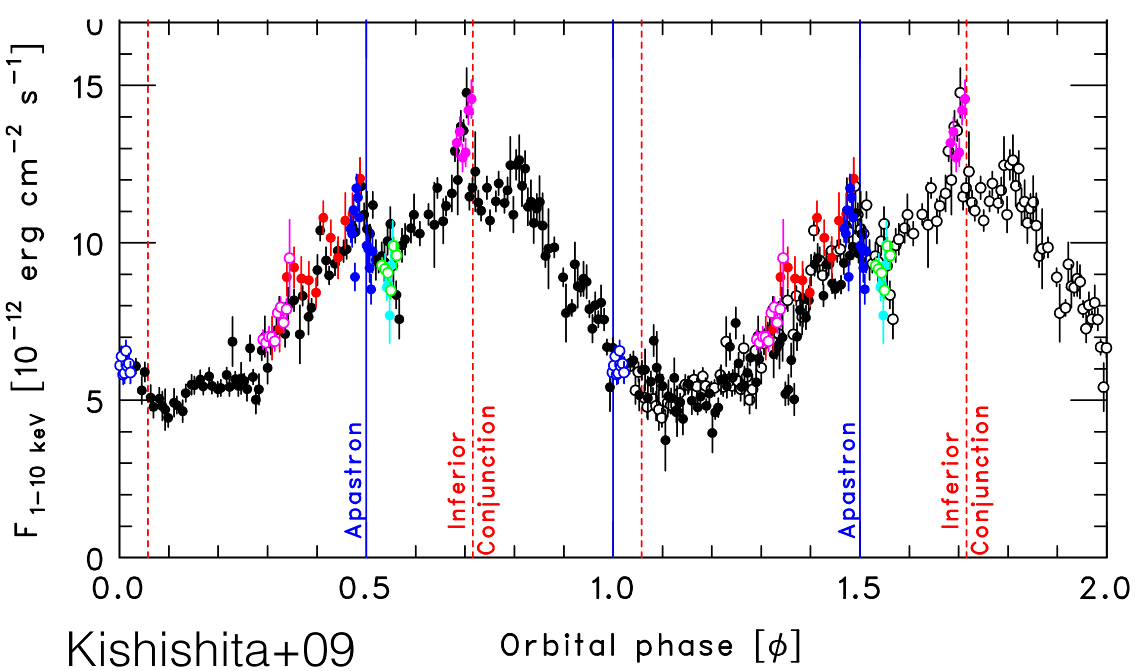
Gamma-ray binary LS 5039

Brightest gamma-ray binary

- Luminosity ~ 1 × 10^{36} erg s^{-1}
- Spectral peak is 10-100 MeV
  Collmar+14
- Orbital modulation of flux is seen

from X-ray to TeV   Takahashi+09, Collmar+14, Fermi+18, Mariaud+15





Effective/Stable Particle Accelerator

- X-ray flux is very stable in ten year scale
  Kishishita+09
- T_{acc} ~ few seconds @20 TeV   Takahashi+09

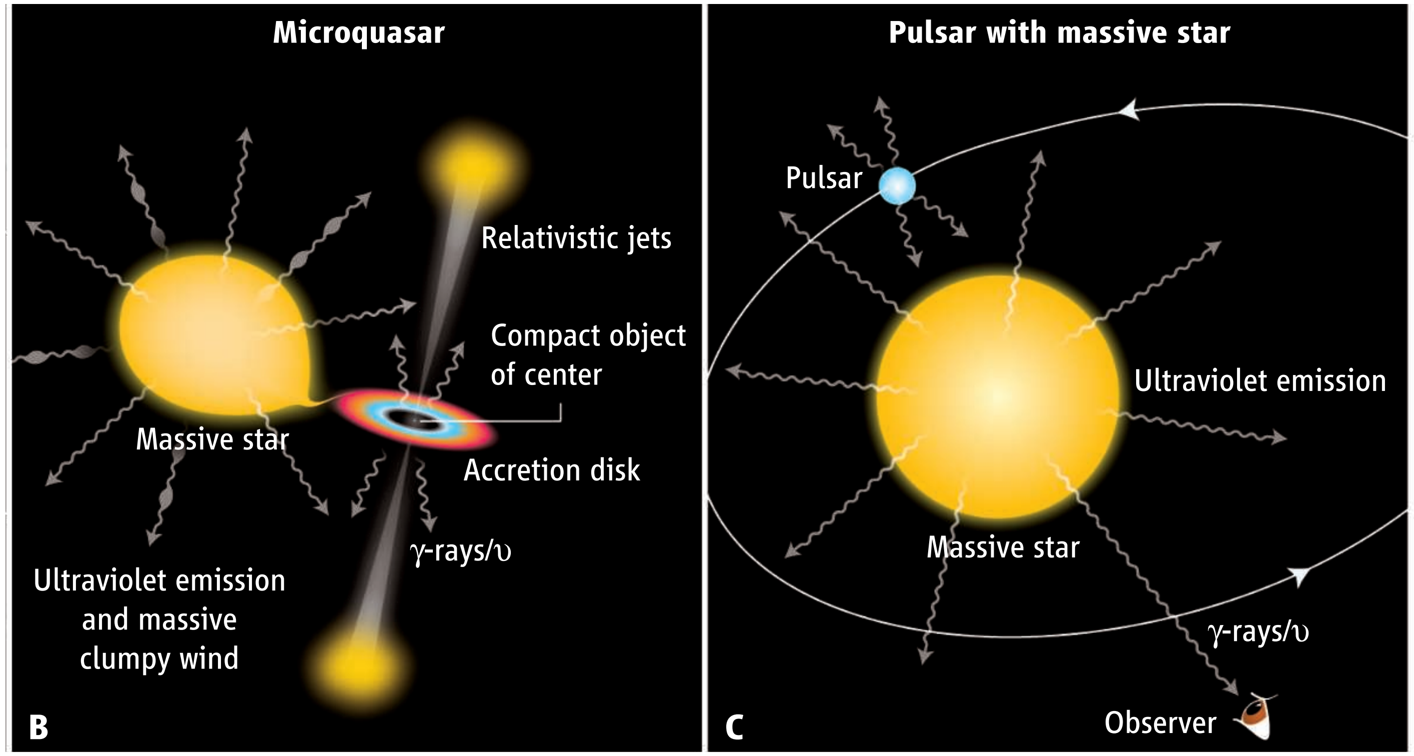
What is the mechanism of particle acceleration?

What makes this source so unusual?

What is the compact object in LS 5039

A key information to understanding the system

Mirabel+12



If it is a Black Hole…

Relativistic jet from BH

If it is a Neutron Star…

Shock between Pulsar and O star

However, whether it is a BH or a NS is still unknown…

Previous Works

McSwain+11: Upper limit below 1 KHz in radio band (4.1-14.5 μJy)

Rea+11: Upper limit from 0.005-175 Hz in soft X-ray band (0.3-10 keV)

We focus on hard X-ray band (> 10 keV) for pulsation search

(low stellar wind absorption, long observation data of Suzaku, NuSTAR)

Pulse Search using Suzaku/NuSTAR

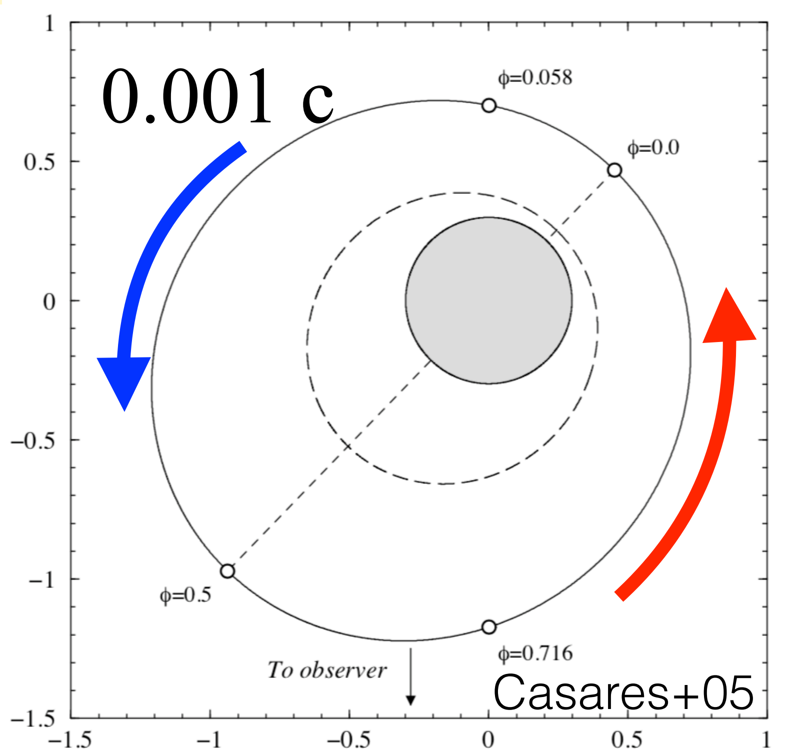
Suzaku/PIN observation: Longest Observation Ever in Hard X-rays

- Observation Epoch: 2007 Sep 09 - 15 (6 days)
- Exposure: 500 ks
- Event Selection: 10 - 30 keV
- Total Event Number: ~ 81000 (~ 8000 from source)

NuSTAR observation: One-orbit Observation in Hard X-rays

- Observation Epoch: 2016 Sep 01 - 5 (6 days)
- Exposure: 346 ks
- Event Selection: 10 - 30 keV
- Total Event Number: ~ 12000

1st Step: Timing Analysis by diving data



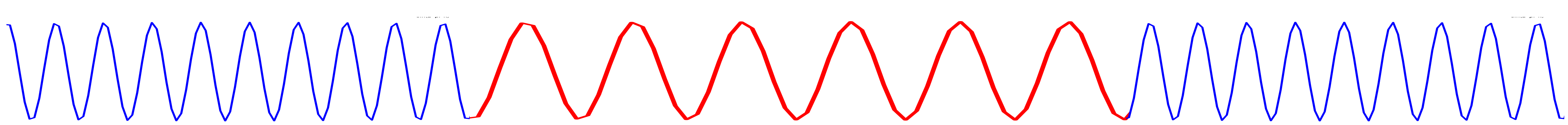
Effect of orbital motion

- Orbital velocity of NS is ~ 0.001 c (Casares+05, Aragona+09, Sarty+11)
  ➔ smears the pulse signal
- Large parameter space,
  ➔ it is difficult to search pulse with correcting the orbital moduration

Simple and Best Way

1. Divide the data into subsets with a time interval of T_{sub}.
   Resolution of timing analysis ($1/T_{sub}$) > Orbital modulation (0.001/P)
   ➔ $T_{sub} < 1000 \times$ Pulse Period
2. Apply Fourier analysis to each subset, and merge the result incoherently

※ To get enough photons in subsets (>10 events), we focus on pulse signal < 1 Hz.



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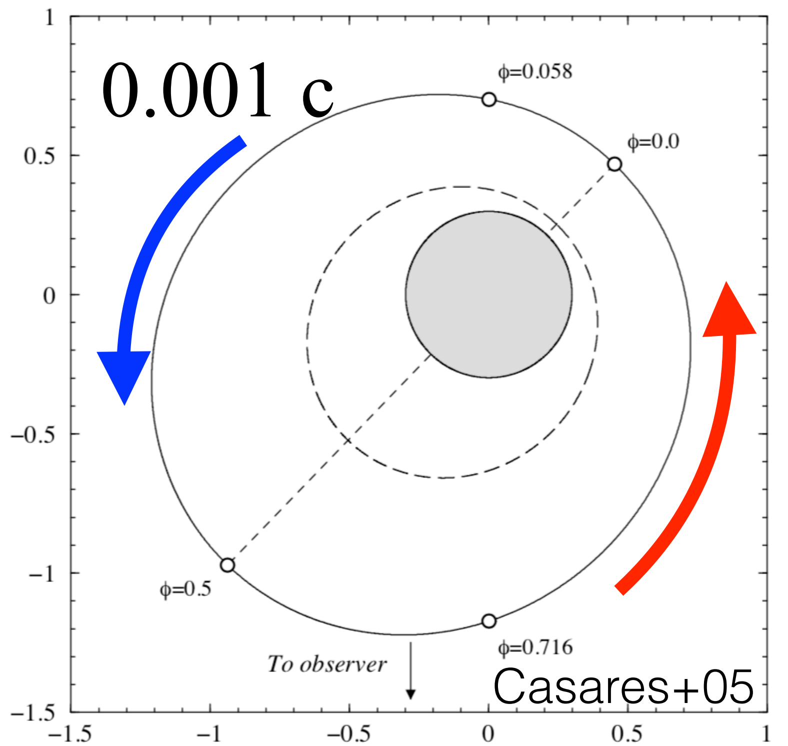

Effect of orbital motion

- Orbital velocity of NS is ~ 0.001 c

  ➔ smears the pulse signal

- Large parameter space,

  ➔ difficult to search pulse with correcting the orbital moduration

Simple and Best Way (no orbital correction)

1. Divide the data into subsets with a time interval of T_{sub}.
   Resolution of timing analysis ($1/T_{sub}$) > Orbital modulation (0.001/P)

   ➔ $T_{sub} < 1000 \times$ Pulse Period

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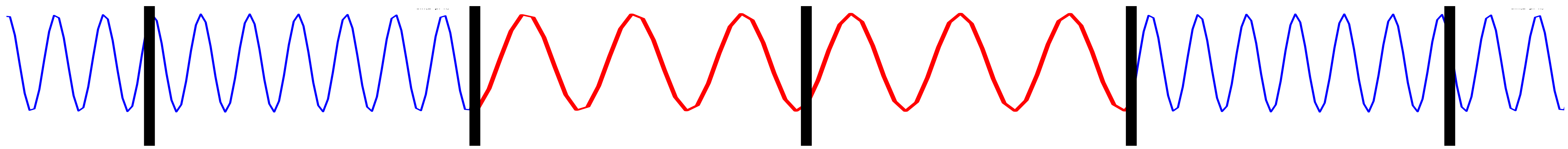
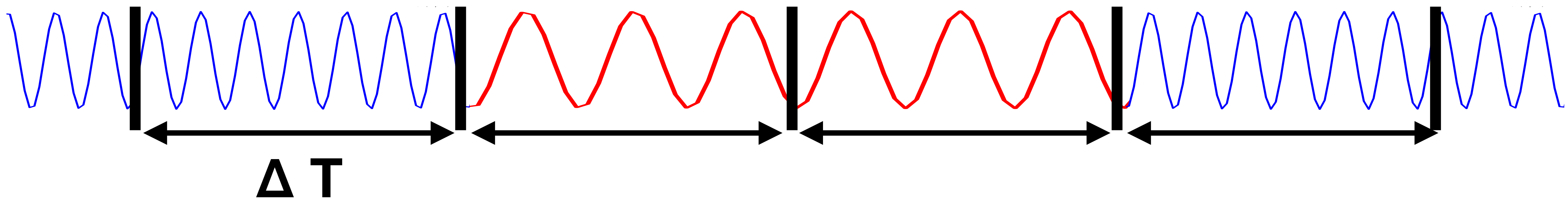
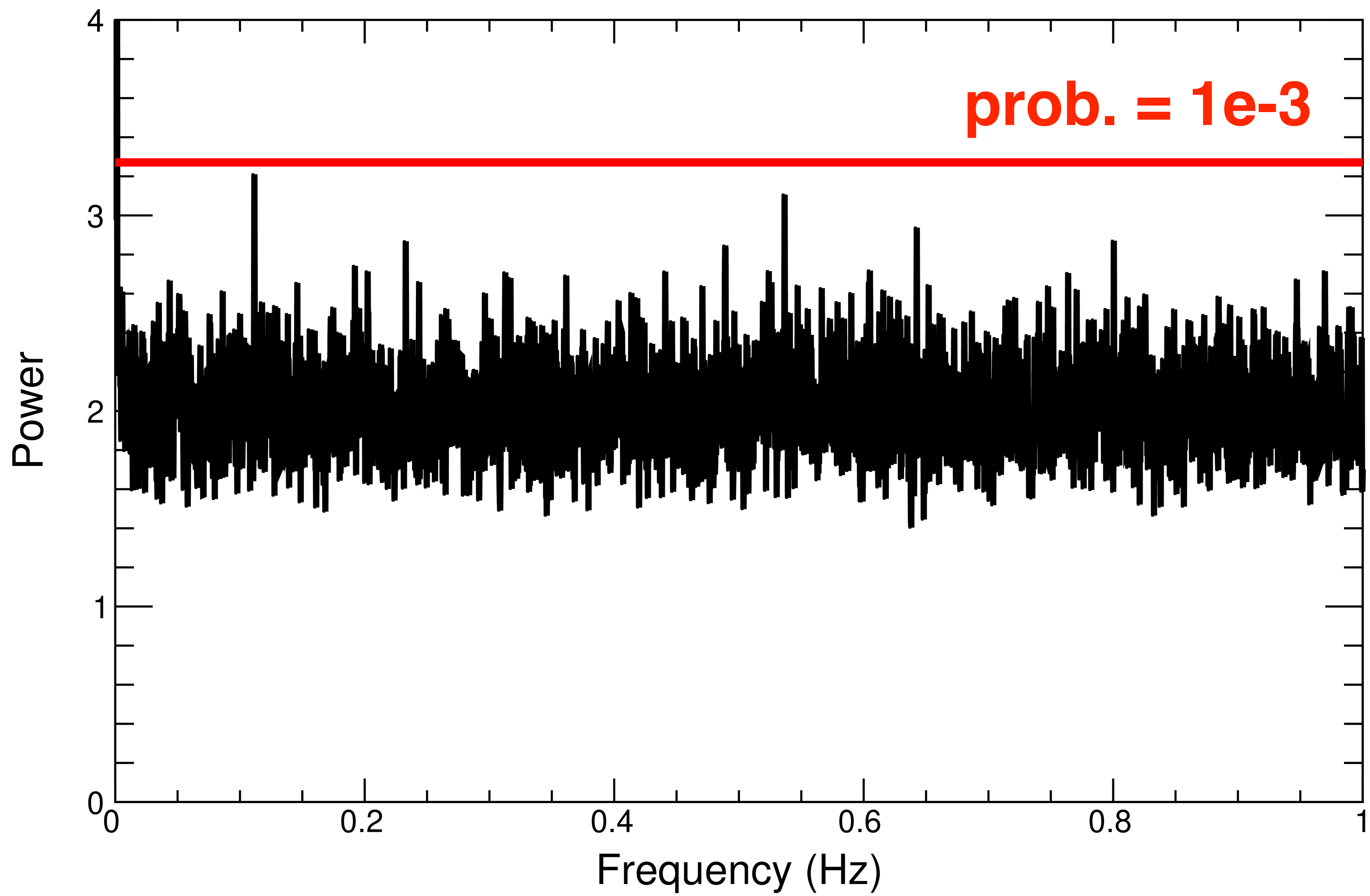


Fourier Analysis with Suzaku



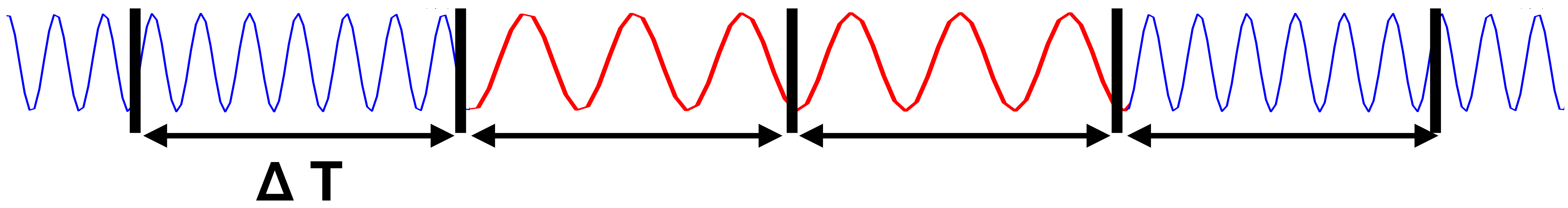


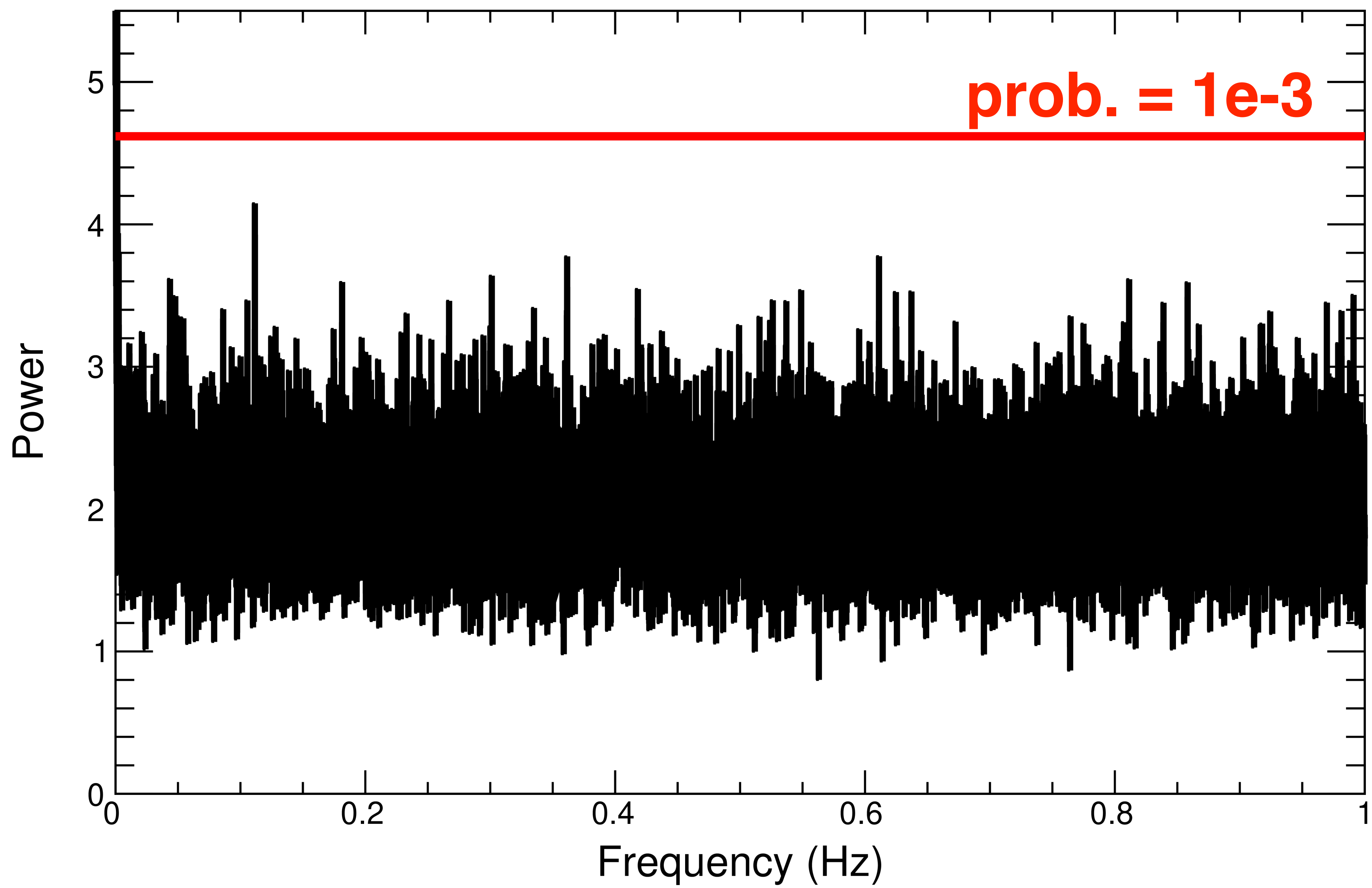
Δ T = 4096 s

Δ T = 8192 s

Δ T = 16384 s

Fourier Analysis with Suzaku





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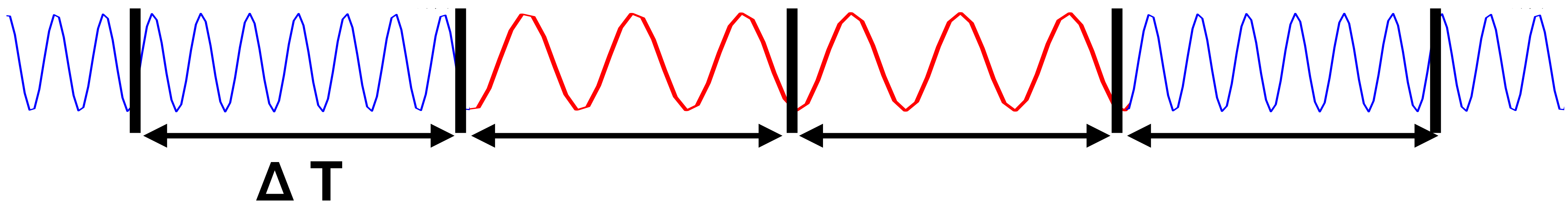

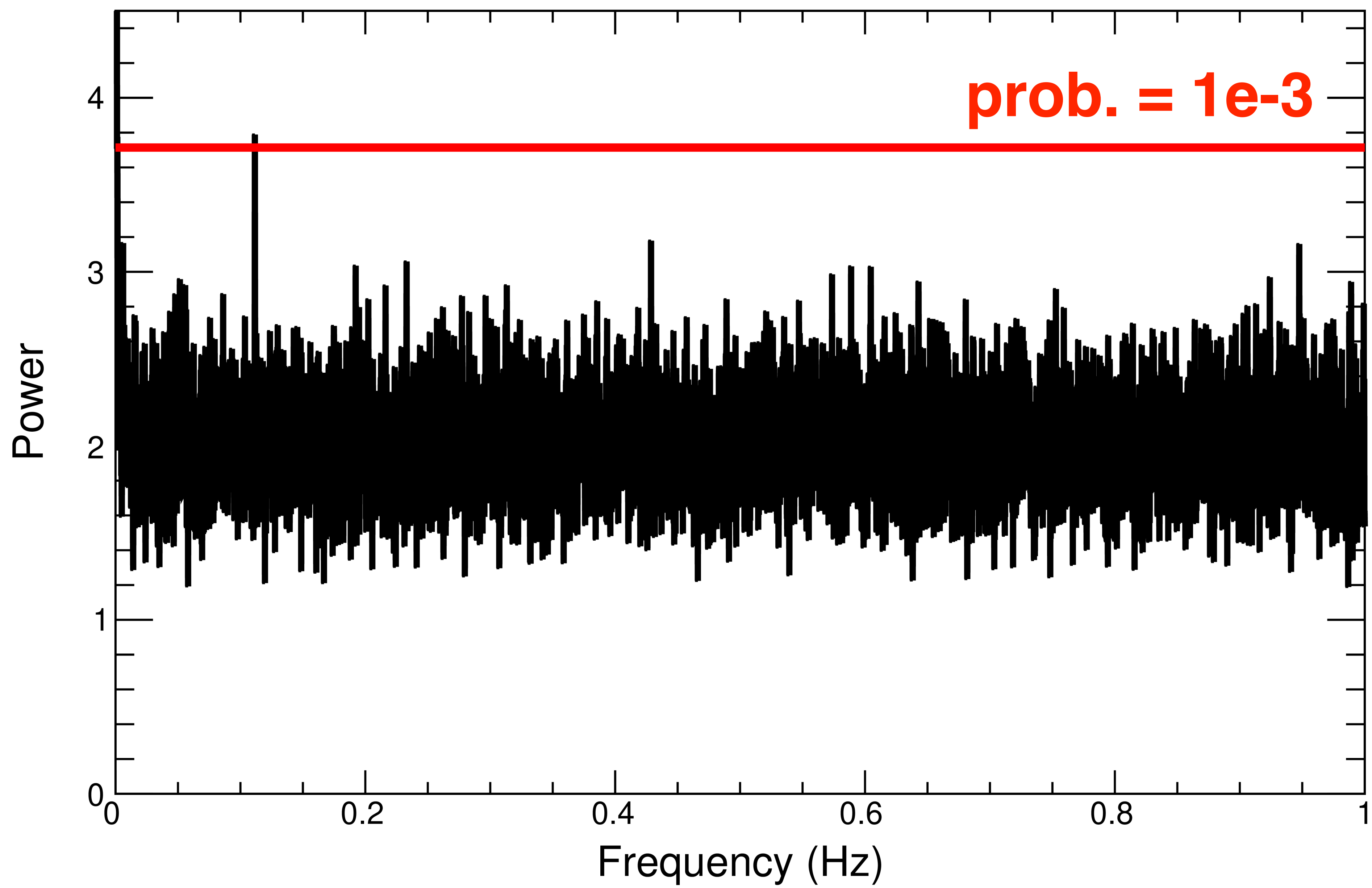

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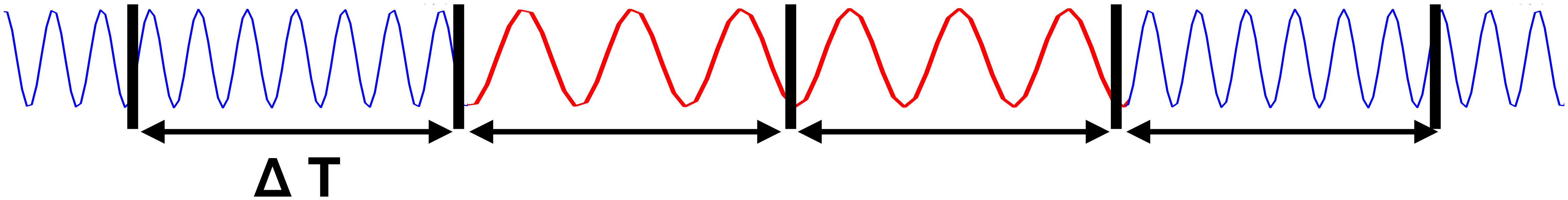
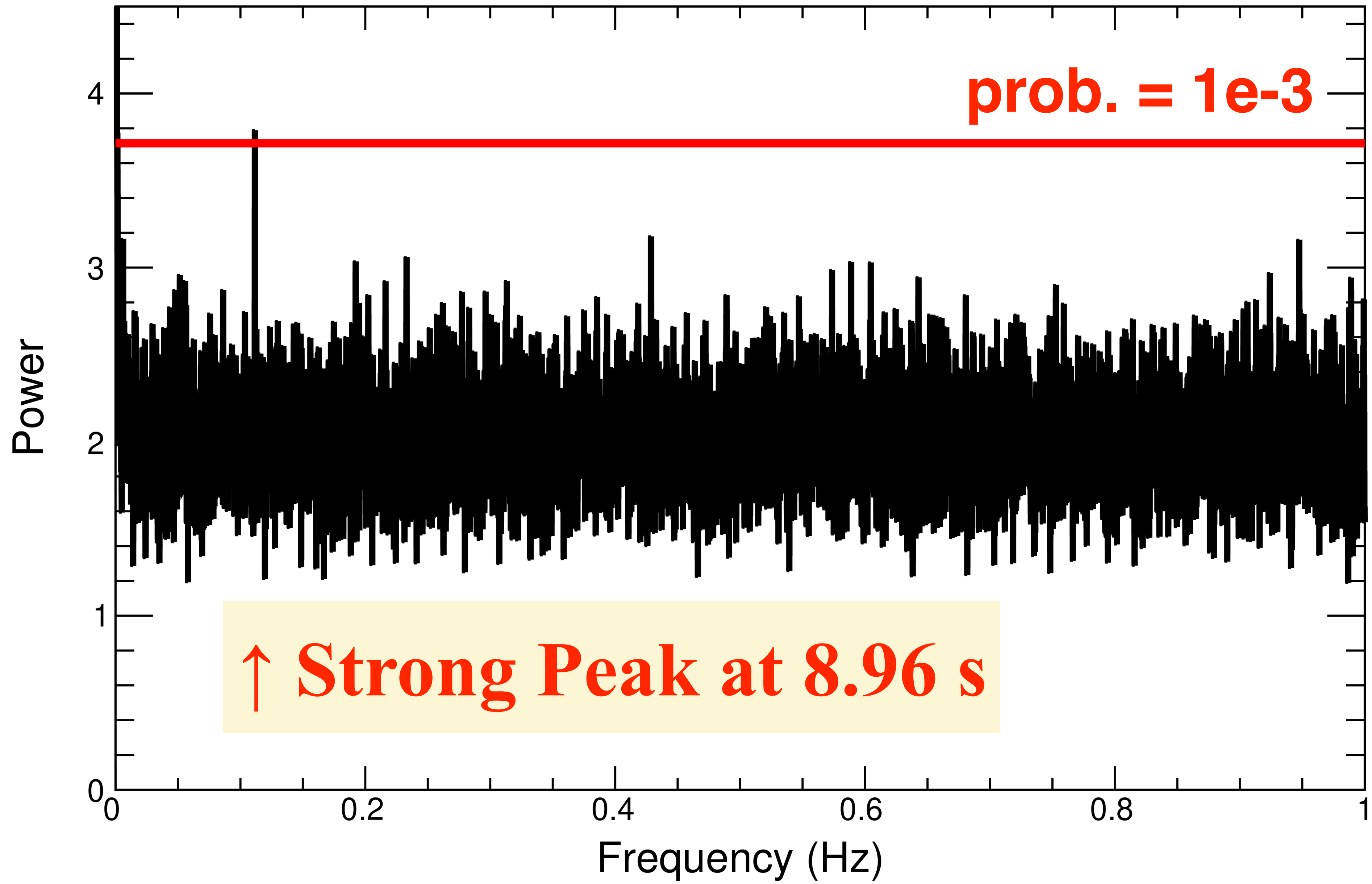




Δ T = 4096 s

Δ T = 8192 s

Δ T = 16384 s

Z^2 analysis

To check the peak at 8.96 s, we analyzed the Suzaku data with Z^2 statistics.

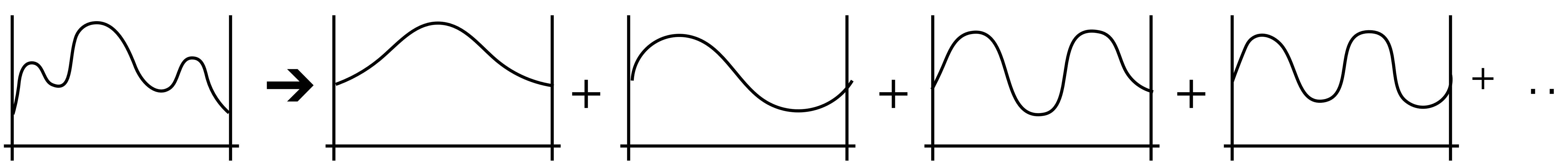
Z^2 statistics (De Jager+89)

A common technique to search a weak periodic signal

Unbinned likelihood analysis (better than ordinary chi-square evaluation)

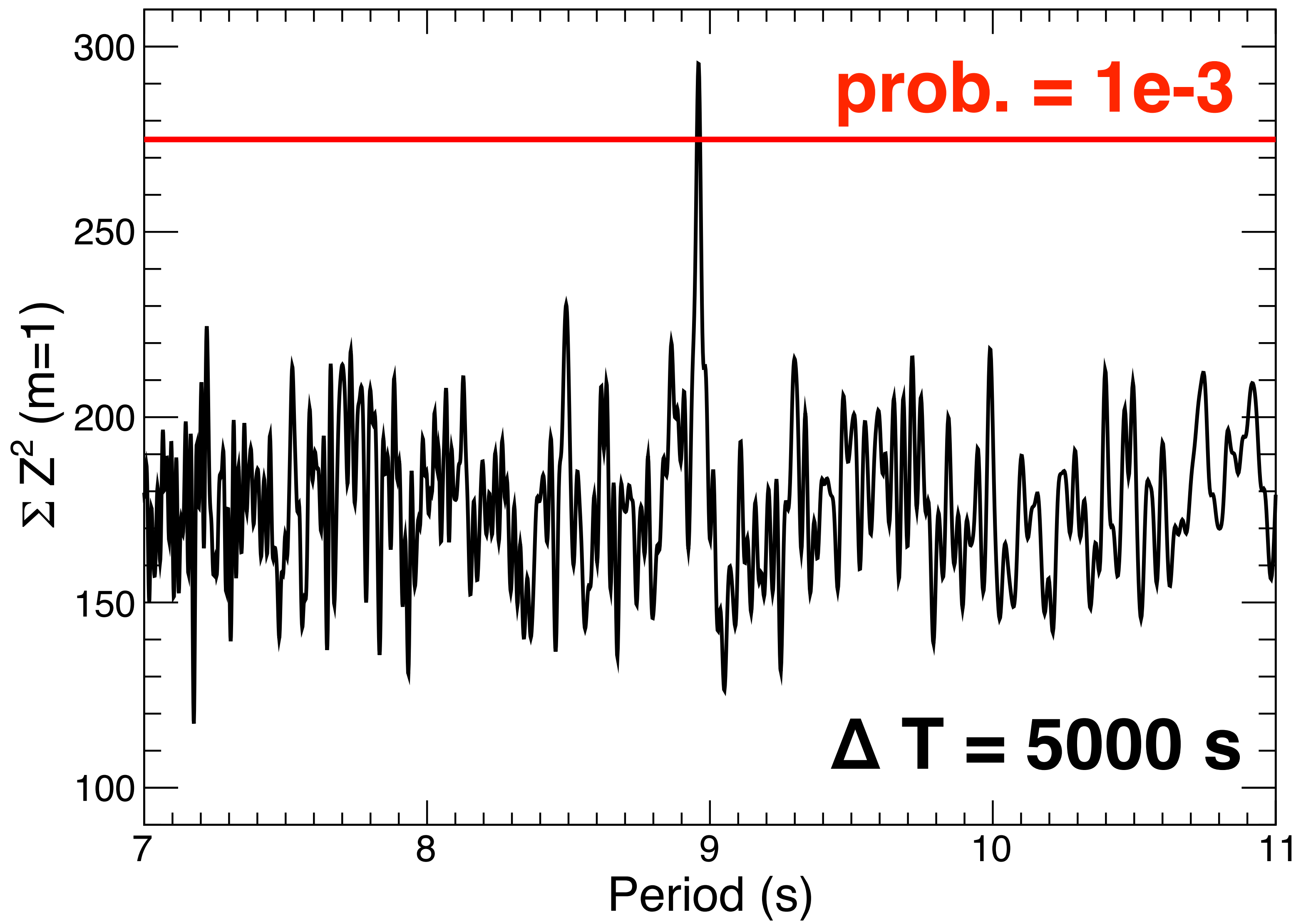
$$Z_m^2 = \frac{2}{N} \sum_{l=1}^{l=m} \left(\left(\sum_i \cos 2\pi l \frac{t_i}{P} \right)^2 + \left(\sum_i \sin 2\pi l \frac{t_i}{P} \right)^2 \right) \simeq \log L$$

1. Make a folded light curve assuming a period.
2. Calculate Fourier component of the obtained profile
3. Sum up the power of the component upto m-th harmonics.



Confirmation of peak with Z^2 statistics

To confirm the peak at 8.96 s, we analyzed the Suzaku data with Z^2 statistics.



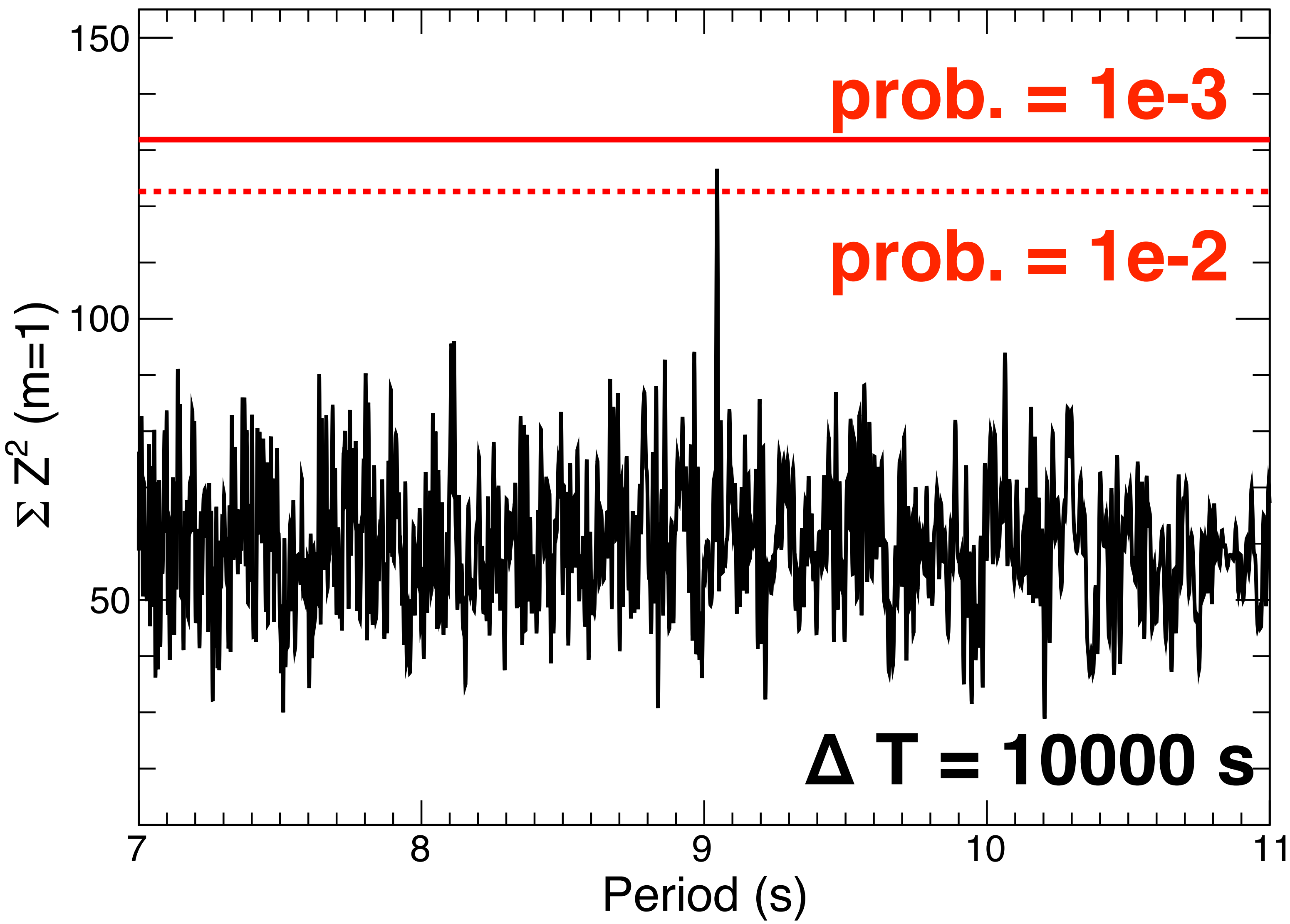
$P = 8.960 \pm 0.009$ s with a chance probability $< 1.4 \times 10^{-4}$

※ Period of peak does not depends on ΔT

Timing Analysis with NuSTAR

We analysis archived NuSTAR data (10-30 keV, gross exp. = 350 ks)

9 year after the Suzaku observation, the number of source event is ~ 11000



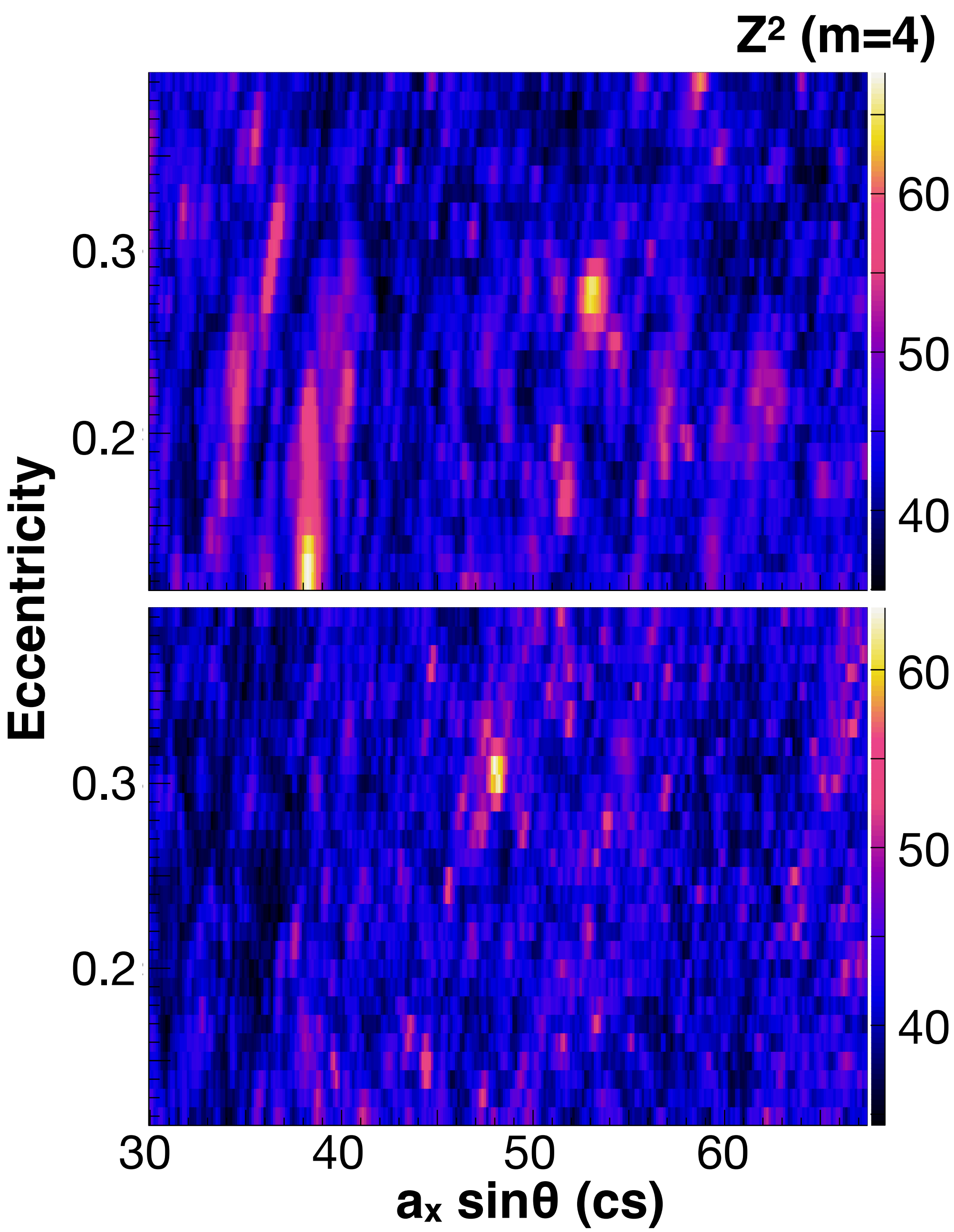
P = 9.045 ± 0.009 s with a change probability of 3×10^{-3}

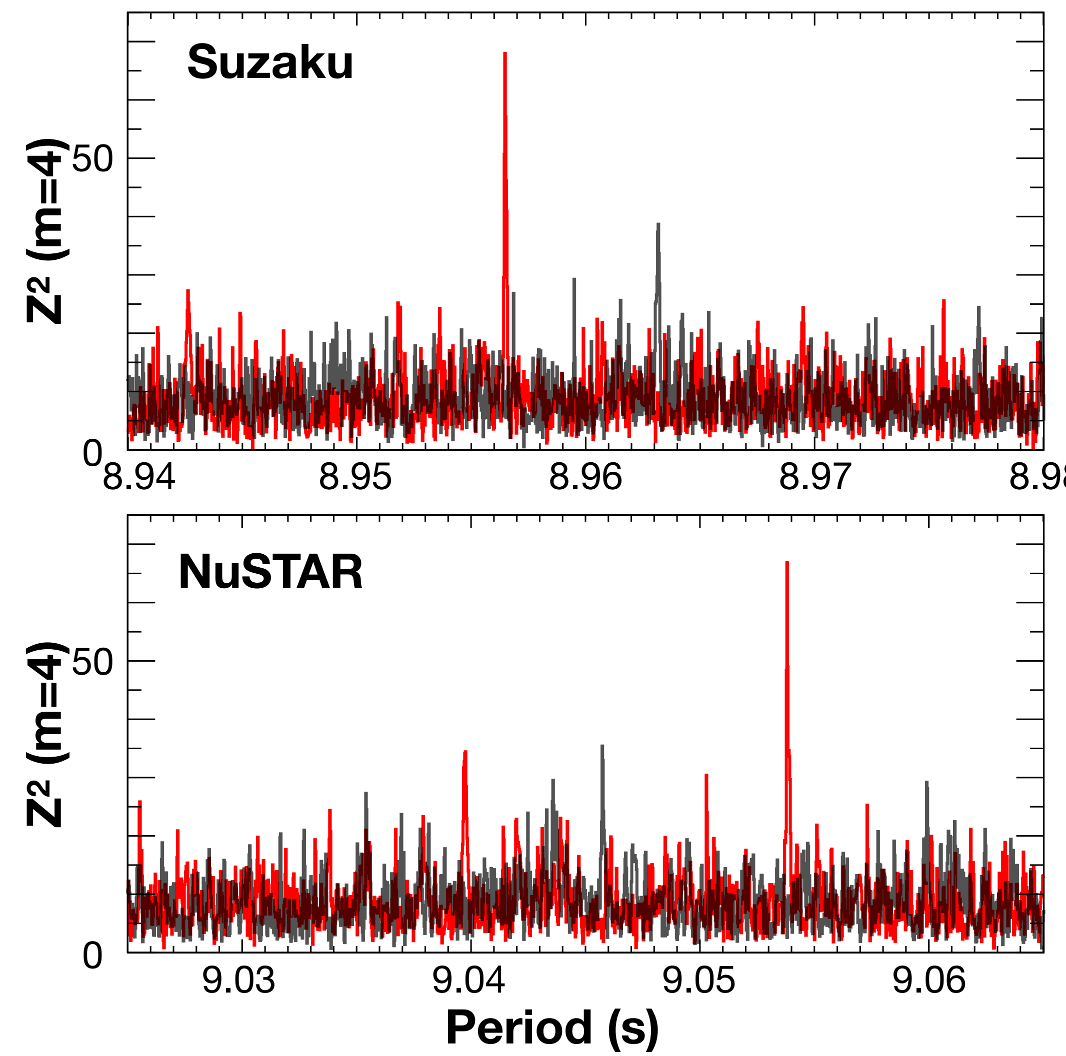
※ Period of peak does not depends on ΔT

※ significance level is lower than that of Suzaku, thus no peak in FFT

Orbital Motion Correction

1. **Assume a set of orbital parameters, and calculate the orbit of NS**
2. **correct the photon arrival time to the time on NS**
3. **apply Z^2 analysis to corrected data. (Here the pulse profile was described with four Fourier harmonics.)**

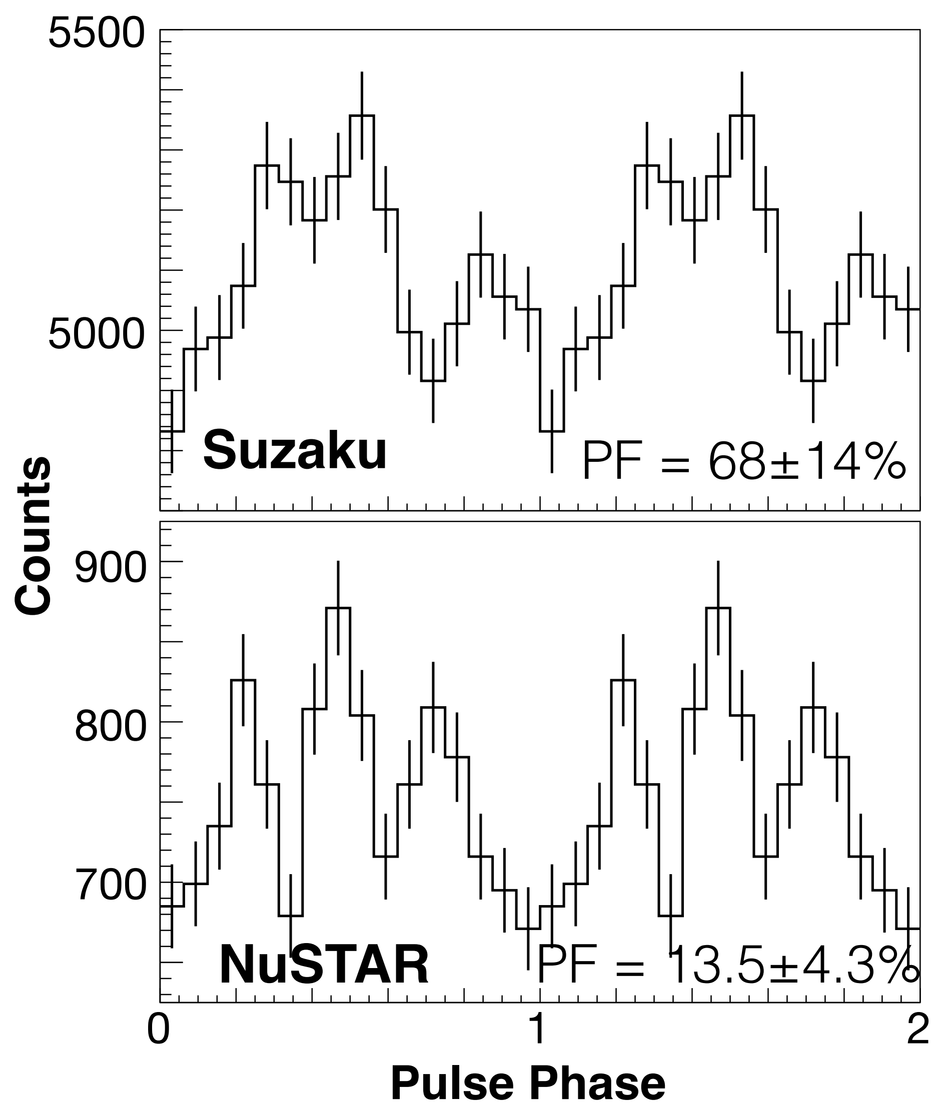




The significance level is improved considerably

Solution of Orbital Parameters

	$a_x \sin\theta$ (cs)	eccentricity	initial phase	omega (deg.)	Pulse period (s)	$Z^2(m=4)$
Suzaku	$53.05^{+0.68}_{-0.51}$	$0.278^{+0.013}_{-0.023}$	$0.067^{+0.008}_{-0.012}$	$54.6^{+5.1}_{-4.1}$	8.95648(4)	67.97
NuSTAR	$48.1^{+0.4}_{-0.4}$?	$0.306^{+0.013}_{-0.012}$?	$0.7285^{+0.0066}_{-0.0040}$	$56.8^{+2.3}_{-4.7}$ ok	9.05381(3)	66.87



- Orbital parameters are consistent with optical solutions
- $a_x \sin\theta$, eccentricity are different from each other slightly
- The compact-object mass has been constrained as 1.23 - 2.35 M⊙.

The similar pulse profiles are obtained

Summery of Observational Result

1. Fourier Analysis with Suzaku (10-30 keV) shows a strong peak at 8.96 s
2. Z^2 analysis (7s-9s) with Suzaku & NuSTAR (10-30 keV) shows a peak at 8.96 s, 9.05s with a chance probability of $< 1.4 \times 10^{-4}$ and 3×10^{-3}
3. No peak was found from 3 - 10 keV in NuSTAR data
4. The obtained pulse profiles are similar though pulse fractions are different (68% of Suzaku, 13% of NuSTAR)
5. The obtained orbital parameters are consistent with optical solutions, but slightly different from each other
6. The compact-object mass has been constrained as 1.23 - 2.35 $M_\odot$.

We conclude that the compact object in LS 5039 is

a neutron star with P of 8.96 s and Pdot of 3×10^{-10} s s^{-1}

What is the energy source of LS 5039 activity (10^{36} erg s^{-1}) ?

spin-down luminosity? accretion?

Kinetic energy of stellar wind? Magnetic field?

What is the Energy Source?

1. **Spin-down Luminosity**

$$L_{\rm LD} = \frac{(2\pi)^2 I \dot{P}}{P^3} \sim 10^{34}\ {\rm erg\ s^{-1}}$$

2. **Accreting Pulsar**
    - Pulse period is increasing
    - No fast time variability like accreting object

3. **Stellar Wind**

$$L_{\rm w} \sim \frac{1}{2}\dot{M}_{\rm w} v_{\rm w}^2 \times \frac{\pi R_{\rm A}^2}{4\pi D_{\rm sep}^2} < 6 \times 10^{31}\ {\rm erg\ s^{-1}}$$

4. **Decay of strong magnetic field**

$$L_{\rm BF} = \frac{B_{\rm NS}^2 R_{\rm NS}^3}{6\tau} \sim 10^{37} \times \left(\frac{B_{\rm NS}}{10^{15}\ {\rm G}}\right)^2 \left(\frac{R_{\rm NS}}{10\ {\rm km}}\right)^3 \left(\frac{\tau}{500\ {\rm yr}}\right)^{-1}\ {\rm erg\ s^{-1}}$$

This is the only scenario that can sustain the luminosity of 1e36 erg/s

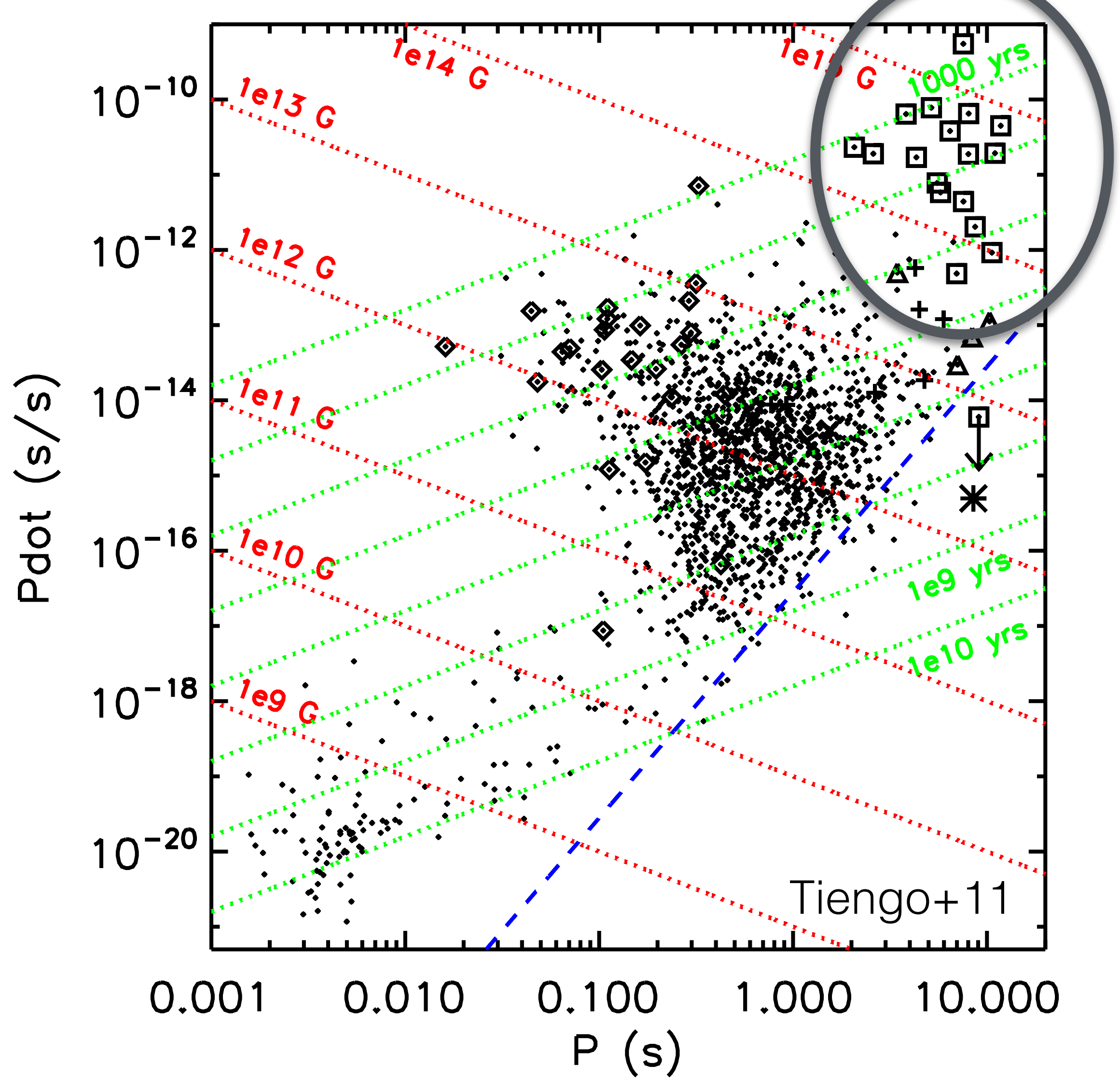
Magnetar Hypothesis

1. **It can only supply the emission energy of 10^{36} erg s-1**

2. **Period of 9s and its derivative is very consistent with isolated magnetars value (2-11 s)**

3. **Strong magnetic field prevents accretion naturally**

Magnetars



$$R_{\rm B} = \frac{2GM_{\rm NS}}{v_{\rm w}^2} \sim 1\times10^8 \times \left(\frac{v_{\rm w}}{2000\ {\rm km\,s^{-1}}}\right)^{-2}\ {\rm m}$$

Bondi-Hoyle Radius < **Alfven Radius**

$$R_{\rm Al} = \left(\frac{B_{\rm NS}R_{\rm NS}^3D_{\rm sep}}{\sqrt{2\dot{M}_{\rm w}v_{\rm w}}}\right)^{1/3} \sim\ 2\times10^8\times\left(\frac{B_{\rm NS}}{10^{11}\ {\rm T}}\right)^{1/3}\left(\frac{\dot{M}_{\rm w}}{10^{-6}M_\odot\ {\rm yr}^{-1}}\right)^{-1/6}\left(\frac{v_{\rm w}}{2000\ {\rm km\ s}^{-1}}\right)^{-1/6}\ {\rm m},$$

We conclude that the compact object in LS 5039 is a magnetar

Magnetar Hypothesis

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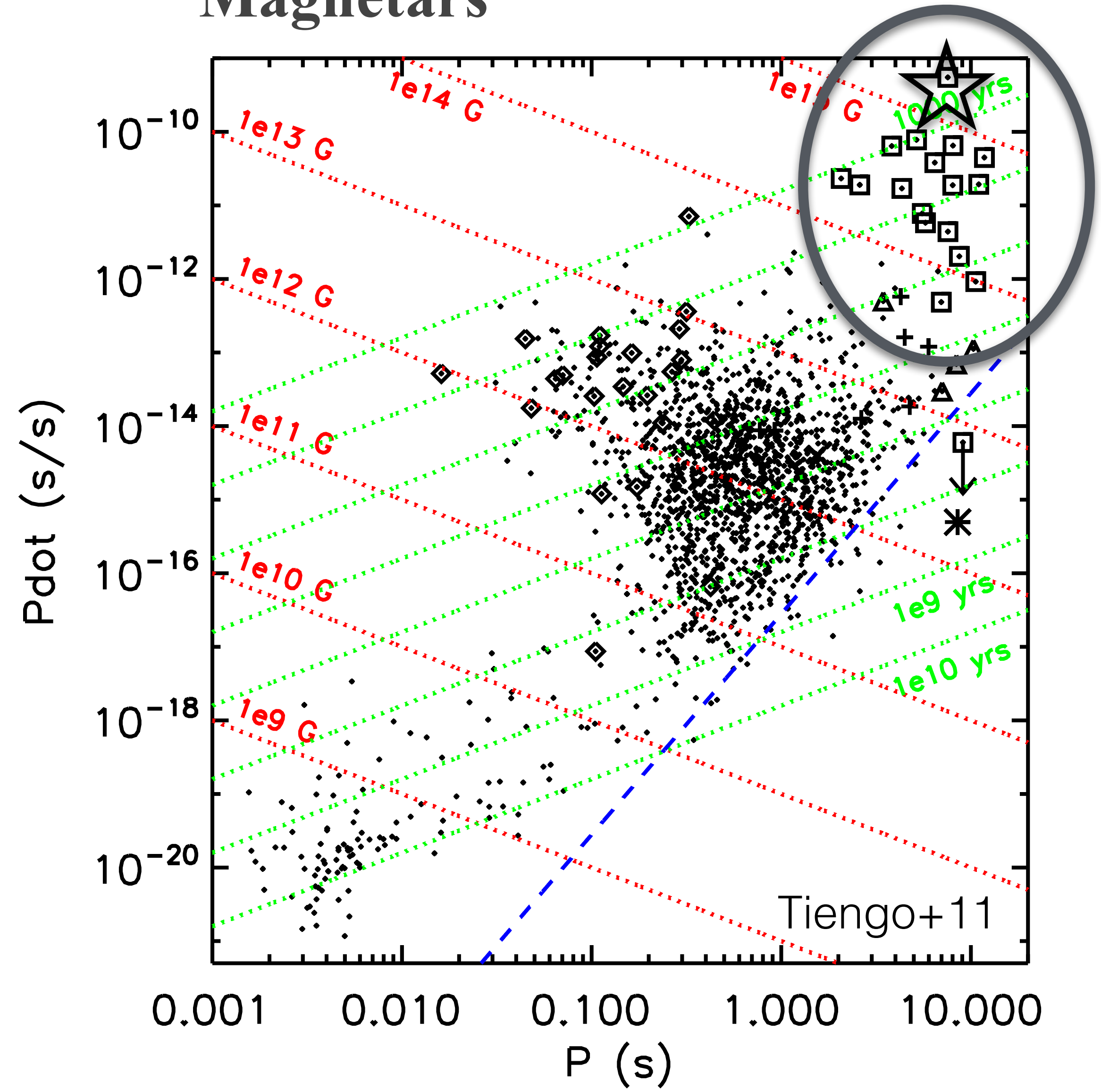

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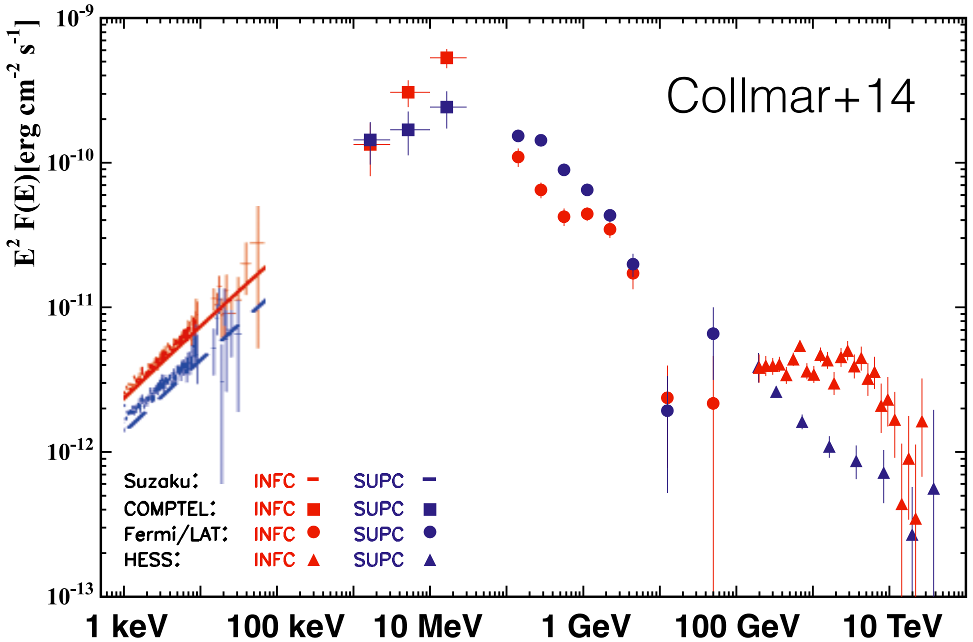
$$R_{\mathrm{Al}} = \left(\frac{B_{\mathrm{NS}} R_{\mathrm{NS}}^3 D_{\mathrm{sep}}}{\sqrt{2\dot{M}_{\mathrm{w}} v_{\mathrm{w}}}}\right)^{1/3} \sim 2 \times 10^8 \times \left(\frac{B_{\mathrm{NS}}}{10^{11}\ \mathrm{T}}\right)^{1/3} \left(\frac{\dot{M}_{\mathrm{w}}}{10^{-6} M_\odot\ \mathrm{yr}^{-1}}\right)^{-1/6} \left(\frac{v_{\mathrm{w}}}{2000\ \mathrm{km\ s^{-1}}}\right)^{-1/6}\ \mathrm{m},$$

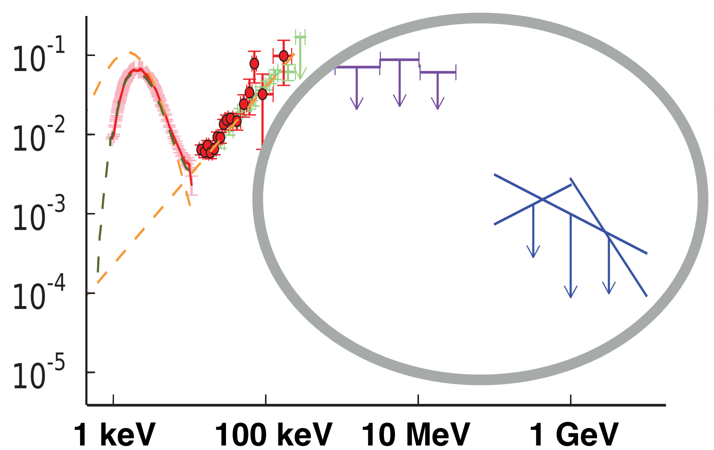
We conclude that the compact object in LS 5039 is a magnetar

Non-thermal Emission in Strong B?

LS 5039

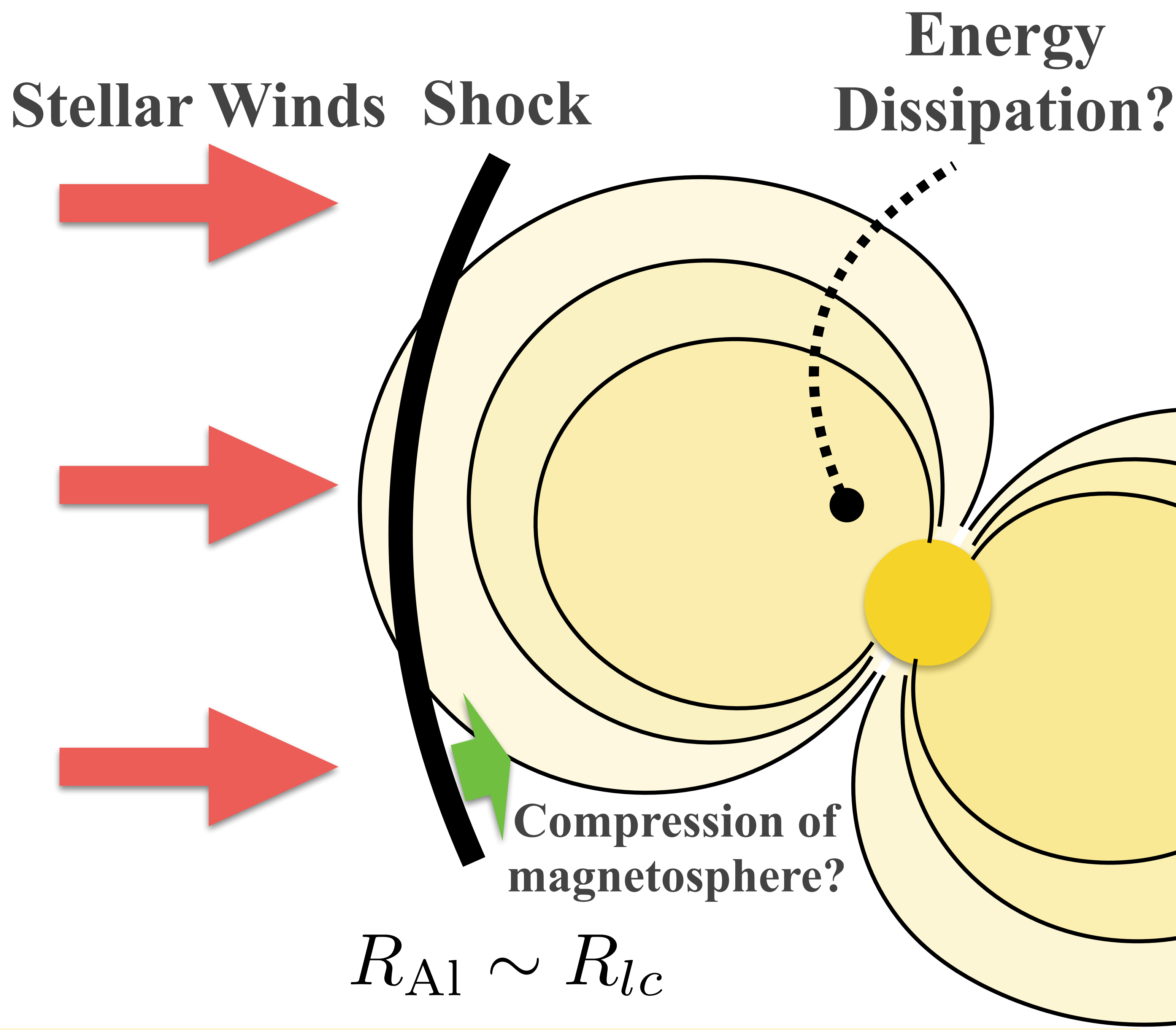


Isolated Magnetar (4U 0142+61)



Lack of the component above MeV

Enoto+11



We suggest that interactions between the dense stellar winds and the strong magnetic fields are responsible for the non-thermal emission (Detail theoretical work is needed)

Current Problems/Future Work

1. **Why the pulse fraction is weaker in NuSTAR observation?**

   Year-scale time variability? Different from soft X-ray component?

2. **Why there is difference in orbital solutions?**

   Some sporadic variations in the pulse phase and/or shape?

   (Instability of magnetic field? Free precession of a magnetar?)

   ➔New long observation in hard X-rays is needed

3. **The system age is very young**
4. **No young SNR association**

$$\tau = P/(2\dot{P}) \sim 500\,\mathrm{yr}$$

➔A scenario of the birth of a magnetar in a binary system is needed

Conclusion

1. Using timing analysis, we found a periodic component from Suzaku (8.96 s) and NuSTAR (9.046 s).

2. It tells that the compact object in LS 5039 is a magnetar with a magnetic field of ~10^{15} G

3. We propose that the non-thermal emission of LS 5039 is generated by interactions between the dense stellar winds and the strong magnetic fields.

5. The first magnetar-binary system?

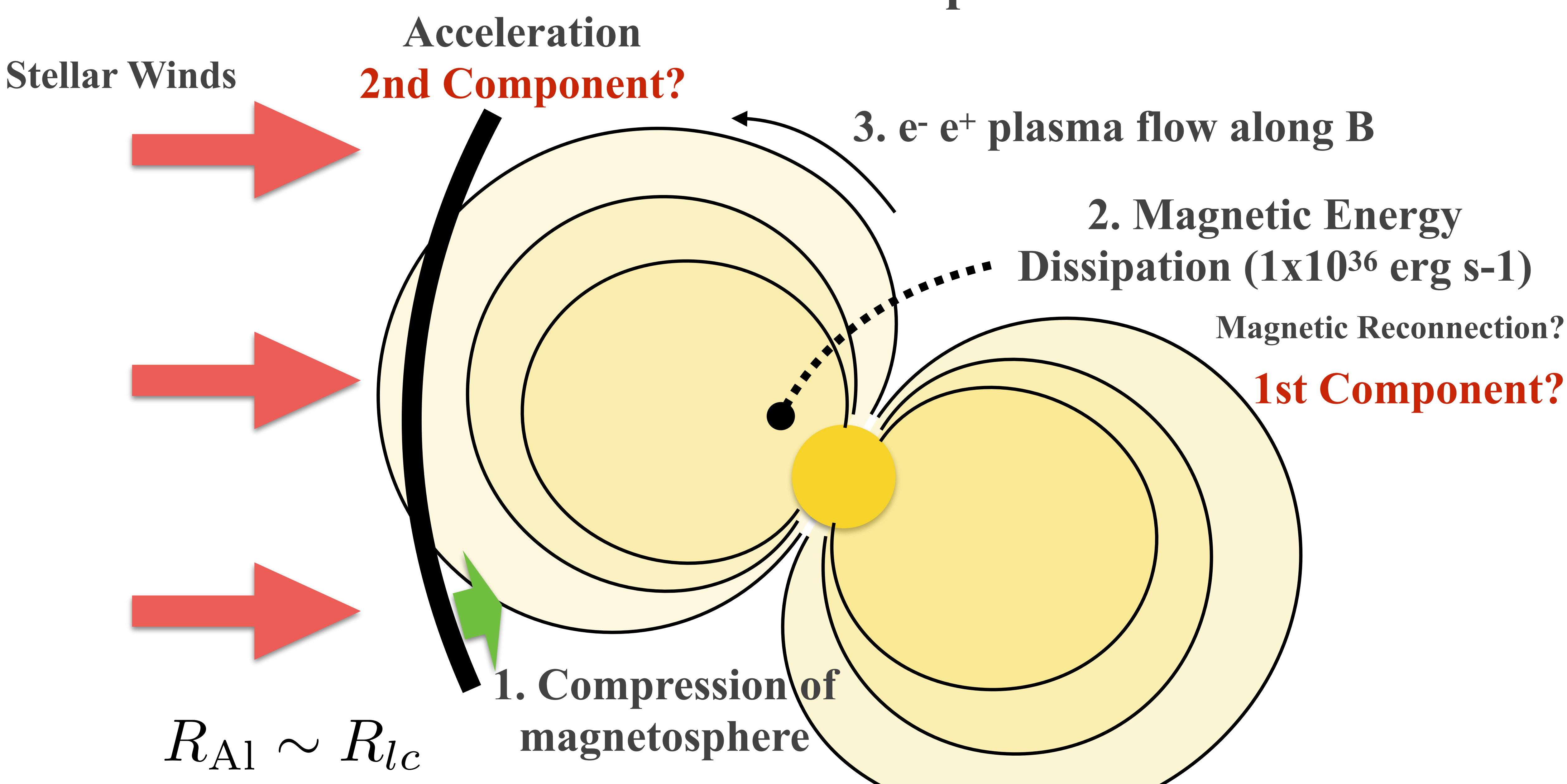
Backup

Non-thermal Emission in Strong B?

Maximum of energy dissipation of magnetic field at Alfven radius

$$L_{\rm A} = \frac{R_{\rm A}^2 B_{\rm NS}^2 c}{2} \left(\frac{R_{\rm NS}}{R_{\rm A}}\right)^6 \sim 10^{27} \times \left(\frac{R_{\rm NS}}{10\,{\rm km}}\right)^6 \left(\frac{B_{\rm NS}}{10^{11}\,{\rm T}}\right)^{2/3} {\rm W}\,.$$

➔ Dissipation must occur near NS



Time Variability in MeV(?)

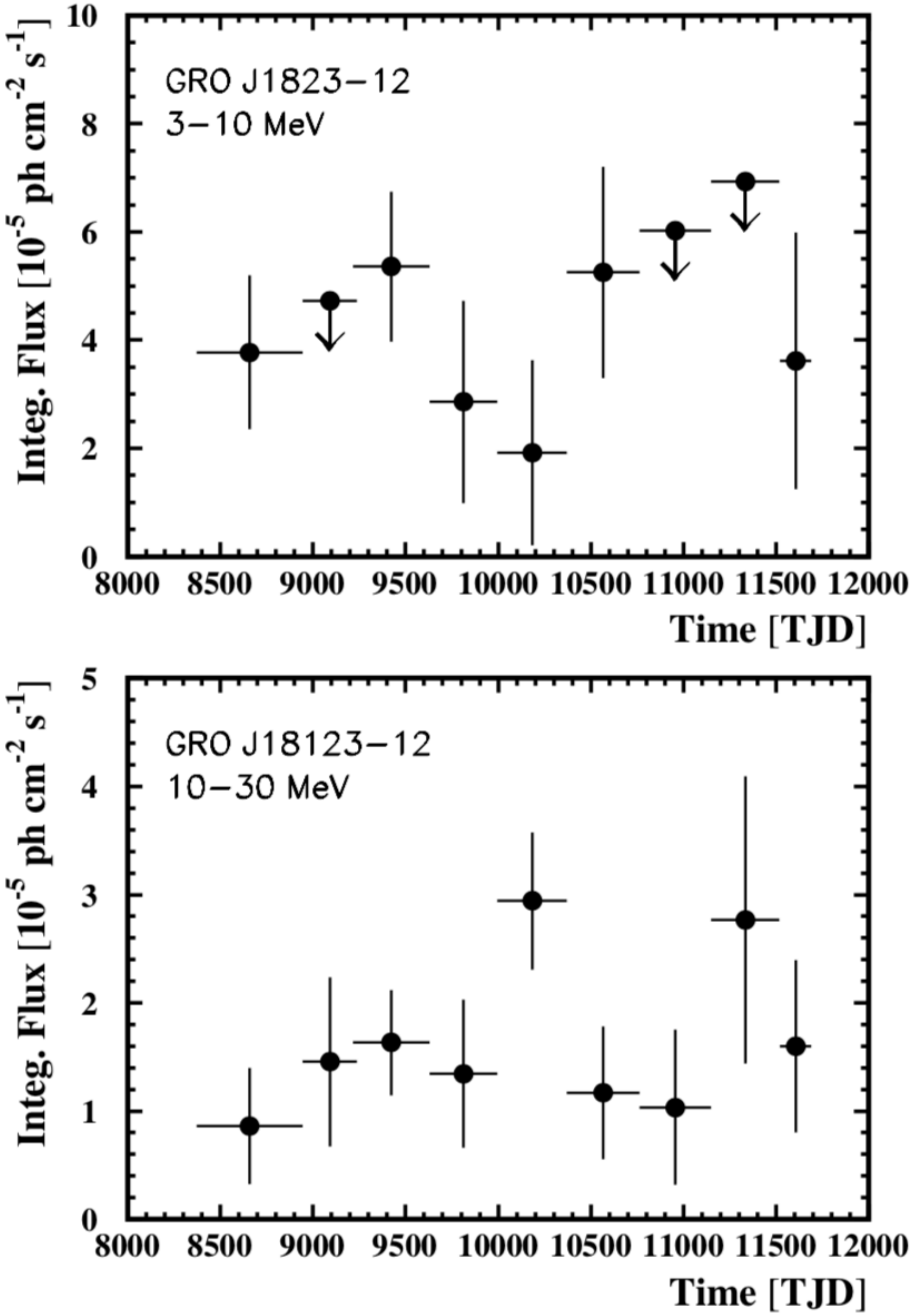
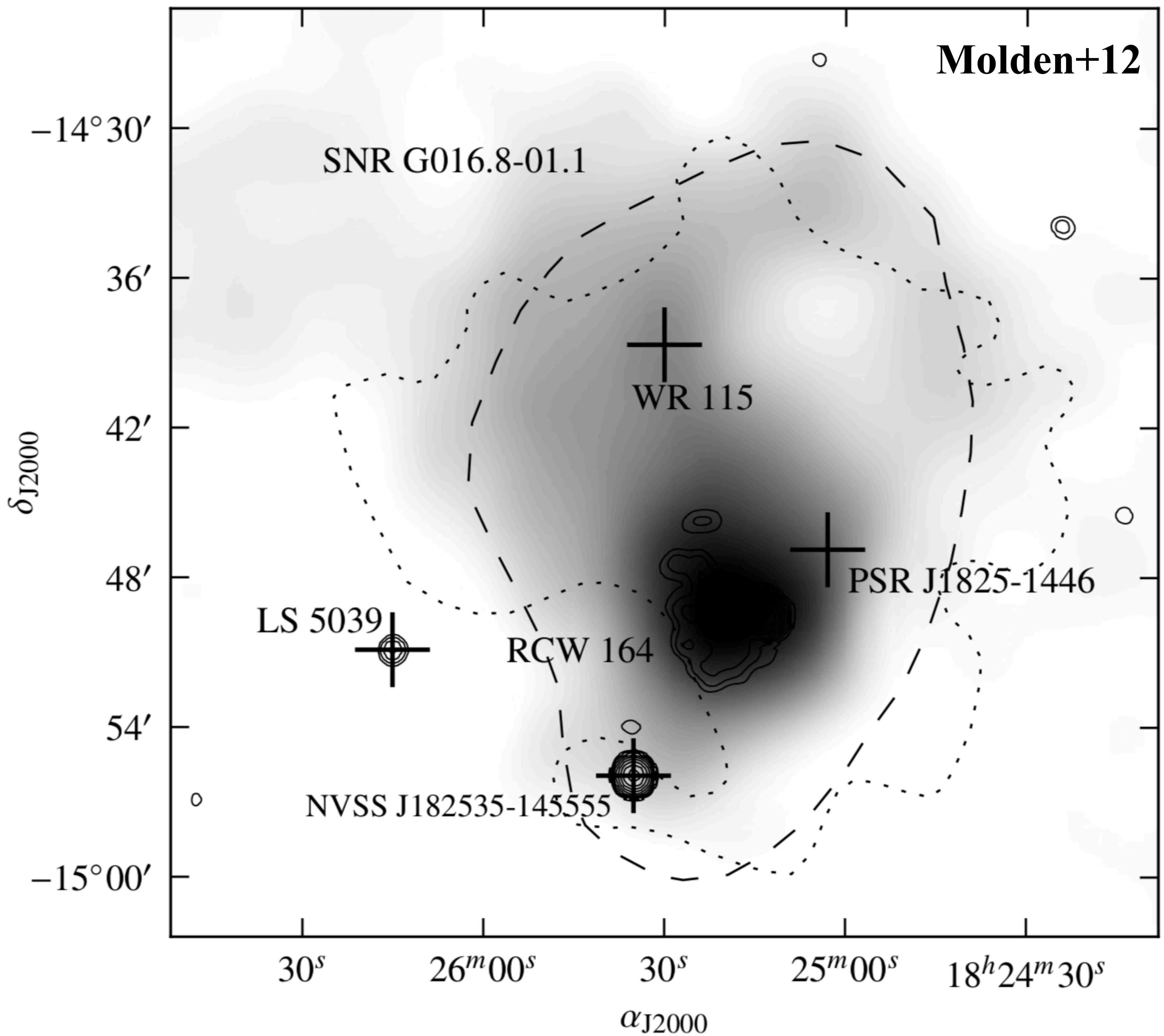


Fig. 2. COMPTEL light curves of GRO J1823-12, fitted at the sky location of LS 5039, in the 3–10 and 10–30 MeV bands. The flux points (integral photon fluxes for the given bandwidth) are averaged over individual CGRO phases or cycles, each covering roughly one year. For the details on the observations see Table 1.

The 3–10 MeV light curve is less conlusive. Detections, although on a low significance level, and non-detections occur along the mission, adding up to a $\sim 6\sigma$-detection for the sum of all data. The 10–30 MeV light curve, however, shows always evidence (at least 1σ) of the source with some hints for time variability. During CGRO Phase IV/Cycle 5, the flux is more than three times higher than during the observations in CGRO Phase I. However, a quantitative analysis by assuming a constant flux results in a low and insignificant probability of 0.60 for a time variable flux. At these highest COMPTEL energies, GRO J1823-12 seems to be a steady MeV-emitter. This agrees with the observations at GeV- and TeV-energies, where the longterm light curves over years are also consistent with a steady source (e.g., Hadasch et al. 2012; Aharonian et al. 2006a).

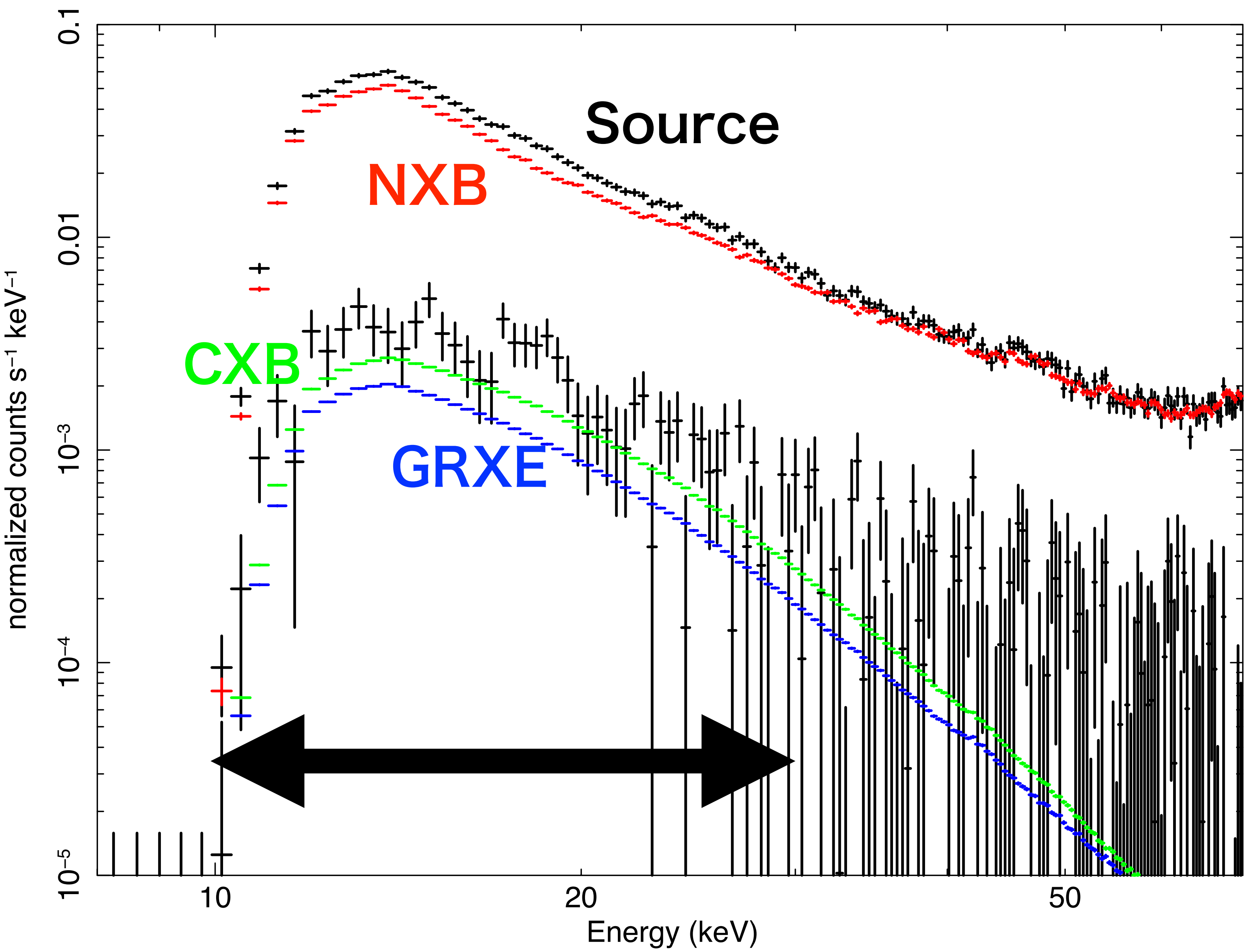
Collmar+14

Contamination Check



Pulse Search using Suzaku/

Suzaku/PIN observation: Longest Observation Ever in Hard X-rays



Observation Epoch

2007 Sep 09 - 15 (6 days)

Gross/Net Exposure

500 ks /180 ks

Event Selection

10 - 30 keV

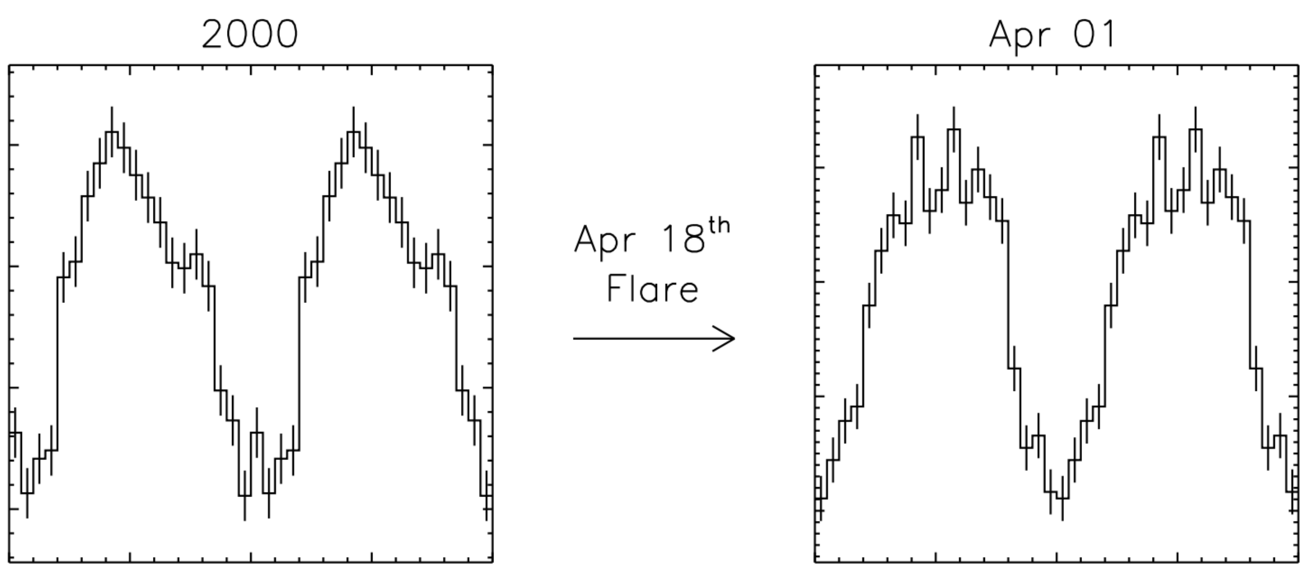
Total Event Number

~ 81000 (~ 8000 from source)

Magnetar Pulse Profile

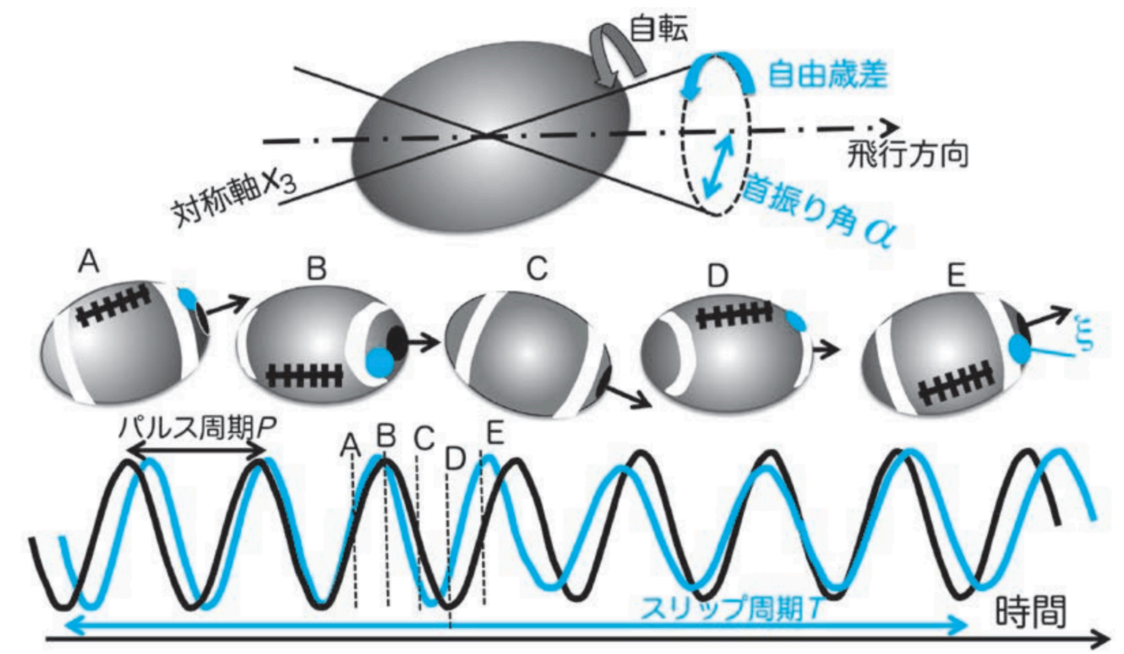
Pulse profile change after burst

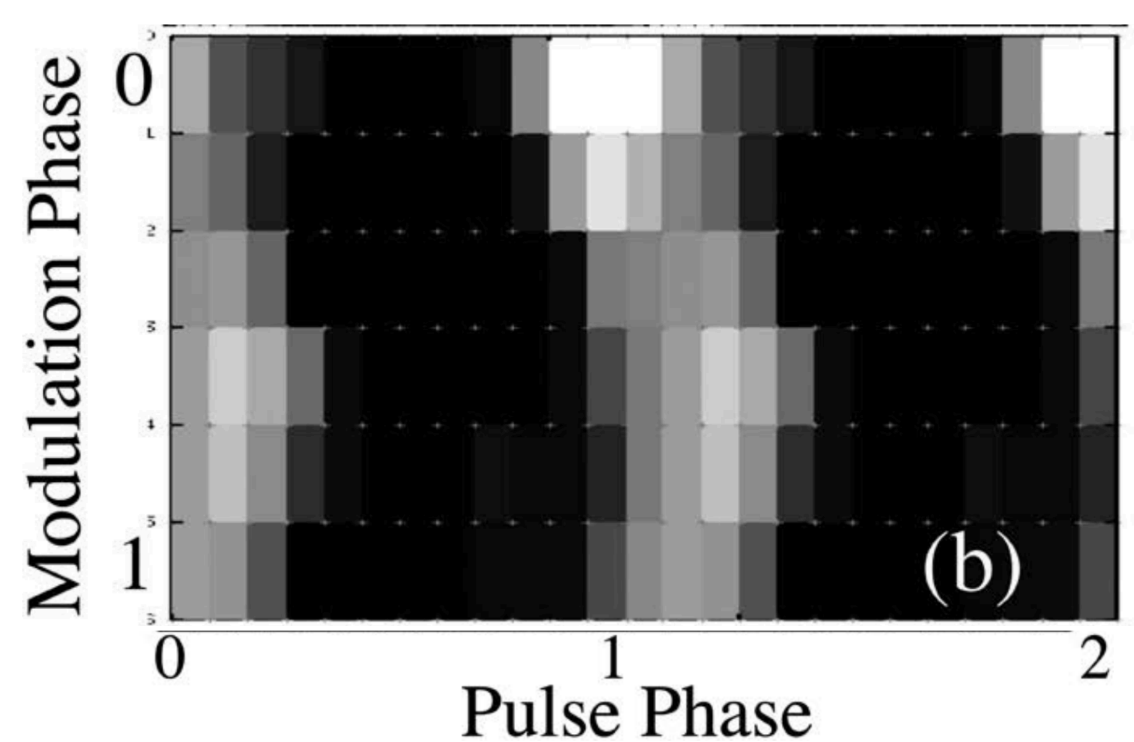
(e.g. Wood+03)



Free precession

(Makishima+14,16)





Z2 statistics

5.1 Z^2 statistics

When we want to test the periodicity of period, P in data, Z^2 statistics is a good tool. This is a common tool to search for the weak pulsation of neutron stars. The concept of this statistics is that we make a folded light curve assuming P, and calculate Fourier powers of that profile. The normalized folded light curve is described as:

$$f(\theta) = \left[1 + 2\sum_{k=1}^{m}(a_k \cos k\theta + b_k \sin k\theta)\right] / (2\pi) \quad (1)$$

$$\theta = 2\pi T/P \quad (2)$$

T is an observed time. The null hypothesis is $f(\theta) = 1/2\pi$.

When the number of events in data is n, a_k, b_k is calculated as below:

$$a_k = (1/n)\sum_{i=1}^{n} \cos k\theta_i \quad (3)$$

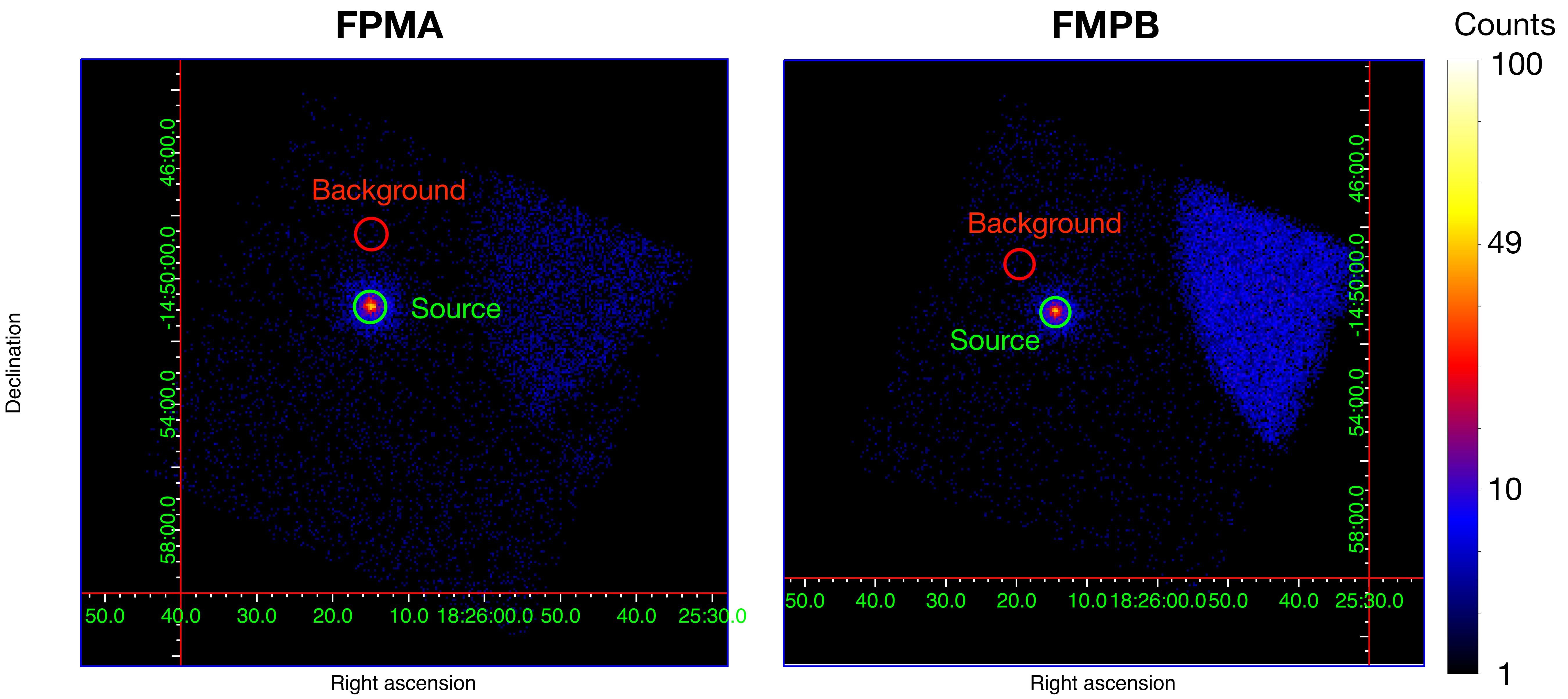
$$b_k = (1/n)\sum_{i=1}^{n} \sin k\theta_i \quad (4)$$

Then, we define Z^2 statistics as:

$$Z_m^2 = 2n\sum_{k=1}^{m}(a_k^2 + b_k^2) \quad (5)$$

m is the parameter to determine the highest order of Fourier power component which we include into Z_m^2. Since the average of $\Sigma_i^n \cos^2\theta_i = n/2$ under null hypothesis and large n, the null distribution of Z_2^m is the same as that of $\chi^2_{k=2m}$ as $n \to \infty$ (de Jager et al., 1989). We can test the existence of the periodicity by calculating the probability of resulting Z_m^2 under $\chi^2_{k=2m}$.

NuSTAR image



Orbital Parameters

	McSwain+2004	Casares+2005	Aragona+2009	Szalai+2010
T (HJD-2450000)	2756.49 ± 0.07	1943.09 ± 0.10*	2825.985 ± 0.053	5017.08 ± 0.06
Porb (day)	4.4267 ± 0.0005	3.90603 ± 0.00017*	3.90608 ± 0.00010	3.906 (adopted)
e	0.48 ± 0.06	0.35 ± 0.04	0.337 ± 0.036	0.24 ± 0.08
Omega (deg.)	268 ± 10	225.8 ± 3.3	236.0 ± 5.8	237.3 ± 21.8
f(m) (Msun)	0.0017 ± 0.0005	0.0053 ± 0.0009	0.00261 ± 0.00036	0.0049 ± 0.0006
aO sin i (Rsun)	1.36 ± 0.12	1.82 ± 0.10	1.435 ± 0.066	1.77 ± 0.15
MO (Msun)	—	22.9+3.4-2.9		
Commets		*: from “all”		