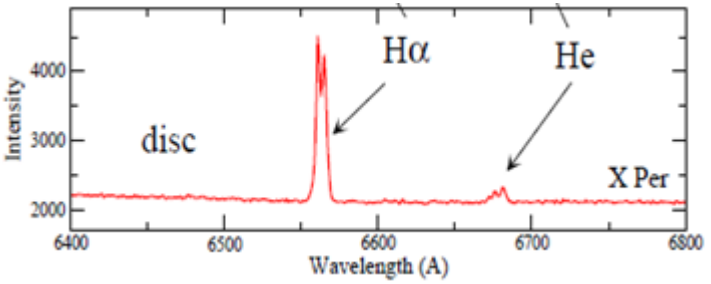
MAXI/GSC observation of X-ray outbursts from Be/X-ray binary pulsars

Motoki Nakajima (Nihon Univ.)

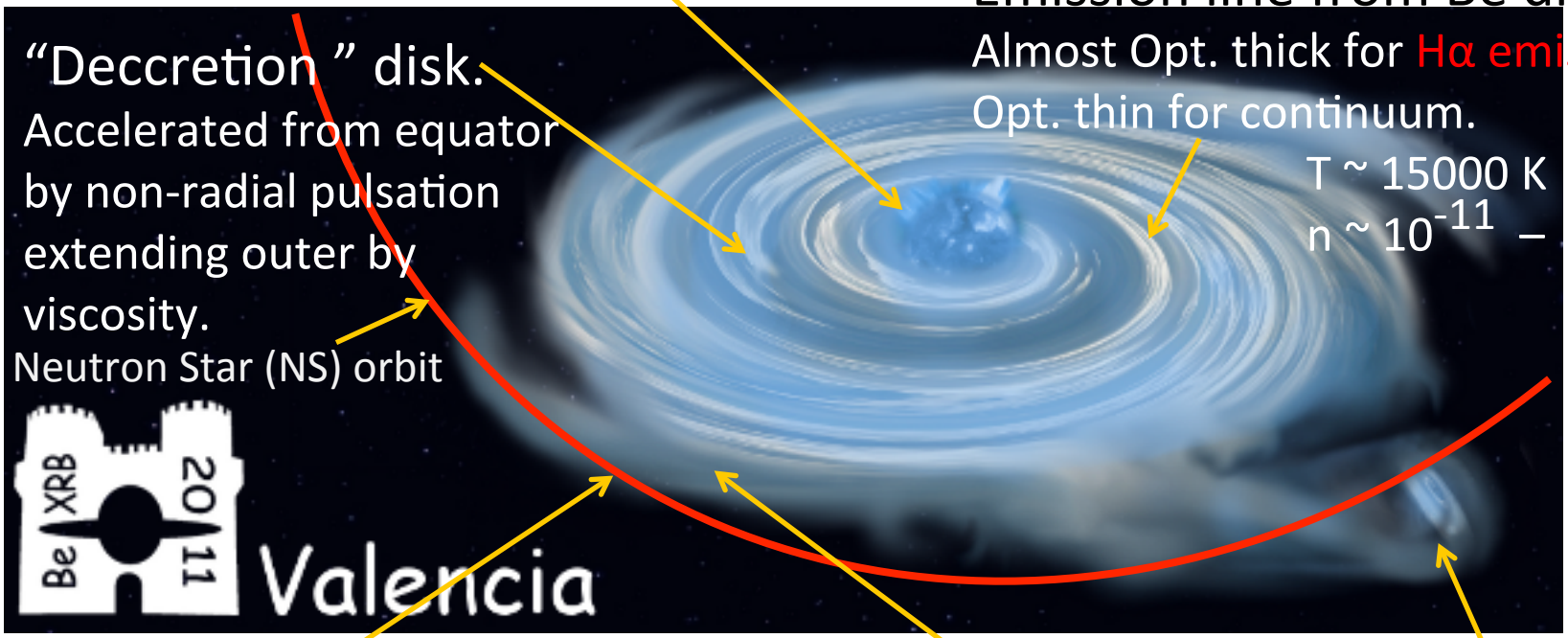
Be X-ray binary pulsars (BeXRBP)



Reig 2011

Almost maximum-rotating B star
(mostly B0-2, ~10 Mo). Elliptical shape.

Emission line from Be disk.
Almost Opt. thick for Hα emission line.
Opt. thin for continuum.
T ~ 15000 K
$n \sim 10^{-11} - 10^{-14} cm^{-3}$

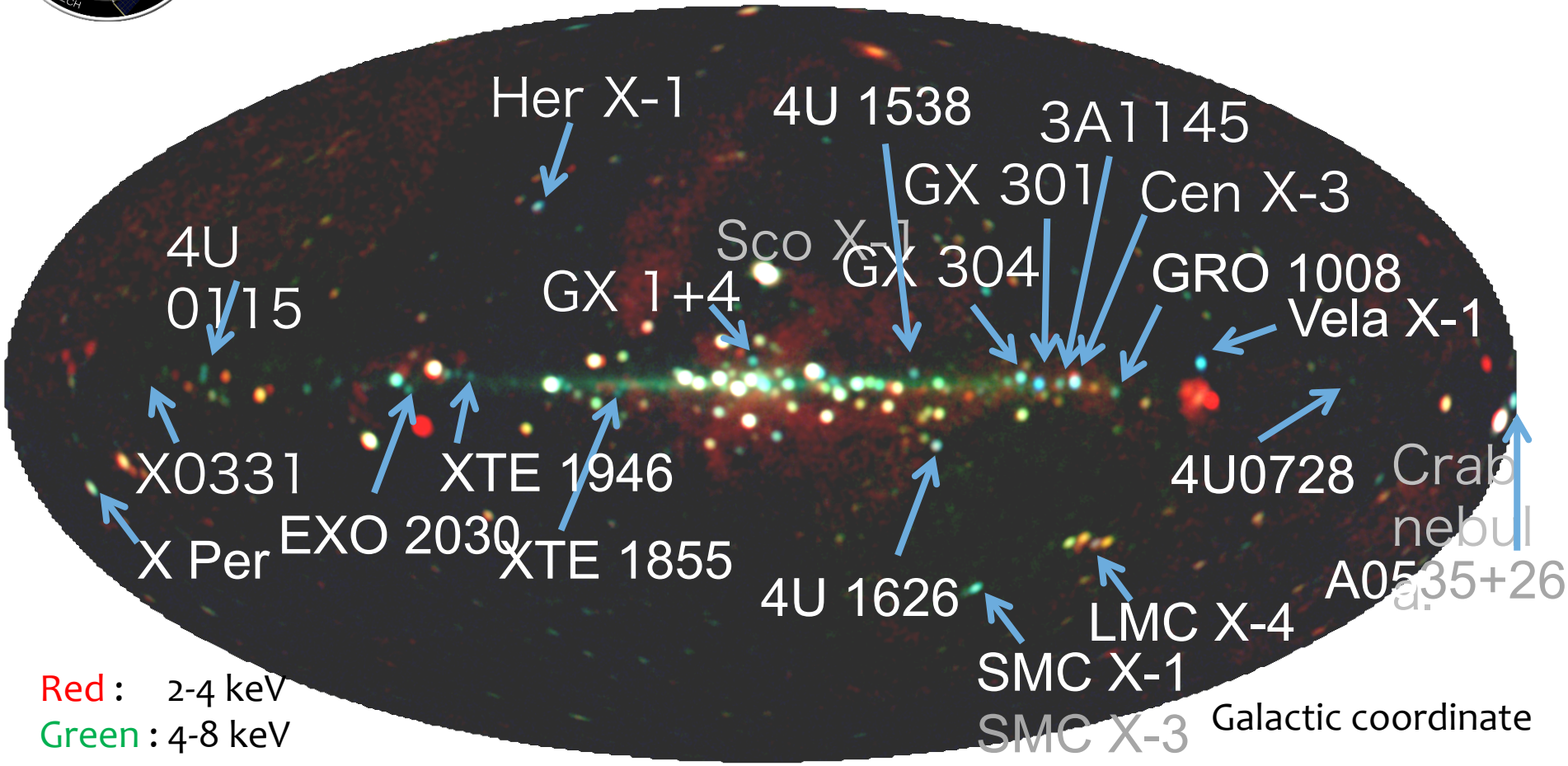


Lagrangian (L1) point sweeps the disk. It is truncated at the distance of L1 at periastron.

When Be disk extends close to L1, it is deformed to one-armed, or warped at the edge.

NS in an eccentric orbit may carry some gas in the Roche lobe.
→ **X-ray Outburst (OB)**

7 years All-sky map by MAXI/GSC



Red : 2-4 keV
Green : 4-8 keV
Blue : 8-16 keV

Blue stars are mostly binary pulsars.

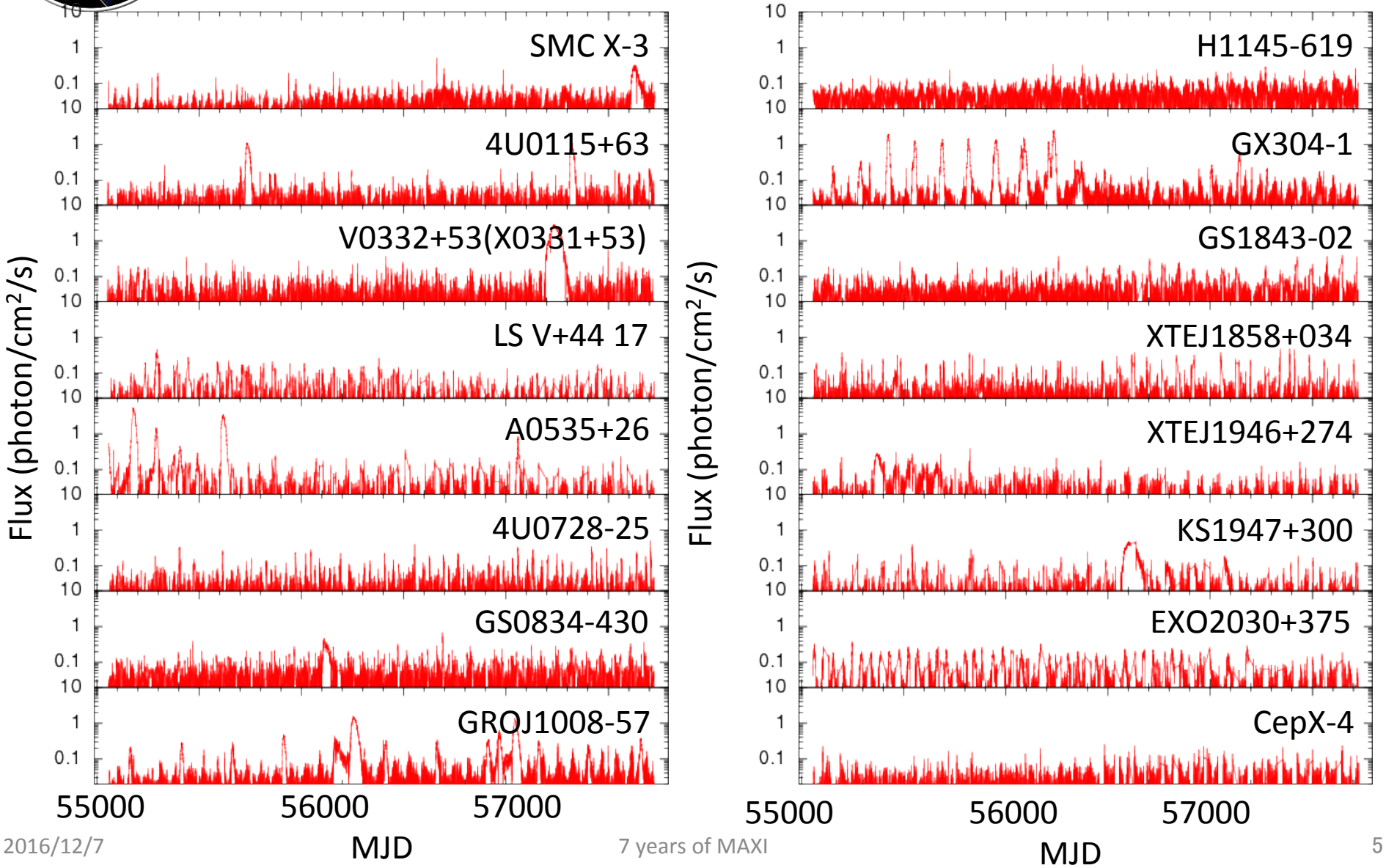
Be X-ray binary pulsars are more than a half of XBPs.

Issued Atel list

Source	Atel number	Source	Atel number
SMC X-3	1	H1145-619	2
4U 0115+63	6	GX 304-1	12
V0332+53(X0331+53)	5	GS 1843-02	2
LS V +44 17	1	XTE J1858+034	1
A0535+26	8	XTE J1946+274	1
4U 0728-25	1	KS 1947+300	1
GS 0834-430	1	EXO 2030+375	1
GRO J1008-57	10	Cep X-4	1

- MAXI team have issued 54 Atels in 7years.
- More than 100 alert mails have been circulated to the mailing .
- By our Atel/alert of BeXRB, several ToO observations were conducted.
  - The Suzaku ToO observations for 2 BeXRBP (GX 304-1 and GRO J1008-57) discovered cyclotron resonance features in the X-ray spectrum

Light curves of Be X-ray binaries
MAXI/GSC 2-20 keV

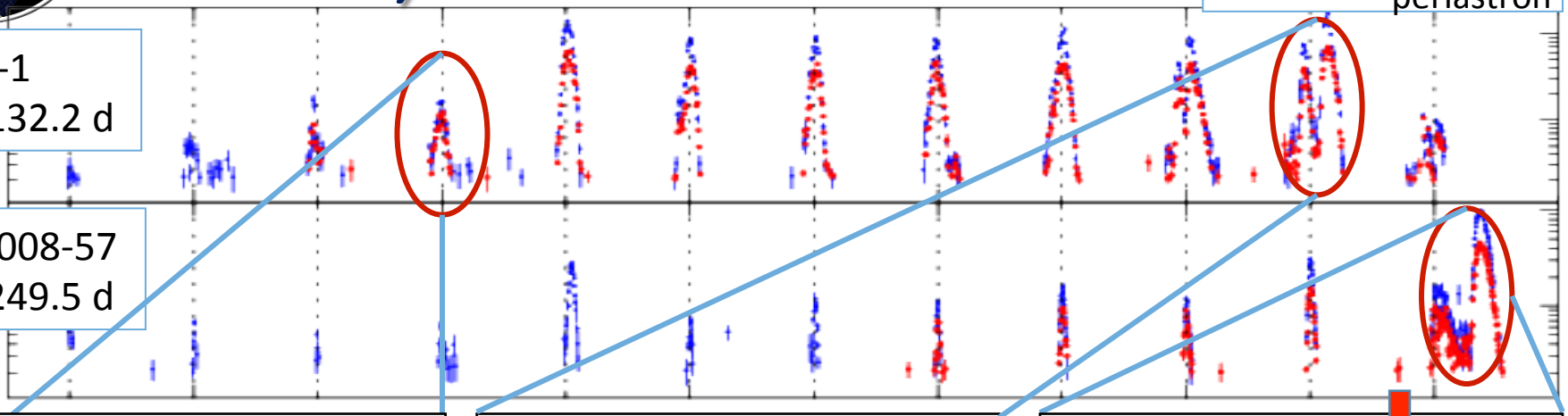


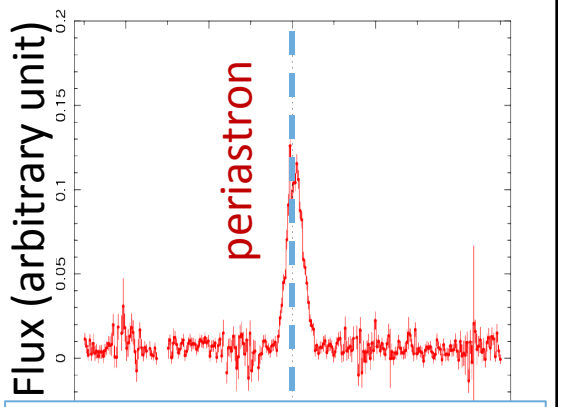
Outburst classification
Normal, Giant outbursts

MAXI/GSC(4-10keV)
Swift/BAT(15-50keV)
vertical lines : periastron

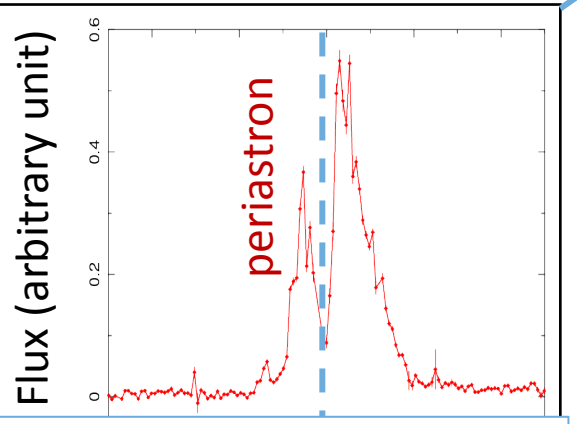
GX304-1
P_{orb} = 132.2 d

GROJ1008-57
P_{orb} = 249.5 d

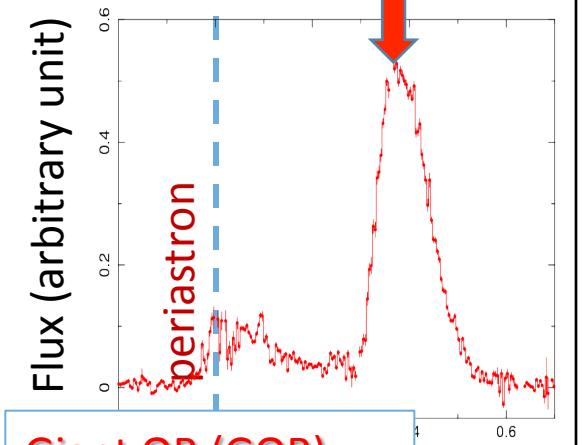




Normal OB (NOB)
OB at periastron
Peak L_x <$10^{36\text{-}37}$erg/s
Truncated Be disk +
RIAF model (Okazaki+'13)



Giant OB (GOB; multi peak)
Multi peaks around periast.
Peak L_x ~$10^{36\text{-}37}$erg/s



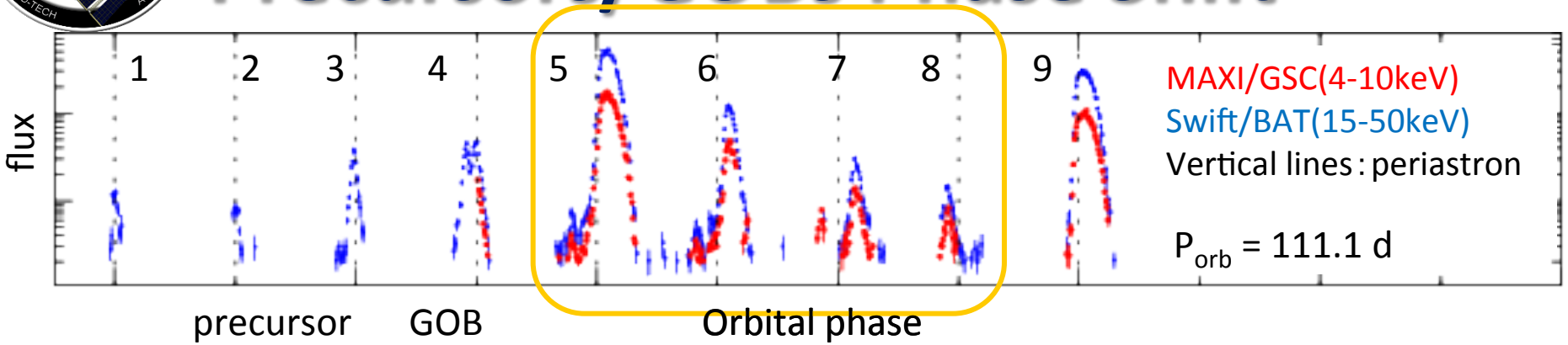
Giant OB (GOB)
OB off periastron
Peak L_x >10^{37}erg/s

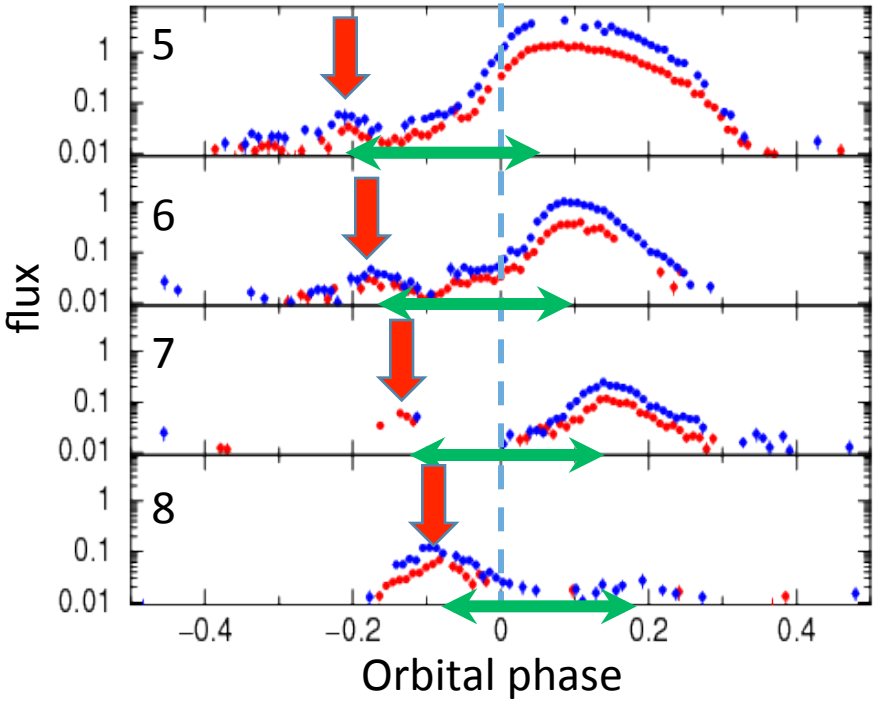
Misaligned (eccentric) Be disk + BHL accretion model (Okazaki+2013)

Topics

1. Outburst orbital phase shift
   - The systematic orbital phase "delay"
   - The systematic orbital phase "advance"
2. GOB periodicity of EXO 2030+375 (poster P-58)
   - Possibility of 20/10 years periodicity in GOB activity
3. Correlation between flux increase rate and peak fluxes in NOBs
4. Suzaku follow-up observations
   - Discovery of the cyclotron resonance lines in GX 304-1 and GRO J1008-57

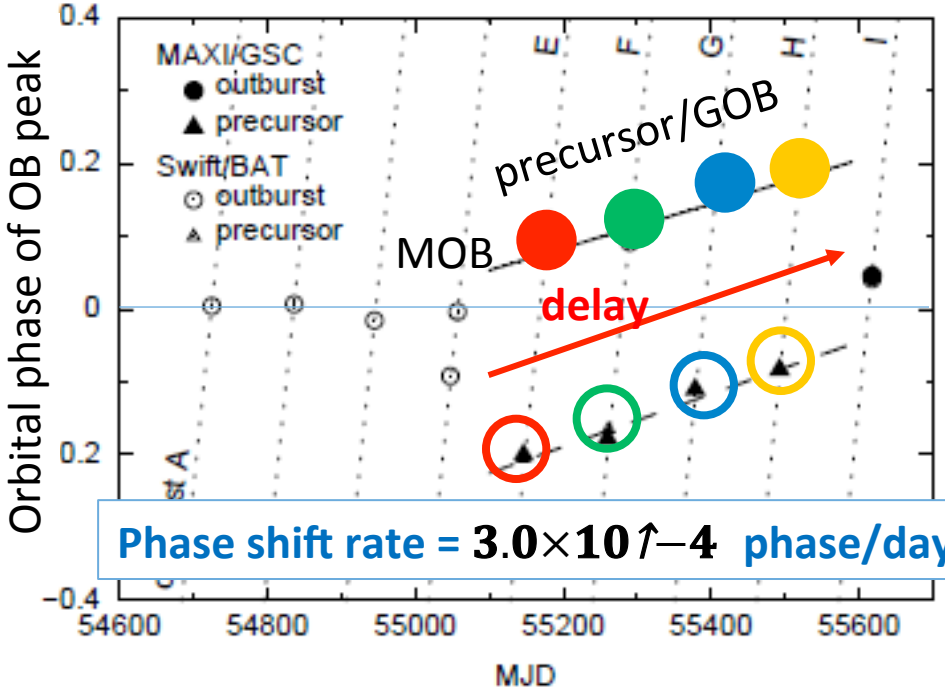
A0535+26
Precursors/GOBs Phase Shift





- The source was active in 2008-2011.
- Detection of consecutive GOBs.
- MAXI detected **precursors** before GOB
- Separation between precursor/GOB are constant and about 30 days (0.27 orbital phase)
- **Period of precursor/GOB is 115 d, not P_{orb} (=111.1 d)**
- In OB-8, intensities of precursor/GOB reversed.

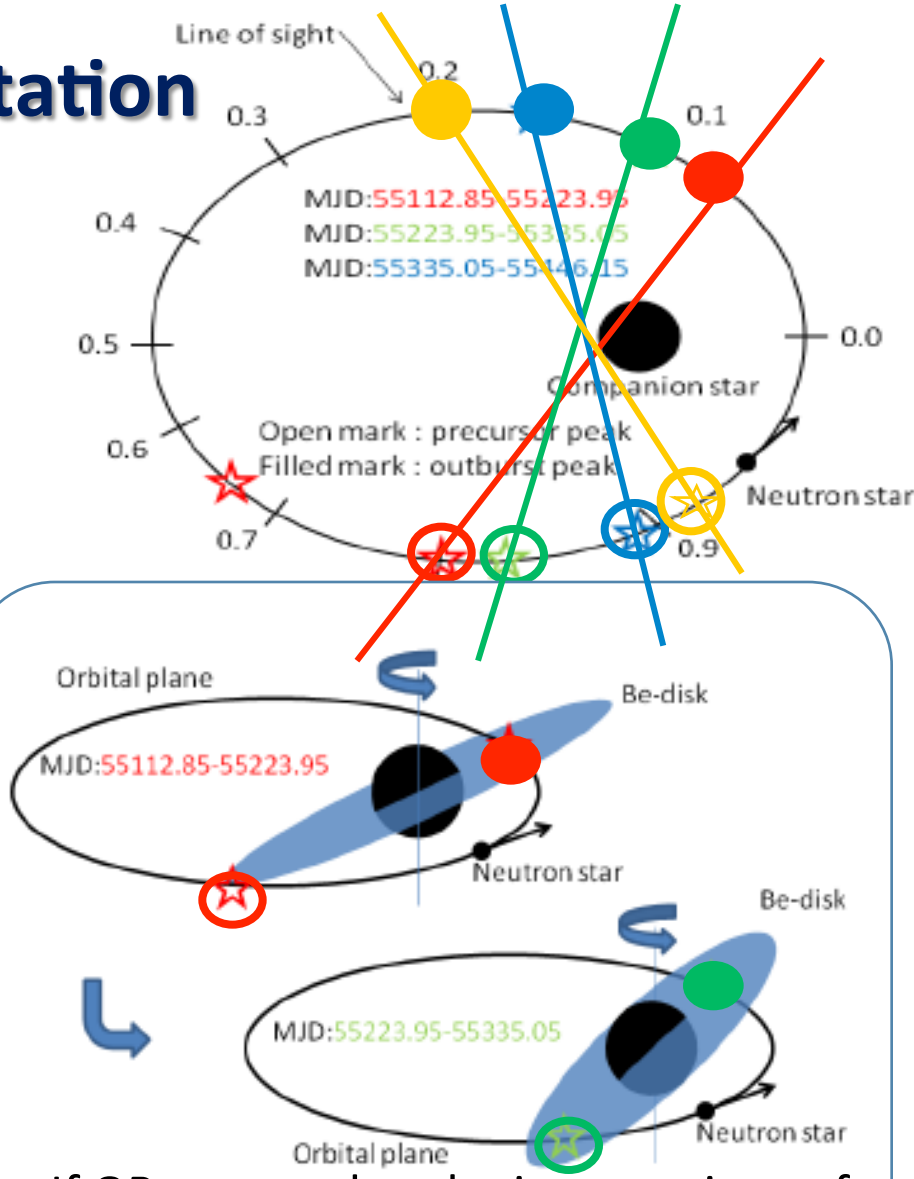
A0535+26 : Interpretation of OB Phase Shift



Phase shift rate = 3.0×10^{-4} phase/day

- **Period of precursor/GOB is 115 d, not P_{orb} (=111.1 d)**
- After MOB, EW of Hα line increased. (Moritani+2011)

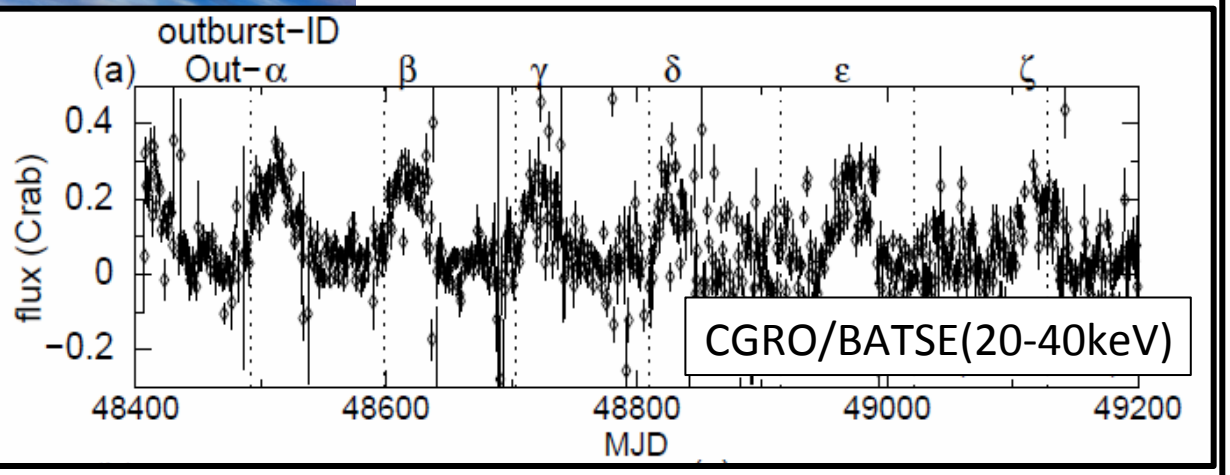
  → emergence of warped Be disk?

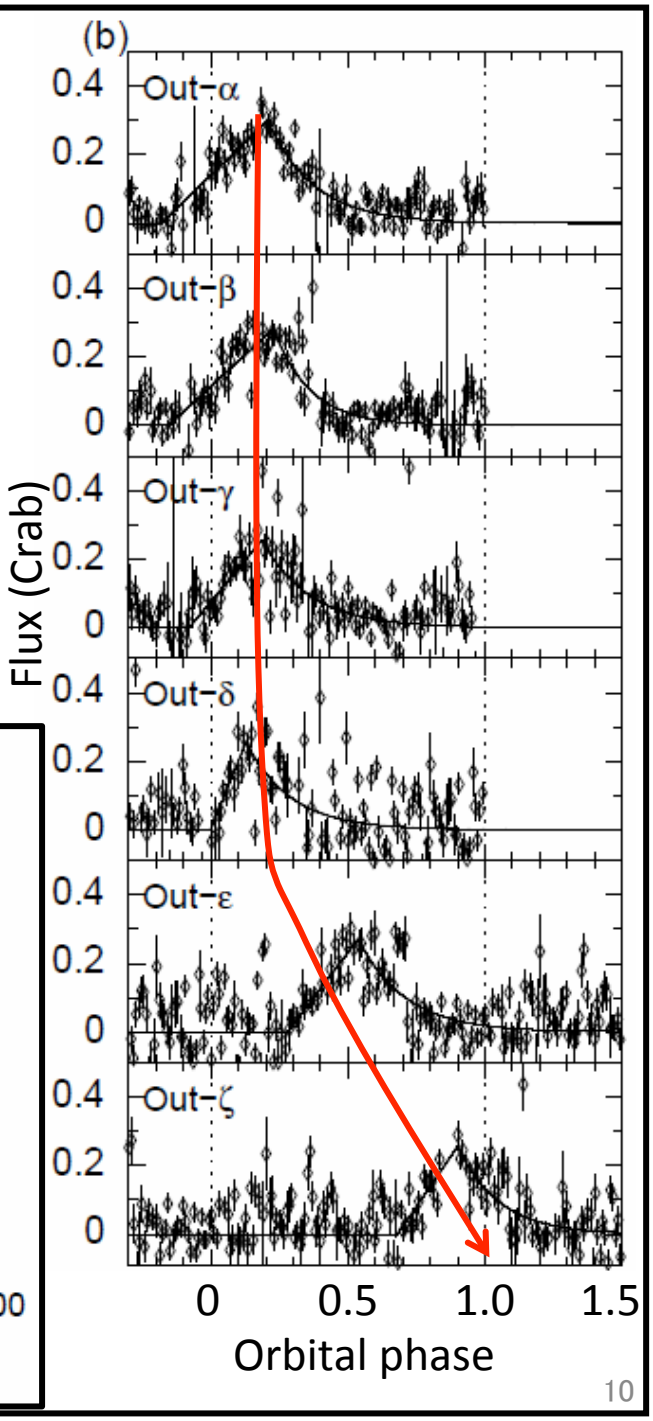


- If OB occurred at the intersections of the NS orbit and the precessing Be-disk, precession P is about 8.7 yr.

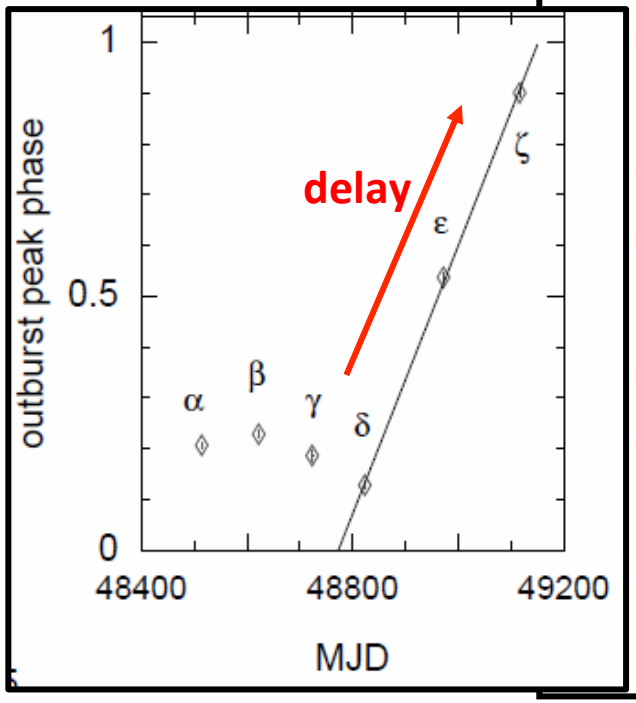
(Okazaki+'13, Moritani+'13, Nakajima+'14)

GS 0834-430 OB Phase Shift

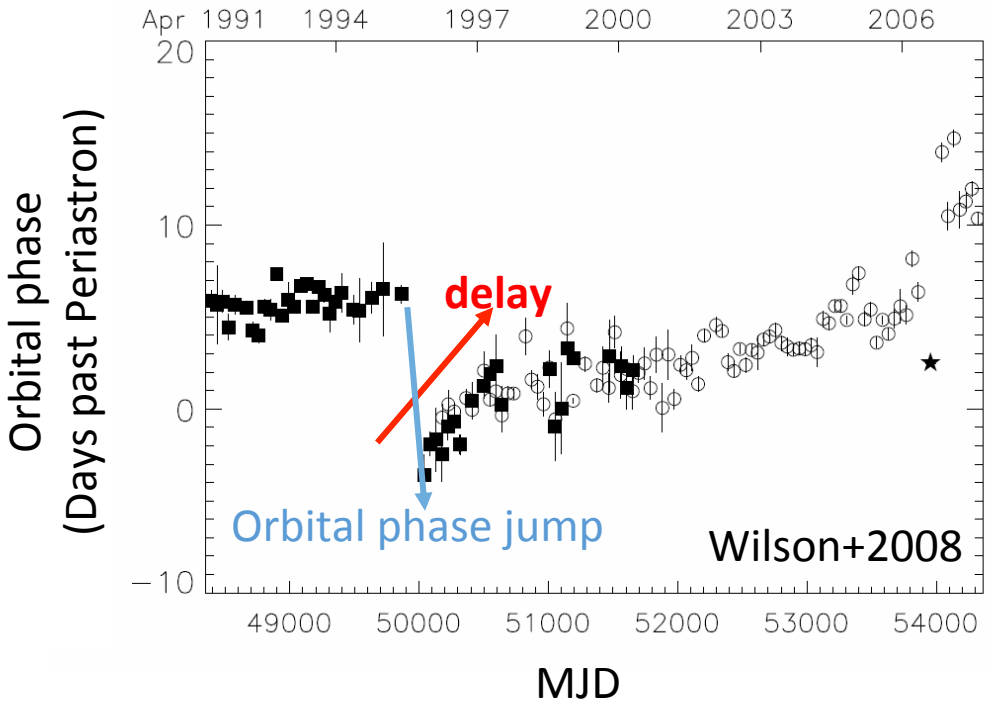




- **First report of OB phase shift (Wilson+1997)**
- OB phase shift was observed as "**delay**".
- The phase shift rate is 2.4×10^{-3} **phase/day**



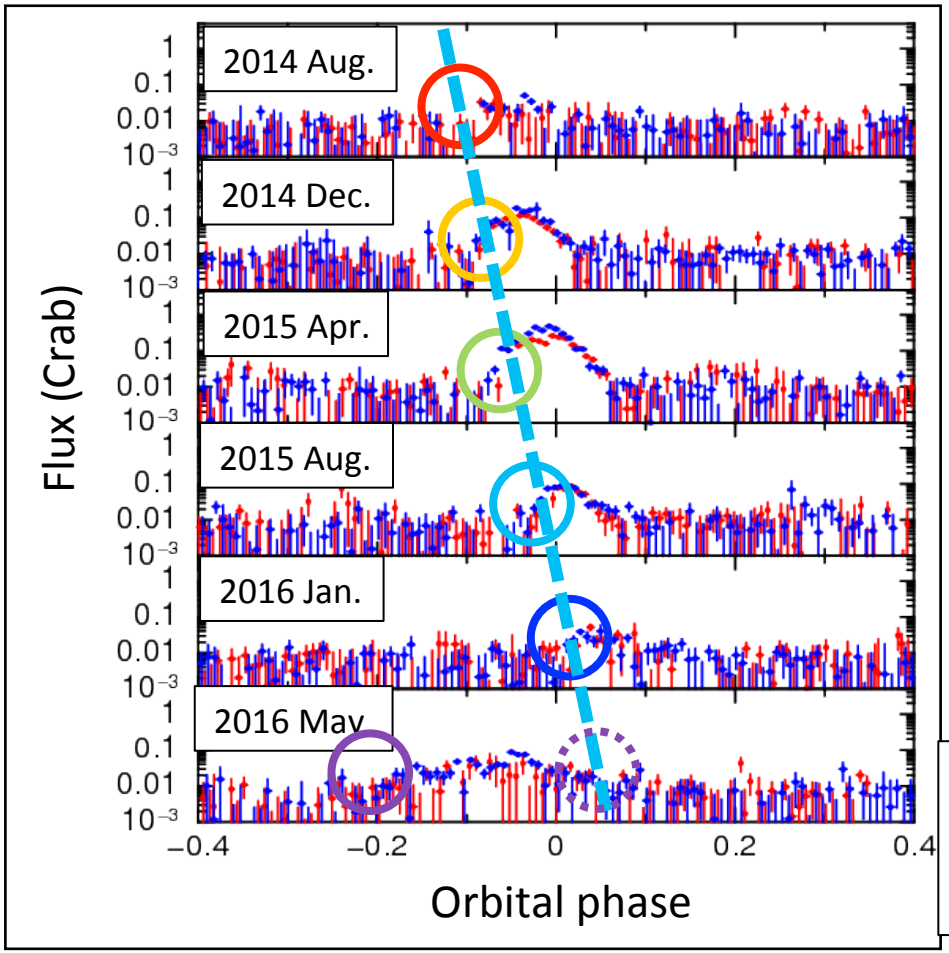
EXO 2030+375 OB Phase Shift

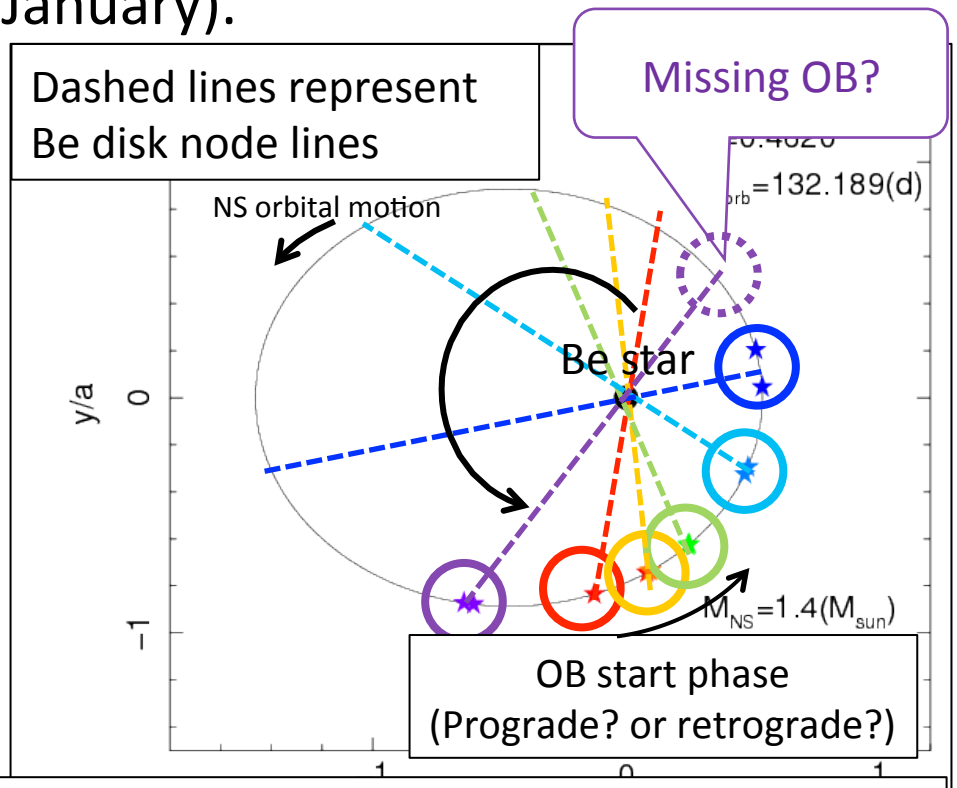


- Wilson+2008 reported the outburst orbital phase shift from EXO 2030+375.
- OB phase shift was observed as "**delay**".
- The phase shift rate is $\mathbf{1.8\times10^{-4}}$ **phase/day**
- Please see also Poster P-58, "Possible regular phenomena in EXO 2030+375" (Eva Laplace)

GX 304-1
Outburst Phase Shift

- (Atel#8592) the onset phases of the outbursts shifted steadily through the five normal outbursts (from ~0.90 orbital phase on 2014 August to 0.02 on 2016 January).

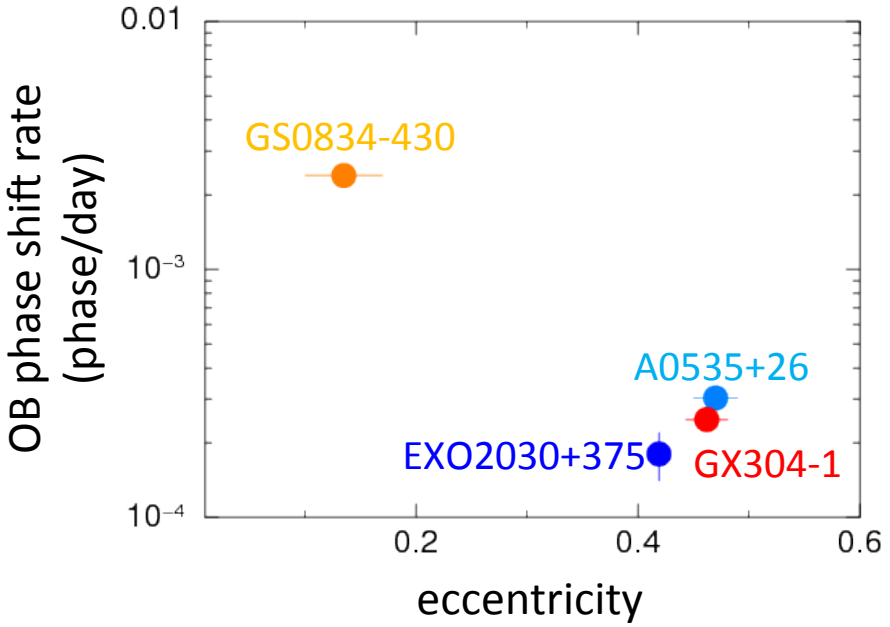




- This phenomenon might be explained by a precessing Be disk which has an asymmetrical density profile .

Comparison of OB Phase Shift

- OB phase shift has been observed from 4 BeXRBPs.
  - common phenomena among BeXRBPs ?
- The phase shift rate does not correlate with Be star type, orbital period and $a_x$sini.
- There is a possibility that a correlation between eccentricities and OB phase shift rate exists.



Topics

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   - ➢ The systematic orbital phase “delay”
   - ➢ The systematic orbital phase “advance”
2. GOB periodicity of EXO 2030+375 (poster P-58)
   - ➢ Possibility of 20/10 years periodicity in GOB activity
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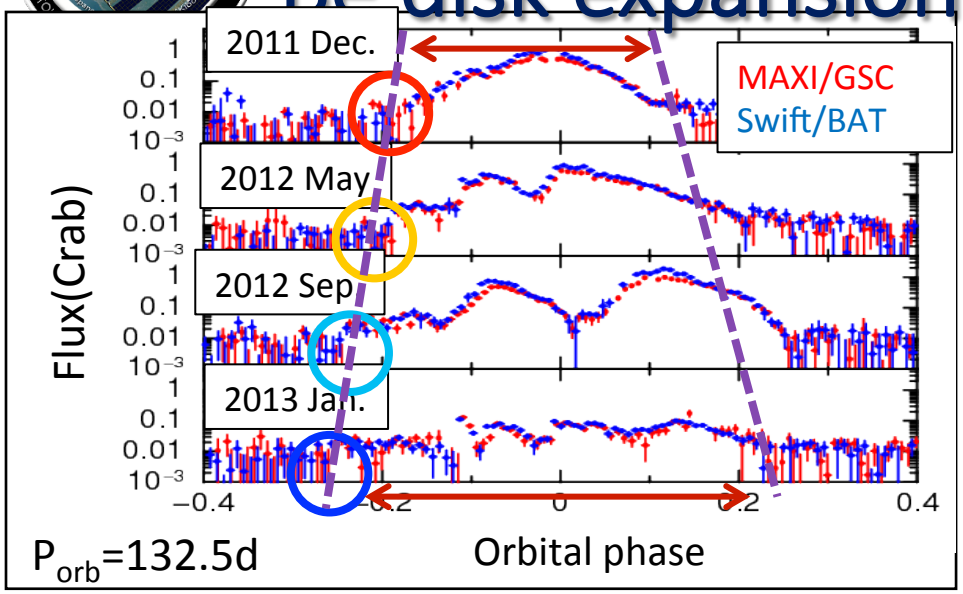
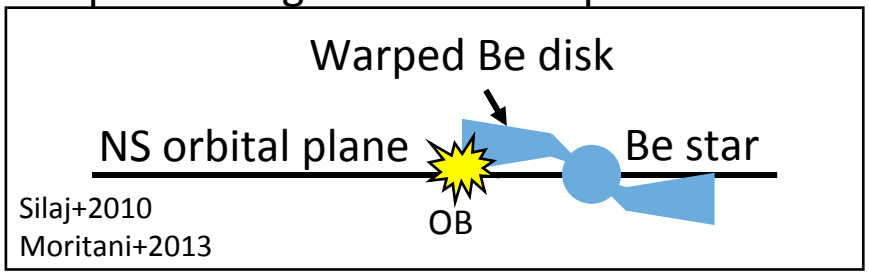
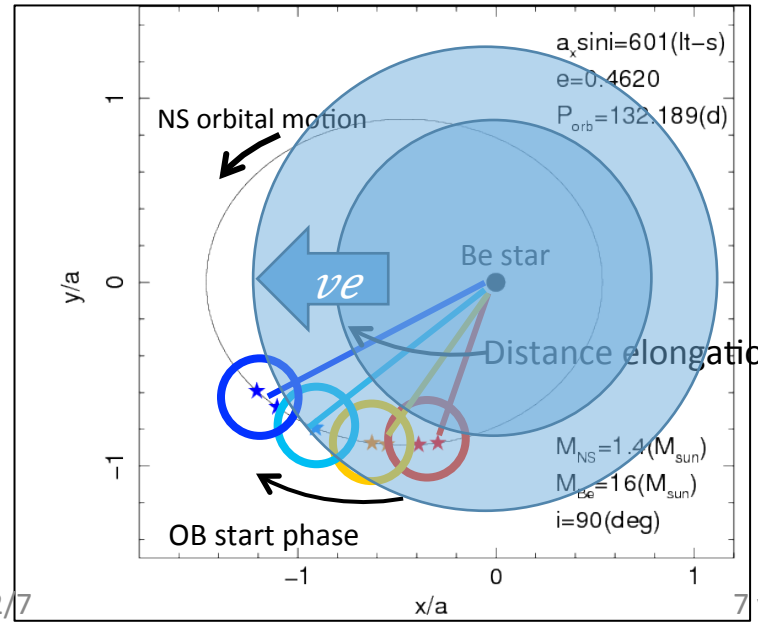
GX 304-1
Be disk expansion



- OB start phase advances to the early orbital phase every revolution.
- Duration of the mass accretion is elongated.
- If the warped Be disk exists, the disk would expand along to the orbital plane.



- OB start phase represents the position where NS contacts with the Be disk. Thus the expansion velocity of Be disk can be derived.



Comparison with Be disk expansion velocity ve

BeXRBP

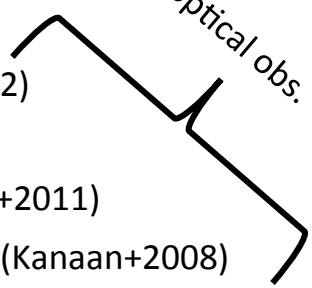
GX304-1 : 2.3 ± 0.2 km/s

A0535+26: 2.3 km/s (Yan+2012)

Isolated Be star

δ Sco : 0.2 km/s (Meilland+2011)

Achernr : 0.27 ± 0.08 km/s (Kanaan+2008)



First measurement of ve by X-ray observation.
The ve of BeXRBPs are larger than isolated ones

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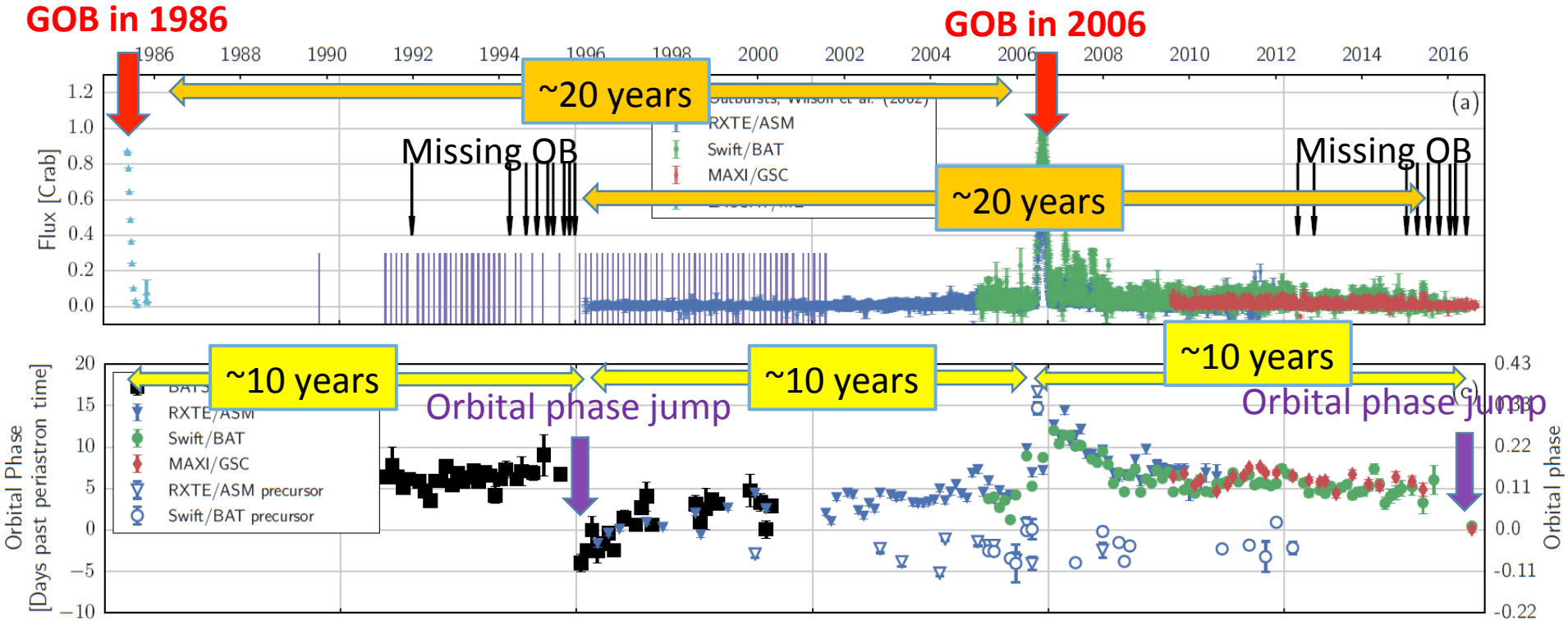
EXO 2030+375:Possible periodicity of GOB

Laplace et al. (2016) and P-58

- EXO2030+375 exhibits a regular outbursts synchronized with P_{orb}=46 d.
- Peculiar time intervals of GOBs, missing OBs and orbital phase jumps.
- There are 2 possibilities
  - Periodicity between GOBs (~20 years)
  - Periodicity between GOB and orbital phase jump (~10 years)

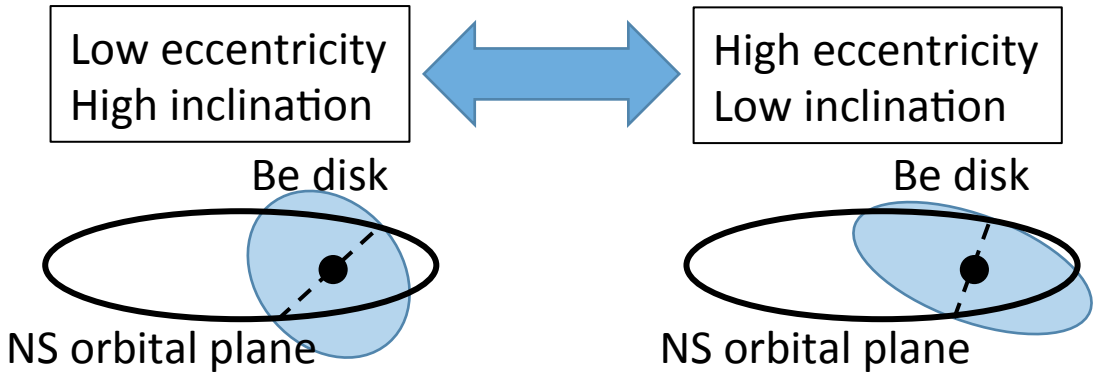


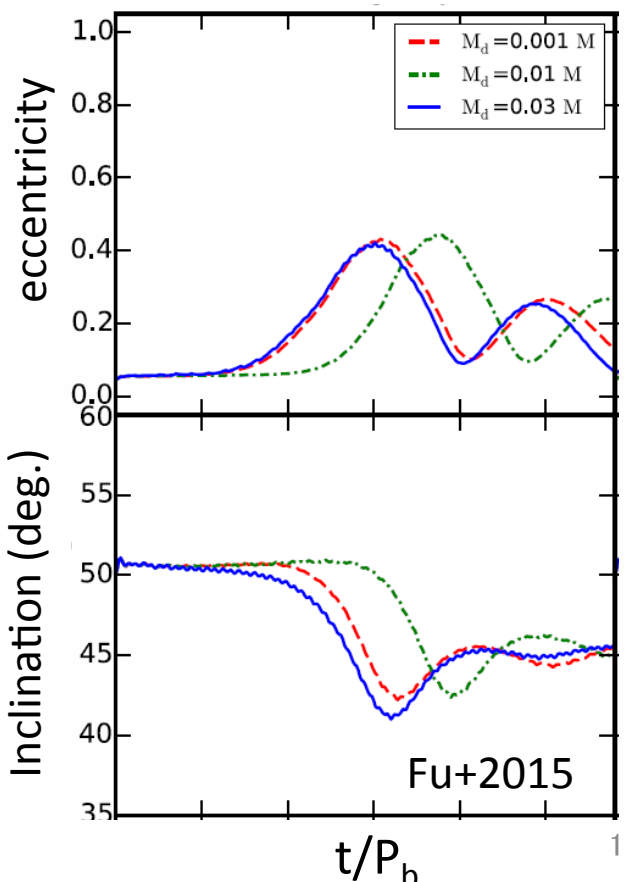
Kozai-Lidov(KL) mechanism in hydrodynamical disk

$$\frac{\tau_{\rm KL}}{P_{\rm orb}} \approx \frac{(4-p)}{\left(\frac{5}{2}-p\right)}\left(\frac{a}{R_{\rm out}}\right)^{\frac{3}{2}}\sqrt{\frac{M_{\rm Be}}{M_{\rm NS}}\left(\frac{M_{\rm Be}}{M_{\rm NS}}+1\right)},$$

a:orbital separation
P:PL index of surface density of Be disk

- KL mechanism
  - Orbital eccentricity and inclination of the object undergo periodical exchange.





Applied to EXO 2030+375 parameters

→ τKL=3820 d (~10.5 years)

The τKL nicely matched with the time interval between GOB and orbital phase jump.

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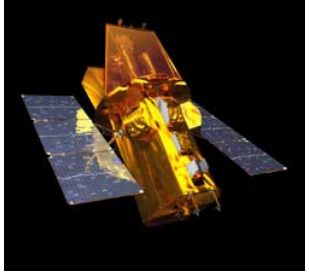
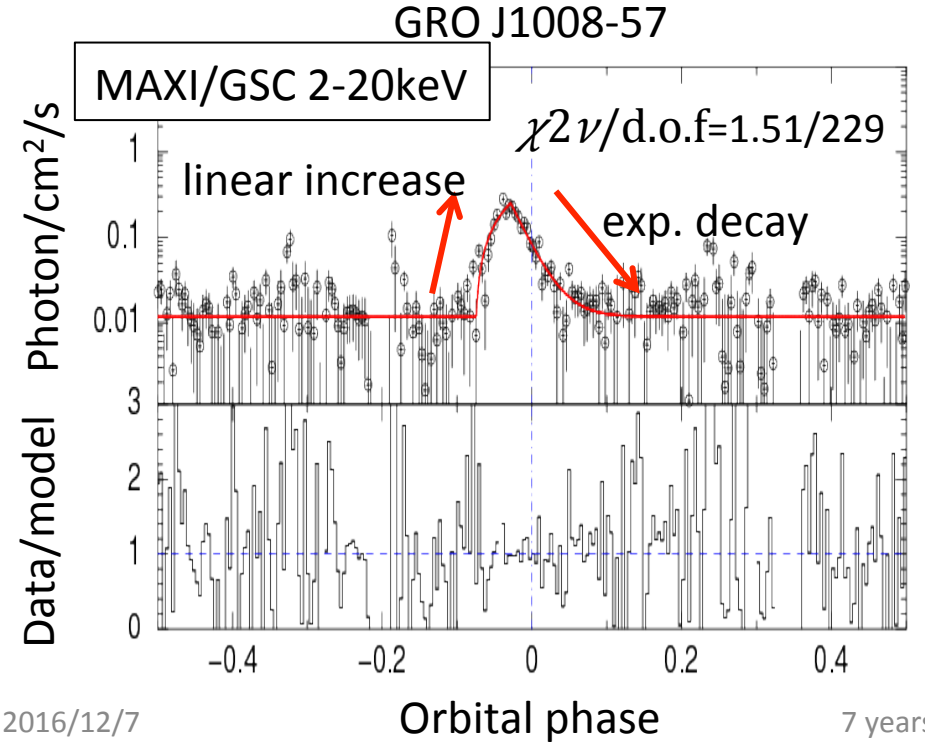
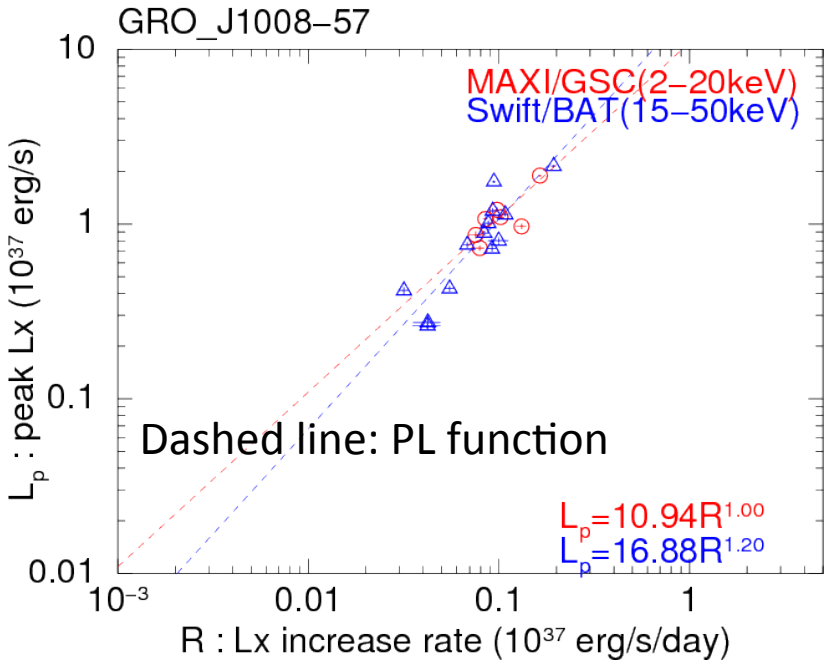
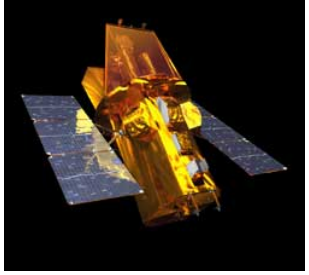


Normal Outbursts
L_x increase rate – peak L_x relation

- Positive correlations between the L_X increase rate and the peak L_X are found in 5 BeXRBPs (GRO J1008-57, GX304-1, EXO 2030+375, V0332+53 and 4U0115+63).
- The relation can be described by power-law (PL) function.
- Each source have a different PL indexes.

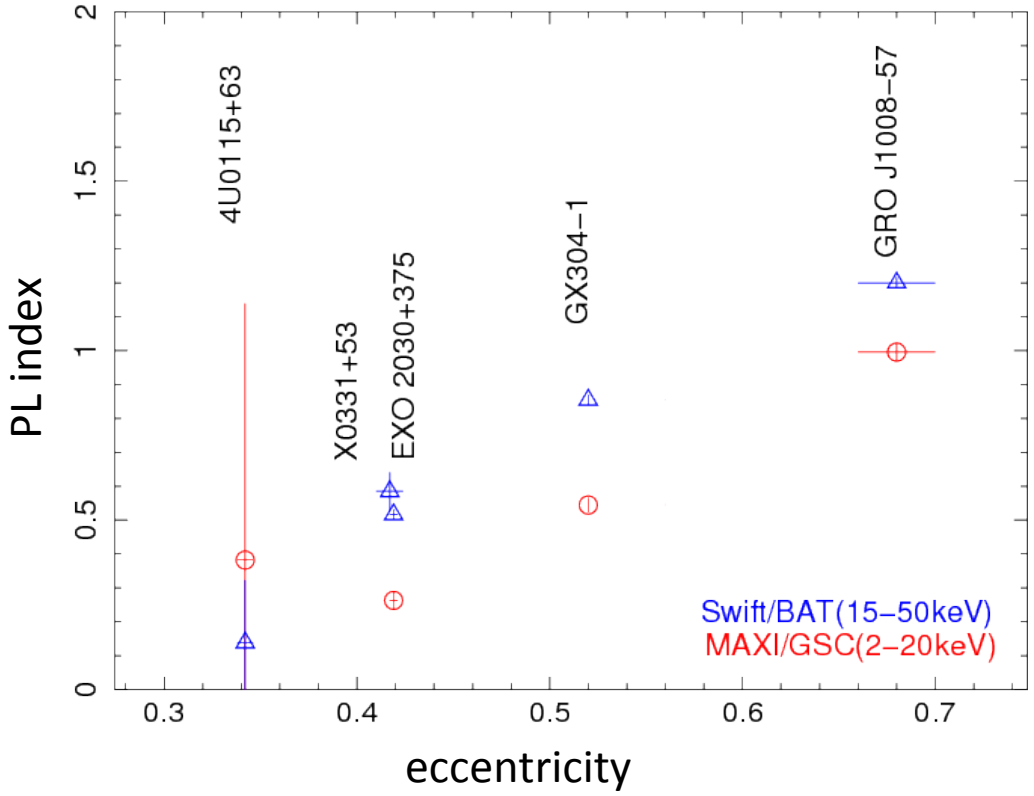


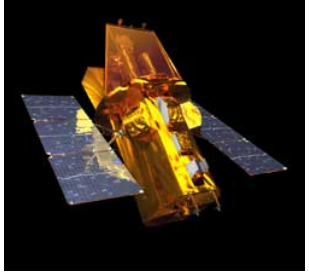




PL index and eccentricity

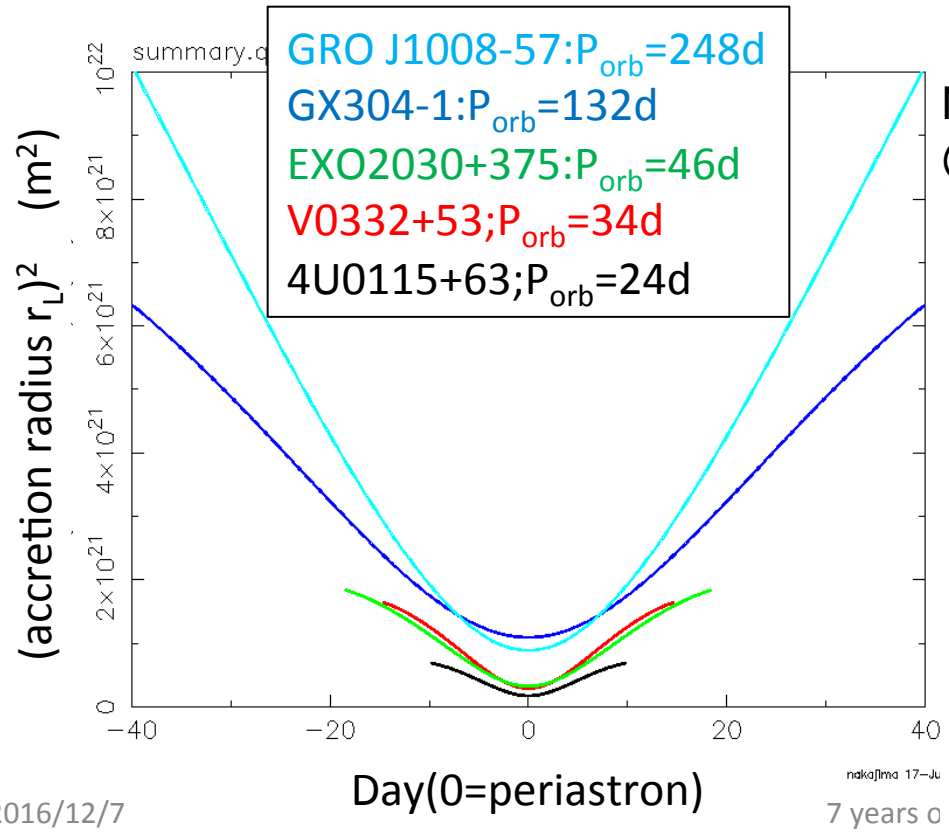
- PL index of L_X increase rate – peak L_X plot does not correlate with Be star type, orbital period and $a_x$sini.
- Positive relation in eccentricity and PL index.

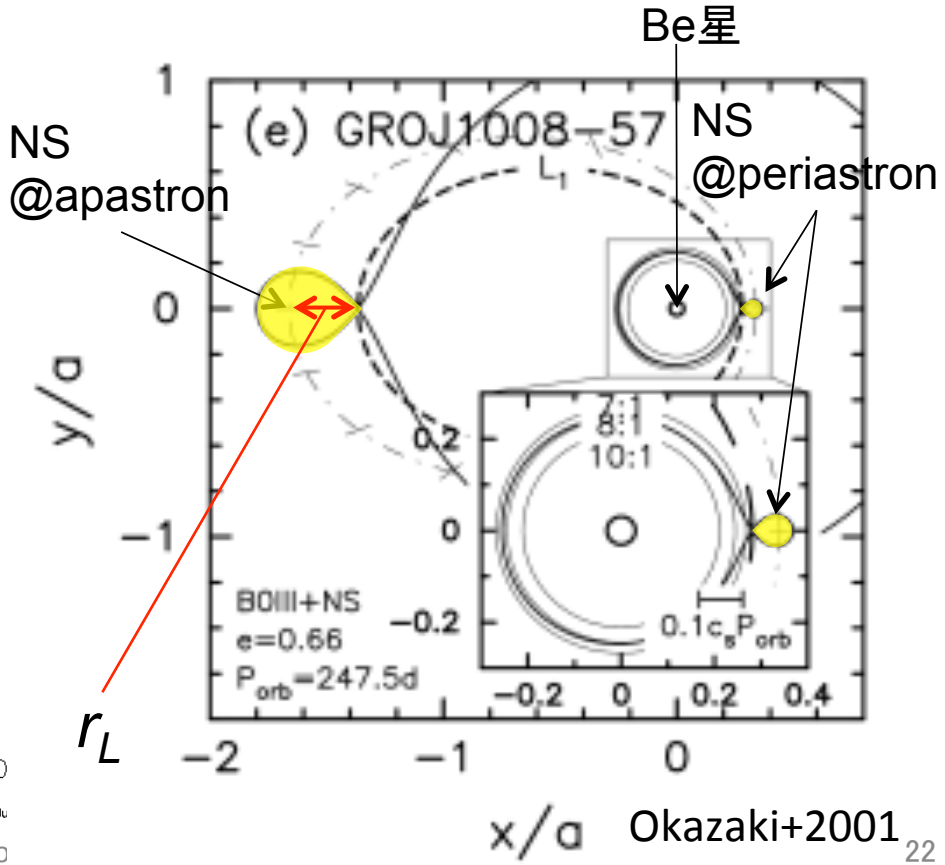




Shrink of accretion radius

- In highly eccentric system, accretion radius r_L rapid shrinks near periastron.
- Further dynamical model and discussion is needed to understand this phenomenon.





Okazaki+2001

7 years o

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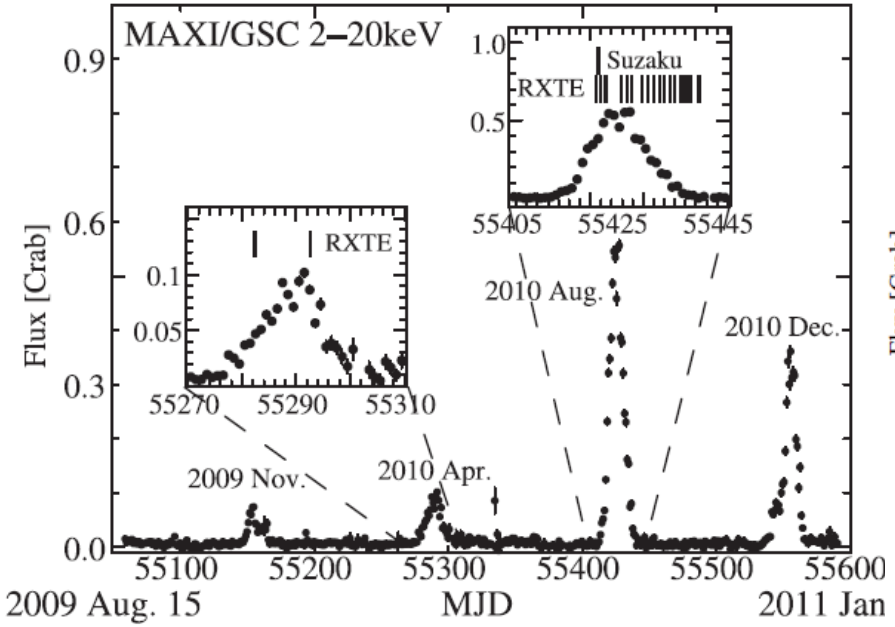
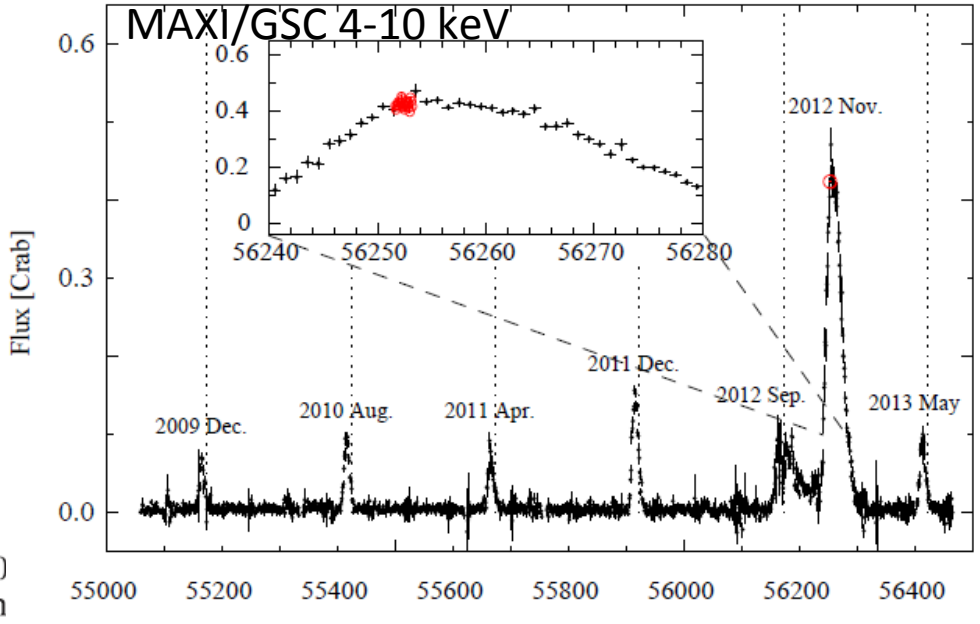
Suzaku and RXTE ToO observations GX304-1 and GRO J1008-57

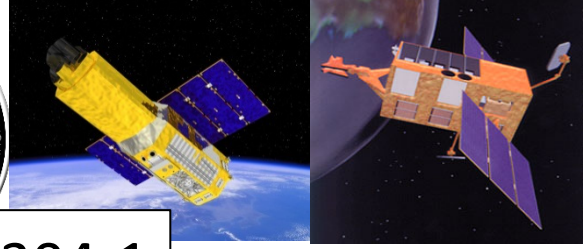
- GX304-1 (Porb=132.5d)
  - Reactive since 2008 June after 30 yrs quiescence.
  - GOB in 2010 August.
  - Suzaku observation at the peak.
- GRO J1008-57 (Porb=249.48d)
  - MAXI detected 14 outbursts in 7 years.
  - After the 5th one, GOB occurred.
  - Suzaku observation almost at



Yamamoto+2011

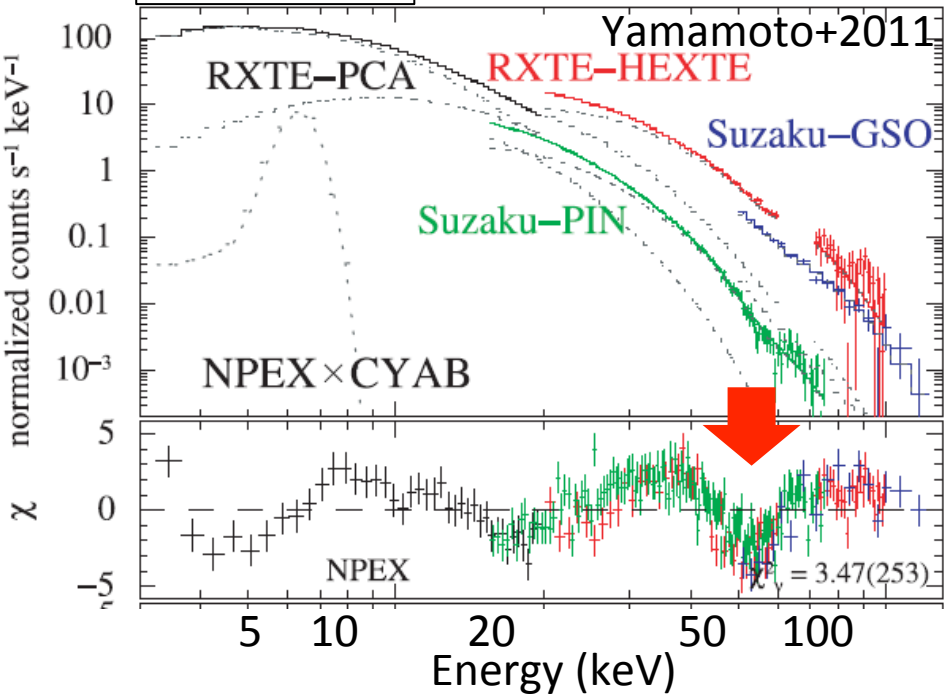


Yamamoto+2014

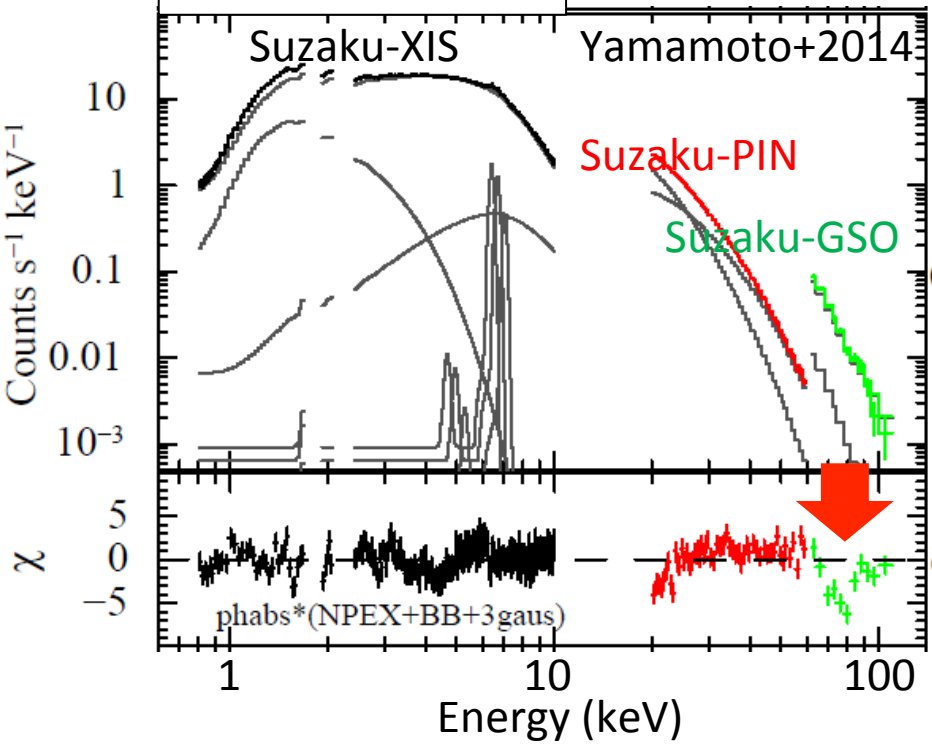


Detection of cyclotron lines

GX 304-1

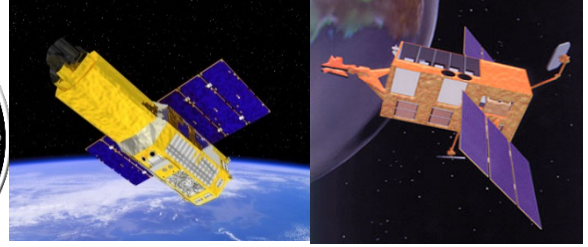


GRO J1008-57

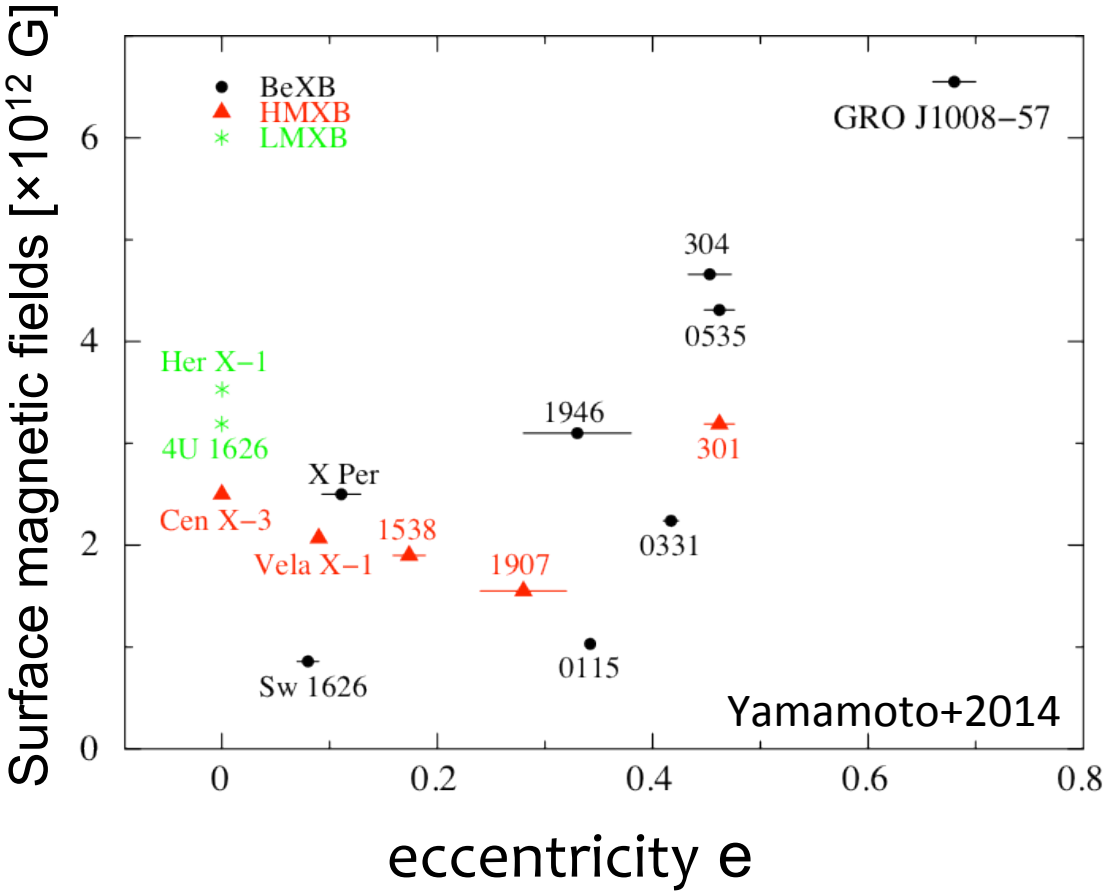


- Discovery of cyclotron line at 54 keV.
- $B = 4.7 \times 10^{12}$ G
- Positive correlation in cyclotron line energies and luminosities.

- Frim detection of cyclotron line at 76 keV.
- $B = 6.7 \times 10^{12}$ G
- Highest cyclotron energy among BeXRBPs.



Eccentricity and magnetic fields



※ 15 pulsars were plotted whose eccentricity is known.

- Positive relation in eccentricity e and magnetic field B.
- Relation with binary evolution model?

Summary

- ✓ MAXI is monitoring Be X-ray binaries.
- ✓ Outburst orbital phase shift
  - ✓ The systematic orbital phase “delay” is observed from 4 BeXRBPs.
  - ✓ The phase shift rate probably depends on orbital eccentricity.
  - ✓ The systematic orbital phase “advance” is observed from GX304-1.
  - ✓ Be disk expansion is most likely scenario.
- ✓ GOB periodicity of EXO 2030+375 (Laplace et al. poster P-58)
  - ✓ Possibility of 20/10 years periodicity in GOB activity.
  - ✓ KL oscillation can explain long term periodicity.
- ✓ Correlation between flux increase rate and peak fluxes in NOBs
  - ✓ The effect of Roche lobe shrink might explain the observed relation.
- ✓ Suzaku follow-up observations
  - ✓ Discovery of the cyclotron resonance lines in GX 304-1 and GRO J1008-57
  - ✓ e-B relation might relate with binary evolution model.


JAXA
MAXI
Monitor of All-sky X-ray Image
Miniature Experiment Module-Kibo
RIKEN
KYOTO-U
NIHON-U
AGU
TOKYO-TECH
OSAKA-U

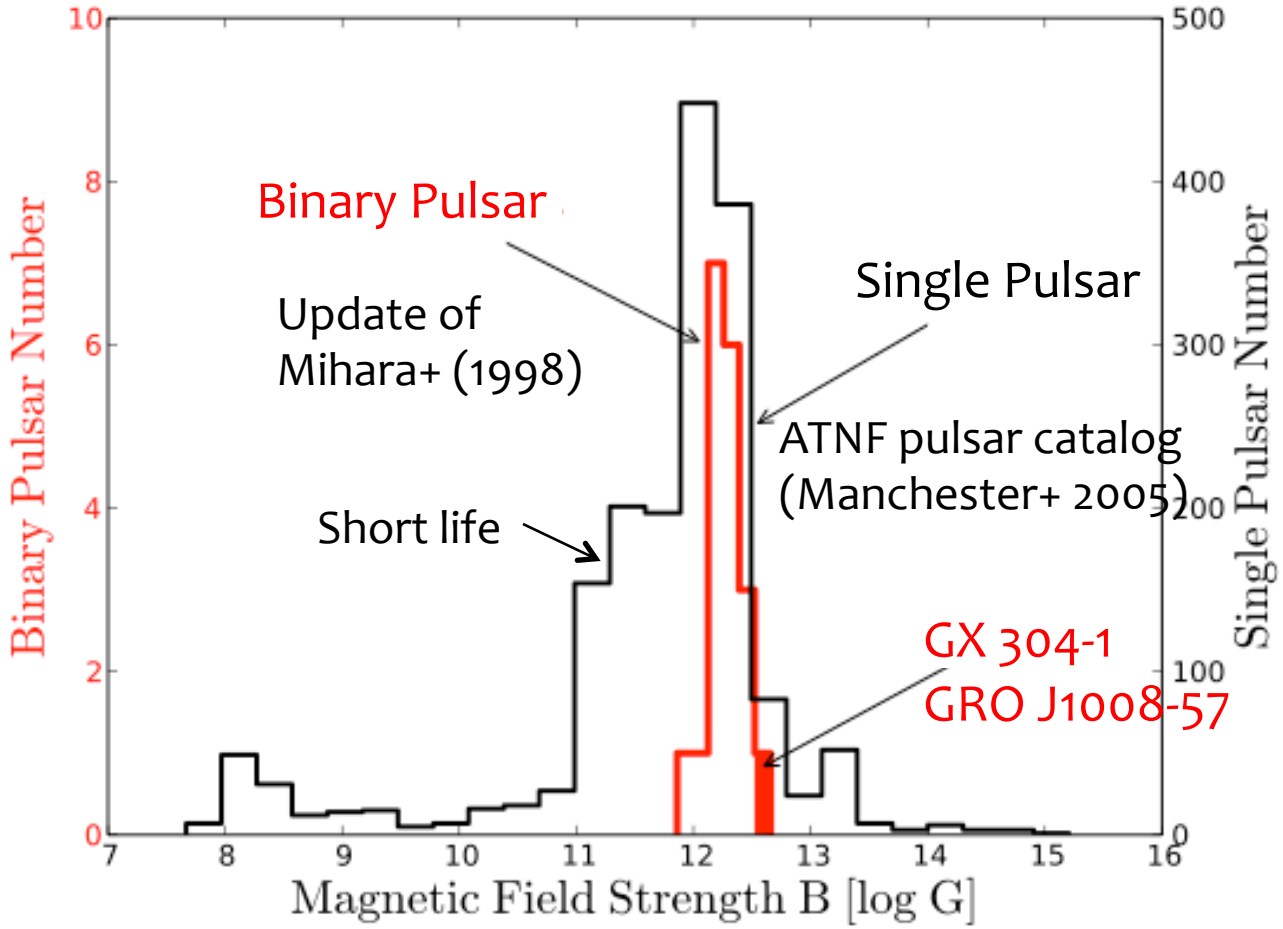
Modeling the Outburst Profile

- The quantitative analysis is needed to understand and compare each outburst profile.
- There are several models to represent the outburst profiles.
  - Gaussian model
  - Asymmetric Gaussian model (Kuhnel+2014)
  - Burst model
  - Triangle shape function

Outline

- Introduction
  - About Be X-ray binary pulsar (BeXRBP)
  - MAXI/GSC observation of BeXRBP
  - Atel
  - Lightcurve
  - Various outburst
  - Individual topics

B distribution of pulsars



18 XBPs
Ginga (6)、
RXTE (5)、
Suzaku (3)
others (4)

MAXI–Suzaku observations added two XBPs in high end.
B peaks at 2×10^{12} G, and distributes to 7×10^{12} G