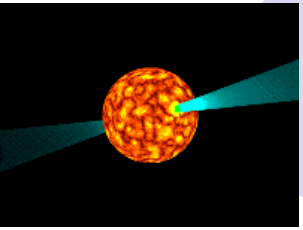
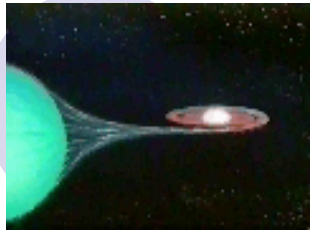


KHz QPOs & millisecond X-ray pulsars in LMXBs



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Collaborators:

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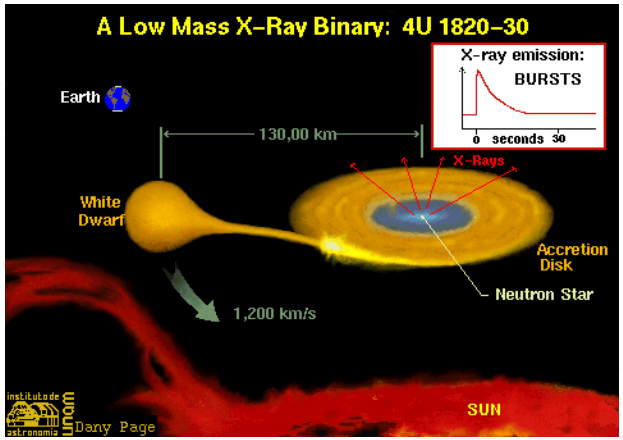
X-ray Astronomy - 60th Anniversary, 2022-0616

Introduction & Background

Background: oscillations of X-ray in millisecond pulsar near neutron star-LMXB show: QPO, spin, strong gravitation-GR, magnetic field, accretion flow, emission, link of MSP-AMXP, etc.

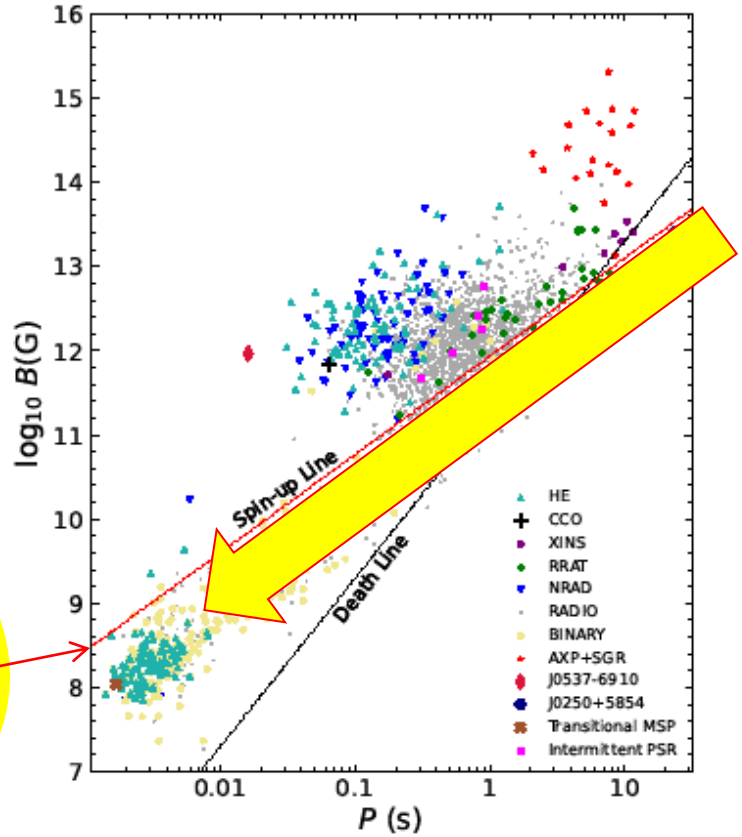
RXTE（1996-2012, ----），NICER，ASTROSAT，HXMT，eXTP

1. kHz QPOs of NS-LMXBs
2. Spins of NS-LMXBs
3. Spin and kHz QPO relations
4. Summary



Relation between LMXBs and Radio millisecond pulsars (MSPs)

Pulsar B-P diagram



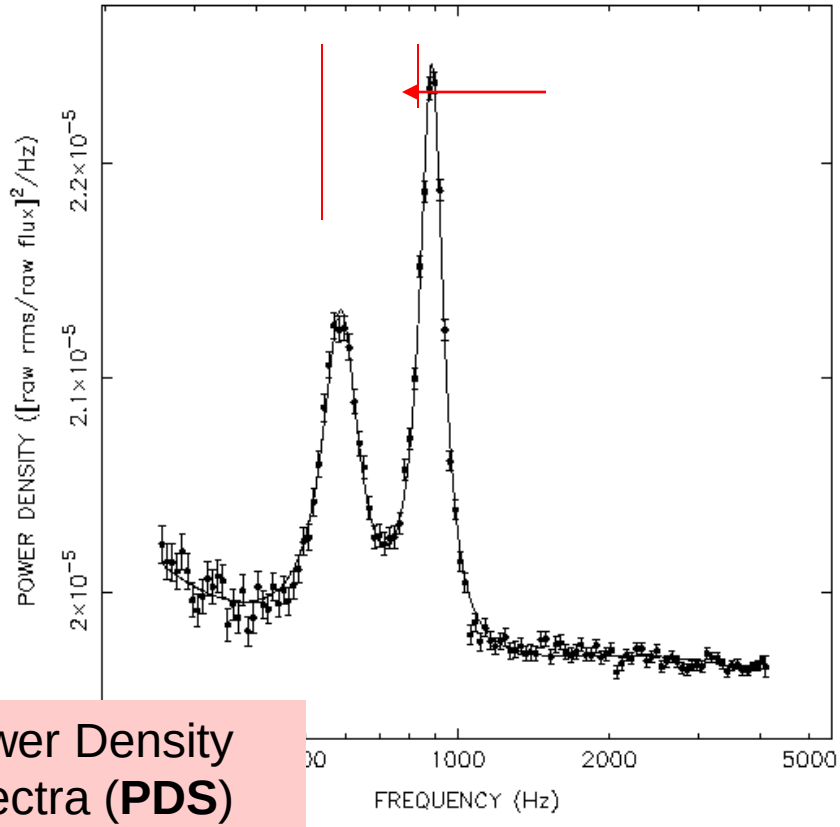
Accretion Spin-up

LMXBs MSPs

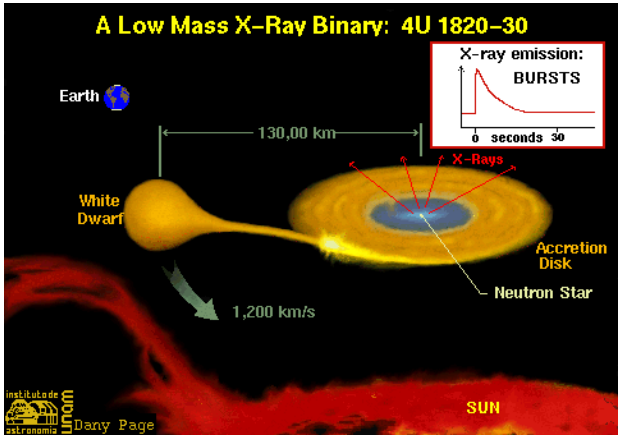
1. kHz QPOs in NS-LMXBs

Mendez & Belloni 2021; van der Klis 2006

Twin kHz QPO difference ~300 Hz



Power Density Spectra (**PDS**)



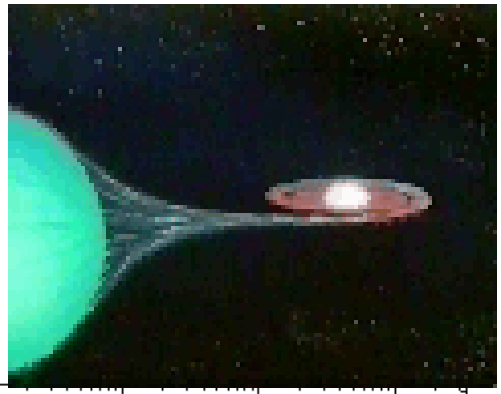
Typically: Twin KHz QPO

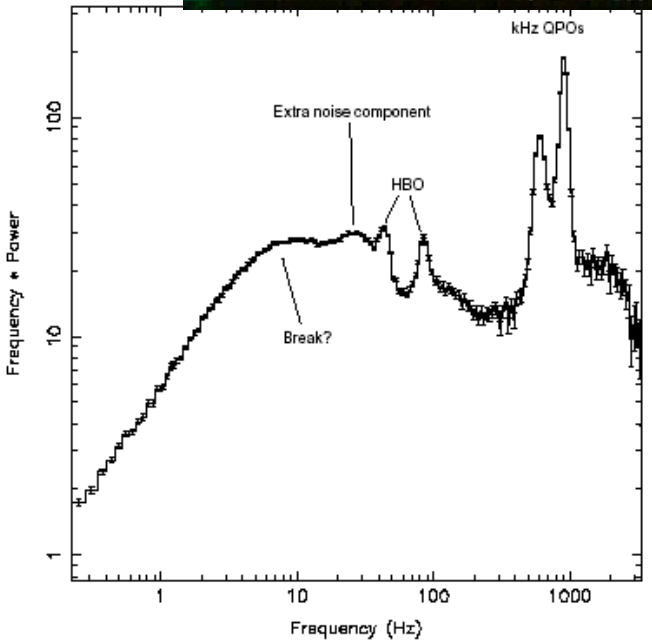
Upper $\nu_2 \sim 1000$ (Hz)

Lower $\nu_1 \sim 700$ (Hz)

~>300 pairs of kHz QPOs

Quasi-Periodic Oscillations (QPOs)





KiloHertz QPOs:

Time scale is orbital time scale at inner accretion disk.

Other band QPOs:

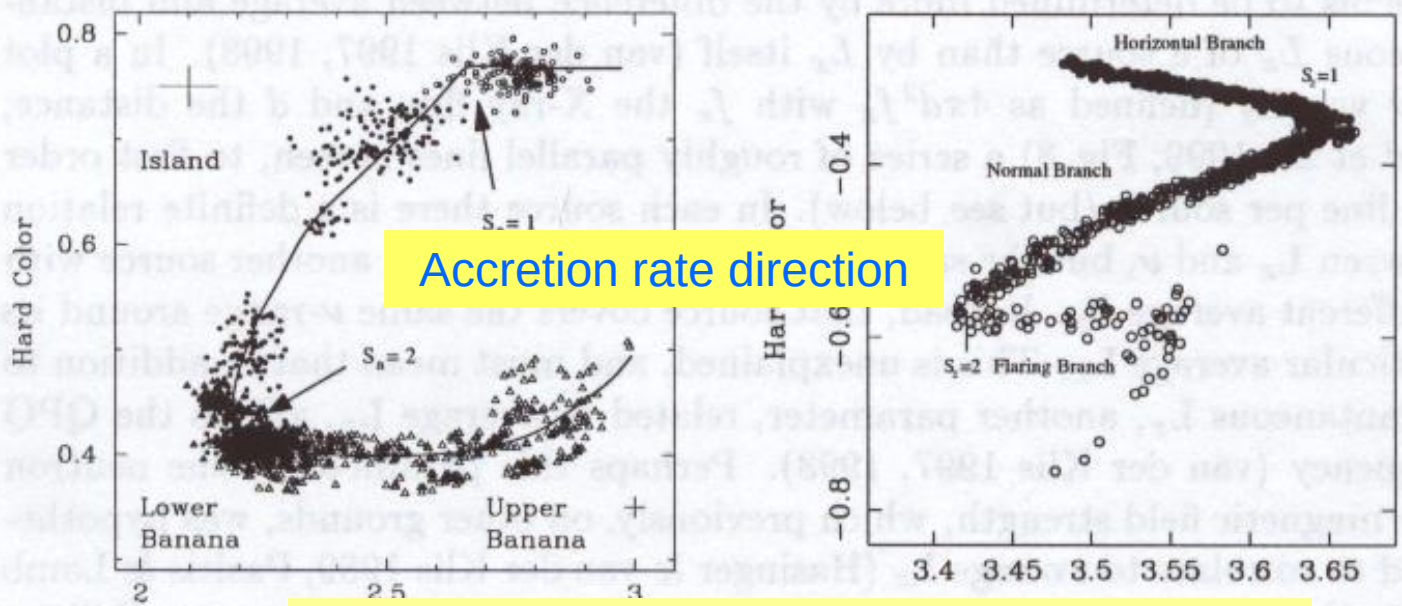
HBO, NBO, Noise

Not understood well !

kHz QPOs in two types of Sources of NS/LMXBs
Atoll ---- Z

~1% Eddington Accretion

~Eddington Accretion



Accretion rate direction

Van der Klis 2006； Mendez & Belloni 2021

Figure 7: Left: X-ray color-color diagram of the atoll source 4U 1608−52. (Méndez et al. 1999) Right: X-ray hardness vs. intensity diagram of the Z source GX 340+0. (after Jonker et al. 1999c) Values of curve-length parameters S_z and S_a and conventional branch names are indicated. Mass accretion rate is inferred to increase in the sense of increasing S_a and S_z. X-ray color is the log of a count rate ratio (3.5–6.4/2.0–3.5 and 9.7–16.0/6.4–9.7 keV for soft and hard color respectively); intensity is in the 2–16 keV band. kHz QPO detections are indicated with filled symbols.

2. Spin frequency
Accreting X-ray millisecond pulsar

--- SAX J1808.4-3658 (AXMPs); 401 Hz (2.49 ms)

Prutruno & Watt 2021; Wijnands et al 2003

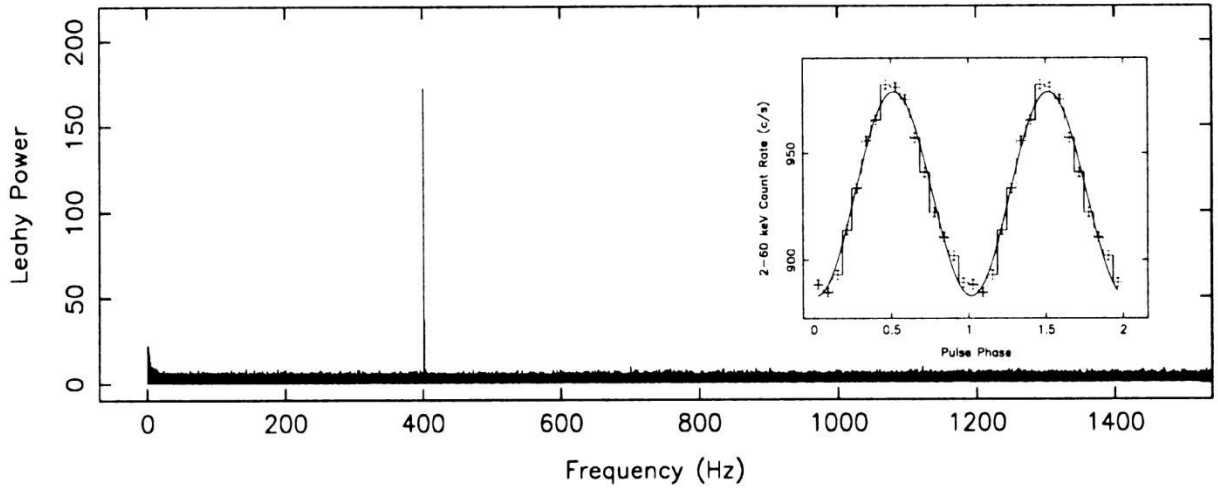
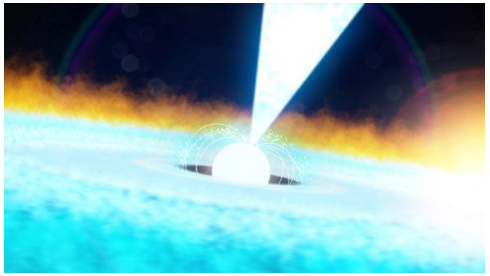
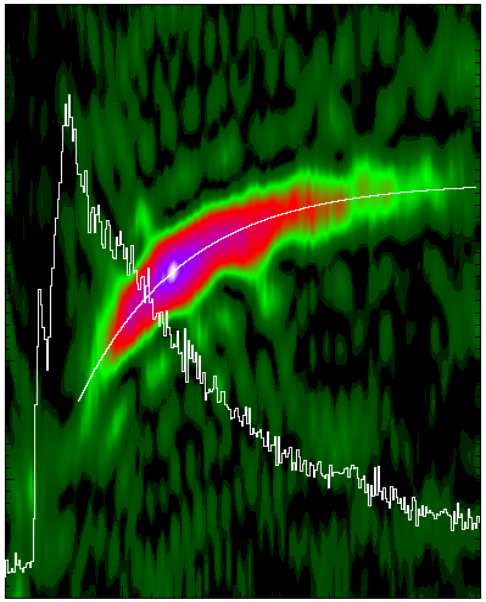


Figure 1: The discovery power spectrum and pulse profile (inset) of the first accreting millisecond X-ray pulsar. Note the low harmonic content evident both from the absence of harmonics in the power spectrum and the near-sinusoidal pulse profile. (after Wijnands & van der Klis 1998b)

2. **Spin frequency –** Type-I X-ray Burst





Samples

4U1728-34, (363 Hz）
SaxJ1808.4-3658 （401 Hz）

Spin+ burst 40 sources

Galloway & Keek 2021

Summary: Spin and kHz QPOs of LMXBs 1996—2022

1. kHz QPOs (~>300 pairs)

127 - 1329 Hz (4U 0614)， Max? :

2. Spin frequency - Burst oscillation (40 samples);

95 - 619 Hz ;

Max=619 Hz (?) Radio MSP 716 Hz

3. HBO, ~ 15-70 Hz, NBO， ～ 5 Hz

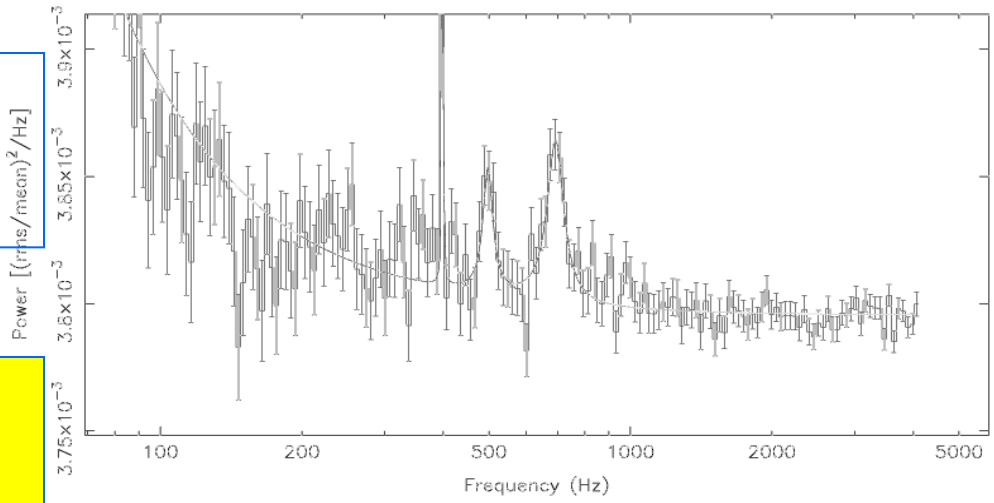
3. kHz QPO difference and spin relation

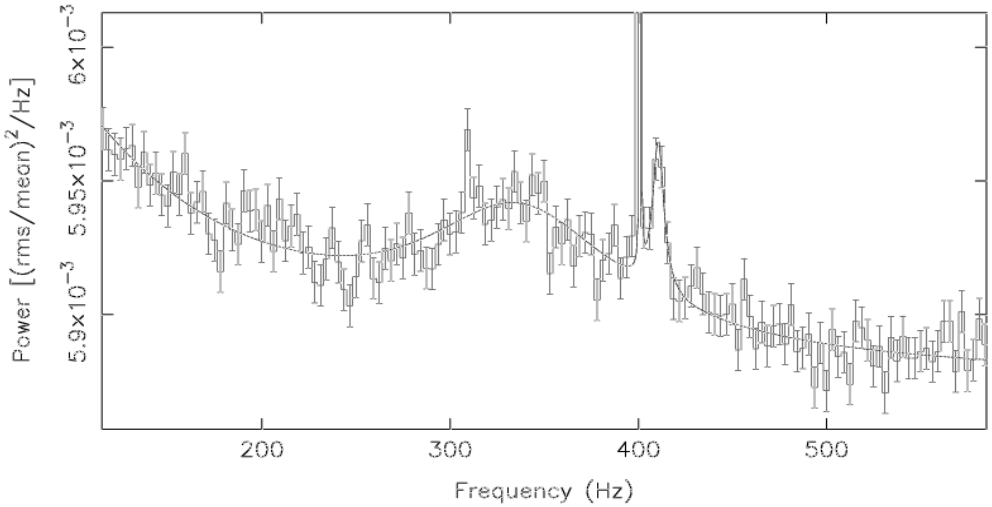
SAXJ 1808.4-3658，Twin kHz QPOs：700 Hz, 500 Hz；Burst--spin: 401 Hz；
Wijnands et al 2003

Burst frequency = spin frequency

XTE 1807-294, twin kHz QPOs, 191 Hz

Zhang F et al 2007





Slow rotator; separation/spin ~ 1
Fast rotator; separation/spin ~ 0.5

Linares & van der Klis 2007

difference of twin kHz QPOs = const?

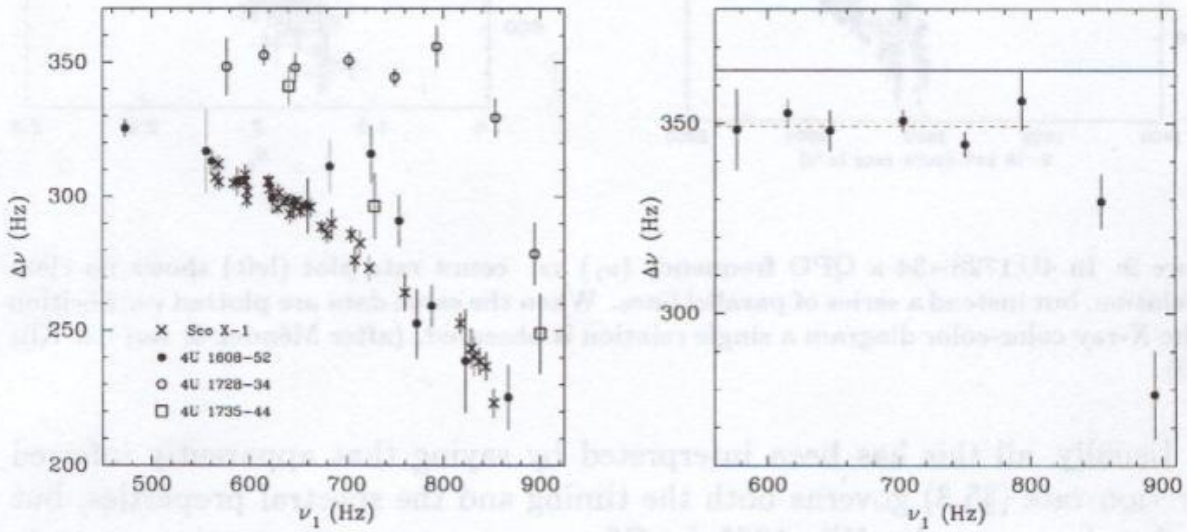


Figure 10: Left: the variations in kHz QPO peak separation as a function of the lower kHz frequency. Right: the data on 4U 1728−34. The burst oscillation frequency is indicated by a horizontal drawn line (Méndez & van der Klis 1999).

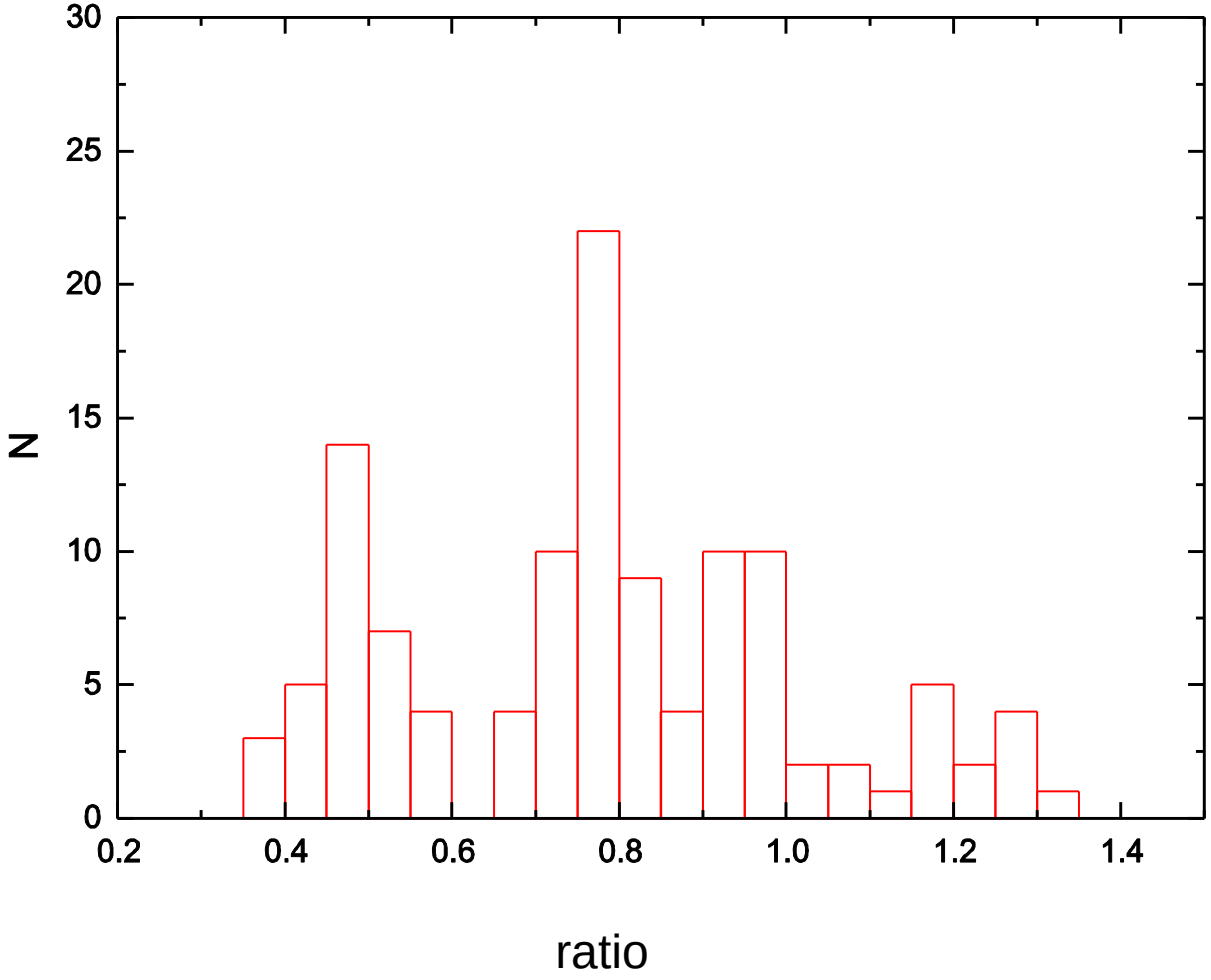
Separation = 173 – 359 Hz for all sources

TWELVE sources with twin kHz QPO & spin frequencies

Millisecond pulsars	sep	spin	ratio
XTE J1807-294	79-247	191	0.94-1.29
SAX J1808.4-3658	195	401	0.49

Atoll sources			
4U 1608-52	224-327	619	0.36-0.53
4U 1636-53	217-329	581	0.37-0.57
4U 1702-43	333	330	1.01
4U 1728-34	271-359	363	0.75-0.99
KS 1731-260	266	524	0.51
4U 1915-05	290-353	270	1.07-1.31
IGR J17191	330	294	1.12
SAX J1750.8-29	317	601	0.53
4U 0614+09	238-382	415	0.57-0.92
Aql X-1	278-280	550	0.51-0.51

Ratio of kHz QPO difference to Spin for 12 sources



Twin kHz QPO relation

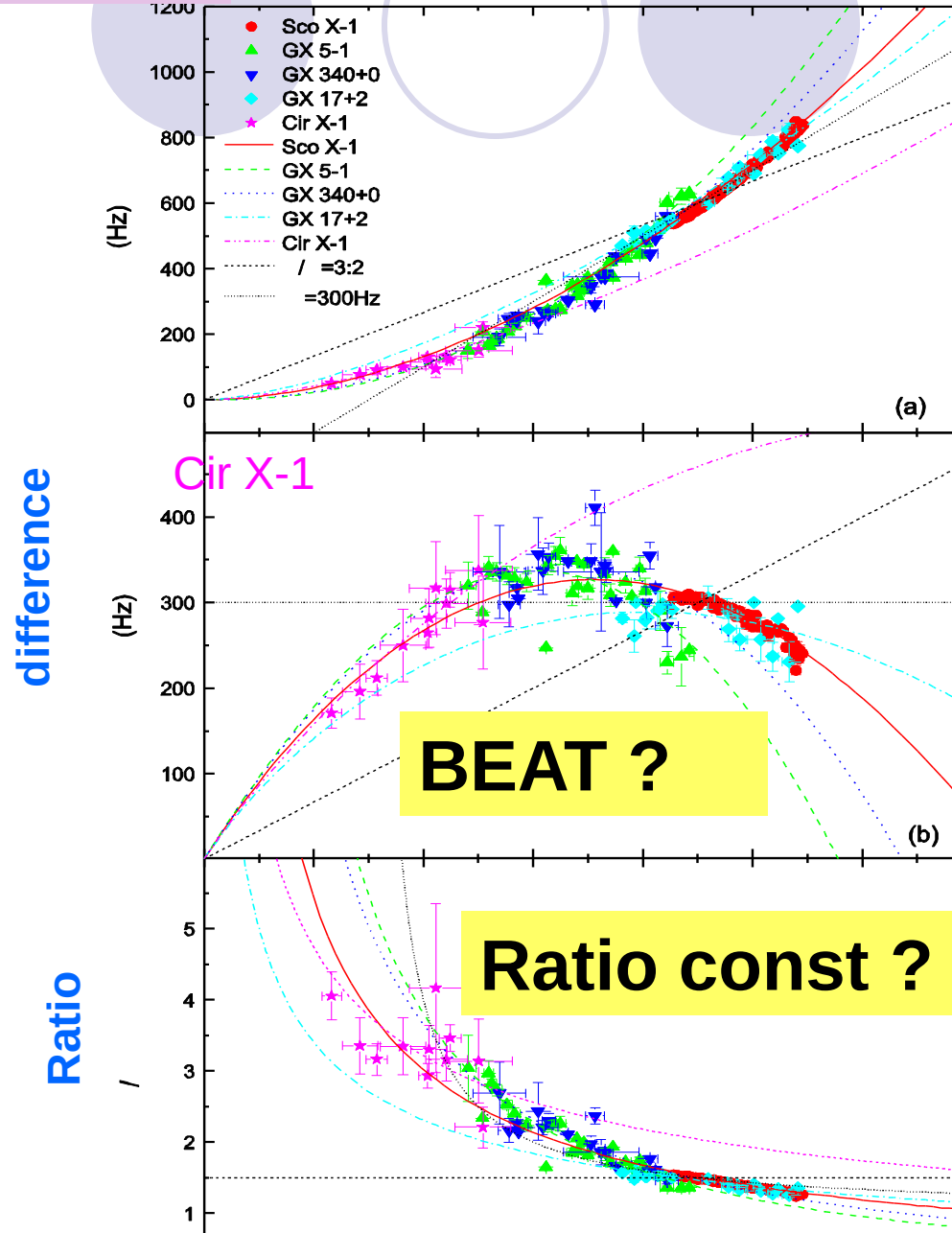
1. separation is constant ? (beat)
2. Linear relation: v2 = *A* v1 +*B* ?
3. Ratio is a constant : 3:2 ?

Non-linear relation

$v_1 = \sim 700.\ (Hz)(v_2/1000Hz)^b$

b ~ 1.6 Atoll Source, e.g. 4U1728

b ~ 1.8 Z Source, e.g. Sco X-1



Models of kHz QPO：
upper frequency = Keplerian Flow

1. Beat model, Miller & Lamb
2. Relativistic precession Model， Stella & Vrtrie
3. Alfven wave model: Zhang, Li XD & zhang,

Beat Model for KHz QPO

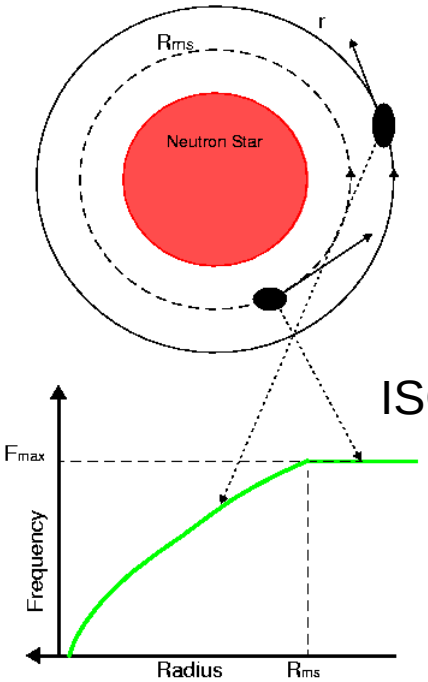
$v_2 = v_{kepler}$

$v_1 = v_{kepler} - v_{spin}$

$\Delta v = v_2 - v_1 = v_{spin}$

…Constant

Relativistic precession model by Stella & Vietri 1999



ISCO Saturation

Einstein's General Relativity: Perihelion precession

Precession Model for KHz QPO,

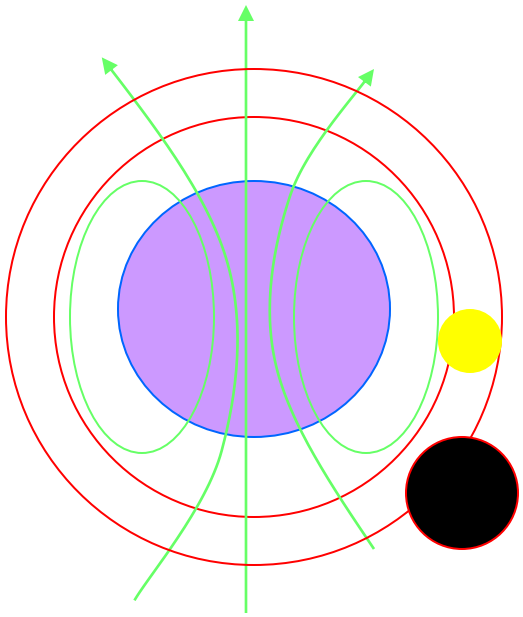
$v_2 = v_{kepler}$

$v_1 = v_{precession} = v_2 [1 - (1 - 3Rs/r)^{1/2}]$

$\Delta v = v_2 - v_1$ is not constant

Alfven wave oscillation MODEL , Zhang 2004; Li & Zhang 2005;

Keplerian Orbital frequency, MHD Alfven wave Oscillation in the orbit



$v_2 = 1850\ (Hz)\ A\ X^{3/2}$

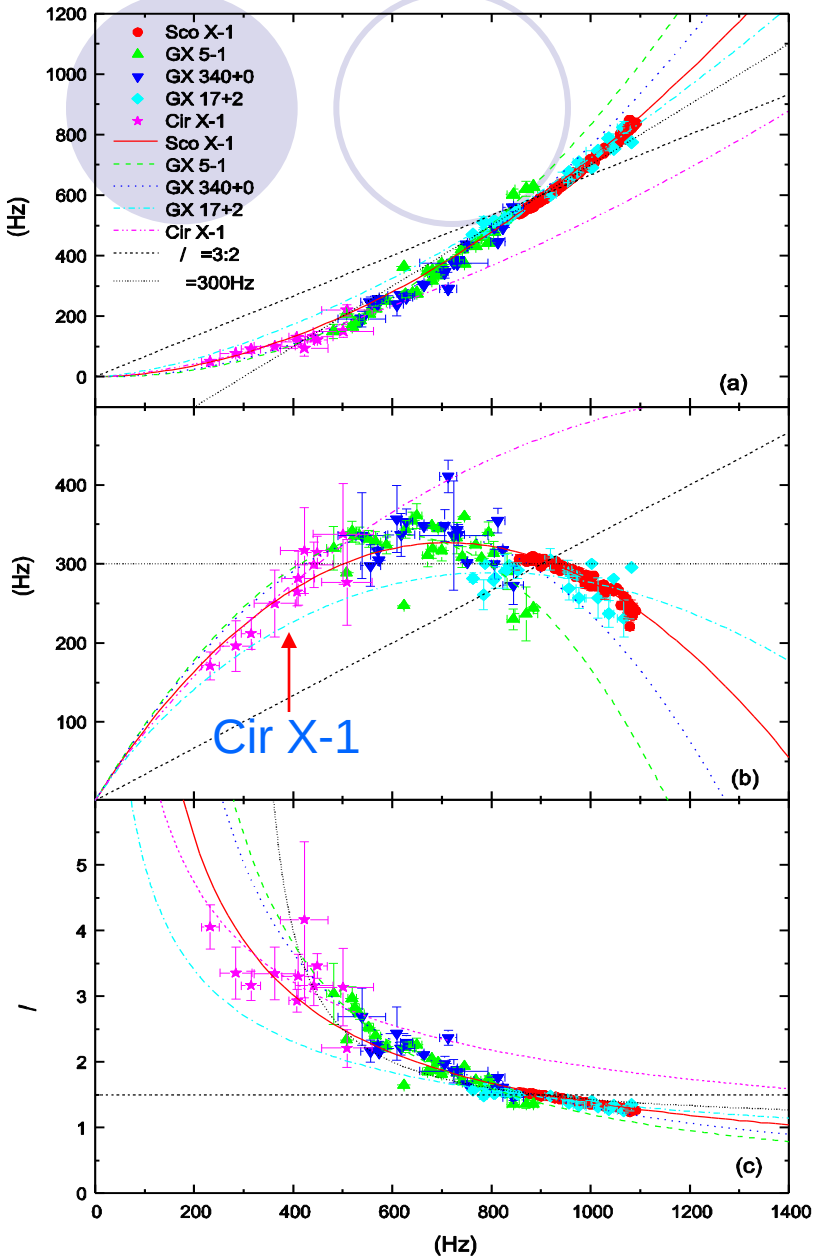
$v_1 = v_2 X\ (1- (1-X)^{1/2})^{1/2}$

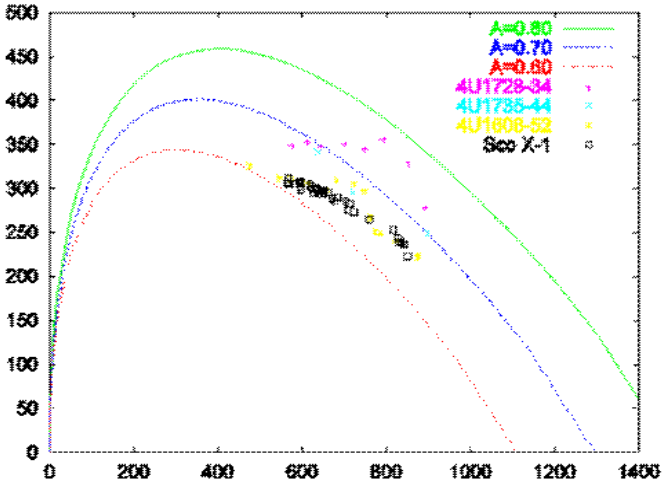
$A=m^{1/2}/R_6^{3/2;}$ $X=R/r$,

m: Ns mass in solar mass

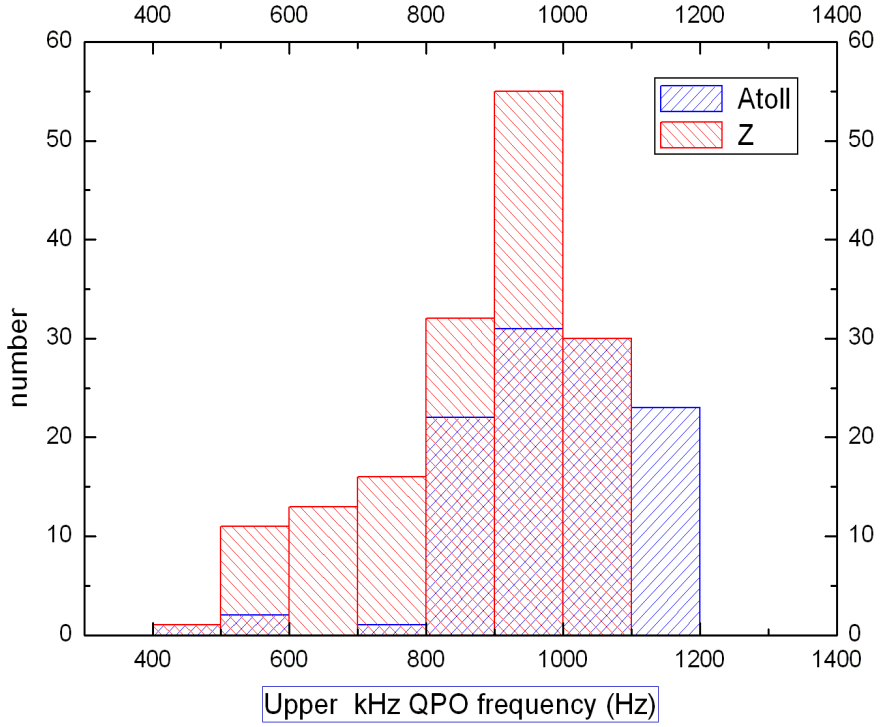
R_6 is NS radius in 10^6 cm

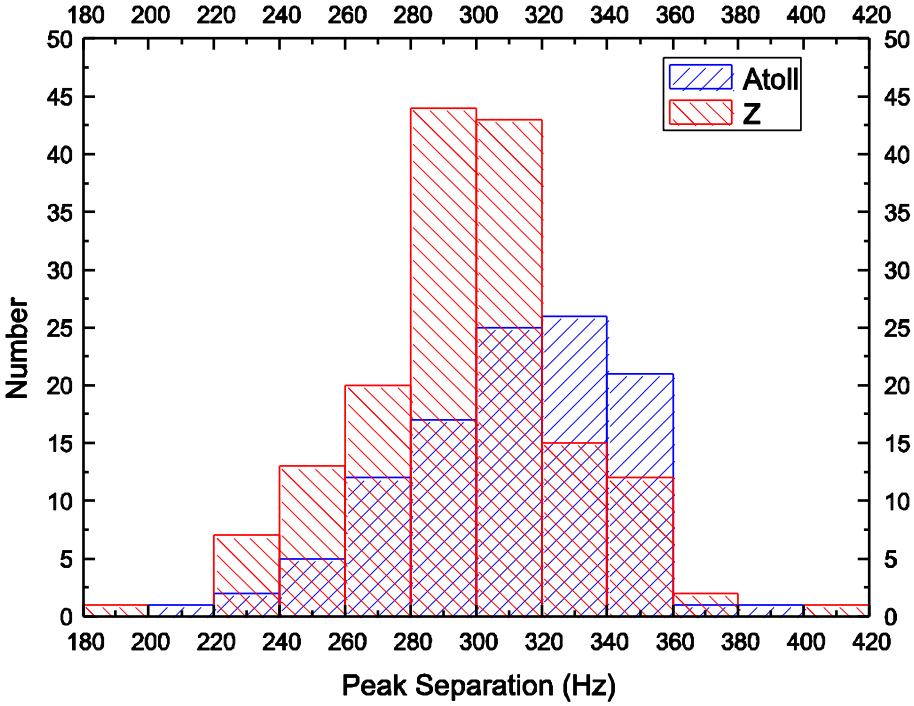
fittings


Sco X-1
GX 5-1
GX 340+0
GX 17+2
Cir X-1
Sco X-1
GX 5-1
GX 340+0
GX 17+2
Cir X-1
/ =3:2
=300Hz
(Hz)
(a)
(b)
Cir X-1
/
(c)
(Hz)

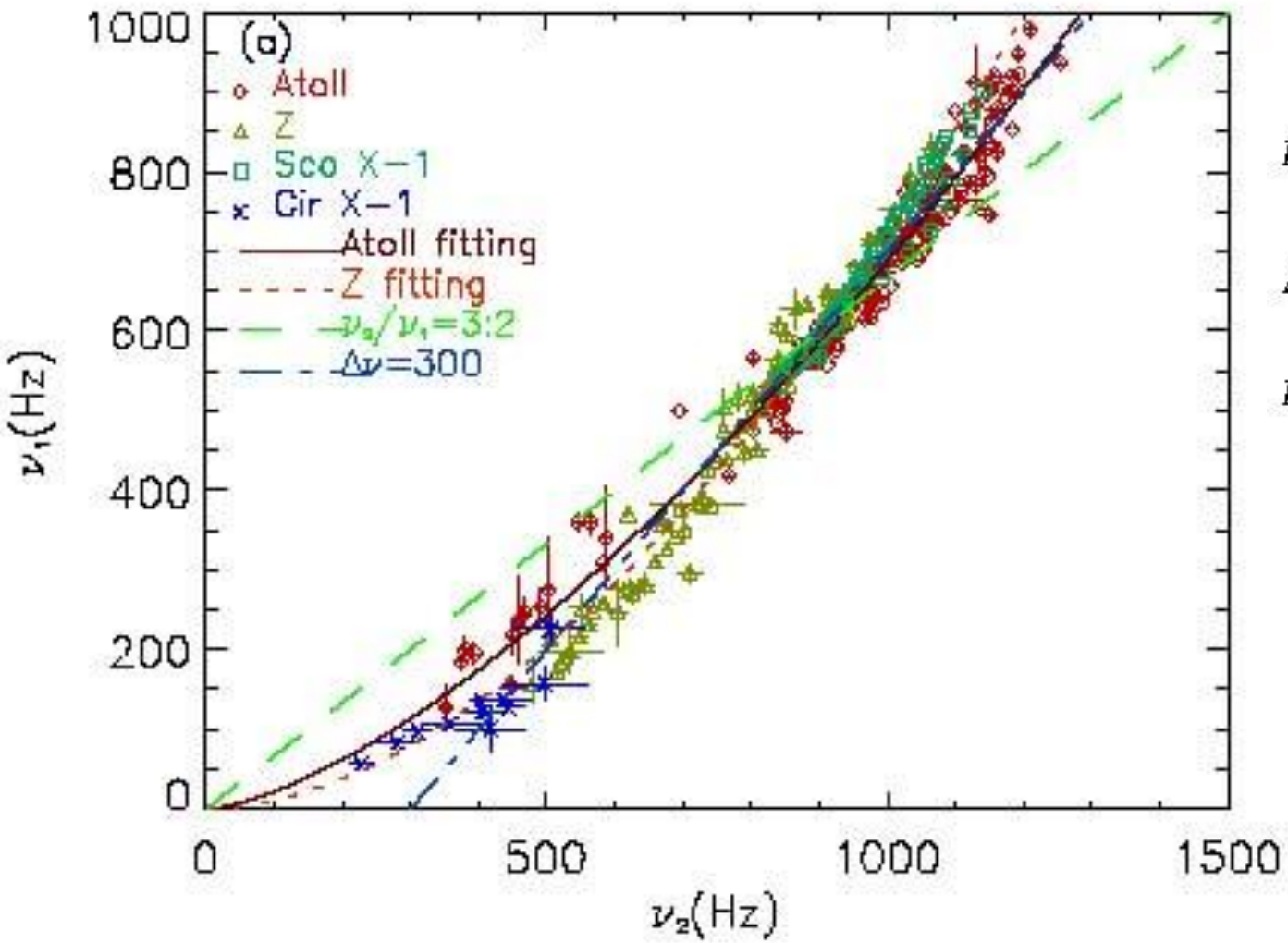

A=0.80
A=0.70
A=0.60
4U1728-34
4U1735-44
4U1608-52
Sco X-1

Twin kHz QPO distribution





模型检验



$$\nu_1 = a(\frac{\nu_2}{1000})^b Hz$$

$$\Delta\nu = 300Hz$$

$$\nu_2/\nu_1 = 3:2$$

拟合结果：指数模型明显优于图另两种模型

Atoll—— $\chi^2/d.o.f. = 1.92$ Z—— $\chi^2/d.o.f. = 1.86$

4. Summary

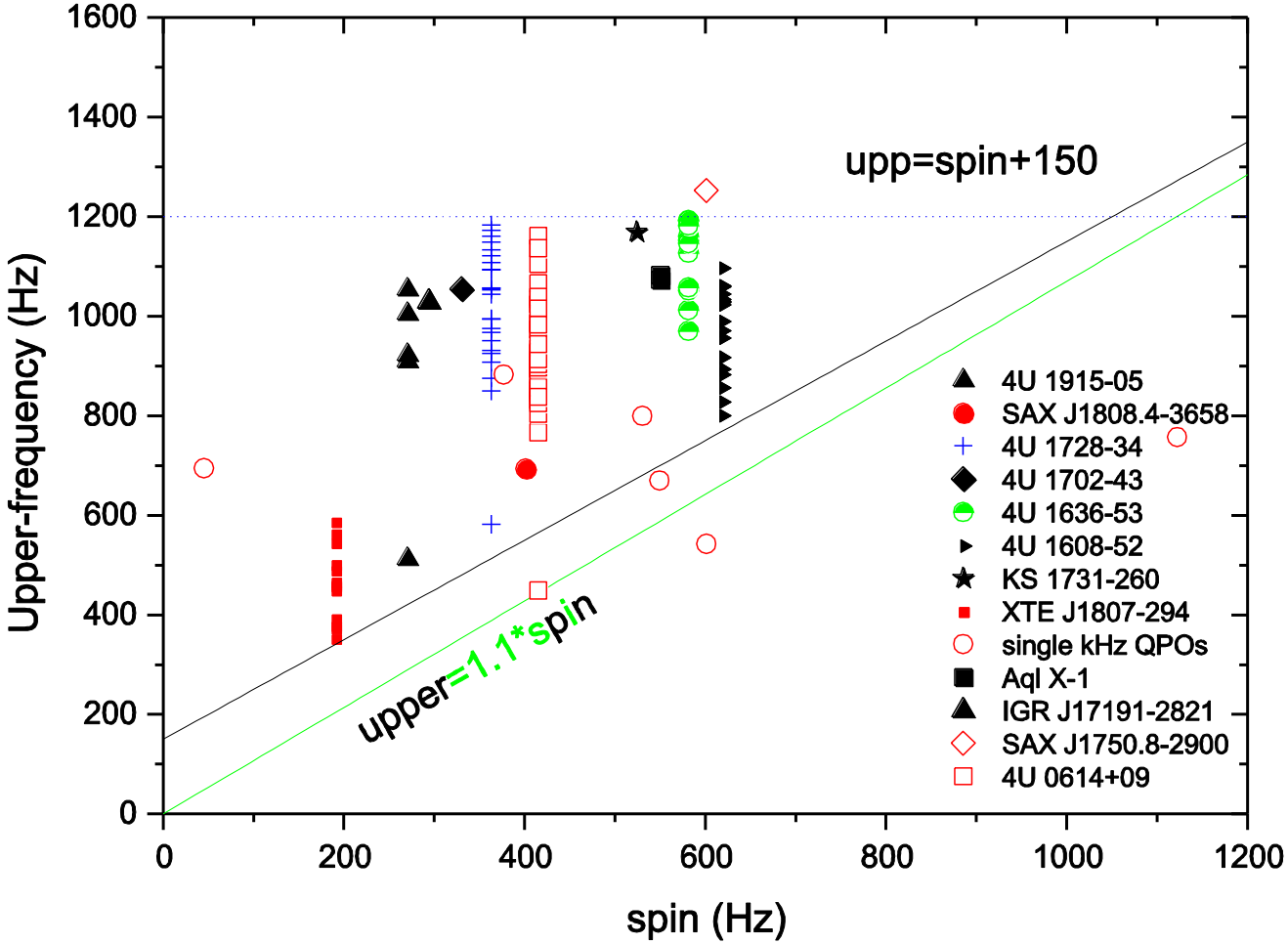
- Spin - kHz QPO relation
  (a) slow/fast rotator 0.5 - 1.0 ; NO
  (b) kHz QPO – Spin ; NO direct - No Beat
  (c) NS twin kHz QPO ratio = 3:2 ? NO
  (c) Av. kHz QPO – spin relation ? Indirect ?

- twin kHz QPOs – nonlinear relation, Yes
- kHz QPOs Model ? Not yet understood well

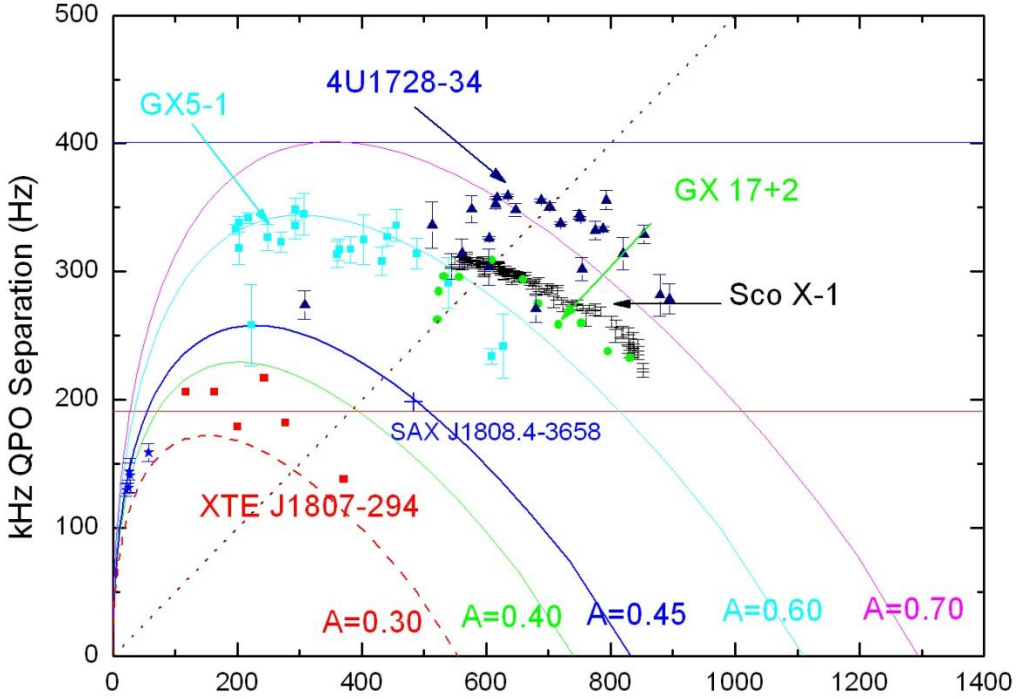
- Questions:
- Radio MSP spin origin ? AMXP? Not same, Wang et al 2021
- Maximum spin >1000 Hz ? Sub-MSP ? Not yet
- Minimum magnetic field of MSP = 10^7 Gauss ?

Thanks

Lower of twin kHz QPO frequency > 1.1 spin frequency



AMXP: special cases of 1.5 shift SAXJ1808.4-365; XTE J1807-294



SAXJ1808.4-365: Wijnands et al 2003; XTE1807-294, F. Zhang et al 2006