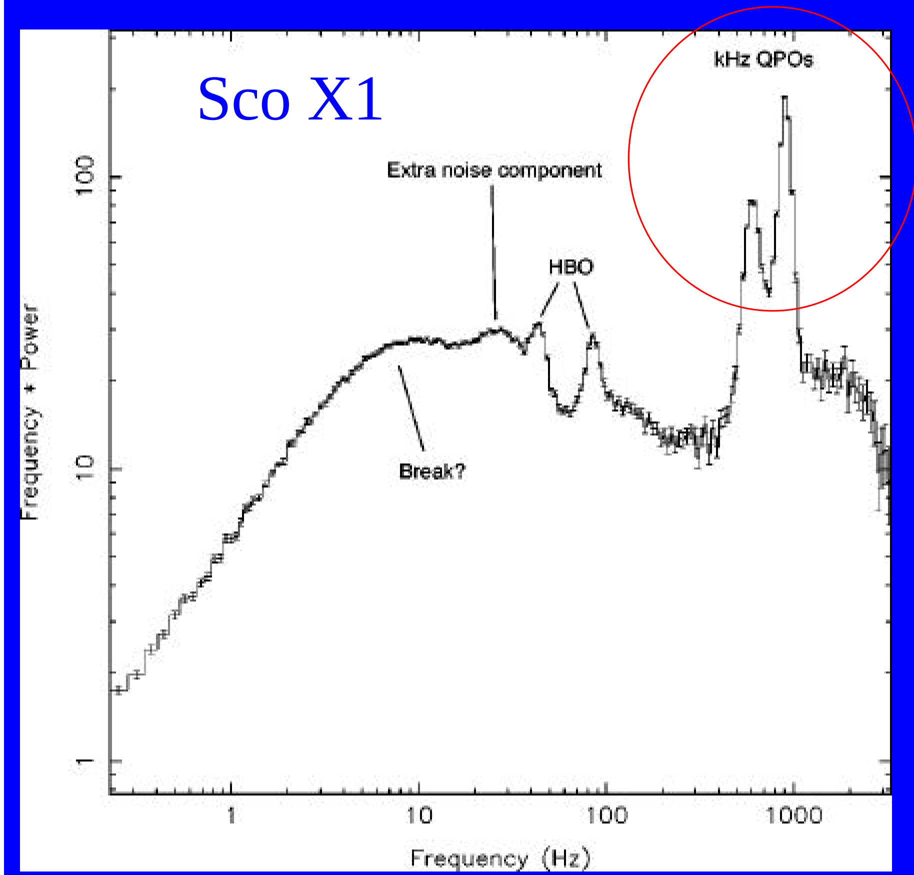
Kilohertz quasiperiodic oscillations (QPOs) in accreting neutron stars

(based on Fred Lamb's slides)



X-ray flux power density spectrum
Wijnands et al. (1998)

Detected in ~ 25 neutron stars

QPOs remarkably coherent (Q $=\nu/d\nu \sim 30$–200)

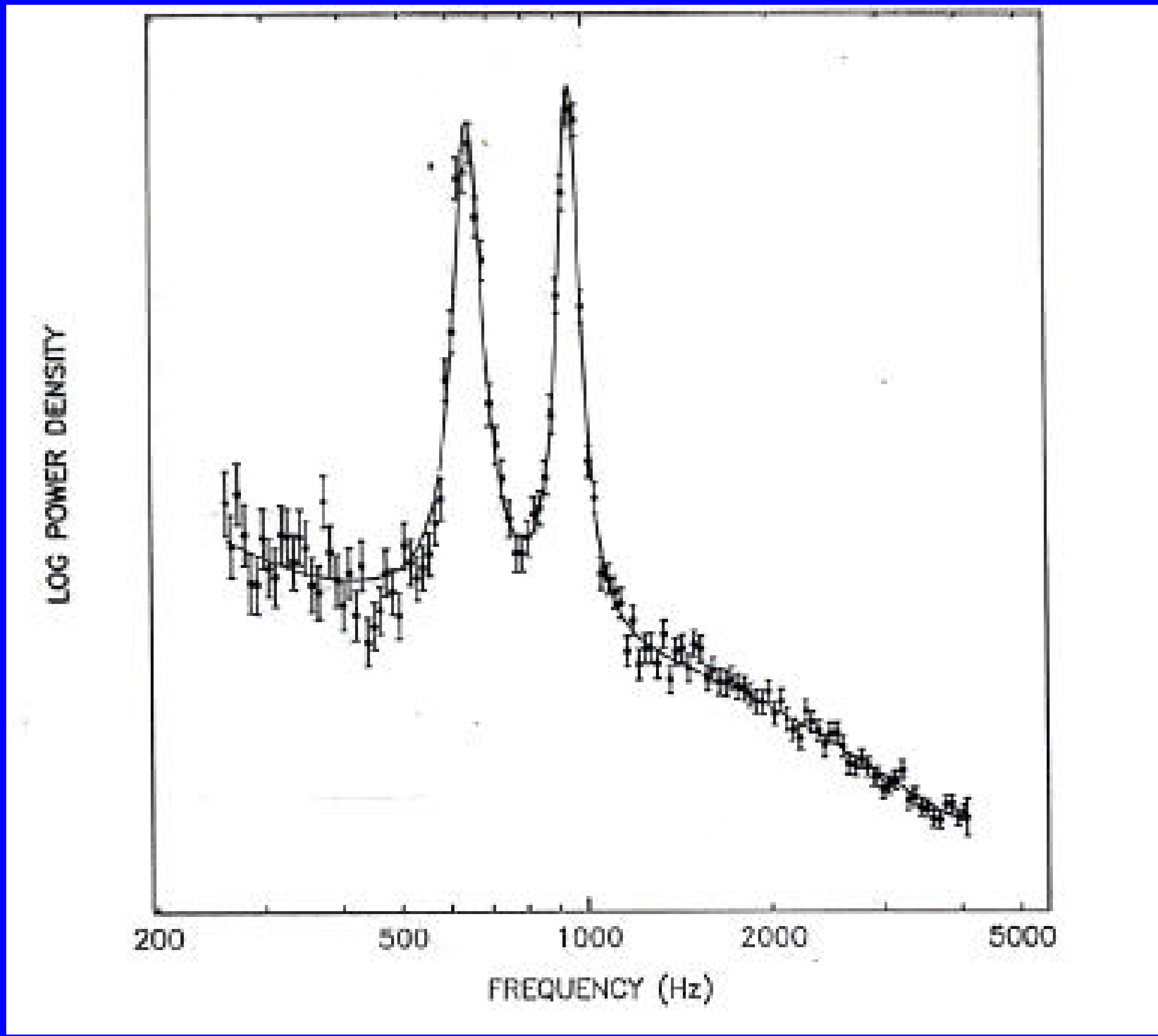
Large amplitude

Usually see 2 simultaneous kHz QPOs (never 3)

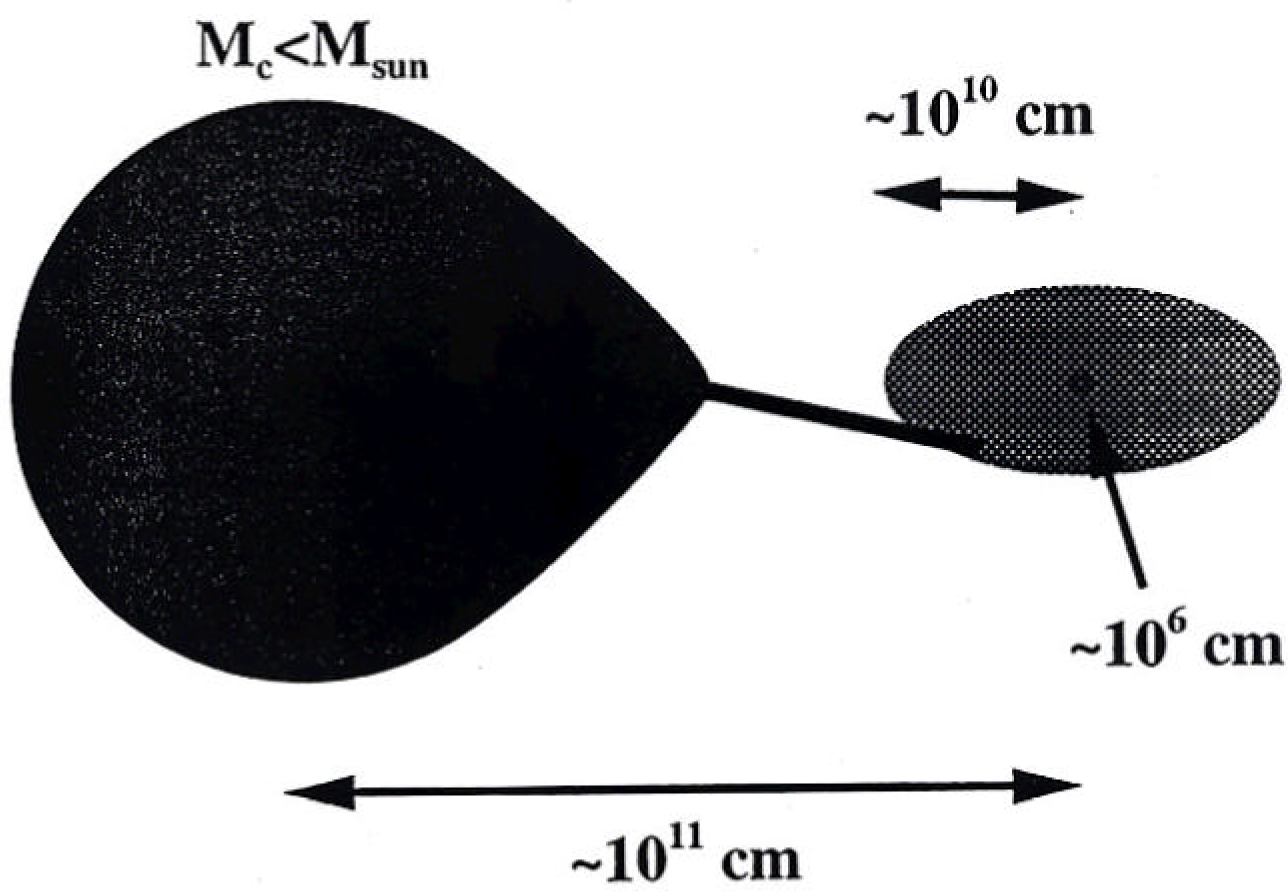
Frequencies of the two QPOs can vary by hundreds of Hz in few hundred seconds, but

Separation $\nu_{QPO} = \nu_{QPO2} - \nu_{QPO1}$ of the two QPOs fairly constant $\sim \nu_{spin}$ or $\sim \nu_{spin}/2$

High frequency QPOs in Sco X-1



Neutron-Star Low Mass X-ray Binaries



$L \sim 0.01 - 1\ L_E \sim 10^{36} - 10^{38}$ erg s^{-1}

$T \sim 10^7 K \Rightarrow \hbar\omega \sim$ keV

Examples of kHz QPO's (~25 detected)

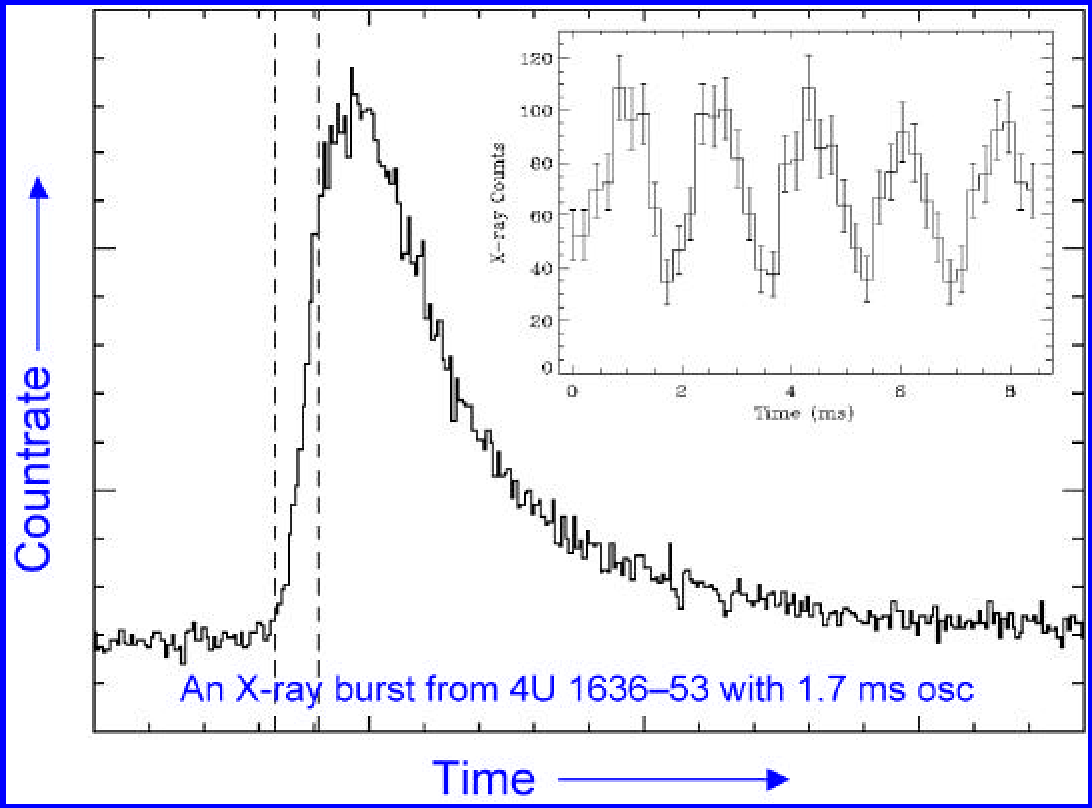
Source	Freq (Hz)	Difference Freq (Hz)
Sco X-1	800-1130	~270
4U 1735–444	1150	—
4U 1728–34	500–1100	360
4U 1608–52	700–900	—
4U 1636–53	800–1170	270
KS 1731–260	900–1200	260
4U 0614+091	400–1150	330
4U 1820–30	550–1170	270
GX 5–1	330–900	320
GX 17+2	680–990	310

Neutron Stars in LMXBs with Known Spins

A: Accretion-powered pulsar; N: Nuclear-powered pulsar; K: pulsar w. kHz QPOs

Spin Rate (Hz)	Object	References
619 NK	4U 1608–52	Hartman et al. 2003
601 NK	SAX J1750.8–2900	Kaaret et al. 2002
598 A	IGR J00291+5934	Markwardt et al. 2004
589 N	X 1743–29	Strohmayer et al. 1997
581 NK	4U 1636–53	Zhang et al. 1996; Strohmayer et al. 1998
567 N	X 1658–298	Wijnands et al. 2001
549 NK	Aql X-1	Zhang et al. 1998
524 NK	KS 1731–260	Smith et al. 1997
435 A	XTE J1751–305	Markwardt et al. 2002
410 N	SAX J1748.9–2021	Kaaret et al. 2003
401 ANK	SAX J1808.4–3658	Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998
373 A	HETE J1900.1–2455	Morgan et al. 2005
363 NK	4U 1728–34	Strohmayer et al. 1996
330 NK	4U 1702–429	Markwardt et al. 1999
314 AN	XTE J1814–338	Markwardt et al. 2003
270 N	4U 1916–05	Galloway et al. 2001
191 AK	XTE J1807.4–294	Markwardt et al. 2003
185 A	XTE J0929–314	Galloway et al. 2002
45 N	EXO 0748–676	Villarreal & Strohmayer 2004

Nuclear-powered msec. pulsars -- Burst oscillations



Surface “hot spot” -- nuclear burning of accreted clump

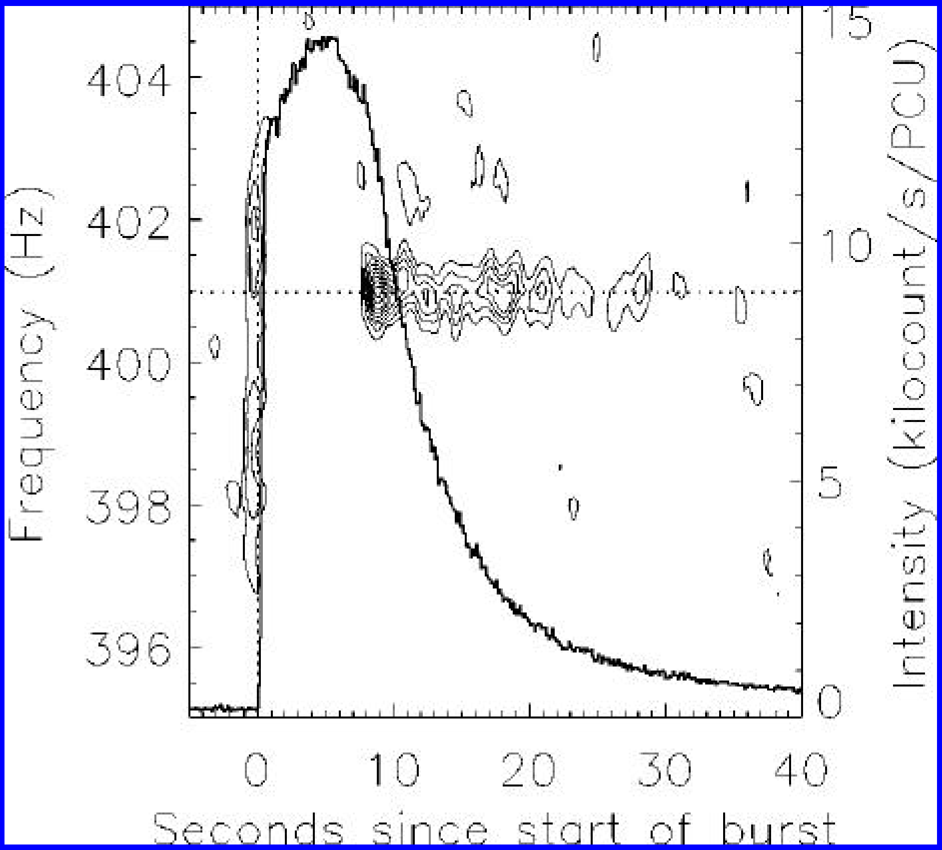
Very bright in X-rays

Pulsation due to rotation at neutron star spin frequency

Oscillations disappear when photospheric radius >> r_* = stellar radius

Burst oscillations SAX J1808.4–3658

(*Chakrabarty et al. 2003*)



4 bursts observed; all show 3–5% oscillations in burst rise and tail

During rise, very fast rise in ν_{burst} -overshoots ν_{spin}

Oscillation disappears at peak during radius expansion

Reappears in tail of burst at

$$\nu_{burst} = \nu_{spin} + 6 \text{ mHz}$$

Firm evidence for $\Delta\nu_{QPO}$ -- ν_{spin} relation

Evidence that n_{QPO2} (upper kHz QPO) is orbital frequency

$\Delta\nu_{QPO}$ relatively stable

In kHz range expected for orbital motion near neutron star

~ ν_{spin} (within 4%–15%) ("slow rotators")

4U 1702–429 (329 Hz: *Markwardt et al. 1999*)

4U 1728–34 (363 Hz: *Strohmayer et al. 1998*

or ~ $\nu_{spin}/2$ (within 0.7%–2%) ("fast rotators")

SAX J1808.4–3658 (401 Hz: *Chakrabarty et al. 2003; Wijnands et al. 2003*)

KS 1731–260 (524 Hz: *Wijnands and van der Klis 1997*)

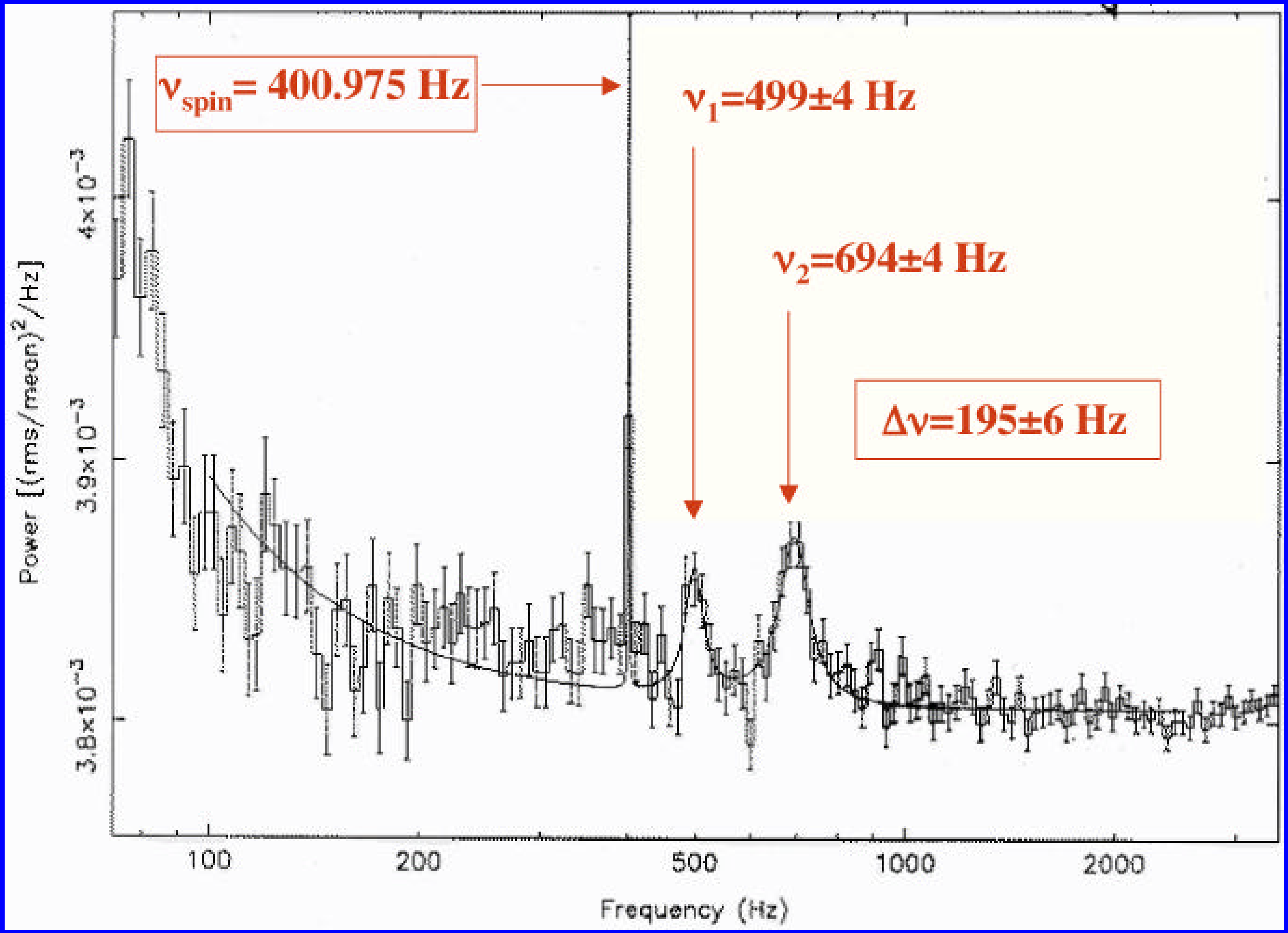
4U 1636–536 (581 Hz: *Méndez et al. 1998*)

4U 1608–522 (620 Hz: *Méndez et al. 97; Chakrabarty & Galloway 2000*)

Often 2 (never 3) kHz QPO indicates single-sideband (beat) phenomenon

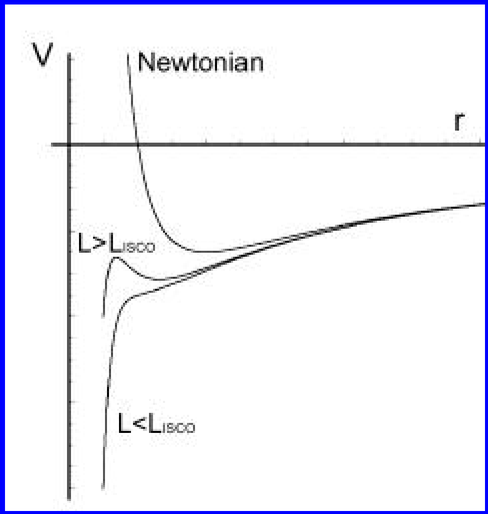
QPOs in accreting X-ray pulsar SAX J1808.4–3658

$$\Delta\nu_{QPO} = \nu_{spin}/2$$



Wijnands et al.

General relativistic circular orbits around a spherically symmetric non-rotating star (mass M_*)



Newtonian: $V_N(r) = -mM_*G/r + L^2/2mr^2$
L = orbital angular momentum,
m = mass of orbiter

GR: Motion in potential $V_{GR}(r) = -mM_*G/r + (1-R_s/r)L^2/2mr^2$
$R_s = 2MG/c^2$ = Schwarzschild radius

For $L < 3^{1/2}\, mcR_s$, or $r < 3R_s$, V_{GR} has no minimum!

Innermost stable circular orbit (ISCO) is at radius $3R_s$
Orbital frequency $2\pi\, \nu_{ISCO} = (M_*G / R_{ISCO}^3)^{1/2}$

ν_{QPO2} = orbital frequency

=> strong constraints on M_* and R_*

Miller, Lamb & Psaltis 1997

Orbital radius R_0 = $[M_* G /(2\pi\, \nu_{QPO2})^2]^{1/3} > R_*$

= neutron star radius

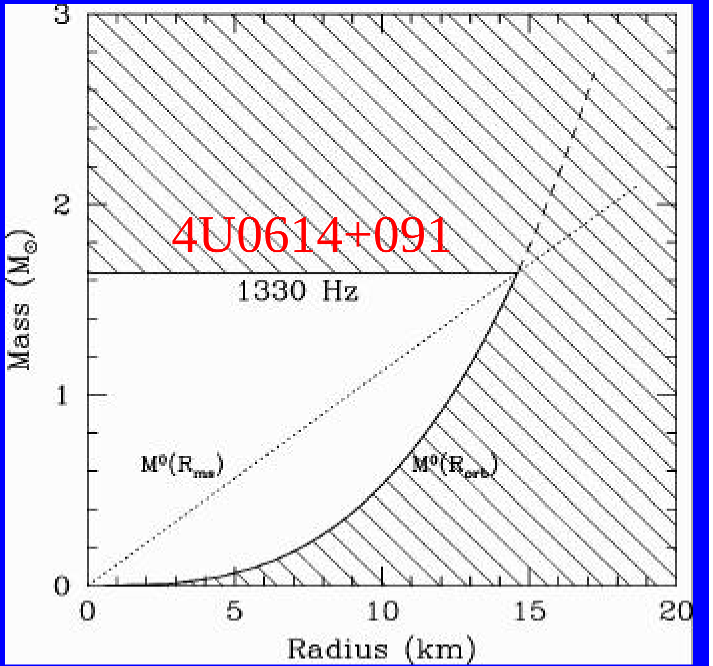
$R_0 > R_{ISCO} = 3\, R_{schwarzschild} = 6 M_* G/c^2$

= radius of general relativistic innermost stable circular orbit

=> $M_* < c^3/(6^{3/2}$£ $2\pi\nu_{QPO2}\, G)$

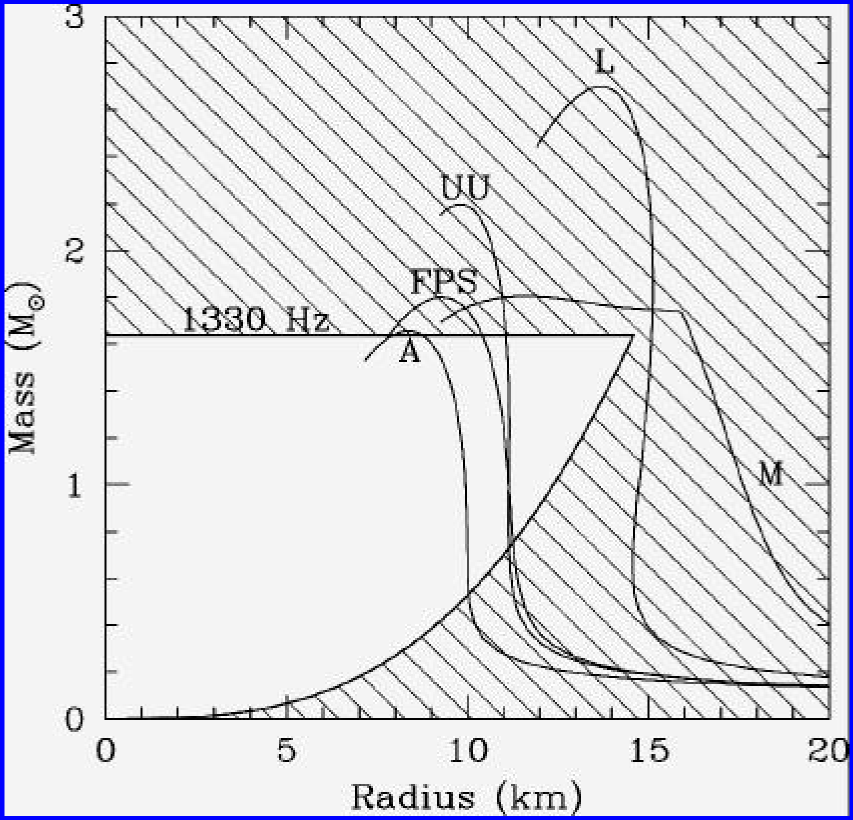
$= (2198/\, \nu_{QPO2}(Hz))\, M$–

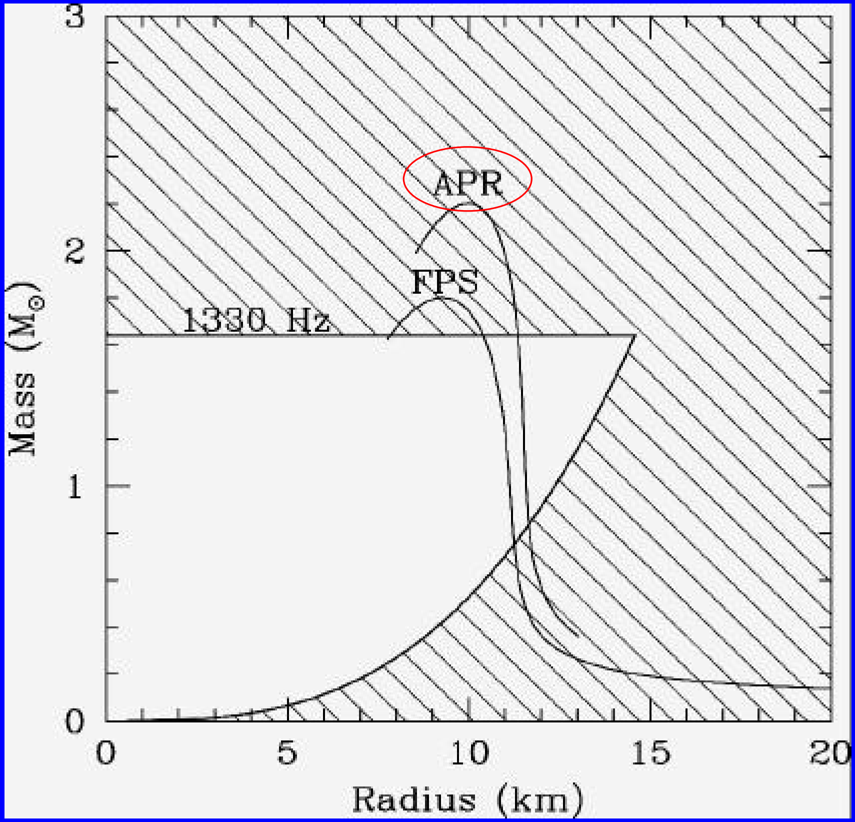
$R_* < c/(6^{1/3}$£ $2\pi\nu_{QPO2})$



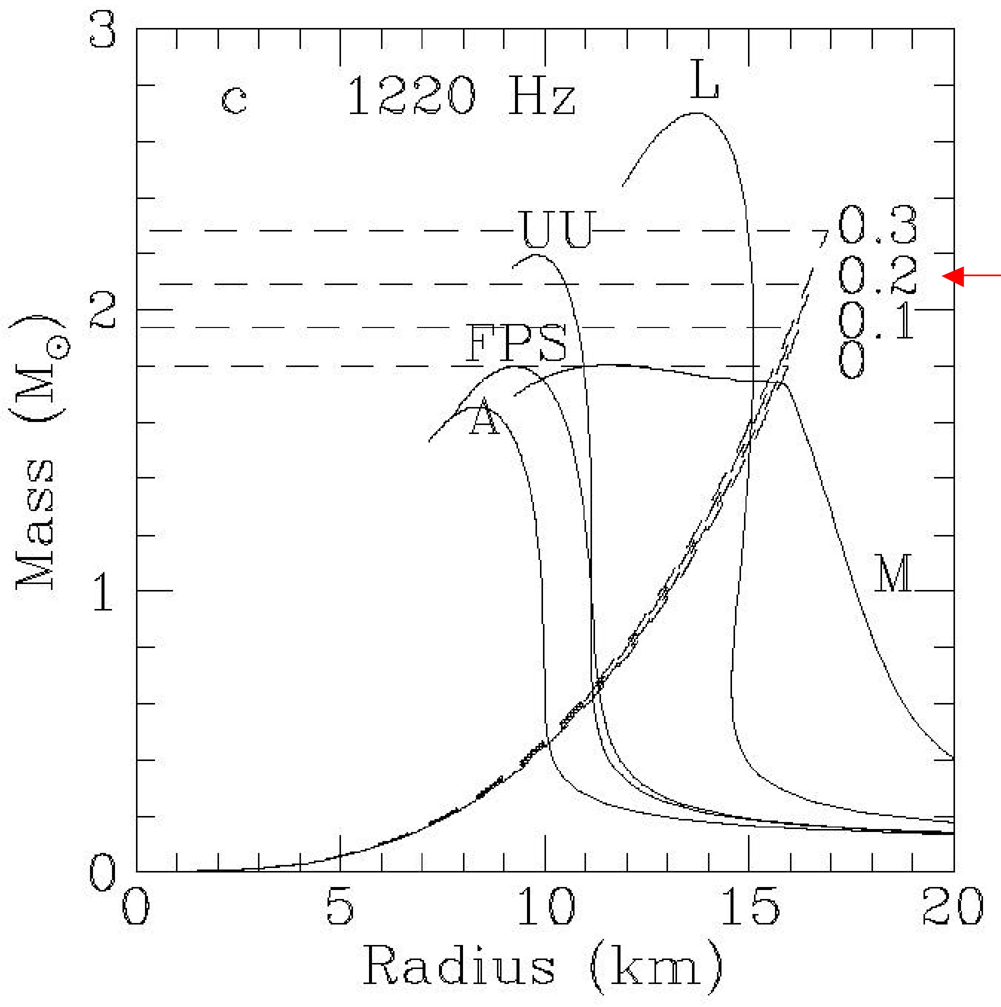
The higher the frequency, the smaller the mass and radius

Constraints on equation of state





Effects of stellar rotation



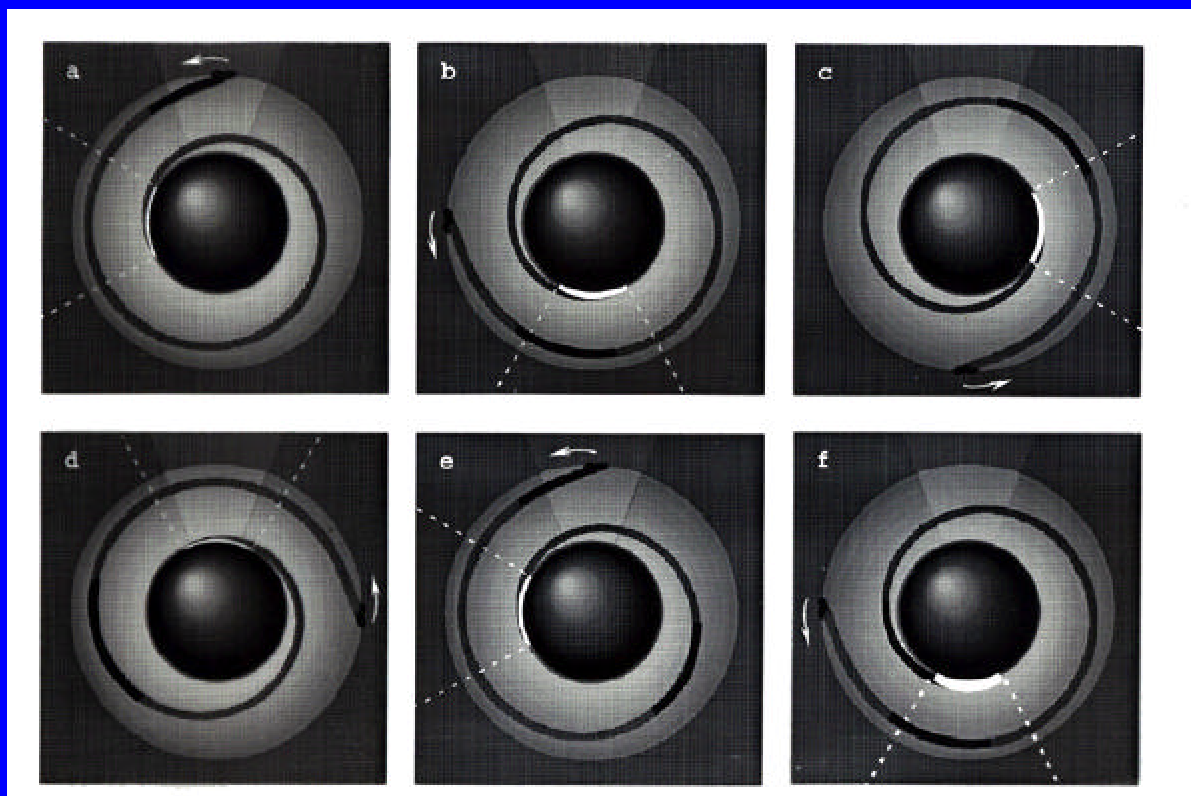
cJ/GM^2

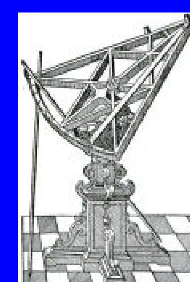
J = angular momentum of neutron star

“Sonic Point” Model: higher frequency determined by ISCO

(*Miller, Lamb & Psaltis 1997*)

Clumpy matter falling on surface of star produces hot spot which rotates at orbital frequency of last stable orbit





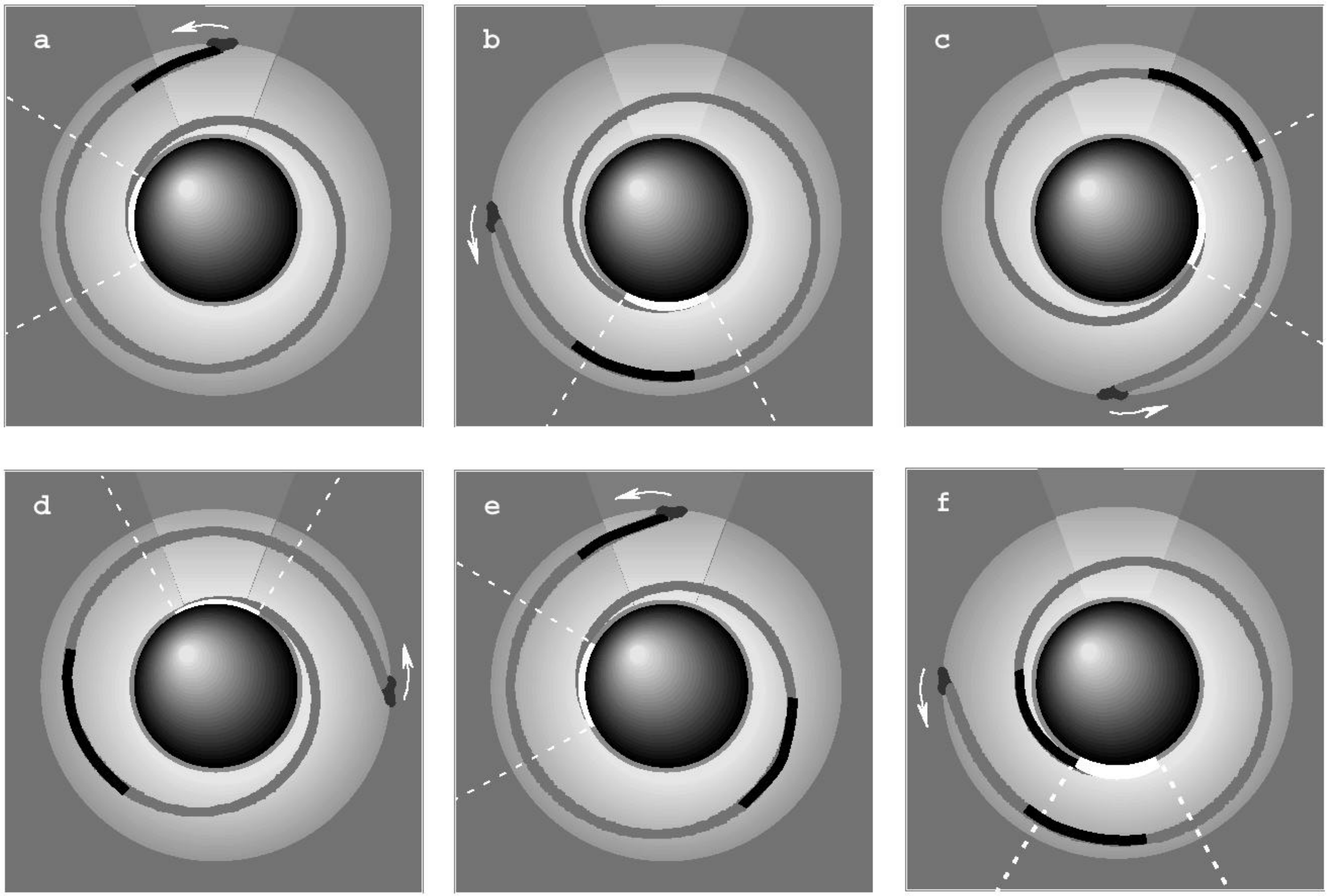
Movies thanks to Fred Lamb

Beat frequency

Clumps of material falling onto star causes » KeV hot spot which rotates at the frequency of the infalling mattter

Neutron star surface is not heated uniformly -- due to channeling effects by weak magnetic field. Secondary x-rays from surface rotate at stellar rotation rate and modulate inward mass flux. Modulation produces frequency component $\nu_{ISCO} - \nu_*$, the frequency of the ISCO in the frame rotating with the star.

$\Delta\nu = 0.5\nu_*$ not consistent with this simple picture; must worry about oscillations in the accretion disk *(Lamb & Miller, astro-ph/0308179).*


a
b
c
d
e
f

If ν_{QPO2} is the ISCO frequency, then have direct measurement of neutron star mass:

$$M_* = c^3/(6^{3/2} \text{£}\ 2\pi\nu_{QPO2}\, G\,)$$

$$=(2198/\ \nu_{QPO2}(\text{Hz})\ )M\text{–}$$

$$R_* =\ c/(6^{1/3} \text{£}\ 2\pi\nu_{QPO2})$$

Ex.: QPO 4U1820-30, $\nu_{QPO2} = 1170$ Hz

=> M~ 2.2-2.3 M–