Timing accreting low-B neutron stars

- Strong field gravity
- Dense matter
- ' Calibrate' BH studies
- Progenitors msec radio pulsars

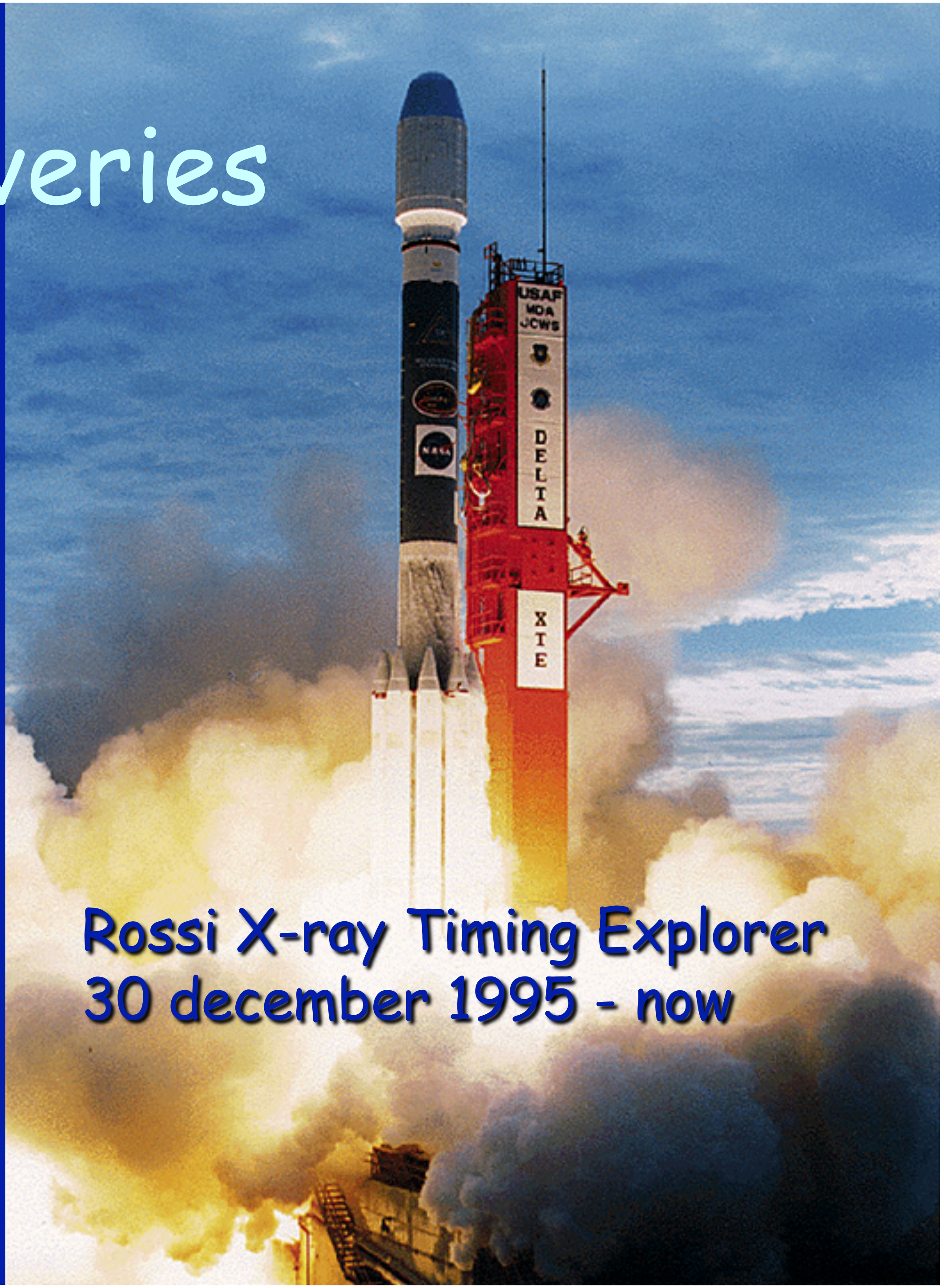
Focus on millisecond variability:

- Dynamical timescale close to NS
  - Strong field gravity
  - R/M
  - Differences w/ BH most obvious
- Spin up to millisecond periods -> radio pulsars

RXTE discoveries

- Kilohertz QPOs
- Burst oscillations
- Accreting millisecond pulsars

- NS hectohertz QPOs
- BH high-frequency QPOs



Rossi X-ray Timing Explorer
30 december 1995 - now

Predictions of millisecond variability

- Random luminosity variations expected 10^{-5}-10^{-2} s
  (Svartzman 1971)
- Millisecond wavetrains due to clumps near ISCO
  (Sunyaev 1973)
- Short-lived periodic signals at neutron star spin frequency during X-ray bursts
  (Livio & Bath 1982)
- Millisecond accreting pulsars predicted from recycling scenario …

  (Bisnovatiy-Kogan & Komberg 1974, Smarr & Blandford 1976, Backus et al. 1982, Alpar et al. 1982, Radhakrishnan & Srinivasan 1982, Fabian et al. 1983, Cheng 1984)

Millisecond frequencies

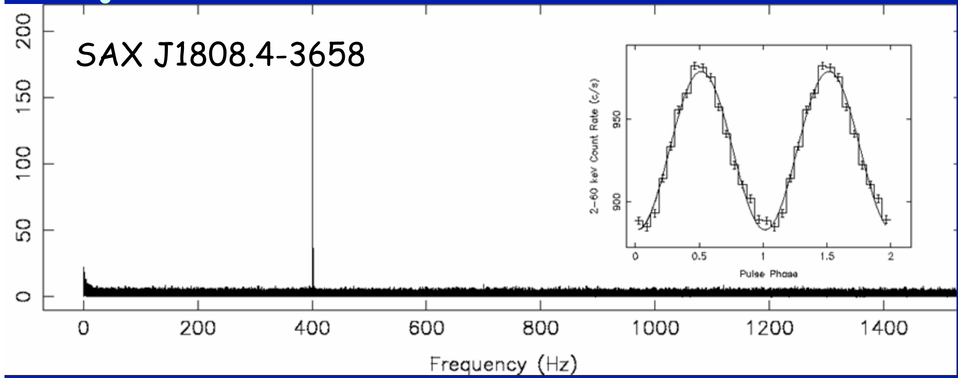
- Spin frequency ν_{spin}
- Pulse frequency ν_{pulse}
- Burst oscillation frequency ν_{burst}
- Twin kHz QPO fequencies $\nu_2 - \nu_2 = \Delta\nu$

} how linked?

pm.

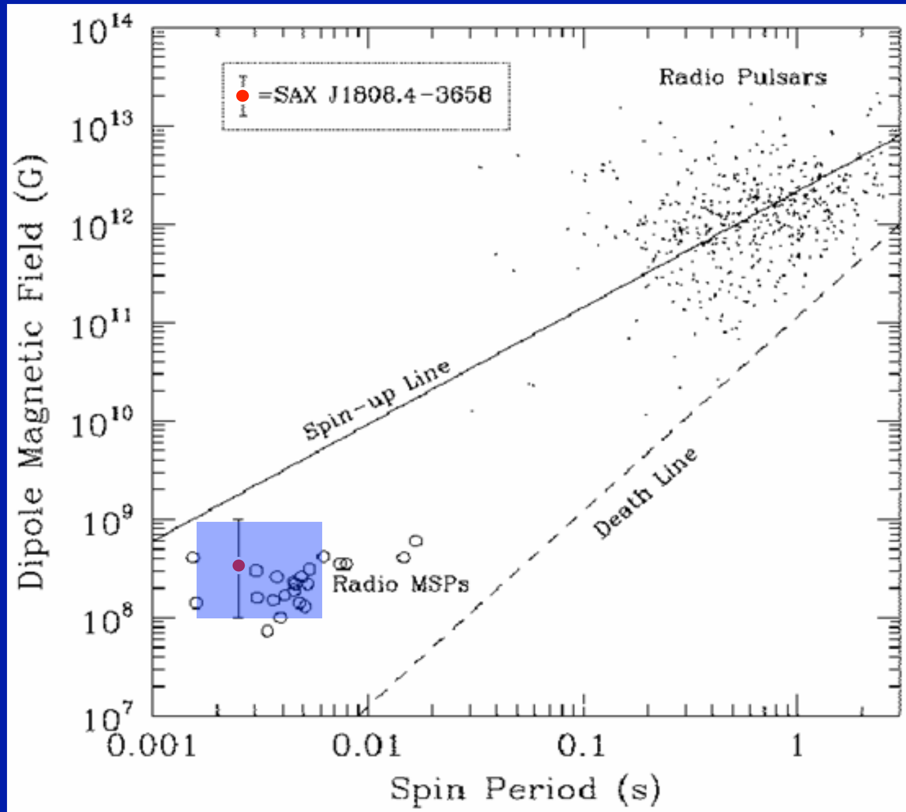
- Hectohertz QPOs
- Slower variability (LF QPO, HBO, NBO, FBO, BLN (break, hump, ℓow, ℓ)
- Link with BHs

Accreting millisecond X-ray pulsars (AMXPs) – 13 now known



Wijnands & van der Klis 1998

- AMXPs confirm that NS in LMXBs can be spun up to millisecond spins (1.67-5.5 ms): recycling in progress
- From accretion theory (B > threading strength; B < centrifugal inhibition; torques): B fields 10^{8-9} Gauss
- Systems can be the progenitors of the msec radio pulsar systems



Psaltis & Chakrabarty 1999

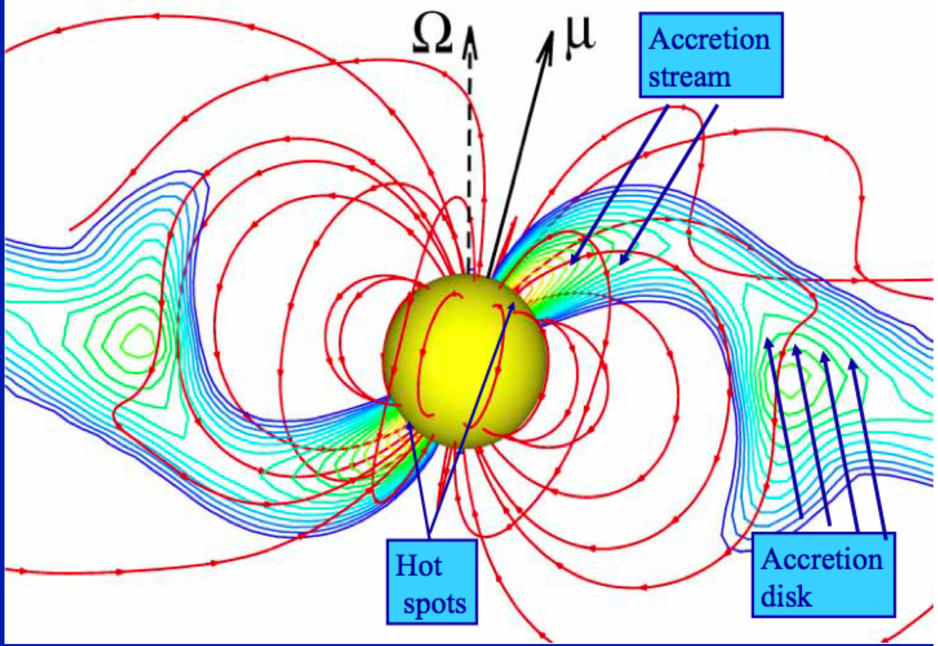
Ergma 1999, Nelson & Rappaport 2003
Rappaport et al. 2004, Lamb 2006
de Loye 2007

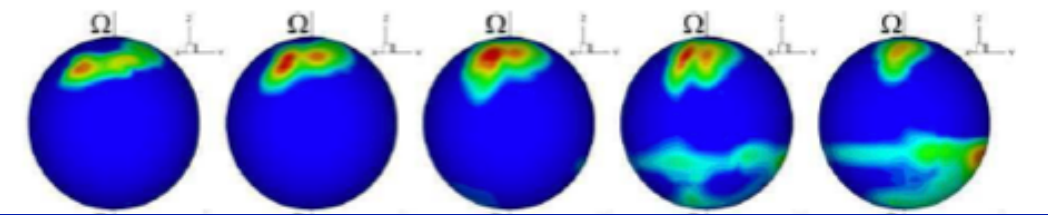
Pulse formation

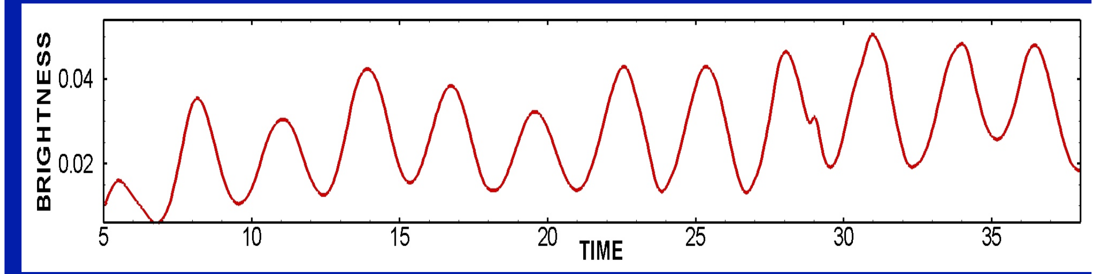
MHD calculations

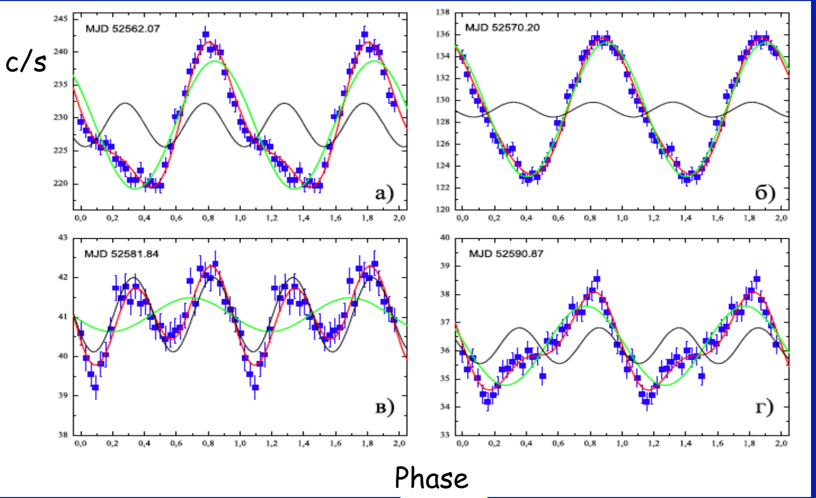
Romanova et al. 2004, Long et al. 2008

Disk, streams and hot spots vary dynamically with time, causing the light curve to deviate from strict periodicity









Poutanen et al. 2003, ...

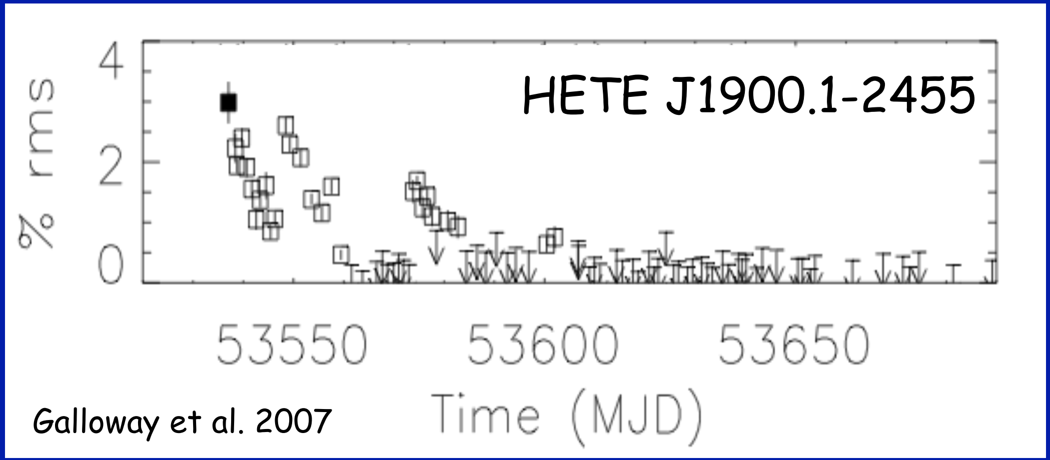
Pulsations and spin

- Pulse shapes tend to be dominated by fundamental, often ~sinusoidal: higher harmonic sometimes detected, but usually much weaker than fundamental
- Upper limits on subharmonics quite good (e.g. 0.014% in SAX J1808.4-3658)
- Consistent with popular model scenarios for pulse formation
- -> pulse frequency is believed to be always the spin frequency: $\nu_{pulse} = \nu_{spin}$

Intermittent & sporadic pulsars

- All AMXPs are transients, usually weak & short outbursts

- Intermittent pulsars:
  - Pulsations turn on and off several times during an outburst
  - HETE J1900.1-2455
  - SAX J1748.9-2021

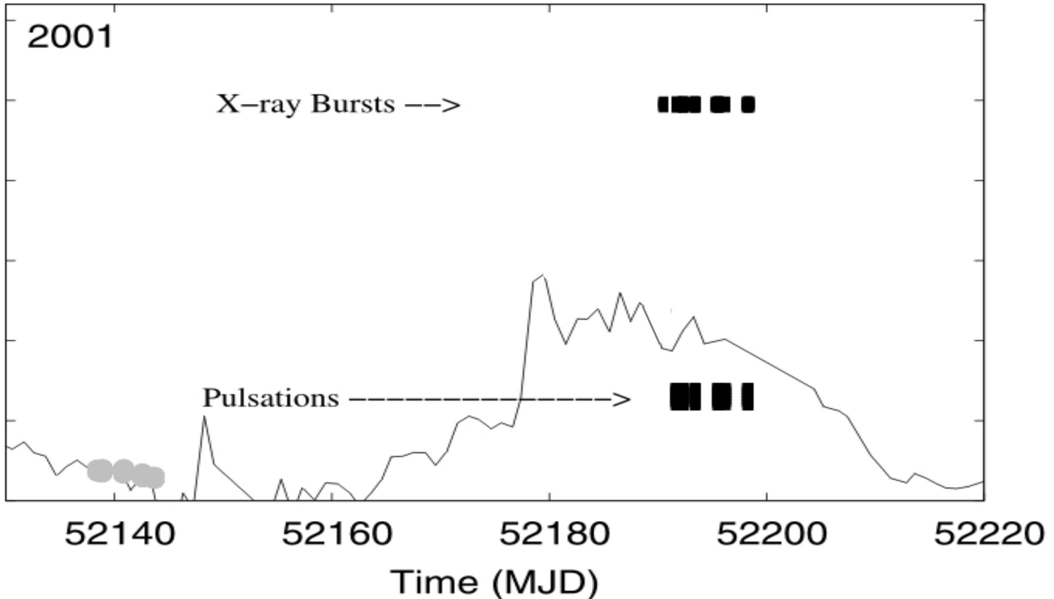


- Sporadic pulsars:
  - Extremely rare pulsation episodes of few 100 s
  - Aql X-1 (bright transient, 150 s of pulsations)
  - 4U 1636-53? (persistent, 800 s of pulsations in peak of superburst)

- Non-pulsars:
  - still the great majority of LMXB neutron stars …

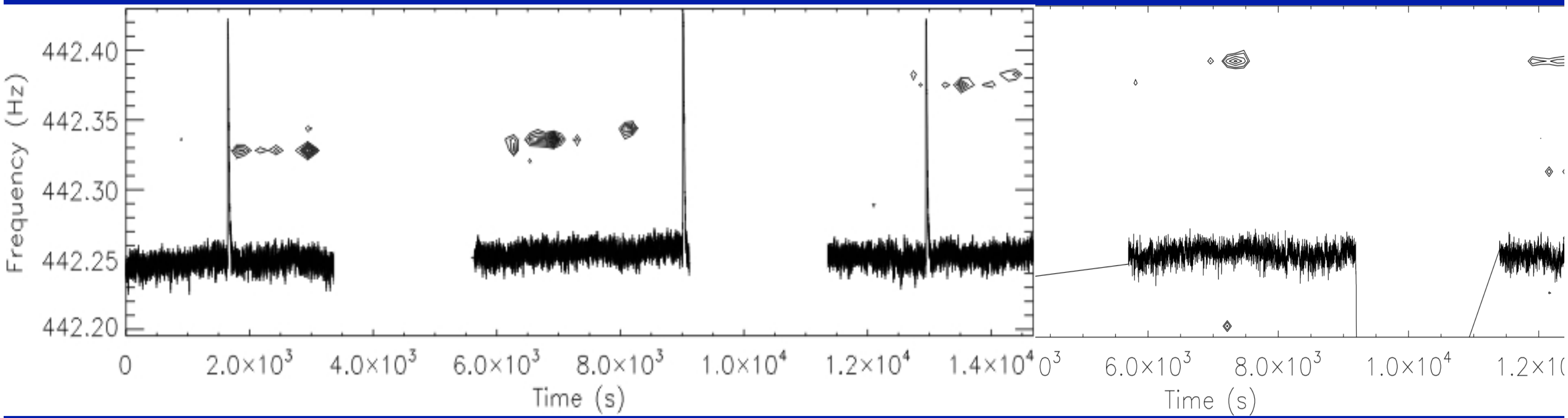
  Why ? Intermittency may provide clues

SAX J1748.9-2021

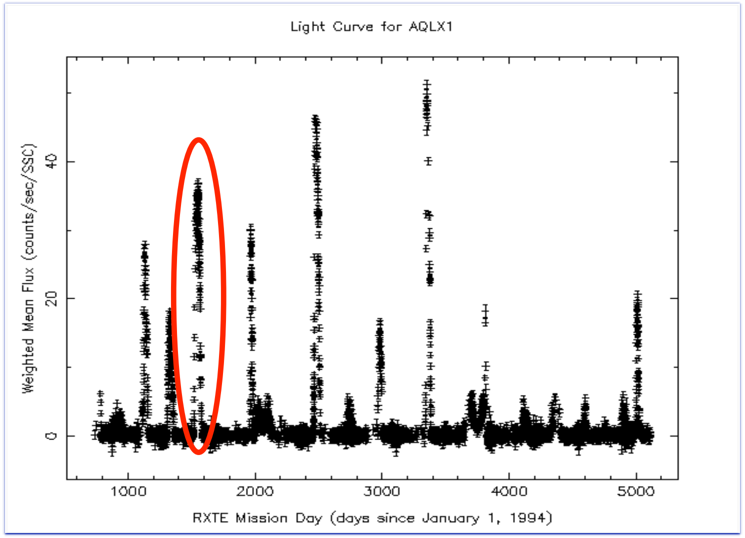


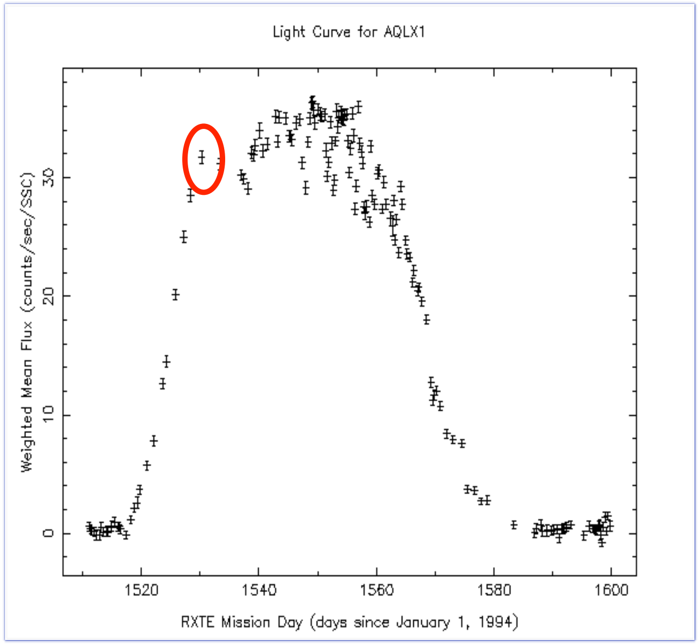
Occurrence of pulsations related to that of bursts, but not a one-to-one correspondence

Altamirano et al. 2008

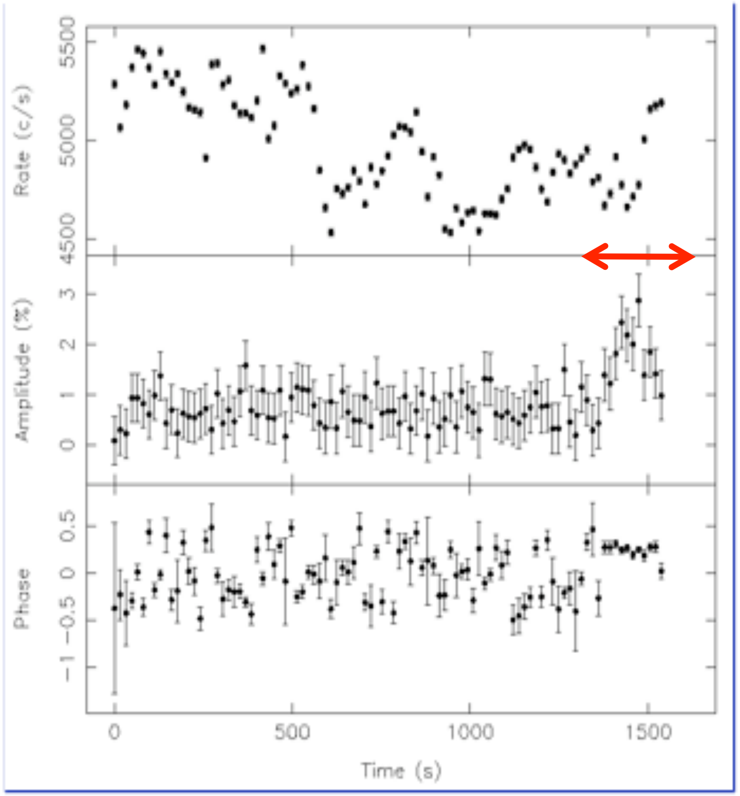


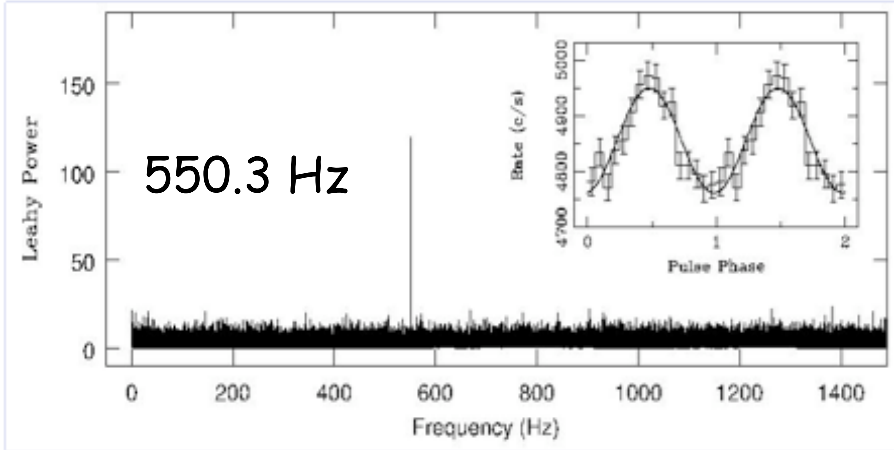
Aquila X-1



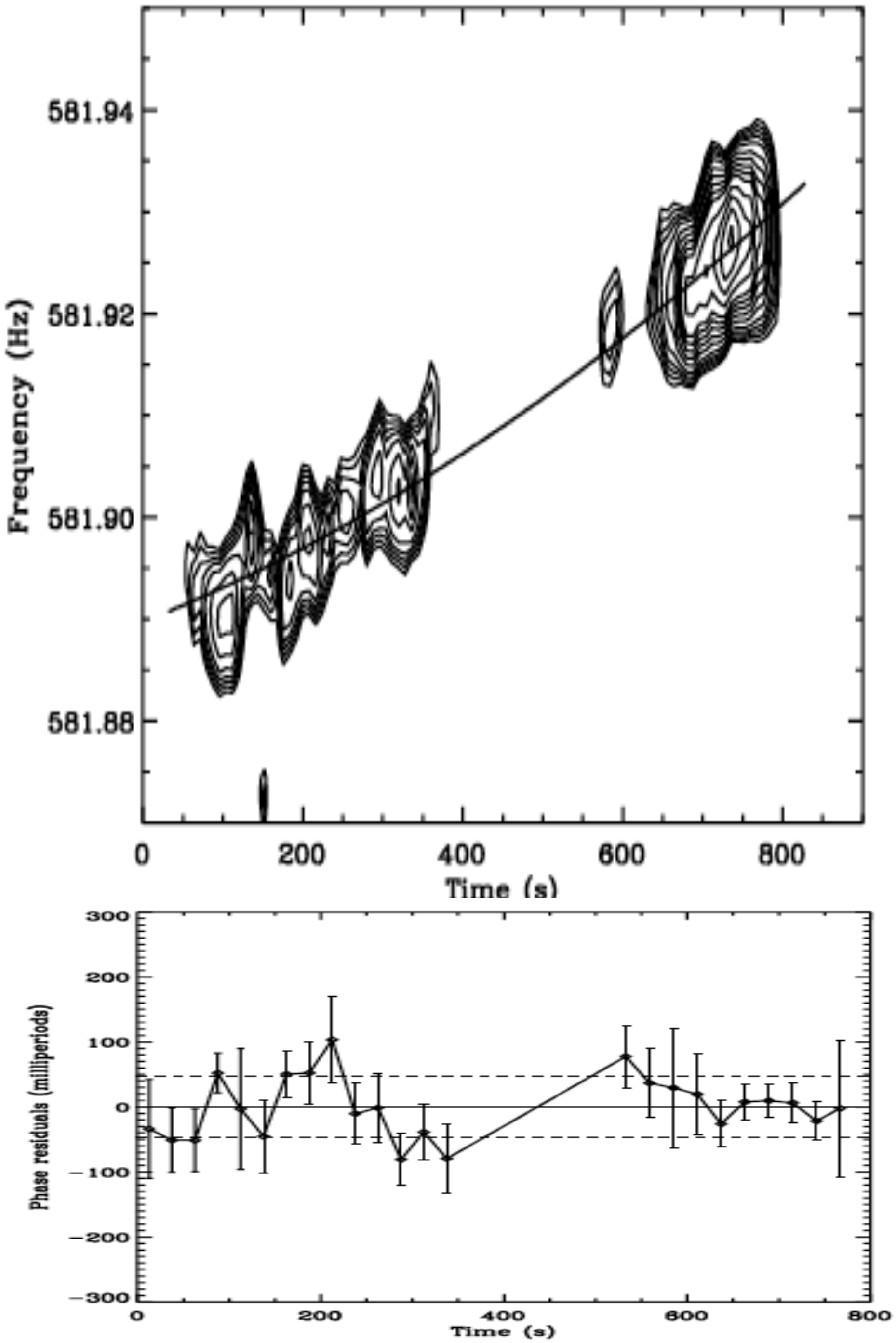


150 s of coherent pulsations in 1.3 Ms of data





Casella et al. 2008



4U 1636-53

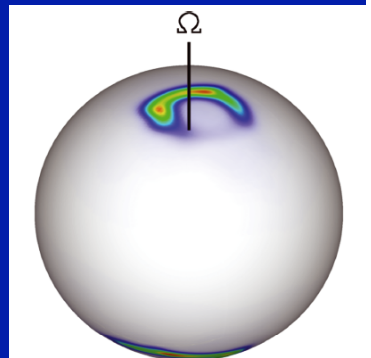
Coherent pulsations were detected during 800 s in the peak of a superburst. Frequency drift was consistent with orbital Doppler shifting.

Strohmayer et al. (2002)

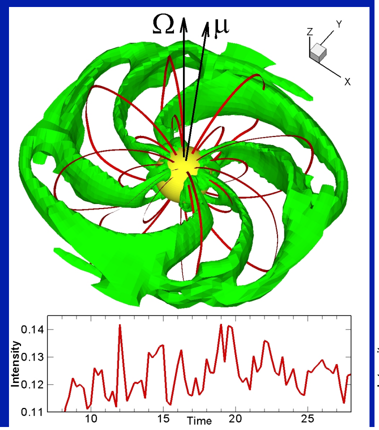
Causes for intermittency, sporadicity, non-pulsation

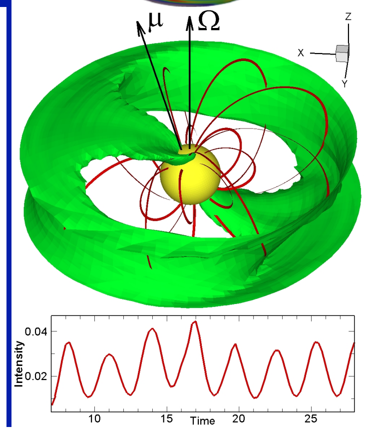
Possible clue: AMXPs have low maximum and time-averaged accretion rates, but not all low $\dot{M}$ sources pulse

- Intrinsically weaker B fields
  - field evolution (ohmic decay, vortex interactions, plate tectonics)
  - but origin radio msec pulsars; doesn't explain intermittency
- Scattering in Comptonizing medium
  - Brainerd & Lamb 1987, Kylafis & Phinney 1989, Titarchuk 2002
  - but Gogus 2007
- Field burying by accreted matter; Cumming 2001
  - Seemed to fit with HETE J1900, bursts might 'unbury' field
  - But same model does not work for 1748, Aql X-1
- Gravitational light bending
  - Wood et al. 1988, Meszaros, Özel 2008

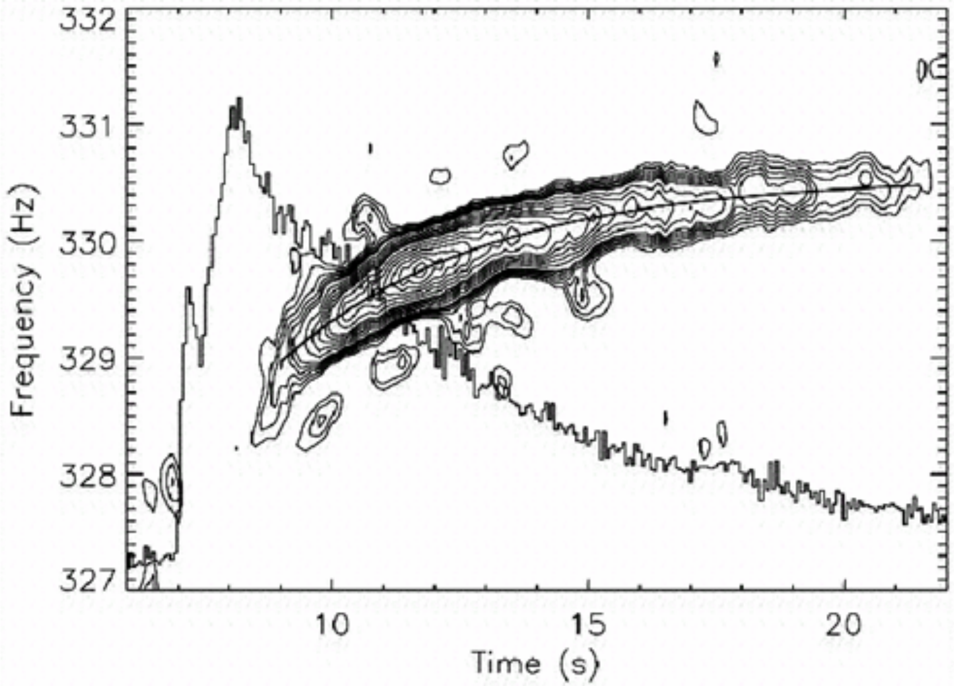


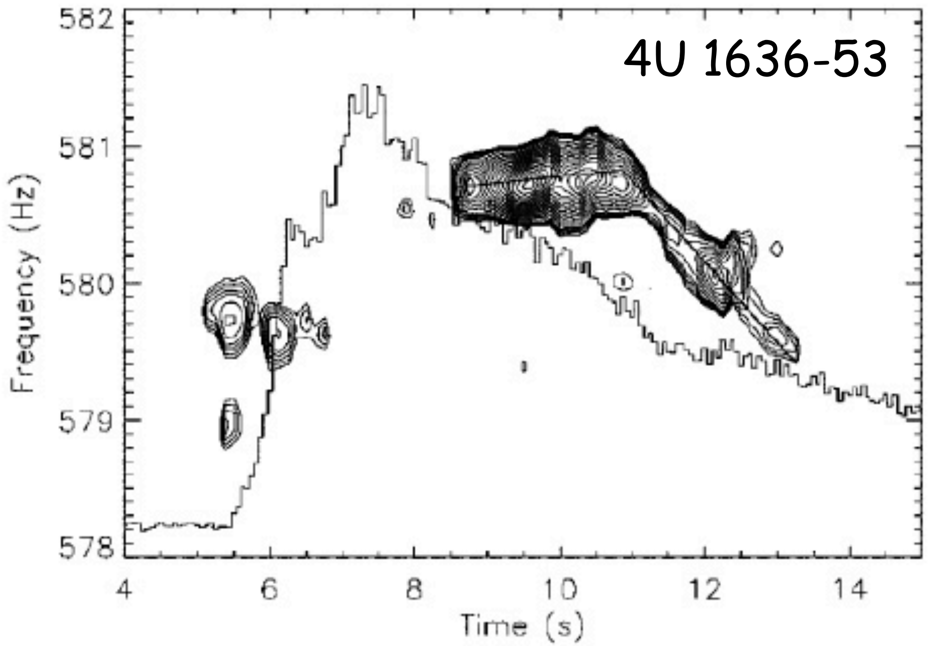
- Unstable MHD flow
  - Romanova et al. 2008, Bachetti et al. 2010
- Near-aligned magnetic and spin axis
  - with wandering hotspots can also explain large pulse shape and phase fluctuations, & QPOs
  - Lamb, Boutloukos et al. 2009, Bachetti et al. 2010



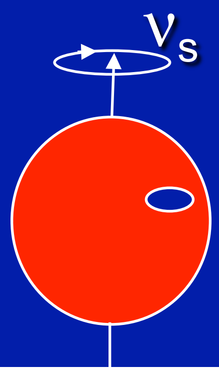


X-ray burst oscillations





Strohmayer et al.

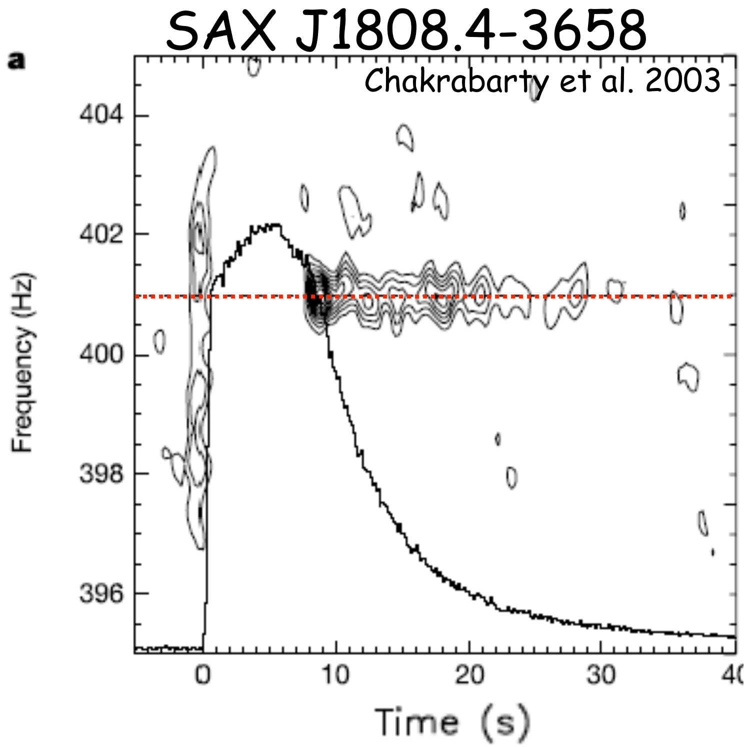


- Type 1 (thermonuclear) bursts
- Anisotropic emission, star spins
- Frequency drifts: J conservation
- Amplitudes can constrain mass, radius

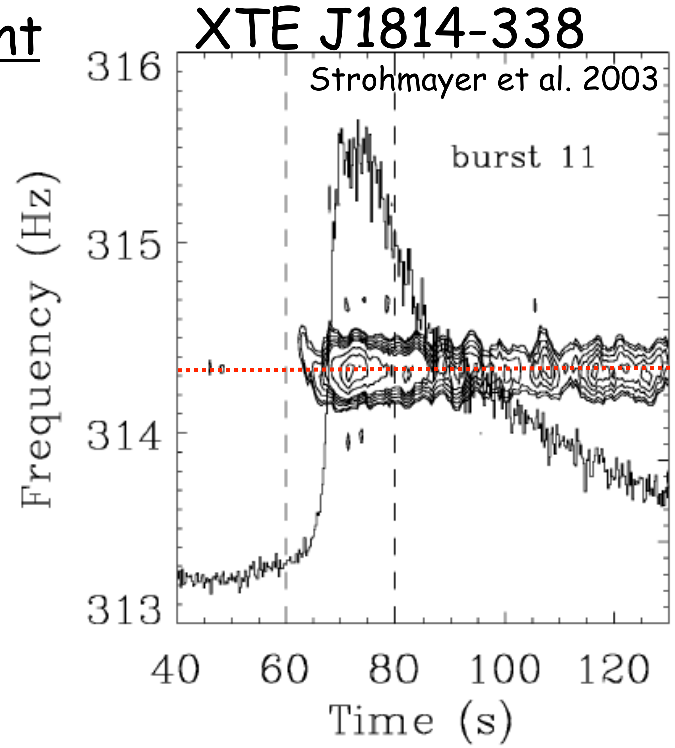
Burst oscillations and spin

- Confirmed burst oscillations reported from 5 AMXPs
  - 3 have stable frequencies very close to spin
  - 2 have drifting frequencies within few Hz of spin

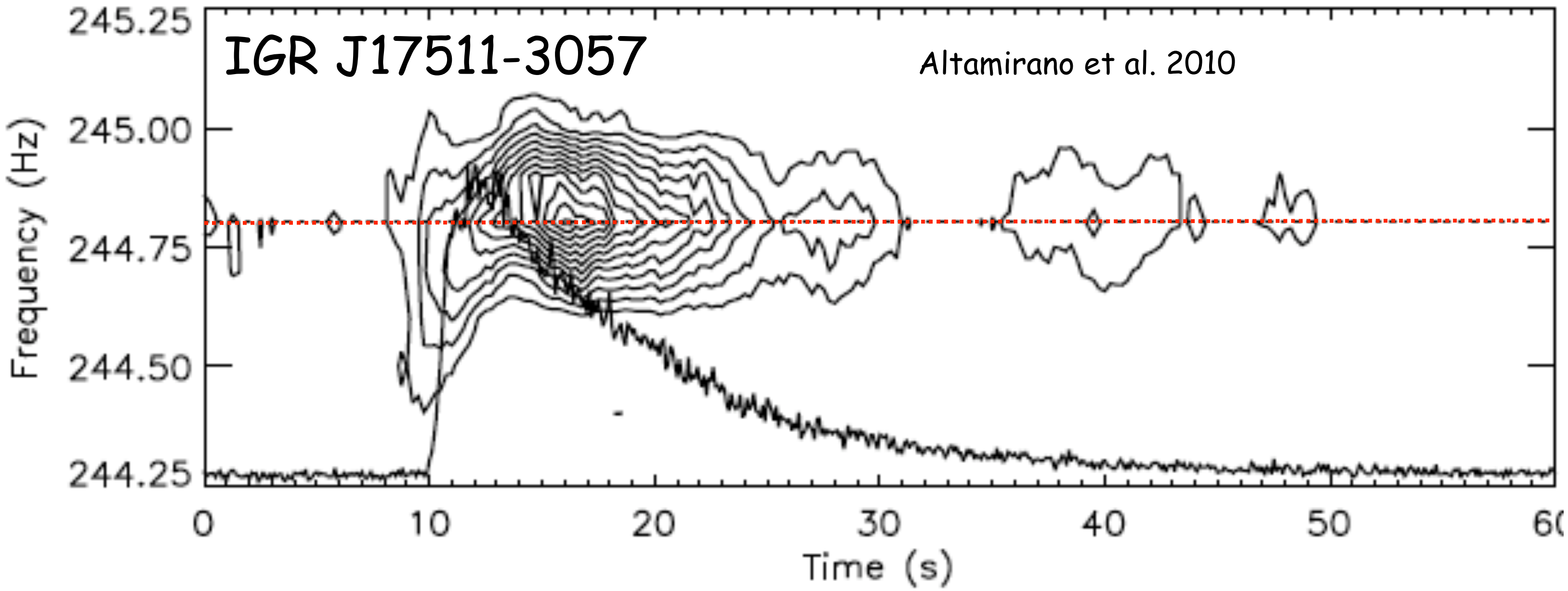
-> it is concluded that always $\nu_{burst} \approx \nu_{spin}$



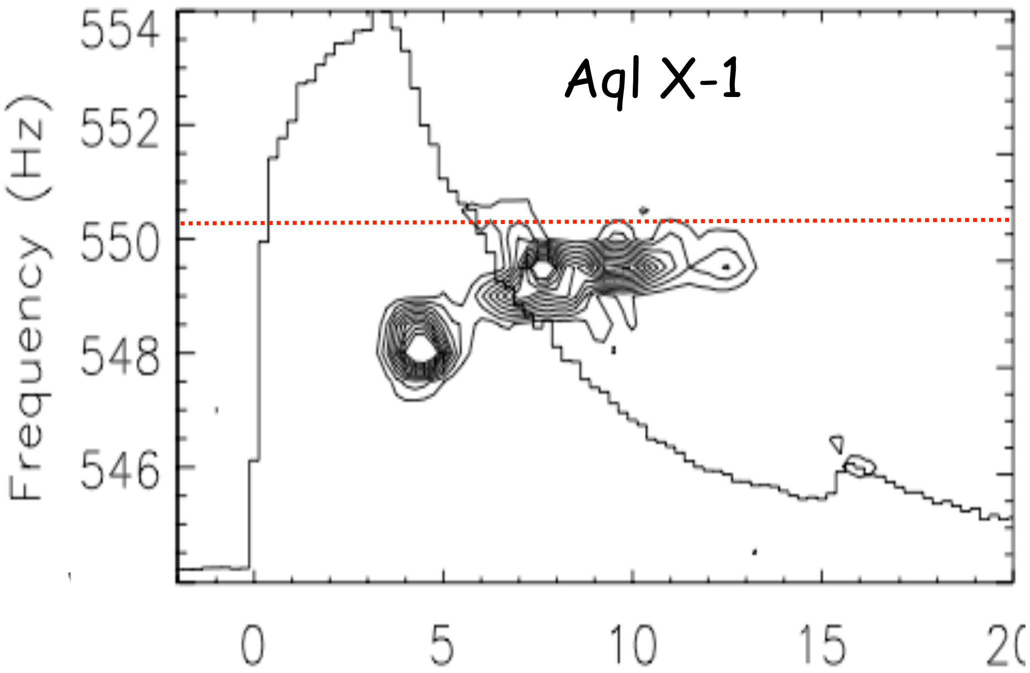
Persistent pulsars

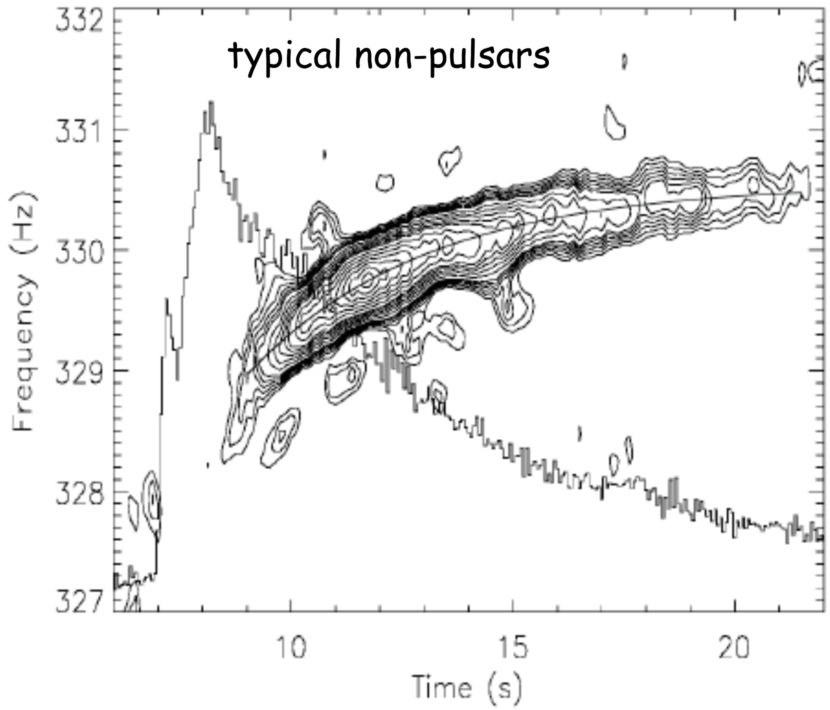


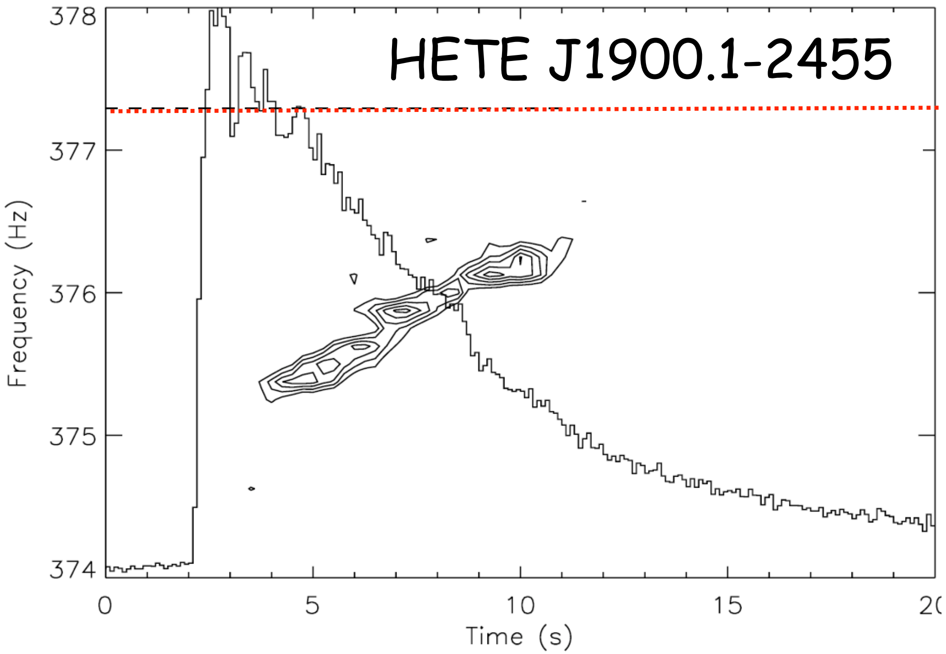
ν_{pulse}



Intermittent pulsars (2)







Confirmed burst oscillations reported from 10 non-pulsars

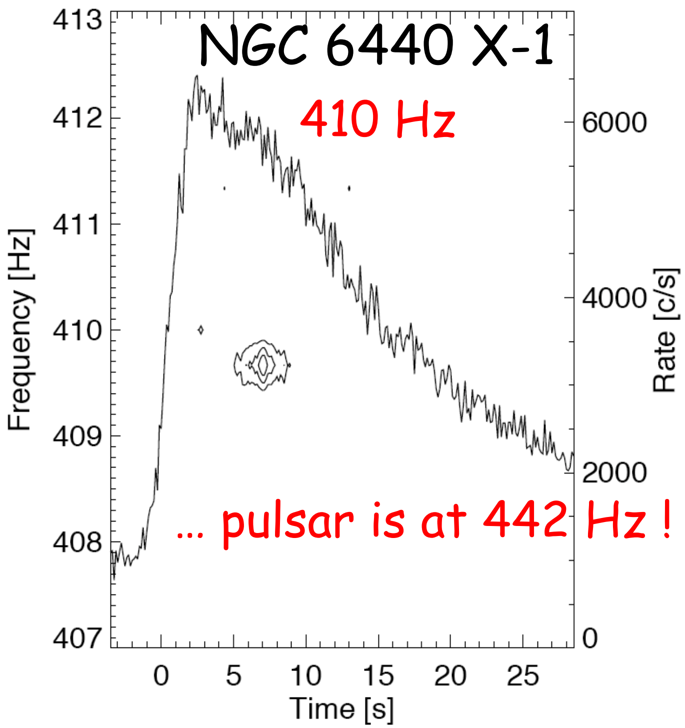
-> their ν_{spin} assumed to be ~ ν_{burst}

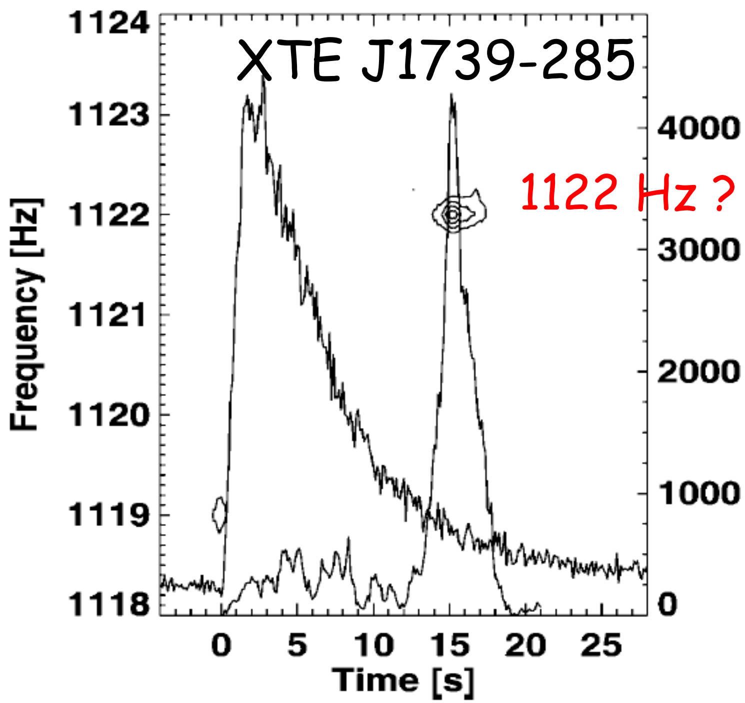
Right now this is true:

- Persistent pulsars show fixed-frequency burst oscillations
- Intermittent, sporadic and non-pulsars show drifting burst oscillations

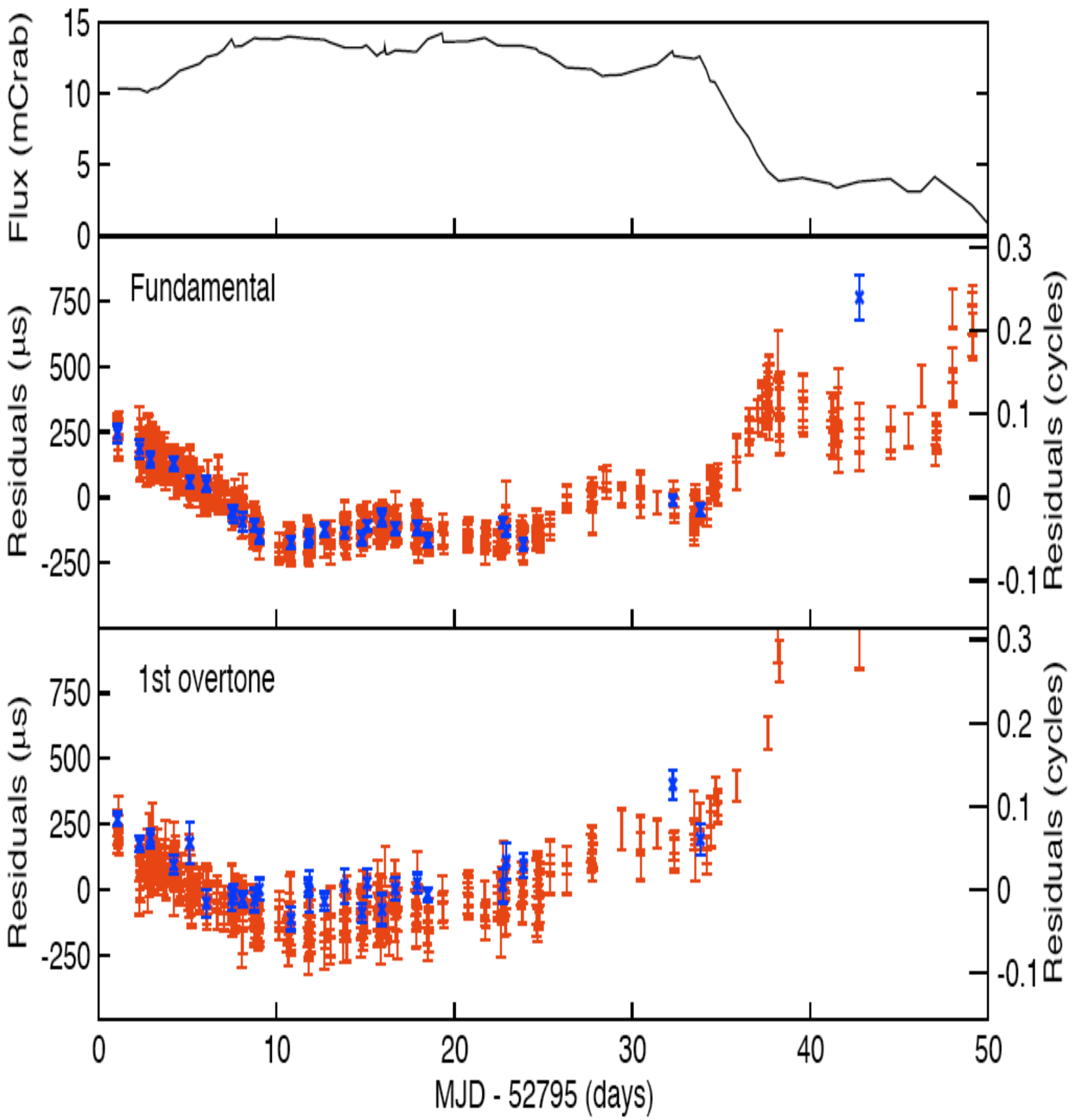
-> It looks like whatever 'grabs' the thermonuclear hot spots (B) makes the pulsar persistent

- Unconfirmed burst oscillations reported from 7 sources (1 AMXP)
  - includes one case where ν_{burst}= 410 Hz was reported, then ν_{spin} = 442 Hz was found





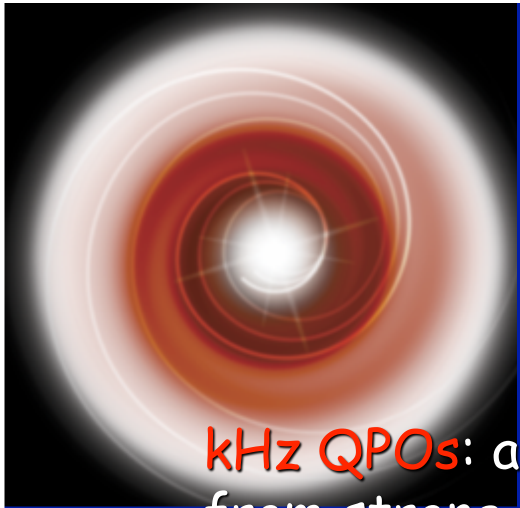
XTE J1814-338



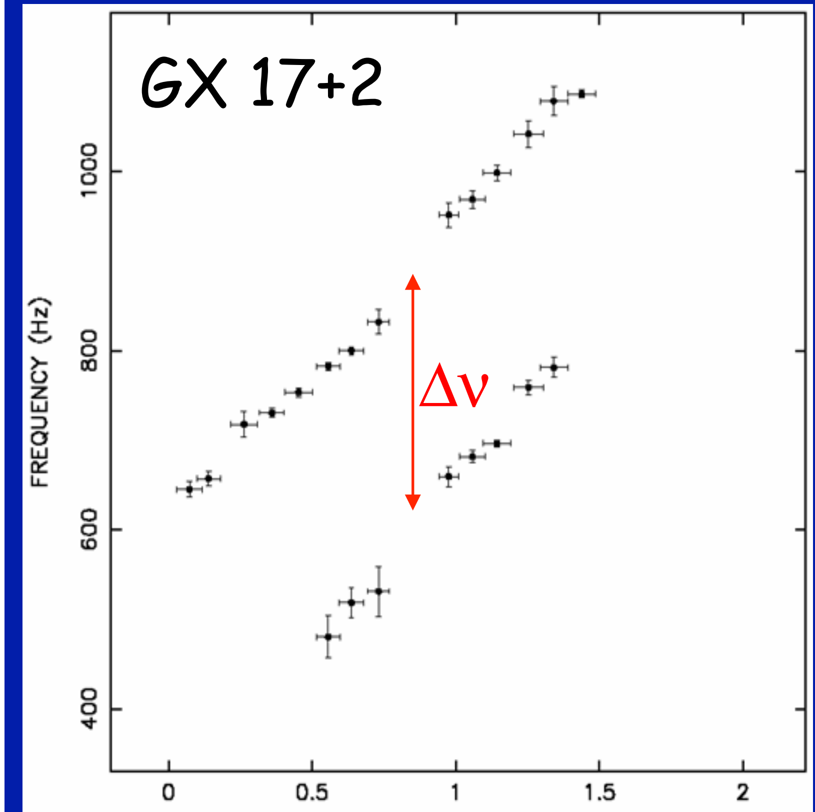
- Burst oscillation phase closely tracks pulse phase jitter
- Wandering accretion hot spot determines where nuclear energy emerges during burst oscillation!
- Eliminates many other scenarios for phase jitter

Watts et al. 2008

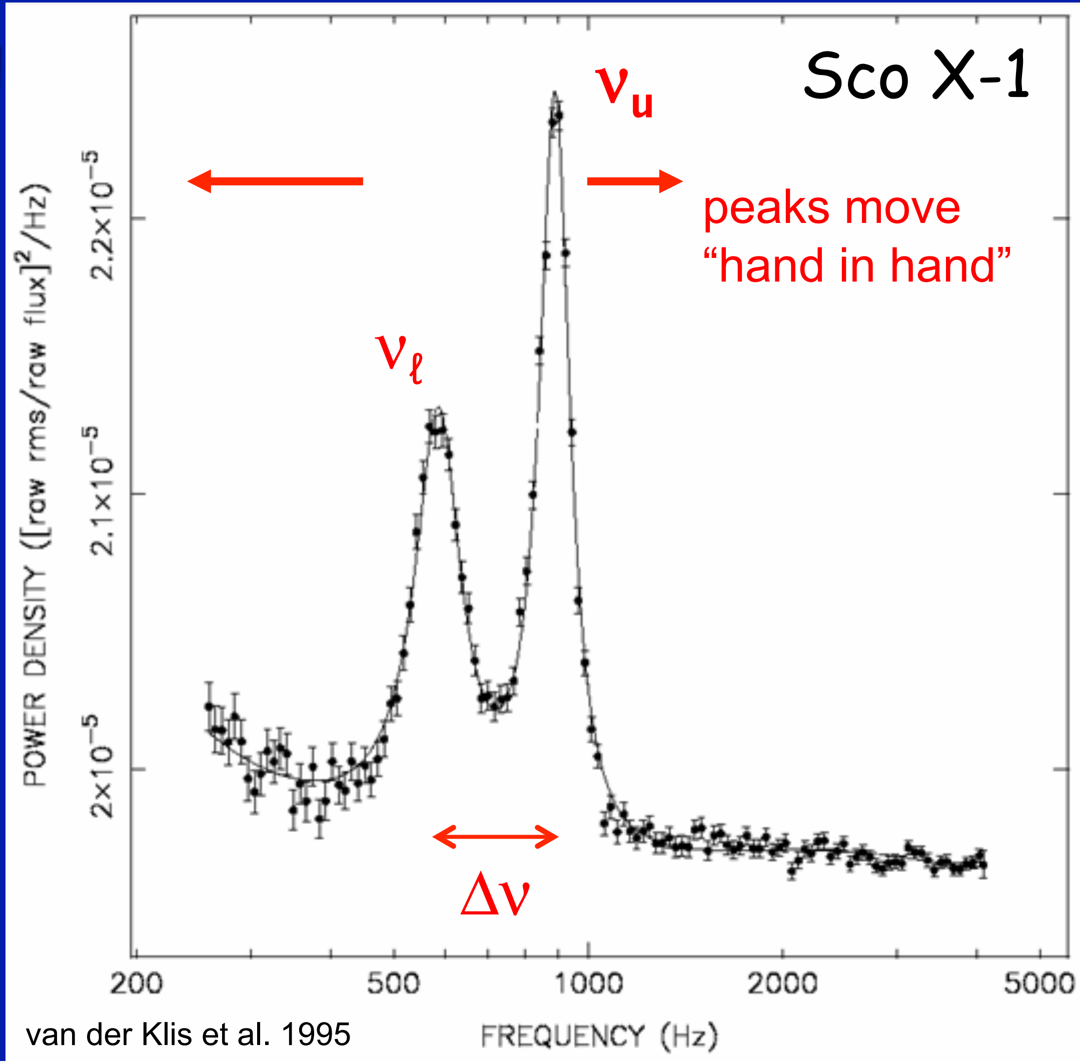
Kilohertz quasi-periodic oscillations



kHz QPOs: a direct signal from strong field gravity

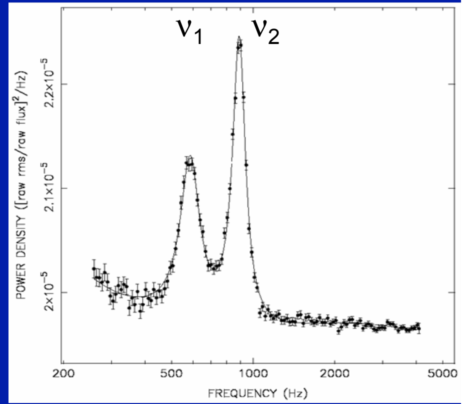


Homan et al. 2002



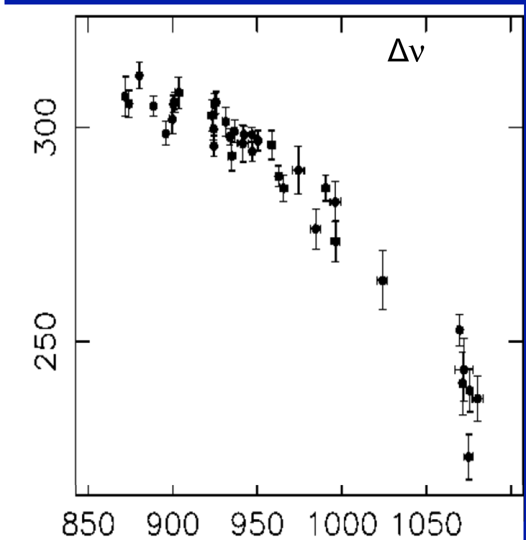
van der Klis et al. 1995

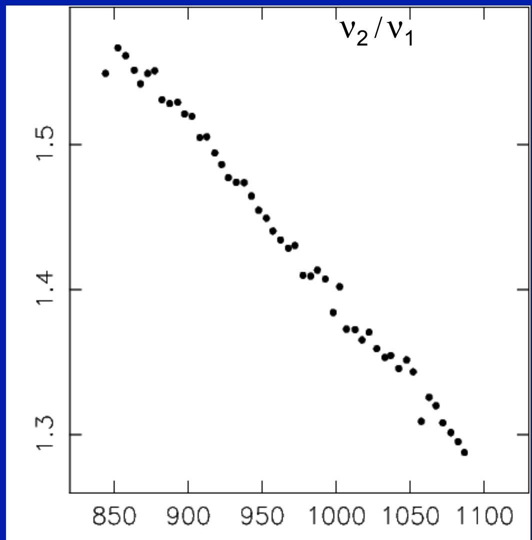
Twin frequency relation



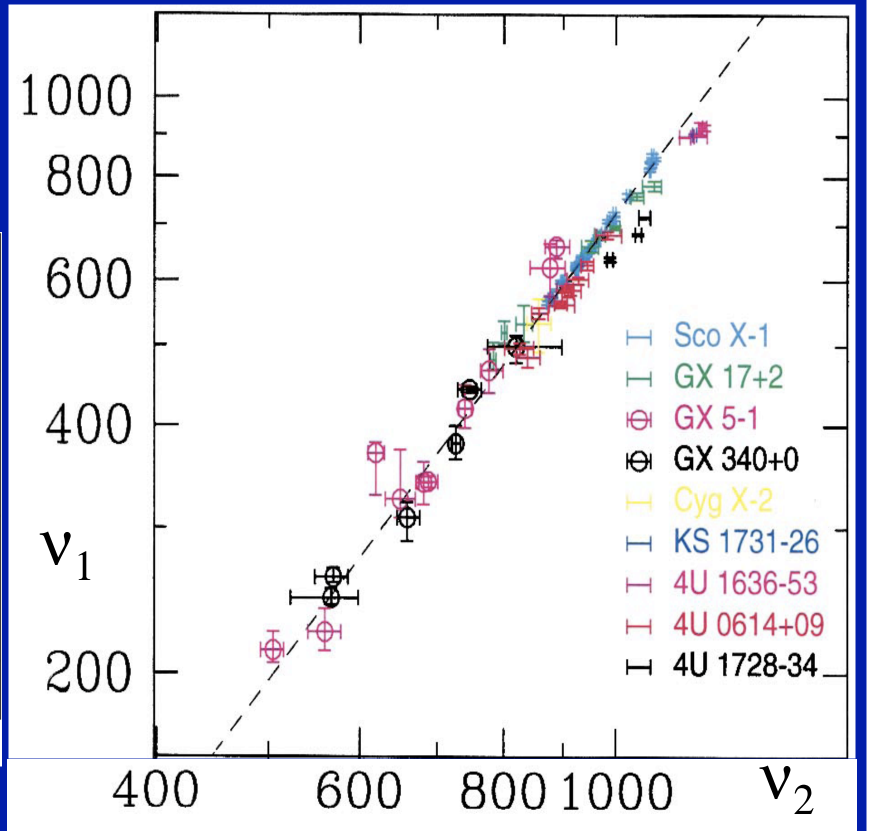
Two strong kHz peaks, moving together in always ~same ν_1 vs. ν_2 relation

- difference $\Delta\nu$ not constant
- ratio ν_2 / ν_1 not constant





van der Klis et al. 1997

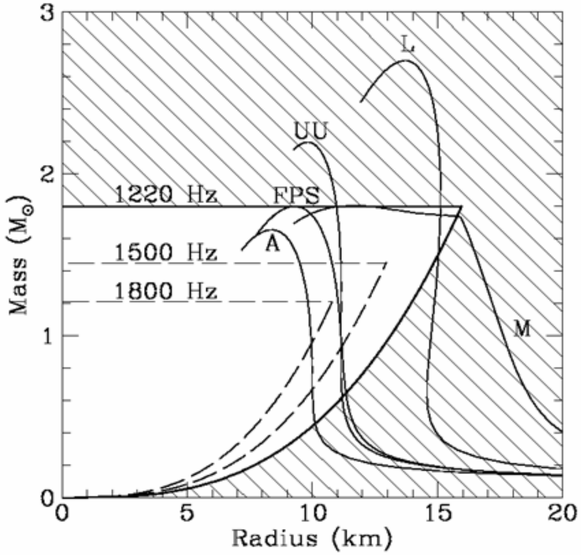


Psaltis et al. 1998

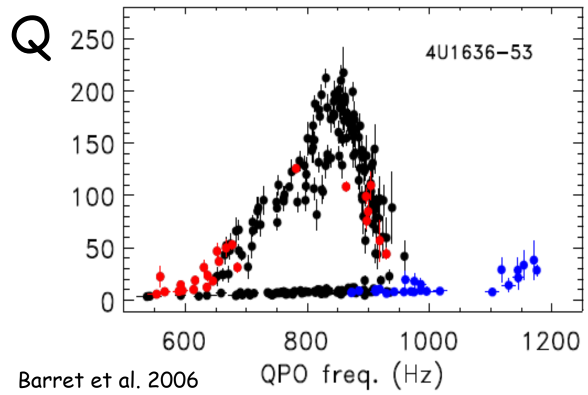
Disk orbital frequency interpretation

- Upper kHz QPO frequency interpreted in most models as GR orbital frequency at preferred radius in the disk (e.g., inner edge)
- If true, immediately constrain neutron star parameters

Miller et al. 1998

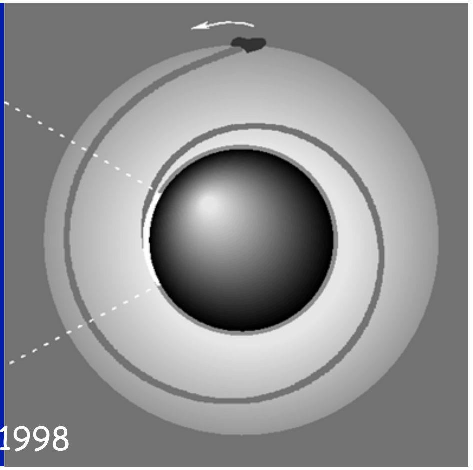


- QPOs vary in frequency, but always ≲1.3 kHz (while observations sensitive to >2kHz)
- An ISCO frequency of 1.3 kHz corresponds to a neutron star mass of ~2 $M_\odot$



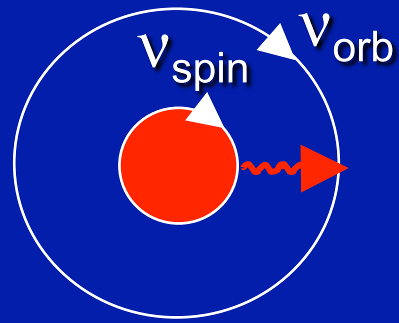
Barret et al. 2006

- Sonic point spiral flow scenario provides a modulation mechanism.
- Somewhat like 'tongues' in Romanova et al. MHD simulations.

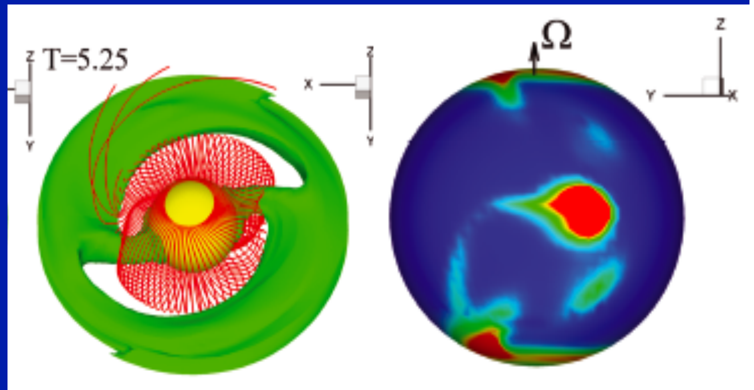


Miller et al. 1998

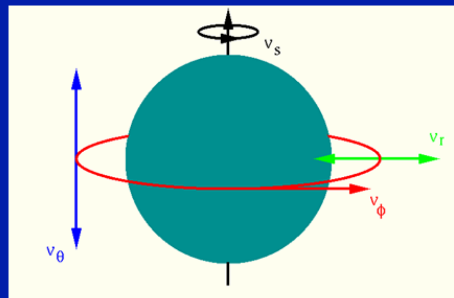
kHz QPO models



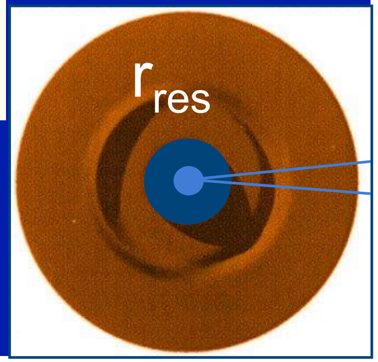
- Beat frequency model
  - Spin and orbit can interact to produce beat (difference) frequency $\nu_{beat} = \nu_{orb} - \nu_{spin}$



- RMHD disk & hot spot frequencies
  - Various radiation-MHD disk modes and surface processes may produce QPOs (talk this session)



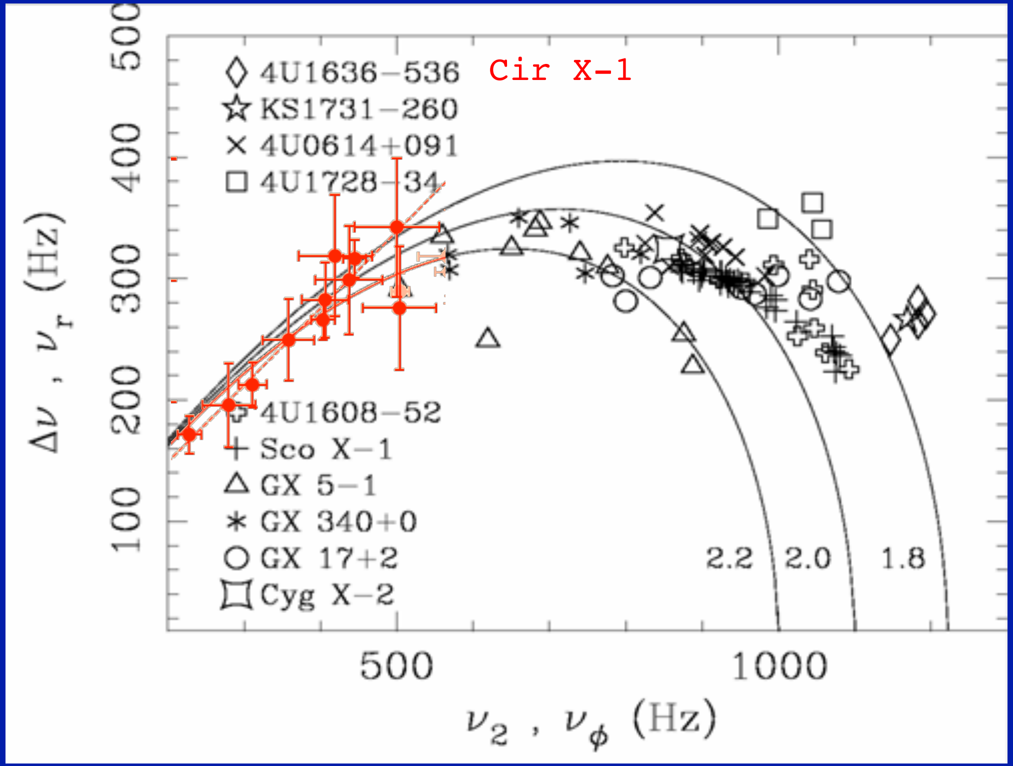
- Relativistic precession
  - Relativistic epicyclic motion provides additional frequencies (radial, vertical, periastron precession, Lense-Thirring)



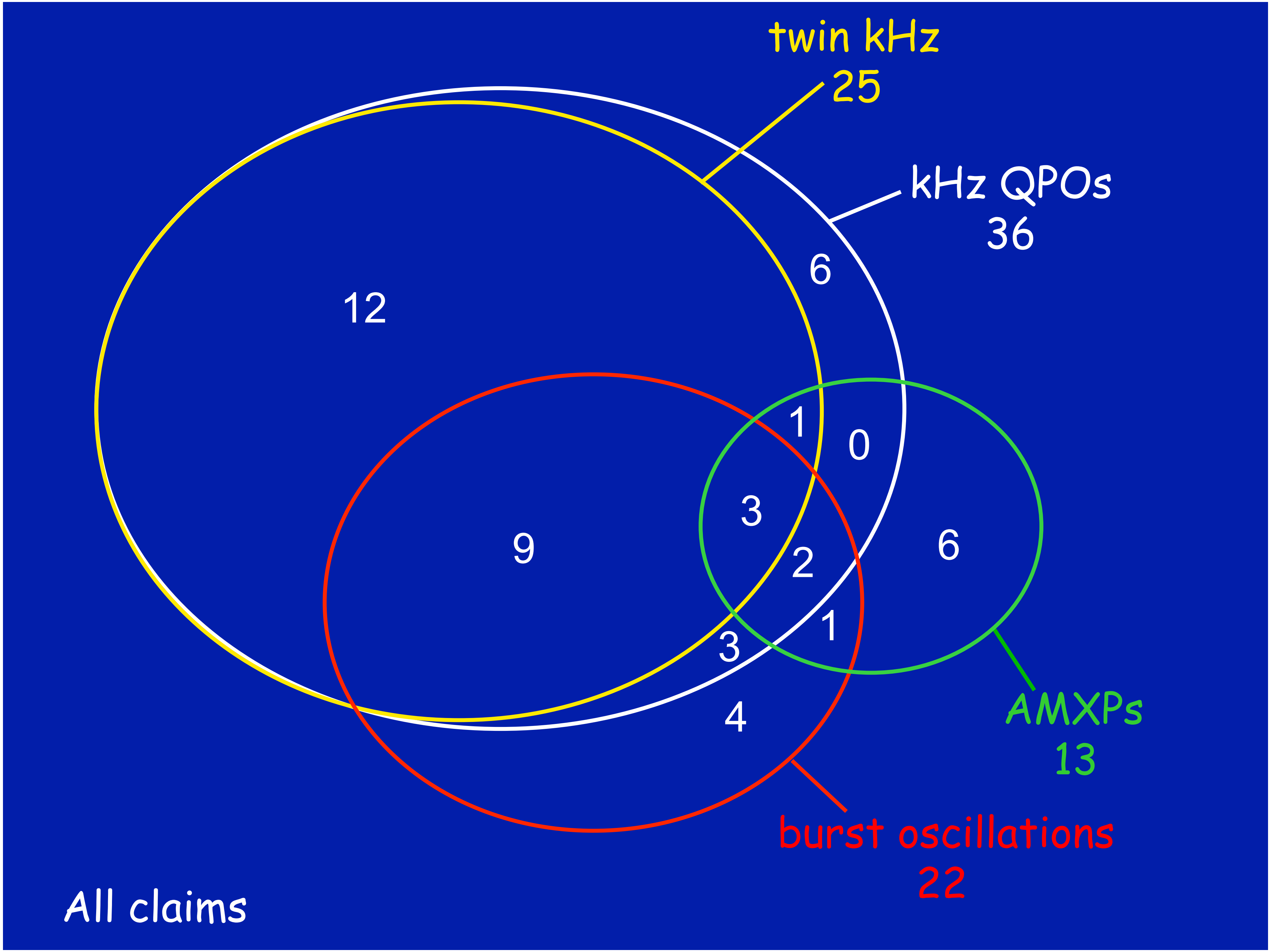
- Relativistic/spin resonances
  - At preferred radii in the disk, GR orbital and epicyclic frequencies, and spin resonate.

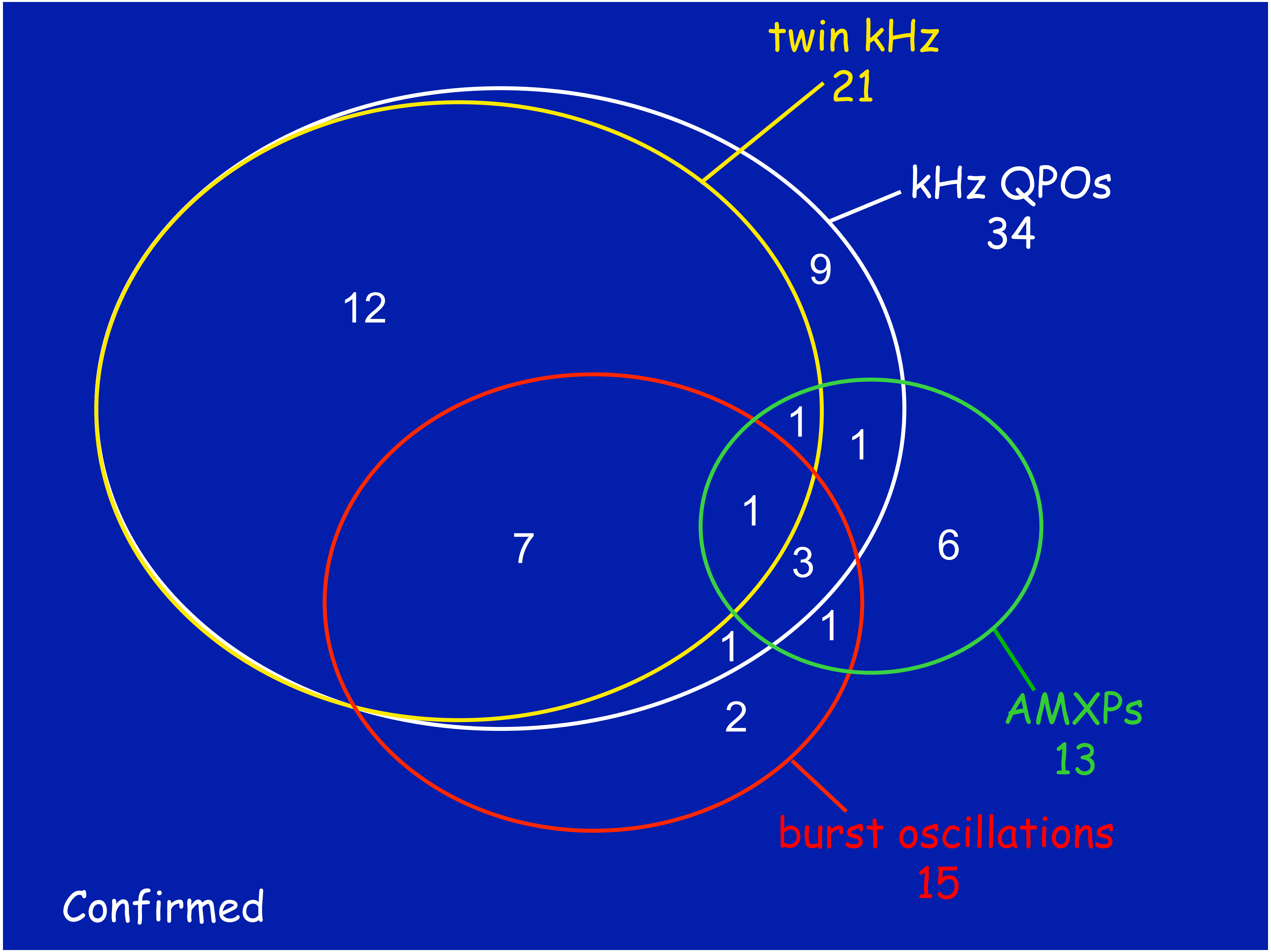
Relativistic precession model

Stella and Vietri 1998, 1999



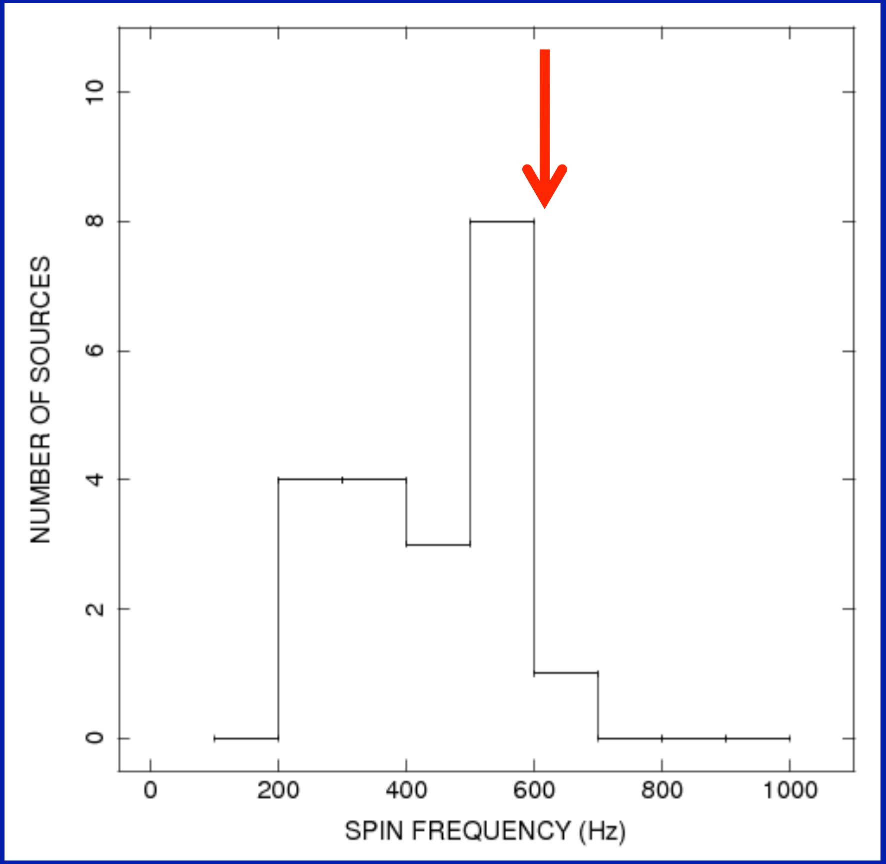
Boutloukos et al. 2006


twin kHz
25
kHz QPOs
36
6
12
1
0
3
9
2
6
1
3
4
AMXPs
13
burst oscillations
22
All claims


twin kHz
21
kHz QPOs
34
12
9
7
1
1
1
3
6
1
1
2
AMXPs
13
burst oscillations
15
Confirmed

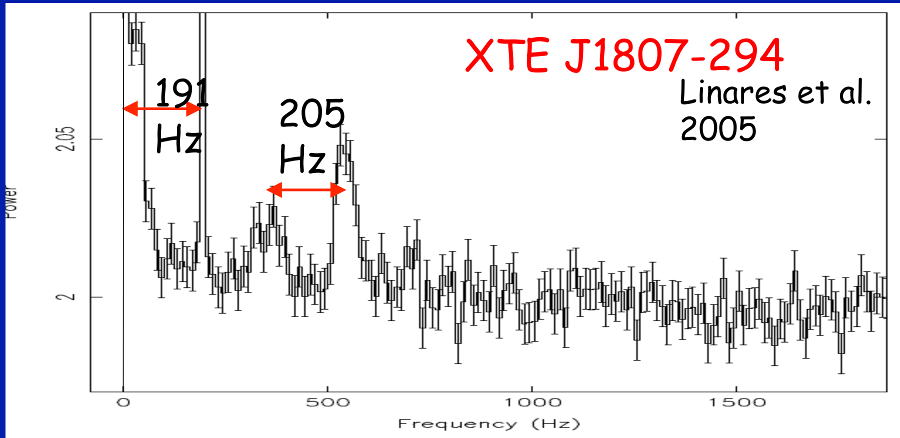
Confirmed millisecond spins

Source	Freq.
Swift J1756.9-2508	182.1
XTE J0929-314	185.1
XTE J1807-294	190.6
NGC 6440 X-2	205.9
IGR J17511-3057	244.8
4U 1915-05	~272
IGR J17191-2821	~294
XTE J1814-338	314.4
4U 1702-43	~330
4U 1728-34	~364
HETE J1900.1-2455	377.3
SAX J1808.4-3658	401.0
XTE J1751-305	435.3
	...

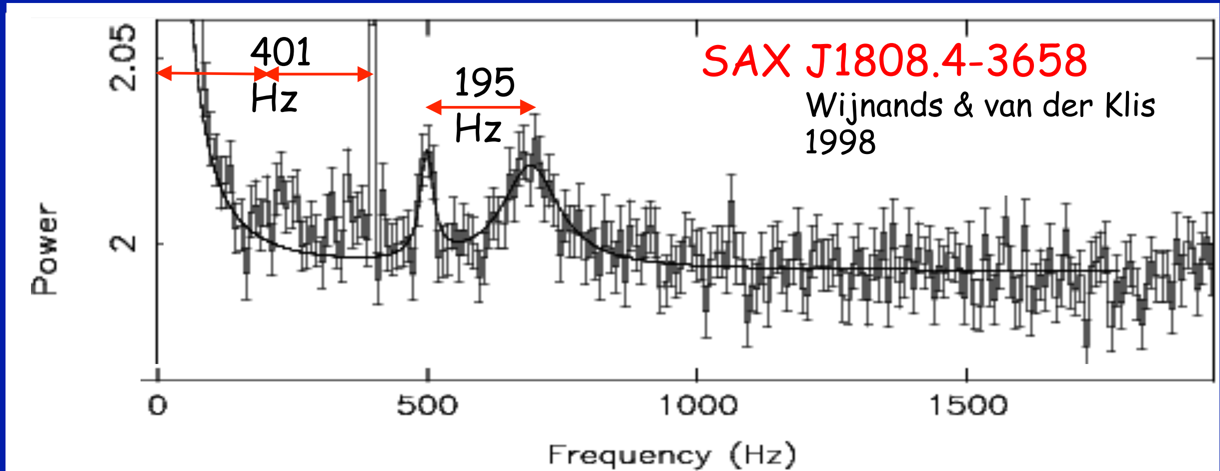


kHz QPOs and spin

- 4 AMXPs have twin kHz:
  - 2 confirmed:
  - SAX J1808.4-3658
  - XTE J1807-294
  - (+ Aql X-1, IGR J17511-3057)



$\Delta\nu \approx$ the spin



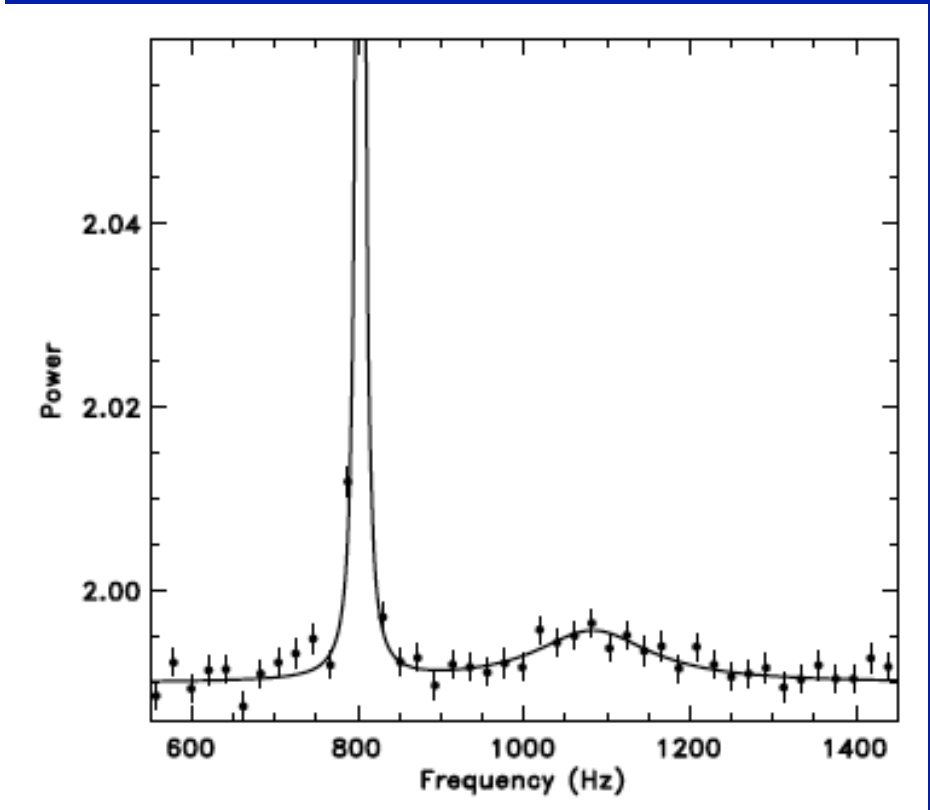
$\Delta\nu \approx$ half the spin.

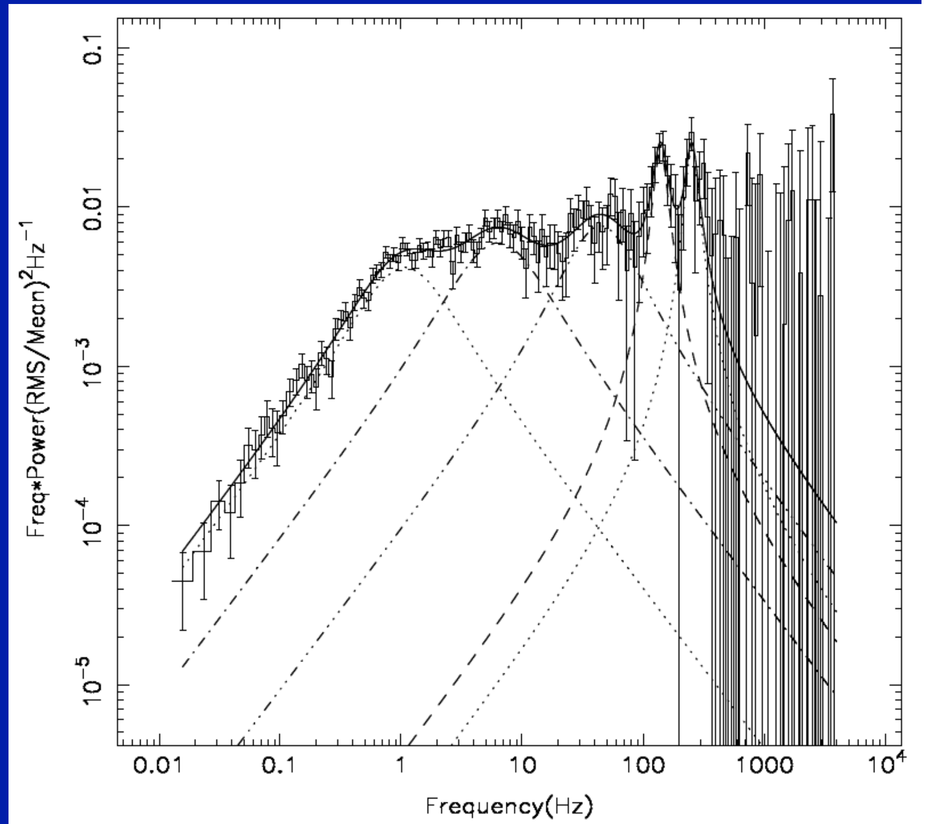
So, direct spin-orbit BFM does not work.

Twin kHz peaks seen only once, at 499 ± 4 and 694 ± 4 Hz.

Then also true: $3\ \nu_1 - 2\ \nu_{spin} = 695 \pm 12 \approx 694 \pm 4 = \nu_2$

Aql X-1 and IGR J17511-3057

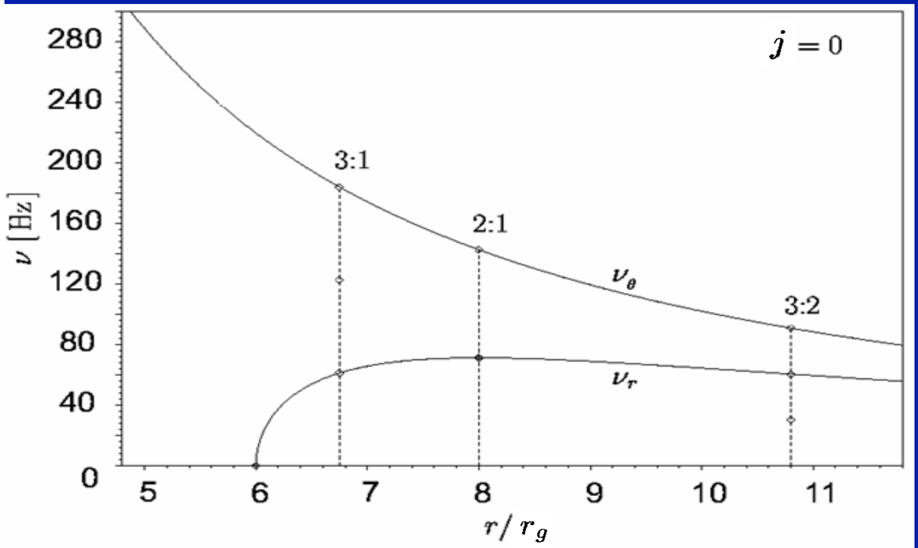


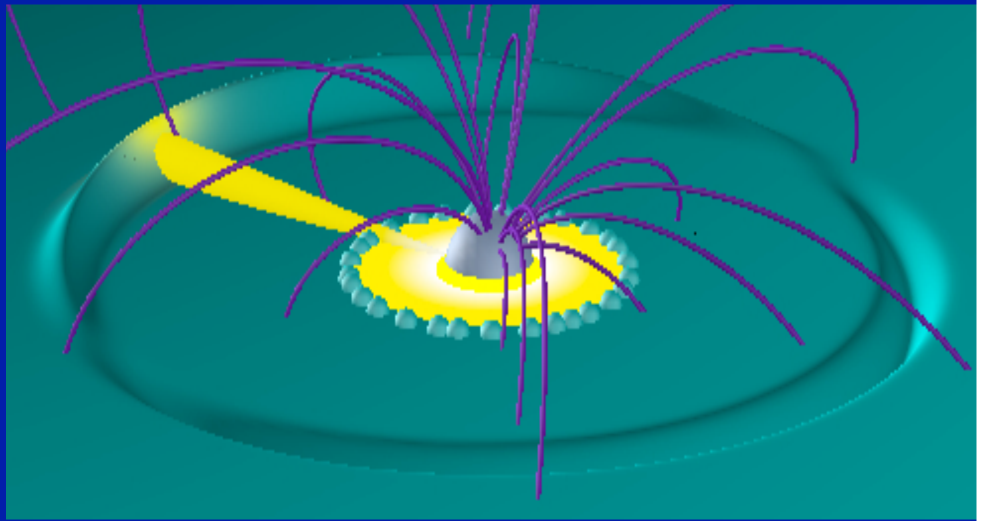


Barret et al. 2008

Kalamkar et al. 2010

Resonance models





'At particular fixed radii in the disk resonances can occur between relativistic orbital and epicyclic frequencies'

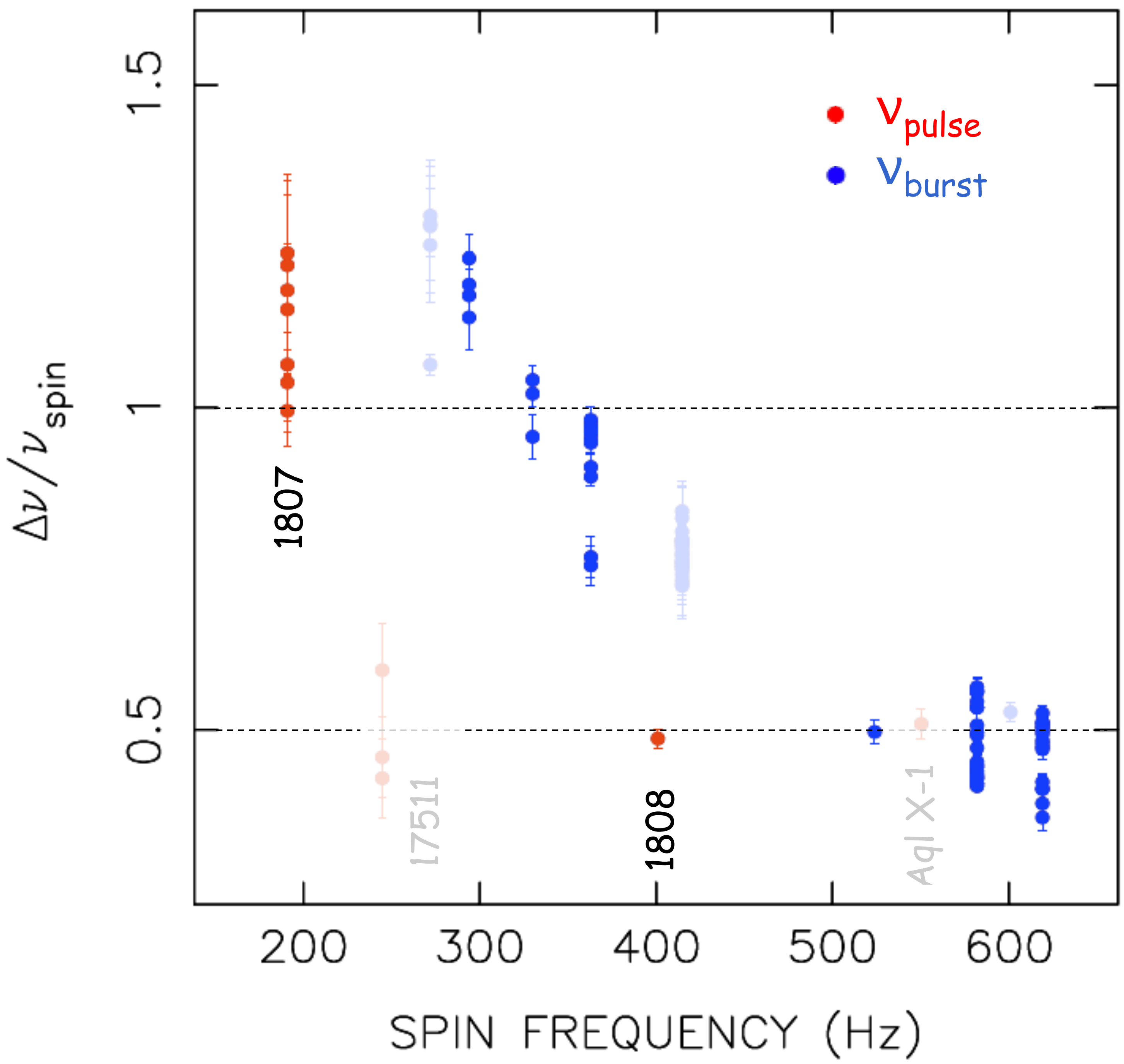
$\nu_1 / \nu_2 = n / m$, e.g., $= 2/3$

Kluzniak and Abramowicz 2001

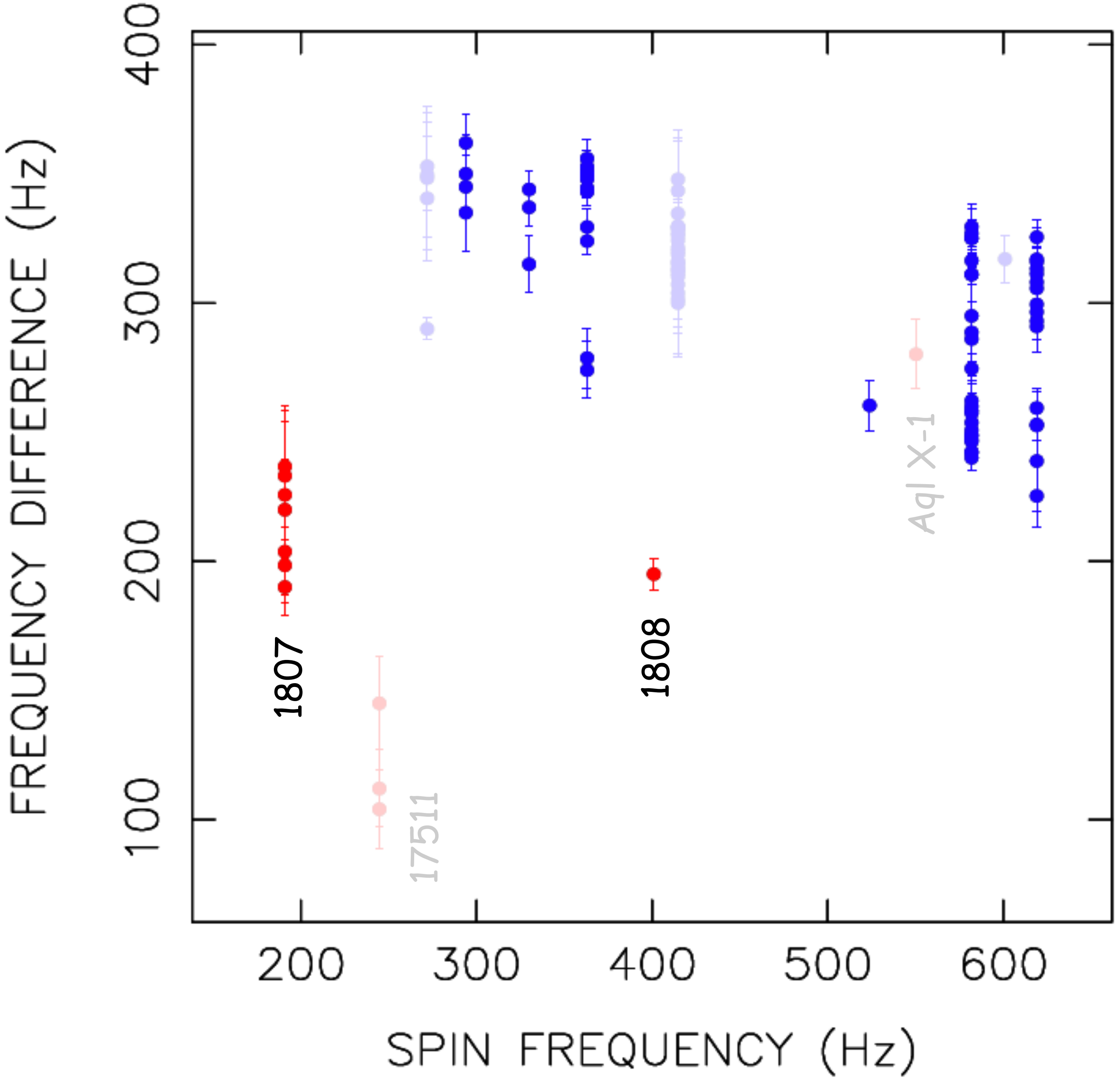
'Under certain conditions such resonances might also involve the spin frequency'

$\nu_1 - \nu_2 = n \nu_{spin} / m$, e.g., $= \nu_{spin} / 2$

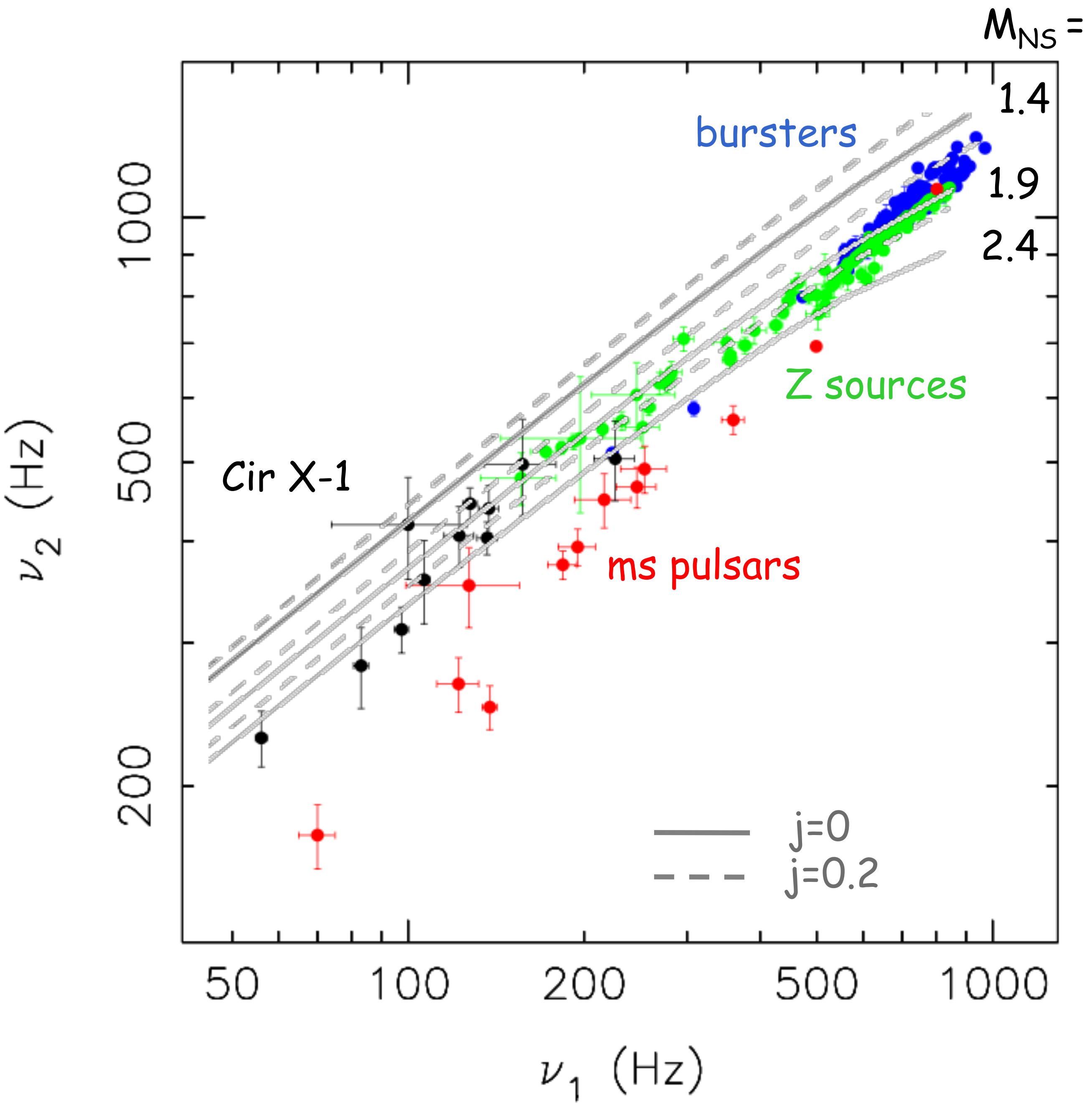
Kluzniak et al. 2004, Lamb and Miller 2004



9 non-pulsar burst oscillators have twin kHz



FREQUENCY DIFFERENCE (Hz)
SPIN FREQUENCY (Hz)
400
300
200
100
200
300
400
500
600
1807
1808
17511
Aql X-1



M_NS =
1.4
1.9
2.4
bursters
Z sources
Cir X-1
ms pulsars
j=0
j=0.2
1000
500
200
50
100
200
500
1000
ν2 (Hz)
ν1 (Hz)

Sum up msec variability

- 13 accreting millisecond pulsars
- 15 burst oscillators, 5 are AMXPs

-> 23 millisecond spins
limit at ~600 Hz

-> Relation pulse intermittency <-> burst freq. drift

- 21 twin kHz QPOs
  - 2 pulsars, 8 burst oscillators (overlap of 1)

-> No simple ν_1, ν_2, ν_{spin} relation

-> Persistent pulsars stand out in their kHz QPO prop's

Towards the next set of instruments

- RXTE Cycle 15 → SWIFT, XMM
- ASTROSAT -> LOFT, AXTAR, Gravitas/IXO
- It has been clear for a while that 10 m^2 will be the real next step for millisecond timing
- Technology now to the point where this might be accomodated in a topical (Explorer class) mission