Timing features in X-ray Astronomy

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Coherent signals: X-ray pulsars

- First detection: Cen X-3
- Uhuru satellite: 1971

DISCOVERY OF PERIODIC X-RAY PULSATIONS IN CENTAURUS X-3 FROM *UHURU*

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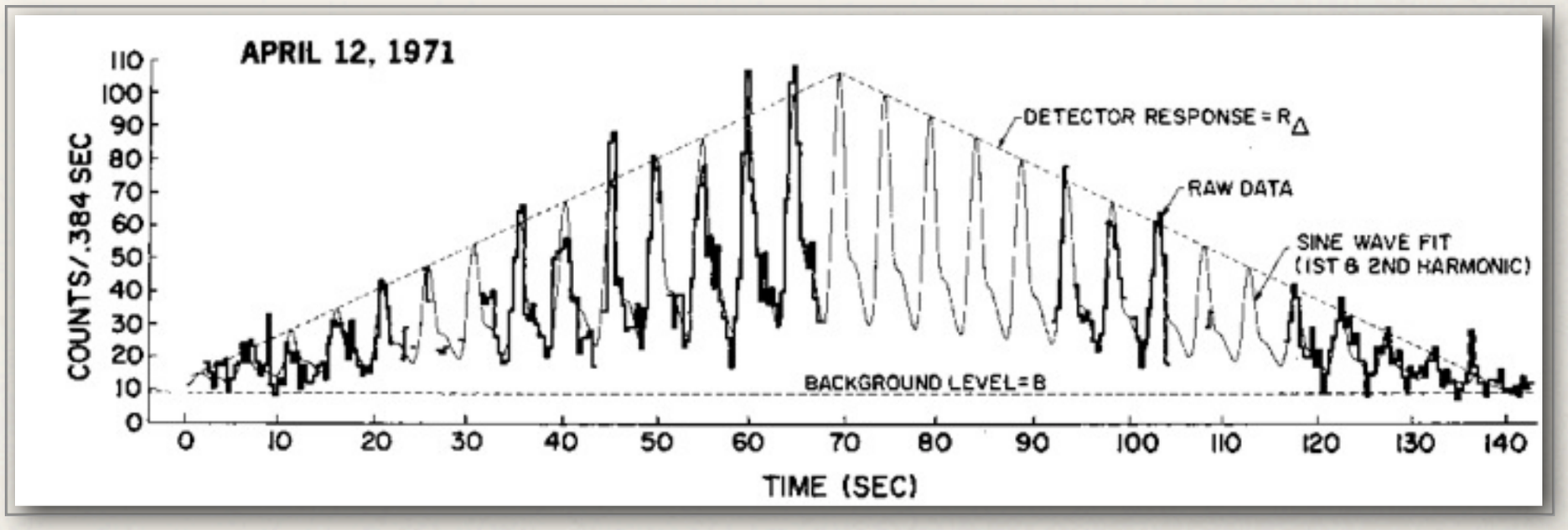
American Science & Engineering, Inc., Cambridge, Massachusetts 02142
Received 1971 May 17

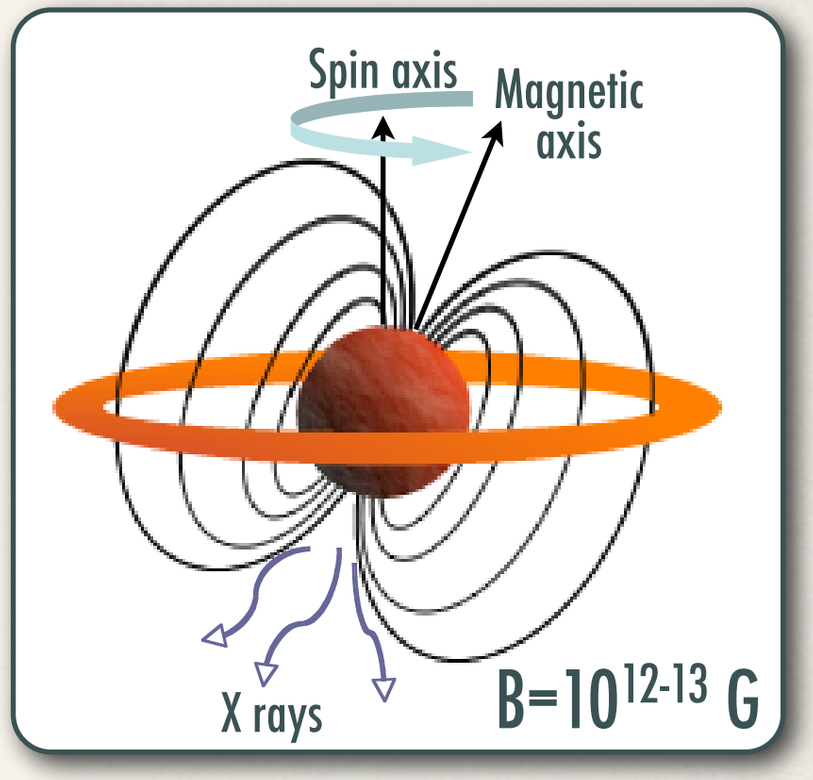
DATA ON X-RAY PULSARS

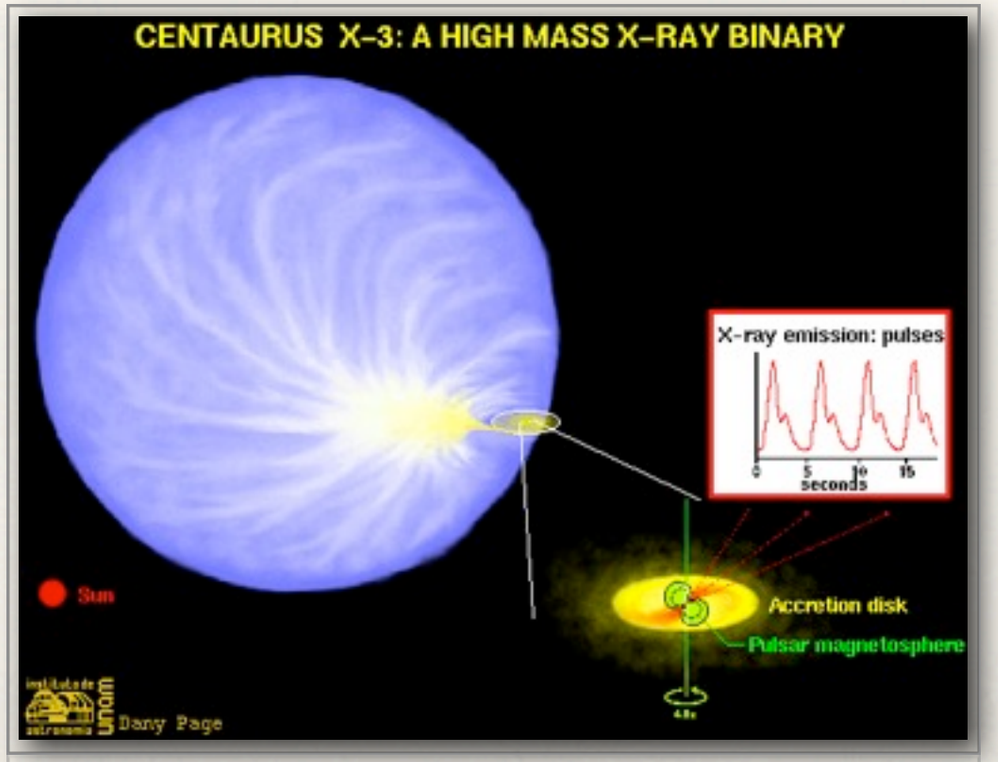
PARAMETER	STAR		
	NP 0532*	Cygnus X-1†	Centaurus X-3
Period τ (seconds)	0.033	0.073 or 0.292 1.1 or 1.3 Possibly >5	4.87



Accreting X-ray pulsars

- Magnetized NS accreting from a non-collapsed star
- A fraction of the X rays are modulated at the spin period

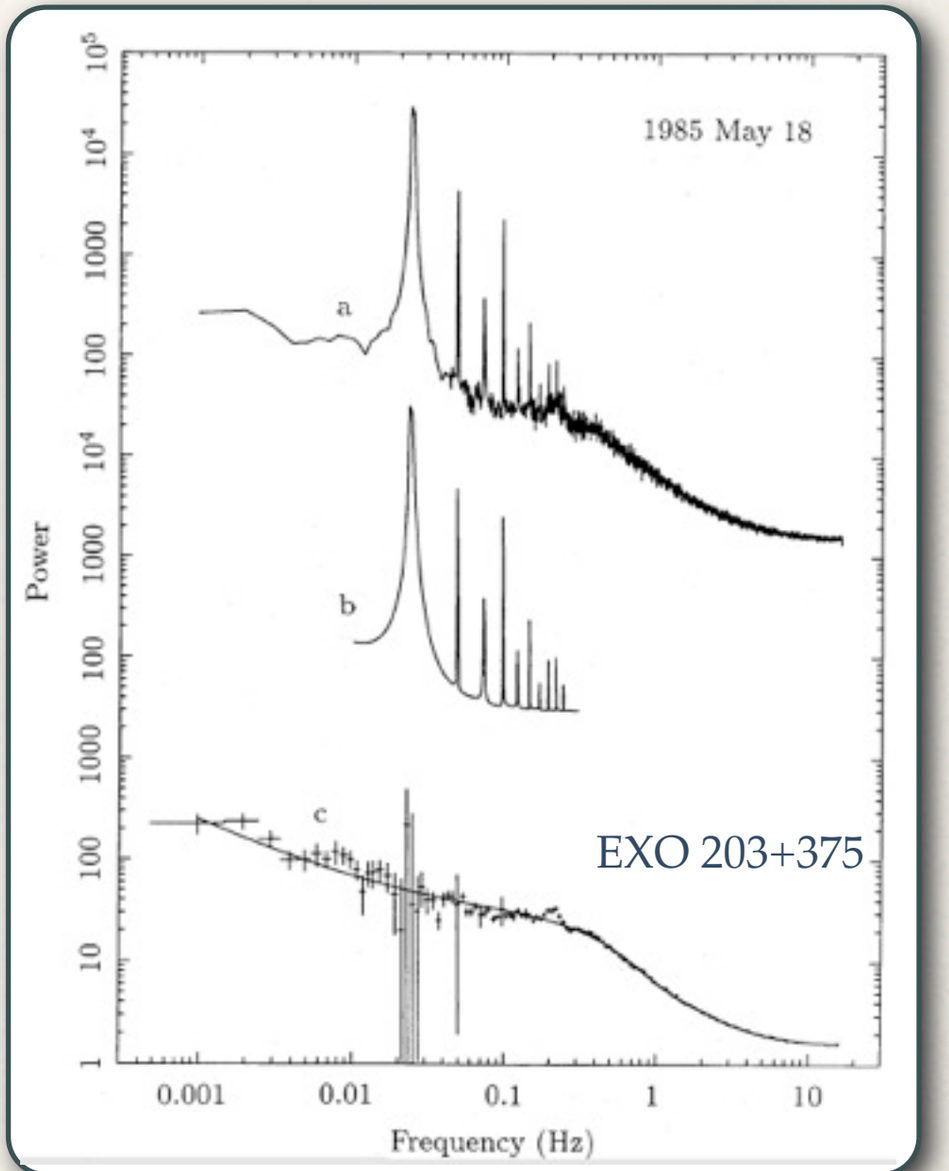


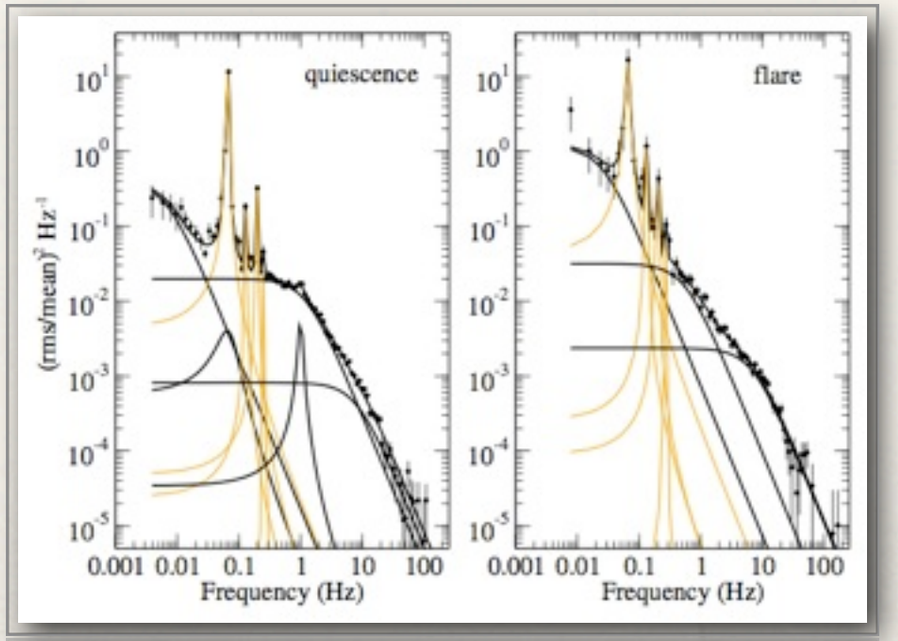


Pulse periods from 69 ms to 3 hr

Accreting X-ray pulsars

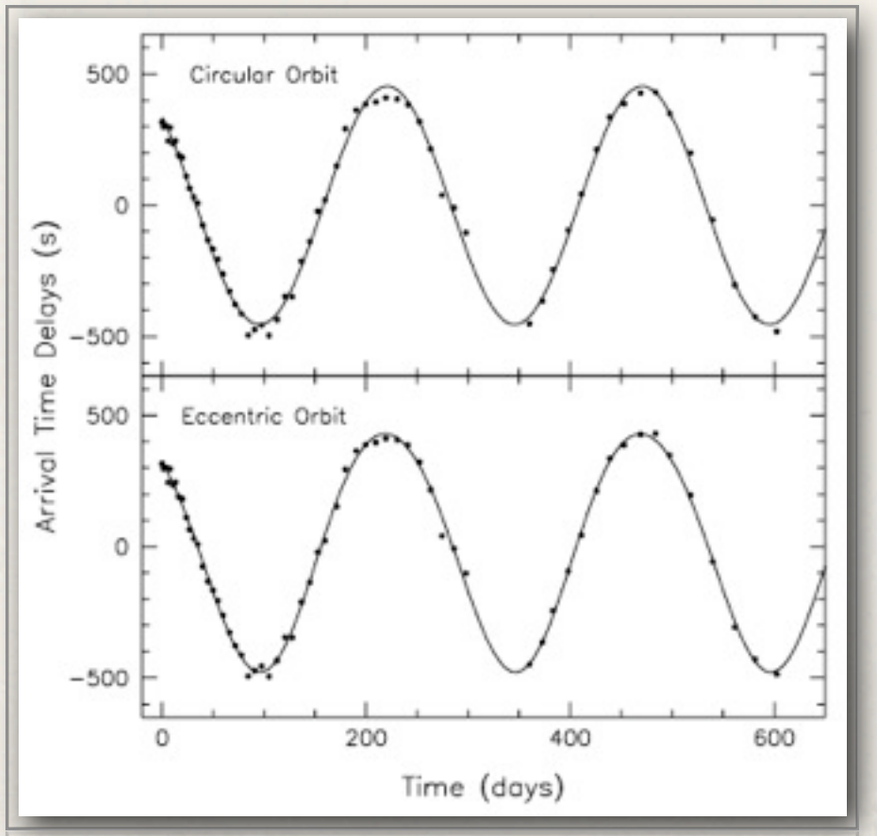
- Periodic signal
- Higher armonics: non-sinusoidal
- Broad noise
- Even Quasi-Periodic Oscillations (QPO)

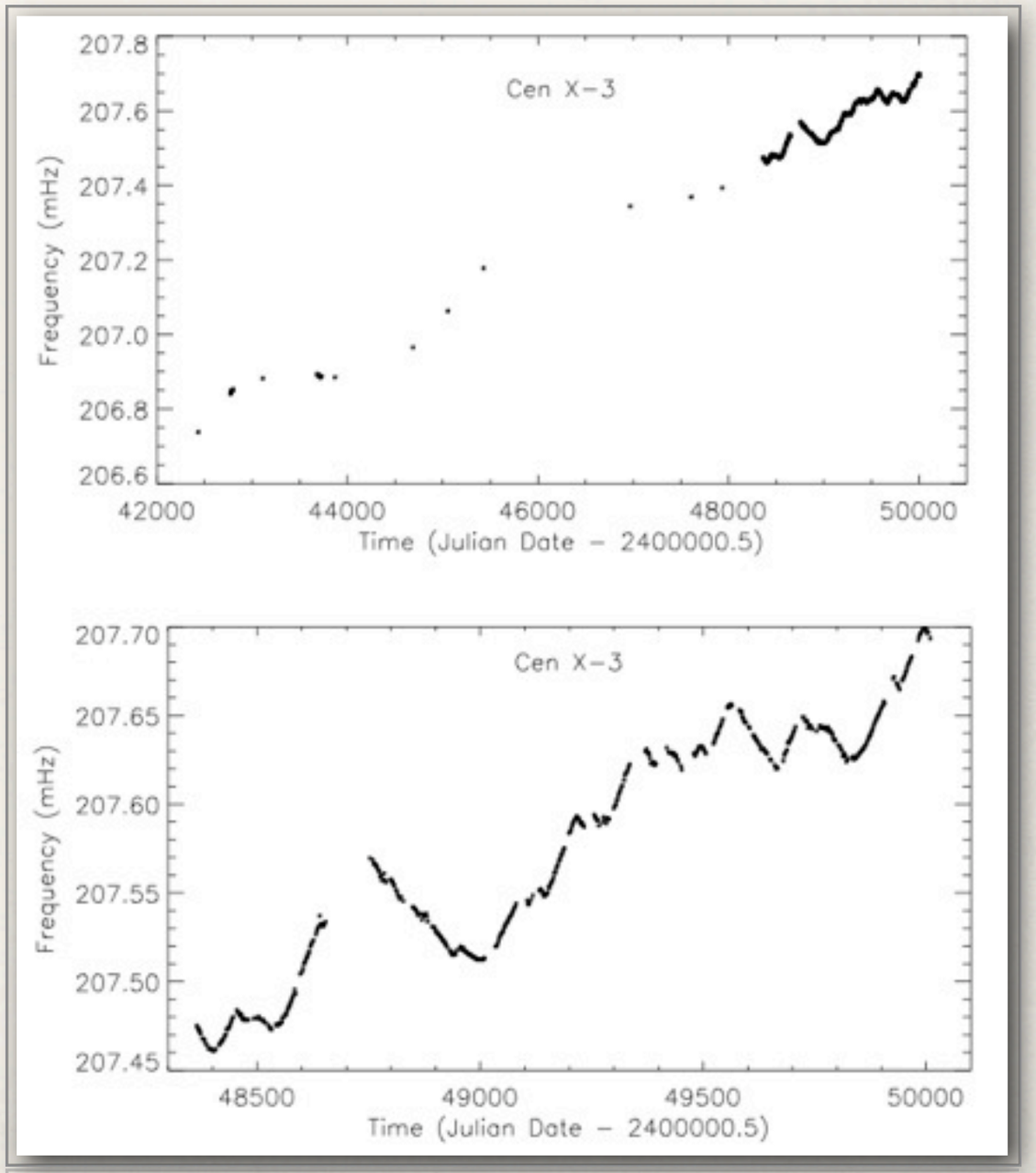




Period variations

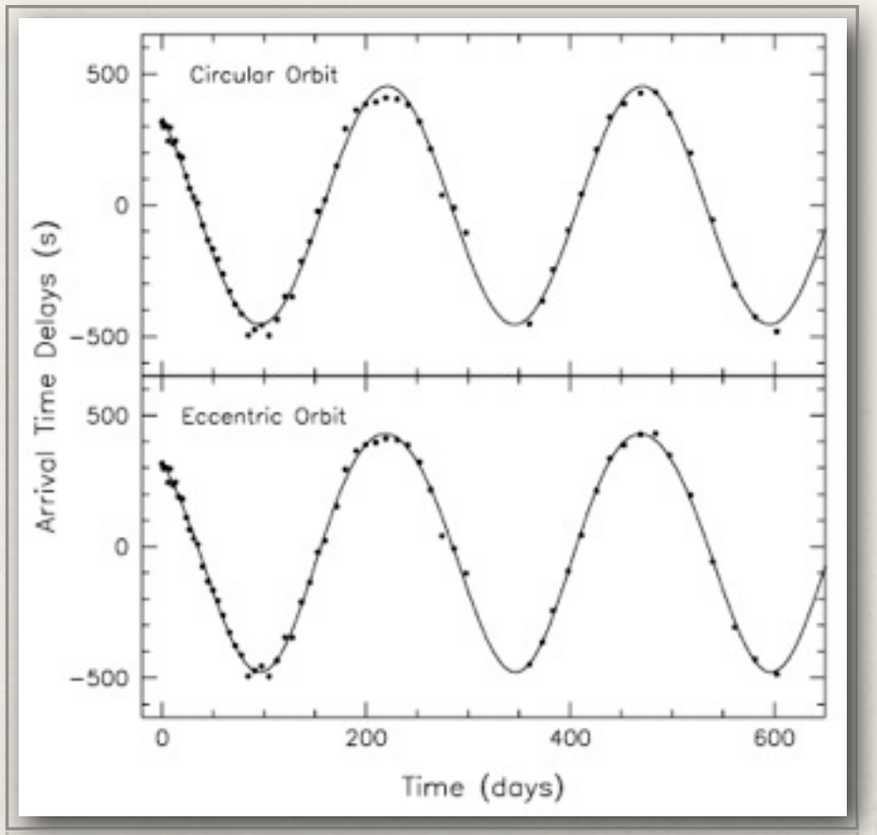
- Orbital variations
- Spin-up due to accretion
- Not steady as expected

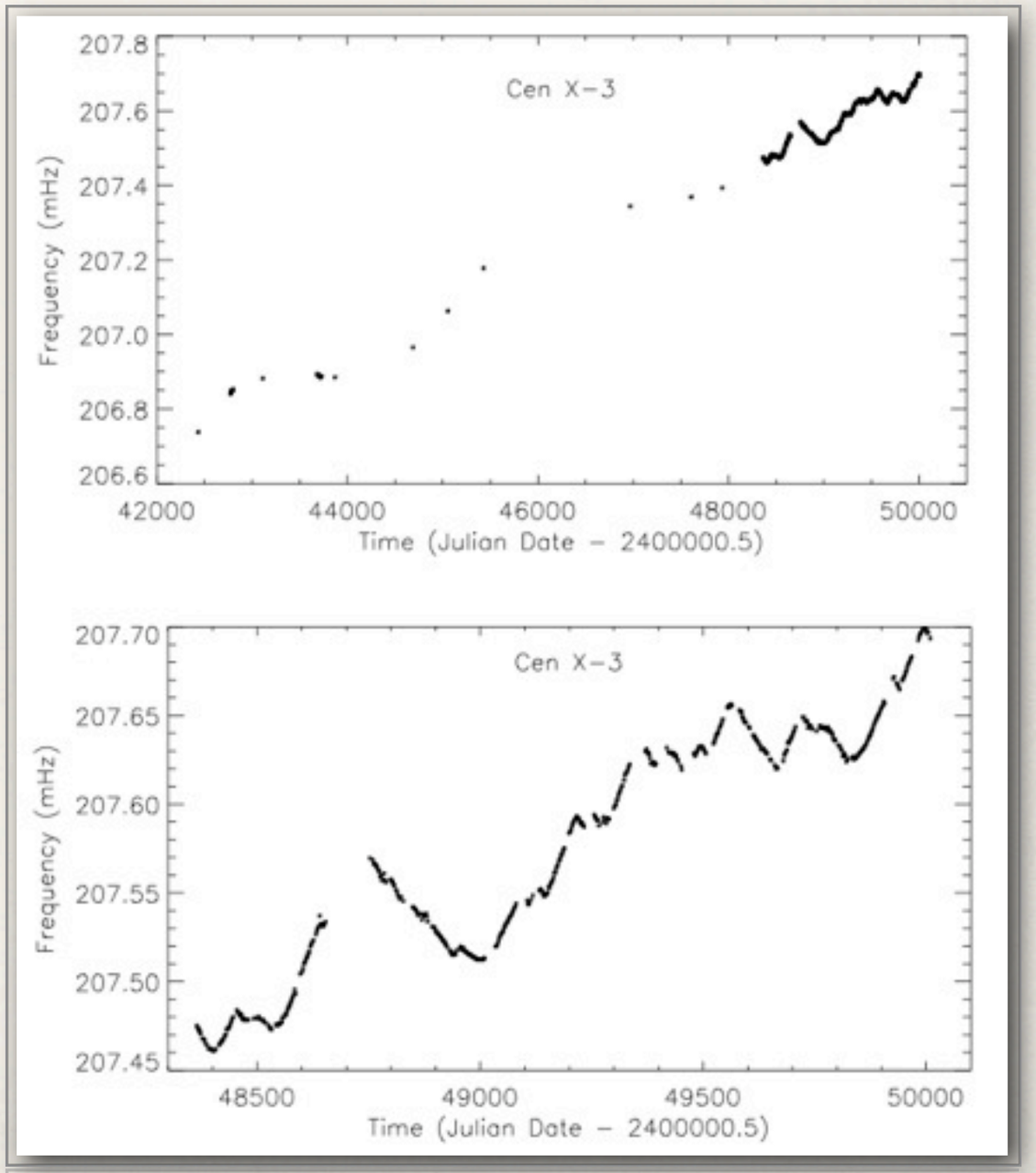




Folding and pulse shape

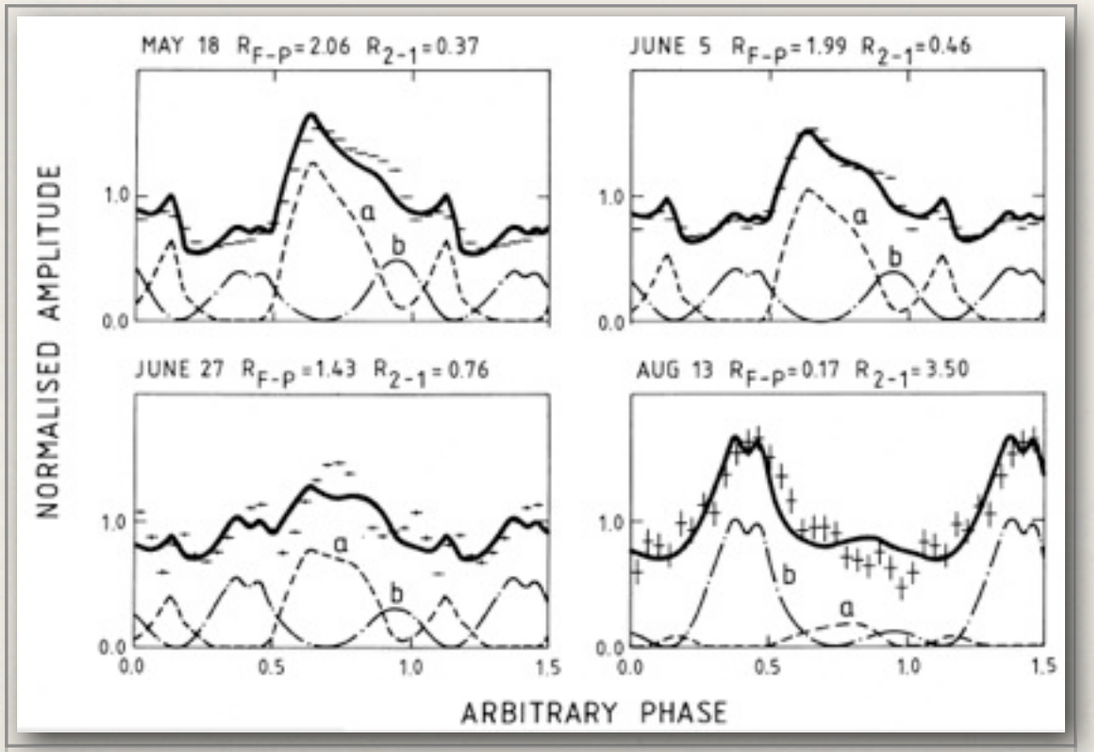
- Orbital variations
- Spin-up due to accretion
- Not steady as expected

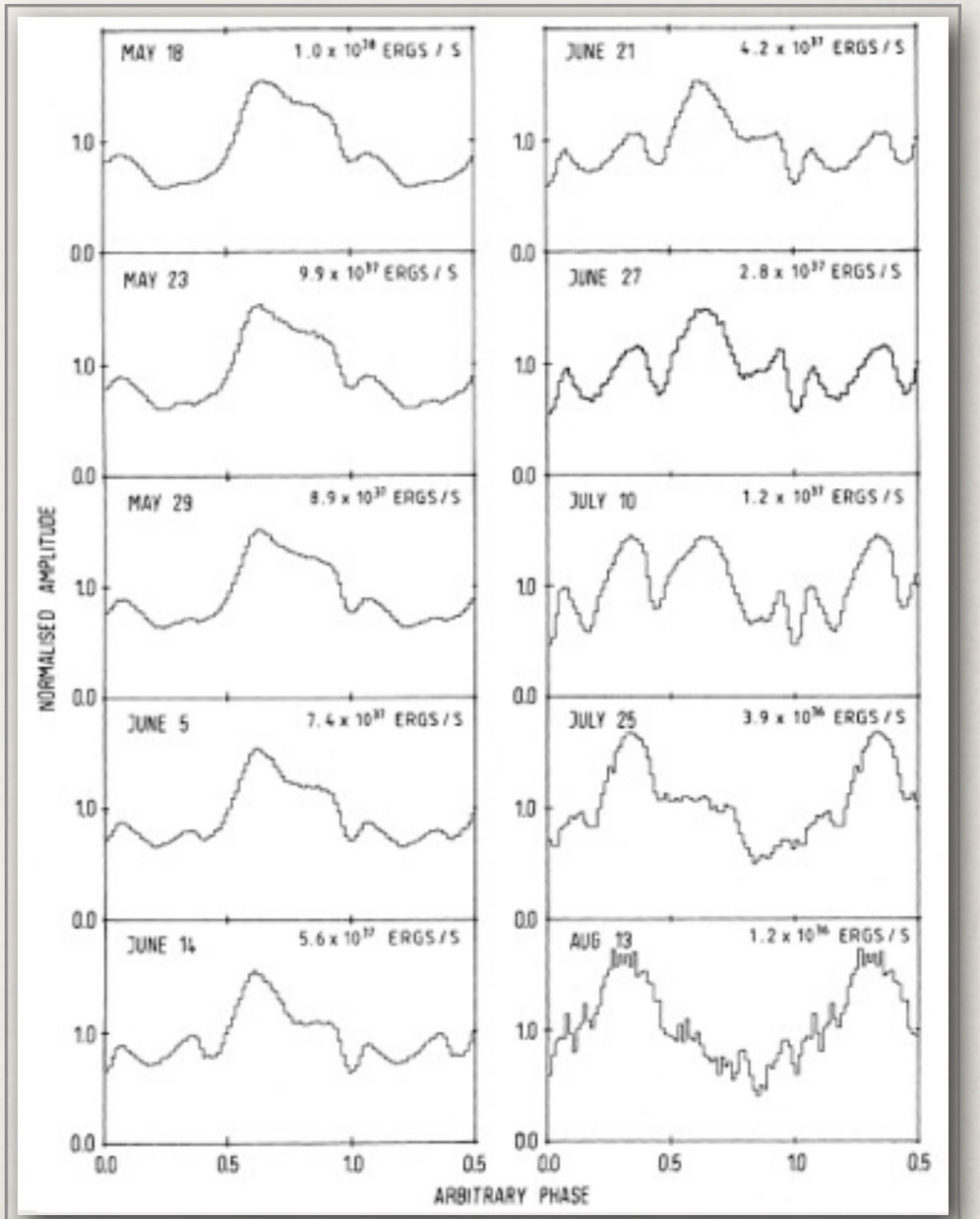




Pulse shapes

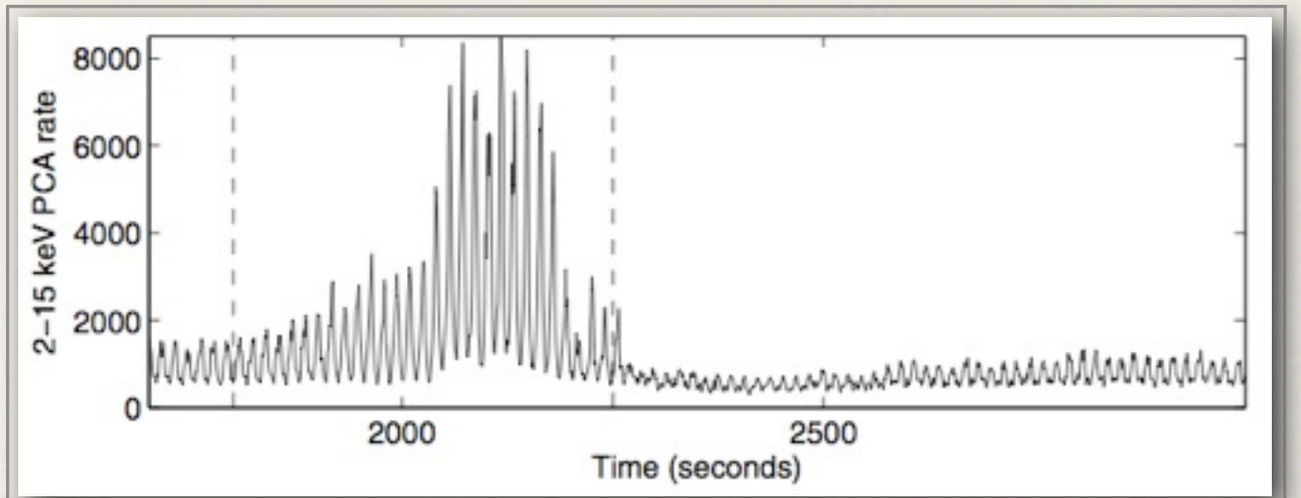
- Pulsations as a function of energy
- Complicated pulse shapes

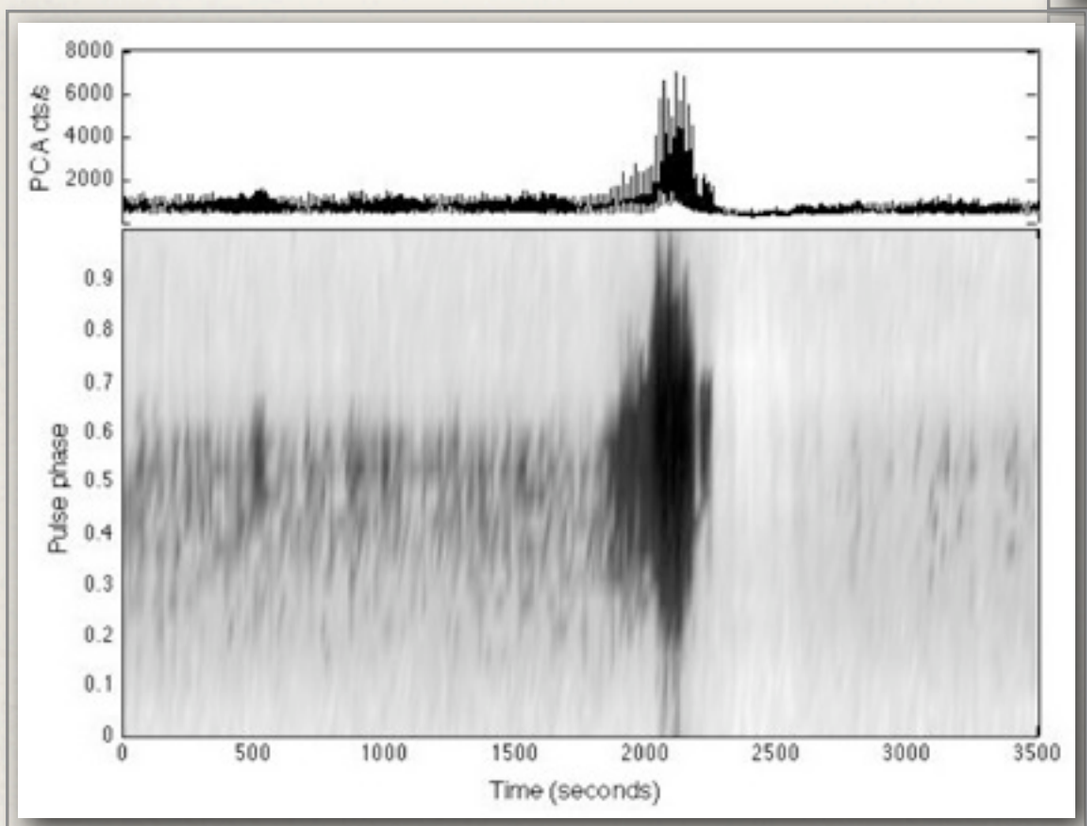


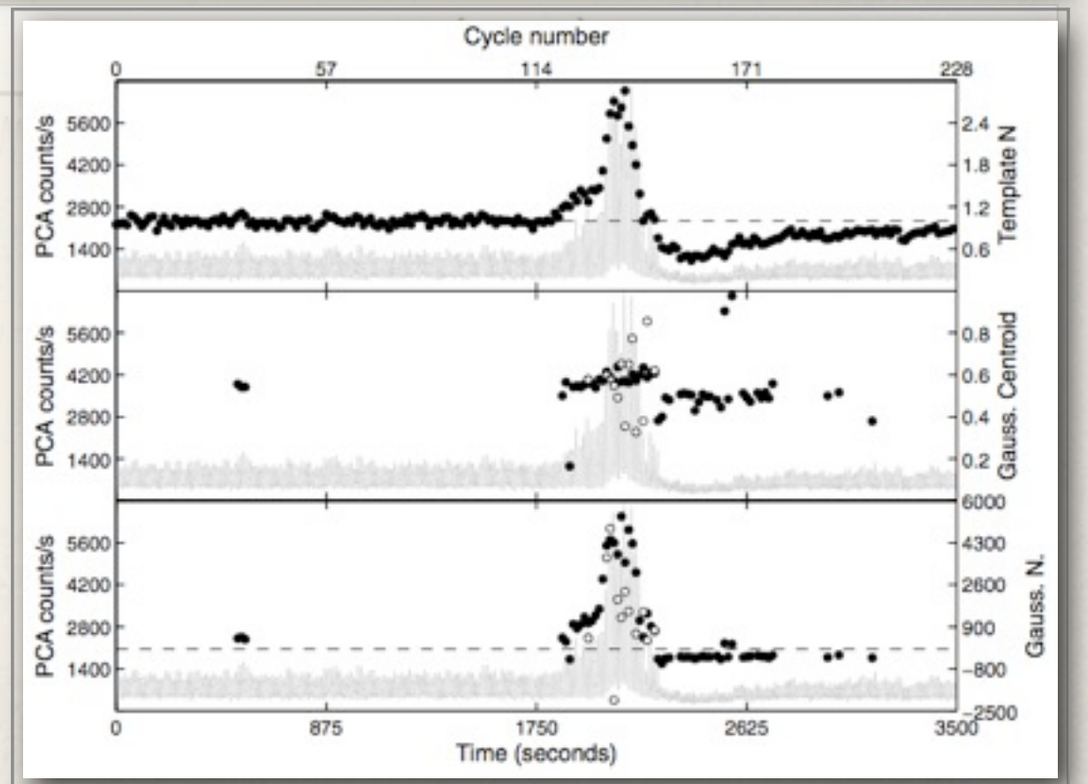


Peculiar objects

- 15s pulsar with “flares”

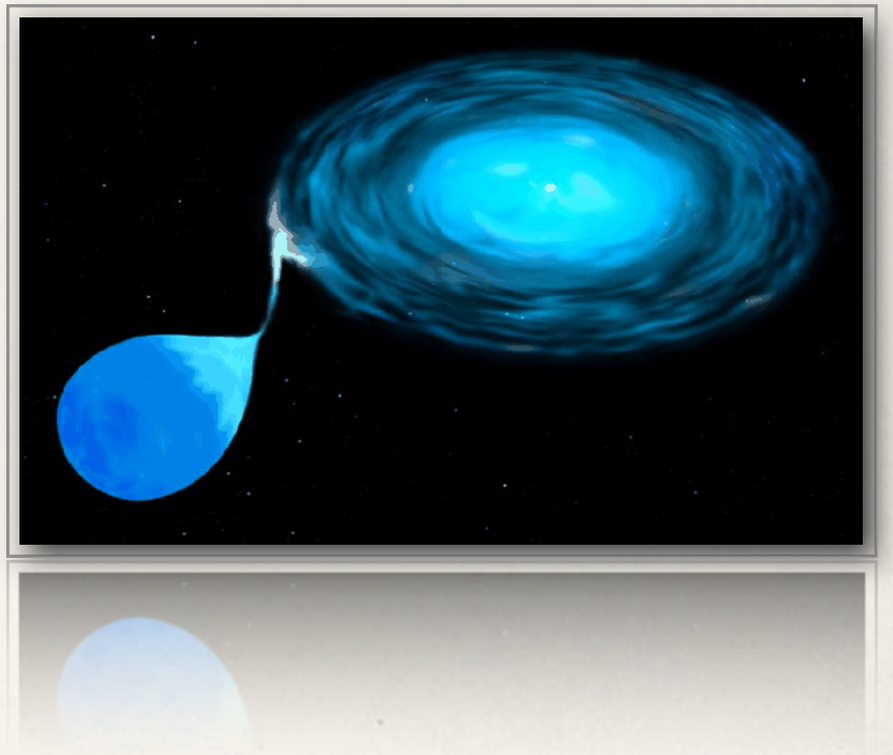






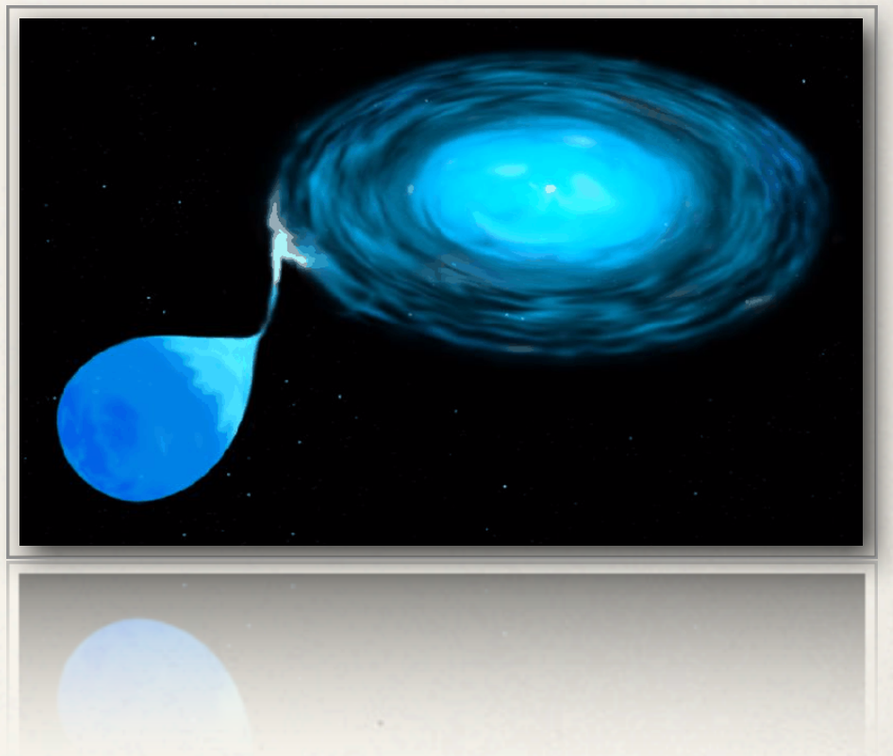
Neutron-star LMXBs

- Magnetic field 10^8-10^9 G
- Some are (ms) pulsars, most are not
- Late spectral type companion
- Accretion disk extends closer to the NS
- Inner disk region: GR effects



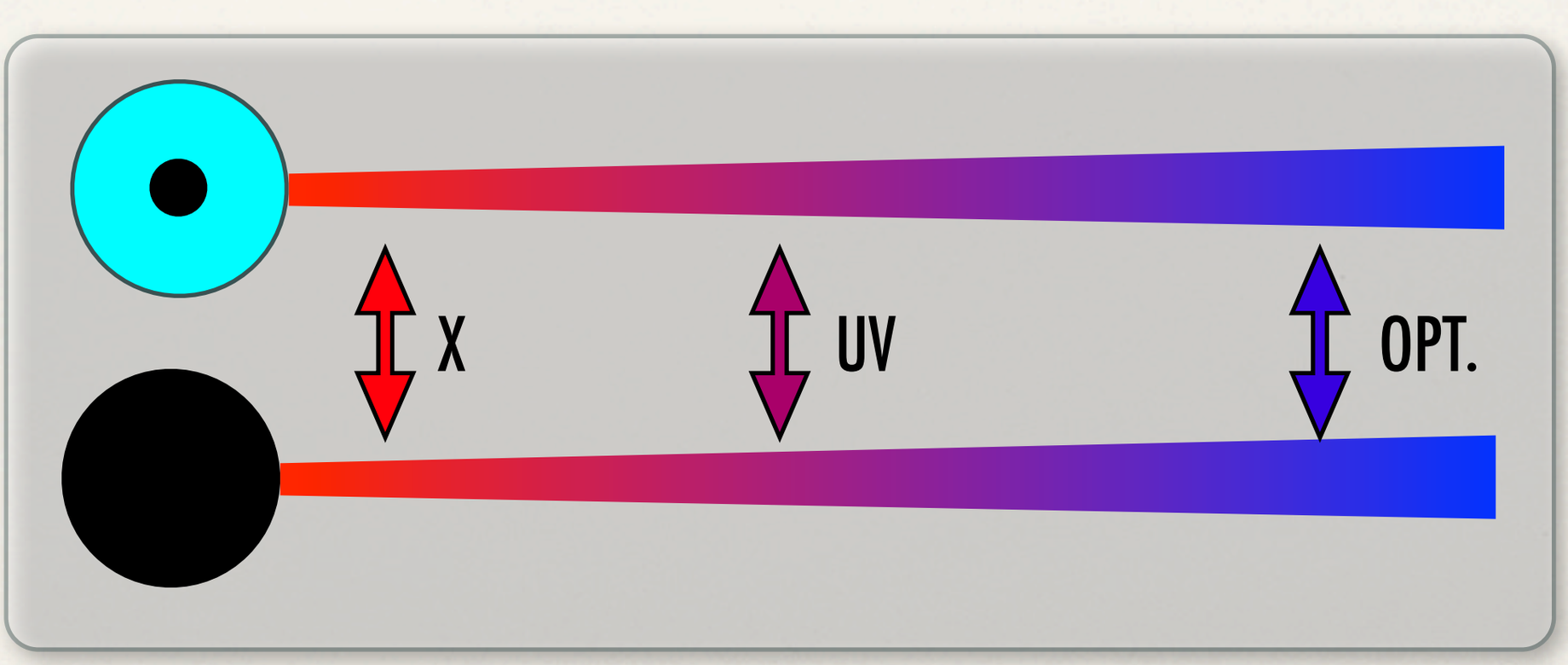
Black-hole LMXBs

- No magnetic field
- None are pulsars
- Late spectral type companion (but not only)
- Accretion disk extends closer to the BH
- Inner disk region: GR effects

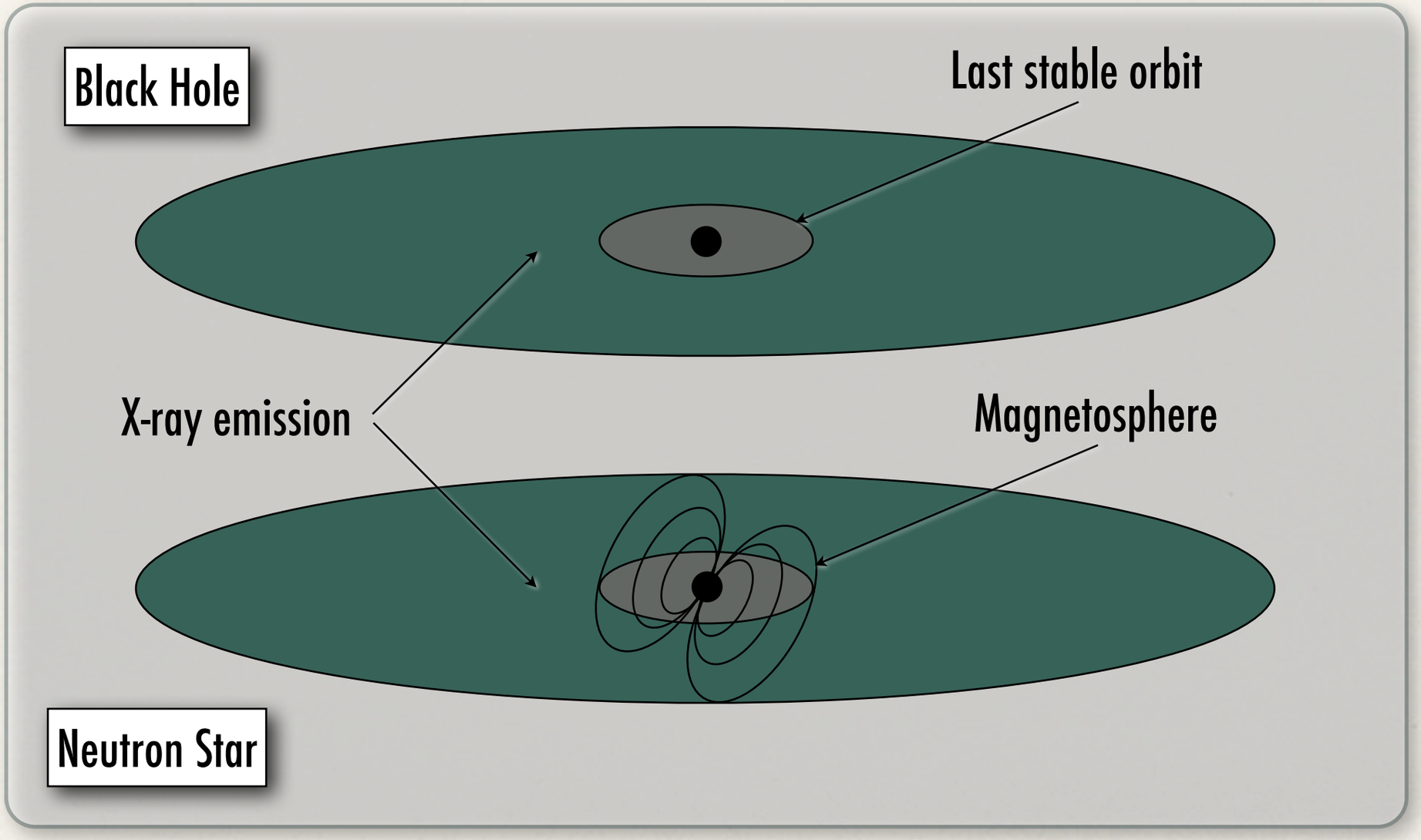


BH vs. NS LMXBs

- Accretion disk structure
- Black hole or neutron star?

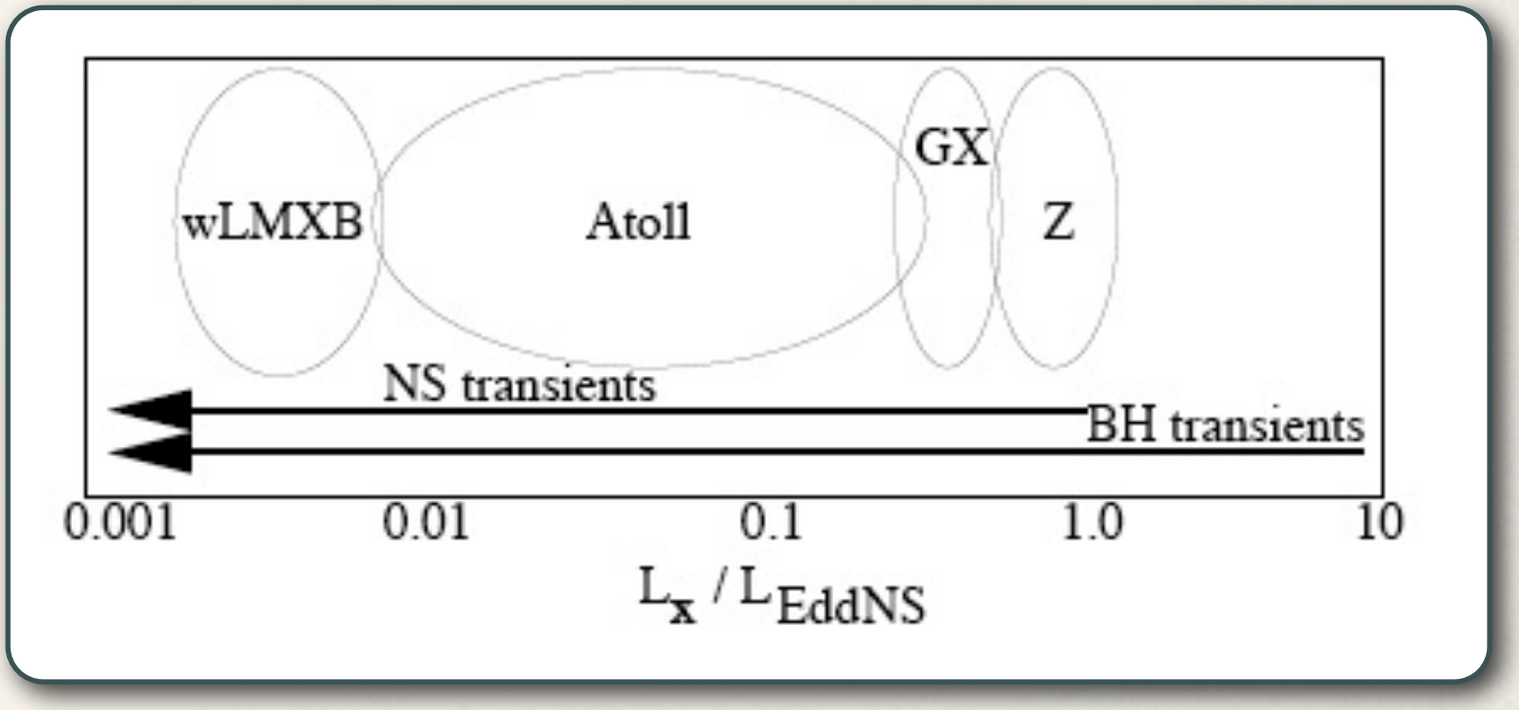


BH vs. NS LMXBs



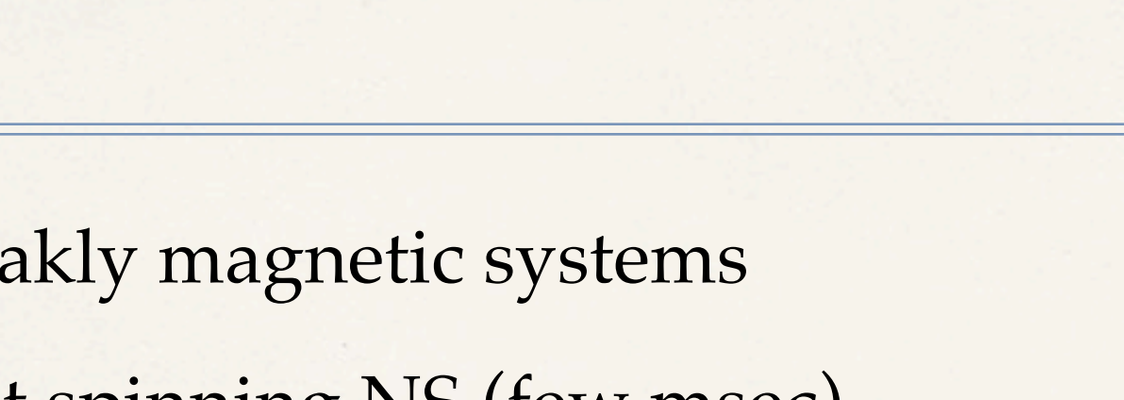
NS LMXBs: source classes

- Z sources
- Atoll sources
- Low-L bursters
- msec X-ray pulsars
- Oddballs (Cir X-1)



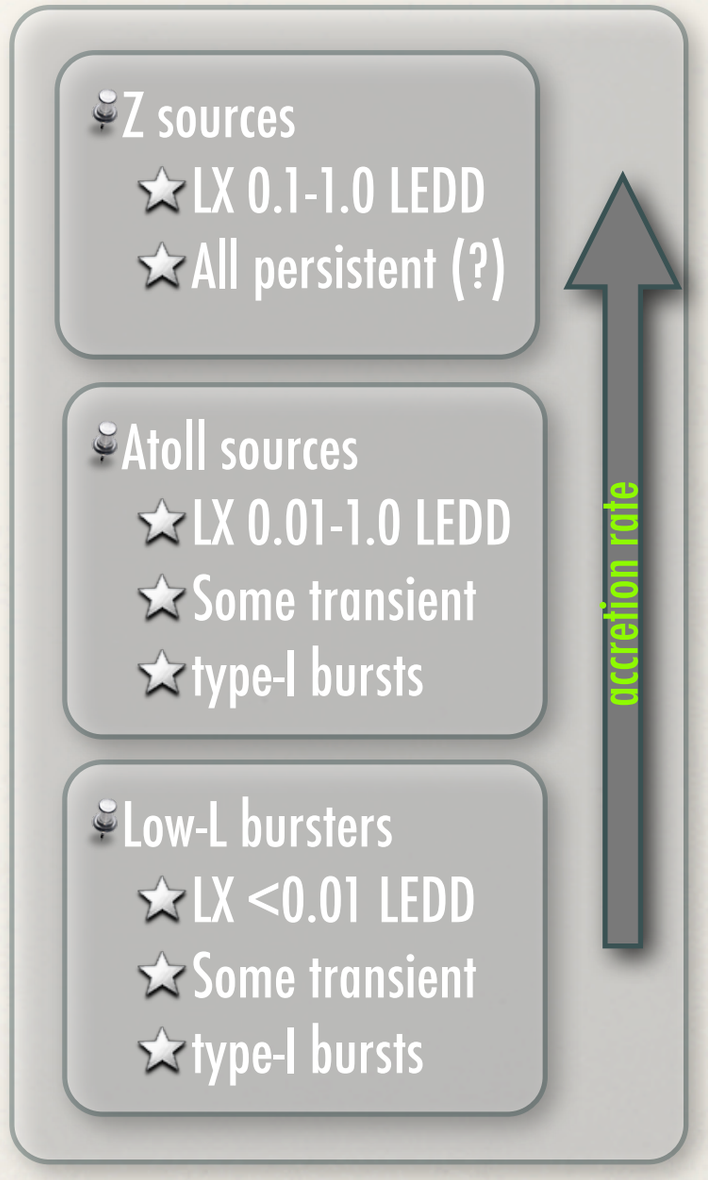
NS LMXBs: source classes

- Weakly magnetic systems
- Fast spinning NS (few msec)
- Characteristic phenomena: X-ray bursts
- Fast aperiodic timing
- Source classes



Z source

Atoll source



Timing properties

THE ASTROPHYSICAL JOURNAL, 172:L13–L16, 1972 February 15

DYNAMIC SPECTRUM ANALYSIS OF CYGNUS X-1

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Institute of Space and Aeronautical Science, University of Tokyo, Tokyo
Received 1971 December 16

ABSTRACT

The oscillatory structure of the counting-rate data trains of Cyg X-1 obtained by the AS&E and the M.I.T. group was studied. Instead of applying the Cooley-Tukey fast Fourier-transform algorithm to the entire data, we obtained the dynamic spectrum by fitting the wave with time sections of the data trains. Also, the Hissagram, which is a quantitative exhibition of the sonagram, was produced for the same train. It was concluded that the oscillation lasts typically for several seconds and its frequency drifts within a few seconds repeatedly.

THE ASTROPHYSICAL JOURNAL, 174:L35–L41, 1972 May 15

SHOT-NOISE CHARACTER OF CYGNUS X-1 PULSATIONS*

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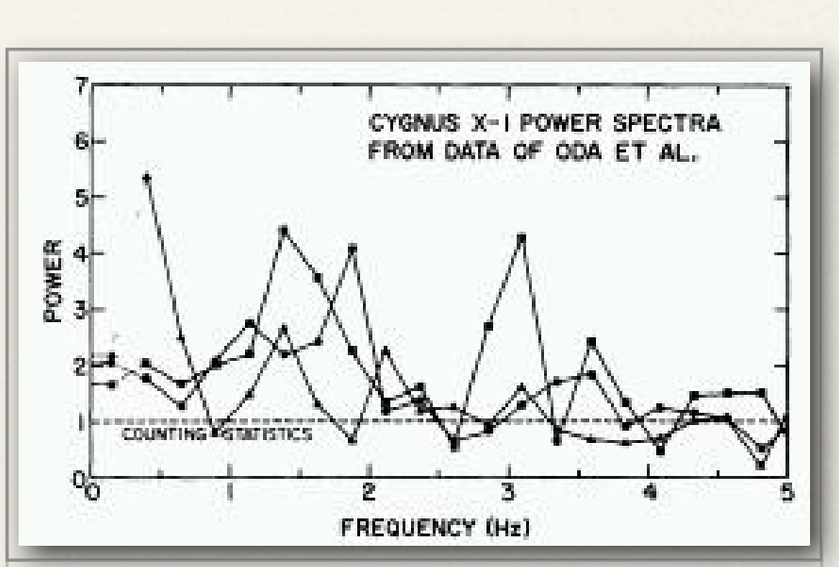
Received 1972 February 22

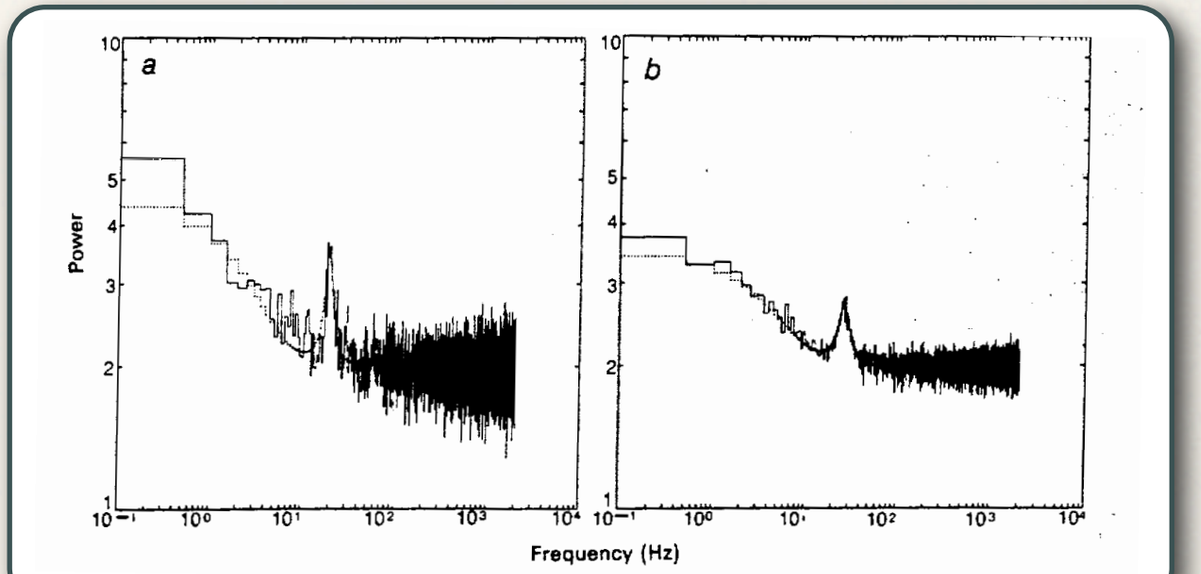
ABSTRACT

The pulsating X-ray source Cyg X-1 has been reported as having various conflicting or changing periodicities, or as being nonperiodic. The reported data have been reanalyzed in an effort to clarify this situation, and are found to be indistinguishable from shot noise due to short overlapping outbursts of X-ray emission, with no true periodicity. Computer-generated shot-noise data have the same appearance and lead to similar power spectra. The observational data are consistent with random pulses which have an effective pulse length of 0.3 ± 0.1 s and occur at varying rates of the order of several hundred per second. The pulse length indicates a maximum source size of ~0.8 light-seconds. It is suggested that some other fluctuating X-ray sources, such as Sco X-1 and Cir X-1, may also have such a shot-noise character.



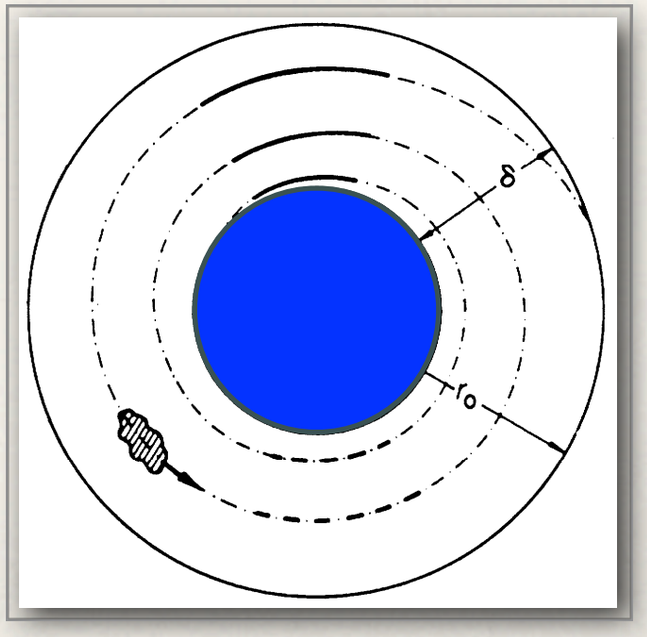
Quasi-Periodic Oscillations (QPO)

- GX 5-1 first source
- Broad and slow features
- Not a pulsar
- No keplerian time scale
- Correlated with count rate (flux?)

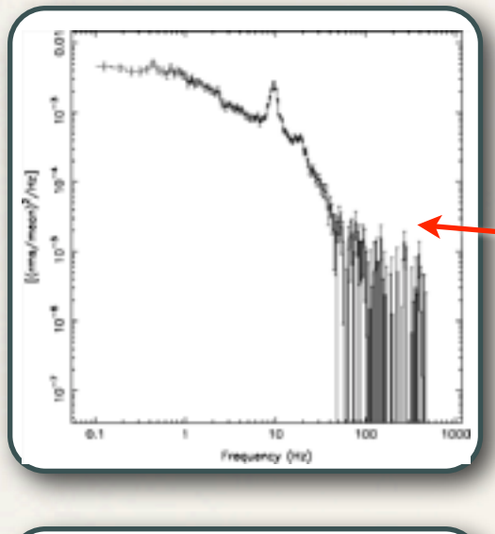


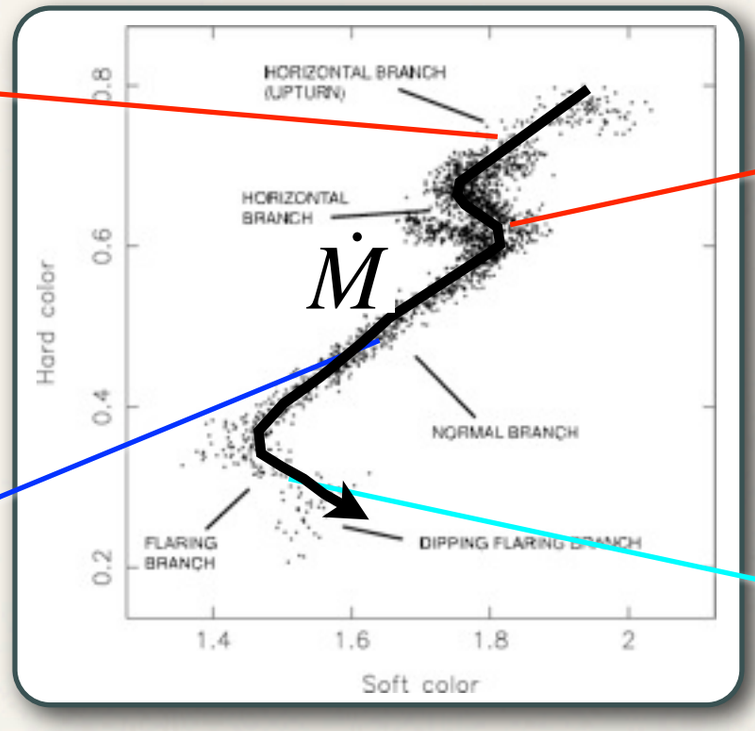
Beat frequency $\omega = \Omega_K(r_A) - \Omega_{spin}$

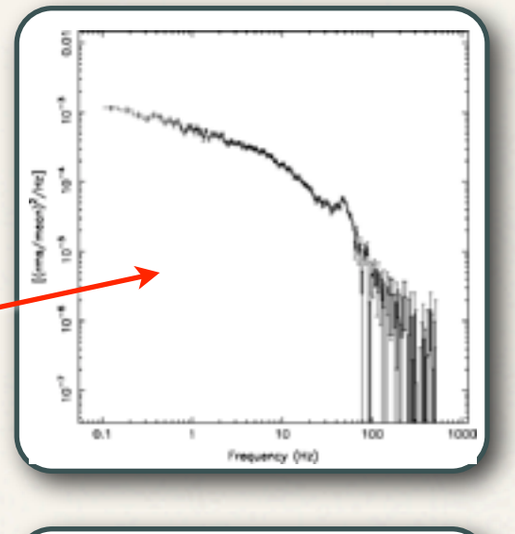
Flux related: $\omega \propto L_{37}^{3/7}$

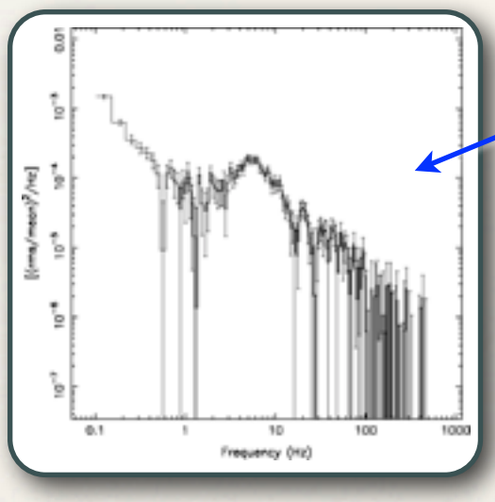


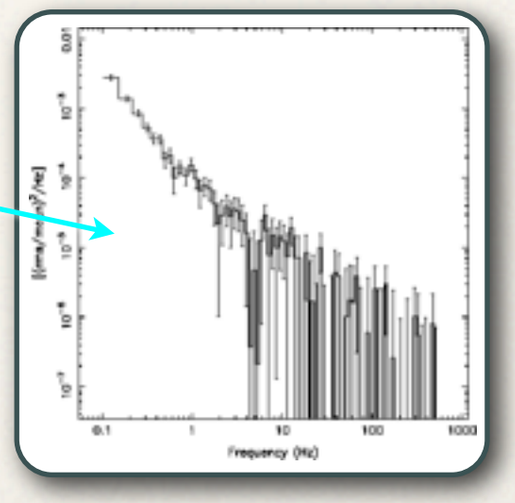
Quasi-Periodic Oscillations (QPO)



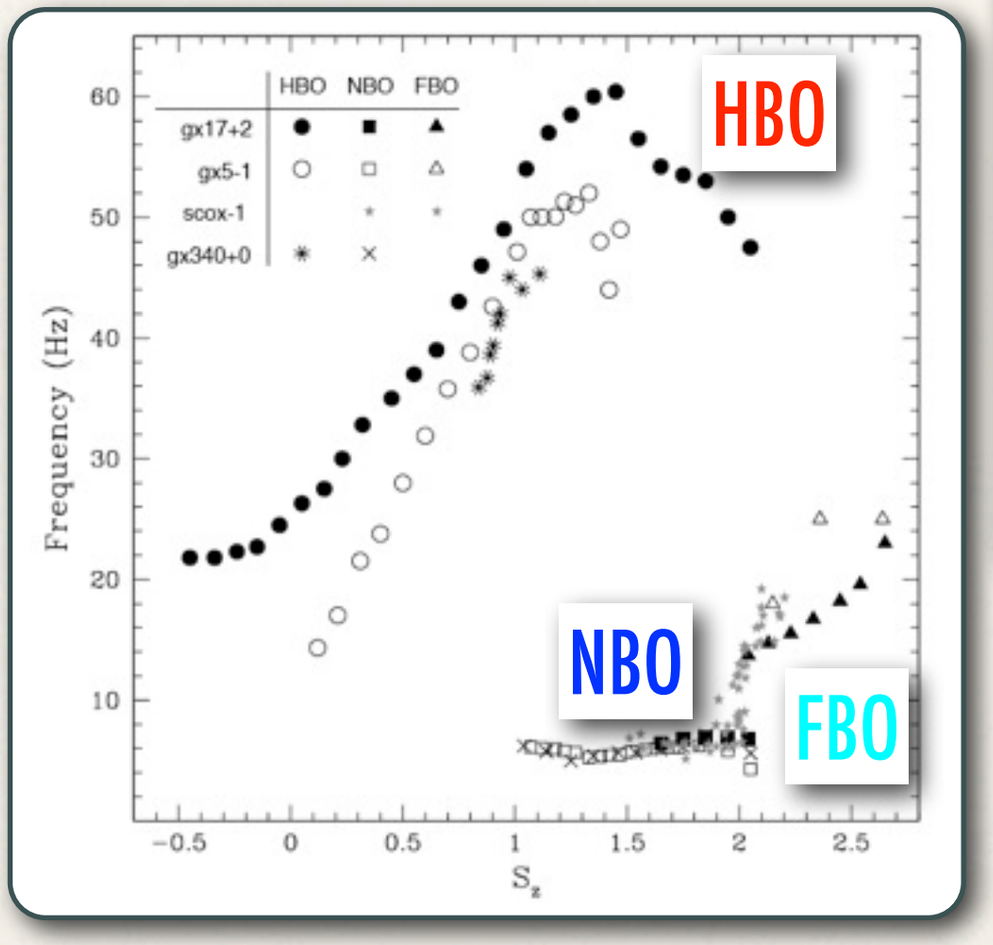


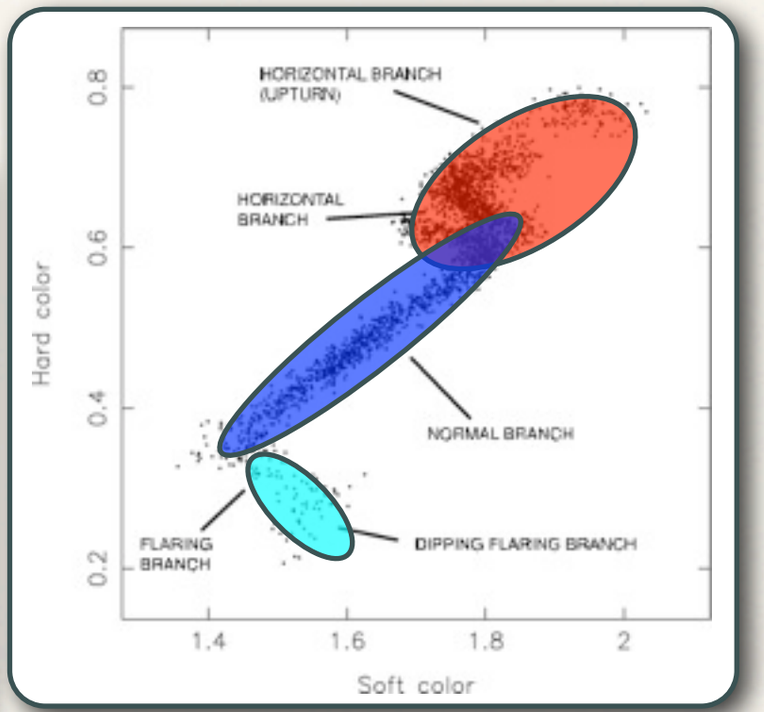






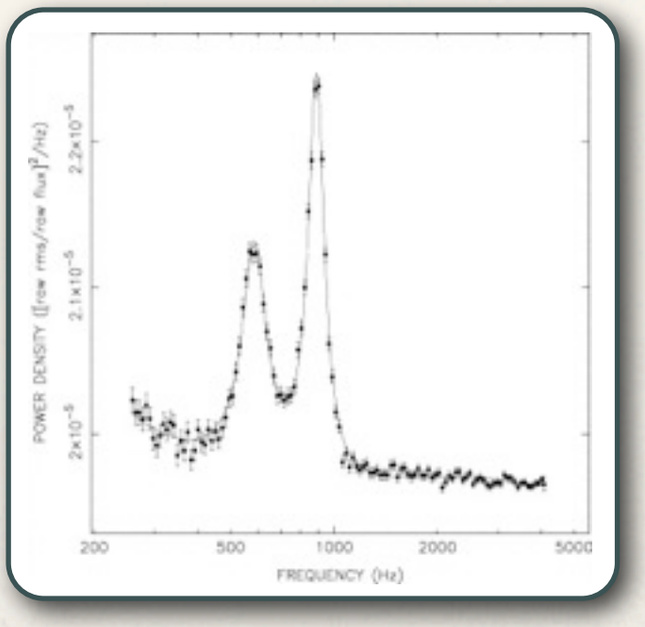
Three QPO types

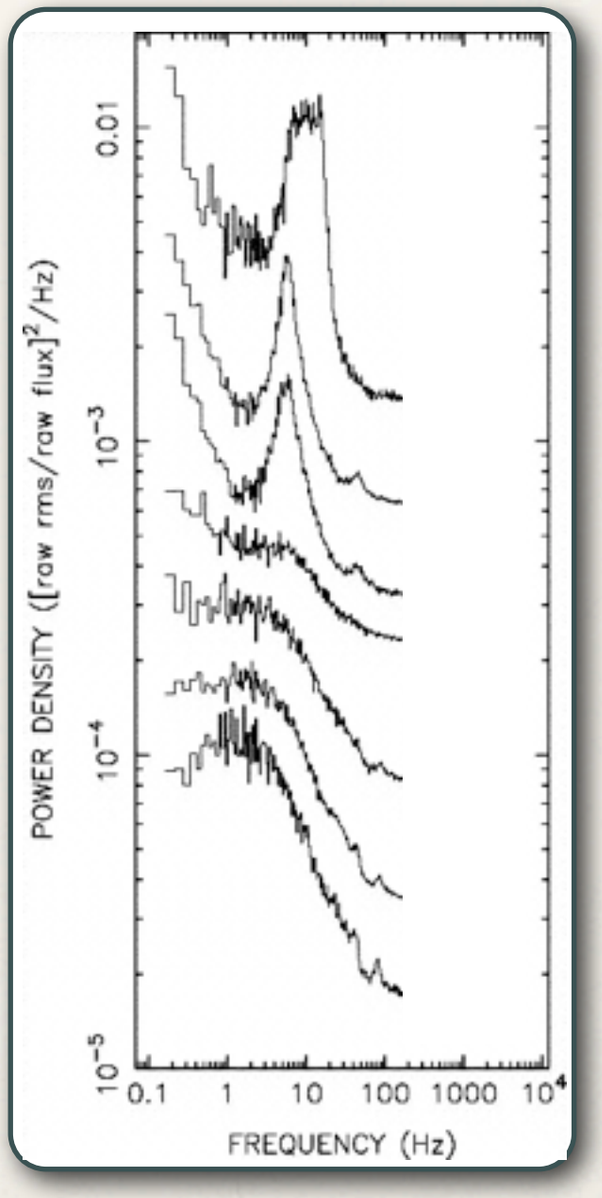




RossiXTE

- Double peaks at high frequency
- Expected range for Keplerian
- Frequency changes
- Sco X-1 first, then other Z and atoll





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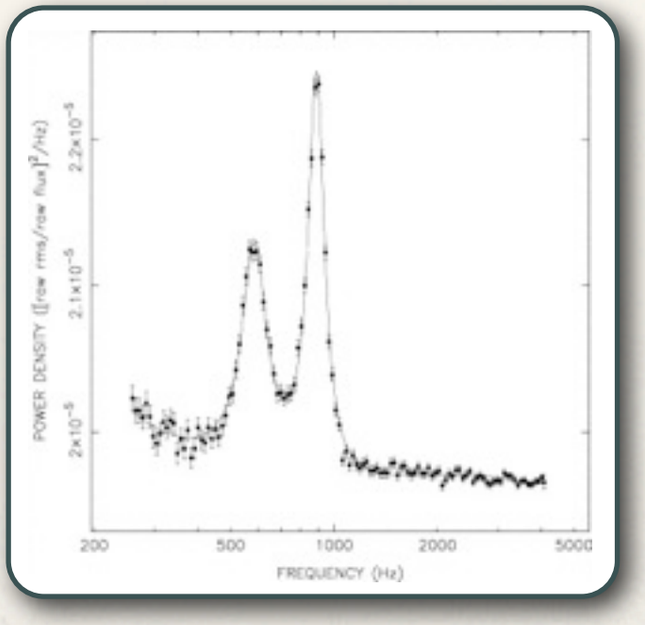
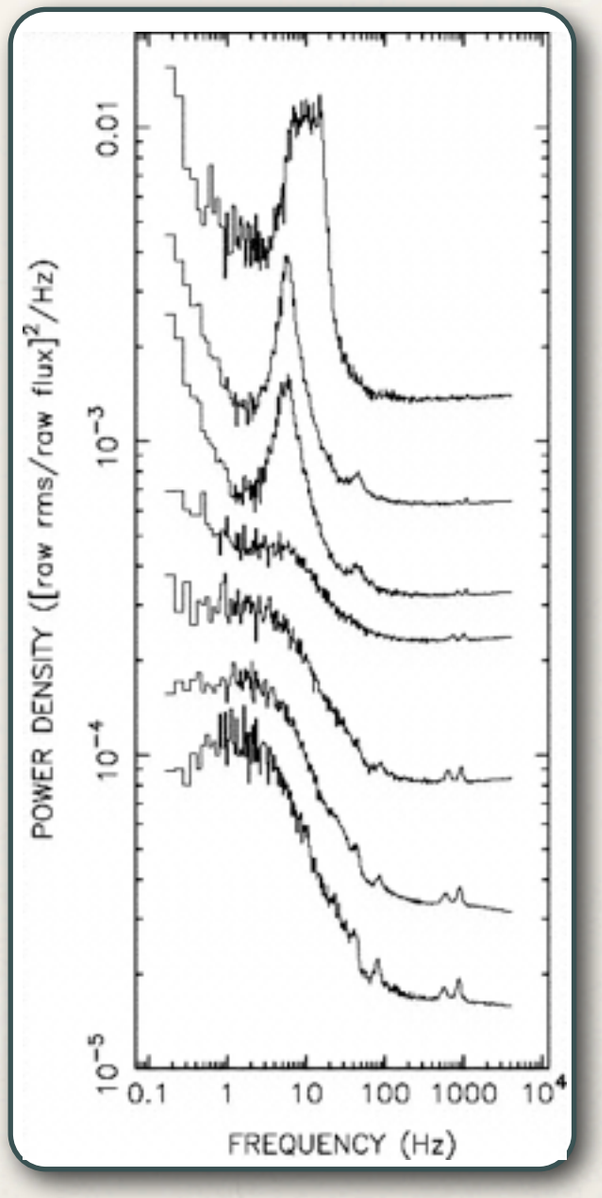
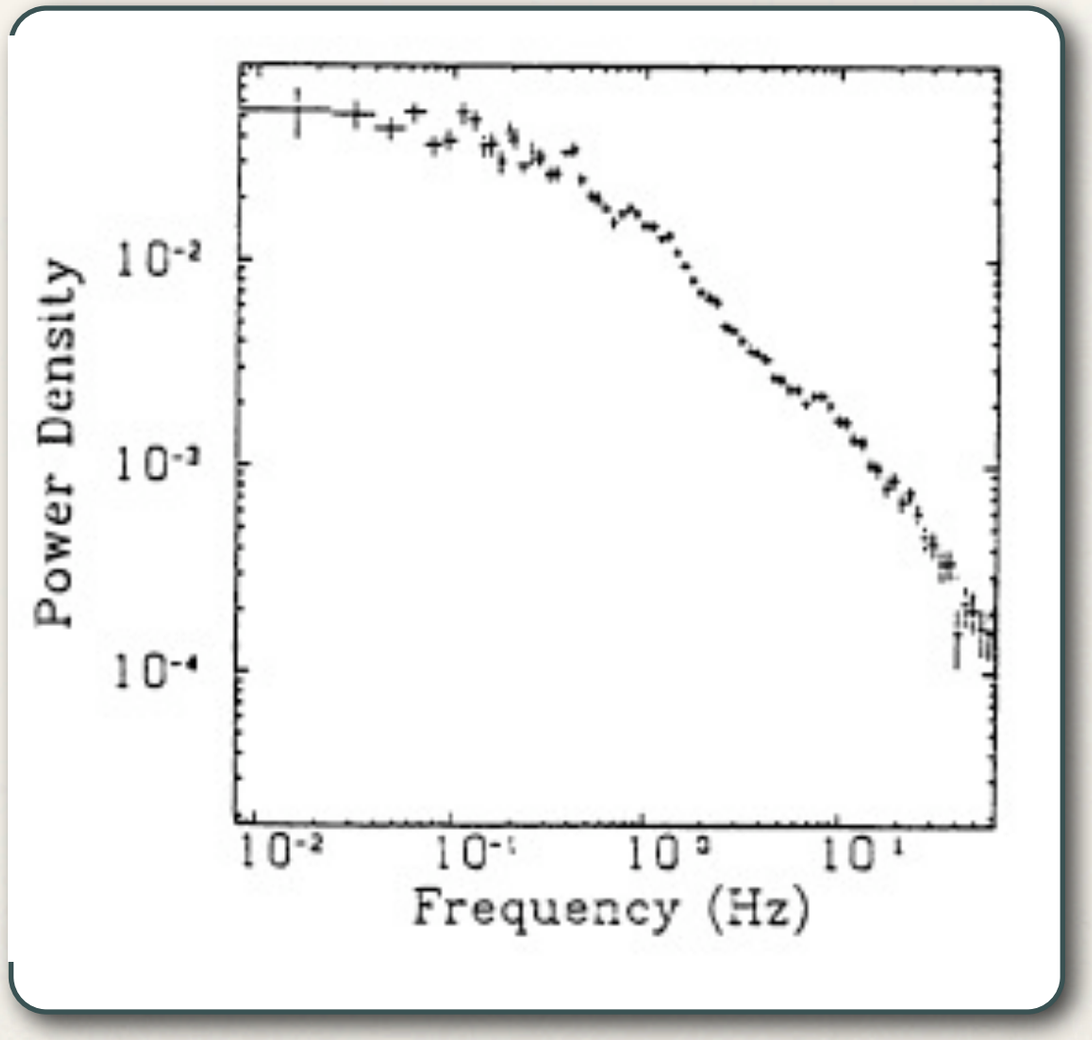




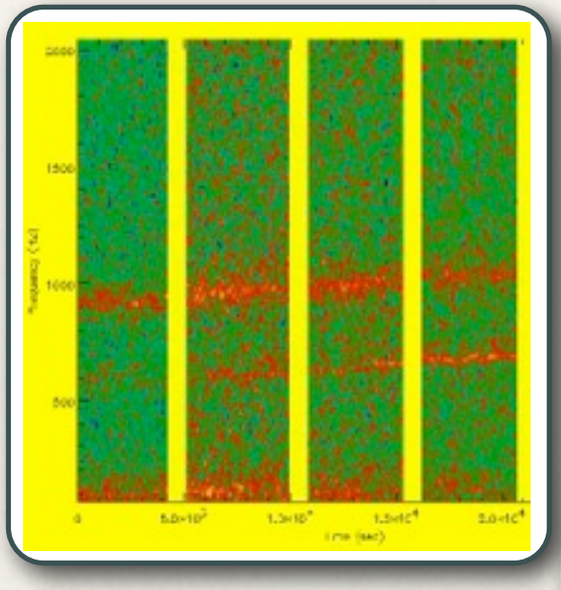
Atoll sources (lower accretion)

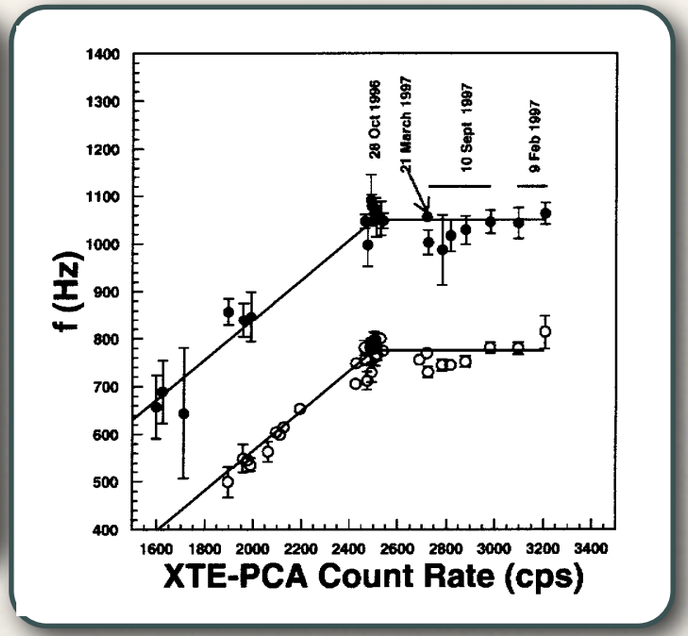
- At low flux: flat-top noise + LFQPO
- Same as low-L bursters

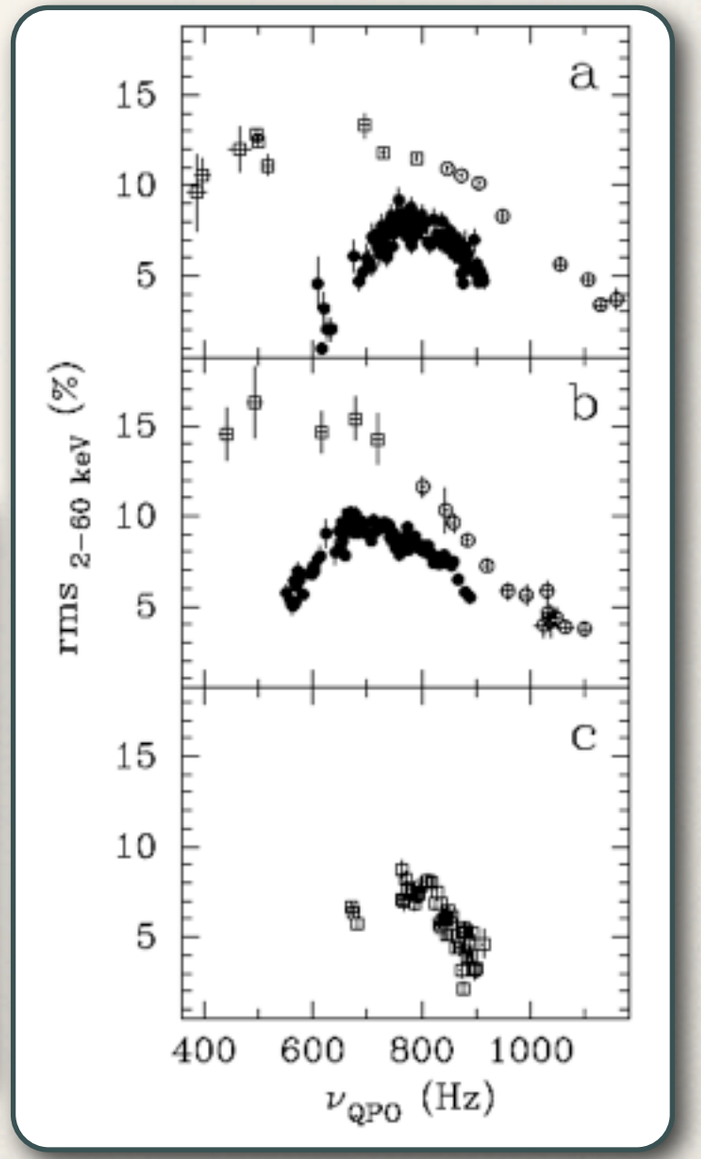


kHz QPO: basic properties

- Seen in nearly all Z and atoll sources
- Twin peaks move in 200-1200 Hz range
- Difference almost constant?
- At extreme frequencies, only one peak

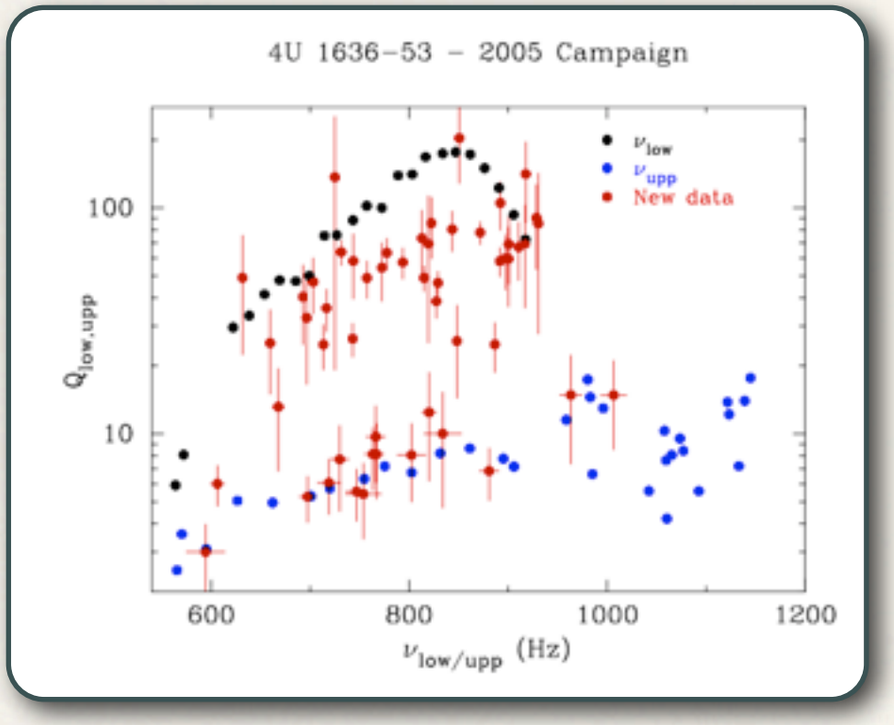


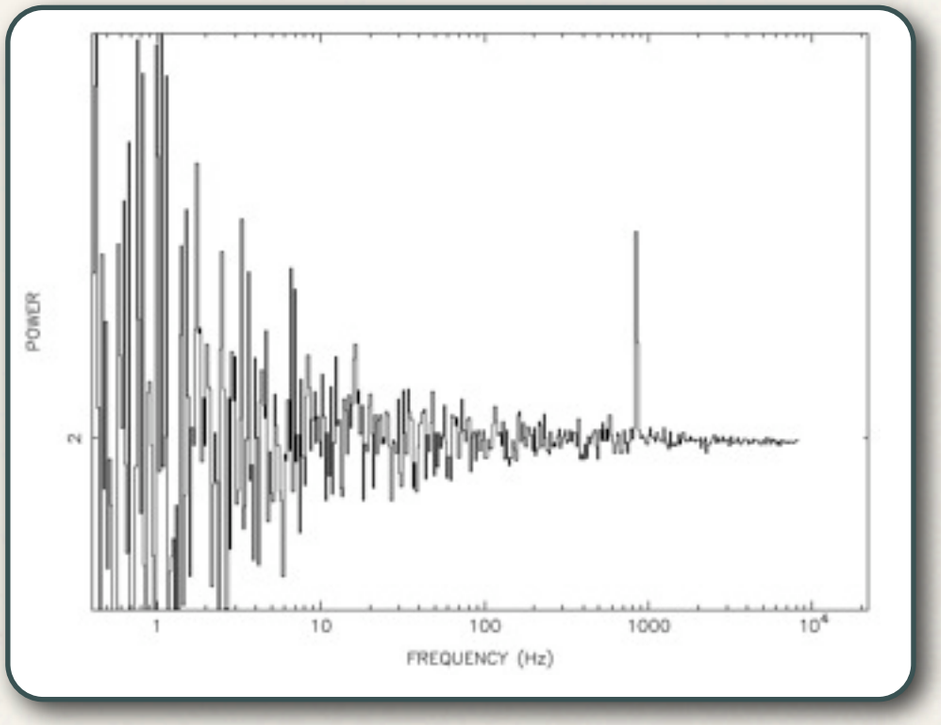




kHz QPO: basic properties

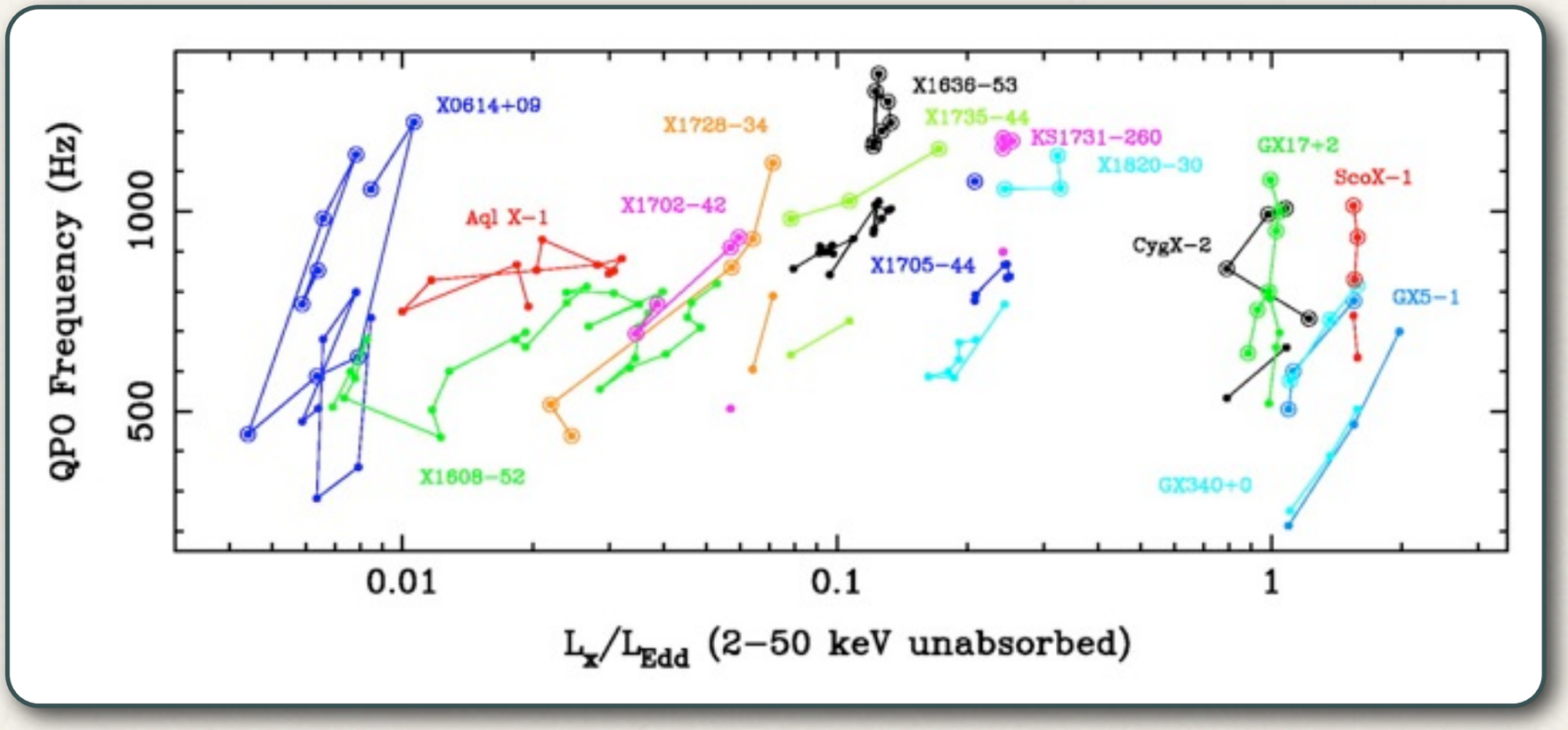
- Q factor can be as high as 200





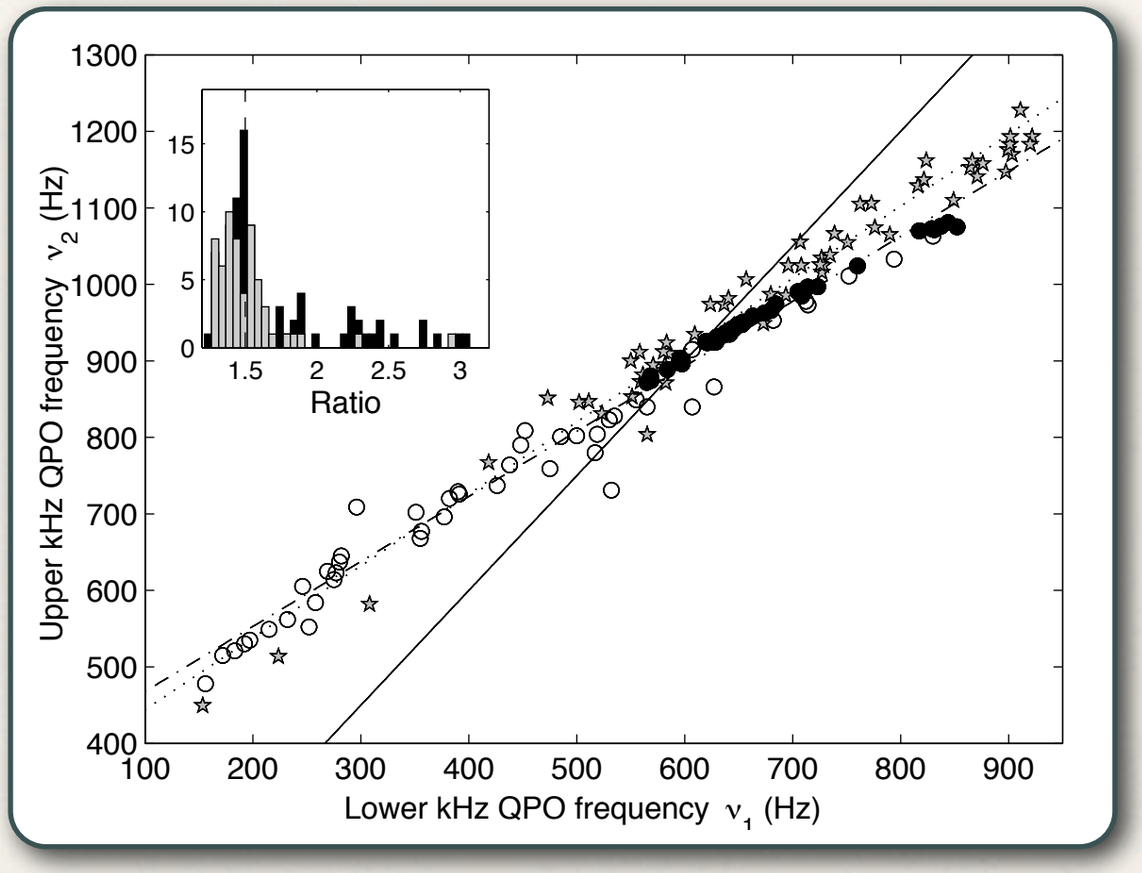
kHz QPO: basic properties

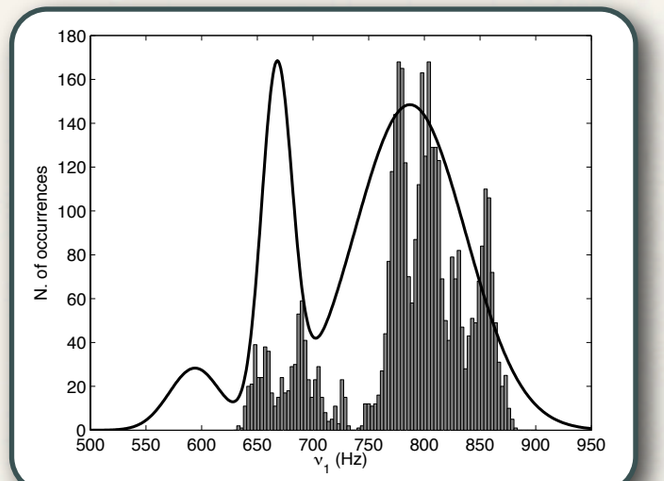
- Frequency shift on “parallel tracks”

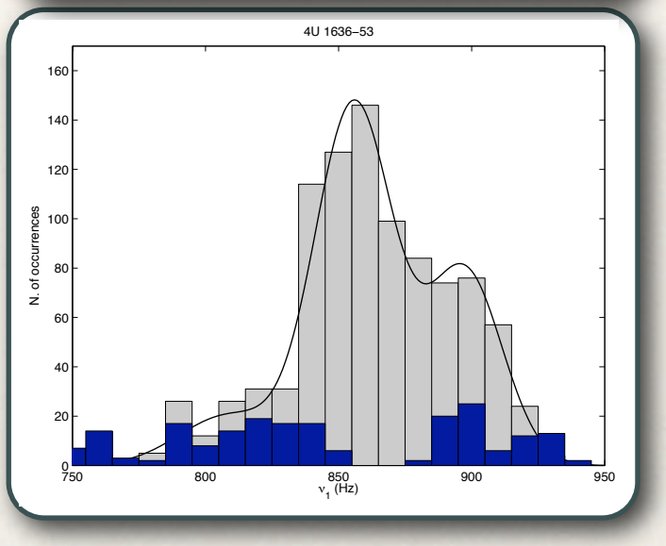


kHz QPO: basic properties

- No preferred frequency or frequency ratio

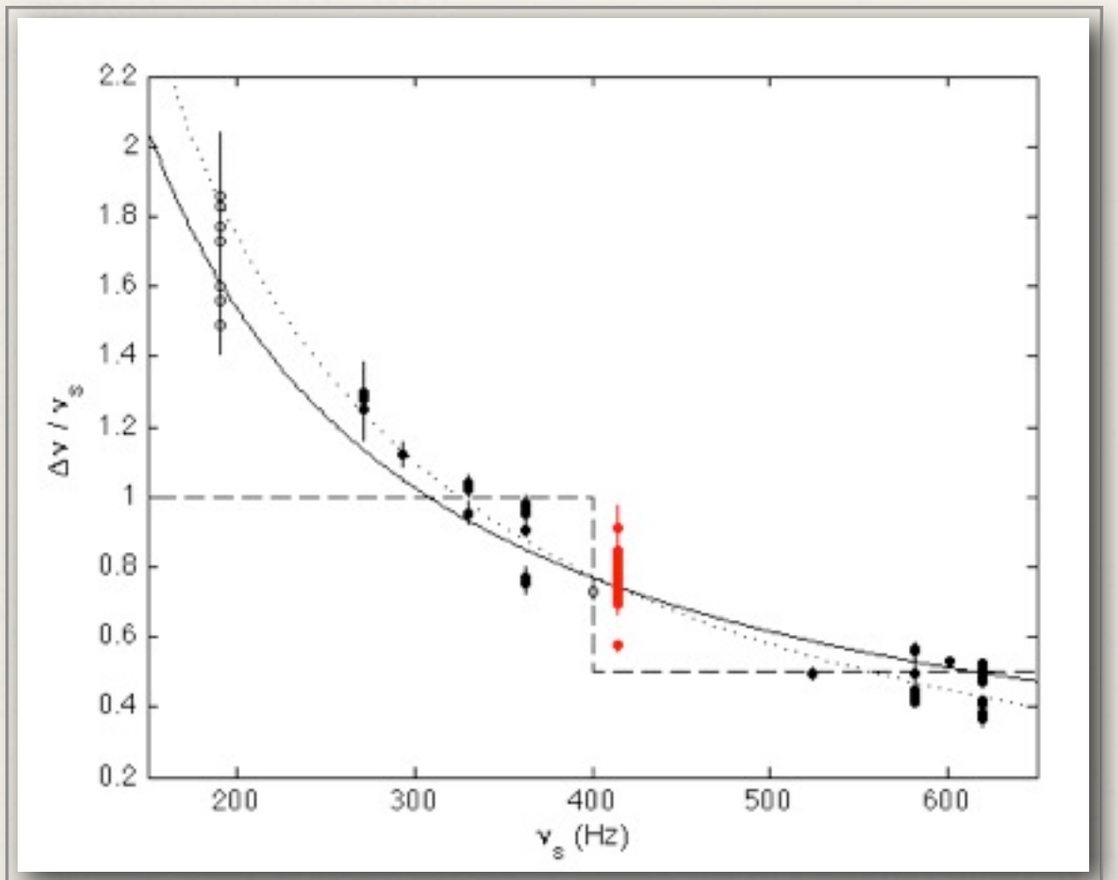


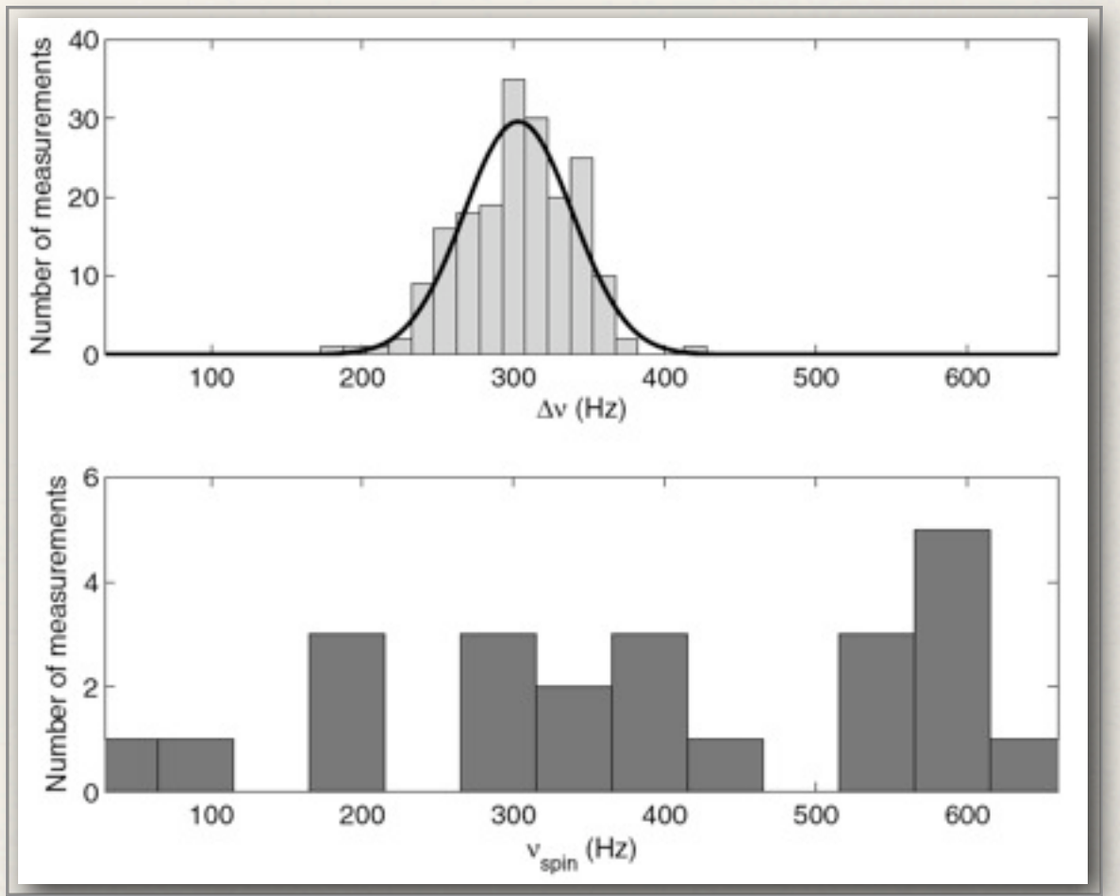




kHz QPO: basic properties

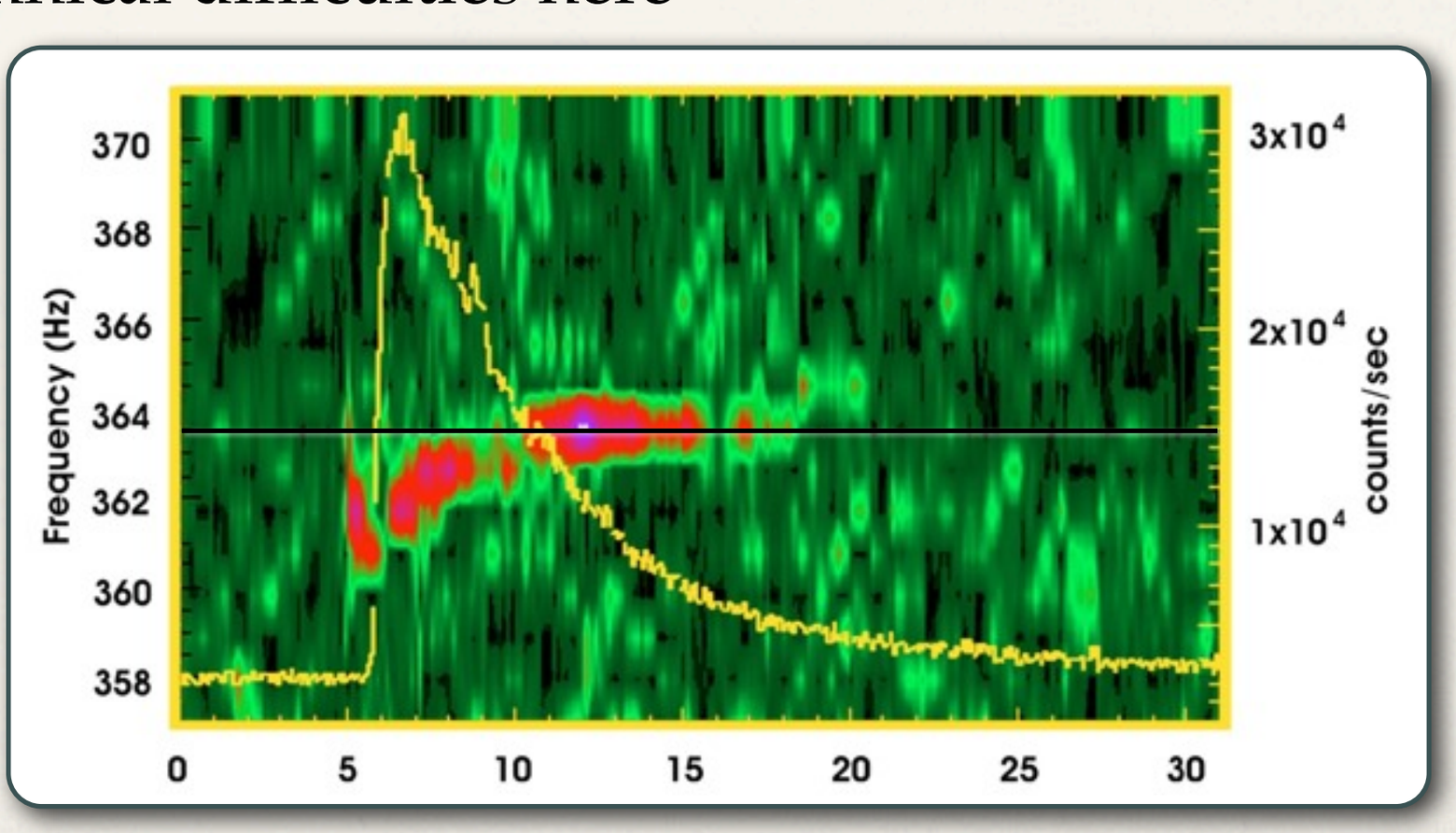
- Relation to source spin?





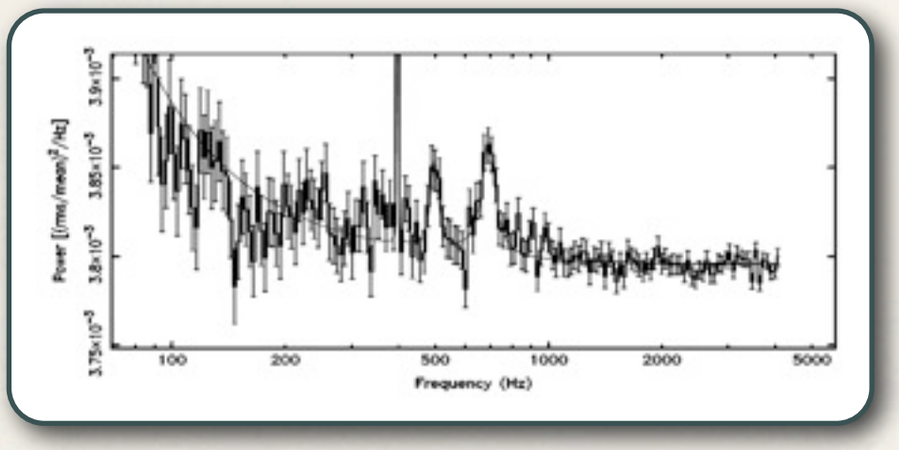
Burst oscillations

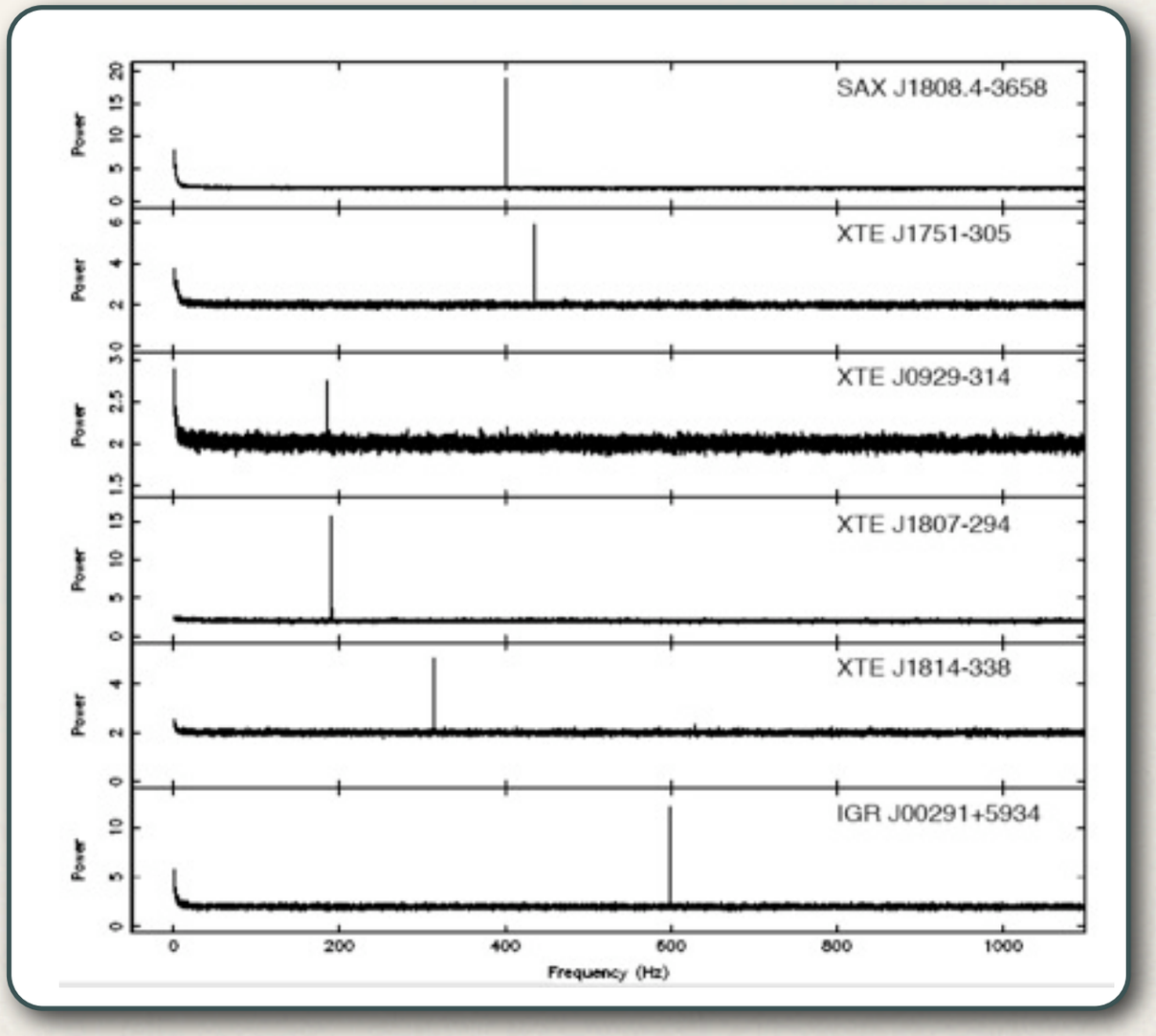
- Coherent oscillations
- Give characteristic frequency
- Lot of technical difficulties here



Accreting msec pulsars

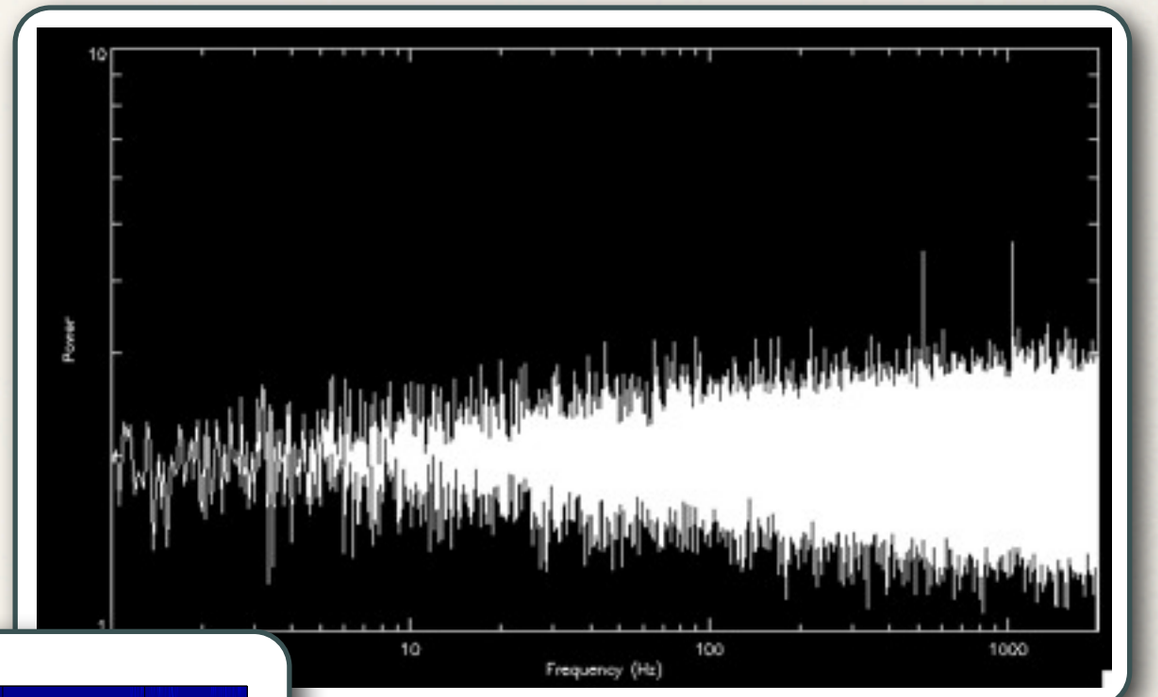
- In 1999 first one found
- 14 known to date
- Faint transients
- 200-600 Hz pulsations

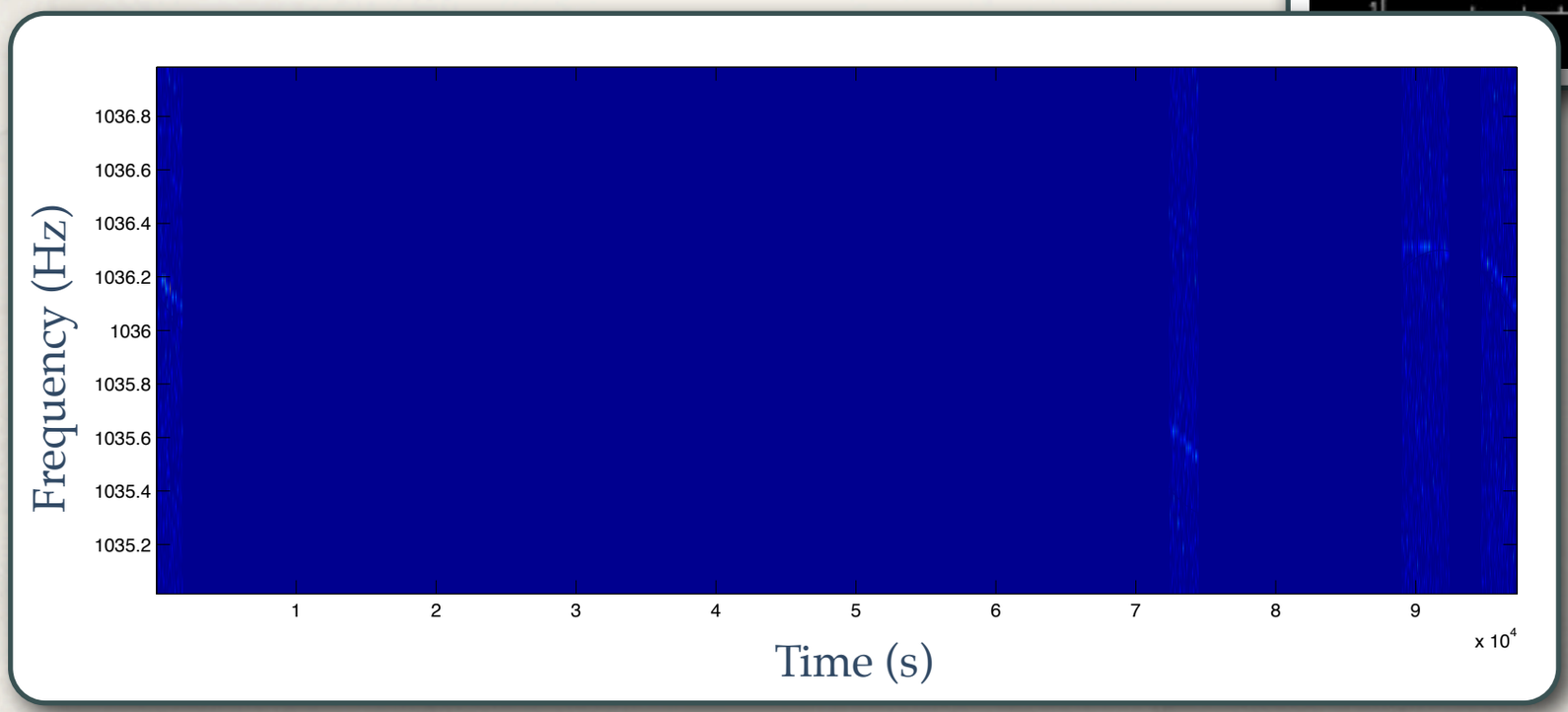




The latest: Swift J1749.4-2807

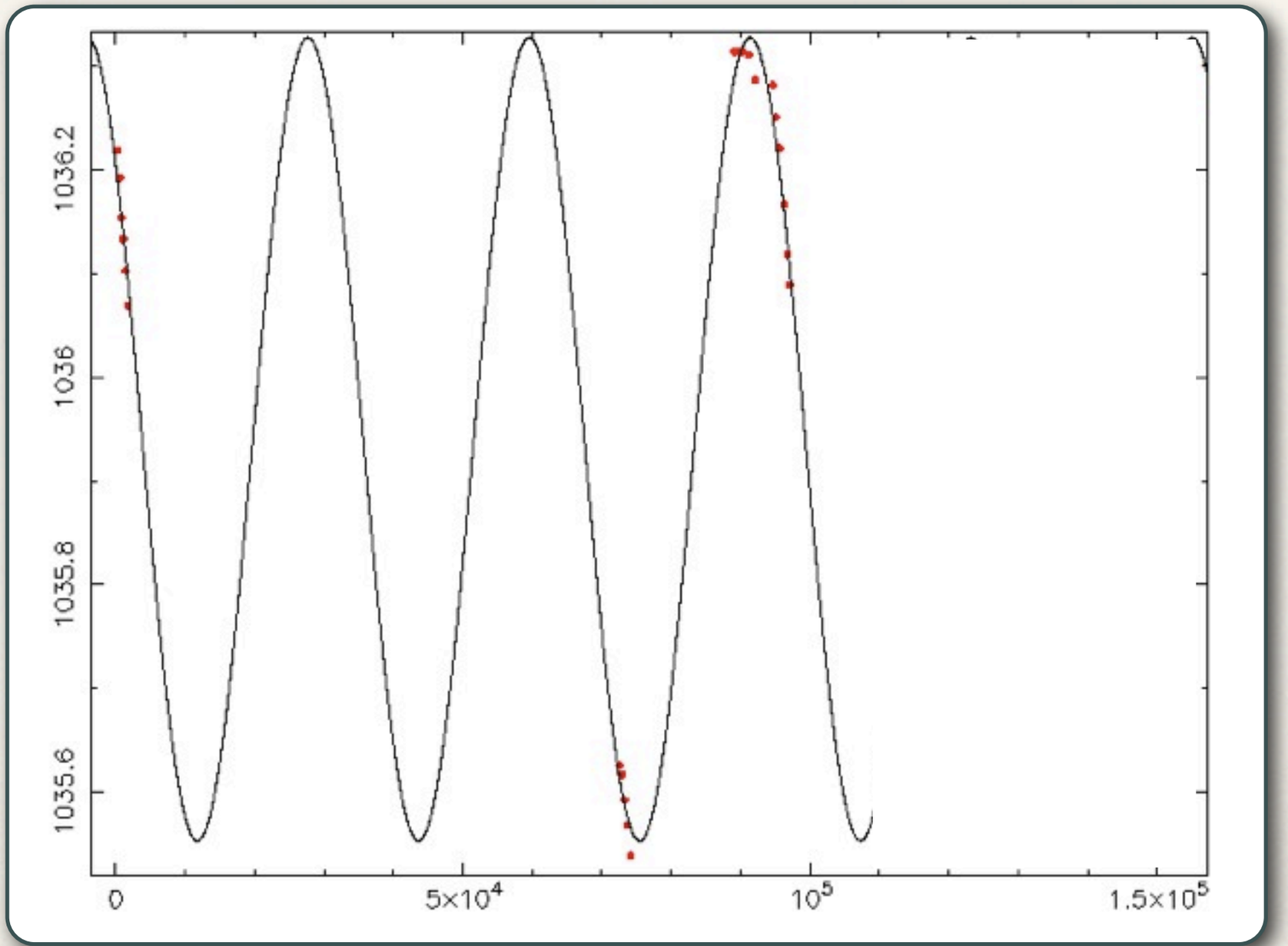
- Pulse: 518 Hz (1036 Hz harmonic)
- Orbit:





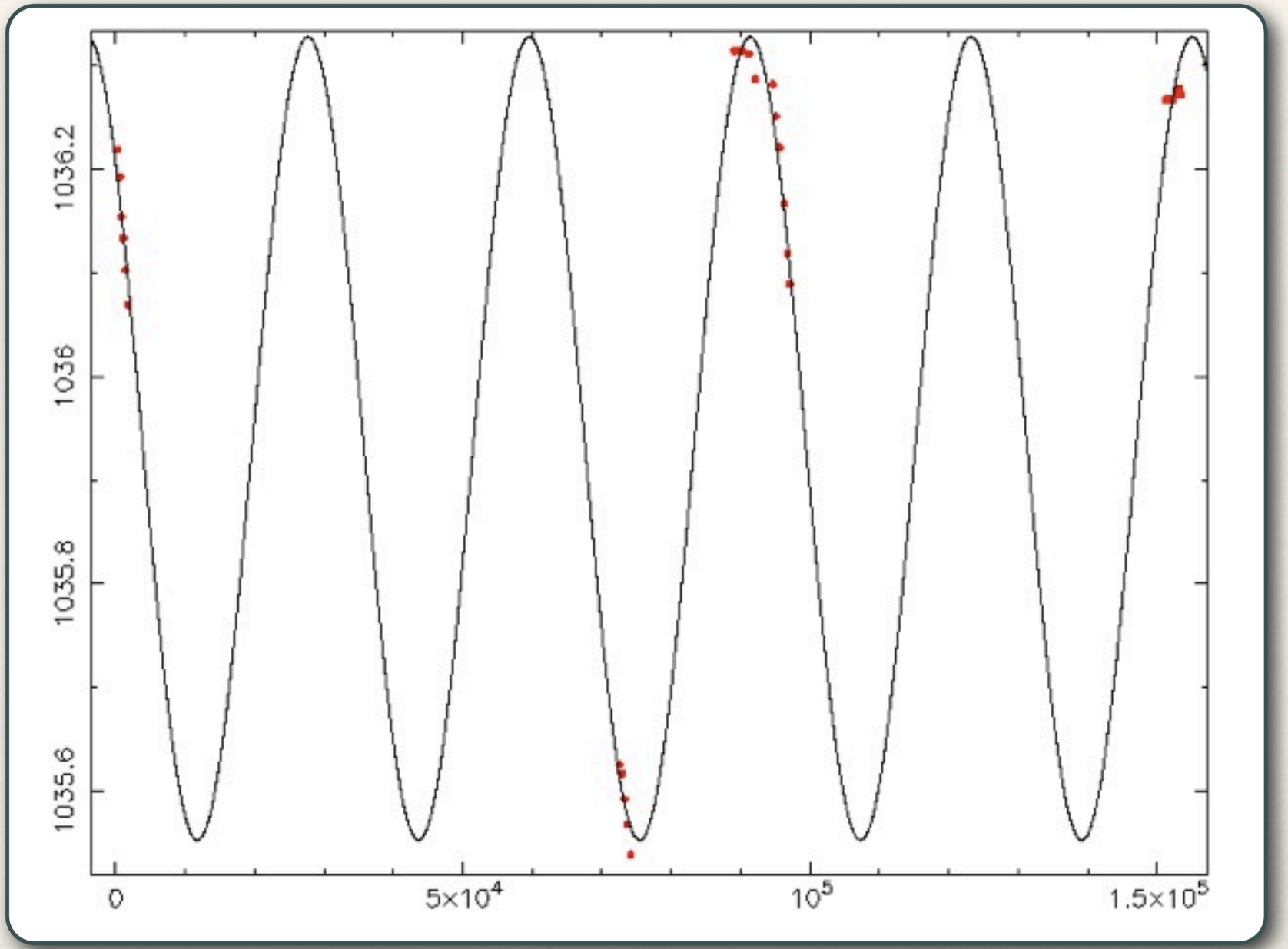
Orbit carpentry

- No barycentric correction



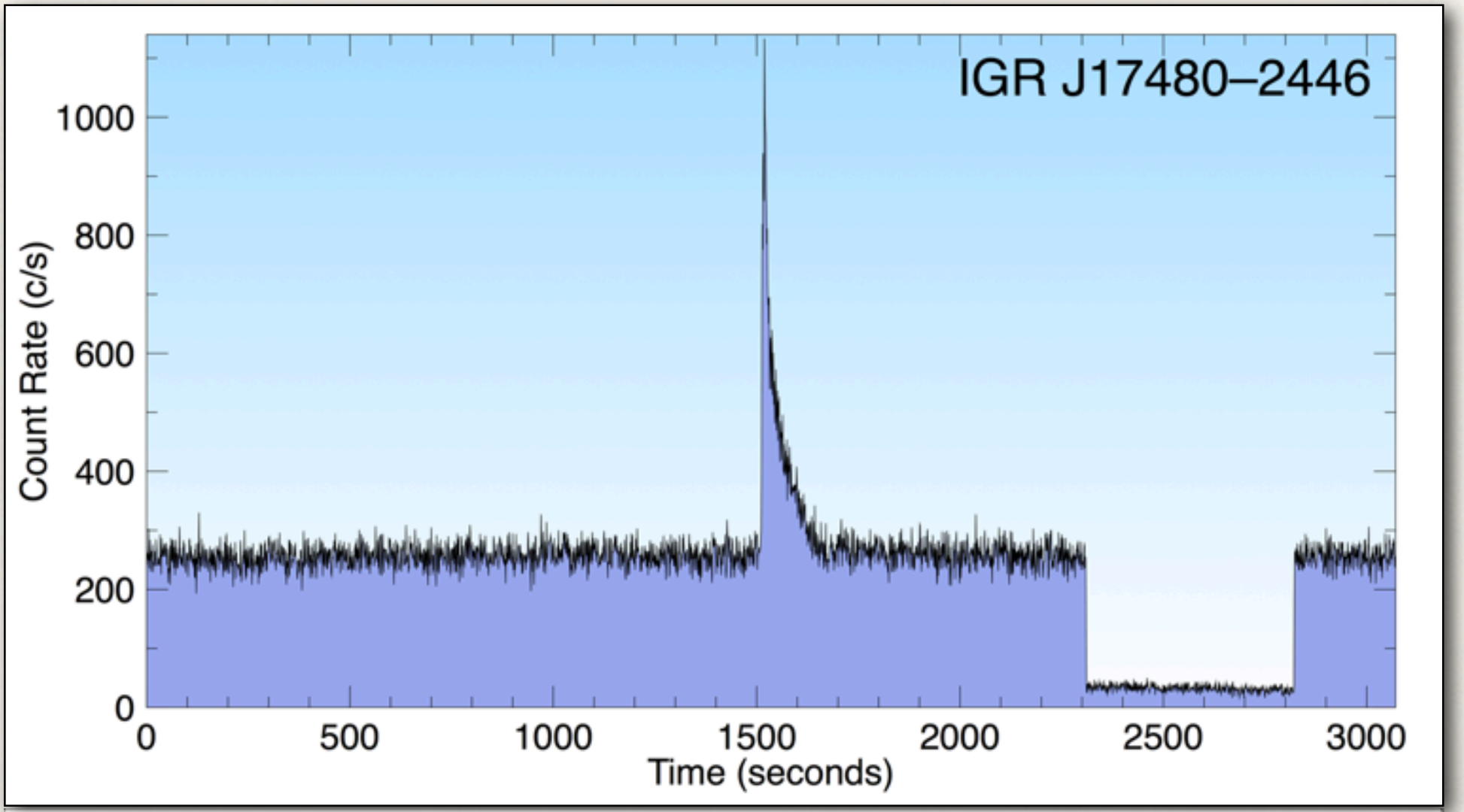
Orbit carpentry

- No barycentric correction



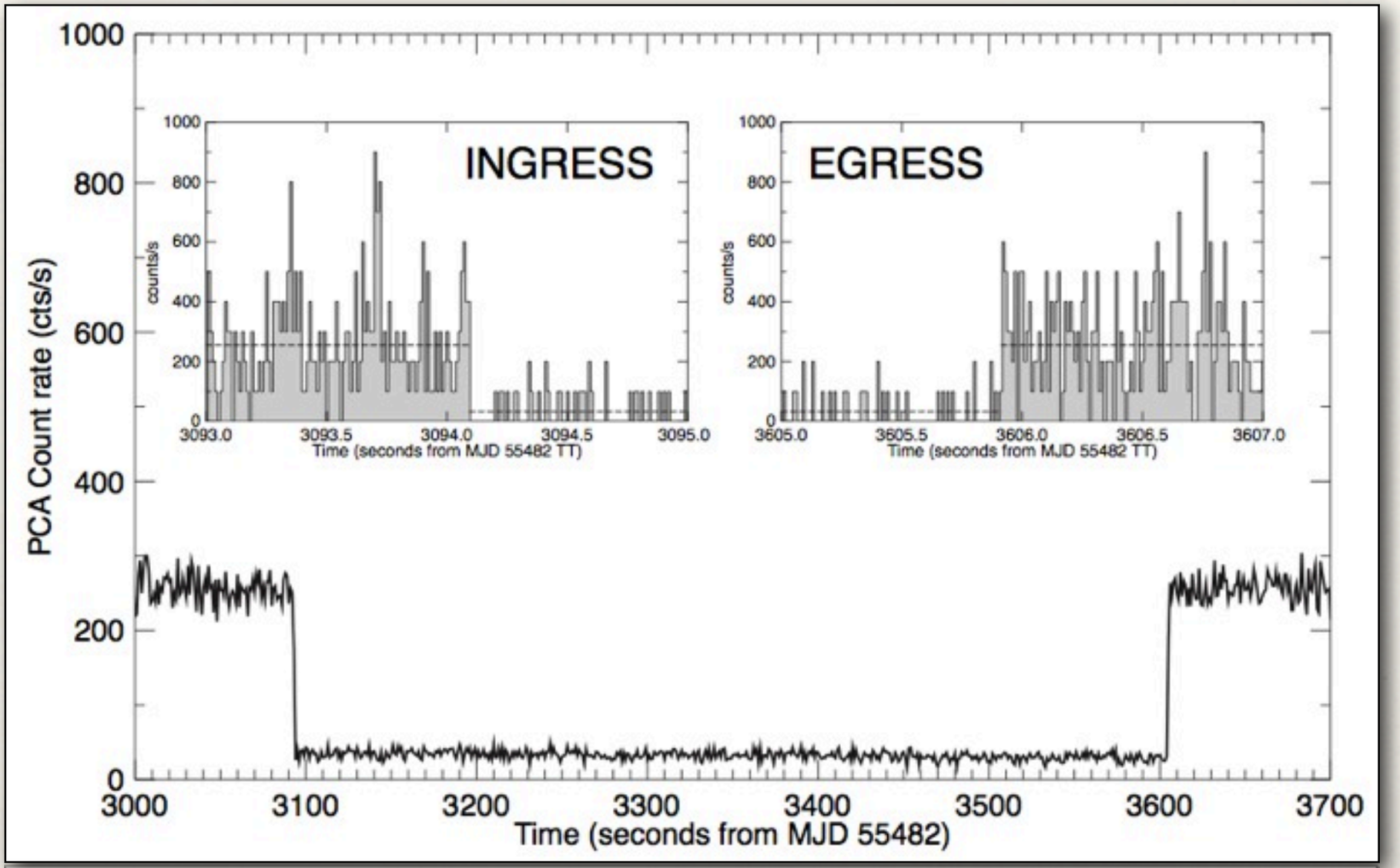
Different timing analysis

- October 2010: a new eclipsing transient accreting ms pulsar

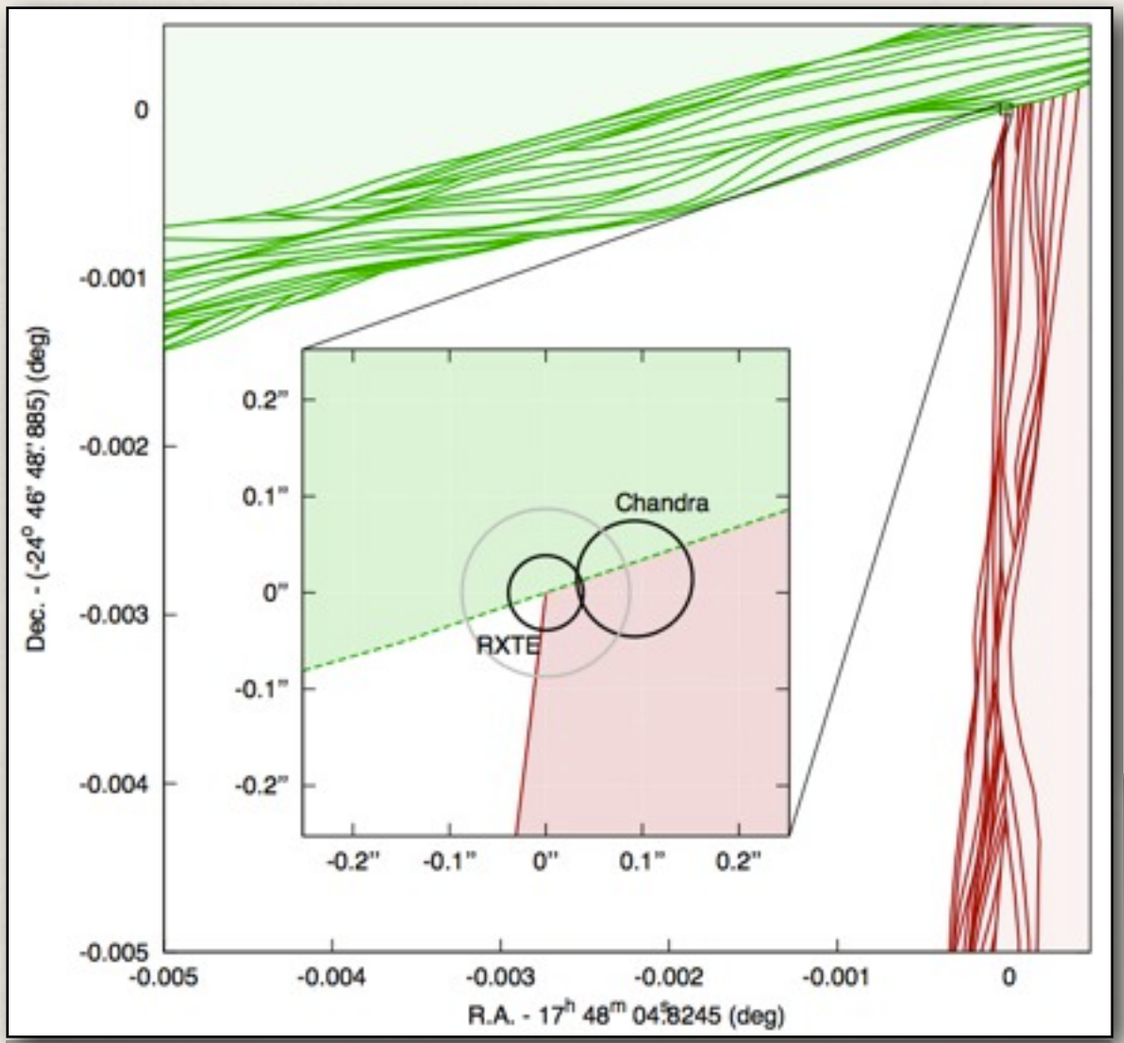


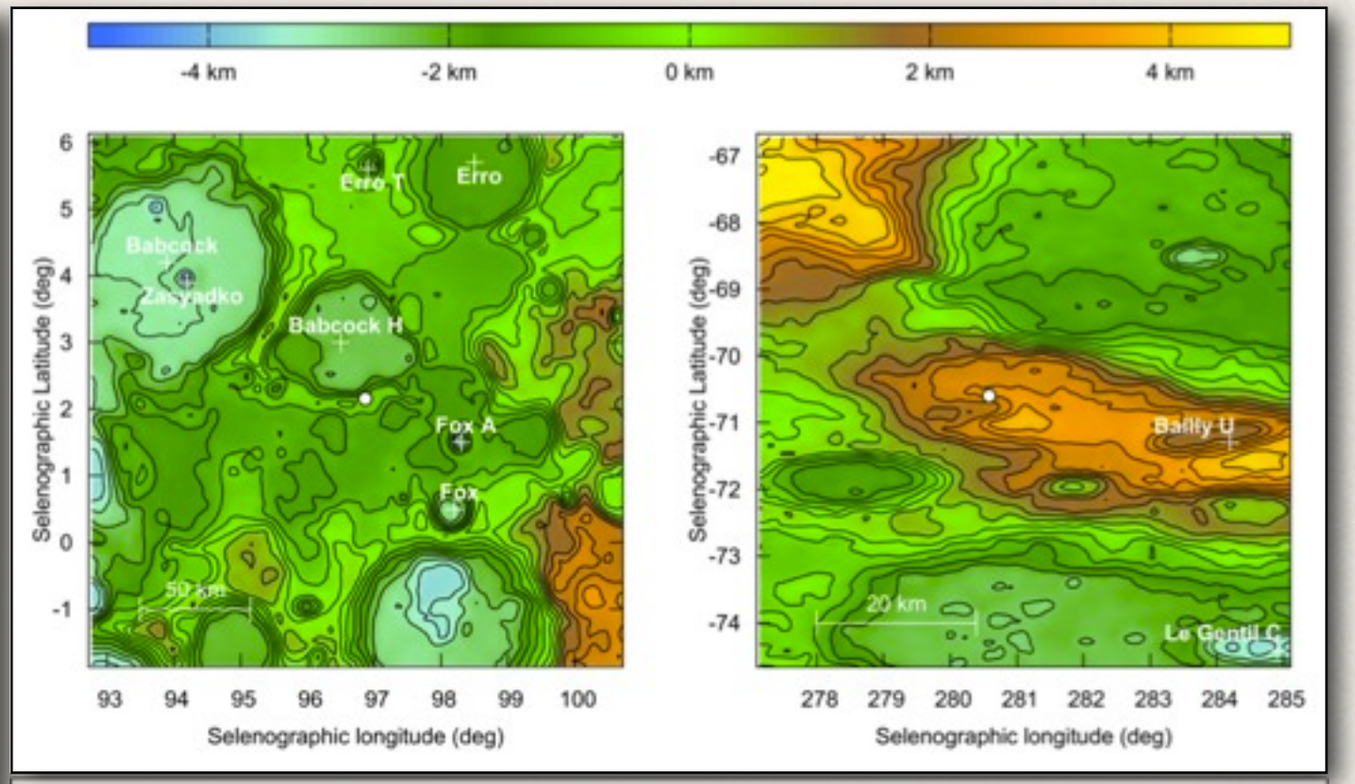
Serendipitous moon occultation

- Requires precise absolute timing



I did not ask for the moon...

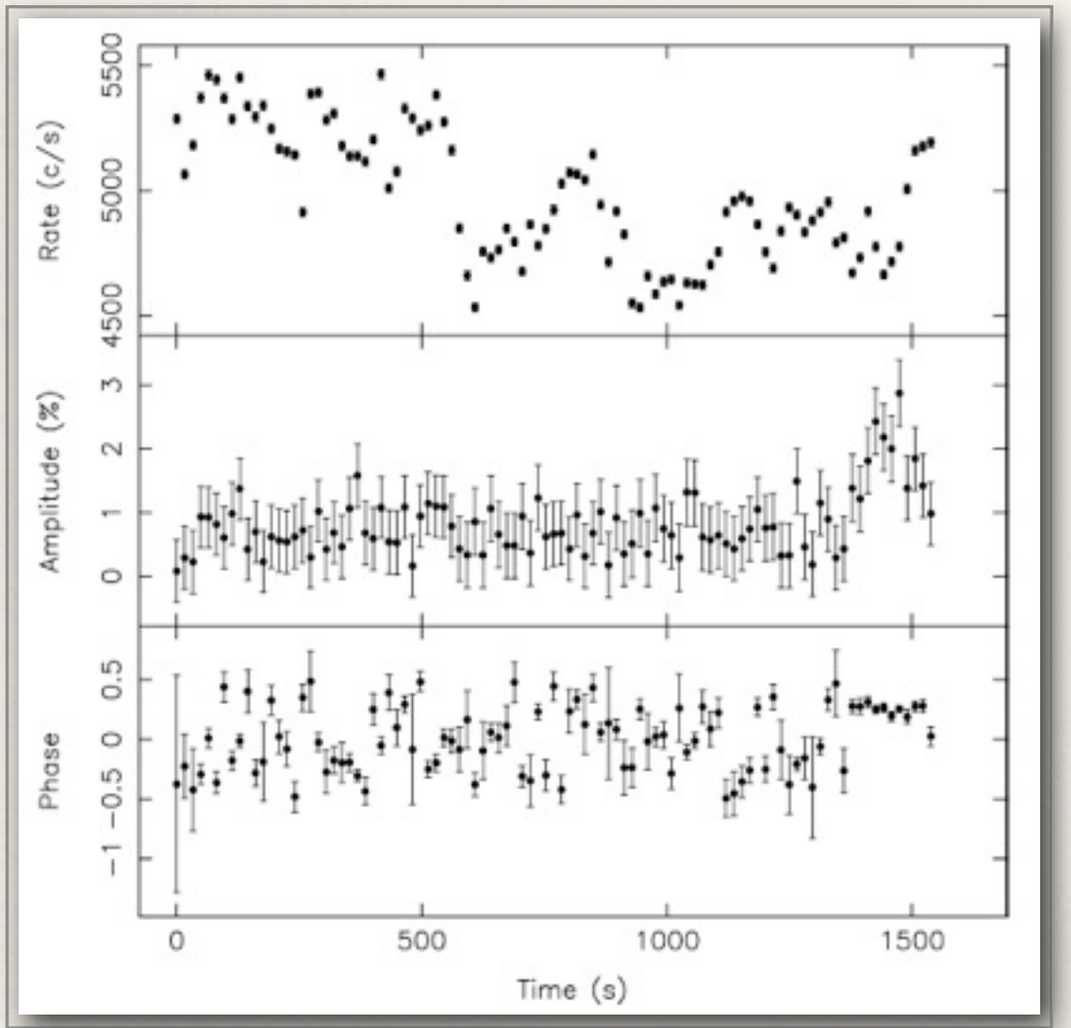


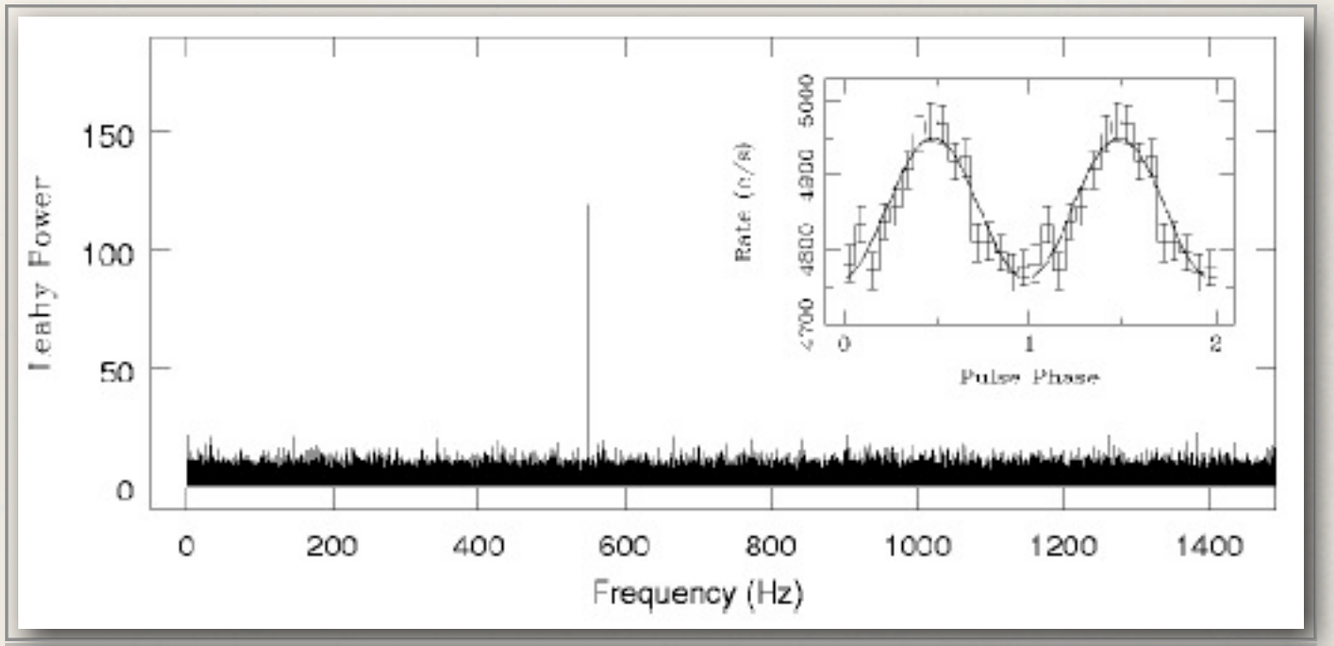


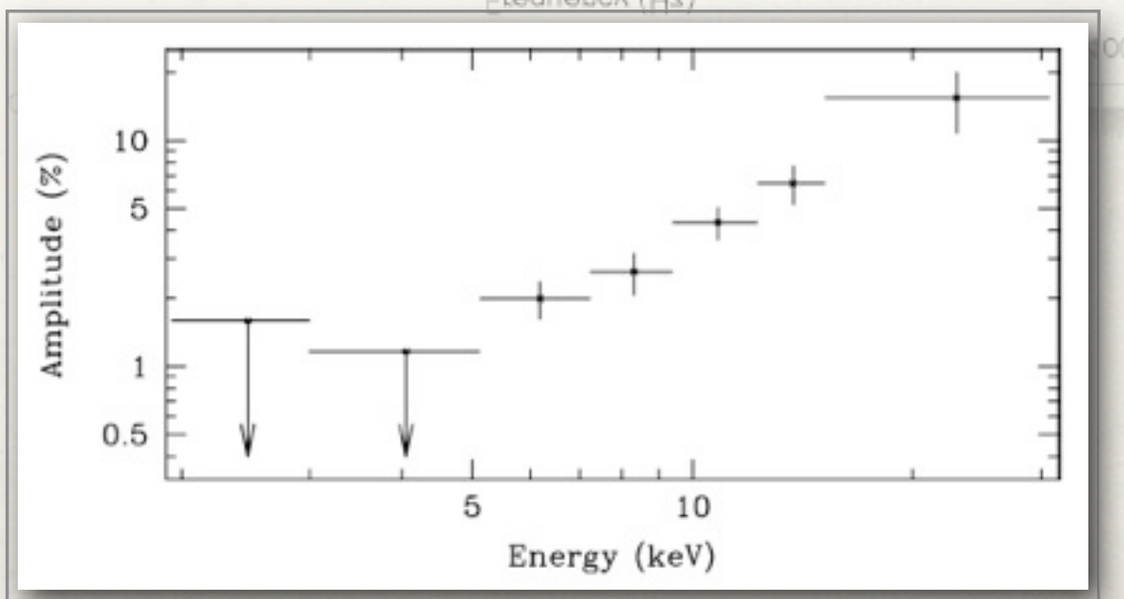
Positional accuracy: 40 μas

Transient pulsations

- Two cases in 2008
- Aquila X-1





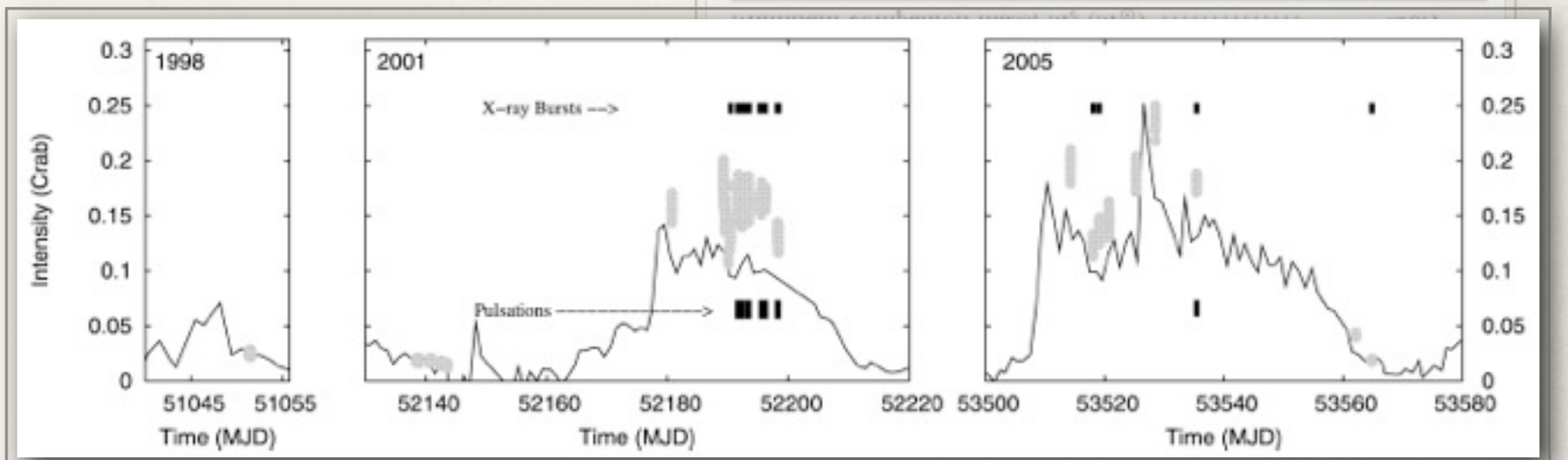


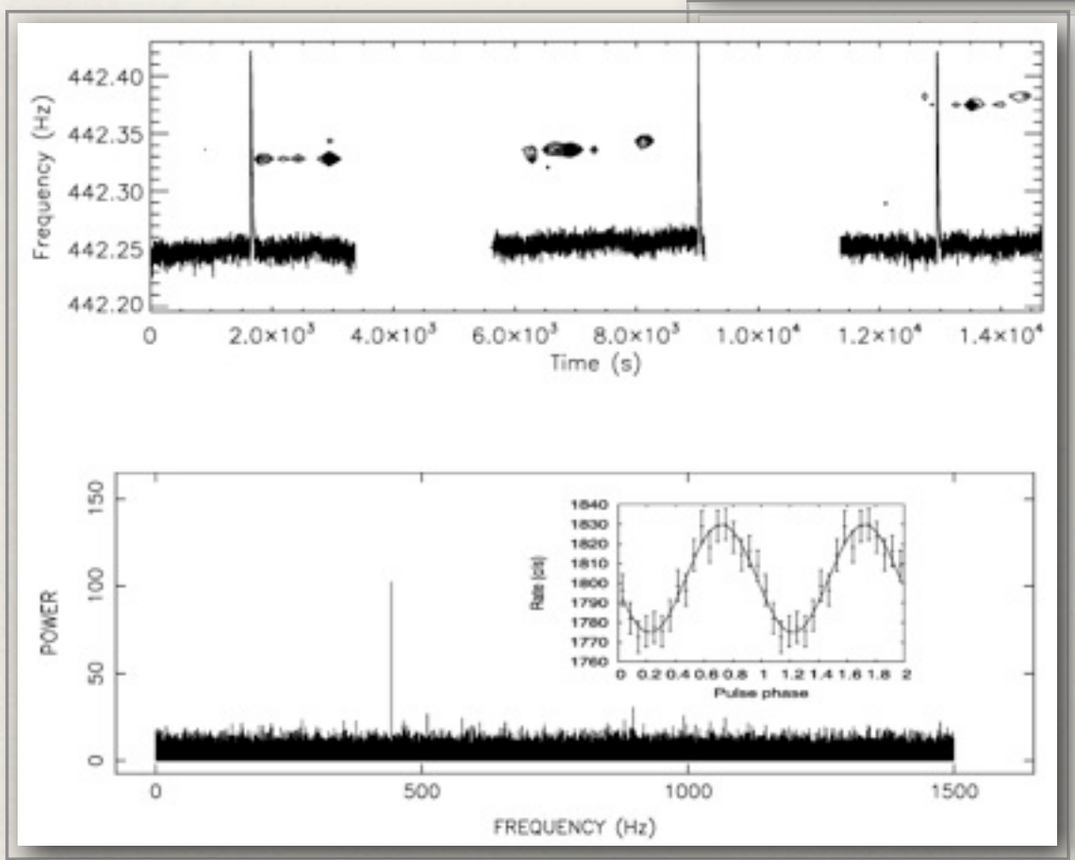
Transient pulsations

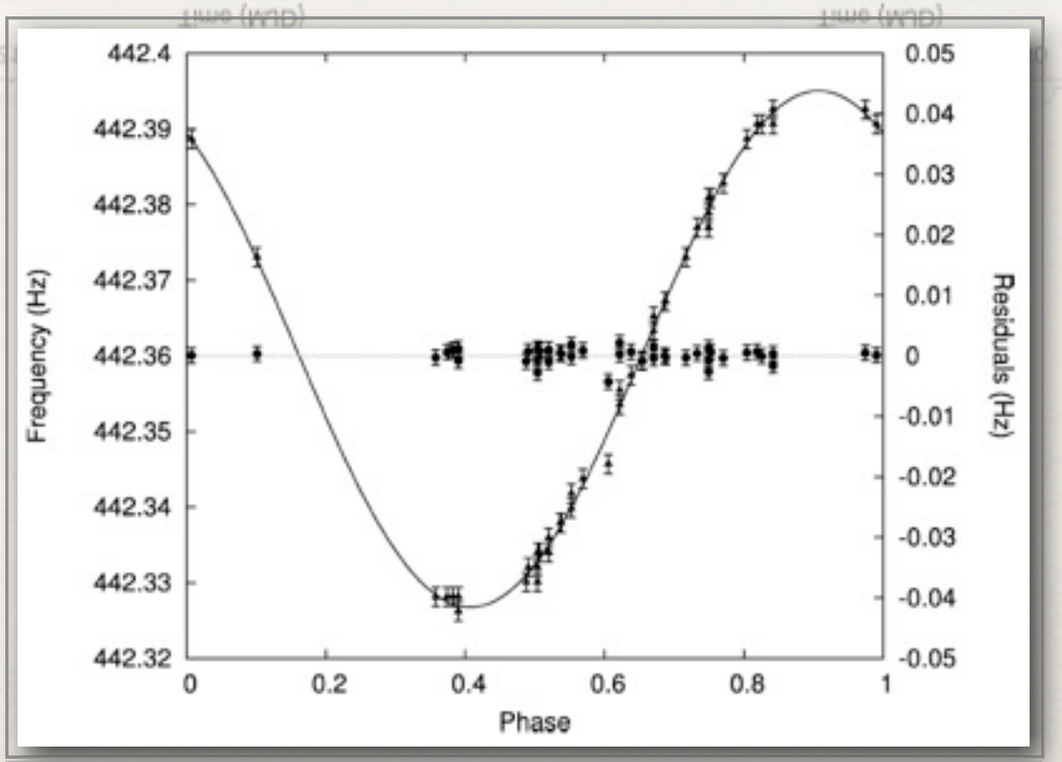
- SAX J1748.9-2021

TIMING PARAMETERS FOR NGC 6440

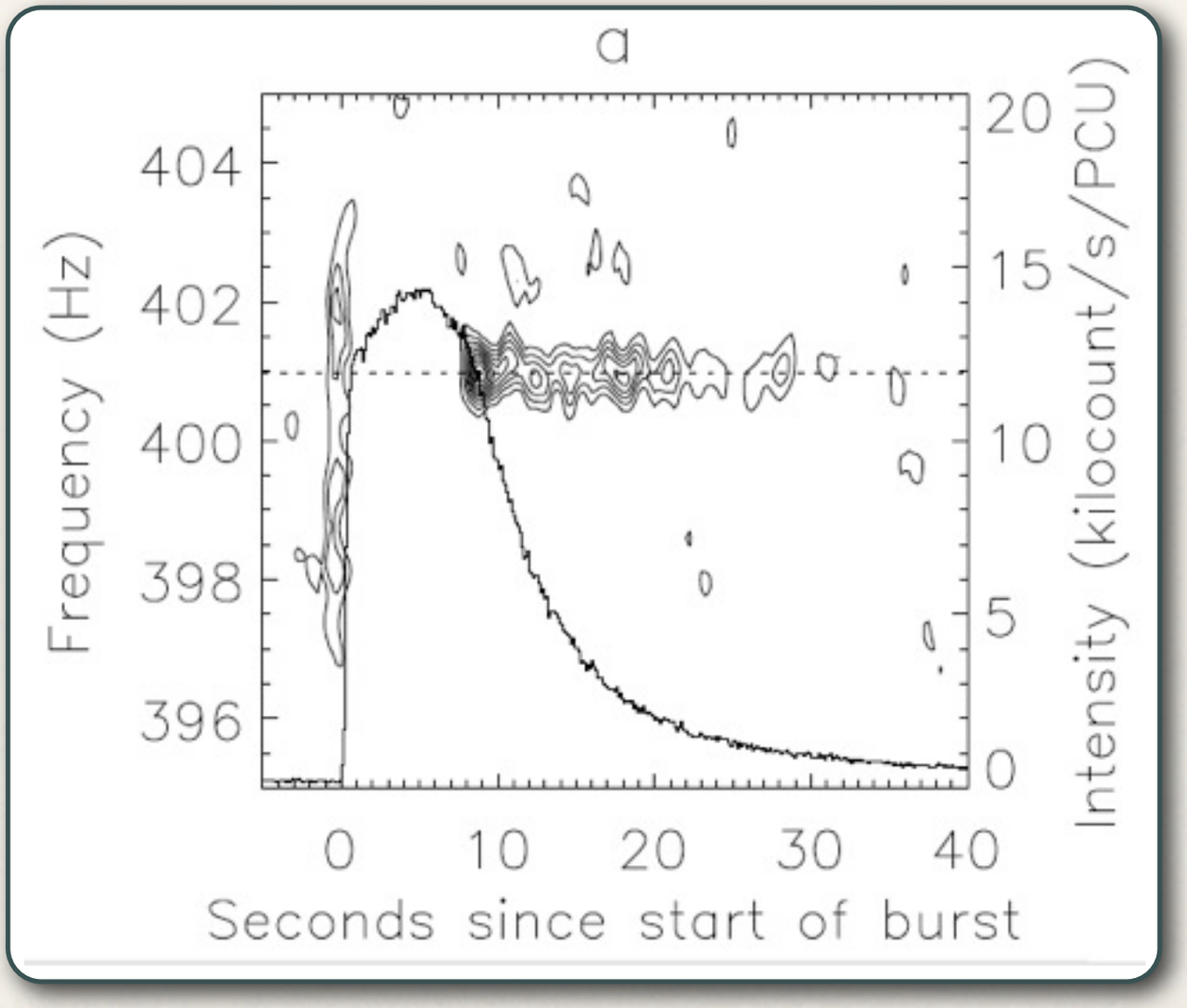
Parameter	Value
Orbital period, P_{bi} (hr)	8.764(6)
Projected semimajor axis, $a_x \sin i$ (lt-s)	0.39(1)
Epoch of 0° mean longitude,[a] T_0 (MJD/TDB)	52190.047(4)
Eccentricity, e	<0.001
Spin frequency, ν_0 (Hz)	442.361(1)
Pulsar mass function, f_x ($\times 10^{-4}\ M_\odot$)	≃4.8
Minimum companion mass, M_c ($M_\odot$)	≳0.1



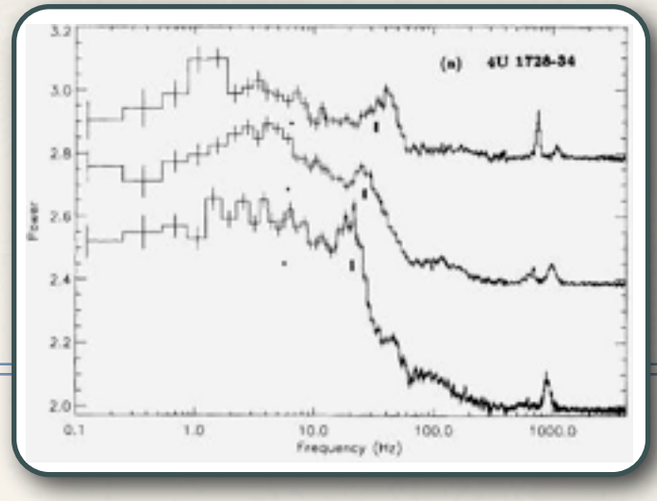




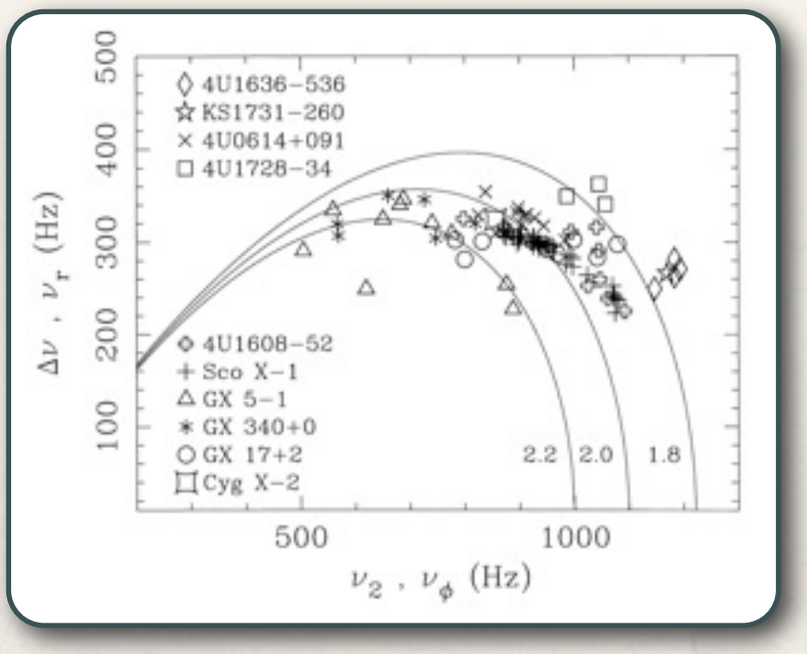
Burst oscillations & spin

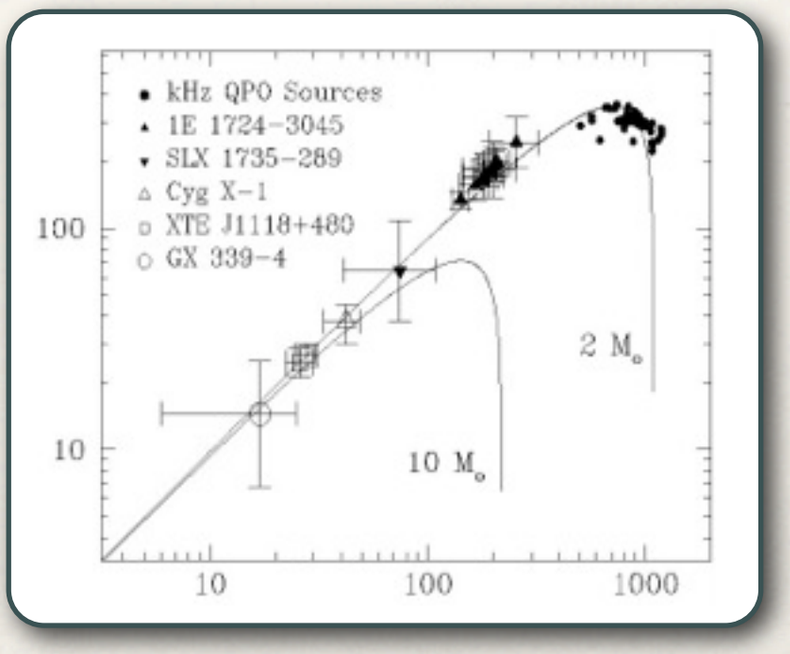


Theoretical models



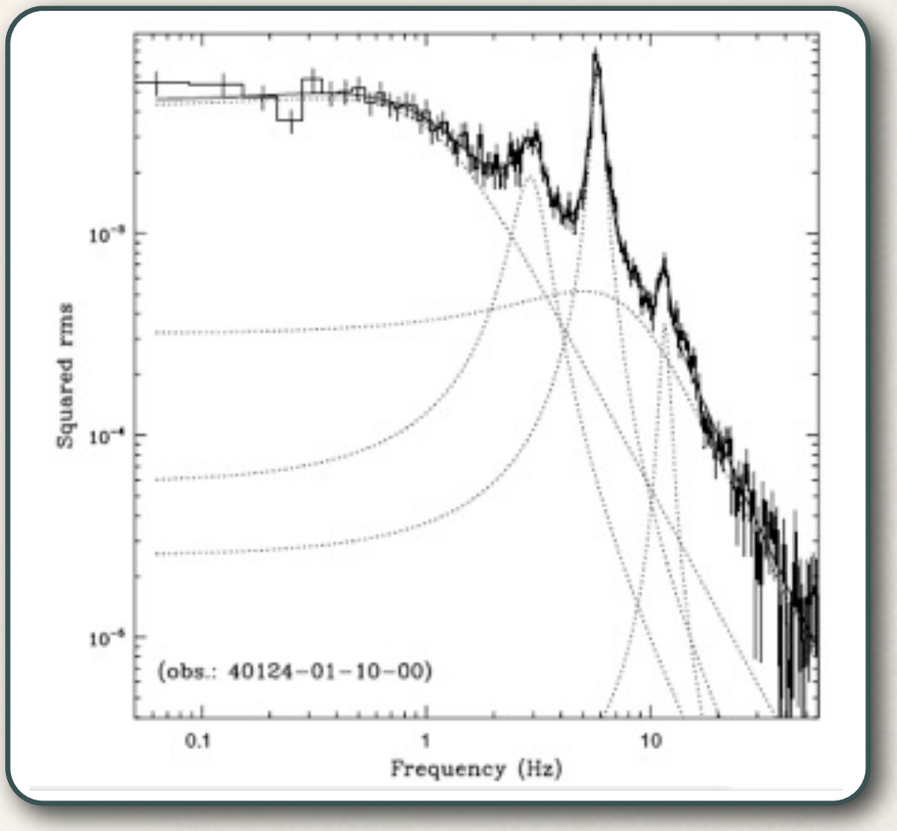
- Identification of frequencies (low-ν QPO, 2 kHz QPO)
- Relativistic Precession Model
- Basic GR frequencies: nodal precession, periastron precession, orbital

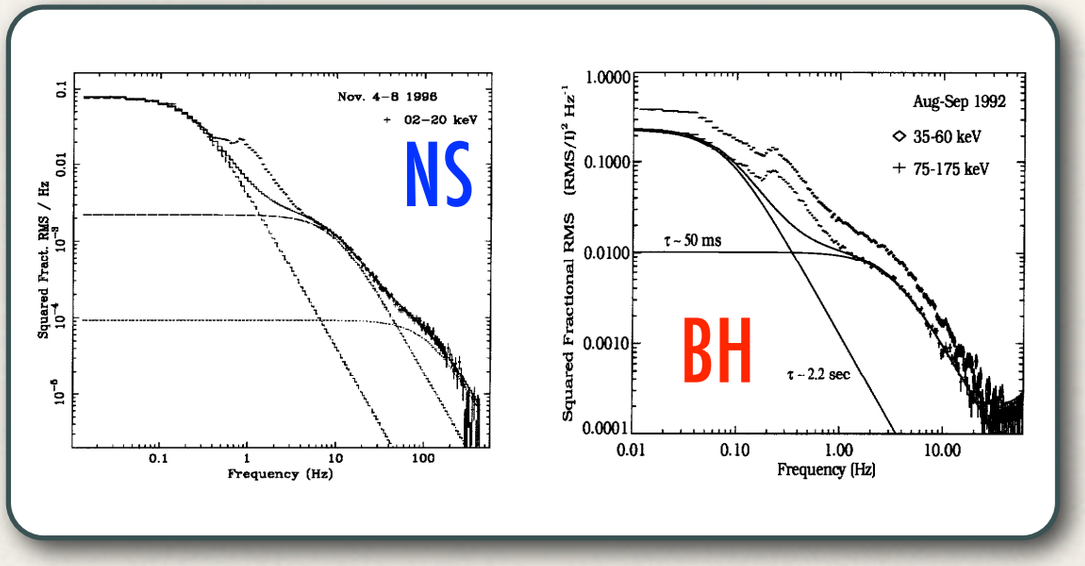




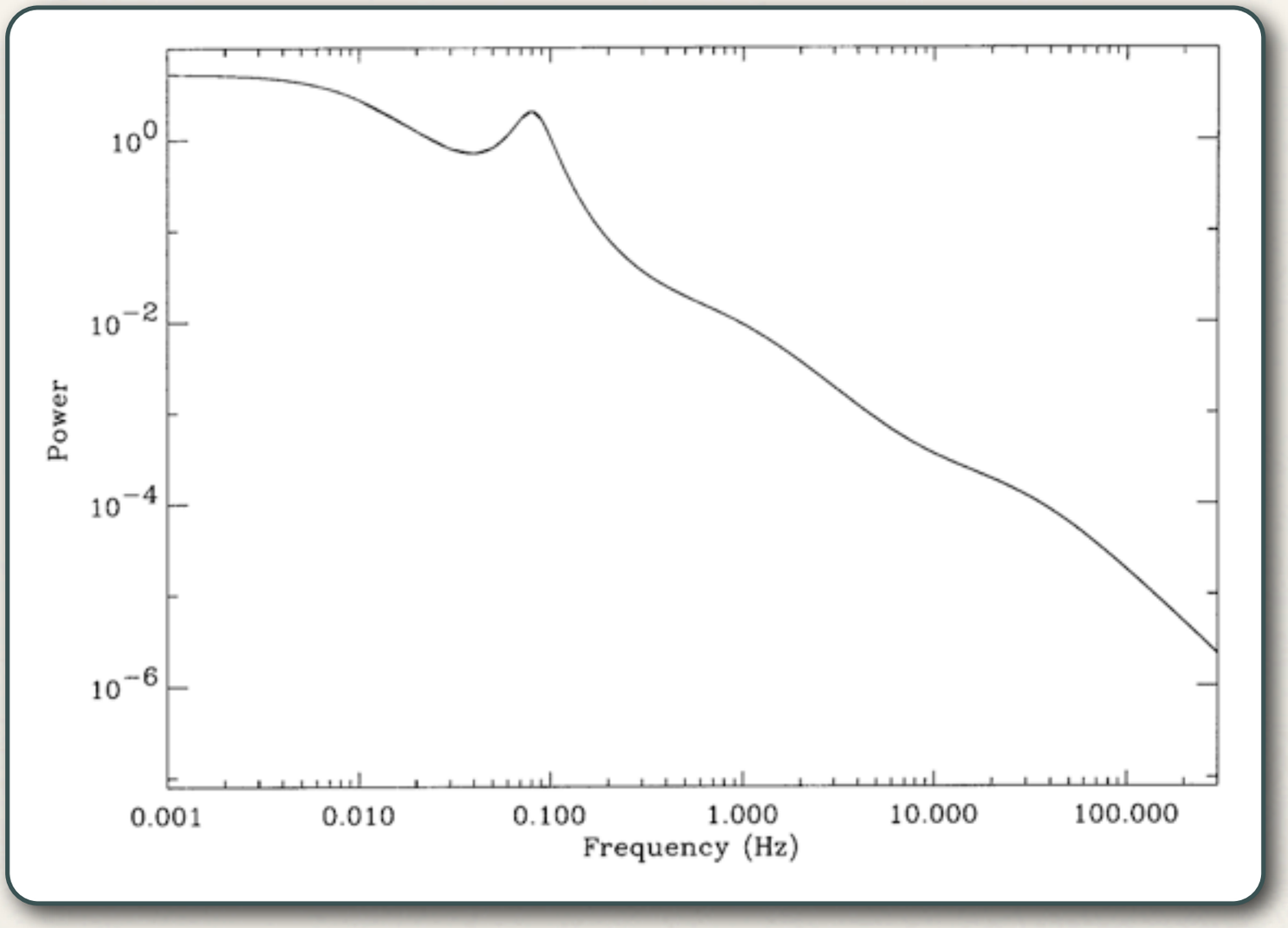
Black-hole binaries: noise

- In some states, flat-top noise
- Also low-ν QPO (next slide)
- Similar to low-L NS

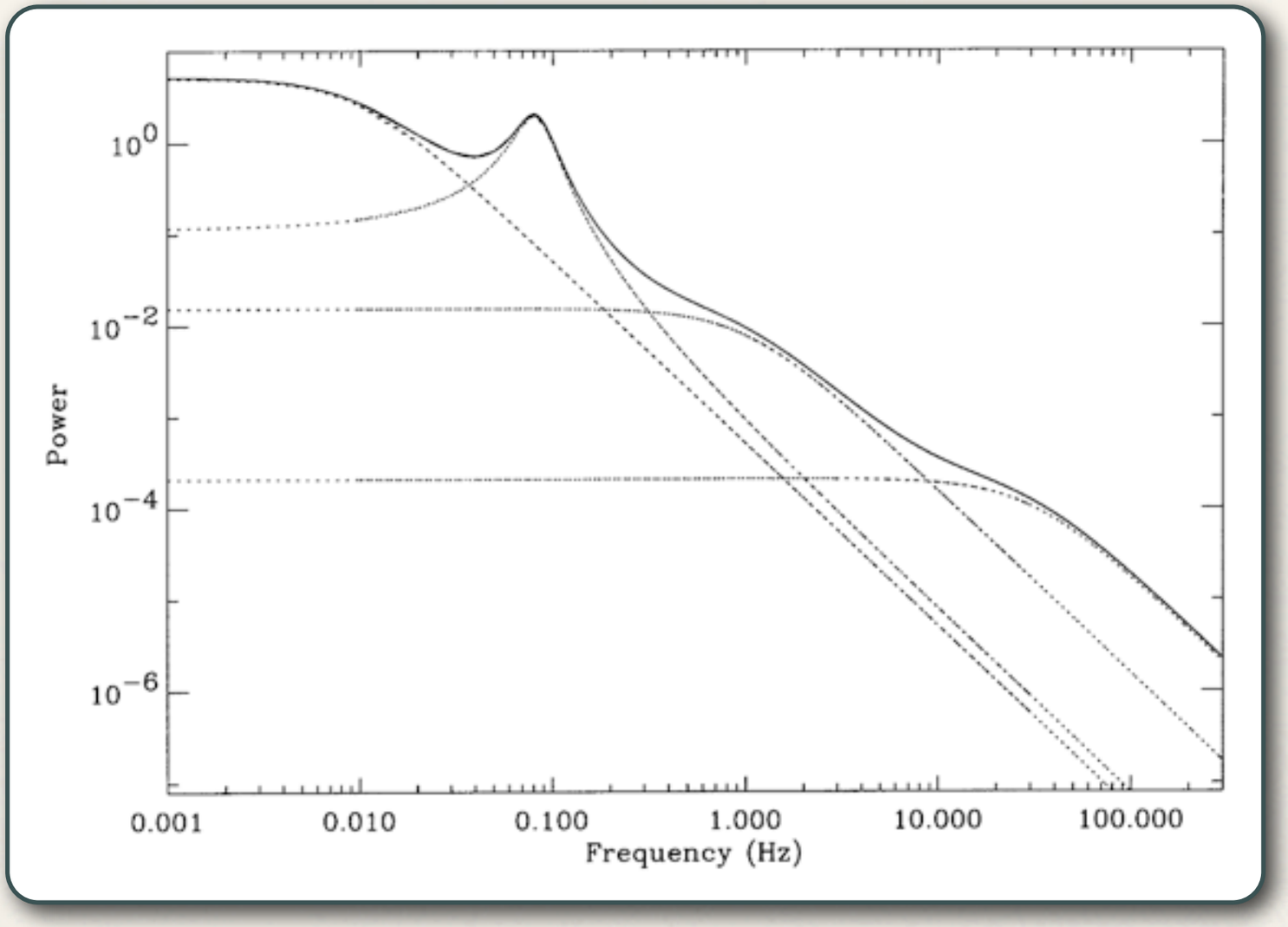




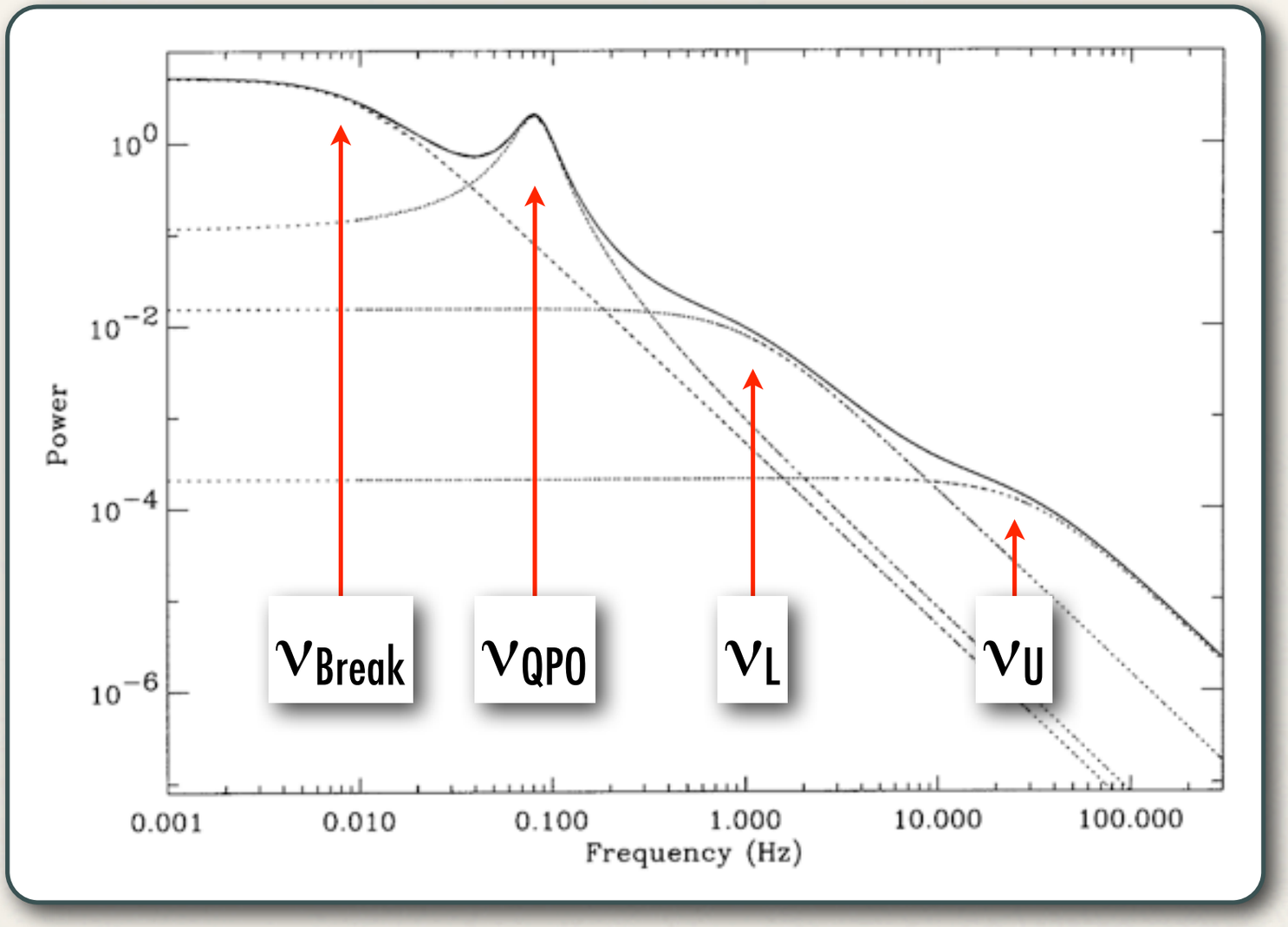
Black-hole binaries: noise



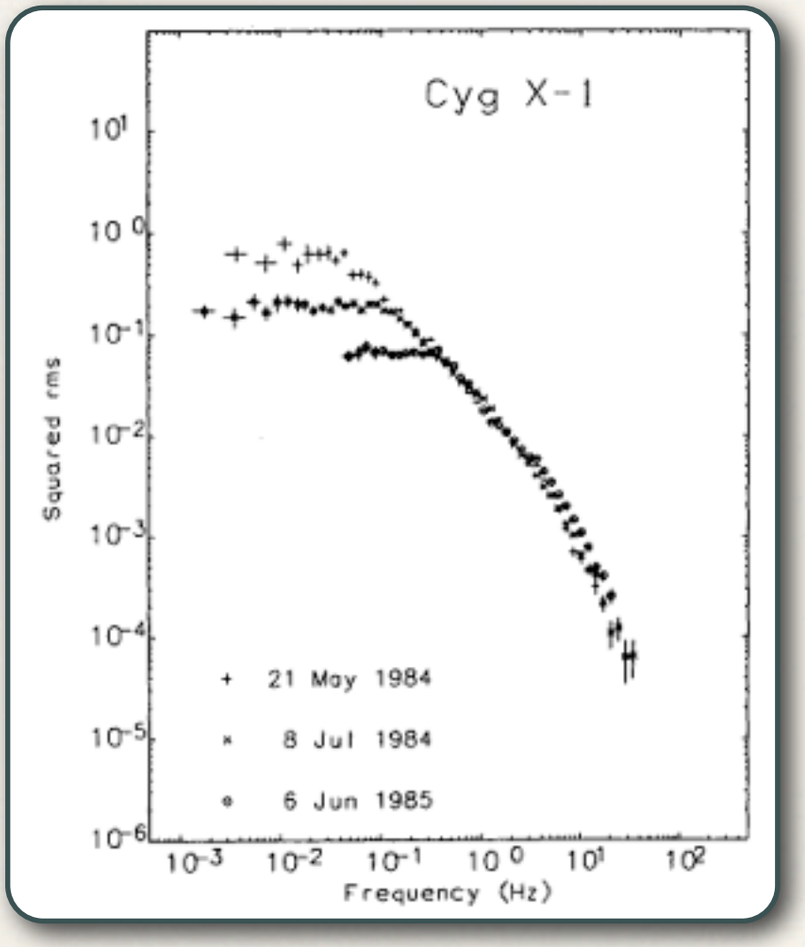
Black-hole binaries: noise

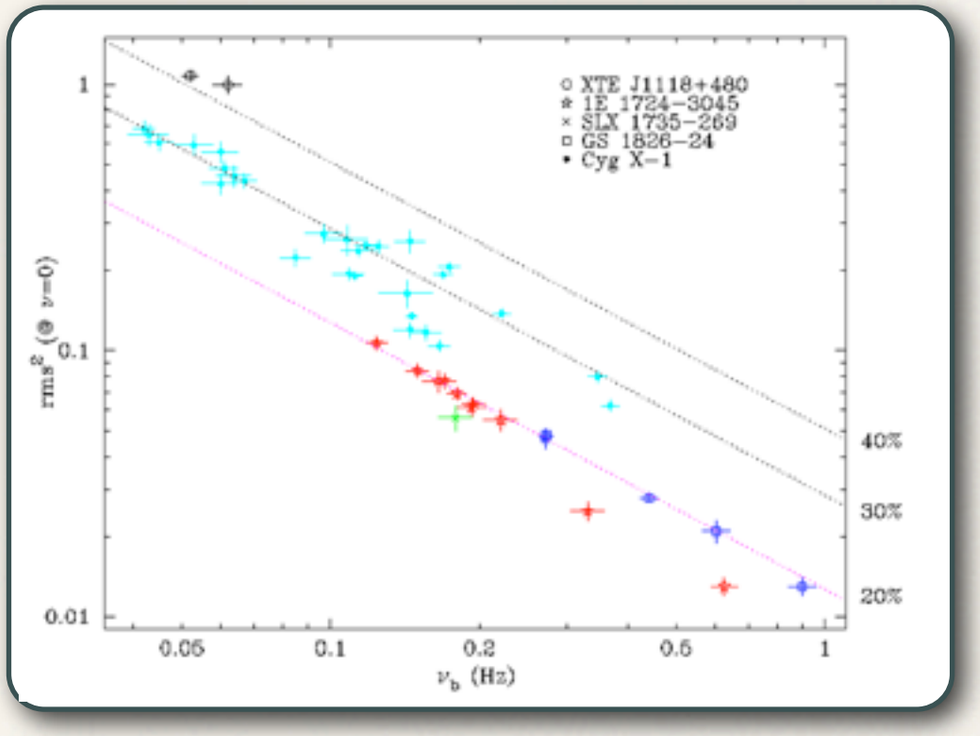


Black-hole binaries: noise



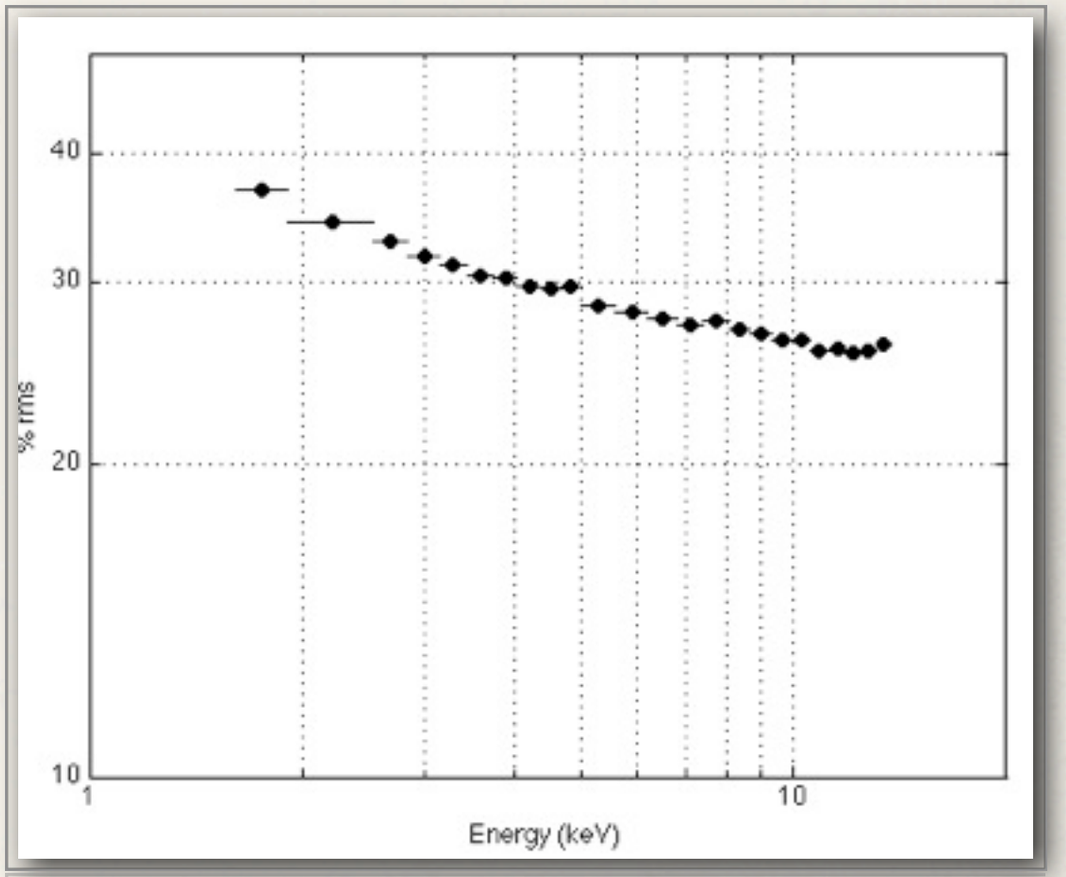
Black-hole binaries: noise

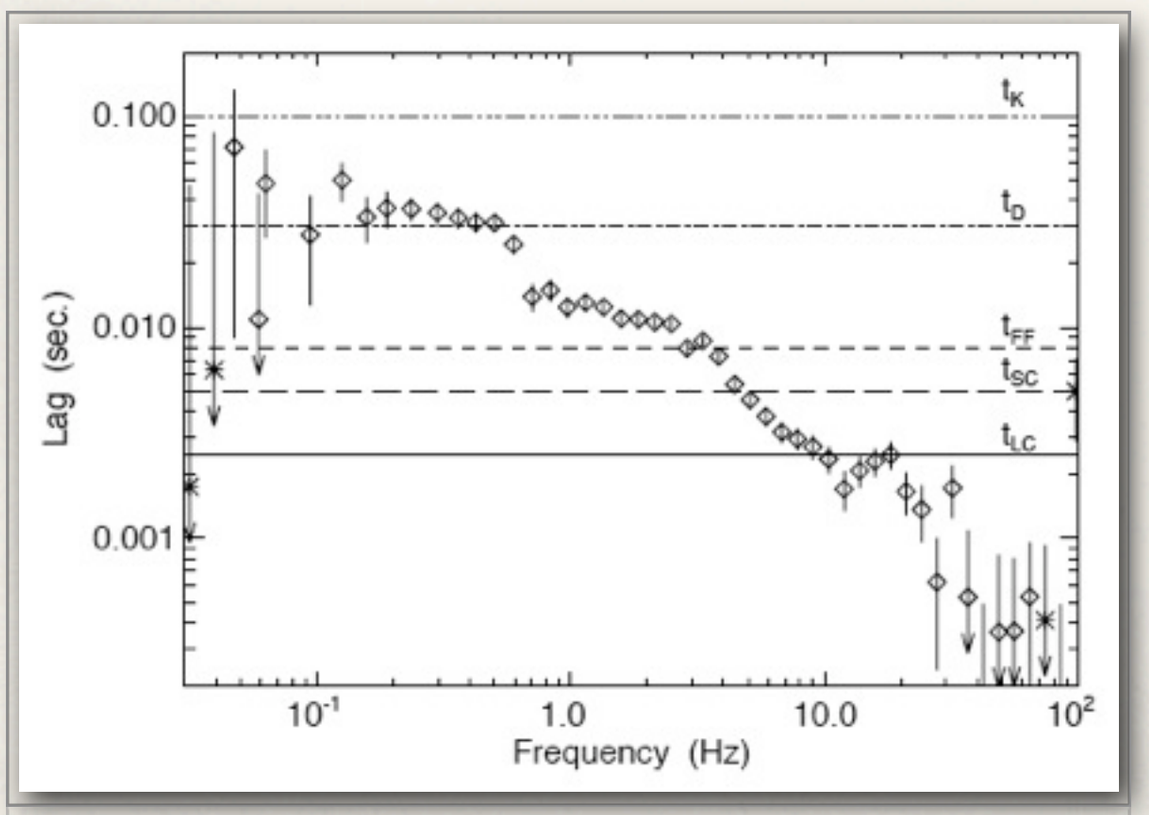




rms & phase lags

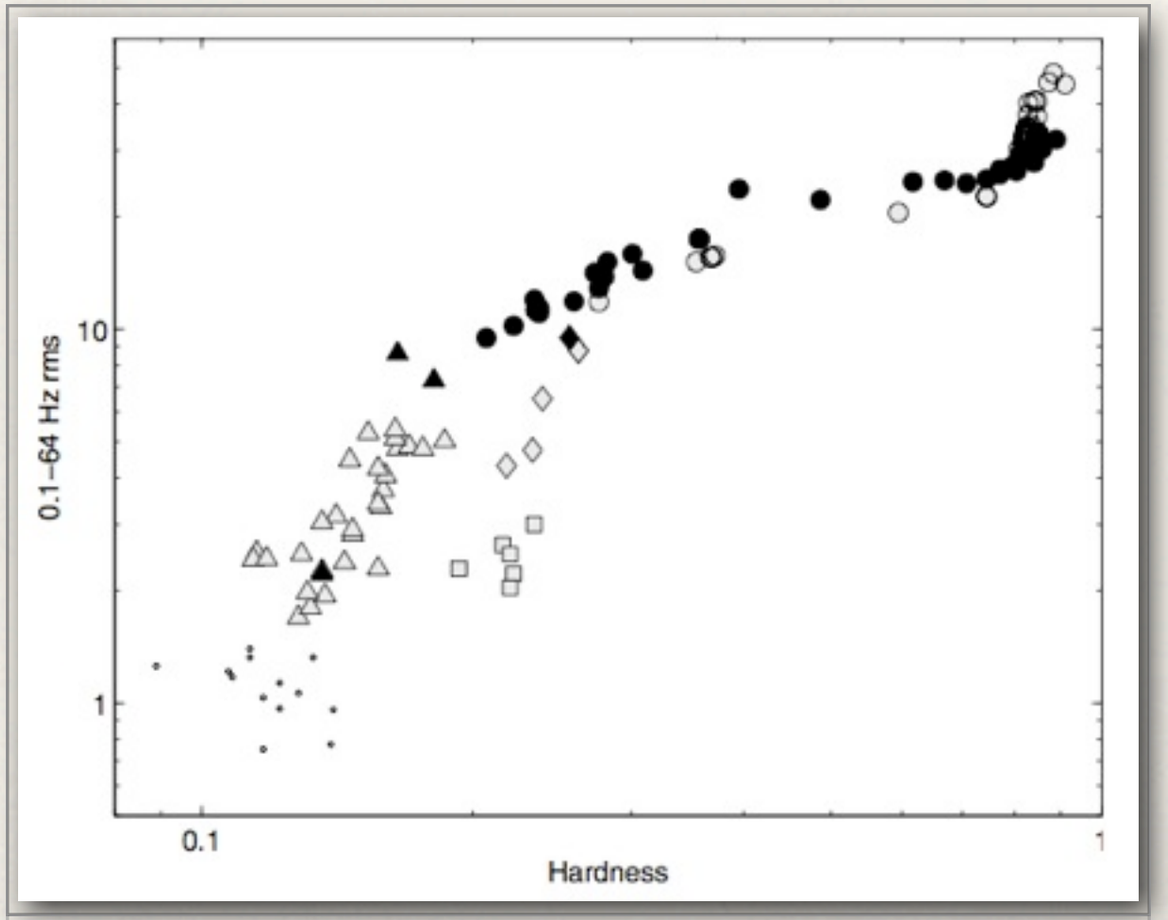
- Rms vs. energy
- Phase-lag spectrum

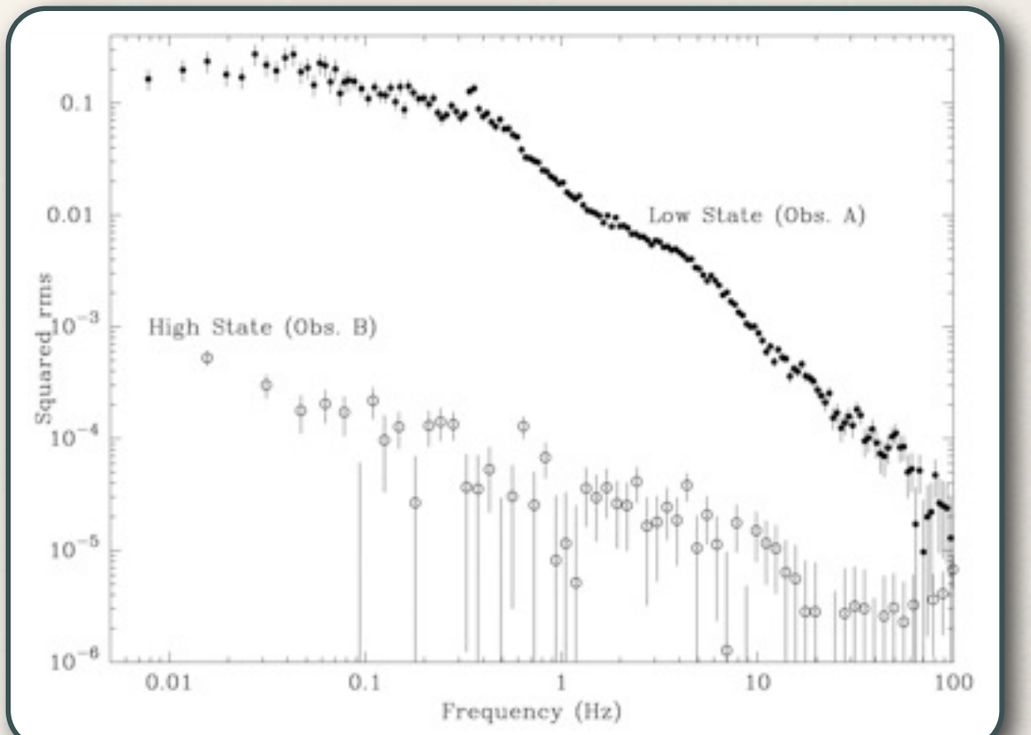




Black-hole binaries: no noise

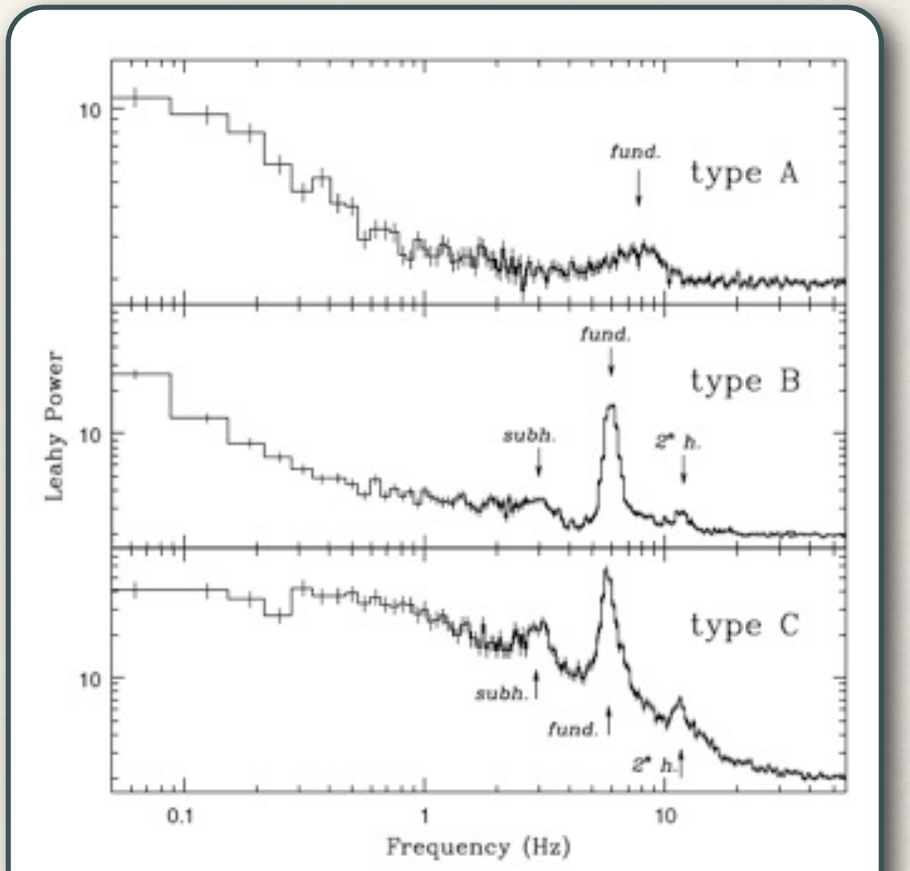
- Can go from 40% down to 1%
- Dependent on energy spectrum





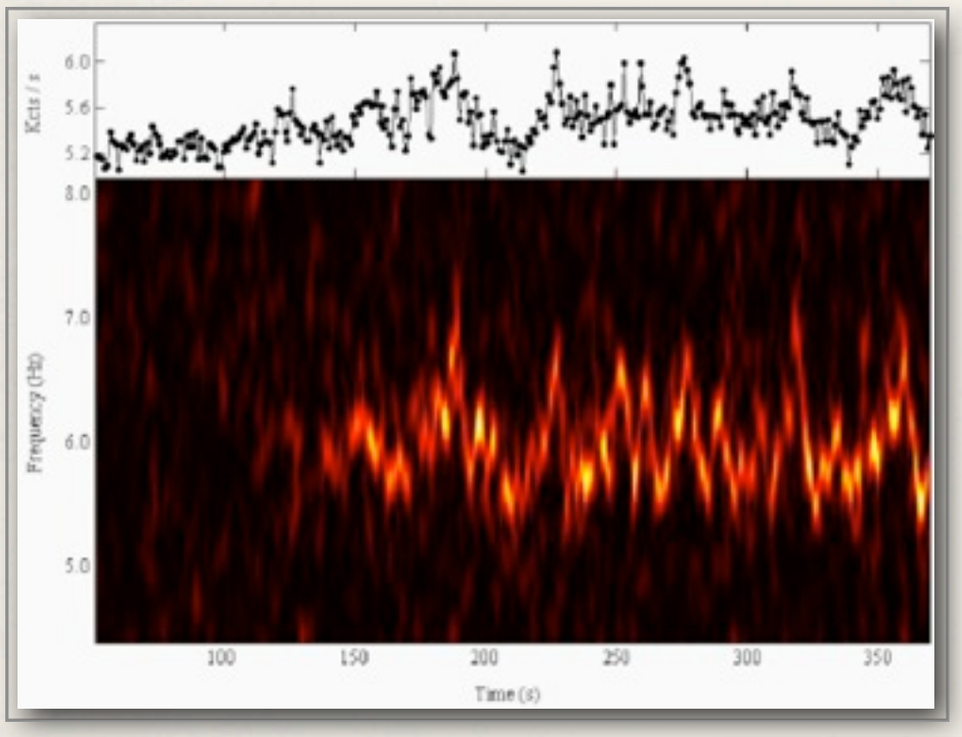
Black-hole binaries: QPO

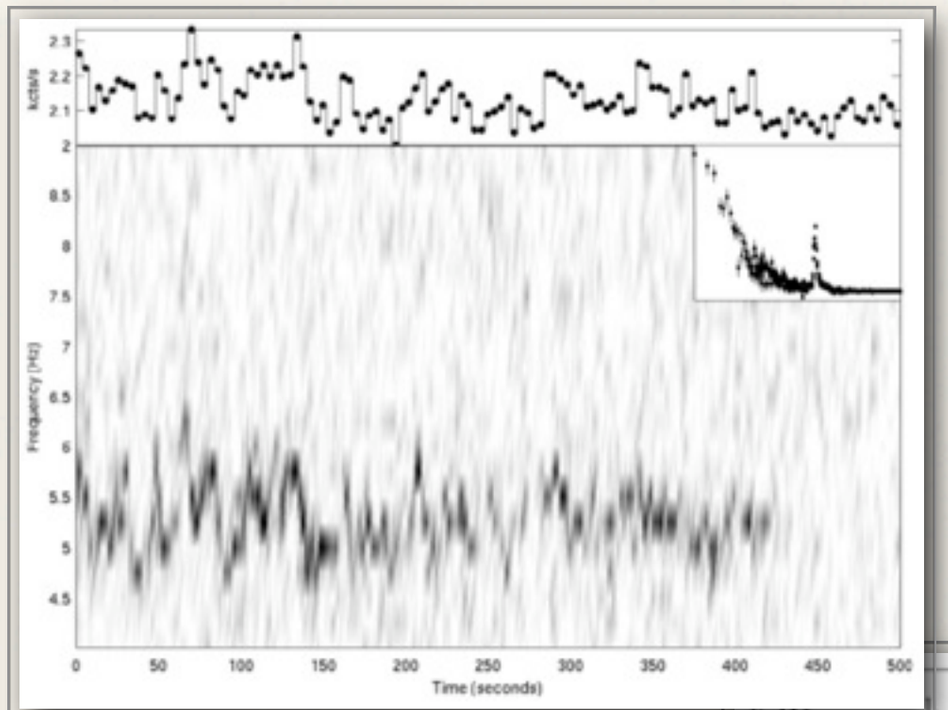
- Low-frequency QPO as in NS
  - Type-C QPO
    - Variable frequency 0.01-15 Hz
- Type-A/B QPO
  - Almost fixed frequency 4-8 Hz



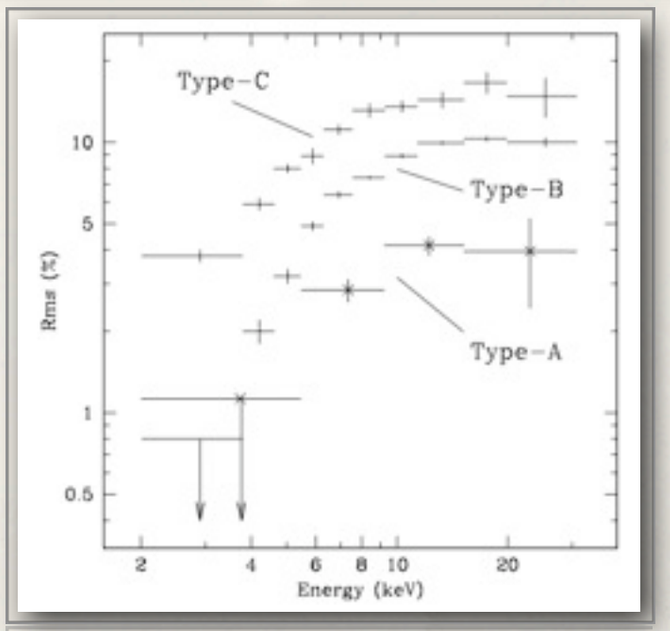
- ☆Type C - HBO
- ☆Type B - NBO
- ☆Type A - FBO

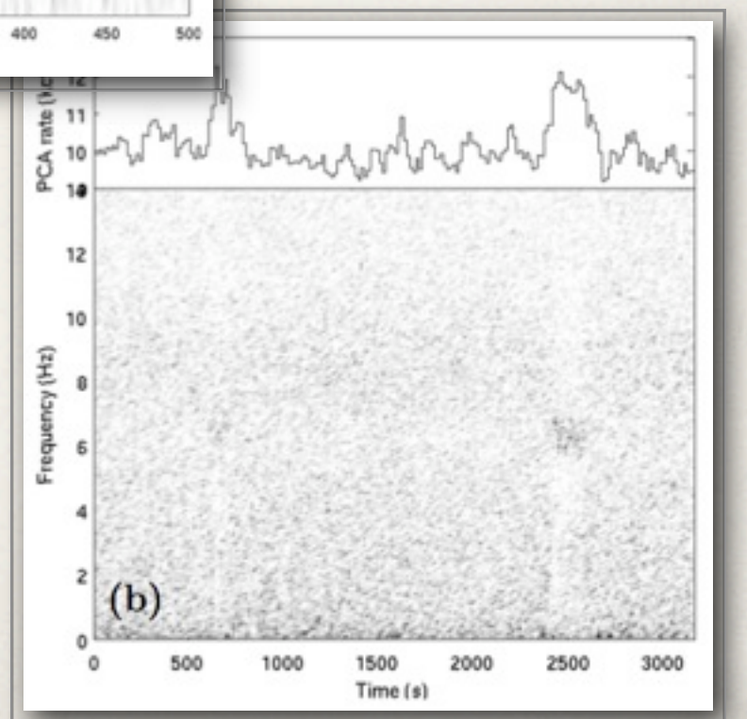
Fast changes of QPO frequencies





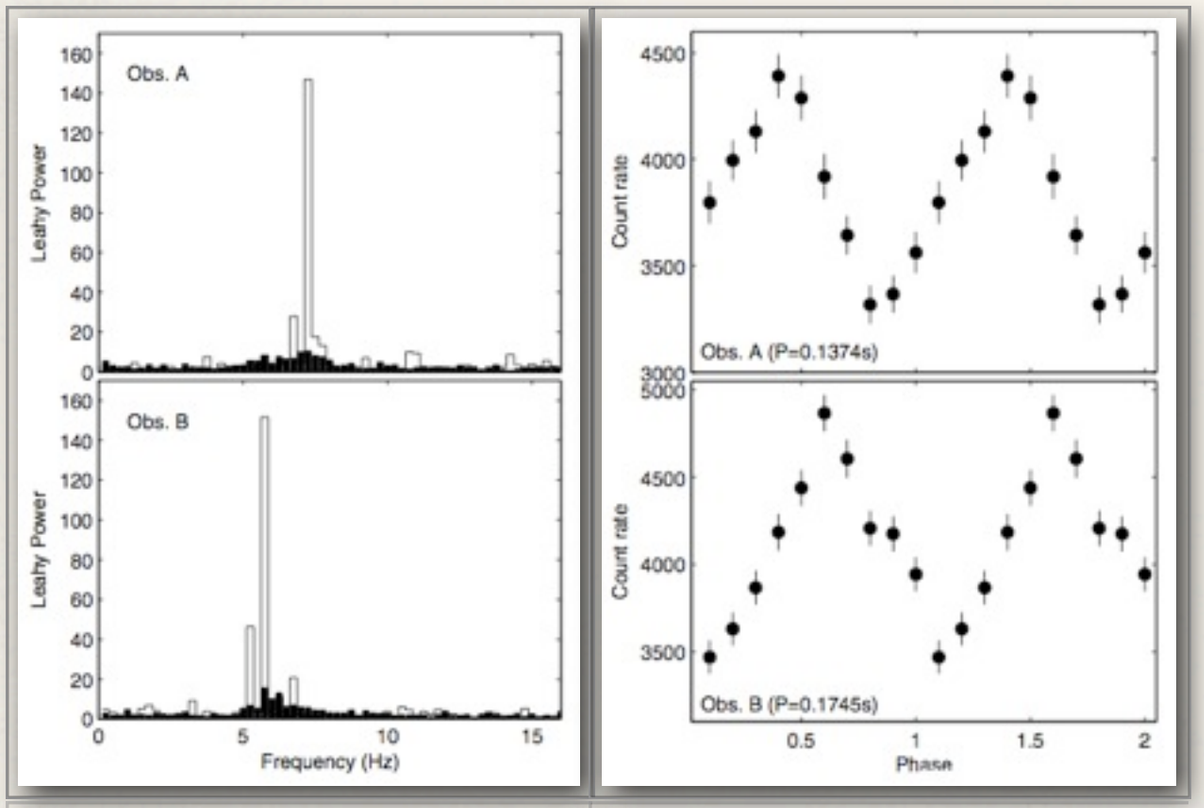
Rms vs. energy:

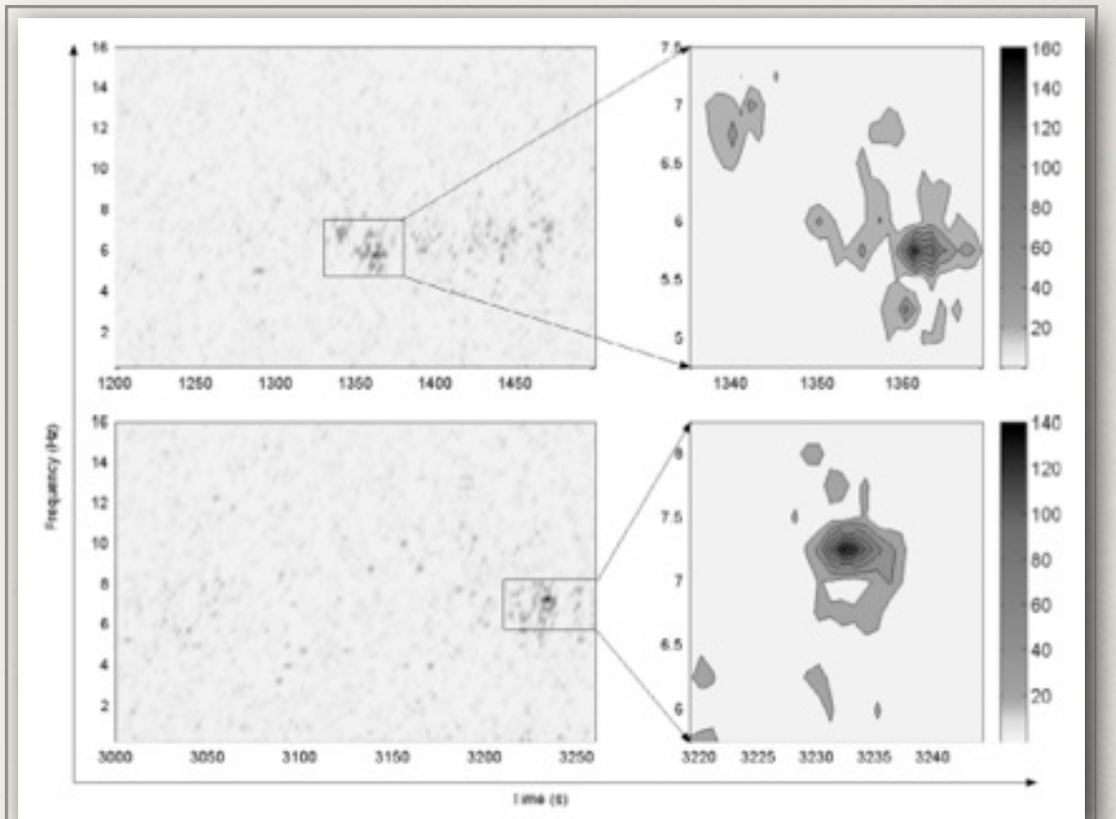




Transient high-Q QPOs

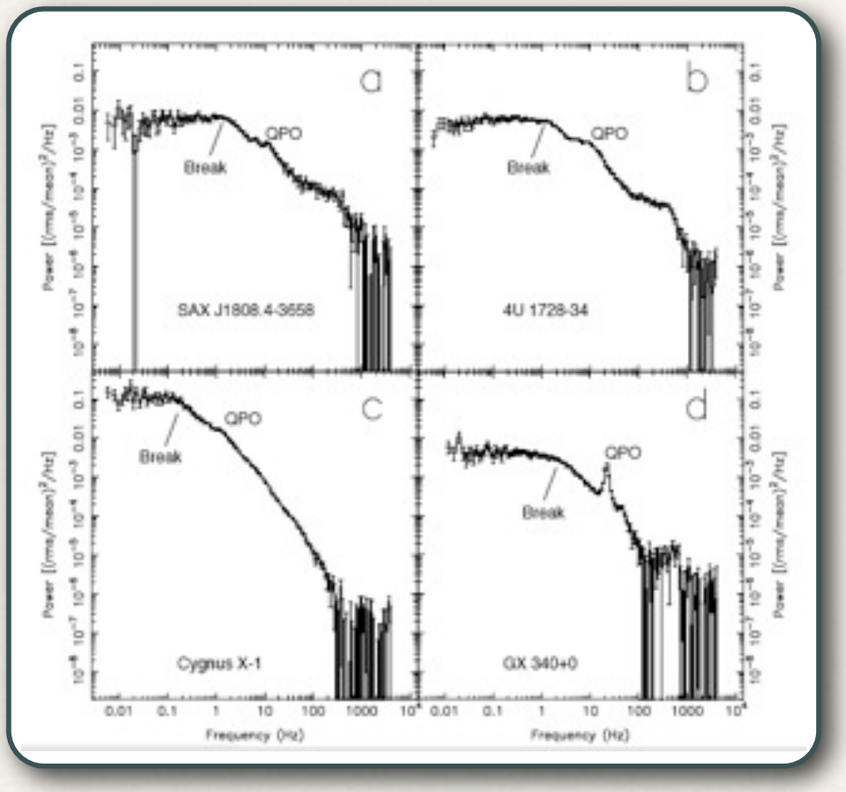
4U 1820-30: 6Hz

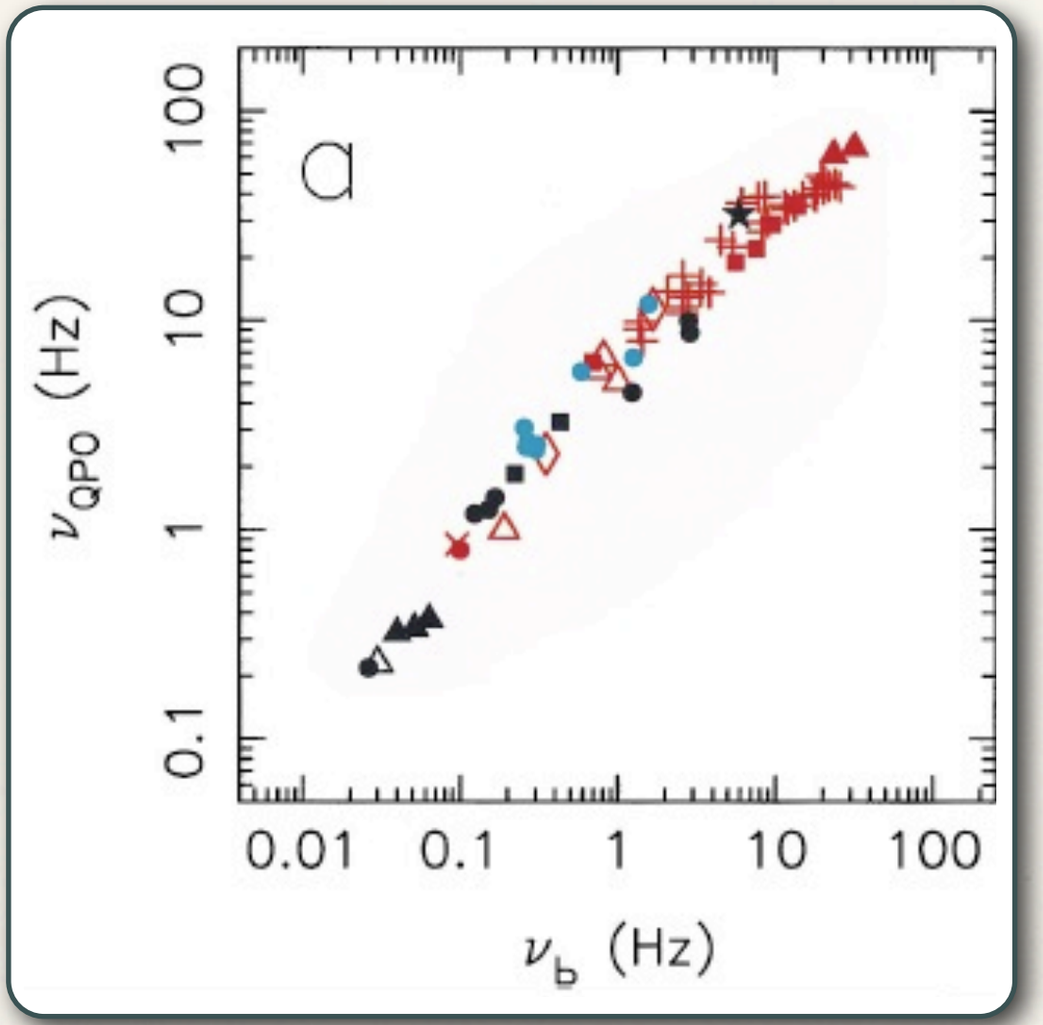




Global correlations

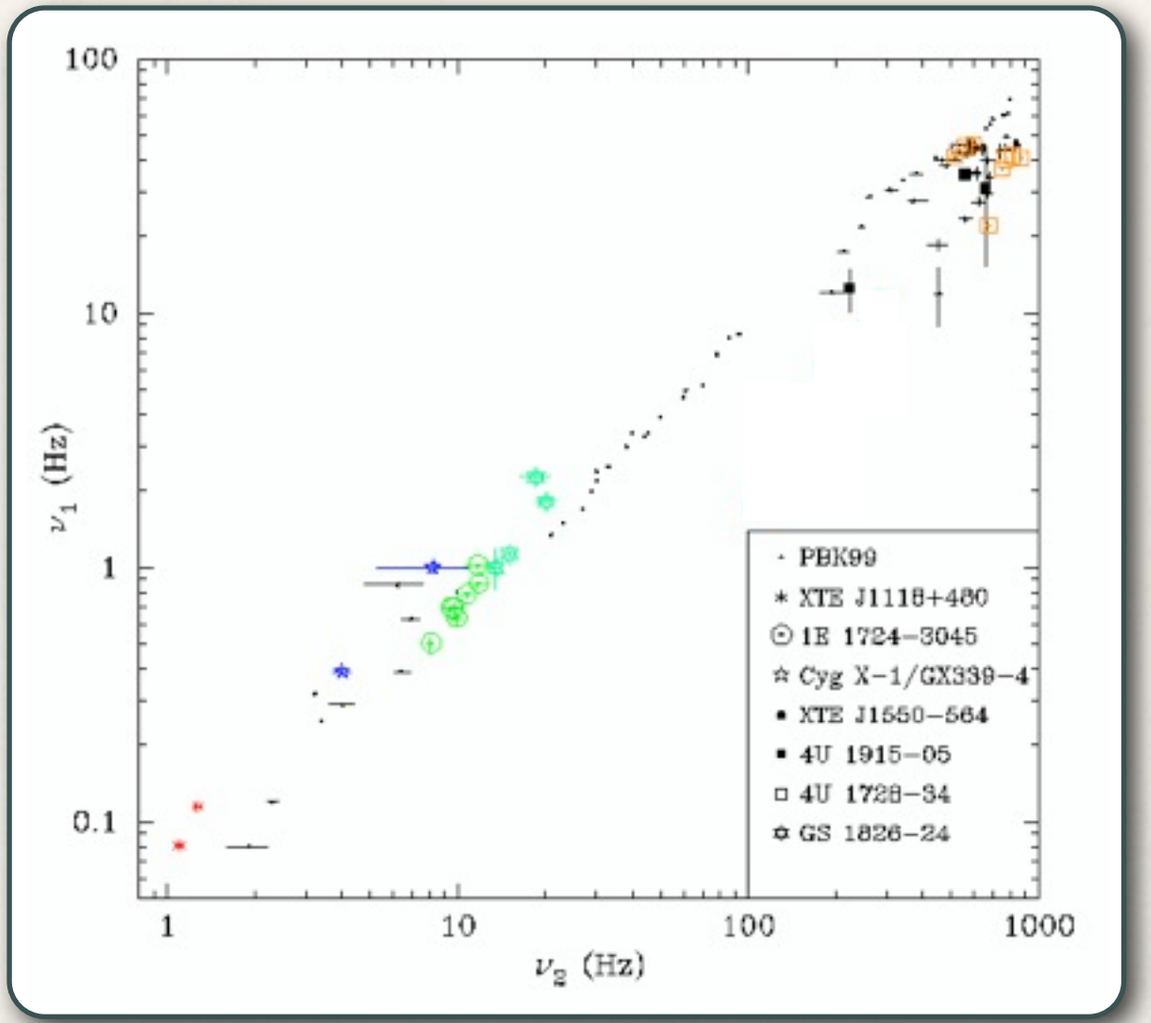
- Noise - LF QPO

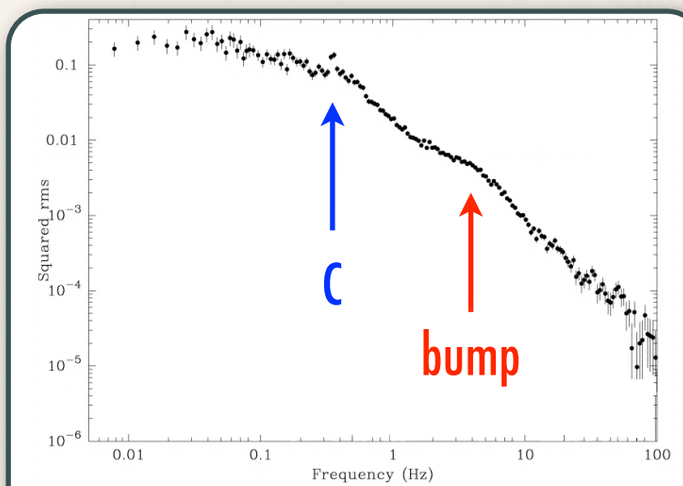


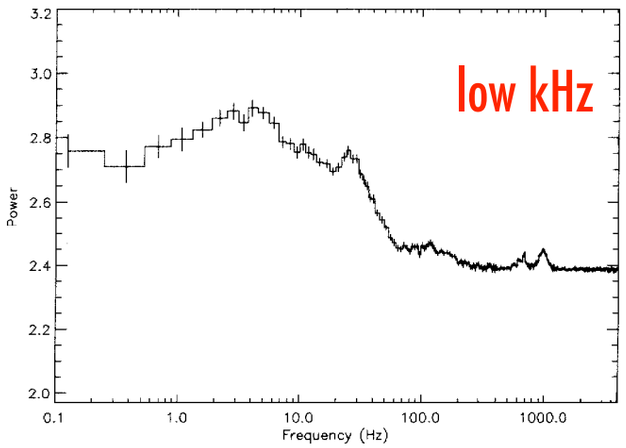


Global correlations

- Lorentzian decomposition here essential

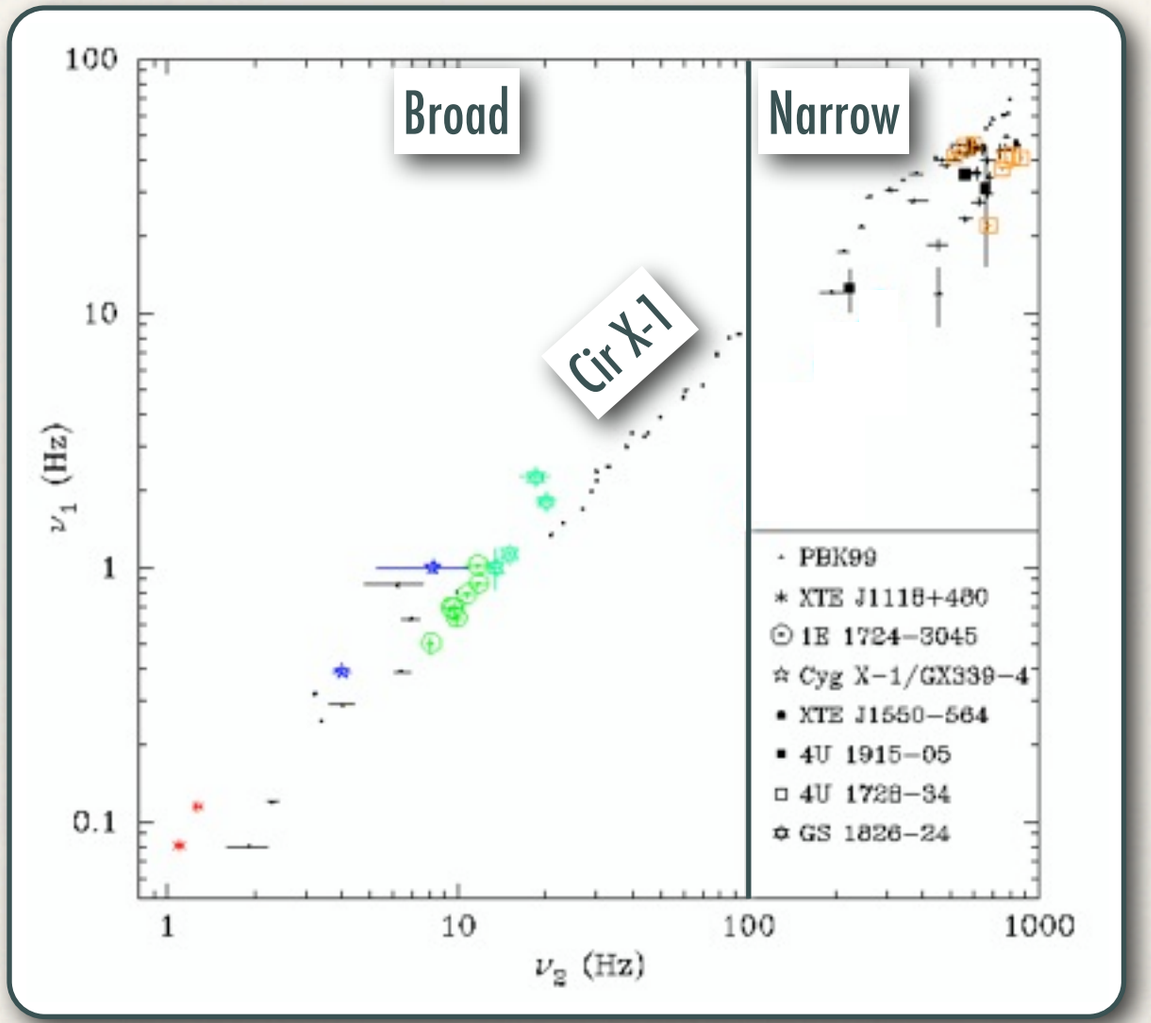


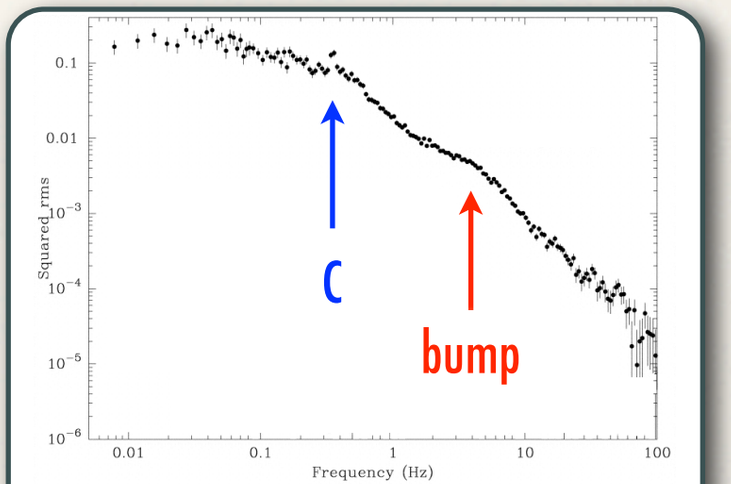


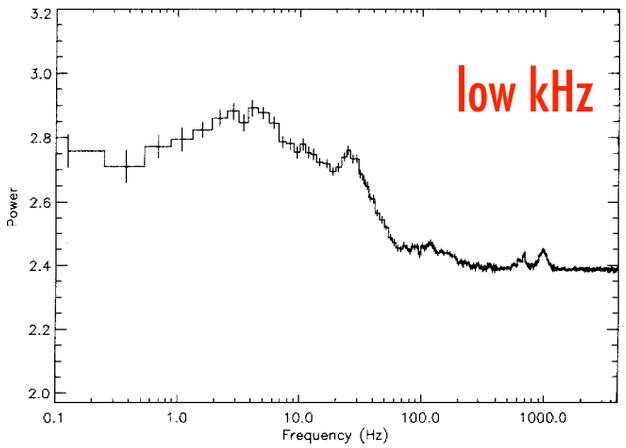


Global correlations

- Lorentzian decomposition here essential

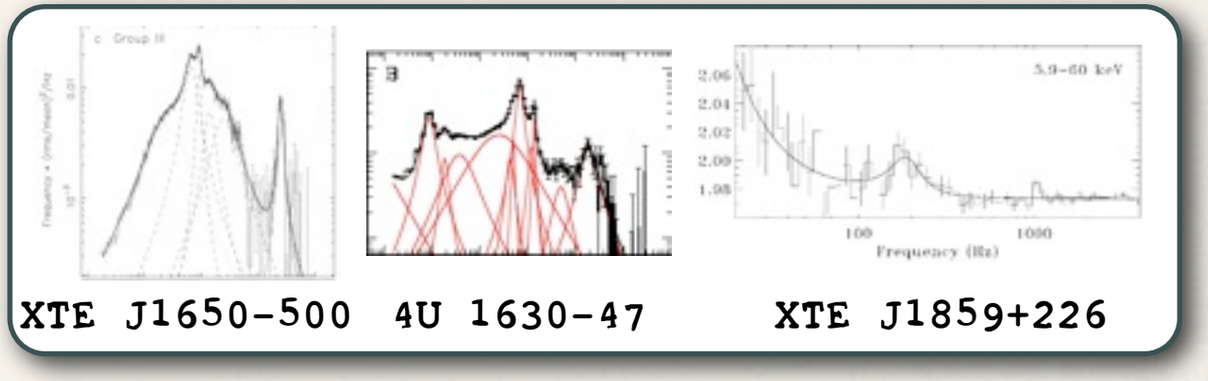


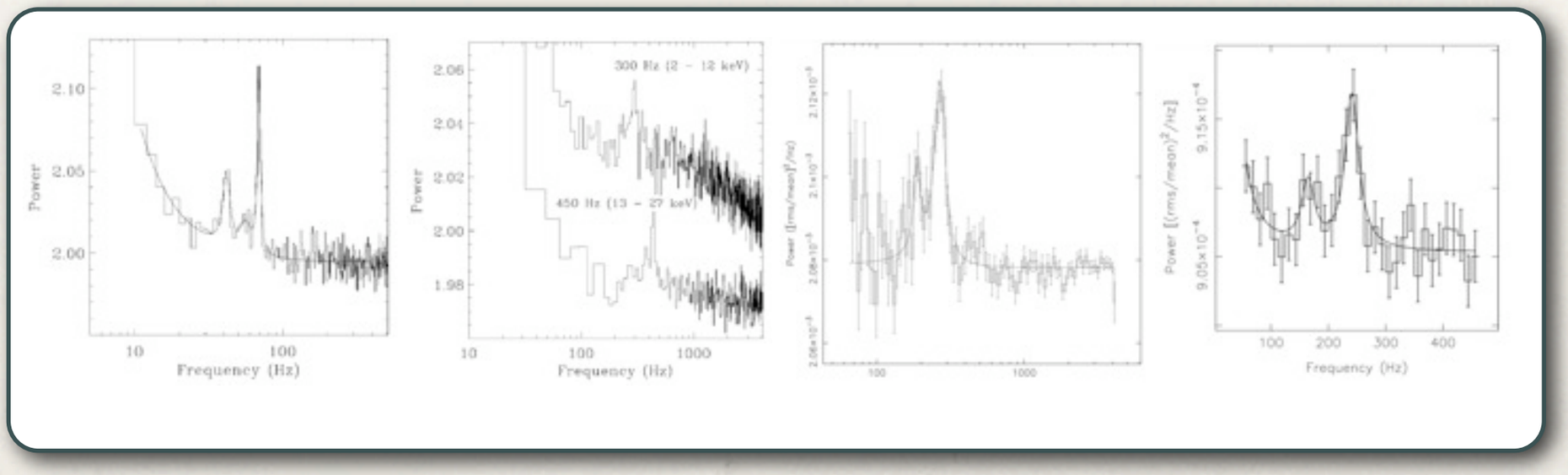




BH High-frequency QPO

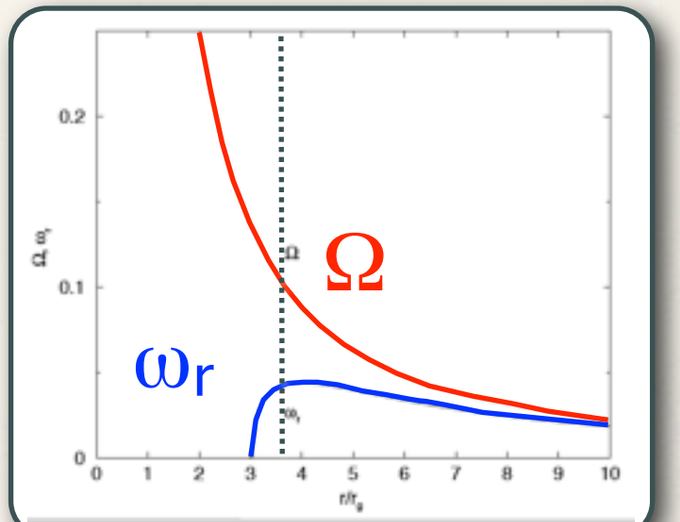
- Frequencies 30-450 Hz
- Weak and rare
- Fixed frequencies
- Some (4/7) come in pairs
- Different from NS kHz QPO



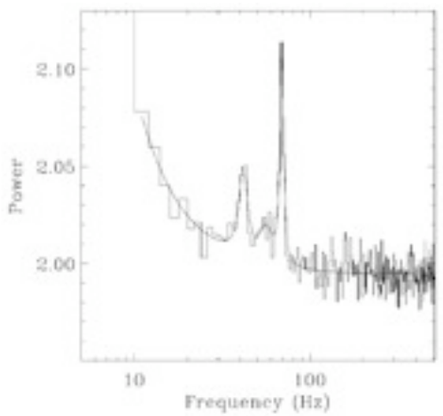


BH High-frequency QPO

- Pairs appear at certain ratios
- Resonance model developed
- Still few points available

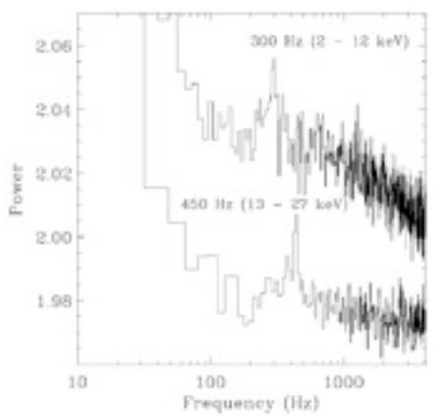


5:3



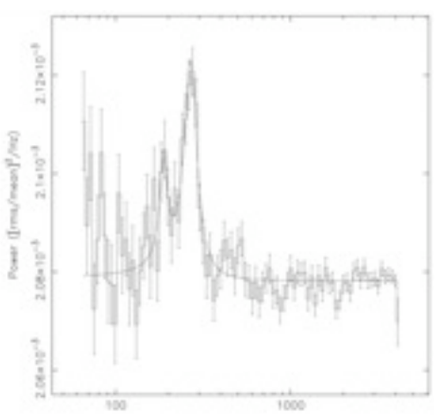
GRS 1915+105

3:2



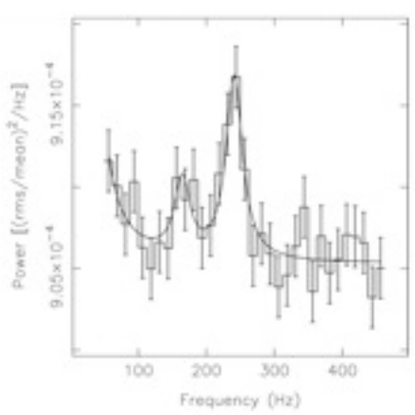
GRO J1655-40

3:2



XTE J1550-564

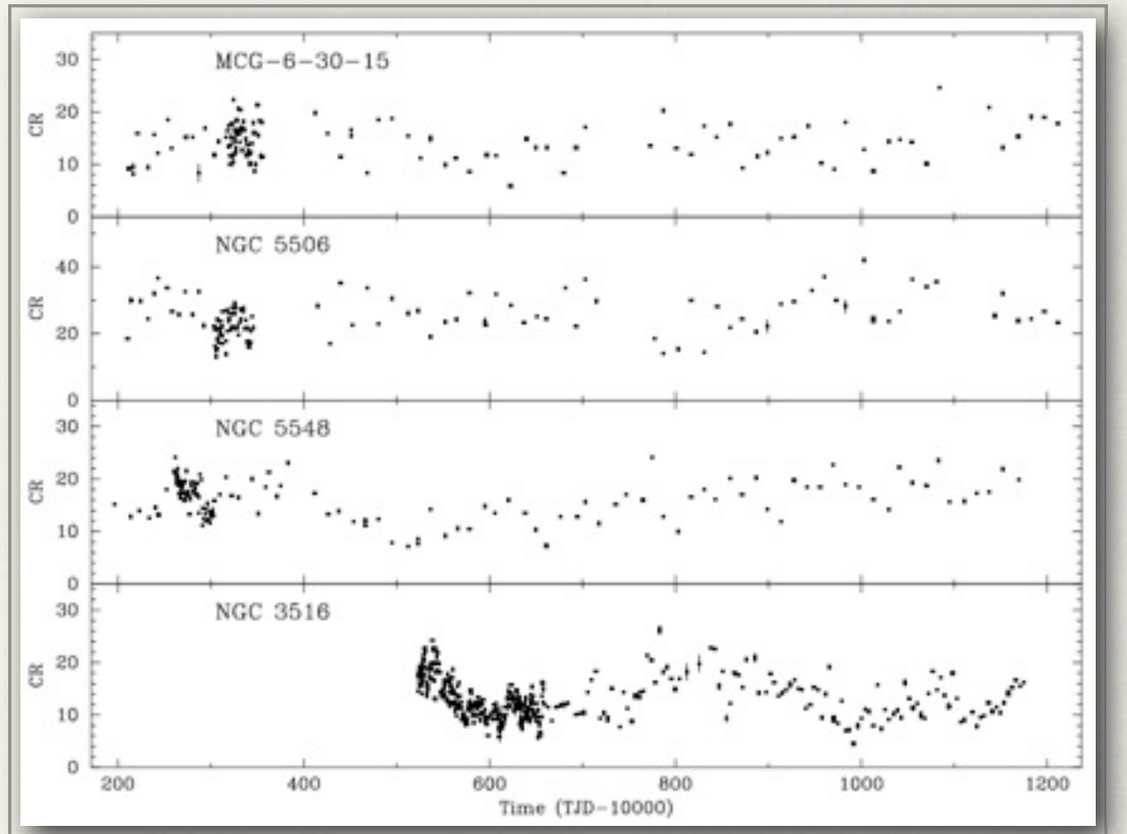
3:2

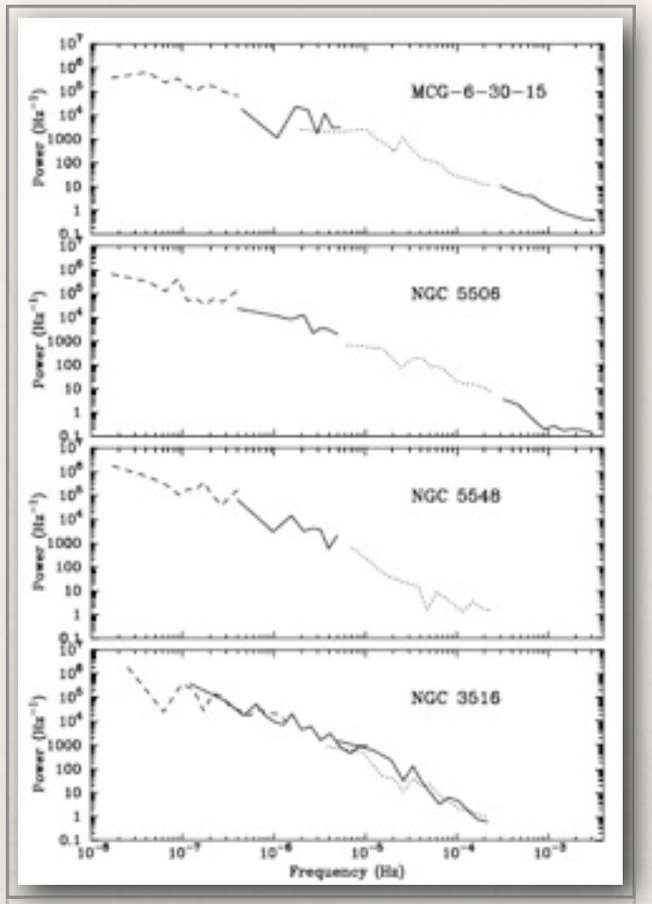


H 1743-322

Long-term periods

- Difficult techniques
- Important for AGN studies
- Analysis then timing





XMM analysis

- Example: QPO in M82