Quasi-Periodic Oscillations: Energy Dependent Time Lags

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Soma Mondal (Taki College, India): Misra & Mondal, 2013, ApJ

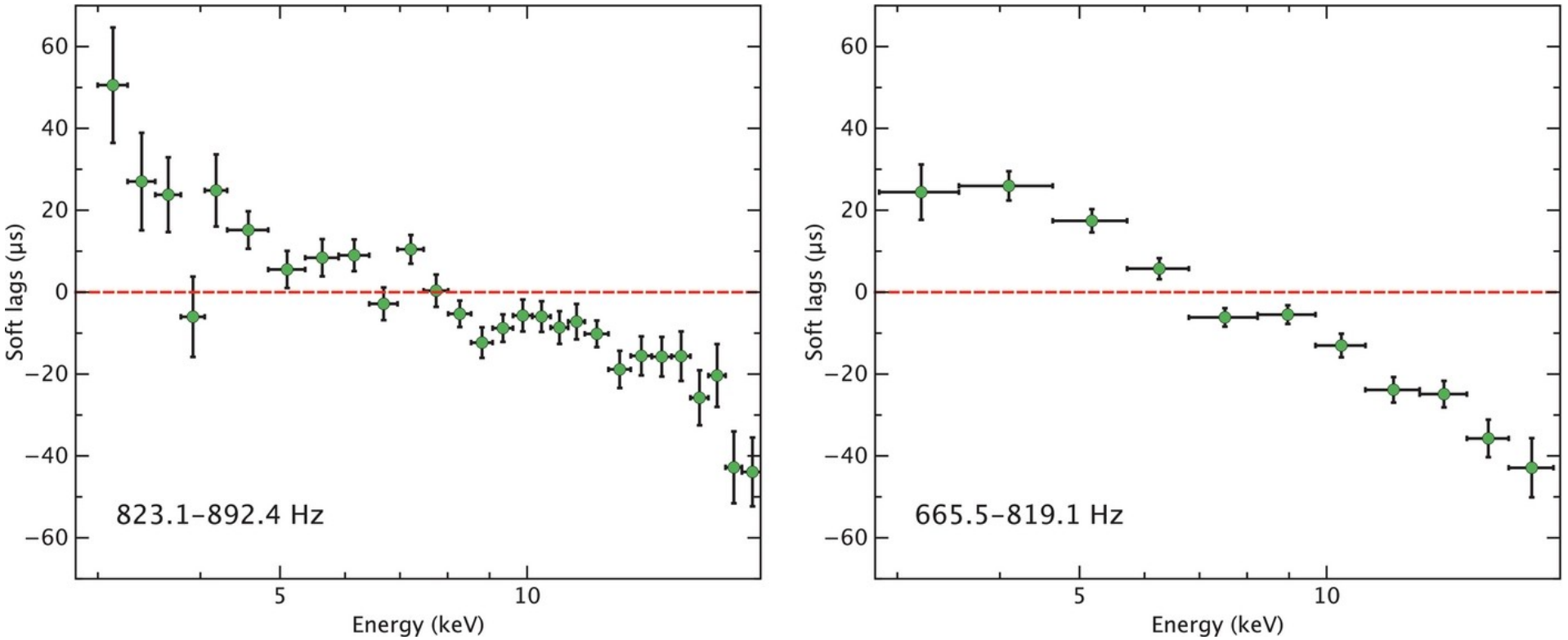
QPOs

- Quasi-periodic Oscillations (QPOs) are observed in X-ray binaries in a wide range of frequencies from milli-Hz – kHz.
- There are several models for the dynamic origin of the different kinds of QPOs but there is no consensus on which of them is correct.

QPOs

- A number of QPOs exhibit energy dependent time lags.
- These time lags between photons of different energies can be used to constrain the radiative process and provide insight into the nature of the QPOs

~50 micro-second time lag in kHz QPOs

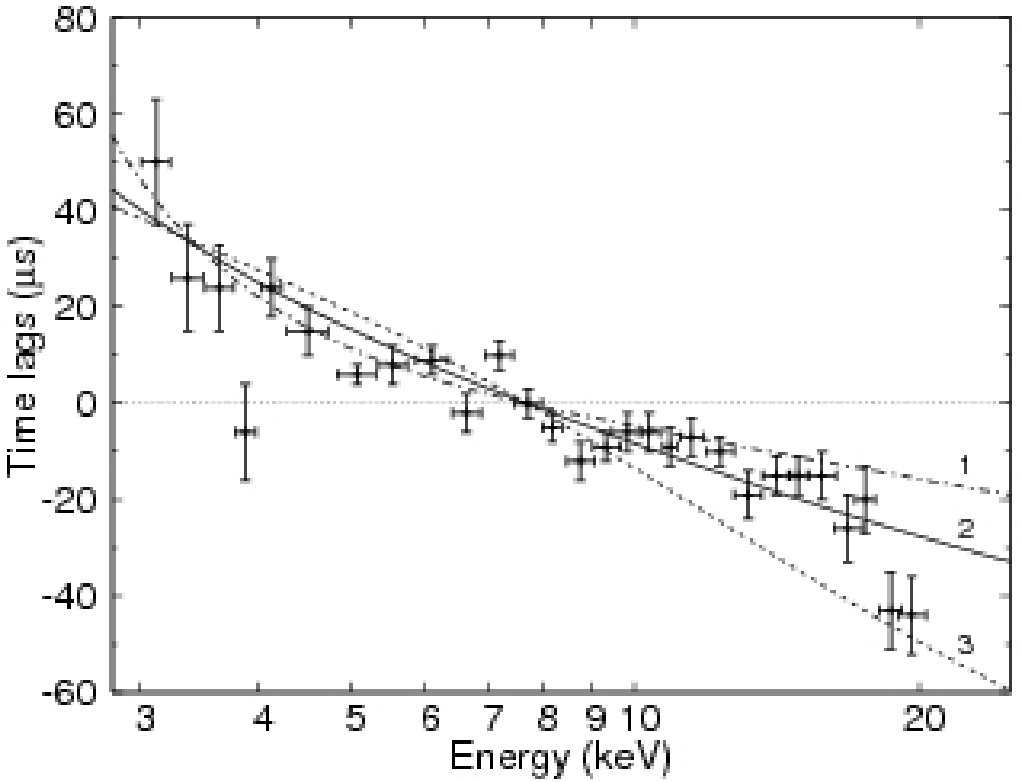


Vaughan et al. 1998; Kaaret et al. 1999 de Avellar et al. 2013 Barret 2013

Causes for micro-second time delays

- Time delay due to Compton scattering. High energy photons scatter more times and hence a delay is introduced.
- Time delay due to reverberation i.e. reflection features delayed with respect to the continuum.

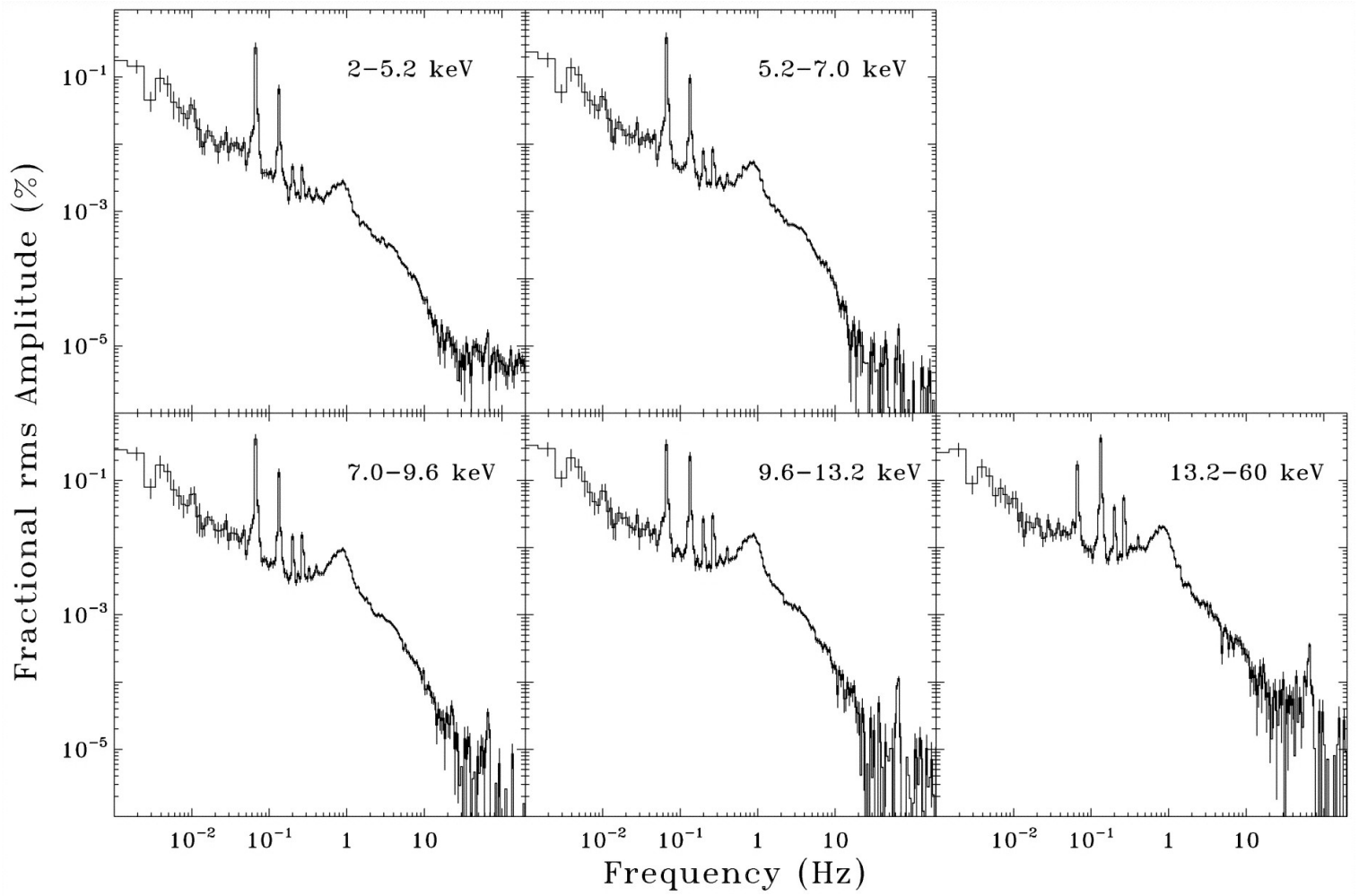
~50 micro-second time lag in kHz QPOs



Comptonization can explain soft lags!!

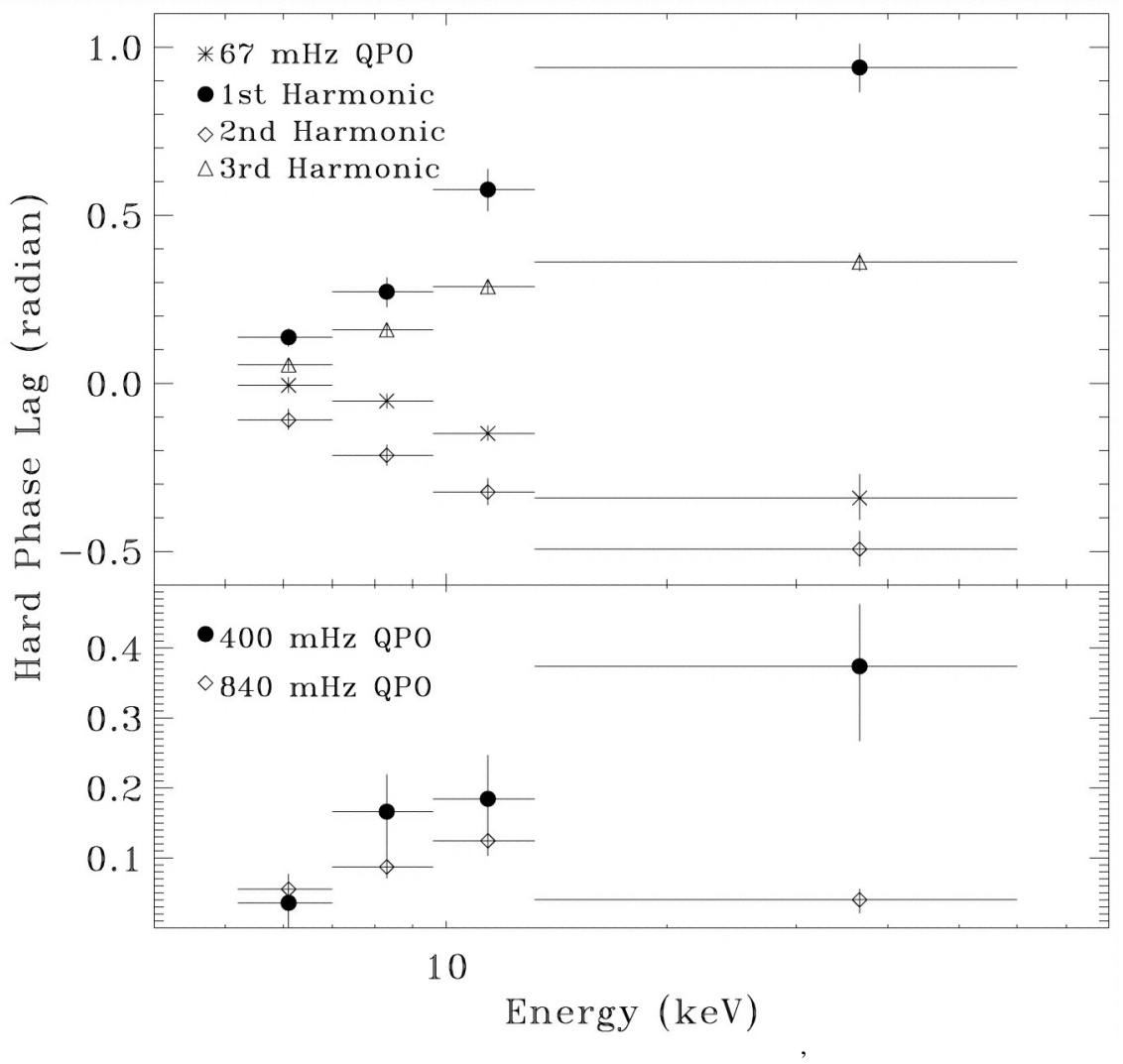
(Lee, Misra & Taam 2001, Kumar & Misra submitted)

67 mHz QPO with harmonics in GRS 1915+105



Cui 1999

Alternating Lags for the QPO harmonics



Cui 1999

Causes for time delays in seconds time-scale

- Precession of a non-uniform disk
- Wave propagation from outer to inner disk (Lyubarskii 1997, Misra 2000, Kotov, et. al. 2001)
- Spectral Evolution due to two parameters whose variation is delayed with respect to each other.

Model for Spectral Evolution

- For a time varying spectrum with two parameters a and b

$$s(E,t) \rightarrow s_o(E) + \Delta s(E,t)$$

$$\Delta s(E,t) = \gamma_a(E)\Delta a(t) + \gamma_b(E)\Delta b(t)$$

For e.g. if $s(E) = A\, E^{-b} e^{-aE}$, then:

$$\frac{\Delta s(E,t)}{s_o(E)} = -E\Delta a(t) - \log(E/E_p)\Delta b(t)$$

Three basic Equations

$$\frac{\Delta s(E,t)}{s_o(E)} = -E\Delta a(t) - \log(E/E_p)\Delta b(t)$$

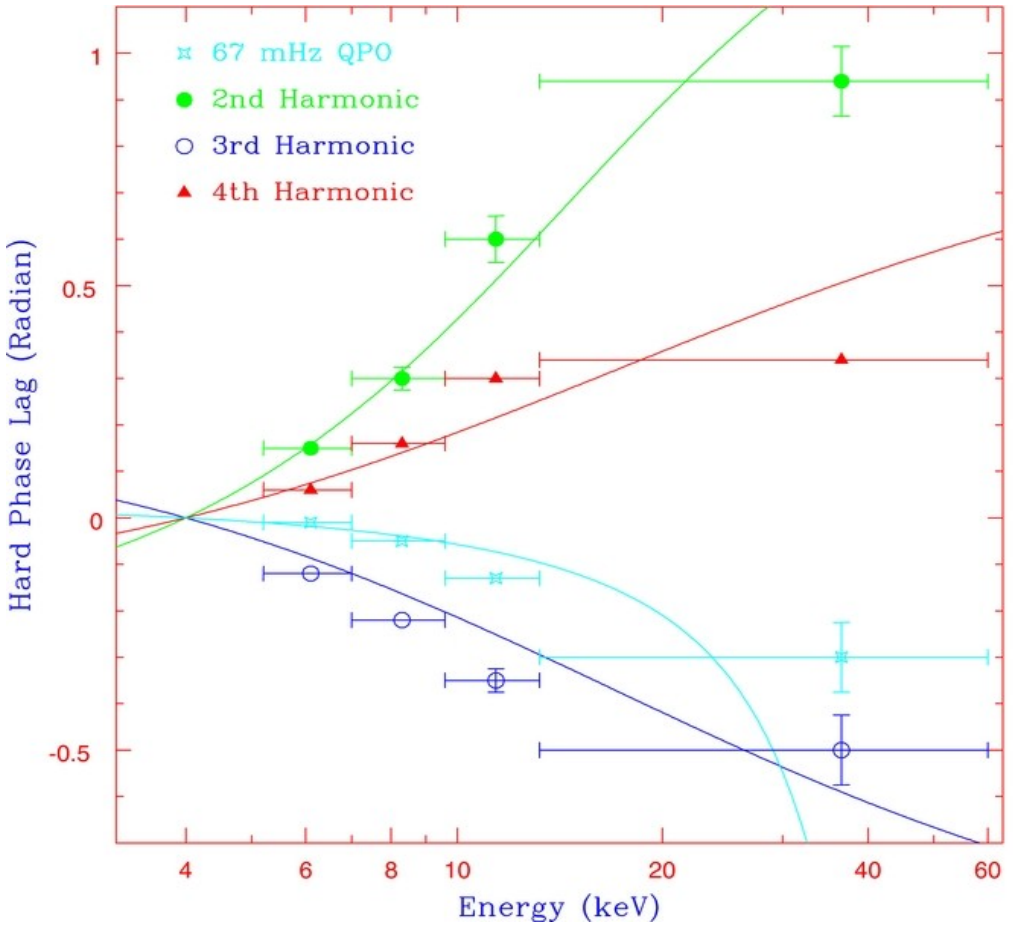
$$\Delta a(t) = R_a(1+\beta\cos(\omega_o t))^4$$

$$\Delta b(t) = F\Delta a(t-t_d) + R_b\beta\cos(\omega_o t)$$

Basic Assumptions

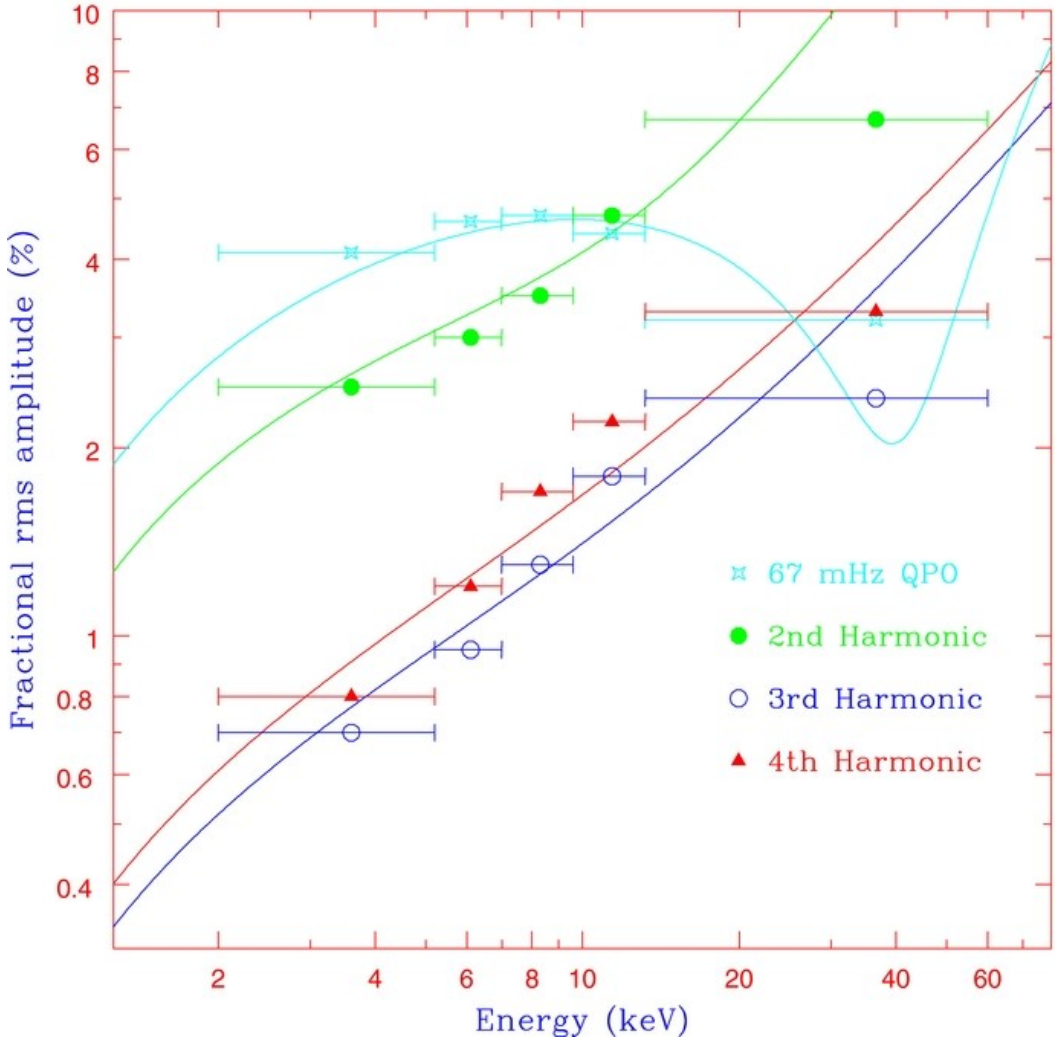
- The spectrum is characterized by two parameters a and b
- The parameter a couples to the underlying driver quadratically.
- The parameter b follows a after some time delay and also directly couples linearly to the driver.

Alternating Lags for the QPO harmonics



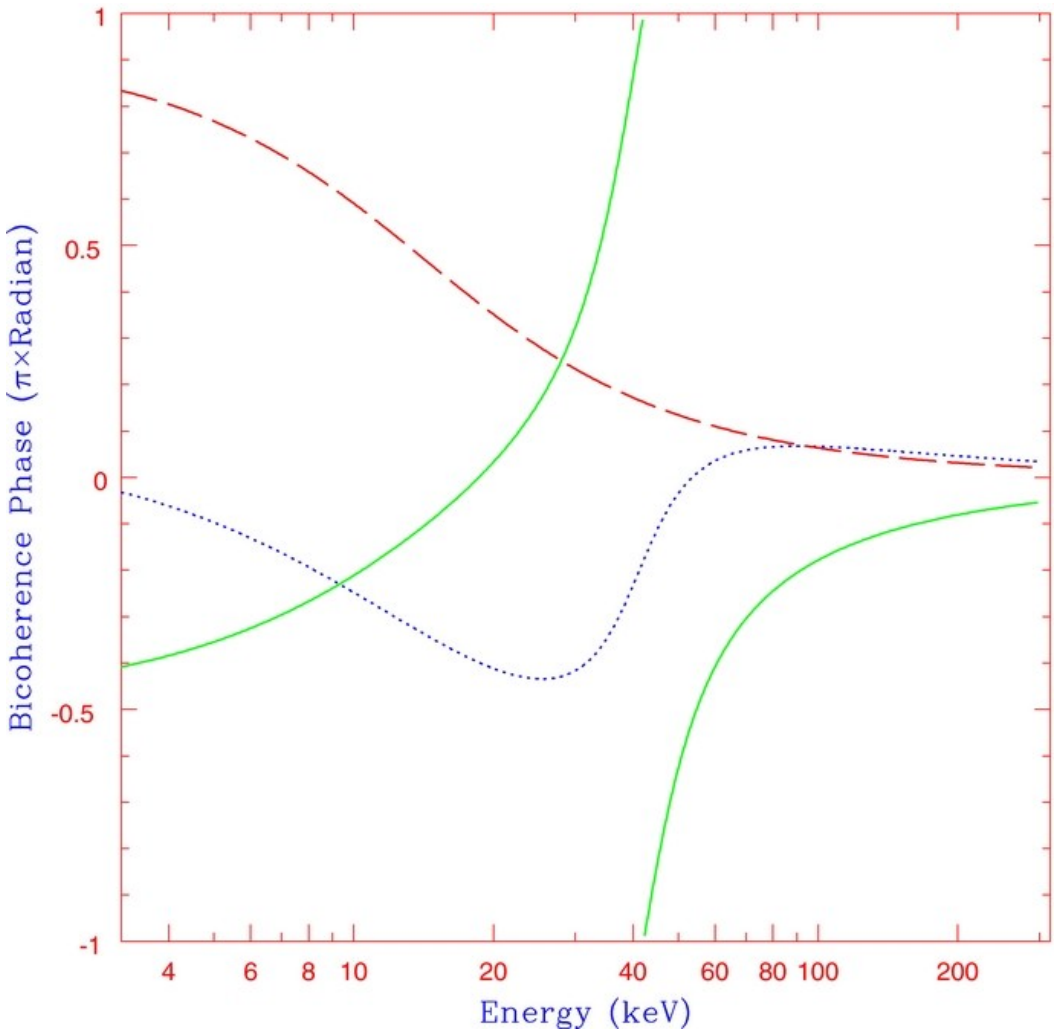
Odd and even harmonics show opposite phase lag!

Alternating Lags for the QPO harmonics



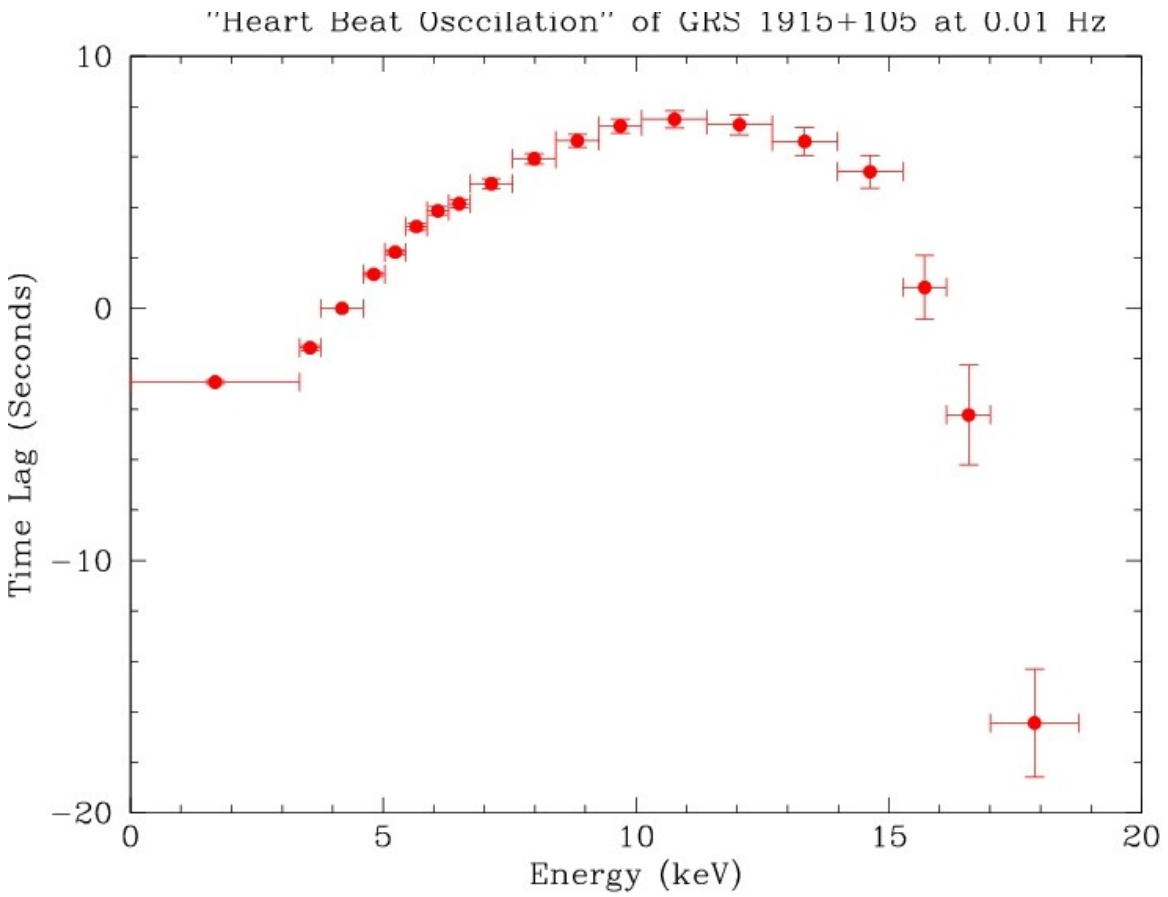
Model also reproduces the fractional r.m.s as it should!

Alternating Lags for the QPO harmonics



Model predicts Bi-coherence functions which can be checked against Further data analysis

Time Lag for another low frequency QPO



Mukerjee et. al. 2014 submitted

Summary

- The complex behavior of time lags as a function of energy can be explained by theoretical and phenomenological models which provide insight into the nature of the system.
- To connect with the actual dynamic model one needs to identify the correct radiative process.