The analysis of QPOs and time lag in ULXs with XMM-Newton

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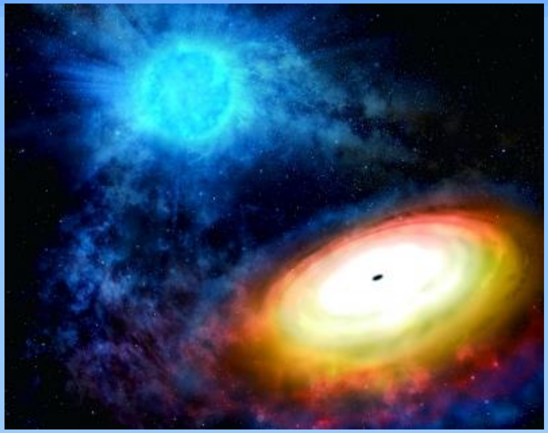
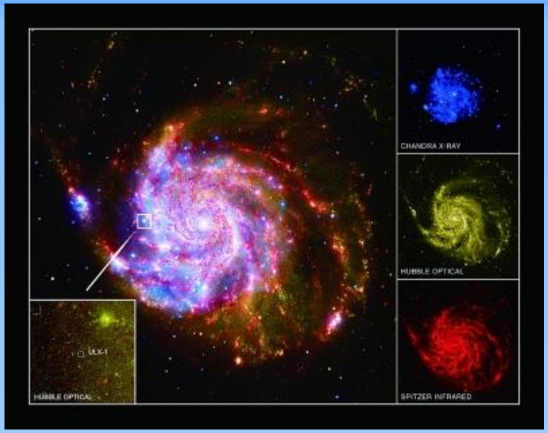
ULX





- Luminosity > $3 \times 10^{39}\ erg/s$
- Outside of the centers of their host galaxies
- Models:
  - intermediate-mass black hole (IMBH)
  - StBH with super-Eddington accretion rates
  - Galactic XRBs beaming relativistic jets

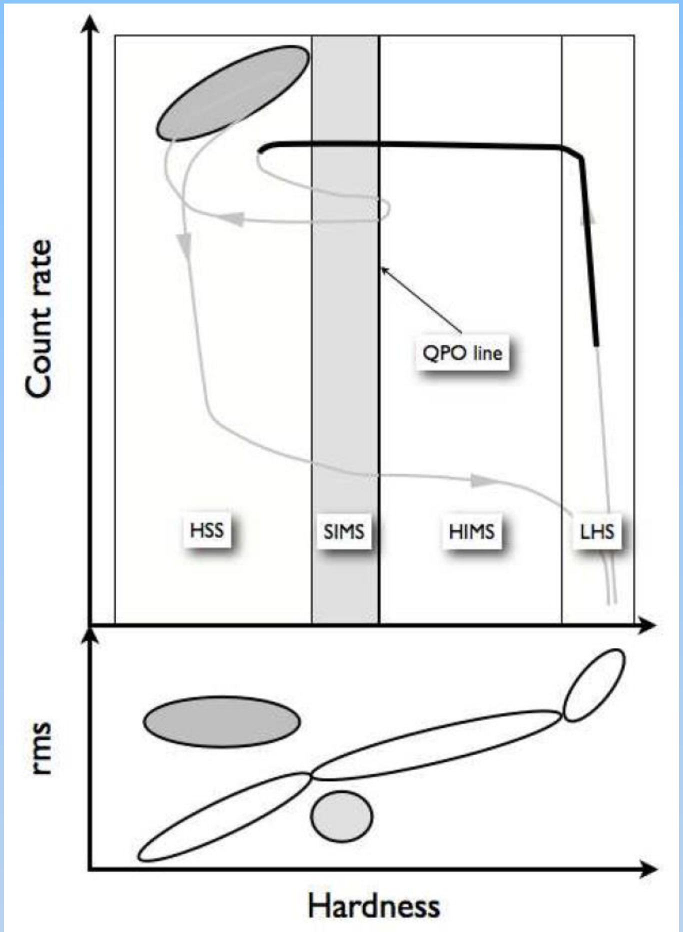
Outline

- Background
- Data Reduction and Analysis
- Results
- Discussion
- Conclusions

Background

- **State transition:**

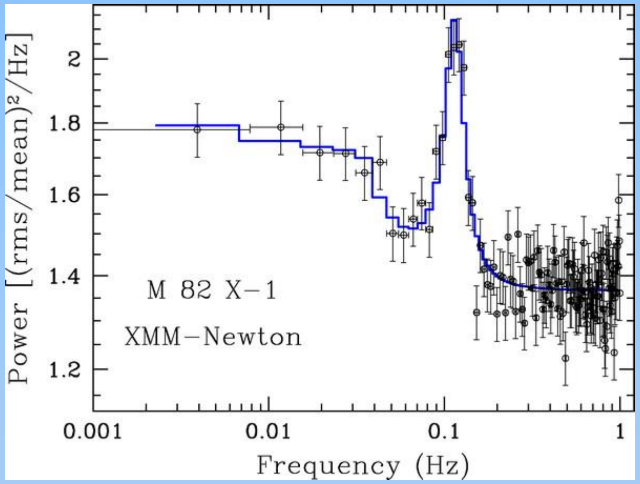
LHS	(1.6<γ<1.7)
HIMS	(2.4<γ<2.5)
HSS	(γ>2.5)
SIMS	
LHS	

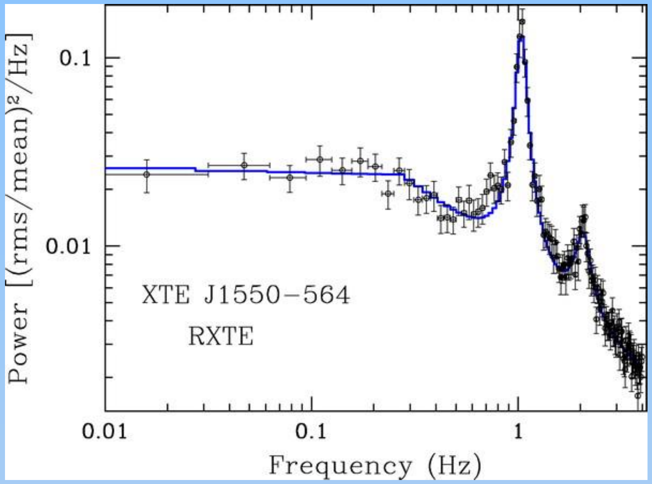


Belloni, 2010, AIPCP, 1248, 107

Background

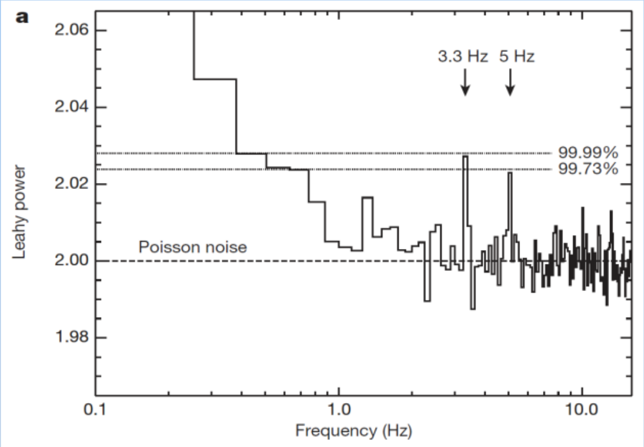
• QPO (quasi-periodic oscillations)





Dewangan et al, 2006, ApJL, 637, L21

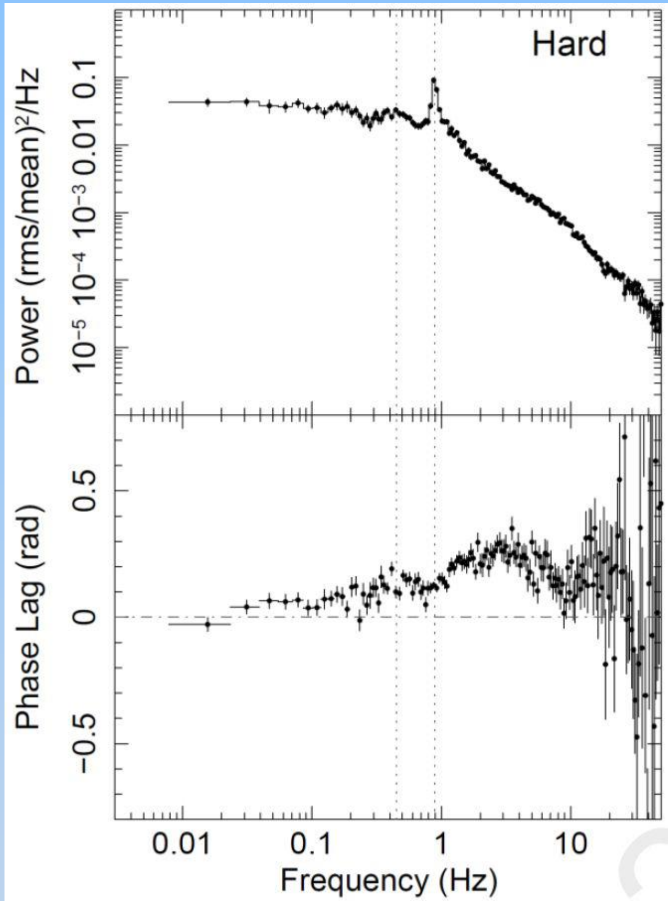
- QPOs in XRB
- Also observed in ULXs
- Used to determine the mass, state



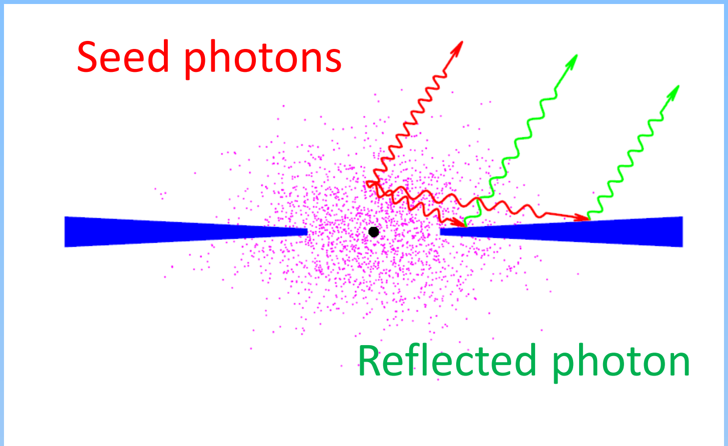
Pasham et al, 2014, Natur, 513, 74

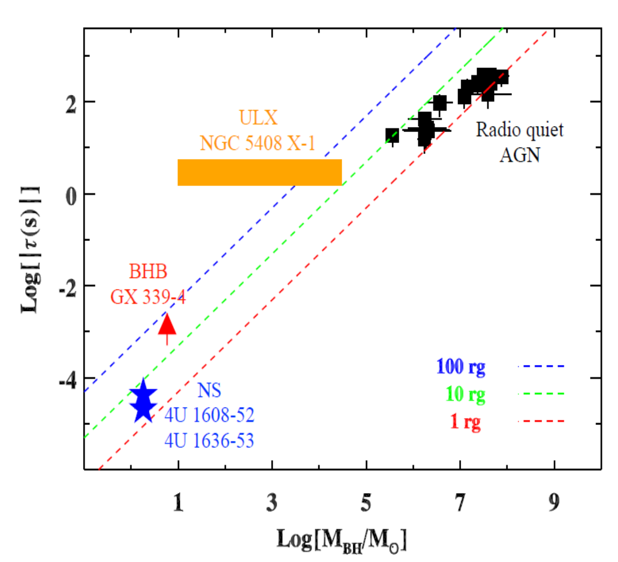
Background

- **Time lag**



Phase lag for GRS 1915+105





De Marco et al, 2013, MNRAS, 436, 3782

Data Reduction

- More than 70 observations of ULXs by XMM-Newton, about 20 ULXs
- Only 5 ULXs show intrinsic variability (QPOs)
- Duration > 20 ks
- Data from EPIC pn and mos
- Energy: 0.3-10 keV

Data Reduction

Sources and Observations

Source Name	Observation ID	R.A.	Decl.	Radius	Duration (s)	Start Date
IC342 X-1	0693850601	$03^h45^m\,55^s\!.50$	+68d 04′ 54.2″	32	59873	2012-08-11 20:06:44
M82 X-1	0206080101	$09^h55^m\,49^s\!.91$	+69d 40′ 44.″4	18	104353	2004 Apr 21 21:36:32
	0657800101				26657	2011 Mar 18 16:31:57
	0657801901				28219	2011 Apr 29 13:16:06
	0657802101				22843	2011 Sep 24 05:09:12
	0657802301				23914	2011 Nov 21 00:49:21
NGC 5408 X-1	0302900101	$14^h03^m\,19^s\!.62$	−41d 22′ 58.″7	32	132251	2006 Jan 13 18:41:00
	0500750101				115694	2008 Jan 13 19:05:27
	0653380201				128913	2010 Jul 17 03:12:59
	0653380301				130882	2010 Jul 19 03:05:13
	0653380401				121019	2011 Jan 26 16:08:59
	0653380501				126367	2011 Jan 28 15:49:01
NGC 6946 X-1	0691570101	$20^h35^m\,00^s\!.63$	+60d 11′ 29.″3	12	119301	2012 Oct 21 17:50:58
Ho IX X-1	0200980101	$09^h57^m\,53^s\!.20$	+69d 03′ 49.″8	32	119166	2004 Sep 26 06:55:52
M82 X-2	0112290201	$09^h55^m\,49^s\!.91$	+69d 40′ 44.″4	18	30558	2001 May 06 09:13:18

Note. Table 1 shows all the observations used in this work. The R.A. and decl. indicate the exact position of the sources used in selecting the source region.

Data Analysis

• PDS and QPOs

1. Light curve:

$$x(0), x(1), x(2), \ldots, x(N\text{-}1)$$

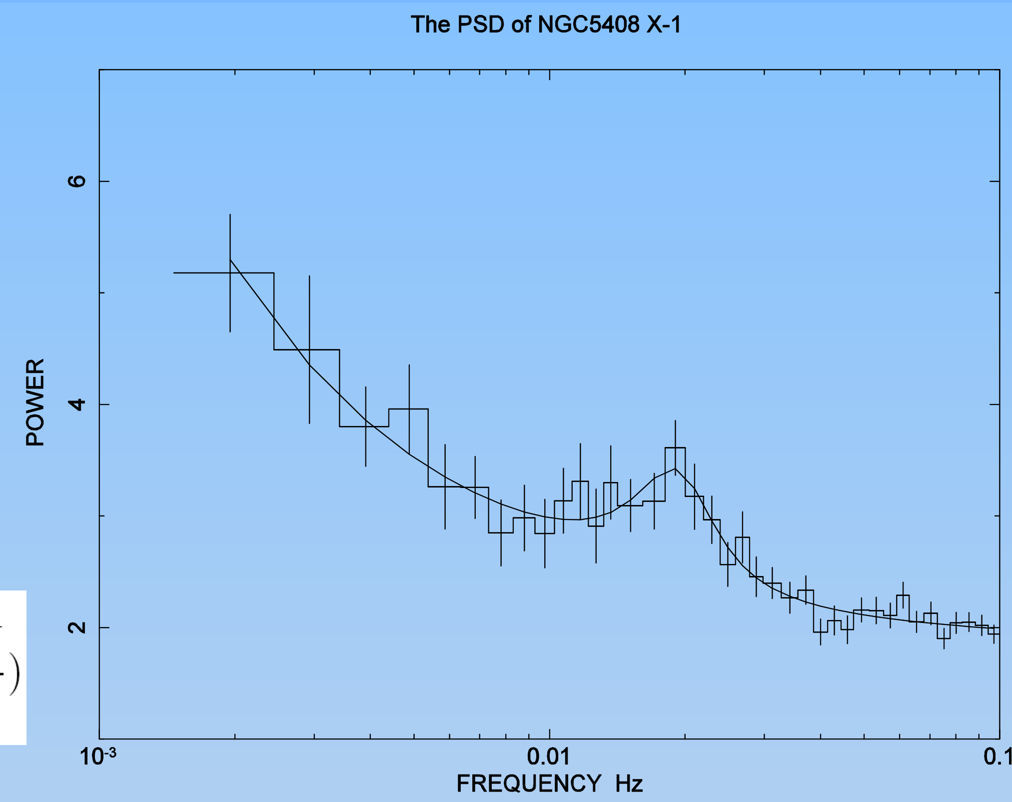
2. FFT:

$$a_j = \sum_{k=0}^{N-1} x(k) e^{i\frac{2\pi jk}{N}} \qquad (j = 0, 1, 2, \ldots, \frac{N}{2})$$

3. PDS:

$$P_j = \frac{2}{N_{tot.ph}} |a_j|^2 \qquad (j = 0, 1, 2, \ldots, \frac{N}{2})$$

Leahy et al, 1983, ApJ, 266, 160



- Leahy normalization, with the Poisson noise level being 2 (a constant)
- a narrow Lorentzian for the QPO feature

Data Analysis

- **Time lag**

1. Two light curve FFT:

$$X_1(f_j),\ \ X_2(f_j),\ (\text{j=0, 1, 2,...,N-1})$$

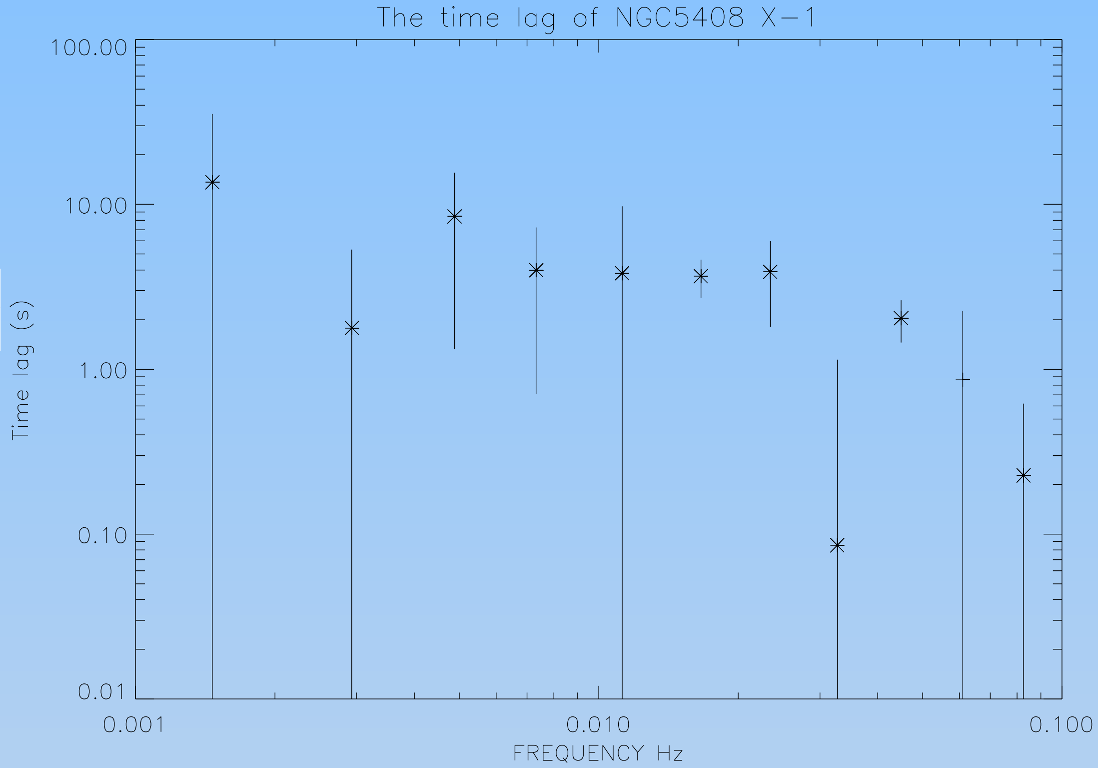
2. Phase lag:

$$\Delta\Phi = arg[X_1(f_j)^* X_2(f_j)]$$

3. Time lag:

$$\tau(f_j) = \frac{\Delta\Phi}{2\pi f_j}$$

Cui et al, 1997, ApJ, 484, 383



- Asterisks indicate negative values (soft lag)
- Crosses indicate positive values (hard lag).

Results

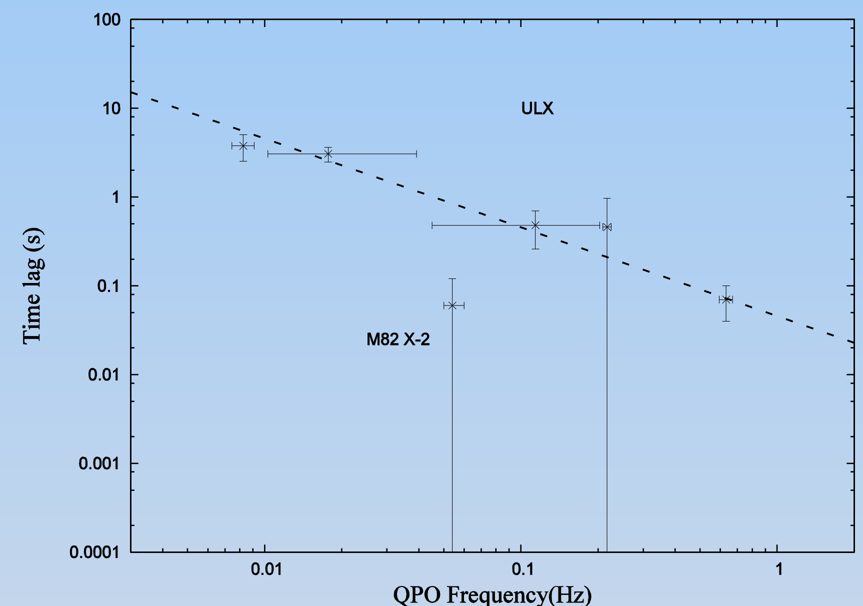
- Analysed all the observations

- QPO:
  - 5 ULX show QPOs
  - Frequency range from 0.008 – 0.6 Hz
  - consistent with previous reports
- Time lag:
  - All soft lag

Sources and QPOs

Source Name	Frequency	FWHM	Model	Energy Range
IC342 X-1	0.6326	0.0764	1	0.3–10.0 keV
M82 X-1	0.1139	0.0258	1	0.3–10.0 keV
NGC 5408 X-1	0.0177	0.0182	1	0.3–10.0 keV
NGC 6946 X-1	0.00825	0.00161	2	0.3–10.0 keV
Ho IX X-1	0.2168	0.0164	1	0.3–10.0 keV
M82 X-2	0.0035	0.0015	1	0.3–10.0 keV

1 represents power law + Lorentzian; 2 represents a broad Lorentzian + Lorentzian.



Discussion

- **Type of QPO:**

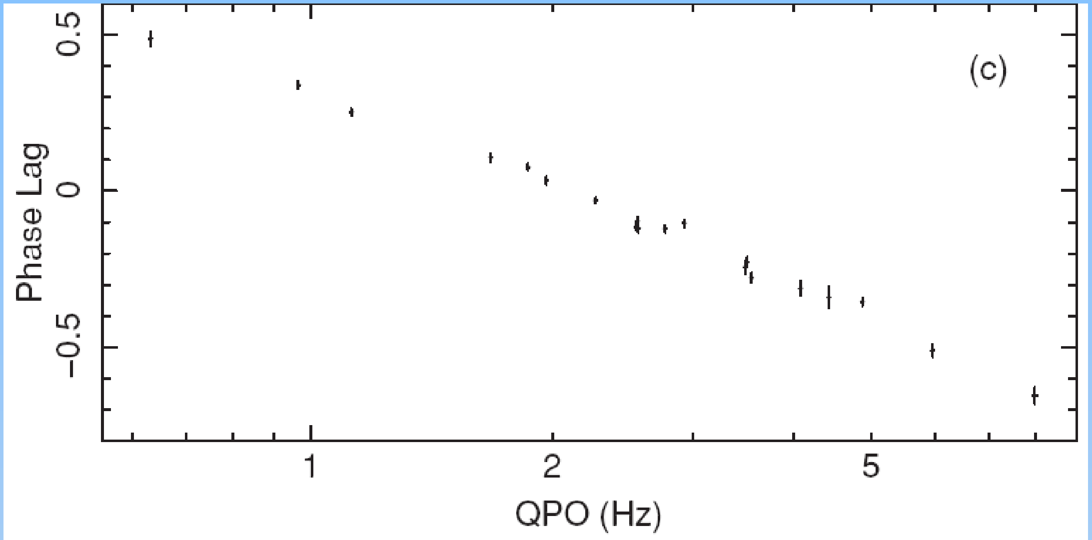
- strong, fast variability confirms their compact nature
- energy spectrum suggests between different states as BHXRBs, especially the transition between the HSS and LHS in which type-C QPOs are often detected
- power spectral shape

Discussion

- **Type of QPO:**

GRS 1915+105

Qu et al, 2010, ApJ, 710, 836



- null hypothesis that the ULX QPO time lags are both hard and soft, and we simply happen to have only seen soft lags so far.
- the p-value is 0.1679

Discussion

- **Type of QPO:**

  - The phase lag at the Type-C fundamental QPO frequency depends significantly on source inclination.

    Van den Eijnden et al, 2017, MNRAS, 464, 2643

  - The Type-C QPO soft lags are associated with high-inclination sources.

  - Type-C QPOs in BHXRBs have a larger amplitude for high-inclination objects.

    Motta et al. 2015, MNRAS, 447, 2059

Discussion

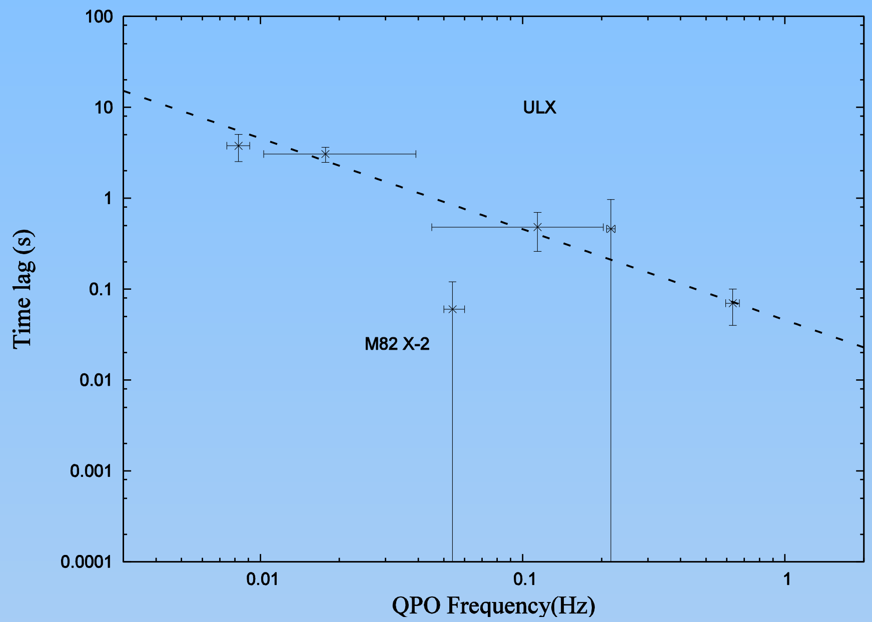
- **The soft time lag:**

- Reverberation
- result of the reflection of X-rays by a geometrically thin and optically thick accretion disc
- lag represents the light travel time between the corona or the central object and the accretion disc.

$$t_1 \sim \frac{r_g}{c} = \frac{GM}{c^3}$$

Discussion

- **The soft time lag:**



- Reverberation
- a constant phase lag
- a linear correlation between time lag and frequency
- For these reasons, we suggest that the reverberation model reasonably explains the soft lag in ULXs.

Conclusions

- QPOs were found in five ULXs.
- ULX QPOs being Type-C QPO analogs.
- Time lags on the QPO frequency always be soft.
- The time lag versus QPO frequency is a linear relation.
- May be the reverberation.
- Intermediate-mass black holes.

Thanks!

If have any questions, please feel free to ask!