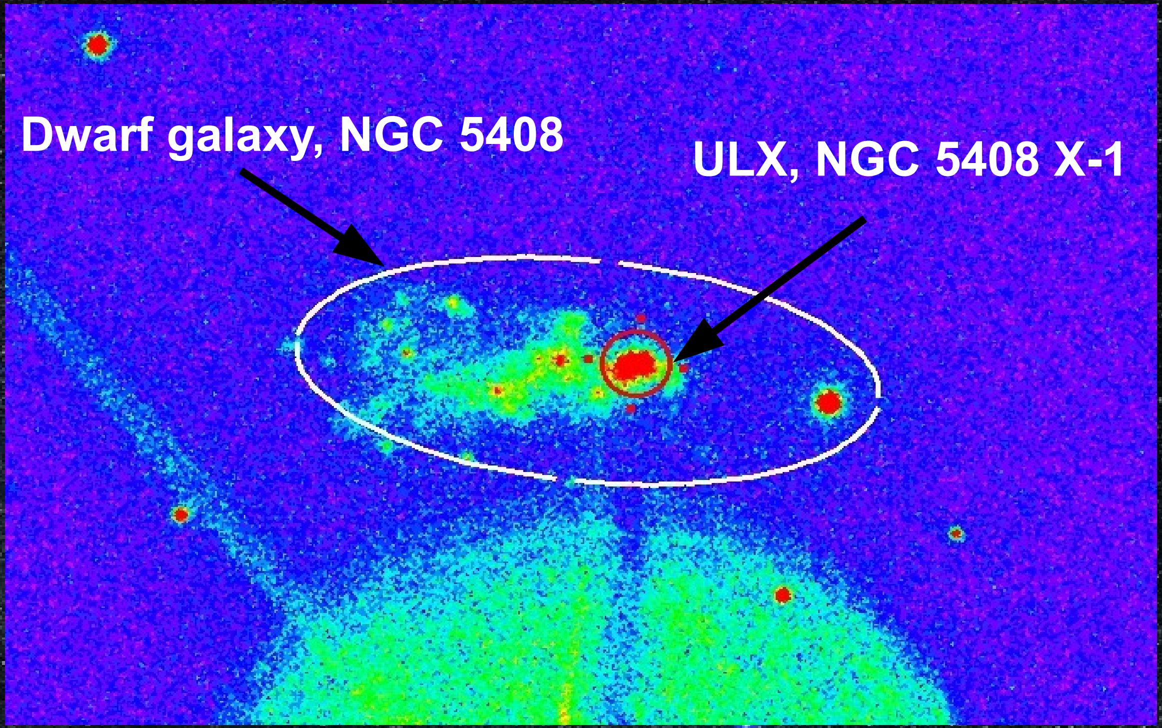
# ULX, NGC 5408 X-1:
# SEARCH FOR CORRELATED TIMING & SPECTRAL BEHAVIOR



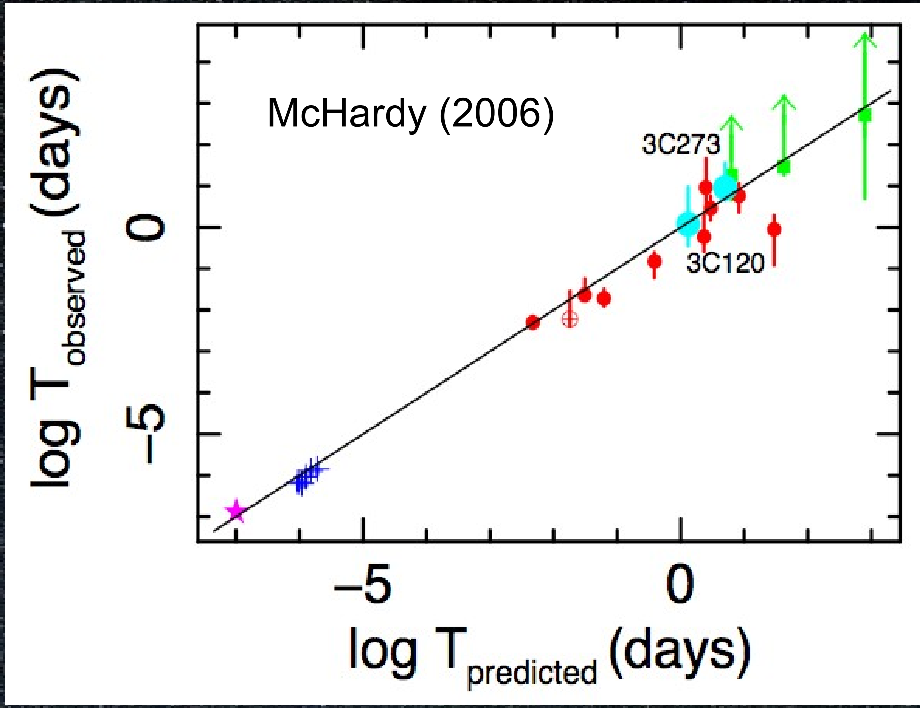

Dheeraj Pasham, University of Maryland, College Park
Tod E. Strohmayer, Goddard space flight center/NASA

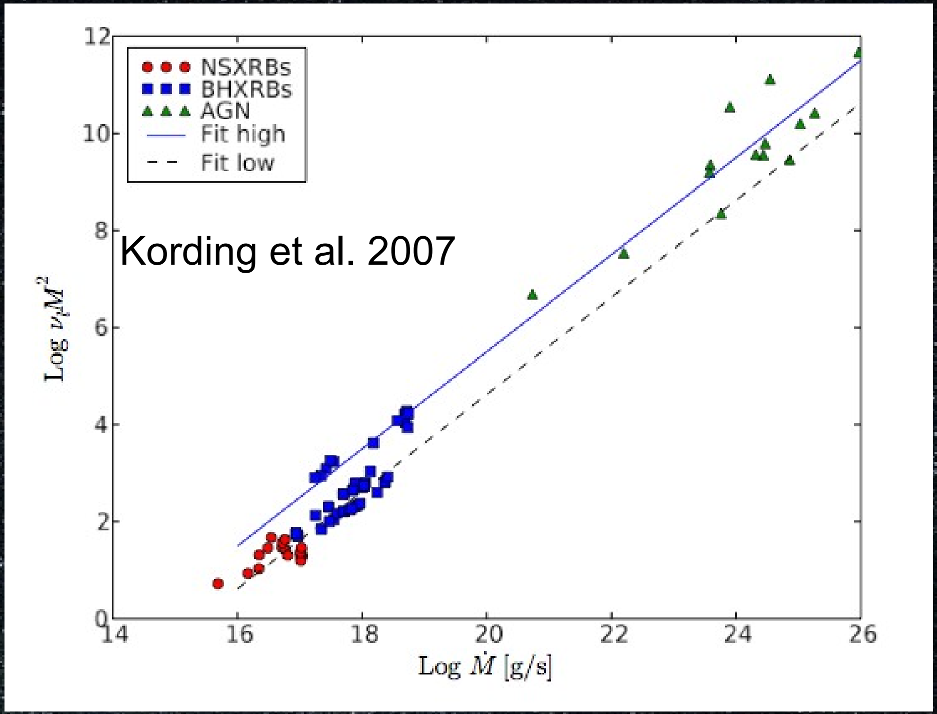
# Introduction

- NGC 5408 X-1 is an ultraluminous X-ray source : ULX
  X-ray (0.3-10.0 keV) luminosity ~ **$2\times10^{40}$ ergs $s^{-1}$**
- Evidence for quasi-periodic behavior : QPOs
- Very rare phenomenon in ULXs
  - Only two other ULXs (M82 X-1, NGC 6946 X-1) show QPOs
  - 3 out of 300 is a big deal ! [ Bias ]
- X-1 show qualitative similarities with stellar mass black holes
  - Energy spectra : Cool disk (kT ~ 0.15 keV) [thermal?] compared to stellar BH, kT ~ 1.0keV
  - Power spectra with characteristic frequencies scaled DOWN by ~ 100
- Here : We search for further similarities with stellar mass BHs
  - Specifically, correlated timing and spectral behavior

# Black hole unification with timing studies

## Mass of compact source : Encoded in timing properties




**Variability plane :**

$\log T_{Break} = A\log M_{BH} - B\log L_{bol} + C$

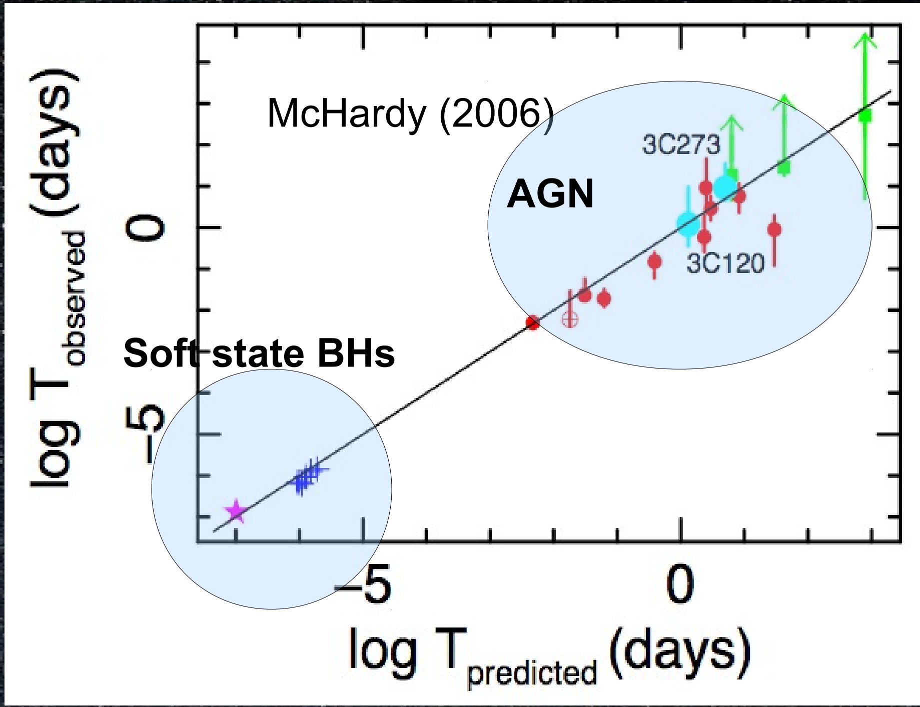
**Timing properties scale with mass of the BH !**

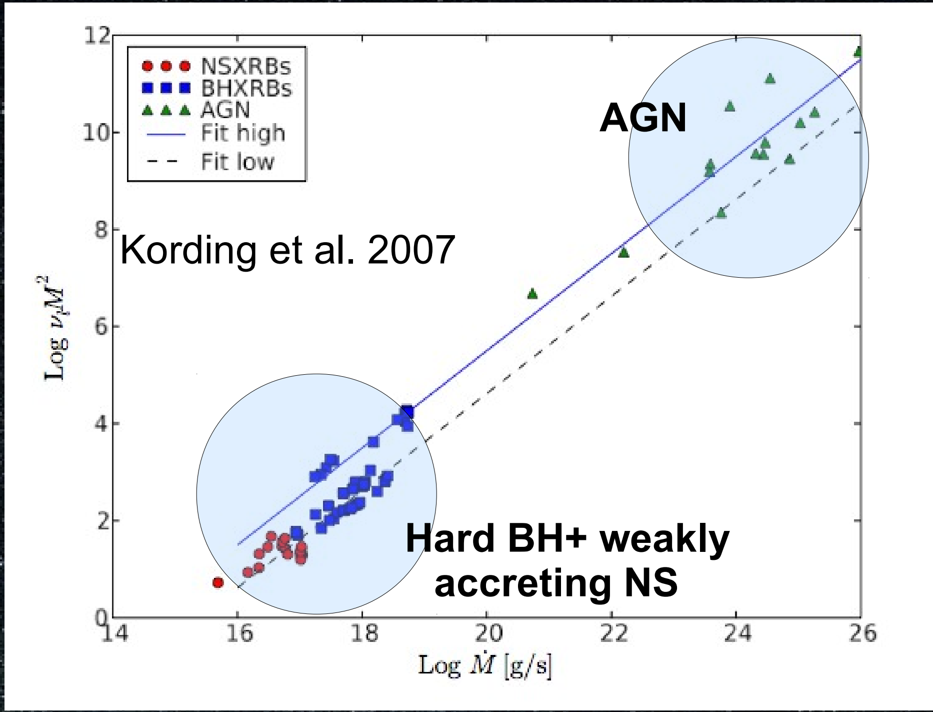
**Variability plane for accreting compact sources (Koerding et al. 2007) :**

**NS + BH + AGN**

# Black hole unification with timing studies

## Mass of compact source : Encoded in timing properties

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**NS + BH + AGN**

**Let's use this information !**

**Talk by Gabriele Ponti**

# Aim :

- Mass of ULXs : Highly debated ! → No consensus
- **No** (direct)dynamical estimates on mass of any ULX, **yet.** **( Roberts et al. 2011 )**
- Indirect methods to estimate the mass

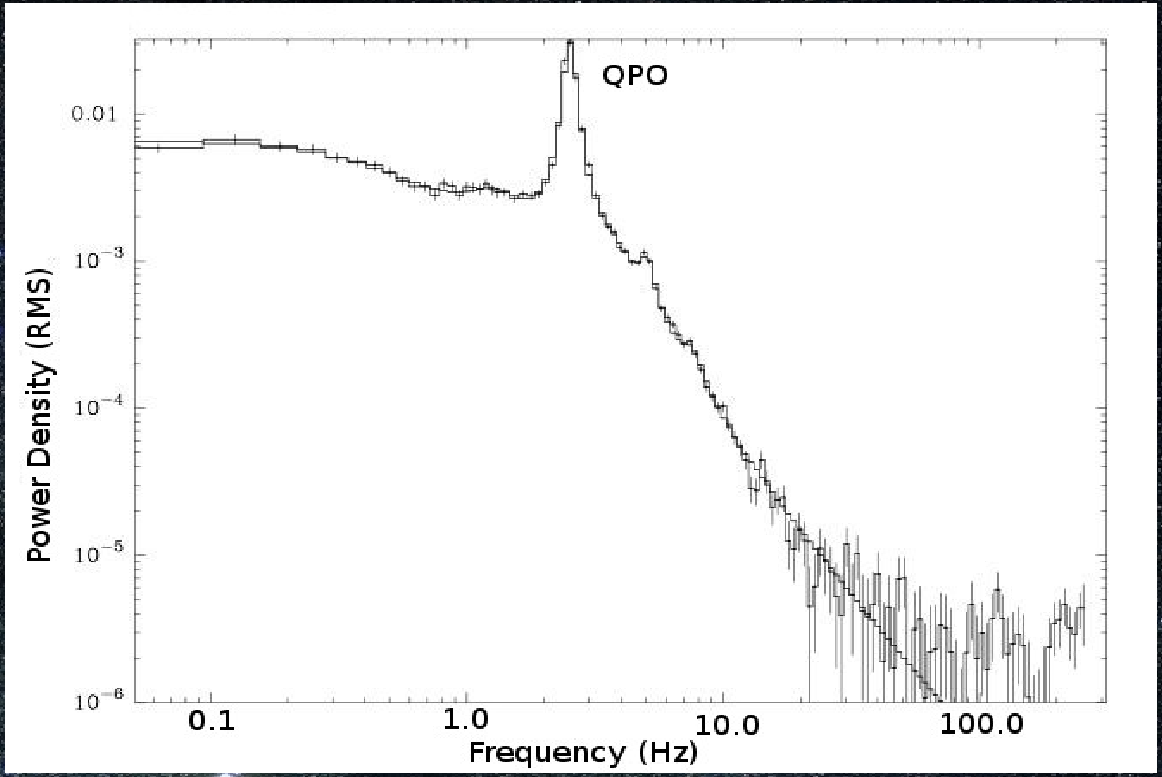
***We attempt to estimate the mass of black hole in X-1 with the aid of timing studies***

# Background :

## What do we know from BHs of known mass ?

# Background : Timing from BHs

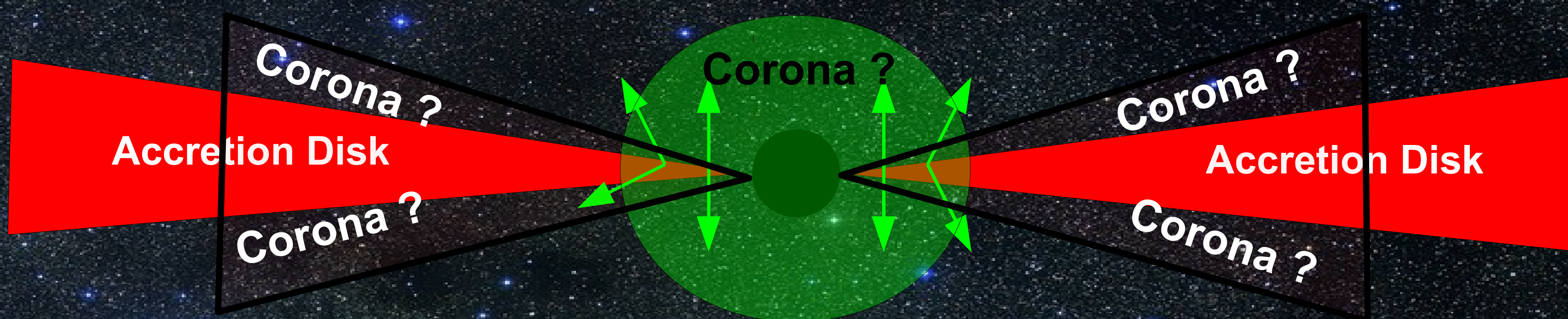
- Multi-epoch observations from certain black hole systems show strong evidence for QPOs
- Variable QPOs ( Centroid frequency variable on timescales of few hours - days)




**Sample power spectrum of GRS 1915 + 105**
**Viagnarca et al. 2003**

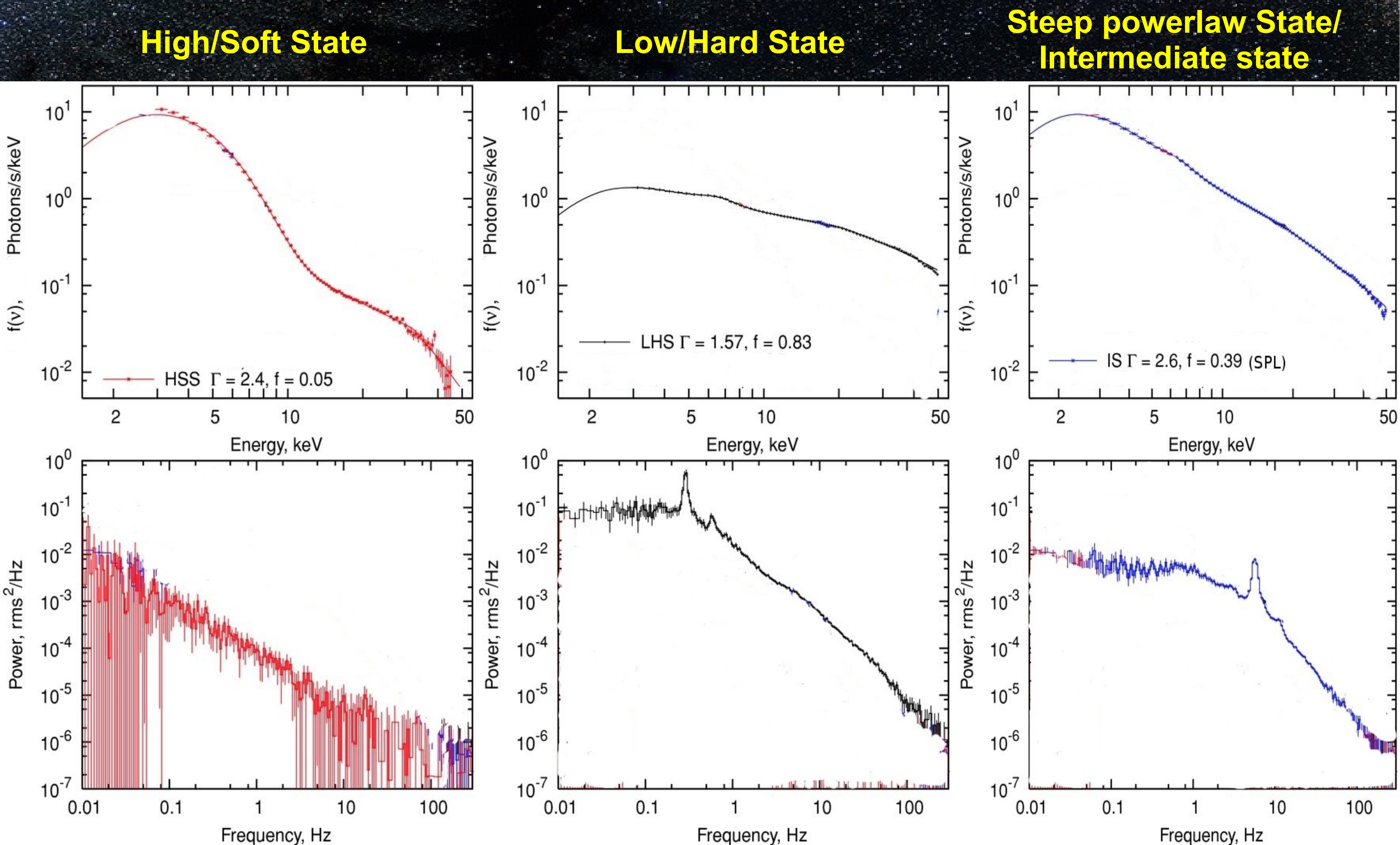
# Background : Energy spectra of BHs

- Phenomenological model within the present context
  - Model : Multicolored disk + powerlaw
  - Soft X-rays (0.2-2.0 keV) : Disk
  - Hard X-rays (2.0-10.0 keV) : Disk photons processed by the corona



# Background : Energy spectra of BHs

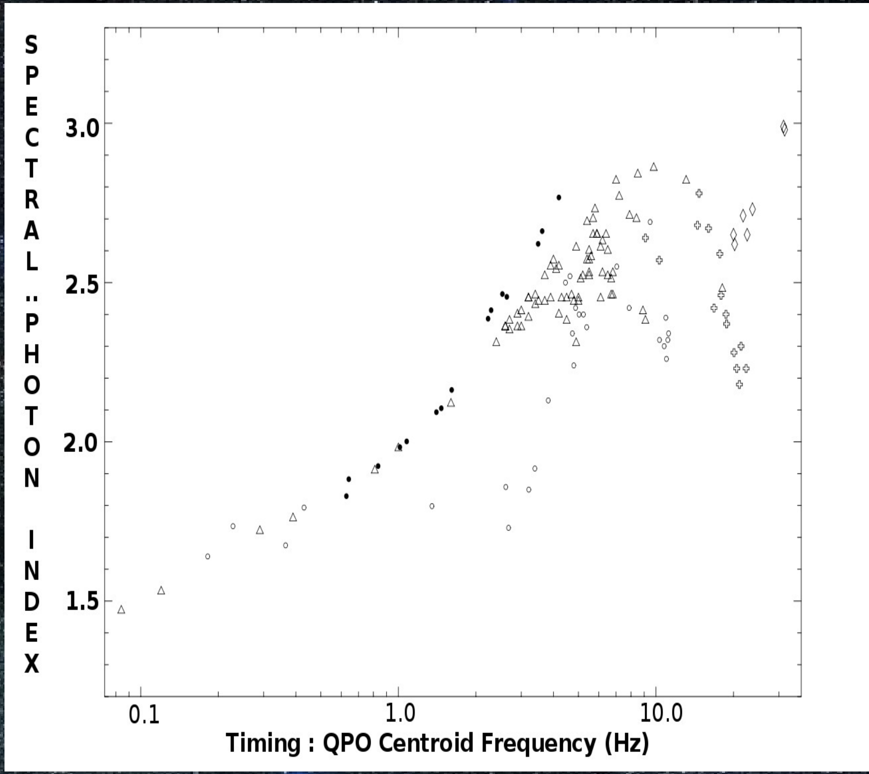
**Model : MCD + Powelaw also used to classify black hole accretion states**



# Stellar mass black hole systems

- Timing and spectral properties are correlated with evidence for saturation !
- Same source : Different correlation paths possible for different "Transition episodes" → Chaos with order !

**Γ Vs QPO frequency**
**Model : Multi-colored Disk + Powlaw**




**Viagnarca et al. 2003**

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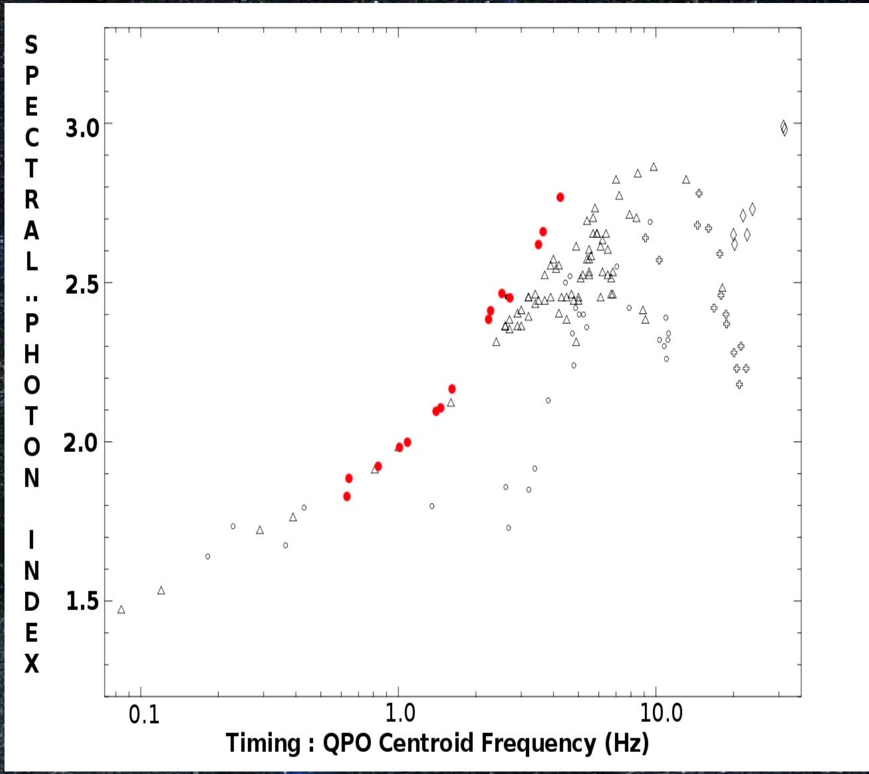


GRS 1915+105

Viagnarca et al. 2003

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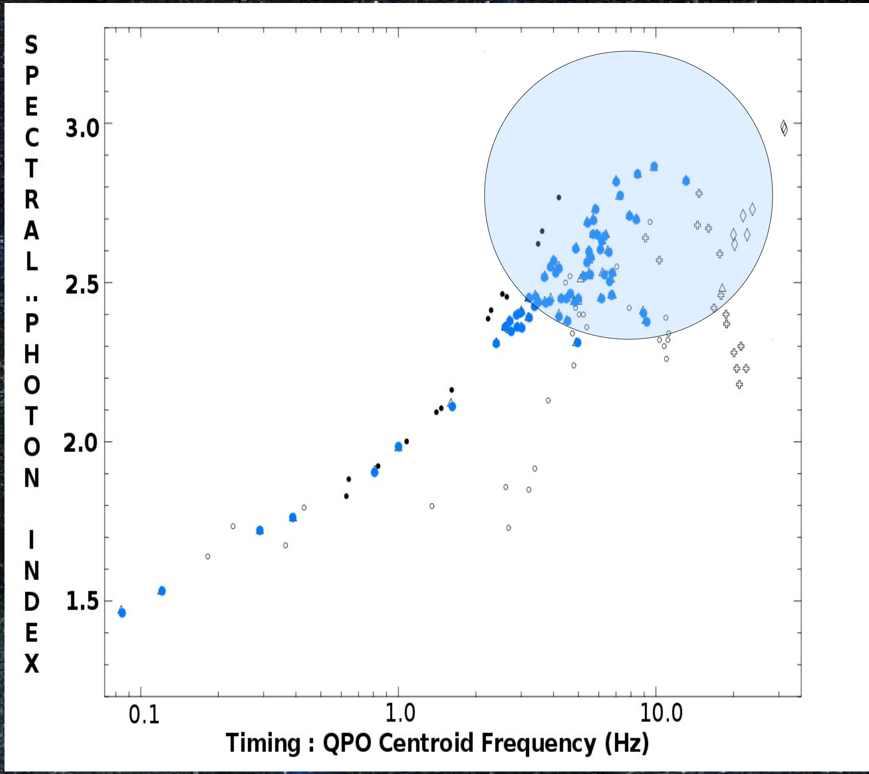


XTE 1550+564

Viagnarca et al. 2003

# Stellar mass black hole systems

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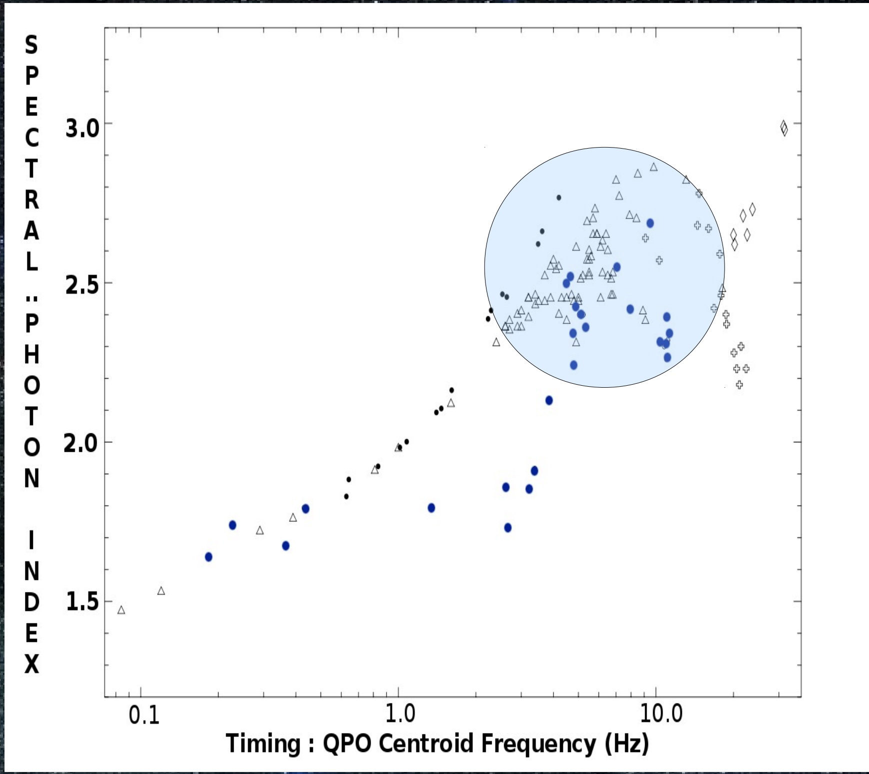


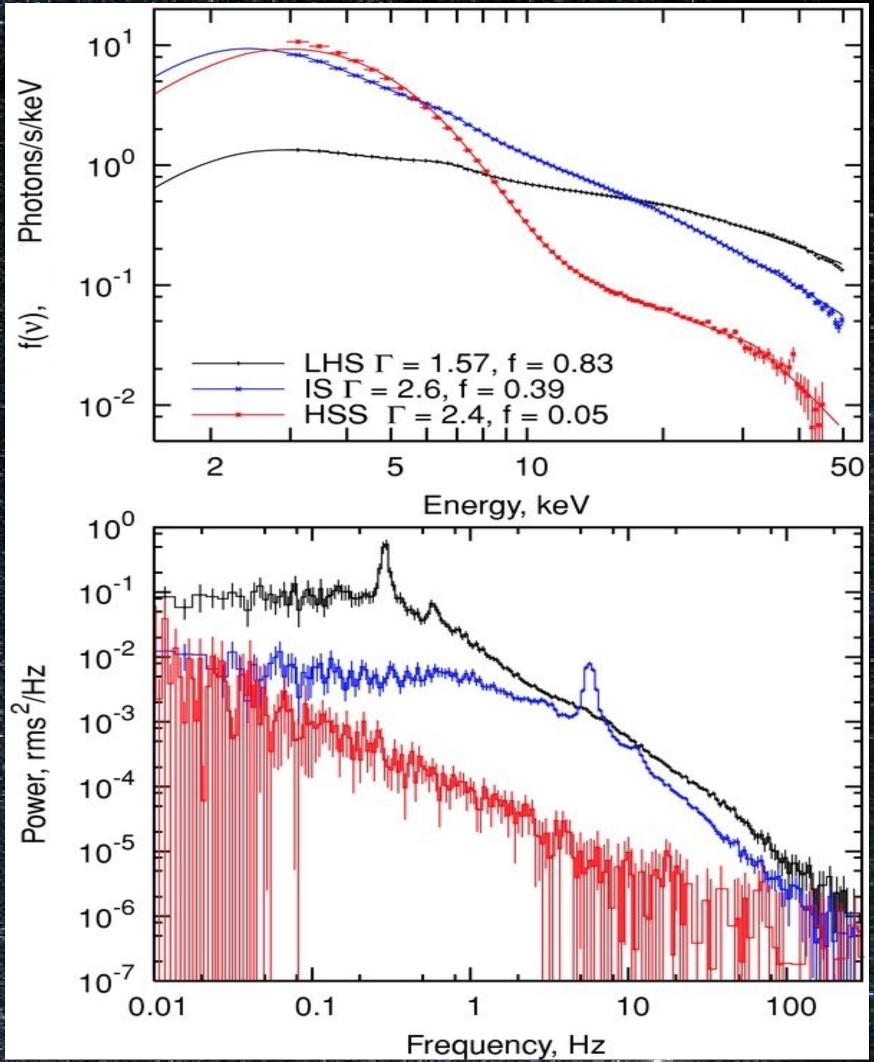

4U 1630-47

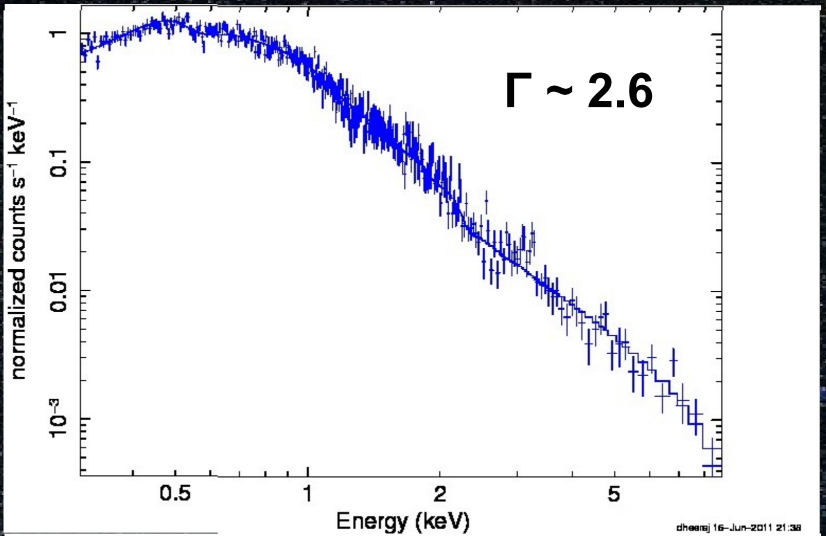
Viagnarca et al. 2003

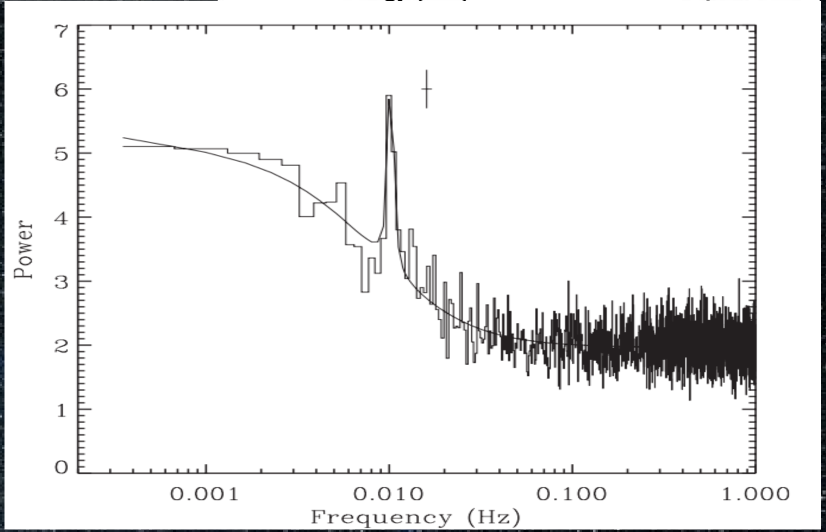
# Summary from BHs : Motivation

- Convincing evidence that timing & spectral properties are correlated in BHs with evidence for saturation
- ULX, NGC 5408 X-1 : shows QPOs
- Search for such correlations in X-1 : Understand this behavior within the context of well studied stellar mass BHs
- Implications on Mass of X-1

# Motivation : Hints for behavior similar to StBHs ?



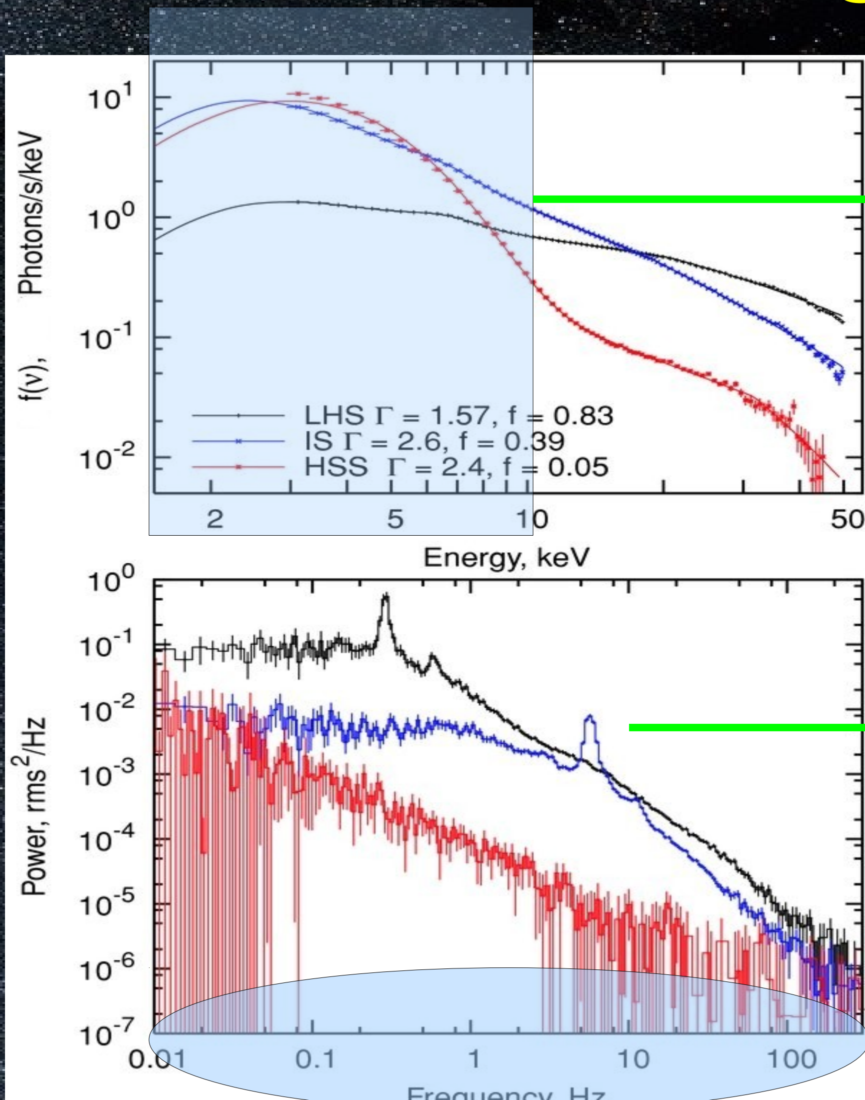



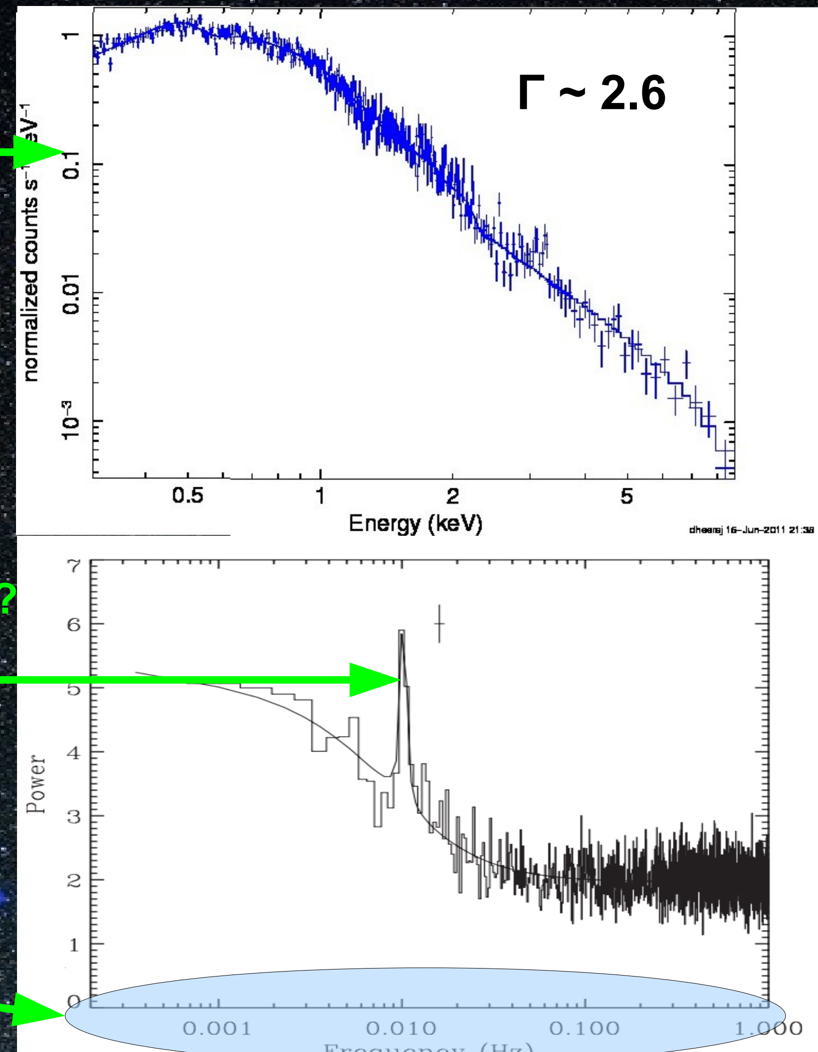

**Galactic black holes :**

**Shaposhnikov & Titarchuk (2009)**

**ULX, NGC 5408 X-1**

# Motivation : Hints for behavior similar to StBHs ?




Type C QPOs ?

Scaled down by a factor ~ 100 !

Galactic black holes :

Shaposhnikov & Titarchuk (2009)

ULX, NGC 5408 X-1

# Motivation : Behavior similar to stellar mass BHs

Phenomenological model : MCD + powerlaw also used to define black hole states

## Steep power law state : Stellar mass black holes

Presence of power-law component with $\Gamma > 2.4$

Disk fraction (Flux) < 80 %

With QPOs in 0.1-30 Hz

RMS (QPOs) > 0.01

## NGC 5408 X-1 : Spectral and timing properties

Power-law component with $\Gamma$ : 2.4 - 2.7

Disk fraction (Flux) : 40 - 60%

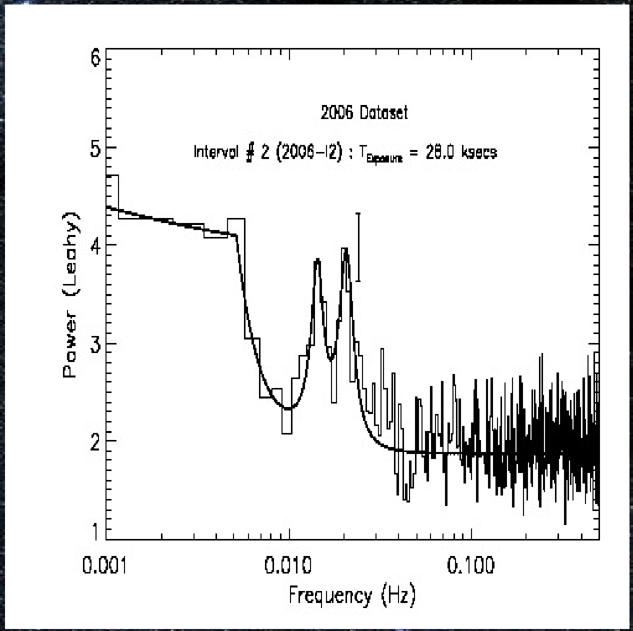
With QPOs in 10-40 mHz

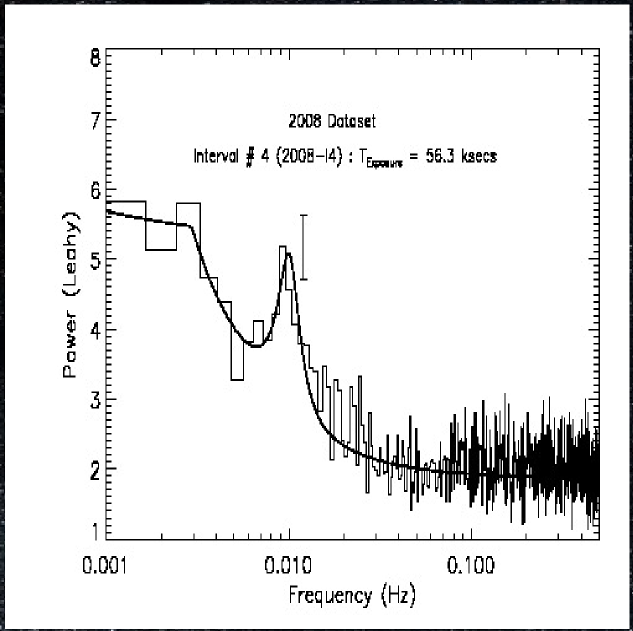
RMS (QPOs) : 0.10-0.25

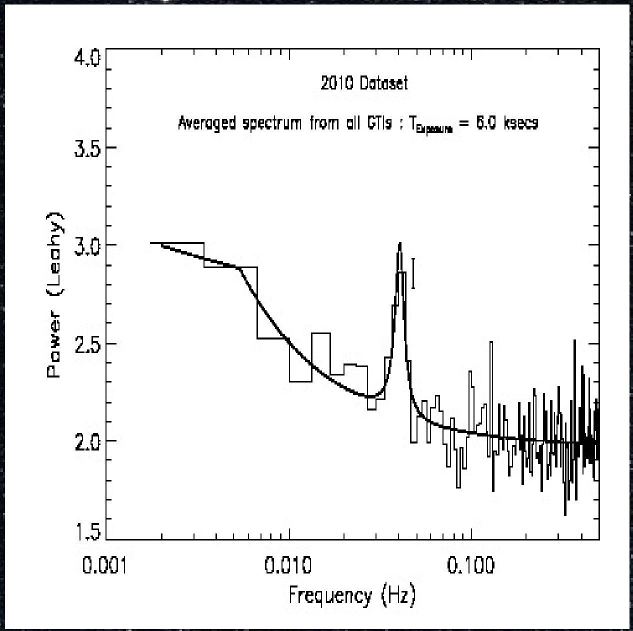
# Data from ULX, NGC 5408 X-1

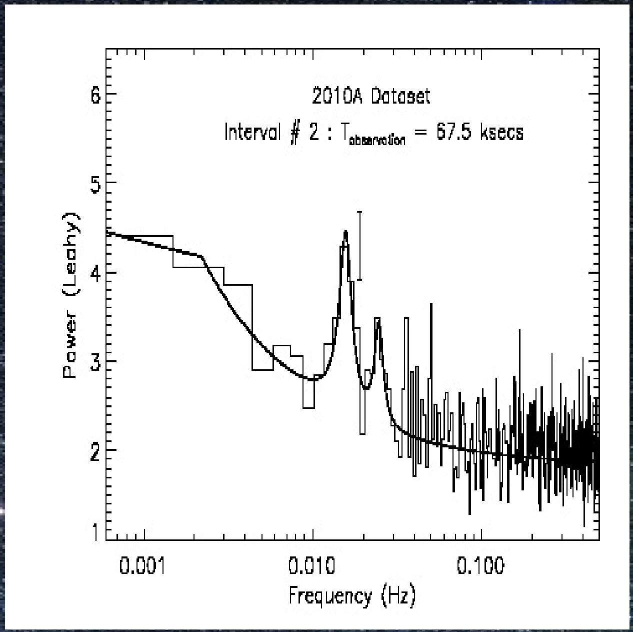
- Initial evidence for similarity with BHs in **Steep powerlaw state:SPL** (Strohmayer et al. 2006)
- New XMM-Newton observations, 4 X 100 ksecs
- QPO phenomenon variable : 8 distinct intervals with strong evidence for QPOs [ From ALL previous observations ]
- QPOs:centroid frequency in range 10 – 40 mHz
- Search for correlations using 8 data points
- XMM : PN only data, flaring eliminated, low background (no background subtraction)

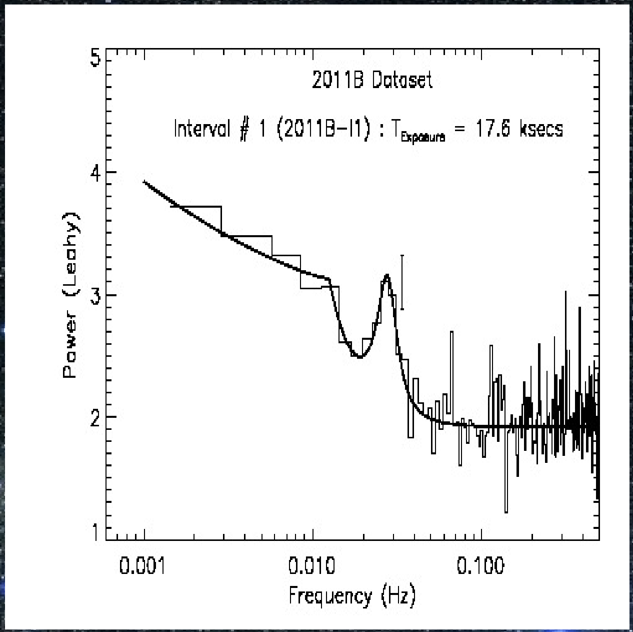
# QPO Detections : Sample power spectra

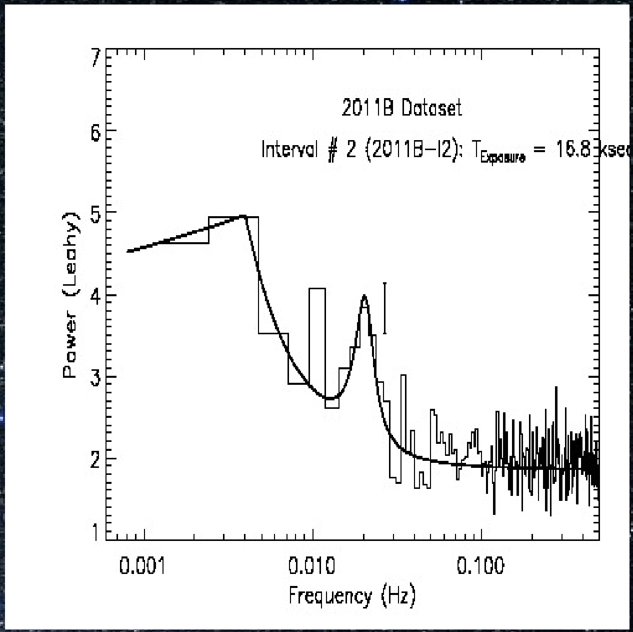


## Search for correlations using Model :

**Multicolored disk**

**+**

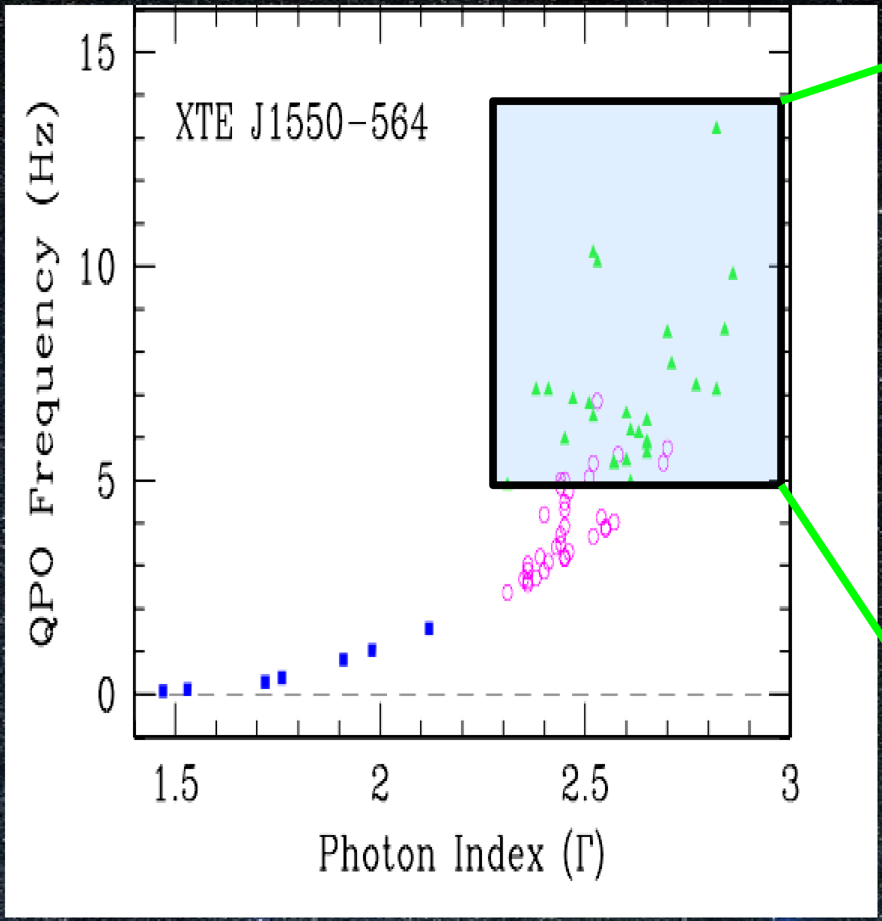
**Powerlaw**

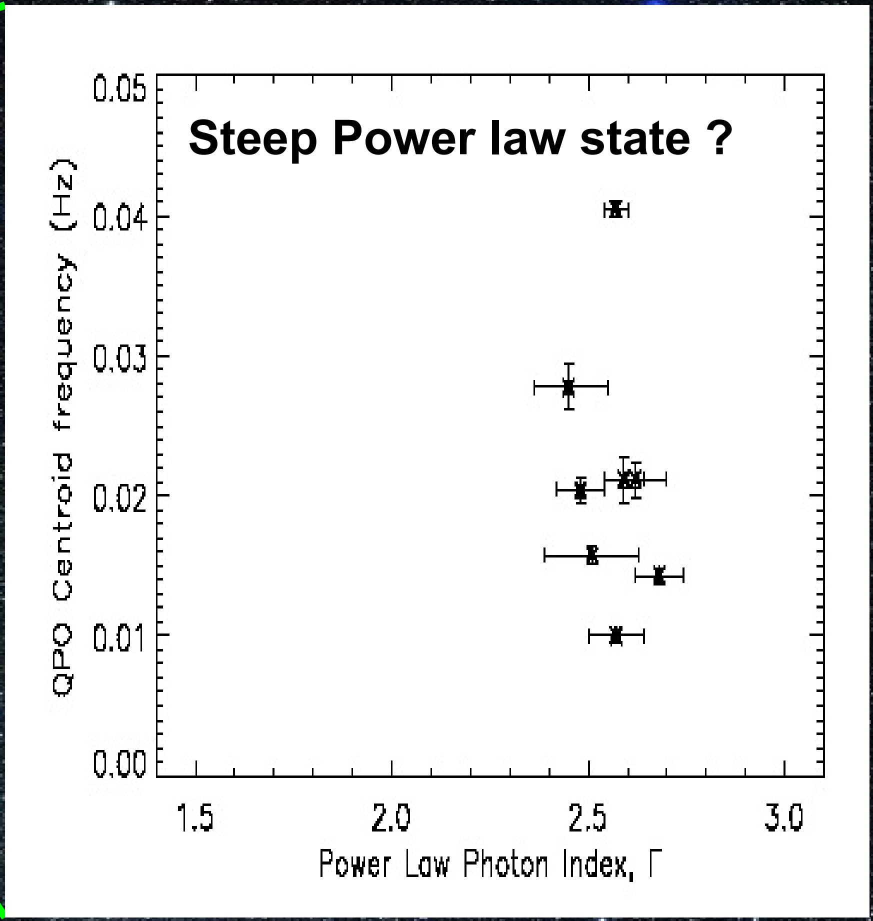
# Photon Index Vs QPO frequency

# Photon Index (Γ) Vs QPO centroid frequency

▲ - *Steep power law state*

ULX, NGC 5408 X-1




McClintock et al. 2009

Present work

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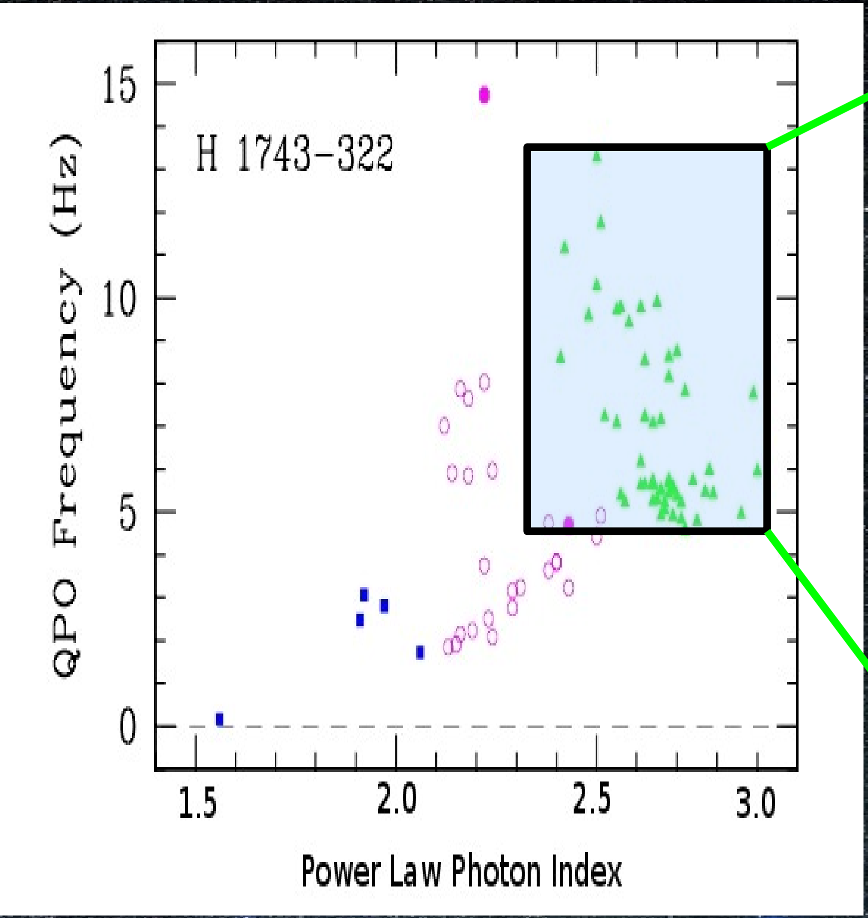


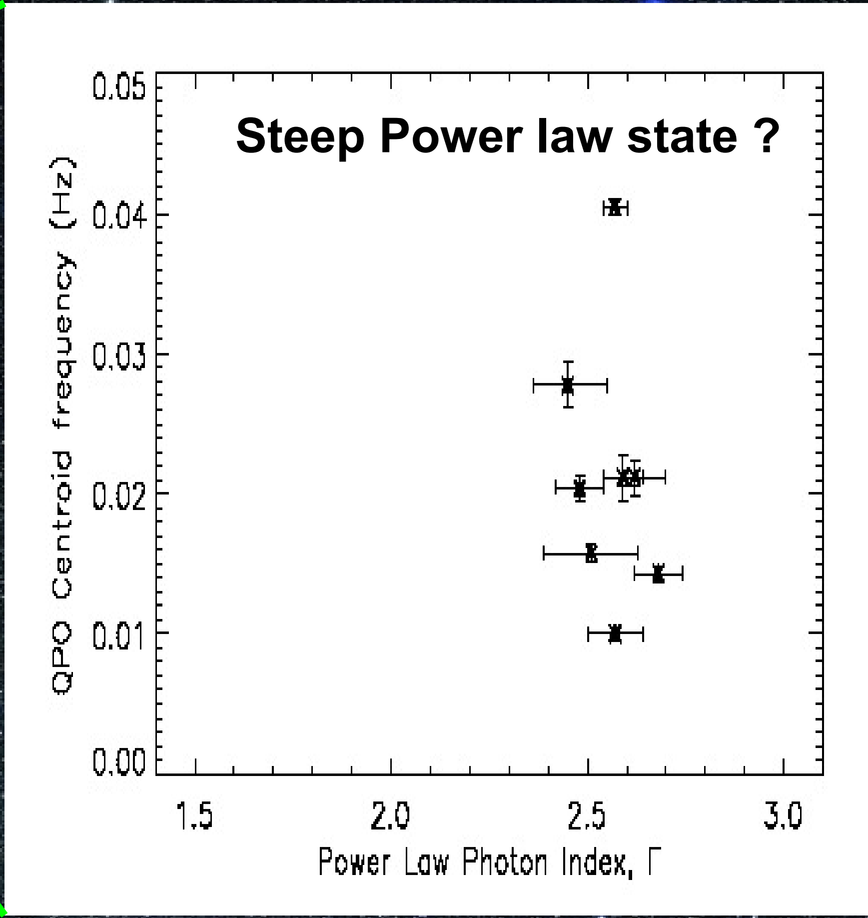


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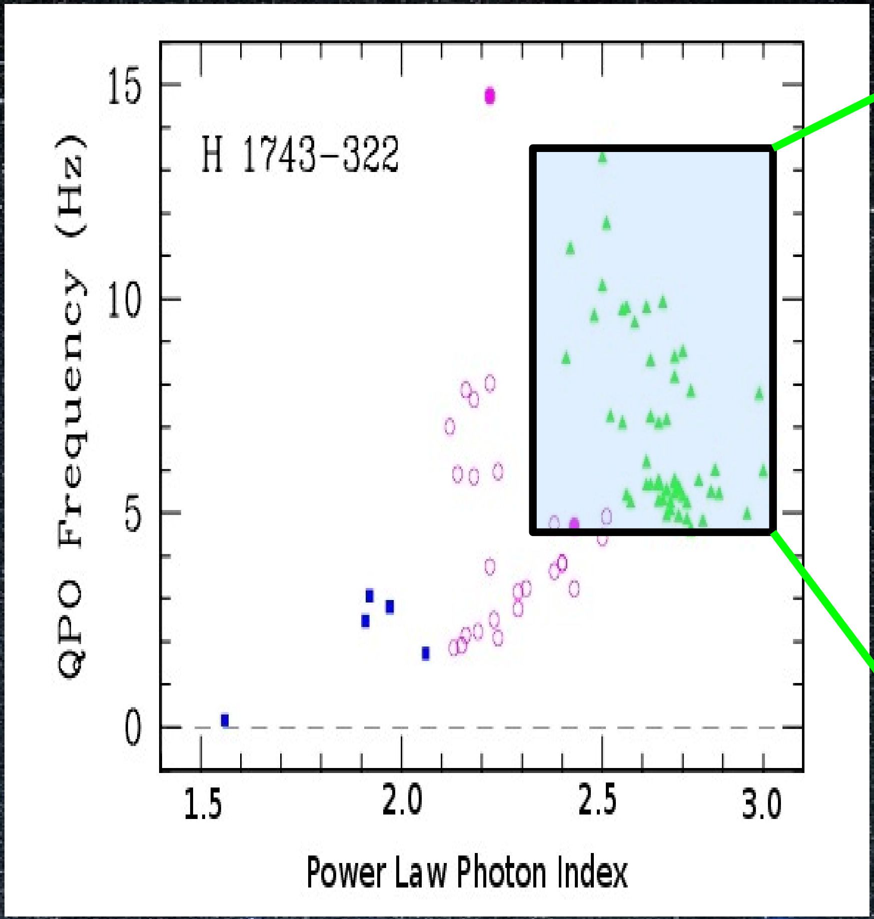


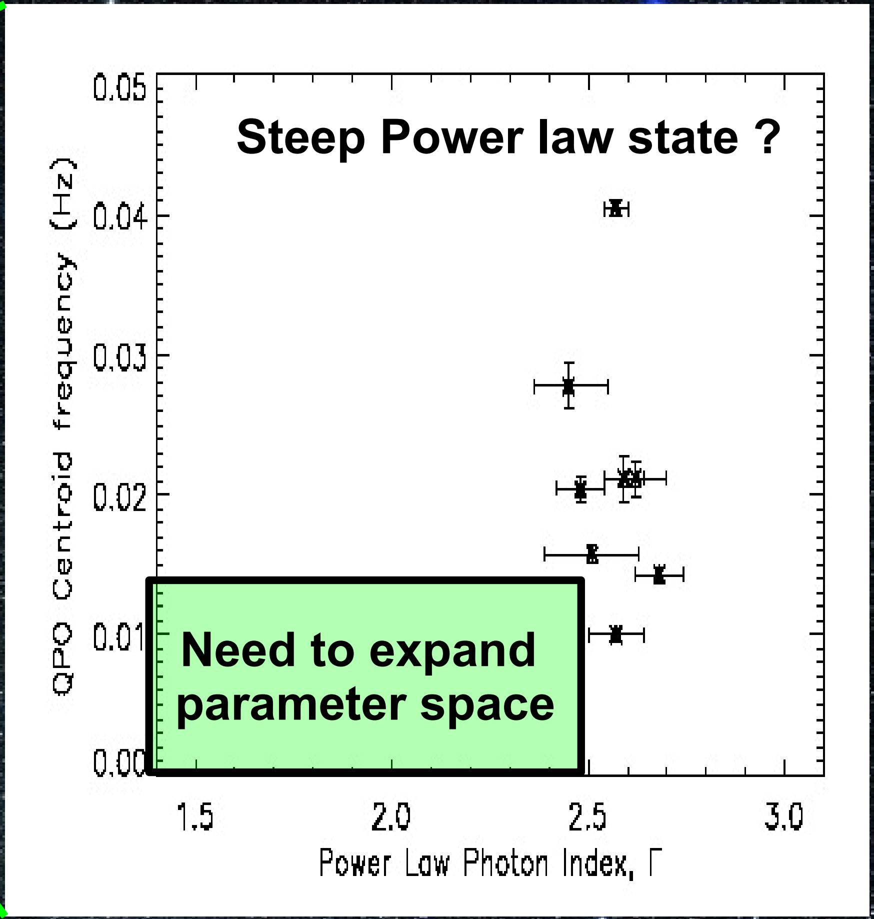


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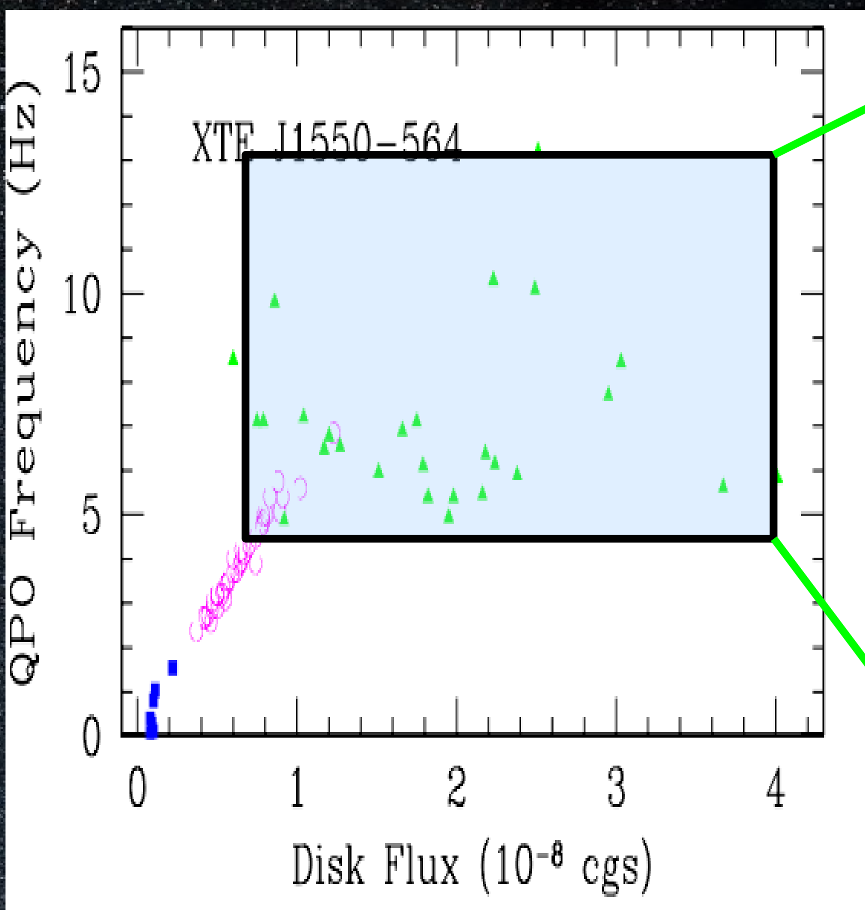
Present work

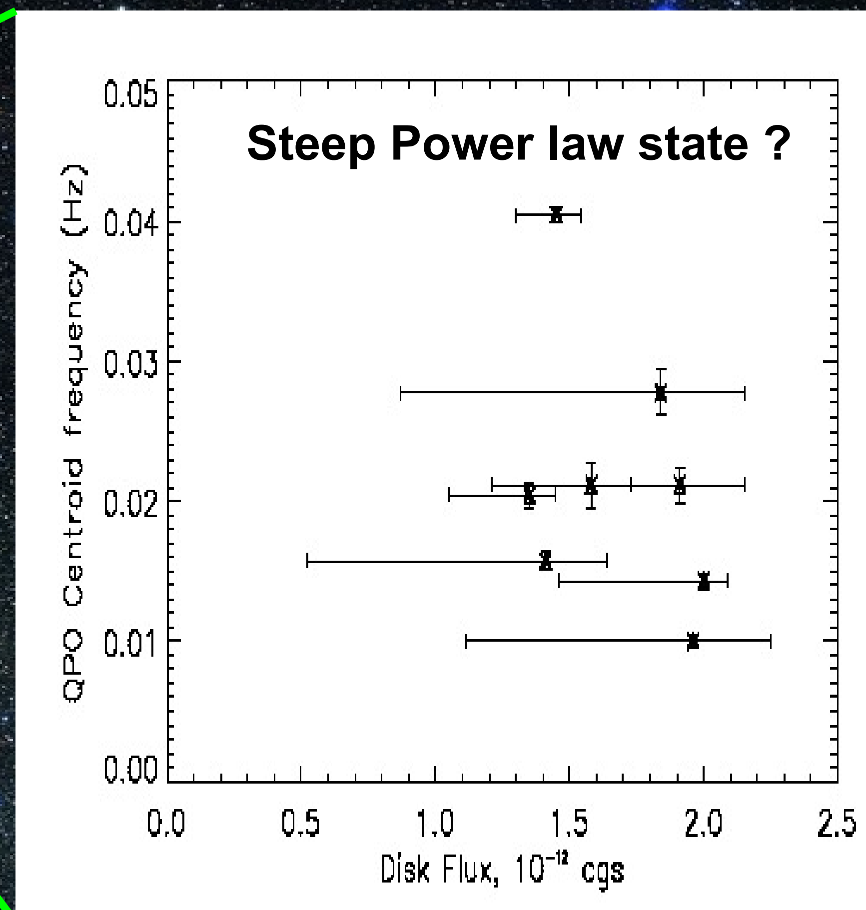
# Disk flux Vs QPO frequency

# Disk flux Vs QPO centroid frequency

▲ - *Steep power law state*

**ULX, NGC 5408 X-1**



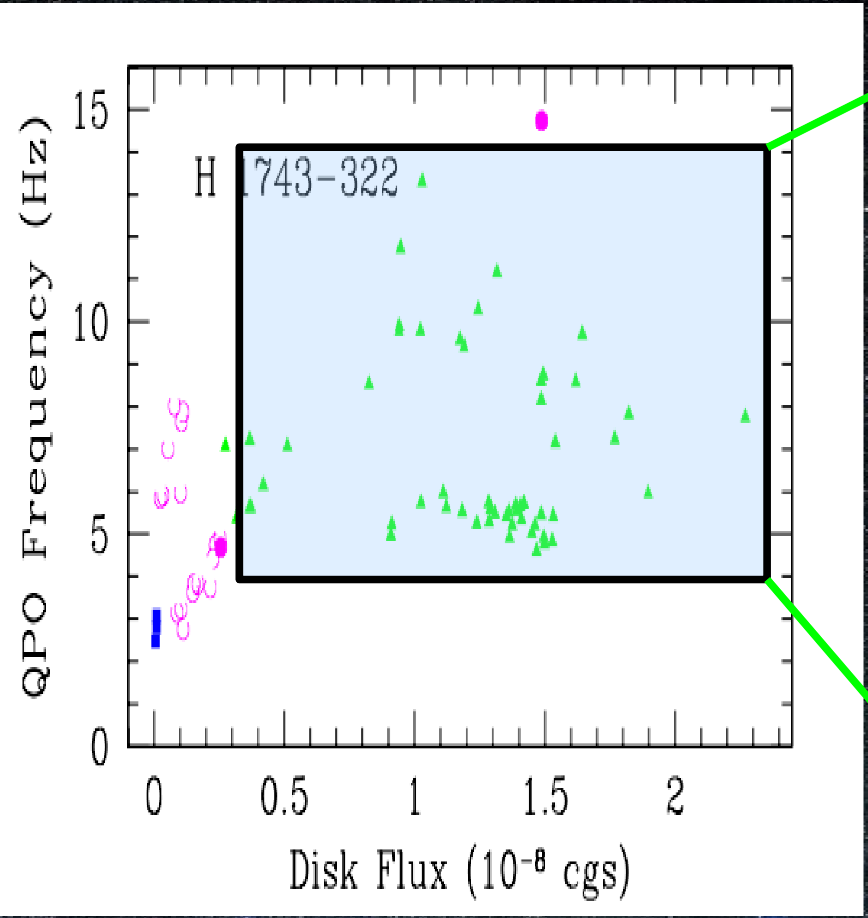

McClintock et al. 2009

Present work

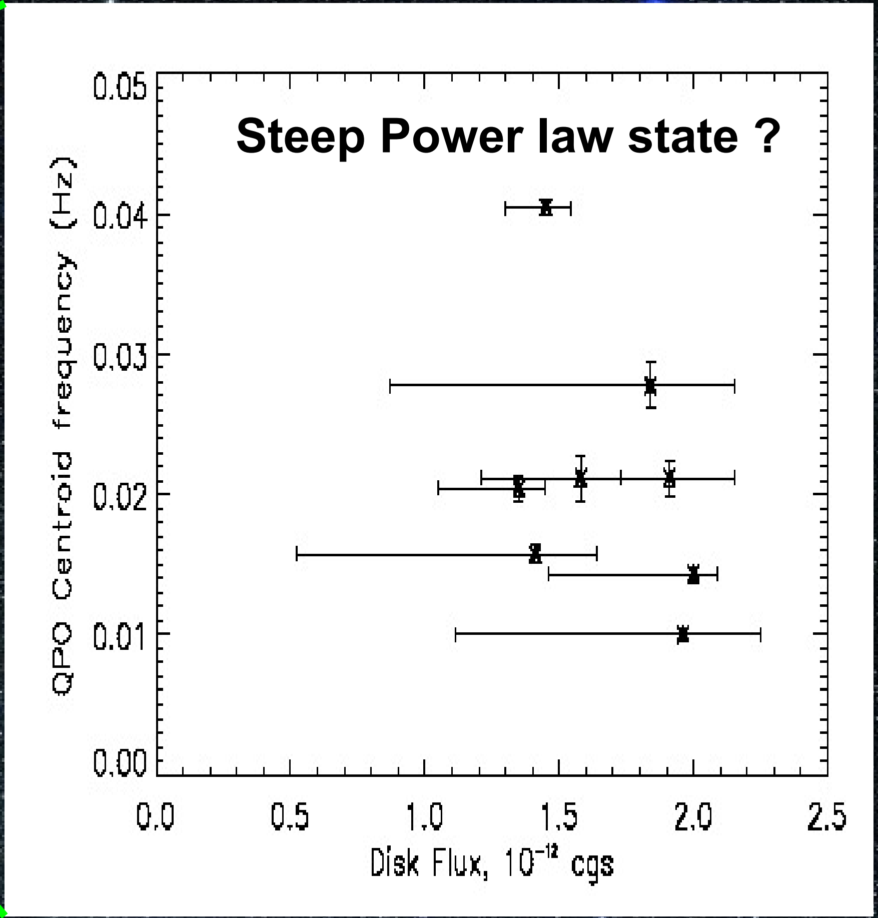
# Disk flux Vs QPO centroid frequency

▲ *- Steep power law state*

**ULX, NGC 5408 X-1**




**McClintock et al. 2009**




**Present work**

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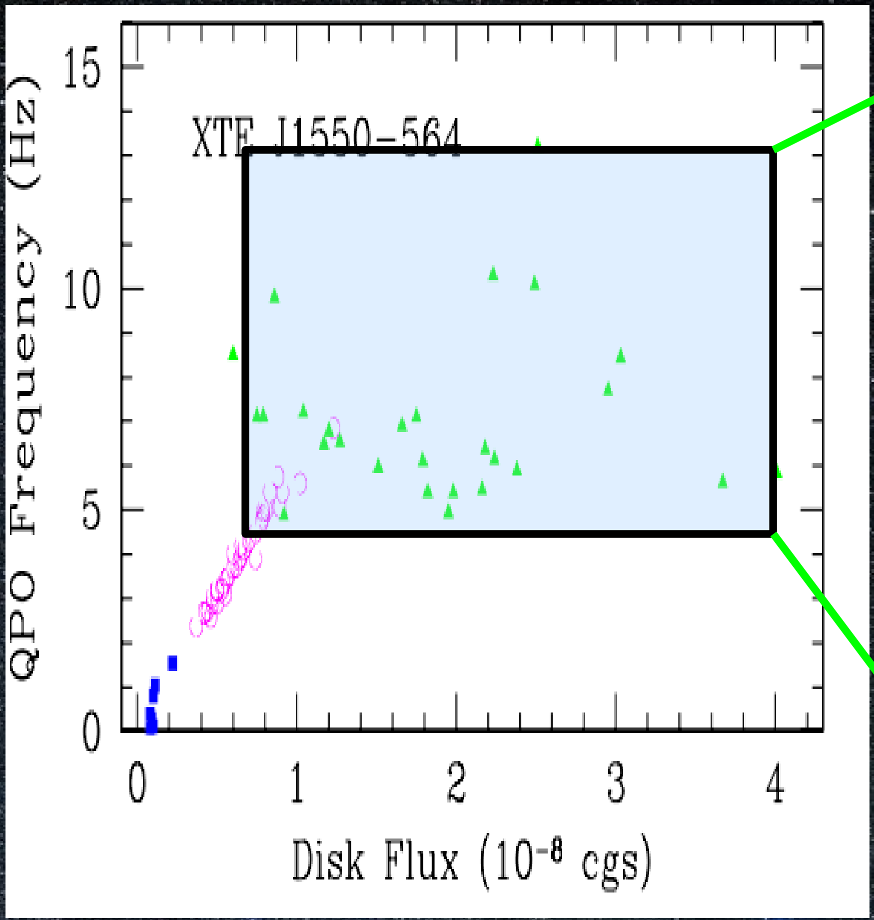
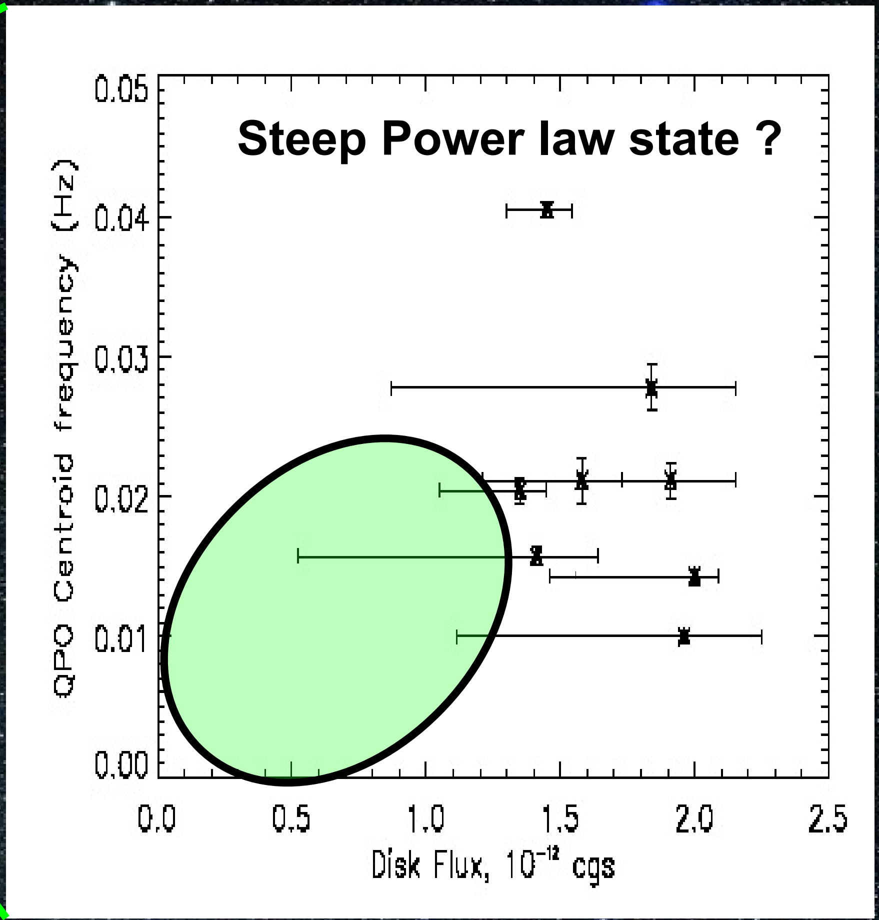


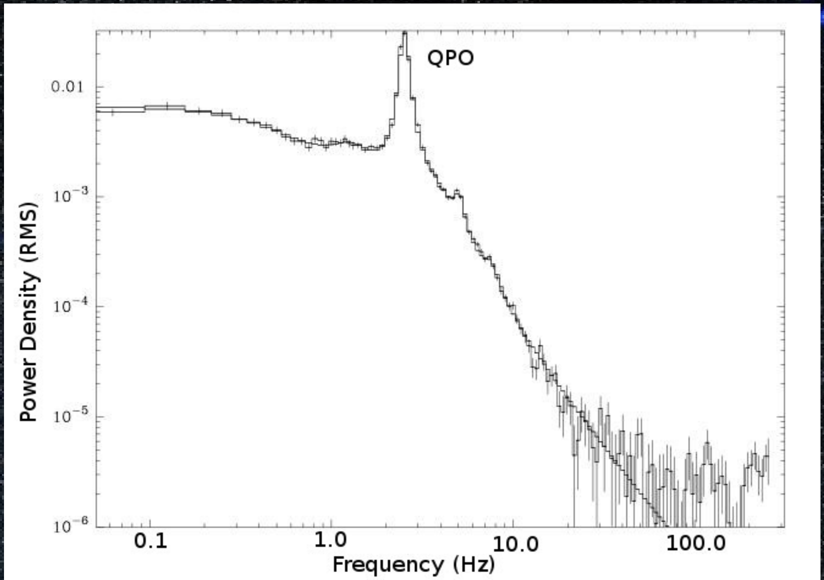

McClintock et al. 2009

Present work

# Mass estimate by direct scaling

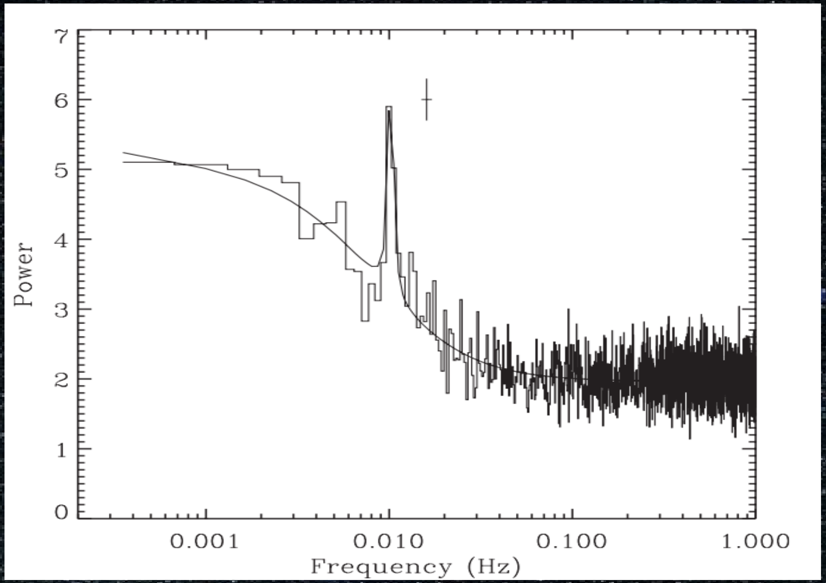
Results consistent with X-1 being in Steep Powerlaw state (SPL)

Stellar mass BH : M ~ 10 $M_o$




SPL : QPOs in 0.1-30 Hz

NGC 5408 X-1




SPL : QPOs in 10-40 mHz

QPO frequencies scale as $1/M_{BH}$

$1/M_{BH}$ scaling → Minimum value $M_{X\text{-}1}$ ~ few x 100 $M_o$

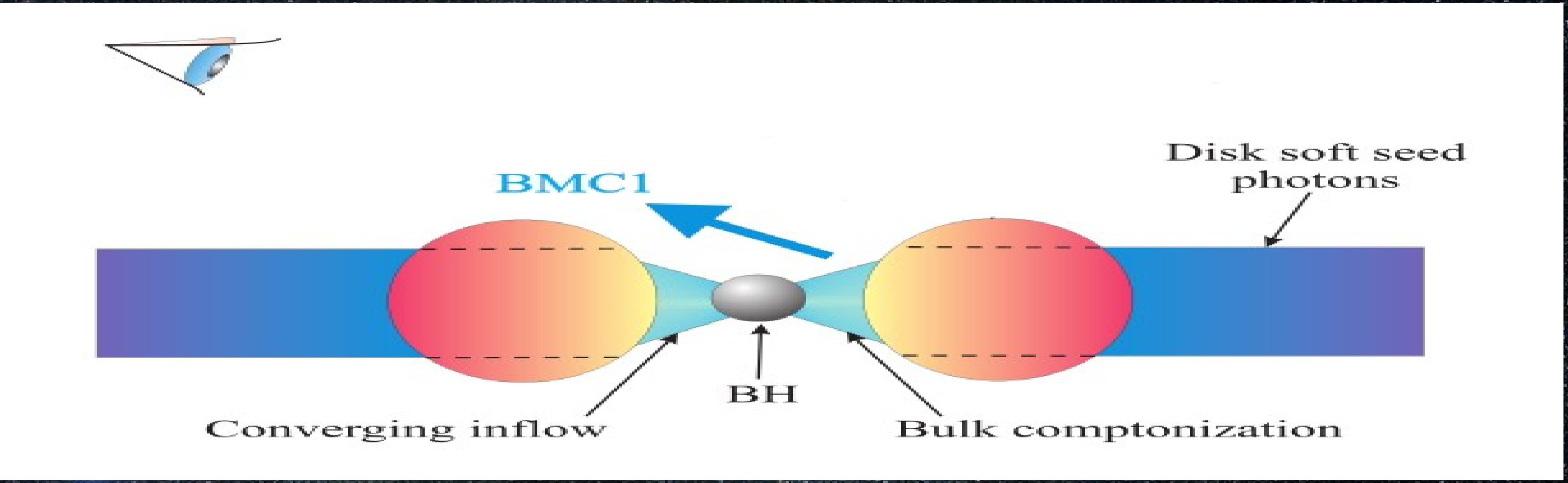
# IMBH Candidate !

# Alternate model :

# Comptonization by bulk motion

# Spectral model : BMC

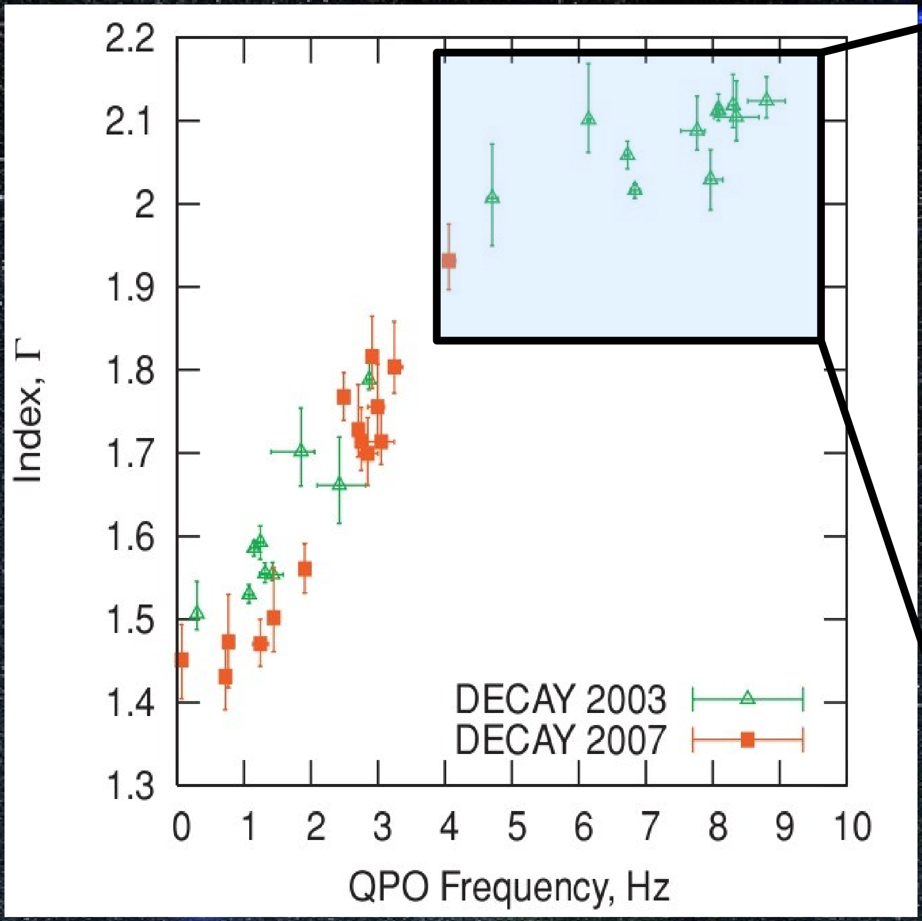
- **Comptonization by bulk motion**
  - **Slightly different physical scenario compared to MCD + powlaw**
  - **Good fit to the energy spectra of X-1**




**Shaposhnikov et al. 2009**

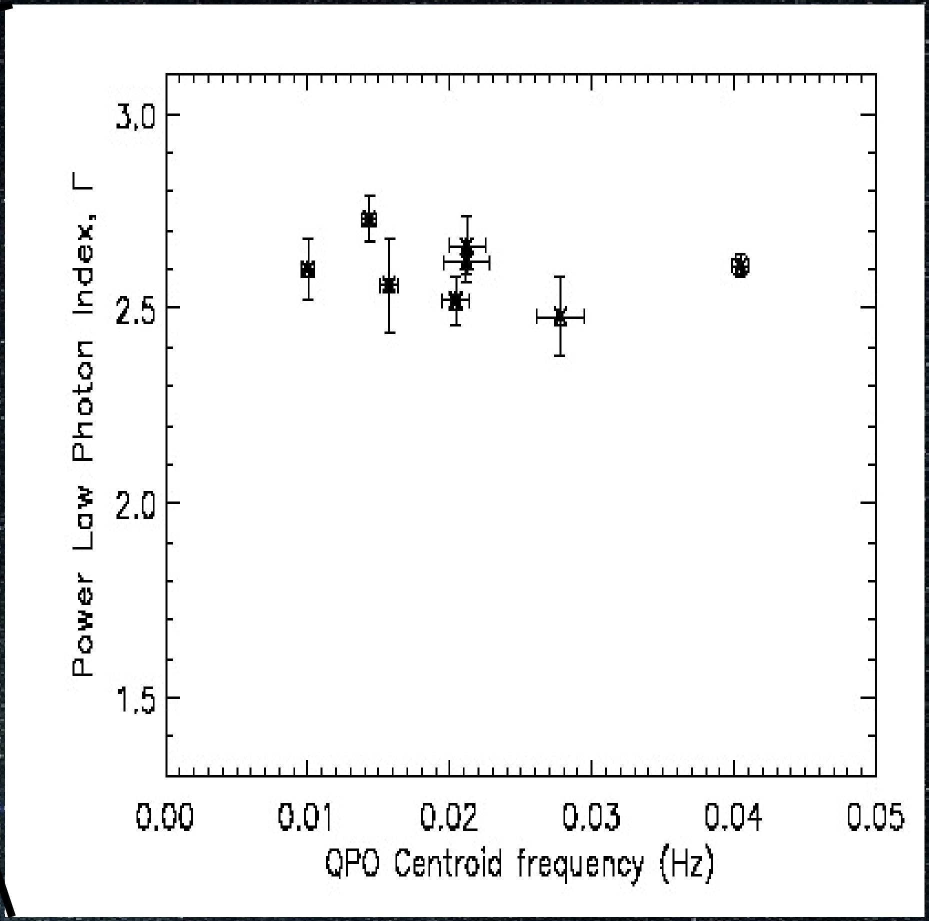
# Photon Index Vs QPO frequency

**Stellar BH : GX 339-4**




**Shaposhnikov et al. 2009**

**ULX, NGC 5408 X-1**




**Present work**

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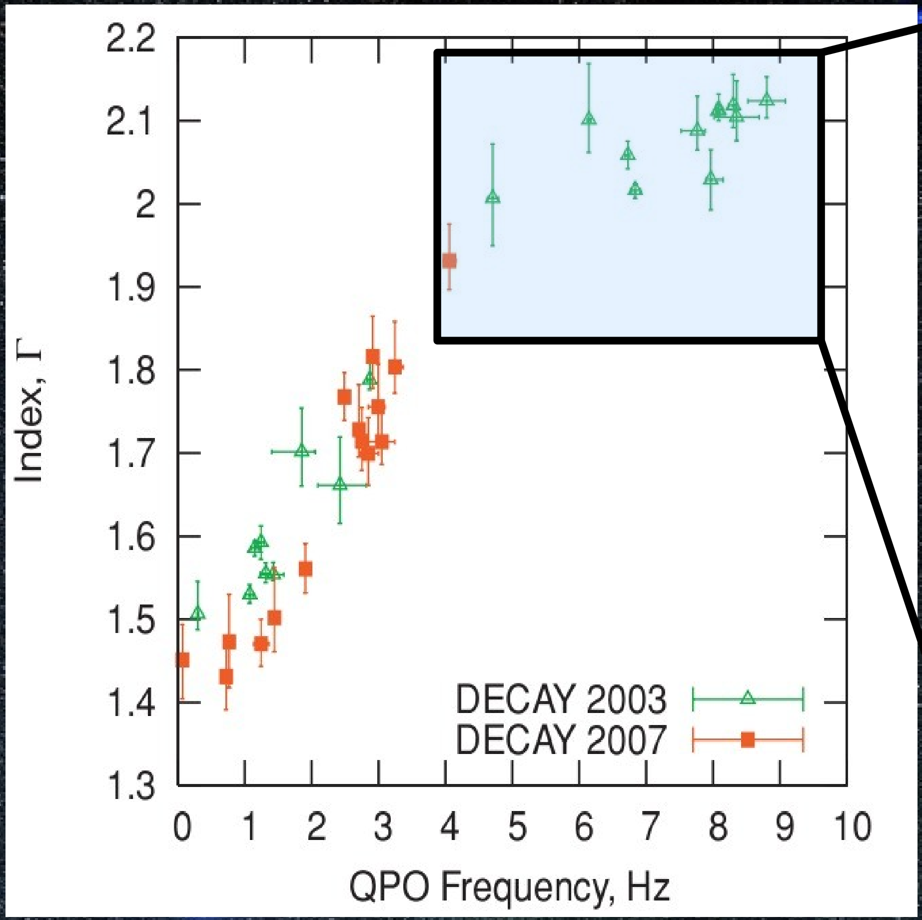


**Shaposhnikov et al. 2009**

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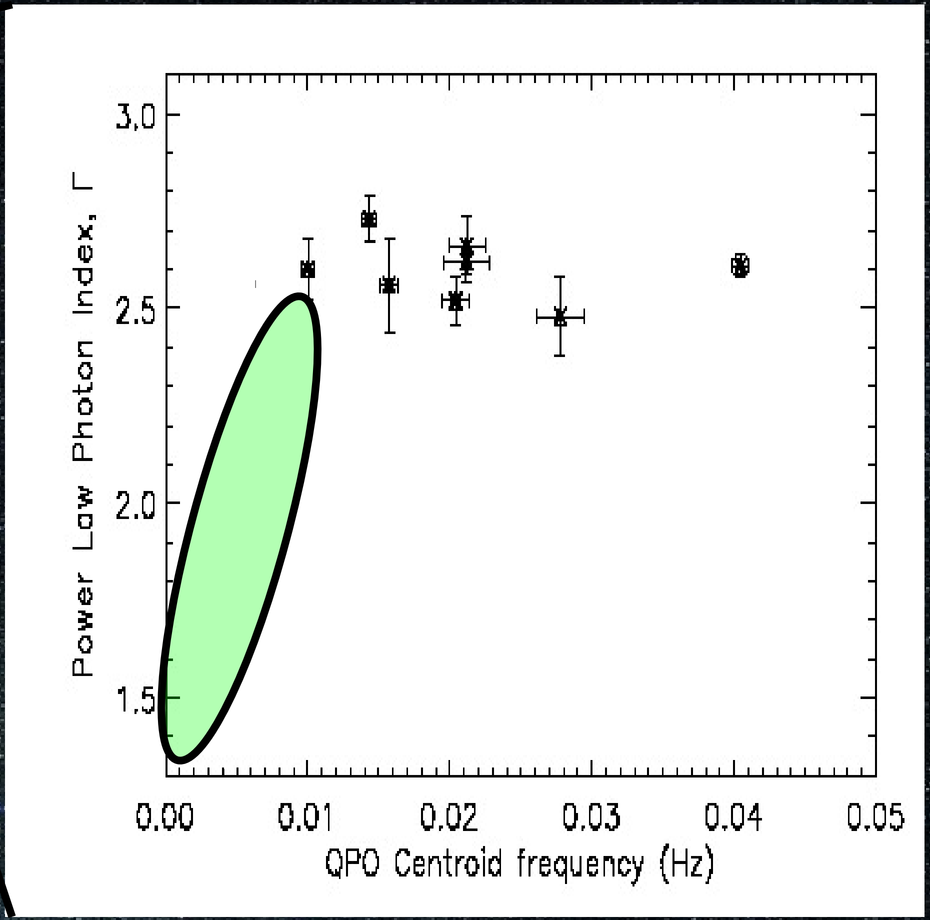
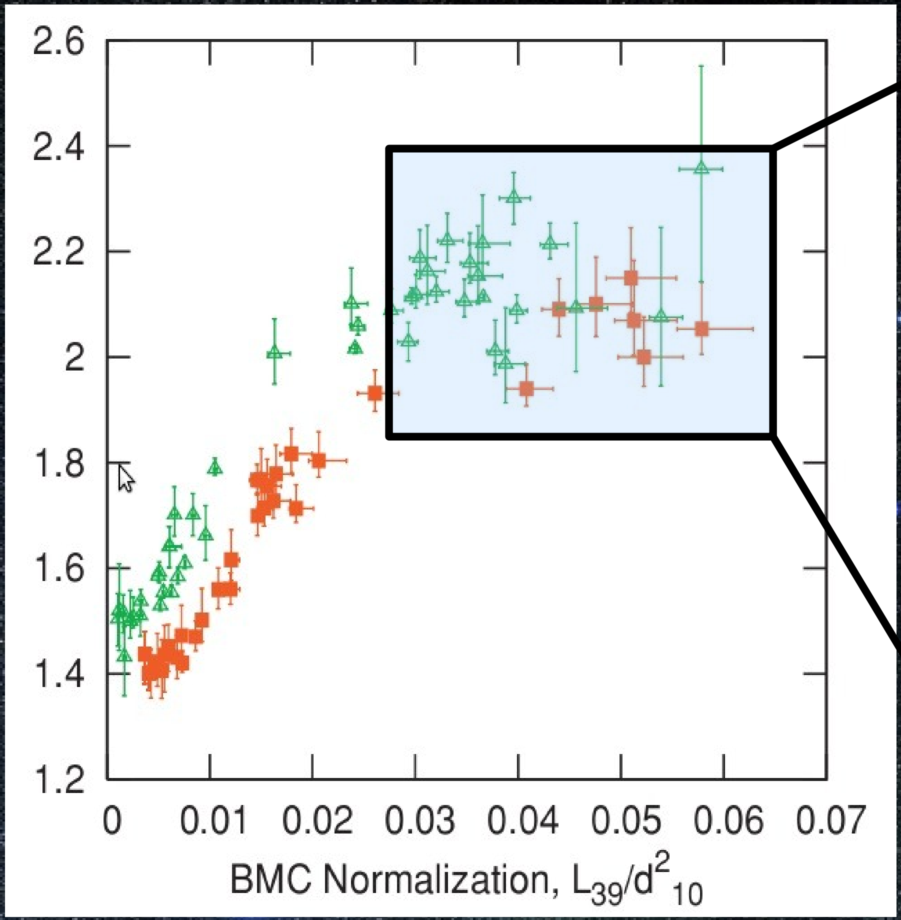


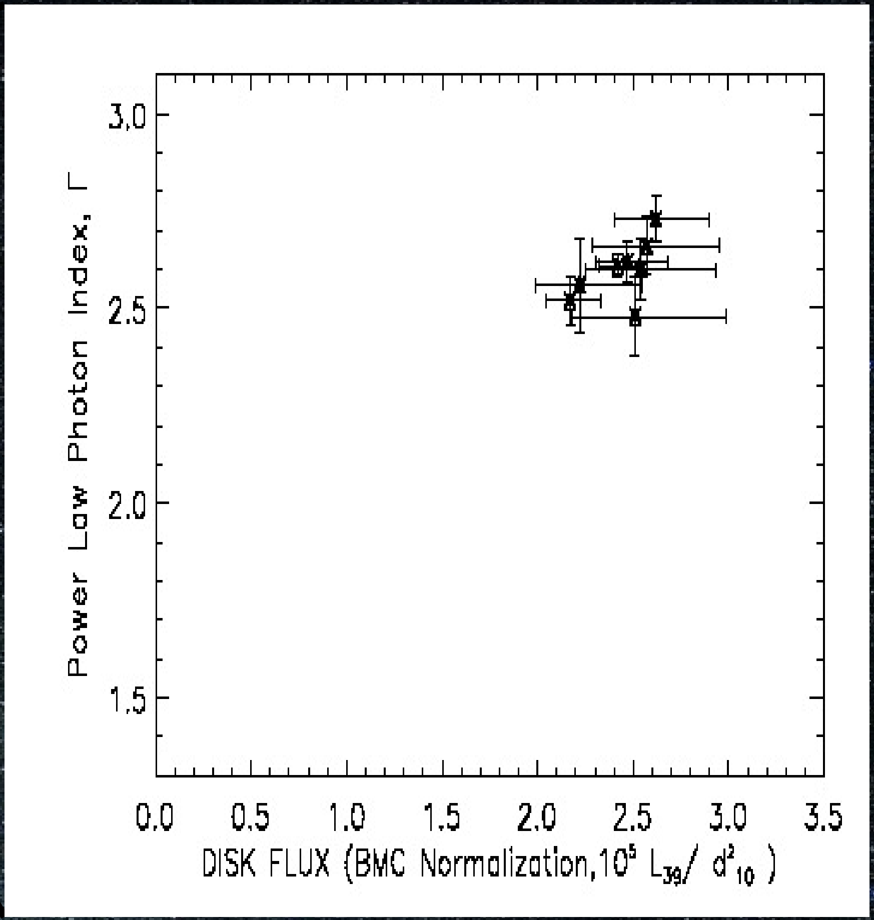

**Present work**

# Photon Index Vs BMC normalization (Disk Flux)

**Stellar BH : GX 339-4**

**ULX, NGC 5408 X-1**




**Shaposhnikov et al. 2009**

**Present work**

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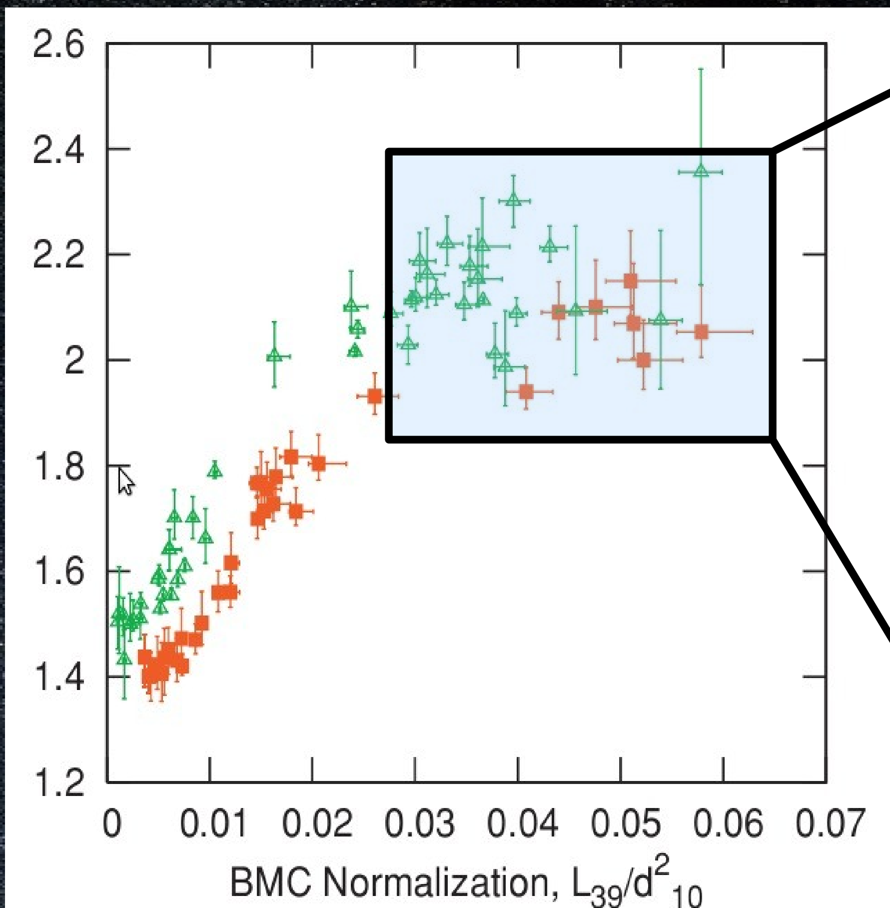
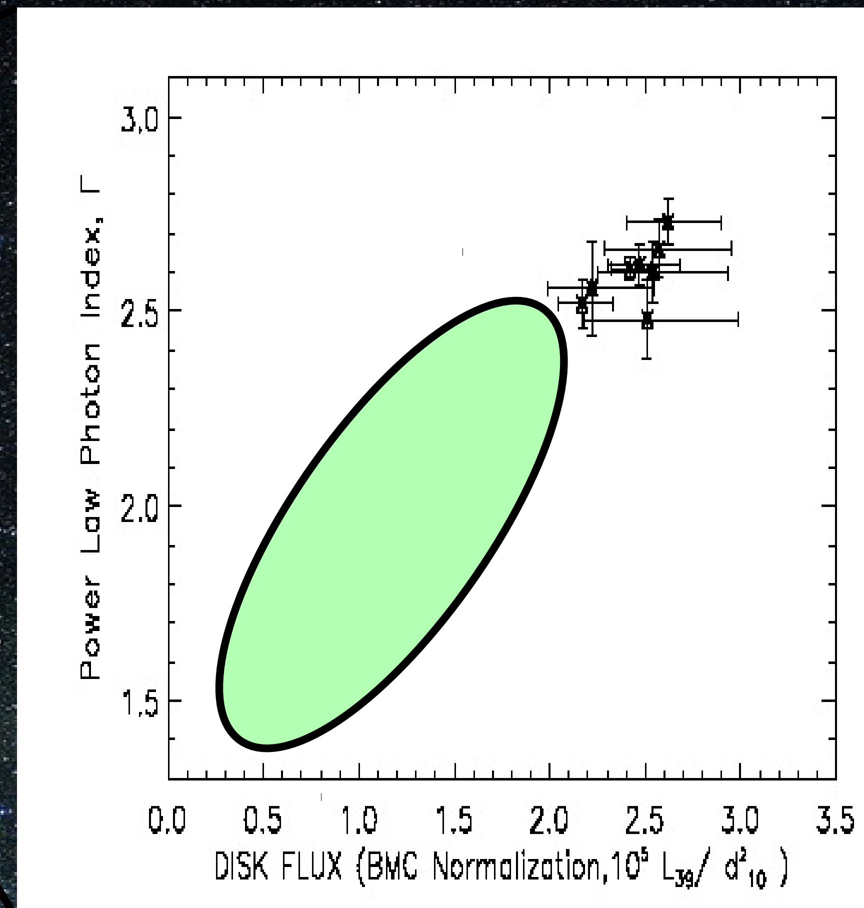
**ULX, NGC 5408 X-1**



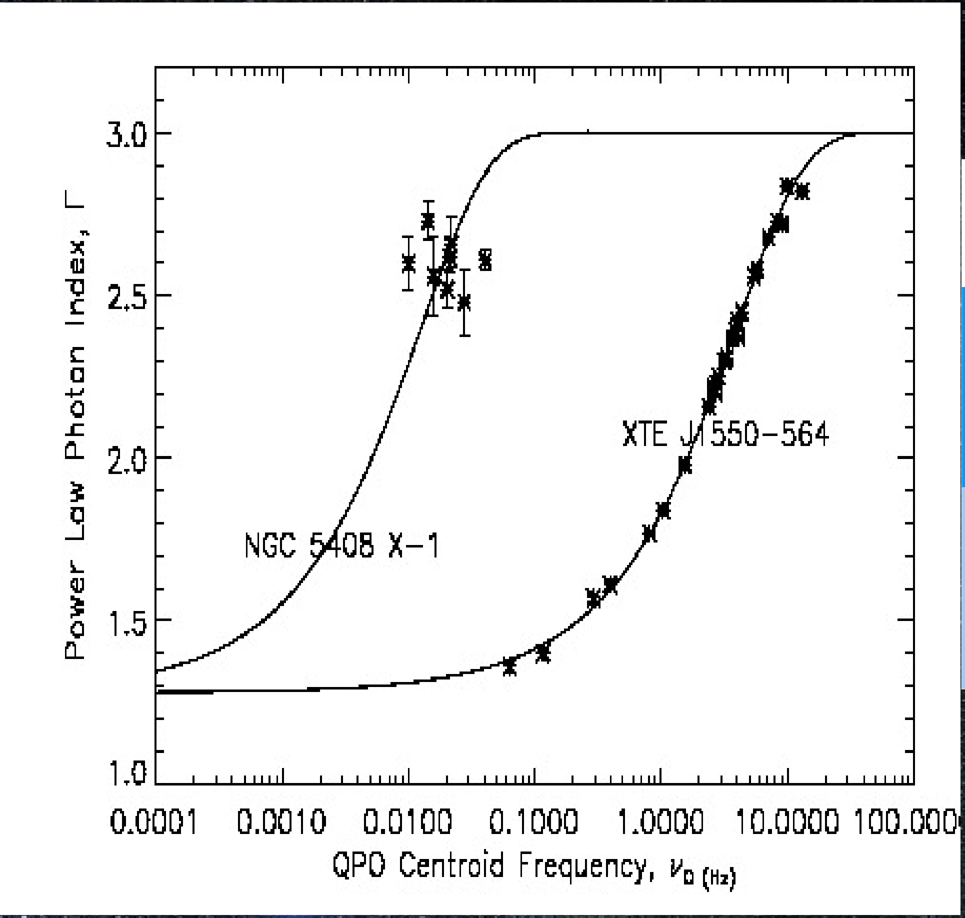




**Shaposhnikov et al. 2009**

**Present work**

# Mass estimate of X-1 : QPO-Γ scaling

**Sample plot showing the scaling**




**Present work**

| Reference Source | Mass Estimate | $L_X/L_{Edd}$ |
|---|---|---|
| XTE J1550 - 564 | $3300^{+1800}_{-1100}$ $M_\odot$ | ~ 0.026 |
| H 1743 - 322 | $2700^{+1100}_{-800}$ $M_\odot$ | ~ 0.032 |

**Mass prediction ~ few 1000 $M_\odot$**

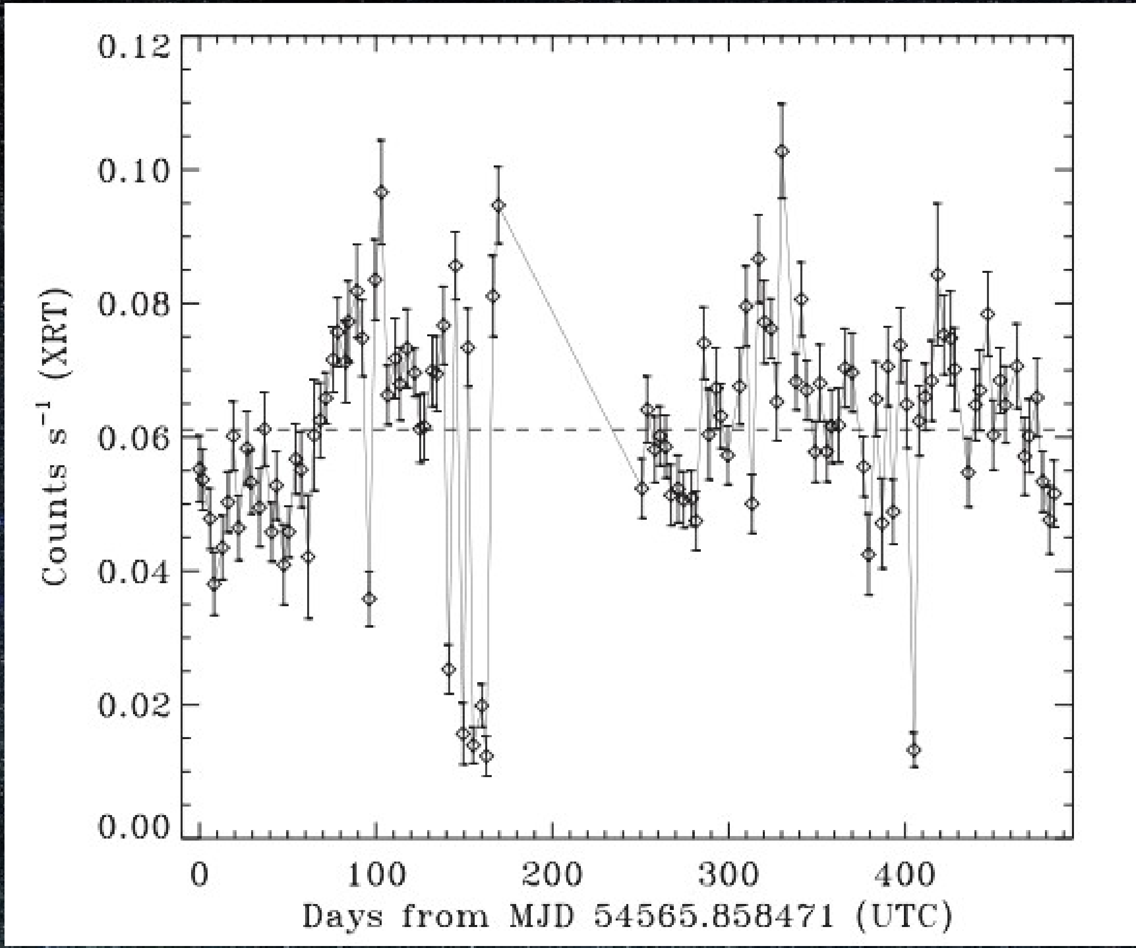
**IMBH Candidate**

# Conclusions

- Wider range of QPOs detected : 10-40 mHz
- Spectral state largely similar to previous observations ($\Gamma \sim 2.5$)
- Examined spectral-timing properties with larger sample of QPO detections
- Results are consistent with "saturated" portion of the spectral-timing relationships in stellar BH systems
- While consistent, the analogy with stellar systems in steep power-law is NOT conclusive
- Need to probe lower $\Gamma$ regime
- If scaling is appropriate, the mass estimates are comparable to previous values : $M_{X-1} \sim$ few 1000 $M_{\odot}$


THANK YOU

# Long Term light curve



# Formula for S/N of a QPO

$$n_\sigma = r^2 \frac{S^2}{S+B}\sqrt{\frac{T_{obs}}{\Delta \nu}}$$

$n_\sigma$ = Confidence level

R =

S = Source count rate

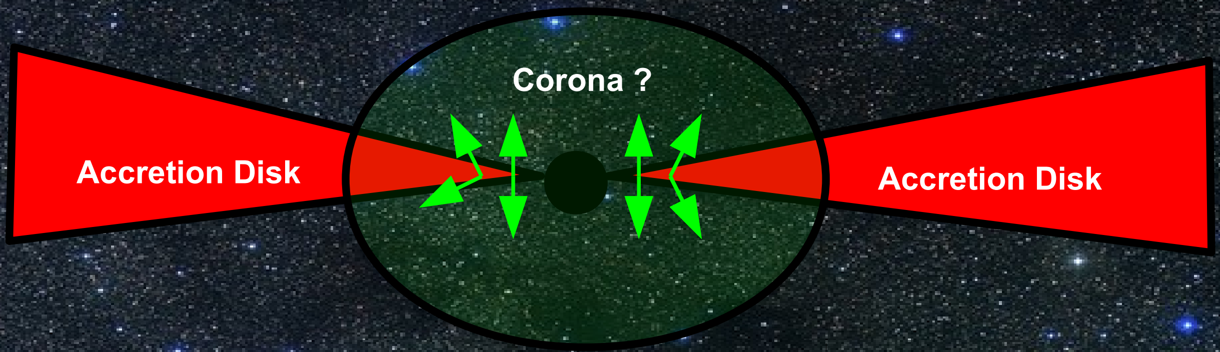
B = Background count rate

$T_{obs}$ = Exposure time interval

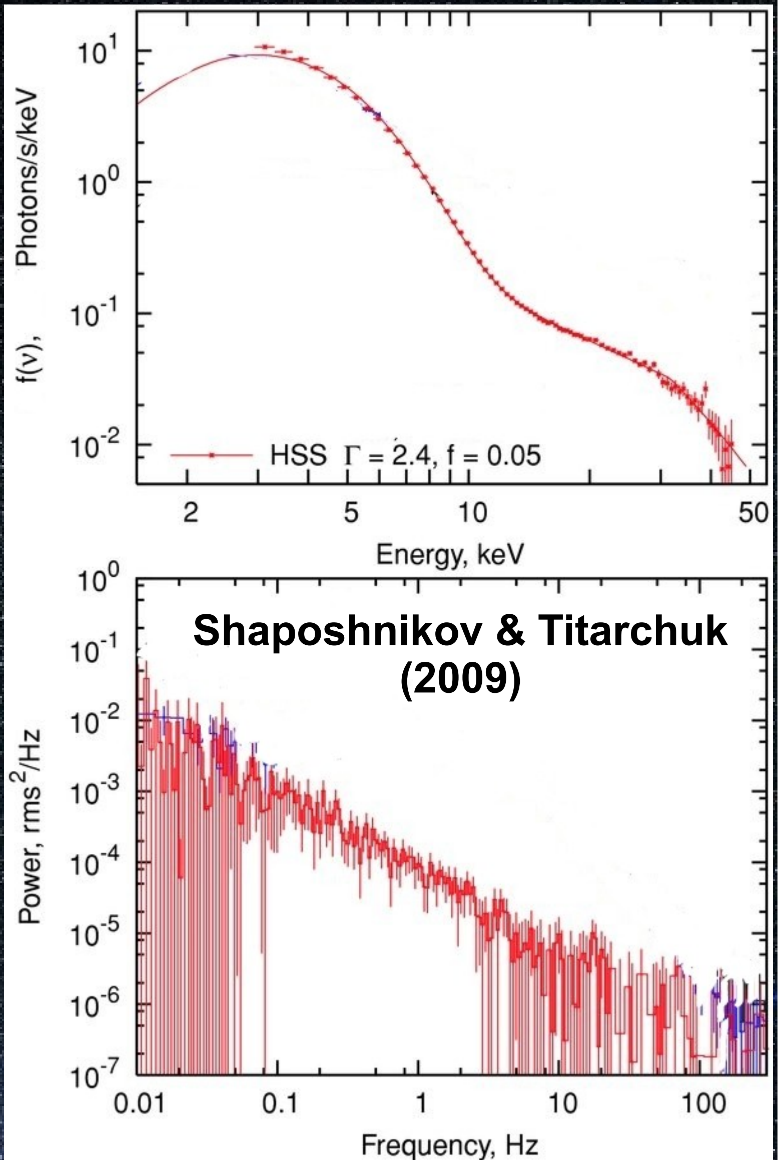
$\Delta v$ = Width of the QPO feature

# Background : Energy spectra of BHs - High/Soft State

- Phenomenological model within the present context
  - Model : Multicolored disk + powerlaw
  - Soft X-rays (0.2-2.0 keV) : Disk
  - Hard X-rays (2.0-10.0 keV) : Disk photons processed by the corona (Power Law)

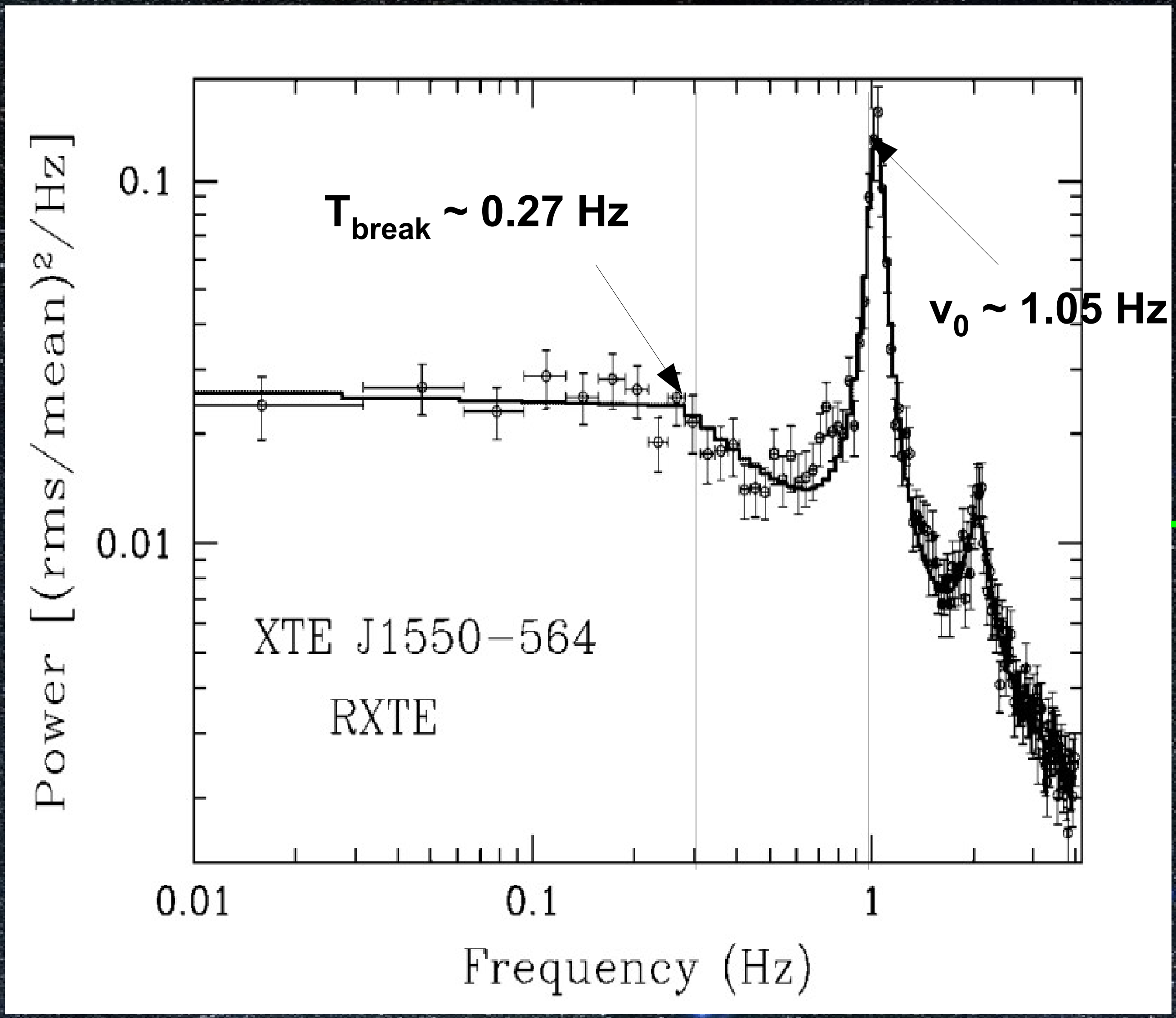



Schematic diagram




High/Soft state →

# Stellar Mass BH : $T_{Break}$ Vs QPO



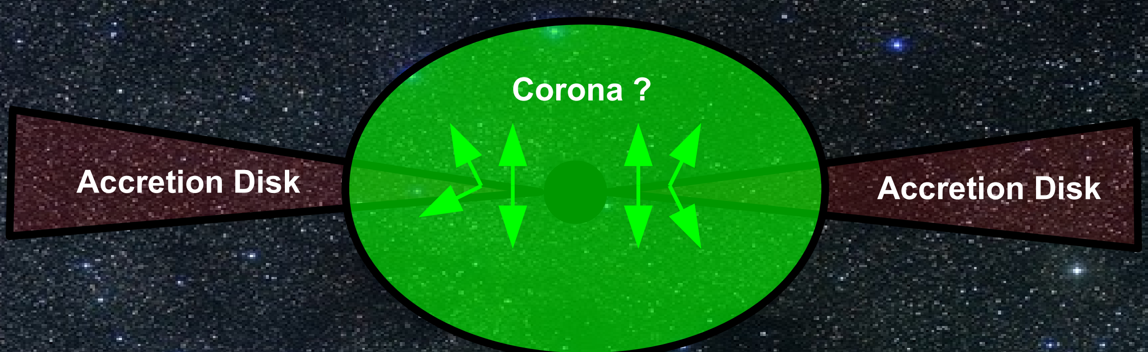

$T_{break} \sim v_0/3$

(Van Der Klis 1999)

$v_0/T_{break} \sim 3\text{-}4$

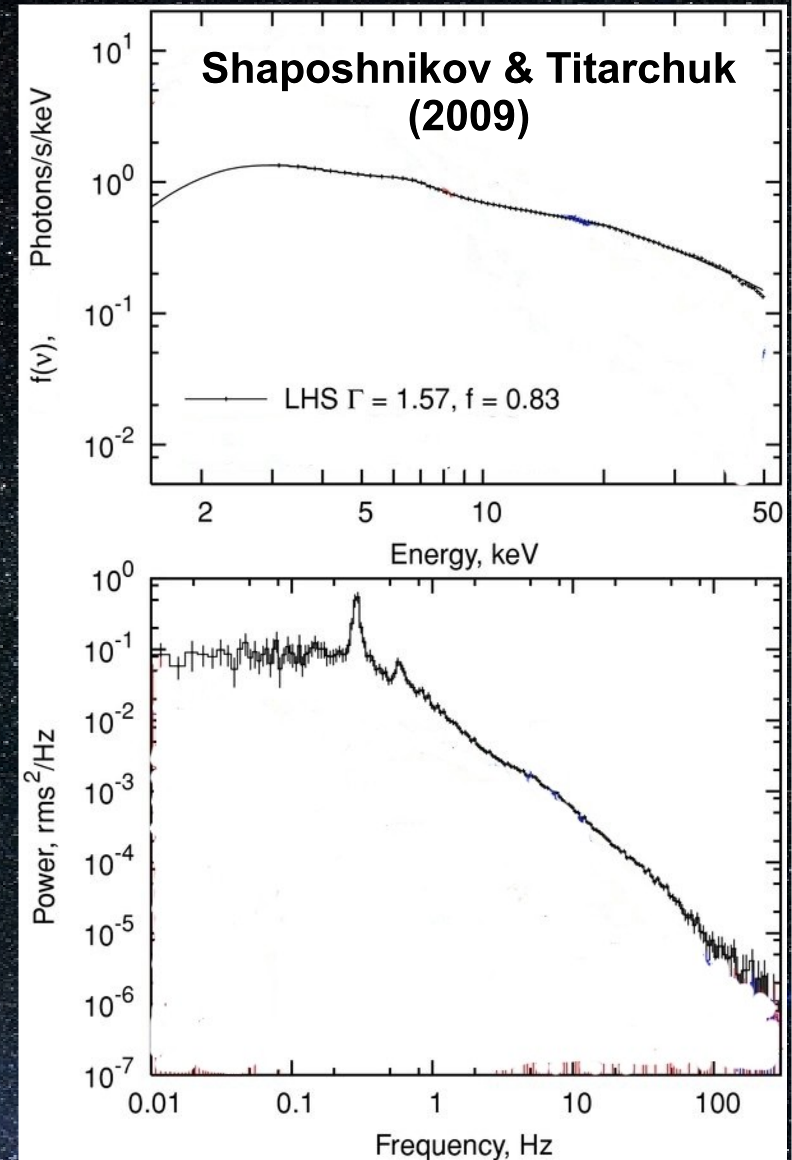
# Background : Energy spectra of BHs
# Low/Hard state

- Phenomenological model within the present context
  - Model : Multicolored disk + powerlaw
  - Soft X-rays (0.2-2.0 keV) : Disk
  - Hard X-rays (2.0-10.0 keV) : Disk photons processed by the corona (Power Law)



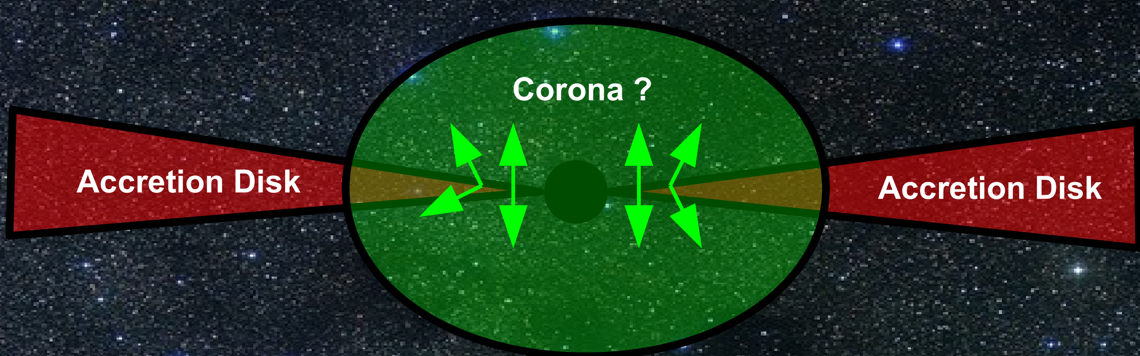

Schematic diagram

Low/Hard state →

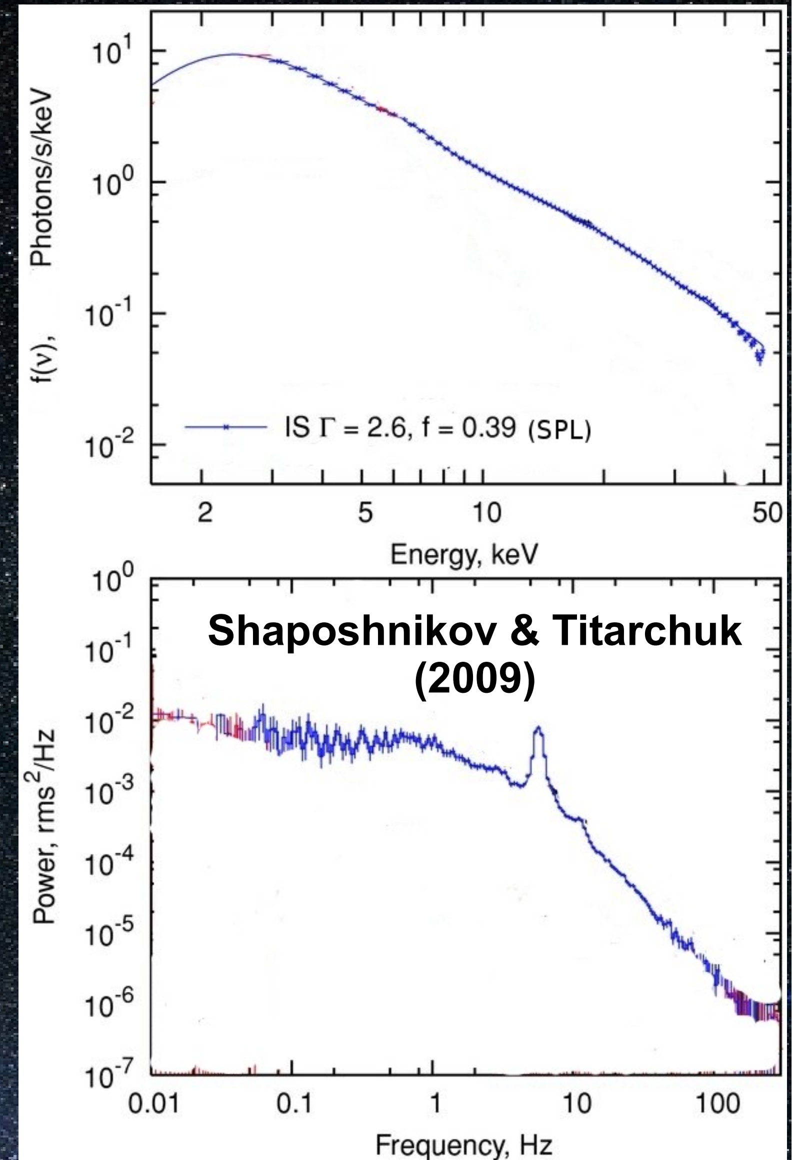


# Background : Energy spectra of BHs
## Intermediate State/Steep powerlaw State

- Phenomenological model within the present context
  - Model : Multicolored disk + powerlaw
  - Soft X-rays (0.2-2.0 keV) : Disk
  - Hard X-rays (2.0-10.0 keV) : Disk photons processed by the corona (Power Law)

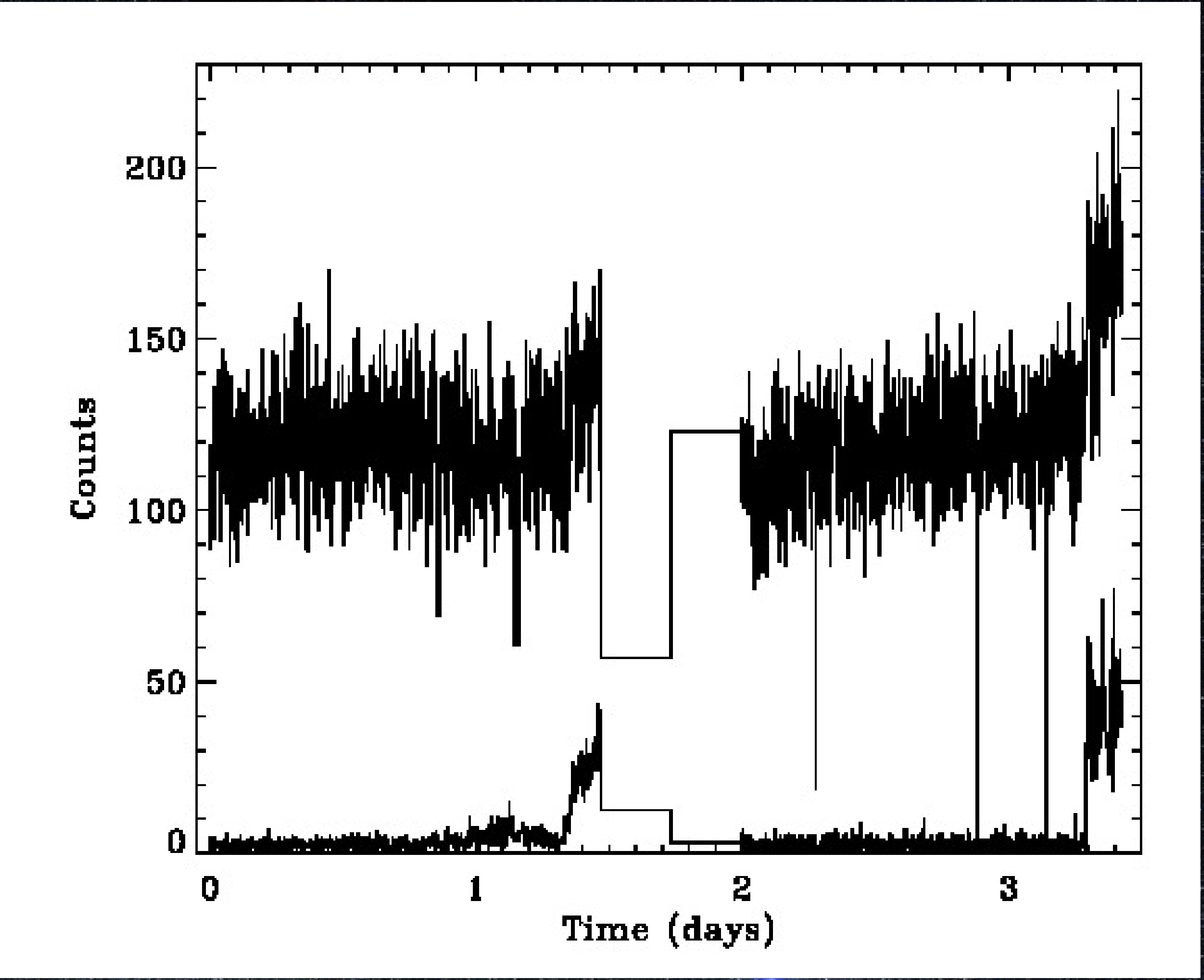



Schematic diagram

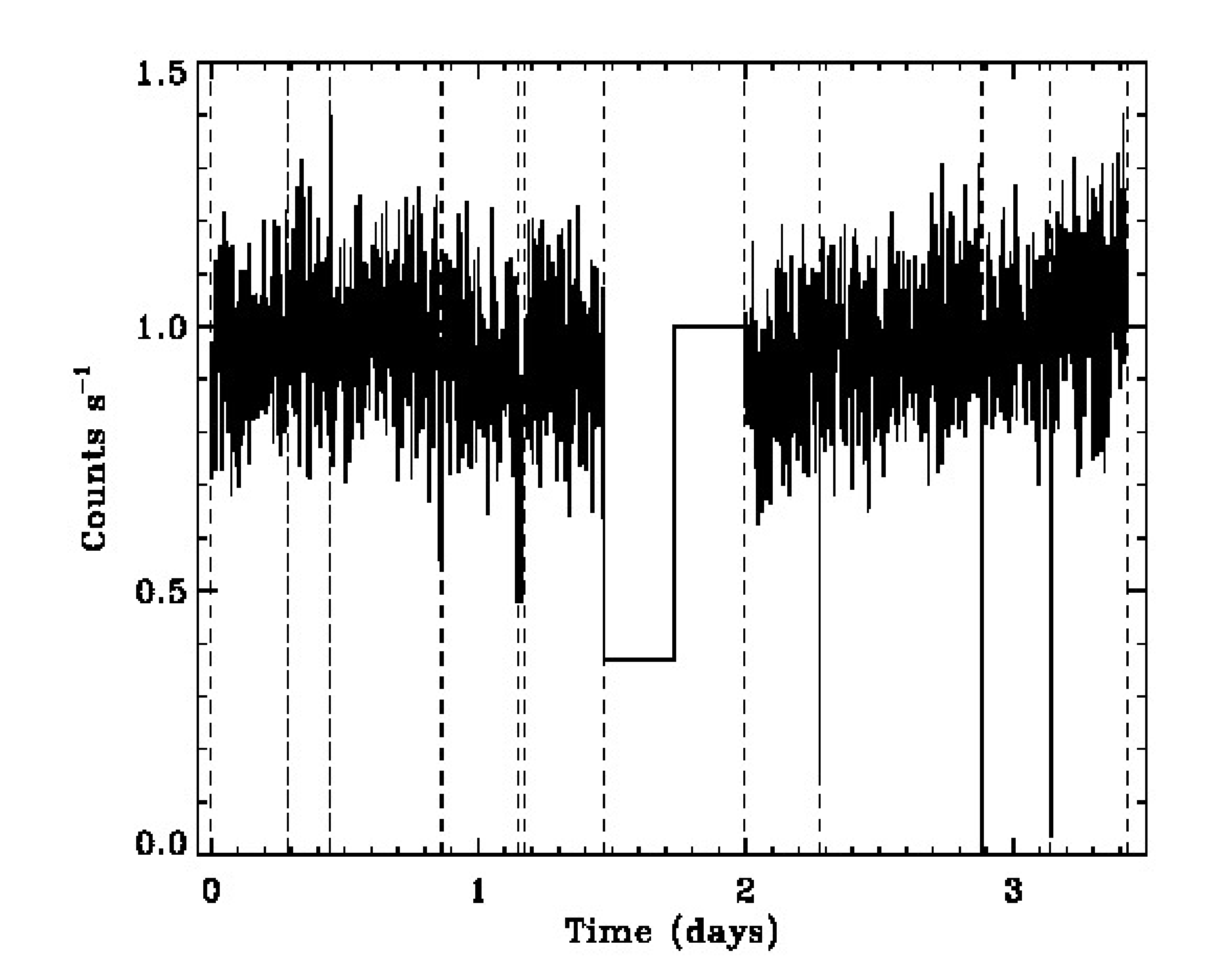



Steep powerlaw state(Intermediate) →

# 2010 Data : PN light curve



# 2010 Data : PN light curve



# Outline

- Introduction
- Background
  - Galactic black holes

PART I : Traditional Model

- Correlations in X-1
  - Mass estimate through QPO frequency scaling

PART II : Alternate Model

- Correlations in X-1
  - Mass estimate through scaling technique
- Conclusions