Investigating the emission properties and the geometry of black hole X-ray binaries

in the outburst cycle

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Outline

- Introduction
- Motivation
- State Transitions and their Classification
- Methodology
- Results
- Discussion
- Future studies

Black Hole

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By definition :

- A region of space having a gravitational field so intense that no matter or radiation can escape.

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- Event horizon $\longrightarrow$ A boundary which no escape is possible.
- Gravitational singularity $\longrightarrow$ a region where the spacetime curvature becomes infinite.

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Kerr BH :

- Event horizon $\longrightarrow$ A boundary which no escape is possible.
- Ring singularity $\longrightarrow$ A region where the spacetime curvature becomes infinite.
- Ergosphere $\longrightarrow$ A region where the gravitational force will hold objects in orbits
- Photon sphere $\longrightarrow$ A region where prevents photons to move freely in space.

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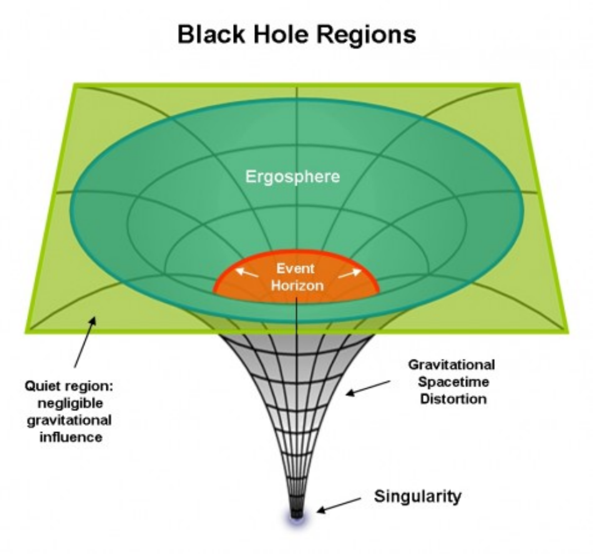

Introduction

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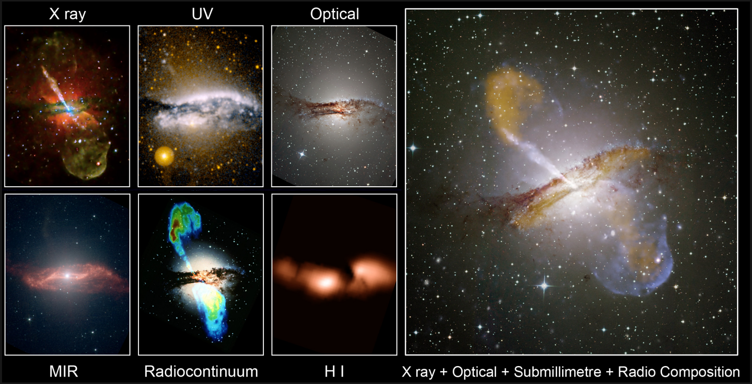

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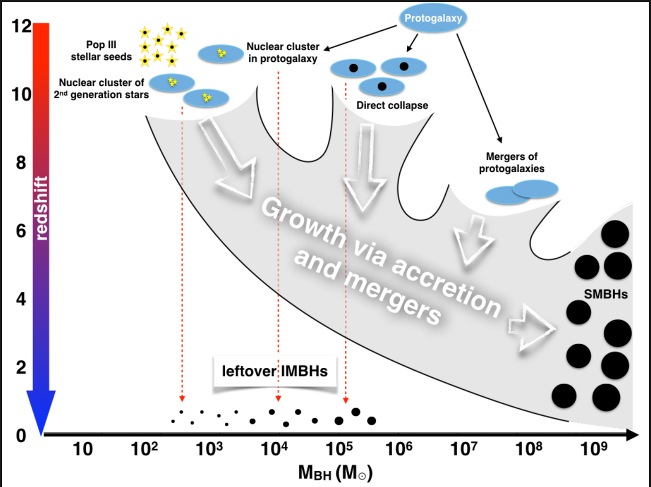
Intermediate Mass BHs $\longrightarrow \sim 10^3$ $M_\odot$ $\longrightarrow \sim 10^3$ KM



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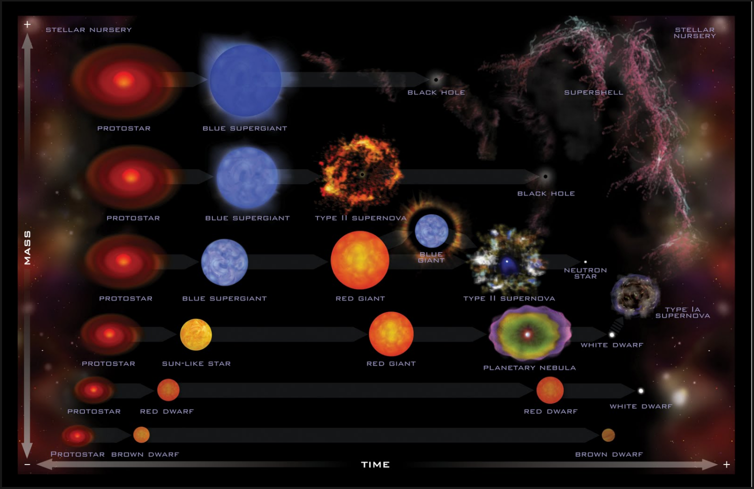

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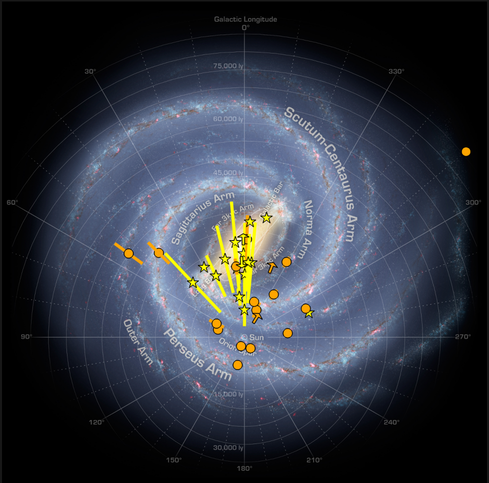

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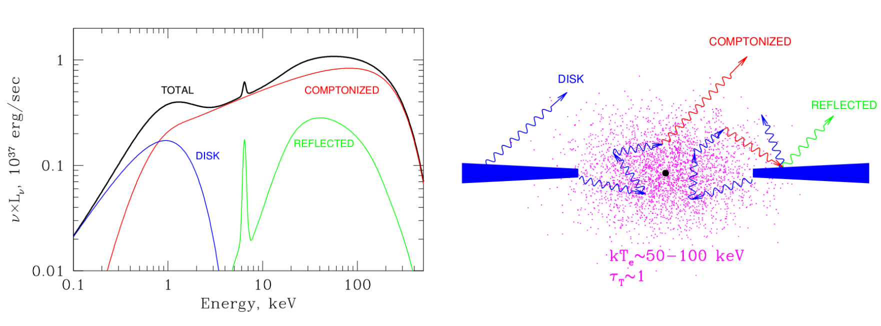

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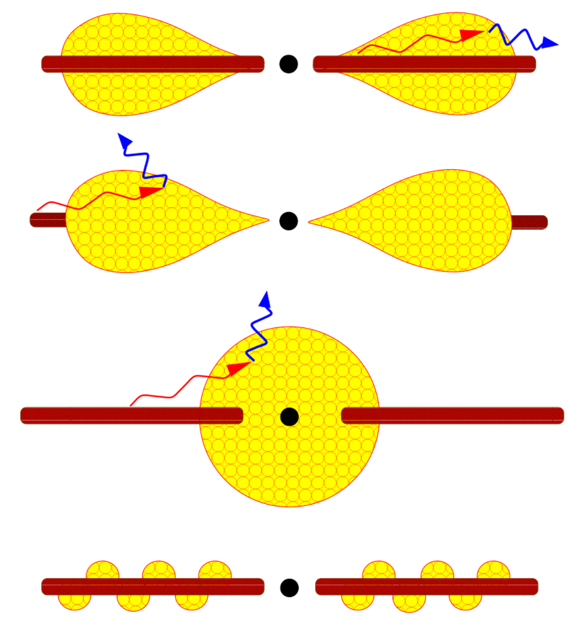

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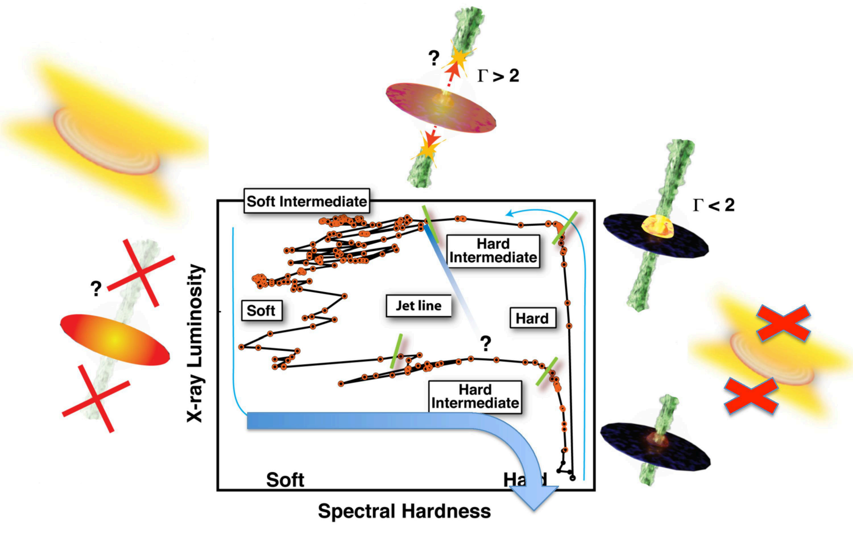

Motivation

- Spectral and timing evolution between states provides information that may help to understand accretion environment.
- Some phenomena such as radio ejections and different type of QPO happen only during state transitions.
- In a outburst cycle, transition between states occurs at different luminosities for rise and decay and by exploring key parameters we can investigate its origin.
- Luminosity distribution of state transition may allow us to test theoretical models.

State Transition

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- Timing features $\longrightarrow$ rms variability, shape of power spectrum, type of QPO, etc...

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In the literature, there are three models that classify the state transition based on observational properties

- Remillard and McClintock classification (2006)
- Belloni classification (Belloni 2010)
- Kalemci classification (Kalemci et. al. 2013)

Remillard and McClintock classification

New State Name (Old State Name)	Definition of X-ray State[a]
Thermal (High/Soft)	Disk fraction[b] $> 75\%$ QPOs absent or very weak: a[c] < 0.005 Weak power continuum: r[d] < 0.075
Hard (Low/Hard)	Disk fraction[b] $< 20\%$ (i.e., Power-law fraction[b] $> 80\%$ $1.4 < \Gamma < 2.1$ Strong power continuum: r[a] > 0.1
Steep Power Law (SPL) (Very high)	Presence of power-law component with $\Gamma > 2.4$ Power continuum: r[d] < 0.15 Either disk fraction[b] $< 80\%$ and 0.1-30 Hz QPOs present with a[c] > 0.01 or disk fraction[b] $< 50\%$ with no QPOs present.

[a] 2–20 keV band.
[b] Fraction of the total 2–20 keV unabsorbed flux.
[c] QPO amplitude (rms).
[d] Total rms power integrated over 0.1–10 Hz.

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Belloni Classification

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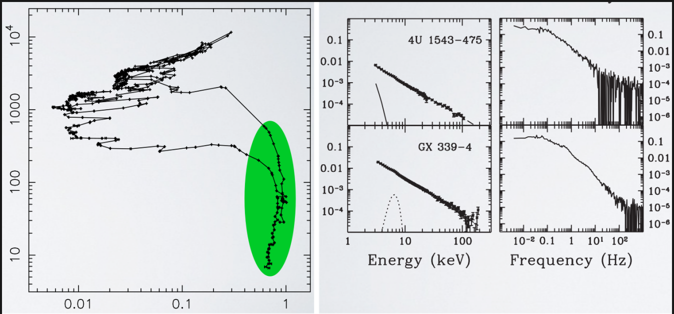
Hard state

$\Gamma \sim 1.7 - 1.9$

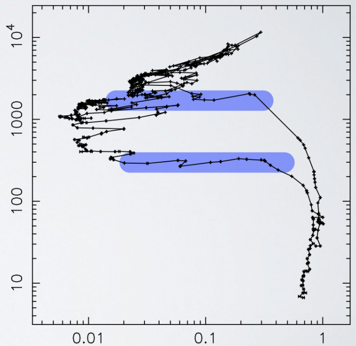
rms $\approx$ 30 %

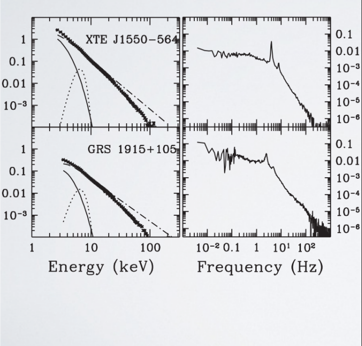
type C QPO



Belloni Classification

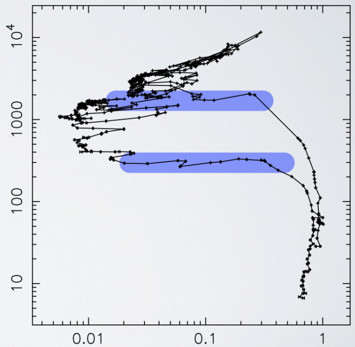
Hard state	$\longrightarrow$	HIMS
$\Gamma \sim 1.7$ - 1.9	$\longrightarrow$	1.9-2.5
rms ≈ 30 %	$\longrightarrow$	10-20 %
type C QPO	$\longrightarrow$	type C

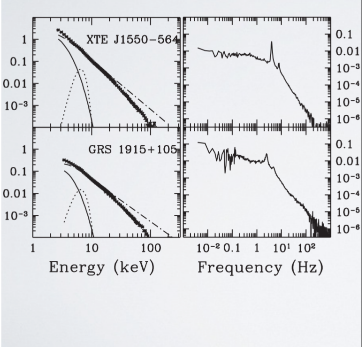




Belloni Classification

Hard state	⟶ HIMS	⟶ SIMS
$\Gamma \sim$ 1.7 - 1.9	⟶ 1.9-2.5	⟶ 2.1 ↑
rms ≈ 30 %	⟶ 10-20 %	⟶ 5-10 %
type C QPO	⟶ type C	⟶ type B





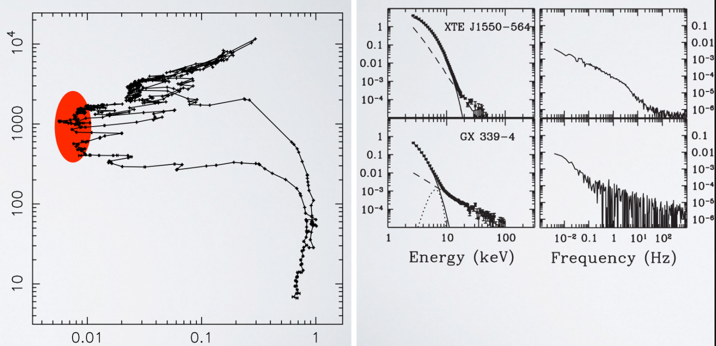
Belloni Classification

Hard state $\longrightarrow$ HIMS $\longrightarrow$ SIMS $\longrightarrow$ Soft state

$\Gamma \sim 1.7$ - 1.9 $\longrightarrow$ 1.9-2.5 $\longrightarrow$ 2.1 $\uparrow$ $\longrightarrow$ 2.1 $\uparrow$

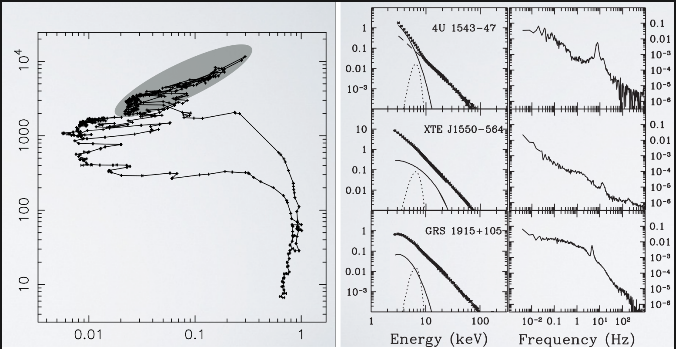
rms $\approx$ 30 % $\longrightarrow$ 10-20 % $\longrightarrow$ 5-10 % $\longrightarrow$ 1-3 %

type C QPO $\longrightarrow$ type C $\longrightarrow$ type B $\longrightarrow$ type C ?



Belloni Classification

Hard state	→	HIMS	→	SIMS	→	Soft state	→	Anomalous state
$\Gamma \sim 1.7 - 1.9$	→	1.9-2.5	→	2.1 ↑	→	2.1 ↑	→	2.5 ↑
rms ≈ 30 %	→	10-20 %	→	5-10 %	→	1-3 %	→	1-3 %
type C QPO	→	type C	→	type B	→	type C ?	→	HF QPO



Kalemci Classification

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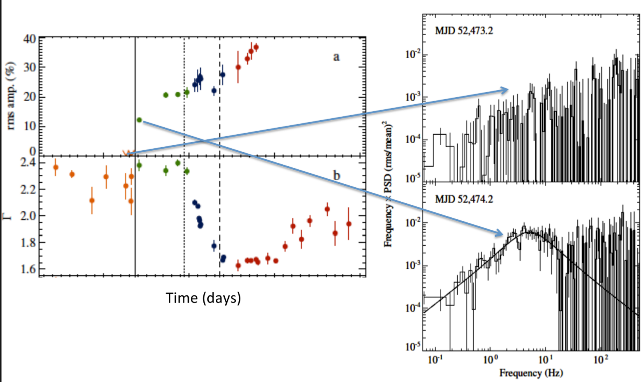
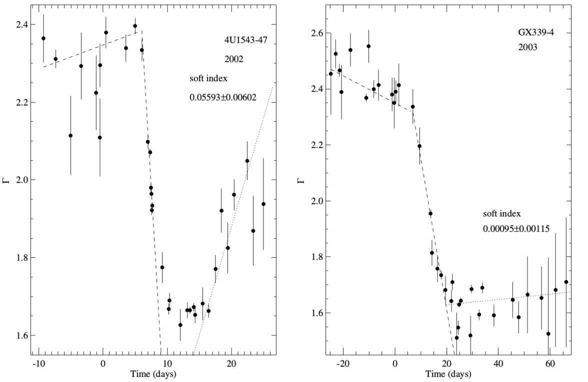
- Timing transition (TT) → abrupt increase in the rms amplitude of variability accompanied with an increase in the power law flux.



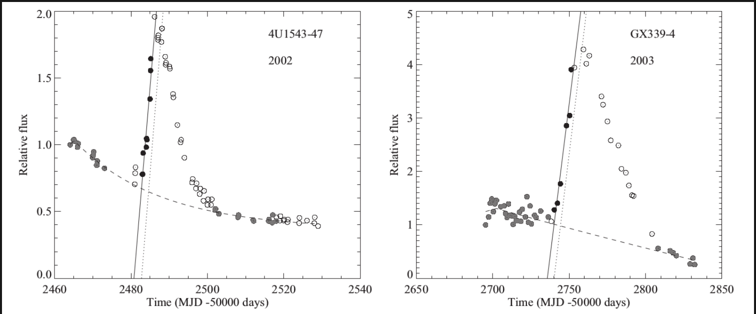
Kalemci Classification

- Timing transition (TT) $\rightarrow$ abrupt increase in the rms amplitude of variability accompanied with an increase in the power law flux.
- Index transition (IT) $\rightarrow$ significant hardening of the spectra.



Kalemci Classification

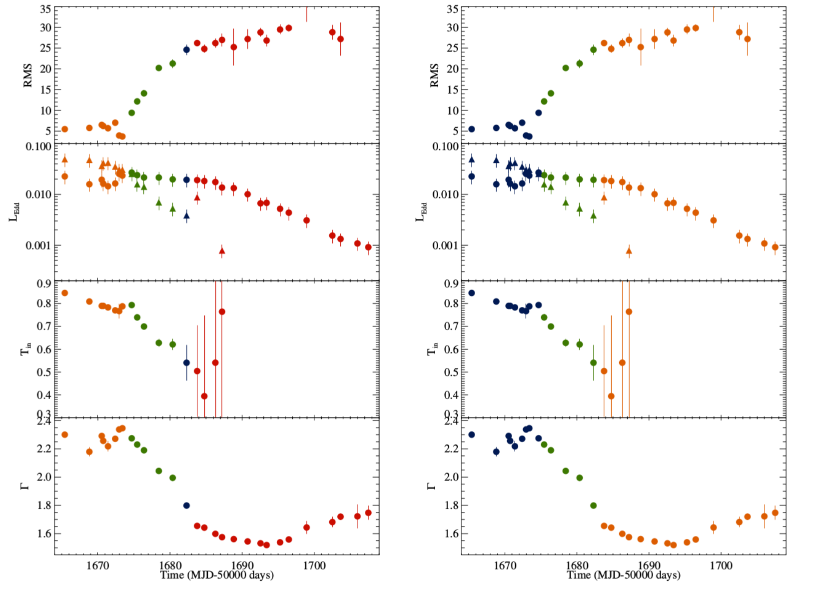
- Timing transition (TT) $\rightarrow$ abrupt increase in the rms amplitude of variability accompanied with an increase in the power law flux.
- Index transition (IT) $\rightarrow$ significant hardening of the spectra.
- Compact jet transition (CJT) $\rightarrow$ increase in the NIR flux and/or radio detection of the compact jet.



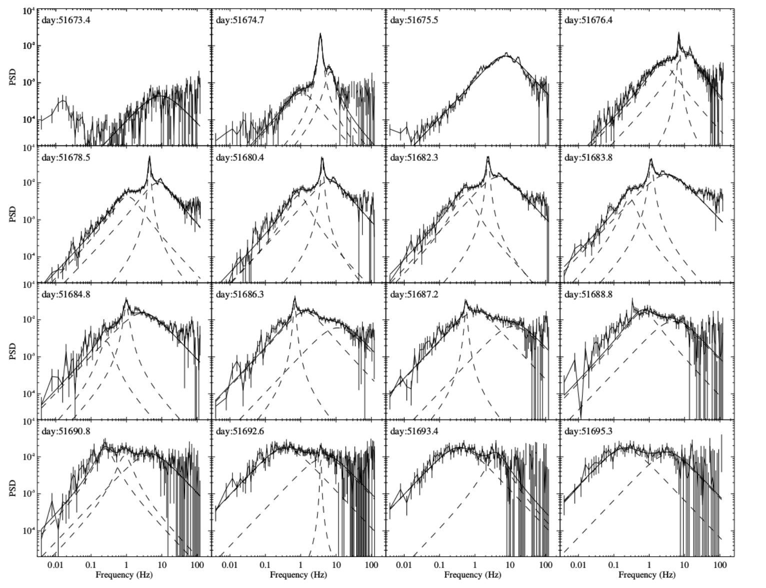
Goal and method

- Determine state transition luminosities in the outburst decay and discuss the distribution for different transitions.
- For spectral analyses classic powerlaw+diskbb + Ftest for Gauss and hecut models.
- For timing, PSDs are fitted with multi Lorentzians to find rms amplitude and get QPO info.
- Both PCA and HEXTE instruments are used in RXTE.
- In analyses XSPEC, IDL and TCL programs are used.
- The analyses were done for 12 BH transient in 20 outburst decays between 1998-2011, and for disk and power-law luminosities separately (720 observations in total).

Parameter evolution of XTE 1550-564 during 2000 outburst



Power spectral density evolution of XTE 1550-564 during 2000 outburst



Results

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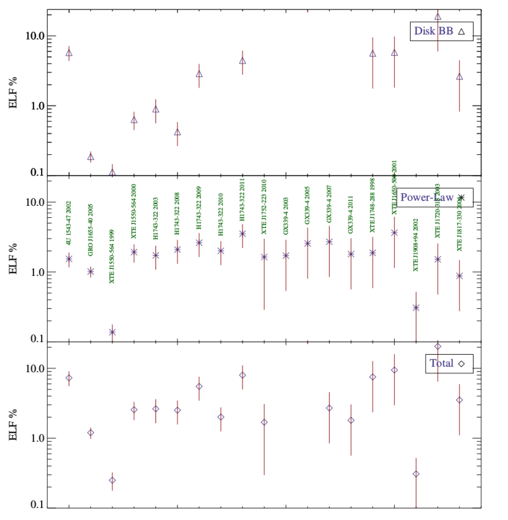
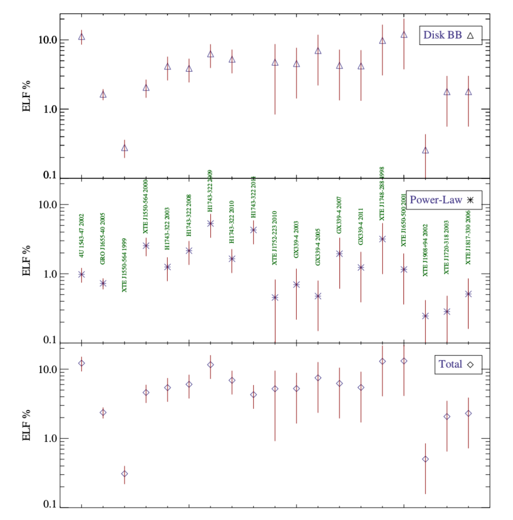
- There seems to be a tight clustering in Power-Law flux around 2.5% EDD luminosity when photon index reaches a constant value. This usually corresponds to compact jet and hard state transition.



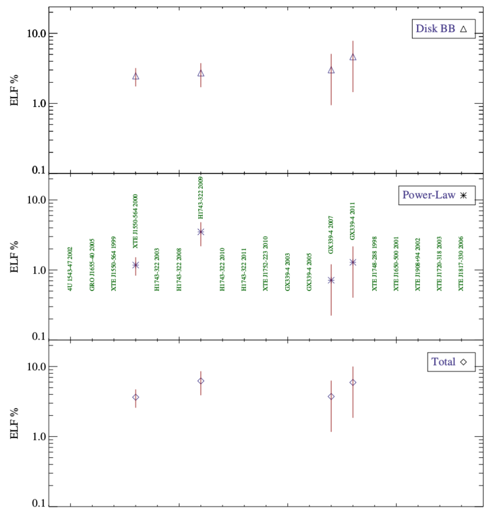
Results

- The disk bb fluxes (DBBF) are clustered around 4% EDD luminosity during the transition to hard intermediate state (HIMS).



Results

- Only 4 sources showed the SIMS transition during the decay. The lack of data prevent us from making any bold claims. However, current data indicate a SIMS transition around 3% of EDD luminosity.



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- The first evidence of clustering is reported in Maccarone (2003)
  - states are not clear
  - data is not as good as we have now
  - there is a critical mistake in luminosity calculation
- Dunn. et. al. (2010) claimed there is no difference in state transition luminosities during rise and decay
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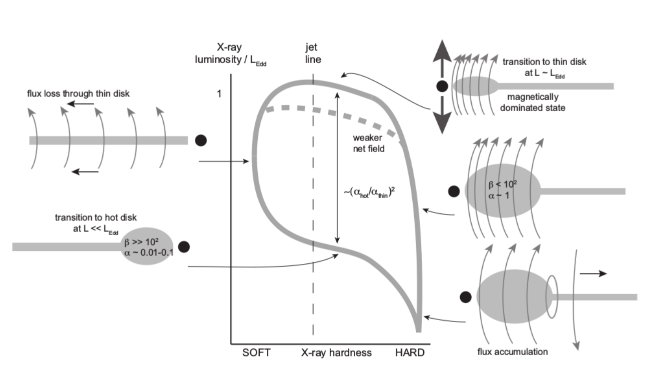
  - have not been performed for several states
  - luminosities have not been calculated for disk and PL separately
- Why 1999 outburst of XTE 1550-564 occurs at very low luminosities? could be an uncommon new state?
- How to quatify clustering !
  - Arithmetic average is not scientifically accurate ☹
  - Better approach ⟶ Weighting the luminosities by the inverses of their standard deviations ☺
  - It is dominated by the error of XTE 1550-564 ☹

- These results support the outburst mechanism proposed by Begelman and Armitage (2013) as they claimed since the net field is too weak to affect viscosity parameter during the decay phase, state transitions must have occur at similar luminosities.



Thank you

Inverse-variance weighting

$$\text{weighted average} \qquad \hat{y} = \frac{\sum_i y_i/\sigma_i^2}{\sum_i 1/\sigma_i^2}$$

$$\text{weighted error} \qquad \hat{e} = \sqrt{\frac{1}{\sum_i 1/\sigma_i^2}}$$

- The weighted mean of PLF is 1.05 $\pm$ 0.11 % excluding XTE J1550-564 1999 and 0.24 $\pm$ 0.04 including XTE J1550-564 1999 during HS transition.
- The weighted mean of DBBF is 0.91 $\pm$ 0.14 % excluding XTE J1550-564 1999 and 0.43 $\pm$ 0.07 including XTE J1550-564 1999 during HIMS transition.
- The weighted mean of DBBF is 2.65 $\pm$ 0.56 % during SIMS transition.

Timing

We fitted all our PDSs with a combination of narrow and broadband Lorentzians of the form:

$$L_{\mathrm{i}}(f) = \frac{R_{\mathrm{i}}^2 \Delta_{\mathrm{i}}}{2\pi[(\Delta_{\mathrm{i}})^2 + (\frac{1}{2}\Delta_{\mathrm{i}})^2]}$$

where:

- i correspond to each Lorentzian component in the fit,
- R_{i} denotes the rms amplitude of the Lorentzian (when integrated over $-\infty$ to ∞),
- Δ_{i} is the full width at half maximum (FWHM),
- f_{i} is the resonance frequency of the Lorentizan.

A useful property of the Lorentzian is the "peak frequency" at which the contribution of the total rms amplitude of the Lorentzian is maximum.

$$\nu_{\mathrm{i}} = f_{\mathrm{i}} \left(\frac{\Delta_{\mathrm{i}}^2}{4 f_{\mathrm{i}}^2} + 1 \right)^{1/2} \qquad Q_{\mathrm{i}} = \frac{f_{\mathrm{i}}}{\Delta_{\mathrm{i}}}$$

Timing

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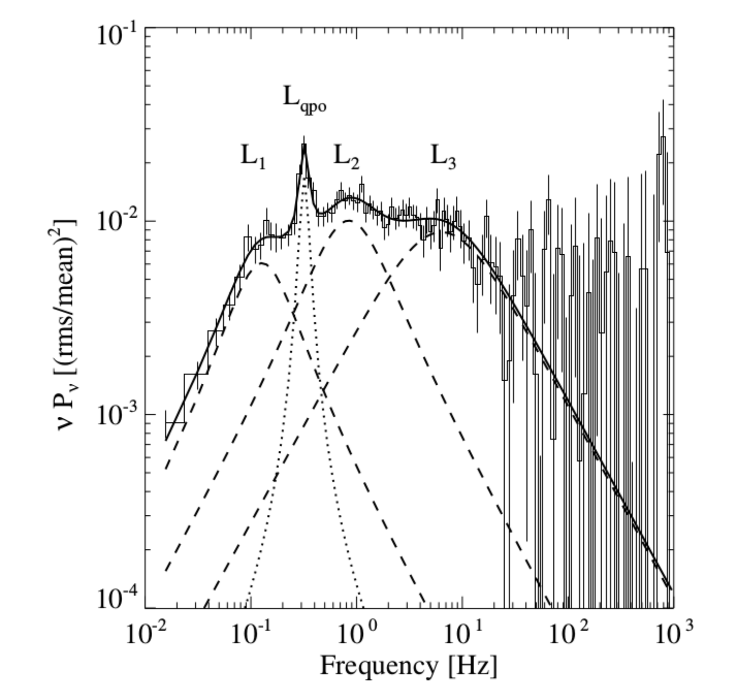

Observational Parameter

Source	Outburst	Mass ($M_\odot$)	Dist. (kpc)	Inclination (°)	Binary period (h)	Binary sep.[a]	N_H[b]	Ref.
4U 1543-47		9.4 ± 1	7.5 ± 0.5	20.7 ± 1.5	26.8	23	0.43	[25, 131]
	2002							
GRO J1655-40		5.4 ± 0.3	3.2 ± 0.2	70.2 ± 1.2	62.4 ± 0.6	38	0.8	[132, 133]
	2005							
GX 339-4		$8 \pm 1.5^{\star}$	8 ± 2	< 60	42.2	25	0.57	[25, 133]
	2003							
	2005							
	2007							
	2011							
H1743-322		8 ± 1.5	8.5 ± 0.8	75 ± 3	...	...	2.3	[134]
	2003							
	2008							
	2009							
	2010							
	2011							
XTE J1748-288		8 ± 1.5	8 ± 2	...	...	...	$11^{\dagger}$	[25]
	1998							
XTE J2012+381		8 ± 1.5	8 ± 2	40	...	...	1.3	[135]
	1998							
XTE J1550-564		9.1 ± 0.6	4.4 ± 0.5	74.6 ± 1.0	37	...	0.65	[136, 137]
	1999							
	2000							
XTE J1650-500		8 ± 1.5	8 ± 2	> 50	7.63	...	0.57	[138, 131]
	2001							
XTE J1908+094		8 ± 1.5	8 ± 2	20.7 ± 1.5	...	...	2.3	[139]
	2002							
XTE J1720-318		8 ± 1.5	8 ± 2	...	...	...	1.2	[140]
	2003							
XTE J1817-330		8 ± 1.5	8 ± 2	...	...	...	0.15	[141]
	2006							
XTE J1752-223		9.5 ± 1.5	6 ± 2	< 49	< 6.8	...	2.3	[131, 133]
	2010							

a Binary separation, in lightseconds.
b The column density of hydrogen on the line of sight in 10^{22} cm^{-2}.
† N_H is not fixed for this source and only the average value is shown in the table.