

Observing the accretion state of Black Hole Transients with *THESEUS*

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**Q (charge), M (mass),
a (spin)**

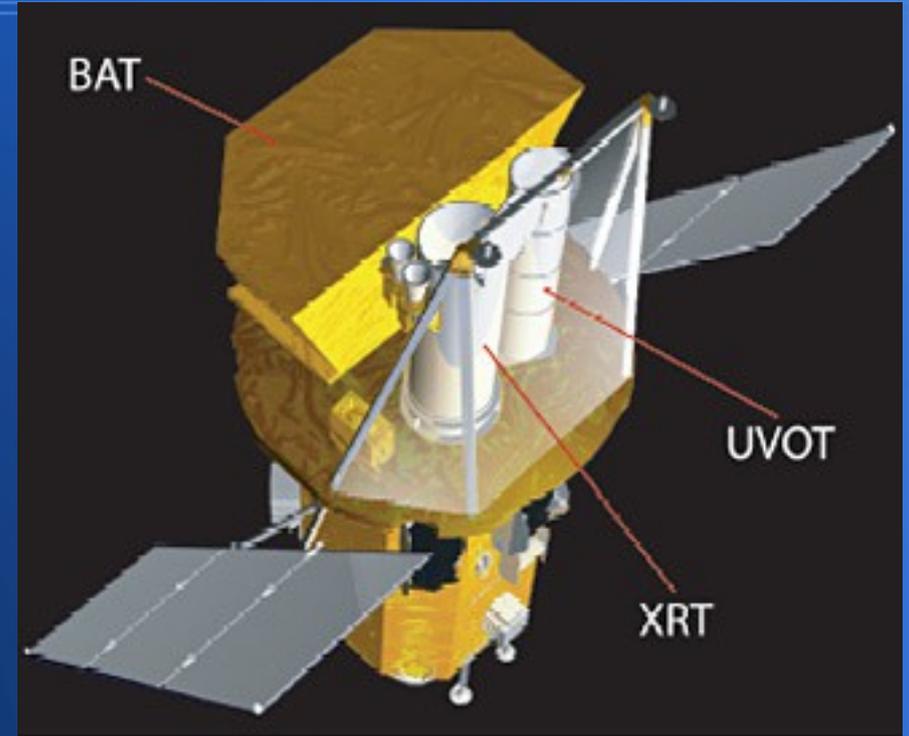
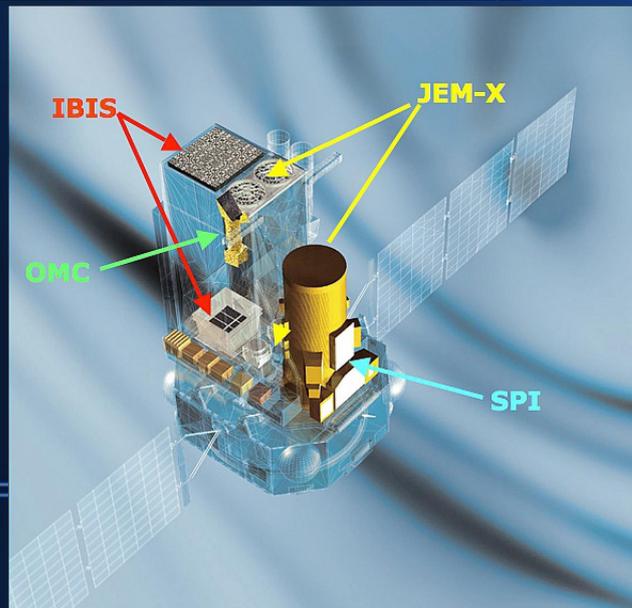
(“no-hair” theorem)



X-ray telescopes



XMM-Newton



Swift

INTEGRAL

The Ultra-Luminous X-ray sources

- X-ray spectroscopy is useful. From the Standard Disc Theory (applicable to sub-Eddington flows) the inner disk temperature scales with the mass of the BH as (Makishima et al. 2000)

$$kT_{\text{in}} \sim M^{-1/4}$$

THIS IS IN THE STANDARD ACCRETION DISC THEORY
(OPTICALLY THICK AND GEOMETRICALLY THIN DISC)

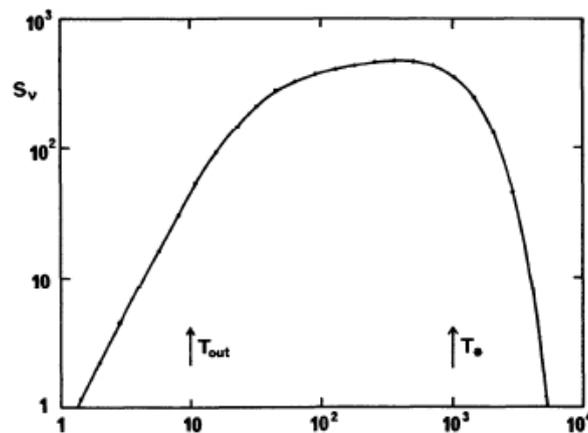
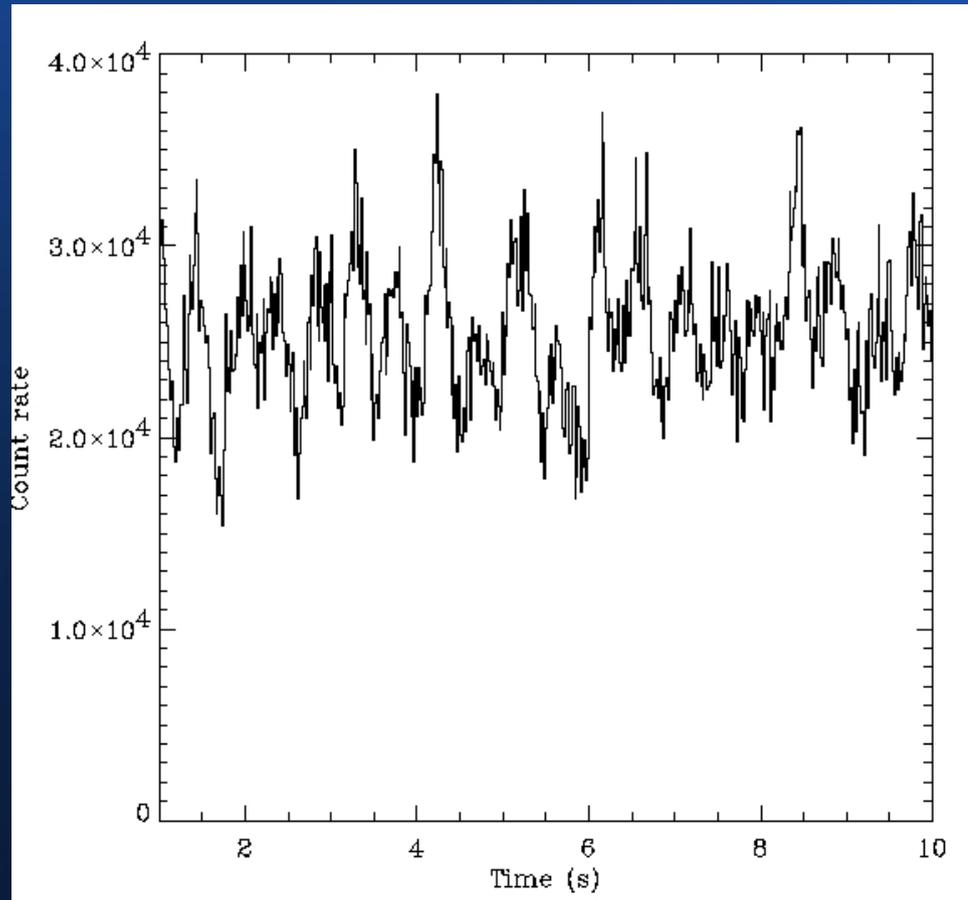


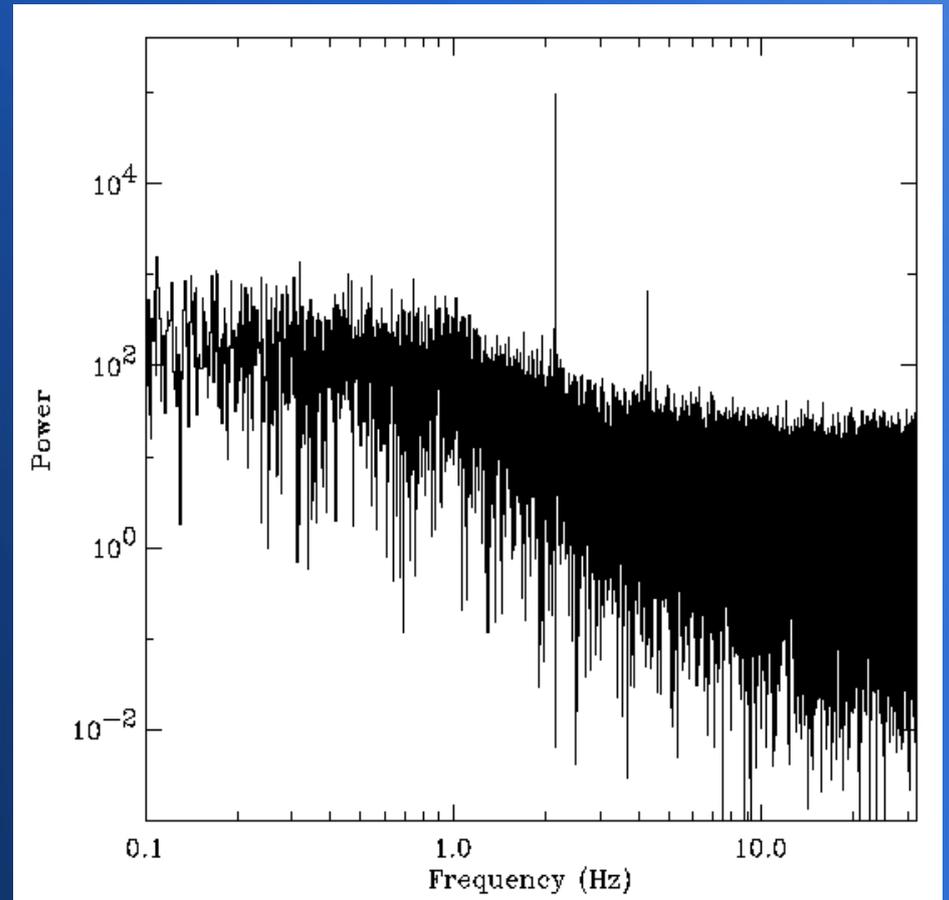
Figure 2 The integrated spectrum of a steady accretion disc that radiates a local black-body spectrum at each point. The units are arbitrary, but the frequencies corresponding to T_{out} , the temperature of the outermost disc radius, and to T_* , the characteristic temperature of the inner disc, are marked.

The X-ray emission: Timing



Light curve

(time domain)



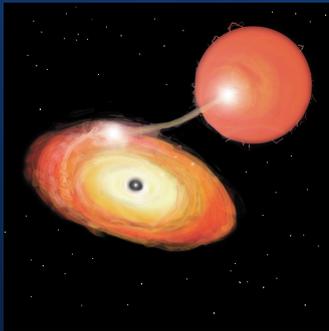
Power Spectrum

(frequency domain)

What can timing tell us?

➤ Timing → characteristic time-scales = **PHYSICS**

➤ Timing measurements can be extremely precise!!



➤ Binary orbits:

➤ Orbital periods

➤ Sizes of emission regions and occulting objects

➤ Orbital evolution

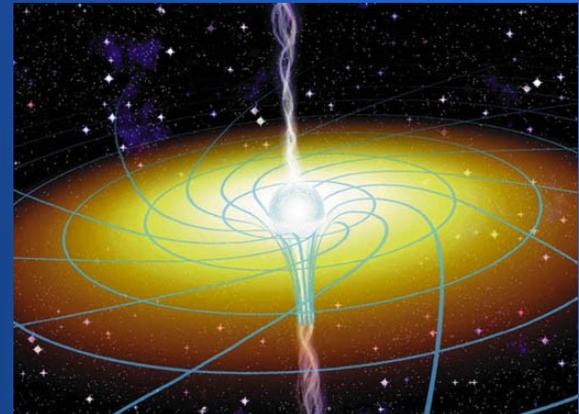
➤ Accretion phenomena (fast variability):

➤ Broadband variability

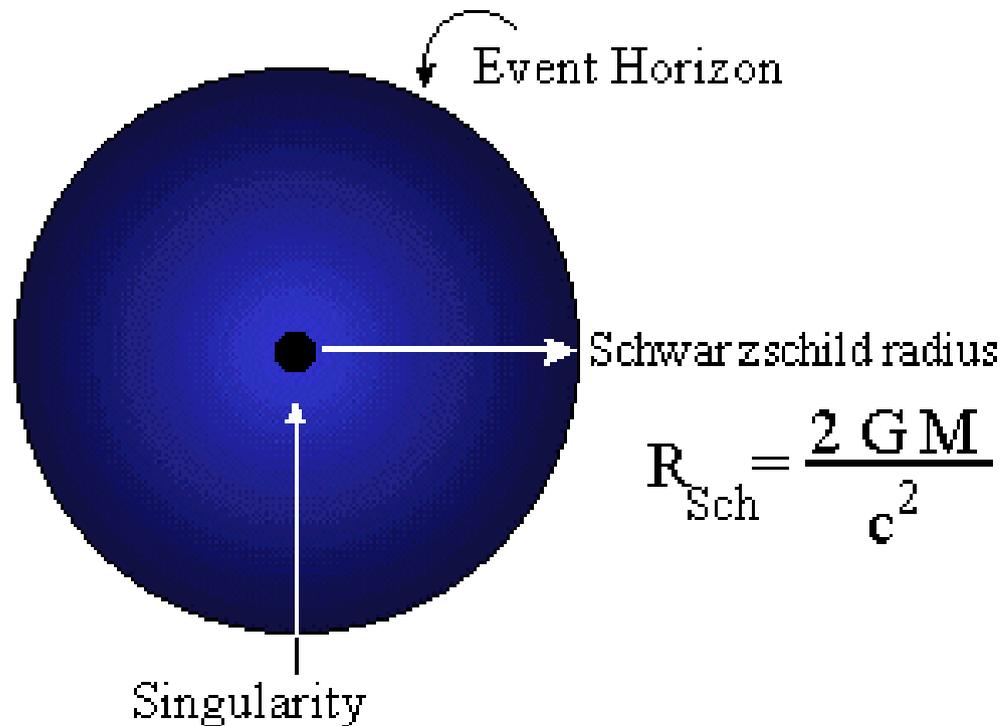
➤ “Quasi-Periodic Oscillations”

➤ Bursts & “SuperBursts”

➤ Energy Dependent Delays (*Phase Lags*)

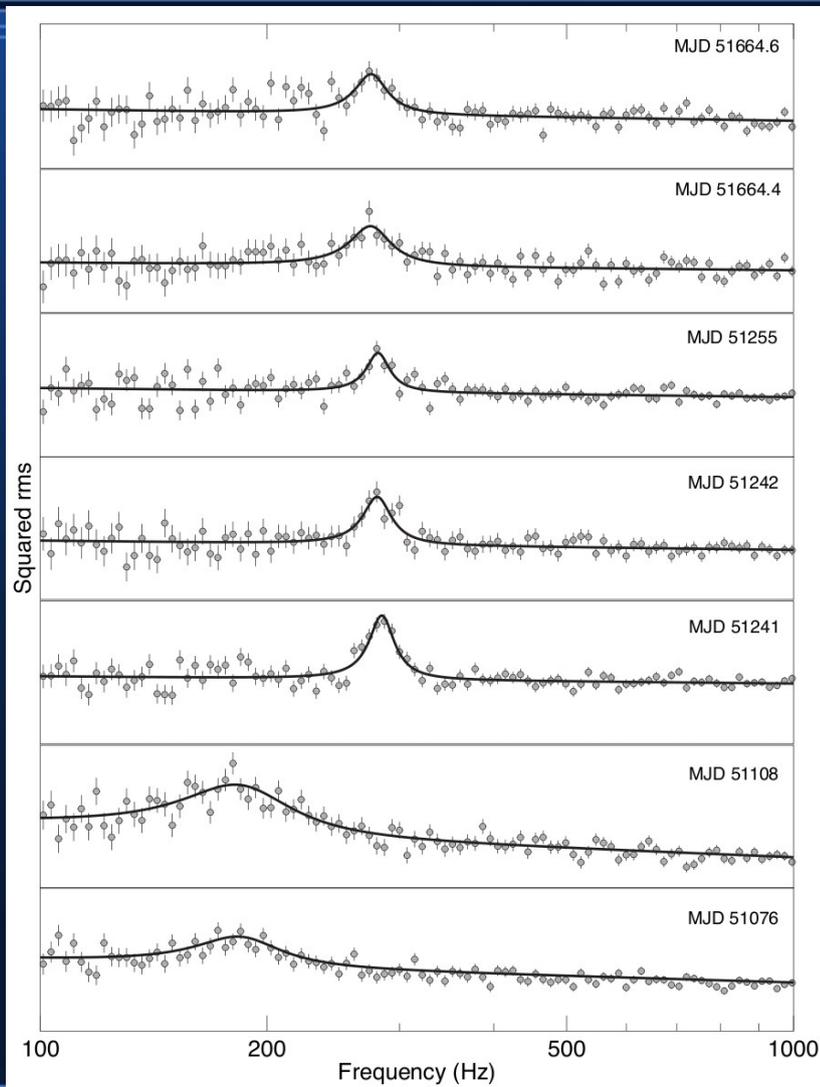


What can timing tell us for accreting black holes?



- If this frequency coincides with the frequency of a particle moving in the ISCO around a (Schwarzschild) BH of mass M , we derive a mass for the BH.
- But this is only for the *High-Frequency QPOs* .

Example: High-Frequency QPOs

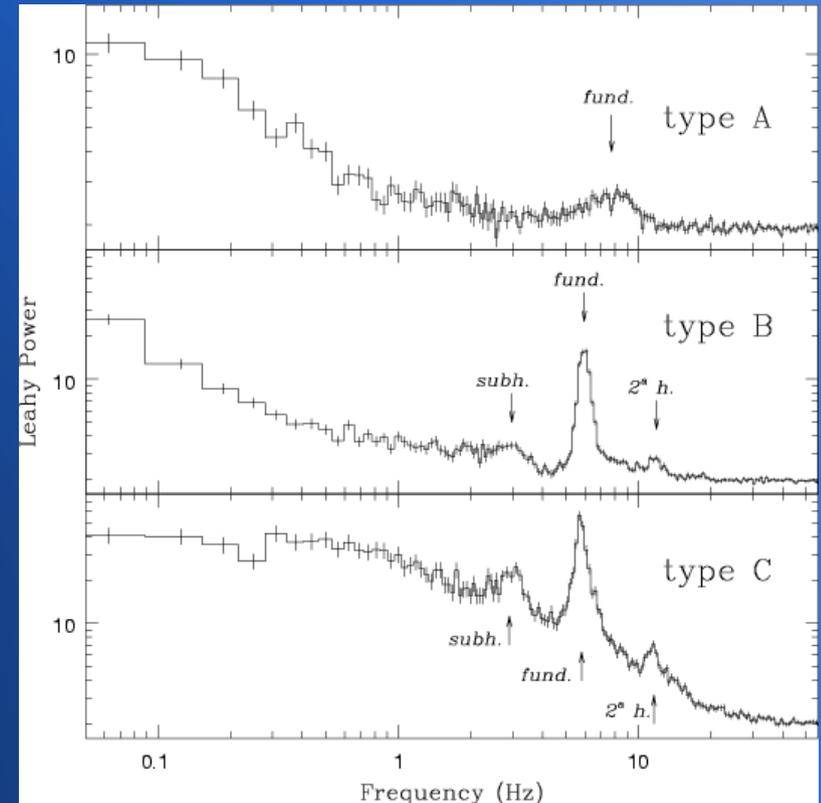


- HFQPOs in stellar-mass BHs (BHBs) are signals at frequencies 35-450 Hz observed in a few systems.

Power Density Spectra of the seven good detections of High-Frequency QPOs for XTE J1550-564 (from Belloni, Sanna, Mendez et al. 2012)

Example: Low-Frequency QPOs

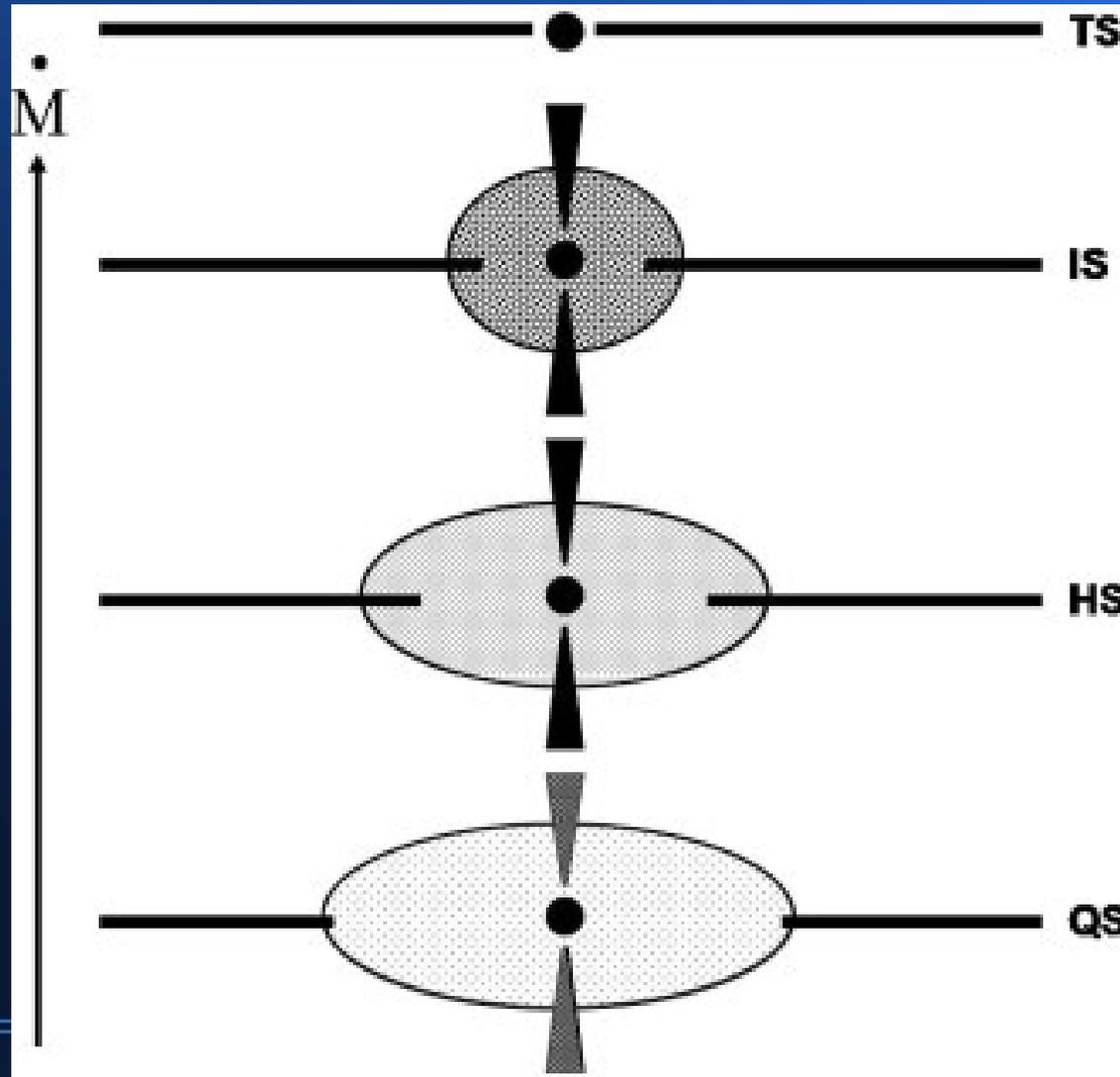
- Come from the inner region of the compact object but NOT from the last stable orbit.
- Different types (A,B,C) depending on their characteristics plus broad band noise associated.
- Type-C LFQPO frequencies scale as $1/M_{\text{BH}}$ (McHardy et al. 2006). They might depend also on the accretion rate (Soria, 2007; Casella+08).



*Low-frequency QPO
classification
(Casella, Belloni & Stella, 2005)*

Accretion states

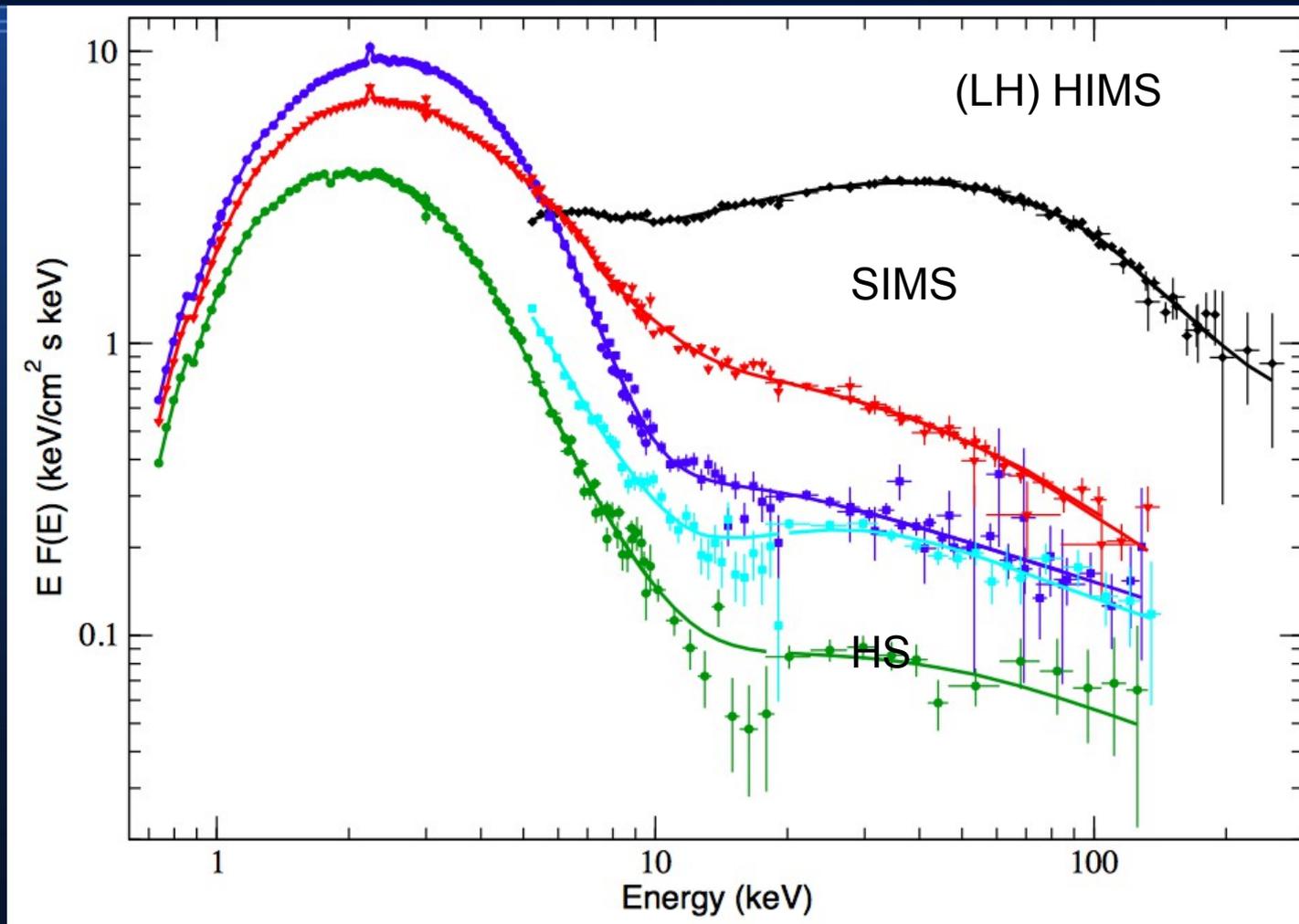
(CANONICAL CLASSIFICATION FOR THE STANDARD THEORY –
Optically thick & Geometrically thin accretion Disc)



(Optically thin
&
Geometrically
thick Corona)

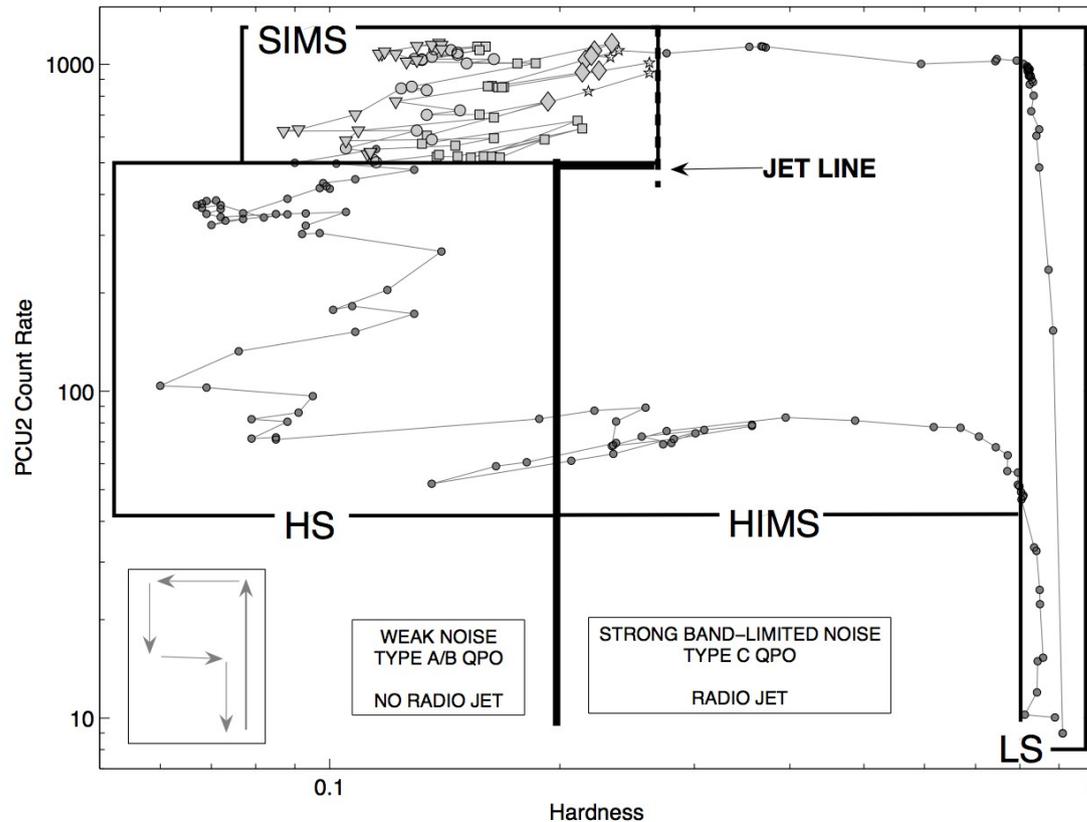
*Esin et al. 97
(ADAF)*

The X-ray energy spectral emission



XMM-Newton and INTEGRAL unfolded spectra of GX 339-4 during observations covering the evolution of low-hard state to high-soft state (Caballero-Garcia et al. 2009)

The X-ray emission: Hardness-Intensity diagram



Highly
secrting
sources do
not show this
diagram

Hardness-Intensity diagram of the 2002/2003 outburst of GX~339-4 as observed by the RXTE PCA. The gray lines mark the state transitions described in the text. The inset on the lower left shows the general time evolution of the outburst along the $\{bf q\}$ -shaped pattern. From Belloni+05.

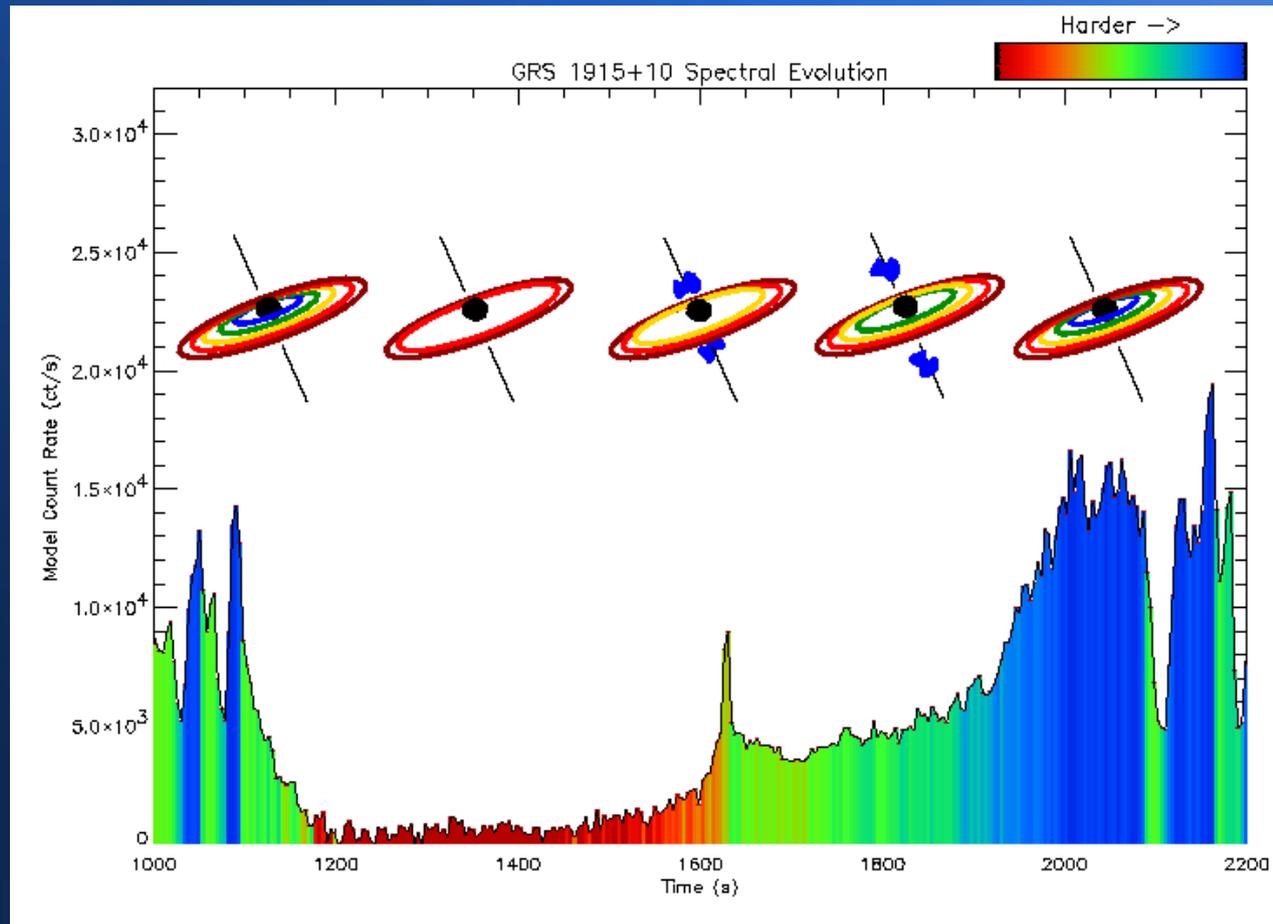
Accretion states

(CANONICAL CLASSIFICATION FOR THE STANDARD THEORY)

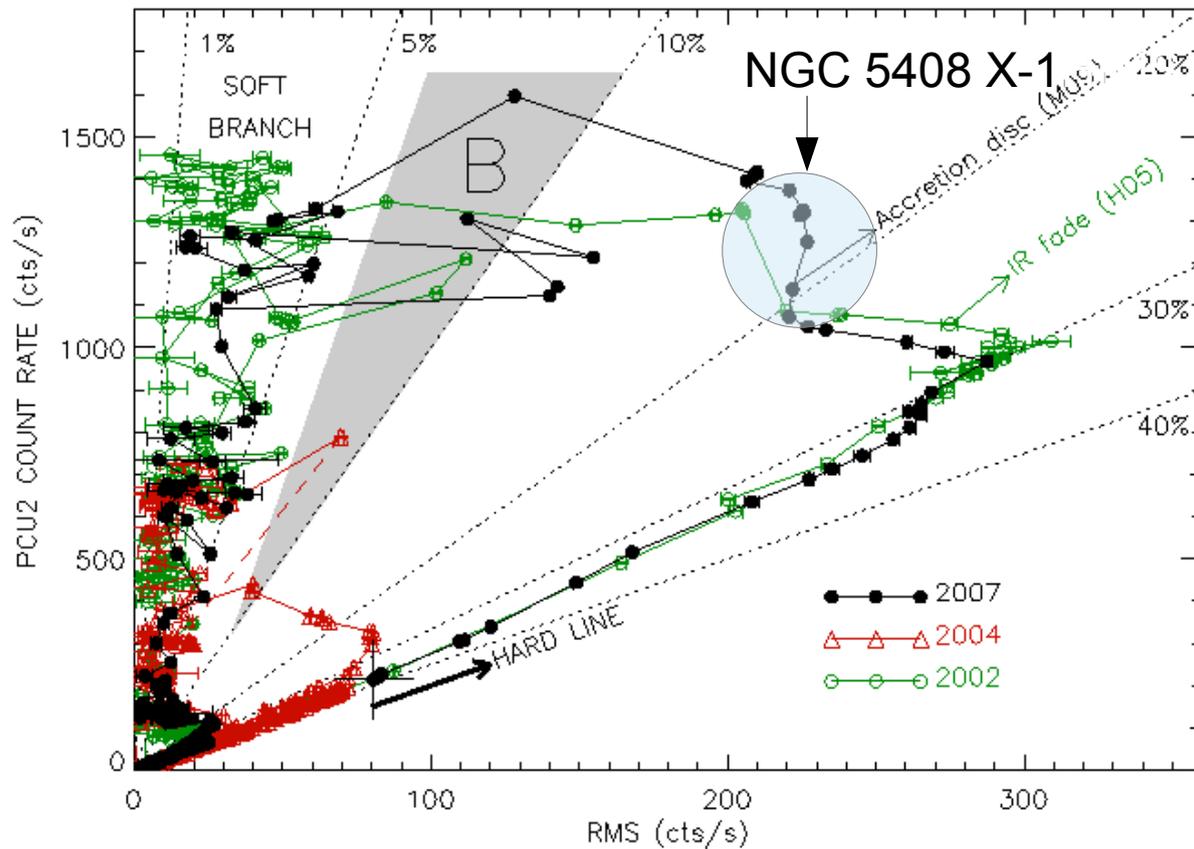
- **Low/hard state (LS):** The X-ray spectrum is characterized by very low disc and very important high-energy emission in the form of a powerlaw with photon index in the range $\Gamma=1.3-1.4$. A high-energy cut-off is usually seen (Sunyaev+80; Grove+98), associated to the kinetic temperature of the thermal distribution of electrons in the Comptonizing corona. Sometimes, low frequency QPOs are observed. Flat-spectrum radio emission is observed, associated to a compact jet ejection (Fender+04).
- **Intermediate (soft/hard) states (SIMS/HIMS):** showing both bright disc and high-energy powerlaw emission components. Photon index is within the range $\Gamma=1.5-2.5$. The few instances of HFQPOs appeared in the SIMS (formerly called as Very/High state). Just before the transition to the SIMS. Fender+04 suggested that the jet velocity increased rapidly, giving rise to a fast relativistic jet.
- **High/Soft state (HS):** the disc component is the dominant in the spectrum, with a weak powerlaw high-energy emission. No core radio emission is observed (Fender+04). Some timing properties (Wijnands+99), that were thought to be characteristic of the LH and HIMS are still present in this state, although in a much weaker form. No high-energy cut-off is observed in this state (Grove+98).

GRS 1915+10

- It is a persistent source that spends decades accreting at near-Eddington rate.
- Its inner disk radius decreases when the accretion rate is decreasing (also when the source flux is decreasing).
- We expect the opposite for a truncated disk (Done et al. 2007). For typical X-ray transients (e.g. GX 339-4), the disk is believed to be truncated at large radii at the beginning of the outburst and the inner edge moves to smaller radii as the mass accretion rate increases (see Esin et al. 1997).
- This accretion dynamics is similar to the one of a thick accretion disc (i.e. “slim” disc).



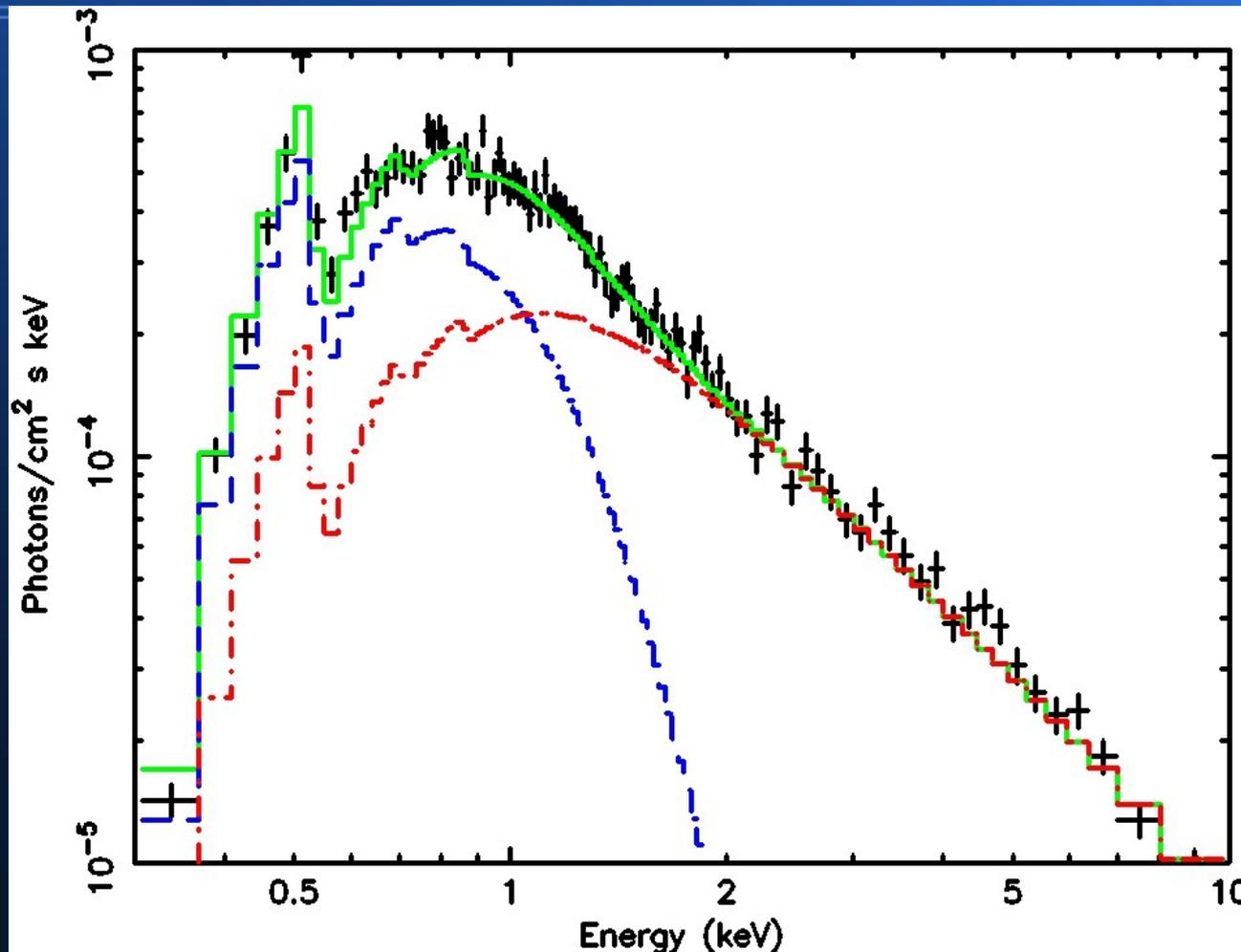
The rms-intensity diagram of GX339-4 (compared to the highly accreting source NGC5408 X-1)



Rms-intensity diagram for the 2002, 2004, 2007 outbursts of GX 339-4 (from Munoz-Darias+11)

- Caballero-Garcia+13 found anti-correlation of NGC5408 X-1 is exactly like found for Black Hole Binaries (BHTs).
- The high level of fast variability (frac.rms 30-40%) indicate a *hard state*.
- Nevertheless, the constant “absolute rms” obtained indicate that NGC5408 X-1 is accreting in the HIMS only.

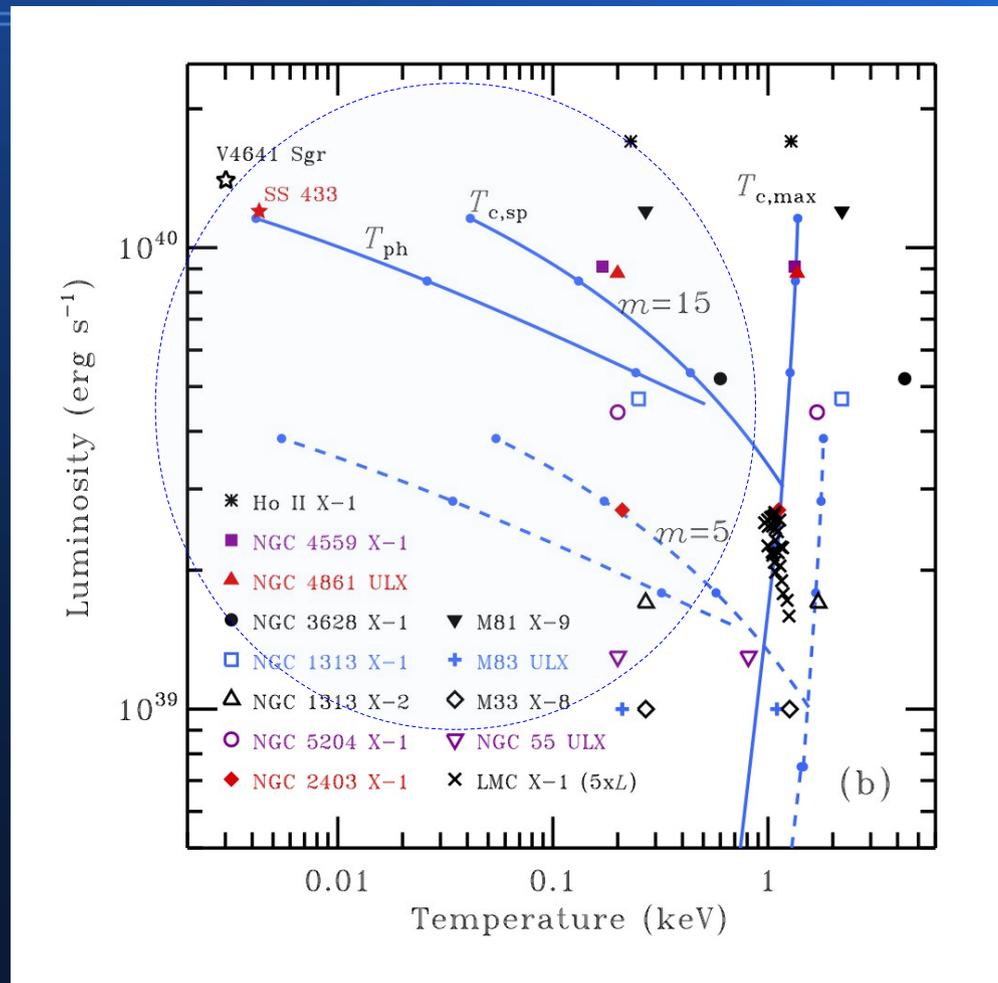
The emitted spectrum in highly accreting sources



The XMM-Newton/EPIC-pn X-ray spectrum of NGC 1313 X-1 is shown (Miller, Fabian, & Miller 2004).

The need of slim-disc models

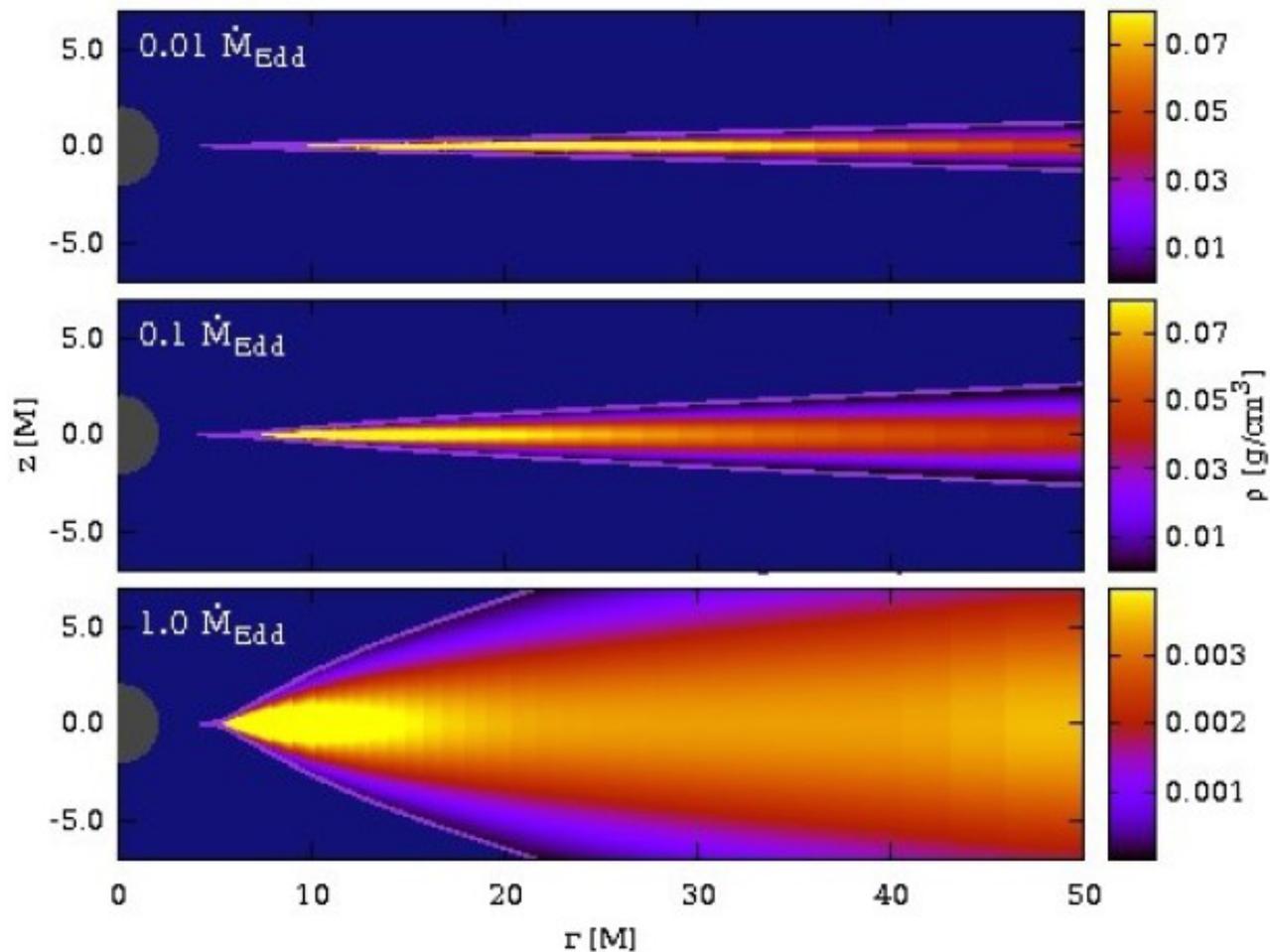
THE
ACCRETION
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REALLY
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THE HIGHLY
ACCRETING
REGIME



X-ray luminosity versus inner disc temperature inferred from X-ray spectral fits for a sample of ULXs and of BHBs. Figure taken from Poutanen et al. (2007).

The SLIM disc model

Analytical solutions



Sadowski+2009

*Abramowicz
+78
("Polish
doughnuts"
and slim
discs)*

The SLIM disc model



*Abramowicz
+78
("Polish
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Current statistics and forecast

- So far 66 BHTs have been catalogued.
- From X-ray data archives 132 outbursts have been detected/followed from 47 BHTs in the period 1996-2015 (7-8 outbursts/year) for Swift/BAT and INTEGRAL/IBIS (Tetarenko et al. 2016).
- It is expected to detect a mean value of 2 new objects per year with THESEUS.
- Moreover, the majority of the BHT outbursts last more than 100 days.

Conclusions

(in general)

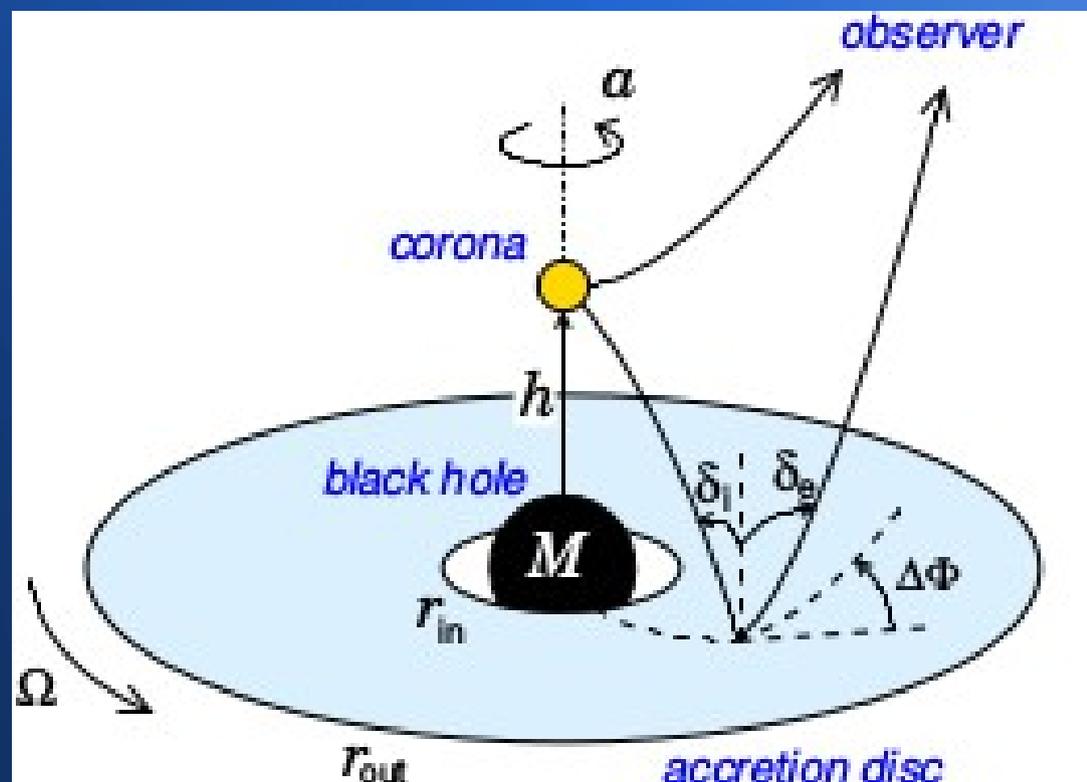
- BH transients show X-ray spectral states characterized by different spectral shapes and timing properties along their outbursts. They are explained in terms of changes in the geometry of the accretion flow around the central object.
- Disentangling the main components that contribute to the overall X-ray energy budget and follow the spectral evolution of the accretion flow will be carried out by *THESEUS* thanks to its wide field of view combined with the broad band energy coverage.
- Simultaneous observations will be triggered with the high spectral resolution X-ray telescope (*Athena*), as well as radio and gamma-ray high sensitivity telescopes (SKA and CTA) which will be complementary to *THESEUS* for a comprehensive accretion/ejection study of these sources.
- *THESEUS* offers the unique capacity to perform strictly simultaneous X-ray and NIR observations. During outburst, IR fluxes are known to trace the X-ray emission, and are thought to be an indicator of the strength of jet activity in BHTs. Thus, simultaneous observations in these bands will lead to advances in our understanding of the jet-disk coupling in BHTs.
- Also an opportunity for investigation of sources in the highly accreting regime (close and/or above the Eddington limit).

**A note about the reflection
component and Fe K lines with
THESEUS**

Reverberation in X-rays

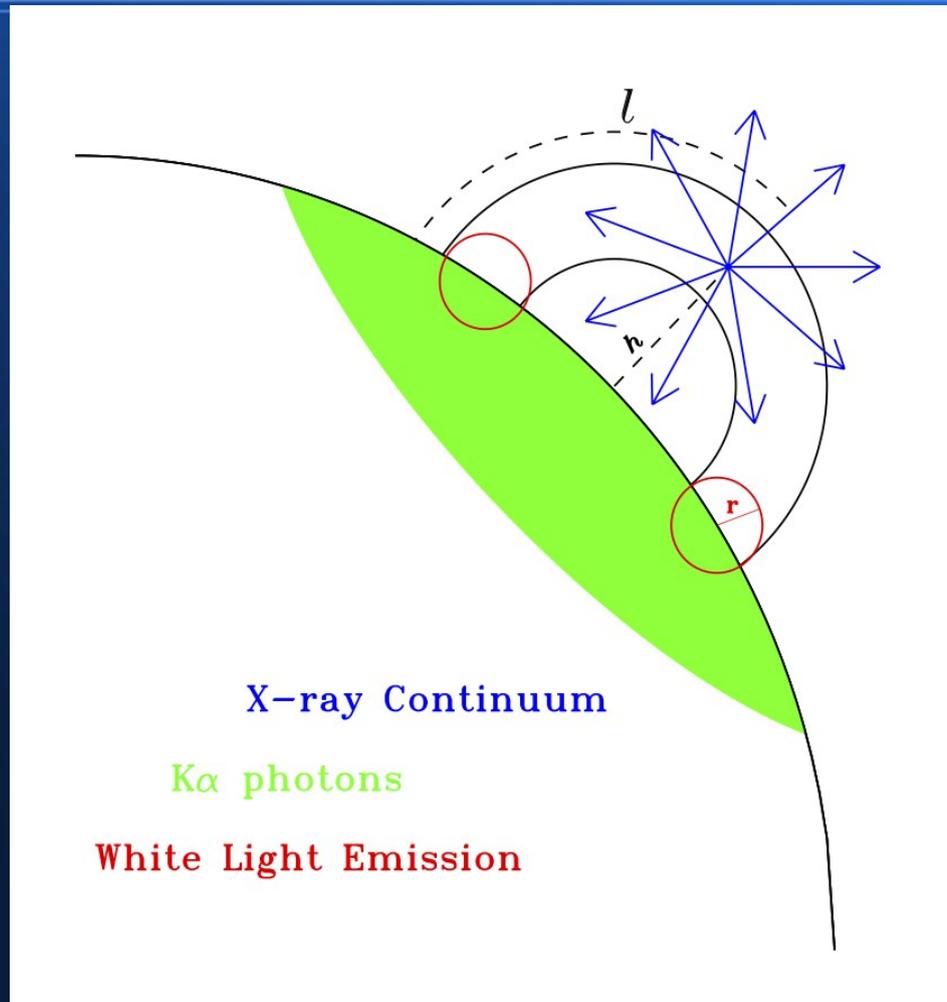
Overview

- X-ray reverberation mapping of the inner parts of the accretion disc → clues to the geometry of the corona.
- Reverberation mapping in the lamp-post geometry of the compact corona → *ionisation profile of the disc* (Chainakun+16; Dovčiak+18, in prep.).
- Light rays: *Fully relativistic ray-tracing code in vacuum* for photon paths from the corona to the disc and to the observer & from the disc to the observer.
- **Goal**: *understanding the lags versus frequency/energy* → model parameters: **height** of the corona, **inclination** of the observer, disc **ionization profile** and black hole **spin**.



The sketch of the lamp-post geometry.
(Credits: Dovčiak+14)

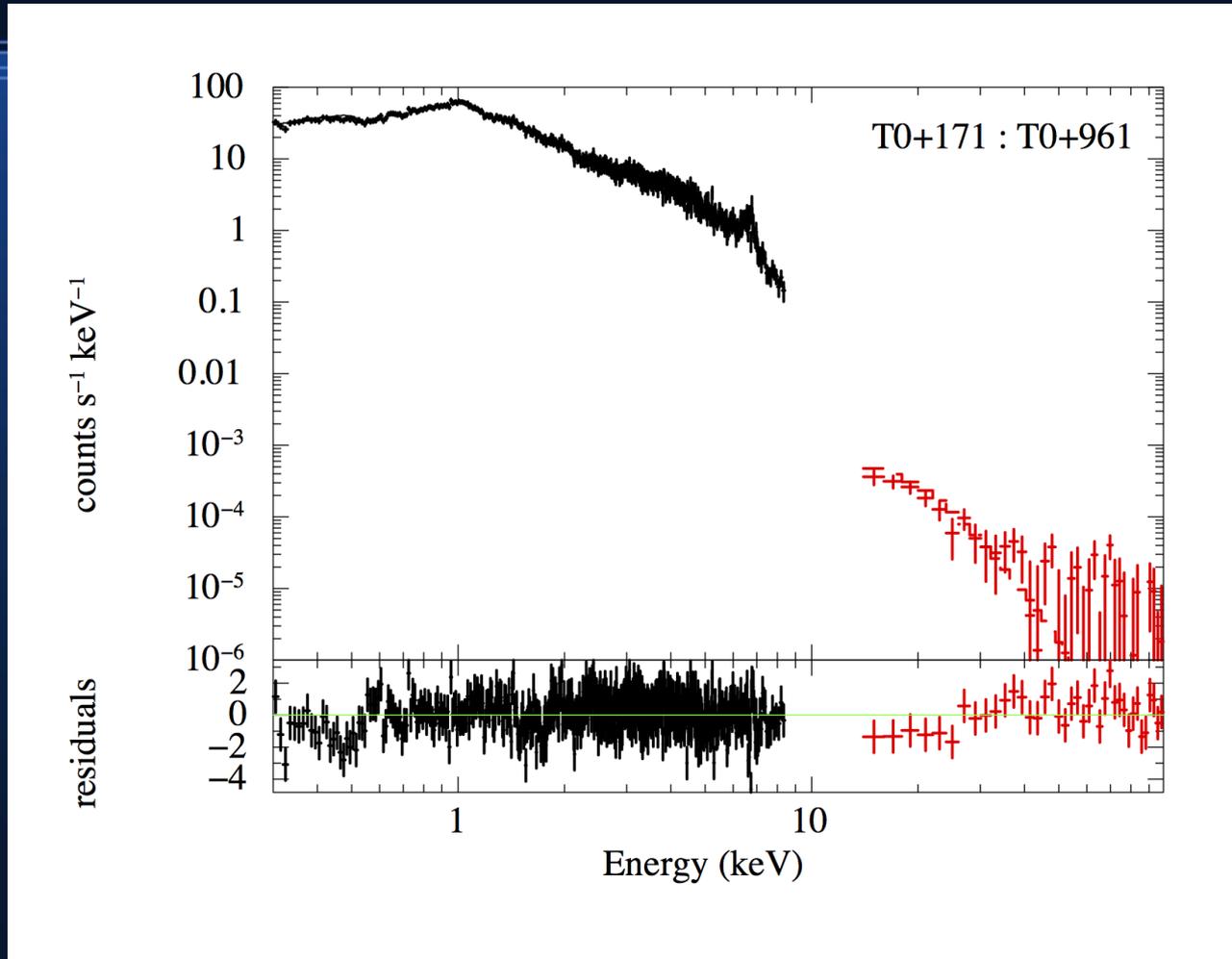
Swift/XRT+BAT



Coronal prominence during a “super-flare” in a flaring star

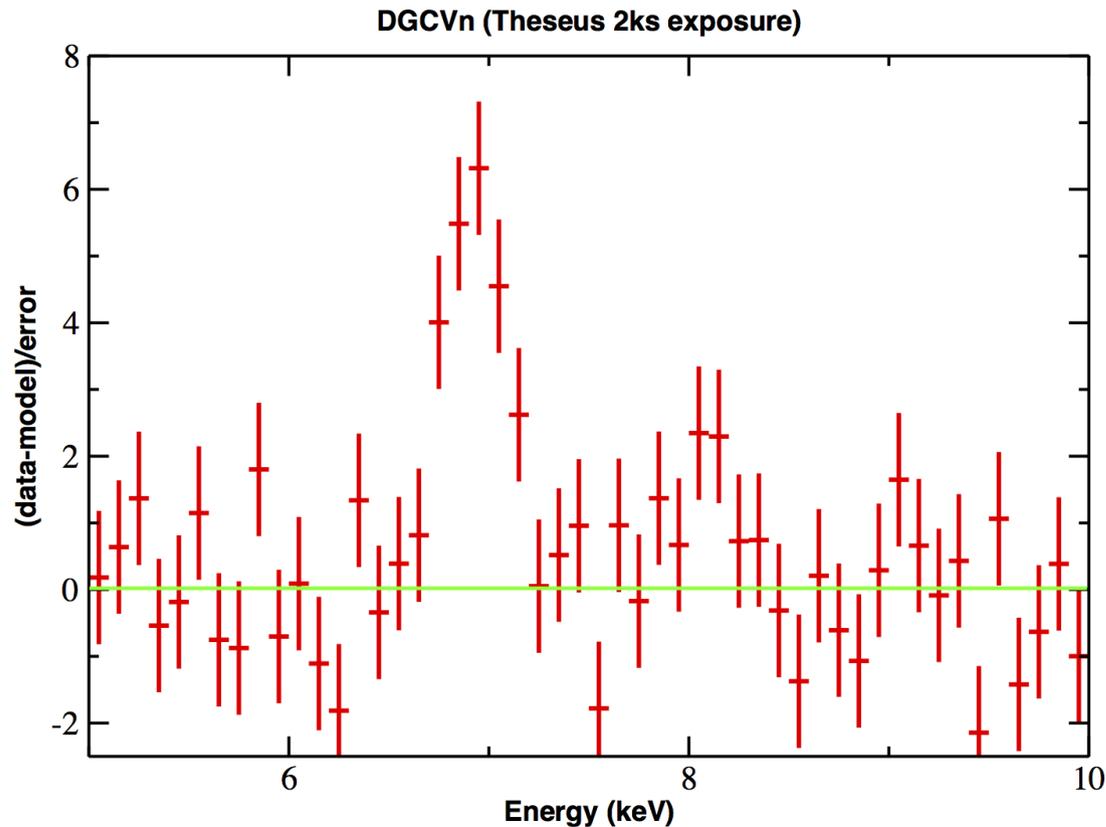
Scheme showing the geometry between the flare photons, emitted as high energy X-ray continuum, the region where the photospheric Fe K photons are emitted, and the probable location of the white light flare (fig.8 from Osten+10).

Swift/XRT+BAT



Joint spectral fit to XRT and BAT data accumulated during the EV Lac superflare of 2008 (Osten+2010).

THESEUS/XGIS



Simulated residuals of a 2 ksec XGIS-X spectrum showing Fe lines from the 280 MK optically thin thermal emission model t to the Swift DG CVn superflare in 2014. For more details: see our paper in the THESEUS Time-Domain W.G. (SWG3) White Paper (Section “Stars”).