State Transitions, Accretion Geometry, and the Origin of the Hard X-ray Radiation in X-ray Binaries

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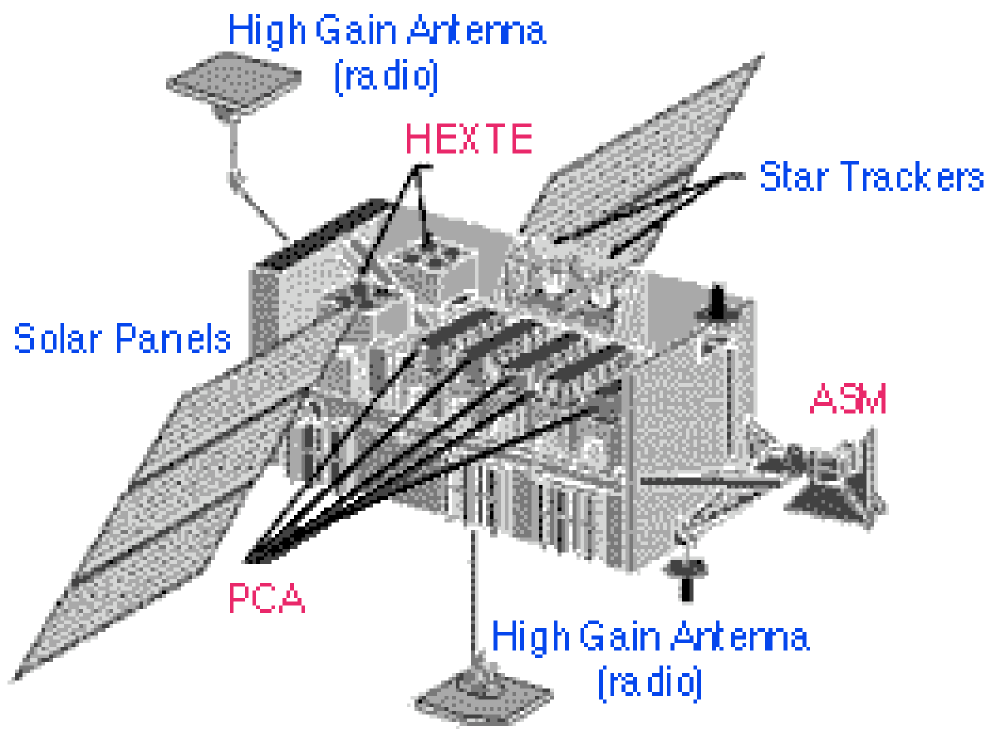
Rossi X-ray Timing Explorer:

An Astronomical Satellite aiming at the 2-250 keV X-ray sky

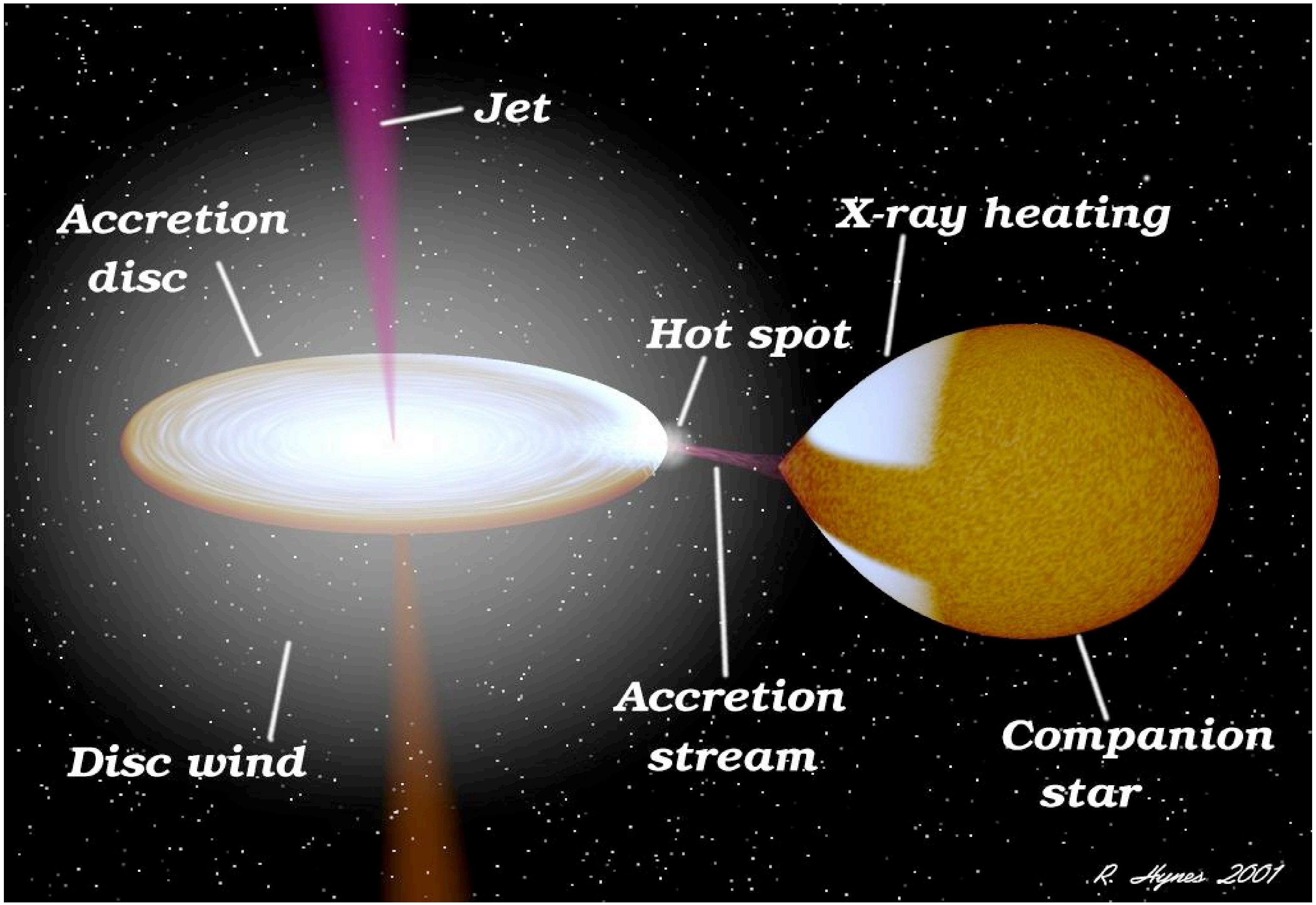


proposed in 1970s, launched in December 1995, will operate up to 2008
This mission has brought a lot breakthroughs.

RXTE/PCA/HEXTE has a very short response time (1-2 days) to target of opportunity determined by its own all sky monitor and other telescopes
-- high time resolution (sub-milliseconds)
-- broadband X-ray energy coverage (2-250 keV)

What are X-ray Binaries ?

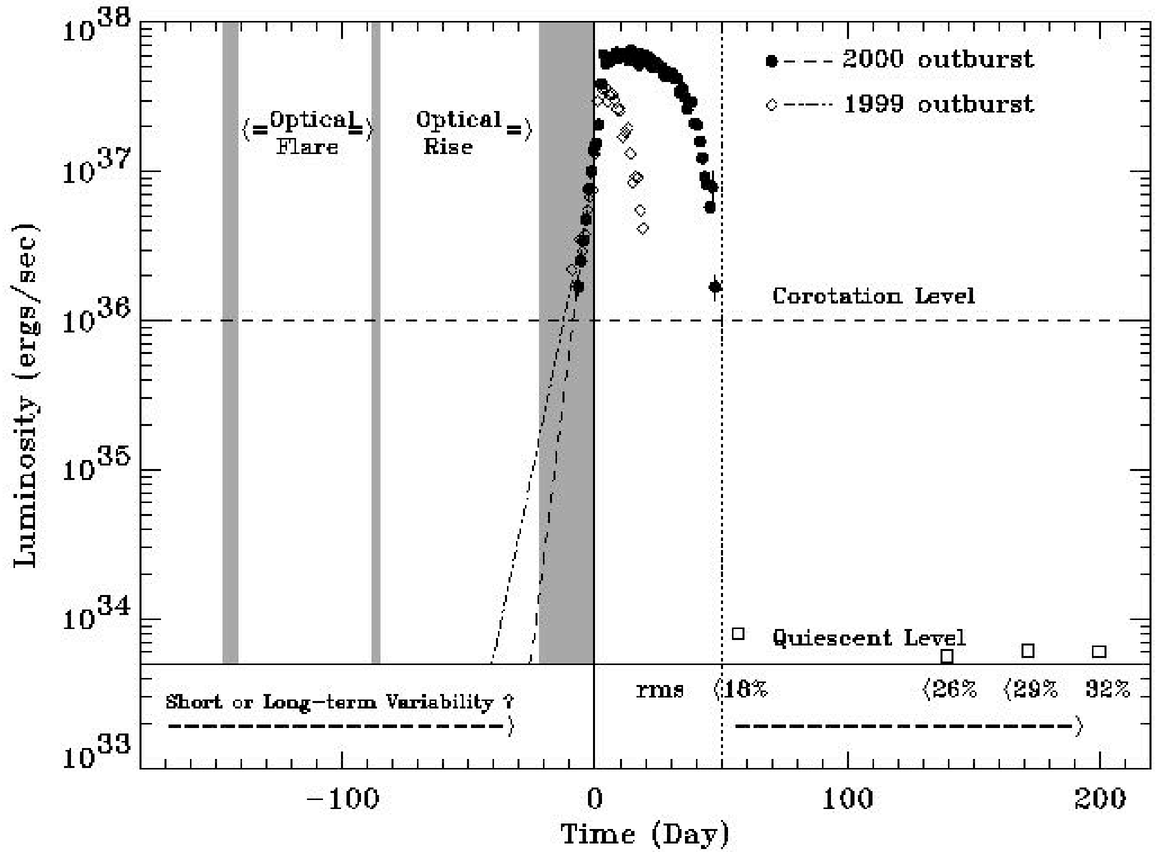
Accreting neutron stars and stellar-mass black holes



Black Hole and Neutron Star Soft X-ray Transients

Large range of mass accretion rate -- accretion through Roche lobe overflow

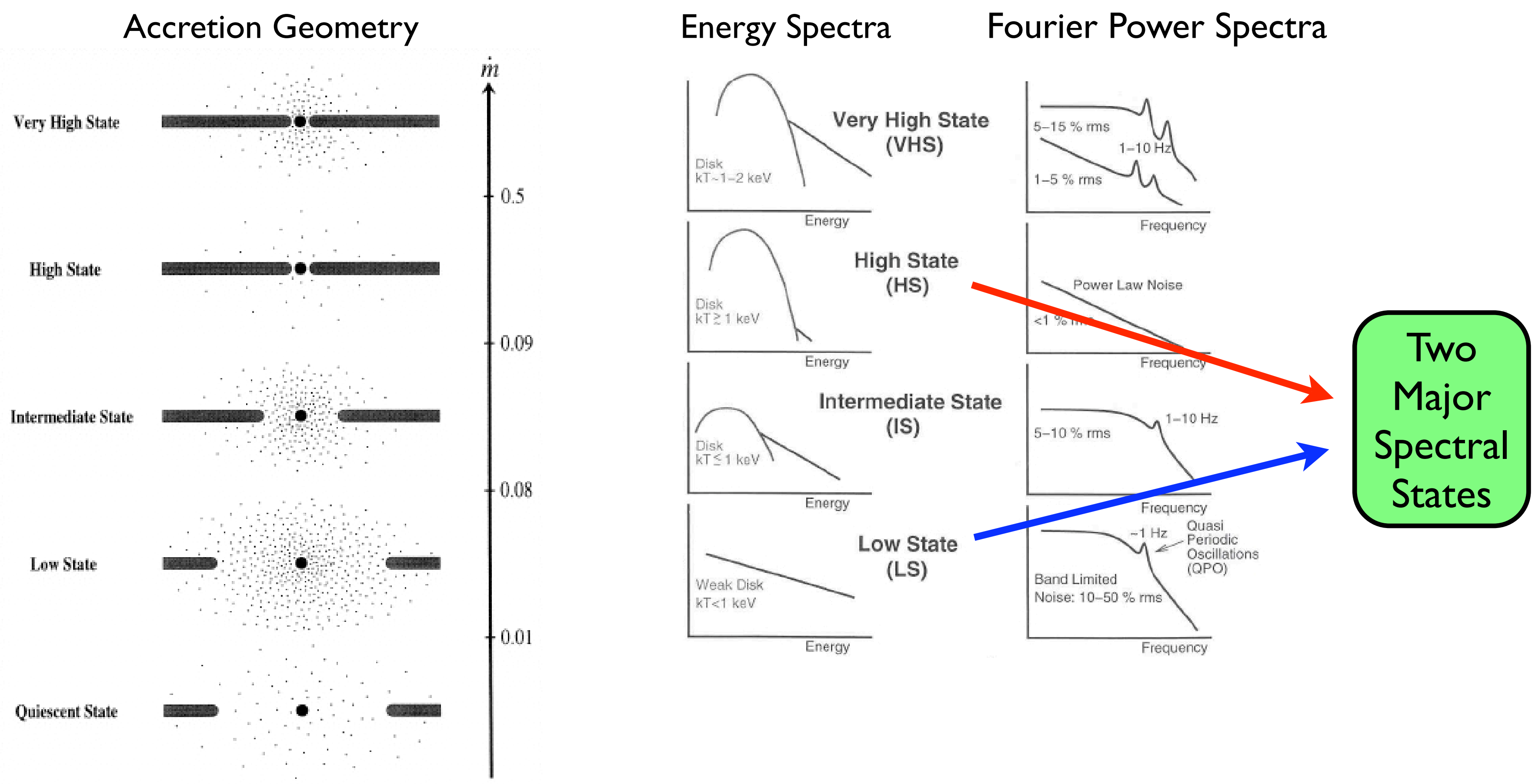
Neutron star soft X-ray transient Aquila X-1: RXTE ASM & Chandra Observations



Quiescence is not really quiescent.

Black Hole Spectral States

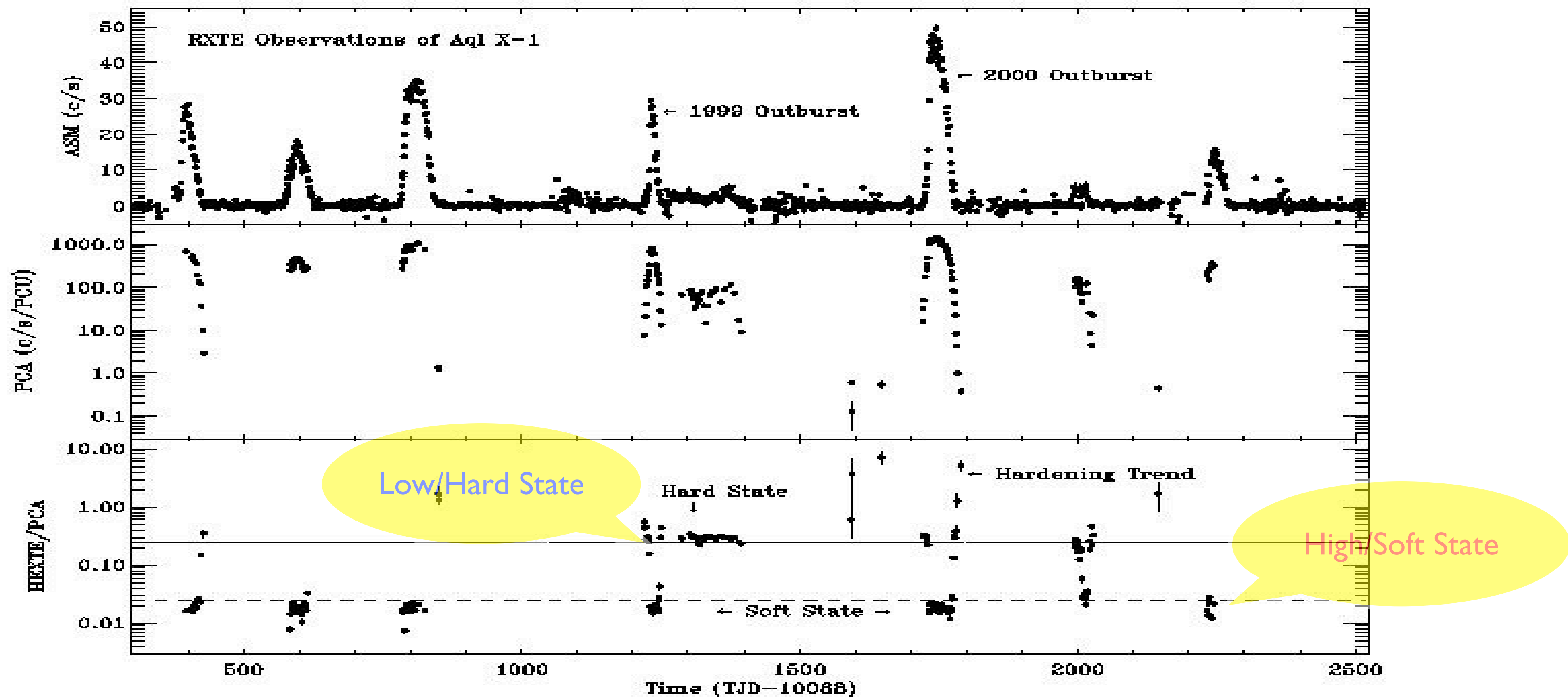
Accretion Geometry and Spectral and Temporal Characteristics -- the "Standard" Picture



Mass accretion rate is the primary parameter in describing the accretion or spectral states. Therefore, there is a relation between the X-ray luminosity and the observed spectral states.

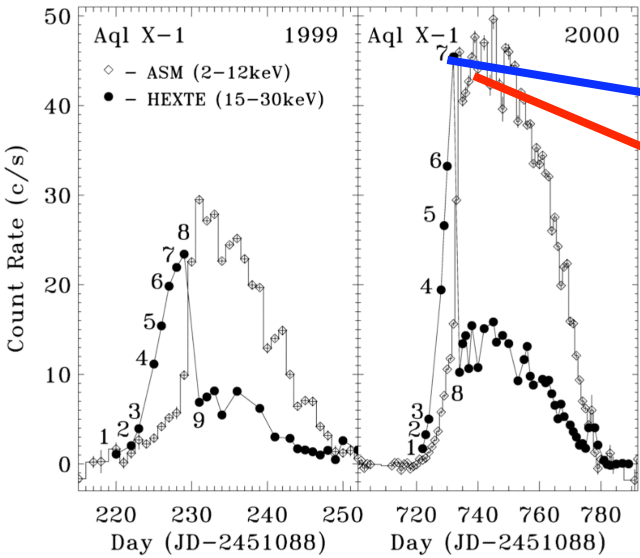
Neutron Star Soft X-ray Transient Aquila X-1

Distinct spectral states and state transitions during the outbursts as observed with the RXTE

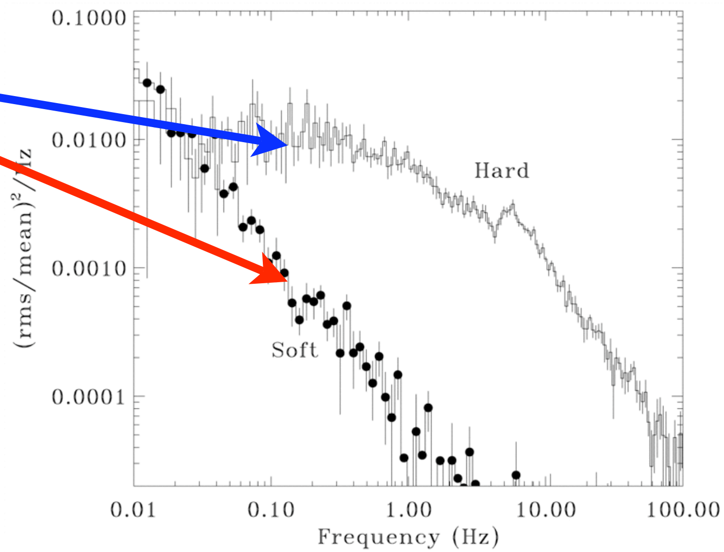


(1) Nearly Identical LH-HS State Transition in Black Hole and Neutron Star Systems

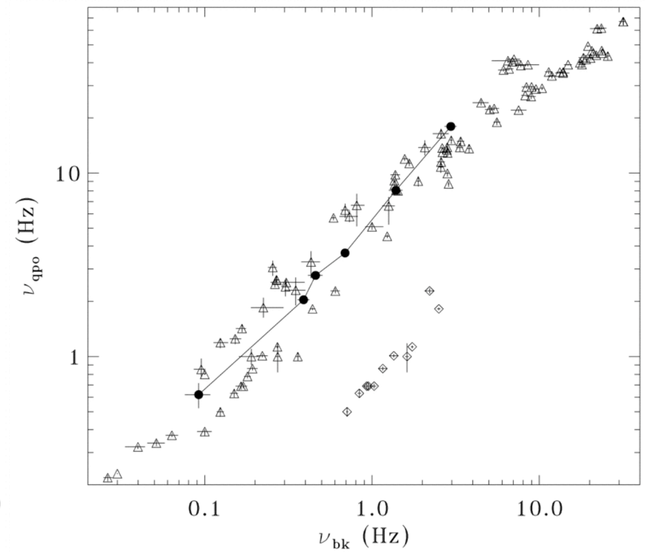
Aquila X-1 (Yu et al. 2003, ApJ, 589, L33)



Preceding hard flares



Transition of Fourier Power Spectra

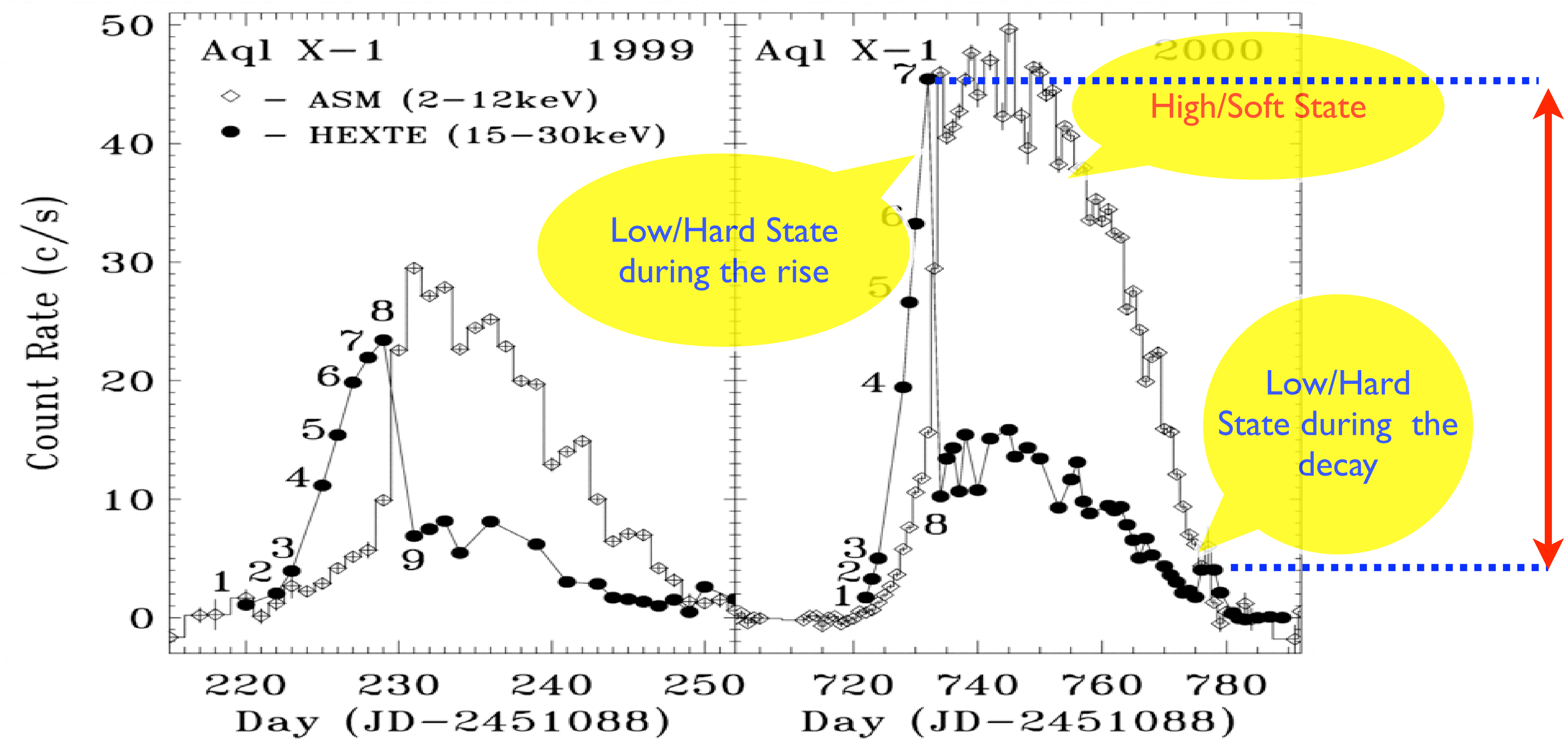


Same QPO & Noise

ADAF solution exists below different luminosity thresholds (in Eddington unit) for neutron star and black hole systems. The accretion flow in the LH state can not be the ADAF.

(2) Similar Hysteresis of State Transitions

The LH-HS state transition occurs at a higher luminosity than the HS-LH transition



Mass accretion rate is not the only parameter that determines the spectral state. Proposed other parameters: past luminosity history (Miyamoto et al. 1995), corona size (height) (Homan et al. 2001; Miller et al. 2006), disk size under a two-flow geometry (Smith, Heindl & Swank 2001), inner disk radius (Zdziarski et al. 2004), disk evaporation (Meyer, Liu & Meyer 2006), etc.

Our Unique Approach

- The (bright) LH states and the HS states, as well as transitions between the two states in neutron star systems and the black hole systems, are probably the same. Therefore, we study both types of sources.

- We study single sources on different occasions (e.g., transitions in different outbursts of the same source). Therefore, unknown source properties, such as the mass of the compact object, binary orbital frequency, companion type, etc., will not bring complexities in the data analysis nor affect our interpretations. The physics behind the phenomena will be on the accretion process and generation of high energy radiation under different accretion set-ups.

- State transitions likely associate with a change of the accretion geometry and a change of the high energy radiation mechanism. Therefore, state transitions are the best time to study accretion geometry and the origin of high energy radiation mechanism.

- The LH state and the LH-HS transition during outburst rise offers the best opportunity, since the LH state are the brightest LH state, and the transition occurs at a higher luminosity because of the hysteresis effect.

The Topics to Explore

- Similarities between neutron star and black hole systems. Different radiation efficiency of the accretion flow would help constrain accretion or jet models.
- What determines spectral states and state transitions other than mass accretion rate ? What physical processes are involved (e.g., evaporation, corona, geometry) ?
- Can we reveal the accretion geometry in the LH state by studying state transitions ?
- The origin of the non-thermal hard X-ray radiation may be revealed when nature tunes system parameters.

Data analysis:
as simple as possible, as direct as possible, in a model independent way (or with as less assumptions as possible), as less detailed as possible, etc.

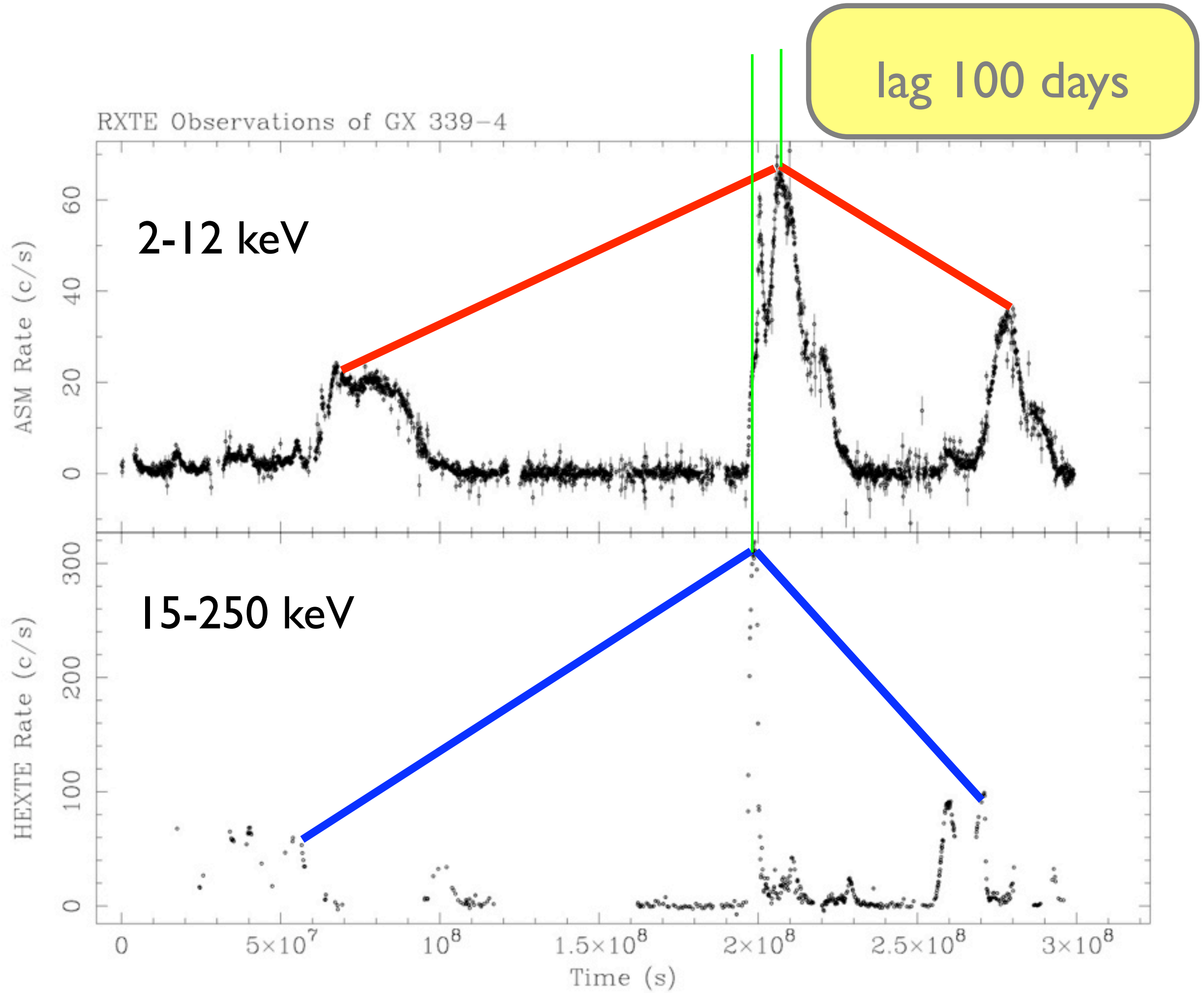
Our Achievements (1)

- Our discoveries of two empirical relations associated with the spectral state transitions:
  - A positive correlation between the luminosity of the LH-to-HS state transition and the peak luminosity of the following HS state
  - ☆ Likely applies to all black hole binaries and neutron star LMXB sources
  - ☆ links the accretion flow that powers the LH state and the accretion flow that powers the following HS state -- suggests a relation between an earlier flow (LH state) and a later flow (HS state, i.e., disk flow)
  - ☆ indicates an early set-up of soft X-ray transient outburst, which can be used to predict the peak luminosity of an outburst or flare

This is the evidence that the mass accretion rate does not determine the LH-HS transition (the ***same*** *transition - the* ***same*** *physical process) !*

Results (1): the Luminosities of the LH-HS Transition and the Outburst Peak

RXTE Observations of the Black hole transient GX 339-4

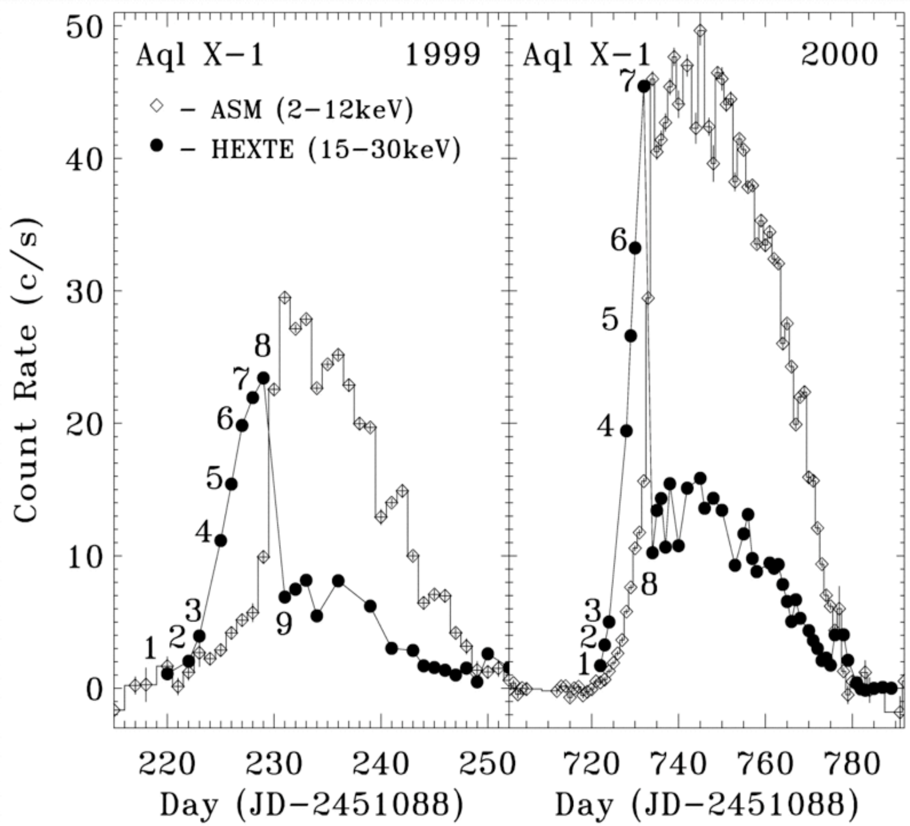


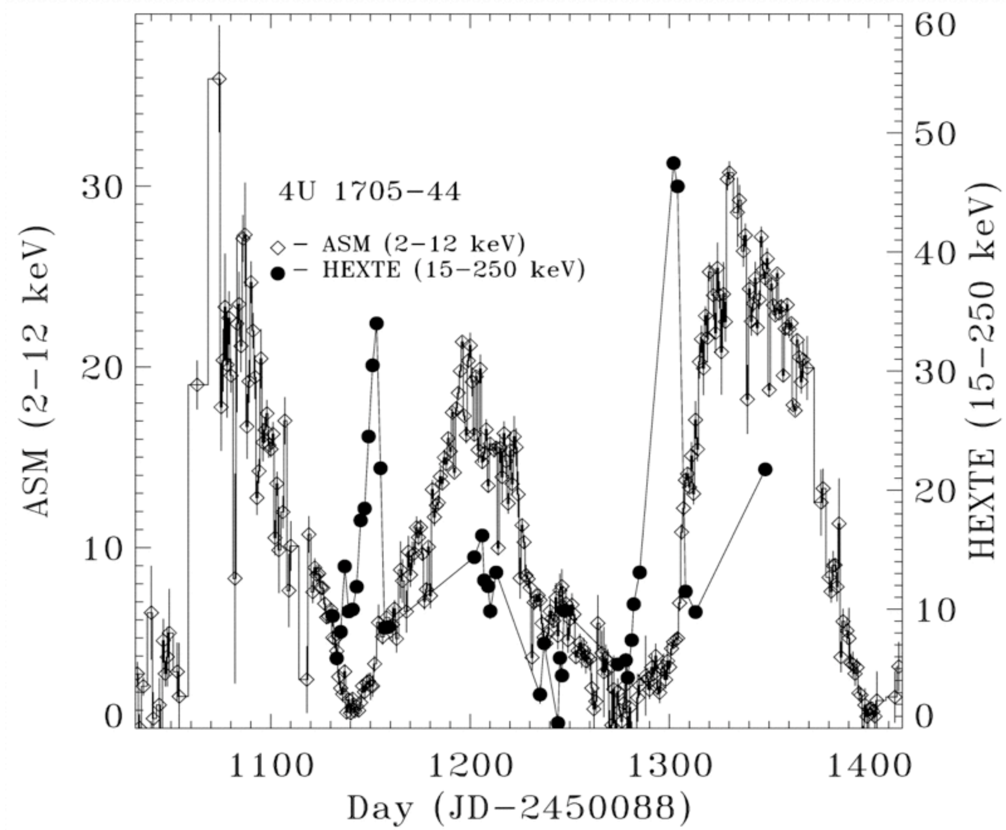
The outburst is set up early. The higher the luminosity of the LH-HS transition is, the brighter the outburst will be --- we can predict the size of an outburst during the rise of the outburst.

Results (1): the Luminosities of the LH-HS Transition and the Outburst Peak

RXTE observations of the neutron star transient Aql X-1 and persistent neutron star LMXB 4U 1705-44

Yu et al. 2003, ApJ, 589, L33; Yu, van der Klis & Fender 2004, ApJ, 611, L121



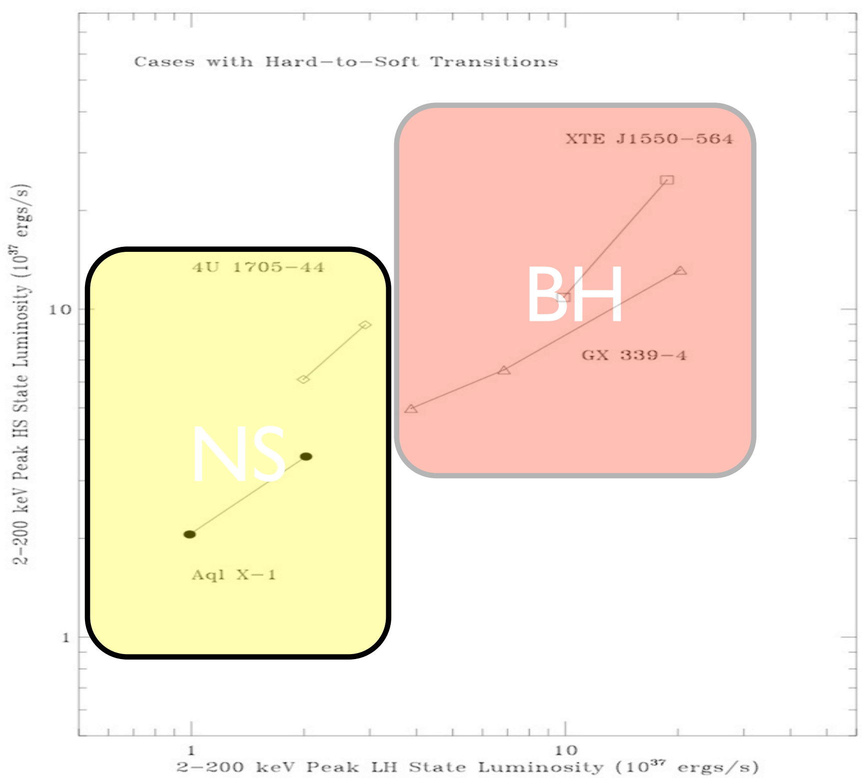


The soft X-ray peak, i.e., the flux peak of the HS state, lags the hard X-ray peak, i.e., the flux peak of the LH state during the rise of an outburst or flare.

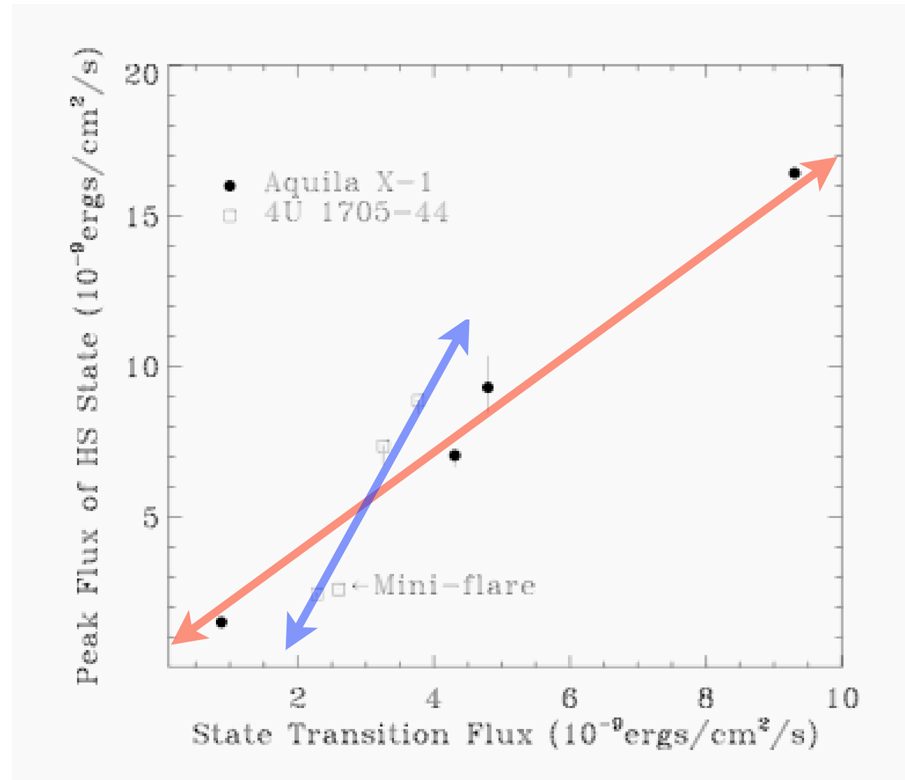
Luminosity of the LH-HS Transition vs. Peak Luminosity of the HS State

A positive correlation is confirmed !

Yu et al. 2007, ApJ, 644, xxxx



Yu & Dolence 2006,submitted; Yu 2007, in preparation



New studies extend the luminosity range to about 5 times lower. Saturation of the nearly linear relation is expected when the Eddington limit is reached in either the LH state and the HS state.

Our Achievements (2)

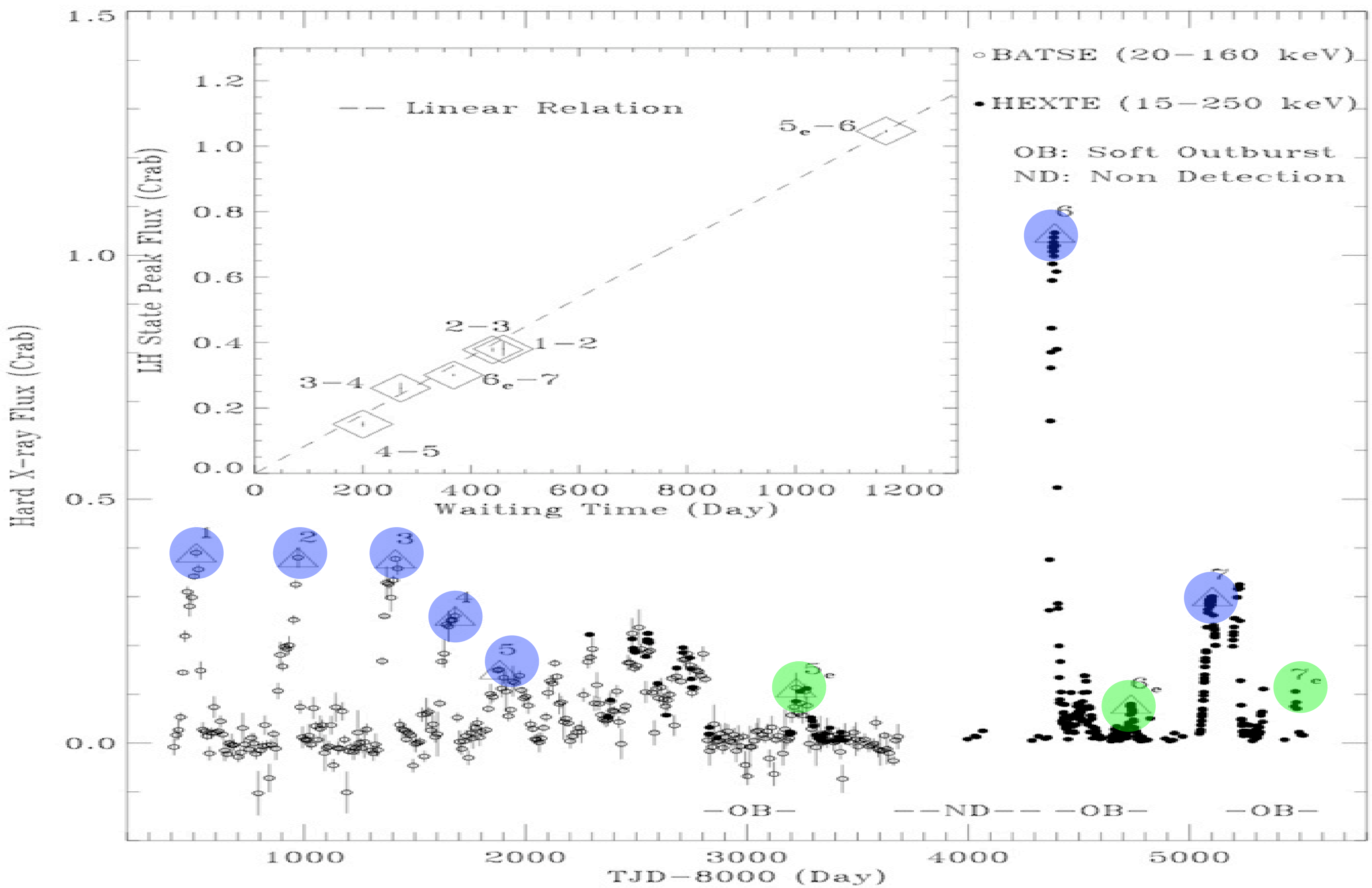
- Our discoveries of two empirical relations associated with the spectral state transitions:
  - A nearly linear relation between the peak flux of the initial LH state and the outburst waiting time in the black hole transient GX 339-4
  - ☆ links the non-thermal power-law spectral component to disk mass
  - ☆ early prediction of the peak flux of the initial LH state (possibly the occurrence of the LH-HS transition)

This is the evidence that the mass in the accretion disk somehow affects the hard X-ray radiation and reveals the role of the outer disk in generating the non-thermal power-law spectral component

Results (2): Peak Flux of the Initial LH state and the Outburst Waiting Time

15 years CGRO/BATSE and RXTE Observations of the Black hole transient GX 339-4

Yu et al. 2007, ApJ, 644, xxxx



Saturation of the nearly linear relation is expected when the Eddington limit is reached

Our Achievements (2)

- Our discoveries of two empirical relations associated with the spectral state transitions:
  - A nearly linear relation between the peak flux of the initial LH state and the outburst waiting time in the black hole transient GX 339-4
  - ☆ links the non-thermal power-law spectral component to disk mass (no model is able to explain this yet !)
  - ☆ early prediction of the peak flux of the initial LH state (possibly used to predict the occurrence of the LH-HS transition - jet physics)

This is the evidence that the mass in the accretion disk somehow affects the hard X-ray radiation. This also reveals the role of the outer disk in generating the non-thermal power-law spectral component.