Spectral States of Transient
Black Hole Binaries

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Outline

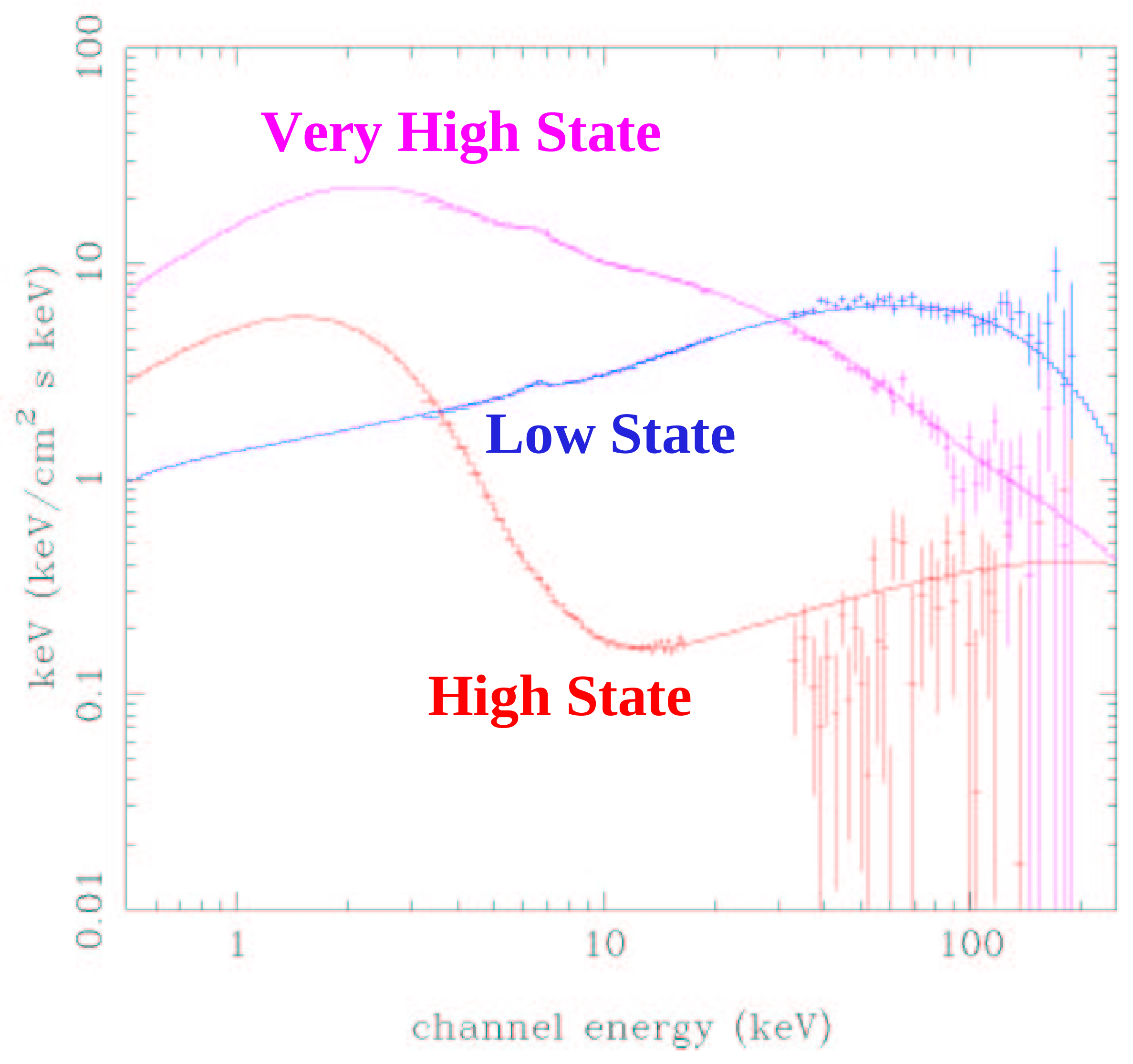
I. Properties of spectral states

II. What drives spectral state transition?

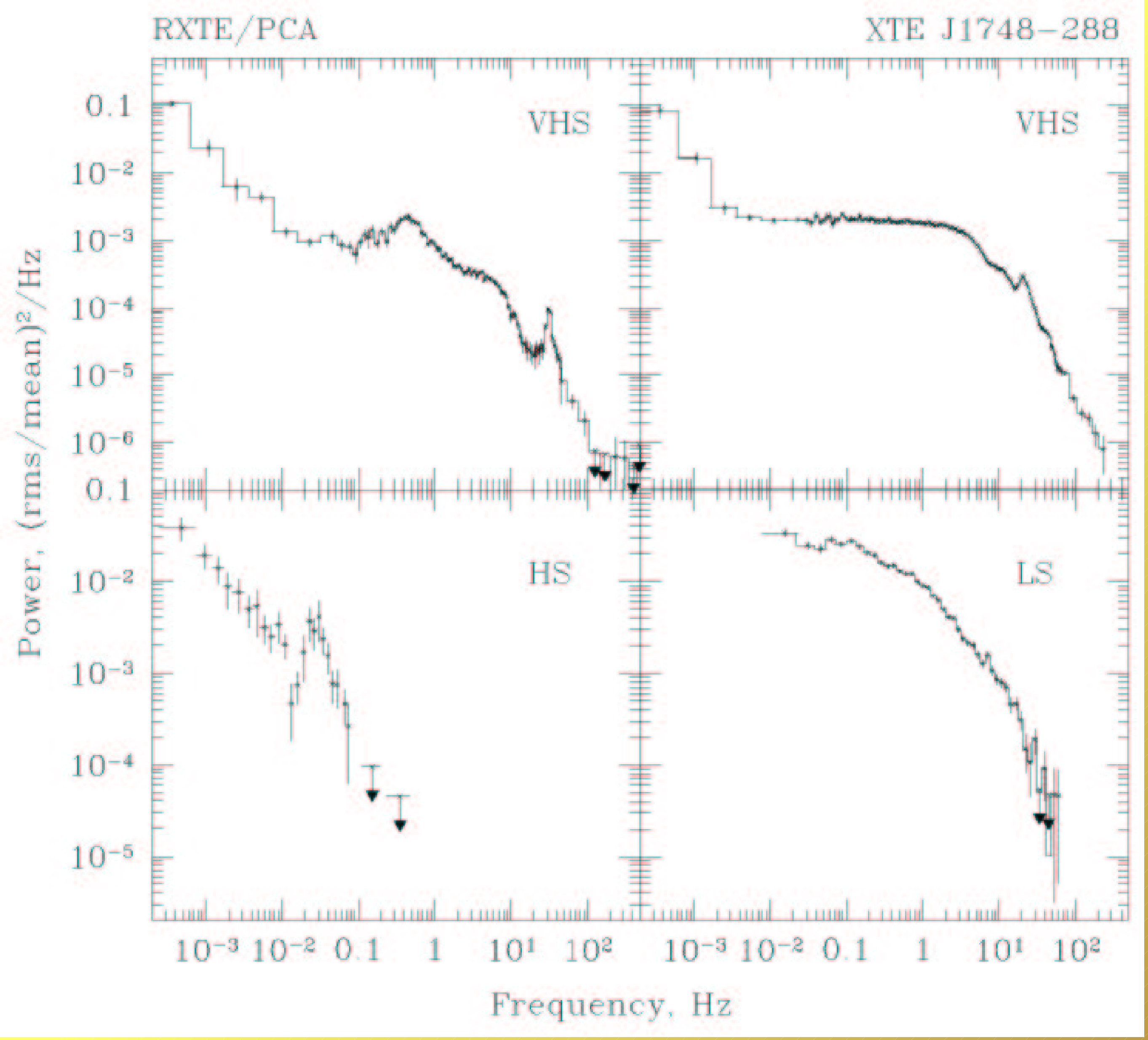
III. Constraints from observations

IV. Remaining questions

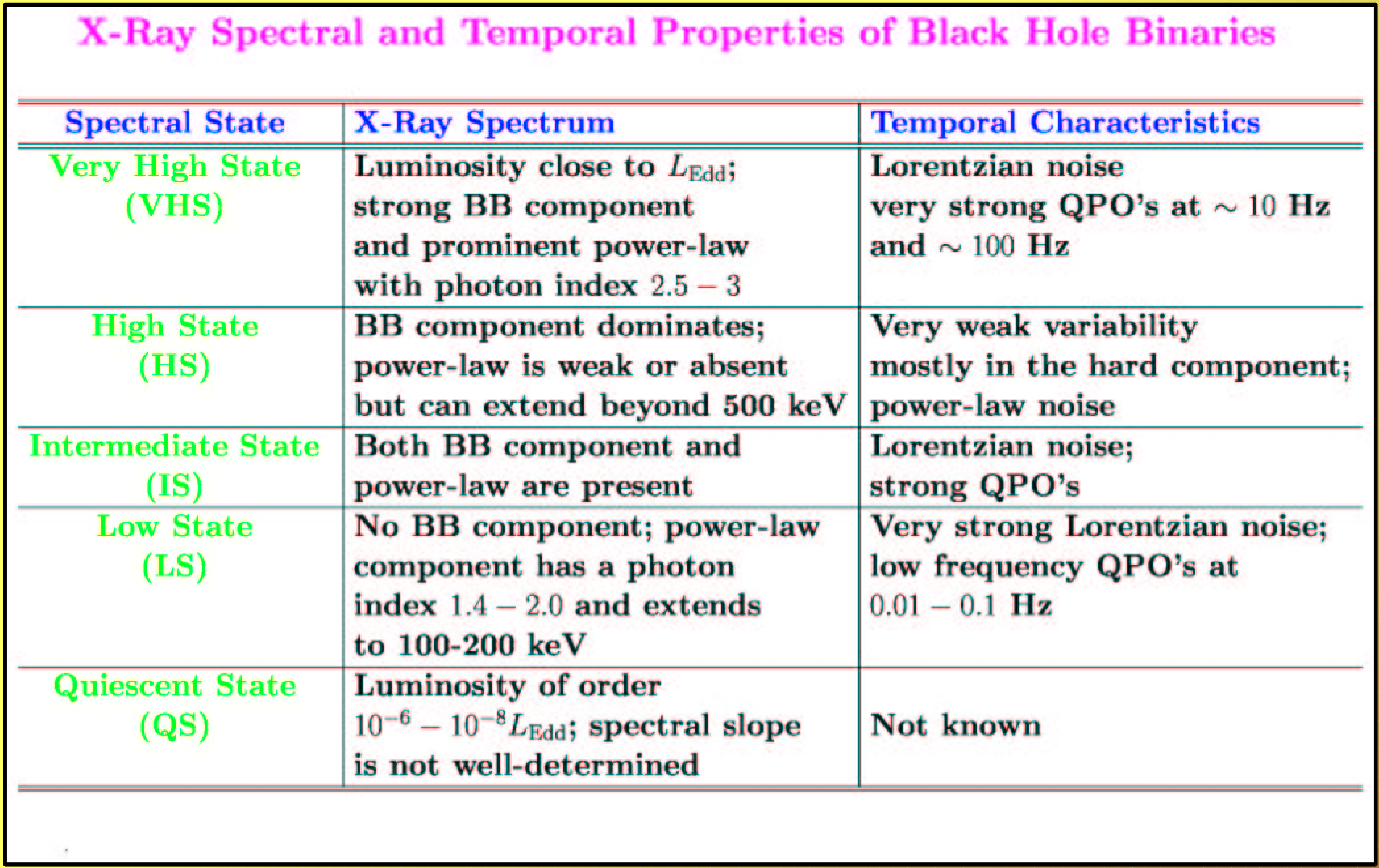
I. Properties of Spectral States



RXTE PCA and HEXTE data from XTE J1550−564, showing three main spectral states, as marked on the figure (from Done 2000).



Typical broad−band power−density spectra of XTE J1748−288 in different spectral states (from Revnivtsev, Trudolyubov & Borozdin 2000).



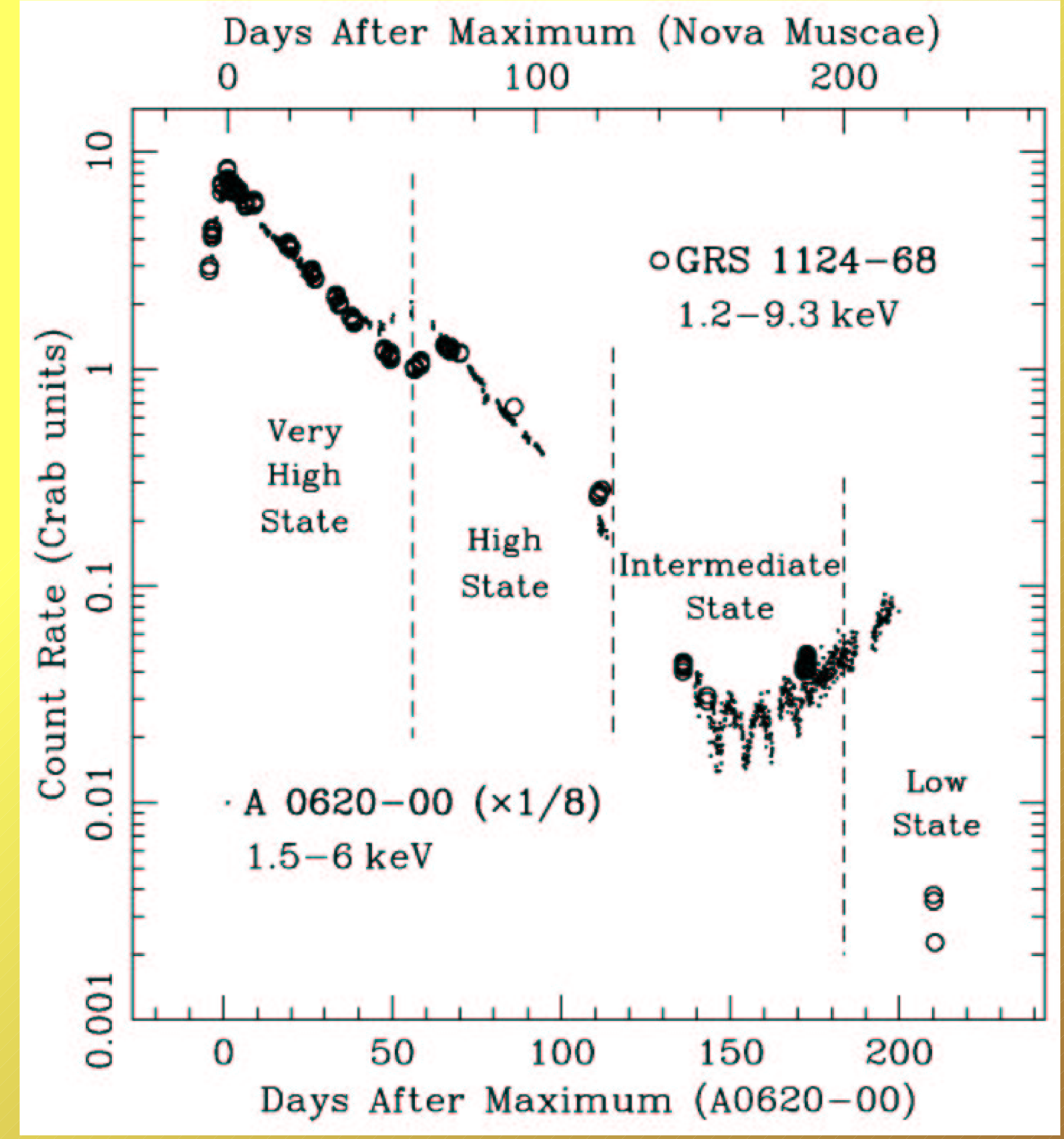
X-Ray Spectral and Temporal Properties of Black Hole Binaries

Spectral State	X-Ray Spectrum	Temporal Characteristics
Very High State (VHS)	Luminosity close to L_{Edd}; strong BB component and prominent power-law with photon index $2.5 - 3$	Lorentzian noise very strong QPO's at ~ 10 Hz and ~ 100 Hz
High State (HS)	BB component dominates; power-law is weak or absent but can extend beyond 500 keV	Very weak variability mostly in the hard component; power-law noise
Intermediate State (IS)	Both BB component and power-law are present	Lorentzian noise; strong QPO's
Low State (LS)	No BB component; power-law component has a photon index $1.4 - 2.0$ and extends to 100-200 keV	Very strong Lorentzian noise; low frequency QPO's at $0.01 - 0.1$ Hz
Quiescent State (QS)	Luminosity of order $10^{-6} - 10^{-8} L_{\mathrm{Edd}}$; spectral slope is not well-determined	Not known

II. What Drives the Spectral State Changes?

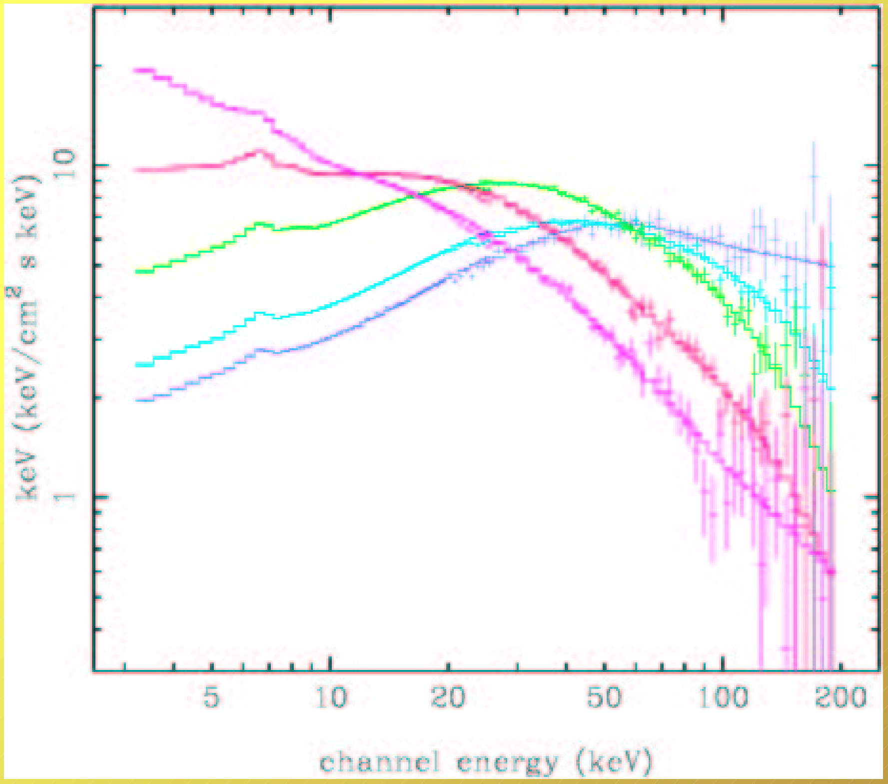
Mass Accretion Rate!

- **Most transients go through the same sequence of spectral states during their decline from outburst.**



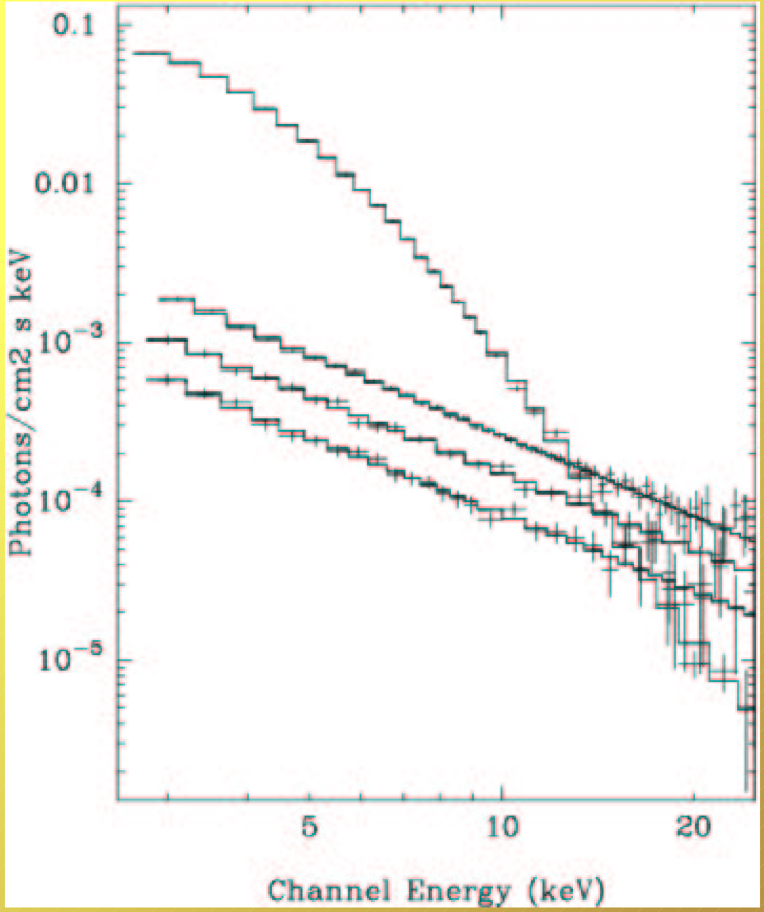
Soft X−ray lightcurves of Nova Muscae (*Ginga LAC*) and A0620-00 (*SAS-3 CSL A*), adopted from Esin et al. (2000)

- **State changes occur in roughly the same order during the rise phase of the outburst. Hard/Soft state changes were observed in A0620−00 (Esin et al. 2002) and XTE J1550−564 (Wilson & Done 2001).**



The spectral transition of XTE J1550−564 from low to very high state (from Wilson & Done 2001).

- Persistent sources with nearly constant accretion rate display only one or two spectral states (e.g. Cyg X−1, LMC X−3), and their mass accretion rate is consistent with that inferred for the transient systems.



The spectral transition of LMC X−3 from high to low state (from Boyd et al. 2000).

It is clear that the mass accretion rate plays the main role in driving the spectral state changes.

The observations of state transitions in persistent sources without dramatic changes in the mass accretion rate, argue for the existence of critical mass accretion rate values.

So what exactly happens near these critical accretion rates?

III. Models of Spectral States

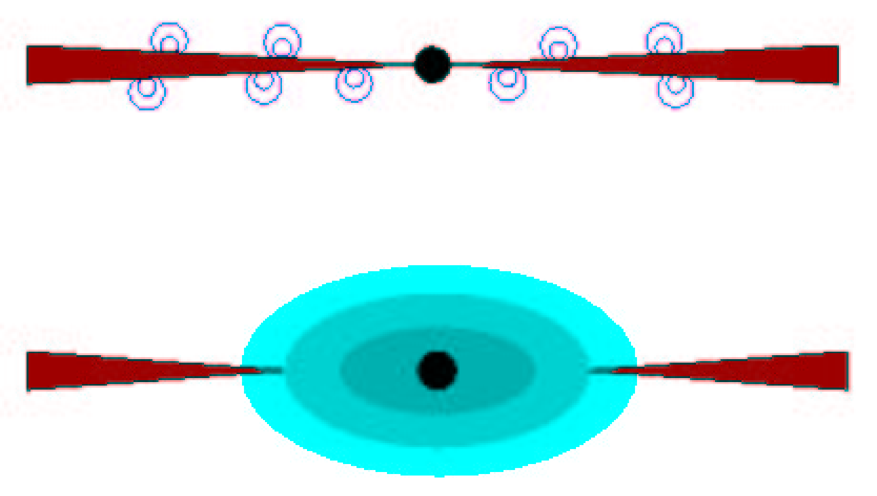
Low State

- Optical observations show signatures of a standard cool accretion disk.

- SS disk cannot produce high energy power−law emission, so hot (T $\simeq 10^9 \mathrm{K} - 10^{10} \mathrm{K}$) plasma must be present.

- Correlation between radio and hard X−ray emission suggests the presence of non−thermal particles (maybe an outflow).

Possible Geometry



- Disk + Corona
- Disk + Hot Flow
- Jets?

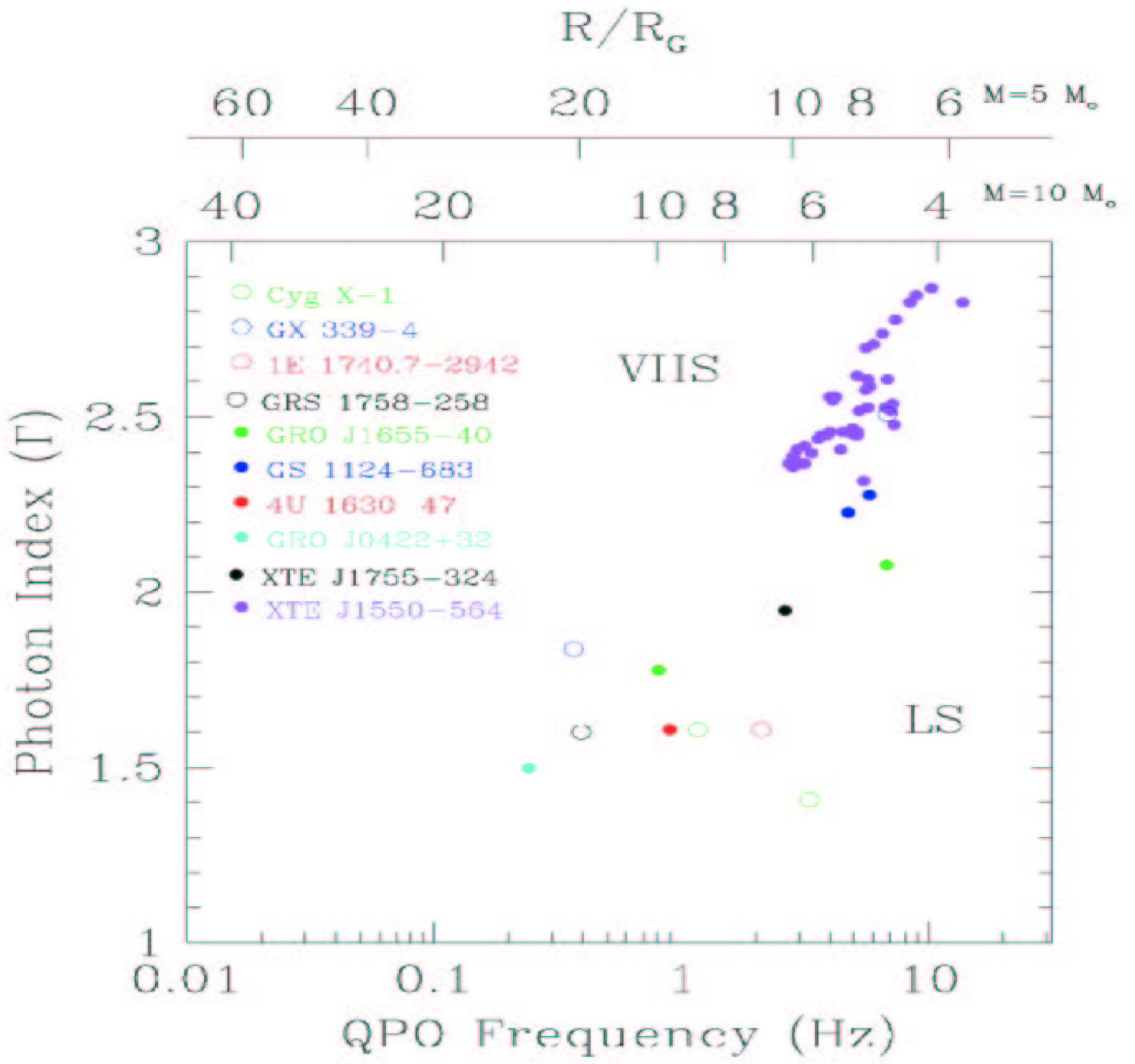
Observational Diagnostics

<u>Main Question:</u> How far in does the standard disk extend?

1. Modeling of reflection and Fe Kα line
2. Interpretation of QPOs
3. Modeling the disk emission

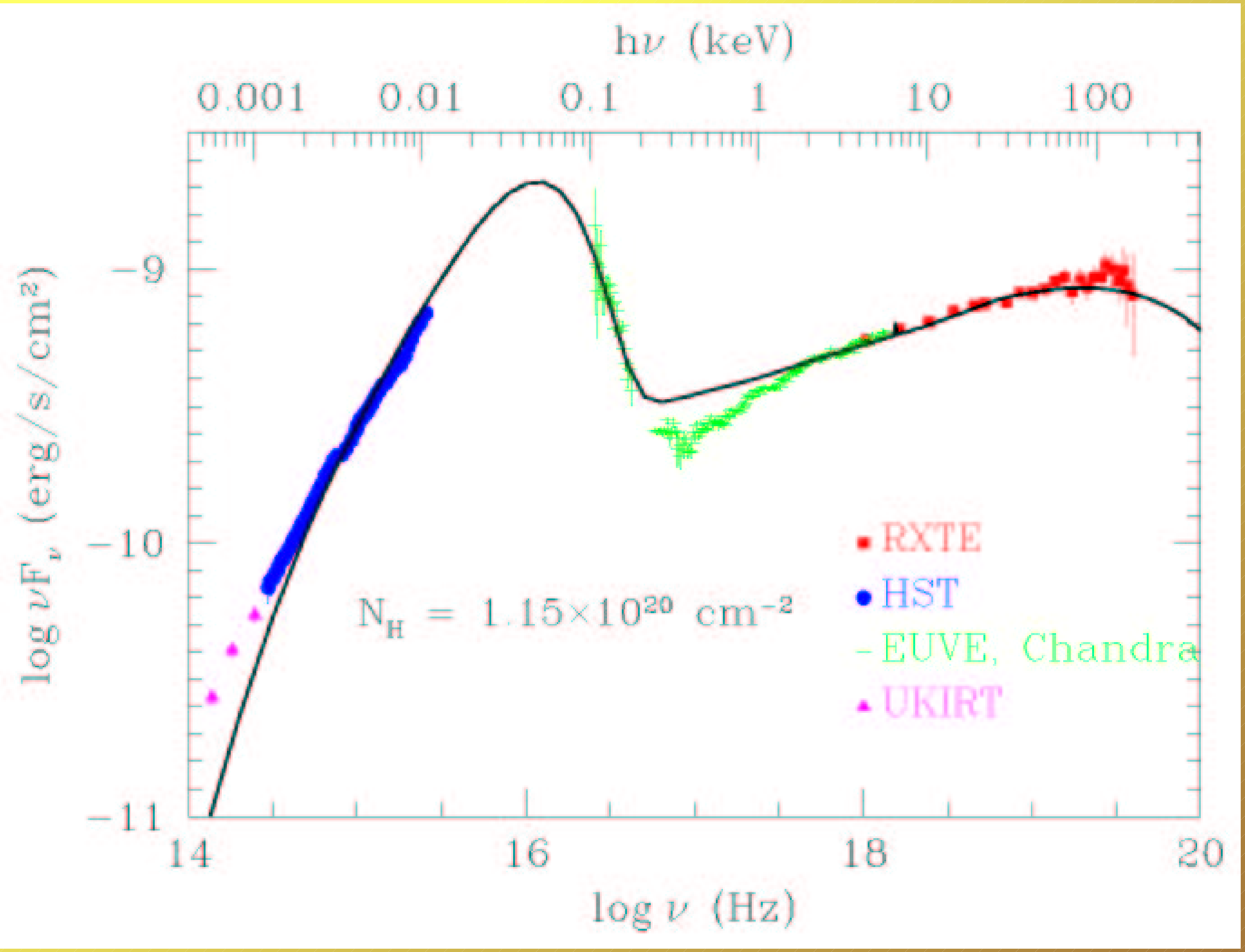
QPO Frequency vs. Hardness

Correlation between the QPO frequency and the spectral index of the power−law emission component (from Di Matteo & Psaltis 1999)



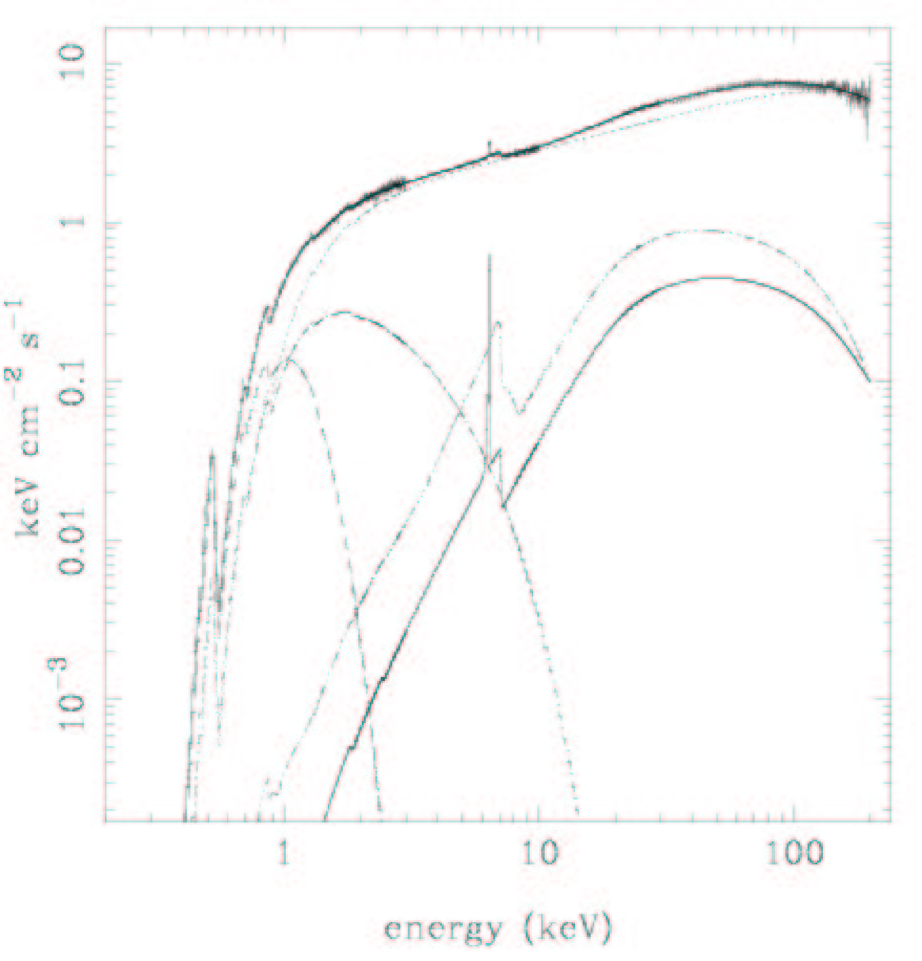
Broadband Observations of XTE J1118+480

Broadband spectrum of XTE J1118+480 at the peak of its outburst (from Esin et al. 2000). The temperature of the blackbody emission component is below ~30eV, so R_{in} ~$60R_s$



BeppoSAX Observations of Cyg X-1

Unfolded spectrum of Cyg X-1 in the low spectral state (Di Salvo et al. 2001). An acceptable fit requires the presence of a thin disk emission component with a temperature of order 130eV. The inner disk radius is consistent with $35R_s - 3R_s$.



Conclusions from Observations

1. Modeling of reflection and Fe Kα line

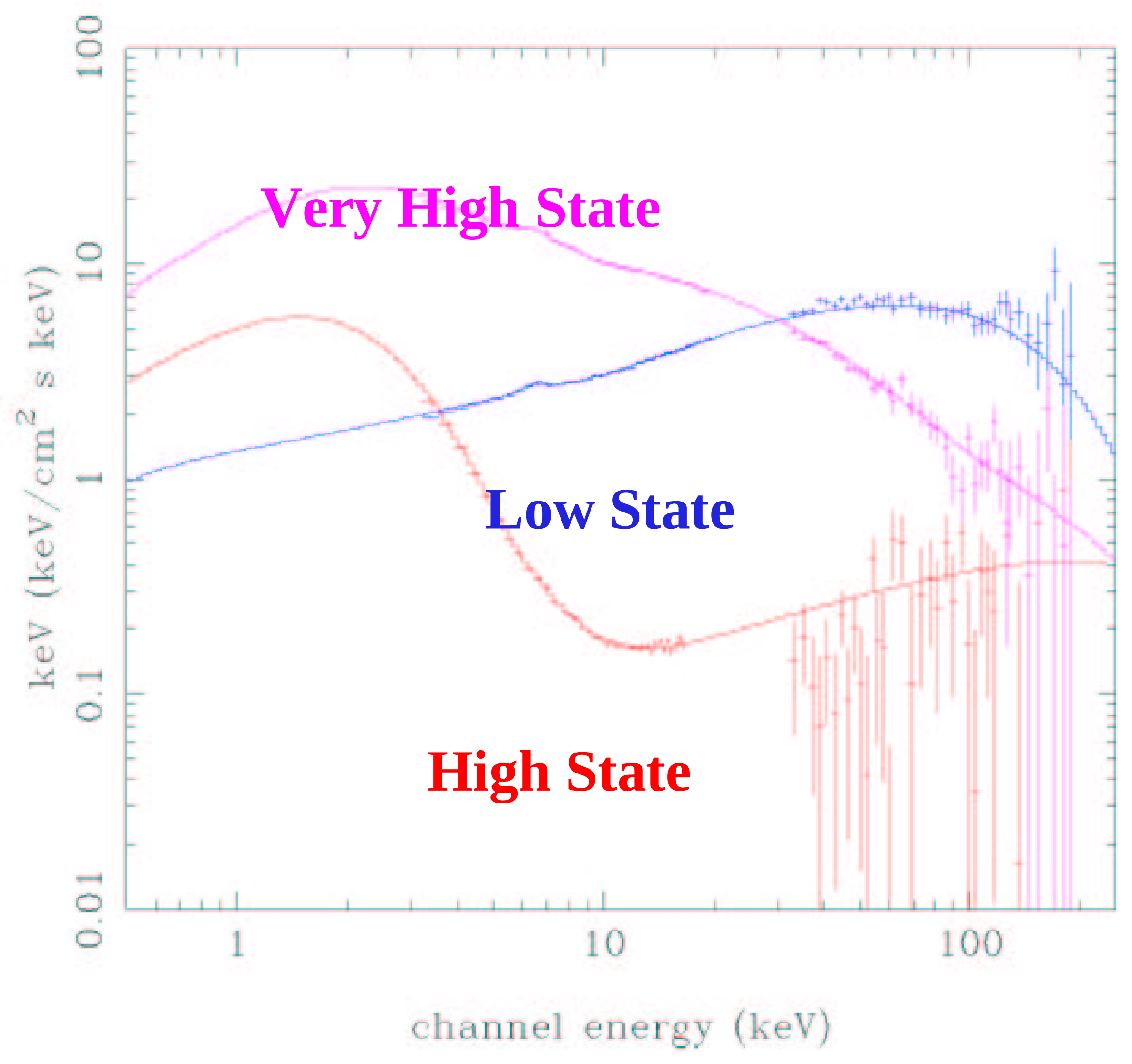
Reflection is suppressed in the low state, which could indicate a truncated OR ionized disk.

2. Interpretation of QPOs and breaks in the power−density spectra.

No real physical model exists, but scaling arguments point to an inner disk radius a few times larger than the radius of the ISCO.

3. Modeling the disk emission

From the two sources observed, Cyg X−1 is consistent with the corona model and XTE J1118+480 is not. Which one is atypical?



RXTE PCA and HEXTE data from XTE J1550−564, showing three main spectral states, as marked on the figure (from Done 2000).

High State

- Cool ‘‘disk" signature is clearly present in the X−ray spectrum, with the characteristic temperature of ~0.3keV.

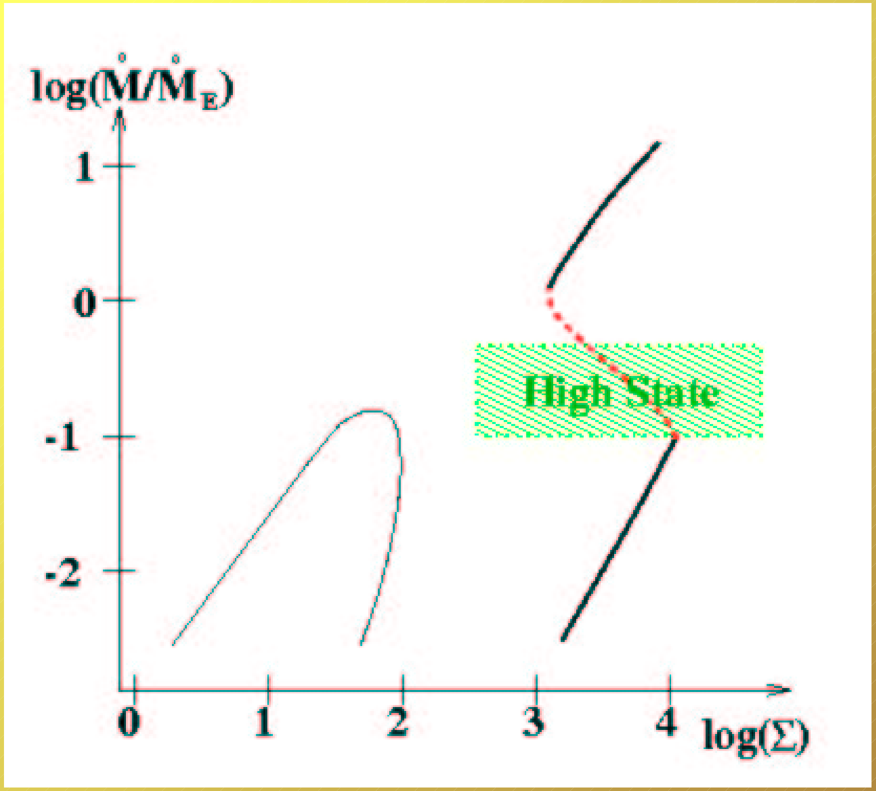
- High energy power−law tail extends in many case beyond 500 keV, strongly suggesting emission from non-thermal particles.

- A standard α–disk model cannot fit some high state spectra. Need extra thermal Comptonization or blackbody component with temperature around ~5keV (e.g. Zycki, Done & Smith, 2001).

High State

BUT:

The high state is associated with a range of accretion rates for which SS disk is both viscously and thermally unstable!



Can numerical simulations clarify the situation (e.g. Turner et al.)?

Thermal Instability: Avoided if viscosity is proportional to P_{gas} rather than P_{tot}.

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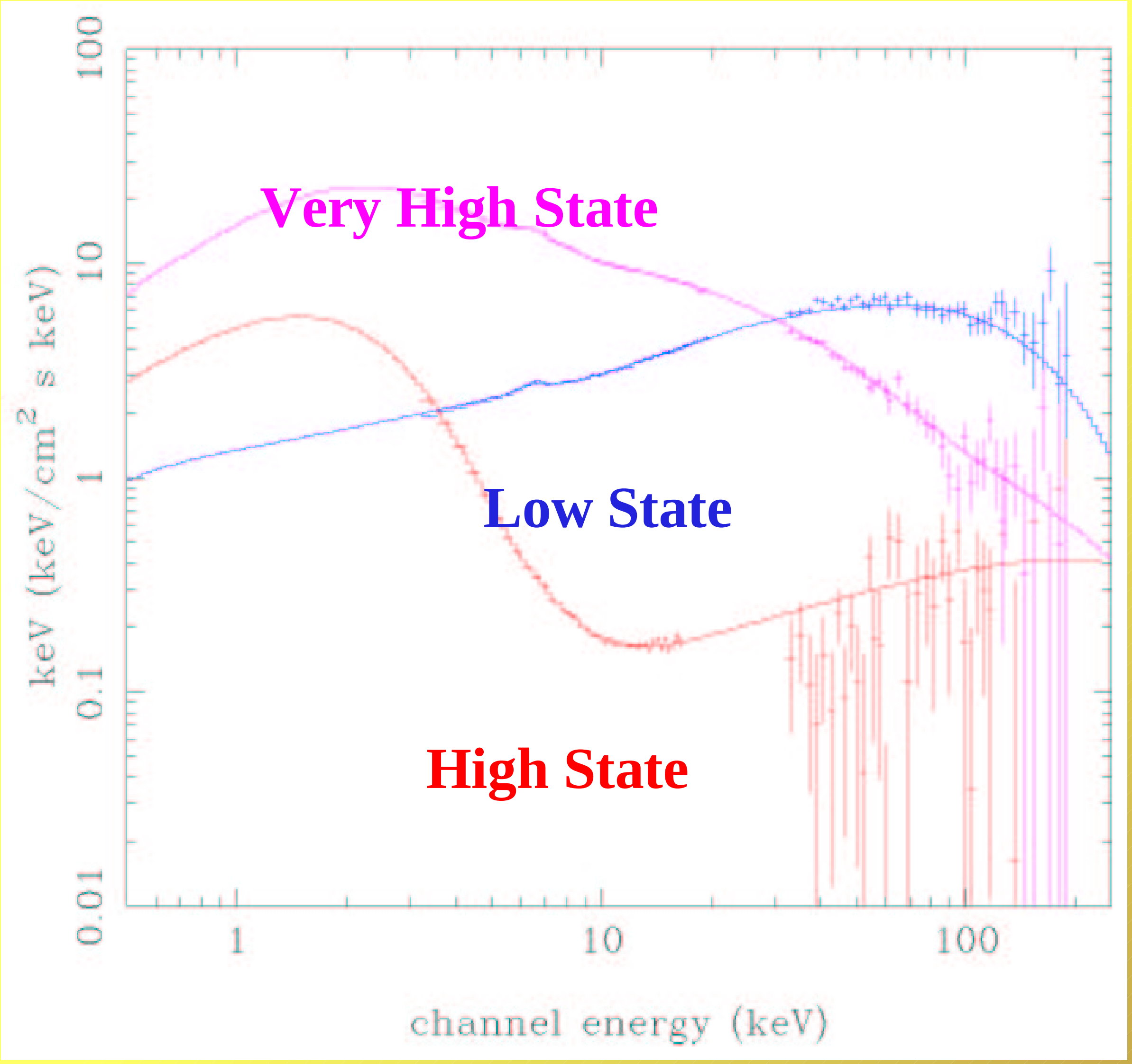
Viscous Instability: Can clumping of the gas seen in simulations alter the disk structure enough to avoid it?



RXTE PCA and HEXTE data from XTE J1550−564, showing three main spectral states, as marked on the figure (from Done 2000).

Very High State

- Cool "blackbody" component and strong non−thermal power−law tail.
- Extra thermal Comptonization component is necessary, suggesting an additional "warm" layer on top of the cold disk (e.g. Kubota et al. 2001; Zycki et al. 2001).
- Strong radio emission is present in all (?) systems, suggesting that jets may play an important role.

Very High State

Total emission can approach Eddington limit, so what is the accretion flow structure we expect?

Slim disk (Katz, Begelman, Abramowicz, Beloborodov), gives dynamics but no spectral models.

What about reflection in soft spectral states?

The complicated continuum shape make it difficult to constrain X−ray reprocessing features.

- **Zycki, Done & Smith (2001) claim a detection of smeared reflection components from highly ionized plasma in GS1124−68 and GRO J1655−40.**
- **Frontera et al. (2001) also report a smeared Fe line and reflection component (with large covering fraction) detection in the High State of Cyg X−1.**
- **Miller et al. (2002) claim a detection of a very broad Fe line in XTE J1650−500.**

IV. Remaining Questions

Low State

- How often is the disk truncated? Are persistent systems different from transients? Are some transients different from others?
- If the disk is not truncated, what mechanism is driving low/high state transitions?
- Why does the low/high state transition occur at different mass accretion rates during rise and decline outburst phases?
- Do jets play a role in forming the high energy spectrum? In all systems or just a subset? How does the presence of jets relate to the position of the inner disk radius? What about variability?

IV. Remaining Questions

High State

- **Why does the disk appear to be stable?**
- **What is driving the transition to the Very High State?**
- **In the context of the corona model, why is the cutoff energy of the power−law component so much larger than in the Low State?**
- **What effect does energy extraction from within ISCO have on the disk spectrum?**
- **Is this state truly absent during the rise phase, and if so, why?**
- **Why is radio emission quenched in this state?**

IV. Remaining Questions

Very High State

- **Need an physical model describing the emission from the near− or super−Eddington accretion flows.**
- **If the disks become very clumpy (as suggested by numerical simulations) what effect does it have on the spectra and timing properties?**
- **Why are the variability properties of this state similar to those of the Intermediate State?**
- **What contribution do jets make to X−ray spectrum?**