X-ray Outbursts from Black Hole Binaries

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Outline

- Status Report on Black Hole Binaries
- X-ray States of Accreting Black Holes
  - Modified State Definitions
  - Outline Applications for General Relativity
  - X-ray States ←→ the Unified Jet Model
- Details on High-Frequency QPOs

Science Goals for BHBs in Outburst

- Locate stellar size black holes

  100% from X-ray astronomy

- Measure Black Hole Properties

  mass (M_x) and spin ($a_* = cJ / GM_x^2$) ; event horizon ?

- Understand Accretion Physics

  different physical structures in each state

  primary variables: M_x dM/dt ; outflow; B geometry; plasma β ?

Recent Reviews and global studies:

McClintock & Remillard 2003; Done & Gierlinski 2003

Fender 2003; Fender & Belloni 2004; Zdziarski & Gierlinski 2004

Inventory: Galactic Black Holes

Dynamical BHBs: $P_{orb} K^3 / 2\pi G = M_x \sin^3(i) / (1 + M_c/M_x)^2$

+ estimates for M_c & sin i

→ $M_x = 4 - 18\ M_o$ (> neutron star limit)

BH Candidates: no pulsations + no X-ray bursts + properties of BHBs

	Milky Way	LMC
BHBs	18	2
BH Candidates	21	0
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total	39	2

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+ estimates for M_c & $\sin i$

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BH Candidates: no pulsations + no X-ray bursts + properties of BHBs

	Milky Way	LMC	RXTE Archive
BHBs	18	2	3200 obs; 11 Msec
BH Candidates	21	0	1300 obs; 4 Msec
----------------------------			
total	39	2	
X-ray persistent	**2**	**2**	
Transients	**37**	**0**	

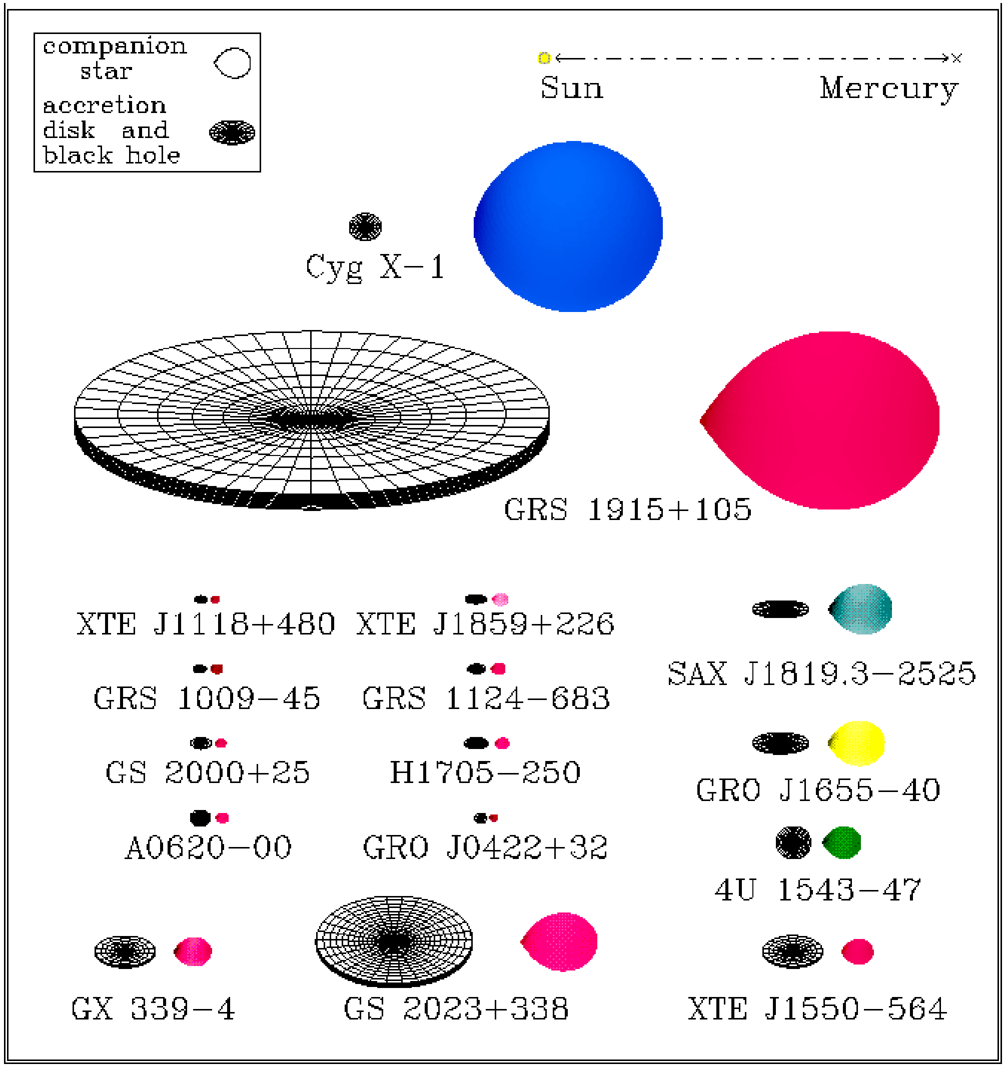
Black Holes in the Milky Way

18 Black-Hole Binaries in the Milky Way

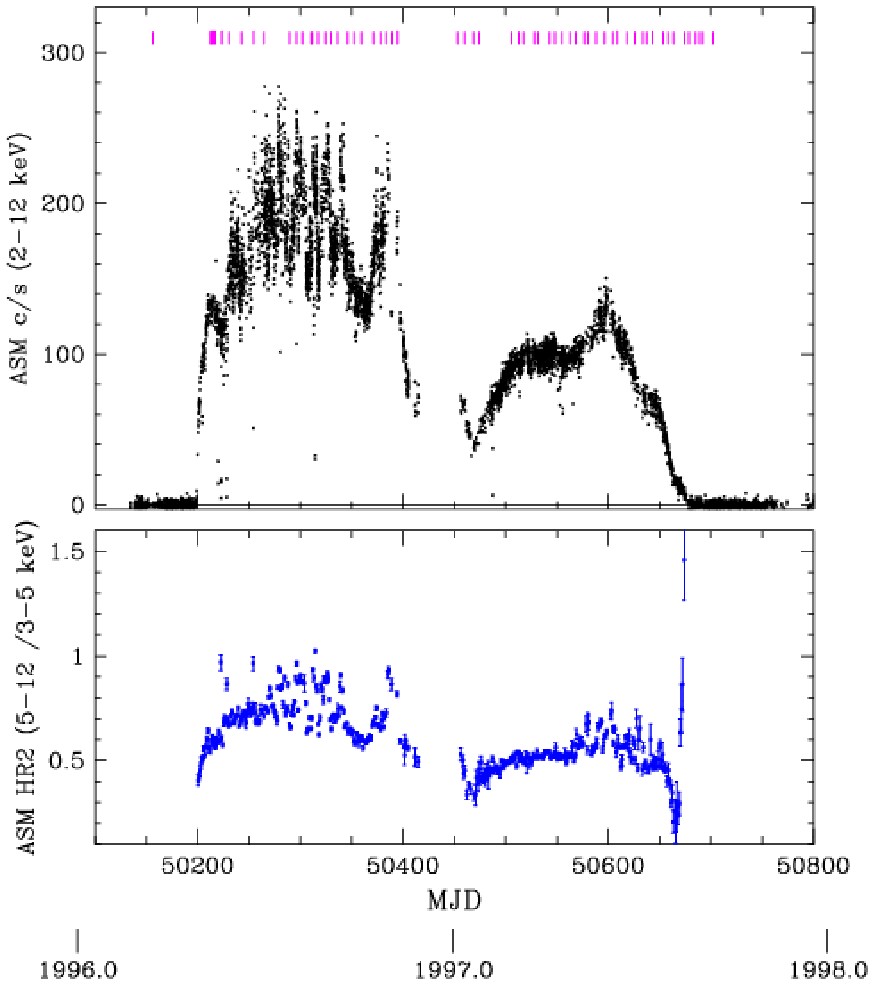
16 fairly well constrained →

(Jerry Orosz)

Scaled, tilted, and colored for surface temp. of companion star.



BH X-ray Transients



GRO J1655-40

Mx = 6.3 ± 0.5 M_o

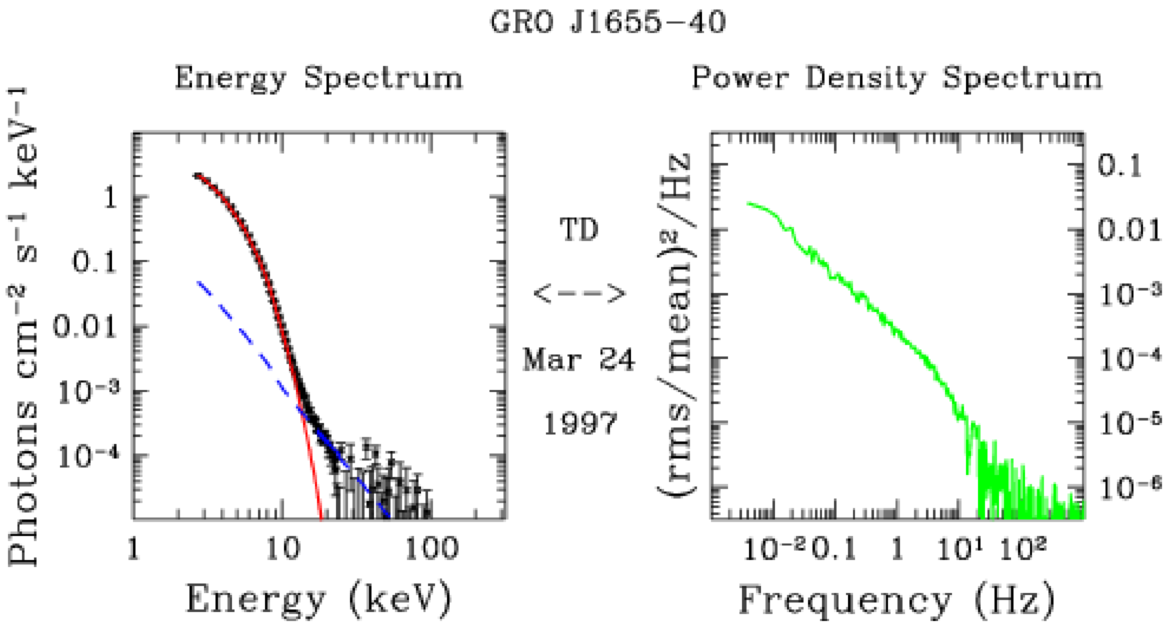
GRO outburst: 1994-95 + jets

RXTE outburst 1996-97, basically radio-quiet

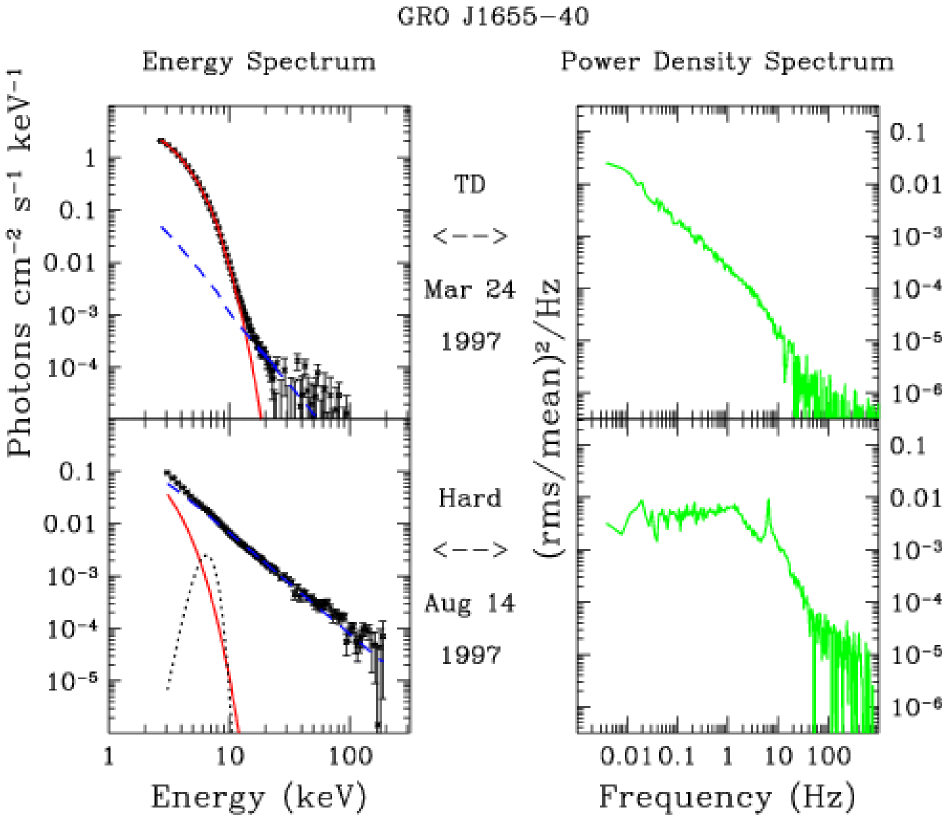
Active Accretion States of BHBs

1. Thermal State
f_{pow} < 20%, no QPOs,

inner accretion disk
classical physics: $T(r) \sim r^{-3/4} \rightarrow L(r) \sim r^{-2}$



Active Accretion States of BHBs



2. Hard State

f_{pow} > 80%, $\Gamma \sim 1.5\text{-}2.1$

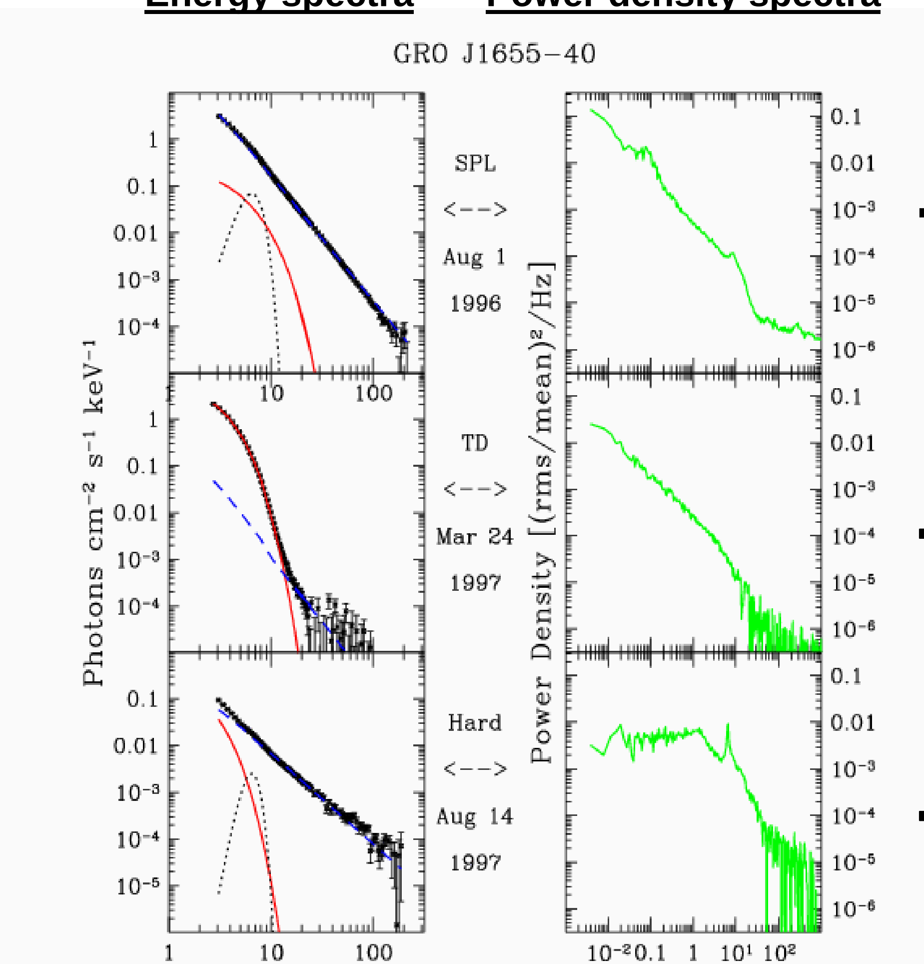
rms (PDS: 0.1-10 Hz) > 10%

steady jet

(inverse Compton or synchrotron)

Active Accretion States of BHBs

Energy spectra **Power density spectra**



Energy (keV) Frequency (Hz)

State **critical physical element**

➔ **3. steep power law** **compact corona**

$\Gamma \sim$ 2.4-3.0, *rms* < 0.15

f_{pow}> 80% or f_{pow}> 20% + QPOs

➔ **thermal** **accretion disk**

f_{pow} < 20%, no QPOs,

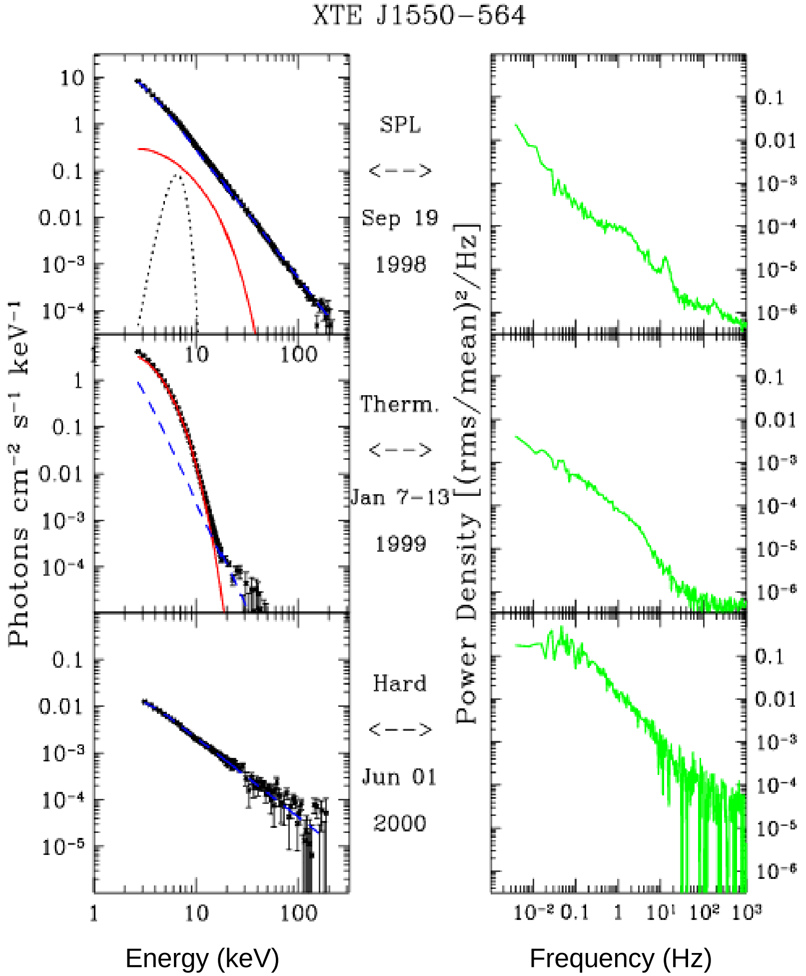
➔ **hard state** **steady jet**

f_{pow} > 80%, $\Gamma \sim$ 1.5-2.1

rms (PDS) > 10%

Physical Models for BHB States

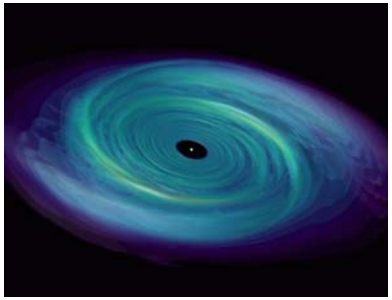
Energy spectra **Power density spectra**



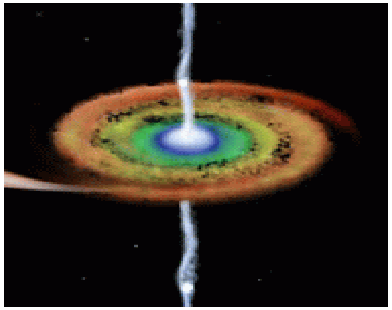
State — **physical picture**

➔ steep power law — Disk + ??

➔ thermal

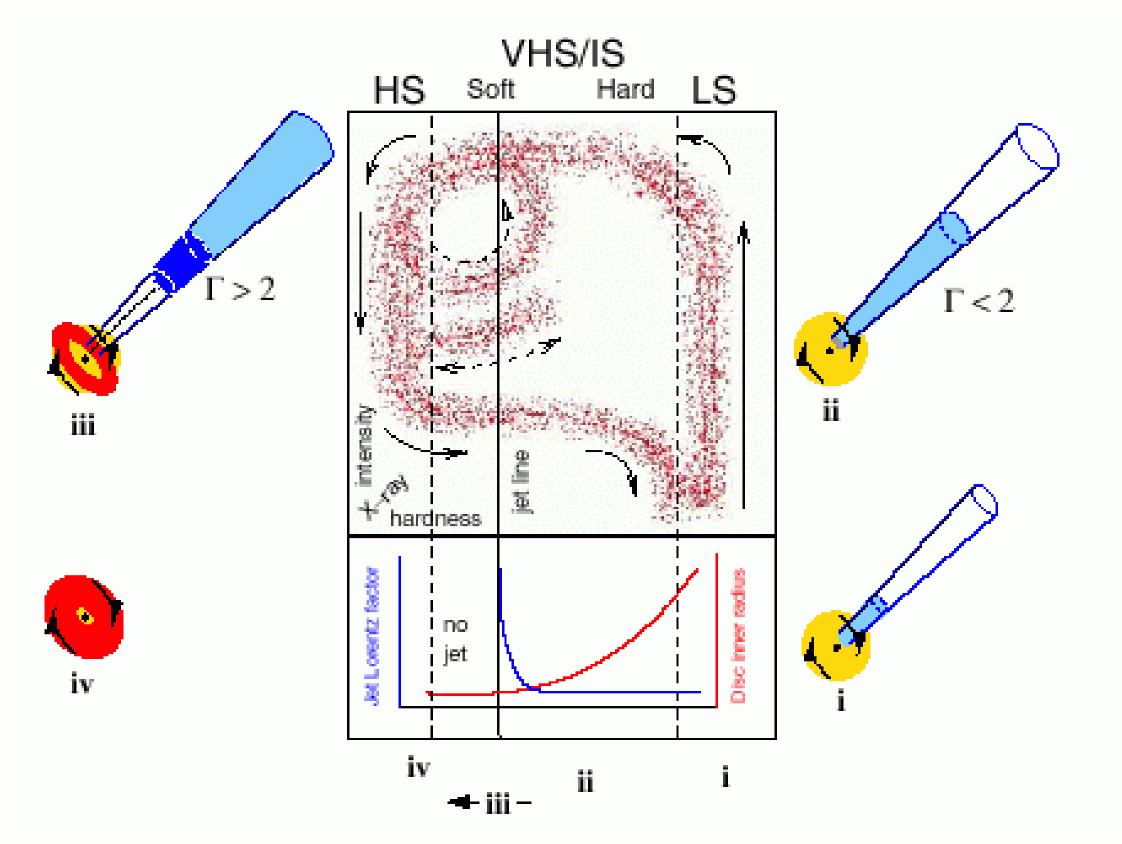


➔ hard state



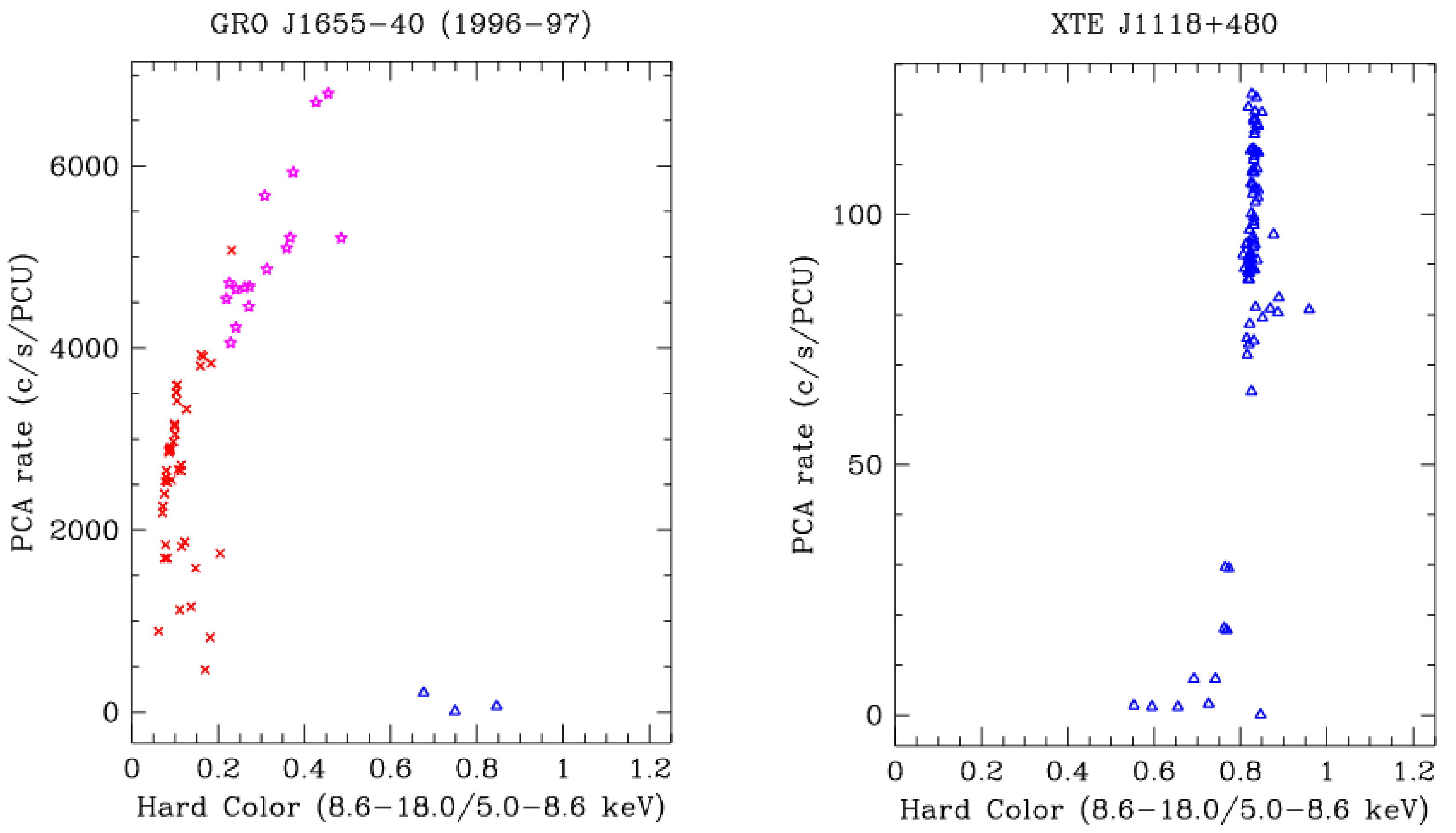
Unified Model for Jets in BH Binaries

Fender, Belloni, & Gallo 2004



Jet Conditions & X-ray States

Δ: HARD STATE
O: INT: hard <-> SPL
* : STEEP POWER LAW
O: INT: thermal <-> SPL
X: THERMAL



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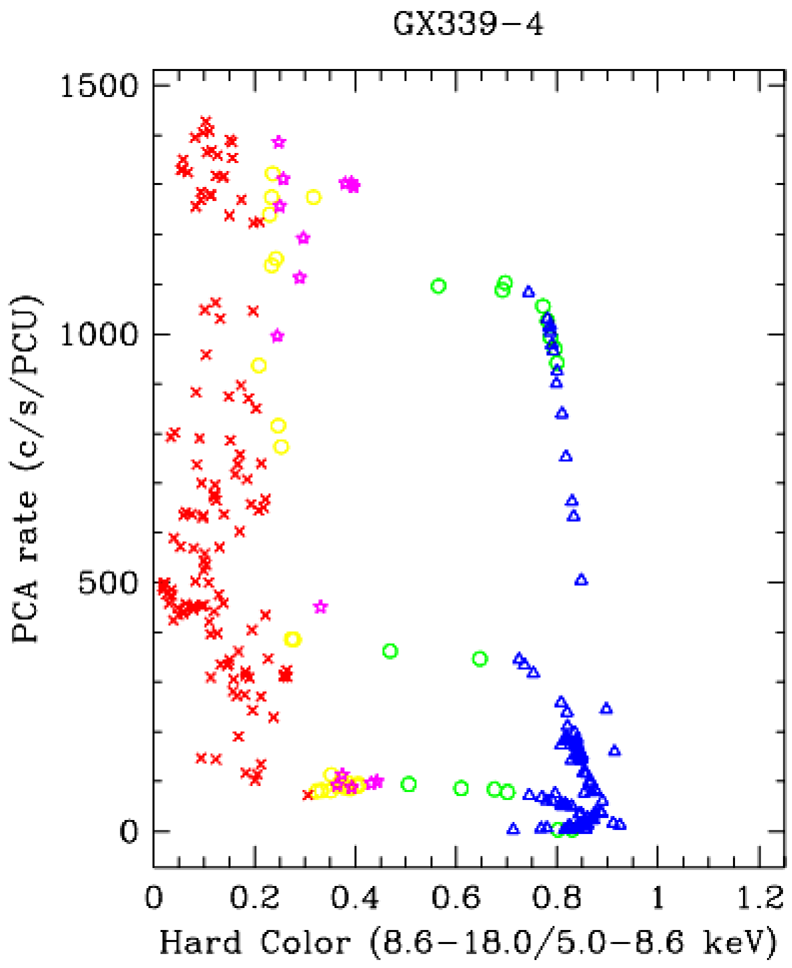

Other multi-state BH transients:

GRS1915+105
4U 1630-47
XTE J1550-564
H1743-322

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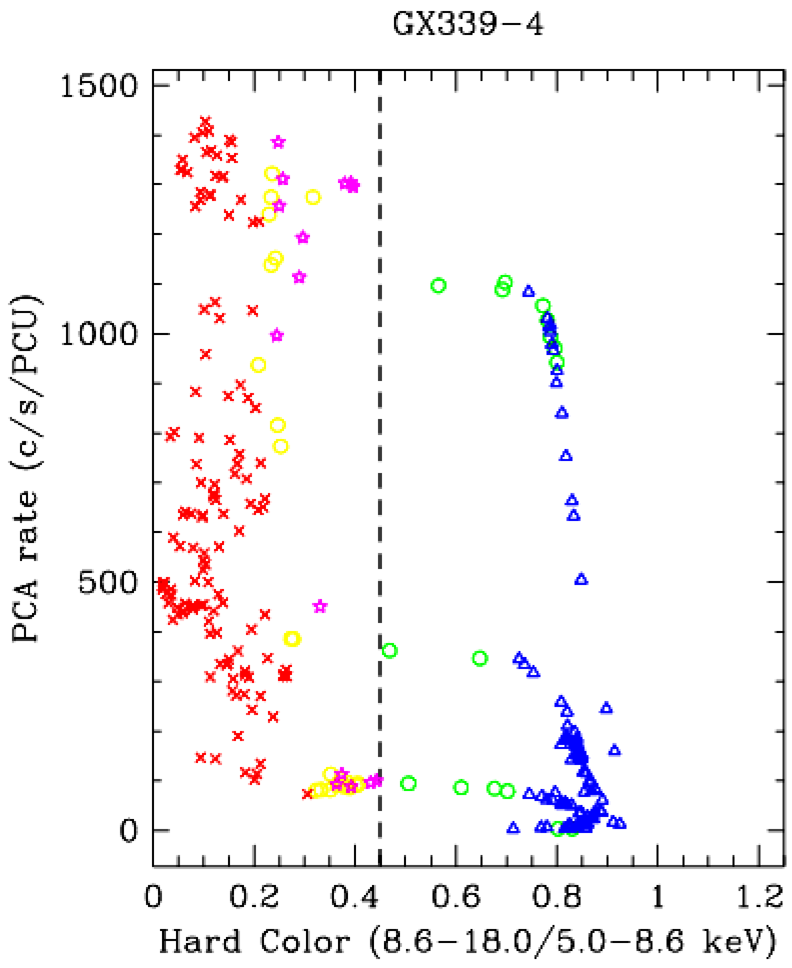
Jet Conditions & X-ray States



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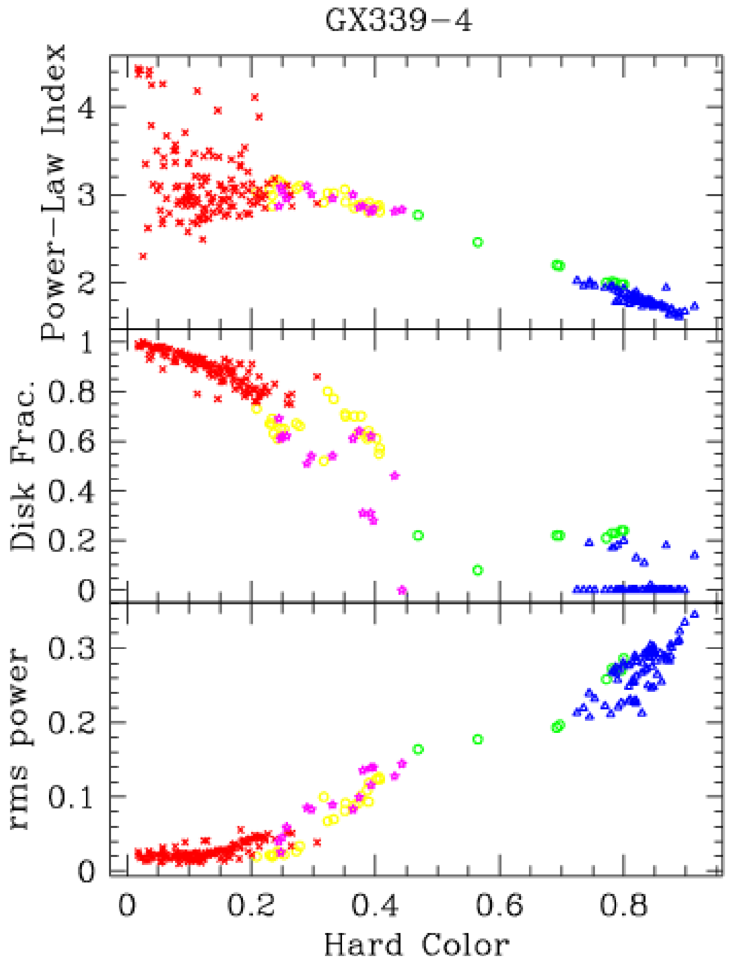
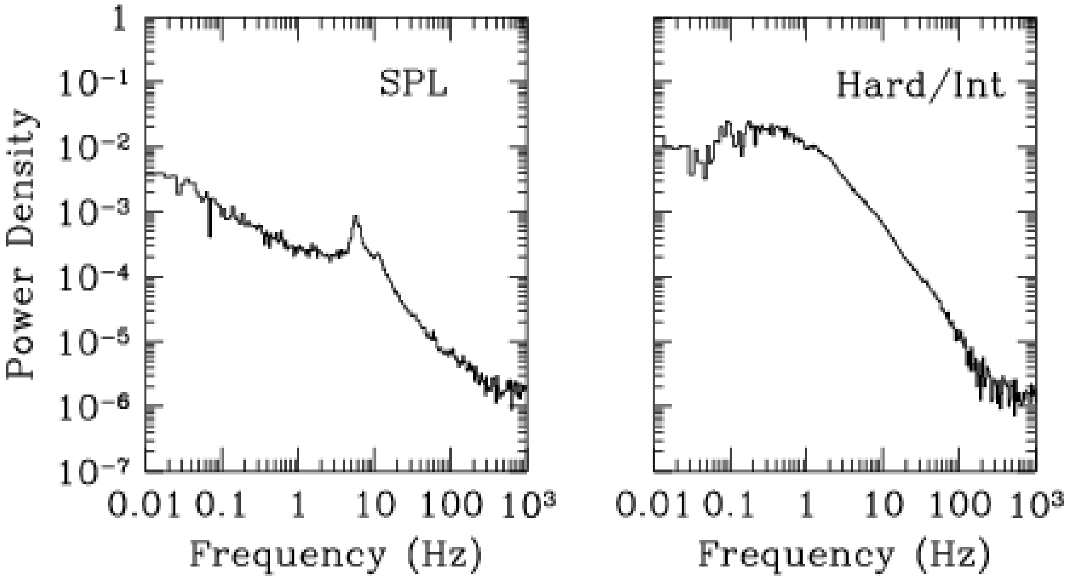
Jet Line vs. X-ray States

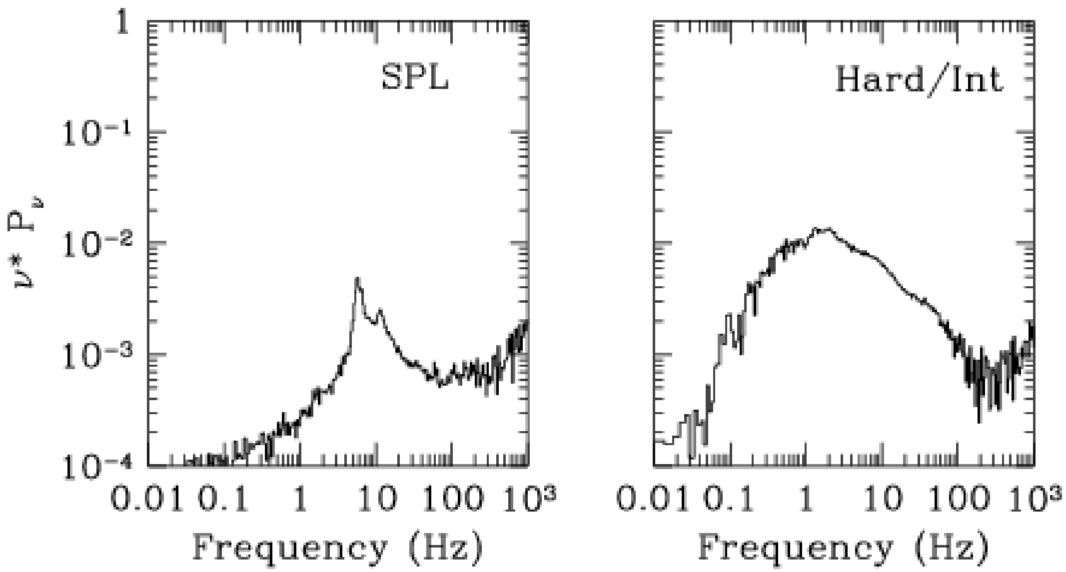


Temporal Signatures of X-ray States



Temporal Signatures of X-ray States

QPOs (0.1-20 Hz)
Common in SPL state



broad power feature near 1 Hz
signature of a steady jet?

Applications for Relativistic Astrophysics

steep power law

High Frequency QPOs — **resonances in strong gravity?**

$\nu_{qpo} = f(M_x, a_*, r_{res})$

Near-Eddington Luminosity — **MHD disk models in GR ?**

thermal state

Thermal Spectrum → N_{DBB}, T_{col} — **GR disk models → measure R_{in} in km ?**

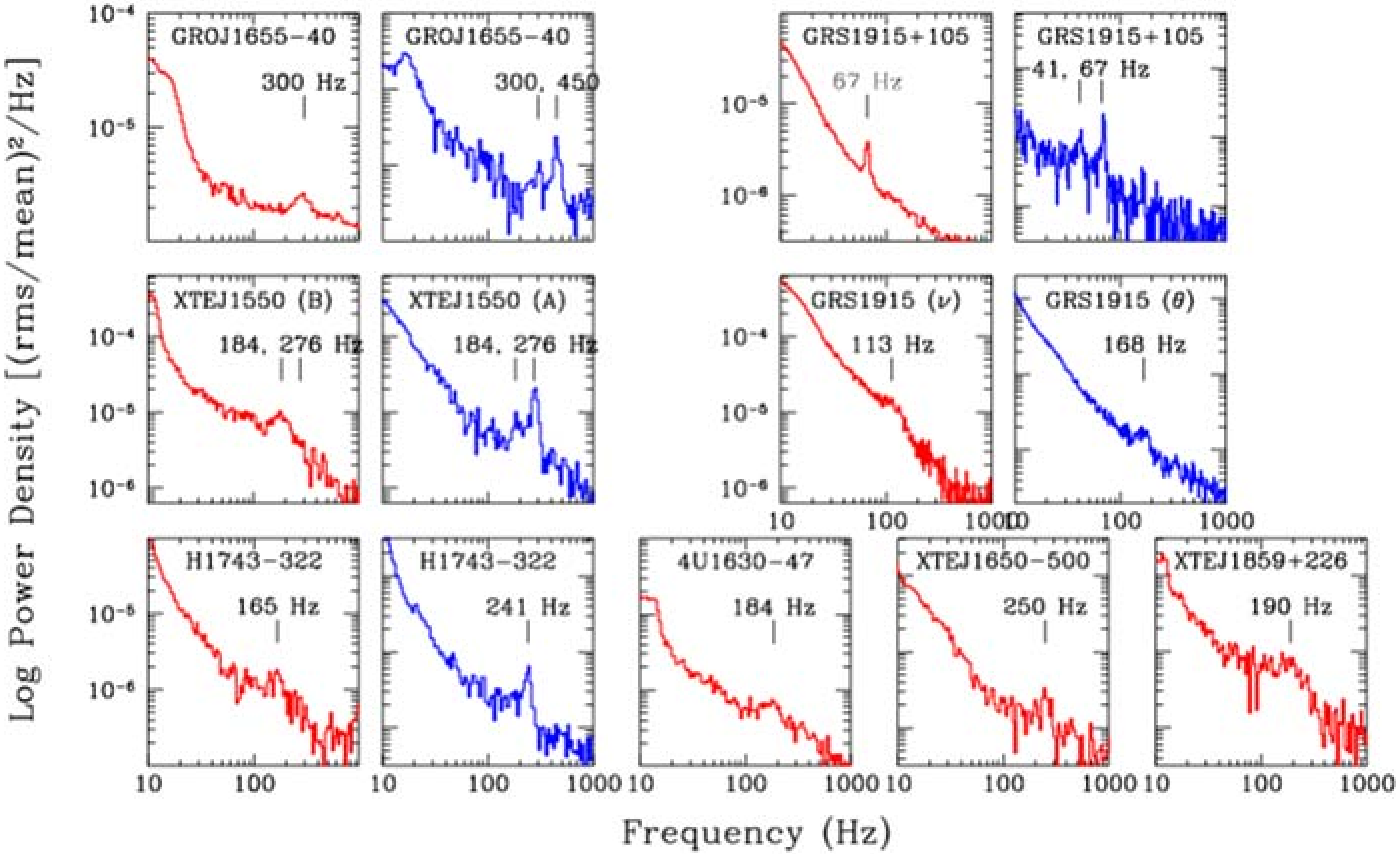
R_{in},= $(N_{DBB} \cos i)^{0.5}\, d^{-1}\, f_{atm}$ f(GR) — **$R_{in}(M_x$, a*) → constrain spin?**

hard state

steady jet / hard power law — **jet properties; jet mechanisms?**

unstable state transitions — **cause of impulsive jets?**

High Frequency QPOs in BHBs & Candidates



High Frequency QPOs

source	HFQPO ν (Hz)
GRO J1655-40	300, 450
XTE J1550-564	184, 276
GRS 1915+105	41, 67, 113, 168
XTE J1859+226	190
4U1630-472	184 + broad features (Klein-Wolt et al. 2003)
XTE J1650-500	250
H1743-322	165, 241
(recent case:	Homan et al. 2004; Remillard et al. 2004)

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4 HFQPO pairs with frequencies in 3:2 ratio

HFQPOs and General Relativity

- **Resonance** in the Inner Disk (Abramowicz & Kluzniak 2001)
  - Turbulence ‘blobs’ and arcs linger at r_{res} ?
  - Resonance related to GR frequencies for 3 coordinates $\{r, \theta, \phi\}$
    → e.g. ν_r, ν_ϕ or ν_r, ν_θ resonance
  - Observers see coordinate frequencies or beats
    … feasible: ray tracing study by Schnittman & Bertschinger 2003
- **Diskoseismology** (Wagoner 1999; Kato 2001)
  - adiabatic perturbation g-modes → ν_o, $4.1\nu_o$
  - ? Add complexities {thick disk, model for SPL, nonlinear effects}
- **Other Models** (e,g. accretion torrus, Rezzolla et al. 2003)

GR Coordinate Frequencies

$$\nu_{r,\,\theta,\,\phi} = f\,(\,M_x,\, a_*,\, r) \quad (r \text{ in units } GM_x/c^2)$$

$$\nu_\phi = c^3/GM_x\,[\,2\pi\, r^{\,3/2}\,(1+ a_*\, r^{\,-3/2})\,]^{-1}$$

$$\nu_r = |\nu_\phi|\,(1 - 6r^{\,-1} + 8a_*\, r^{\,-3/2} - 3a_*^2\, r^{\,-2})^{1/2}$$

$$\nu_\theta = |\nu_\phi|\,(1 - 4a_*\, r^{\,-3/2} + 3a_*^2\, r^{\,-2})^{1/2}$$

see Merloni et al. 1999

Investigation for neutron star QPOs by Stella et al. 1999

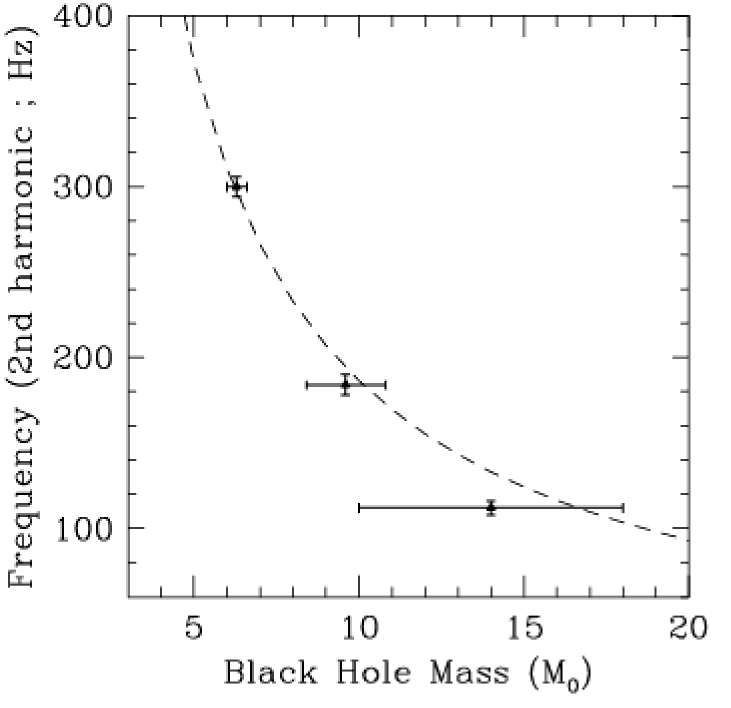
QPO Pairs vs. BH Mass

GROJ1655, XTEJ1550, GRS1915

ν_{qpo} at $2\nu_o$: ν_o = 931 Hz / M_x

- Same QPO mech. And same a_*
  - a_* ~ 0.3-0.4 if QPOs are ν_ϕ and $\nu_\phi - \nu_r$
  - Compare subclasses

while model efforts continue.



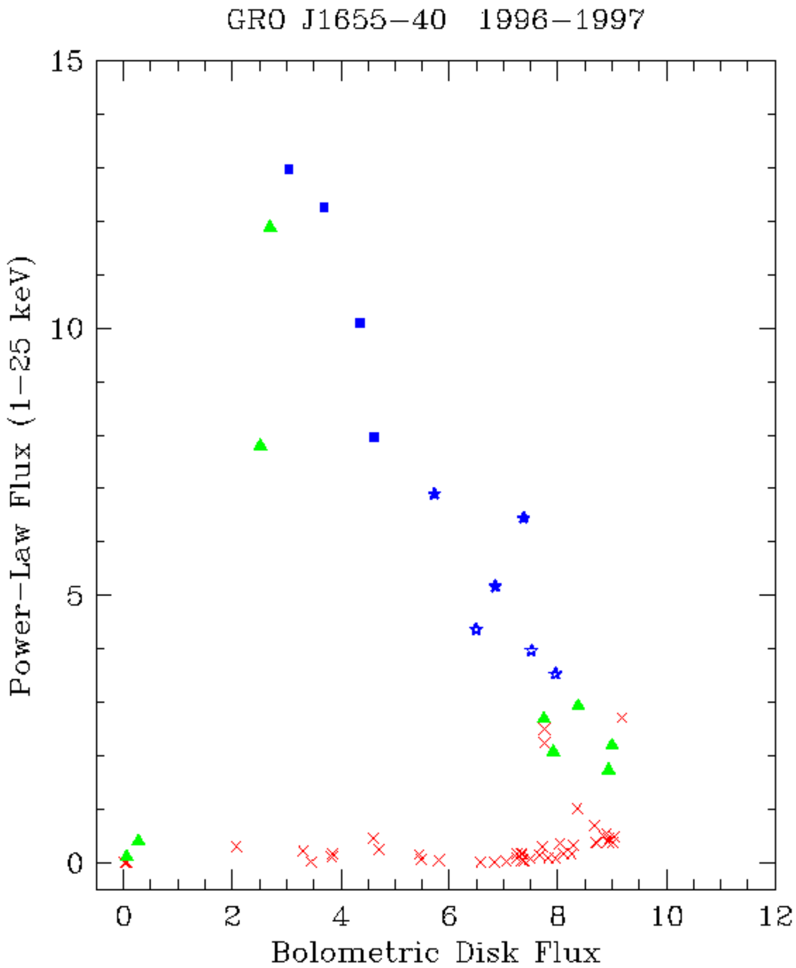
Combining X-ray Timing & Spectroscopy

GRO J1655-40

x: thermal (no QPOs)

Δ: SPL + only Low-Freq. QPOs

***: SPL + LFQPOs + HFQPOs;**



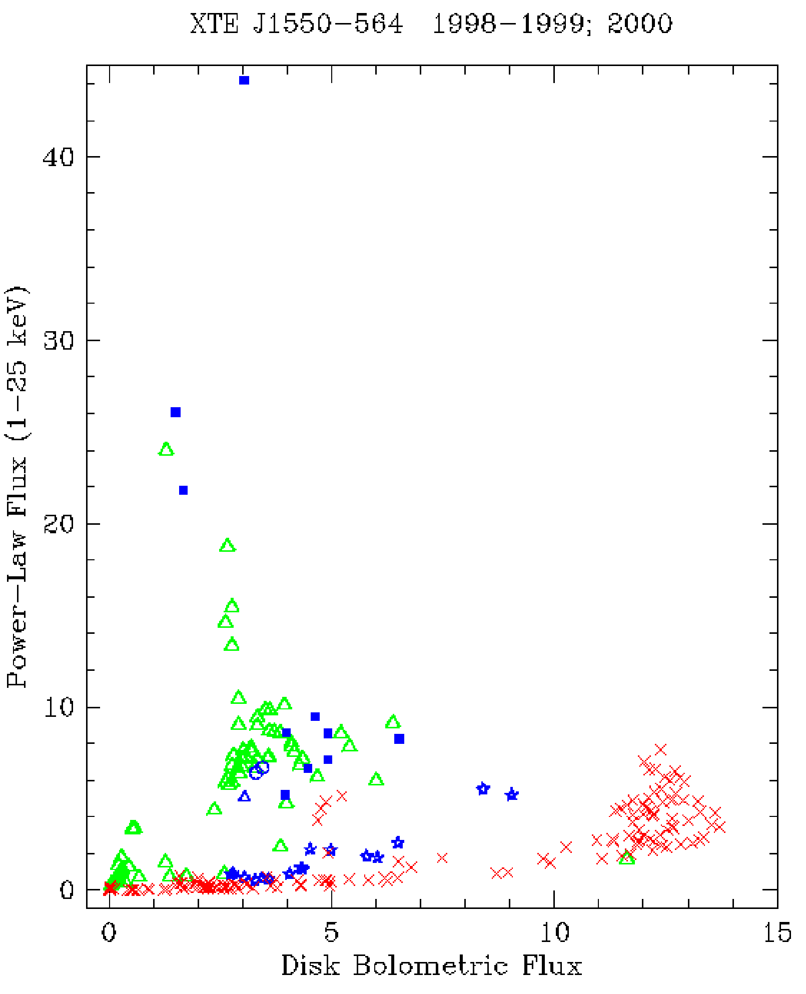
Combining X-ray Timing & Spectroscopy

XTE J1550-564

x: no QPOs, thermal dom.

Δ: only Low-Freq. QPOs
(0.05-20 Hz; SPL, Hard, or INT)

SPL + LFQPOs + HFQPOs;
(at Hz: 184(), 276(*), other (o))



X-ray Spectral Lines & Secondary Components

Deduce disk/pow structures ?

- Broad Fe Kα Emission Lines

  (Profiles with spin? …which states?)

  Balucinska-Church & Church 2000;
  Miller et al. 2002a,b,c; Martocchia et al. 2002

- Disk Reflection Spectra

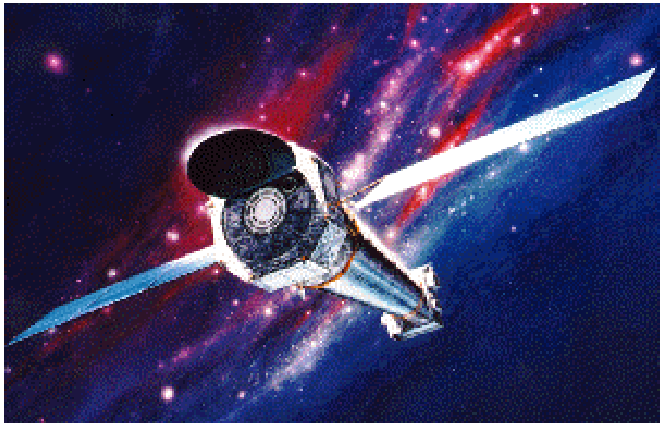
  (Reflection vs. states?)

  e.g. Done et al. 1999; Done & Nayakshin 2001

- Spectral Lines from Hot Gas

  disk atmosphere? …outflow? …vs. state?

  Lee et al. 2001; Miller et al. 2004



Conclusions

- All 3 states of active accretion in BH binaries offer specific applications for relativistic astrophysics.

- There are 2 different ‘soft’ states (thermal & steep power law).

- Non-thermal states appear to have distinct temporal signatures:
  1 Hz (very broad) for hard state / steady jet; ~5 Hz for SPL

- Outstanding Problems:
  - Origin of Steep Power Law component (? MHD instability → QPOs).
  - Kerr-disk spectral models; difficult, yet 1000+ thermal spectra await.