Gamma-Ray Variability of Cyg X-1

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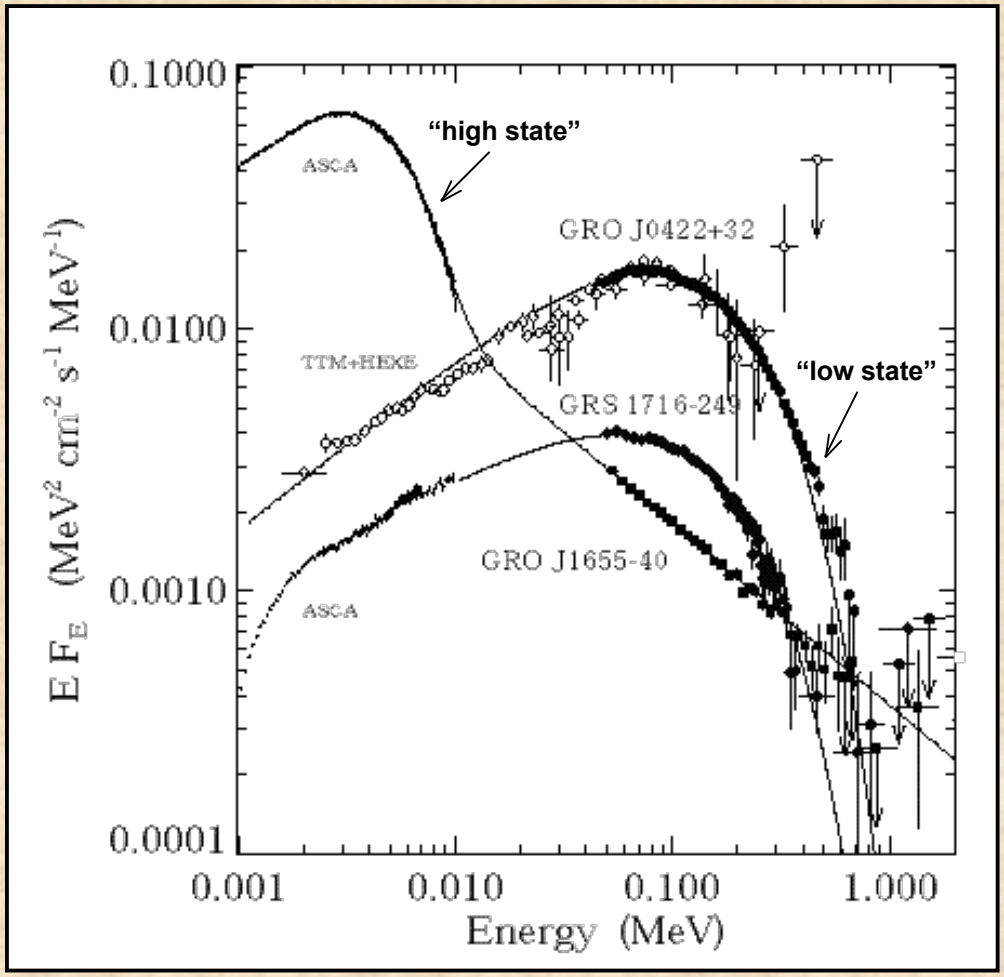
Spectral States of Galactic Black Holes

The behavior of Cygnus X-1 is much like that seen in other galactic black hole sources.



(from Grove et al. 1998)

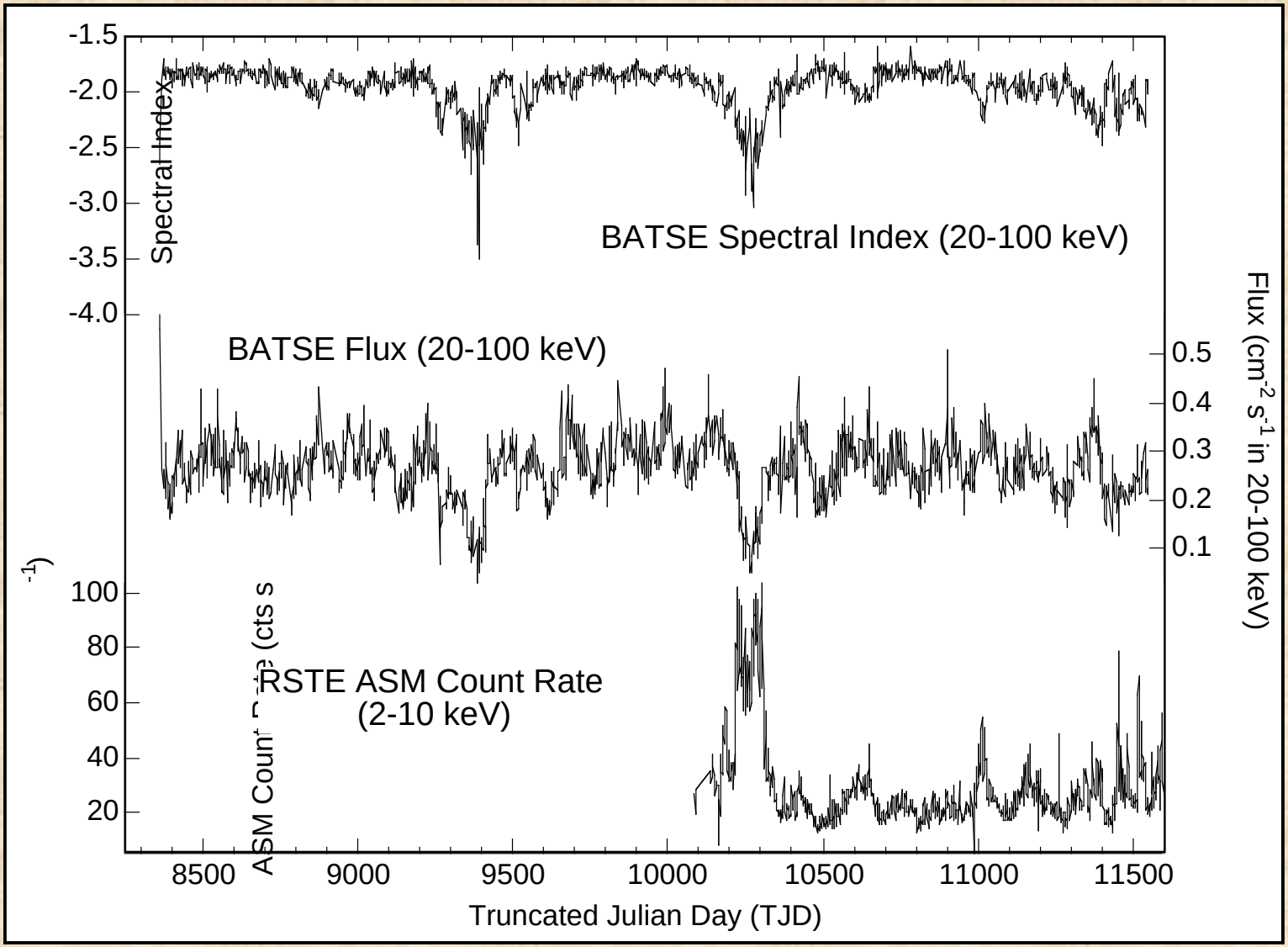
LOW STATE
"hard" X-ray spectrum

HIGH STATE
"soft" X-ray spectrum

The nature of the variability at energies > 1 MeV has not previously been established.

Long-Term Variability of Cyg X-1

These data cover nearly the entire CGRO mission.



Low (Hard) State Spectrum

McConnell et al., ApJ, 543, 928 (2000)

- **Contemporaneous broad-band spectrum using data from BATSE, OSSE and COMPTEL.**
- **Data selected for those periods with consistent hard X-ray flux.**
- **Photon spectrum shows evidence for emission out to ~ 5 MeV.**
- **Latest analysis now incorporates full response information for both BATSE and OSSE.**
- **Standard Comptonization models are inadequate above ~1 MeV.**
- **Hybrid thermal / non-thermal models (which assume some unspecified electron acceleration process) can provide an acceptable fit.**

The spectrum requires a non-thermal component at high energies.

Hybrid Thermal / Non-Thermal Models

COMPPS

Poutanen & Svensson, ApJ, 470, 249 (1996)

Models the steady-state electron spectrum as a Maxwellian plus some non-thermal power-law tail.

Assumes spherical source geometry.

Parameterized by :

- **the electron temperature (kT_e) fi thermal Maxwellian component**
- **power-law index (p_e) of the non-thermal component**
- **range (g_{min} and g_{max}) of the non-thermal component**
- **optical depth (τ)**

Hybrid Thermal / Non-Thermal Models

EQPAIR

Coppi, MNRAS, 258, 657 (1992)
Poutanen & Coppi, Physica Scripta, T77, 57 (1998)
Gierlinski et al., MNRAS, 309, 496 (1999)

Calculates the steady-state form based on the *input* of a non-thermal power-law spectrum.

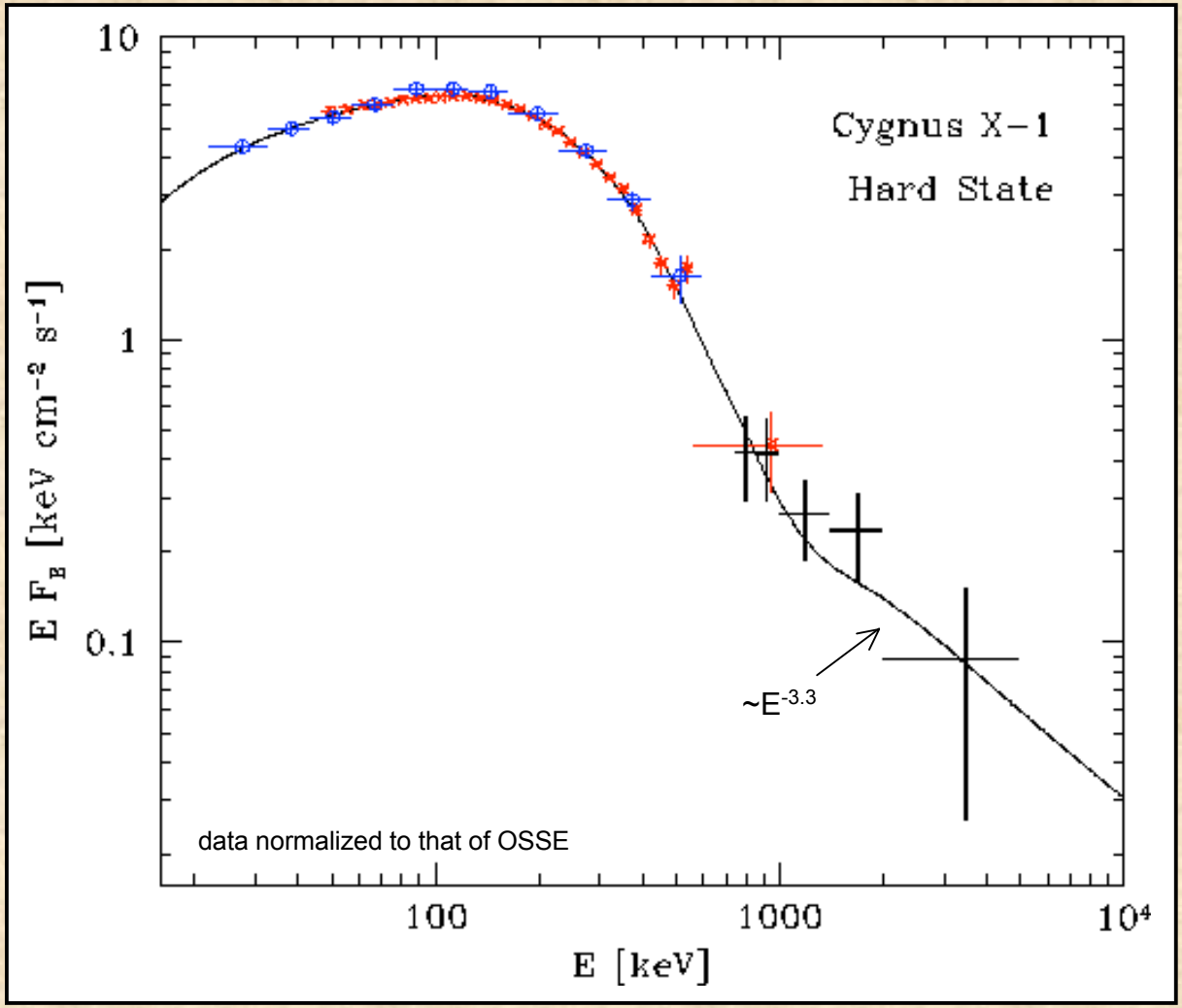
Assumes spherical source geometry.

Parameterized by:

- **hard compactness (l_h) fi power supplied to electrons**
- **soft compactness (l_s) fi power supplied by soft seed photons**
- **nonthermal compactness (l_{nth} / l_h) fi $l_h = l_{nth} + l_{th}$**
- **power-law index (p_e) of the injected non-thermal component**
- **range (g_{min} and g_{max}) of the injected non-thermal component**
- **total optical depth (τ)**
- **optical depth due to ionization electrons (τ_i)**

Average Low (Hard) State Spectrum

McConnell et al., ApJ, 543, 928 (2000)
McConnell et al., ApJ, 572, in press (2002)



Contemporaneous CGRO Data (1991-1994)

BATSE (20-600 keV)

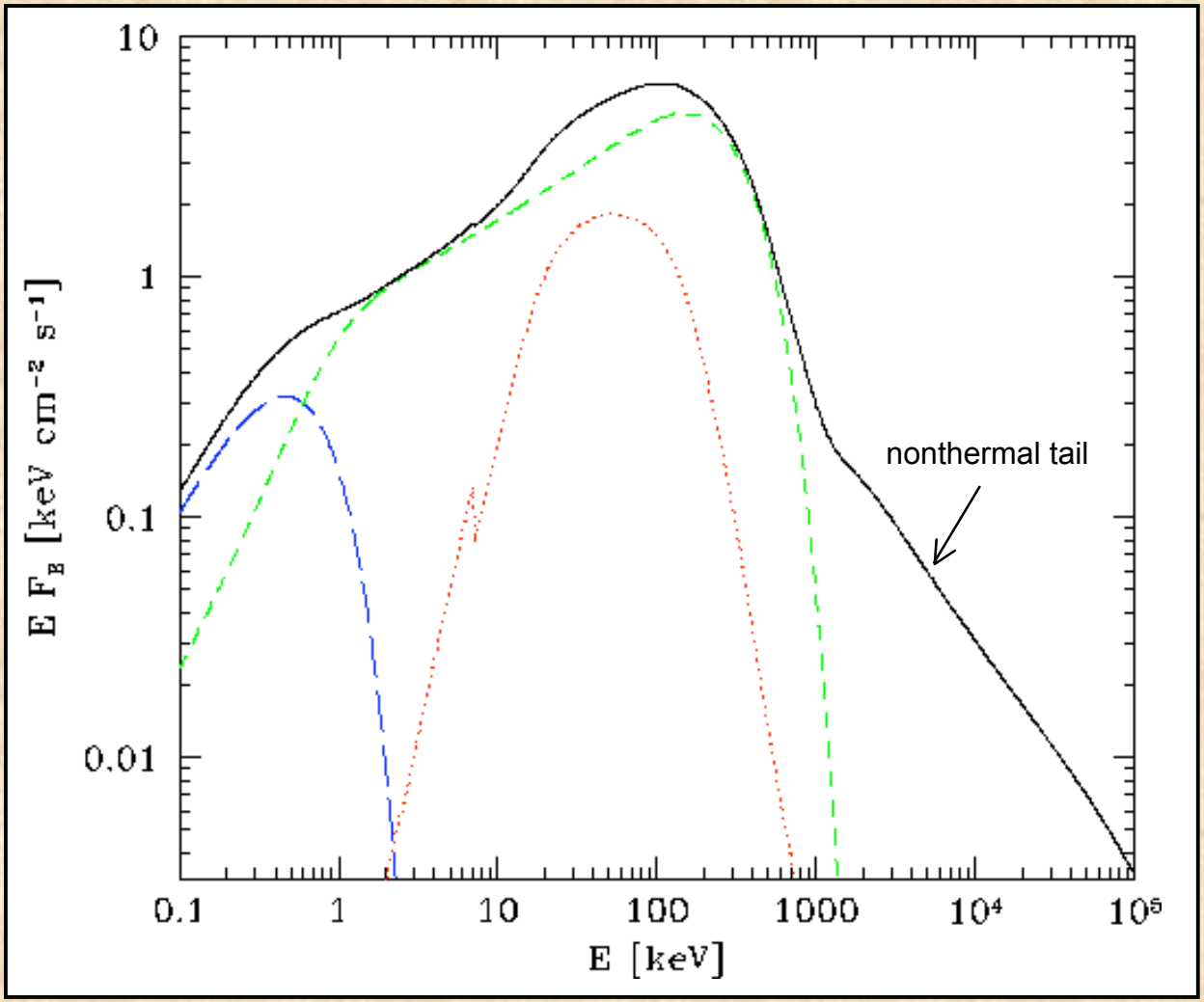
OSSE (50-1200 keV)

COMPTEL (750-5000 keV)

Data fit with EQPAIR model

Average Low (Hard) State Spectrum

McConnell et al., ApJ, 572, in press (2002)



Components of EQPAIR model:

blackbody

thermal electron scattering

Compton reflection

total spectrum

COMPTEL High (Soft) State Data

» **Most COMPTEL data collected during the low X-ray state.**

» **COMPTEL also collected data during two high state periods:**

- ***CGRO Viewing Period 318.1***
  February 1-8, 1994. Not seen by COMPTEL.
  Consistent with extrapolation of hard X-ray spectrum.

- ***CGRO Viewing Period 522.5***
  June 14-25, 1996. Significant signal seen by COMPTEL.
  Consistent with extrapolation of hard X-ray spectrum.
  (Level of hard X-ray flux higher than that during VP 318.1.)

Here we report on the results from an analysis of high state data collected during VP 522.5 and its comparison with the average low state spectrum.

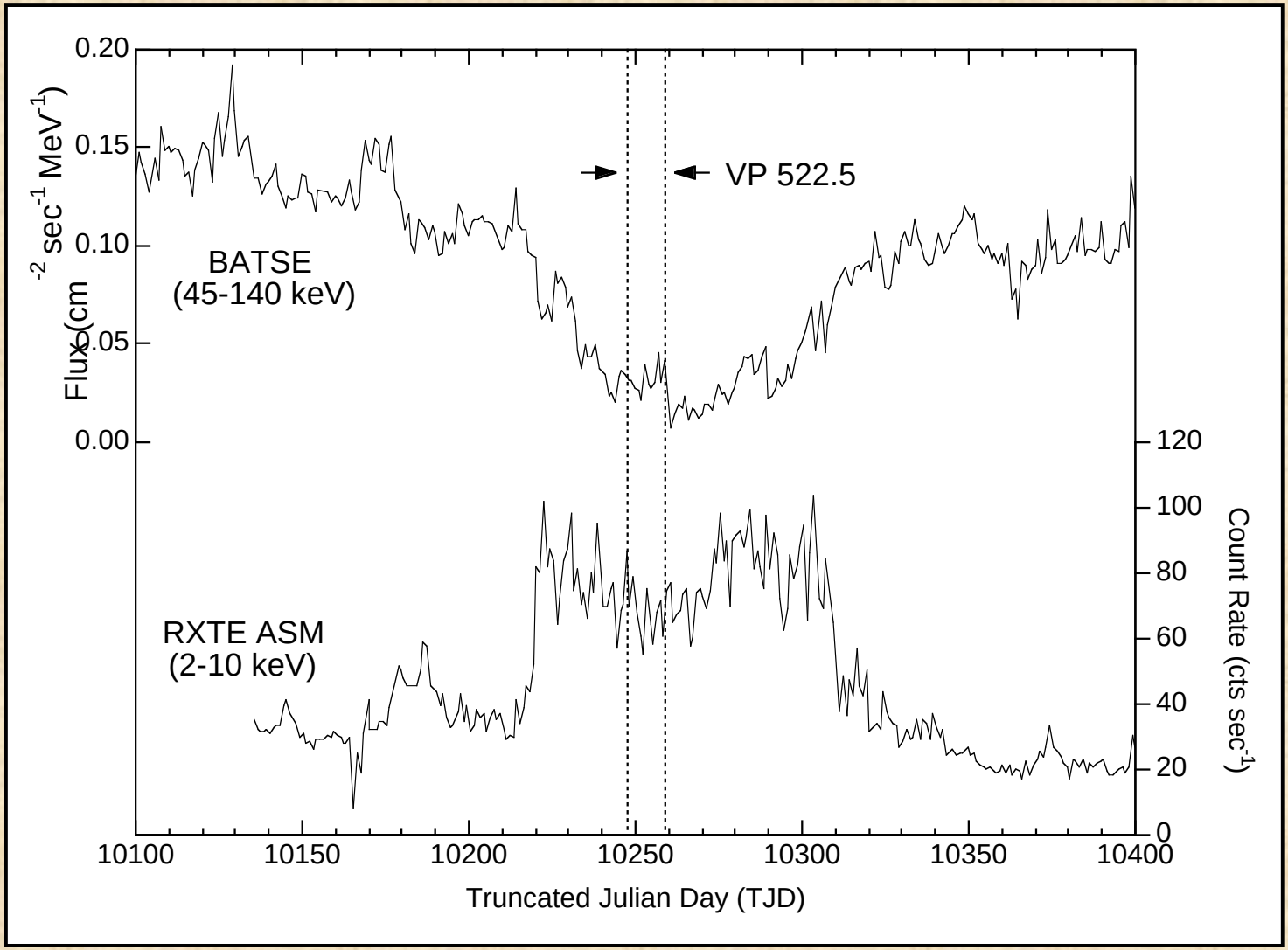
CGRO Viewing Period 522.5
(Target-of-Opportunity – high X-ray state)

- **Soft X-ray increase began on 10 May 1996 (RXTE, 2-12 keV).**
- **Soft X-ray peak flux at 2 Crab on 19 May 1996 (pre-flare ~ 0.5 Crab)**
- **Correlated decrease in hard X-rays (BATSE, 20-200 keV).**
- **CGRO declared a target-of-opportunity (ToO) on June 13.**
- **CGRO pointing (OSSE, COMPTEL, EGRET) began on June 14.**
- **CGRO Z-axis pointed 5° from Cygnus X-1.**
- **ToO observation (CGRO viewing period 522.5) lasted 11 days.**

This high state period is clearly seen in the X-ray time history (panel 3) between TJD 10200 and TJD 10350.

Cyg X-1 Flux Variability - 1996

The time period covered by CGRO Viewing Period 522.5 is noted.

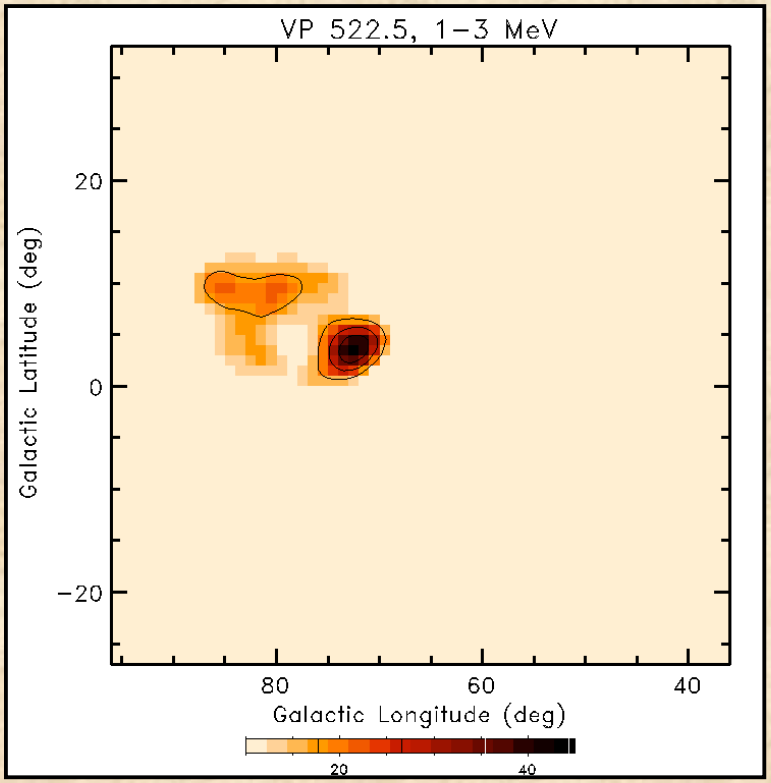


COMPTEL Imaging - VP 522.5

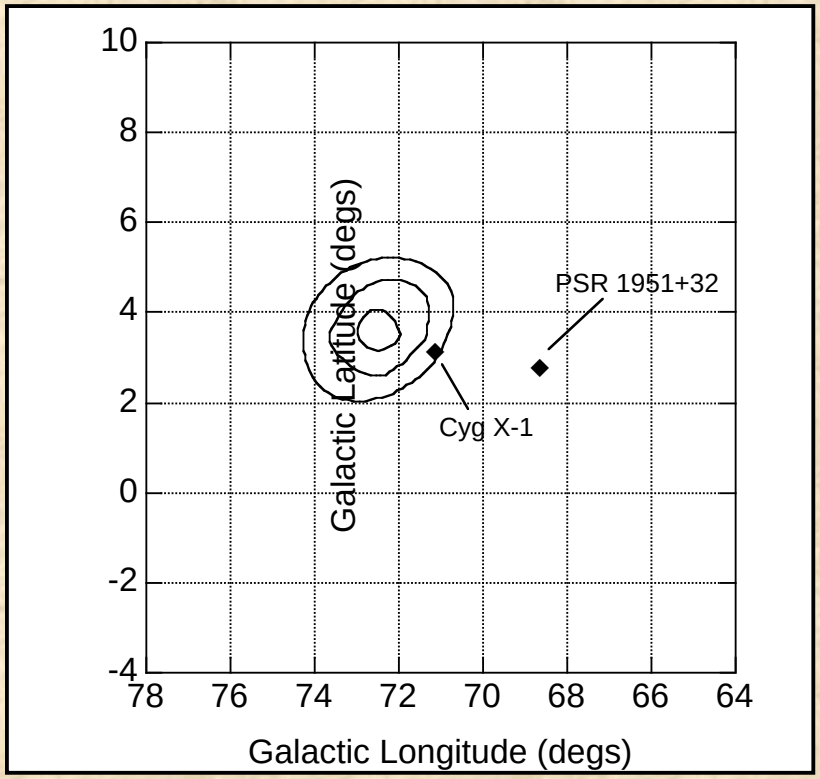
The 1-3 MeV COMPTEL image exhibited an unusually strong signal.

No signal was visible at lower energies (0.75-1 MeV).

This alone suggested that something unusual.



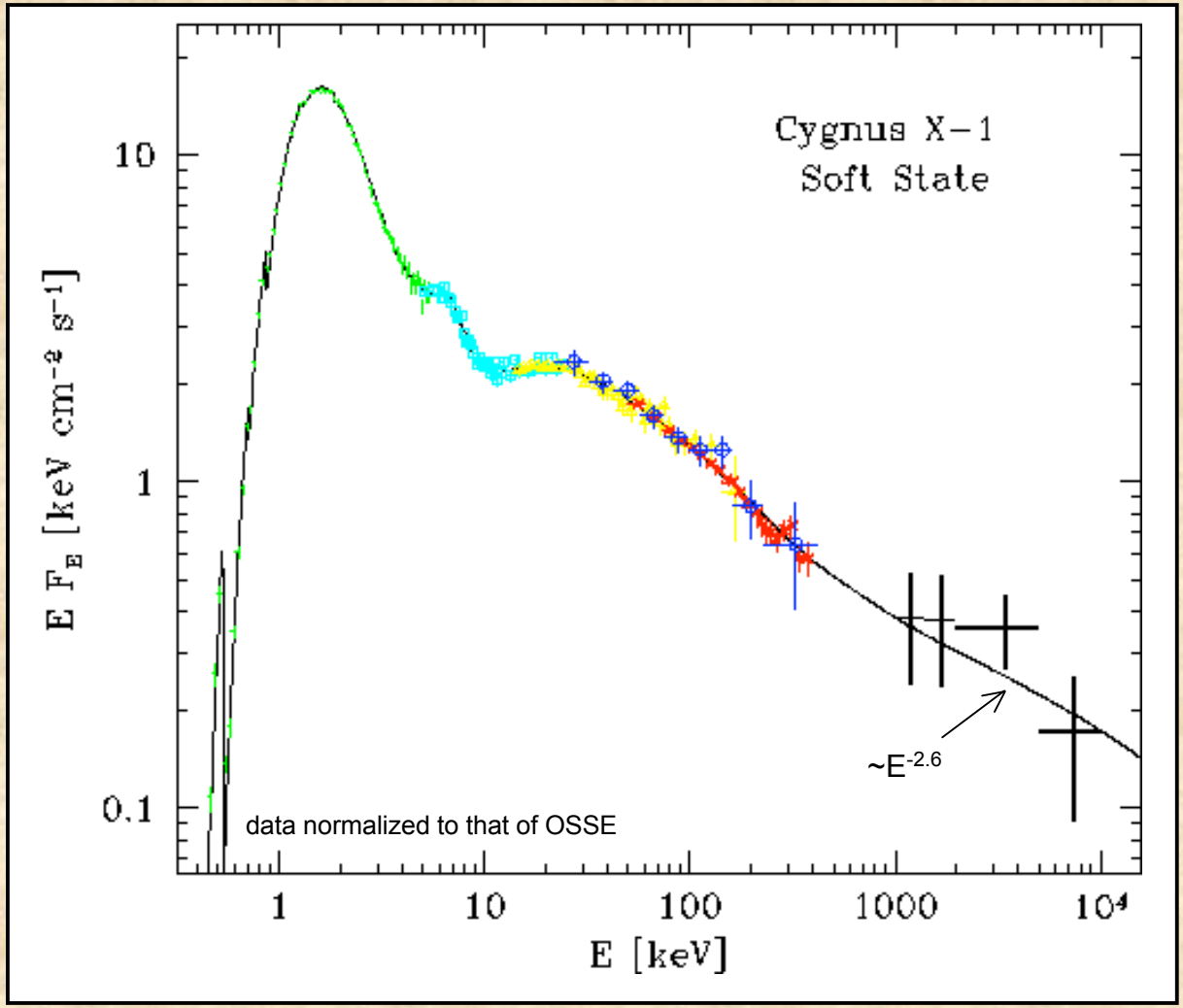
Likelihood Map



Location Contour Map
(note different scale)

BeppoSAX-CGRO High State Spectrum

McConnell et al., ApJ, 572, in press (2002)



CGRO VP 522.5 (14-25 June 1996):

BATSE
(20-600 keV)
OSSE
(50-1200 keV)
COMPTEL
(750-5000 keV)

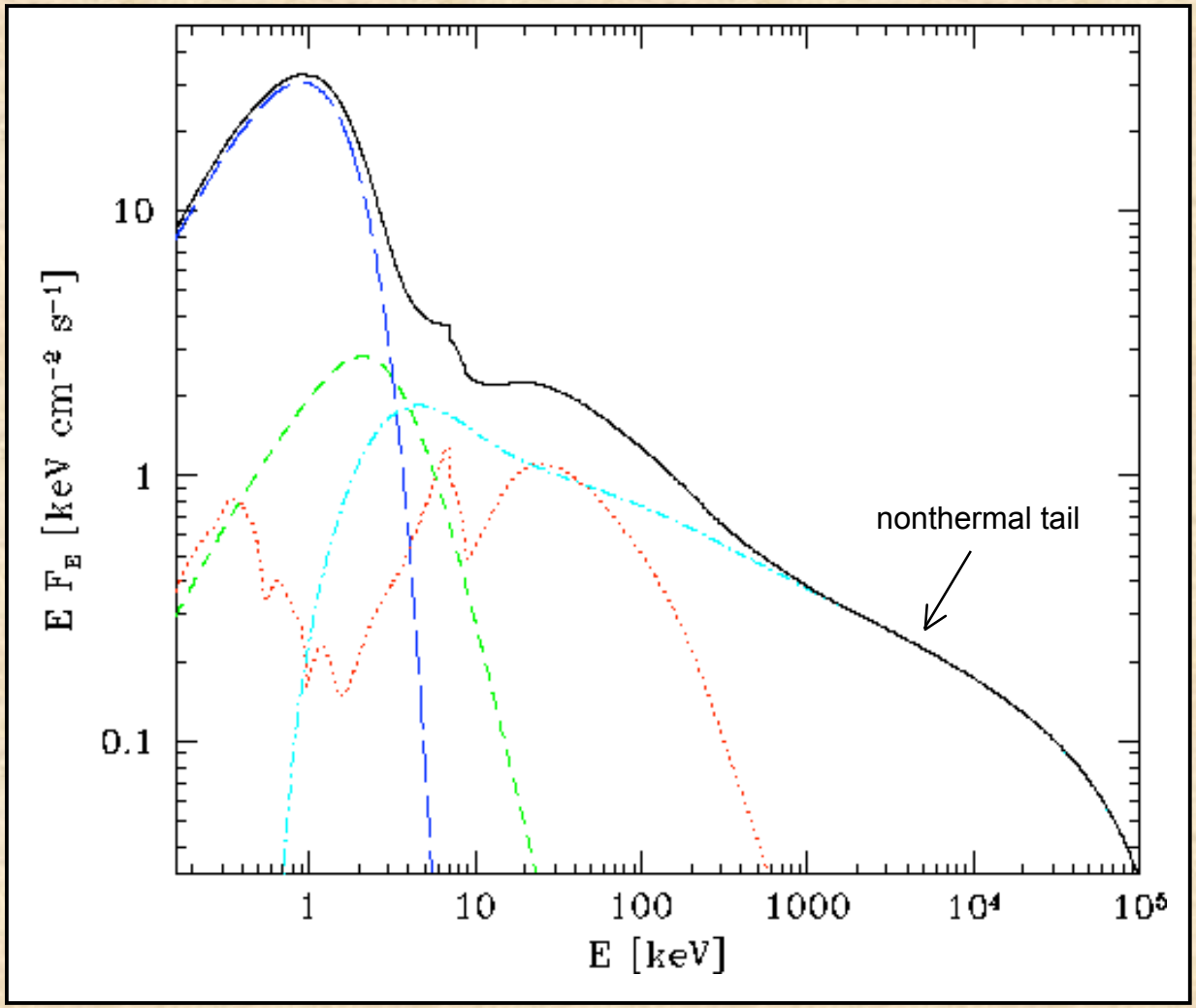
BeppoSAX (22 June 1996):

LECS
(0.1-10 keV)
HPGSPC
(4-120 keV)
PDS
(15-300 keV)

Data fit with EQPAIR model

BeppoSAX-CGRO High State Spectrum

McConnell et al., ApJ, 572, in press (2002)



Components of EQPAIR model:

blackbody

thermal electron scattering

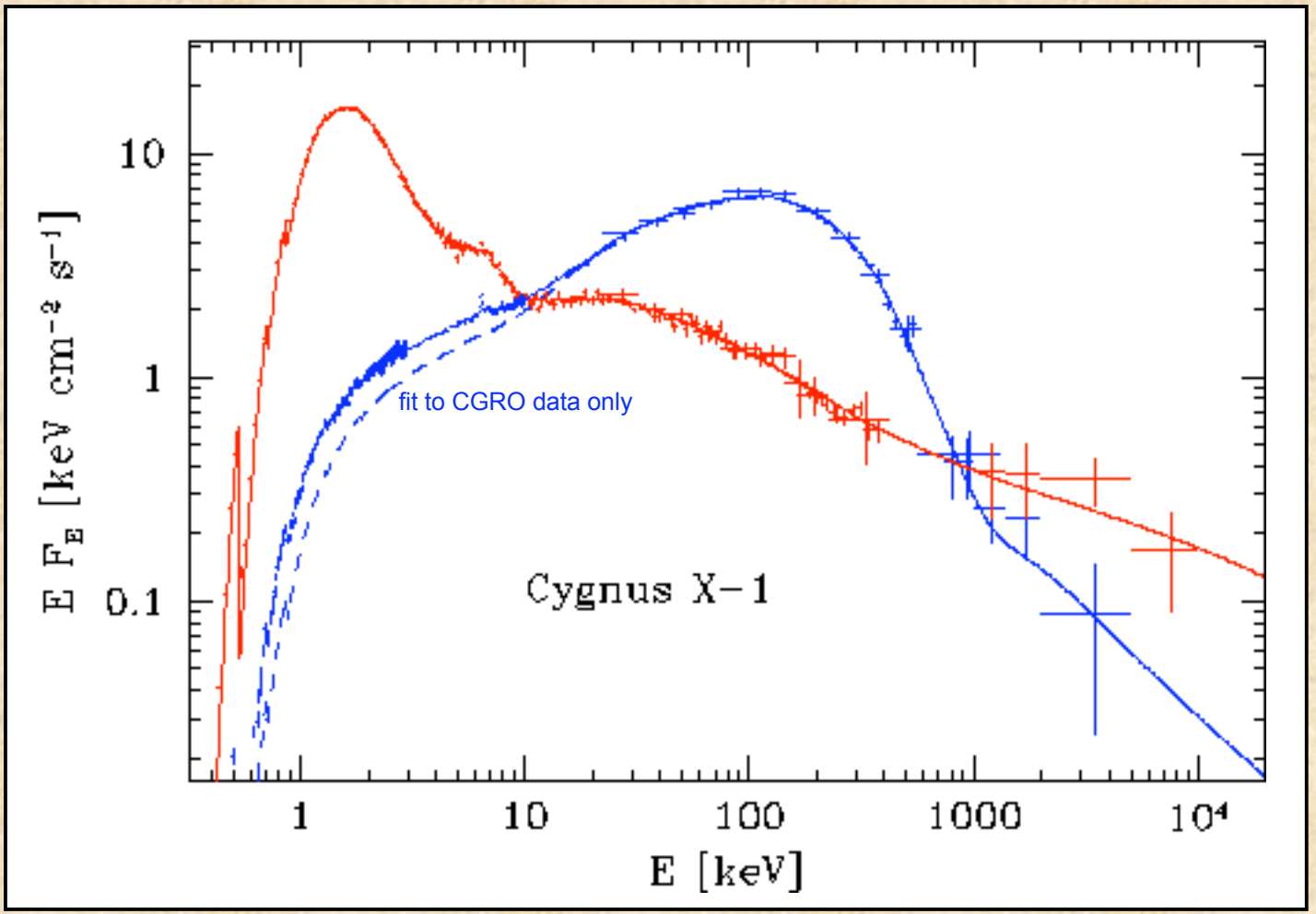
Compton reflection

non-thermal electron scattering

total spectrum

Broadband Spectral Variability

This plot shows the broad-band spectra for both the low (hard) state (incorporating a typical BeppoSAX low state spectrum) and the high (soft) state.



Low State vs. High State Comparison

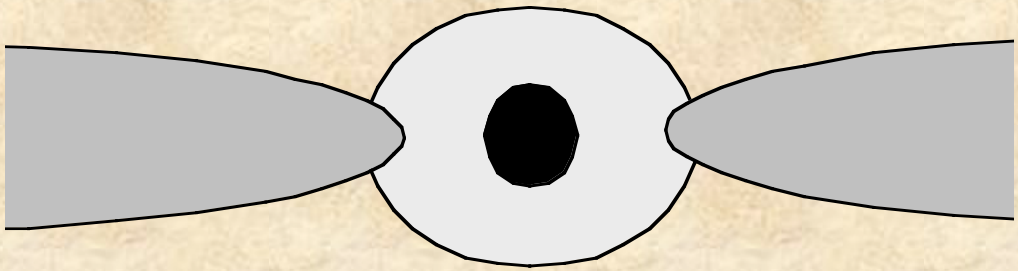
Based on spectral fits with EQPAIR model

Hard State "low"	Soft State "high"	
$t \approx 1.0 - 1.5$	$t \approx 0.1$	optically thinner in soft state
$I_{nth} / I_h \approx 0.08$	$I_{nth} / I_h \approx 0.68$	non-thermal component more significant in soft state
$L \approx 0.01 \times L_{edd}$	$L \approx 0.04 \times L_{edd}$	larger luminosity in soft state

Physical Interpretation

The results are generally consistent with models that suggest a change in the inner disk radius
(e.g., Poutanen & Coppi, 1998; Gierlinski et al. 1999)

LOW X-RAY STATE



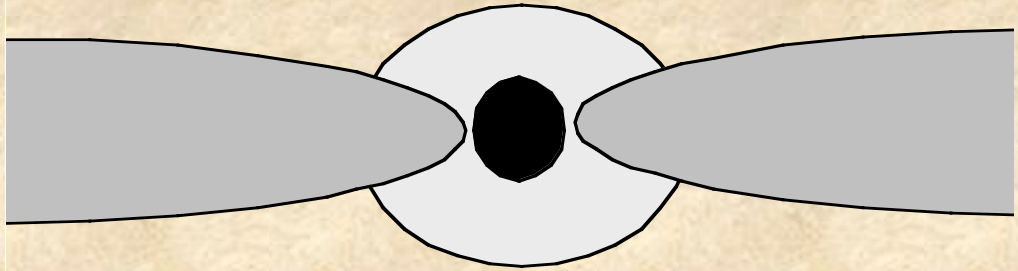
LOW STATE

R_{in} of thermal disk is large

more energy in corona

thermal component dominates

HIGH X-RAY STATE



HIGH STATE

R_{in} of thermal disk is small

more energy in disk

pronounced blackbody component

non-thermal component dominates

Summary

- **Composite CGRO spectra for both the low and high X-ray states (combined with BeppoSAX data in high state).**
- **The spectra exhibit bimodal spectral behavior, as seen in other galactic black hole candidates, with pivot point near 1 MeV.**
- **Power-law spectrum of high state spectrum extends to at least 10 MeV, with no evidence for any cutoff.**
- **Hybrid thermal/non-thermal models can describe the data.**
- **The results are generally consistent with a smaller inner disk radius for the high state (with more pronounced non-thermal component).**