Microquasars

Katja Pottschmidt (UCSD)

September 2006 – Sommerakademie der Studienstiftung, La Villa

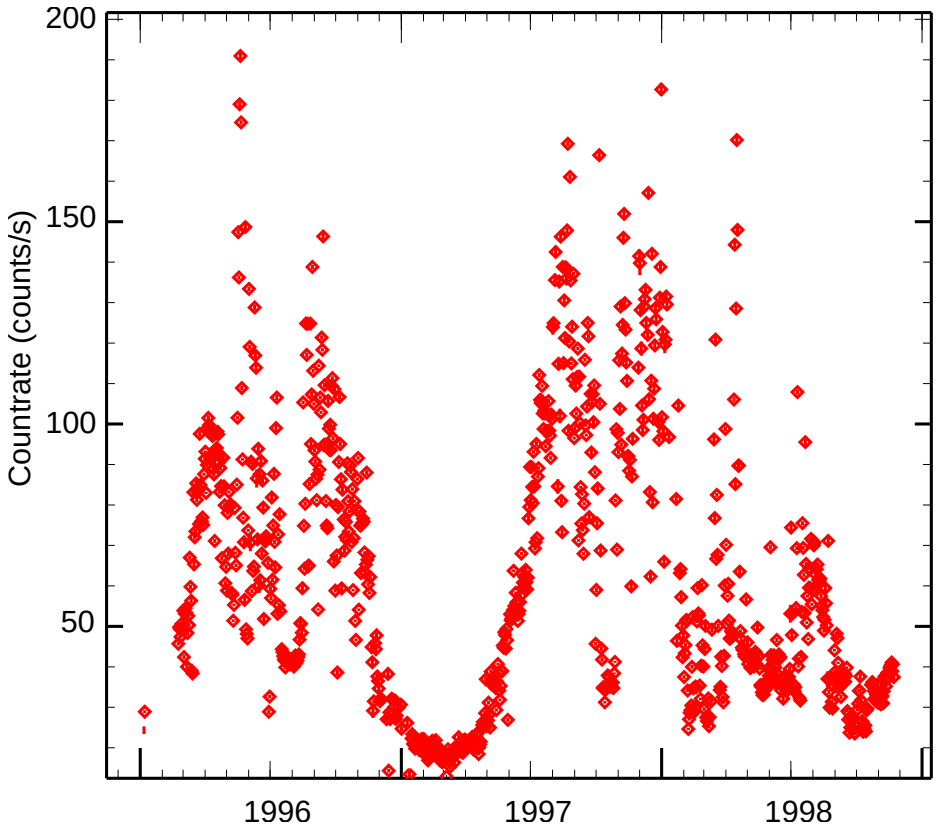
Black Hole X-ray Binaries (BHXRB) with:

- resolved radio jets
  $\longrightarrow$ small scale analogon for radio quasars
  $\longrightarrow$ initiated discovery that all BHXRBs have jets
  $\longrightarrow$ initiated disk-jet connection models

- high-ν X-ray quasi-periodic-oscillations (QPOs)
  $\longrightarrow$ initiated unification of NS and BH QPOs

Jets/QPOs not unique for microquasars but probably enhanced due to black hole spin.

Discovery Of Two New X-Ray Transients



RXTE/ASM 1.3-12 keV lightcurve of 1915.

Data from `http://xte.mit.edu`.

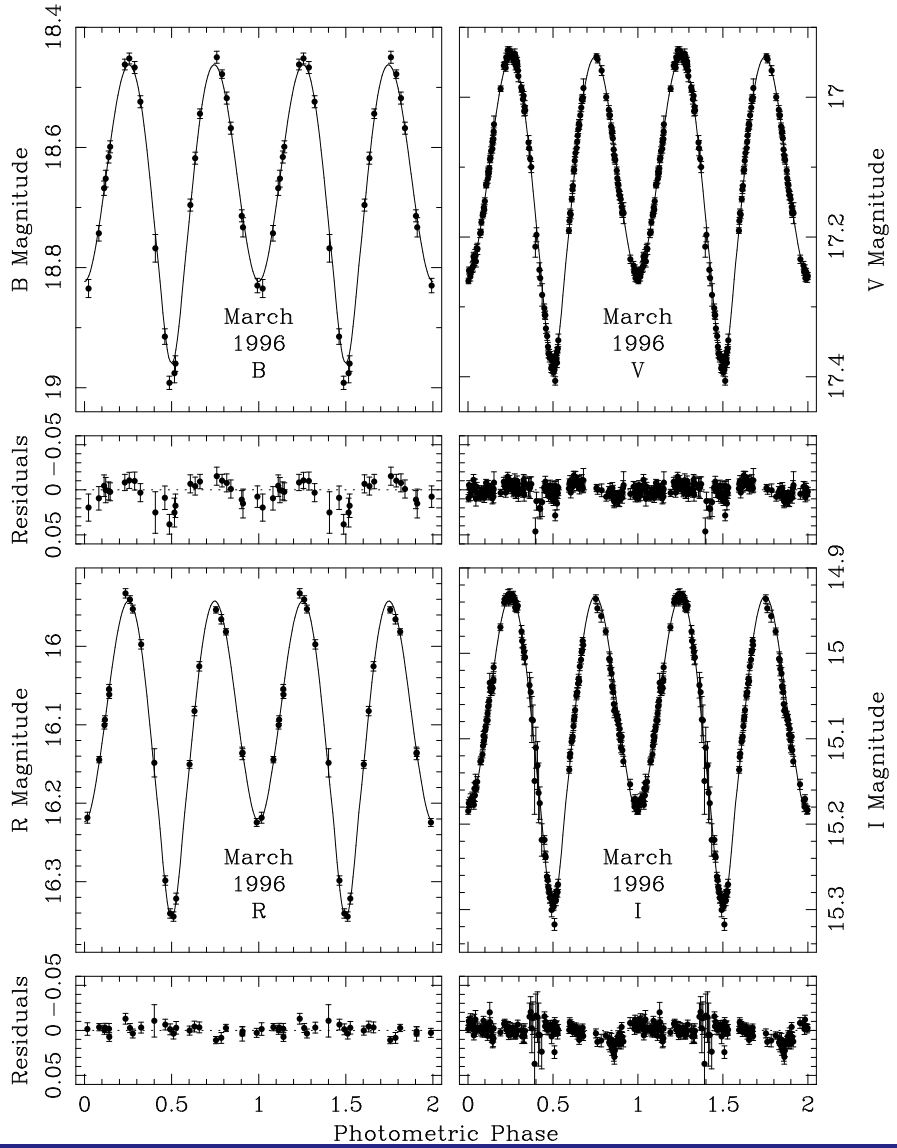
GRS 1915+105

- 1992 with *Granat*
  (Castro-Tirado et al. 1992)
- K/M-star → LMXB
- $D \sim 12.5 \pm 1.5\,\mathrm{kpc}$
  $M_{\mathrm{BH}} \sim 14 \pm 4\,\mathrm{M}_\odot$
  (Greiner 2001)

GRO J1655−40

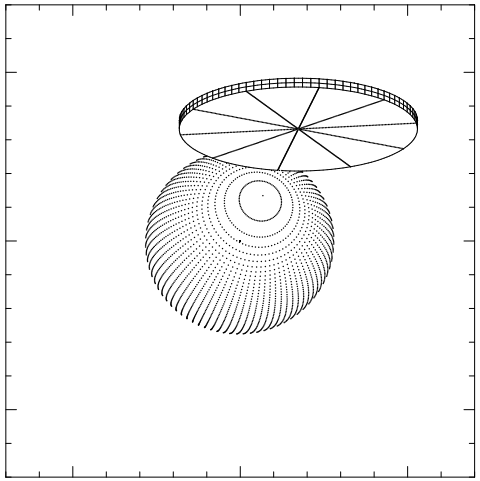
- 1994 with *CGRO*
  (Zhang et al. 1994)
- F-star → LMXB
- $D \sim 3.2 \pm 0.2\,\mathrm{kpc}$
  $M_{\mathrm{BH}} \sim 7.01 \pm 0.22\,\mathrm{M}_\odot$
  (Orosz and Bailyn 1997)

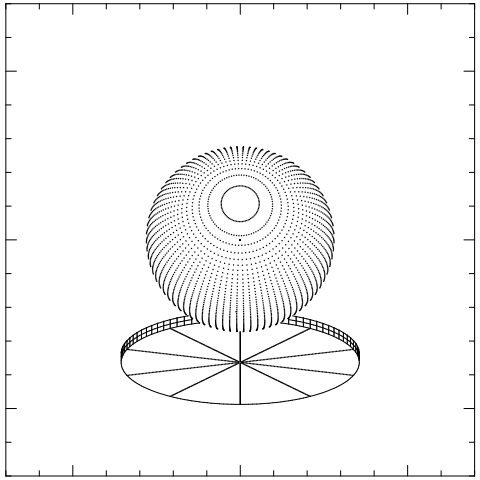
GRO J1655−40: System Geometry



Orosz & Bailyn 1997

GRO J1655−40: System Geometry





Orosz & Bailyn 1997

optical/IR lightcurve & spectrum →

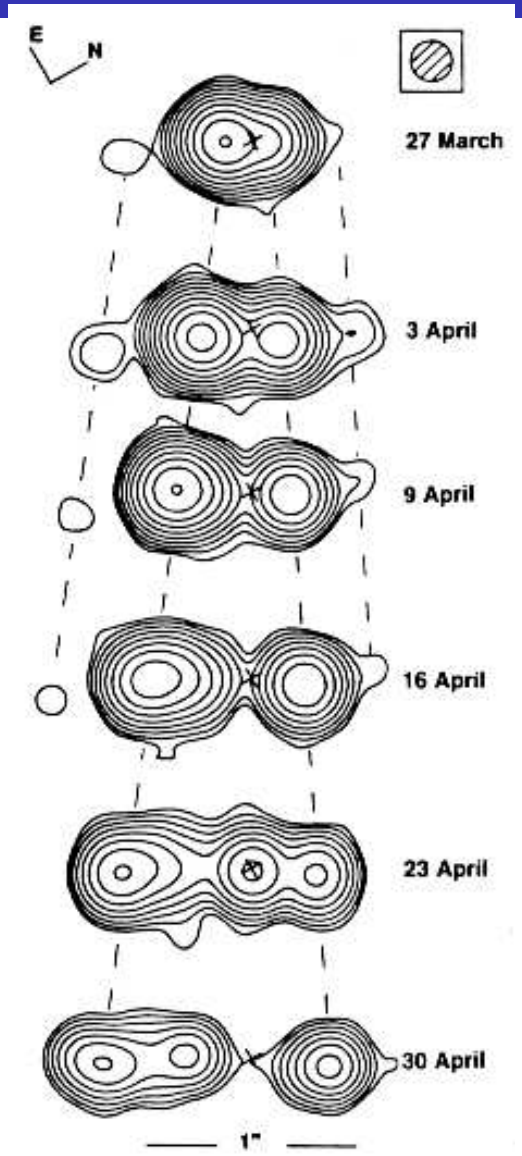
- period $P = 2.62157 \pm 0.00015\,\mathrm{d}$
- inclination $i = 69.50 \pm 8^\circ$
- radial velocity v_r
- companion mass $M_{\text{F-star}}$

$\Rightarrow$ mass function $f(v_r, P) = 3.24 \pm 0.09\,\mathrm{M}_\odot$

$$\Rightarrow M_{\text{BH}}(f, M_{\text{F-star}}, i)$$

Example: phase 170° (top) & 0° (bottom).

First Resolved X-Ray Binary Radio Jets!



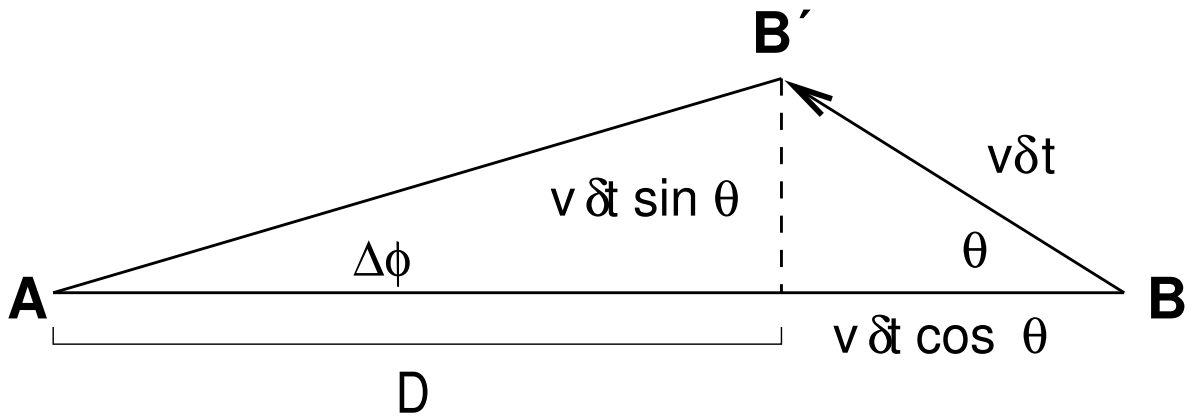
- March/April 1994 VLA
  (Mirabel & Rodríguez 1994)
- ballistic motion of discrete "blobs"
- $v_r = (0.65 \pm 0.08) \times c$
  $v_a = (1.25 \pm 0.15) \times c$

$\Rightarrow$ Apparent Superluminal Motion

- approaching jet brighter,
  fluxes consistent with

$\Rightarrow$ Relativistic Beaming

Superluminal Motion: A Geometrical Effect

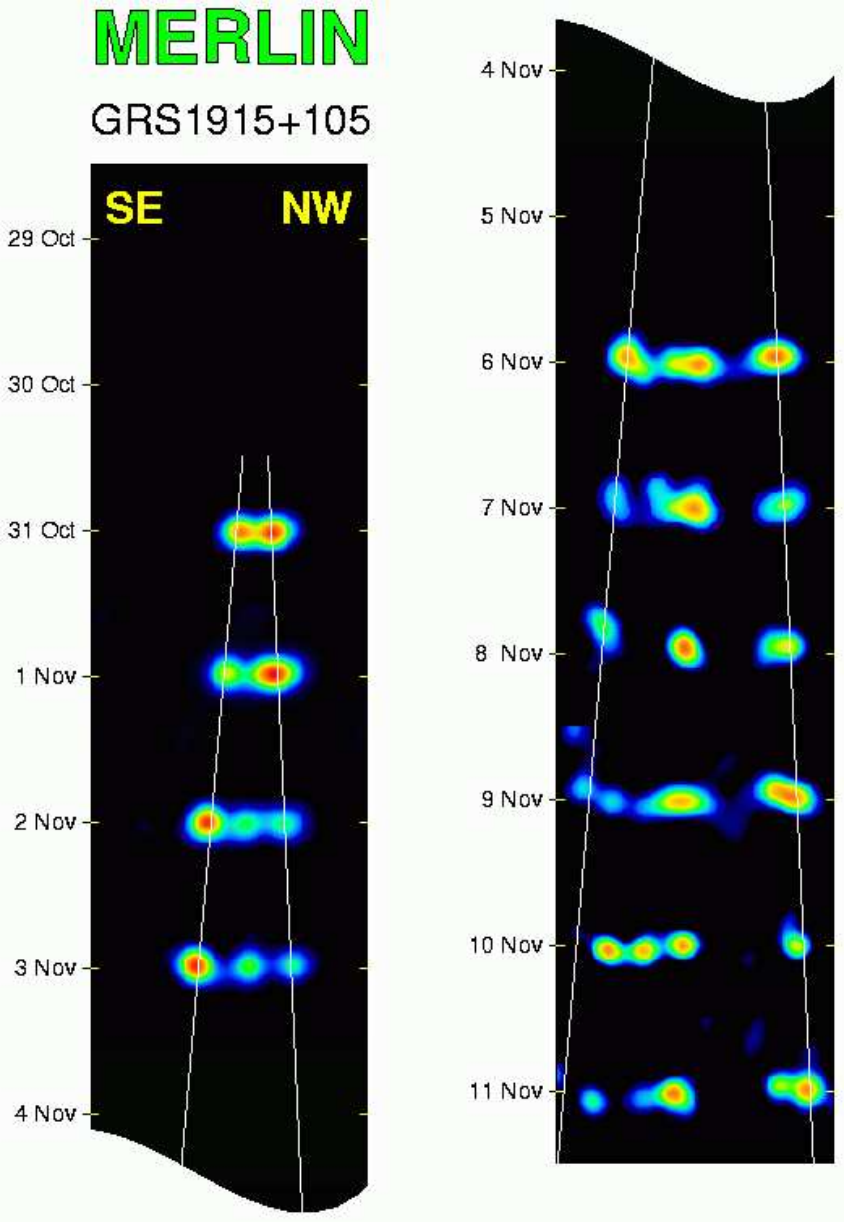


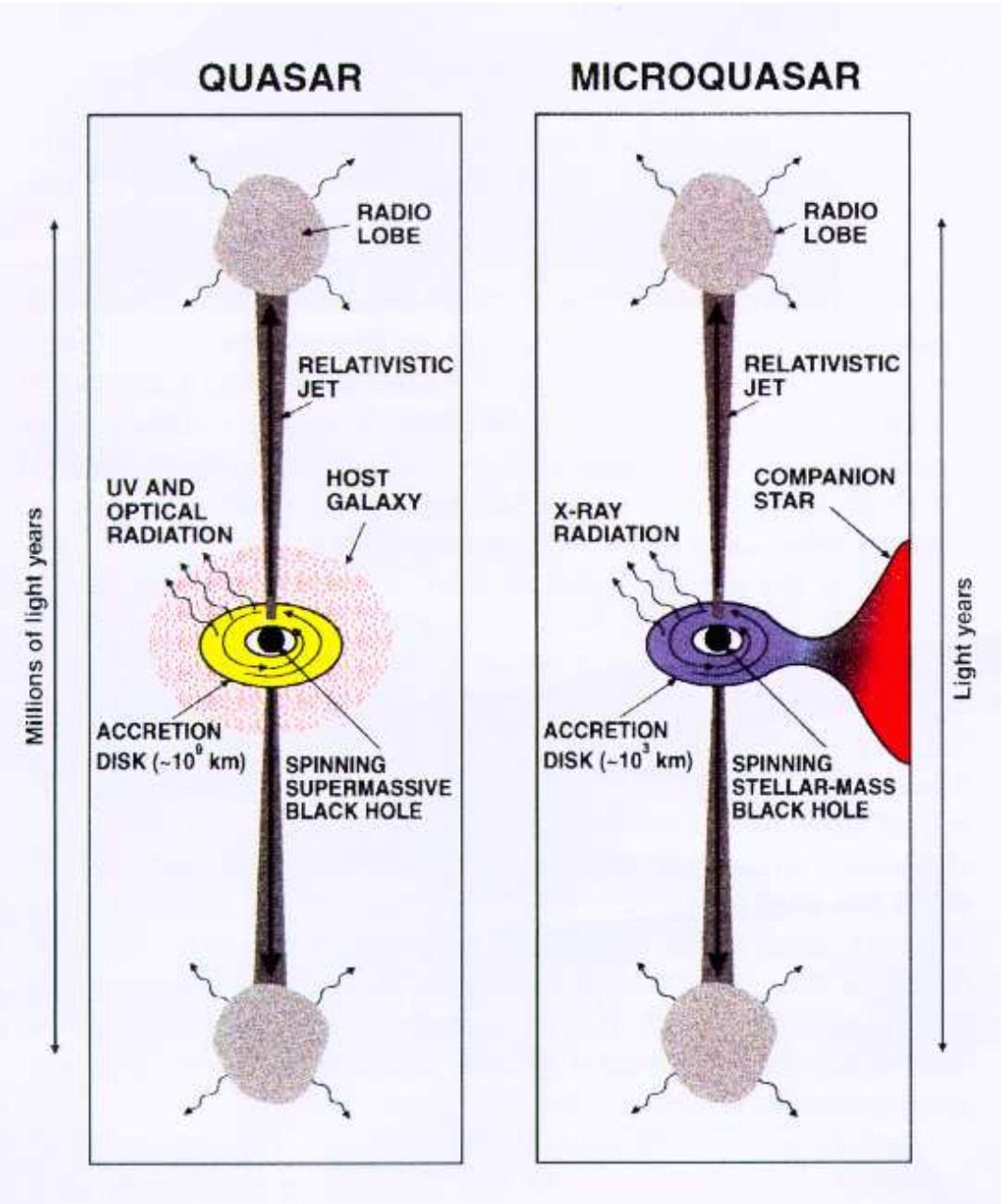
- moving blob with velocity v
- light emitted at positions B and B' with time difference δt
- observer A measures translation velocity (*see jet presentation*)

$$\beta_{\mathrm{T}} = \frac{\beta \sin(\Theta)}{1-\beta \cos(\Theta)}$$

- with $\beta_{\mathrm{T}}^{-} = 0.65$ and $\beta_{\mathrm{T}}^{+} = 1.25$:

$$\beta = (0.92 \pm 0.08)$$
$$\Theta = (70 \pm 2)^{\circ}$$


MERLIN
GRS1915+105
SE
NW
29 Oct
30 Oct
31 Oct
1 Nov
2 Nov
3 Nov
4 Nov
4 Nov
5 Nov
6 Nov
7 Nov
8 Nov
9 Nov
10 Nov
11 Nov

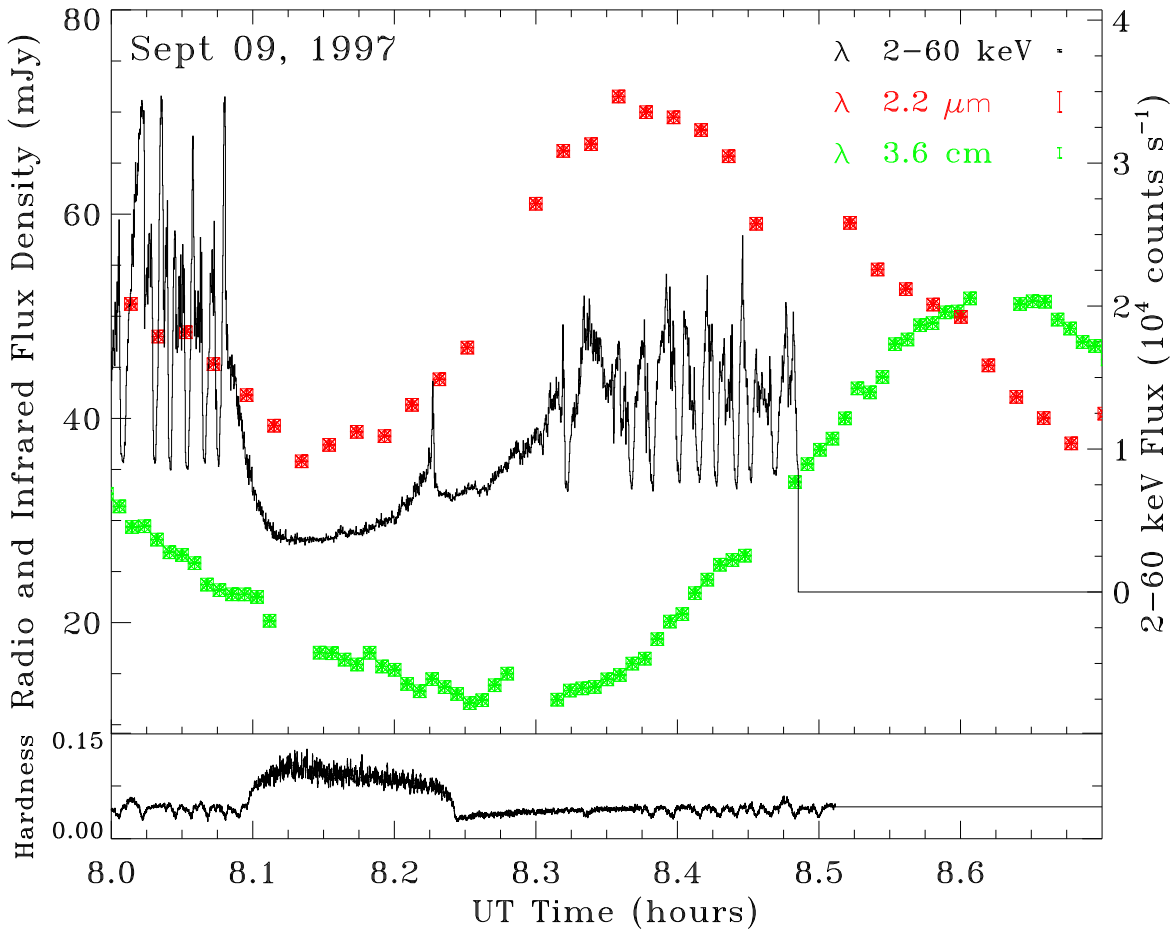


- SLM so far only in AGN (e.g., 3C273)
- dynamical time scale (Kepler)

  $t \propto \sqrt{r^3/m}$
- m, r scale as $\sim 10^6$
  $\rightarrow$ minutes instead of centuries
  $\rightarrow$ study radio, IR, X-ray variability of MQs to understand quasars

(Mirabel & Rodríguez 1994)

GRS 1915+105: Correlations

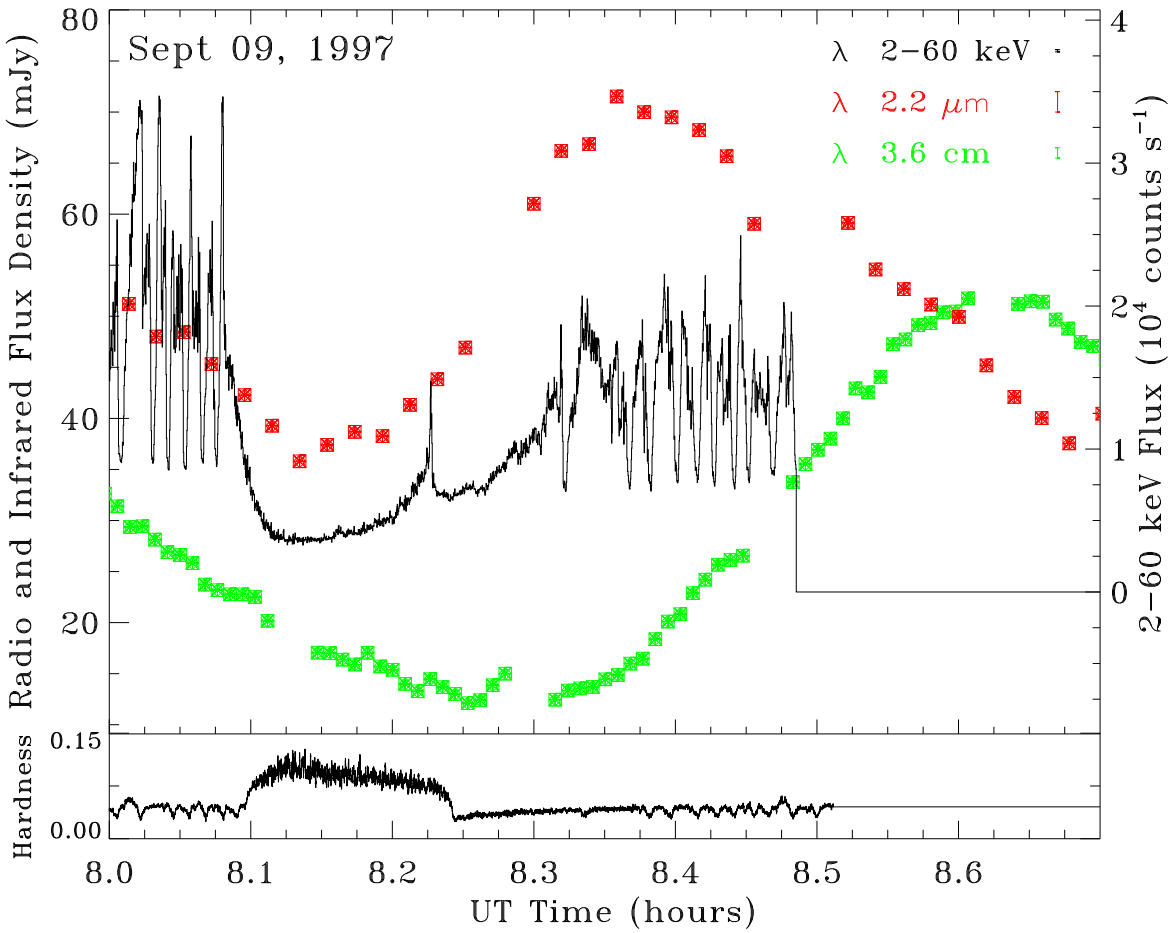


X-ray (*RXTE*/PCA) & **IR** (*UKIRT*) & **radio** (*VLA*) lightcurves (Mirabel et al. 1998).

- 1994-1997: discovery of radio/IR/X-ray correlations on time scales of min–d

⇐ Sept. 1997: (almost) unique example

GRS 1915+105: Correlations

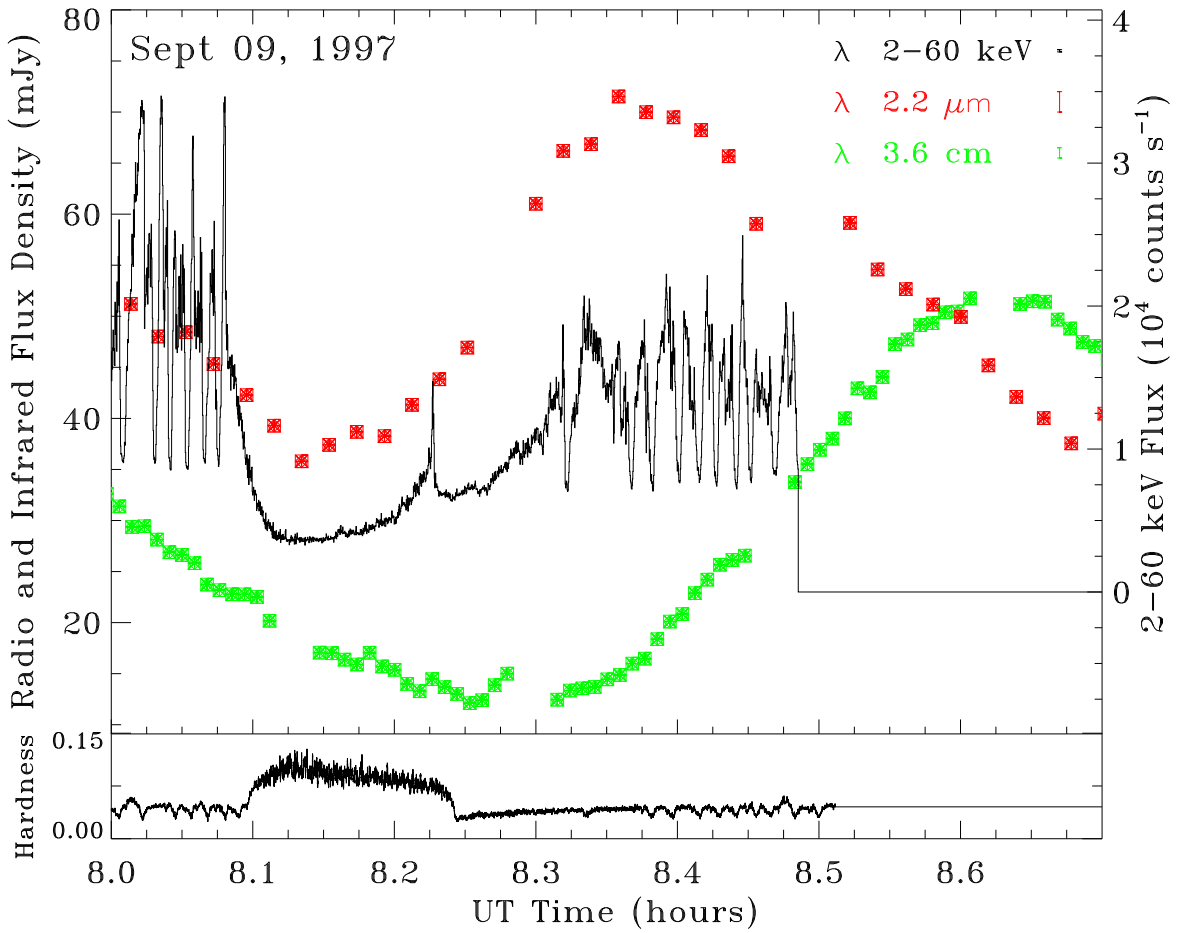


X-ray (*RXTE*/PCA) & **IR** (*UKIRT*) & **radio** (*VLA*) lightcurves (Mirabel et al. 1998).

- X-rays: dip, < 1 min spike
- IR: 20 min flare starts at X-ray spike
- radio: 16 min delay

⇐ Sept. 1997: (almost) unique example

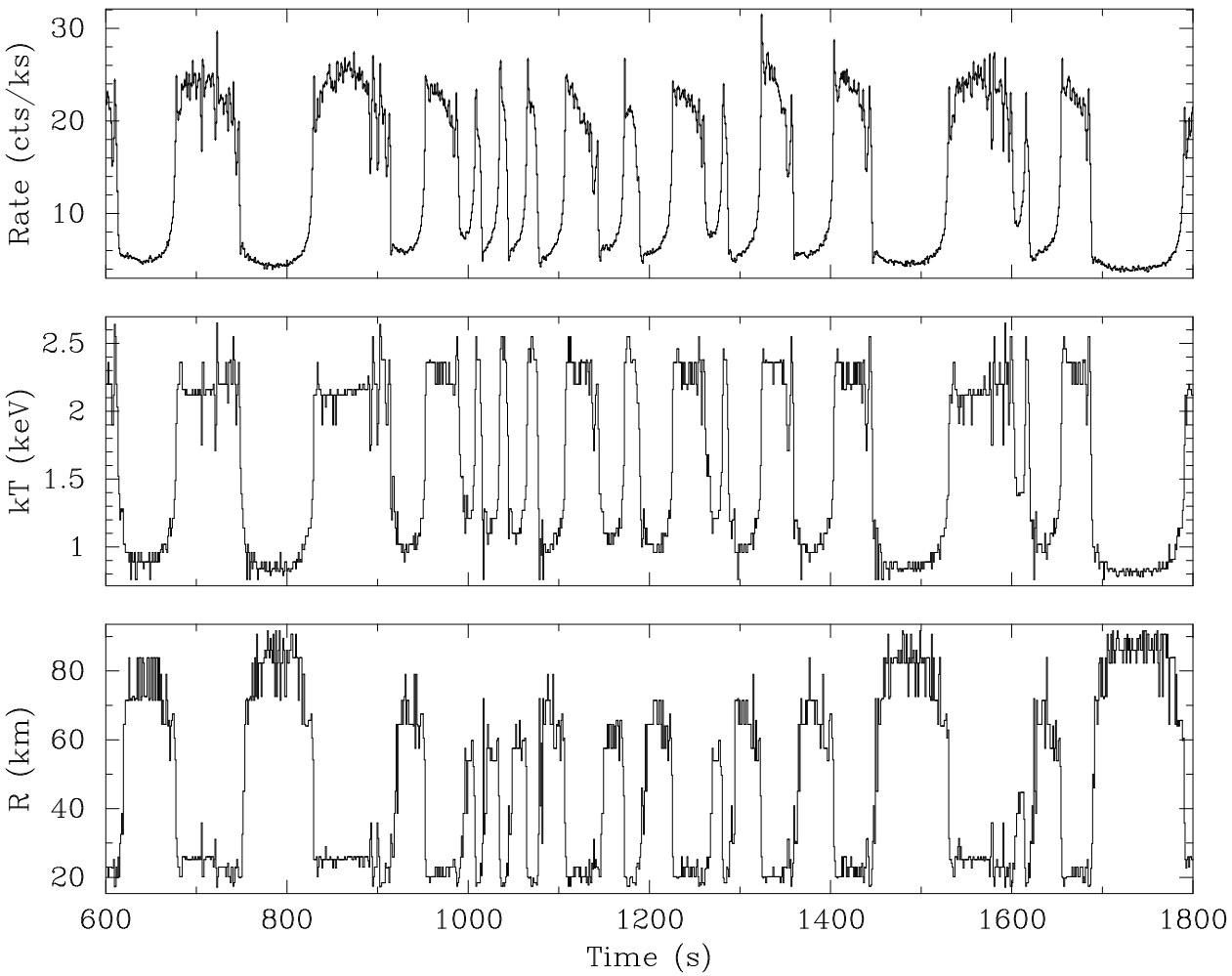
GRS 1915+105: Correlations



X-ray (*RXTE*/PCA) & **IR** (*UKIRT*) & **radio** (*VLA*) lightcurves (Mirabel et al. 1998).

- IR/radio consistent with adiabatic expansion of Synchroton emitting material

Expulsion of inner accretion disk as minijets?



RXTE/PCA lightcurve and inner accretion disk temperature kT & radius R from fits to *RXTE*/PCA spectra (1 s exposures, Belloni et al. 1998). Further support for disk expulsion.

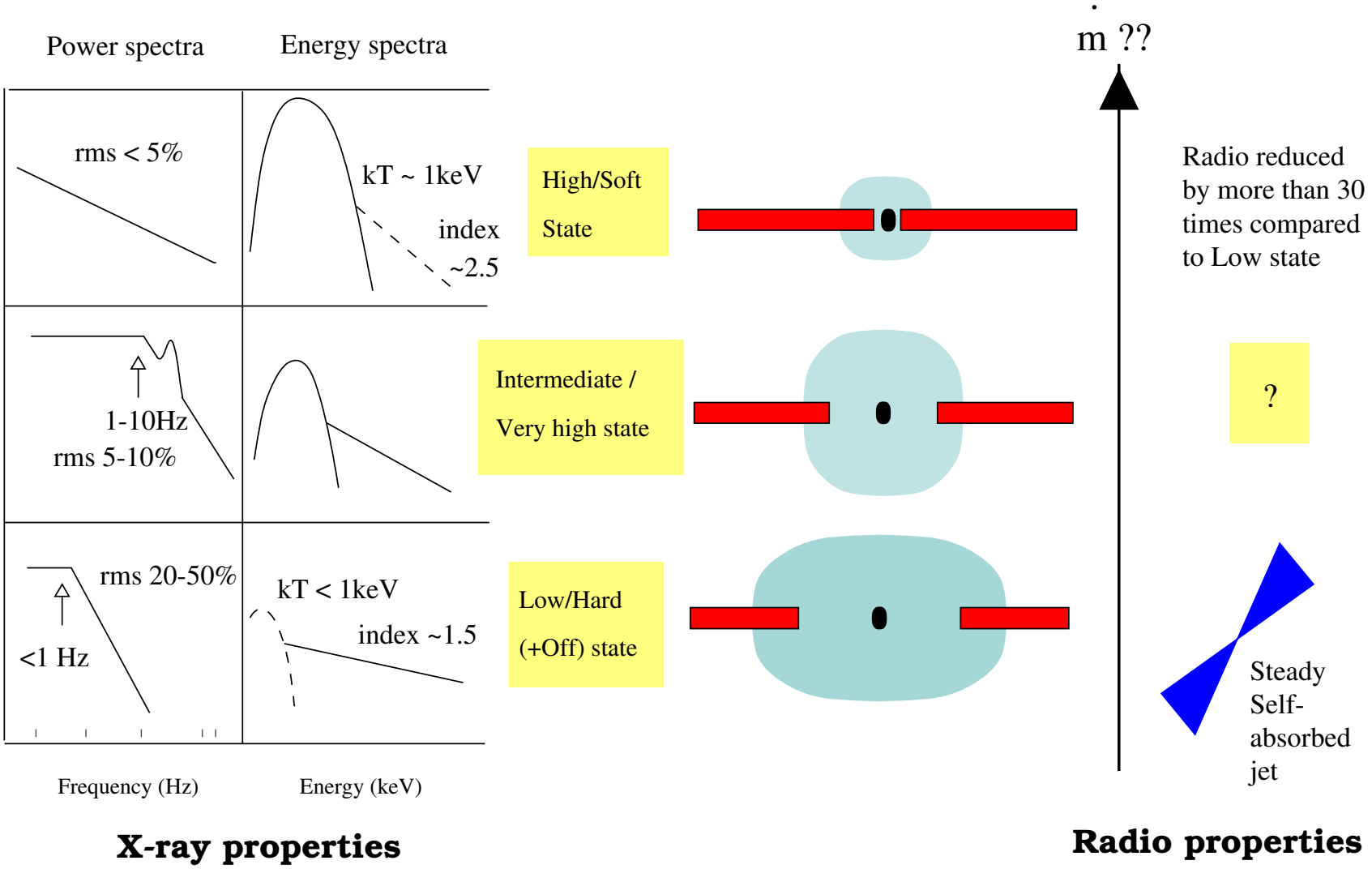
And from here . . . :

. . . boom of radio BHXRB X-ray and radio monitoring programs, evolution of disk/jet states model
(*see HMXB and LMXB presenations*).

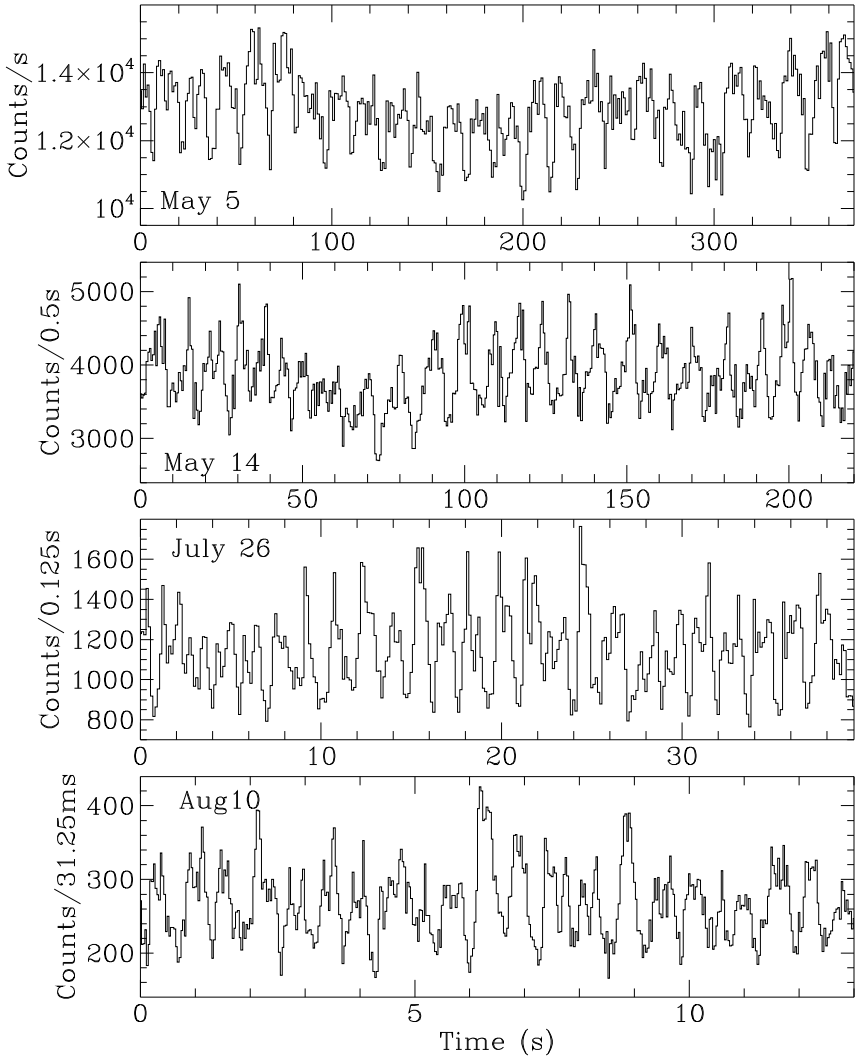
How do the MQs fit in?

- classification of spectra & lightcurves:
  $\rightarrow$ states "A, B, C"
  $\rightarrow$ about a dozen sub-states (for GRS 1915+105)
- but: MQs accrete near $L_{\rm edd}$, often displaying both, soft + hard spectral components

$\Rightarrow$Very High State phenomenology


Power spectra
Energy spectra
rms < 5%
kT ~ 1keV
index ~2.5
1-10Hz
rms 5-10%
rms 20-50%
<1 Hz
kT < 1keV
index ~1.5
Frequency (Hz)
Energy (keV)
X-ray properties
High/Soft State
Intermediate / Very high state
Low/Hard (+Off) state
ṁ ??
Radio reduced by more than 30 times compared to Low state
?
Steady Self-absorbed jet
Radio properties

QPO Zoo



1915, PCA (Morgan, Remillard, & Greiner 1997)

- example:
  14.3 s, 9.1 s, 1.5 s, 0.6 s
  $\rightarrow$ 0.07–1.8 Hz
- generally in BHXRBs:
  up to a few 100 Hz
  (“hectohertz”)
- in NS X-ray binaries:
  “kilohertz”

$\nu_{\rm ISCO} \sim (1580/m_{1.4})$ Hz

high-ν QPOs $\Leftrightarrow$ near ISCO

Power Spectral Density

- use the Discrete Fourier Transform $X_j = X(\nu = j/N\Delta t)$ to evaluate the variability in an evenly spaced time series $x_k = x(t = k\Delta t)$:

$$X_j = \sum_{k=0}^{N-1} x_k \exp(2\pi ijk/N) \quad \text{, for } j = 1 \ldots N/2$$

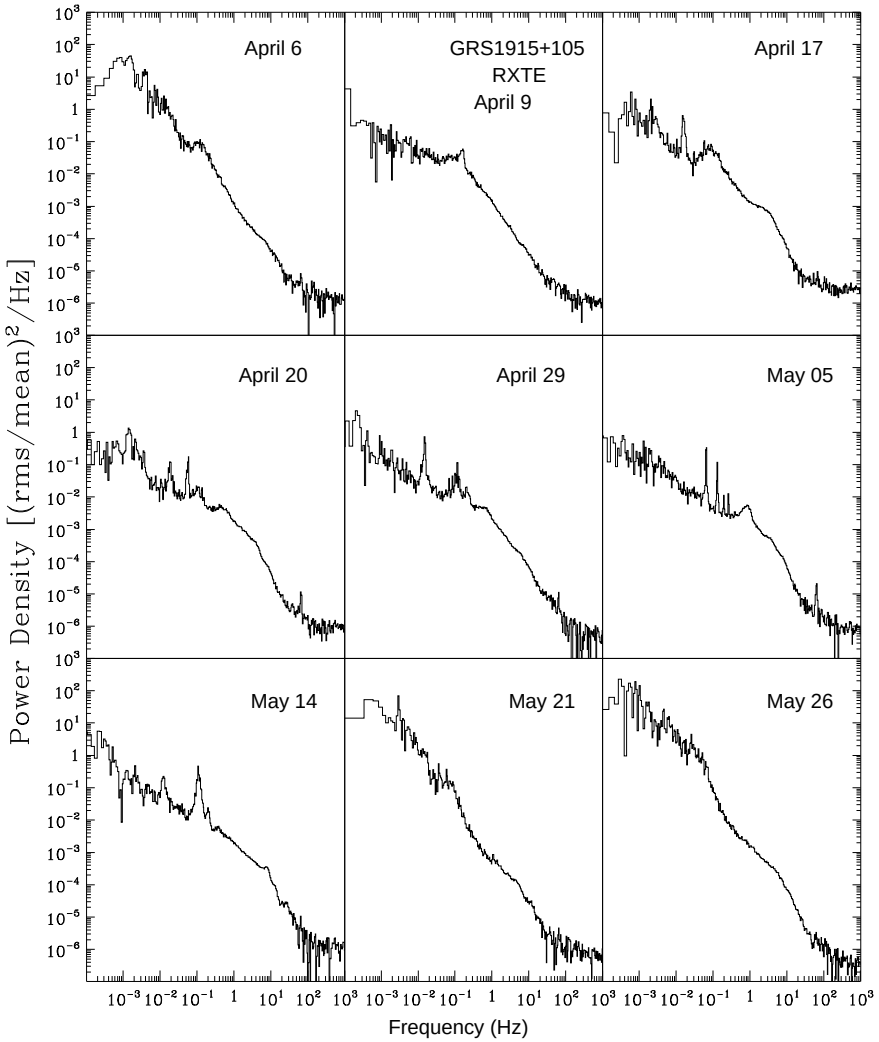
- the Power Spectral Density is given by

$$\text{PSD} = A_{\text{norm}} \langle X^*{}_j X_j \rangle$$

where $\langle \ldots \rangle$ denotes averaging over data segments and where A_{norm} is a normalization constant

- the PSD describes the contribution of a given frequency to the total variance of the lightcurve (power)
$A_{\text{Miyamoto}} \Leftrightarrow [(\text{rms}/\langle \text{ rate } \rangle)^2/\text{Hz}]$

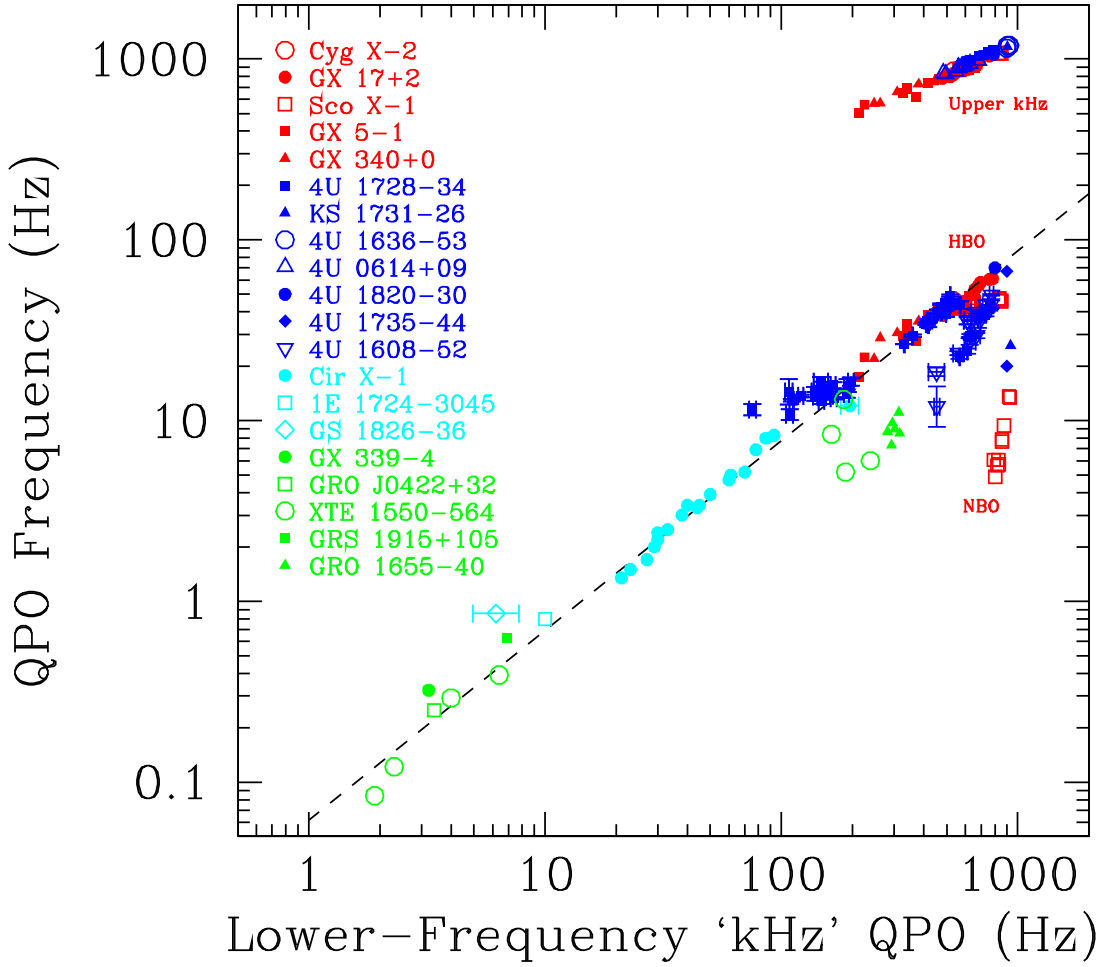
Parameters characterizing QPOs



1915, PCA (Morgan, Remillard, & Greiner 1997)

- "center frequency"
  e.g., resonance of Lorentzian
- "relative rms amplitude": $\sqrt{\int \mathrm{QPO} d\nu}$
  e.g., $\mathrm{rms}_{67} = 0.5 - 1.6\,\%$
- "Q": $\nu_{\mathrm{center}} / \Delta\nu_{\mathrm{FWHM}}$
  e.g., $Q_{67} \approx 20$

Correlations between QPO frequencies

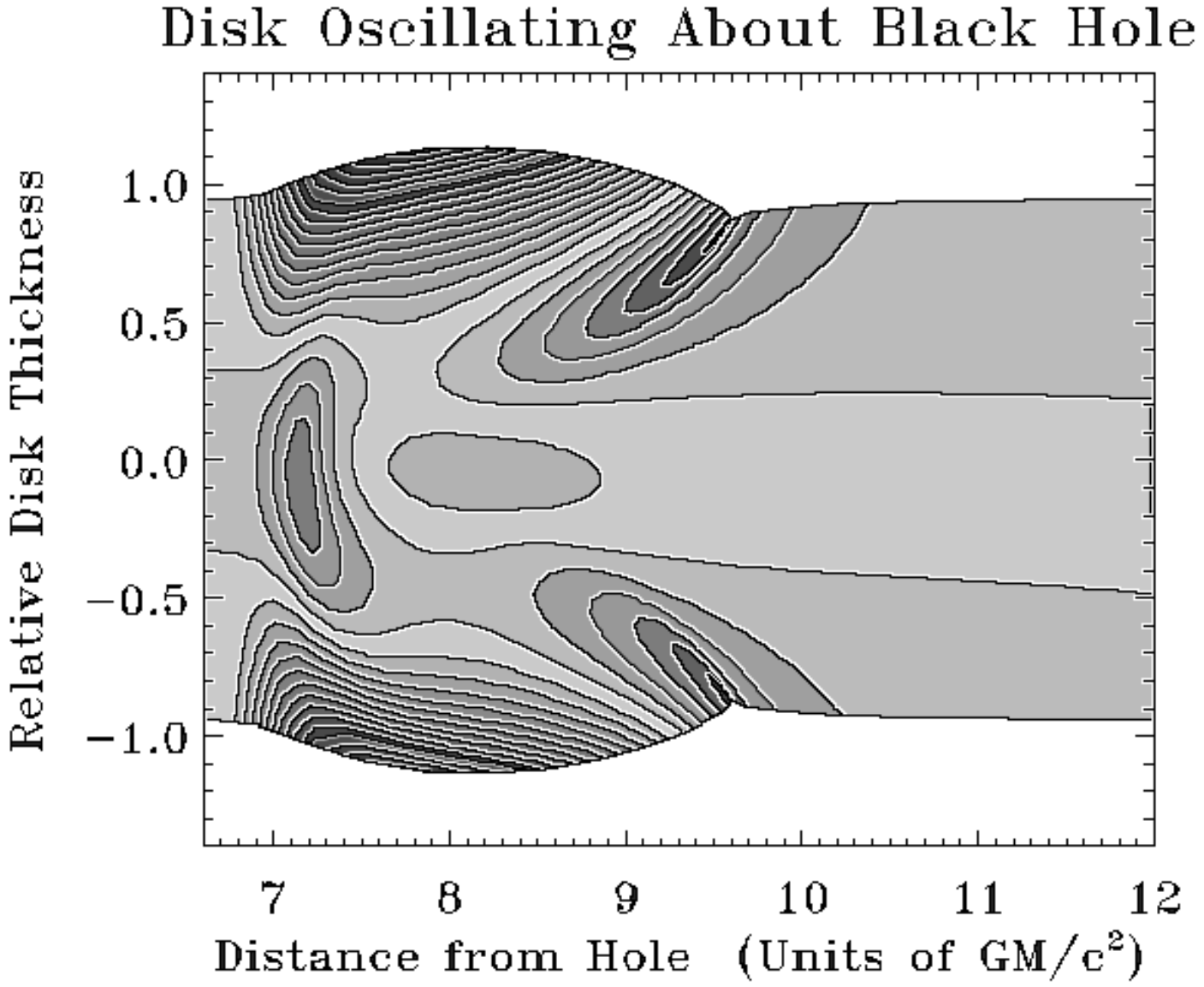


Psaltis, Belloni, & van der Klis 1999

- green: BHXRBs
  others: NSXRBs

⇒ QPOs do not depend on existence of surface

⇒ Accretion Disk Oscillations?



pressure gradient → $\Delta L_{\rm disk}$, $\Delta L_{\rm corona}$?? (Nowak, priv. comm)