Interpreting the High Frequency QPO Power Spectra of Accreting Black Holes

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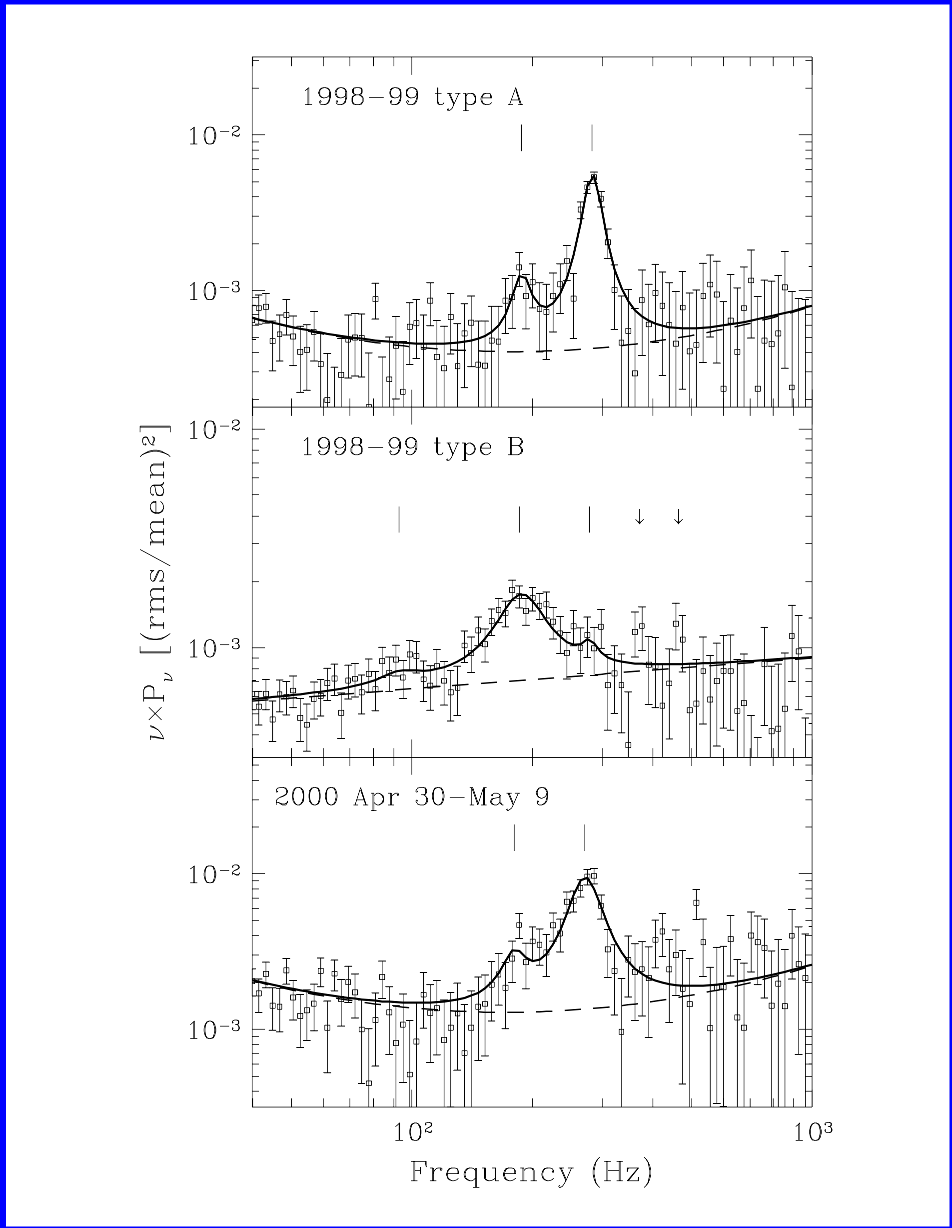
Outline

- Background/Hot Spot Model
- Phase Broadening
- Frequency Broadening
- Harmonic Damping
- Comparison with Data

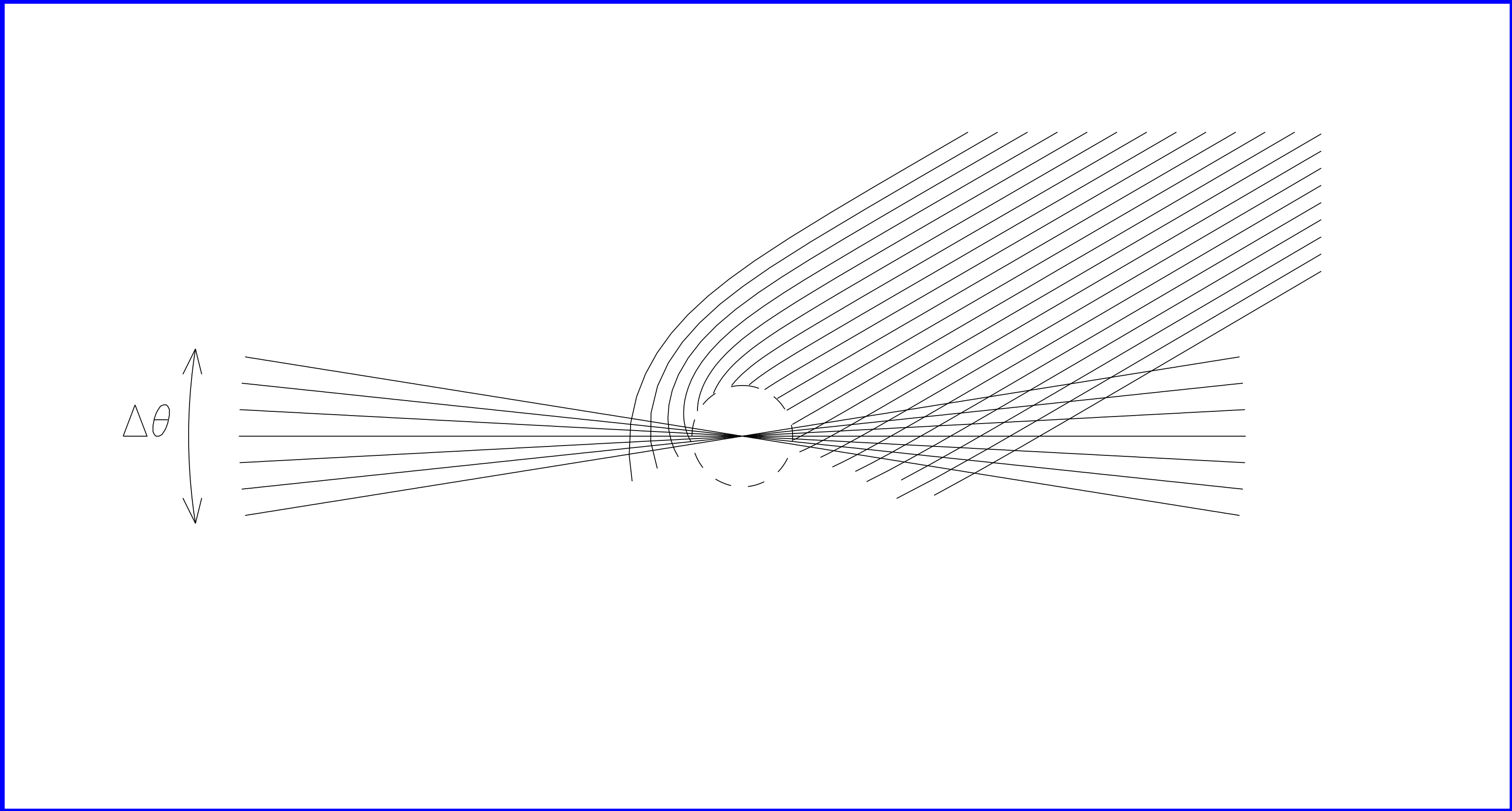
Recent RXTE observations show QPOs at commensurate frequencies with integer ratios



XTE J1550−564
GRO J1655−40
Miller et al. (2001)
Remillard et al. (2002)
H1743−322
Homan et al. (2004)
Remillard et al. (2004)

Hot Spot Model

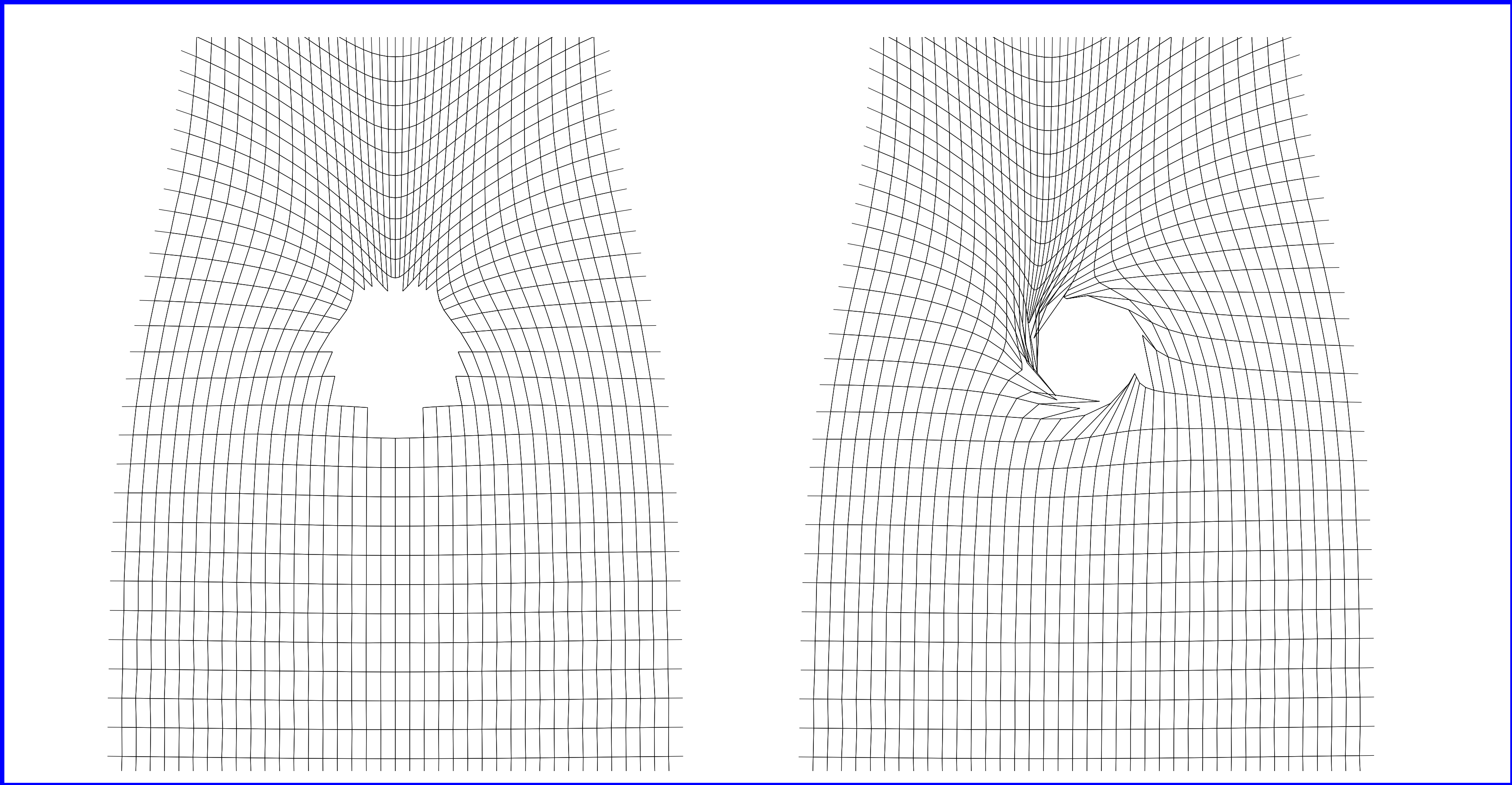
Photons are ray-traced backwards in time from a distant observer through a finite-thickness computational grid.



Schnittman & Bertschinger (2004)

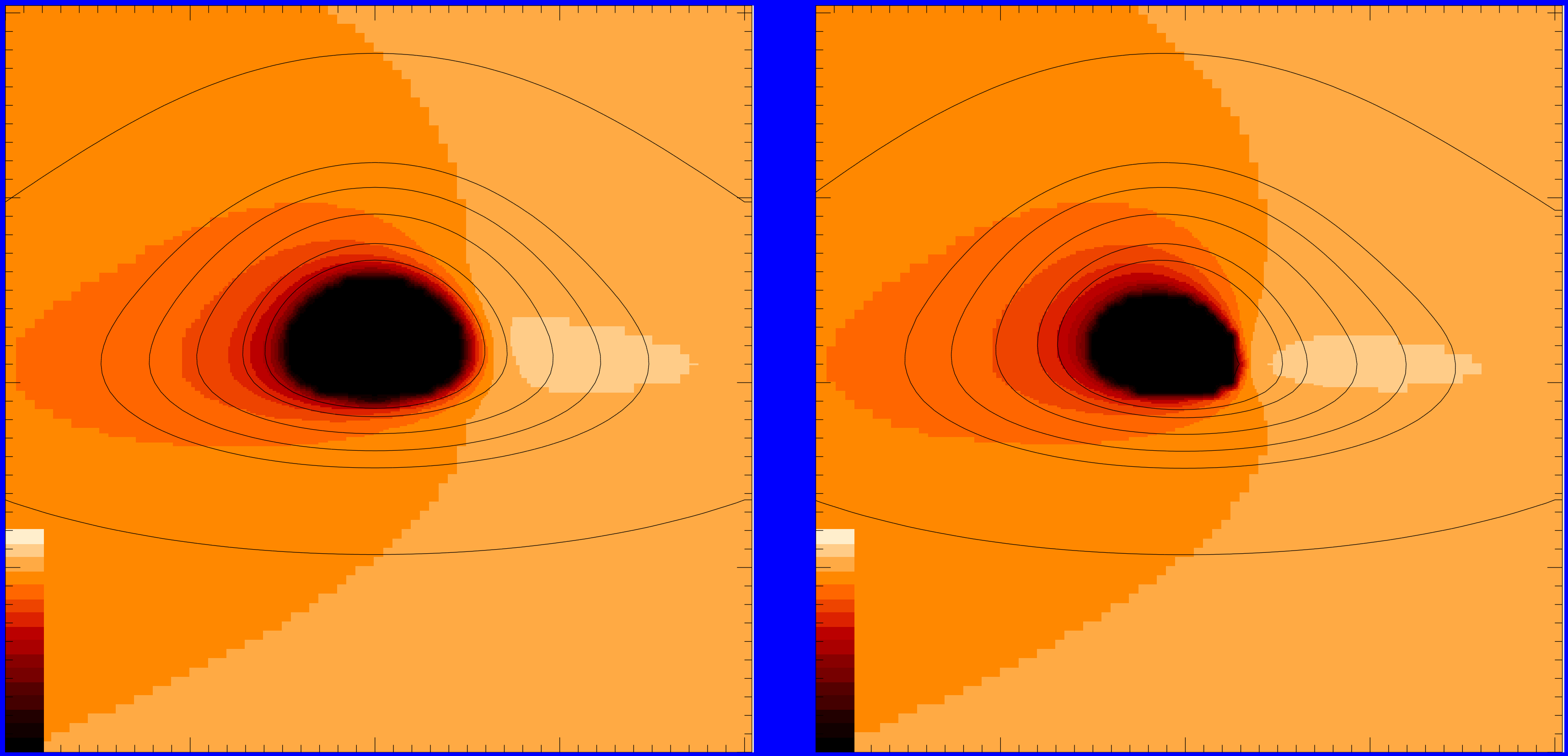
Photons projected on the plane of the accretion disk are bent towards the black hole

$a/M = 0, i = 60^o$ $a/m = 0.95, i = 60^o$



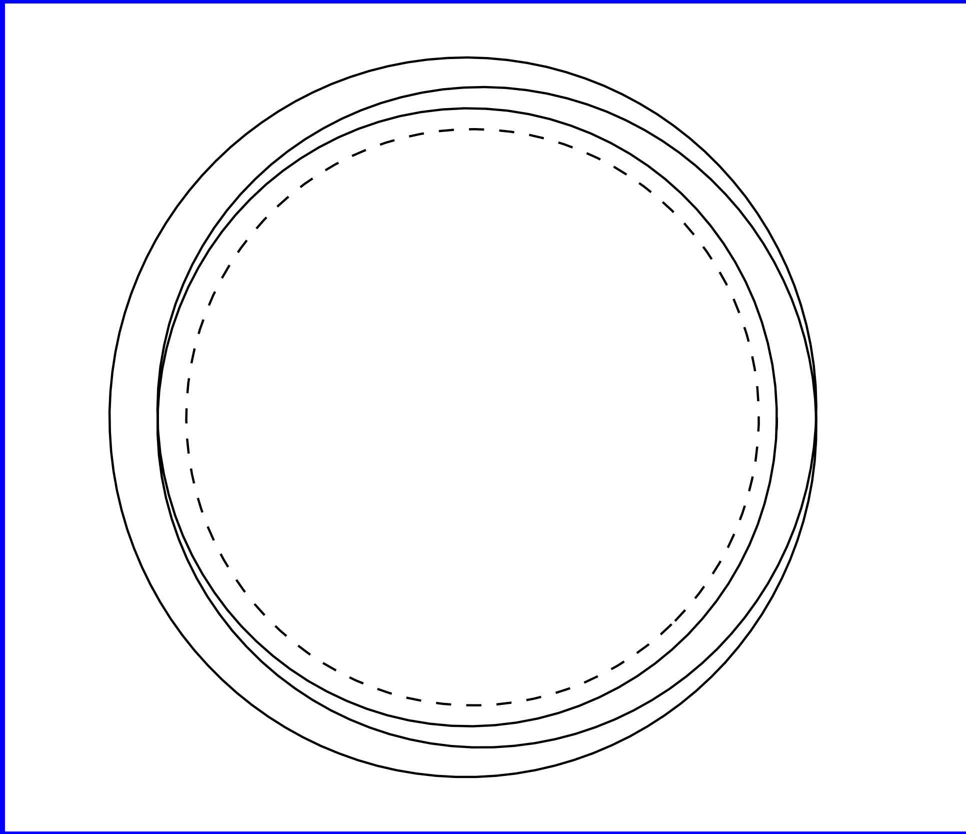
Monochromatic line emission from the disk produces a relativistically redshifted image

$a/M = 0 \quad i = 60^o$ $\qquad$ $a/m = 0.95 \quad i = 60^o$



Light curves are calculated by integrating emission from hot spots orbiting along geodesic orbits

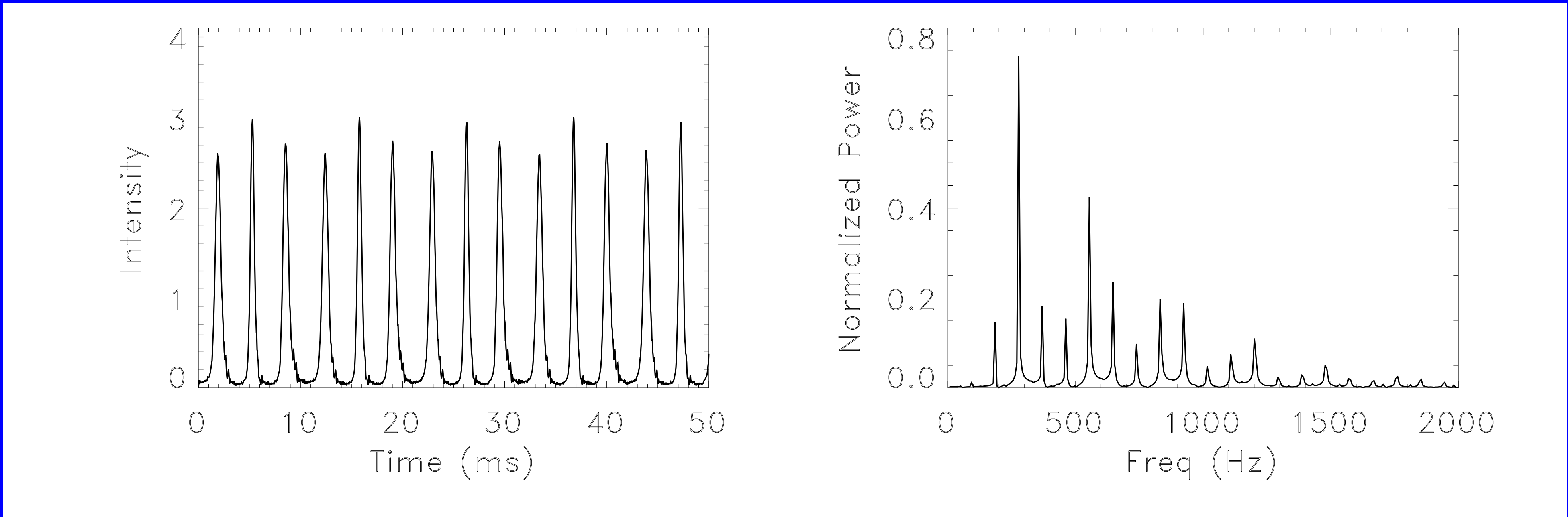
$$e \equiv \frac{r_{max} - r_{min}}{r_{max} + r_{min}} \approx 0.1 \qquad R_{\mathrm{ISCO}} = 4.23M \qquad \nu_\phi = 3\nu_r$$



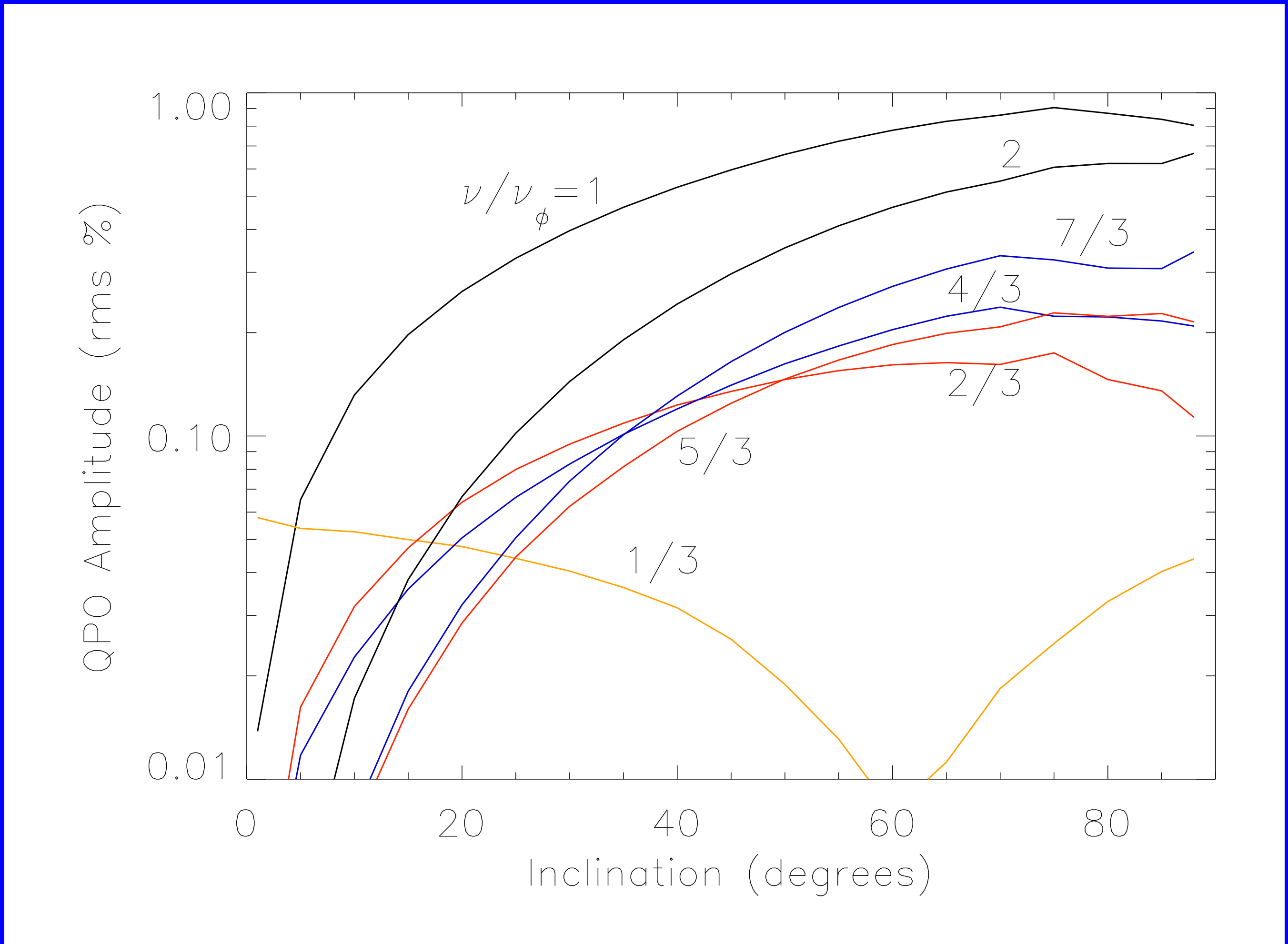
The power spectrum of the X-ray light curve shows the characteristic coordinate frequencies of the hot spot orbit

$M = 10 M_\odot \quad a/M = 0.5 \quad r/M = 4.887$

$\nu_\phi = 285$ Hz $\qquad \nu_r = 95$ Hz



Higher inclination systems giver higher amplitude QPOs and stronger harmonic modes



Random Phase Broadening

We model the light curve as a superposition of periodic functions with random phases

Each segment of the light curve can be written

$$f(t) = \sum_j A_j \sin(2\pi\nu_j t + \phi_j)$$

The hot spot lifetimes have an exponential distribution

$$dN(T) = N_{\mathrm{spot}} \frac{T_f}{T_l^2} e^{-T/T_l} dT$$

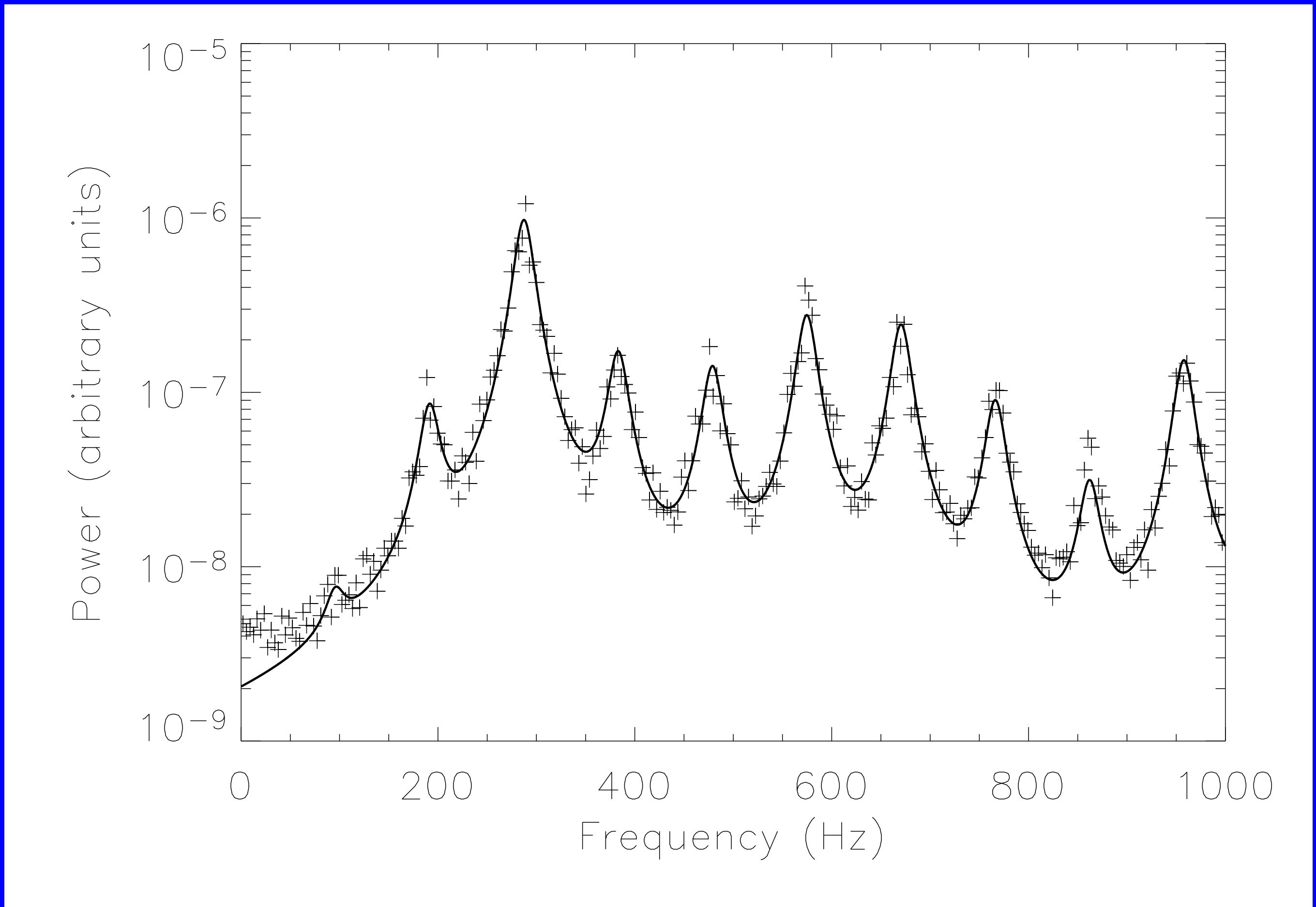
Each peak in the power spectrum is a Lorentzian of width

$$\boxed{\Delta\nu_{\mathrm{phase}} = \frac{1}{2\pi T_l}}$$

van der Klis (1989)

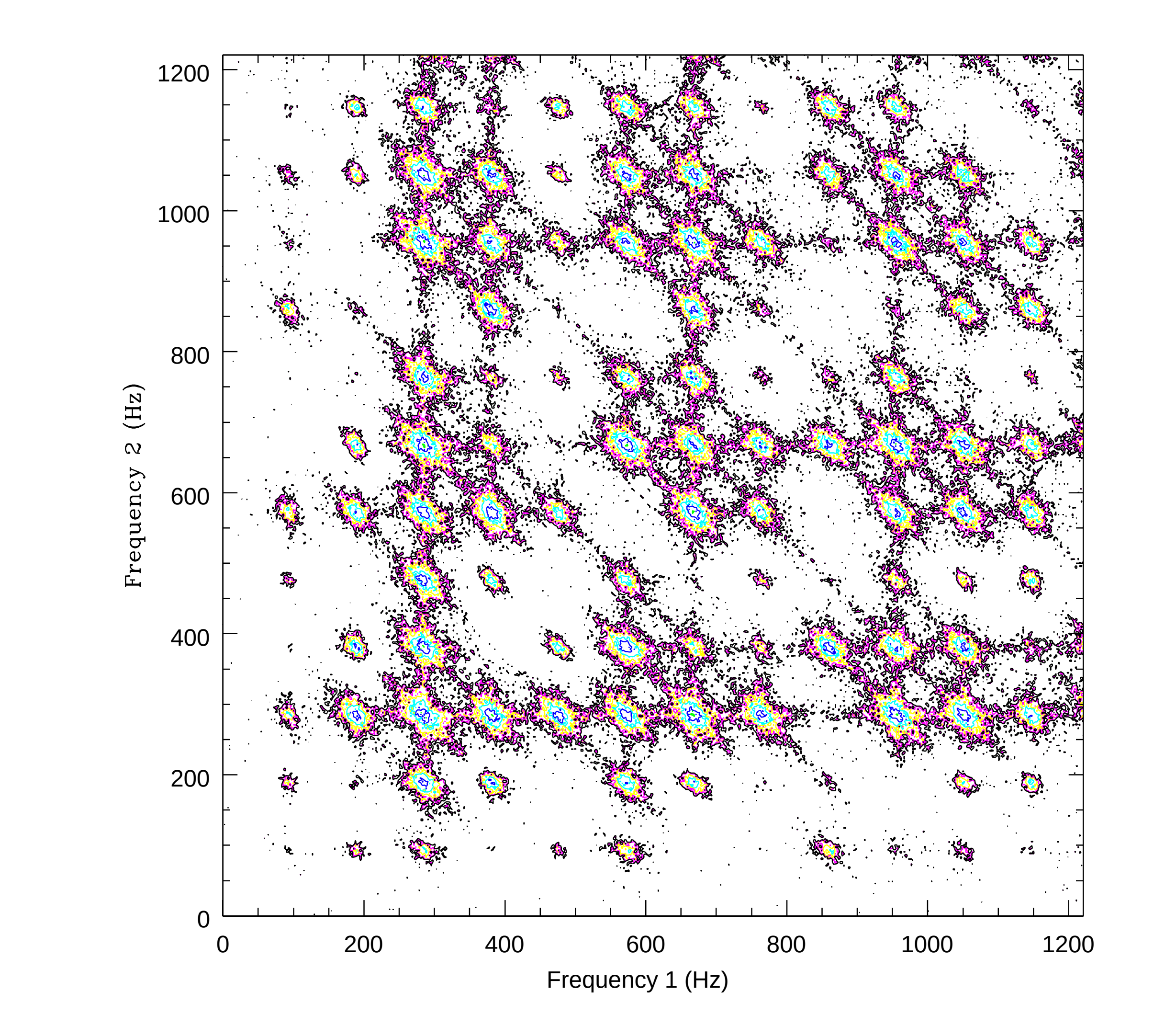
We can verify the analytic results with a simulated light curve

$\Delta\nu = 11$ Hz $\quad T_l = 14.5$ msec ≈ 4 orbits



Schnittman (2004) [astro-ph/0407179]

The bicoherence spectrum shows symmetric broadening around the coordinate frequencies

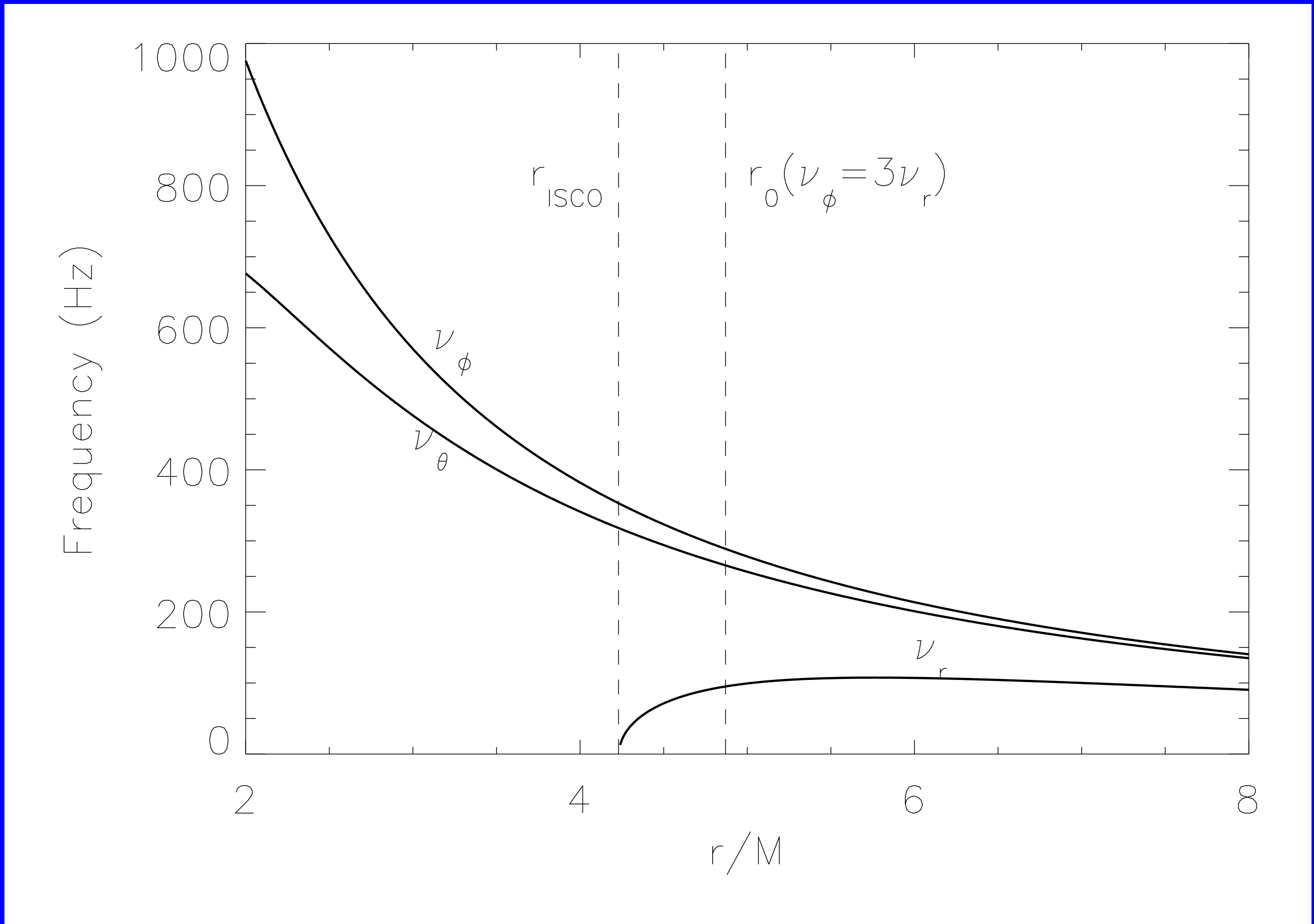


Maccarone & Schnittman (2004), in preparation

Coordinate Frequency Broadening

Kerr orbits have three distinct coordinate frequencies

$M = 10M_\odot \quad a/M = 0.5$



e. g. Bardeen, Press, & Teukolsky (1972)
Merloni et al. (1999)

A finite distribution in orbital radii gives a characteristic width to the coordinate frequencies

We assume a Lorentzian distribution around the 3:1 radius r_0, so the distribution in frequency space is also a Lorentzian

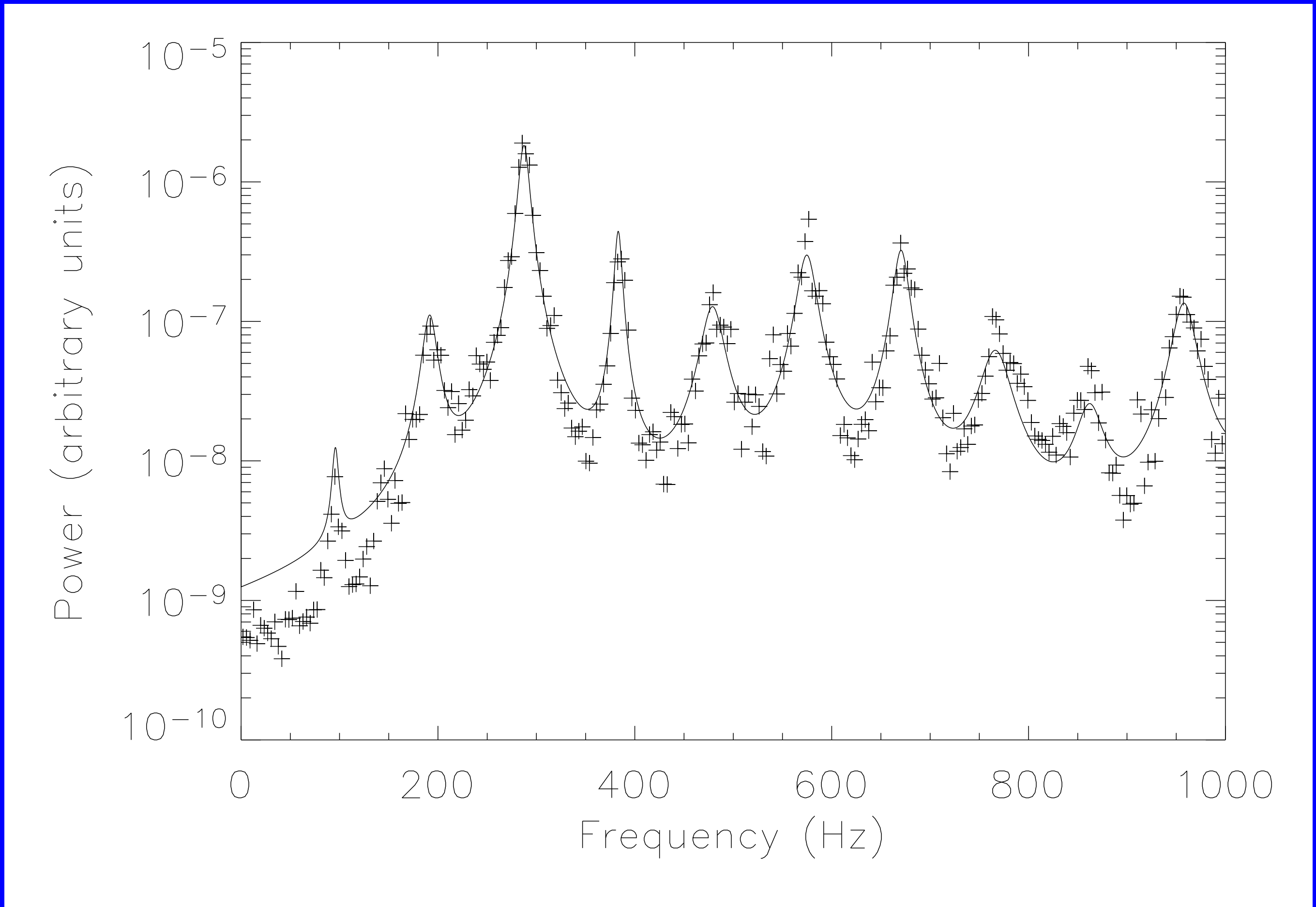
$$P(\nu_j)d\nu_j = \frac{d\nu_j/(\pi\Delta\nu_j)}{1+\left(\frac{\nu_j-\nu_{j0}}{\Delta\nu_j}\right)^2}$$

The QPO power is focused around the harmonics and beat modes with $\nu = n\nu_\phi \pm \nu_r$. Each peak will have a different width given by

$$\boxed{\Delta\nu_{\rm freq} = \Delta r\left(n\frac{d\nu_\phi}{dr} \pm \frac{d\nu_r}{dr}\right)_{r_0}}$$

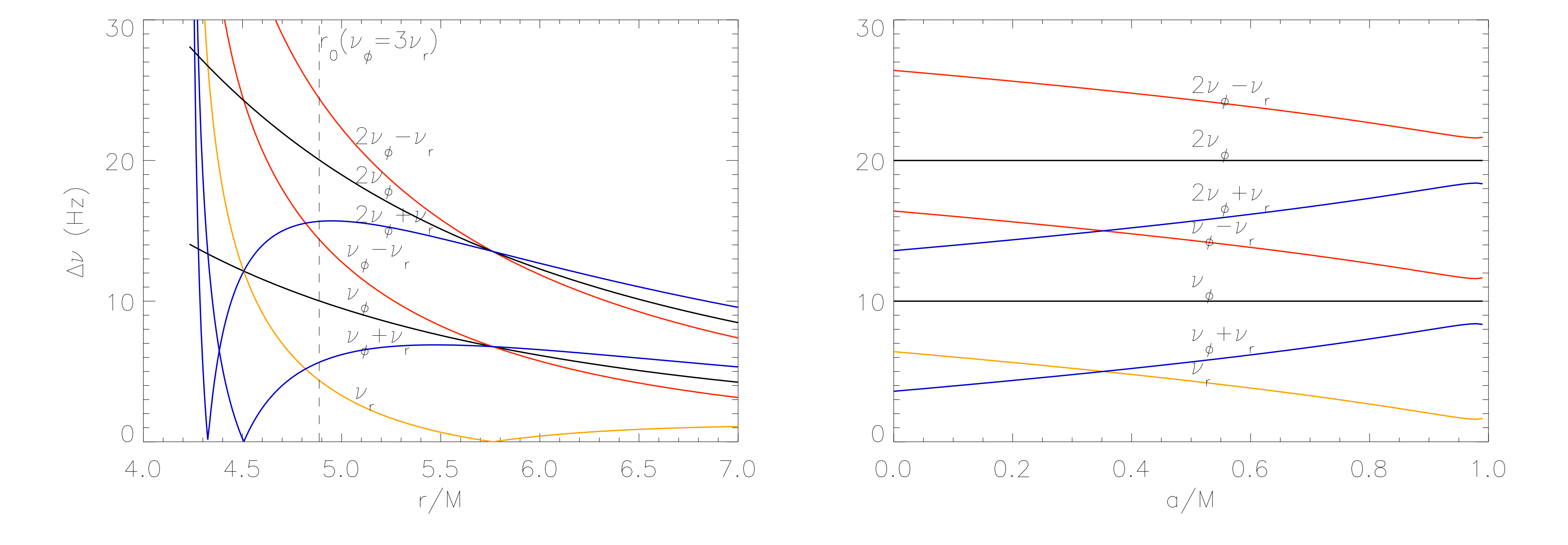
The net power spectrum is made up of convolved Lorentzian peaks

$\Delta\nu_{\rm phase} = 1.5\ \rm Hz \qquad \Delta\nu_{\rm freq} \approx 4 - 20\ \rm Hz$

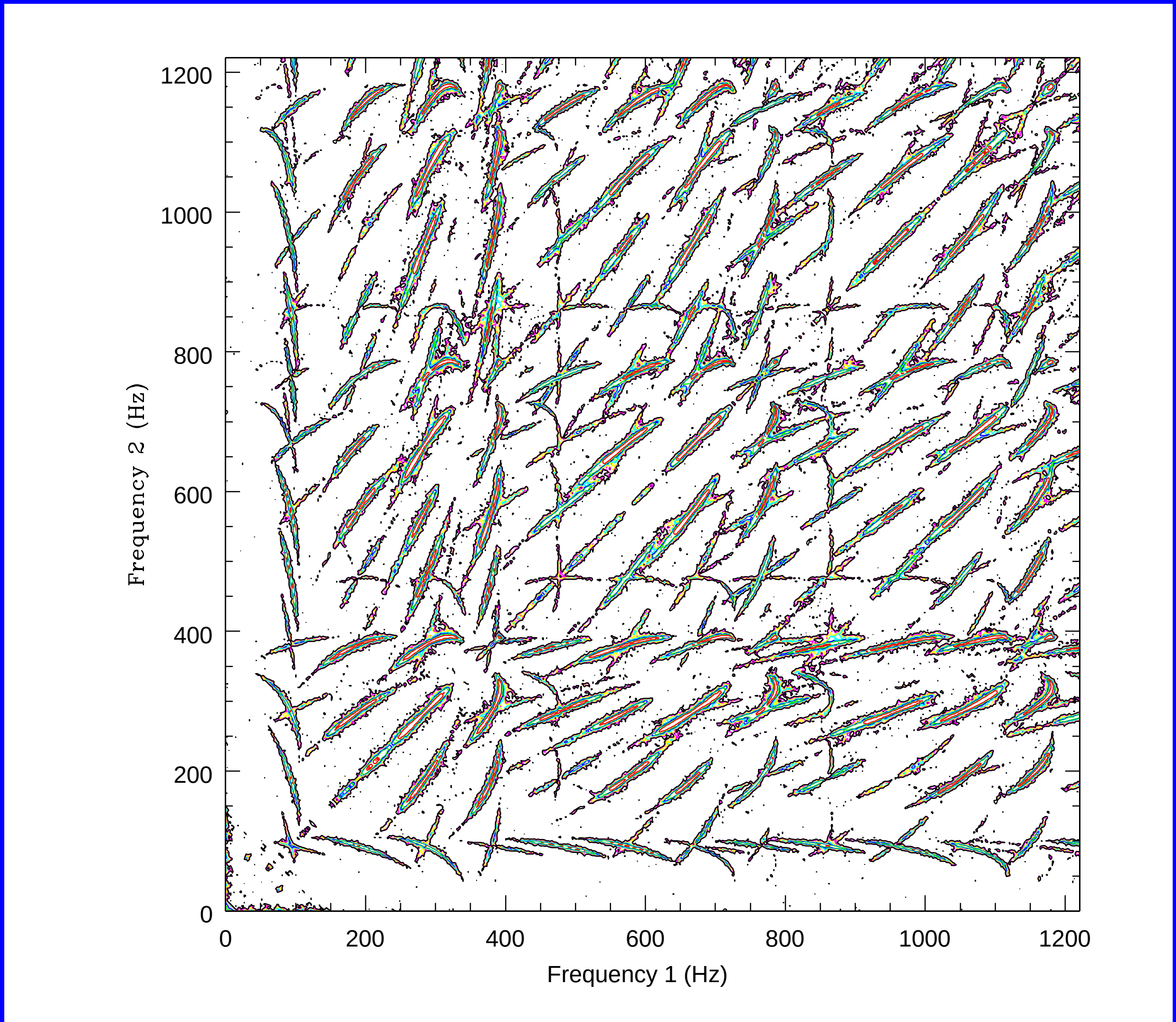


By measuring the widths of multiple QPO peaks, we should be able to map out the GR metric around the hot spot orbits

$a/M = 0.5$ $\qquad$ $r = r(\nu_\phi = 3\nu_r)$



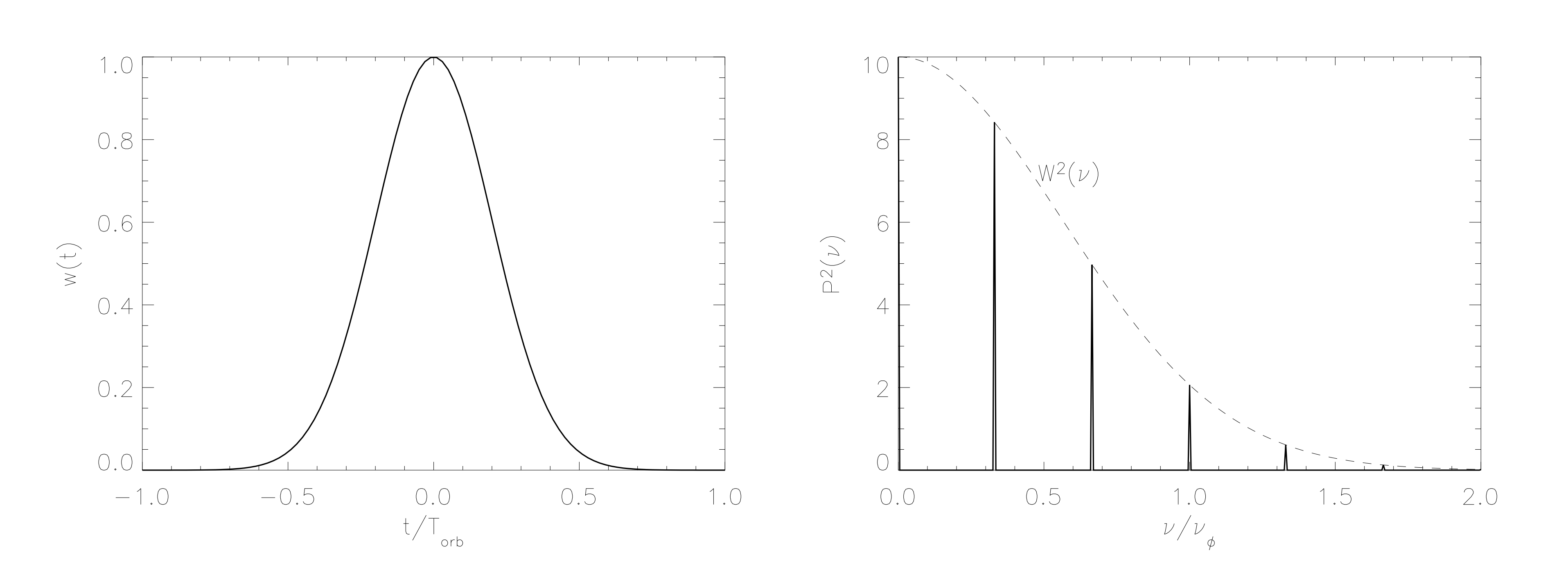
The bicoherence could be used to map out the space-time around the resonant orbits



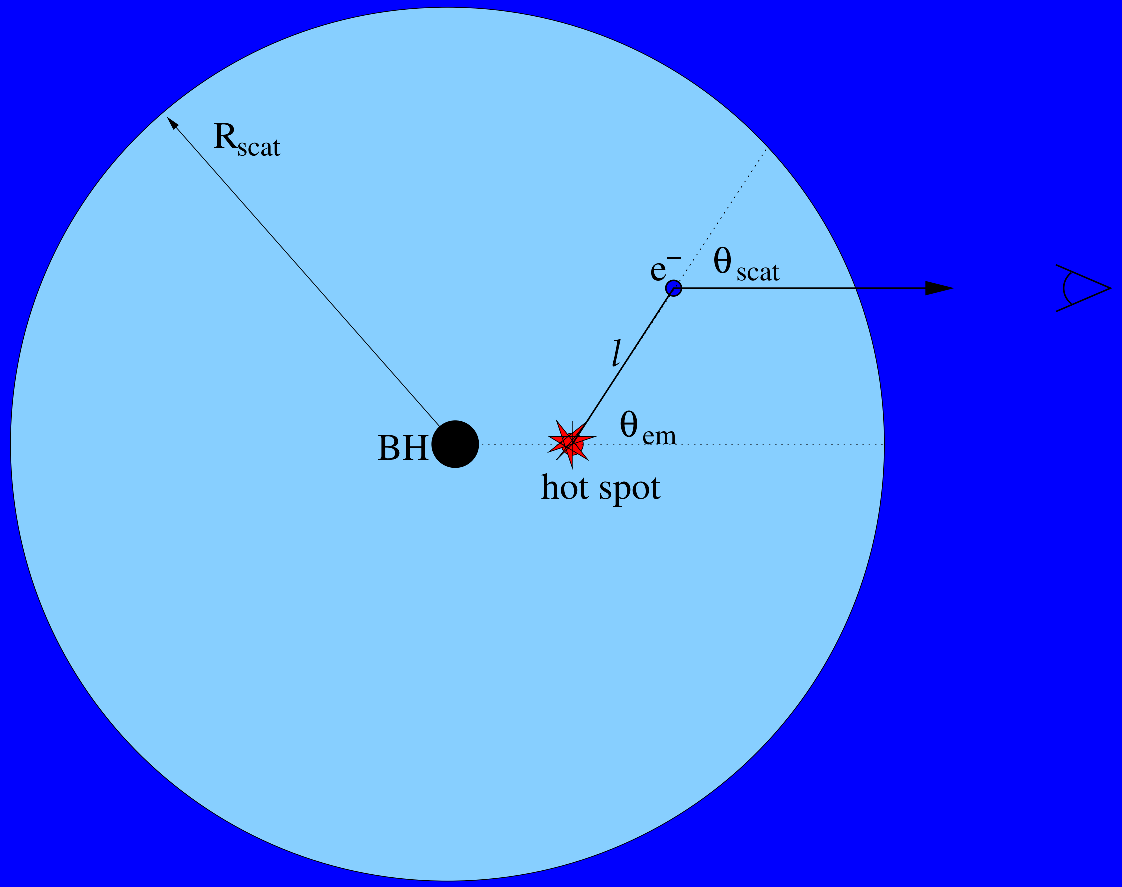
Harmonic Damping

Stretching the hot spot into an arc damps out higher harmonics while increasing the low frequency power

$T_{\mathrm{window}} = \Delta\phi / \Omega_\phi$ $\qquad$ $\Delta\phi \approx 180^\circ$



We include a simple electron scattering model to study the effect of a low-density corona on the power spectrum



Each scattered photon has an additional time delay to the observer

The probability of scattering after a distance l is

$$P(l)dl = \frac{dl}{\lambda_{\mathrm{es}}} e^{-l/\lambda_{\mathrm{es}}}$$

Our geometry requires $\theta_{\mathrm{em}} = \theta_{\mathrm{scat}}$, giving the differential cross section as

$$\frac{d\sigma}{d\theta} = \frac{3}{8}\sigma_T \sin\theta(1+\cos^2\theta)$$

Integrating over all forward-scattered photons ($\theta < \pi/2$), we find the average additional path length to be

$$D_{\mathrm{scat}} = \frac{7}{16} l$$

Coronal scattering smears out the light curve in time

Scattering once in the corona adds a time delay Δt to each photon, giving an effective convolution in time with window function

$$w_{\mathrm{scat}}(\Delta t) = \frac{1}{T_{\mathrm{scat}}} e^{-\Delta t / T_{\mathrm{scat}}}$$

The characteristic time delay T_{scat} is given by

$$T_{\mathrm{scat}} = \frac{D_{\mathrm{scat}}}{c} = \frac{7}{16} \frac{\lambda_{\mathrm{es}}}{c}$$

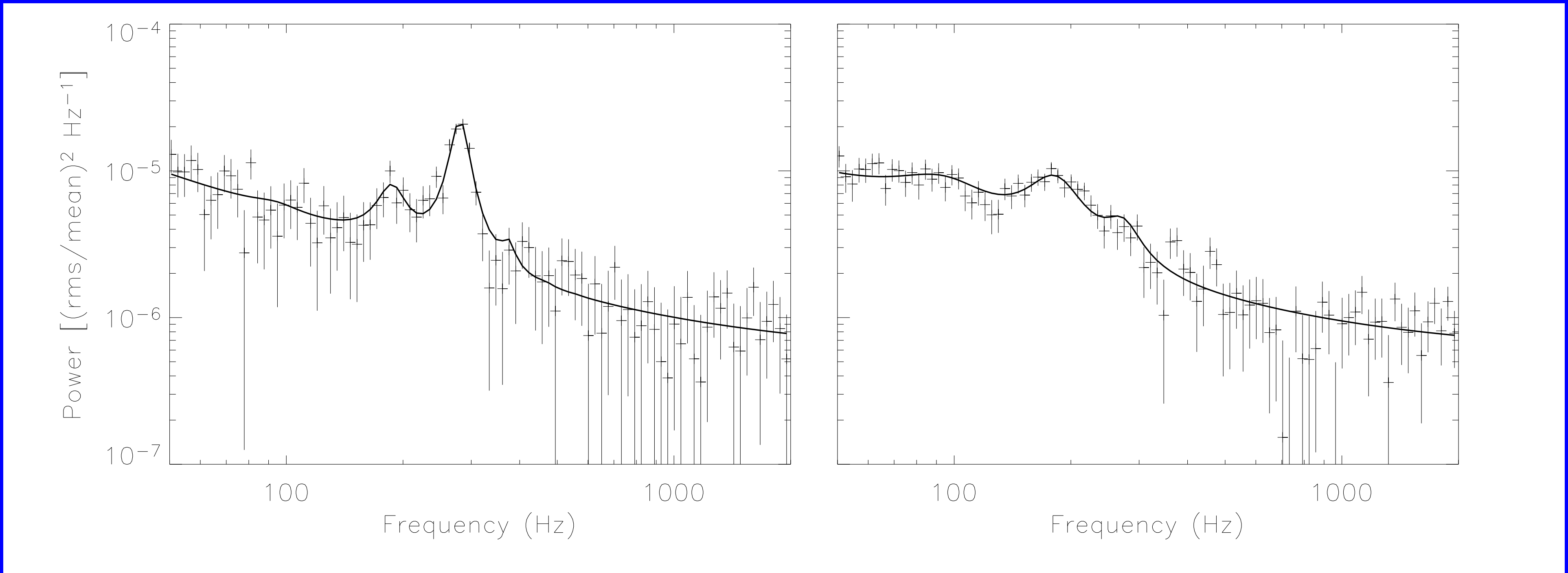
The corresponding power spectrum is damped by a Lorentzian

$$\boxed{W^2_{\mathrm{scat}}(\nu) = \frac{1}{1 + (2\pi T_{\mathrm{scat}} \nu)^2}}$$

Comparison with Data

The complete hot spot model can be applied successfully to the QPO observations of XTE J1550–564

type "A" type "B"



Remillard et al.(2002)

The two QPO types can be characterized by different hot spot lifetimes and arc lengths

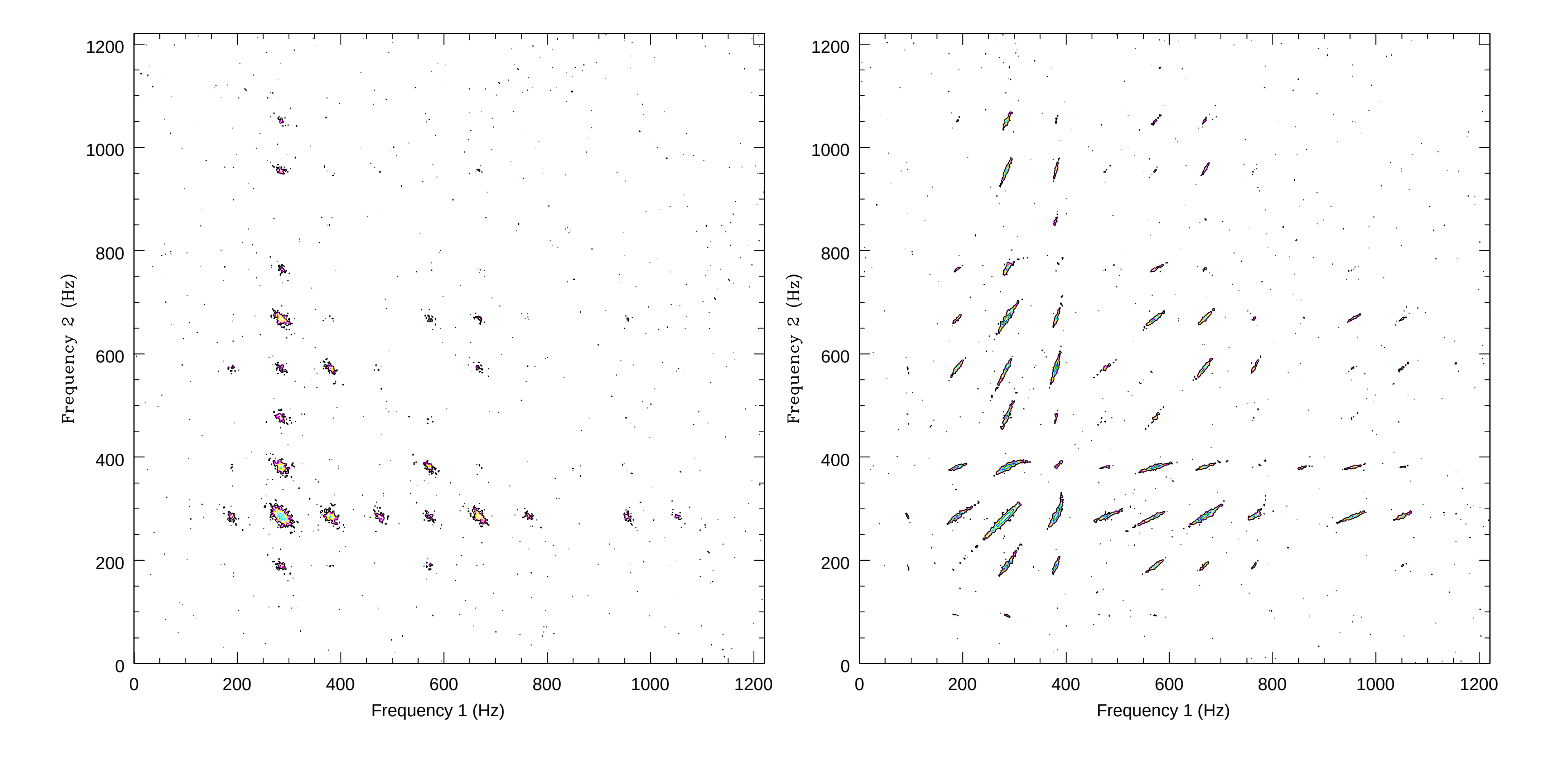
Model parameters for QPOs from XTE J1550-564
(1σ) confidences are shown in parentheses

Parameter	**Type A**	**Type B**
orbital frequency ν_ϕ (Hz)	280.1(2.4)	270.5(12)
lifetime T_l (ms)	10(2.0)	5(1.5)
(orbits)	2.8(0.55)	1.4(0.4)
resonance width Δr (M)	0.02(0.05)	0.025(0.12)
scattering length λ_{es} (M)	5(10)	10(20)
arc length $\Delta\phi$ (°)	155(30)	285(20)
flux ratio $\frac{I_{\text{hotspot}}}{I_B+I_{\text{hotspot}}}$	0.085(0.025)	0.38(0.05)

A next-generation X-ray timing mission could distinguish between QPO broadening mechanisms by measuring the bicoherence

phase broadening

frequency broadening



Summary/Conclusions

- The geodesic hot spot model successfully matches the frequencies and amplitudes of multiple QPO peaks

- The superposition of multiple hot spots with random phases and a distribution of orbital radii explains the shape and widths of the QPO peaks

- Higher harmonic modes are damped by arc shearing and coronal scattering

- Additional data and increased sensitivity will allow us to verify/constrain/rule out the hot spot model