Radiation Transport Around Kerr Black Holes

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Doctoral Thesis Defense

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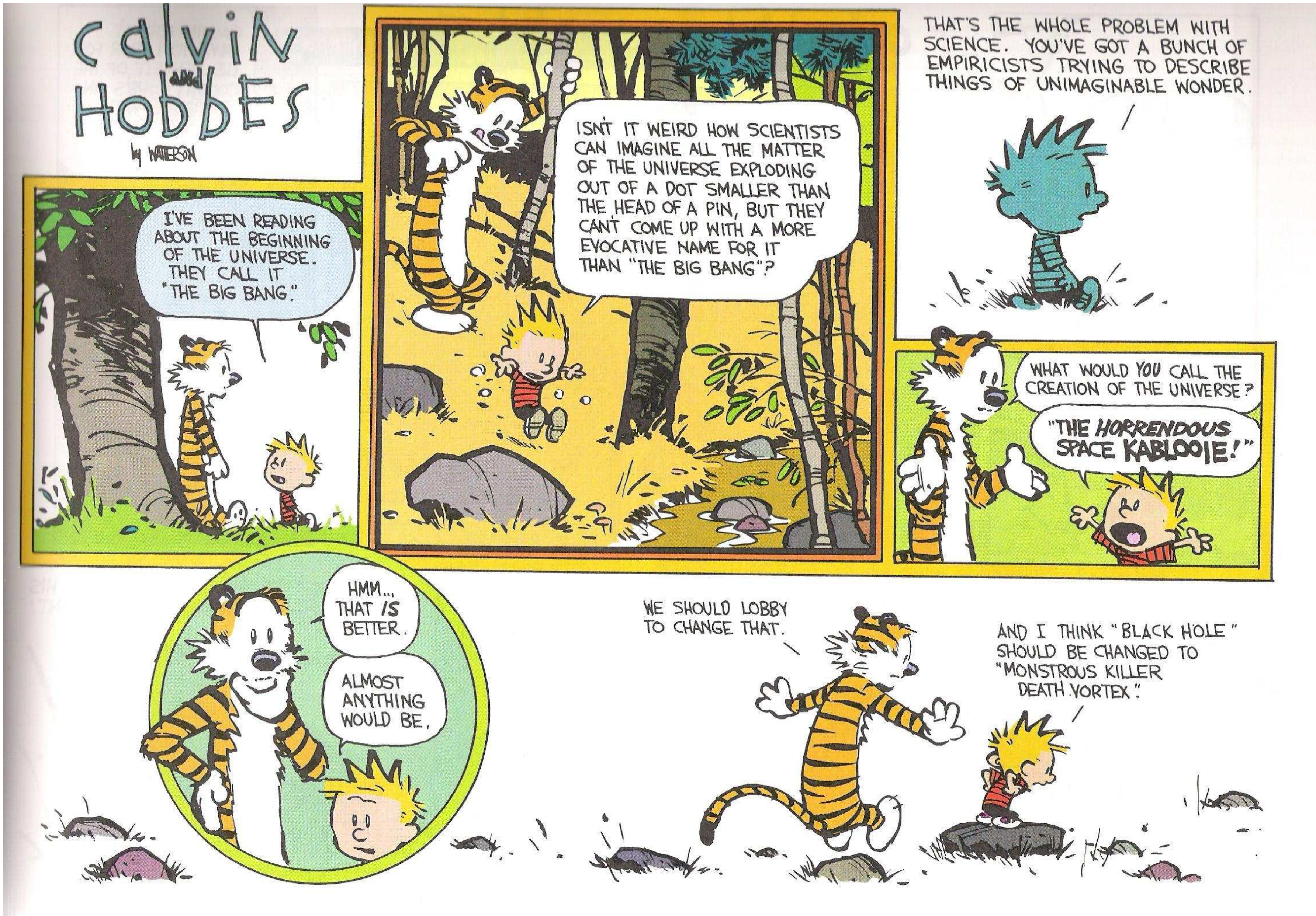
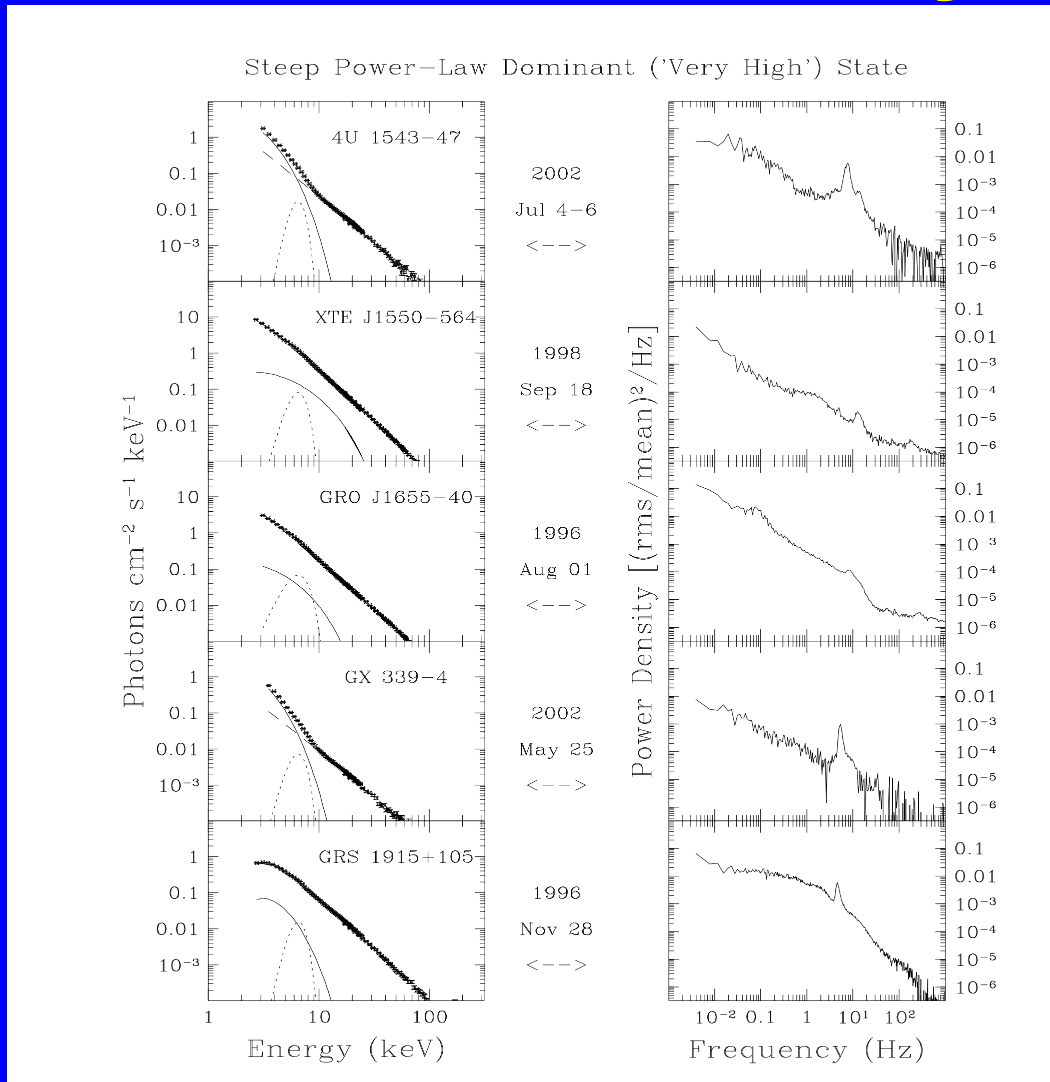

Calvin and Hobbes
by WATTERSON
I'VE BEEN READING ABOUT THE BEGINNING OF THE UNIVERSE. THEY CALL IT "THE BIG BANG."
ISN'T IT WEIRD HOW SCIENTISTS CAN IMAGINE ALL THE MATTER OF THE UNIVERSE EXPLODING OUT OF A DOT SMALLER THAN THE HEAD OF A PIN, BUT THEY CAN'T COME UP WITH A MORE EVOCATIVE NAME FOR IT THAN "THE BIG BANG"?
THAT'S THE WHOLE PROBLEM WITH SCIENCE. YOU'VE GOT A BUNCH OF EMPIRICISTS TRYING TO DESCRIBE THINGS OF UNIMAGINABLE WONDER.
WHAT WOULD *YOU* CALL THE CREATION OF THE UNIVERSE?
"THE *HORRENDOUS* SPACE **KABLOOIE**!"
HMM... THAT *IS* BETTER.
ALMOST ANYTHING WOULD BE.
WE SHOULD LOBBY TO CHANGE THAT.
AND I THINK "BLACK HOLE" SHOULD BE CHANGED TO "MONSTROUS KILLER DEATH VORTEX."

Outline

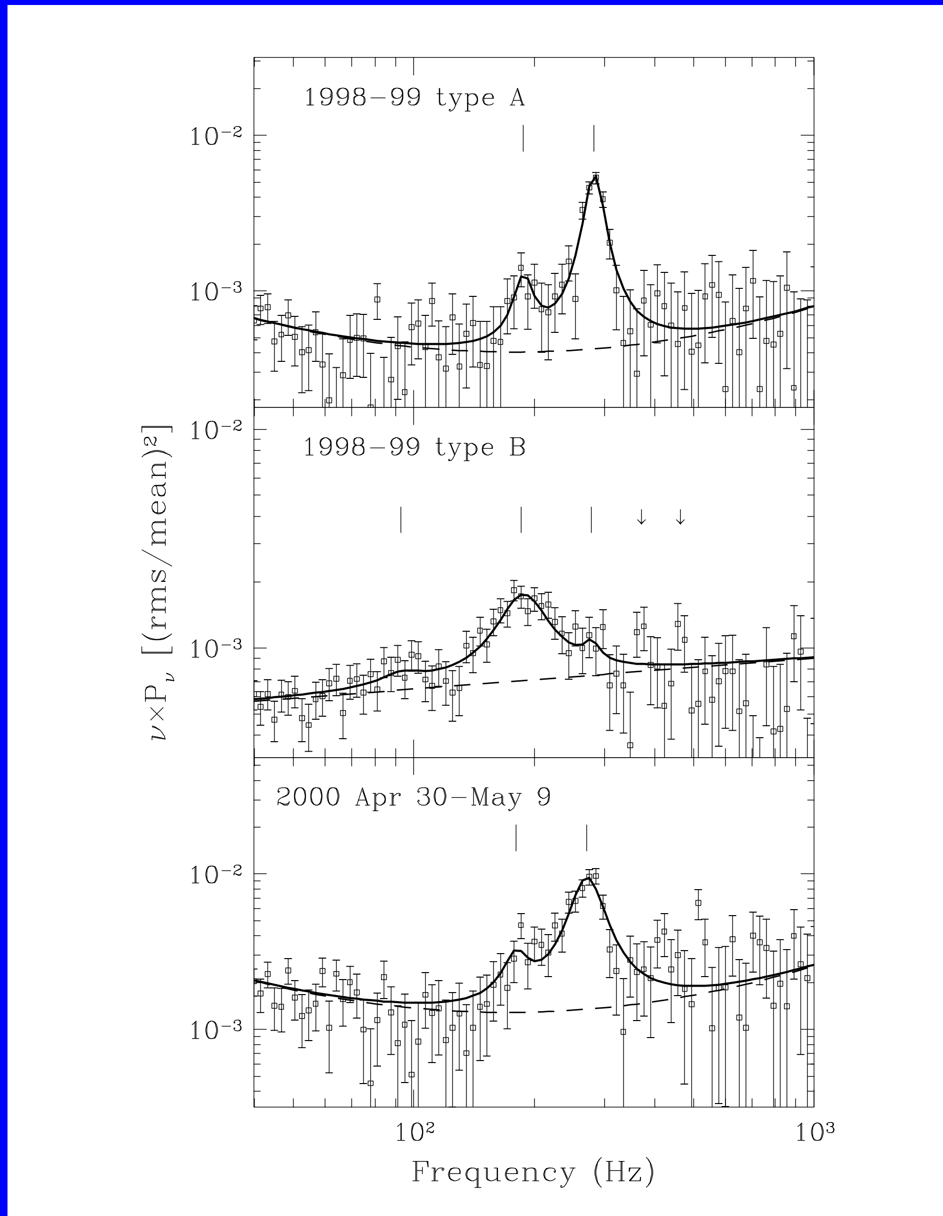
- Background/Motivation
- Ray Tracing
- Hot Spot Model
- Peak Broadening
- Harmonic Damping
- Comparison with Data
- Monte Carlo Electron Scattering

RXTE observations of black holes in the steep power law state show a variety of QPOs



McClintock & Remillard (2004)

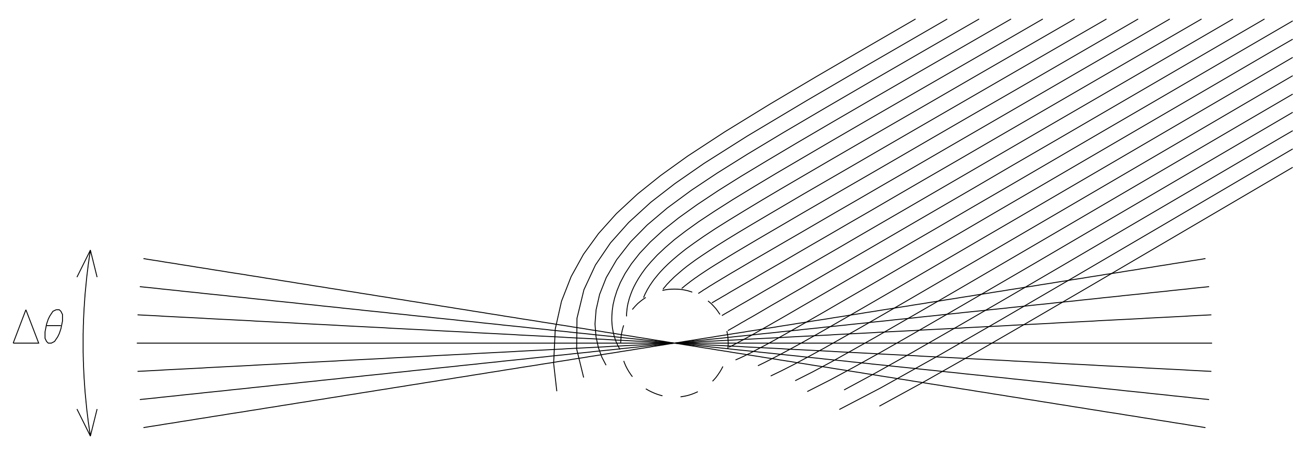
Many of the high frequency QPOs appear at commensurate frequencies with integer ratios



XTE J1550–564
GRO J1655–40
Miller et al. (2001)
Remillard et al. (2002)
GRS 1915+105
Remillard et al. (2003)
H1743–322
Homan et al. (2004)
Remillard et al. (2004)

Ray Tracing / Hot Spot Model

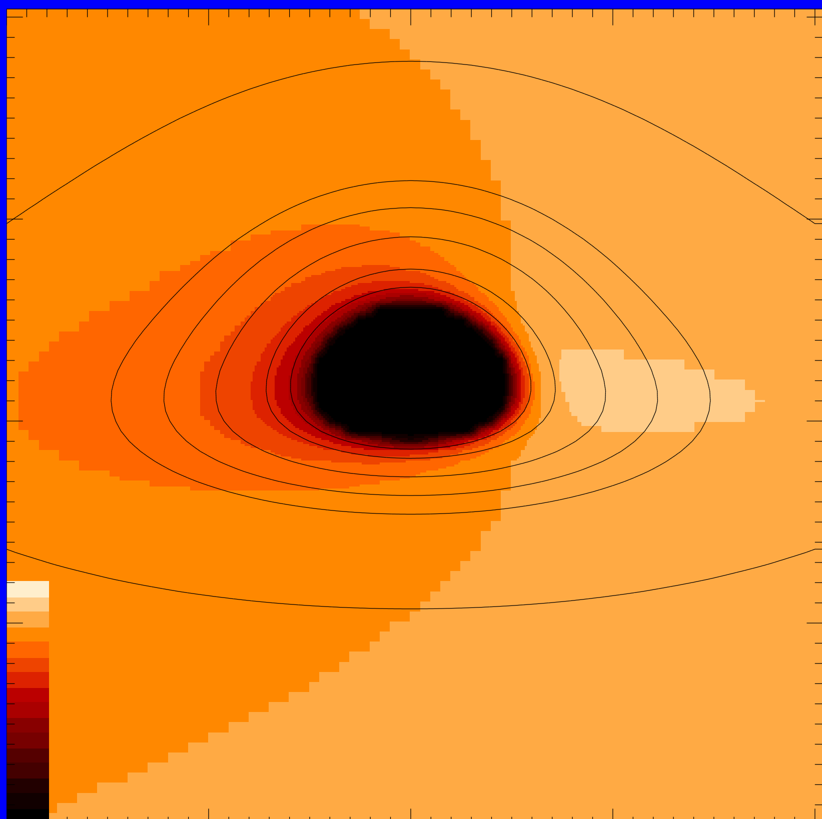
Photons are ray-traced backwards in time from a distant observer through a finite-thickness computational grid.



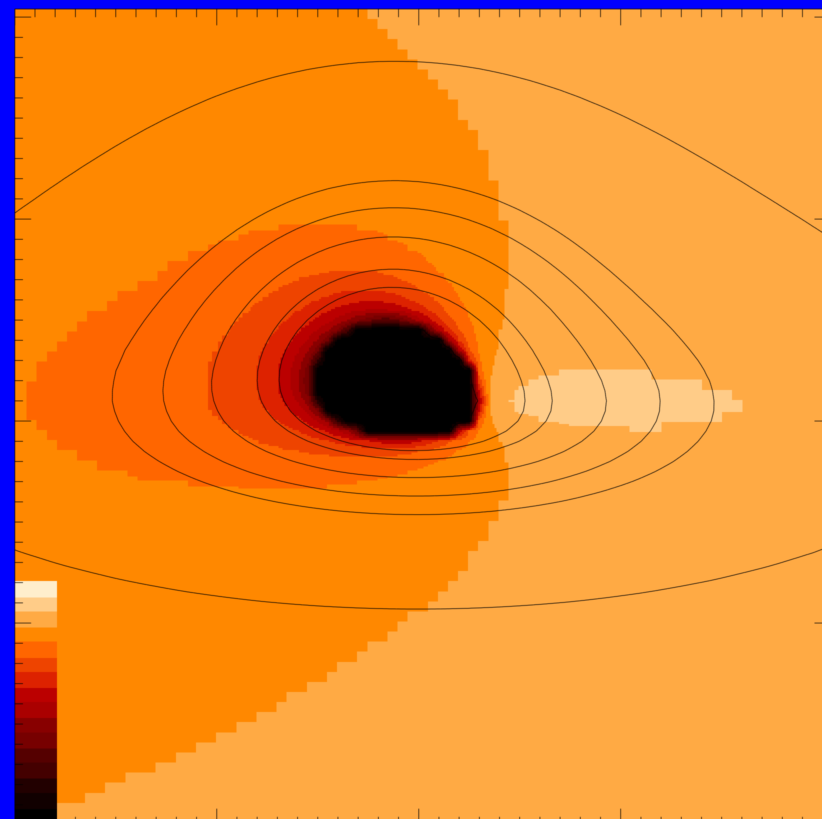
Schnittman & Bertschinger (2004)

Monochromatic line emission from the disk produces a relativistically redshifted image

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

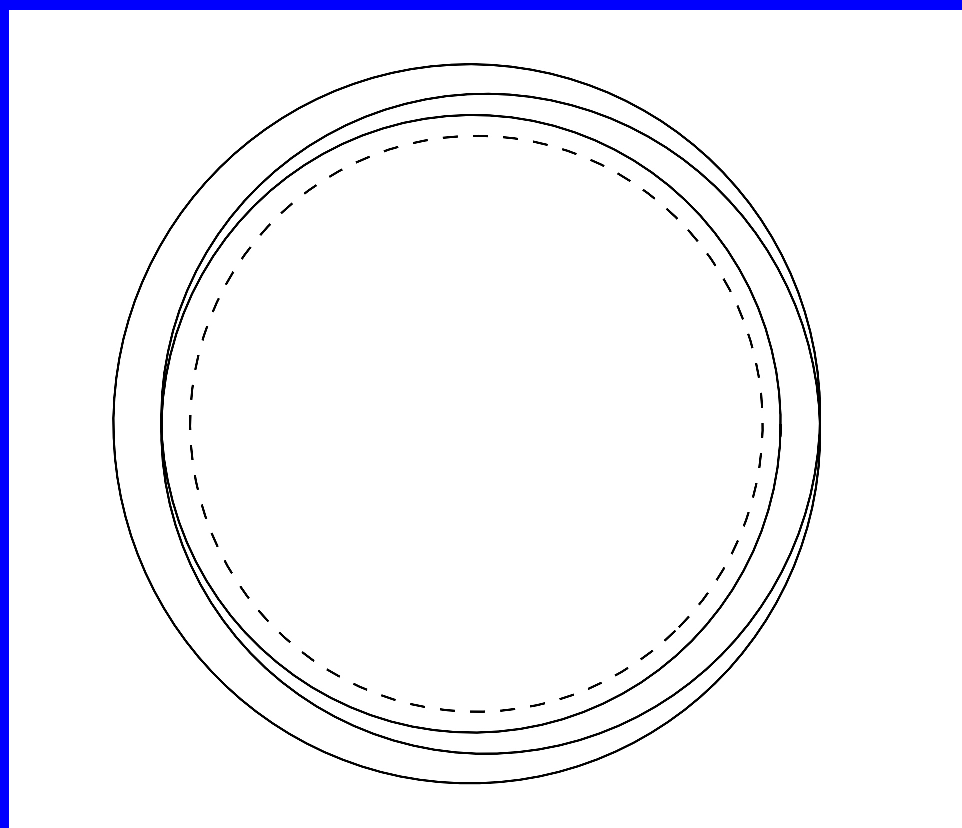


$a/m = 0.95 \quad i = 60^o$



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

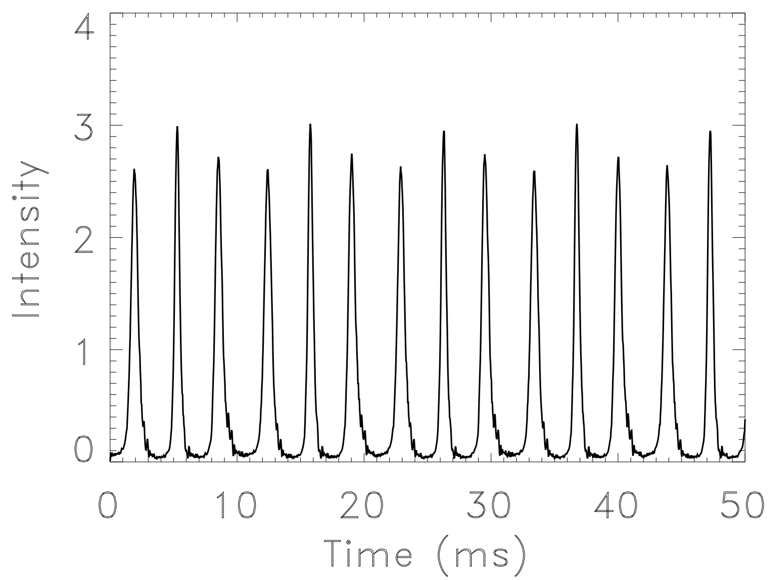
$$a/M = 0.5 \quad R_{\rm ISCO} = 4.23M \quad \nu_\phi = 3\nu_r \quad e \equiv \frac{r_{max} - r_{min}}{r_{max} + r_{min}} \approx 0.1$$

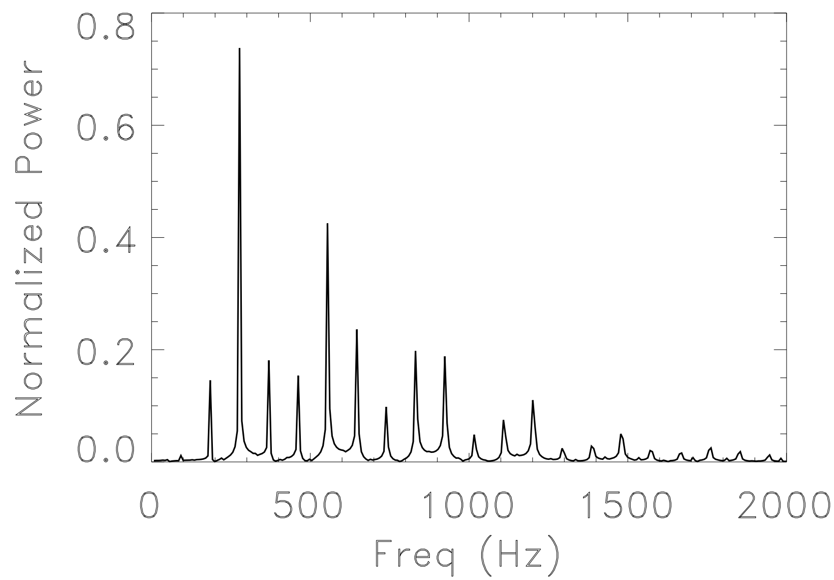


The power spectrum of the X-ray light curve shows the characteristic coordinate frequencies of the hot spot orbit

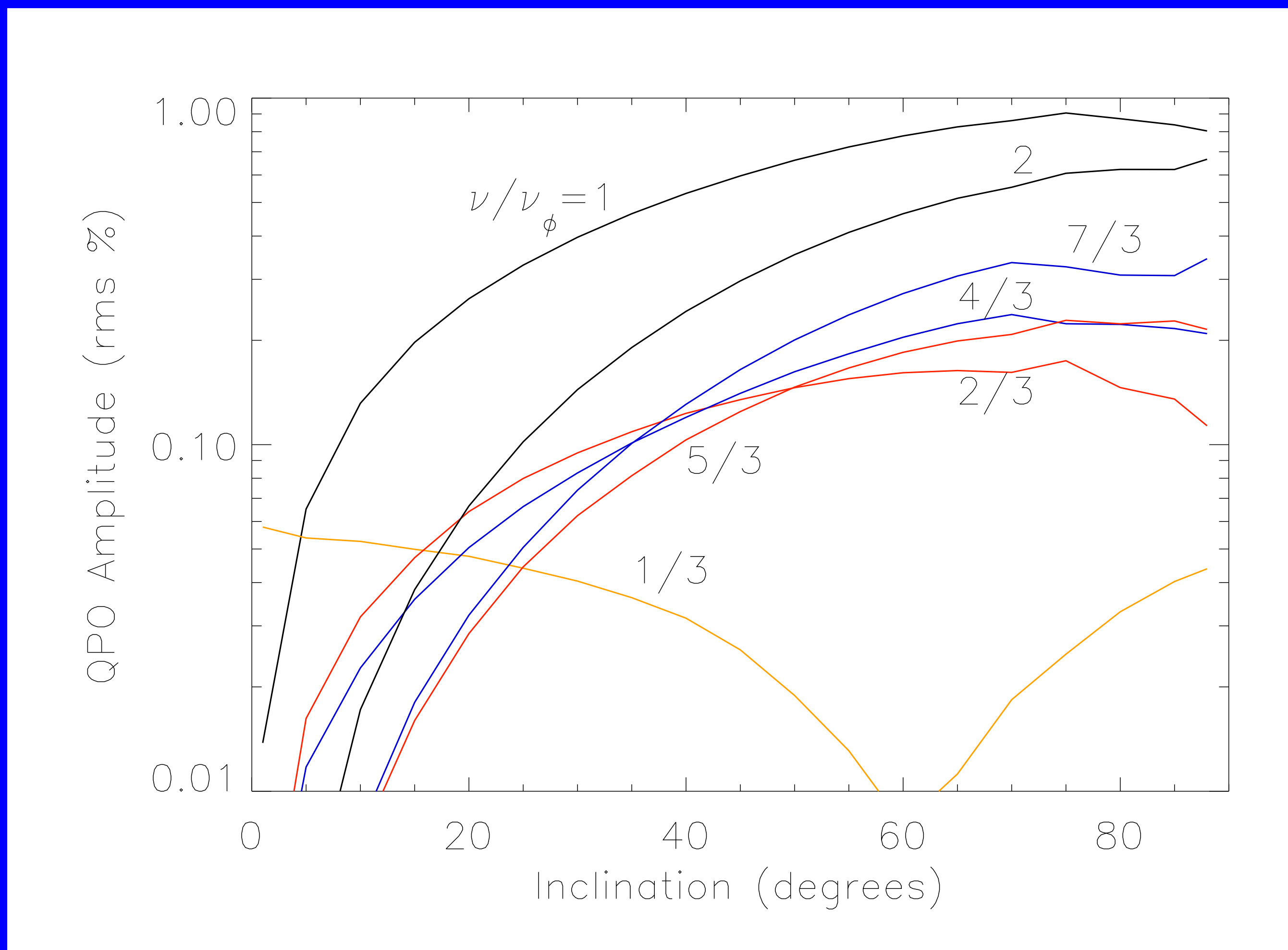
$M = 10M_\odot \quad a/M = 0.5 \quad r/M = 4.887$

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





Higher inclination systems giver higher amplitude QPOs and stronger harmonic modes



Peak 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

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

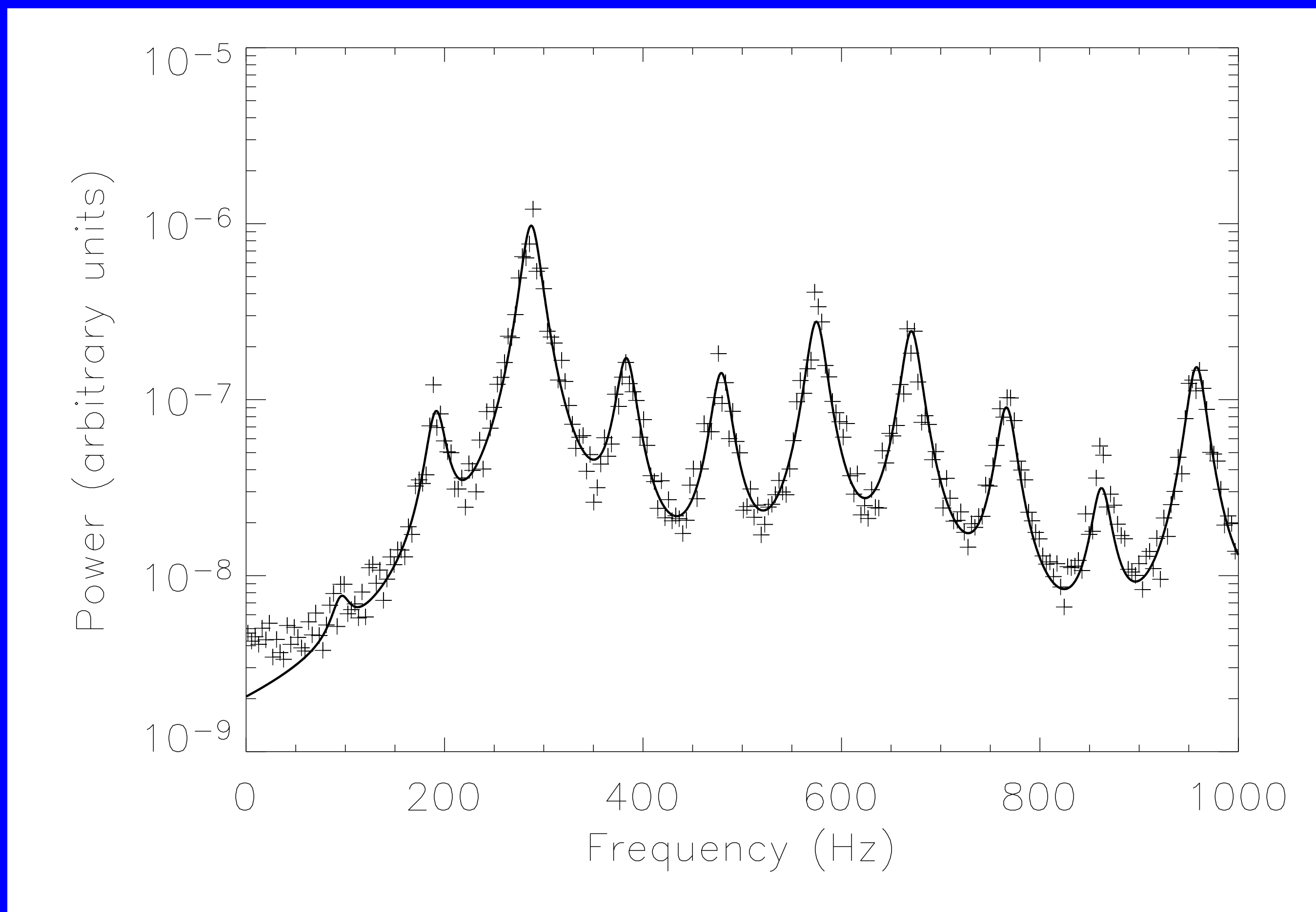
Each peak in the power spectrum is a Lorentzian of width

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

van der Klis (1989)

We can verify the analytic results with a simulated light curve

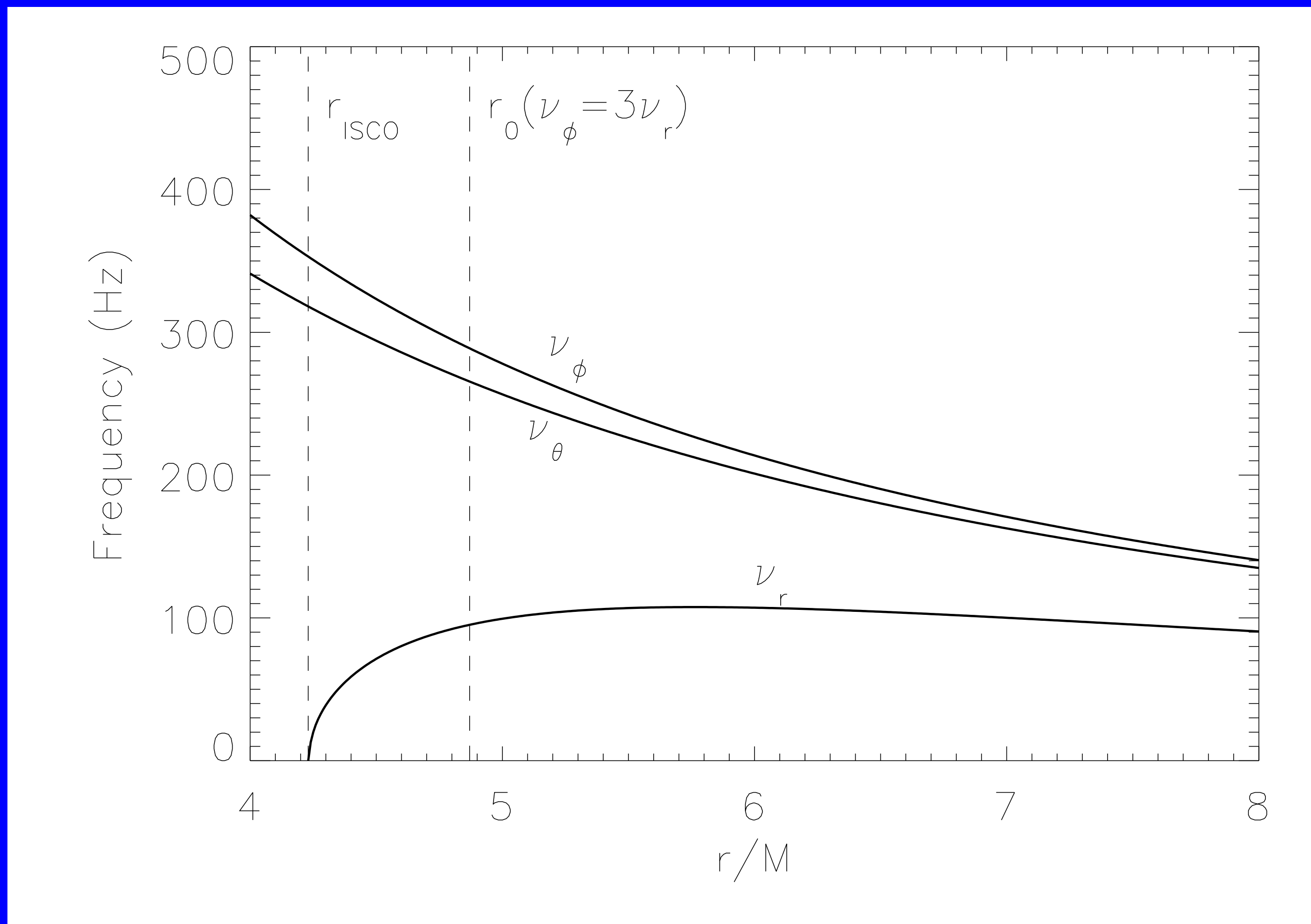
$\Delta\nu_{\text{phase}} = 11$ Hz $\quad T_l = 14.5$ msec ≈ 4 orbits



Schnittman (2005) [astro-ph/0407179]

Kerr orbits have three distinct coordinate frequencies

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



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

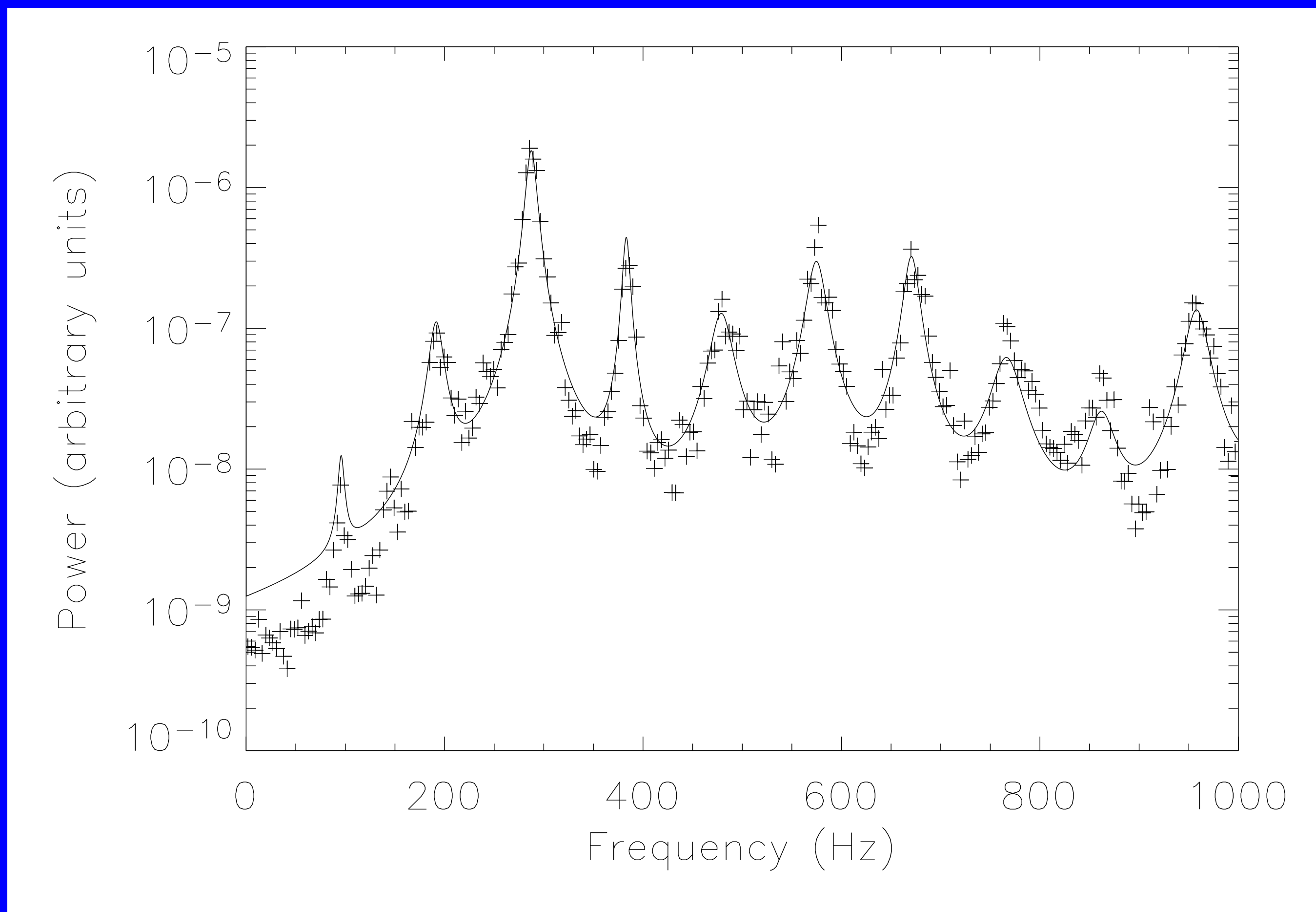
$$P(\nu_j)d\nu_j = \frac{d\nu_j/(\pi\Delta\nu_j)}{1+\left(\frac{\nu_j-\nu_{j0}}{\Delta\nu_j}\right)^2}$$

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

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

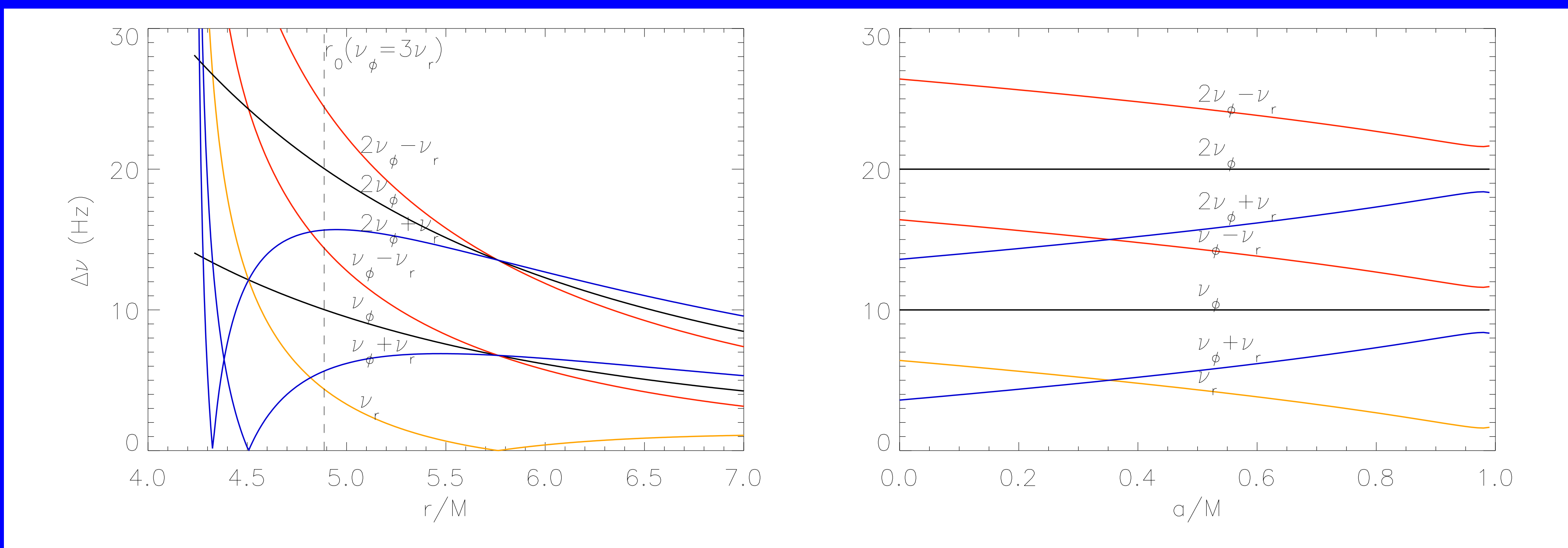
The net power spectrum is made up of convolved Lorentzian peaks of different widths

$\Delta\nu_{\text{phase}} = 1.5$ Hz $\quad \Delta\nu_{\text{freq}} \approx 4 - 20$ Hz



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

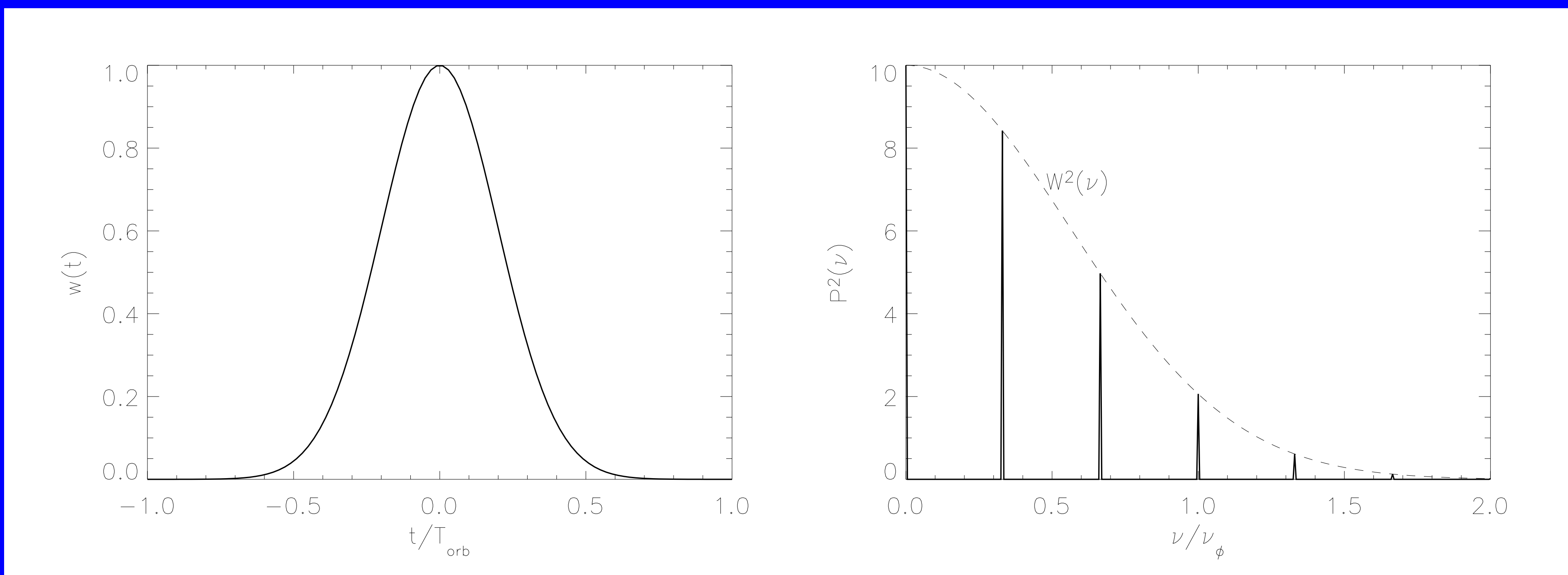
$a/M = 0.5$ $\qquad$ $r = r(\nu_\phi = 3\nu_r)$



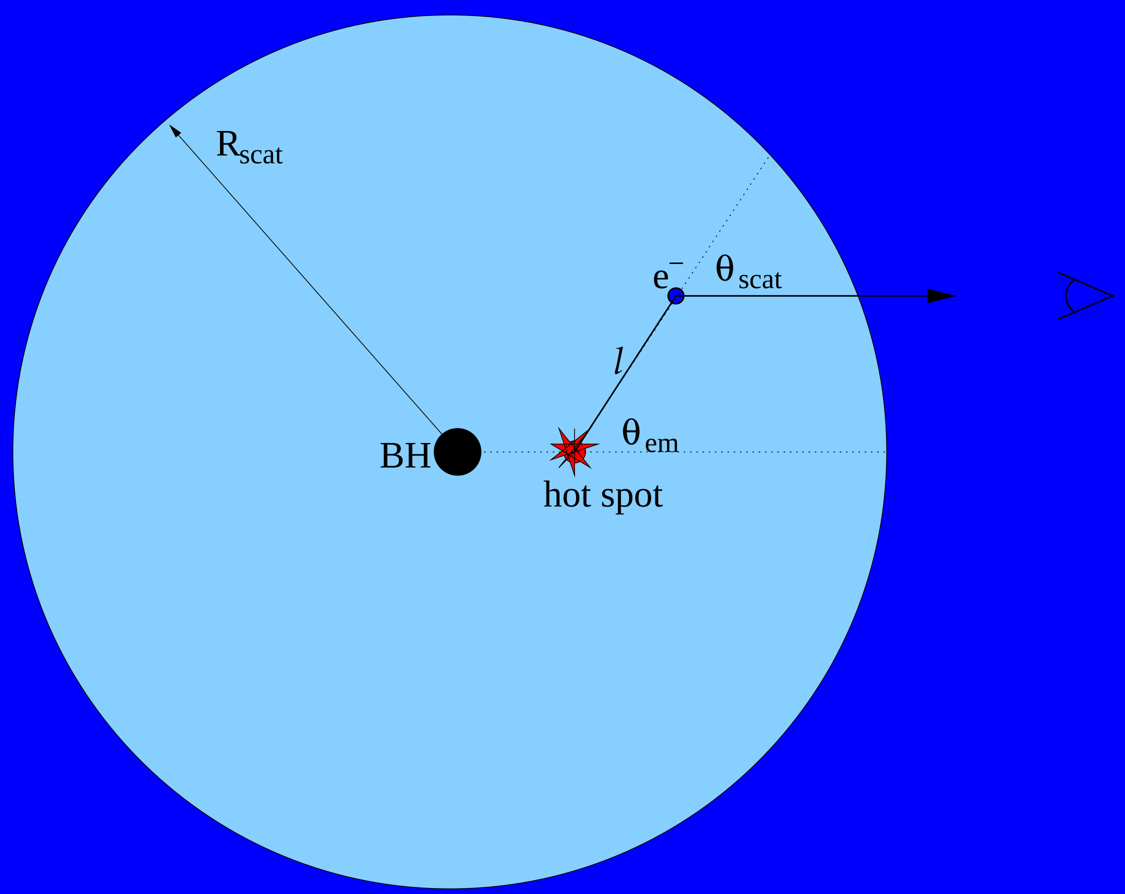
Harmonic Damping, Comparison with Data

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

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



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



Coronal scattering smears out the light curve in time

Each scattering event 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 the light crossing time for the corona

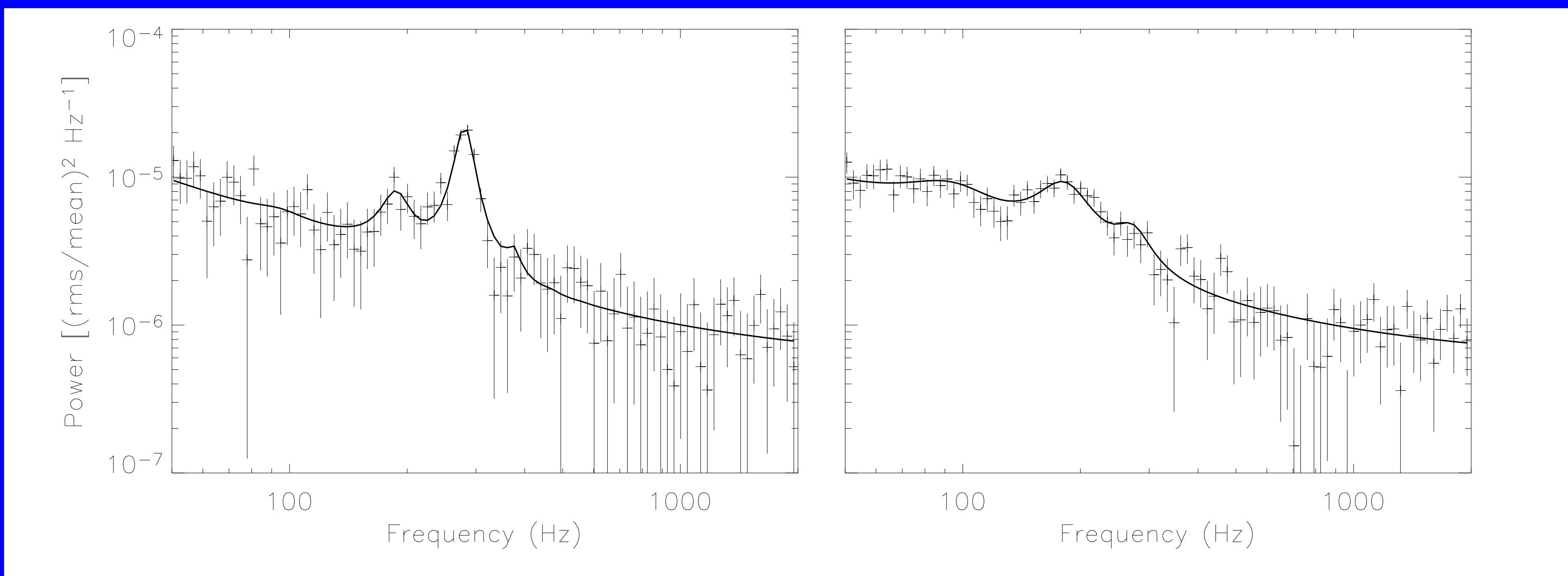
$$T_{\mathrm{scat}} \sim \frac{D_{\mathrm{scat}}}{c}$$

The corresponding power spectrum is damped by a Lorentzian

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

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)

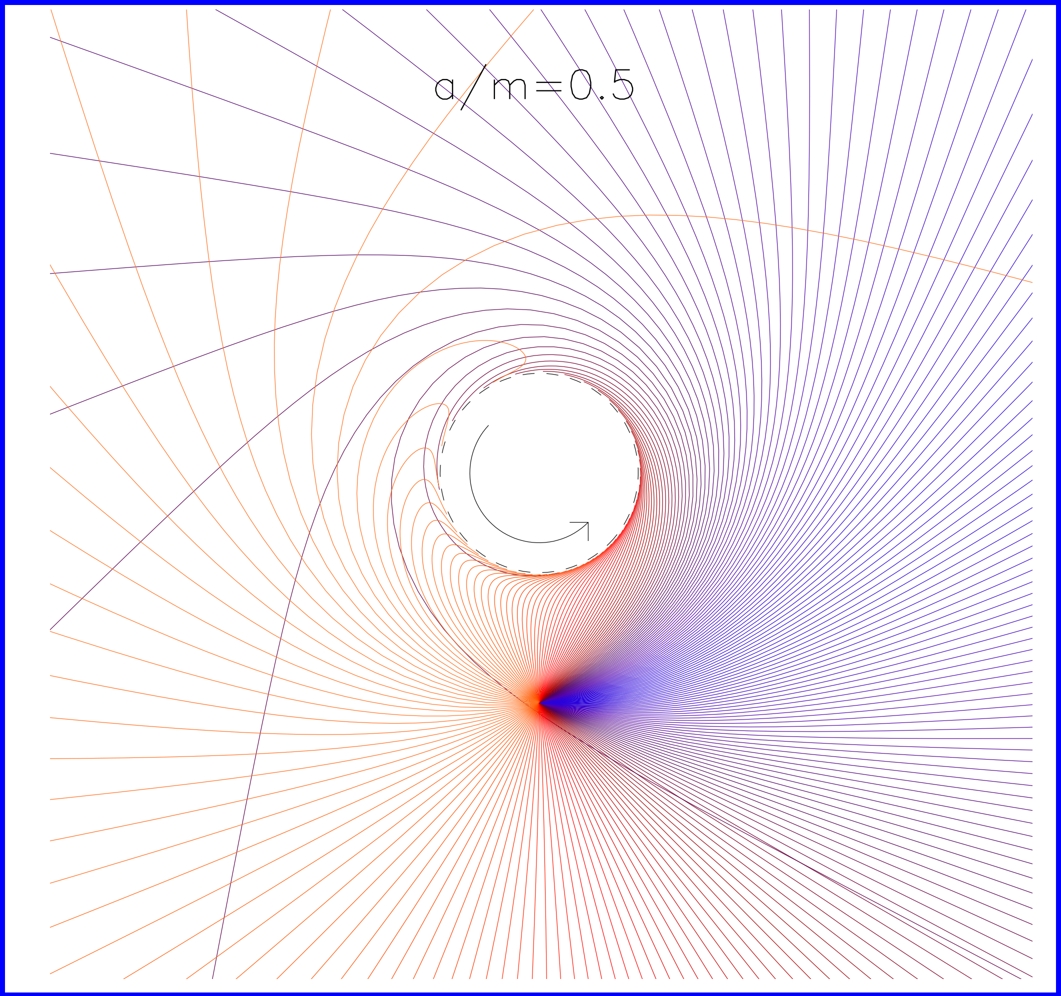
The two QPO types can be characterized by different hot spot lifetimes and arc lengths

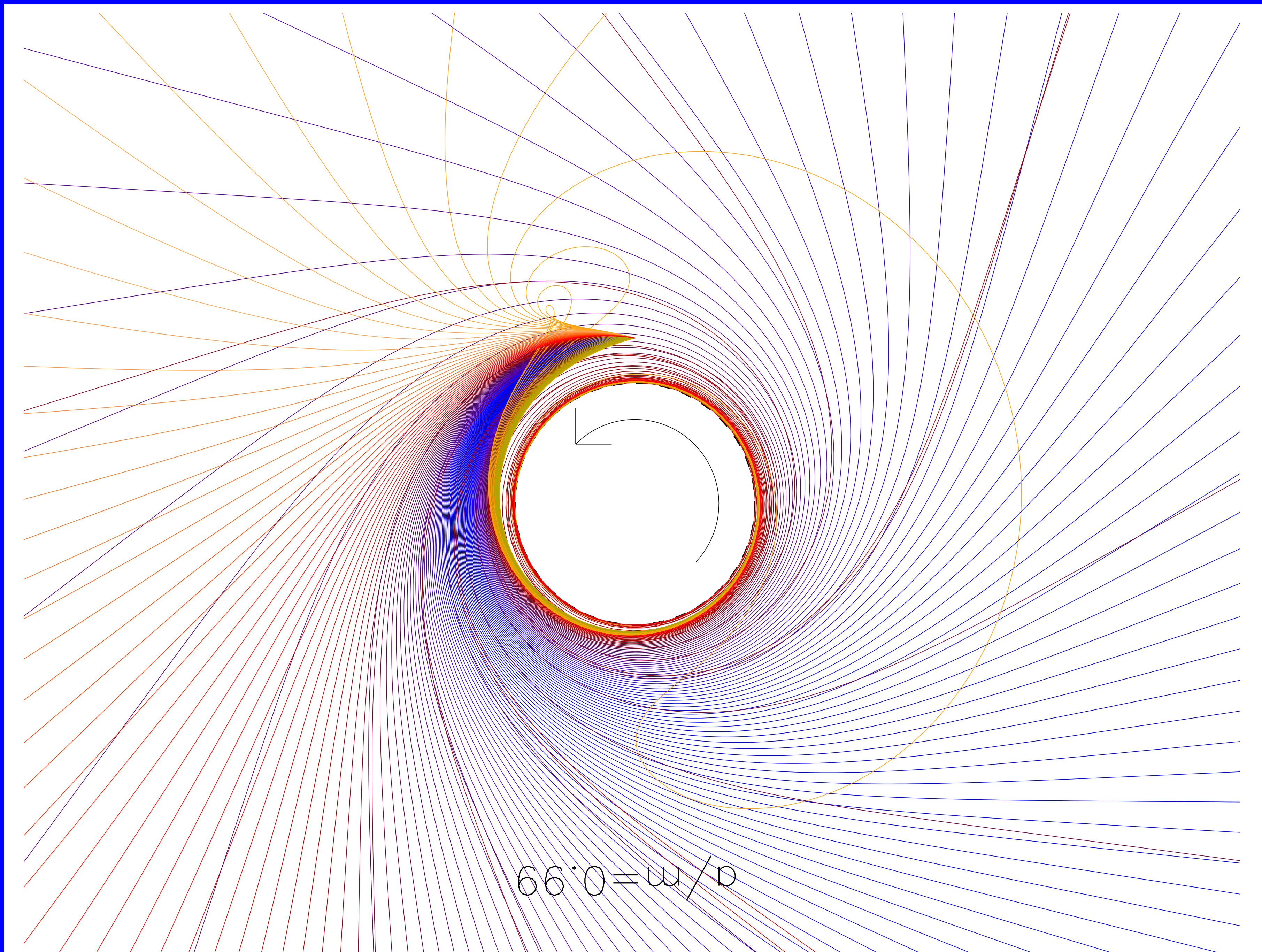
Model parameters for QPOs from XTE J1550-564
(1σ) confidences are shown in parentheses

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 $\frac{I_{\mathrm{hotspot}}}{I_B+I_{\mathrm{hotspot}}}$	0.085(0.025)	0.38(0.05)

Electron Scattering

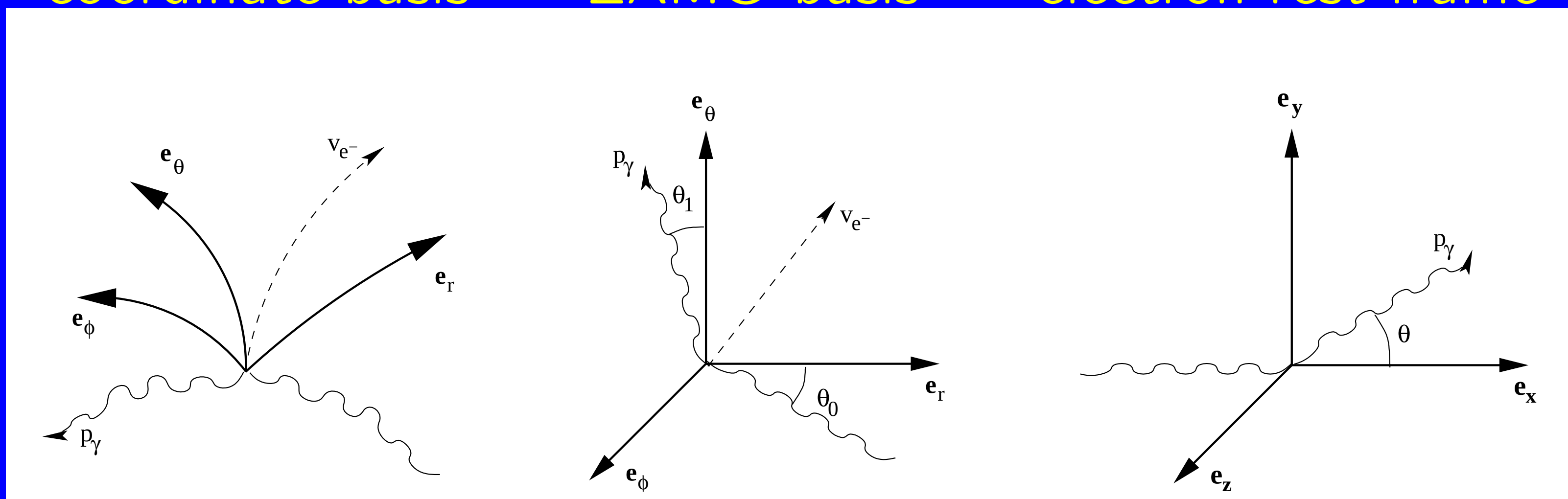
Photons are ray-traced from an isotropic emitter to a distant observer




a/m=0.99

Photon-electron scattering is computed in the rest frame of the electron

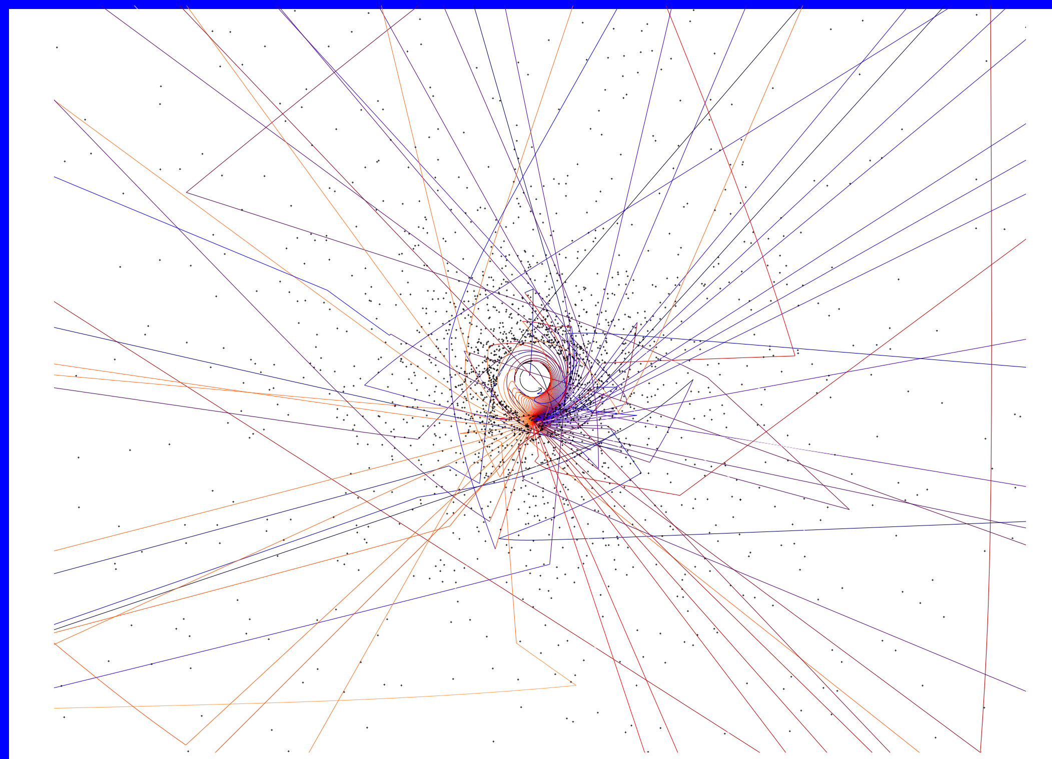
coordinate basis ZAMO basis electron rest frame



We assume a Thomson scattering cross section for unpolarized photons:

$$\frac{d\sigma_T}{d\Omega} = \frac{r_0^2}{2}(1 + \cos^2\theta)$$

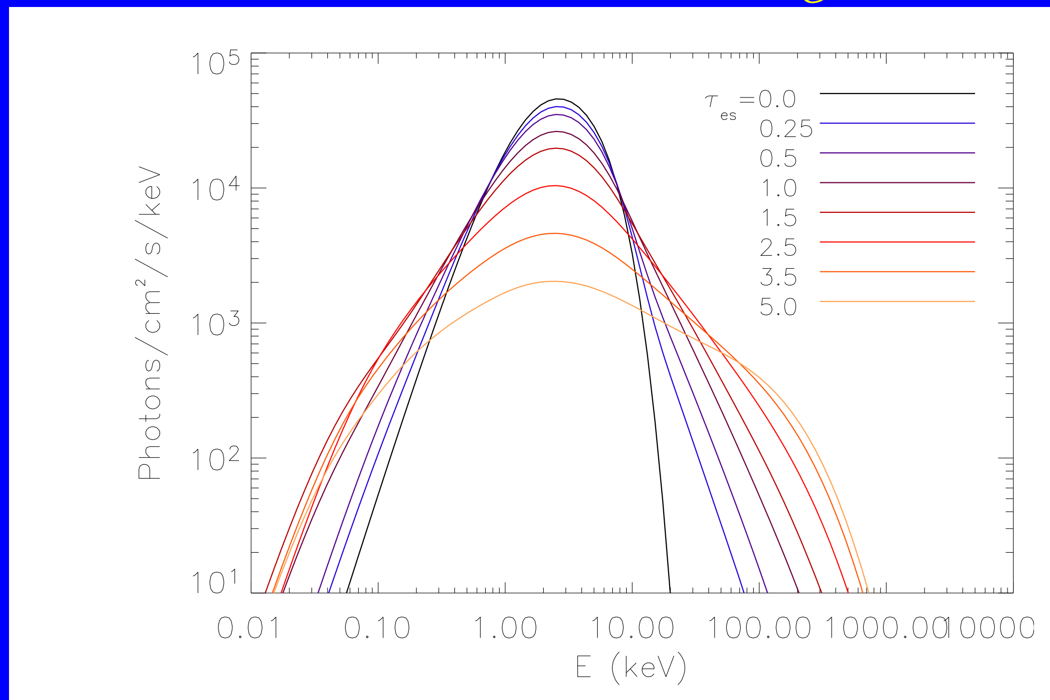
For a corona with an ADAF-type density profile, most of the scattering events occur close to the hot spot



$$\rho_e(r) \sim r^{-3/2} \qquad T_e(r) \sim r^{-1}$$

Narayan & Li (1994)

A thermal distribution of seed photons is modified by a high-energy power-law tail, cut off at $h\nu \sim kT_e$

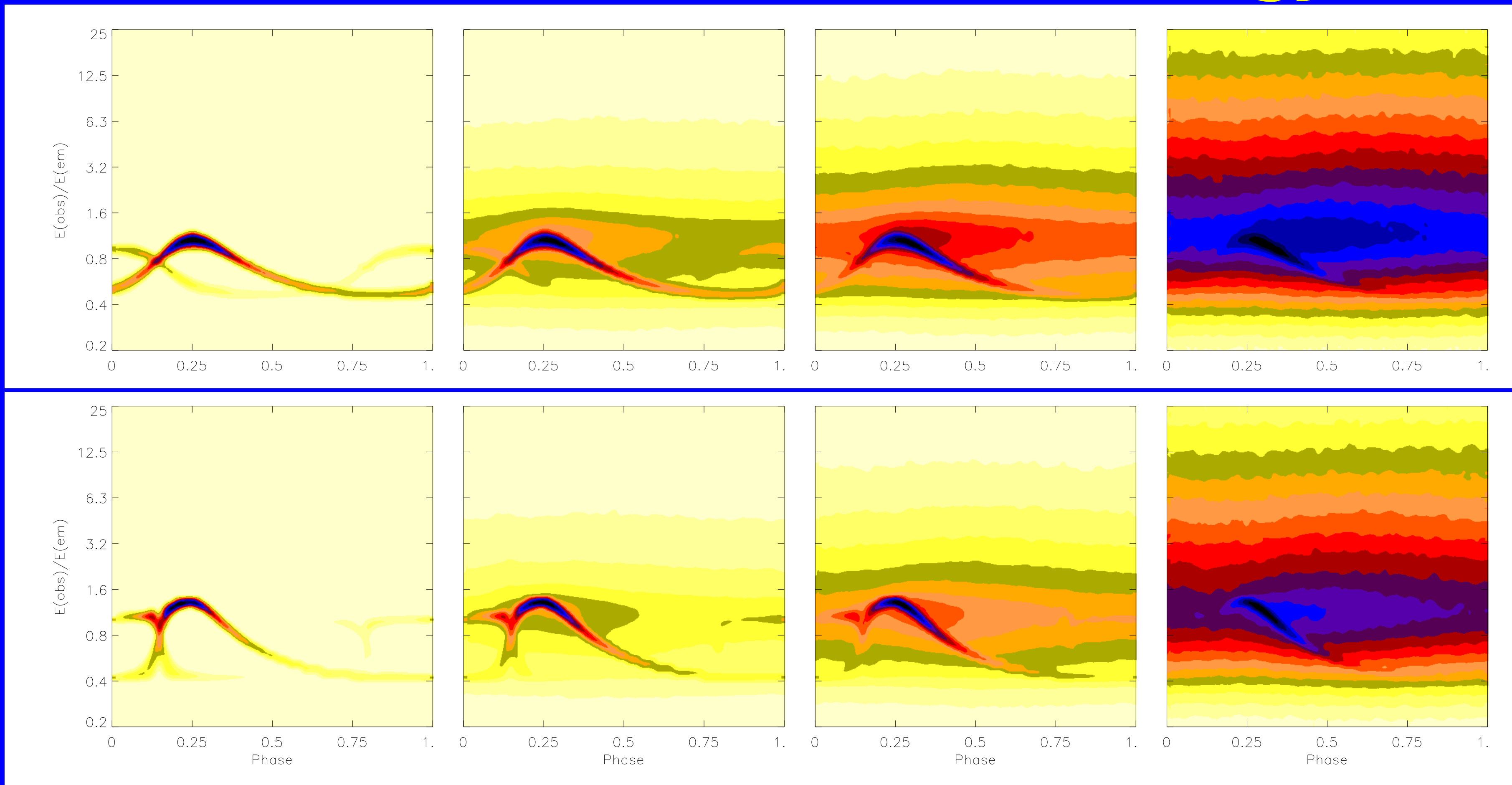


$$N_\nu \propto \nu^{2+m}, \qquad m = -\frac{3}{2} - \sqrt{\frac{9}{4} + \frac{4}{y}}$$

where the Compton y parameter for nonrelativistic electrons is

$$y = \frac{4kT_e}{m_e c^2}\max[\tau_{es}, \tau_{es}^2]$$

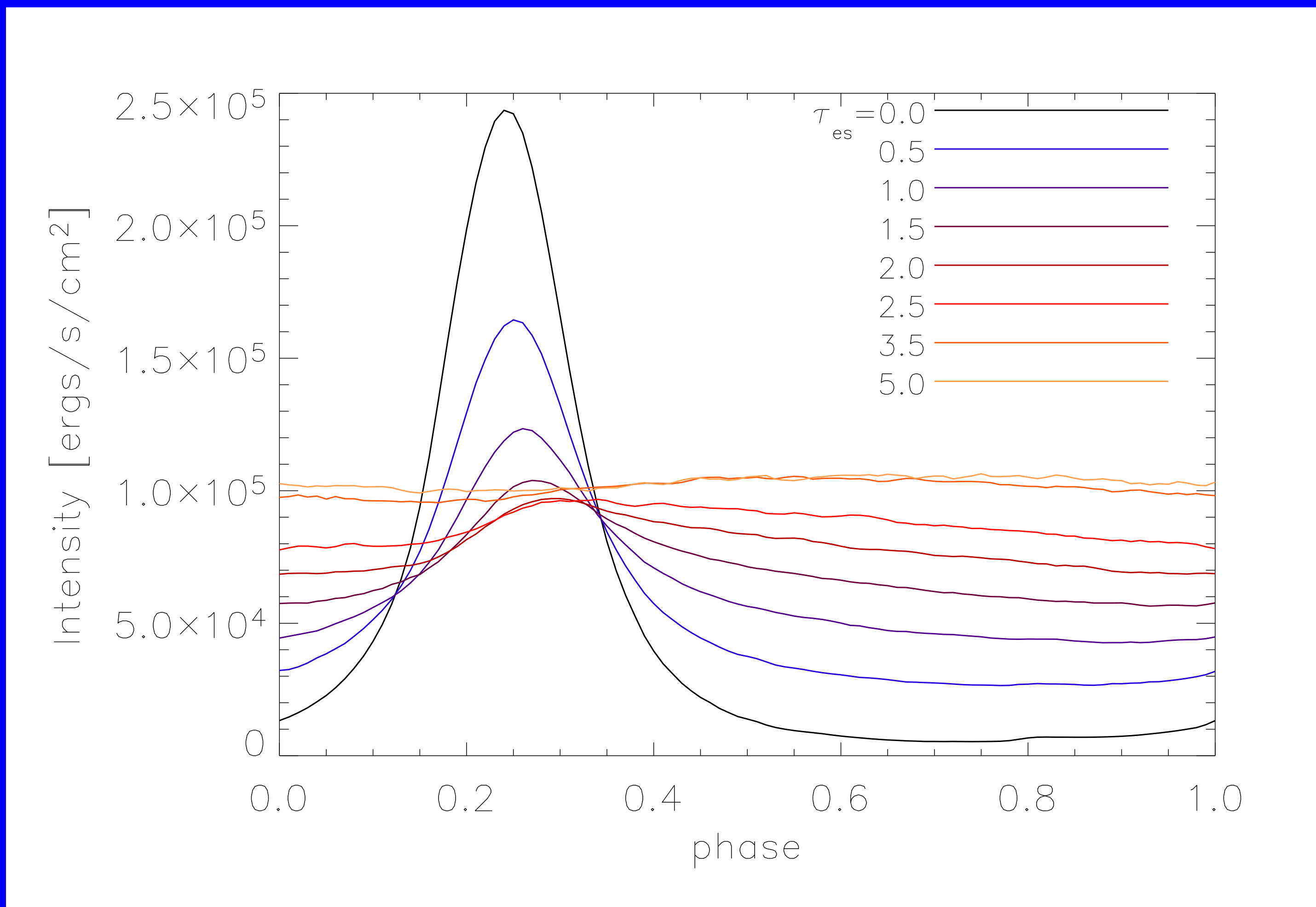
The phase-resolved hot spot spectra get smeared out in time and energy



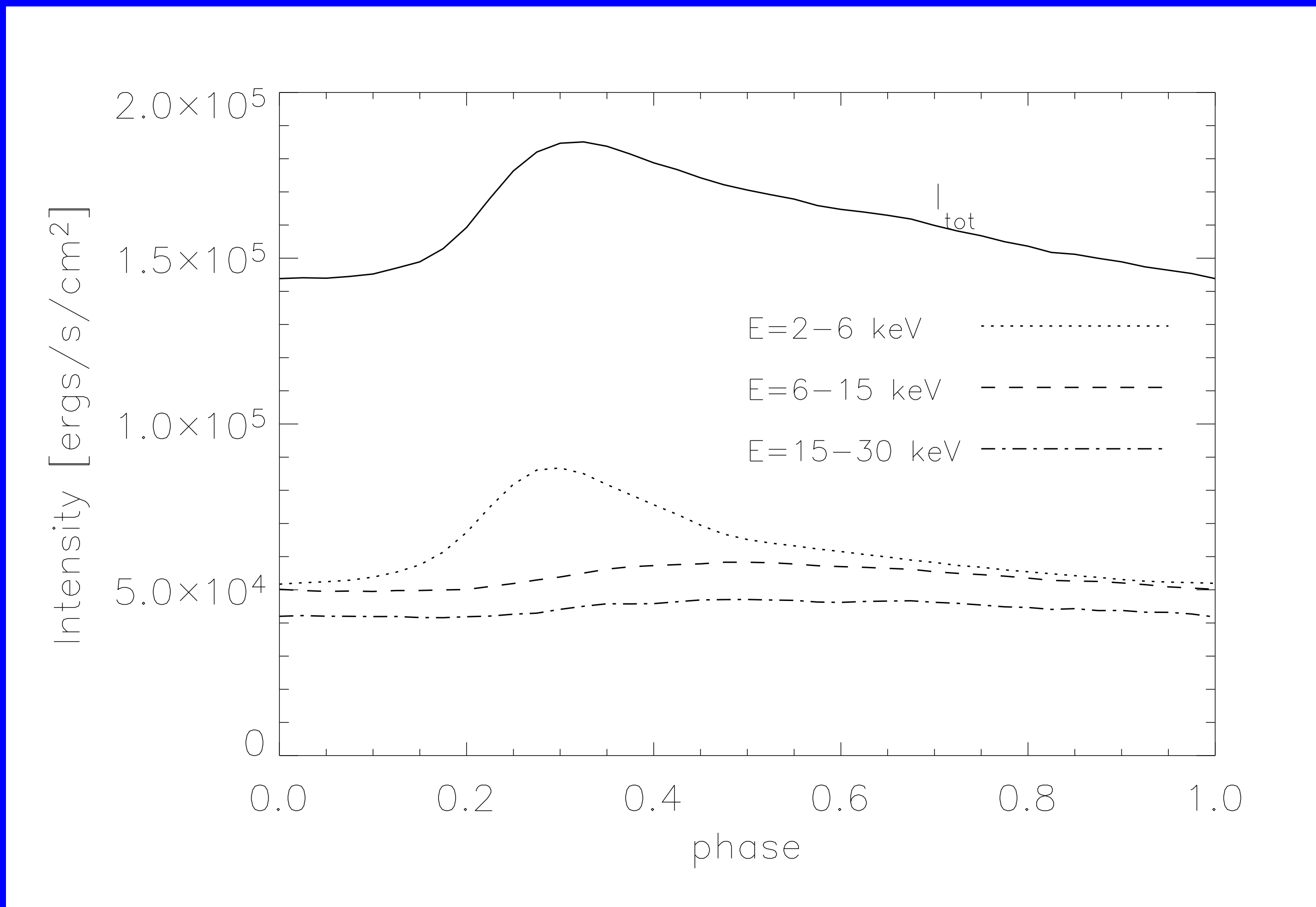
Top panels: Inclination $i = 45°$, optical depth $\tau_{es} = [0, 1, 2, 4]$

Bottom panels: Inclination $i = 75°$, optical depth $\tau_{es} = [0, 1, 2, 4]$

The X-ray light curves have decreasing rms amplitude and shifted peaks with increasing τ_{es}



The higher energy photons have increased phase shifts



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.
- By measuring the power-law index of the continuum, we can infer the Compton y parameter. Along with an ADAF model for the corona, we should be able to independently determine the optical depth $\tau_{\rm es}$ and electron temperature T_e.

Summary/Conclusions (con't)

- The high-energy QPO photons are most likely *not* inverse-Compton scattering events (due to the high amplitude fluctuations), but rather come directly from the hot spot itself.
- This suggests that the hot spot is either a non-thermal emitter, or is at a much higher temperature than a $\sim$ 1 keV thermal disk.
- Future work will include polarization and analysis of *RXTE* data with an attempt at performing phase-resolved spectroscopy.
- Additional data and increased sensitivity will allow us to verify/constrain/rule out the hot spot model as well as other QPO models.

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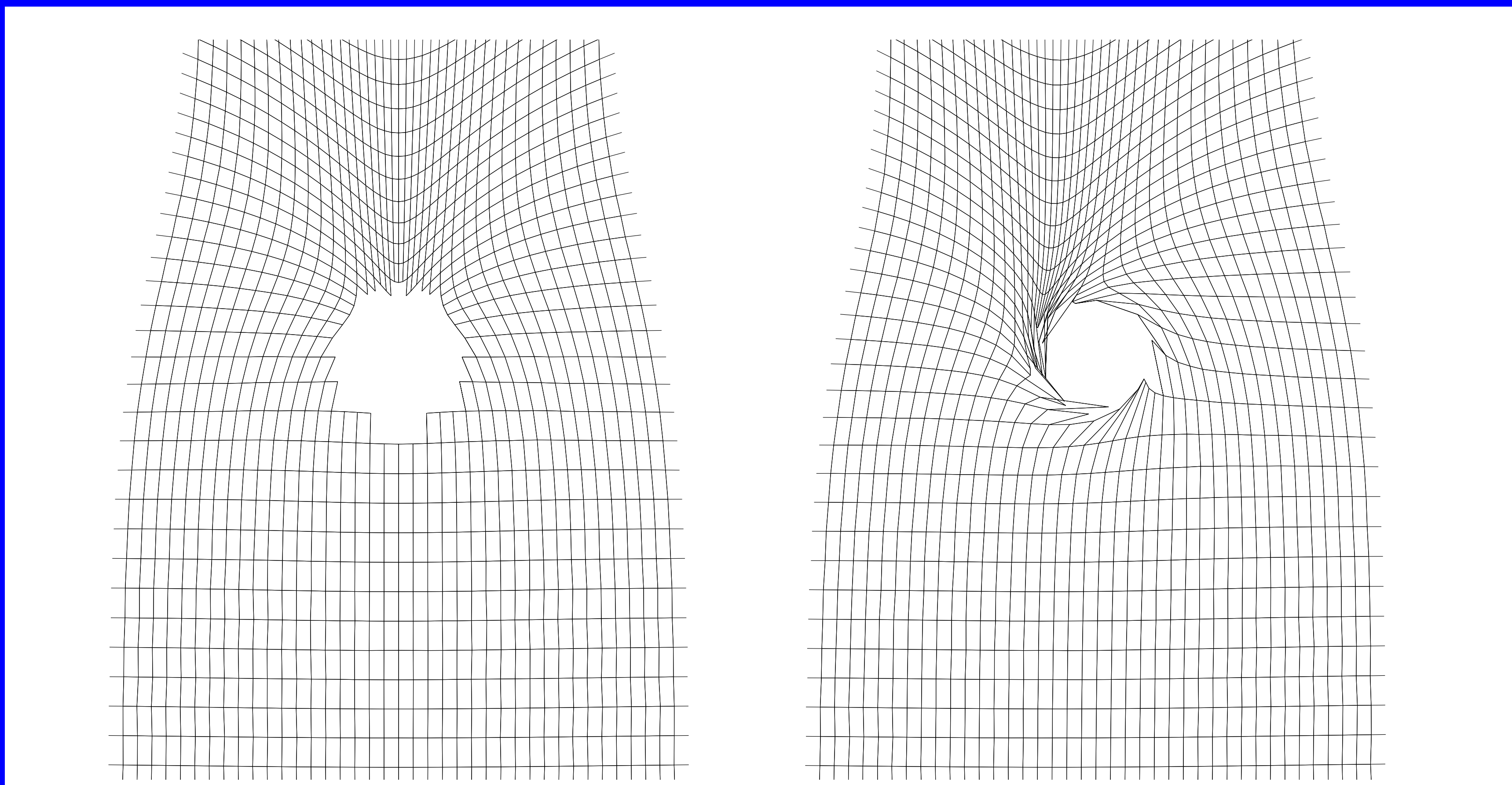
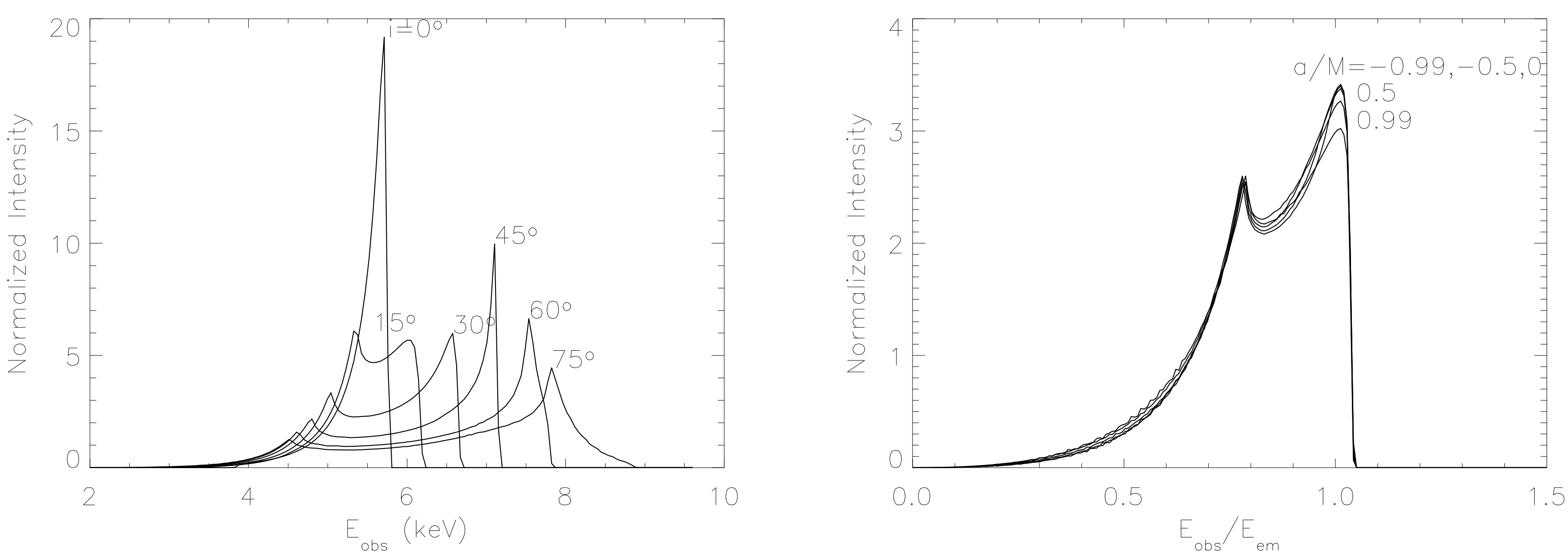
Photons projected on the plane of the accretion disk are bent towards the black hole

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

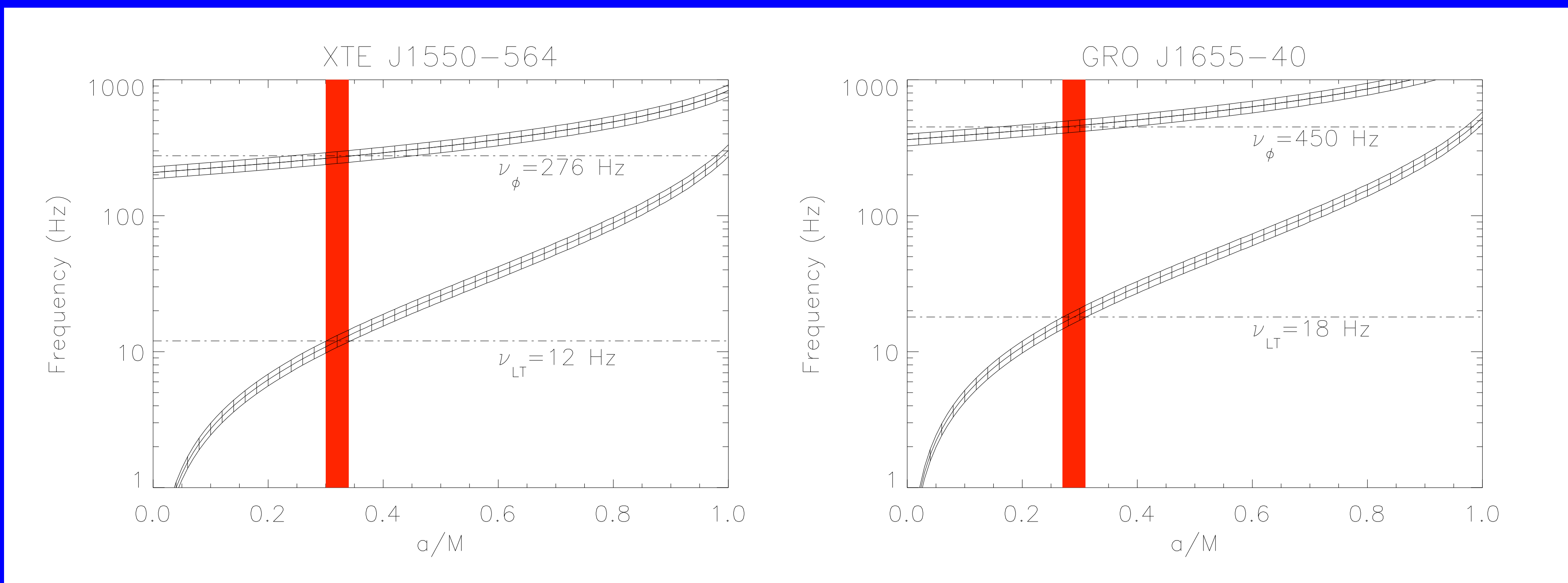


The broadened iron emisson lines are sensitive to inclination but not spin



By identifying low frequency QPOs with Lense-Thirring precession, we can determine BH mass *and* spin

$M = 8.9 \pm 0.9 M_\odot$	$M = 5.1 \pm 0.5 M_\odot$
$a/M = 0.32 \pm 0.02$	$a/M = 0.28 \pm 0.02$



cf. Remillard et al. (2002)