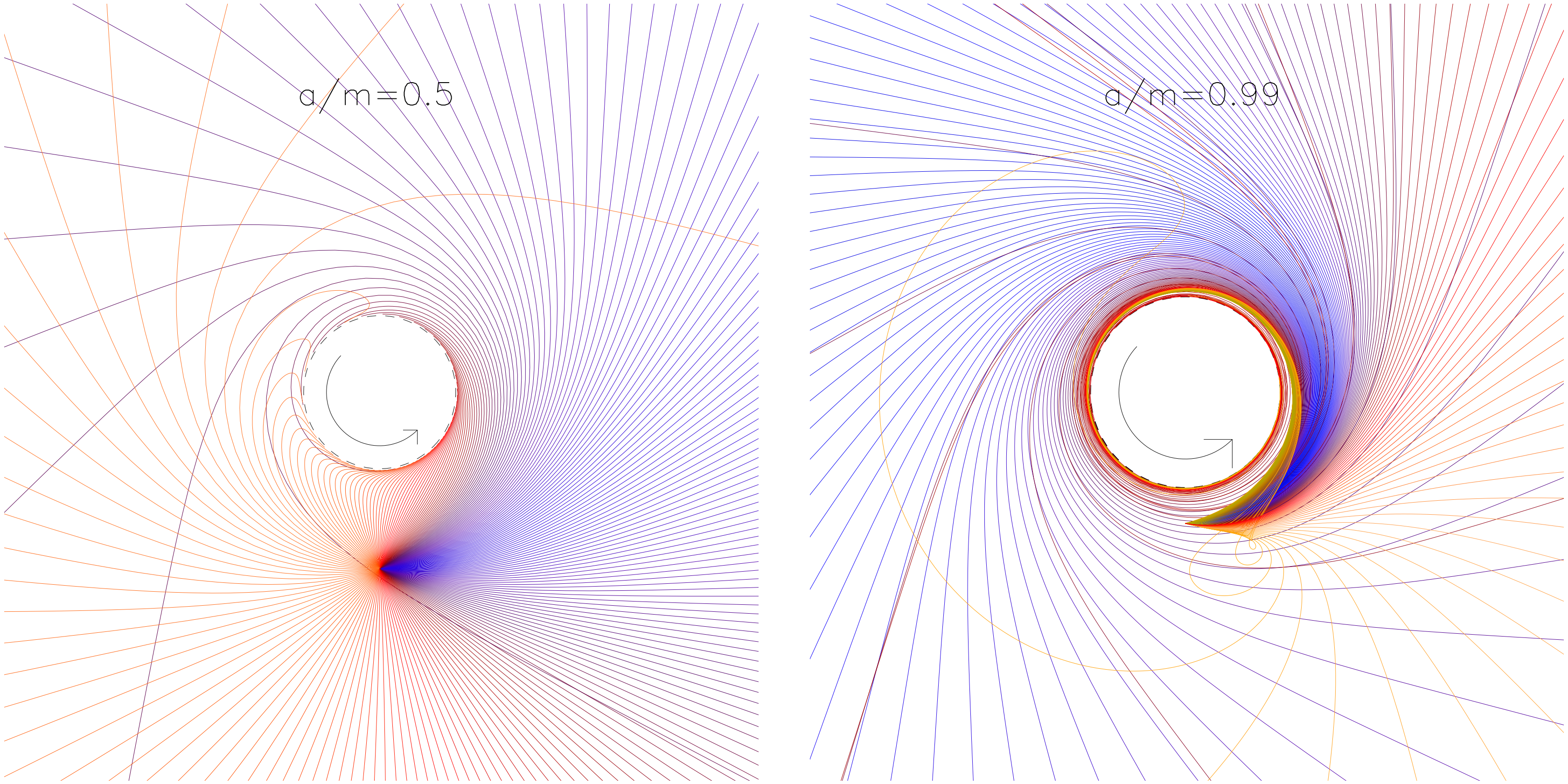
Coronal Electron Scattering of Hot Spot Emission Around Black Holes

Jeremy Schnittman

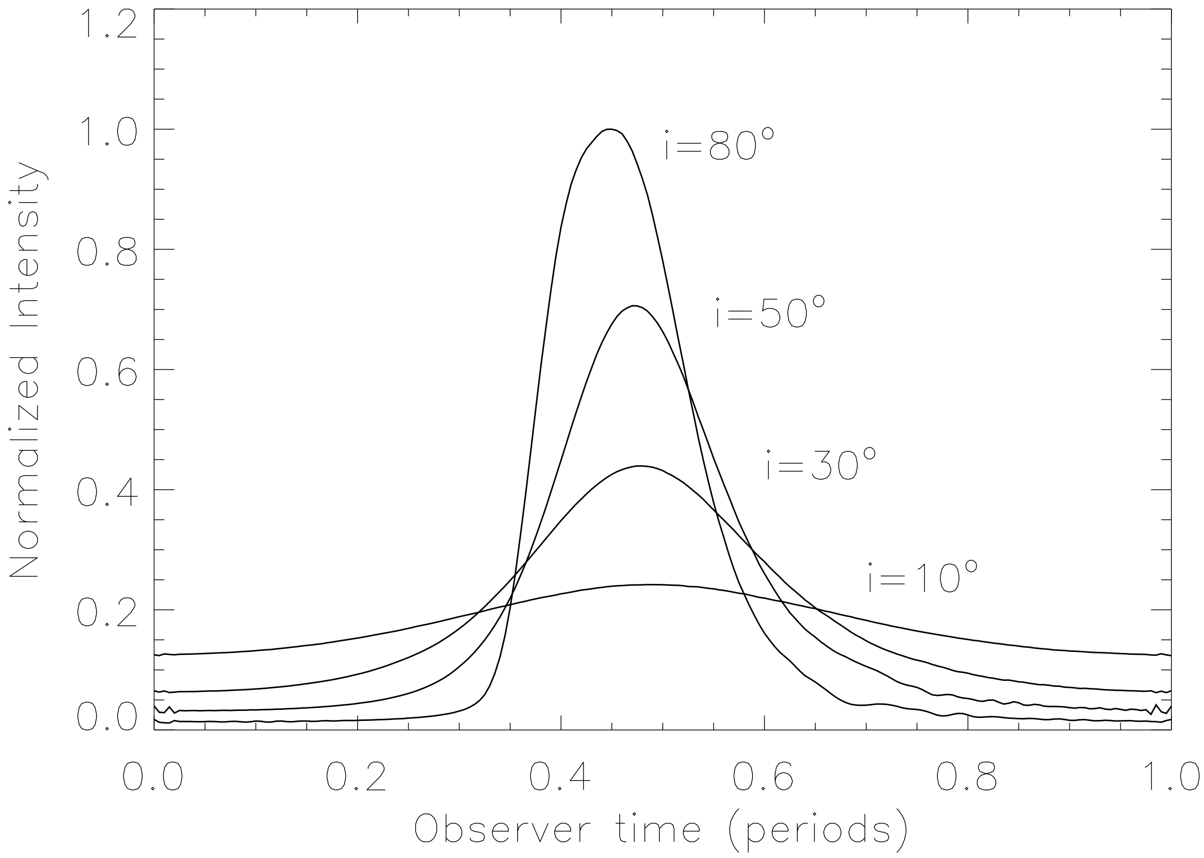
Massachusetts Institute of Technology

Hot Spot Model

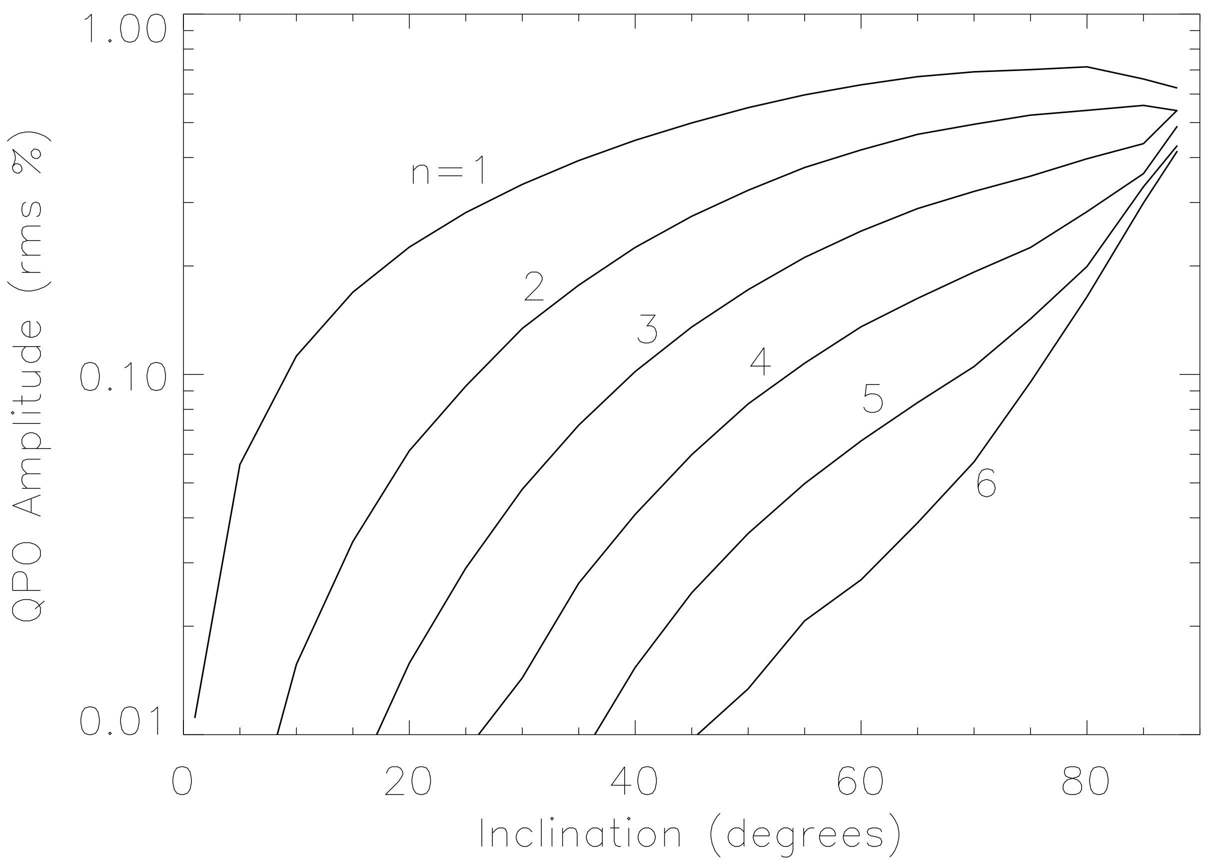
Photons are ray-traced through the Kerr metric from an isotropic emitter to a distant observer



The relativistic beaming and gravitational lensing of the hot spot determine the shape of the X-ray light curves

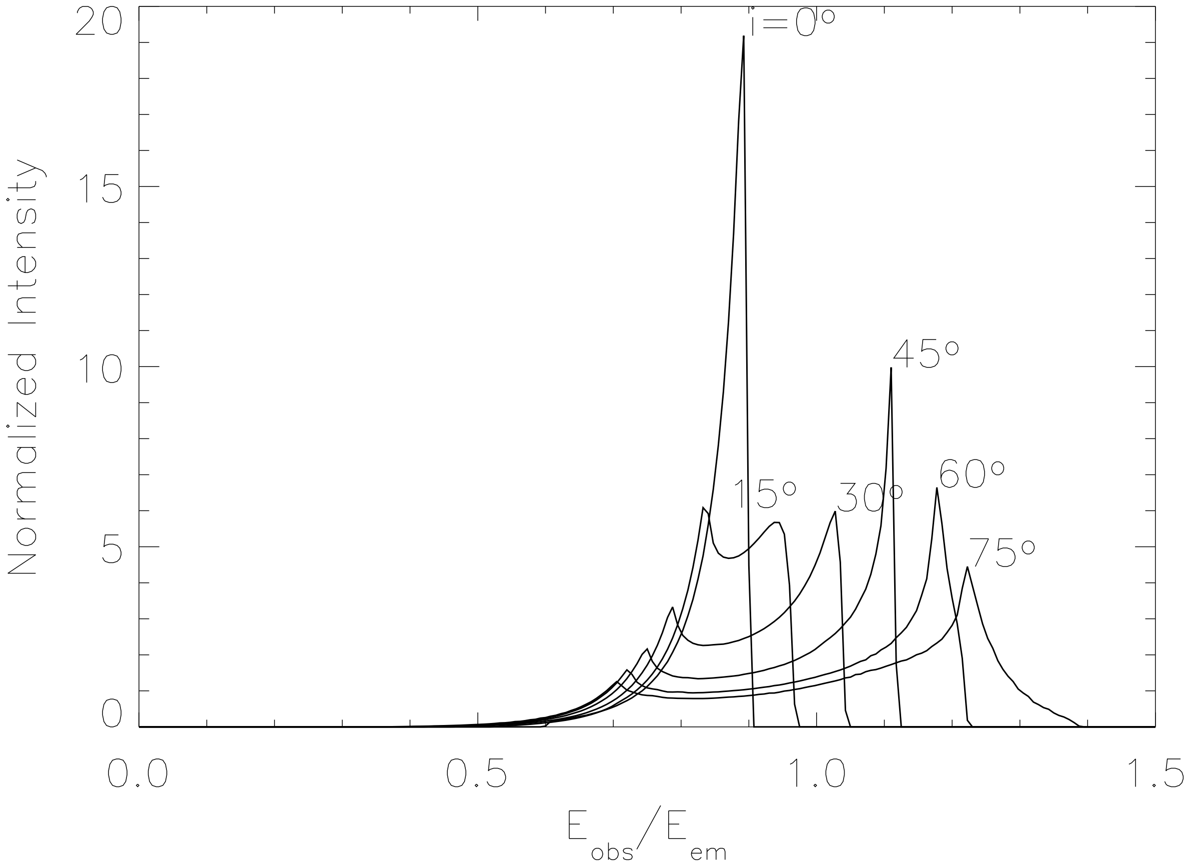


Higher inclination systems giver higher amplitude QPOs and stronger harmonic modes



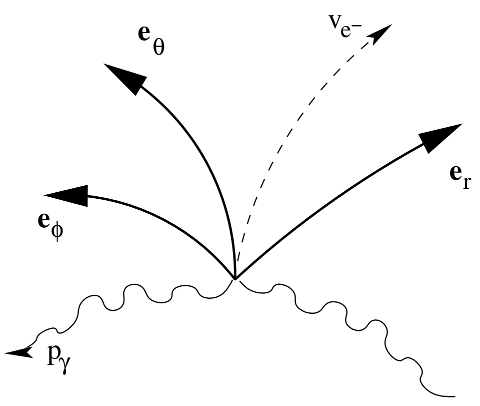
(Schnittman & Bertschinger 2004)

Higher inclination systems also have broader emission line features

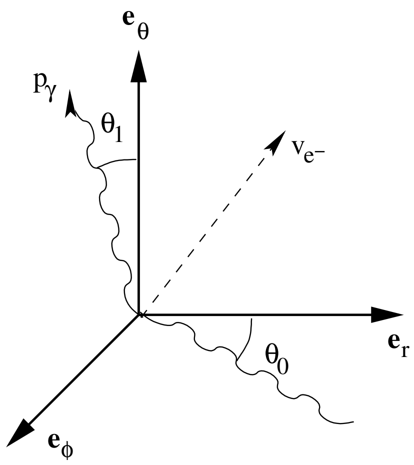


Physics of Scattering

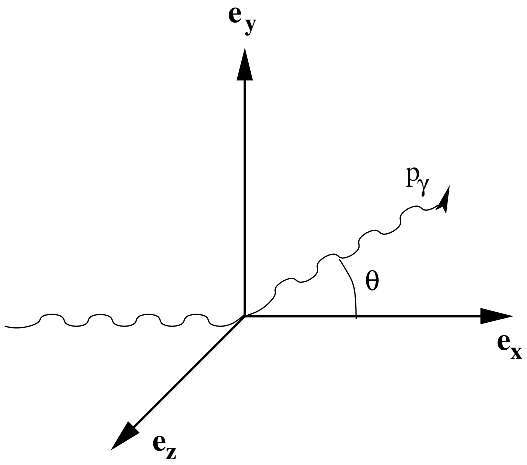
Photon-electron scattering is elastic in the rest frame of the electron



coordinate basis



orthonormal ZAMO basis

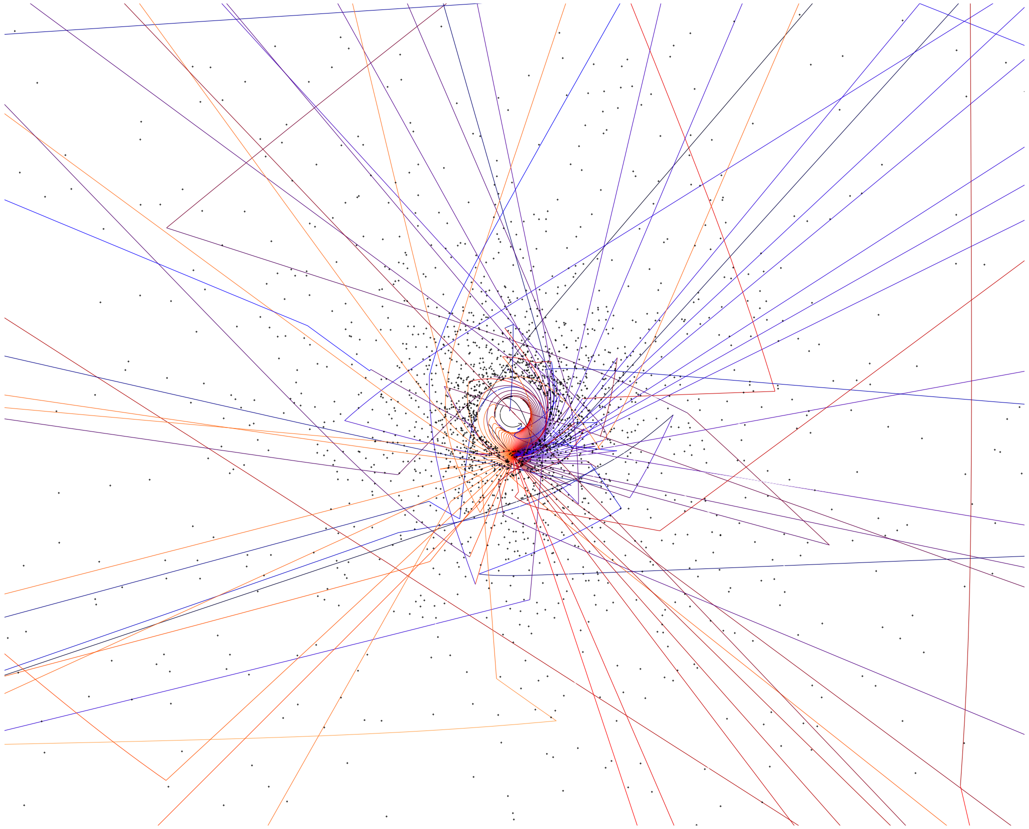


electron rest frame

We assume a Thomson scattering cross section for unpolarized photons:

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

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)

The hot electrons transfer energy to the cooler photons via the inverse-Compton process

Define a "lab frame" K such that the electron moves along the x-axis with velocity $\beta = v_x/c$ and the photon is incident at an angle θ_0 with respect to this axis. In the electron rest frame K', the photon is scattered at an angle θ' with respect to the x'-axis. The Doppler shift formula gives (Rybicki & Lightman, 1979):

$$\begin{aligned} \epsilon_0' &= \epsilon_0 \gamma (1 - \beta \cos\theta) \\ \epsilon_1 &= \epsilon_1' \gamma (1 + \beta \cos\theta'), \end{aligned} \tag{2}$$

where $\gamma = 1/\sqrt{1-\beta^2}$, ϵ_0 is the photon energy before scattering, and ϵ_1 is the post-scattering energy in the lab frame.

In the electron frame, conservation of energy and momentum gives

$$\epsilon_1' = \frac{\epsilon_0'}{1 + (\epsilon_0'/m_e c^2)(1 - \cos\theta')}. \tag{3}$$

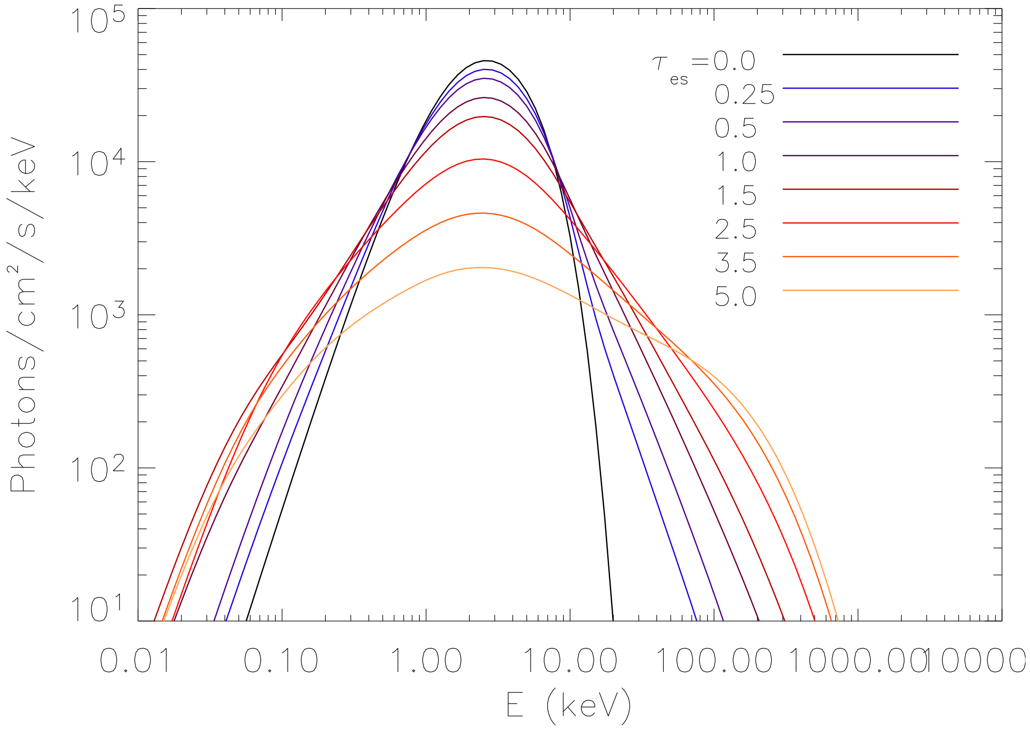
For seed photons from a thermal hot spot at $T_{\rm hs} \sim 1$ keV, $\epsilon \ll m_e c^2$ so we can generally assume elastic scattering with $\epsilon_1' \approx \epsilon_0'$. Then averaging over all angles θ (isotropic) and θ' (weighted by eqn. 1), we find that the typical scattering event boosts the photon energy by

$$\frac{\epsilon_1}{\epsilon_0} \approx \gamma^2. \tag{4}$$

For electrons with a thermal velocity distribution, this factor can be written

$$\gamma^2 \approx \left(1 - \frac{2kT_e}{m_e c^2}\right)^{-1} \approx 1.6 \qquad \text{for } T_e \approx 100 \text{ keV}. \tag{5}$$

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



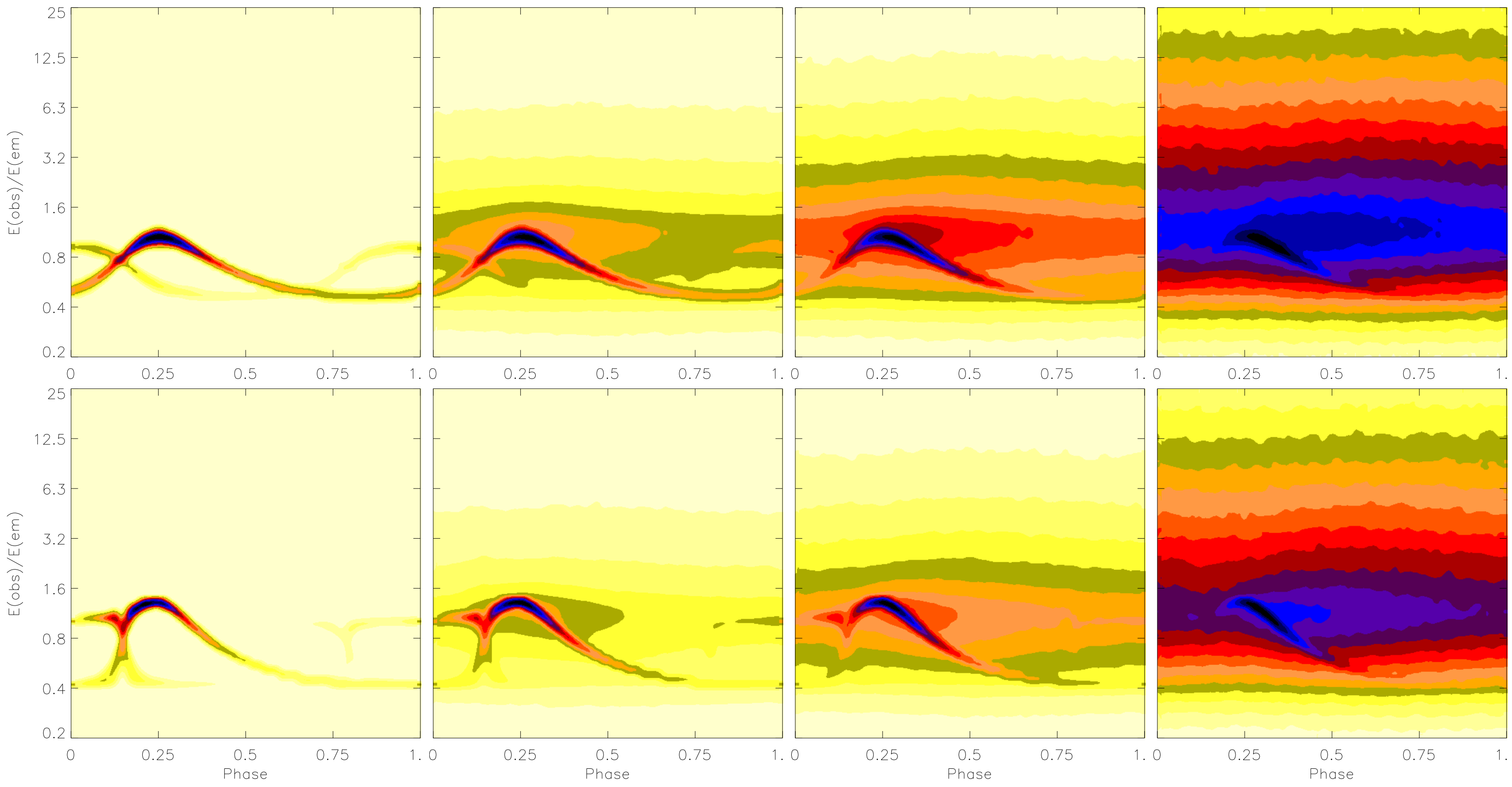
$$N_\nu \propto \nu^{2+m}, \qquad m = -\frac{3}{2} - \sqrt{\frac{9}{4} + \frac{4}{y}} \tag{6}$$

where the Compton y parameter for nonrelativistic electrons is

$$y = \frac{4kT_e}{m_e c^2} \max[\tau_{\rm es}, \tau_{\rm es}^2] \tag{7}$$

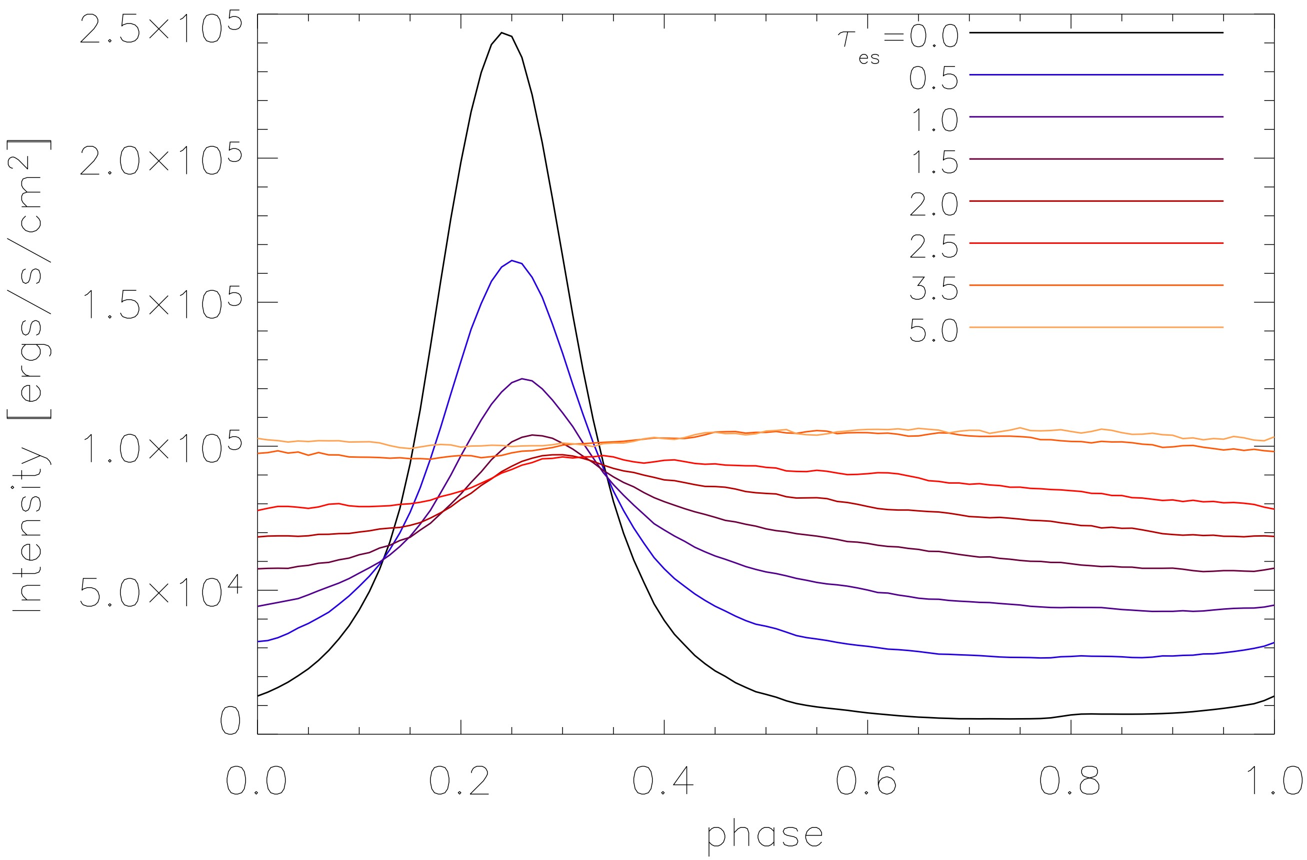
Modified Light Curves

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

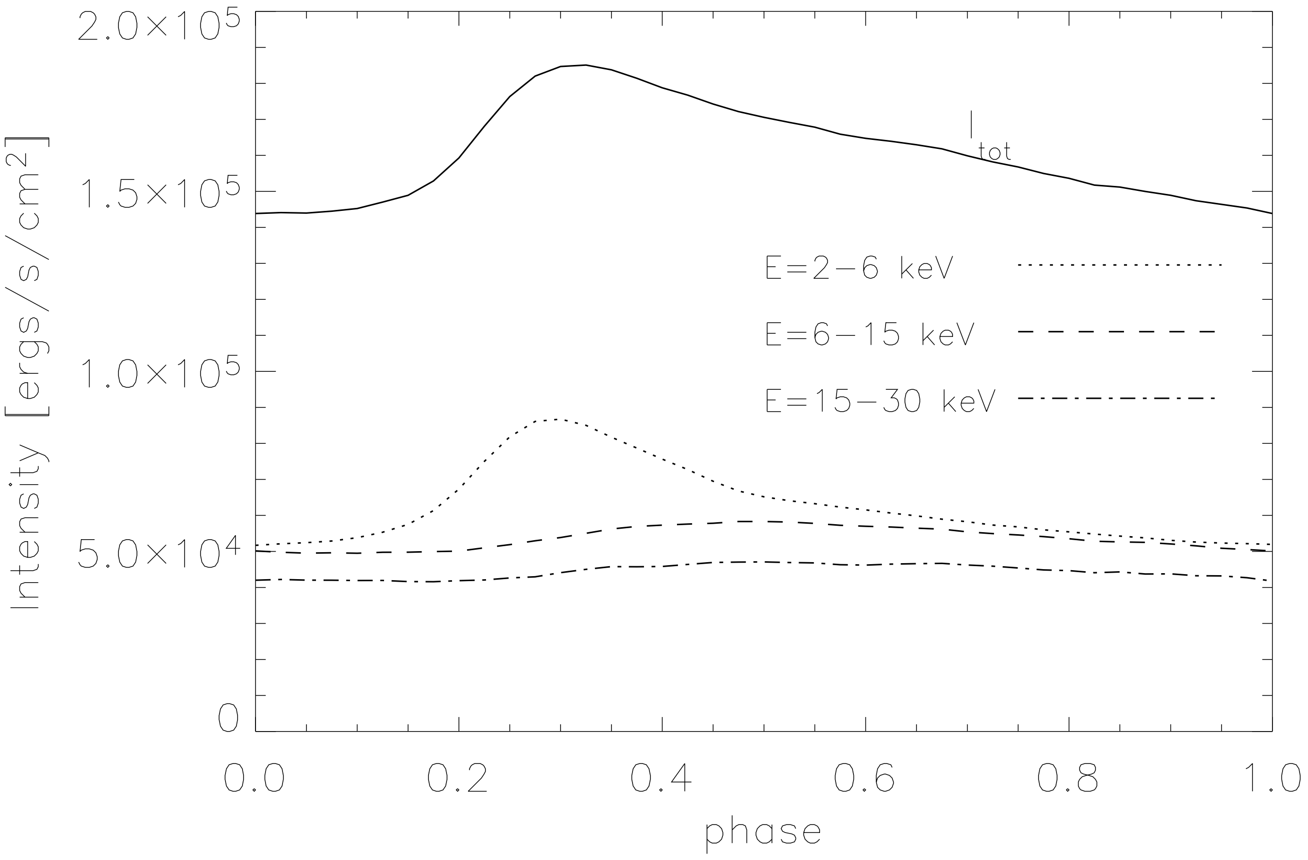


Top panels: Inclination $i = 45°$, optical depth $\tau_{\rm es} = [0, 1, 2, 4]$
Bottom panels: Inclination $i = 75°$, optical depth $\tau_{\rm es} = [0, 1, 2, 4]$

The X-ray light curves have decreasing rms amplitude and shifted peaks with increasing $\tau_{\rm es}$



The higher energy photons have increased phase shifts



Summary/Conclusions

- *Rossi X-ray Timing Explorer* (*RXTE*) observations of high-frequency QPOs from black hole sources show a few significant features (McClintock & Remillard 2004):

  HFQPOs are typically seen in the "Steep Power-Law" spectral state

  Distinct lack of higher harmonic overtones in the power spectrum

  Larger rms amplitude in higher energy channels (6-30 keV)

- 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.
- The smearing out in time of the hot spot light curve can account for the damping of harmonic modes in the QPO power spectrum (Schnittman 2004).
- 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 strongly non-thermal emitter, or is at a much higher temperature than a ~ 1 keV thermal disk.
- Future work will include polarization and analysis of *RXTE* data with an attempt at performing phase-resolved spectroscopy.