Investigating X-ray time-lags in AGN using a two-blobs model

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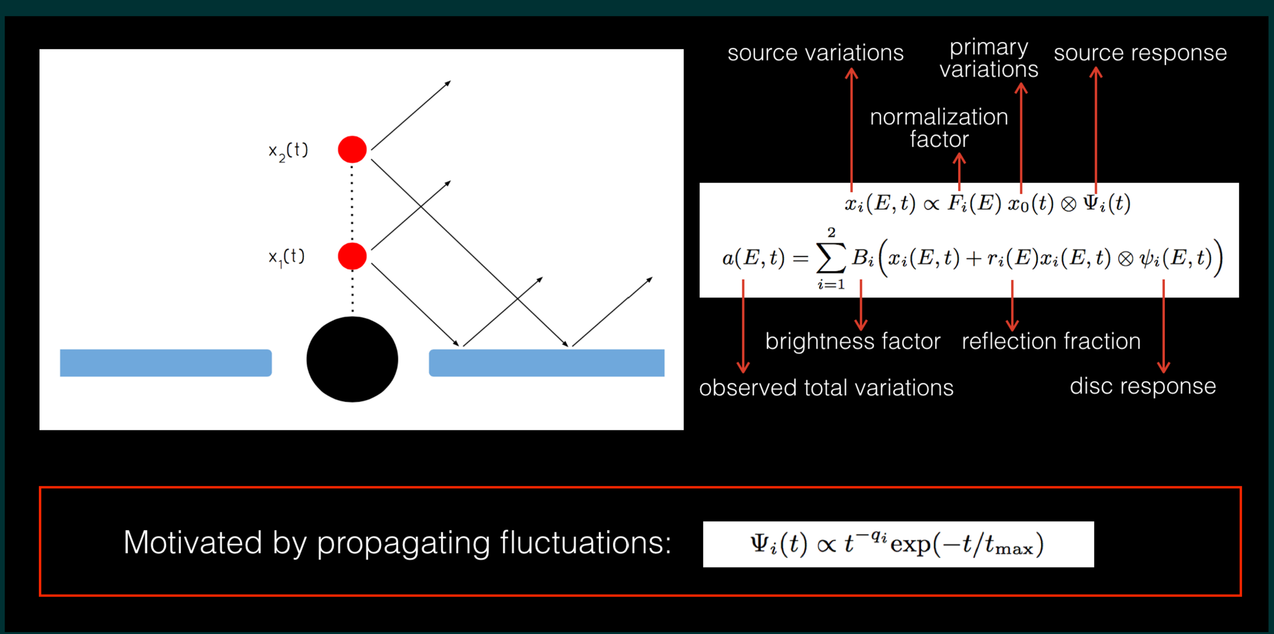
ABSTRACT

We present a two-blobs model based on ray-tracing simulations to investigate X-ray reverberation in AGN. This model consists of two X-ray point sources illuminating an accretion disc that produce the high-frequency reverberation lags, i.e., the time-delays of the observed reflection photons after the direct continuum photons. These lags are associated with the light-crossing time between the source and the disc, so measuring them allow us to probe the extreme region closet to the event horizon. We show how the two-blobs model predicts both positive-hard and negative-soft (reverberation) time lags at low and high frequencies, respectively. We assume the variations of two X-ray sources are triggered by the same primary variations, but allow them to respond in different ways. The variations of each source induce a delayed accretion disc response and then the total lags are affected by the combination of both source and disc responses. Various different source geometries and source responses are investigated. We show that the two-blobs model can reproduce the observed X-ray reverberation, including the observed lag-energy, in some specific cases such as PG 1244+026 where there is the strong Fe K lags but no soft lags at energies < 1 keV. The second X-ray source is able to dilute the reverberation lags at low energies.

TWO-BLOBS GEOMETRY

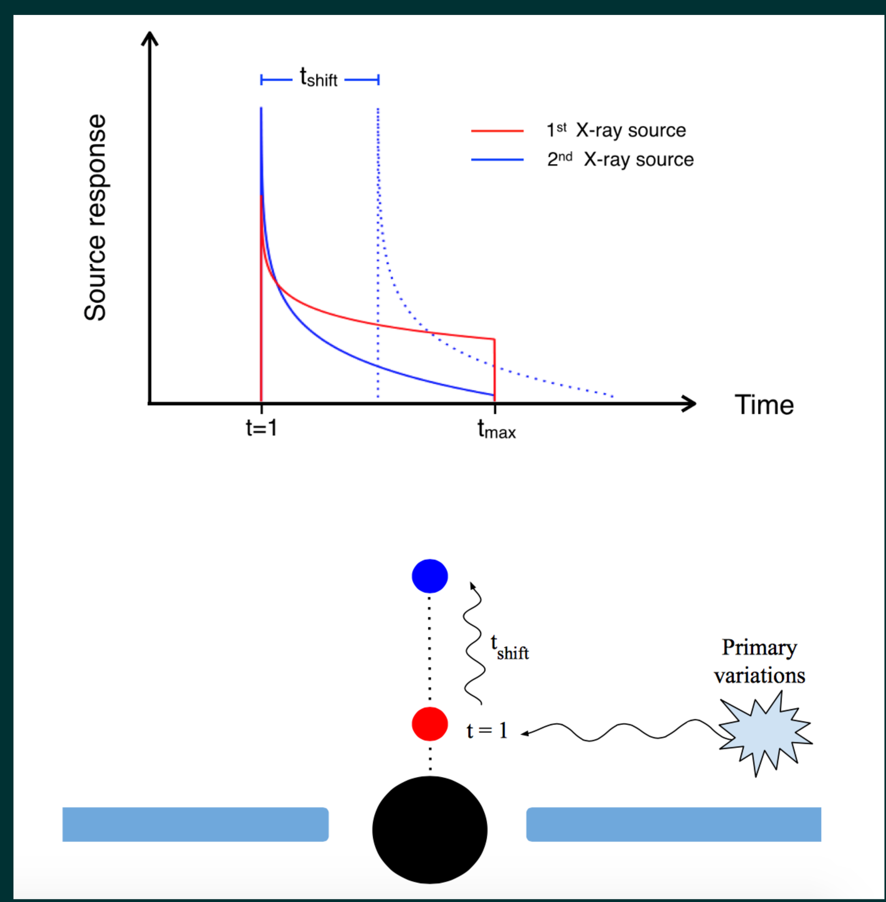
We consider an accretion disc illuminated by two X-ray sources. The variability of each X-ray source is modelled by assuming a source response function describing how that source responds to the primary variations. Ray tracing is used to integrate the photons from the sources to the disc and to the observer, to compute the disc response function (*Wilkins & Fabian 2013; Cackett et al. 2014; Emmanoulopoulos et al. 2014; Chainakun & Young 2015; Chainakun et al. 2016*). The disc is allowed to have a radial density profile with the ionization parameter of each disc element is proportional to the total illuminating flux from both X-ray sources. Measuring time delays between the reflection and the continuum X-rays (reverberation lags) that relate to their different light-travel time provides constraints on the locations of the X-ray sources. We aim to model these reverberation lags together with the low-frequency hard lags possibly produced through the propagating fluctuations on the disc.



Left: a sketch of the geometry and also equations used to produce the intrinsic source and observed X-ray variations. The subscript i=1 and 2 identify the parameters of the first (lower) and the second (upper) X-ray sources, respectively.

SOURCE RESPONSES

In the propagating fluctuation framework (e.g., *Arevalo & Uttley 2006*), the source is harder towards the centre and is modulated by fluctuations that have propagated inwards, so the softer region responds first causing the hard lags. In other words the softer flux dominates at first before the harder flux gradually takes over. We apply this concept by assuming some primary variations induce the propagation effects. These effects are imparted to the central X-ray sources in the way that one of the source responds more at the beginning before the other source responds more towards the end. The simplest way to model the impulse source response is: $\Psi_i(t) \propto t^{-q_i} \exp(-t/t_{\max})$

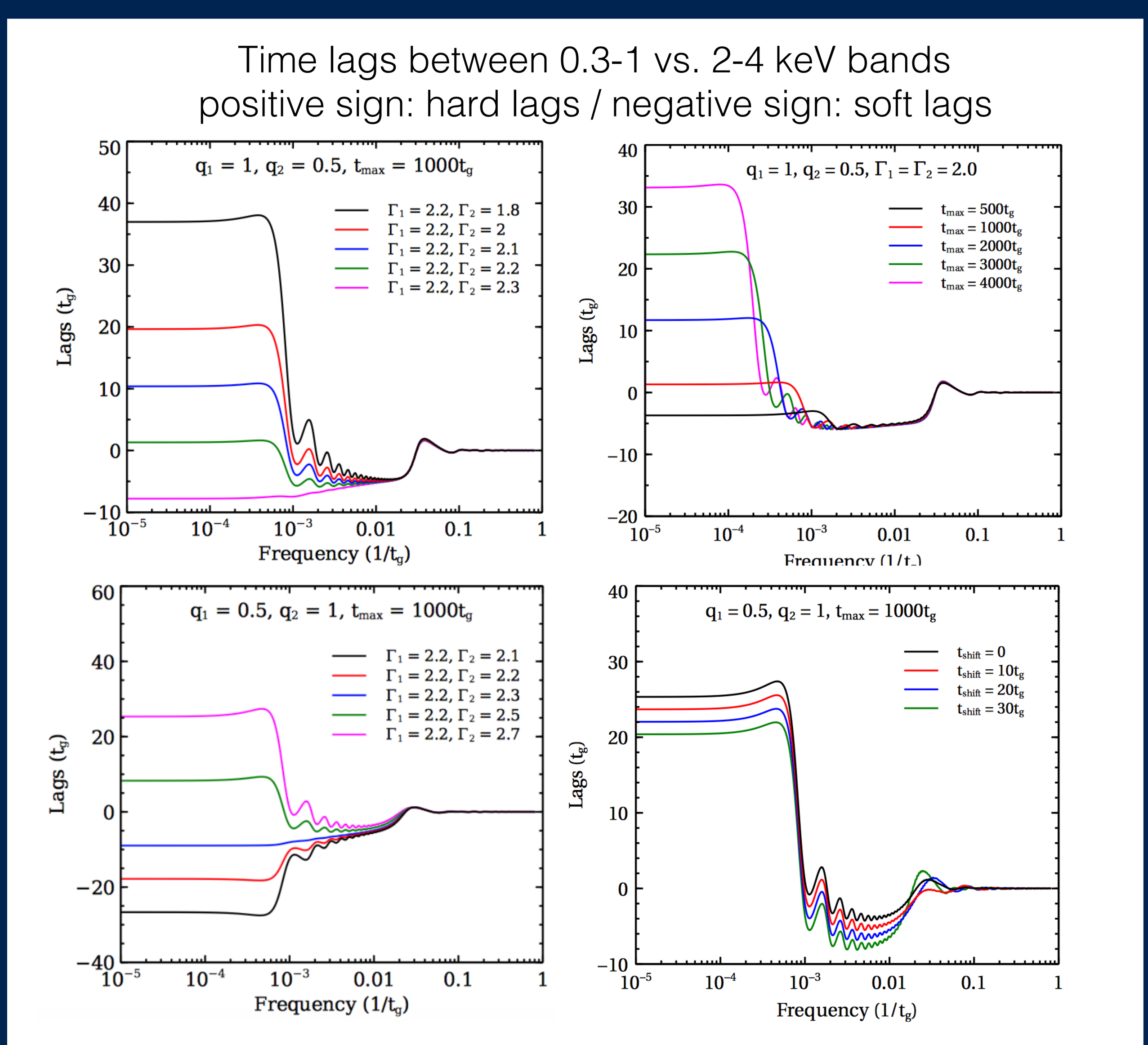


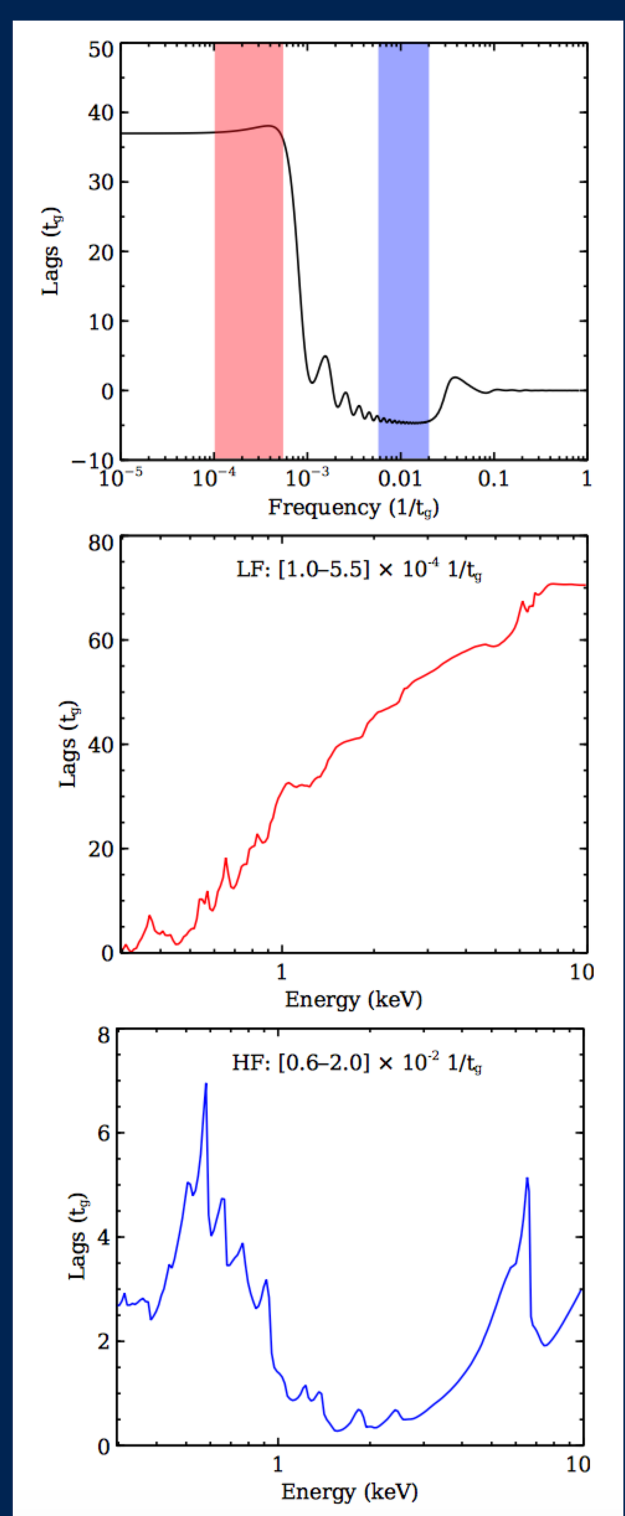
Left: examples of the modelled impulse source response functions. The maximum responses are set at t=1 and decrease with time towards the cut-off at $t_{\max}$. The responses are shaped by the parameter q. The lower panel illustrates a physical scenario relating to our model parameters. Primary variations produce fluctuations on the mass accretion rate which are propagated inwards and first seen by the lower X-ray source. The fluctuations then are propagated up from the lower to the upper source taken the time $t_{\rm shift}$.

PREDICTED TIME-LAGS

Once the observed X-ray variations (i.e., light curves) for all energy bands are obtained. Time lags are calculated in the standard way using the argument of the cross-spectrum from the Fourier transforms of the light curve pairs (*Nowak et al. 1999*). To investigate how time lags change when the source and disc responses are combined, we fix the reverberation parameters at $h_1=5r_g$, $h_2=8r_g$, $i=30^{\circ}$. The disc is highly ionized at the centre and is less ionized further out. The figure below (left) shows frequency-dependent time lags varying with our model source parameters: q_1, q_2, $t_{\max}$, $t_{\rm shift}$ and photon index (Γ). The other parameters, when not stated, are kept constant at Γ_1=2.2, Γ_2=2.7, $t_{\max}=1000t_g$ and $t_{\rm shift}$=0. The figure below (right) shows the predicted lag-energy spectra extracted at low and high frequency ranges. At low frequencies we see the lags increasing with energy while at high frequencies the reverberation takeover and we clearly see the traditional features of the X-ray reverberation that relate to the inner disc reflection. These characteristic properties of time lags switching at low and high frequencies have been commonly observed in many AGN.

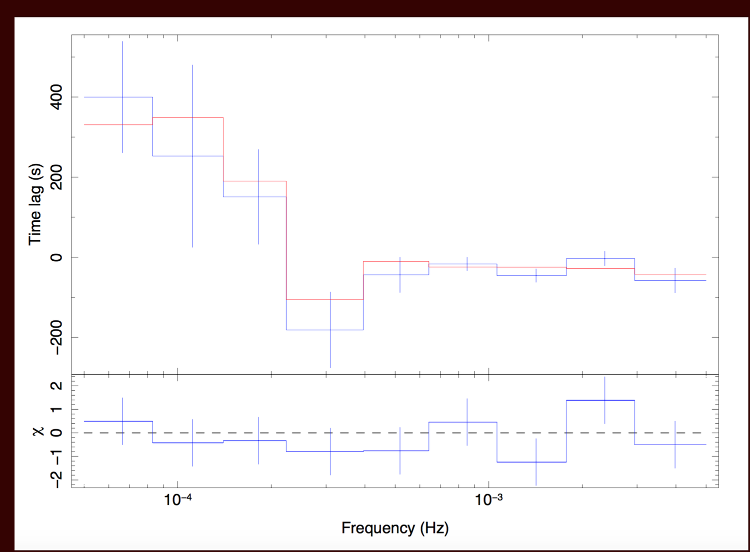
Our results suggest the positive and negative lags are found together when the harder source responds more than the softer source at late time. If the upper source is softer (harder), increasing $t_{\rm shift}$ produces larger soft (hard) lags.

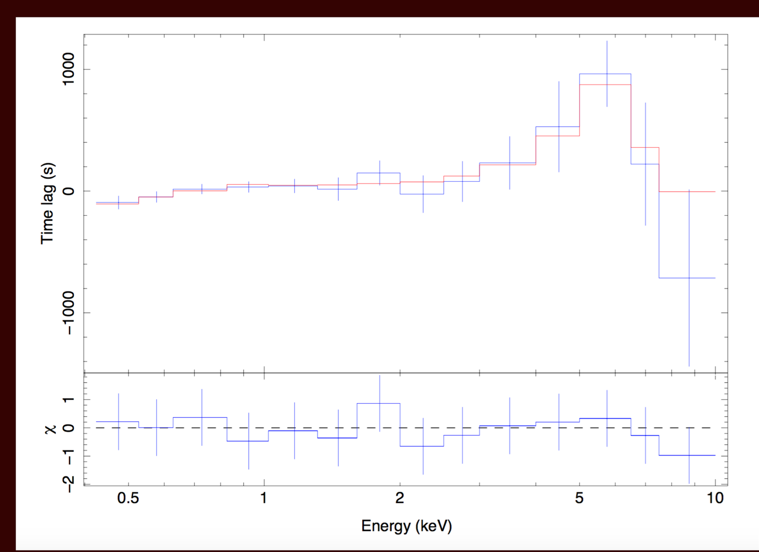




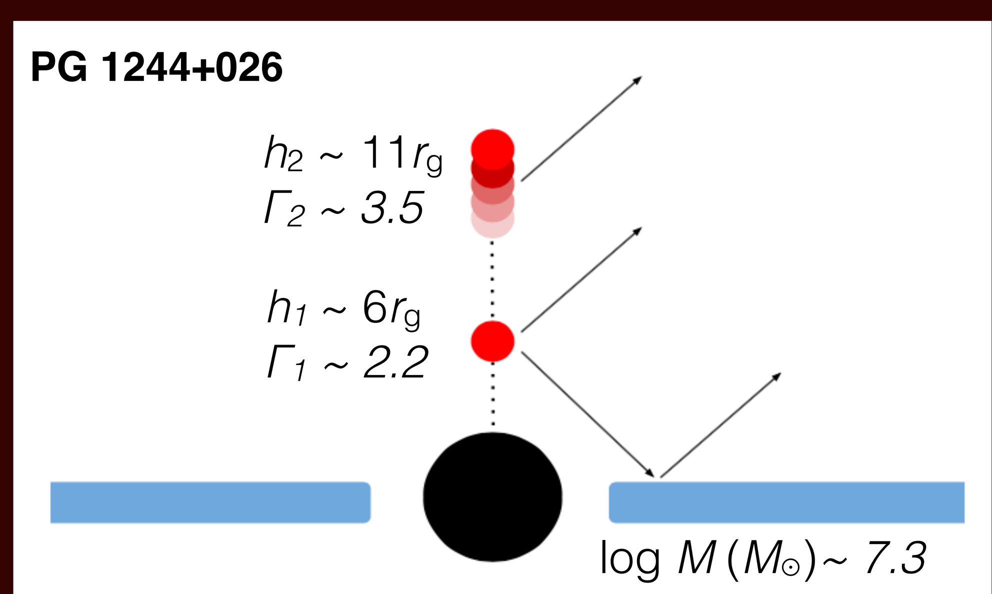
PG 1244+026

Previous observations showed that the lag-energy spectrum of PG 1244+026 at the frequency range of (0.9–3.6)×10^{-4} Hz exhibits strong Fe K lags but no soft lags at energies < 1 keV (*Kara et al. 2014*). These properties could not be produced under the standard lamp-post assumption. We then try to fit the two-blobs model to the lag-frequency and lag-energy spectra of this AGN. The results are shown in below figures (blue is the data and red is the models).





Although we fit both data set separately, their best fitting parameters are quite comparable suggesting an agreement on the same geometry, presented in below figure.



The model requires a very small amount of the reflection flux from the upper X-ray source. This source then should move rapidly upwards so that its emission is beamed away from the accretion disc.

We find that the upper source produces very soft X-rays. The absence of reflection flux from the upper source makes its soft continuum a contamination component diluting the total soft-excess reverberation lags. We interpret the upper source as an outflow or a relativistic jet that produces the soft X-rays which are varying on comparable time-scales to the lower-source variations. The variations of two sources may be triggered by the same mechanism (e.g., some perturbations such as from the propagating fluctuations). They, however, responds in slightly different way (q_1 and q_2 are slightly different). Furthermore, we find no evidence of the fluctuations propagating up between two sources ($t_{\rm shift}$ is very small). The two-blobs scenario is a step towards realistic modelling of a full extended source geometry.

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