Soft X-ray lags in AGN: a (biased) review

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Some open questions (among many others):

general spectral components and their variability mechanisms
the innermost accretion flow, X-ray emitting region, jets and winds
the central engine environment (winds/BLR/torus in AGN)
the evolution across outbursts (binaries) and cosmic time (AGN)
the impact of AGN on their surroundings
Acrreting BH

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Acrreting BH: the X-ray view

all modified by absorption, often in the form of outflowing ionized gas
X-ray reflection

![Diagram of X-ray reflection](image)

![Graph showing energy spectrum and counts per unit energy](image)
X-ray reflection

rest frame spectrum
observed spectrum

$E^2 F(E)$

Energy (keV)

$\xi = 2 \times 10^2$
X-ray lags in AGN light curves

Spectral analysis alone often ambiguous (especially for broad features)
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Let’s turn to variability
A clear soft (negative) lag detection in 1H 0707-495

Fabian et al. 09
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Fabian et al. 09

[Graphs and charts showing data analysis and results related to the detection of a soft lag in the specified source.]

Energy (keV)

Counts/sec

TIME (days)

Energy (keV)

Ratio
A clear soft (negative) lag detection in 1H 0707-495

~ $10^2 - 10^3$ Hz in a BH binary (Poisson noise dominated)

this is then new territory for accreting BH
The case of 1H 0707-495

Zoghbi et al. 10,11

low frequencies
The case of 1H 0707-495

Zoghbi et al. 10,11

Low frequency lags are similar to what is seen in BH binaries (lag increases with energy separation) and in a similar range of (mass-scaled) Frequencies

Leading interpretation: inwards propagating fluctuations (explains also other properties)
The case of 1H 0707-495

High frequency lags are different to what is seen in BH binaries and show a much more complex pattern.

To understand the lag-energy spectrum at high frequencies, the photon spectrum can be useful.
The case of 1H 0707-495
The case of 1H 0707-495
Soft X-ray lags in a sample of variable AGN

De Marco et al. 13

At high frequency (depending on BH mass) the soft X-ray excess emission lags the X-ray continuum.

The amplitude of the lag is proportional to BH mass and corresponds to a few $r_g$ if interpreted as light-crossing-time.
Lags at Fe K energies

X-ray lags detected at Fe K energies are now detected in 7 sources.

The lags amplitude appears to scale with BH mass, as the soft lags do.
Lags at Fe K energies

X-ray lags of both the soft excess and Fe K line correspond to distances of few $r_g$ pointing towards a common origin in the innermost accretion flow
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\[ \xi = 2 \times 10^2 \]
Lags at Fe K energies

Only one of the signatures of reflection is left out: the Compton hump @ 20-30 keV
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The NuSTAR contribution

NuSTAR is the first X-ray observatory capable of imaging in the hard X-rays (3-80 keV) enabling to accurately account for contamination and background and with good sensitivity.

The good sensitivity means that X-ray variability analysis can be carried out almost at the same level as with XMM-Newton in the hard X-rays, at least in X-ray bright AGN.
The NuSTAR contribution

SWIFT J2127.4 is a NLS1 galaxy for which a BH spin of \(~0.6\) was measured (GM et al. 09 + Sanfrutos et al. 13 + others) and NuSTAR confirms the presence of a strong relativistic reflection component.
The NuSTAR contribution

Kara et al. 14

NuSTAR lags detection: Fe K and Compton hump!
The NuSTAR contribution

Kara et al. 14

NuSTAR confirms the Compton hump lag in other sources as well: the lag spectrum is fully consistent with the reflection component as derived from the photon spectrum
Conclusions

X-ray lags strongly suggest that the X-ray variability in accreting BH comprise contributions from reprocessing.

At high frequencies (fast variability) both the soft excess and Fe K line energy band lag the intermediate energies, likely dominated by the continuum emission.

One single reprocessed component peaking in the soft X-ray band and at Fe K is the simplest explanation.

NuSTAR observations reveal lags at 20-30 keV that are fully consistent with the Compton hump contribution, meaning that all reflection signatures are now detected confirming our initial interpretation.

This is an almost model-independent description of what X-ray reflection from partially ionized gas looks like.

The amplitudes of the lags in the soft excess, Fe K, and Compton hump are consistent with each other, and they correspond to only few $r_g$ in terms of light-crossing-time.
Thank you!

(backup slides on some theory / modeling available)
Some theory

Simple lamp-post geometry: a primary source of X-rays with power-law energy spectrum is located on the symmetry axis at height $h$

Photons are followed in full GR

a) from the source to the observer at infinity
b) from the source to the accretion disc

c) from the disc to infinity

to calculate

the observed primary flux and
the disc irradiation
the observed reflected flux
Some theory

To compute the local reprocessed component, the code is coupled with the reflionx reflection model where we can vary

- the reflection directionality (isotropic or not)
- the ionization profile on the disc (as a function of self-consistent irradiation and local disc density)

Relativistic effects are fully considered

- Doppler and gravitational energy shifts
- Light bending
- Beaming
- Light travel time

We consider the response to a flash of primary emission (approximated with a delta function)
Reflected

Continuum

Total

Emmanoulopoulos et al. 14
Effects of source h

lags get longer with h, lags have lower frequencies,

and (e.g. light bending models) X-ray flux increases with h

→ longer and lower frequency lags at higher flux levels expected
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Zogbi et al. 12