Modelling thermal reverberation in Active Galactic Nuclei

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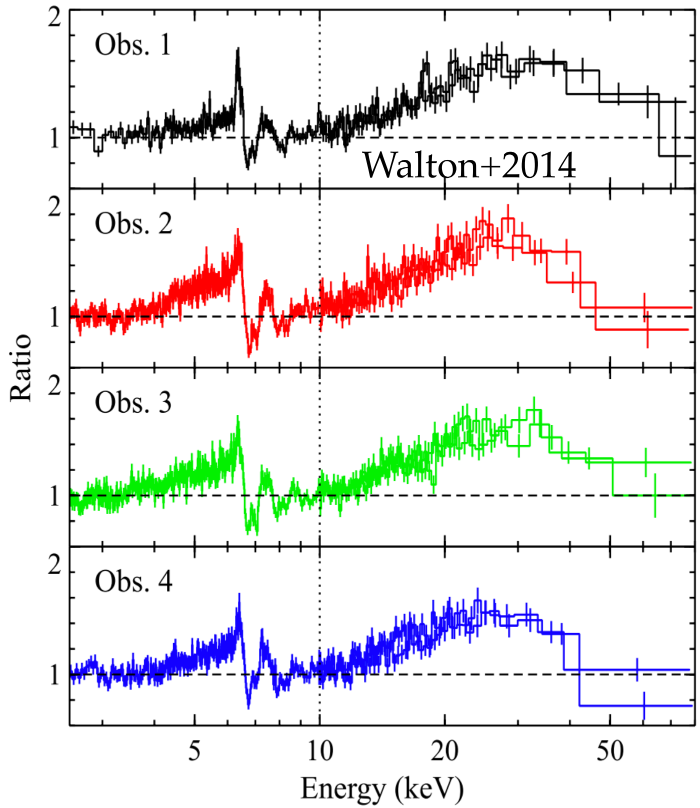
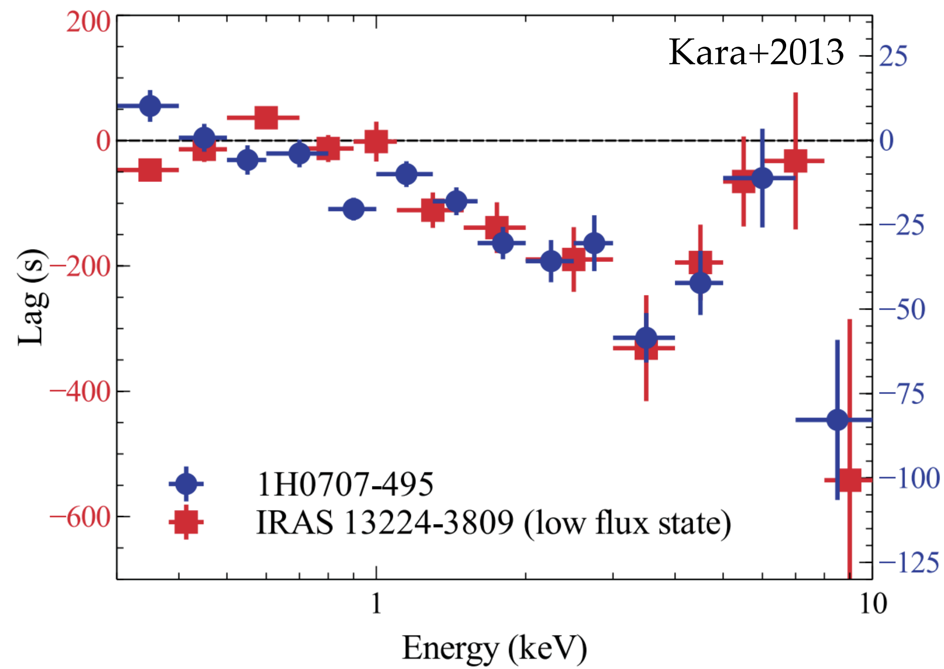
X-ray illumination





See also: Zoghbi+14, Marinucci+14, Nardini+16, Walton+20, …

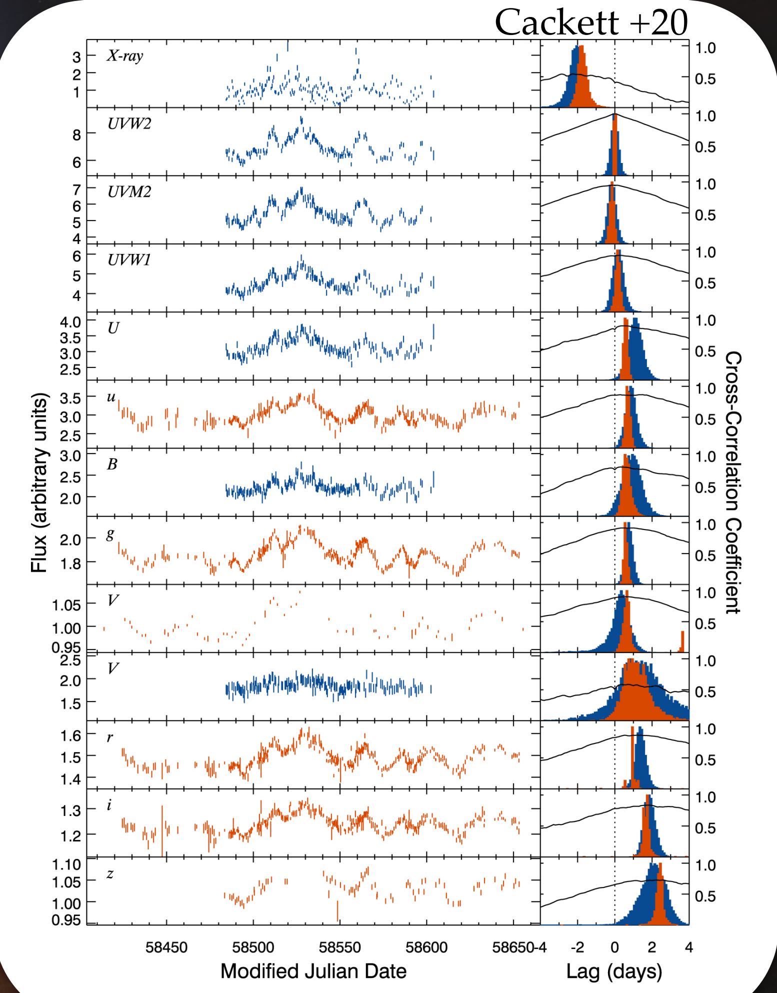
See also: Emmanoulopoulos+14, Epitropakis+16, Kara+16, Chainakun+16, Alston+20…

Thermal Reverberation - Past results

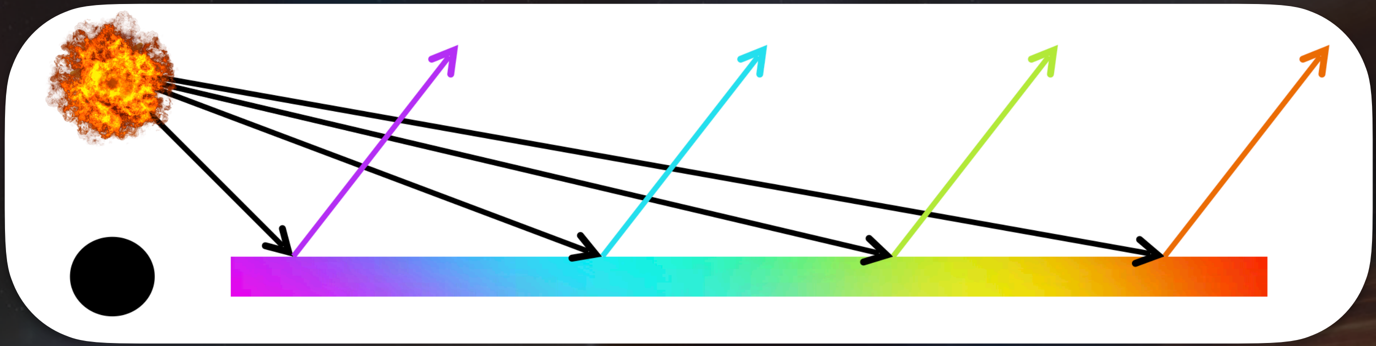
- Long monitoring in nearby bright AGN revealed the presence of a UV/optical continuum time lag that increases with increasing wavelength.

- This cannot be due to fluctuations in the accretion rate, as those fluctuations propagate inward and should give the opposite effect.

- The most plausible explanation is that this is due to thermal reverberation due to the irradiation by a central source.



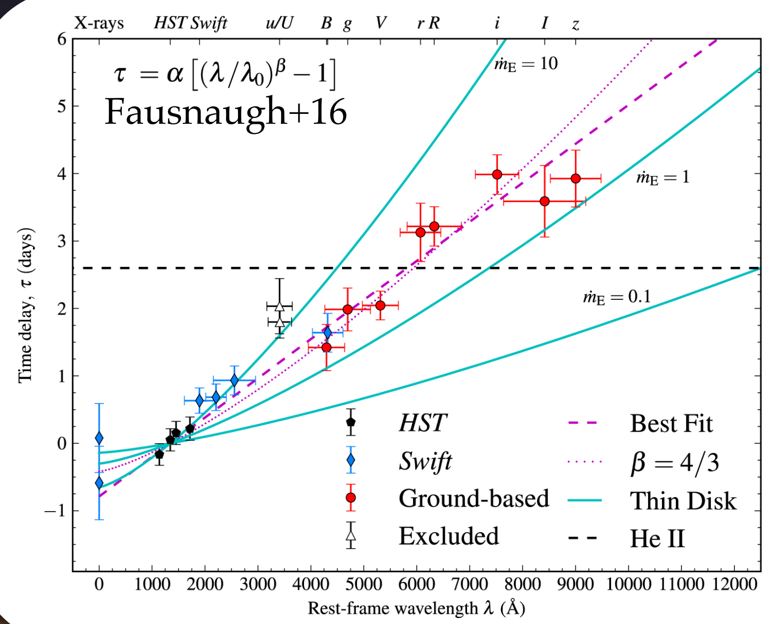
Thermal Reverberation - Past results



i) the shape agrees with the predictions of a standard Shakura-Sunyaev disc

ii) but not the amplitude

⇒ Are the accretion discs larger than expected?



A new model to fit **(not only)** the time lags

We investigated this issue assuming a simple lamp-post geometry:

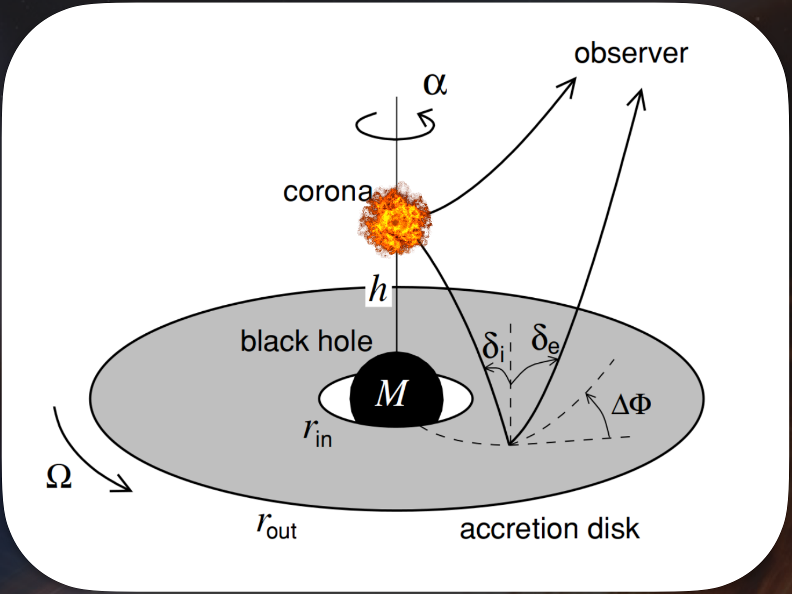
1) taking into account all **simple and general relativity** effects in the propagation of light from the source to the disc, and from the disc to the observer.

2) Measuring the **disc reflection** flux taking into account the ionisation state of the disc.

Model set-up

Parameters:

- BH spin
- BH mass
- Accretion rate
- X-ray luminosity
- X-ray source height
- X-ray spectral shape
- Outer radius of the disc



Lamp-post geometry

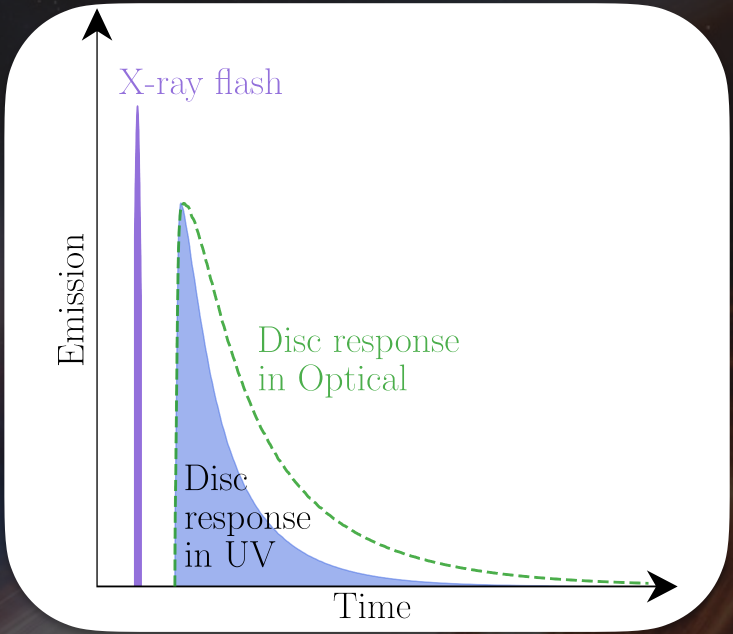
$$F_{\rm abs}(R,t) = F_{\rm inc}(R,t) - F_{\rm ref}(R,t)$$

$$T_{\rm new}(R,t) = \left[\frac{F_{\rm abs}(R,t) + F_{\rm NT}(R)}{\sigma}\right]^{1/4}$$

$$\boxed{\Psi(\lambda, t_{\rm obs}) = \frac{F_{\rm tot}(\lambda, t_{\rm obs}) - F_{\rm NT}(\lambda, t_{\rm obs})}{L_{\rm X,Edd}\Delta t}}$$: Response function

$$F_{\rm obs}(\lambda,t) = F_{\rm NT}(\lambda) + \int_0^{+\infty} L_{\rm X}(t-t')\ \Psi(\lambda,t')\ {\rm d}t'$$

Disc response function



We estimated the “response function” (Ψ) to an X-ray flash in various wavelengths, for all the parameters.

From that we can estimate the average time-lag at each wavelength being the centroid of the response function:

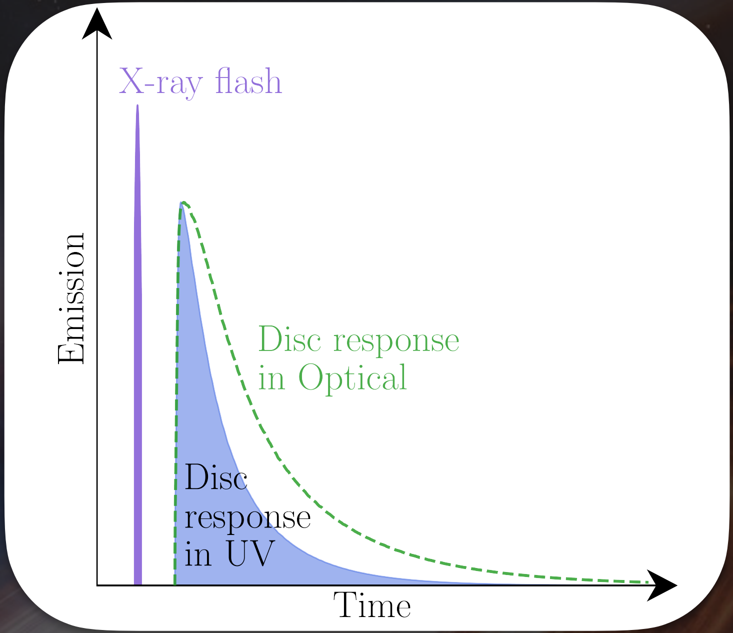
$$\langle \tau(\lambda) \rangle = \frac{\int t\Psi(\lambda, t)\mathrm{d}t}{\int \Psi(\lambda, t)\mathrm{d}t}$$

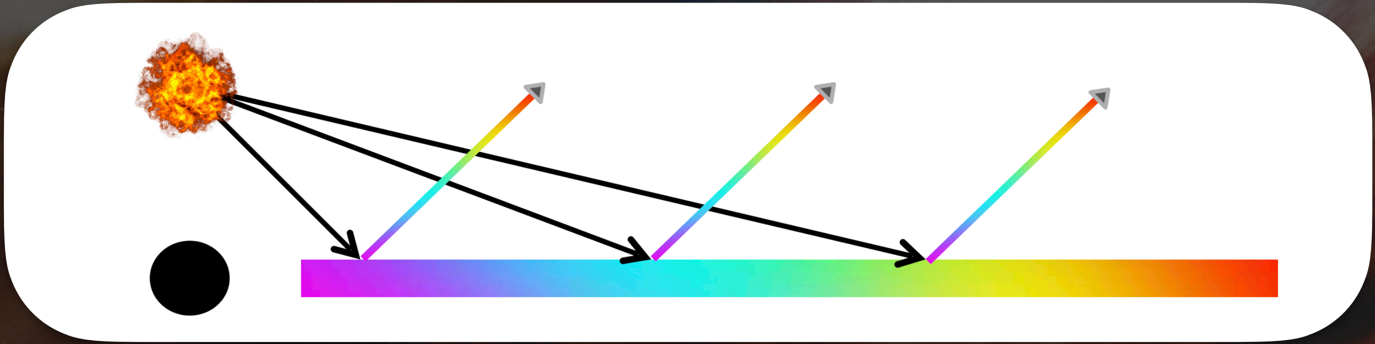
Results presented in
Kammoun et al. (2019, 2021a,b, 2023 sub.)

Disc response function

1) Response functions start simultaneously at all bands.

2) The response functions last more at longer wavelengths because, as time passes, we detect disc elements which are located further out, hence they are cooler, so they do not emit at UV, but they contribute to optical bands.





All radii emit at all wavelengths (thermal emission) !

Time-lag modelling

Including all these effects:

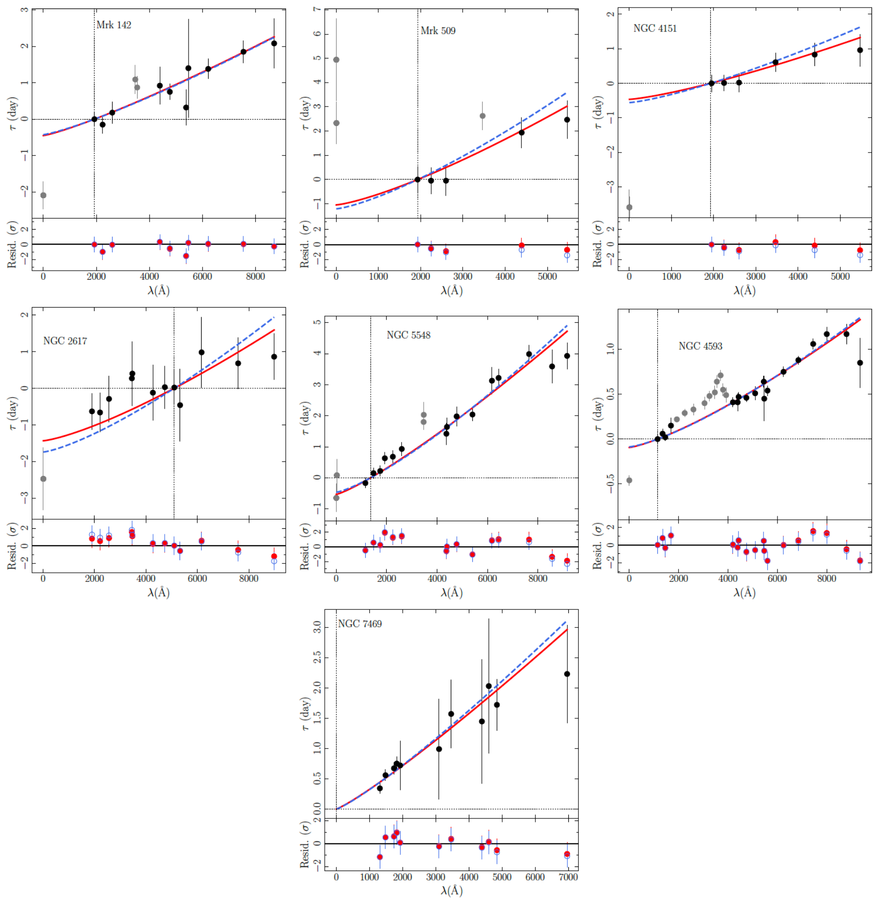
$$\tau(\lambda) = A(h_{10})M_7^{0.7} f_1(\dot{m}_{0.05}) f_2(L_{\mathrm{X},0.01})\lambda_{1950}^{B(h_{10})}$$

for spin 0 and 1 and $f_{\mathrm{col}} = 2.4$

→ knowing M and L_X (from X-ray spectral analysis), we can fit for **height and $\dot{m}$**

We applied our model to the existing time-lag spectra for 7 sources + Fairall 9 + Mrk 817 by Kara et al. (2021)

⇒ A standard accretion disc explains the observed shape and amplitude.



Kammoun et al. 2021b

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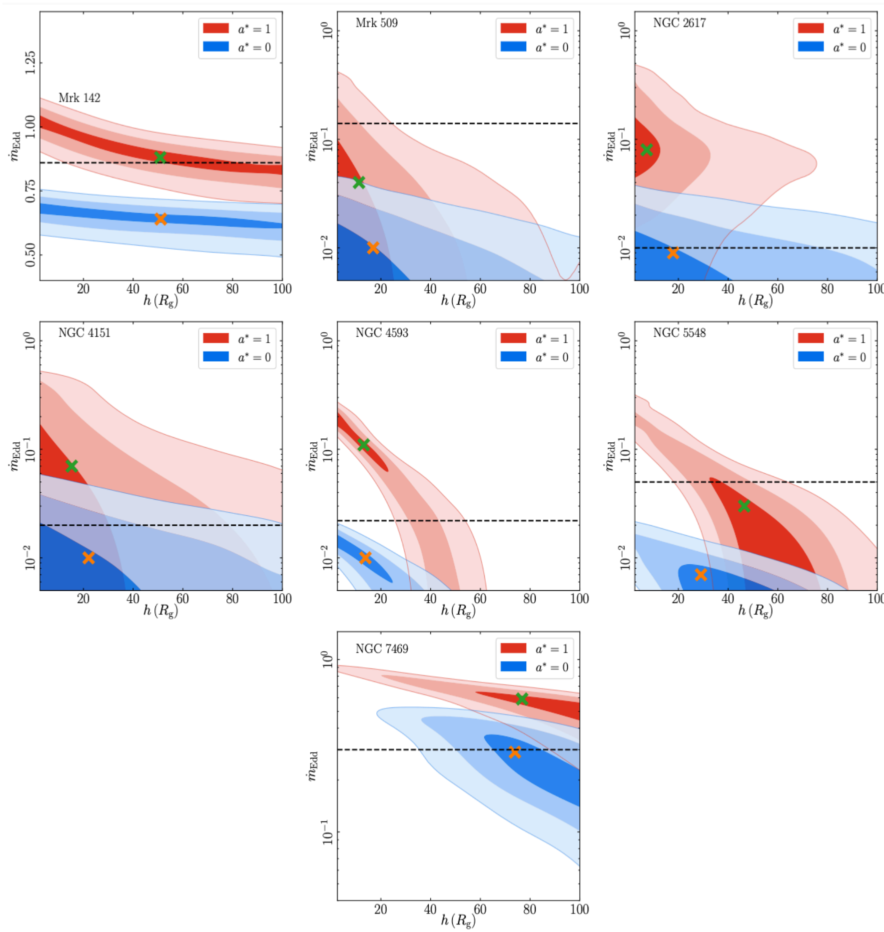


Kammoun et al. 2021b

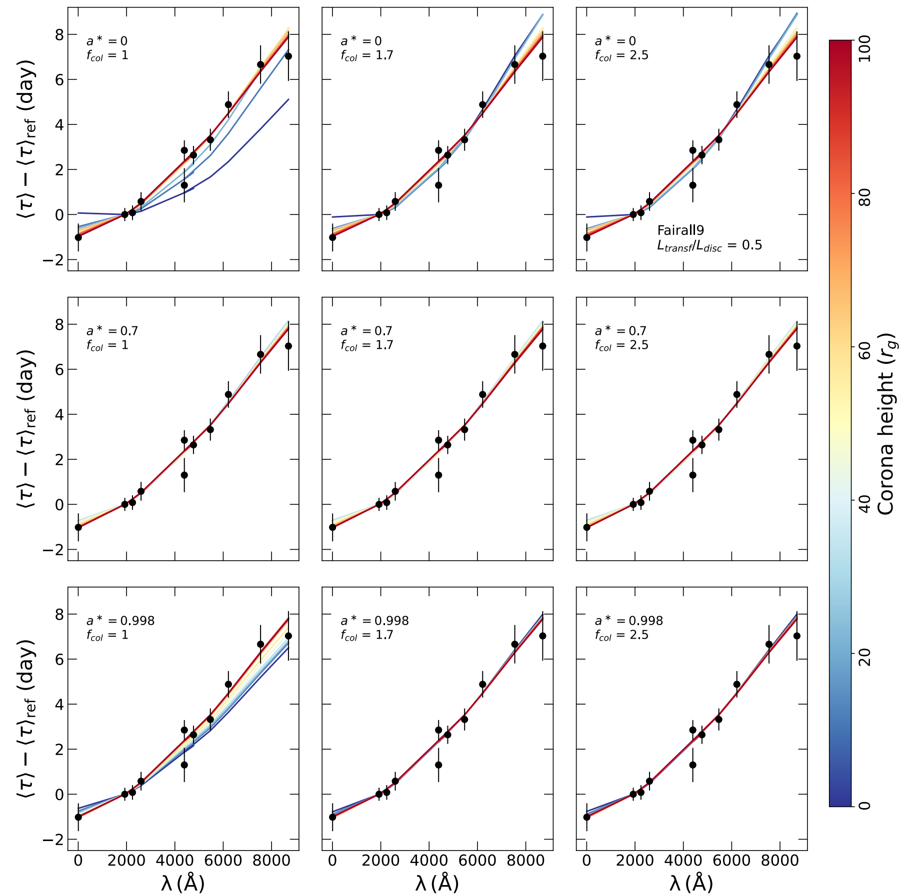
Time-lag modelling - a novel approach

An updated code (Python interface) to simulate and fit the time lags with more options and flexibility compared to the previous analytic approximation

Parameters:

- Spin
- BH mass
- Height
- Accretion rate
- Colour correction factor
- Outer disc radius
- X-ray power:
    - Internal to the disc
    - External to the disc

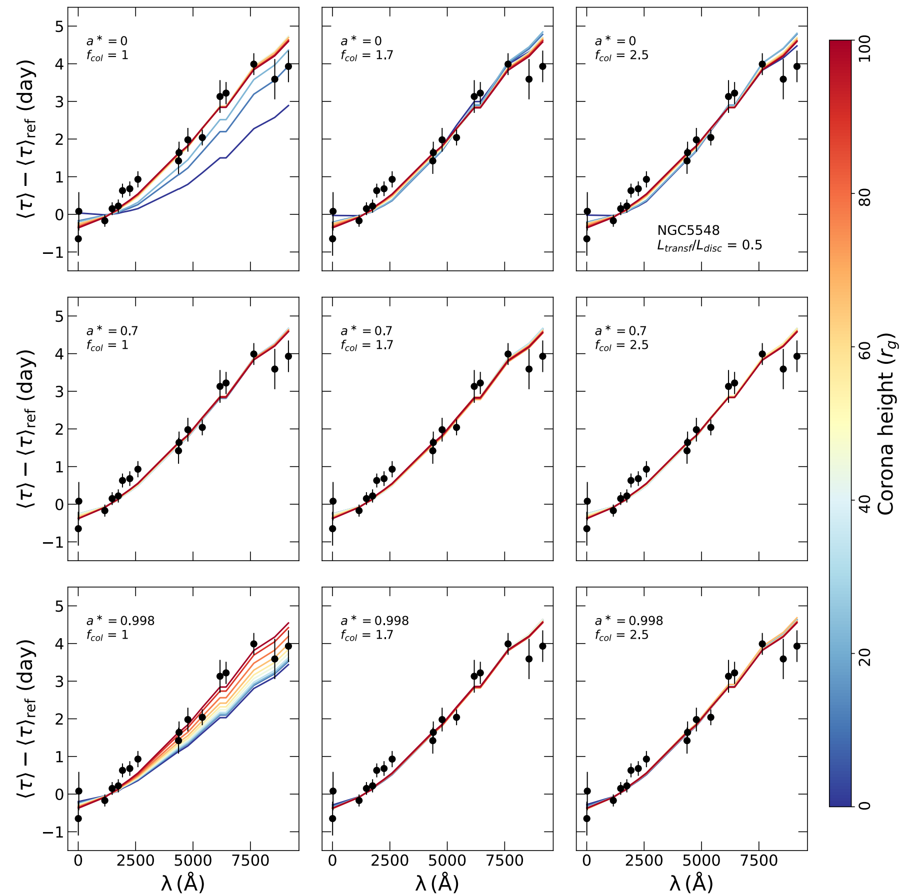
Time-lag modelling - a novel approach



Kammoun et al. 2023 submitted

Fairall 9

Time-lag modelling - a novel approach



Kammoun et al. 2023 submitted

NGC 5548

Time-lag modelling - a novel approach

	NGC 4593		
$L_{\rm transf}/L_{\rm disc} = 0.5$	$a^* = 0.7$	$f_{\rm col} = 1.7$	$h \in [5.6; 42.7]\,r_{\rm g}$
	$a^* = 0.998$	$f_{\rm col} = 1.7$	$h \geq 64\,r_{\rm g}$
$L_{\rm transf}/L_{\rm disc} = 0.9$	$a^* = 0$	$f_{\rm col} = 1.7$	$h \in [28.5; 64]\,r_{\rm g}$
	$a^* = 0.7$	$f_{\rm col} = 1.7$	$h \geq 42.7\,r_{\rm g}$
	$a^* = 0.998$	$f_{\rm col} = 1.7$	$h \geq 64\,r_{\rm g}$
		$f_{\rm col} = 2.5$	$h \in [5.6; 8.4]\,r_{\rm g}$
	NGC 5548		
$L_{\rm transf}/L_{\rm disc} = 0.5$	$a^* = 0$	$f_{\rm col} = 1.7$	$h \geq 8.4\,r_{\rm g}$
	$a^* = 0.7$	$f_{\rm col} = 1.7$	$h \geq 64\,r_{\rm g}$
	$a^* = 0.998$	$f_{\rm col} = 2.5$	$h \in [5.6; 28.5]\,r_{\rm g}$
$L_{\rm transf}/L_{\rm disc} = 0.9$	$a^* = 0$	$f_{\rm col} = 2.5$	$h \in [18.9; 28.5]\,r_{\rm g}$
	$a^* = 0.998$	$f_{\rm col} = 2.5$	$h \in [18.9; 42.7]\,r_{\rm g}$
	Fairall 9		
$L_{\rm transf}/L_{\rm disc} = 0.9$	$a^* = 0$	$f_{\rm col} = 1.7$	$h \geq 64\,r_{\rm g}$
		$f_{\rm col} = 2.5$	$h = 8.4\,r_{\rm g}$
	$a^* = 0.7$	$f_{\rm col} = 1.7$	$h \geq 64\,r_{\rm g}$
	$a^* = 0.998$	$f_{\rm col} = 1.7$	$h = 96\,r_{\rm g}$
	Mrk 817		
$L_{\rm transf}/L_{\rm disc} = 0.1$	$a^* = 0$	$f_{\rm col} = 2.5$	$h \geq 5\,r_{\rm g}$
	$a^* = 0.7$	$f_{\rm col} = 2.5$	$h \geq 28.5\,r_{\rm g}$
$L_{\rm transf}/L_{\rm disc} = 0.5$	$a^* = 0$	$f_{\rm col} = 2.5$	$h = 96\,r_{\rm g}$

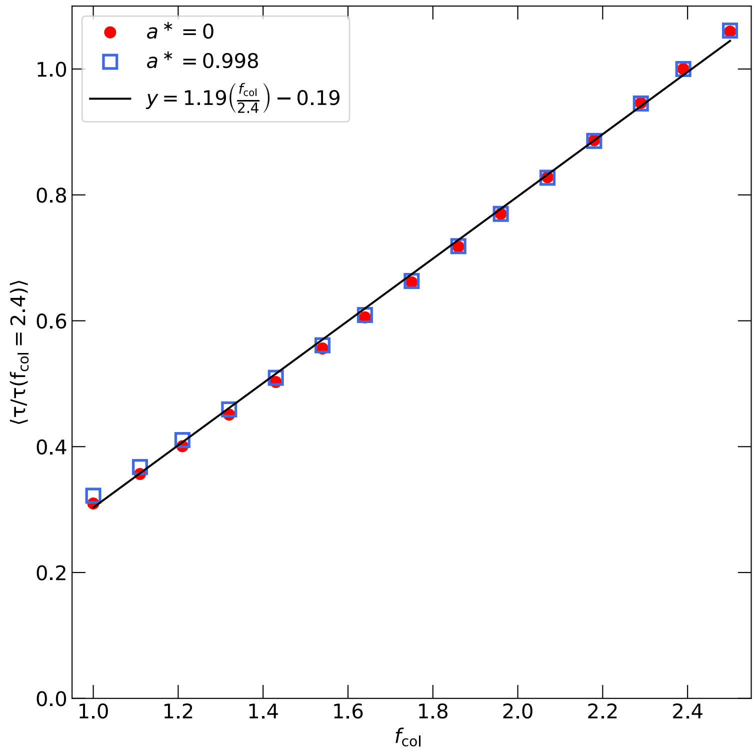
Kammoun et al. 2023 submitted

Time-lag modelling - a novel approach

We also updated the analytic prescription for the external power case, including the effect of $f_{\rm col}$

$$\tau(\lambda) = A(h_{10}) M_7^{0.7} f_1(\dot{m}_{0.05}) f_2(L_{X,0.01}) f_3(f_{\rm col}) \lambda_{1950}^{B(h_{10})}$$

$$f_3(f_{\rm col}) = 1.19 \left(\frac{f_{\rm col}}{2.4}\right) - 0.19$$



Kammoun et al. 2023 submitted

Conclusions

- An X-ray illuminated standard accretion disc can explain the observed UV/optical continuum time lags in AGN.

- A colour correction $f_{\rm col} > 1$ seems to be needed in all cases.

- This can model can also explain:
    - The time-averaged SED in NGC 5548 (Dovčiak et al., 2022)
    - The multi-wavelength power spectra (Panagiotou et al., 2020, 2022)
    - The disc-size problem in lensed QSOs (Papadakis et al., 2022)
    - The time-resolved SED in NGC 5548 (Kammoun et al. in preparation)

- We have a new code that can be used to simulate and fit the observed time lags.