“Accretion disc thermal reverberation in the lamp post geometry”

I. Papadakis (Uni. of Crete/IA, FORTH)
&
(E. Kammoun, Dep. of Astronomy, Uni. of Michigan
& M. Dovciak, Czech Academy of Sciences)

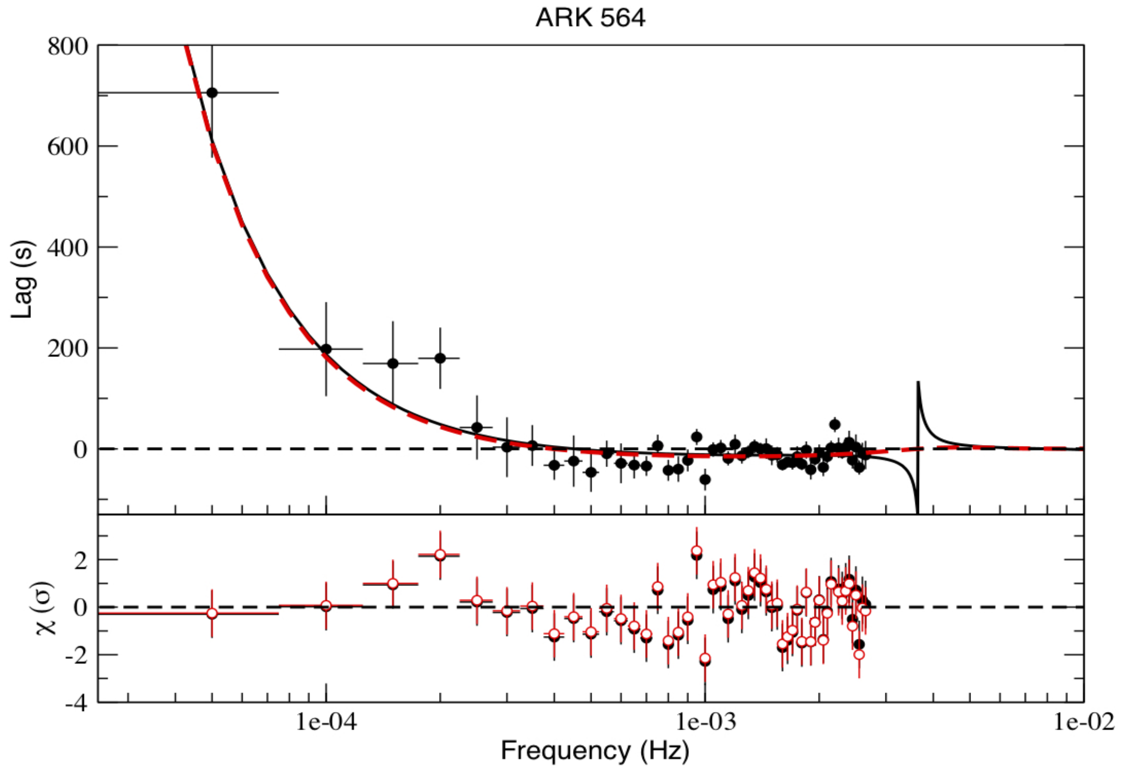
(Kammoun, Papadakis, & Dovciak, 2019, ApJ, 879, L24)

Motivation:

“An independent set of constraints on the source geometry comes from fast time variability. The reflected emission should respond to fast fluctuations in the X-ray source brightness, so that it is a lagged and smoothed version of the continuum light curve. The lag is related to the timescale for light to travel between the X-ray source and the reflecting disc, so could give a direct measure of the mean distance of the disc from the source.” (from the proposal's text).

Example:

A point-like X-ray source, located at ~2.5 r_g above the central BH can explain the “negative” time-lags at high frequencies in Ark 564.



Caballero-Garcia M. et al, 2018, MNRAS, 480, 2650

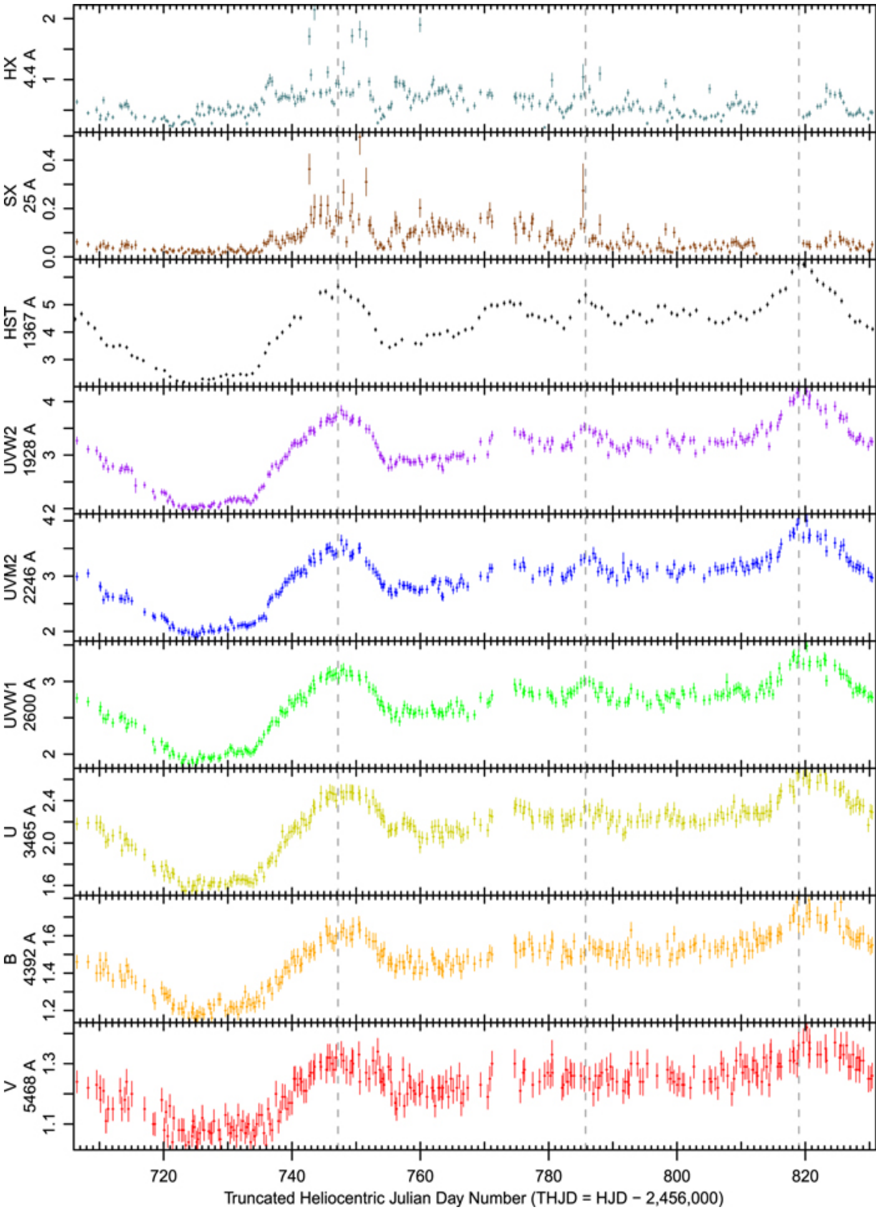
BUT, IN THIS CASE:

Part of the X-rays will be absorbed, the disc temperature will increase, and the disc UV/optical emission (in **AGN**) will also increase.

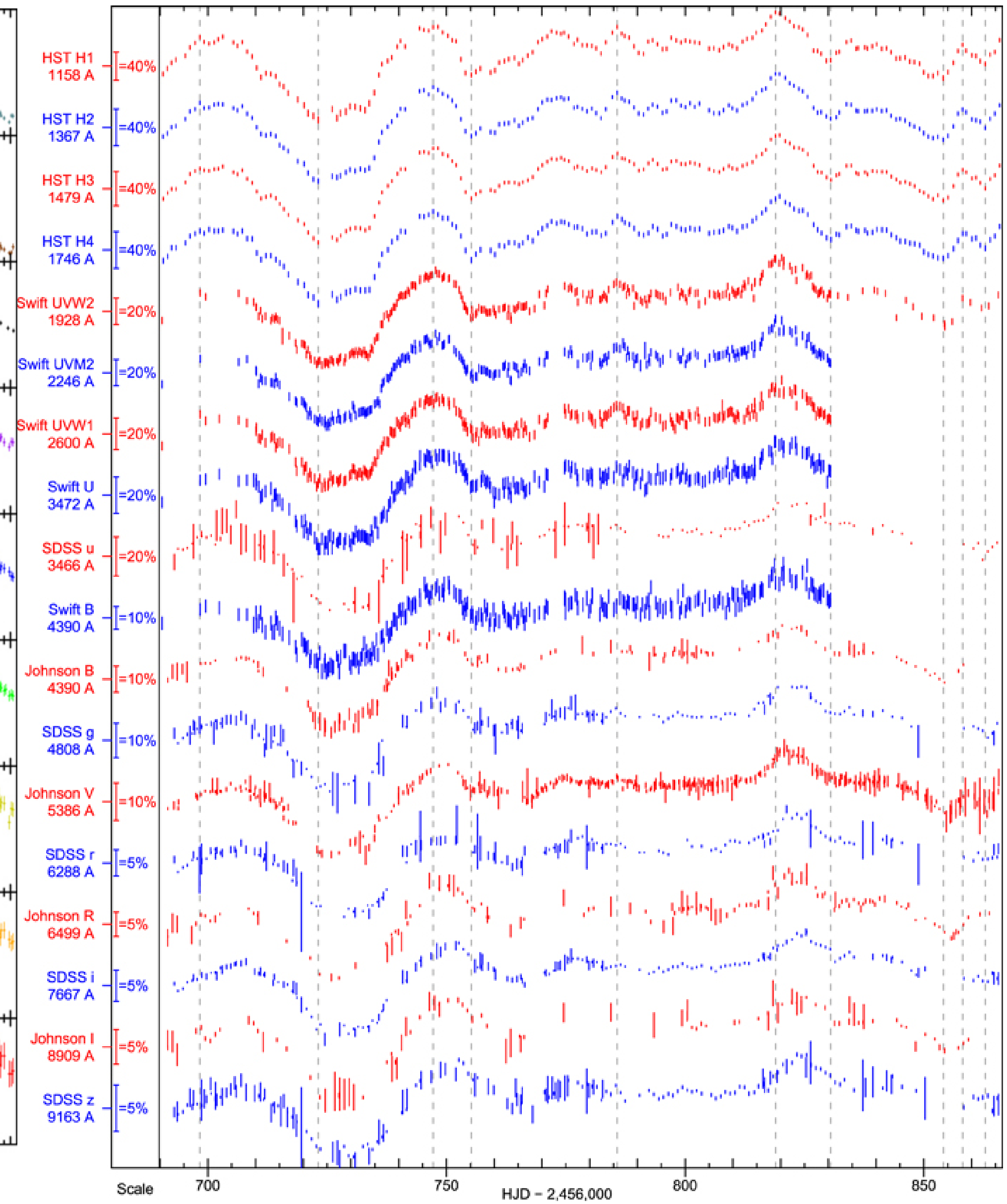
IF the X-rays are variable, **THEN** the reprocessed UV/optical emission will also be variable, and delayed, with respect to X-rays. The delays ("time-lags") should increase with increasing wavelength.

The *thermally reprocessed* emission should also respond to variations in the X-ray source brightness, so the *variable emission in the UV/optical bands* should be a lagged and smoothed version of the X-ray light curve. The lags should be related to the timescale for light to travel between the X-ray source and the absorbing disc, so could give a direct measure of the mean distance of the disc from the source.

Edelson et al, 2015, ApJ, 806, 129



Fausnaugh et al, 2016, ApJ, 821, 56



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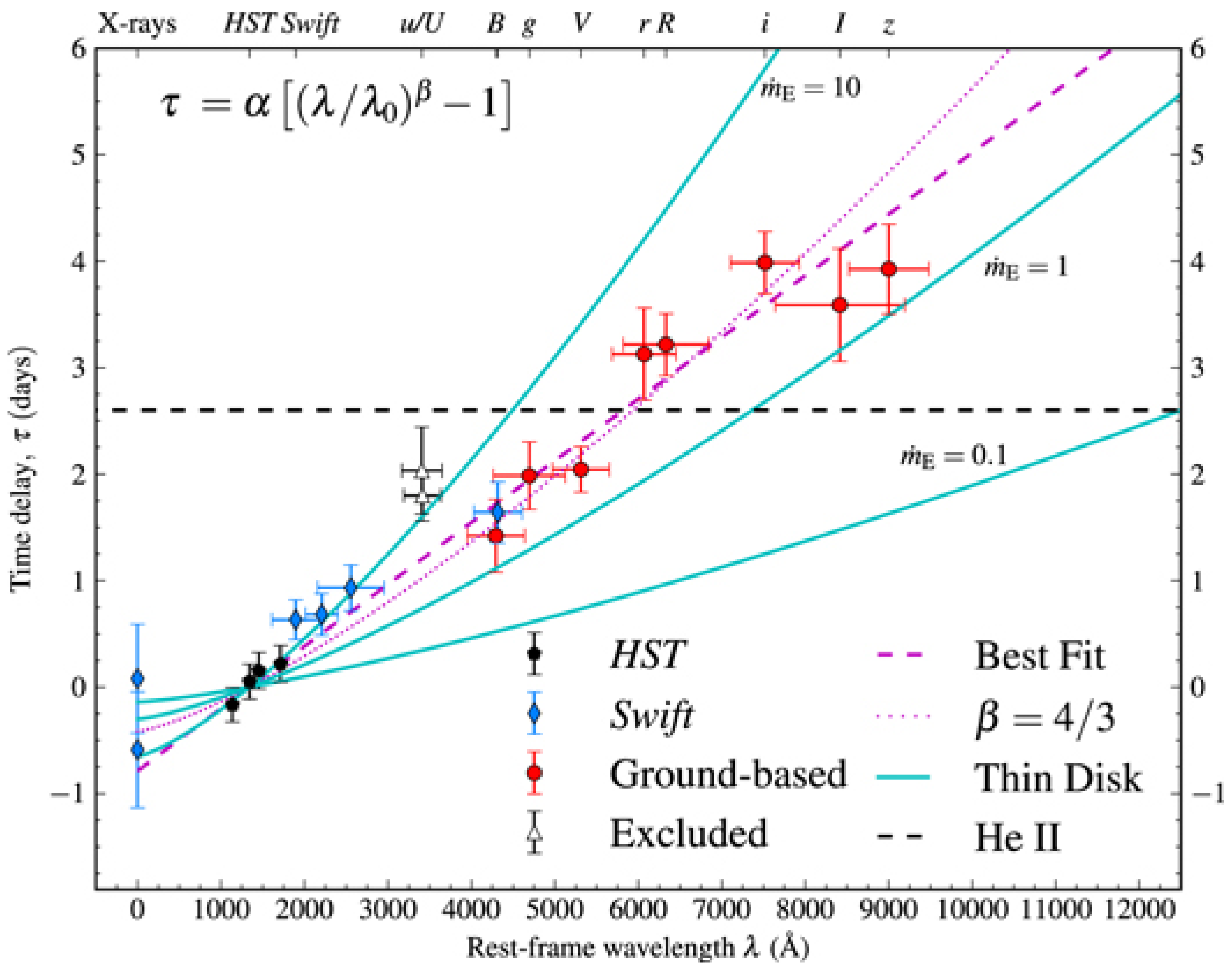
Fausnaugh et al (2016) have modeled the UV/optical "time lags vs λ" (ie the "time-lags spectrum") in NGC5548, and found that:

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

ii) but not the amplitude



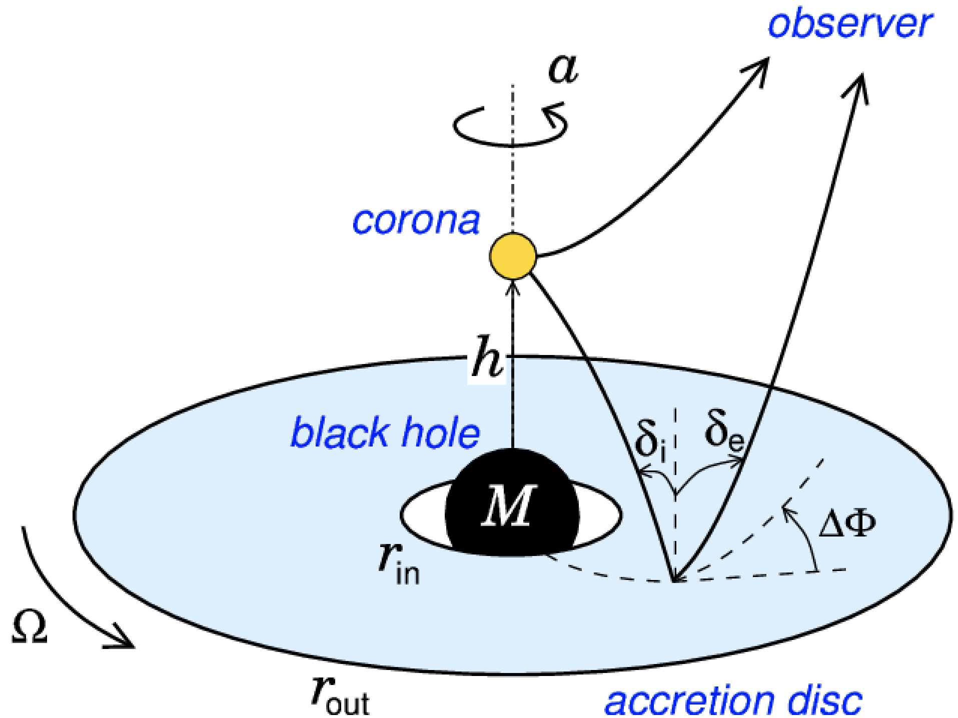
However, the relation between the time lag and wavelength does not depend only on BH mass and accretion rate.

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

1) taking into account relativistic effects in the propagation of light from the source to the disc, and from the disc to the observer, and

2) measuring the disc reflection flux, taking into account the ionization state of the disc.

The Model Set-up

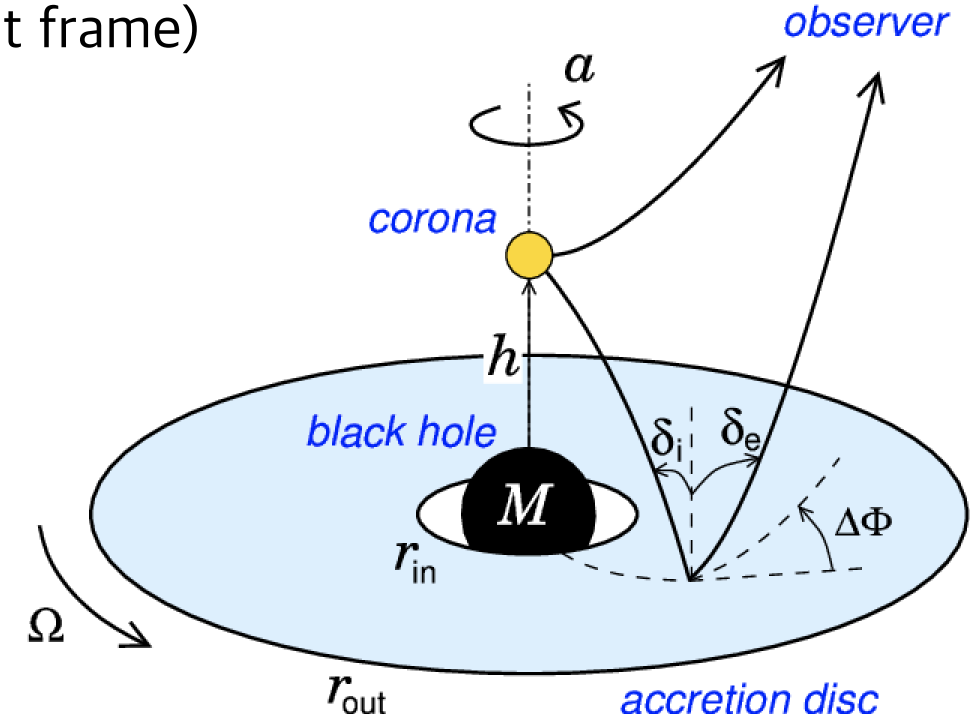


Accretion disc:

- Accretion rate, $\dot{m}$
- Keplerian, co-rotating with BH
- Novikov-Thorne temperature profile with a color temperature correction factor of 2.4
- From $r_{in}=r_{ISCO}$ to $r_{out}=10^4\ r_g$
- a =0 and a =1

X-ray source

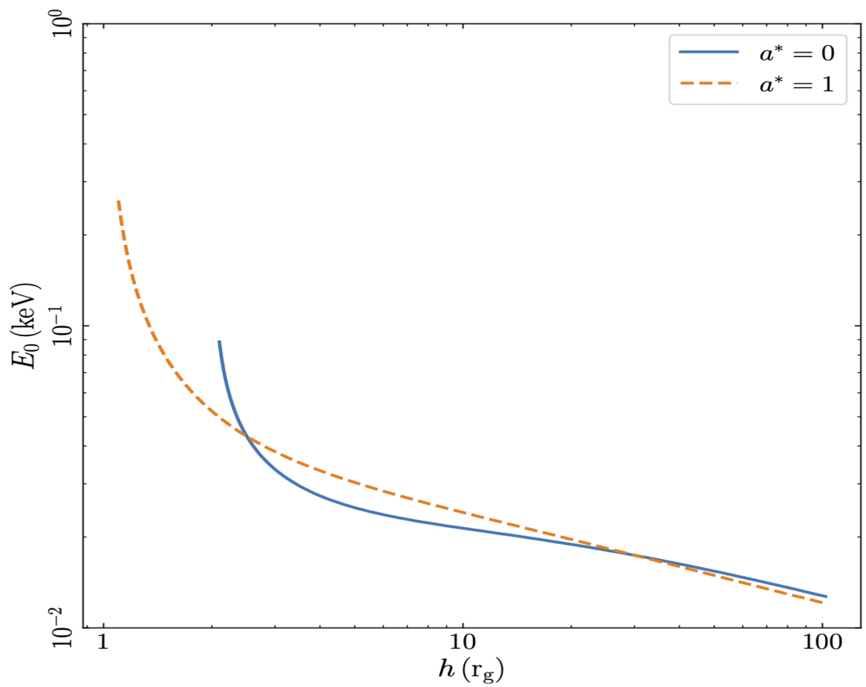
- emits isotropically (in rest frame)
- $F_X = N(t)E^{-\Gamma}\exp(E/E_C)$,



The total X-ray flux ($L_{X,tot}$) depends on N(t), Γ, E_C, and the low-energy cut off, E_0. It is important to compute it correctly, in order to determine the disc ionization correctly.

1) The normalization of the X-ray spectrum is set by the **observed** $L_{(2\text{-}10keV,obs,Edd)}$. Depending on **h**, we use it to estimate the intrinsic $L_{(2\text{-}10\ keV,int,Edd)}$ (both $L_{(2\text{-}10keV)}$ and are defined in terms of L_{edd}).

2) E_0 depends on the energy of the seed photons arriving at the X-ray source at a given height above the disc. The correct determination is important for the estimation of $L_{X,tot}$ (specially for steep Γ).



$$E_0 \propto \left[\frac{\dot{m}/\dot{m}_{Edd}}{0.01}\frac{1}{M_6}\right]^{1/4}$$

mdot=0.01, BH mass = 10^6 solar

3) A free parameter of the model is $E_{C,obs}$. The model then computes $E_{C,intr}$, depending on **h**. The high-energy cut-off may be important for the determination of $L_{X,tot}$ in the case of flat Γ.

4) Knowing Γ, $E_{0,int}$, $E_{C,int}$, and $N(t)_{int}$ (in the corona rest frame), we can estimate the X-ray luminosity that will shine each disc element (in its rest frame), in order to determine its ionization.

5) Then, we compute the flux of the X-ray reflected spectrum, $F_{ref}(r)$.

To do this we use the `xillver-a-Ec5` tables (Garcia J.A. et al,2016, MNRAS, 462, 751) given $E_0(r)$ and $E_C(r)$, locally, as seen by the disc. The use of these tables is necessary in order to compute the X-ray reflection flux for different $E_C(r)$, but that implies that we have assumed that the disc density is 10^{15} cm^{-3} (in all cases).

The best way to investigate
the **correlation** between the X-rays and the the UV/opt bands
is to compute
the **response** of the disc (in each UV/opt band) to an X-ray flush.

Computation of the disc response.

i) Assume an X-ray flare ($\mathbf{F_{x,obs}}$) which happens at time t=0.

ii) Compute $\mathbf{F_{x,int}}$ and $\mathbf{F_{inc}(r, t)}$, X-ray flux incident to the disc at a radius r, and at time t (taking into account all relativistic effects).

iii) Estimate ionization profile of the disc, $\mathbf{F_{refl}(r,t)}$ (assumed to be equal to the integral of the reflected spectrum from $E_0(r,t)$ to infty) and, finally,

$$\mathbf{F_{abs}(r,t) = F_{inc}(r,t) - F_{ref}(r,t)}$$

Flux absorbed by the disc, and then:

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

Then,

a) we identify all the disc elements that a distant observer will detect at t_{obs}

b) we compute their total flux, in a given wavelength band $\Delta\lambda$ (λ_{min}–λ_{max}), using $T_{new}(r,\varphi, t_{obs})$,

c) and we subtract this flux from the flux that the disc elements would emit if their temperature were equal to $T_{NT}(M_{BH},\dot{m},r)$

This flux difference defines the "disc response function",

$\Psi_{\Delta\lambda}(t_{obs})$,

as follows:

$$\Psi_{\Delta\lambda}(t_{obs}) = \frac{F_{new}(\Delta\lambda, t_{obs}) - F_{NT}(\Delta\lambda)}{L_{2-10\,keV,\,obs,\,Edd}\,\Delta T}$$

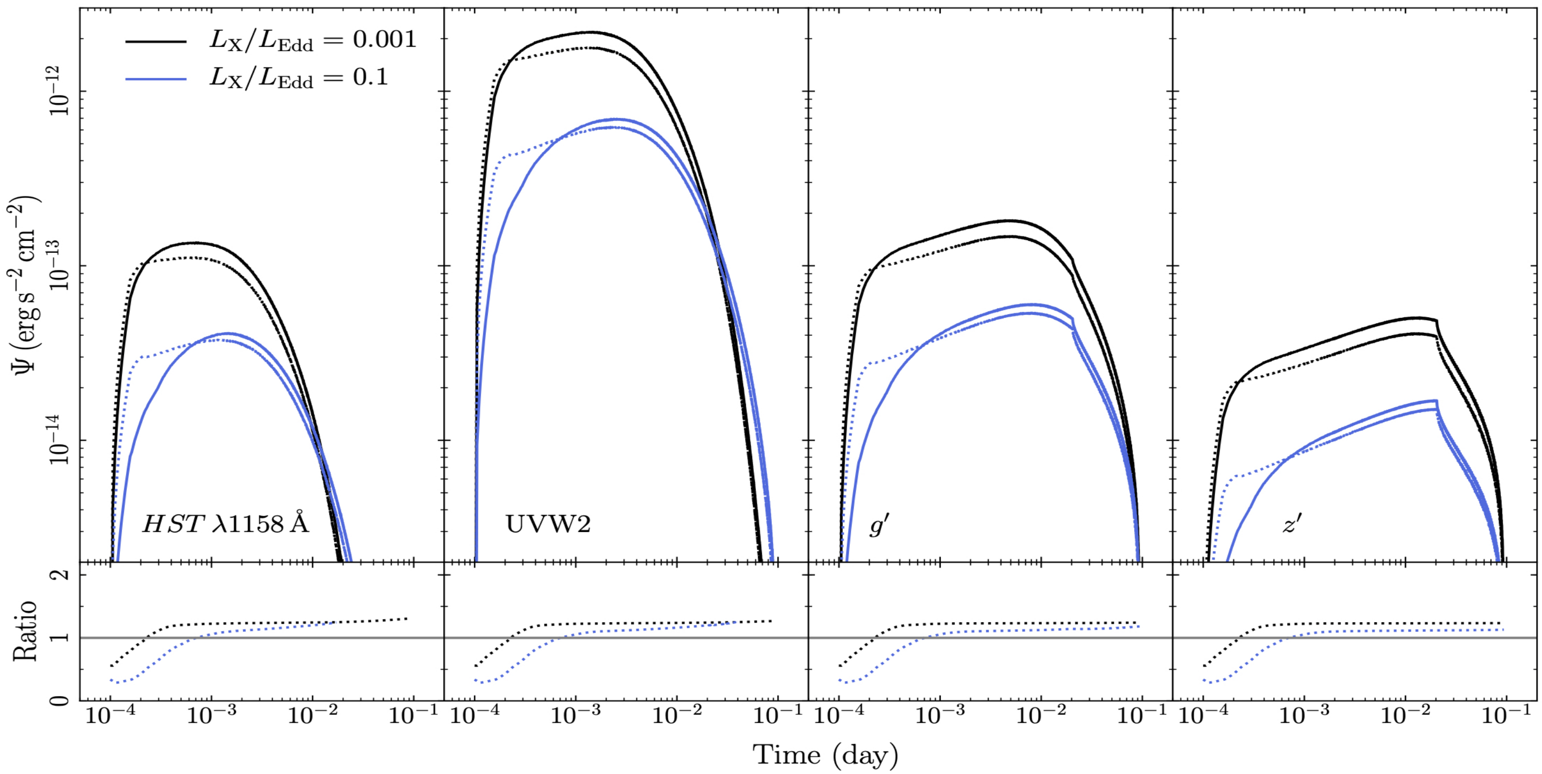
This function shows the extra disc emission, in a given wavelength band, Δλ, as a function of time, due to disc absorbing X-rays, so that the total disc emission in Δλ will be equal to:

$$F_{total}(\Delta\lambda, t_{obs}) = F_{NT}(\Delta\lambda) + \int_0^\infty L_X(t')\,\Psi_{\Delta\lambda}(t_{obs} - t')\,dt'$$

Difference between responses when:

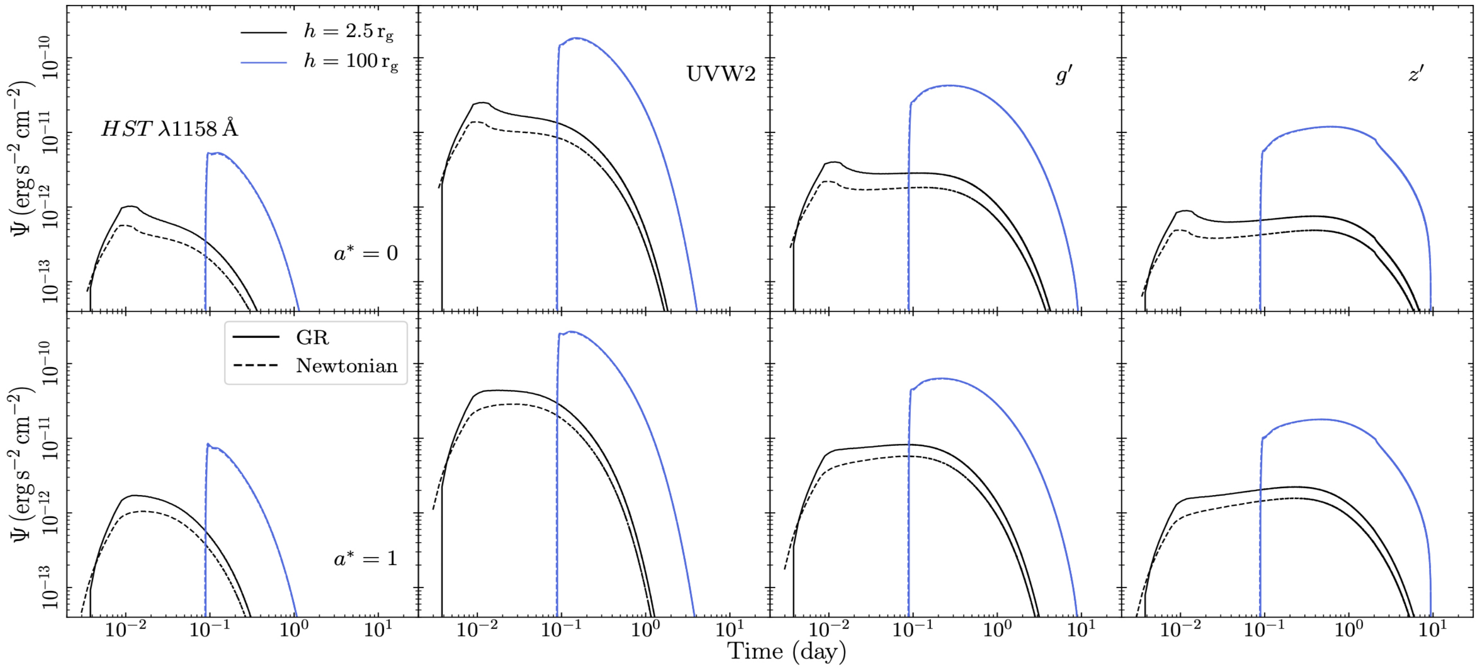
1) we take into account the ionization state of the disc and compute the reflected flux (solid lines)

and **2)** we use a fixed albedo, of 0.3 (dashed lines)



M=10^5, mdot=0.1, h=10 r_g, Γ=2

Difference between responses when:
1) we take into account GR effects (solid lines)
and 2) we use Newtonian approximation (dashed lines)



Parameter		Range
BH spin	a^*	**0, 1**
Accretion rate	$\dot{m}/\dot{m}_{\rm Edd}$	0.005, 0.01, 0.02, **0.05**, 0.1, 0.2, 0.5
Lamp-post height	h ($\rm r_g$)	2.5, 5, **10**, 20, 40, 60, 80, 100
BH mass	$M_{\rm BH}$ (10^8 $\rm M_{\odot}$)	0.01, 0.05, **0.1**, 0.5, 1
Photon index	Γ	1.5, 1.75, **2**, 2.25, 2.5
Iron abundnace	$A_{\rm Fe}$ (solar)	0.5, **1**, 2, 4, 10
Inclination angle	θ (deg.)	5, 20, **40**, 60, 80
Inner radius	$R_{\rm in}$	$R_{\rm isco}$, 10 $\rm r_g$, 100 $\rm r_g$
Outer radius	$R_{\rm out}$ ($\rm r_g$)	500, 100, 5000, **10000**
High-energy cutoff	$E_{\rm cut}$ (keV)	50, **150**, 300, 500
X-ray luminosity	$L_{\rm X}/L_{\rm Edd}$	0.001, 0.0025, 0.005,
		0.01, 0.025, 0.05, 0.1, 0.25, 0.5

Knowing Ψ, we estimated:

a) their centroid:

$$\tau(\Delta\lambda)=\frac{\int t\Psi_{\Delta\lambda}(t)\,dt}{\int \Psi_{\Delta\lambda}(t)\,dt}$$

This is assumed to be a good indicator of peak of the cross-correlation between X-rays and the emission in the opt/UV band - Δλ.

But note: $$CCF_{X-vs-\Delta\lambda}(\tau)=\int_{-\infty}^{+\infty}\Psi_{\Delta\lambda}(\tau')\,ACF_X(\tau-\tau')\,d\tau'$$

R

b) The average "thermal reverberation fraction":

$$R_{rev}(\Delta\lambda)=\frac{\int_0^{+\infty} L_{X,Edd}\,\Psi_{\Delta\lambda}(t')\,dt'}{F_{NT}(\Delta\lambda)}$$

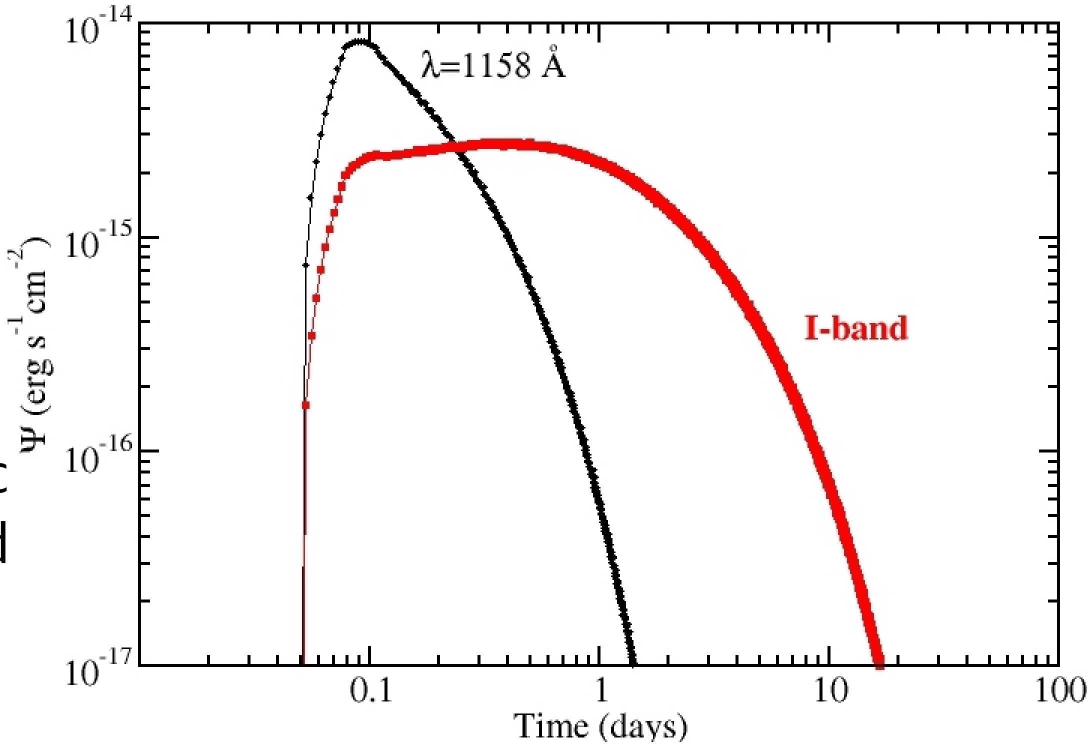
The time-lags vs wavelength, and the reverberation fraction can be used to explain observations.

The disc response functions

$\dot{m}$=0.25% of $\dot{m}_{Eddd}$, h=10 r_g

1) Response functions start simultaneously at all bands

2) They 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.

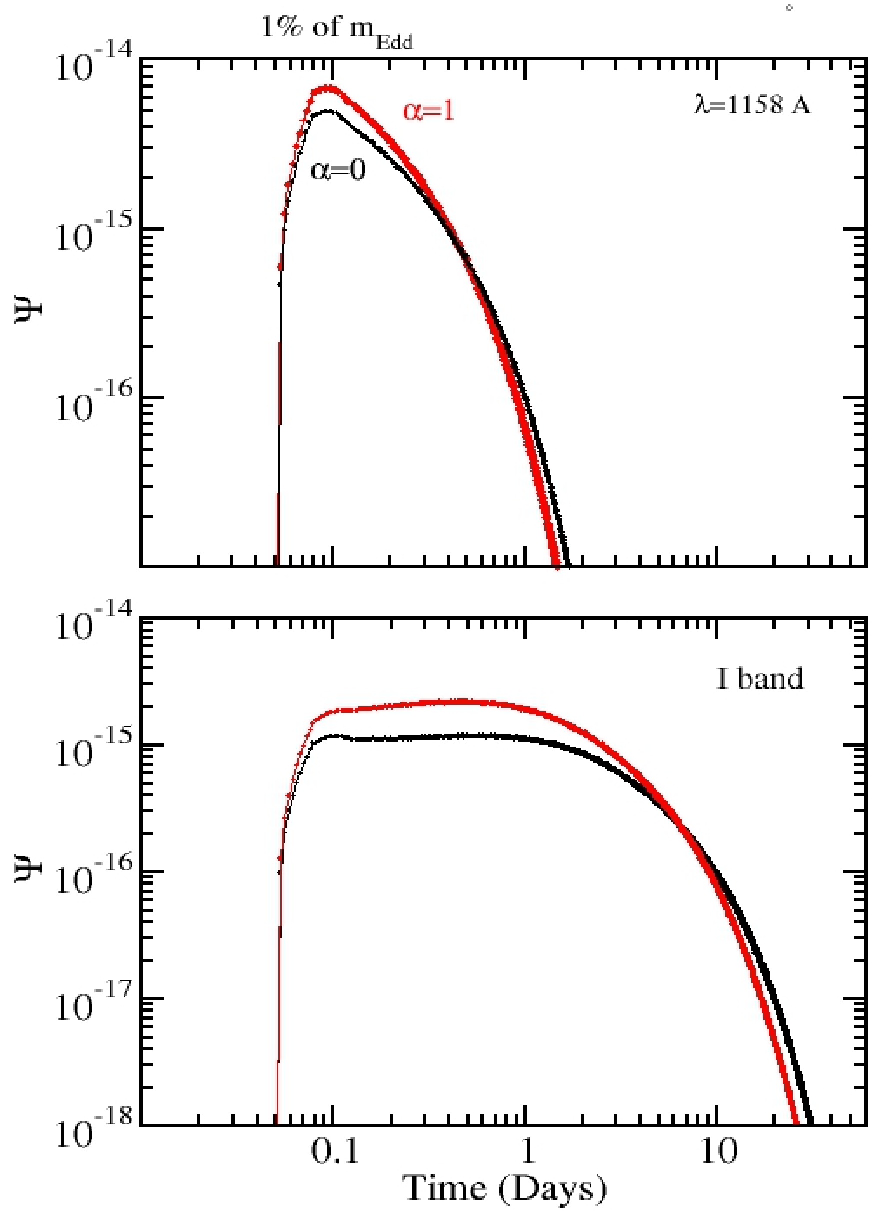


Response functions have

i) a larger amplitude and

ii) are narrower

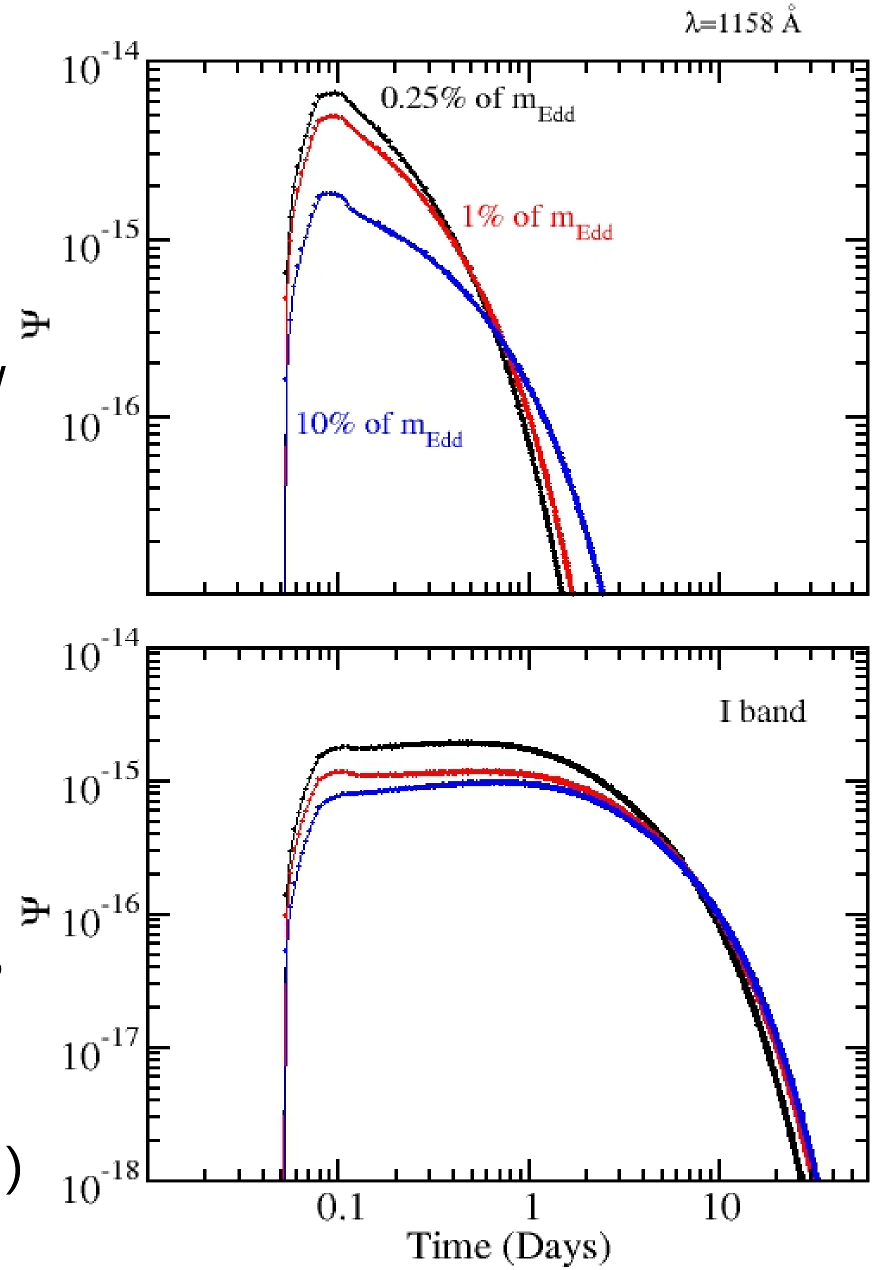
in the α=1 case.



Dependence on $\dot{m}$

1) The amplitude increases with decreasing accretion rate (that's because $F_{abs}>>F_{NT}$ at low accretion rates).

2) The width decreases with decreasing accretion rate. Response functions decrease when the Wien part of the BB spectrum contributes to the band we observe. This happens at earlier times when the accretion rate is low, because the overall temperature is small.)

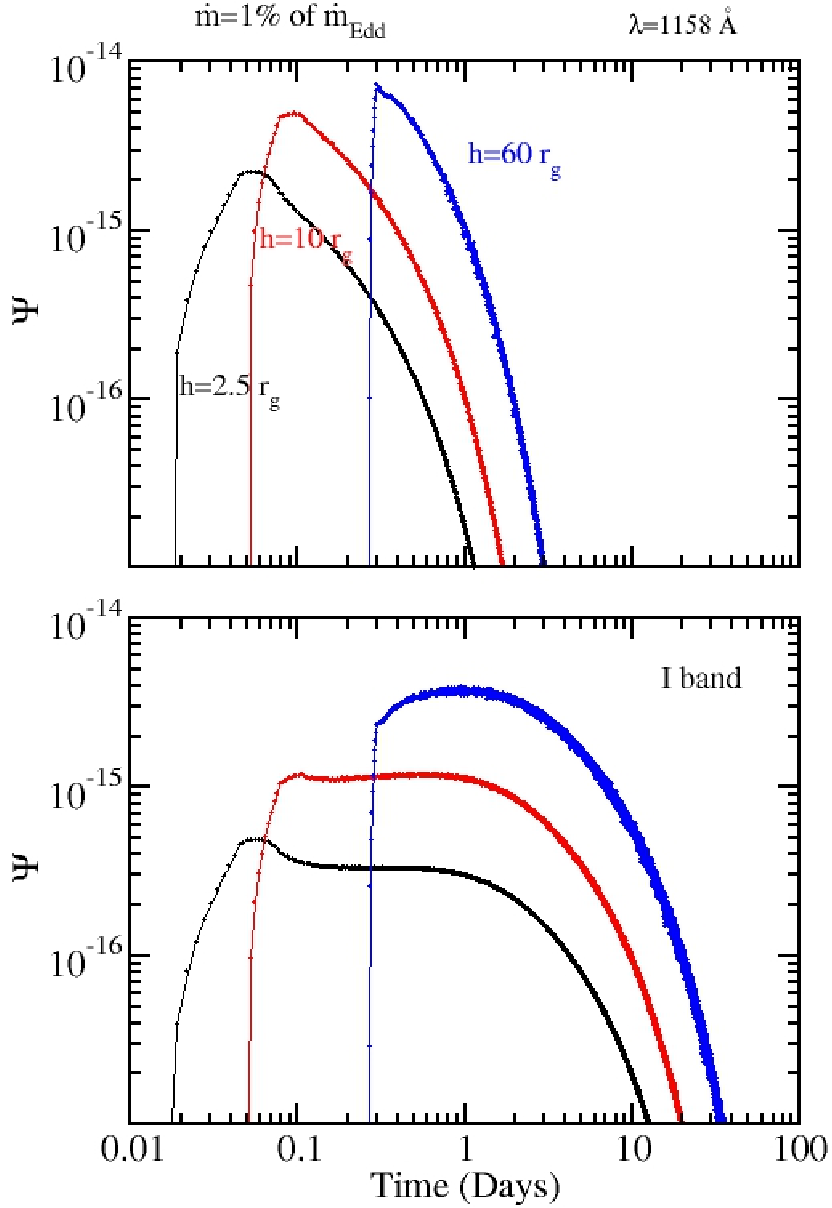


Dependence on height

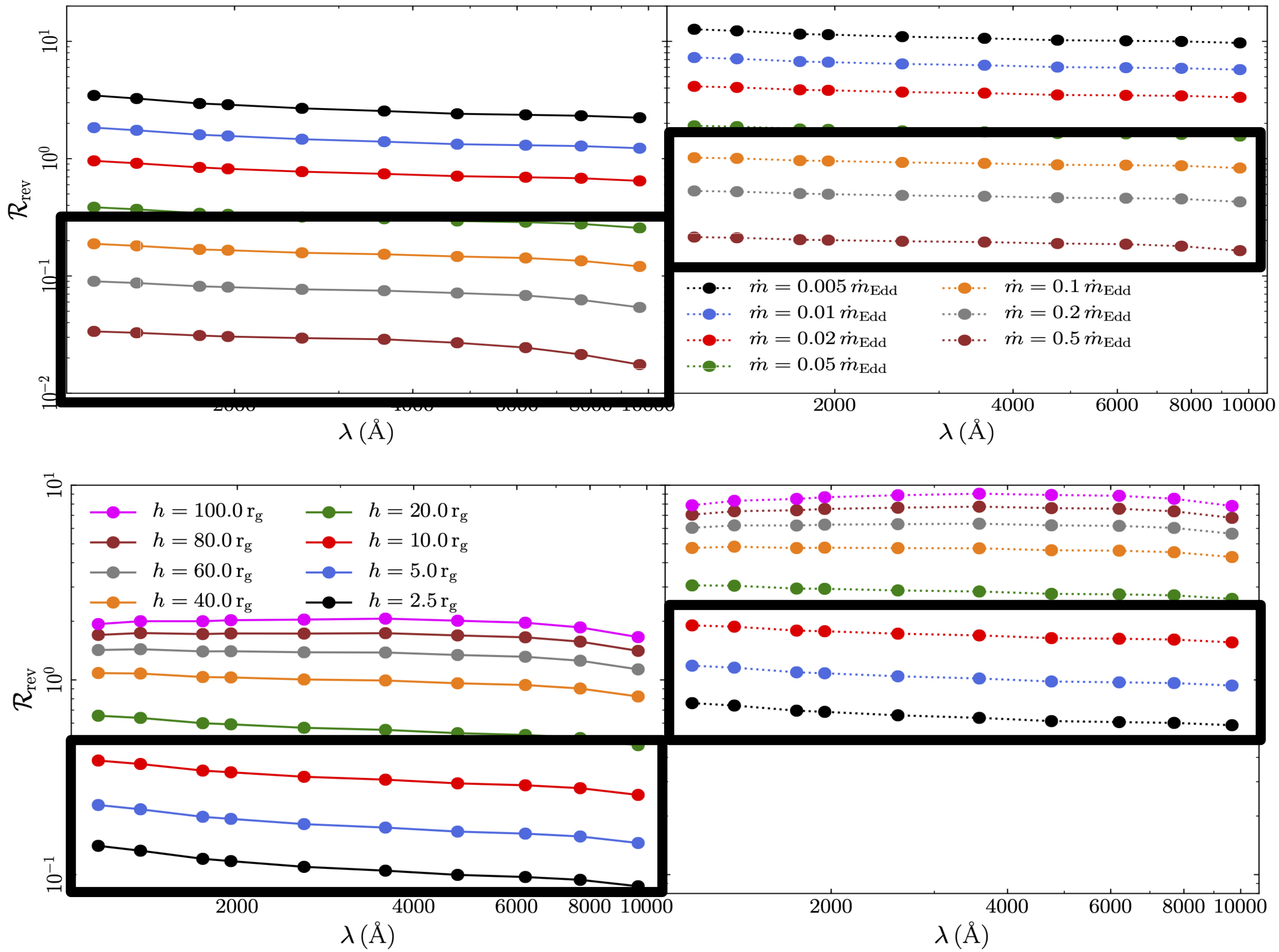
1) As the height increases, the response functions start at later times, and last longer.

2) The amplitude increases with increasing height.

This is probably due to the fact that the incident angle to the disc (measured with respect to the vertical) decreases with increasing height, + (in the inner disc) disc is less ionised, so F_{ref} decreases (hence F_{abs} increases).



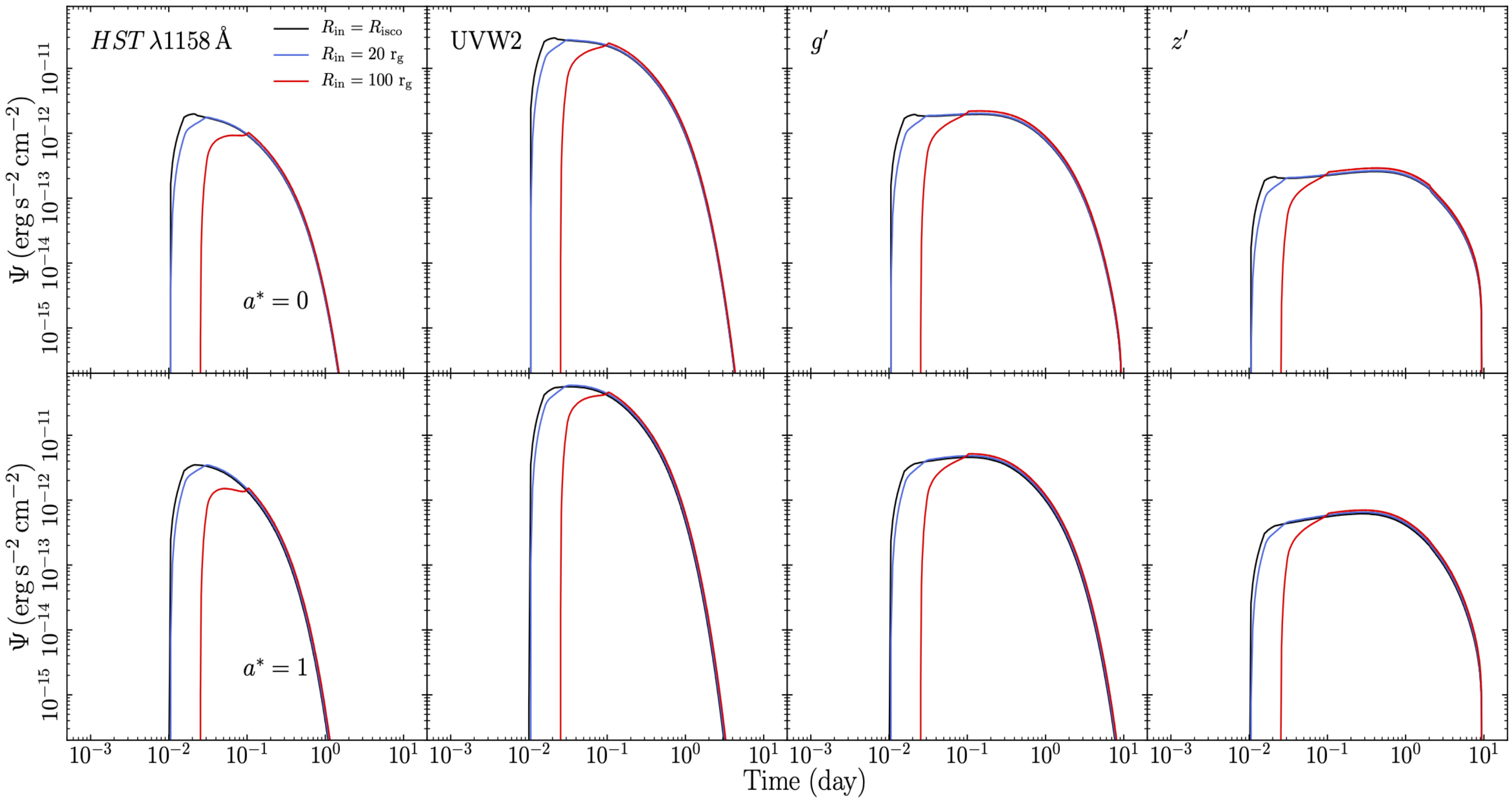
The case of the **high m_dot**, **low h** AGN.



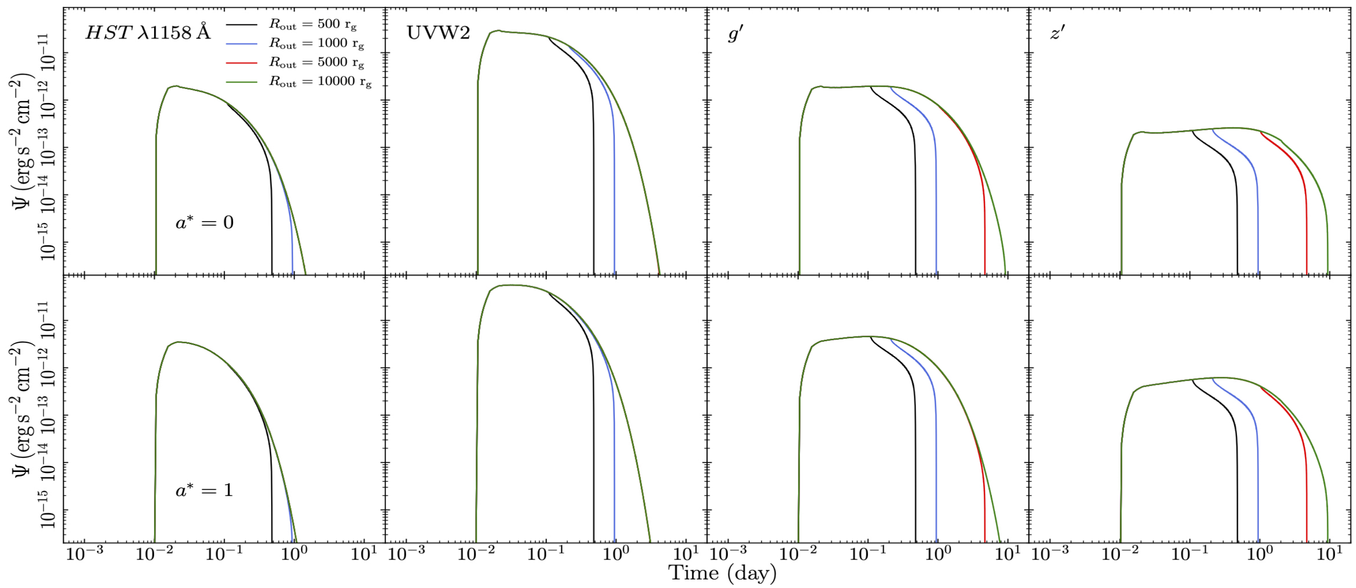
Could explain the lack of correlation between **X-rays and UV** in highly variable X-ray sources?

Then, R could be quite small

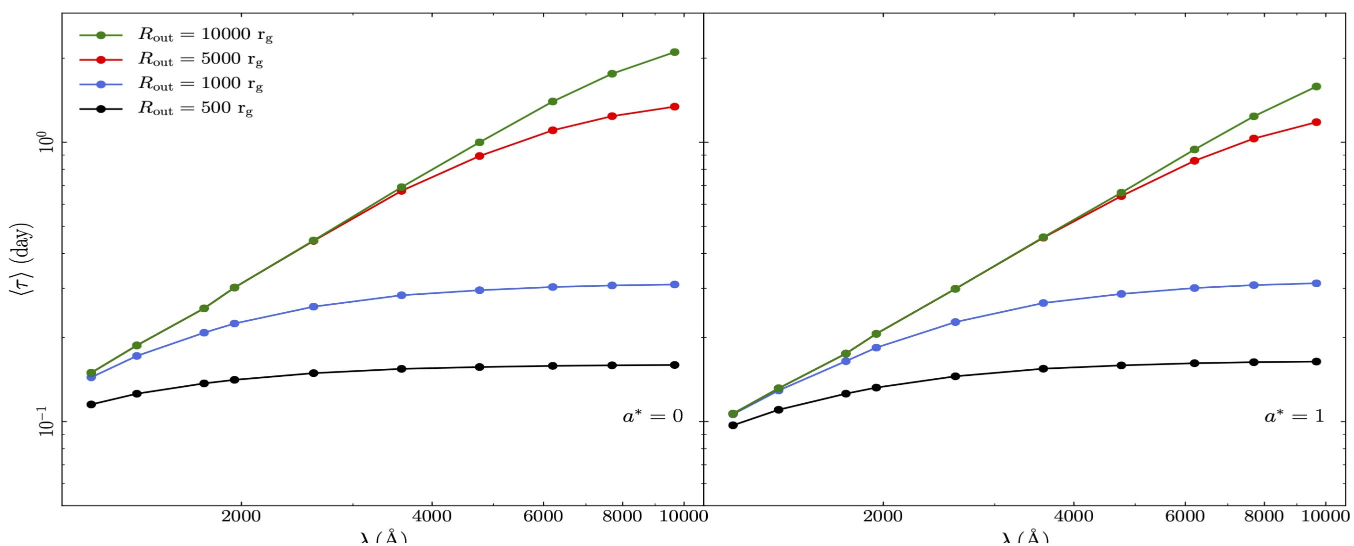
Dependence on R_{in} ...



... and on R_{out}



HST λ1158 Å
UVW2
g′
z′
R_out = 500 r_g
R_out = 1000 r_g
R_out = 5000 r_g
R_out = 10000 r_g
a* = 0
a* = 1
Ψ (erg s⁻² cm⁻²)
Time (day)



R_out = 10000 r_g
R_out = 5000 r_g
R_out = 1000 r_g
R_out = 500 r_g
⟨τ⟩ (day)
a* = 0
a* = 1
2000
4000
6000
8000
10000
λ (Å)

Fitting model time-lags to the data of NGC5548

- $M_{BH}=5\times10^{7}\ M_{\odot}$, observed $L_{(2\text{-}10\ \mathrm{keV})}= 0.34\%\ L_{Edd}$ (Mathur S. et al 2017, ApJ, 846, 55)
- We computed model response functions in ten energy bands (HST λ1158, 1367, & 1746, *Swift* UVW2, UVW1, and *U,B,V,R,I* filters).
- 8 accretion rates: 0.25, 0.5, 0.75, 1, 2.5, 5, 7.5 and 10% of $\dot{m}_{Edd}$
- 8 heights: 2.5, 5, 10, 20, 40, 60, 80, 100 r_g
- spin parameter 0 and 1

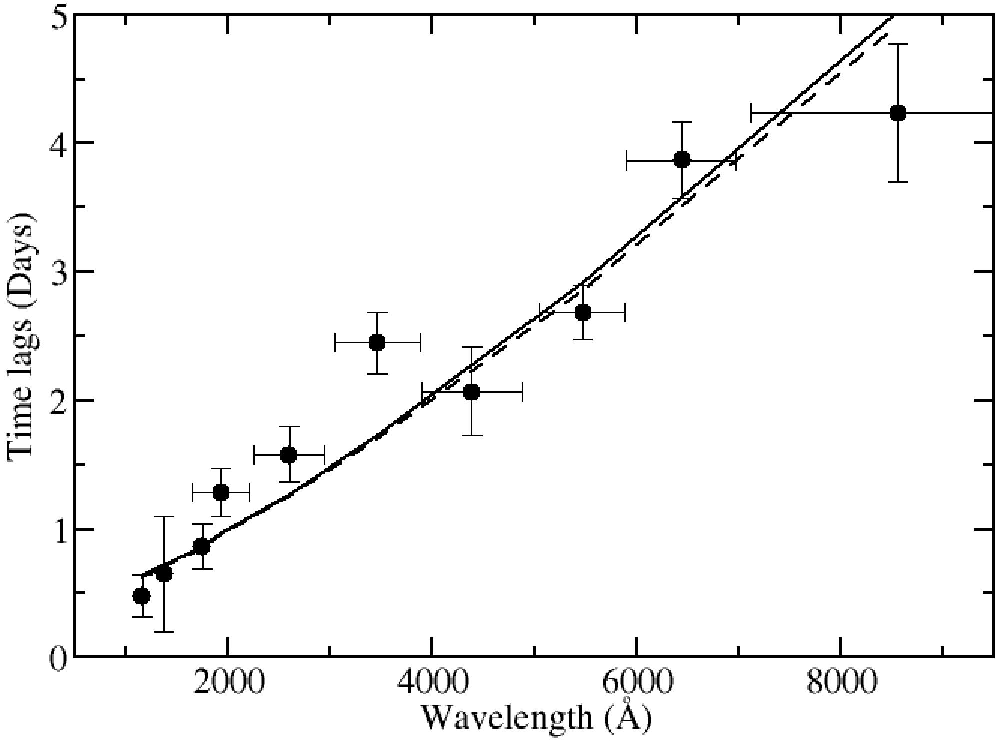
For each combination of ($\dot{m}$, h, α) we computed the centroid of the transfer function as a function of wavelength.

We ended up with 128 model "time-lags spectra", and we fitted them to the data (ie the observed time-lags spectrum).

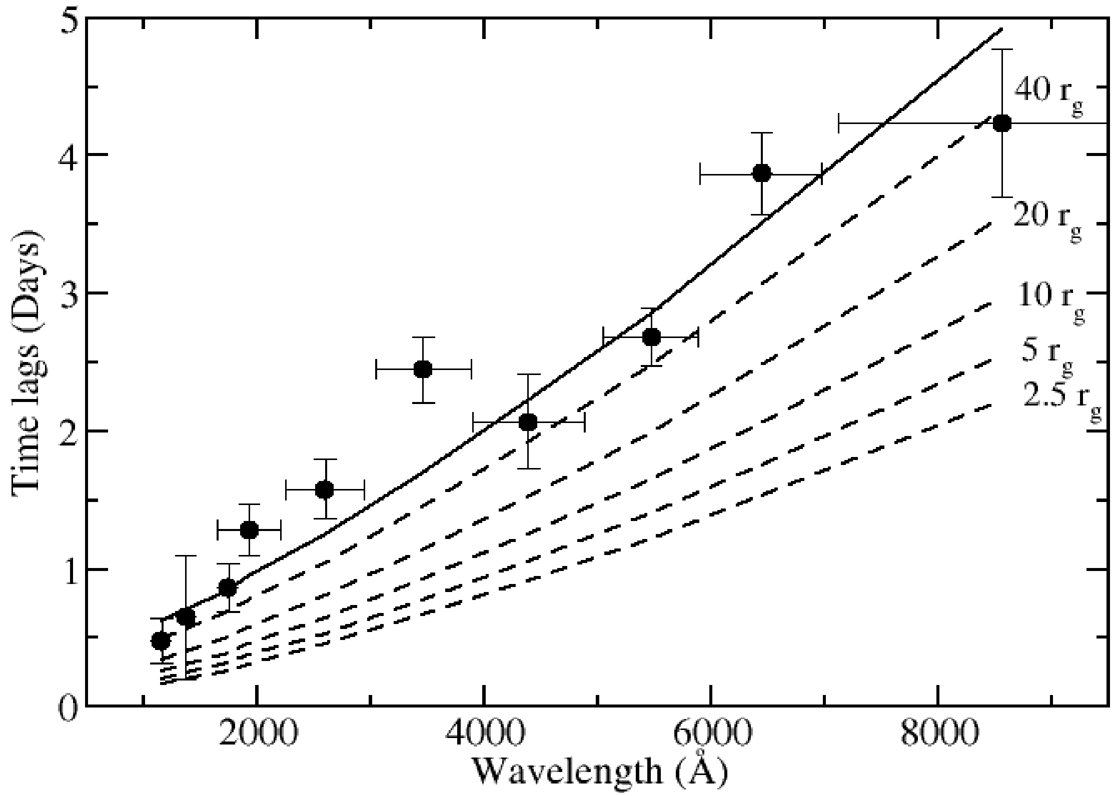
Best-fit results

α=0: χ^2=10.8/7 dof, h= 60 r_g, $\dot{m}$=0.25% of $\dot{m}_{Edd}$(<2.5%, 3σ limit)

α=1: χ^2=10.7/7 dof, h=60 r_g, $\dot{m}=1^{+1.5}_{-0.5}$ percent of $\dot{m}_{Edd}$

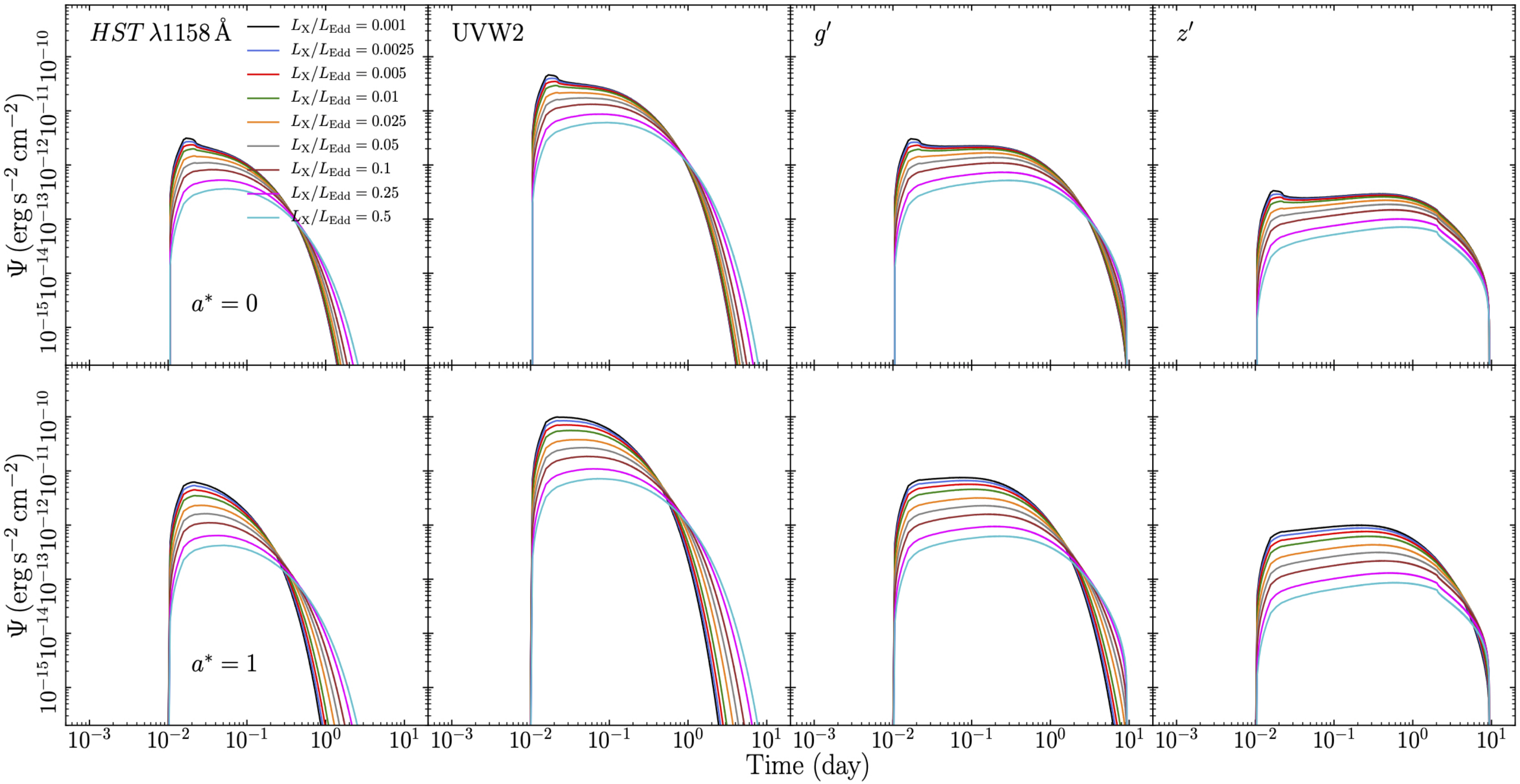


The UV/optical, continuum time-lags in NGC5548 are fully consistent with a Novikov-Thorne disc, which accretes at ~1% of the Eddington limit, as long as h≧40 r_g (3σ limit).



BUT

The response of the disc to X-rays is **NON** linear



The responses Ψ are normalized to L_X,

so they should be on top of each other.

In this case the following question is correct:

$$F_{total}(\Delta\lambda, t_{obs}) = F_{NT}(\Delta\lambda) + \int_0^{\infty} L_X(t')\,\Psi_{\Delta\lambda}[t_{obs} - t', L_X(t')]\,dt'$$

Maybe, if an AGN is not highly variable (i.e. if $L_{X,max}/L_{X,min}<2-3$), the shape of the response may not be that different. But this has to be investigated.

But, certainly, for low BH mass systems (ie NLS1s), which show variability amplitudes of the order of 5 or even 10, on "short" time scales, this is certainly not the case.

Obviously, in this case, quantities like the centroid of the response function, and the thermal reverberation fraction do not correspond to something that can be measured in practice.

THIS IS WORK IN PROGRESS - MORE RESULTS IN THE (NEAR) FUTURE.