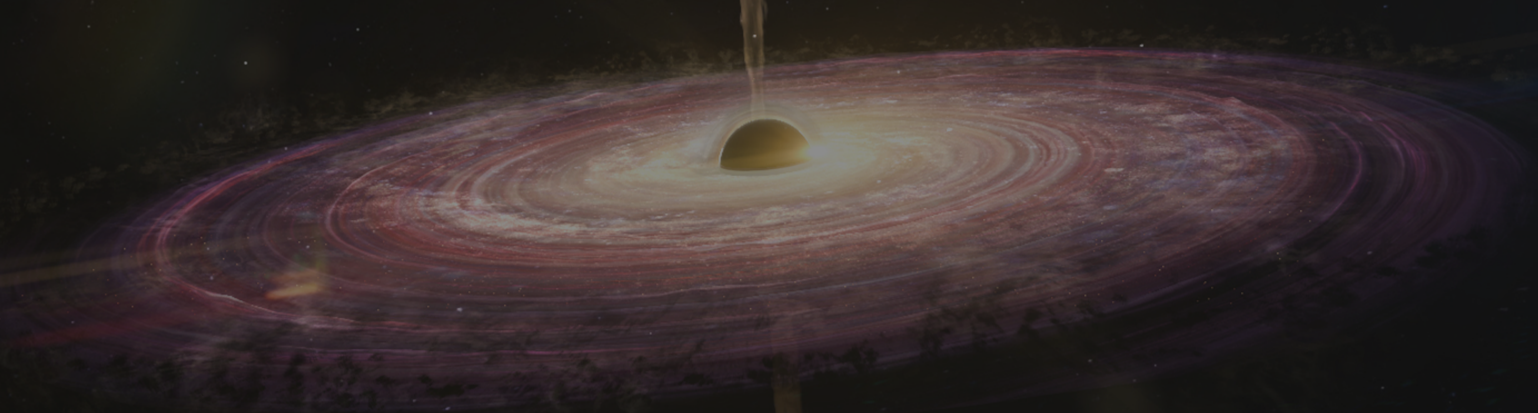
Modelling thermal reverberation in Active Galactic Nuclei



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in collaboration with M. Dovčiak, I. Papadakis, C. Panagiotou, W. Zhang, L. Robin

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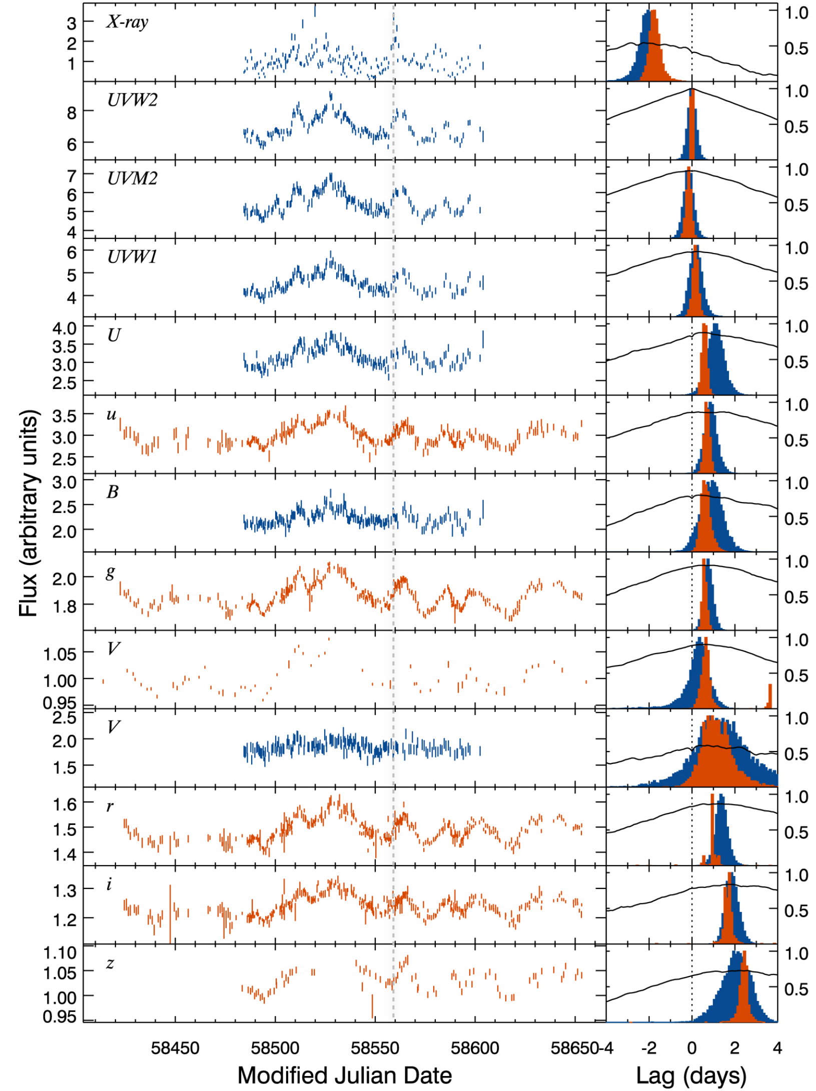
Introduction

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

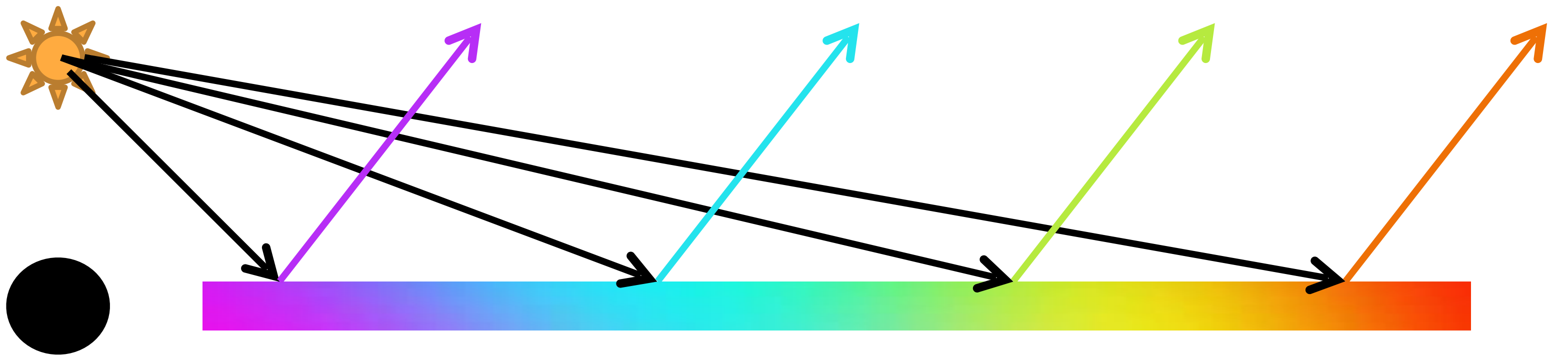
- This cannot be due to fluctuations in the accretion rate, as those fluctuations propagate inward and should give the opposite effect.

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

Cackett +20



Introduction - Past Results



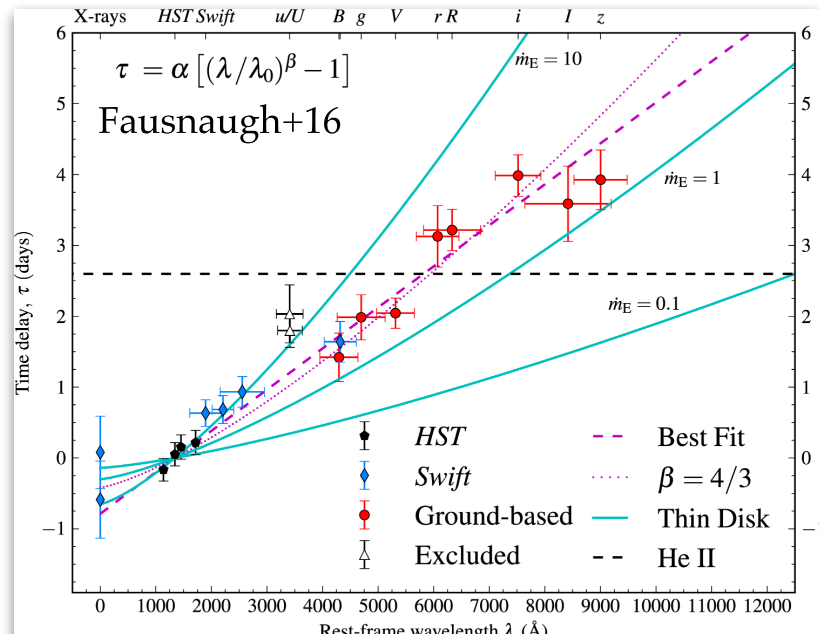
$$\tau = \frac{R}{c}$$

Time lag = light crossing time

$$T(R) \propto R^{-3/4}$$

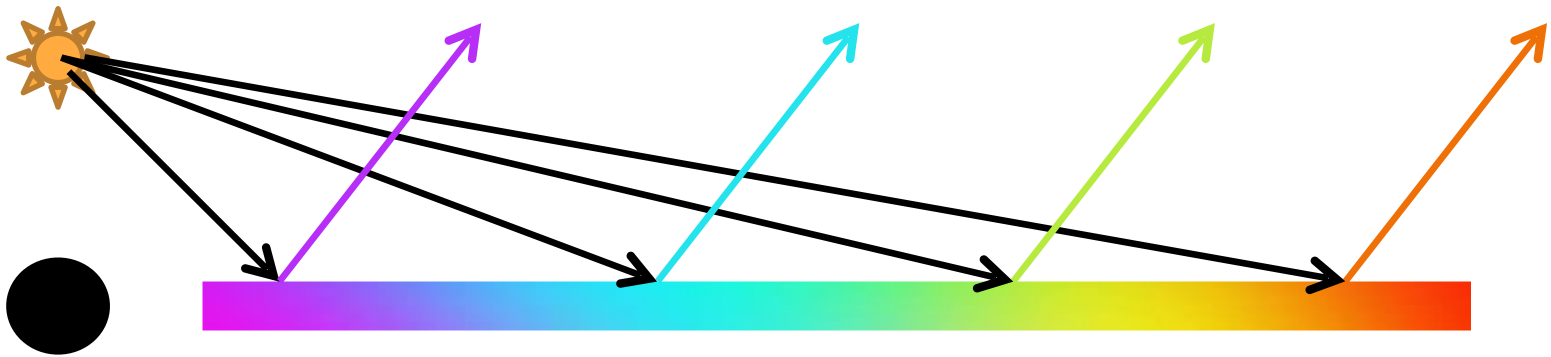
$$T(R) \propto \lambda^{-1}$$

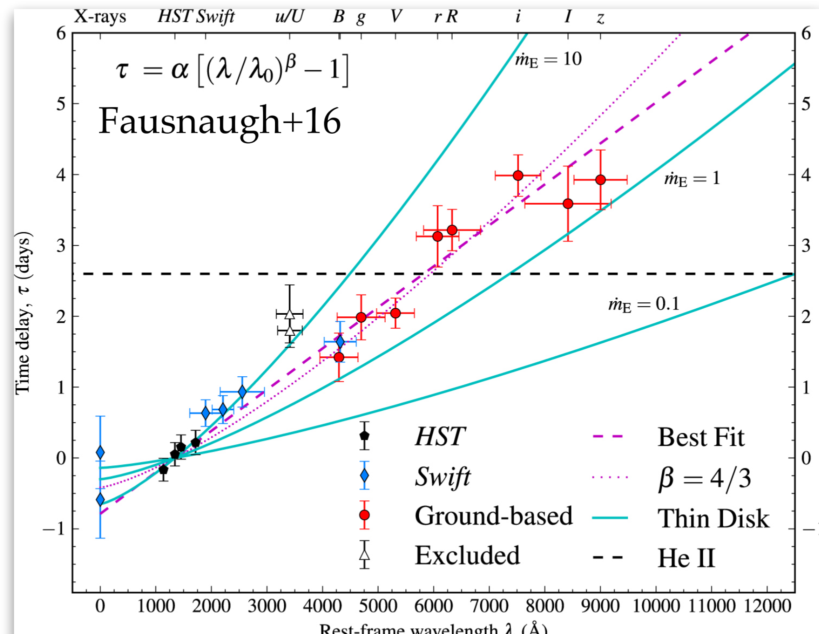
$$\tau \propto (M\dot{M})^{1/3}\lambda^{4/3}$$



Cackett+07,18,20, Edelson+15,19, McHardy+18, Fausnaugh+16, Pahari+20, Hernandez Santisteban+20, Kara+21 …

Introduction - Past Results





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

ii) but not the amplitude

A new model to fit the time lags

… However, the relationship 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 (see M. Dovčiak's talk):

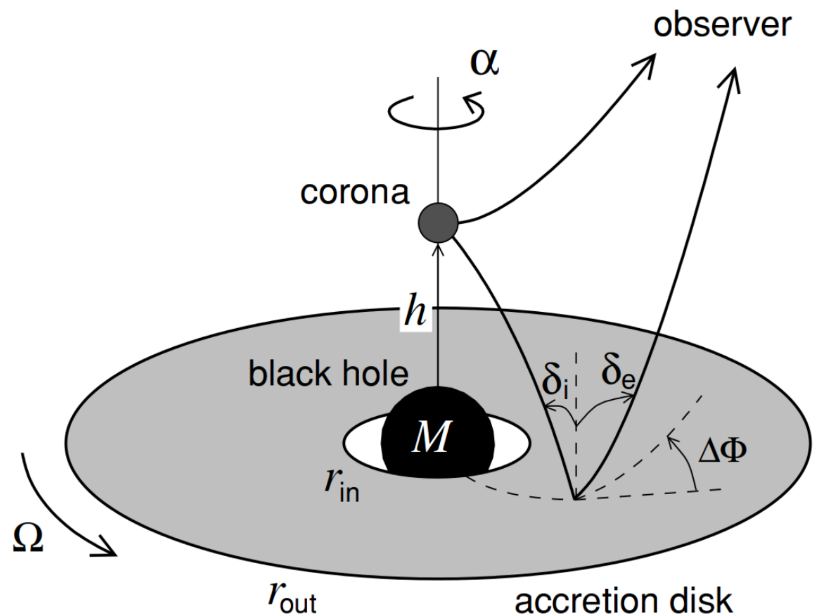
1) taking into account all **simple and general relativity effects** in the propagation of light from the source to the disc, and from the disc to the observer

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
- Inner and outer disc radii



$$F_{abs}(R, t') = F_{inc}(R, t') - F_{ref}(R, t')$$

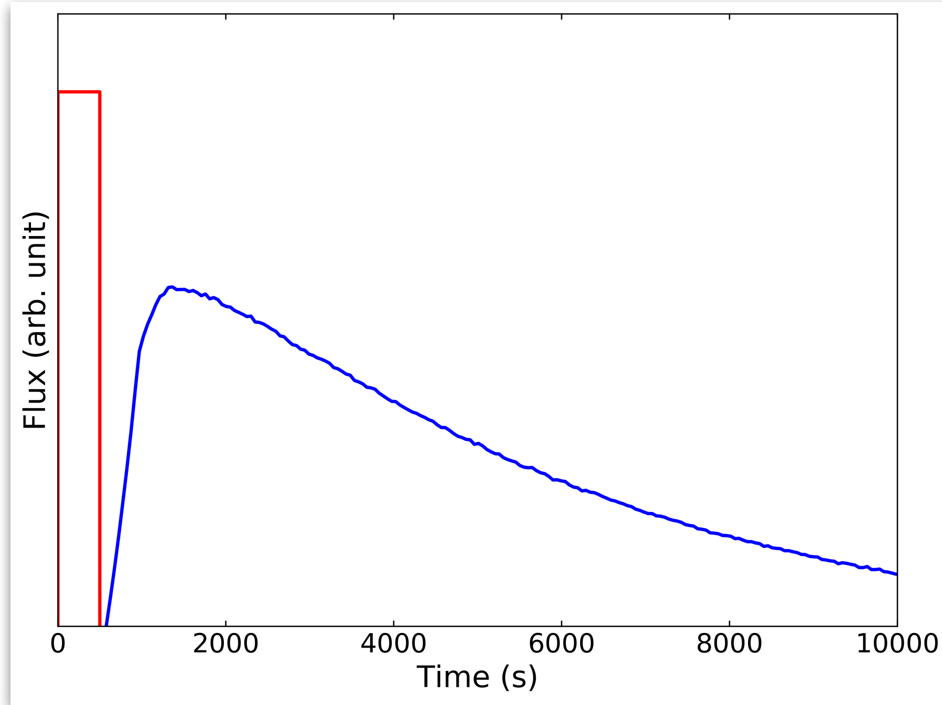
$$T_{new}(R, t') = \left(\frac{2F_{abs}(R, t') + F_{NT}(R, t')}{\sigma} \right)^{1/4}$$

Disc response function

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

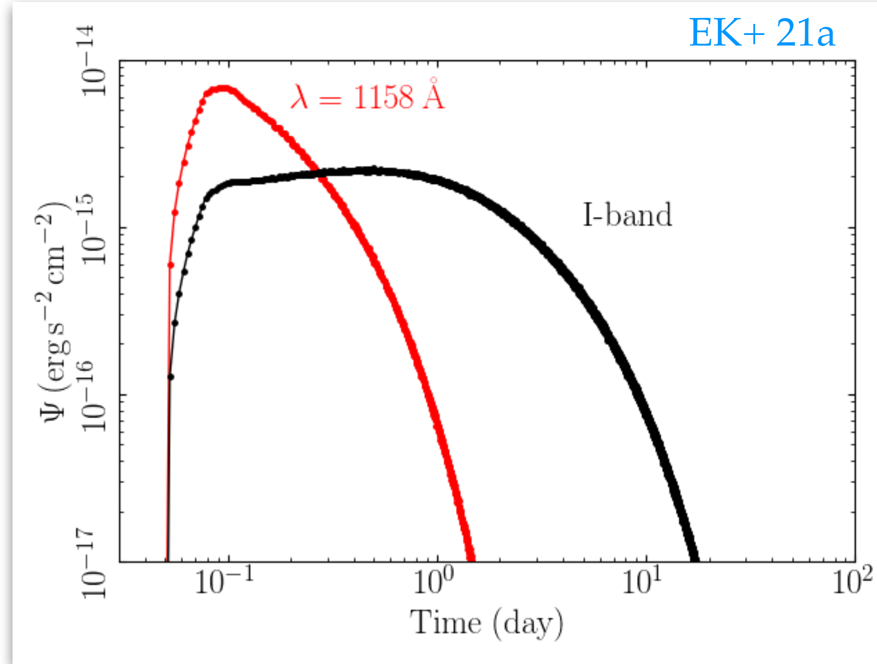
From that we can estimate the average time-lag at each wavelength being the centroid of the response function:

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

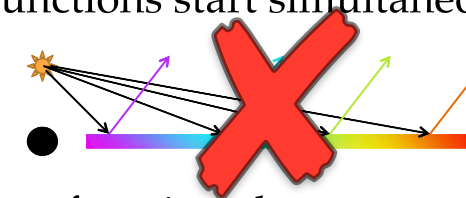


Results presented in
Kammoun et al. (2019, ApJL, 879, L24)
Kammoun et al. (2021a, ApJ, 907, 20)
Kammoun et al. (2021b, MNRAS, 503, 4163)

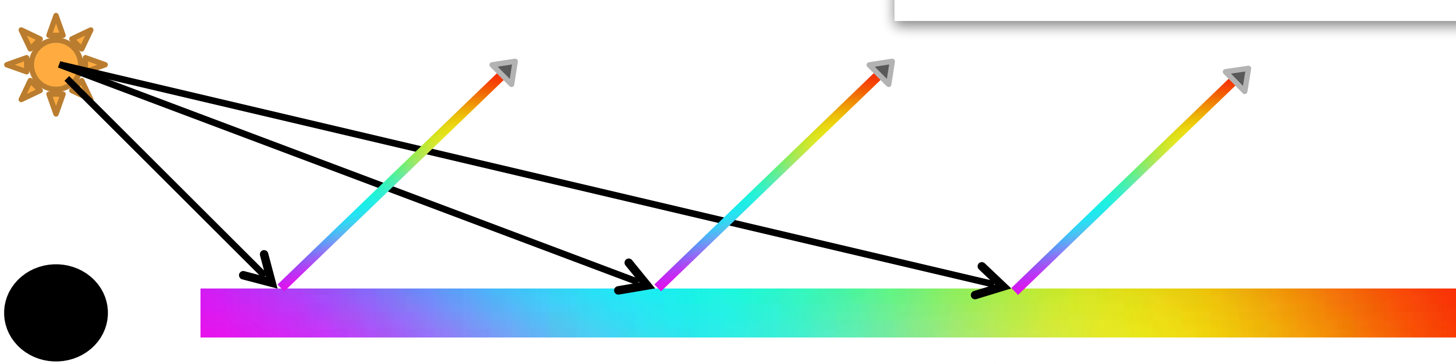
Disc response function



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.



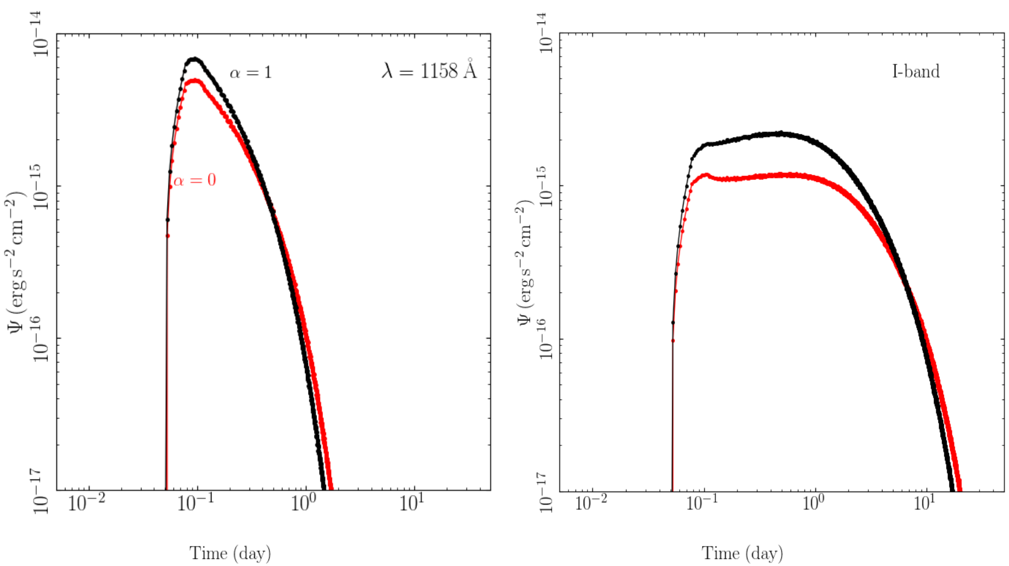
All radii emit at all wavelengths (thermal emission) !

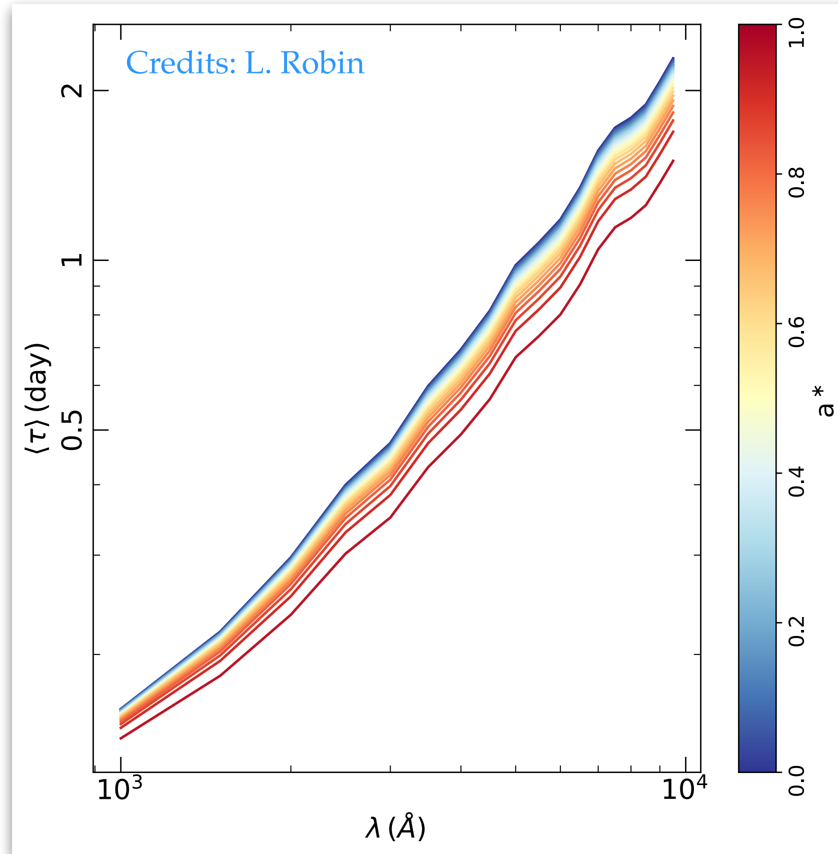
Disc response function

Dependence on the spin

For higher spins, the response functions are

i) larger in amplitude and
ii) narrower

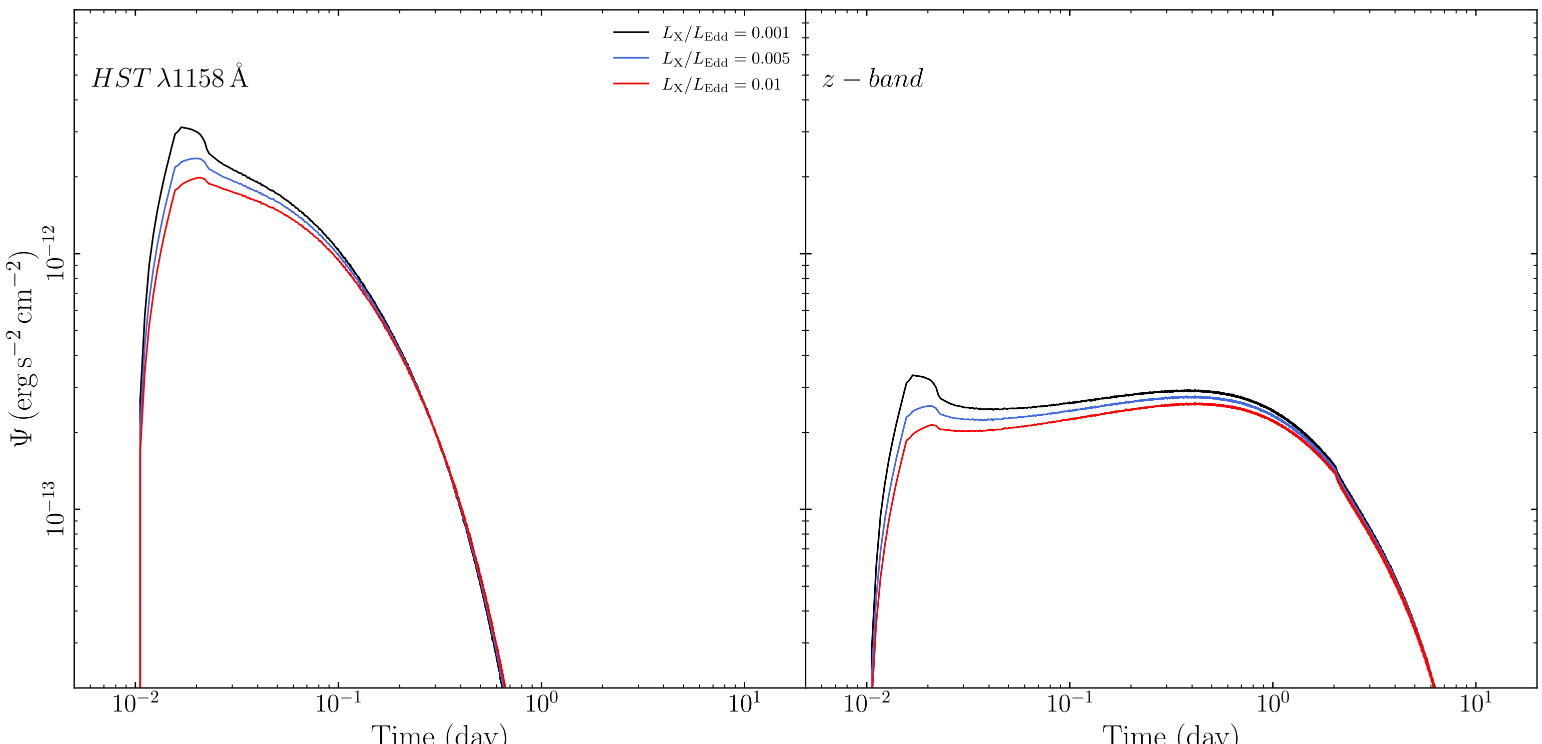




Disc response function

Dependence on the X-ray luminosity

→ Non-linear behaviour with changing L_X



Time-lag modelling

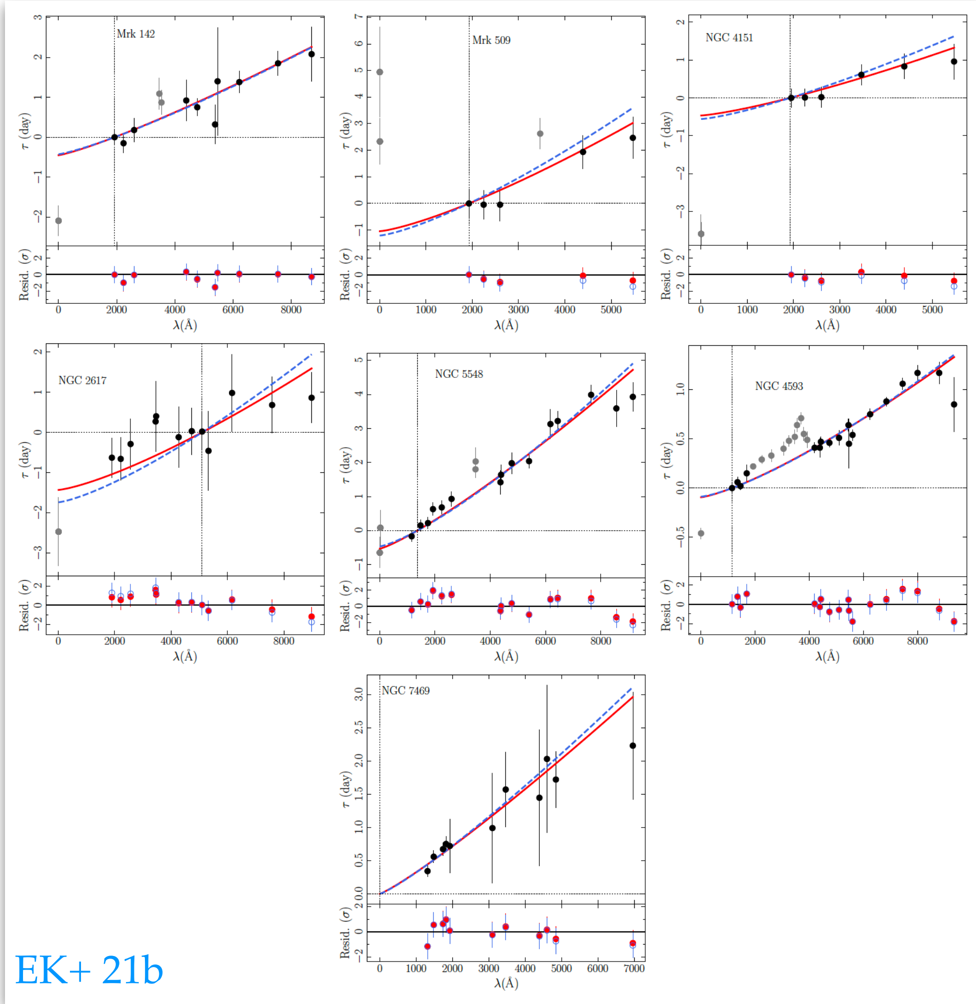
But also…
Dependence on the **height, luminosity, mass, accretion rate…**

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

for spin 0 and 1
→ 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 (7 sources)

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



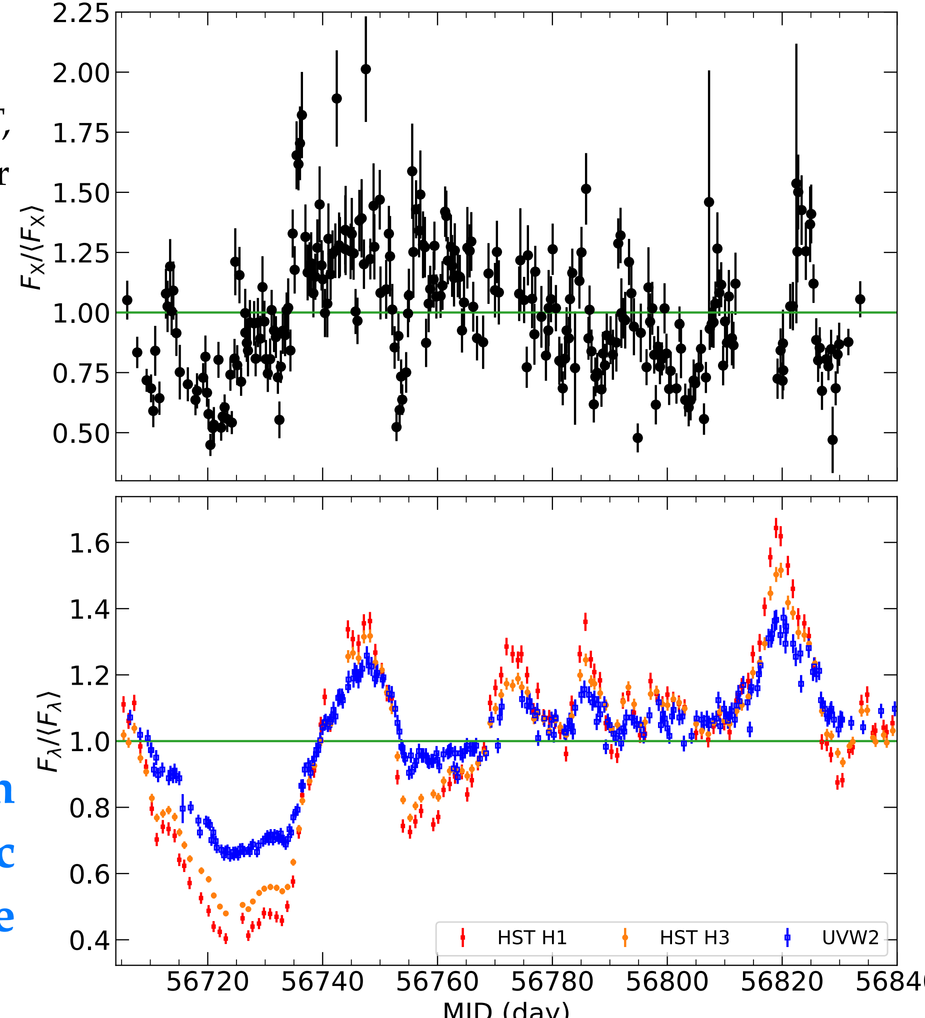
EK+ 21b

The case of NGC 5548

- The first source to be intensively monitored with HST, Swift/XRT/UVOT, and ground-based telescopes over more than 130 days.

- Low X-ray to UV/optical correlation:
  - **Are the X-rays really driving the UV/optical variability?**

- The standard accretion disc model needs high accretion rates to explain the observed time-lags.



Given this unprecedented data set, can thermal reverberation from the disc explain the variability, time lags, and the energetics in this source?

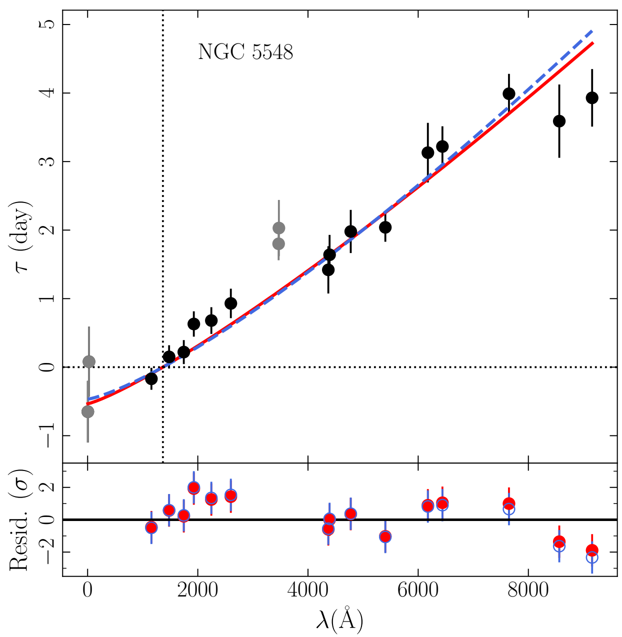
The case of NGC 5548

The time-lags are well fitted with a thermal reverberation model:

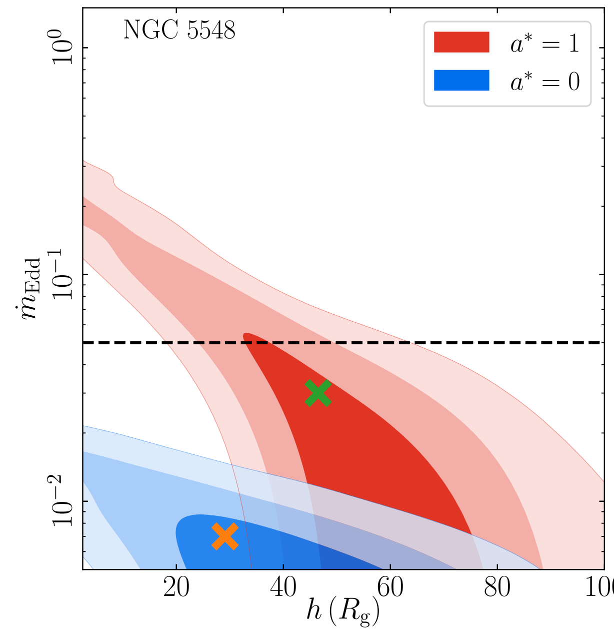
$$a^* = 0 \longrightarrow h \in [23\,\mathrm{r_g},\, 60\,\mathrm{r_g}];\;\; \dot{\mathrm{m}}_{\mathrm{Edd}} < 0.008$$

$$a^* = 1 \longrightarrow h \in [32\,\mathrm{r_g},\, 80\,\mathrm{r_g}];\;\; \dot{\mathrm{m}}_{\mathrm{Edd}} < 0.06$$

$f_{\mathrm{col}} = 2.4$



EK+ 21b



The case of NGC 5548

Using our model we were able to fit **simultaneously** the UV/optical power spectra and the time lags

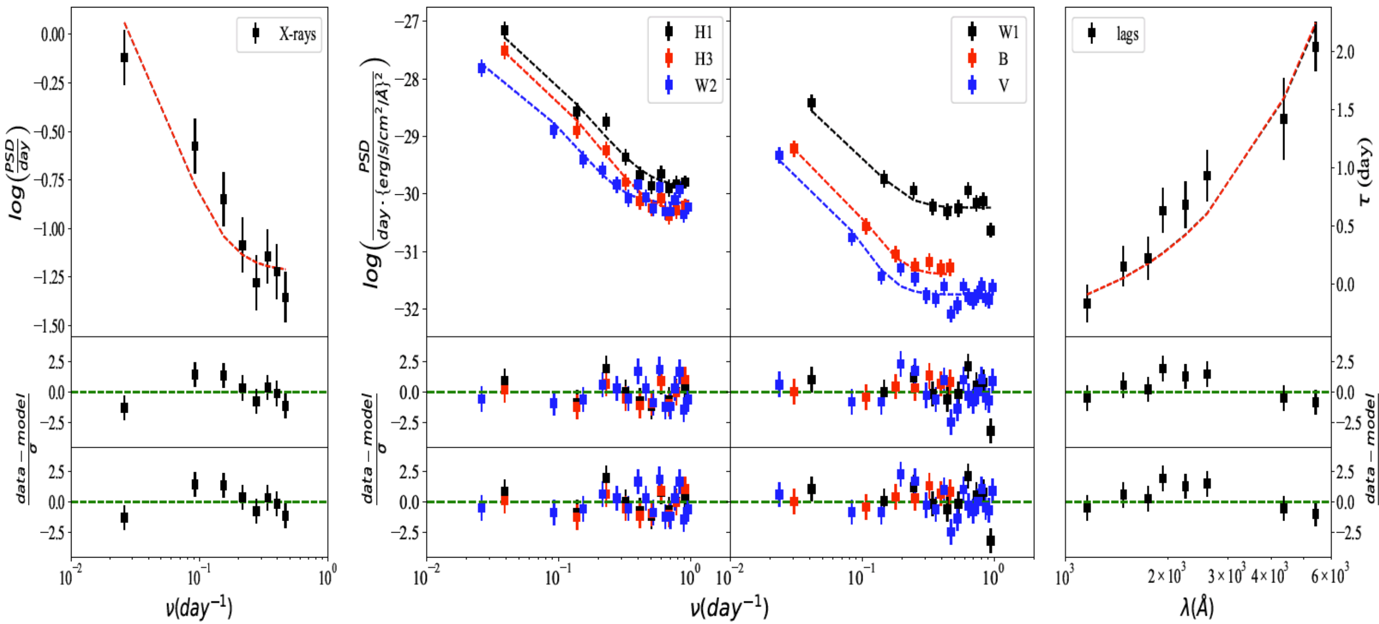
$a^* = 0 \longrightarrow h \in [23\,r_g,\ 60\,r_g];\ \dot{m}_{Edd} < 0.008$

$a^* = 1 \longrightarrow h \in [32\,r_g,\ 80\,r_g];\ \dot{m}_{Edd} < 0.06$

$a^* = 0 \longrightarrow h \in [30\,r_g,\ 45\,r_g];\ \dot{m}_{Edd} < 0.01$

$a^* = 1 \longrightarrow h \in [40\,r_g,\ 50\,r_g];\ \dot{m}_{Edd} \in [0.02,\ 0.06]$

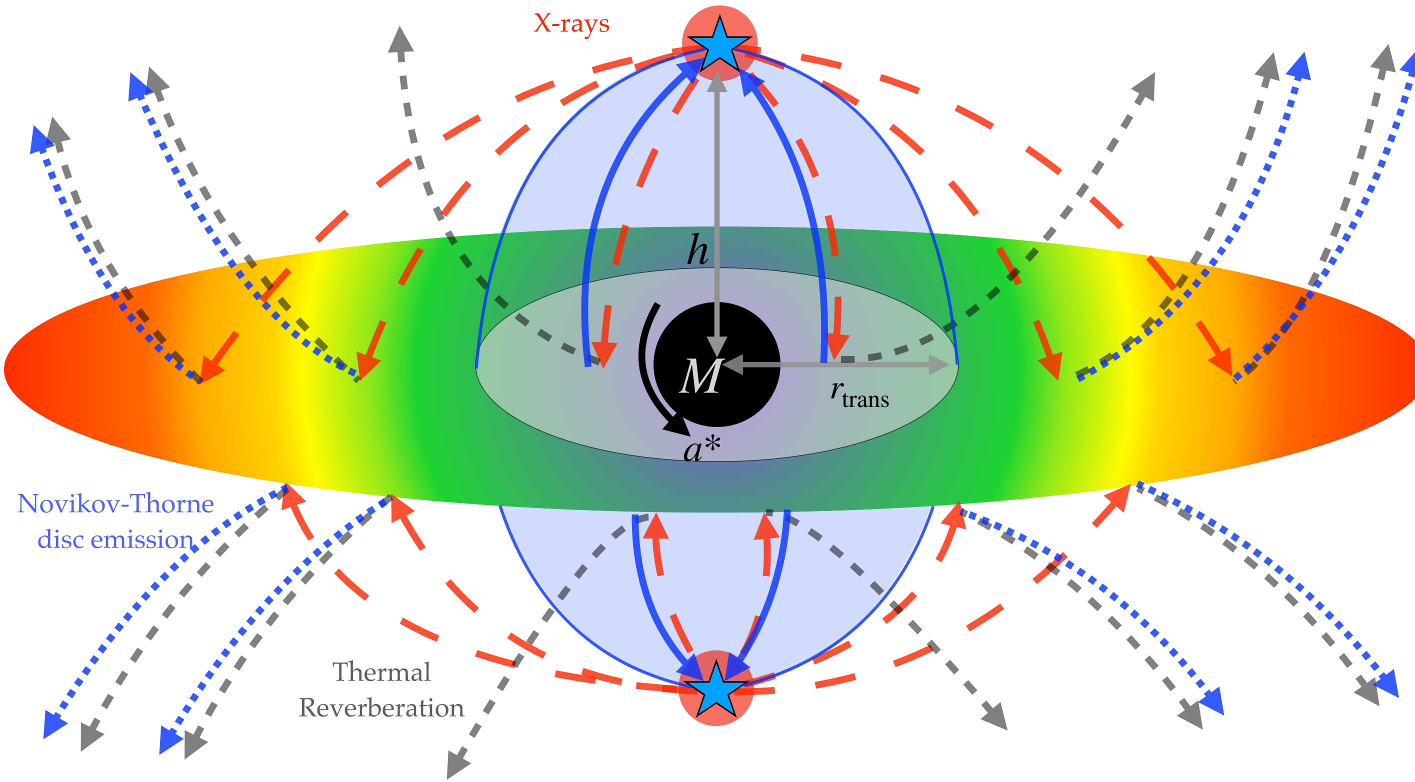
$f_{col} = 2.4$



Panagiotou, Papadakis, EK+20
Panagiotou+22, in preparation

The case of NGC 5548

- KYNSED is a model that can be used to fit the broadband SED of X-ray irradiated accretion discs (see M. Dovčiak's talk).



The case of NGC 5548

- KYNSED is a model that can be used to fit the broadband SED of X-ray irradiated accretion discs (see M. Dovčiak's talk).

- Assuming thermal reverberation, **simultaneous X-ray/UV/optical fitting will lead to erroneous results**

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

$\Rightarrow$ The UV / optical data point we see on time (t_0) is the result of wha the X-rays have been doing for the last ($t_0 - \Delta t$)

- Solution:
  1) Use the time-averaged SED over long timescales
  2) Choose time intervals by integrating the X-rays sufficiently enough over the past time, according to the chosen wavelengths.

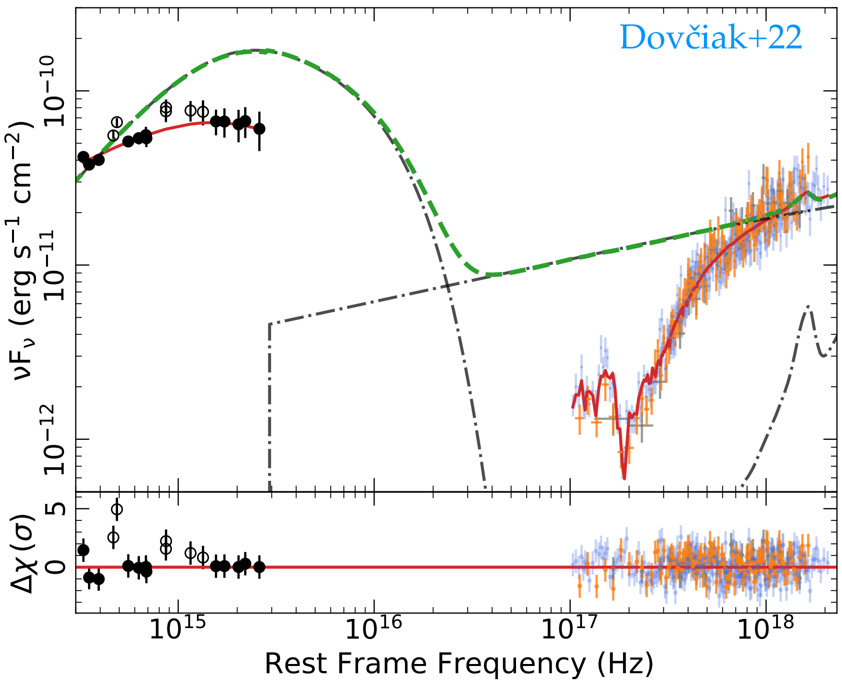
The case of NGC 5548

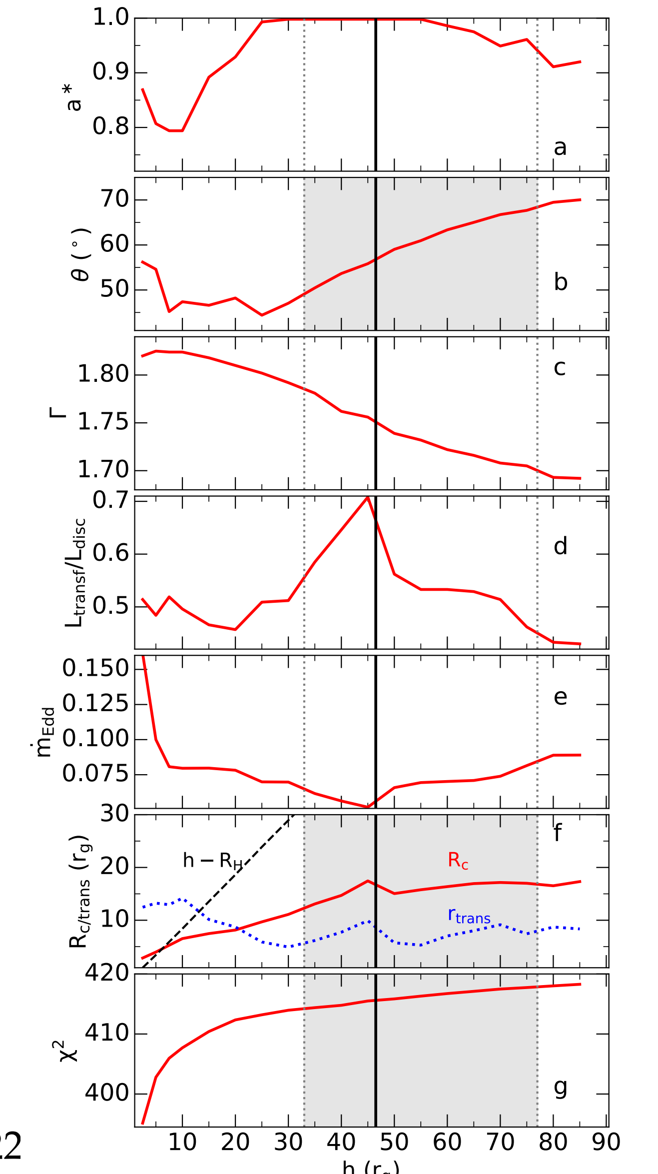
Time-averaged SED:

$a^* > 0.94$ $\theta \in [49°,68°]$

$\dot{m}_{Edd} \in [0.052,0.085]$ $R_c \in [12\ r_g, 17.5\ r_g]$

$L_{trans}/L_{disc} \in [0.45,0.7]$ $E(B-V) = 0.12 \pm 0.02$





The case of NGC 5548

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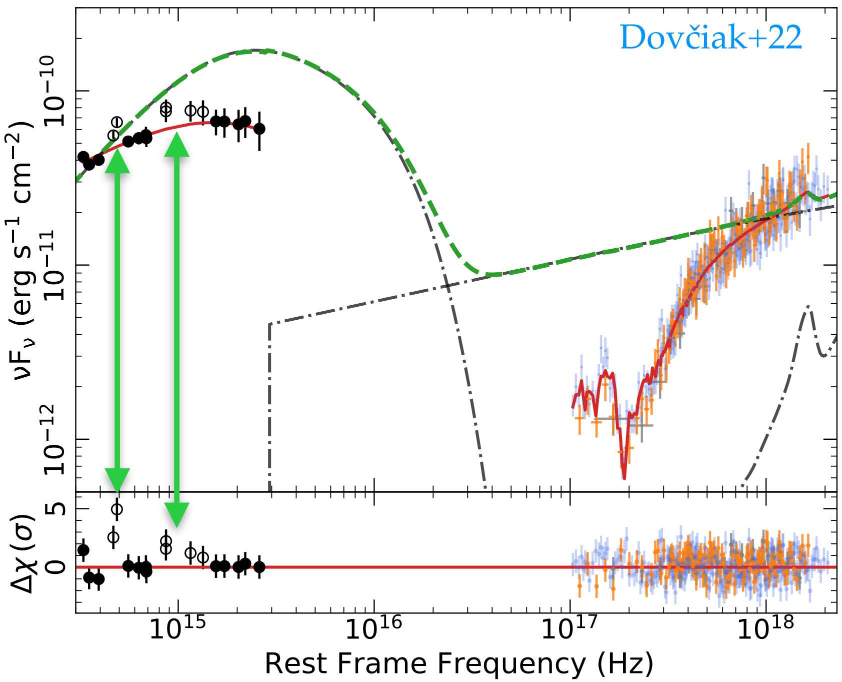
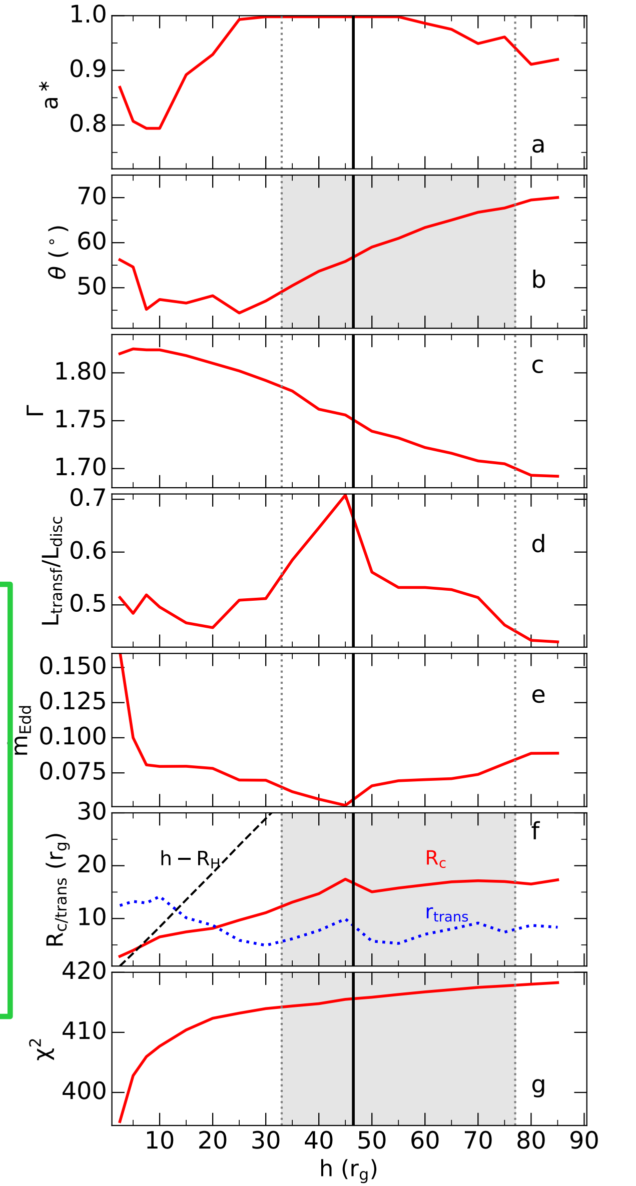


BLR contribution in the U- and R-bands of ~20-30%

→ consistent with the " Balmer jump" and Hα results by Fausnaugh+16



Conclusions

- Using ***standard accretion disc models***, thermal reverberation can explain:

1. The observed UV/optical time lags in AGN,
2. The observed UV/optical power-spectra
3. The broadband, time-average, SED

Work in progress:

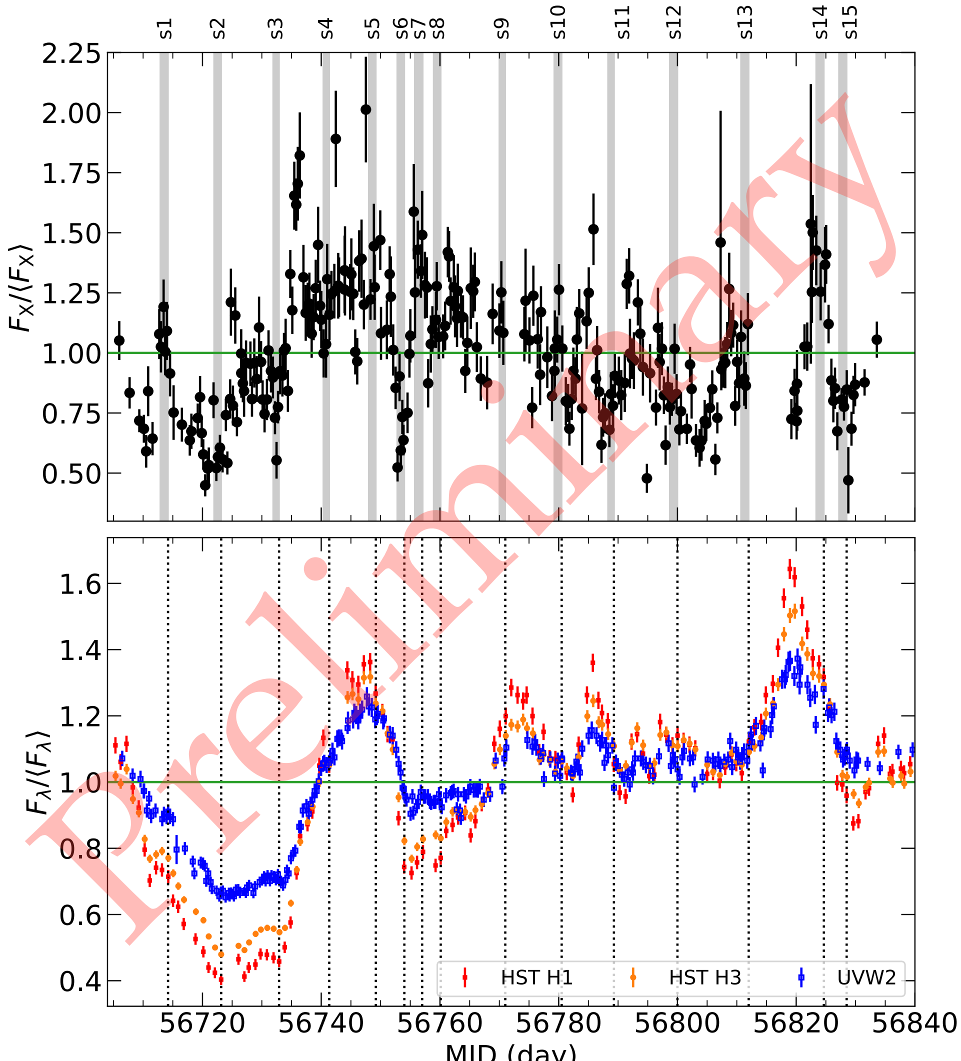
- Model the time-resolved SED:
    - Hints of cooling/heating of the corona (EK+22 in preparation)

- Improve the fitting technique of the time-lag spectra (L. Robin, EK+ in preparation)

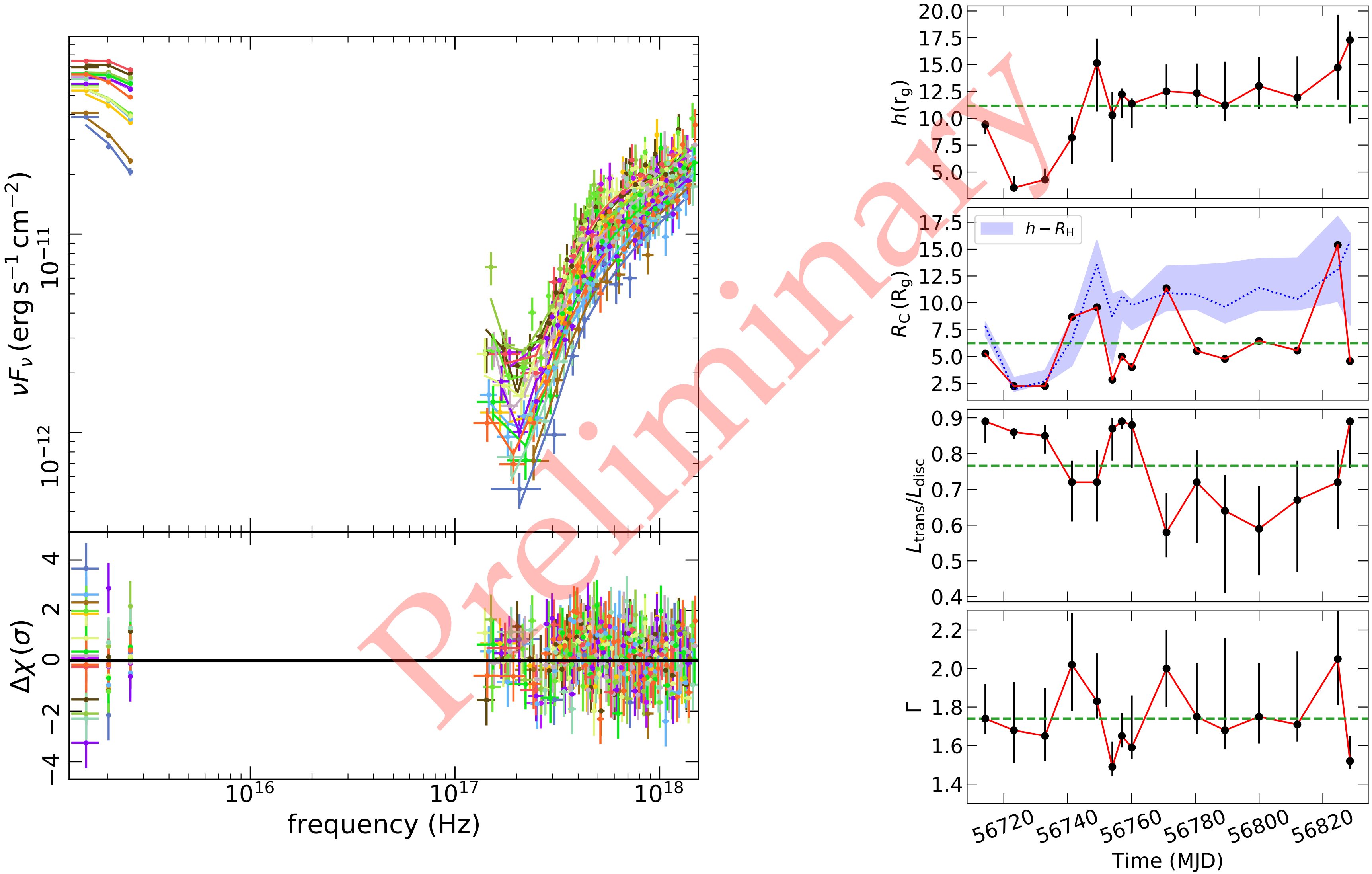
- Explaining the disc-size problem in lensed QSOs (I. Papadakis+22, submitted)

- Extend the analysis to other sources...

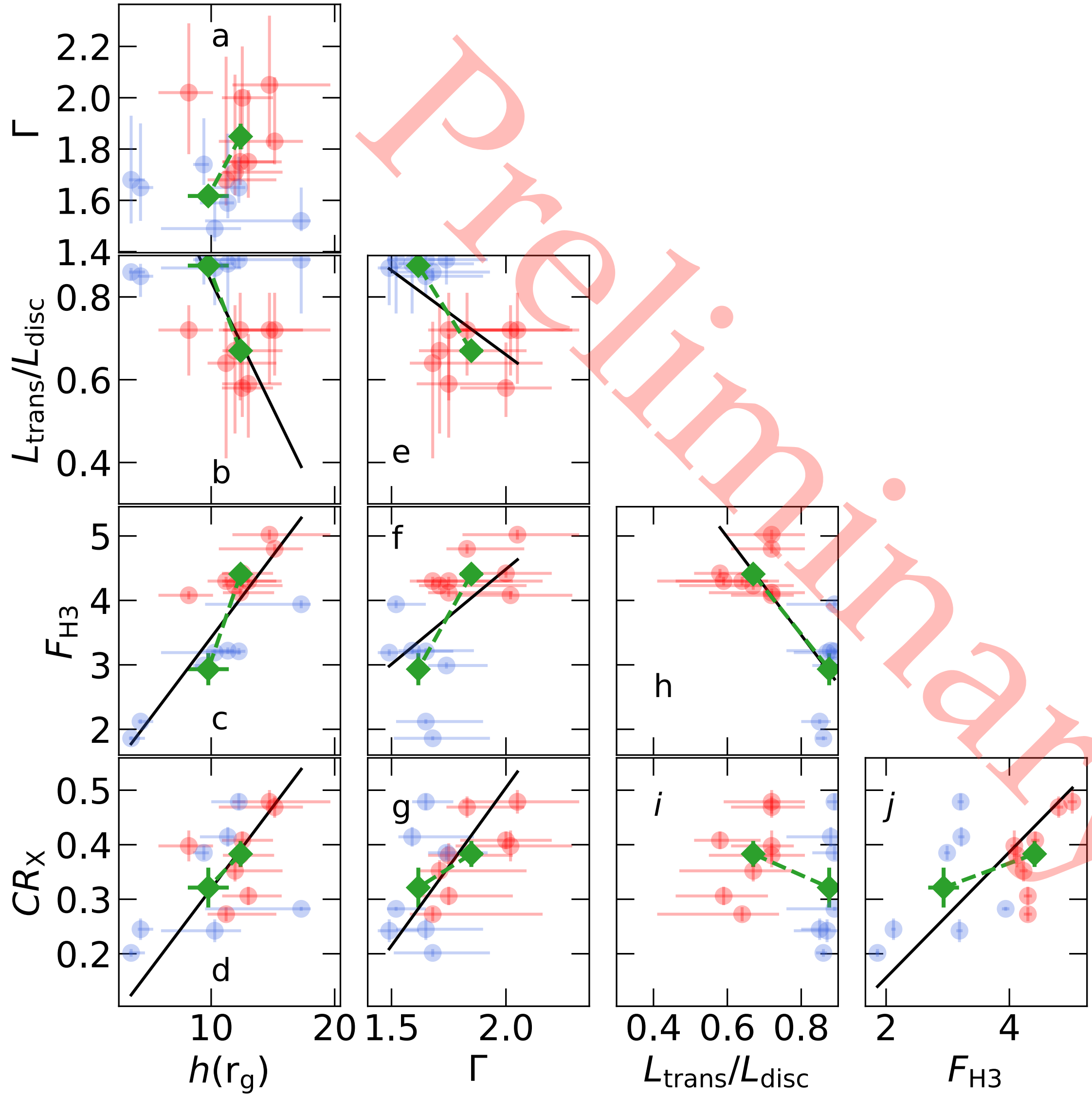
Thank you!



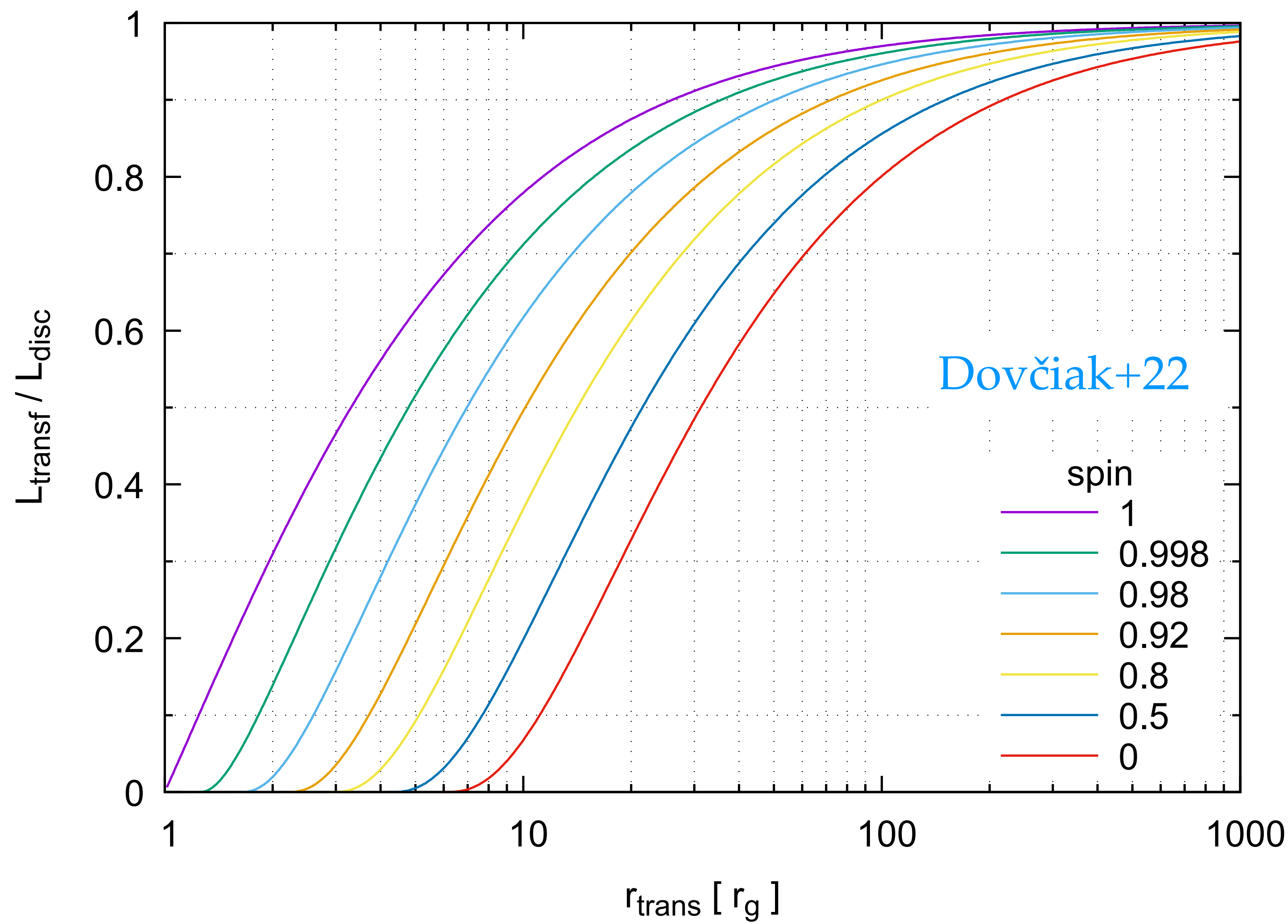
s1
s2
s3
s4
s5
s6
s7
s8
s9
s10
s11
s12
s13
s14
s15
2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
$F_X/\langle F_X \rangle$
1.6
1.4
1.2
1.0
0.8
0.6
0.4
$F_\lambda/\langle F_\lambda \rangle$
HST H1
HST H3
UVW2
56720
56740
56760
56780
56800
56820
56840
MJD (day)
Preliminary



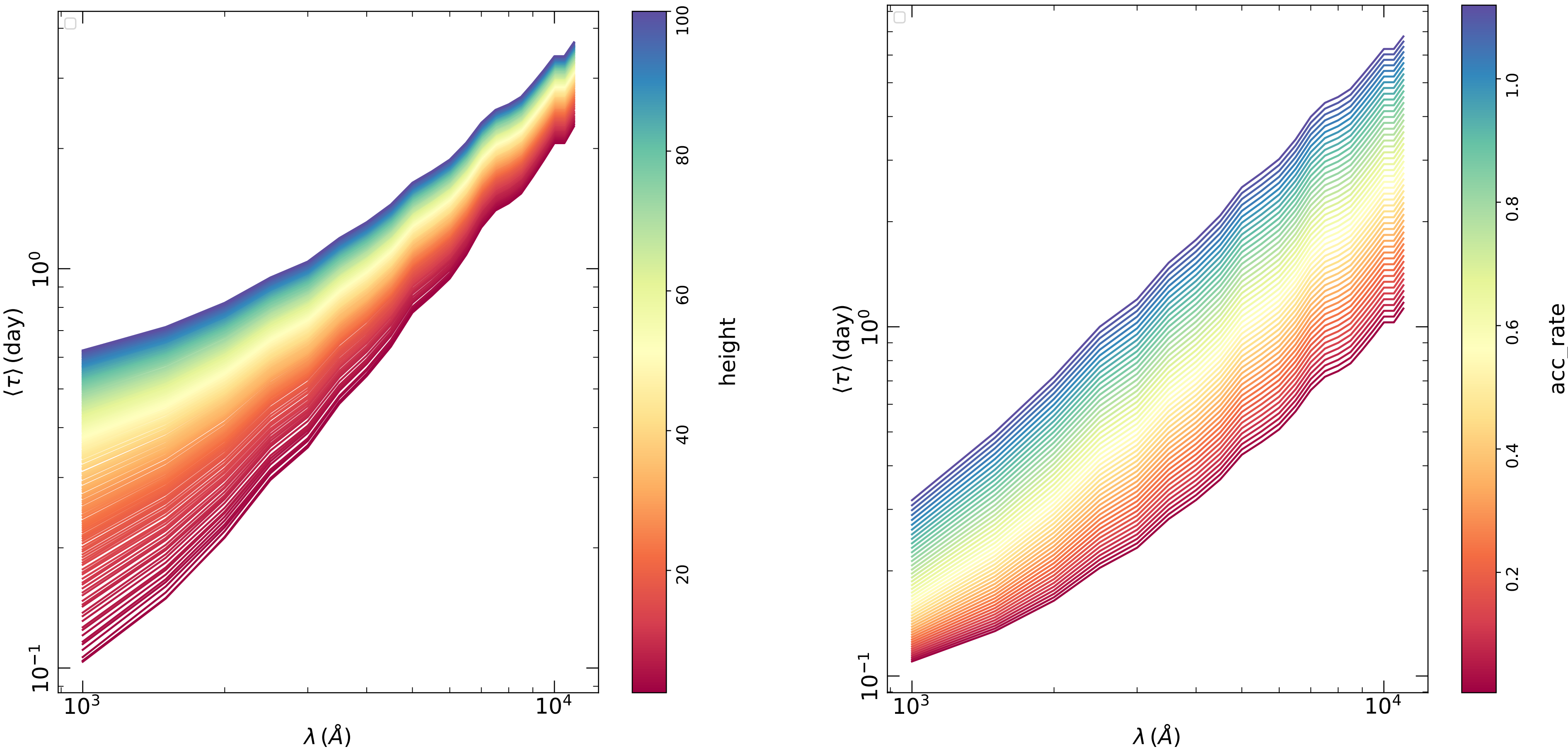
$\nu F_\nu\,(\mathrm{erg\,s^{-1}\,cm^{-2}})$
10^{-11}
10^{-12}
$\Delta\chi\,(\sigma)$
4
2
0
−2
−4
10^{16}
10^{17}
10^{18}
frequency (Hz)
$h(\mathrm{r_g})$
20.0
17.5
15.0
12.5
10.0
7.5
5.0
$h - R_\mathrm{H}$
$R_\mathrm{C}\,(\mathrm{R_g})$
17.5
15.0
12.5
10.0
7.5
5.0
2.5
$L_\mathrm{trans}/L_\mathrm{disc}$
0.9
0.8
0.7
0.6
0.5
0.4
Γ
2.2
2.0
1.8
1.6
1.4
56720
56740
56760
56780
56800
56820
Time (MJD)



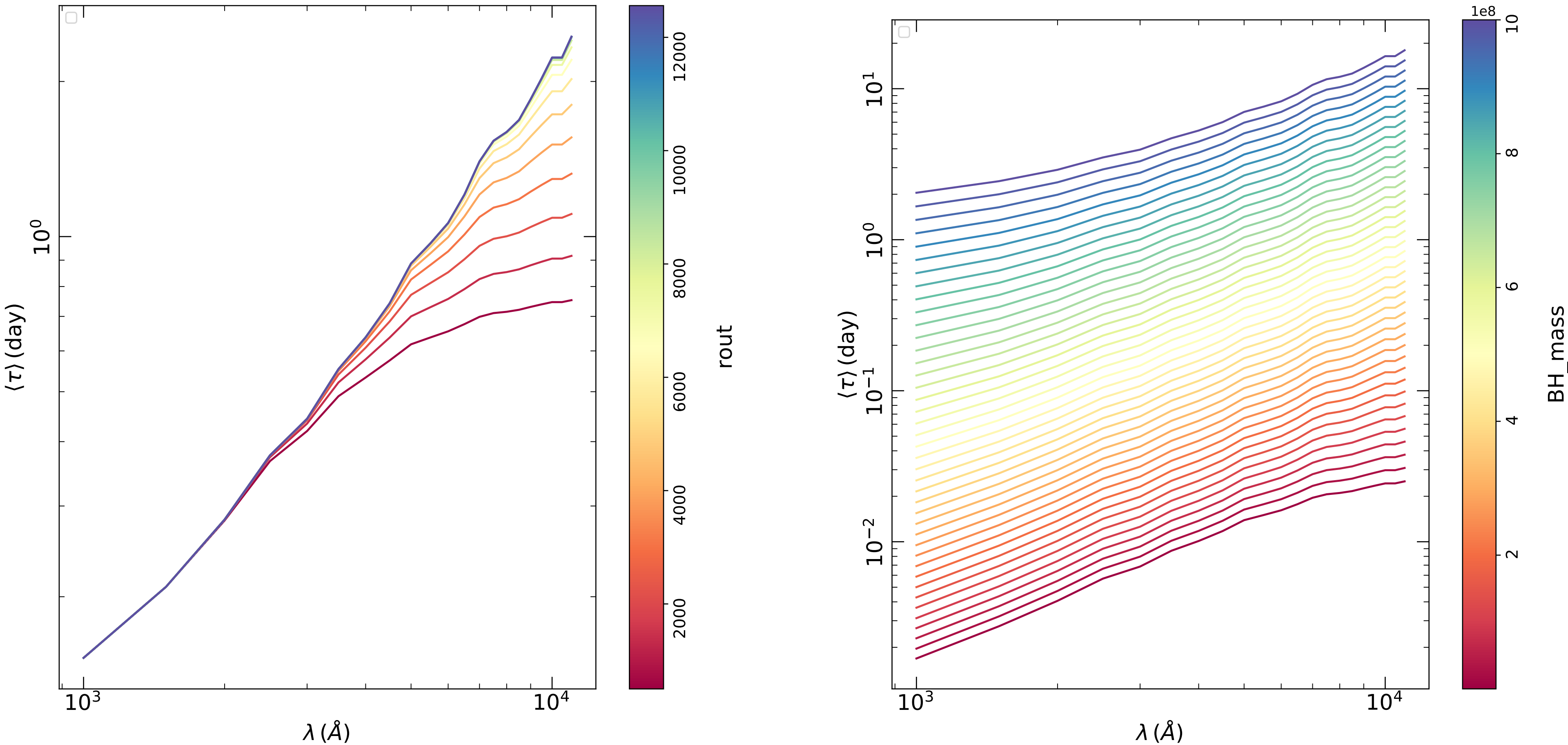
a
b
c
d
e
f
g
h
i
j
Γ
2.2
2.0
1.8
1.6
1.4
$L_{\rm trans}/L_{\rm disc}$
0.8
0.6
0.4
$F_{\rm H3}$
5
4
3
2
$CR_{\rm X}$
0.5
0.4
0.3
0.2
10
20
1.5
2.0
0.4
0.6
0.8
2
4
$h(\rm r_g)$
Γ
$L_{\rm trans}/L_{\rm disc}$
$F_{\rm H3}$



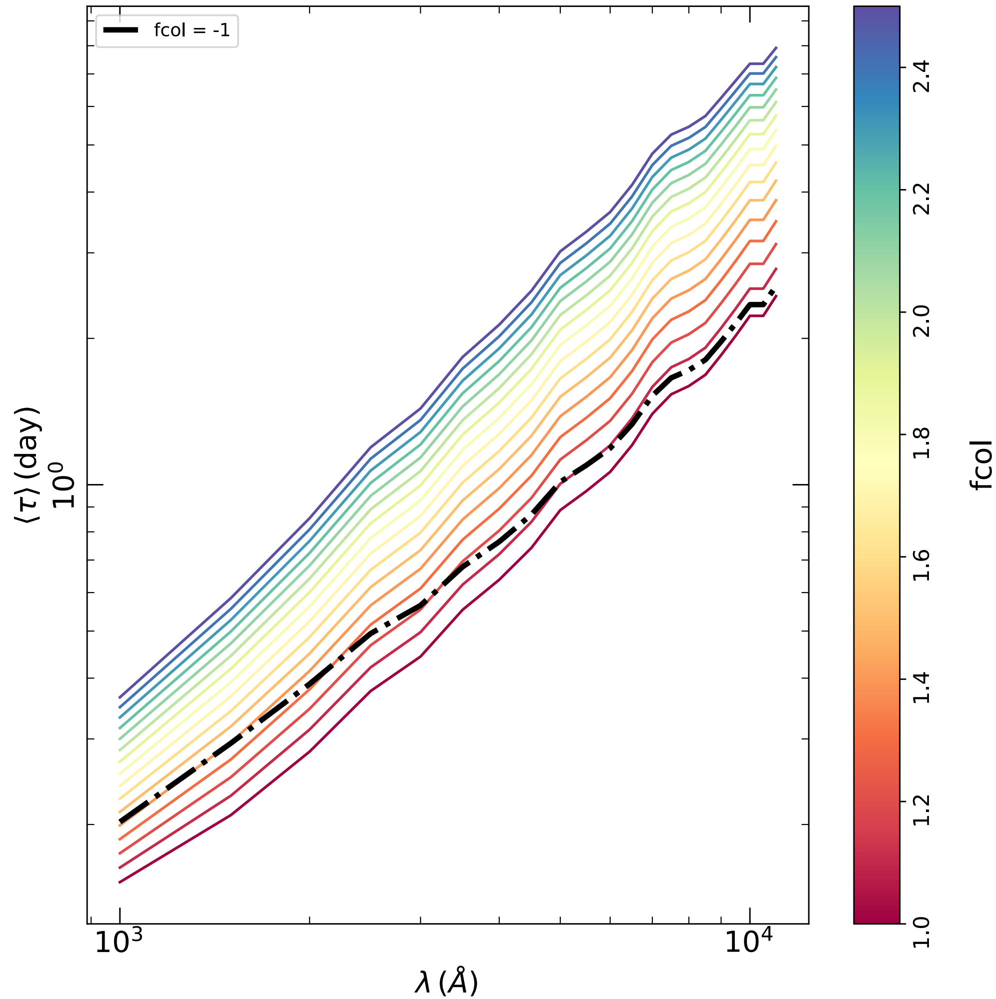
Dovčiak+22
spin
1
0.998
0.98
0.92
0.8
0.5
0
L_transf / L_disc
r_trans [r_g]
0
0.2
0.4
0.6
0.8
1
1
10
100
1000



⟨τ⟩ (day)
λ (Å)
height
acc_rate



$\langle\tau\rangle$ (day)
10^0
10^3
10^4
$\lambda\,(\AA)$
rout
2000
4000
6000
8000
10000
12000
10^1
10^0
10^{-1}
10^{-2}
$\langle\tau\rangle$ (day)
10^3
10^4
$\lambda\,(\AA)$
1e8
BH_mass
2
4
6
8
10



fcol = -1
⟨τ⟩ (day)
10^0
10^3
10^4
λ (Å)
fcol
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4