Results from the use of the X-ray reverberation model KYNREFREV in XSPEC in the lamp-post

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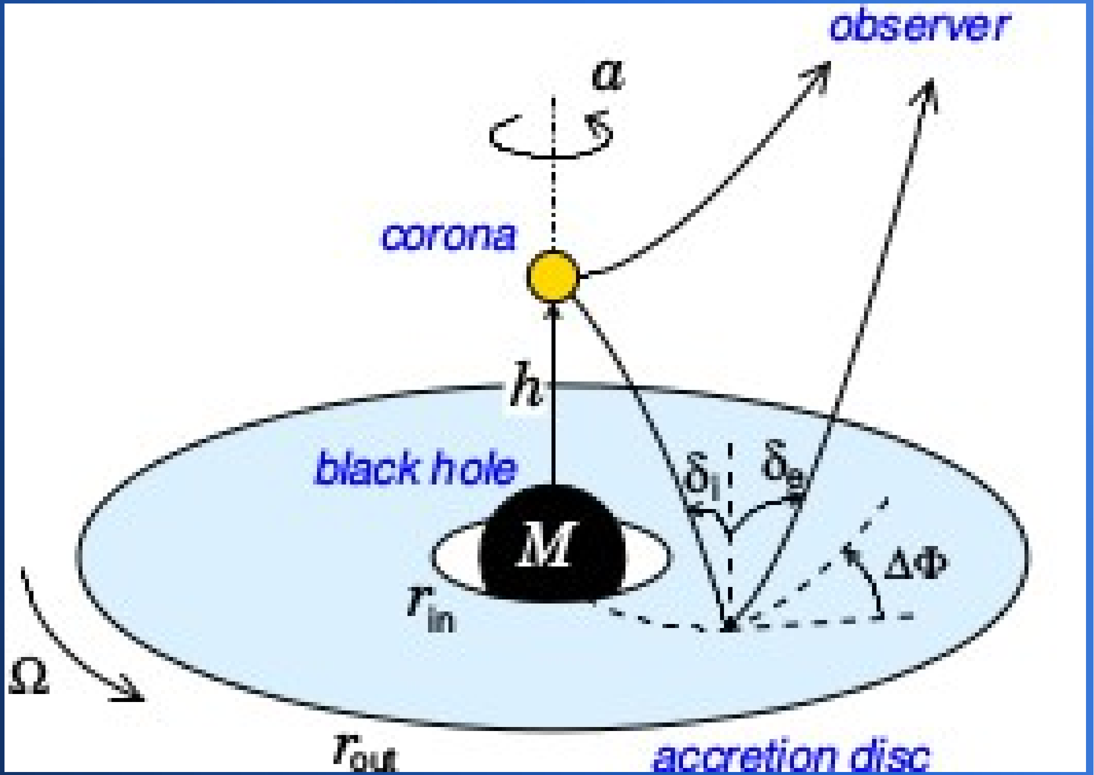
Reverberation in X-rays

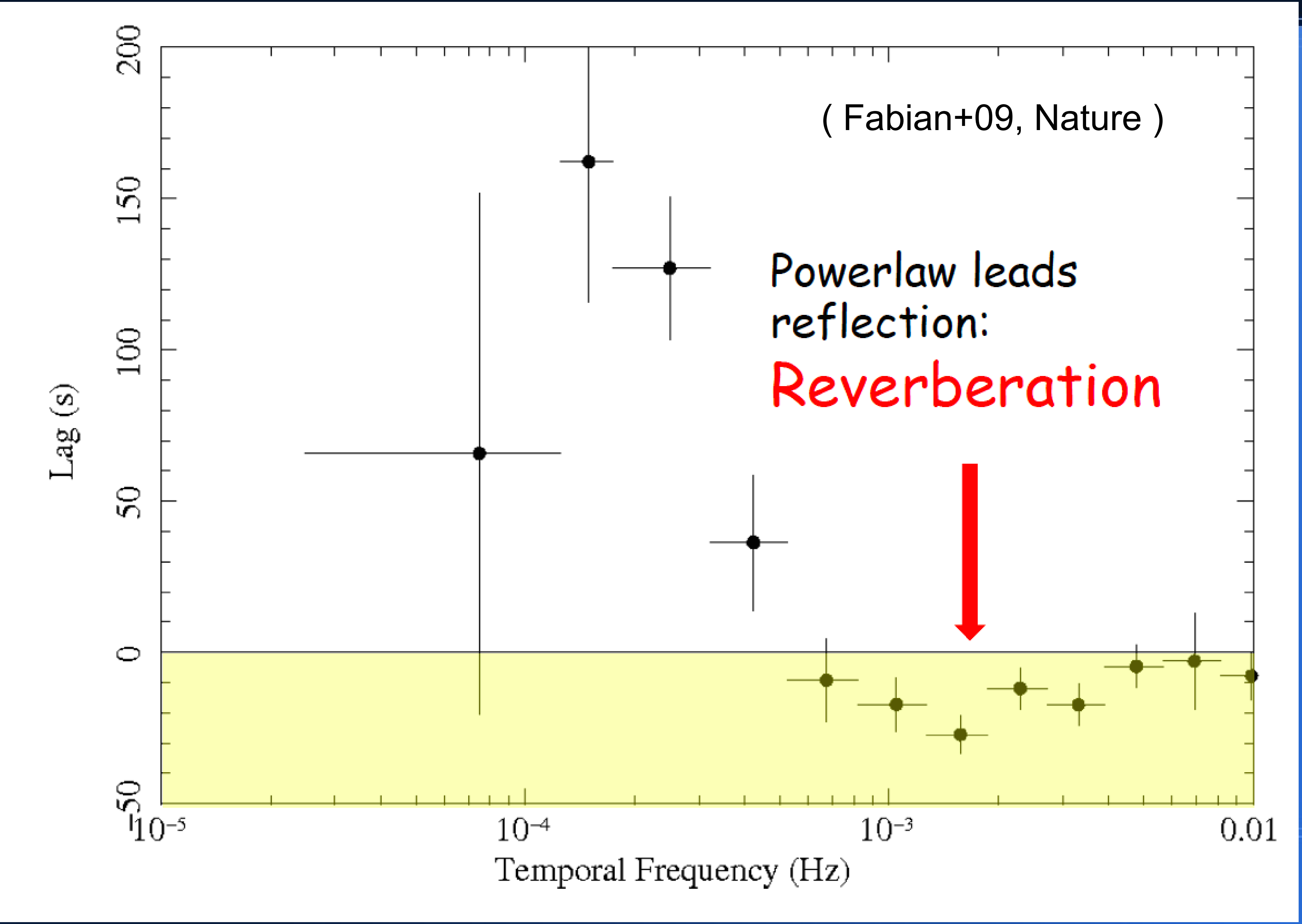
Overview

- X-ray reverberation mapping of the inner parts of the accretion disc → clues to the geometry of the corona.
- Reverberation mapping in the lamp-post geometry of the compact corona → *ionisation profile of the disc (Chainakun+16;* Dovčiak+18, in prep.).
- Light rays: *Fully relativistic ray-tracing code in vacuum* for photon paths from the corona to the disc and to the observer & from the disc to the observer.
- **Goal**: *understanding the lags versus frequency/energy* → model parameters: **height** of the corona, **inclination** of the observer, disc **ionization profile** and black hole **spin**.



The sketch of the lamp-post geometry.
(Credits: Dovčiak+14)

X-ray Soft/negative=reverberation lags

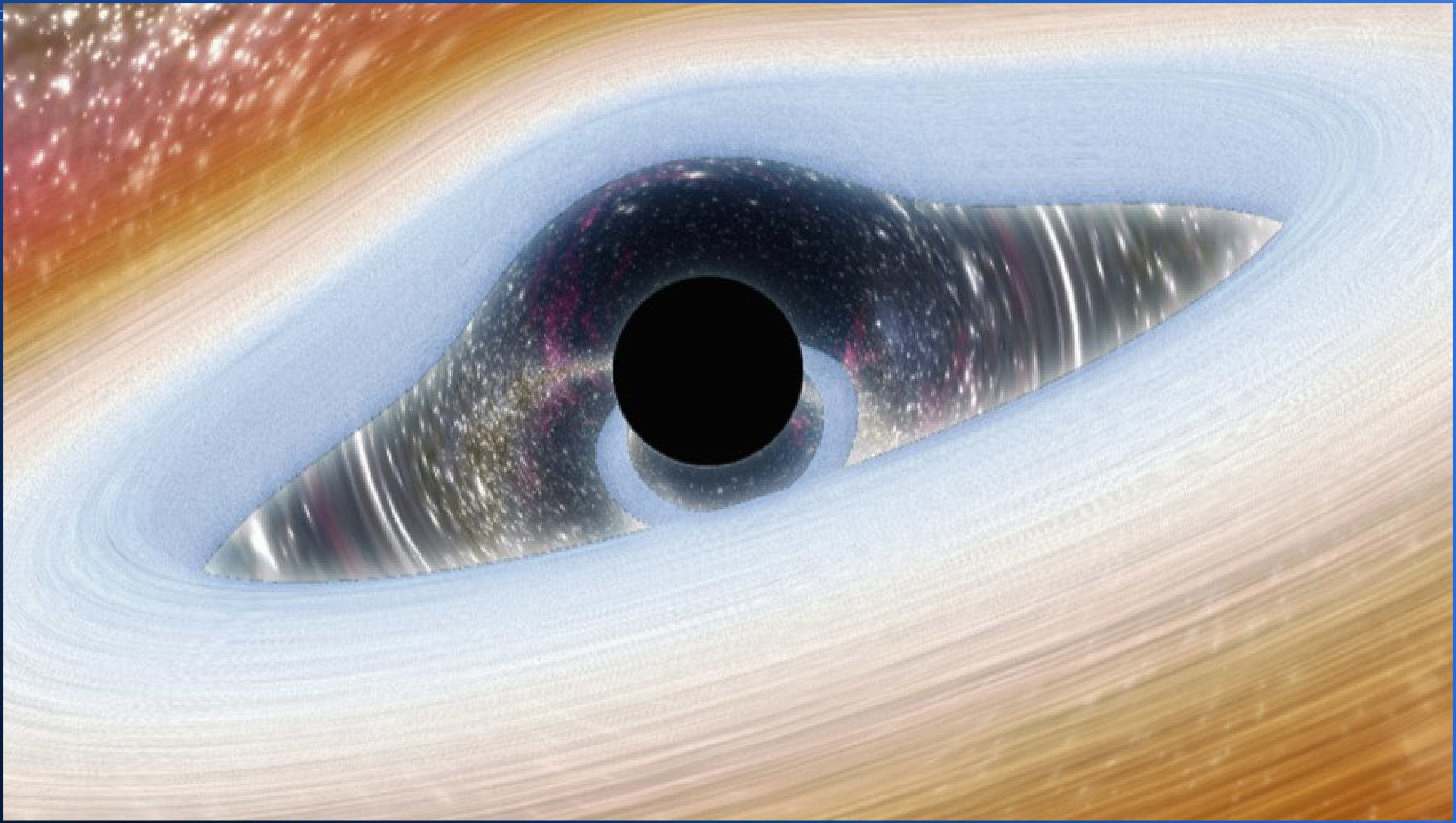


The model: *"The relativistic reflection model in the lamp-post geometry (KYNREFREV)"*

Description of the model KYNREFREV

- Black hole: Spinning BH, with mass M and dimensionless spin parameter a = 0 -1
- Accretion disc: co-rotating, Keplerian, geometrically thin, optically thick, *ionised* disc extending from r_{in} up to r_{out} (GM/c^2).
- Corona: **hot point-like plasma** on the rotation axis at height ***h*** and emitting power-law radiation, $F_p \sim E^{-\Gamma} e^{-E/Ec}$.
- Observer: with an inclination angle Θ_o with respect to the symmetry axis of the disc.
- Light rays: *Fully relativistic ray-tracing code in vacuum* for photon paths from the corona to the disc and to the observer & from the disc to the observer.
- Reflection: REFLIONX (Ross & Fabian, 2005), tables for constant density slab illuminated by the power-law incident radiation used to compute the re-processing in the ionised accretion disc.
- The ionisation of the disc, ξ → amount of the incident primary flux (dependent on the luminosity of the primary source, height of the corona and mass of the black hole) → density of the accretion disc (different *density radial profiles* are used).
- Several limb brightening/darkening prescriptions for directionality of the re-processed emission.

The model: *“The relativistic reflection model in the lamp-post geometry (KYNREFREV)”*

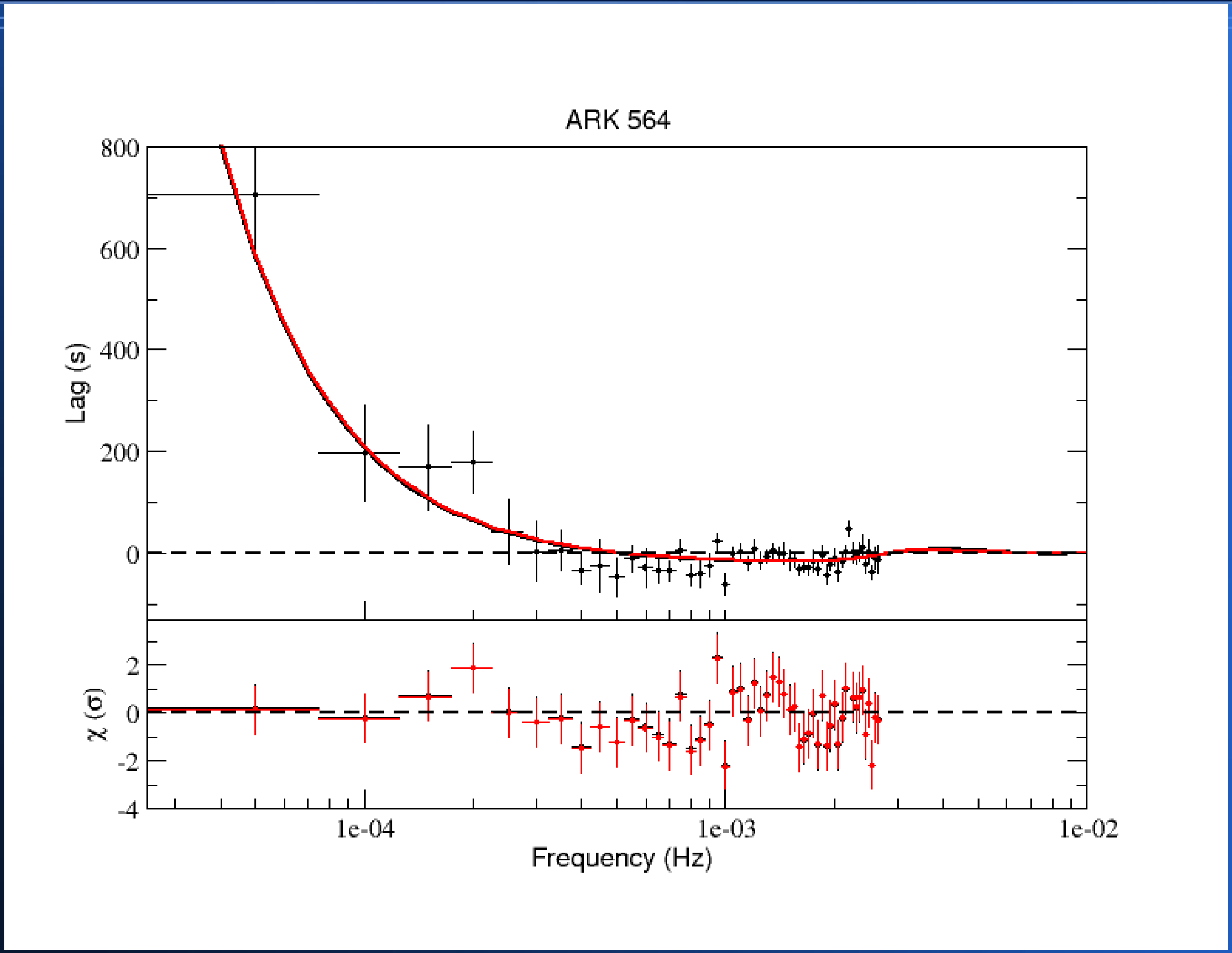


Artistic representation of the effects of Strong Gravity around an accreting black-hole

Fits with XSPEC using KYNREFREV: Observational data

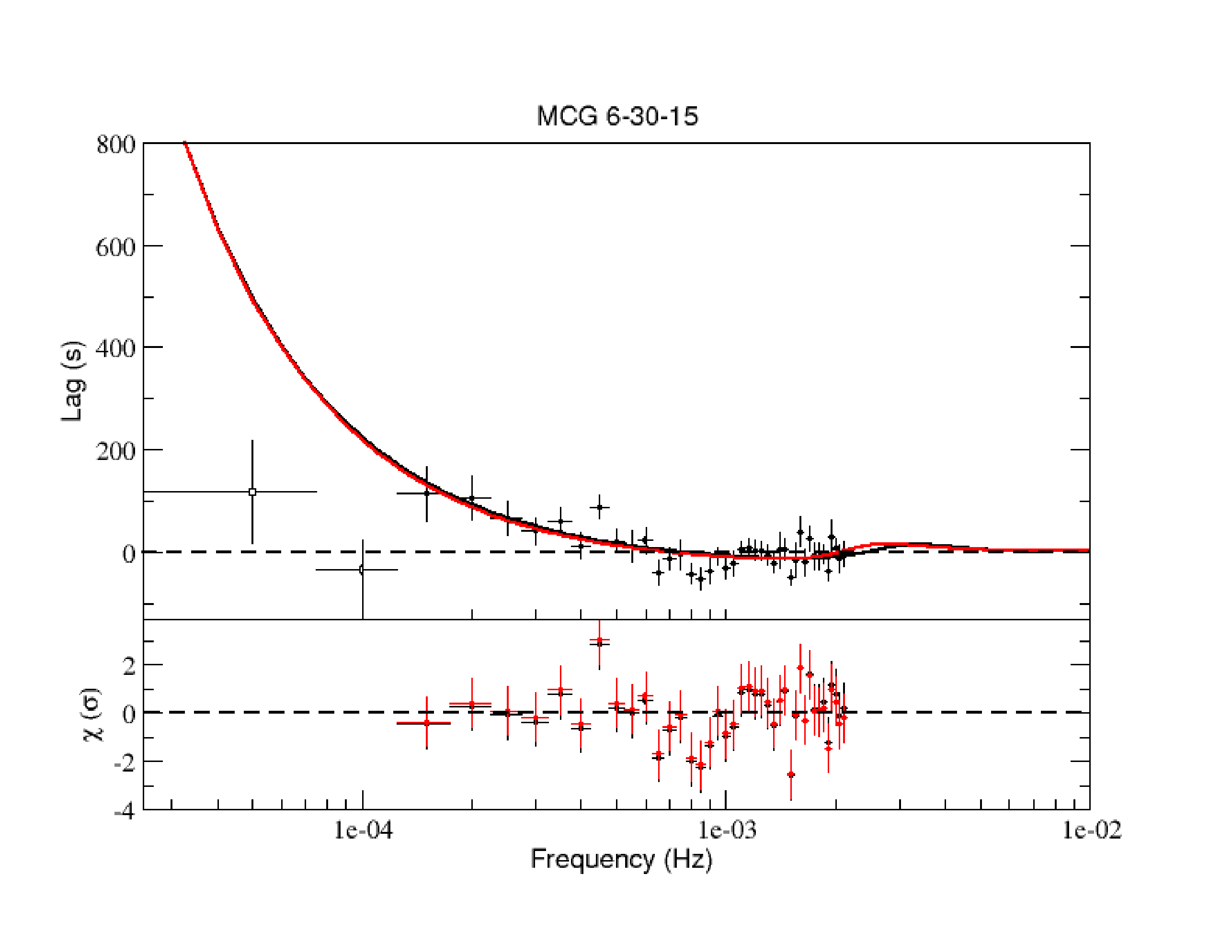
- We have produced time-lags from a sample of 3 AGN (with a mass of ~10^6 $M_{\odot}$): **ARK 564**, **MCG 6-30-15**, **1H0707-495**
- Applying statistical procedures (Epitropakis & Papadakis+16) the whole (*XMM-Newton*) light curve was divided in 20 ks segments in different energy bands.
- We used also the *phenomenological* prescription of Epitropakis & Papadakis+17 for the continuum (hard) time-lags.
- We fitted the (0.3-1/1-10 keV) time-lags versus frequency **global spectra** with the KYNREFREV model.
- We obtain very good fits in gral. (χ^2_u ~ 1) with a run-time of the order of seconds (i.e. alike normal X-ray energy-spectral fitting) → For use in XSPEC (and very efficient) method !

Fitting the data (<u>using XSPEC</u>):
ARK 564



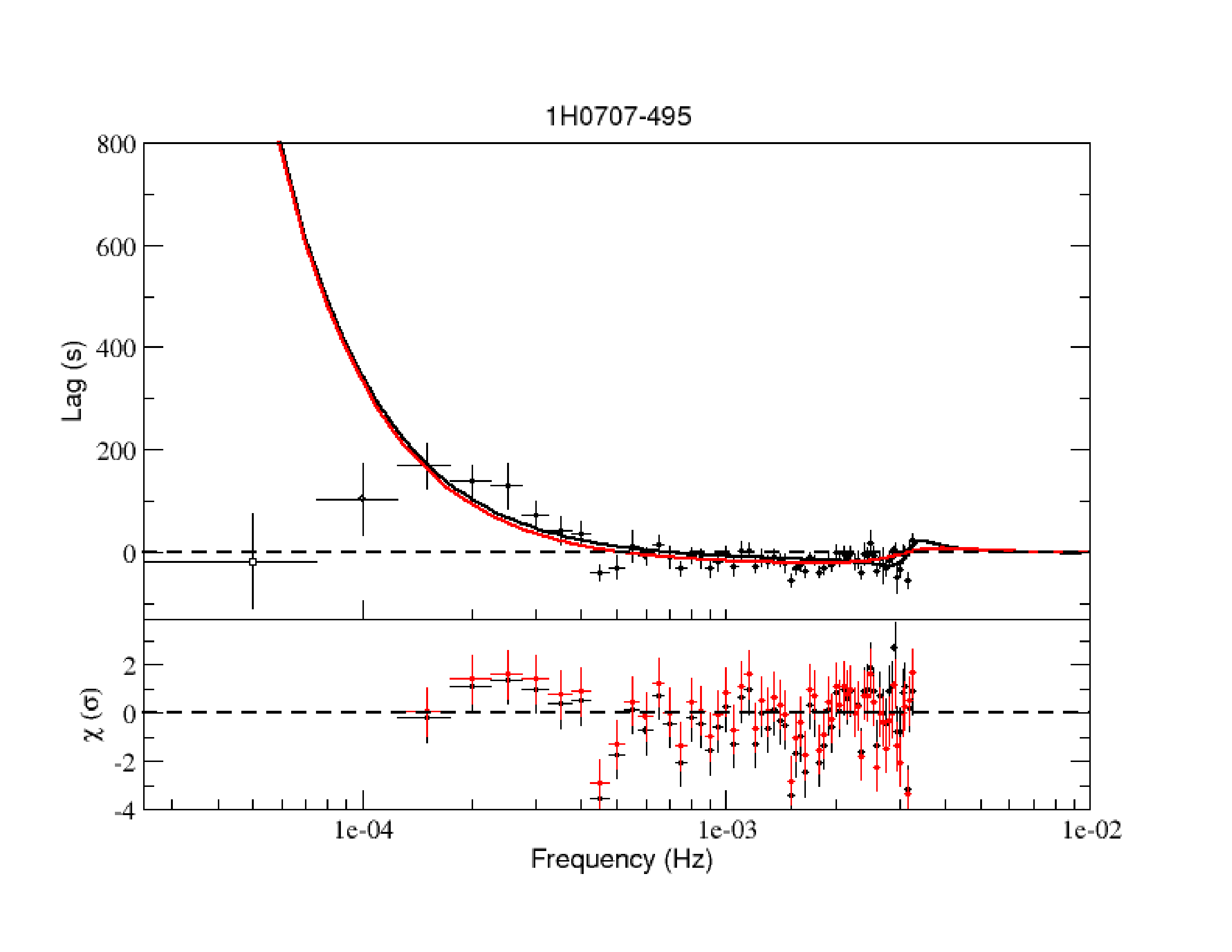
The soft lag-frequency fitted global spectrum of ARK 564 (0.3-1 vs. 1-10 keV) as obtained using XSPEC.

Fitting the data (using XSPEC):
MCG 6-30-15



The soft lag-frequency fitted global spectrum of MCG 6-30-15 (0.3-1 vs. 1-10 keV) as obtained using XSPEC.

Fitting the data (using XSPEC):
1H0707-495



The soft lag-frequency fitted global spectrum of 1H 0707-495 (0.3-1 vs. 1-10 keV) as obtained using XSPEC.

First main goal:

Can we constrain the spin of the BH from the X-ray reverberation time-lags (*taking into account all the effects of GR*)

?

Fits with XSPEC: Results

a (GM/c)	$0.99^{(f)}$	$0.0^{(f)}$
ARK 564 ($M_8 = 0.023^{(f,a)}$, $\Gamma = 2.5^{(f)}$)		
θ_0 (deg.)	$\leqslant 14$	$\leqslant 60$
h (r_g)	$2.8^{+0.4}_{-0.5}$	$2.2^{+0.4}_{-0.1}$
Density (10^{15} cm^{-3})	$0.20^{+0.23}_{-0.12}$	12^{+7}_{-10}
A	$(8.4\pm1.2)\times10^{-5\,(t)}$	–
s	$1.60\pm0.03^{(t)}$	–
χ^2/ν	1.42 (70/49)	1.40 (69/49)
p-value	0.027	0.03
MCG 6-30-15 ($M_8 = 0.016^{(f,b)}$, $\Gamma = 2.0^{(f)}$)		
θ_0 (deg.)	$\leqslant 30$	$\leqslant 60$
h (r_g)	3.8 ± 0.5	3.4 ± 0.8
Density (10^{15} cm^{-3})	170 ± 150	11^{+11}_{-9}
A	$(2.7\pm0.4)\times10^{-3\,(t)}$	–
s	1.25 ± 0.03	–
χ^2/ν	1.37 (49/36)	1.34 (48/36)
p-value	0.07	0.08
1H 0707-495 ($M_8 = 0.023^{(f,c)}$, $\Gamma = 2.5^{(f)}$)		
θ_0 (deg.)	22^{+4}_{-5}	21^{+9}_{-11}
h (r_g)	3.6 ± 0.3	3.1 ± 0.3
Density (10^{15} cm^{-3})	190^{+50}_{-40}	$3.8^{+2.1}_{-1.3}$
A	$(4.1\pm0.4)\times10^{-4\,(t)}$	–
s	$1.50\pm0.03^{(t)}$	–
χ^2/ν	1.42 (84/59)	1.53 (90/59)
p-value	0.018	0.005

*Parameters obtained from the fits: 1) a/M; 2) Theta_o; 3) Density and 4) H**eight***

Phase wrapping (*effect from GR*)

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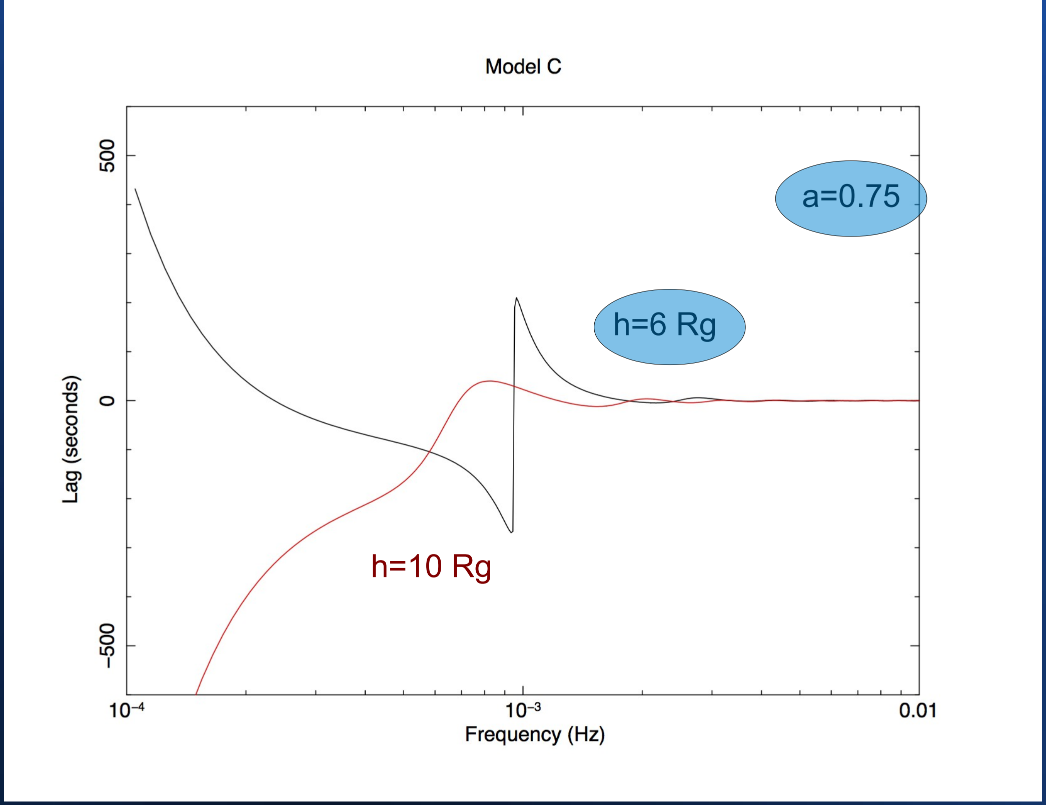
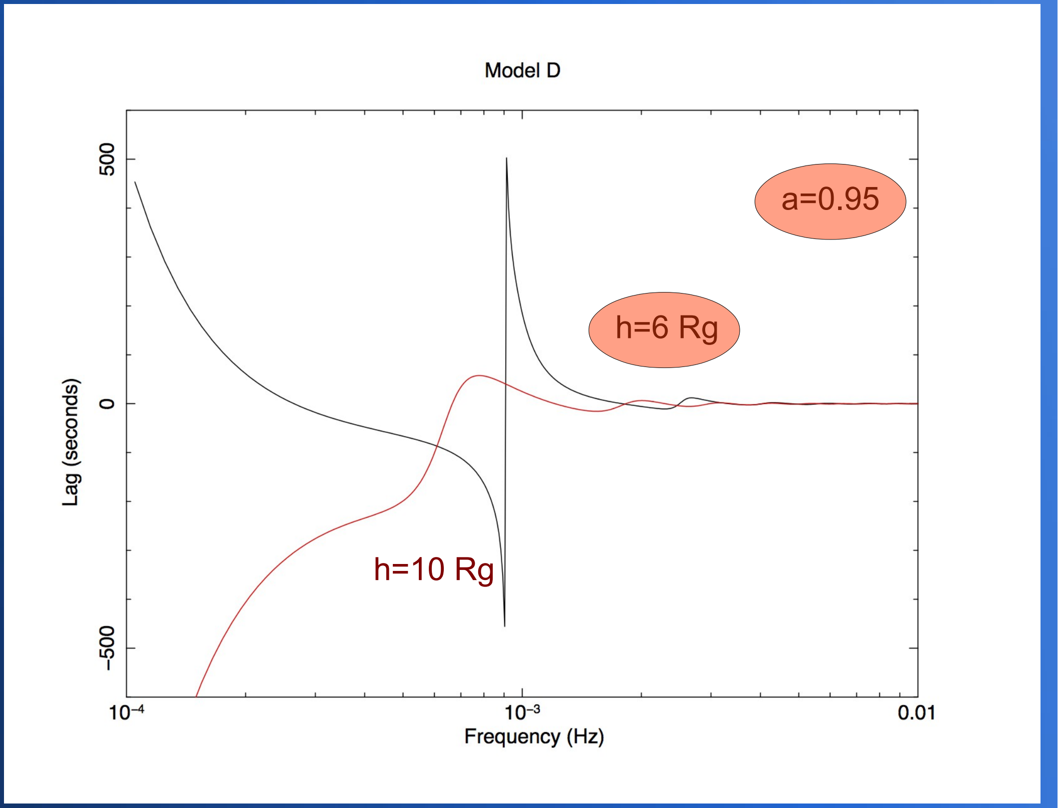




Extrapolated to higher frequencies fitted models for IRAS 13224-3809 with the obtained value for spin given the data (0. 74± 0. 02) and for a highly spinning BH obtained from sectroscopy (0. 95) at left and right, respectively. See Caballero-Garcia et al. (2017)

Warning:

The combination of
low height ($h<3r_g$)+high spin
is a <u>forbidden configuration</u>
(*because phase-wrapping has not been observed*)
!

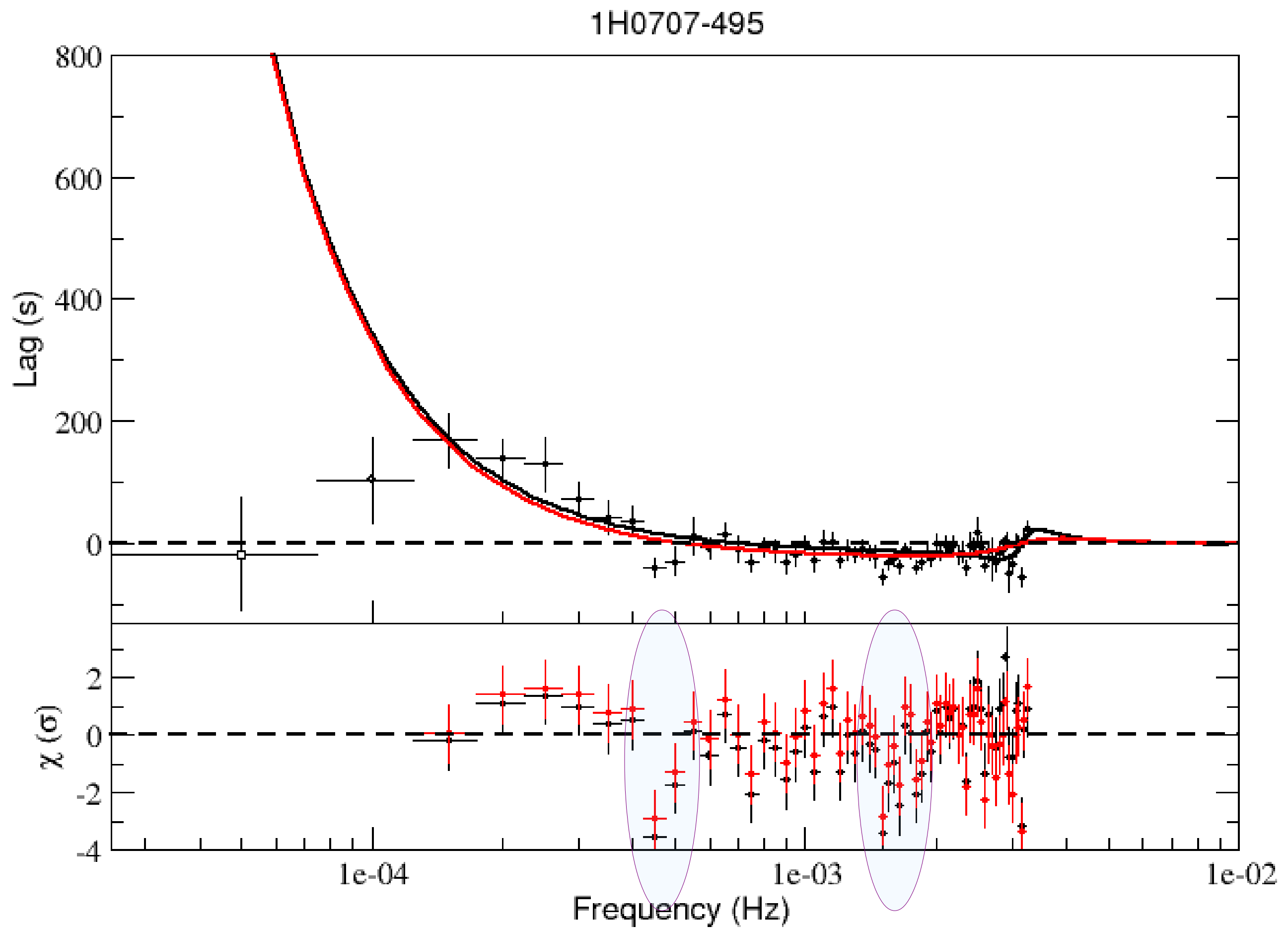
Fits with XSPEC: Results (I)

- Previous studies: Emmanoulopoulos+14 (E14), Epitropakis+16 differences because the ionization of the disc is now included !
- Inclination angle obtained (Θ_o) is always *medium-low*.
- The values obtained for the height are low (***$h\sim4r_g$*), *irrespective of the spin value considered.*** But **higher** than in E14 (because reflection increases with ionization !).
- 1H 0707-495 *has the lowest phase-wrapping frequency* (due to the very high reflection), thus enabling us to *discard the low-height+highly spinning solution*.
- The **hypothesis of a non-spinning BH in 1H 0707-495 is not supported by our fits**. This is in agreement with previous spin estimates provided *from spectroscopy* (e.g. Brenneman+13,14; see discussion in Caballero-Garcia+18, MNRAS).

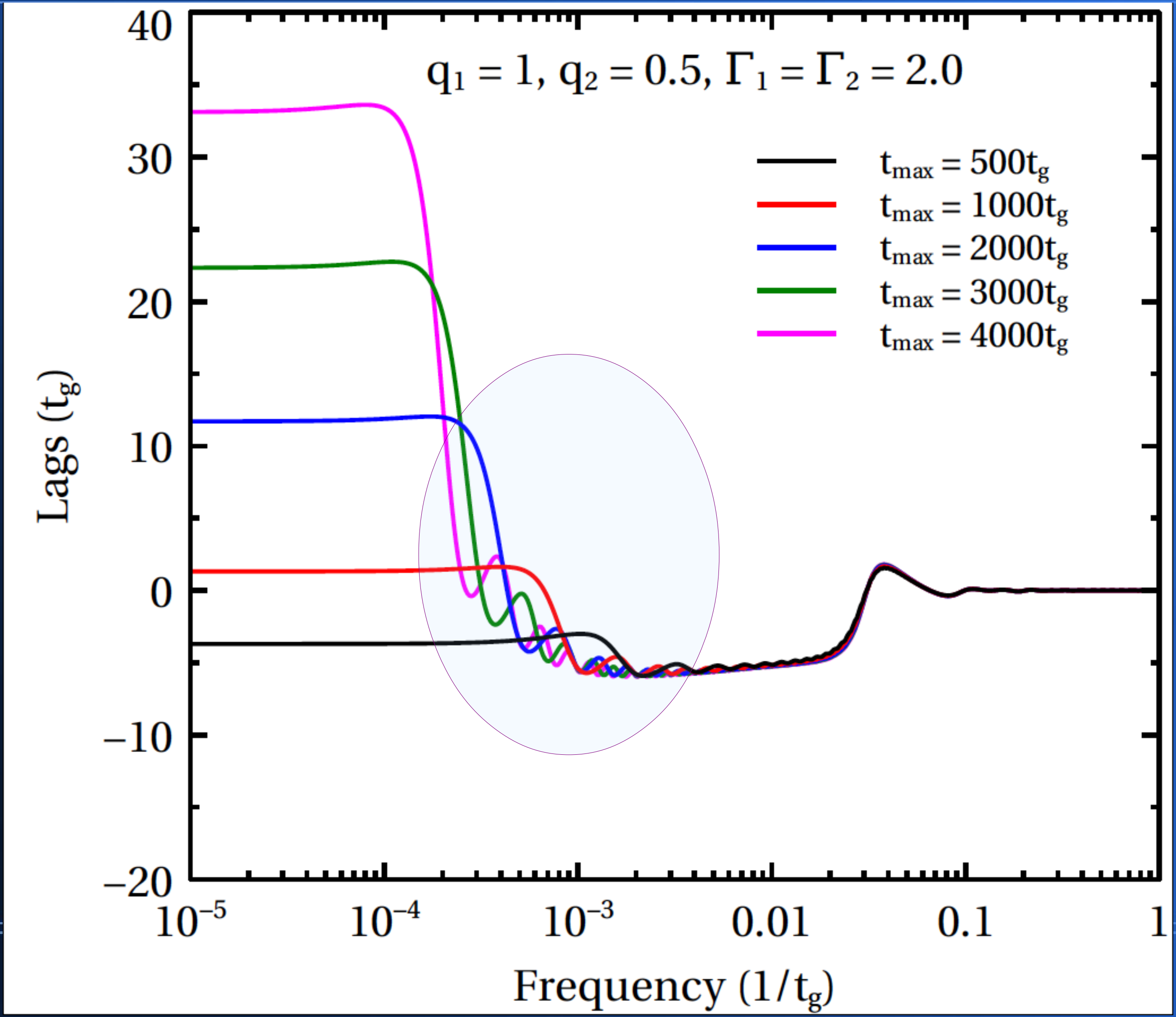
Second main goal:

Can we constrain the geometry of the corona from the X-ray reverberation time-lags (*taking into account all the effects of GR*) ?

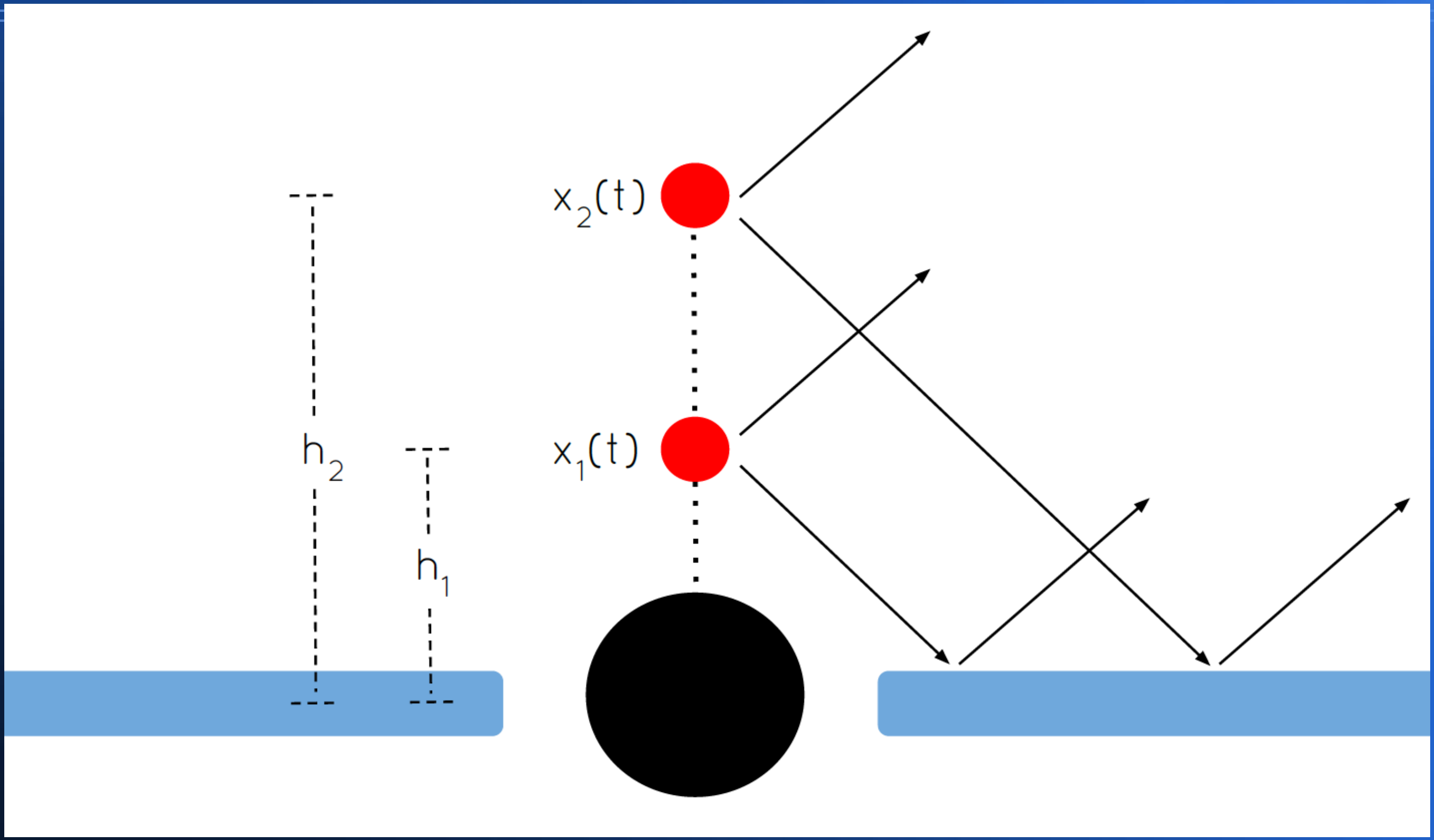
Fits with XSPEC: Results (II)



Model for extended coronae:
Chainakun & Young (2017)



Model for extended coronae:
Chainakun & Young (2017)



Sketch of the "two-blobs" model where two X-ray sources are located on the rotation axis of the black hole. We define $x_i(t)$ as the time dependent amplitude of the X-ray sources where the subscripts i=1 and 2 refer to the lower and upper sources, respectively. The source heights are h_1 and h_2 (from Chainakun & Young, 2017).

Conclusions

- First lamp-post reverberation model taking into account all known physical aspects is **ready for use into XSPEC** (Dovčiak+18, in prep.; Caballero-Garcia+18, MNRAS).
- KYNREFREV is very **well suited for obtaining the height *h* of the lamp-post corona.**
- **We are working further to solve phase wrapping effects in order to get realistic values for the spin parameter.**
- **The code includes thermal reverberation from the accretion disc and new XILVER tables (Garcia+16; not used in this presentation).**
- The lamp-post is the first approximation !!! More work is needed in the future in order to address *possible* ***(other) extended coronae geometries***.

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