KYNREFREV: implementation of an X-ray reverberation model in XSPEC

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et al.

Forthcoming publications

***1) M. Dovčiak**, M. D. Caballero-Garcia (ASU CAS, Prague), A. Epitropakis, I. Papadakis (D. of Physics, Heraklion), et al.*

*(to be submitted in ApJS) → **The model.***

Applications to the data:

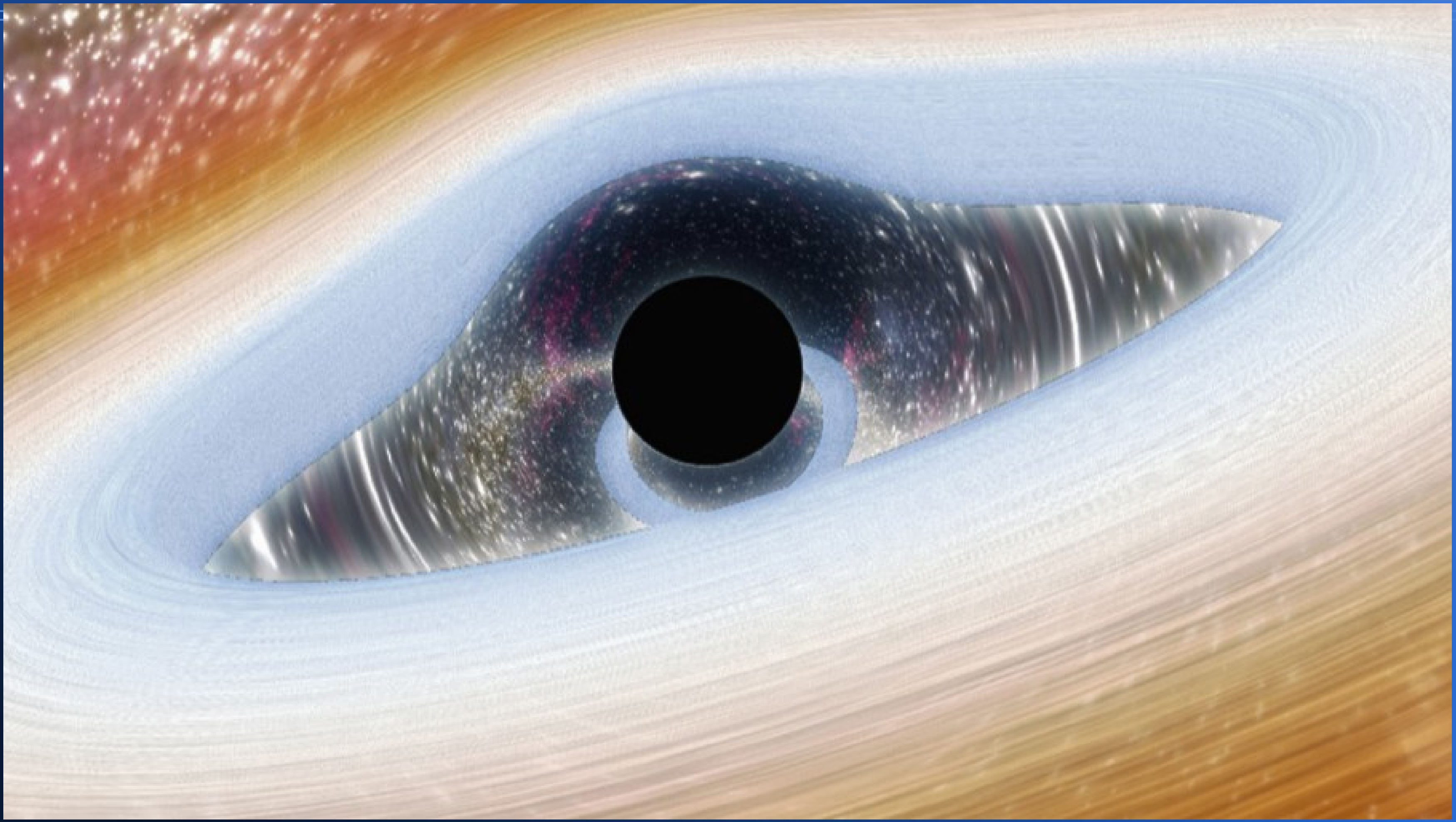
***1) M. D. Caballero-Garcia,** M. Dovčiak, J. Svoboda, E. Kara, A. C. Fabian & V. Karas (to be submitted to MNRAS, 2016) → on IRAS13224-3809*

***2) M. D. Caballero-Garcia**, M. Dovčiak, A. Epitropakis, I. E. Papadakis, G. Miniutti, et al. → on a list of sources (including **1H0707-495**).*

(to be submitted in MNRAS, 2017)

*3) **M. D. Caballero-Garcia**, M. Dovčiak, A. Epitropakis, I. E. Papadakis, J. Svoboda, V. Karas et al. (proceedings of this meeting!)*

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

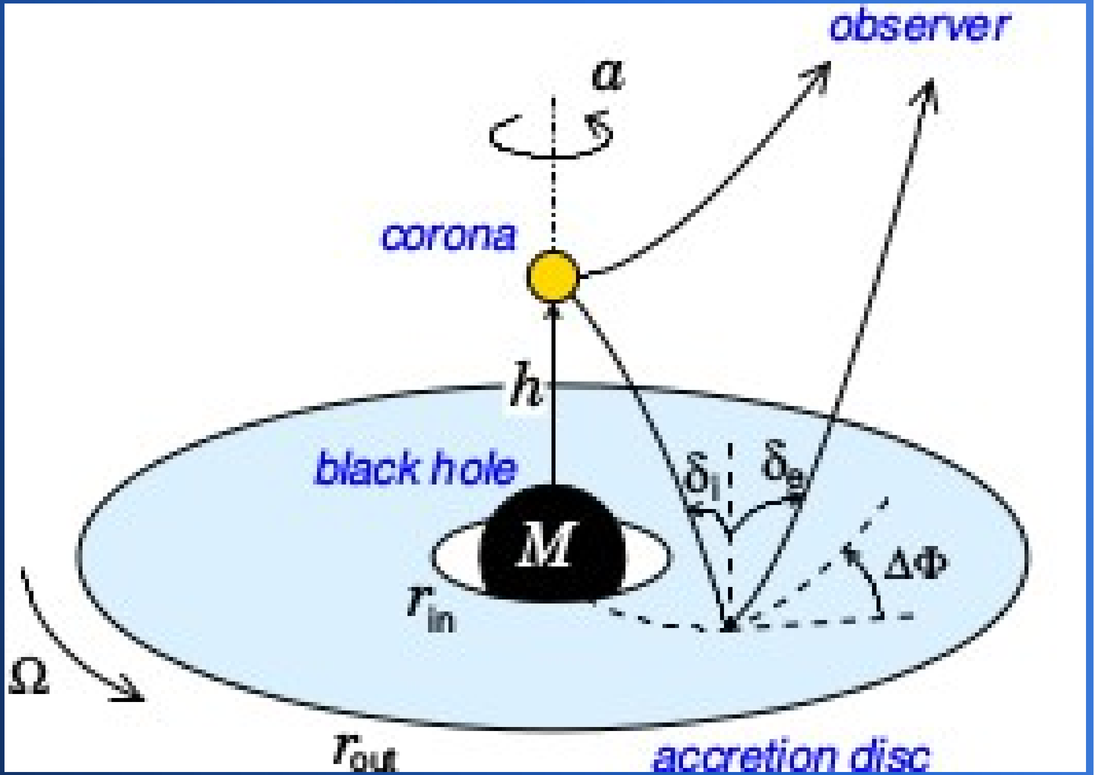


Artistic representation of the effects of Strong Gravity around an accreting black-hole

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 of the disc (Chainakun+16,* Dovčiak+17).
- **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)

Reverberation in X-rays

Observational discovery

- The analysis of continuous monitoring of the 1H0707-495 during 4 orbits of the *XMM-Newton* satellite in January 2008.
- The *discovery of a relativistically smeared Fe L (~1 keV)* line led to the discovery of X-ray reverberation in X-rays.
- **Discovery paper**:

"Broad line emission from iron K- and L-shell transitions in the active galaxy 1H0707-495"

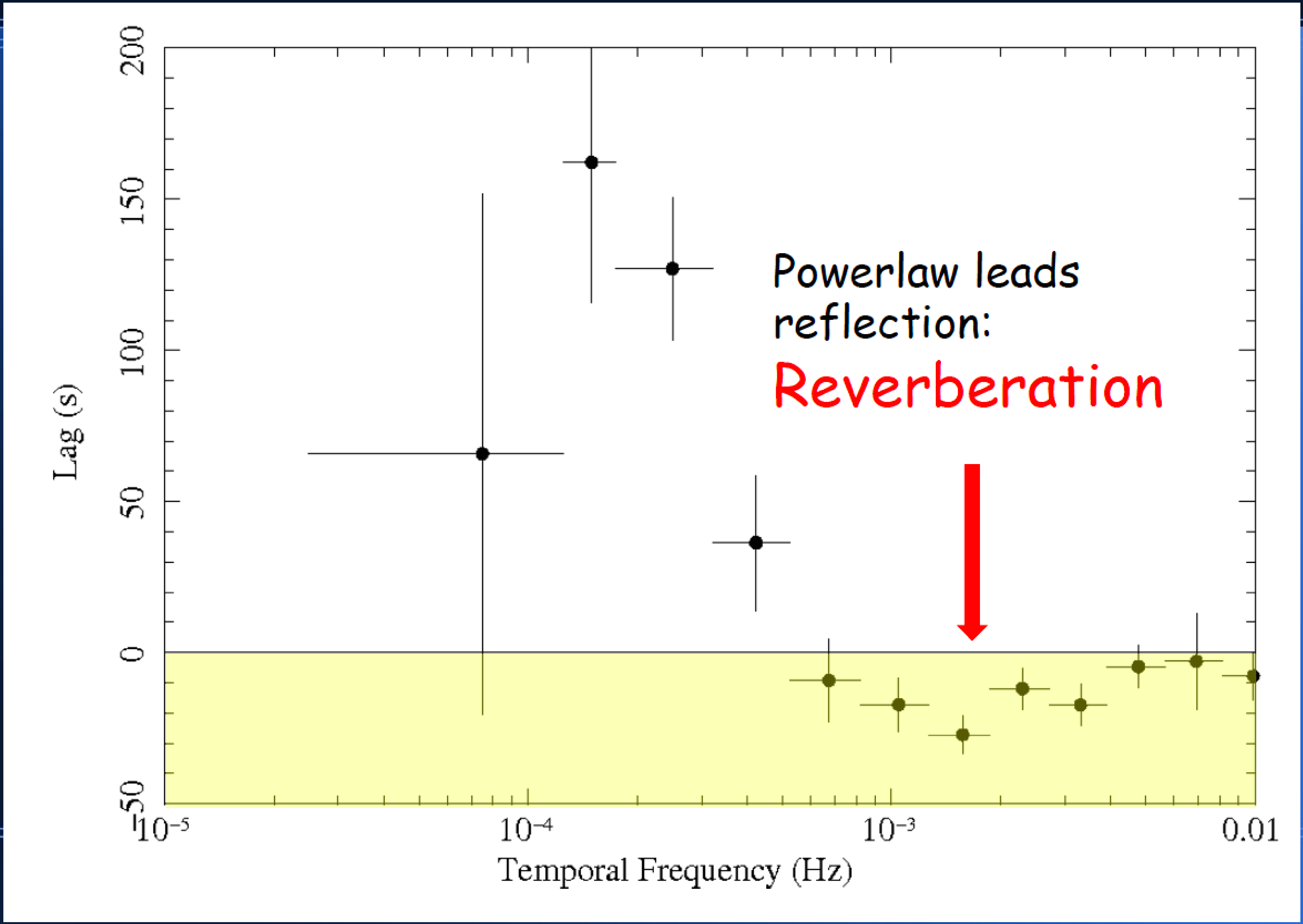
Fabian, Zoghbi, Ross, Uttley, Gallo, Brandt, Blustin, Boller, **Caballero-Garcia**,

et al.

(2009, Nature, 459, 540)

(240 citations so far)

X-ray Soft/negative=reverberation lags



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

Parallel theoretical developments

- Model based on the properties of the accretion disc in the *strong gravity regime* (Dovčiak, Karas & Yaqoob, 2004) → KYRLINE, KYCONV
- Model adapted for use in XSPEC under the lamp-post geometry (Dovčiak et al., 2014) → X-ray spectral studies
- Model adapted for studies of *reverberation mapping* in the lamp-post geometry of the compact corona illuminating the accretion disc in AGN (Dovčiak et al., 2014b) → X-ray spectral and timing studies
- Model adapted for use in XSPEC for simultaneous *spectral and reverberation mapping studies* of black holes *in the whole mass range* (Dovčiak, Caballero-Garcia+ 2017) → KYNREFREV
- *Analysis of X-ray reverberation data (i.e. X-ray time lags) in a sample of Seyfert galaxies using this model with XSPEC* (Caballero-Garcia, Dovčiak+, 2017)

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

The model components

- Black hole: Schwarzschild or maximally rotating Kerr, with mass M and dimensionless spin parameter a = 0 -1
- Accretion disc: co-rotating, Keplerian, geometrically thin, optically thick, *ionised* disc extending from the ISCO up to $r_{out} = 1000\ GM/c^2$.
- Corona: **hot point-like plasma** on the rotation axis at height ***h*** and emitting power-law radiation, $F_p \sim E^{-\Gamma} e^{-E/E_c}$, with a sharp low energy cut-off at 0.1 keV and $E_c = 300$ keV.
- Observer: located at infinity, inclination angle Θ_o with respect to the symmetry axis of the disc.

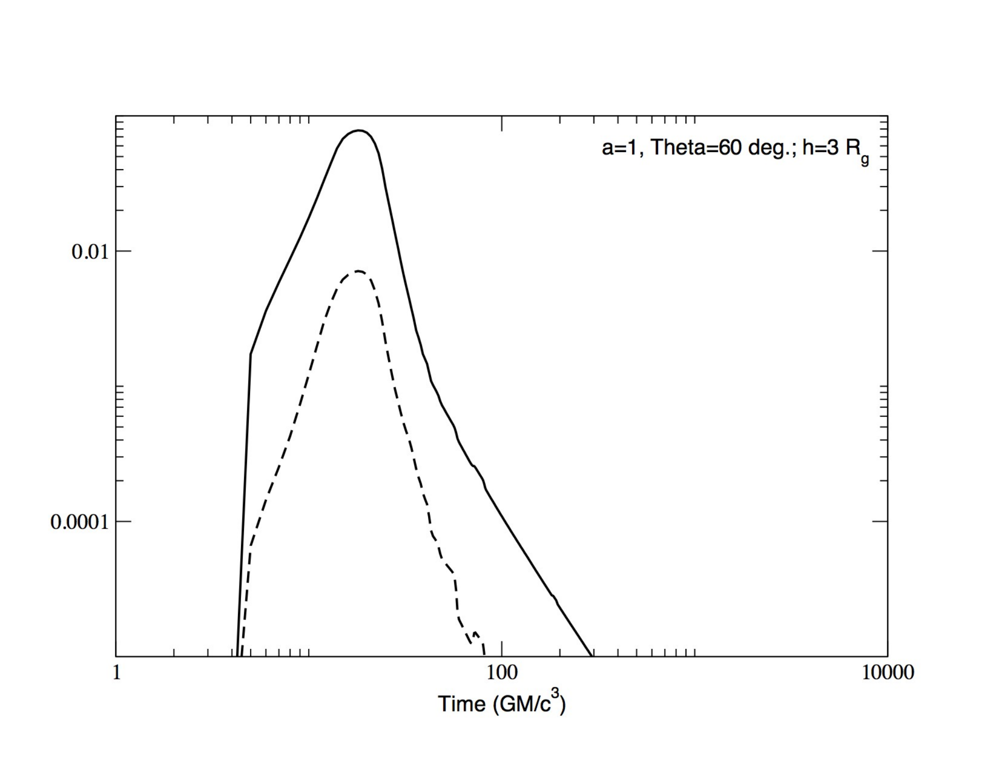
The model: *"The relativistic reflection model in the lamp-post geometry"*

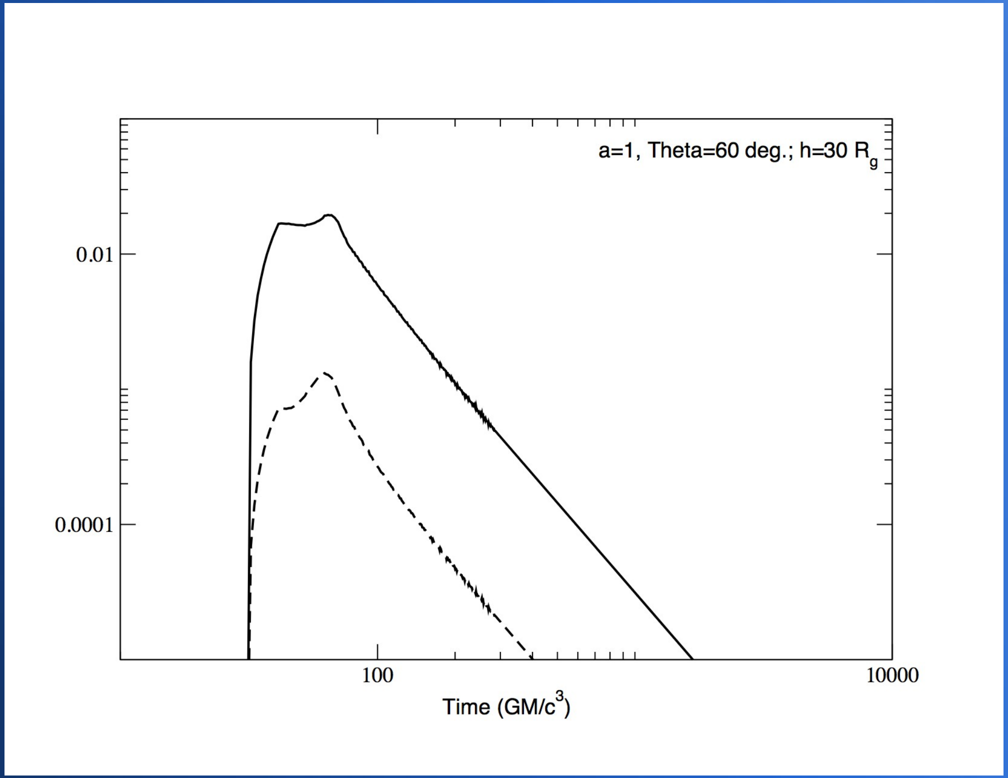
Approximations

- 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"*

Light curves ("observed") reflection

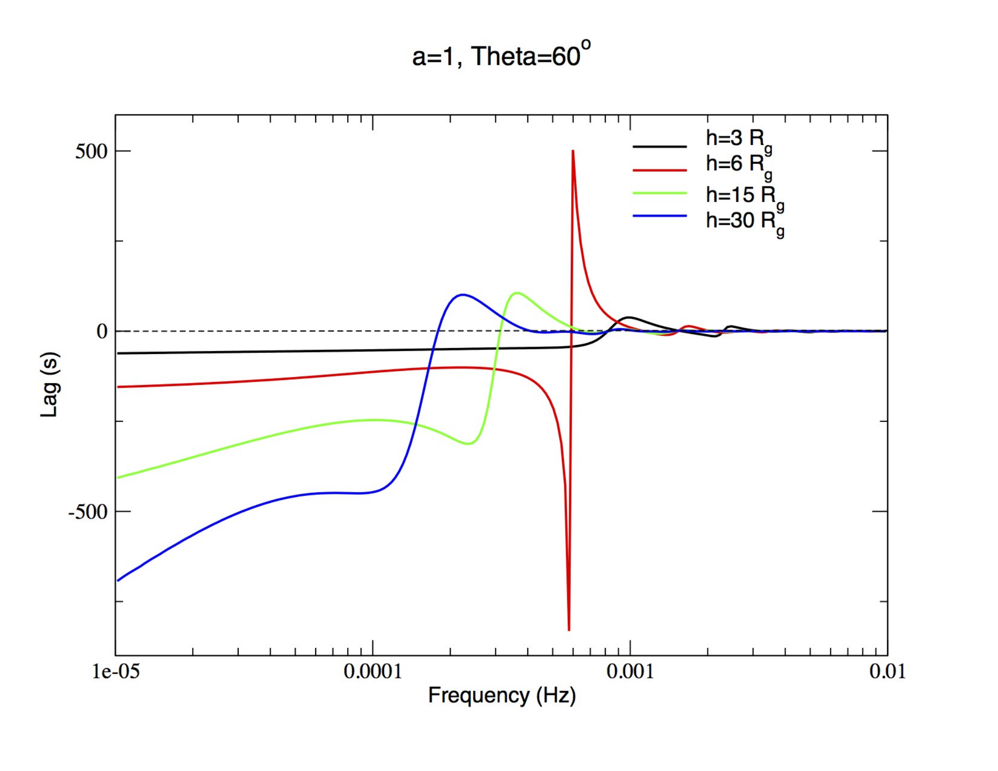


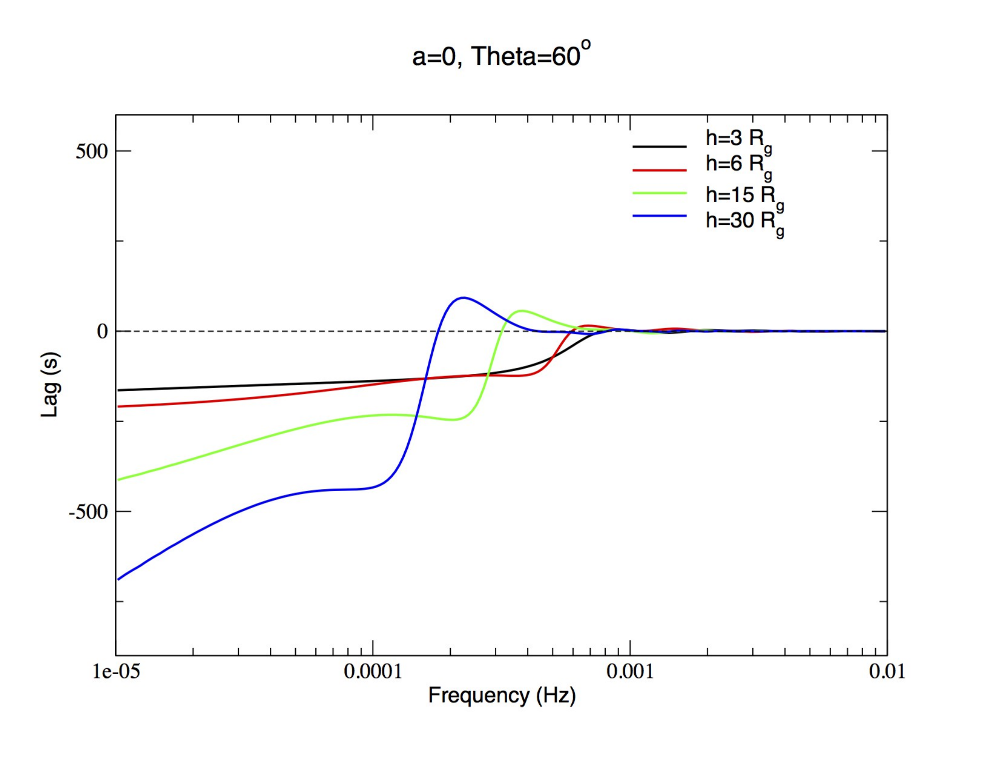


Soft (0.3-0.8 keV versus 1-3 keV) light curves.

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

Soft lags vs. frequency





Soft (0.3-0.8 keV versus 1-3 keV) lag frequency "spectra". Notice the "phase wrapping" (left panel).

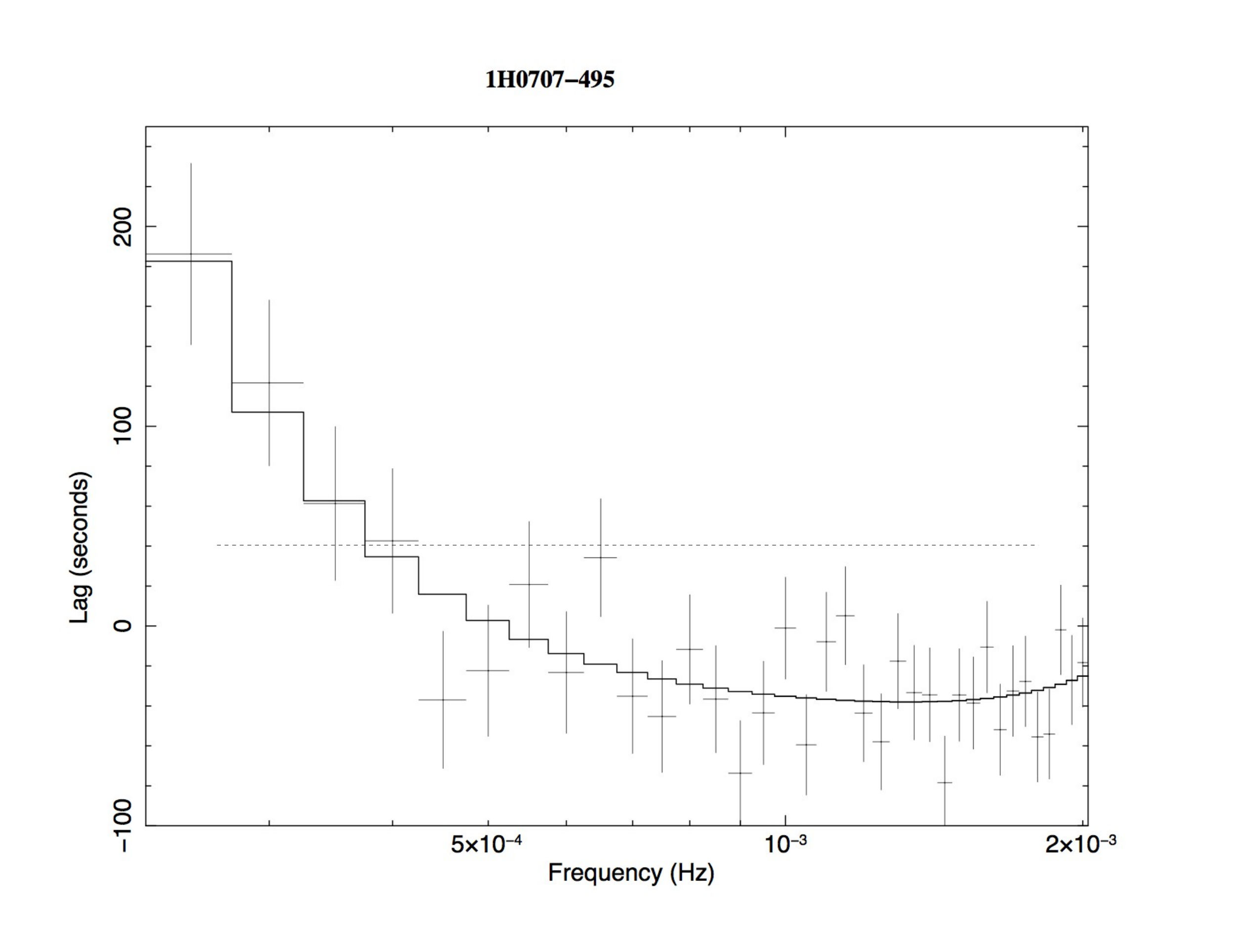
The model: *"The relativistic reflection model in the lamp-post geometry"*

Fits with XSPEC

- We have produced time-lags from 1H0707-495 from 20 ks segments in different energy bands taking the 2-4 keV reference energy band.
- We fitted the 0.3-1 keV time-lags versus frequency **global spectrum** with the KYNREFREV model. → Novel (and very efficient) method !
- We obtain a very good fit ($\chi^2_\upsilon \sim 1$) with a run-time of the order of seconds (i.e. alike normal X-ray energy-spectral fitting).
- The values for the parameters obtained are well-constrained and in agreement with Emmanoulopoulos+14 (with exception of the parameters ***h* and** Θ_o – since the ionization of the disc is now included !).

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

Fitting the data (using XSPEC)



The soft lag-frequency fitted global spectrum of 1H0707-495 (0.3-0.8 keV versus 1-3 keV) as obtained using XSPEC.

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

Results

- a/M= 0.25 (± 0.12) GM/c
- Θ_o ***= 54 (± 9) deg.***
- M/M_8= 0.026 (± 0.002) $M_\odot$
- ***h= 5.0 (± 0.7)*** R_g

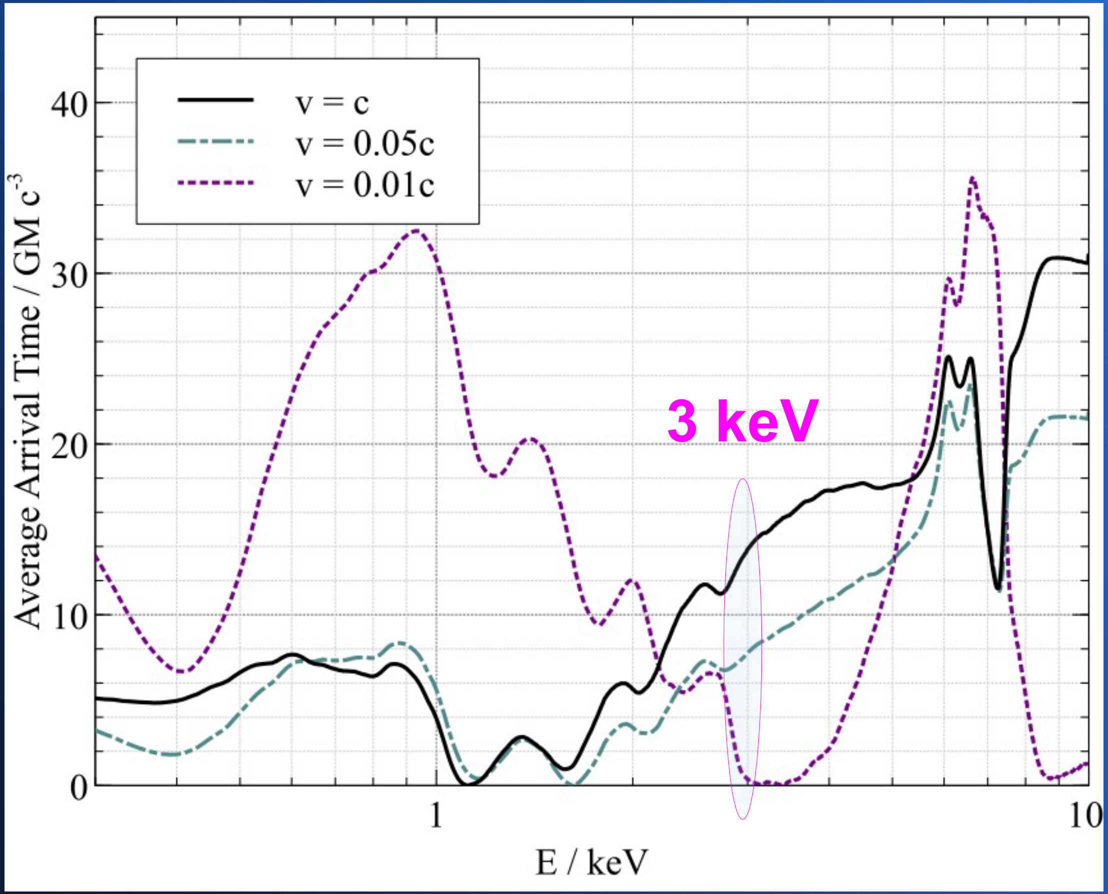
```
XSPEC12>erro 1. 1

     1      0.129378     0.377104    (-0.135715,0.112011)
     2       45.2714      62.4317    (-9.96668,7.19363)
     8     0.0243153      0.02822    (-0.0023808,0.00152394)
     9       4.30455      5.77545    (-0.852618,0.618287)
    13       7.38253      28.8112    (-8.42029,13.0084)
    33   3.67934e-06  4.69613e-06    (-5.0839e-07,5.0839e-07)
    34       2.15282      2.18612    (-0.0178511,0.0154438)
```

Parameters: 1) a/M; 2) Theta_o; 8) M/M8; 9) ***height****; 13) density; 33) and 34) amplitude and photon index low-frequency hard lags.*

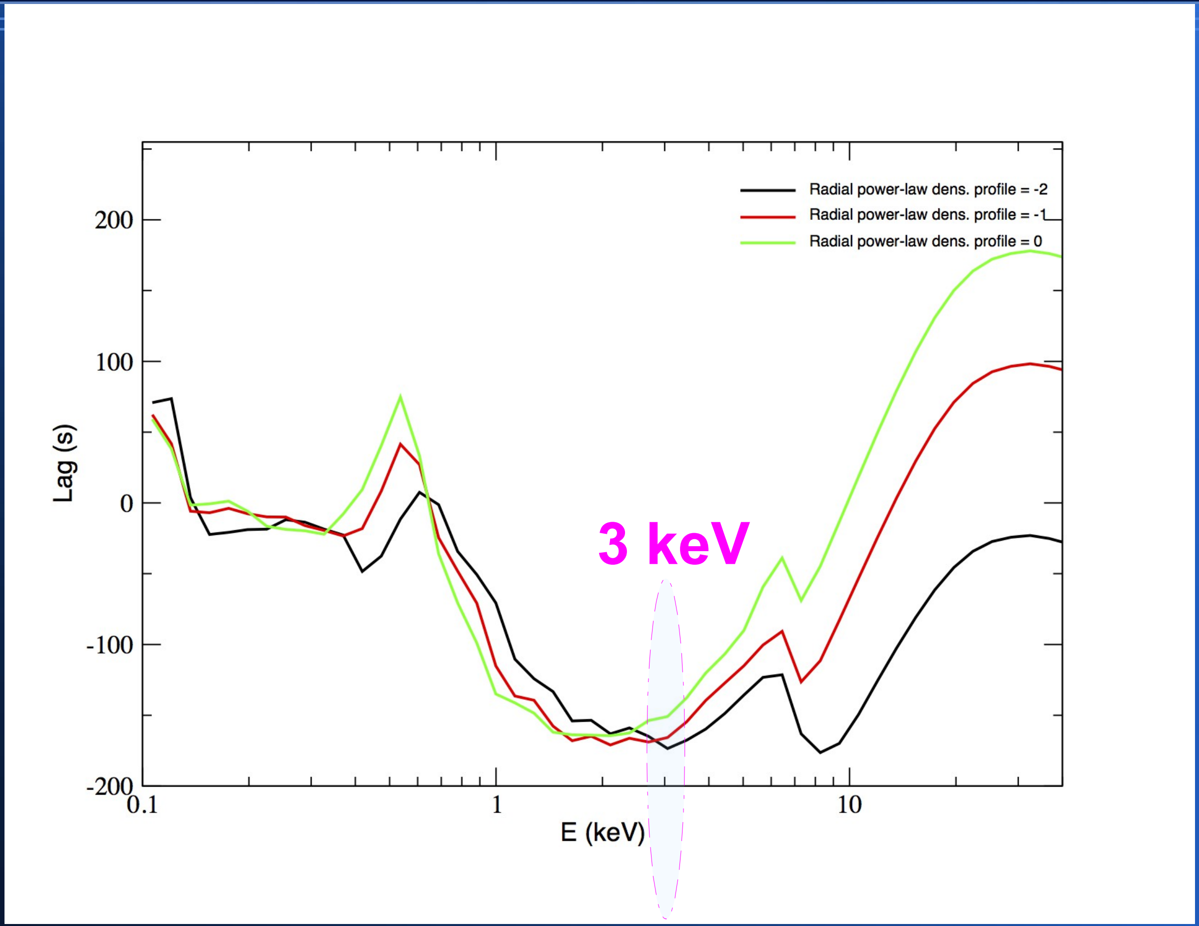
On the need of an extended corona (?!)

Discussion (*comparison with recent work*)



The average arrival times of photons as a function of energy where the accretion disc is illuminated by a vertically collimated corona extending between 1.5 and 10 r_g above the singularity. The overall arrival time including both continuum and reflected photons is shown for fluctuations propagating at varying speed.
(from Wilkins+16)

Our model



Lag (in seconds) diluted by primary radiation versus energy (keV) with respect to the (0.1-10 keV) energy band at the frequency of 10^{-4} Hz. Different radial power-law density profiles of -2 (black), -1 (red) and 0 (green) have been considered. The mass of the BH is $M=10^7\ M_{№}$ and the adimensional spin, inclination of the observer and height of the primary source are $a = 1$, $\theta = 30^o$ and $h = 3\ R_g$, respectively.

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

Conclusions

- First lamp-post reverberation model taking into account all known physical aspects is **ready for use into XSPEC** (Dovčiak, Caballero-Garcia, Epitropakis, Papadakis +, to be submitted in ApJS).
- Comparison with the recent reverberation model based on extended coronae (Wilkins+16) *does not support the emergency for the use of extended coronae* still.
- Nevertheless, more work is needed in the future in order to address possible extended coronae geometries (taking into account all the possible physical effects).
- To address this goal, collaborative efforts (like FP7-Strong Gravity project) are absolutely mandatory.

Acknowledgements

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STRONGGRAVITY

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2013 - 2017