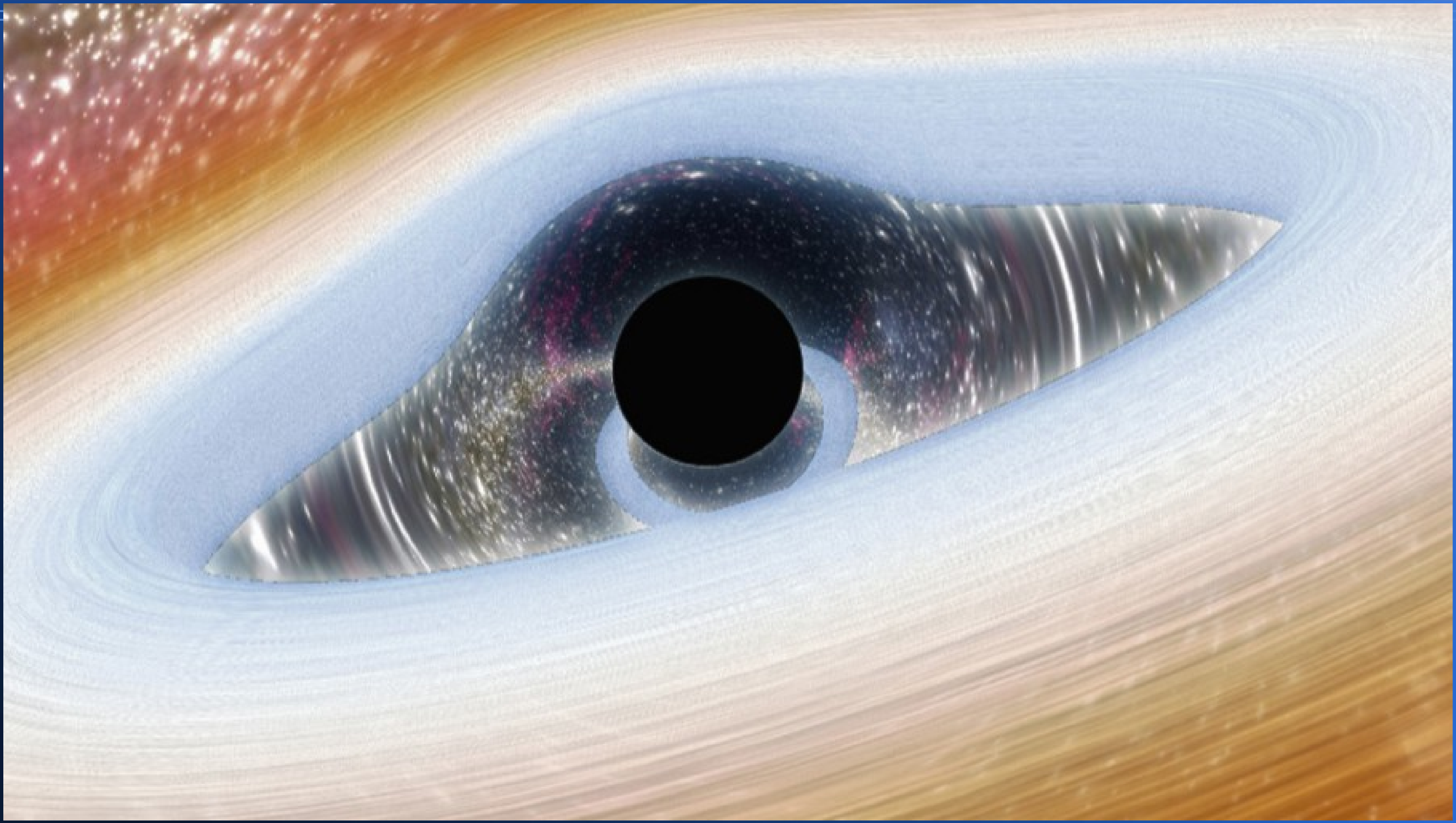
The very first results from the use of the X-ray reverberation model KYNREFREV in XSPEC

M. D. Caballero-Garcia, M. Dovčiak *(ASU-CAS, Prague),*
A. Epitropakis, I. E. Papadakis (D. of Physics, Heraklion),
J. Svoboda, V. Karas (ASU-CAS, Prague),
E. Kara (U. of Maryland, US), A. C. Fabian (U. of Cambridge, UK), G. Miniutti (CAB-INTA, Spain)
et al.

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

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**:

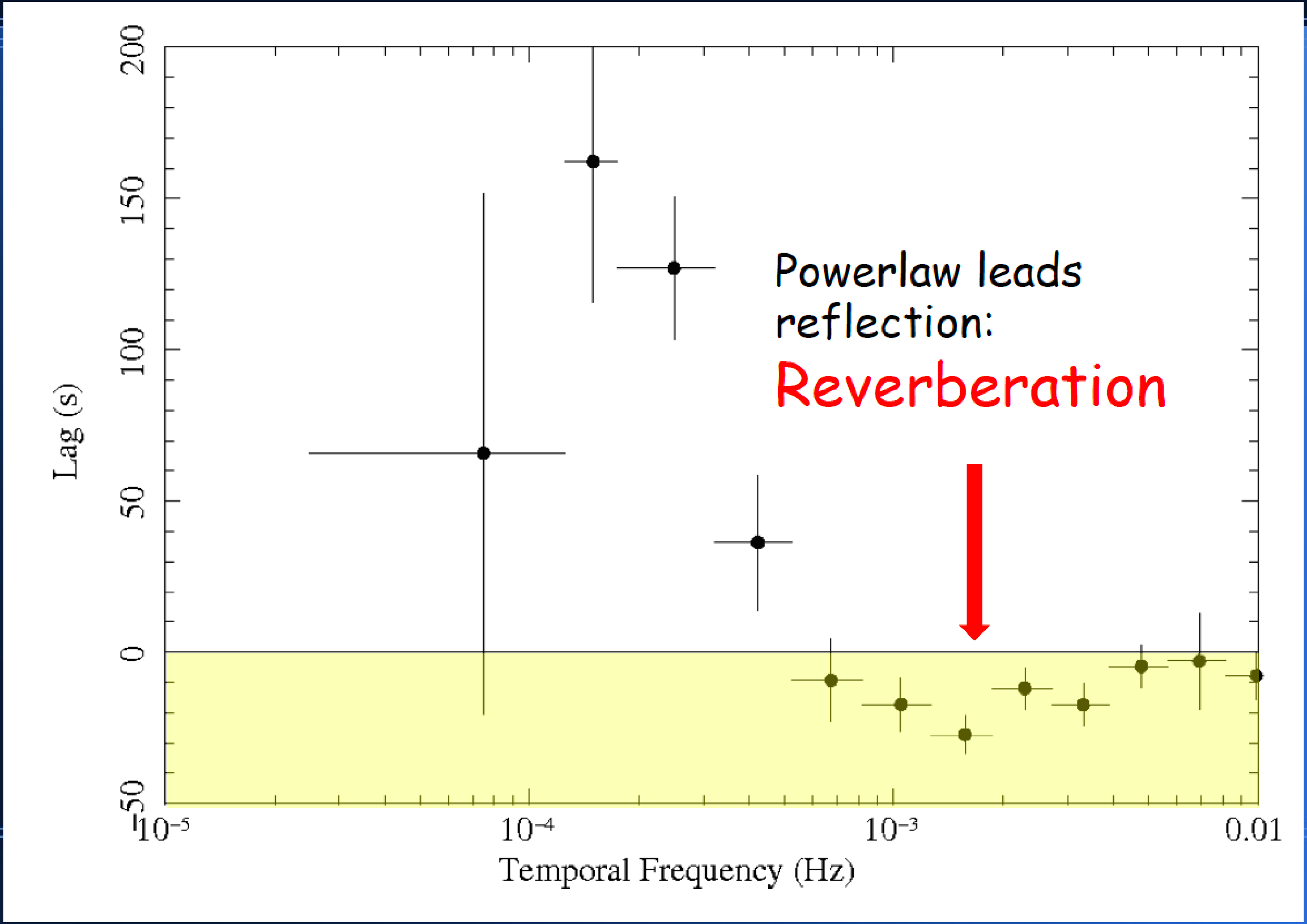
"Broad line emission from iron K- and L-shell transitions in the active galaxy 1H0707-495"

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

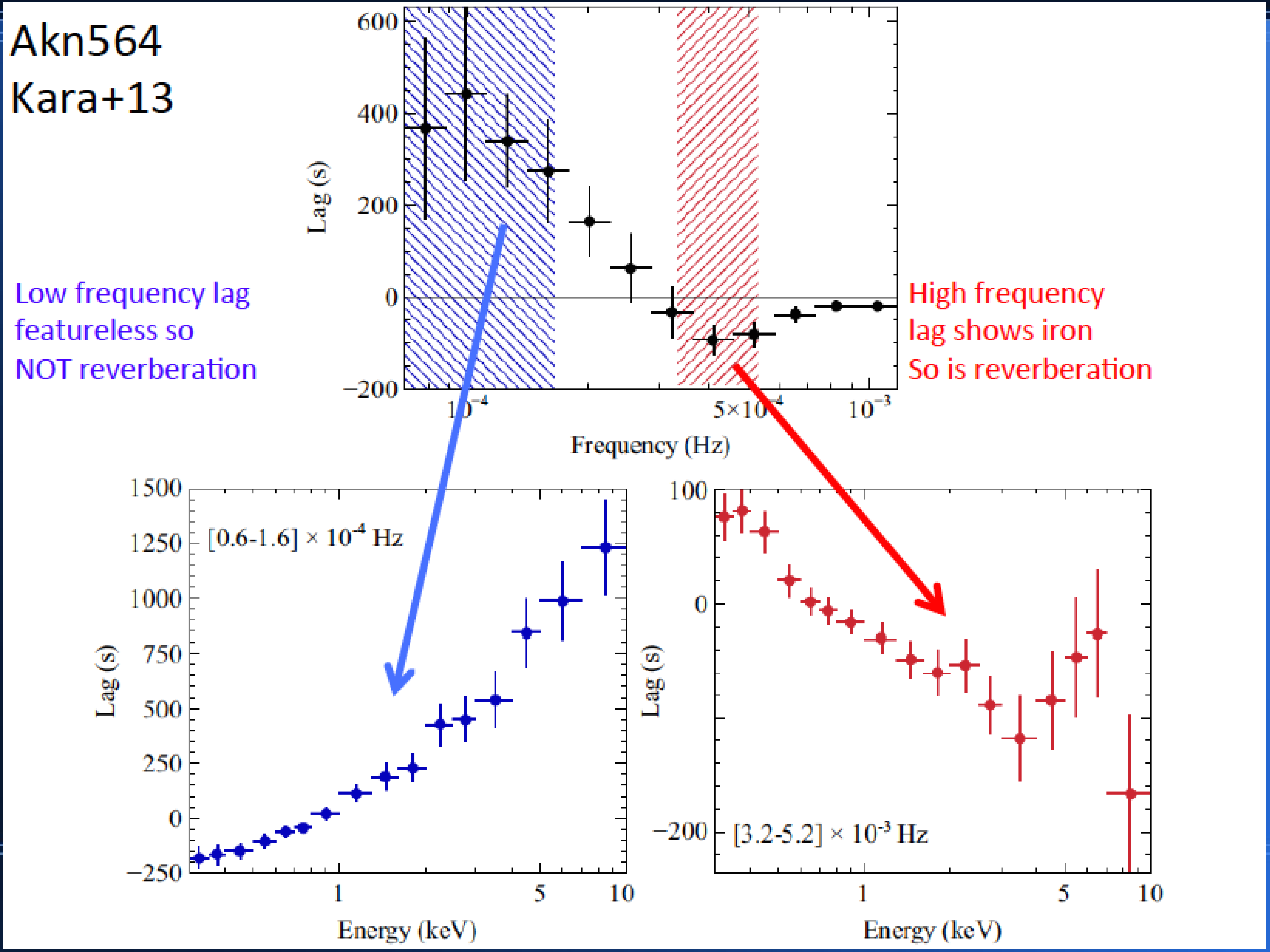
(2009, Nature, 459, 540)

(240 citations so far)

X-ray Soft/negative=reverberation lags



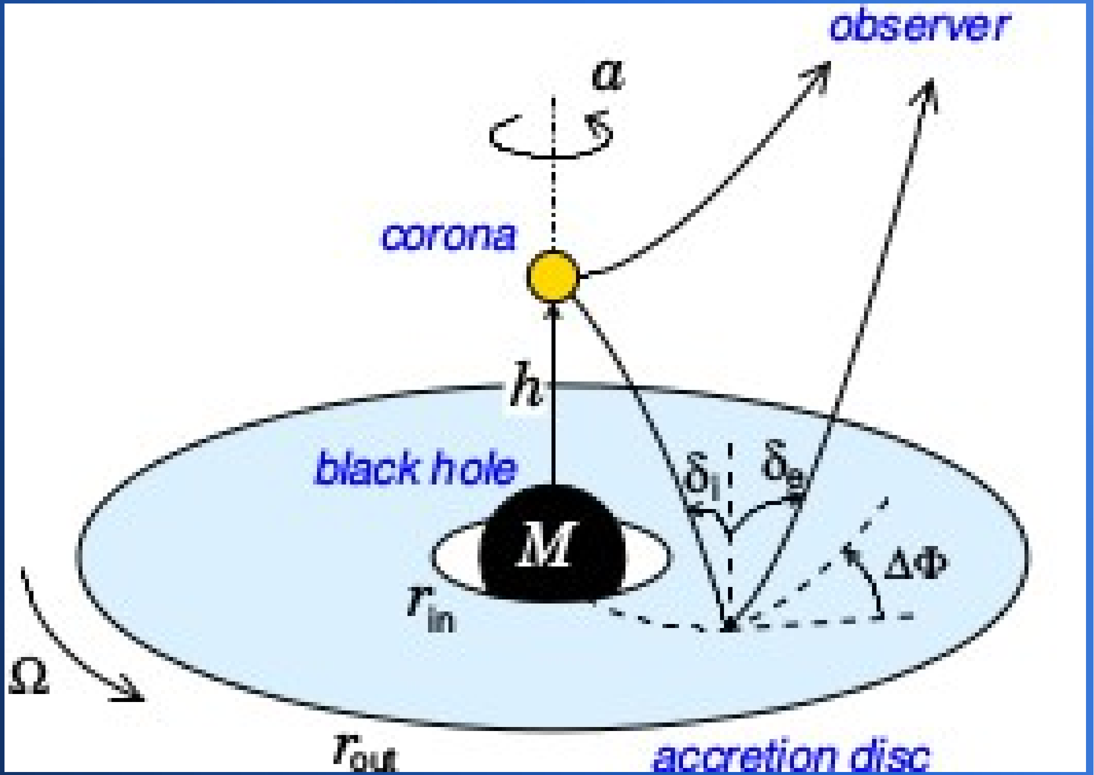
X-ray Soft/negative=reverberation lags



Reverberation in X-rays

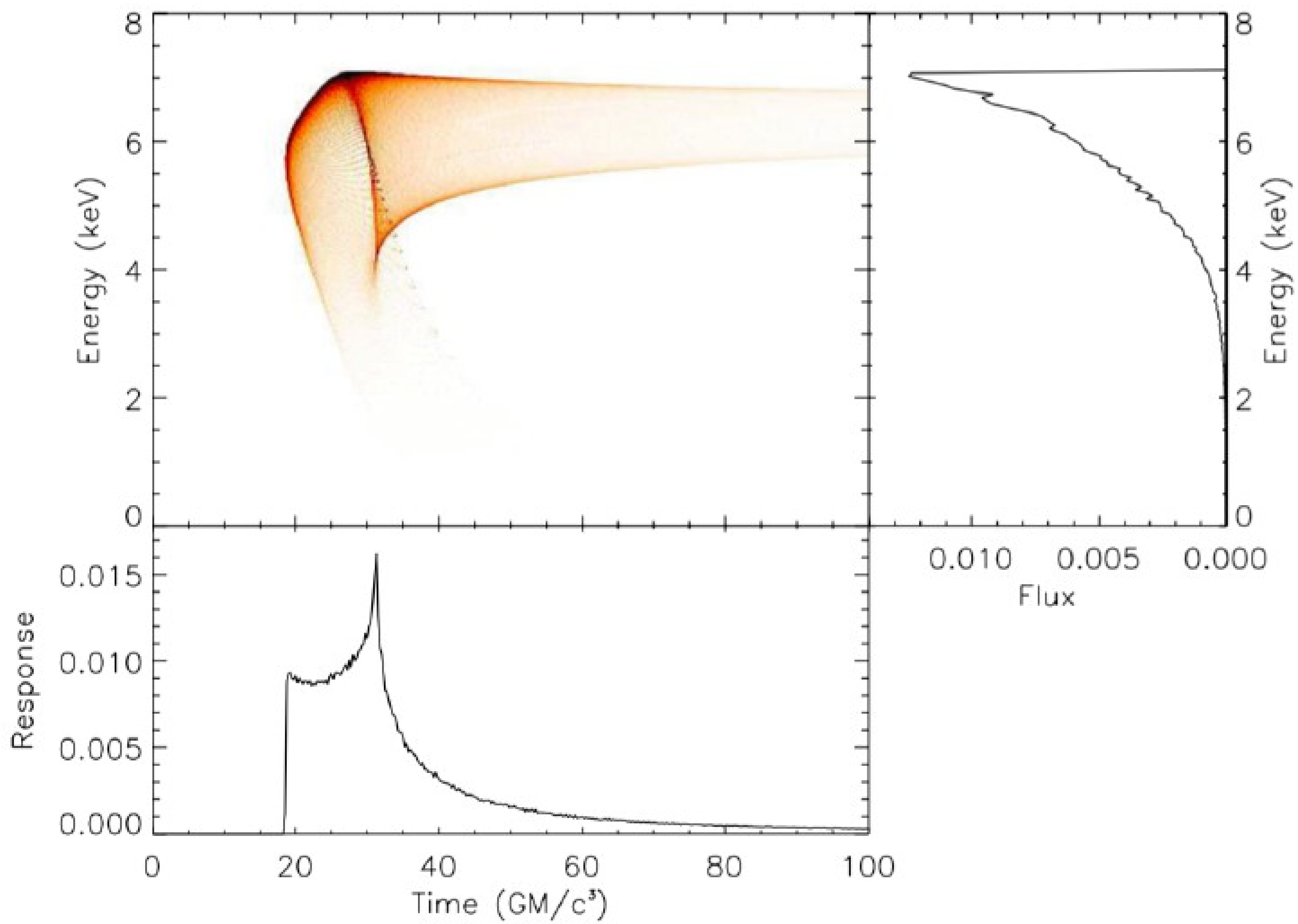
Overview

- 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



Cackett+14 after Campana+Stella95, Reynolds+99

Reverberation in X-rays

In our work we refer as "transfer function" the *relative response* of the disc to the illumination:

$$\phi_\Gamma(E,t) = \frac{\mathrm{F}_\Gamma}{\mathrm{F}_\mathrm{p}}$$

where $\mathrm{F}_\mathrm{T}(E,t)$ is the time dependent observed reflected flux from the disc as a response to a flare[2] that would be observed as $\mathrm{F}_\mathrm{p}\delta(t)$.

The Fourier transform of the transfer function is calculated as:

$$\hat{\phi}_\Gamma(E,f) = \mathrm{A}_\Gamma(E,f)\mathrm{e}^{i\phi_\Gamma(E,f)}$$

with amplitude $\mathrm{A}_\Gamma(E,f)$ and phase $\phi_\Gamma(E,f)$ (which is sometimes referred to as transfer function in other works).

Reverberation in X-rays

One can calculate the lag of the signal, computed from the total phase at energy bin E with respect to the total phase at some reference energy bin:

$$\tau(E, f) = \frac{\Delta\phi_{\rm tot}(E, f)}{2\pi f}$$

To determine the response function of the disc, we assume that the primary X-ray source isotropically emits a flare of duration equal to 1 t_g. Upon being illuminated, each area element of the disc "responds" to this flare by isotropically and instantaneously emitting a "reflection spectrum" in its rest-frame. We assume

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

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, $F_p \sim E^{-\Gamma} e^{-E/Ec}$, 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.

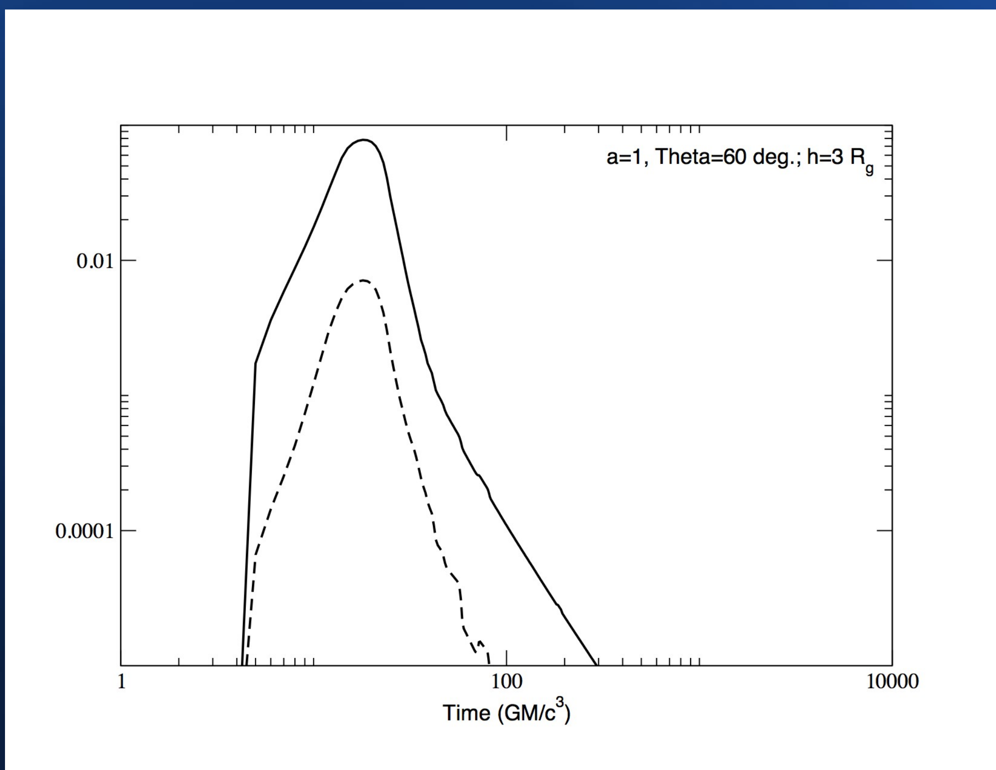
The model: *“The relativistic reflection model in the lamp-post geometry”*

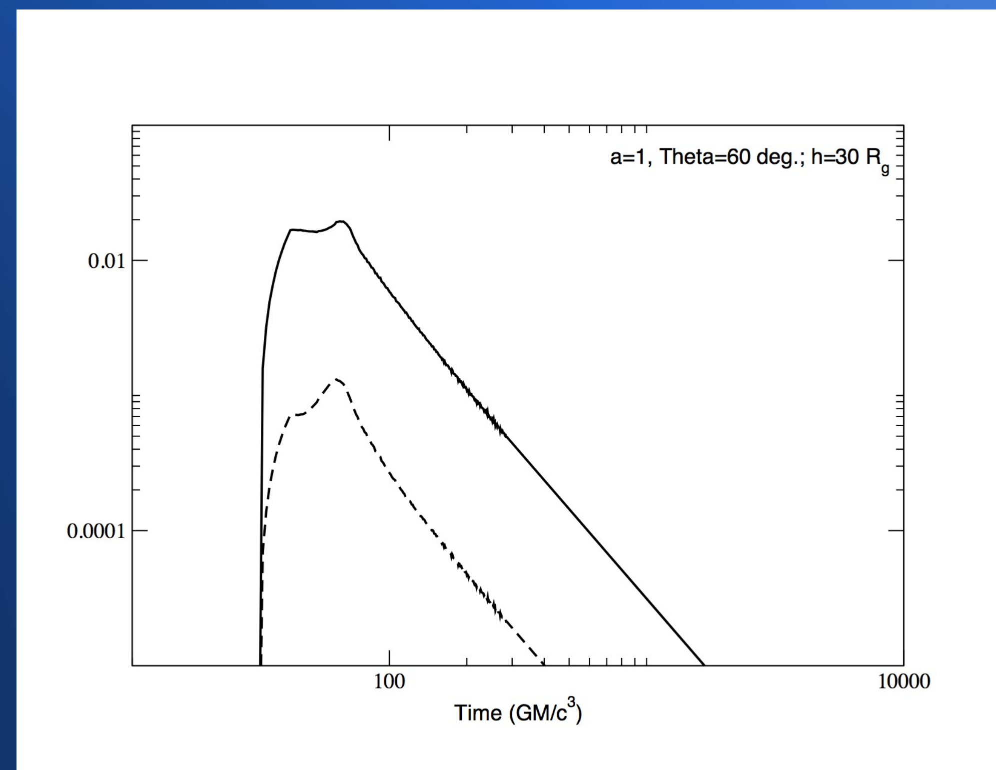
Approximations

- 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

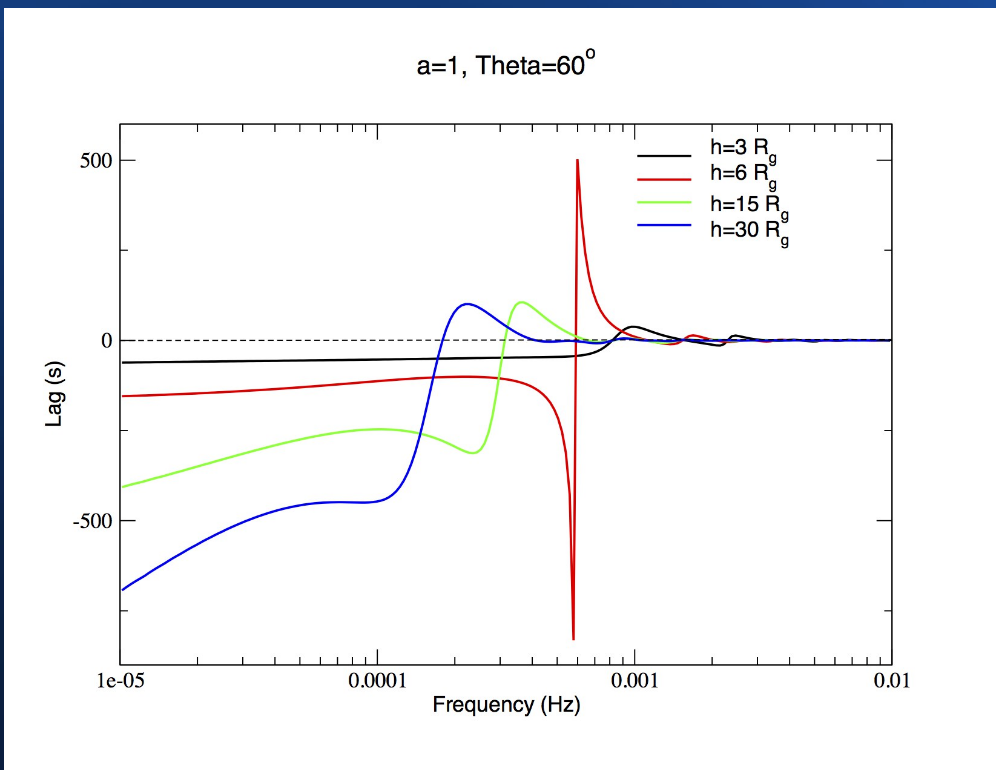


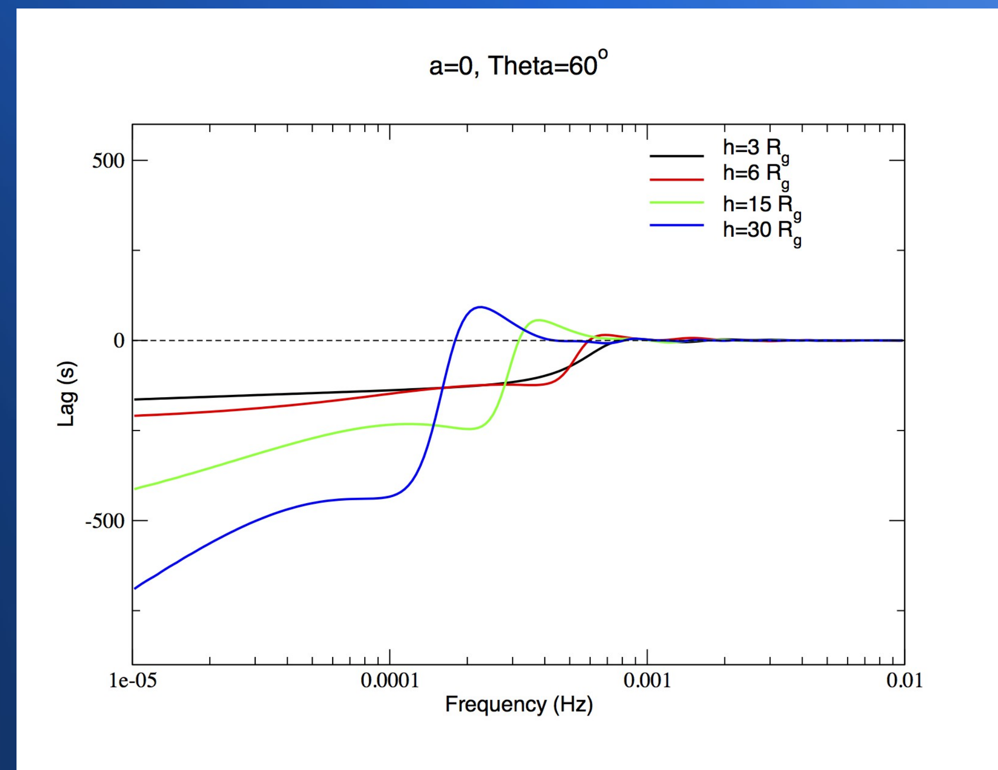


Soft (0.3-0.8 keV versus 1-3 keV) light curves.

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).

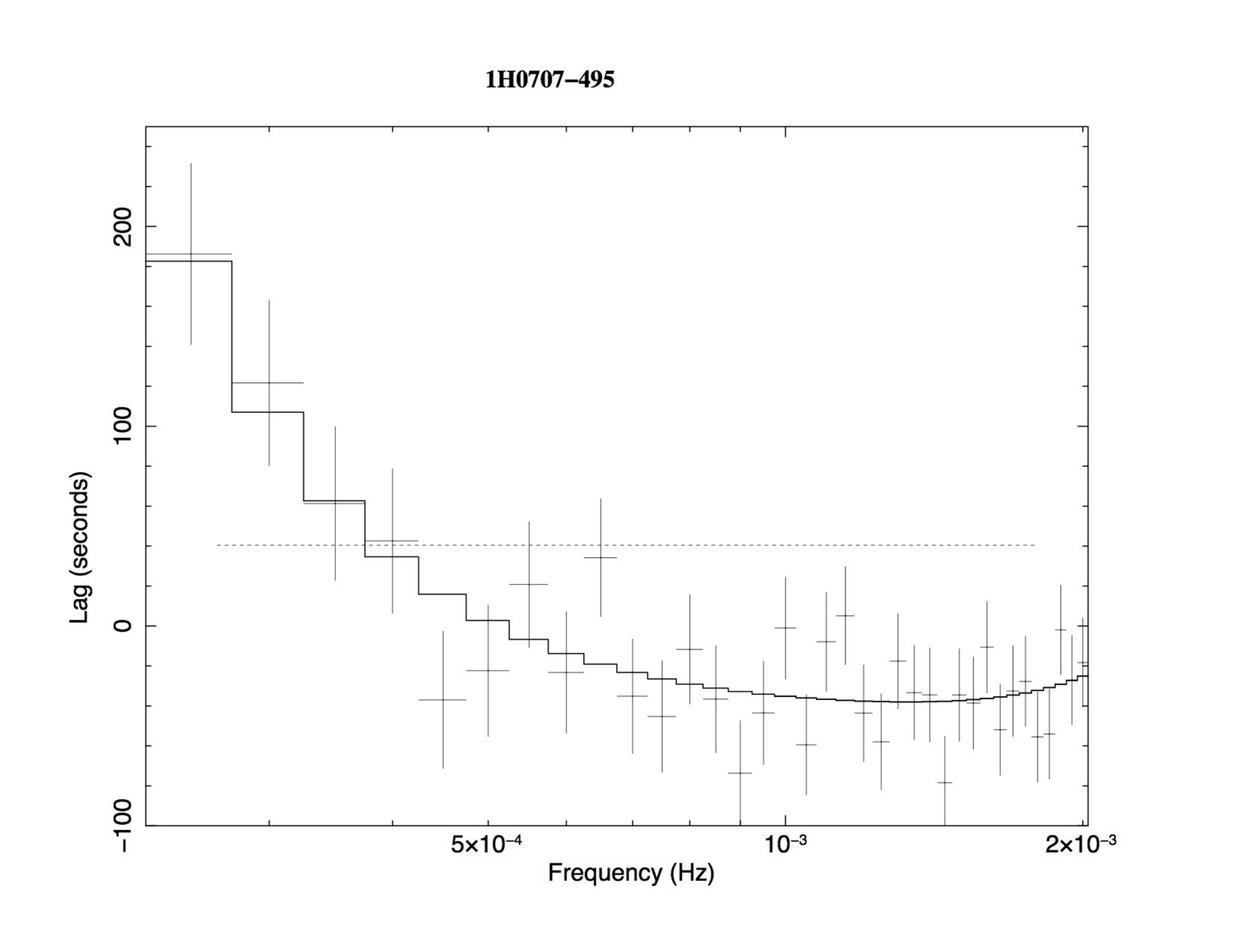
The model: *“The relativistic reflection model in the lamp-post geometry”*

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 in XSPEC (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

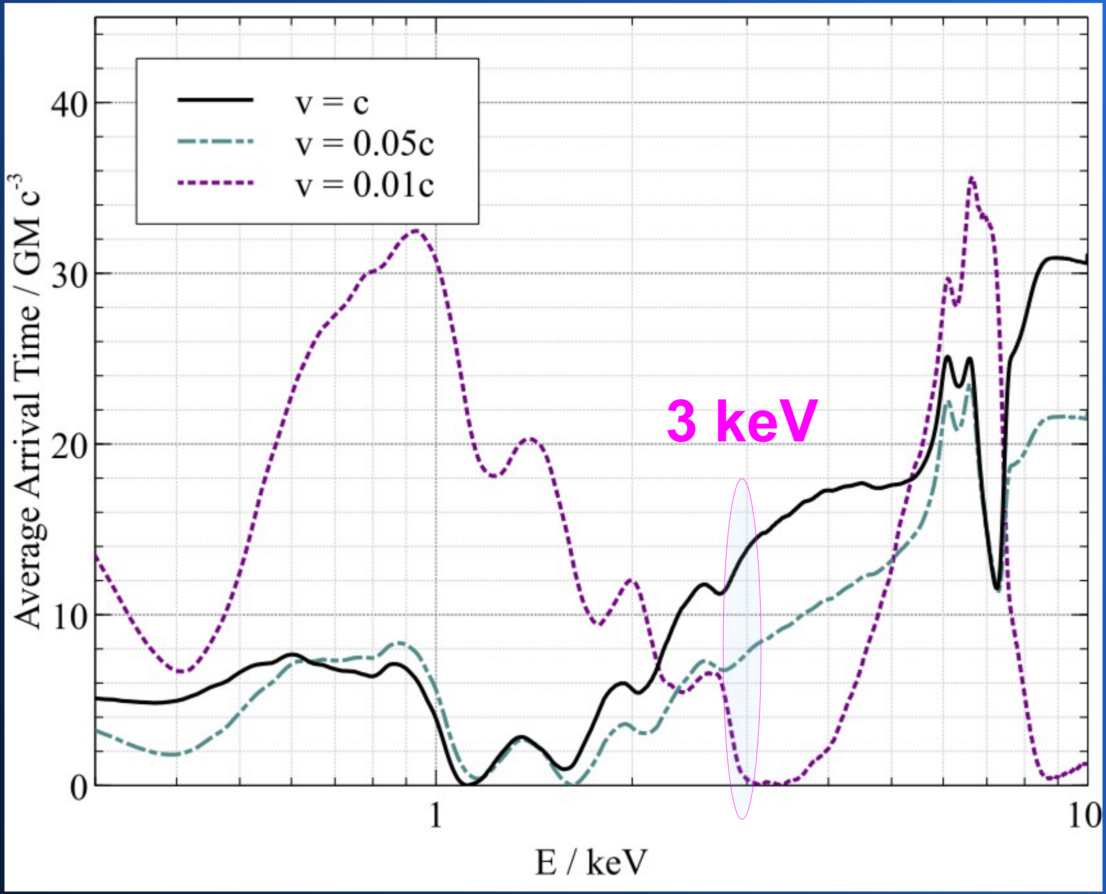
```
XSPEC12>erro 1. 1

     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.*

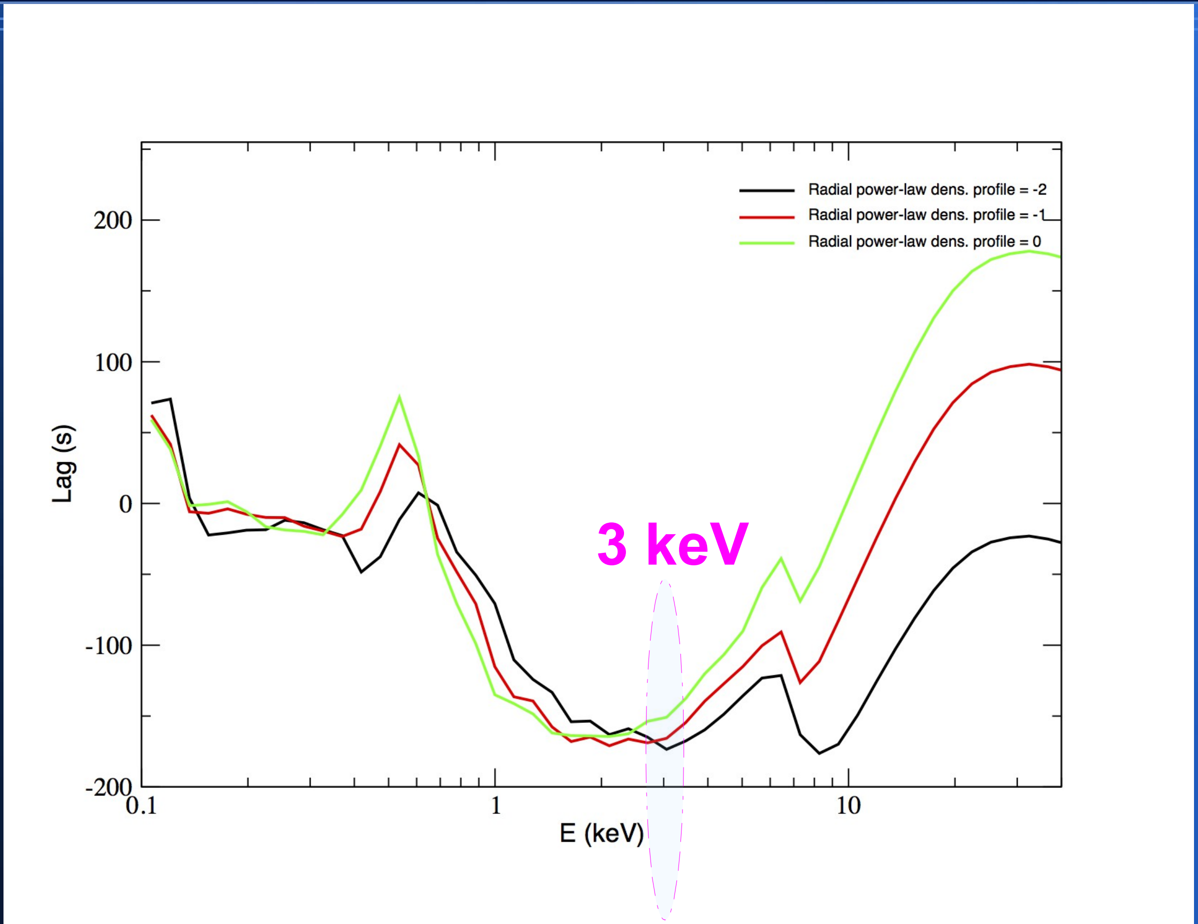
On the need of an extended corona (?!)

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 **vertically extended** coronae* still.
- Nevertheless, more work is needed in the future in order to address *possible **(other) extended coronae geometries*** (taking into account all the possible physical effects we observe from the data).
- To address this goal, collaborative efforts (like FP7-Strong Gravity project) are absolutely mandatory.

Acknowledgements

Financial support provided by the European "Seventh Frame-work Programme (FP7/2007-2013) under grant agreement # 312789".

Period of the project's realization 1.1.2013 – 31.12.2017

STRONGGRAVITY

EU FP7-SPACE research project 312789

2013 - 2017