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

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

Forthcoming publications

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

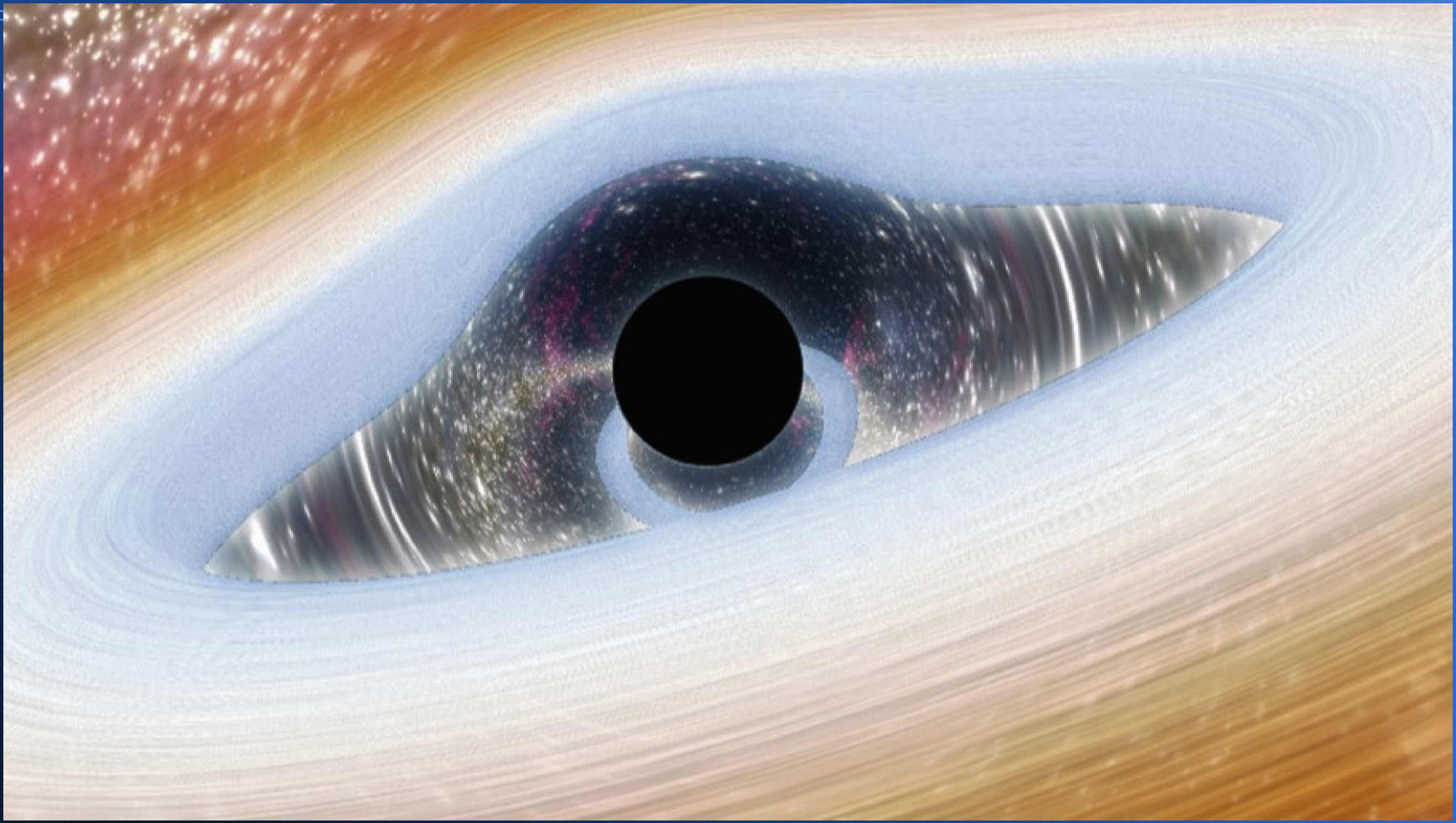
*(<u>to be submitted in ApJS</u>) → **On the model***

*2) **M. D. Caballero-Garcia**, A. Epitropakis, M. Dovčiak, I. E. Papadakis, G. Miniutti, et al.*

*(<u>to be submitted in MNRAS</u>) → **On the data (using the model)***

Contents

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



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

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

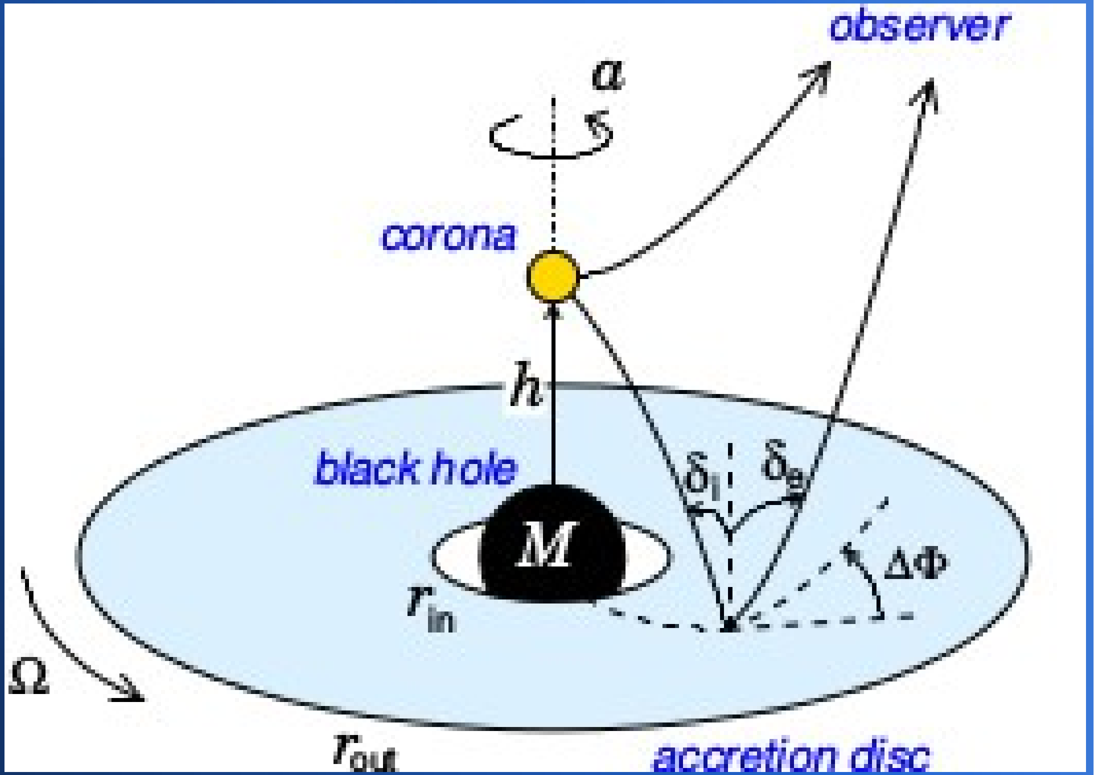
History

- 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, Epitropakis, Papadakis, Miniutti, +, in prep.) → KYNREFREV
- *Analysis of X-ray reverberation data (i.e. X-ray time lags) in a sample of Seyfert galaxies using this model using XSPEC* (Caballero-Garcia, Epitropakis, Dovčiak, Papadakis, Miniutti, +, in prep.)

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

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*.
- The theoretical lag versus frequency and 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)

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”*

Parameters

- There are *36 variable parameters*. Most of them are fixed to their recommended values.
- The most important ones (*some of them* to be modified by the user) are:

Physical

- a/M – BH angular momentum ($-1 \leq a/M \leq 1$)
- Θ_0 – observer inclination (degrees)
- M/M_8 – BH mass ($10^8\ M_{\odot}$)
- h – height on the axis of the primary source (GM/c^2)
- t_f – duration of the flare (GM/c^3) → 10 → NO LONGER USED

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

Resolution

- Define the resolution of the code & related with the speed of the code.
- The most important ones (*some of them* to be modified by the user) are:
  - ΔT – length of the time bin (GM/c^3) → 1
  - ntbin – number of time bins (defines where the linear extrapolation starts) → NO LONGER USED
  - n_{rad} – number of grid points in radius → 500 (*)
  - n_{phi} – number of grid points in azimut → 180 (*)
  - nt – number of time subbins per one time bin (critical in the speed of the code & fixed to 1) → NO LONGER USED
  - nthreads – how many threads should be used for computations (fixed to 4 BUT CAN BE ANY NUMBER). CODE IS PARALLELIZED.

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

Output (OUTSIDE XSPEC – *for developers only*)

- The length of the response function to the flash (box-shaped) and/or of the primary flux component.
- The time-integrated spectrum of the reflection (i.e. response) component and/or the primary flux component.
- The real and imaginary part, the amplitude and the phase of the FFT of the response funcion and delays at each energy range and time bin.
- Nomenclature of the files:

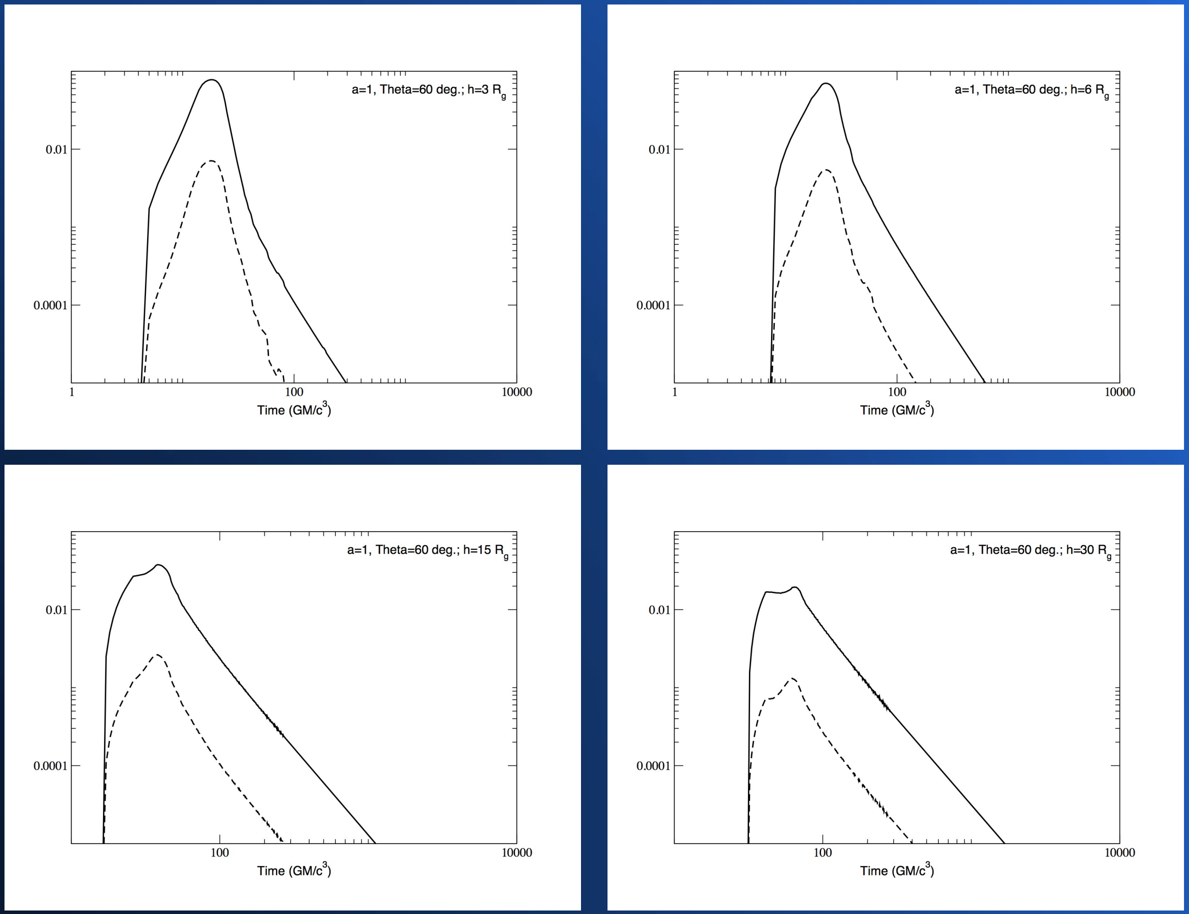
kyreflionx_AAA_BB_CCCC_DDD.txt

kyreflionx_AAA_BB_CCCC_DDD....dat

where AAA, BB, CCCC and DDD are *100x the horizon value (100 for a=1 and 200 for a=0)*, the *inclination in degrees*, *10x the height and 10x the duration of the flare, respectively*.

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

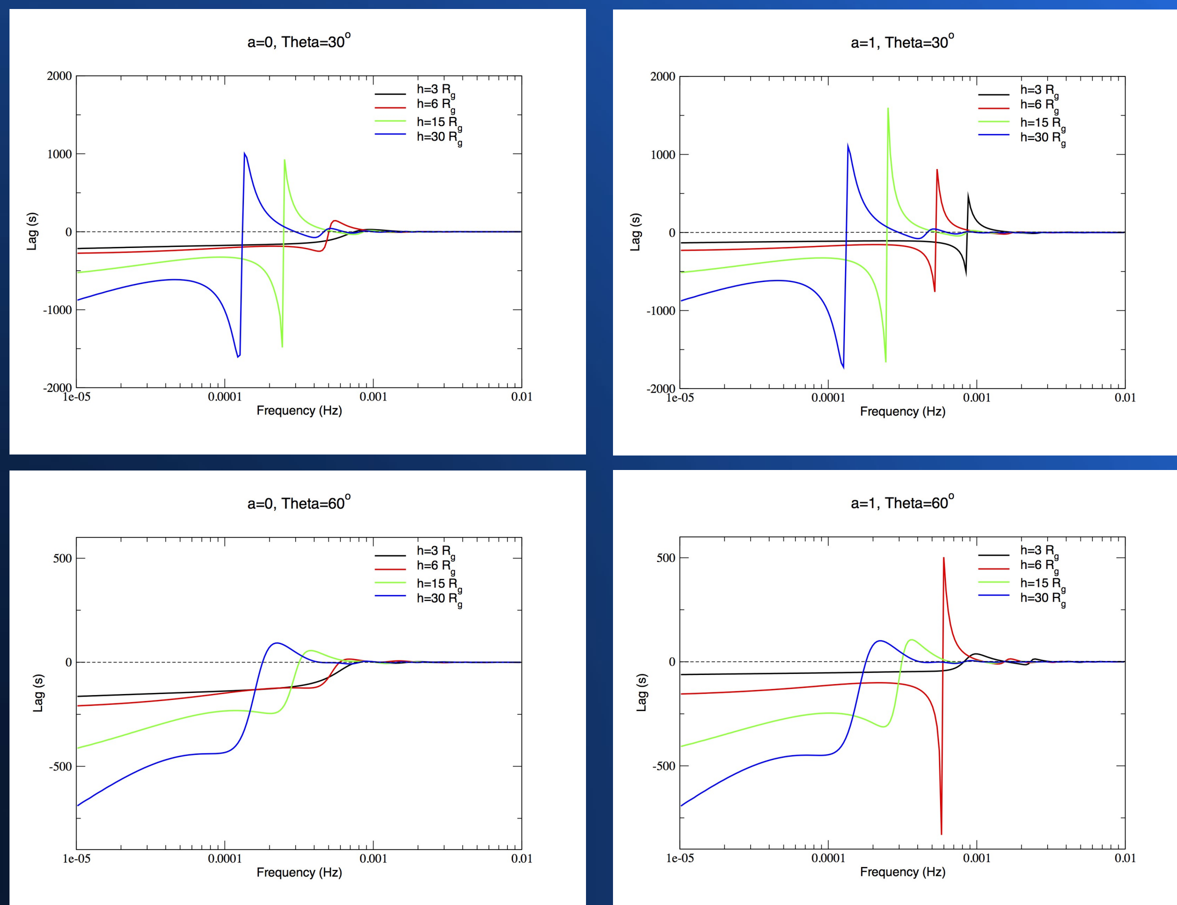
Output (<u>outside XSPEC</u>) → Light curves “observed” reflection



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

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

The model (<u>outside XSPEC</u>) → Soft lags vs. energy/frequency



Left: *Soft (0.3-0.8 keV versus 1-3 keV) lag spectrum.*

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

How to get these results (*for developers only*)

- *Time lags* can be easily calculated from the output XSPEC files (*bands*phase*tot*.dat).
- The oscillations of the lag-frequency dependence are due to *wrapping* of the Fourier phase of the disc response.
- No need for the user to worry about details of the *transfer function* (defined inside the code).

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

Recent developments

- We speeded up the code by pondering resolution parameters (**every run now takes a few seconds only**).✓
- We fine-tuned the *parameters* ↔ *code* to better account for strong relativistic effects at the innermost regions → no intervention/knowledge by the user.✓
- Extrapolation of the tail or break due to outer radius. ✓
- The user can set up the **frequency and the energy range** that corresponds to **observations**.✓

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 spectrum with the KYNREFREV model.
- We obtain a very good fit ($\chi^2_{\nu} \sim 1$) 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 parameter ***h*** **–** we will explore it further).

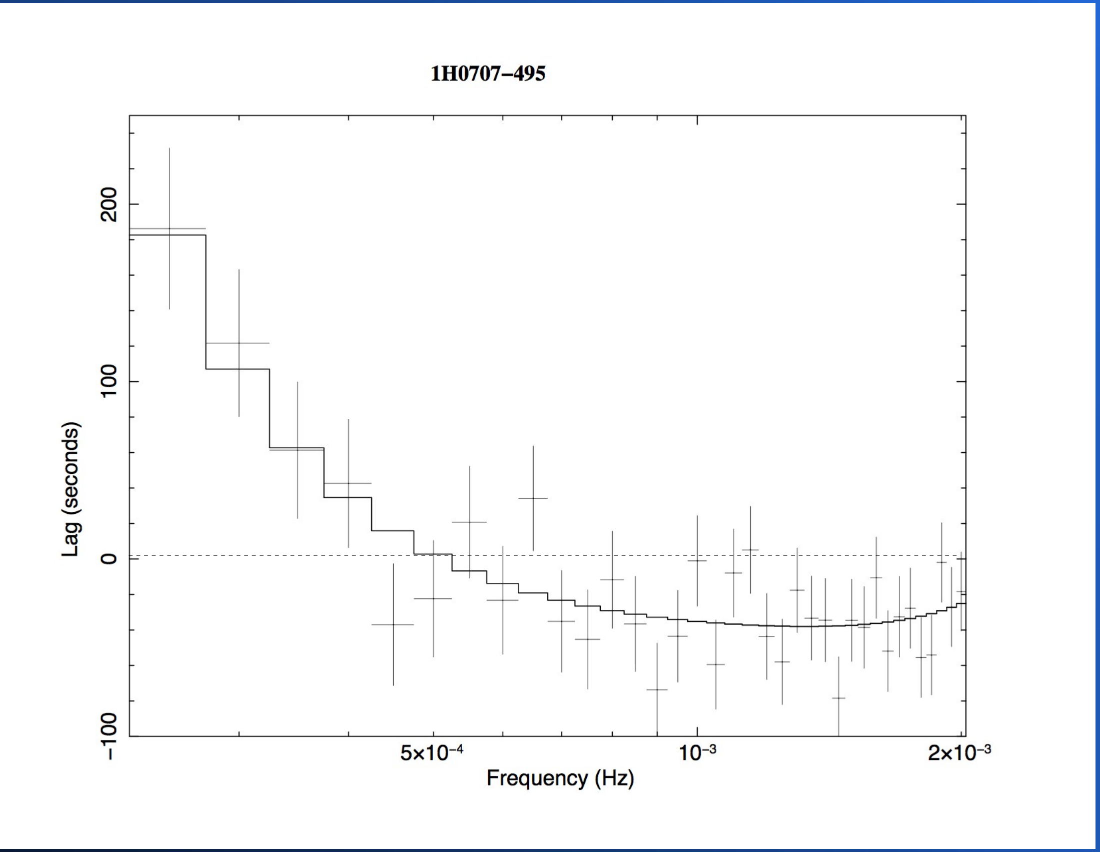
```
========================================================================
Model kynrefrev<1> Source No.: 1   Active/On
Model Model Component  Parameter  Unit     Value
 par  comp
   1    1   kynrefrev  a/M        GM/c     0.819245     +/-  763.288
   2    1   kynrefrev  theta_o    deg      1.59747E-04  +/-  2.96530E+06
   3    1   kynrefrev  rin        GM/c^2   1.00000      frozen
   4    1   kynrefrev  ms                  1            frozen
   5    1   kynrefrev  rout       GM/c^2   1000.00      frozen
   6    1   kynrefrev  phi        deg      0.0          frozen
   7    1   kynrefrev  dphi       deg      360.000      frozen
   8    1   kynrefrev  M/M8                2.44593E-02  +/-  5.79559
   9    1   kynrefrev  height     GM/c^2   5.22045      +/-  1918.00
  10    1   kynrefrev  PhoIndex            2.00000      frozen
  11    1   kynrefrev  L/Ledd              -4.57698E-02 +/-  6.05774E+04
  12    1   kynrefrev  Np:Nr               1.00000      frozen
  13    1   kynrefrev  density             42.6074      +/-  5.66822E+07
  14    1   kynrefrev  den_prof            0.0          frozen
  15    1   kynrefrev  abun                1.00000      frozen
  16    1   kynrefrev  alpha      GM/c^2   -6.00000     frozen
  17    1   kynrefrev  beta       GM/c^2   0.0          frozen
  18    1   kynrefrev  rcloud     GM/c^2   0.0          frozen
  19    1   kynrefrev  zshift              0.0          frozen
  20    1   kynrefrev  limb                0.0          frozen
  21    1   kynrefrev  tab                 2            frozen
  22    1   kynrefrev  sw                  2            frozen
  23    1   kynrefrev  ntable              80.0000      frozen
  24    1   kynrefrev  nrad                -4488.00     frozen
  25    1   kynrefrev  division            -1.00000     frozen
  26    1   kynrefrev  nphi                180.000      frozen
  27    1   kynrefrev  deltaT     GM/c^3   1.00000      frozen
  28    1   kynrefrev  nt_ratio            1.00000      frozen
  29    1   kynrefrev  t1/f1/E1   s/Hz/keV 0.300000     frozen
  30    1   kynrefrev  t2/f2/E2   s/Hz/keV 0.800000     frozen
  31    1   kynrefrev  Eref1      keV      1.00000      frozen
  32    1   kynrefrev  Eref2      keV      3.00000      frozen
  33    1   kynrefrev  dt/Af      s/-      7.14241E-06  +/-  6.13740E-04
  34    1   kynrefrev  k/qf                2.08903      +/-  9.49142
  35    1   kynrefrev  xsw                 16           frozen
  36    1   kynrefrev  nthreads            4.00000      frozen
  37    1   kynrefrev  norm                1.00000      frozen
________________________________________________________________________


Fit statistic : Chi-Squared =          27.79 using 36 PHA bins.

Test statistic : Chi-Squared =          27.79 using 36 PHA bins.
 Reduced chi-squared =        0.9926 for     28 degrees of freedom
 Null hypothesis probability =   4.755007e-01
 Weighting method: standard
```

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

Fitting the data (using XSPEC)



The soft lag-frequency fitted 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"*

```
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.*

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

Installation instructions

- For the installation inside XSPEC:

  - Get the source files (**contact M. Dovciak**).

  - KY tables: *KBHlamp_qt.fits*, *KBHtables80.fits*

  - REFLION(x) tables: *reflion.mod*, *reflionx.mod*

- The code is compiled inside XSPEC, by doing:

  - *initpackage kynrefrev lmodel.dat /path_to_kynrefrev*

- For use inside XSPEC:

  - *lmod kynrefrev /path_to_kynrefrev*

  - *mo kynrefrev*

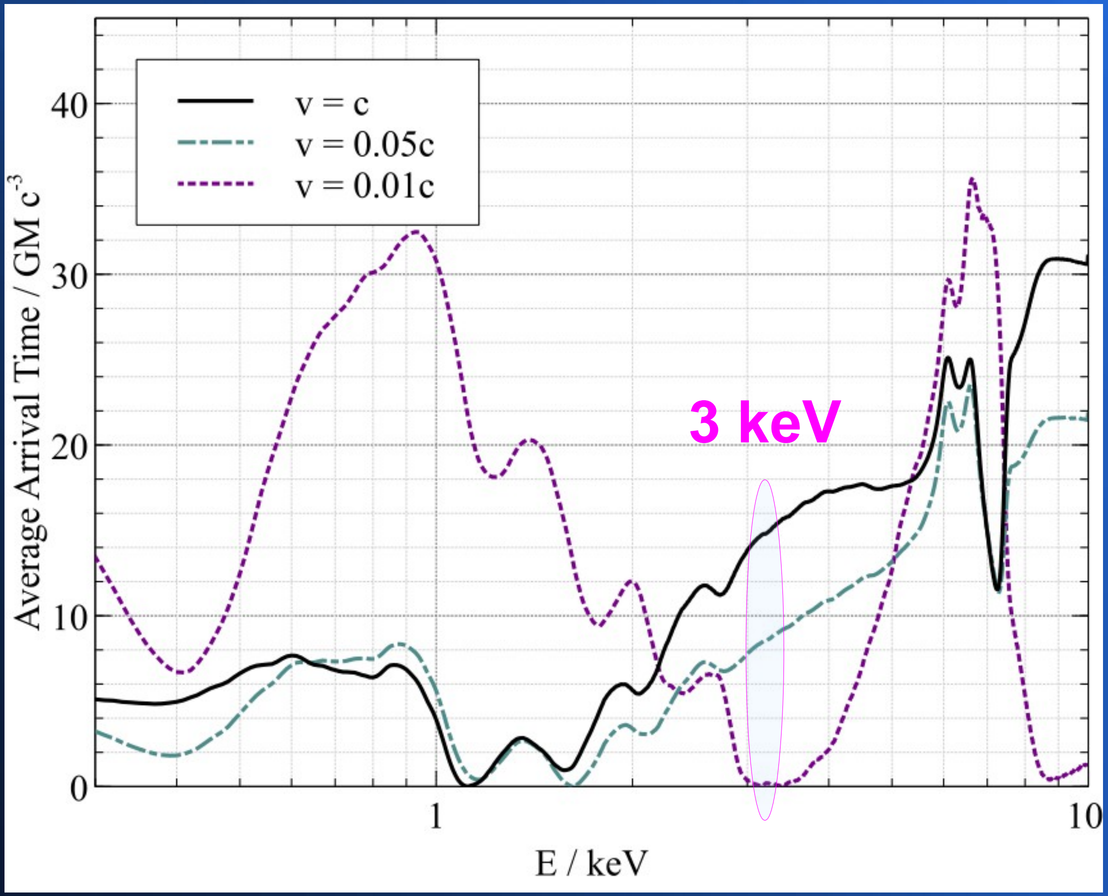
The model: *“The relativistic reflection model in the lamp-post geometry”*

Plans for the future

- More physical prescription of the *radial density of the disc* (Novikov-Thorne). [Now we are using a *phenomenological power-law*]
- Models for neutral disc by Rene Goosmann+NOAR, XILLVER and REFHIDEN.
- **More distant future**: off-axis flares and extended corona.

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

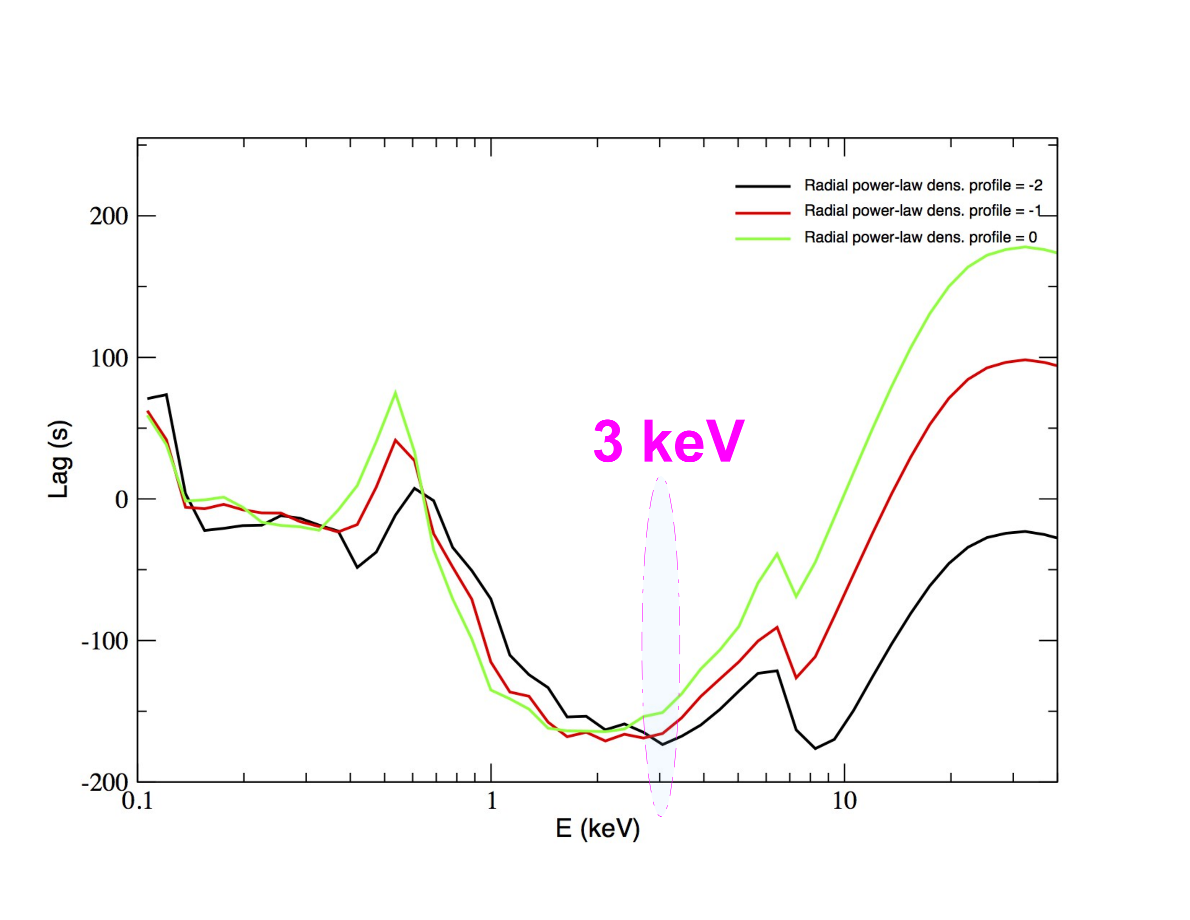
Discussion (*comparison with recent work*)



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)

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

Discussion



(Paper in prep. *) 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, θ = 30° 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

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