Implementing an X-ray reverberation model in XSPEC

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(to be submitted in ApJS)

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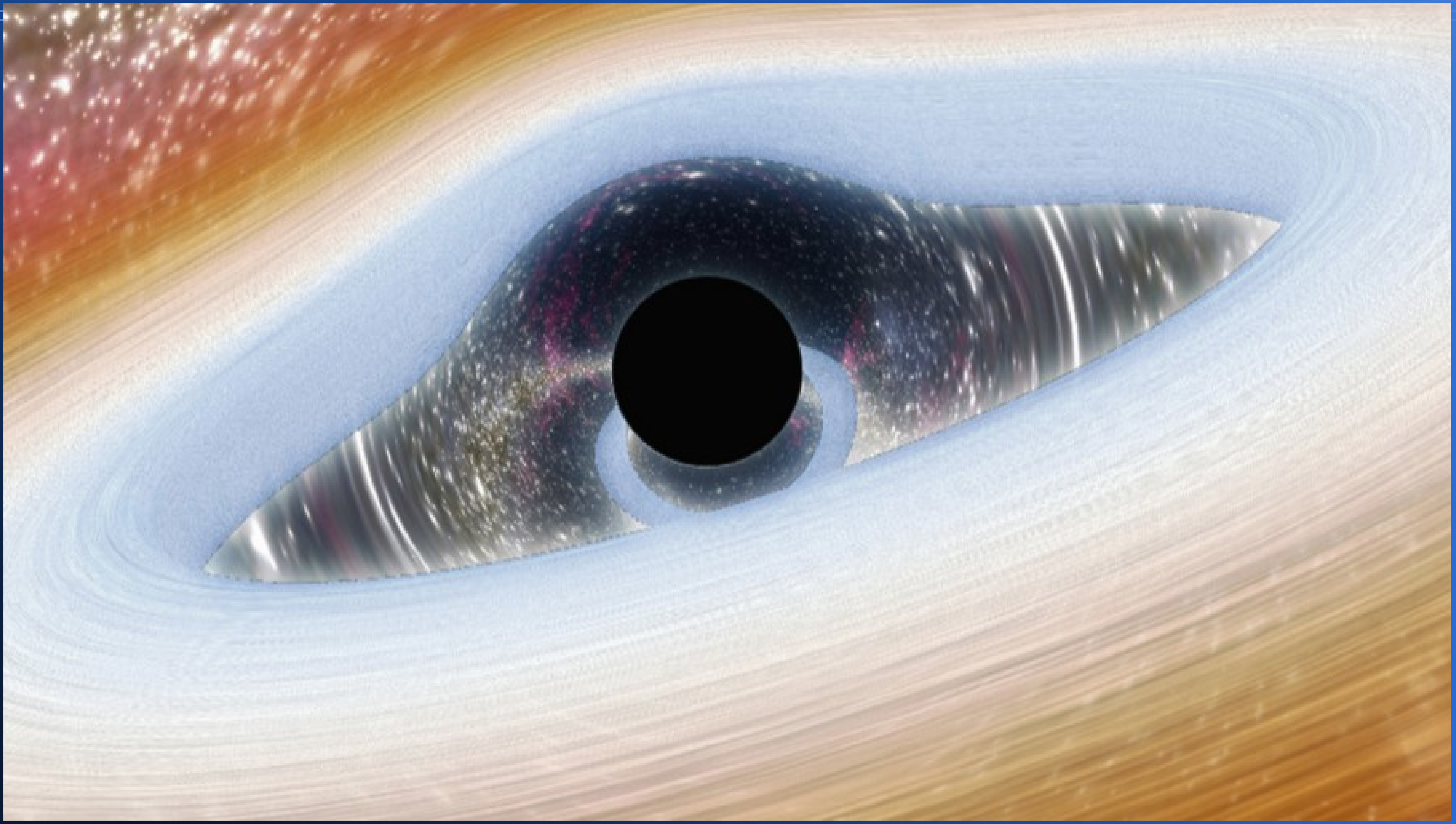

Artistic representation of the effects of Strong Gravity around an accreting black-hole

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

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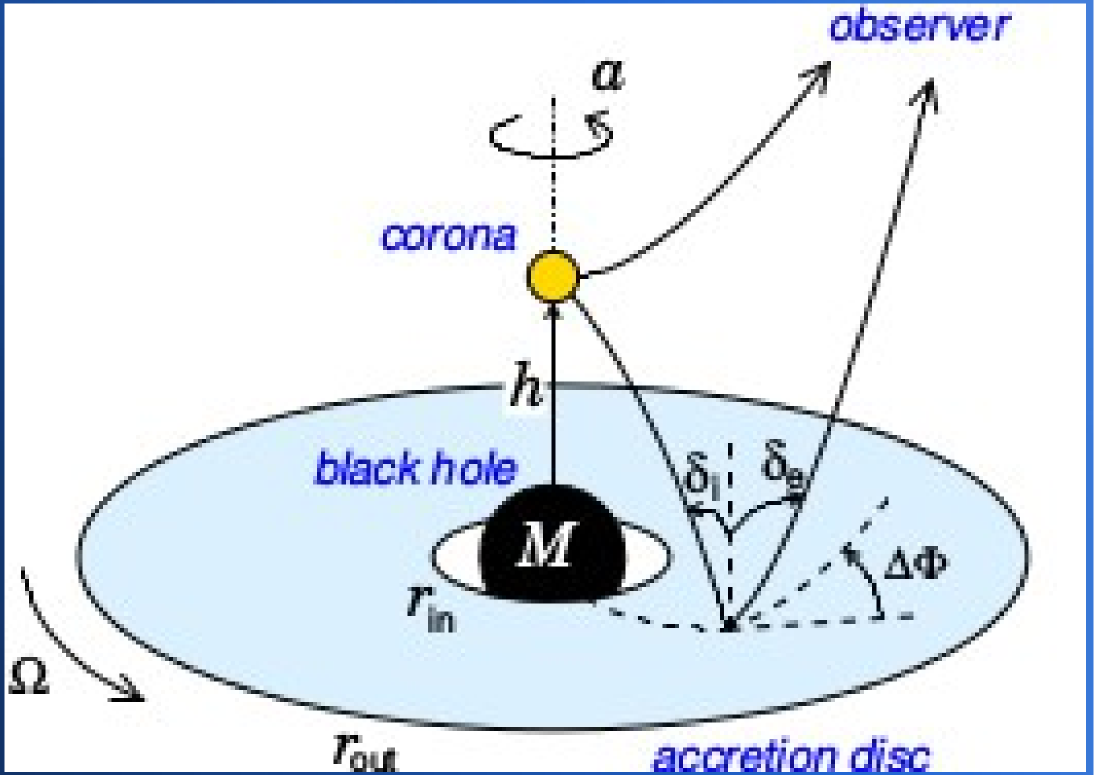
Overview

- 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.

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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.

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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 → <u>NO LONGER USED</u>

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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) → <u>NO LONGER USED</u>
  - 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) → <u>NO LONGER USED</u>
  - nthreads – how many threads should be used for computations (fixed to 4 BUT CAN BE ANY NUMBER). <u>CODE IS PARALLELIZED</u>.

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Output (OUTSIDE XSPEC)

- 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*.

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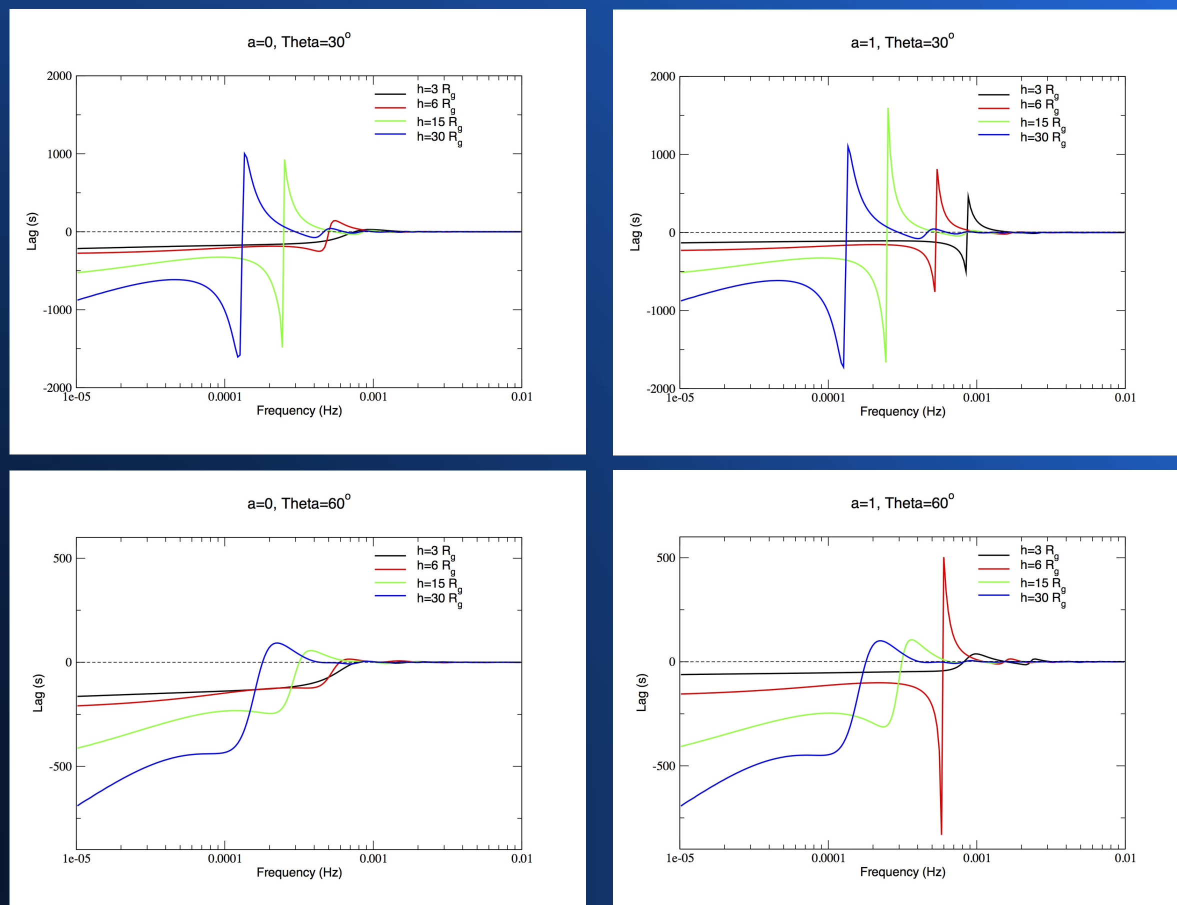
Output (<u>inside XSPEC</u>) → Soft lags vs. energy/frequency



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

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How to get these results

- *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).

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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*

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Recent developments

- We speeded up the code by pondering resolution parameters (**<u>every run now takes a few seconds only</u>**).✓
- 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 **<u>observations</u>**.✓

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Plans

- 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.

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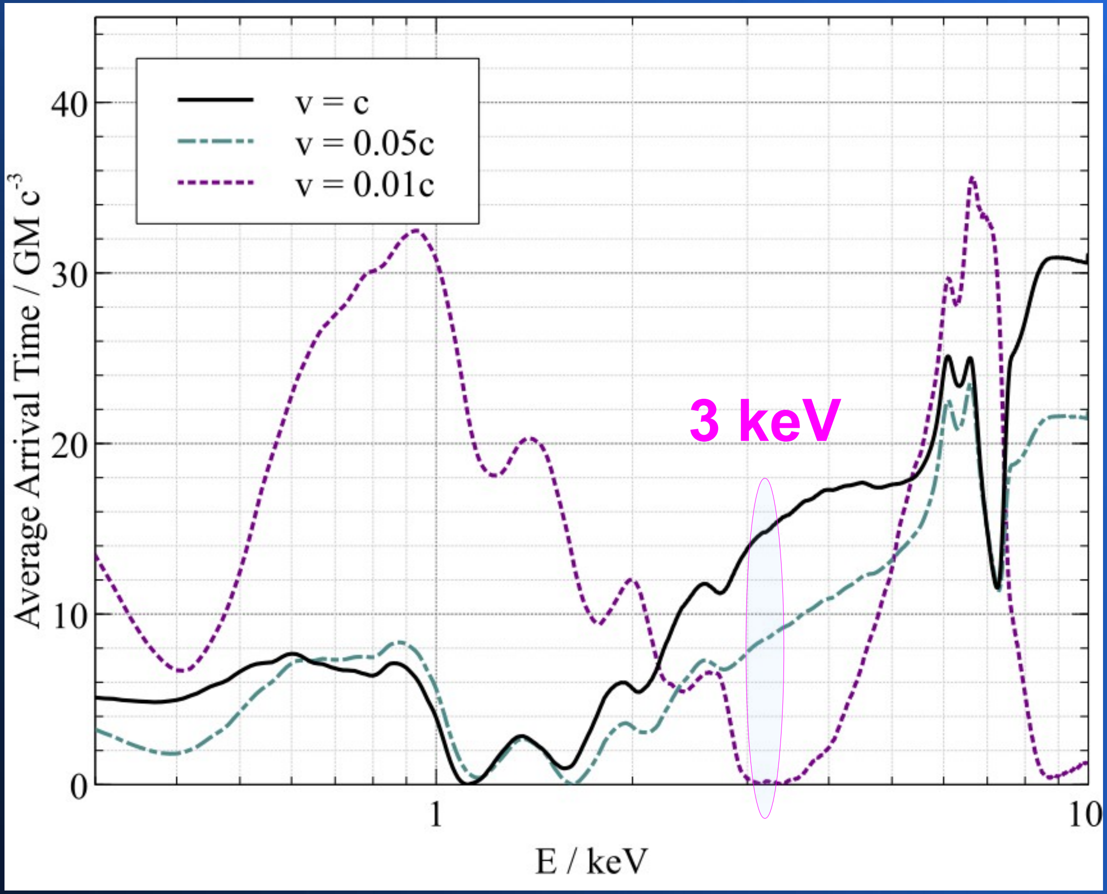
Discussion (*comparison with recent work*)



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)

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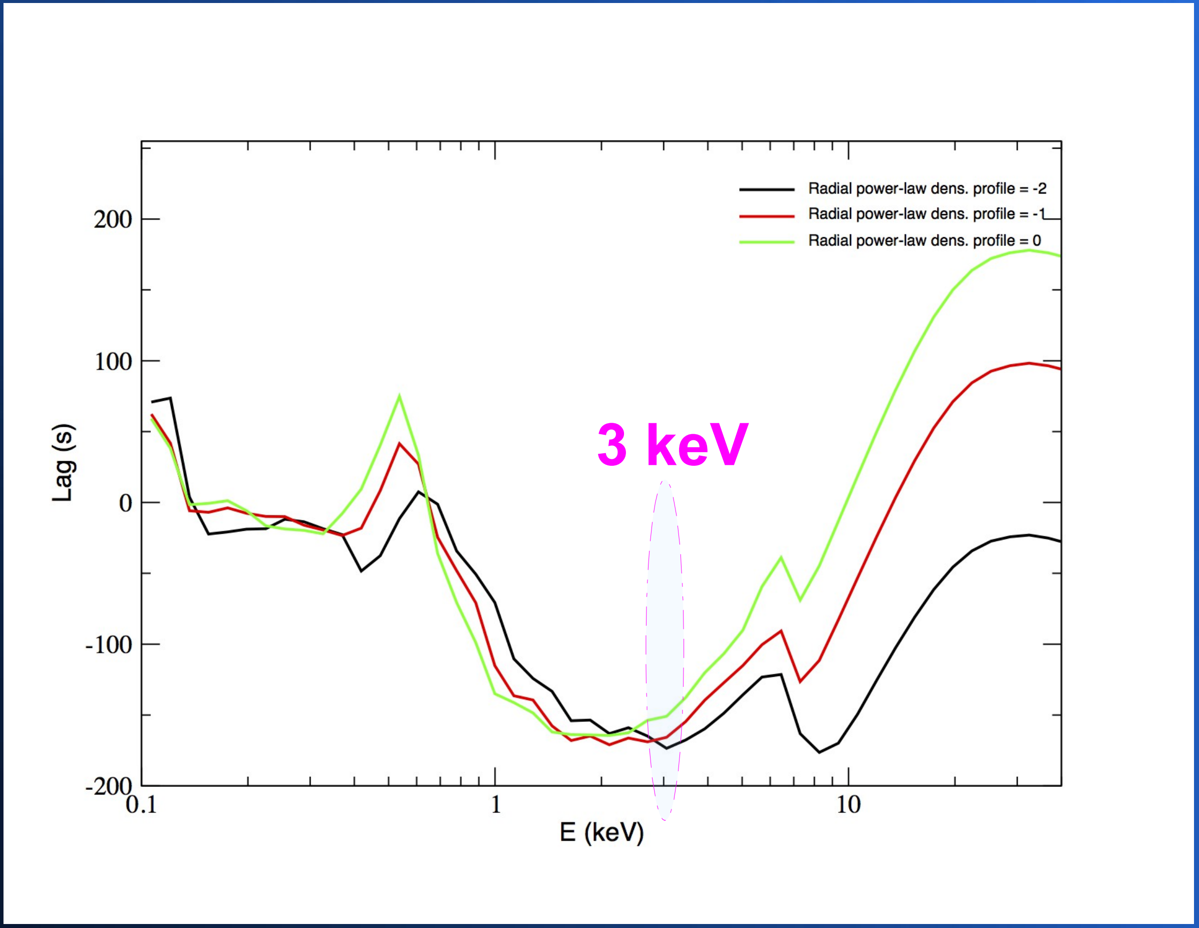
Discussion



(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.*

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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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