Implementing an X-ray reverberation model in XSPEC

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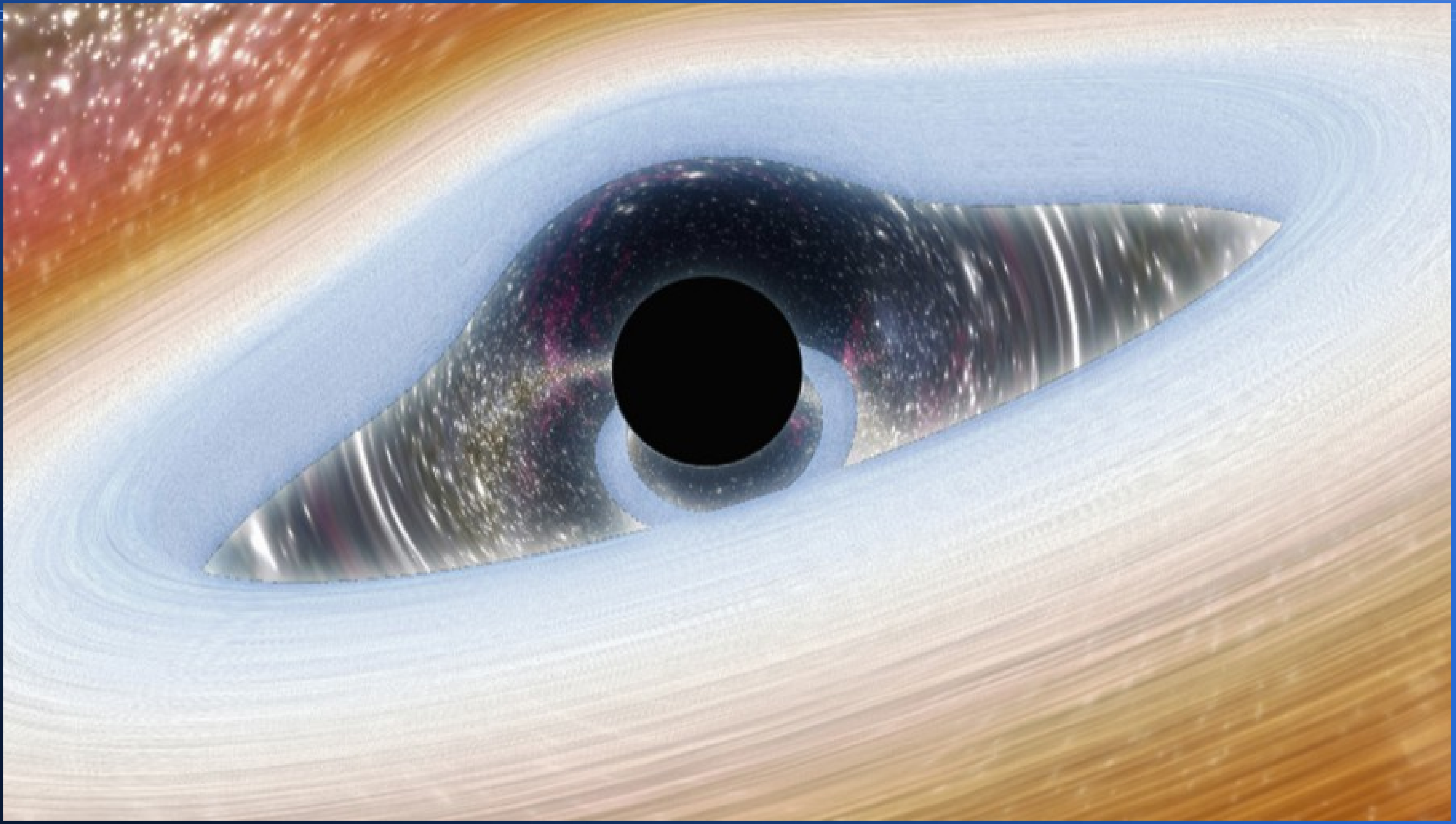


Artistic representation of the effects of Strong Gravity around an accreting black-hole

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

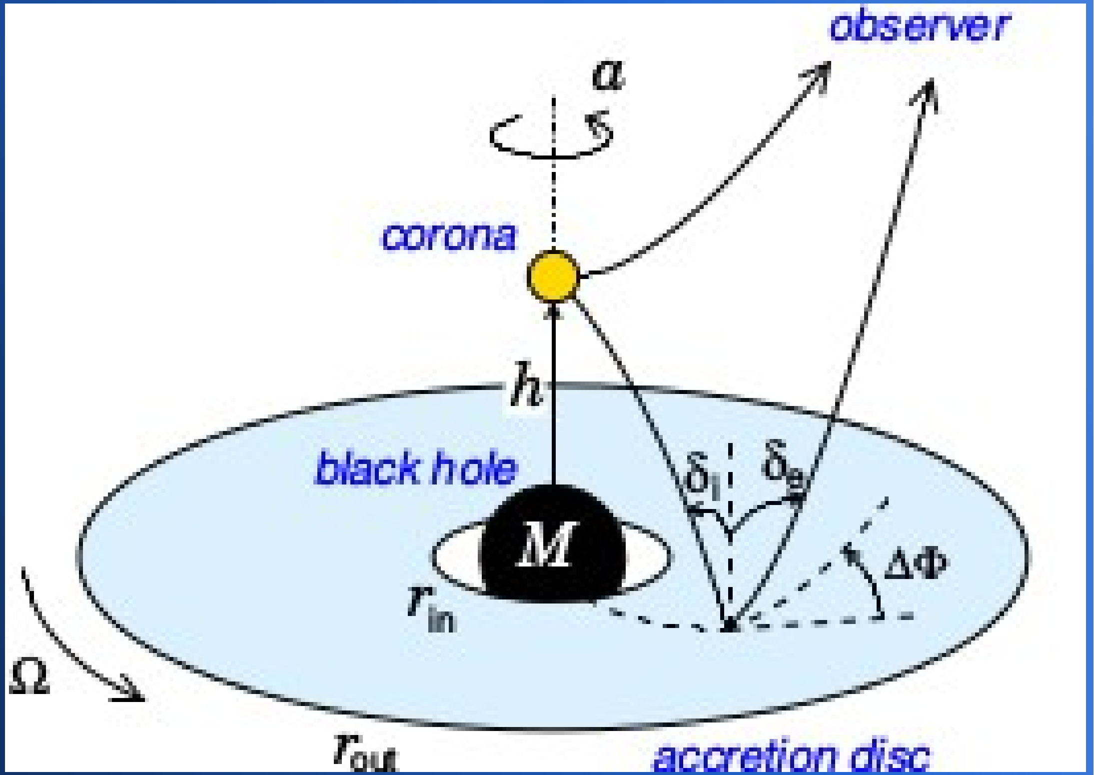
History

- Model based on the properties of the accretion disc in the *strong gravity regime* (Dovciak, Karas & Yaqoob, 2004) → KYRLINE, KYCONV
- Model adapted for use in XSPEC under the lamp-post geometry (Dovciak 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 (Dovciak 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* (Dovciak, Caballero-Garcia, Epitropakis, Papadakis, Kara, Miniutti +, in prep.) → KYNREFREV

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: Dovciak+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 *34 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) $\rightarrow$ 10

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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) → 728 (256? *)
  - 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).
  - nthreads – how many threads should be used for computations (fixed to 4).

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Output

- 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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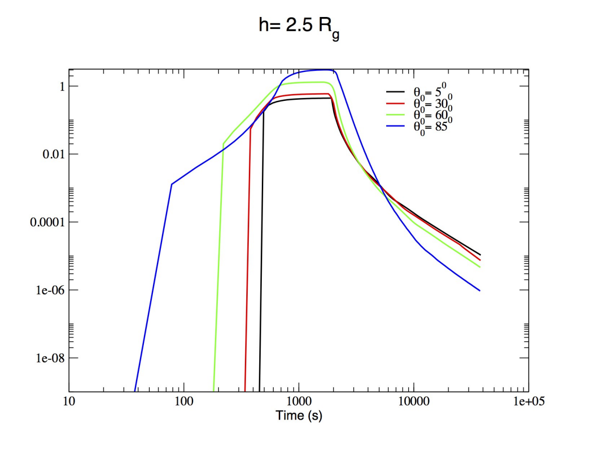
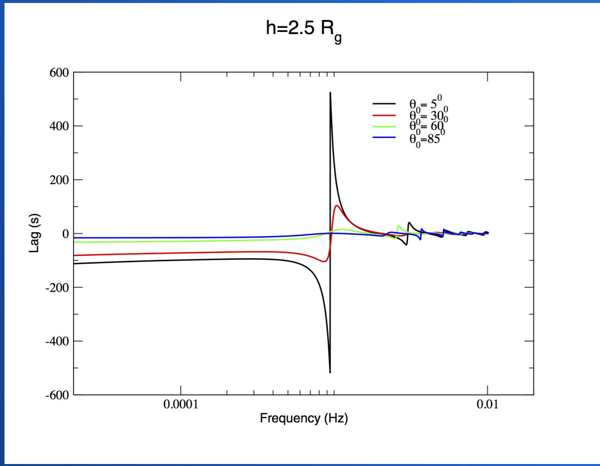
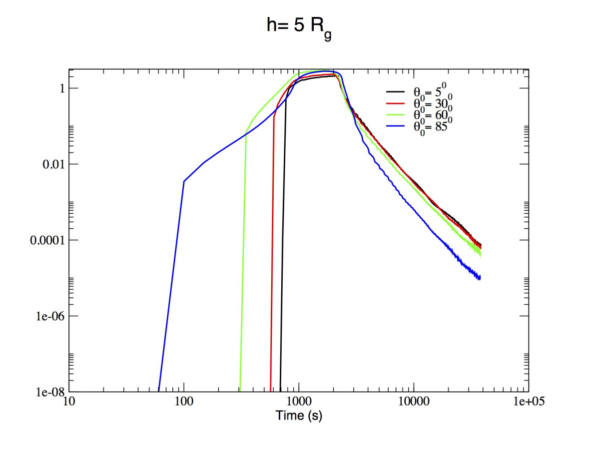
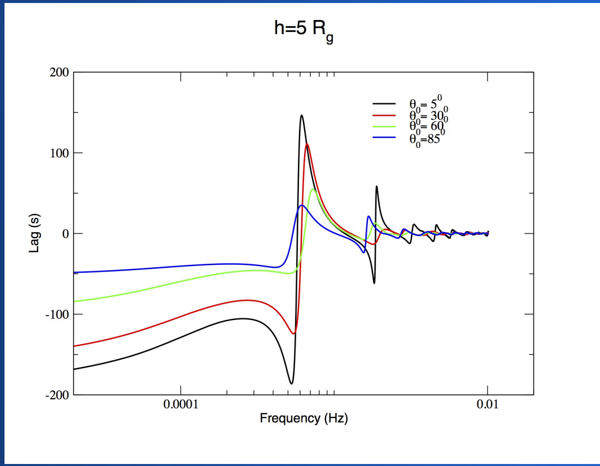
Transfer function & Soft lags









***Left**: Transfer function in the total (0.3-40 keV) energy band. **Right**: 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

- *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.
- We have corrected “a posteriori” for *time-lag flipping*.

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Installation instructions

- For the installation inside XSPEC (*Warning: model still under development!*):

  - 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 (**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.

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Plans

- **Near future**:

  - Extrapolation of the tail or break due to outer radius;

  - Set up the frequency range that corresponds to **observations**.

- More physical prescription of 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 (1/3)

- **Input parameters of KYNrefrev** (***for the fitting with XSPEC***):

  - How (where) to define energy bands for lags vs. frequency dependence;

  - How (where) to define frequency bins for lag vs. energy dependence (currently only one frequency or integrated result up to the 1st zero freq. Implemented).

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Discussion (2/3)

- **<u>Output parameters of KYNrefrev</u>.** *What should we provide and in what way*:

  - Energy dependences: spectrum, lags vs. energy, imaginary and real parts.

  1) Currently only one can be provided (it is defined by a switch-parameter);
  2) These are provided for a certain time (i.e. it is a flash, not real observation) and the properties are frequency integrated over the whole time & up to zero frequency or in a given freq. range → How to define them.
  3) Should we use “ifl” in some way for defining real or imaginary parts?
  4) How to provide the frequency dependences in different energy bands.

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Discussion (3/3)

- **Results of KYNrefrev:**

  - What about negative values (for the spectra) – is it an issue in XSPEC?

  - How to provide the frequency dependences in different energy bands – currently XSPEC handles only energy dependences.

  - Should the whole Fourier Transform (FFT) be done by XSPEC itself?

  - What should be provided by the model?

  - Possible problems if some additional actions need to be performed, e.g.:

  Correction due to the use of the box function instead of the delta function, i.e. FFT result has to be divided by the sinc function.

  - Feedback from the group regarding the KYNrefrev model.

  - Any protocols/conventions to be implemented into the code I/O ?

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