The innermost region of accreting stellar-mass black holes: corona/jet/ISCO

New physical model with disc–corona interaction

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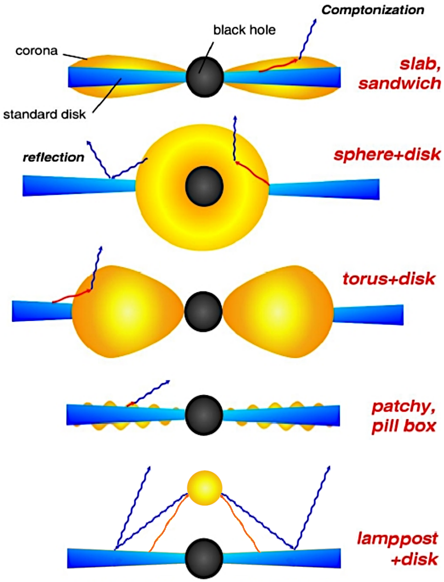
Introduction



Mueller (2004)

- corona vs. hot inner accretion flow vs. (base of) jet
- Monte Carlo codes for radiative transfer inside hot corona including relativistic effects & polarisation:
  - Schnittman & Krolik (2010, 2013) → PANDURATA
  - Zhang, Dovčiak & Bursa (2019) → MONK
  - Krawczynski & Beheshtipour (2022) → KerrC
- POP et al. → JED
- Swensson & Zdziarski (1994)
- Kubota & Done (2018) → AGNSED
- Dovčiak, Papadakis, Kammoun & Zhang (2022) → KYNSED

Power transferred to corona from accretion disc

Total power at infinity released by the NT accretion disc:
(Novikov & Thorne, 1973)

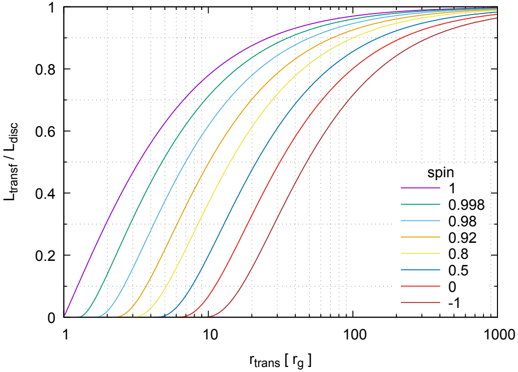
$$\begin{aligned} L_{\rm disc} &= 2\pi \int_{r_{\rm ISCO}}^{\infty} \sigma T_{\rm NT}^4(r)[-U_t(r)]\, r\, \mathrm{d}r \\ &= \eta \dot{M} c^2, \quad \eta = 1 + U_t(r_{\rm ISCO}) \end{aligned}$$

Power at infinity released by the NT accretion disc $< r_{\rm transf}$:
(see e.g. eq. (3.171) in Kato, Fukue & Mineshige, 1998)

$$\begin{aligned} L_{\rm transf} &= 2\pi \int_{r_{\rm ISCO}}^{r_{\rm transf}} \sigma T_{\rm NT}^4(r)[-U_t(r)]\, r\, \mathrm{d}r \\ &= [\mathscr{C}^{-1/2}\mathscr{G} - r_{\rm trans}^{-1}\mathscr{B}^{-1}\mathscr{Q} + U_t(r_{\rm ISCO})]\dot{M}c^2 \end{aligned}$$

Power transferred to corona if 100% efficiency is assumed:

$$L_{\rm transf,c} = \frac{1}{2} L_{\rm transf}\, [U_{\rm c}^t]^2$$



Corona emission

The scattered photon flux – power law with cut-off:

$$f_{\mathrm{X,c}}(E) \equiv \frac{\mathrm{d}N}{\mathrm{d}t\,\mathrm{d}\Omega\,\mathrm{d}E} = A_{\mathrm{c}}\, E^{-\Gamma} \exp(-E/E_{\mathrm{cut,c}}), \quad E > E_{0,\mathrm{c}}$$

The corona luminosity:

$$L_{\mathrm{X,c}} = 4\pi \int_{E_{0,\mathrm{c}}}^{\infty} E\, f_{\mathrm{X,c}}(E)\, \mathrm{d}E = L_{\mathrm{transf,c}} + (1 - \mathrm{e}^{-\tau})\, \Delta S_{\mathrm{c}}\, L_{\mathrm{BB,c}}$$

$$L_{\mathrm{BB,c}} = 2\sigma \int_{r_{\mathrm{trans}}}^{r_{\mathrm{out}}} \frac{T_{\mathrm{d}}^4(r)}{g^4(r) f_{\mathrm{col}}^4(r)} \frac{\mathrm{d}\Omega_{\mathrm{c}}}{\mathrm{d}S}(r)\, r\, \mathrm{d}r$$

Number of scattered photons:

$$N_{\mathrm{c}} = 4\pi \int_{E_{0,\mathrm{c}}}^{\infty} f_{\mathrm{X,c}}(E)\, \mathrm{d}E = (1 - \mathrm{e}^{-\tau})\, \Delta S_{\mathrm{c}}\, N_{\mathrm{BB,c}}$$

$$N_{\mathrm{BB,c}} = 2\sigma_{\mathrm{p}} \int_{r_{\mathrm{trans}}}^{r_{\mathrm{out}}} \frac{T_{\mathrm{d}}^3(r)}{g^3(r) f_{\mathrm{col}}^4(r)} \frac{\mathrm{d}\Omega_{\mathrm{c}}}{\mathrm{d}S}(r)\, r\, \mathrm{d}r$$

Size of corona:

$$\Delta S_{\mathrm{c}} = U_{\mathrm{c}}^{t}\, \pi R_{\mathrm{c}}^2$$

$$E_{0,\mathrm{c}} = \frac{L_{\mathrm{BB,c}}}{N_{\mathrm{BB,c}}}$$

Accretion disc – reflection and absorption

Incident flux:

$$F_{\rm inc}(r) = \frac{g(r)}{U_{\rm c}^t}\frac{{\rm d}\Omega_{\rm c}}{{\rm d}S}(r)\frac{L_{\rm X,c}}{4\pi}$$

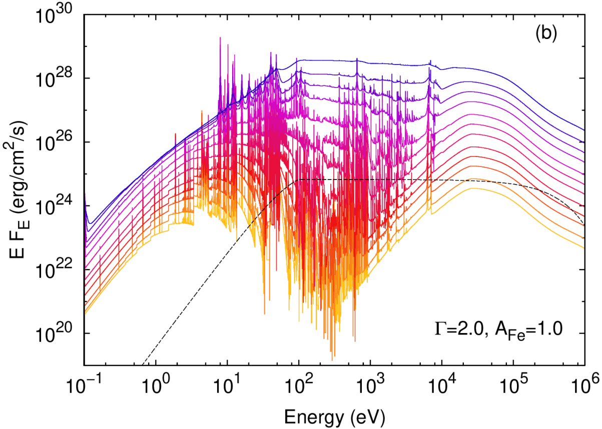
Reflected flux, $F_{\rm refl}$ – given by XILLVER tables (Garcia et al., 2013, 2016)

Absorbed (thermalised) flux:

$$F_{\rm abs}(r) = F_{\rm inc}(r) - F_{\rm refl}(r)$$

Disc temperature:

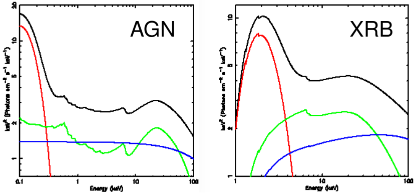
$$\begin{aligned} T_{\rm d}(r) &= f_{\rm col}(r)\left[\frac{F_{\rm acc}(r)+2F_{\rm abs}(r)}{\sigma}\right]^{1/4} \\ F_{\rm acc}(r) &= 0, \qquad r < r_{\rm trans} \\ F_{\rm acc}(r) &= F_{\rm NT}(r), \quad r > r_{\rm trans} \end{aligned}$$

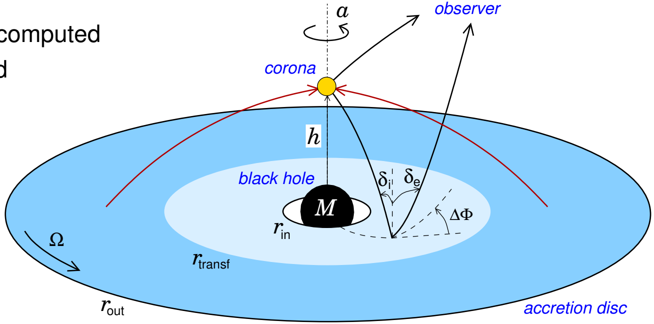


Garcia et al. (2013)

Disc–corona interaction and iteration of computations

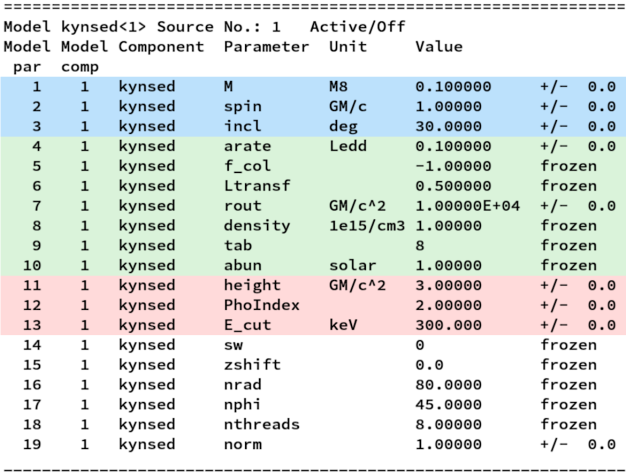
- disc thermal emission entering the corona must be known in order to compute total X-ray luminosity of the corona
- disc thermal emission depends on its illumination through thermalisation of the absorbed part of the corona X–ray emission
- iterative scheme:
  - initially $L_{\mathrm{X,c}} = L_{\mathrm{transf}}$ (the incoming thermal flux is neglected)
  - then F_{inc}, F_{refl}, F_{abs} and new $T_{\mathrm{d}}(r)$ are computed
  - then $L_{\mathrm{BB,c}}$, $N_{\mathrm{BB,c}}$ and $E_{0,\mathrm{c}}$ are computed
  - new $L_{\mathrm{X,c}}$ is computed $\rightarrow$ next iteration
  - we stop iterations when both $L_{\mathrm{X,c}}$ and $E_{0,\mathrm{c}}$ change by less than 1%
- resulting $T_{\mathrm{d}}(r)$, $E_{0,\mathrm{c}}$ and $L_{\mathrm{X,c}}$ are used to compute the final observed spectrum (thermal component, primary X-ray flux as well as reflection)
- all relativistic effects are included





KYNSED model parameters

- **central black hole**
- **accretion disc**
  - → Keplerian, geometrically thin, optically thick
  - → colour correction
  - → power extraction – inactive disc $< r_{\mathrm{trans}}$
  - → increase of temperature due to illumination
  - → local re-processing given by XILLVER – variable E_{cut} version preferred
- **compact corona**
  - → point source approximation
  - → isotropic power-law with cut-offs



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Model Model Component  Parameter  Unit     Value
 par  comp
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   3    1   kynsed     incl       deg      30.0000      +/-  0.0
   4    1   kynsed     arate      Ledd     0.100000     +/-  0.0
   5    1   kynsed     f_col               -1.00000     frozen
   6    1   kynsed     Ltransf             0.500000     frozen
   7    1   kynsed     rout       GM/c^2   1.00000E+04  +/-  0.0
   8    1   kynsed     density    1e15/cm3 1.00000      frozen
   9    1   kynsed     tab                 8            frozen
  10    1   kynsed     abun       solar    1.00000      frozen
  11    1   kynsed     height     GM/c^2   3.00000      +/-  0.0
  12    1   kynsed     PhoIndex            2.00000      +/-  0.0
  13    1   kynsed     E_cut      keV      300.000      +/-  0.0
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  15    1   kynsed     zshift              0.0          frozen
  16    1   kynsed     nrad                80.0000      frozen
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  18    1   kynsed     nthreads            8.00000      frozen
  19    1   kynsed     norm                1.00000      +/-  0.0
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```

KYNSED model parameters

- Further output via `xset` command:
  - → corona emission:

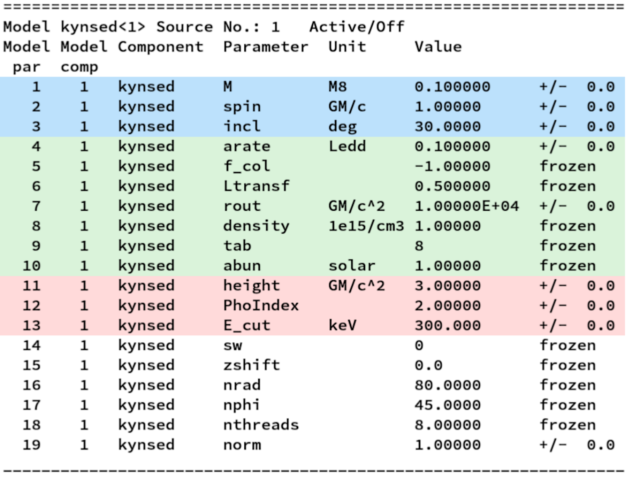
    E_0[keV]

    $L_{\mathrm{X,c}}$ and $L_{\mathrm{X,obs}}[L_{\mathrm{Edd}}]$ in 2-10 keV
  - → corona properties:

    τ, $n_{\mathrm{e}}[\mathrm{cm}^{-3}]$, $R_{\mathrm{c}}[r_{\mathrm{g}}]$
  - → reflection fraction $F_{\mathrm{refl}}/F_{\mathrm{prim}}$
  - → radii in r_{g}:

    r_{h}, r_{isco}, r_{trans}
  - → ionisation parameter:

    ξ_{in}, ξ_{out}



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   7    1   kynsed     rout       GM/c^2   1.00000E+04  +/-  0.0
   8    1   kynsed     density    1e15/cm3 1.00000      frozen
   9    1   kynsed     tab                 8            frozen
  10    1   kynsed     abun       solar    1.00000      frozen
  11    1   kynsed     height     GM/c^2   3.00000      +/-  0.0
  12    1   kynsed     PhoIndex            2.00000      +/-  0.0
  13    1   kynsed     E_cut      keV      300.000      +/-  0.0
  14    1   kynsed     sw                  0            frozen
  15    1   kynsed     zshift              0.0          frozen
  16    1   kynsed     nrad                80.0000      frozen
  17    1   kynsed     nphi                45.0000      frozen
  18    1   kynsed     nthreads            8.00000      frozen
  19    1   kynsed     norm                1.00000      +/-  0.0
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```
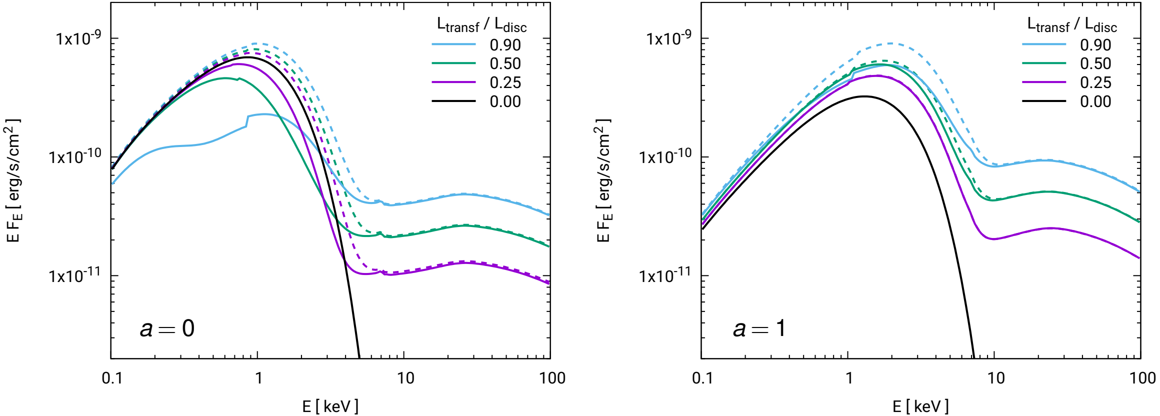

Dependence on power transferred to corona

$$M = 10 M_\odot, \dot{M} = 0.01 \dot{M}_{\rm Edd}, h = 3\, r_{\rm g}, \Gamma = 2, E_{\rm cut} = 300\, {\rm keV}, \theta_{\rm o} = 45^\circ, D = 10\, {\rm kpc}$$

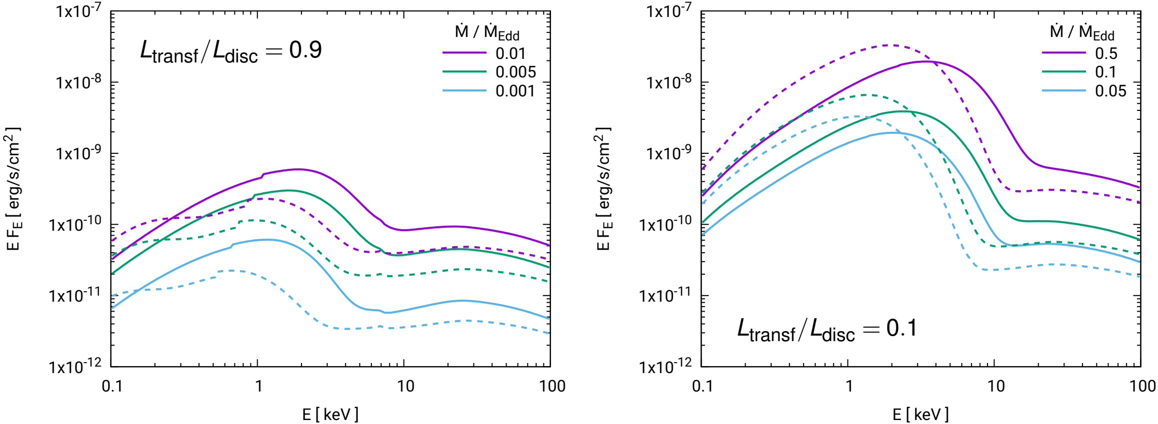


dashed → external source of energy

- non-rotating BH (*left*) has larger inactive region heated only by illumination (due to larger $r_{\rm trans}$)
- additional heating due to illumination in case of highly spinning BH (*right*) increases disc temperature

Dependence on accretion rate

$M = 10 M_\odot, h = 3\,r_g, \Gamma = 2, E_{cut} = 300\,\mathrm{keV}, \theta_o = 45^\circ, D = 10\,\mathrm{kpc}$

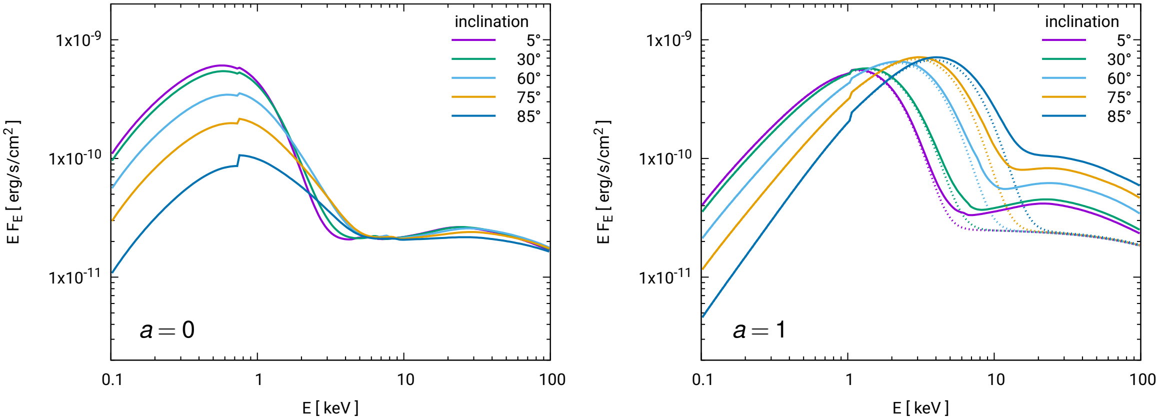


solid → $a = 1$, dashed → $a = 0$

- low accretion rates and high power transferred to corona (left) → possible low/hard state
- high accretion rates and low power transferred to corona (right) → possible high/soft state

Dependence on inclination

$$M = 10 M_{\odot},\, \dot{M} = 0.01\, \dot{M}_{\mathrm{Edd}},\, L_{\mathrm{transf}} / L_{\mathrm{disc}} = 0.5,\, h = 3\, r_{\mathrm{g}},\, \Gamma = 2,\, E_{\mathrm{cut}} = 300\,\mathrm{keV},\, D = 10\,\mathrm{kpc}$$

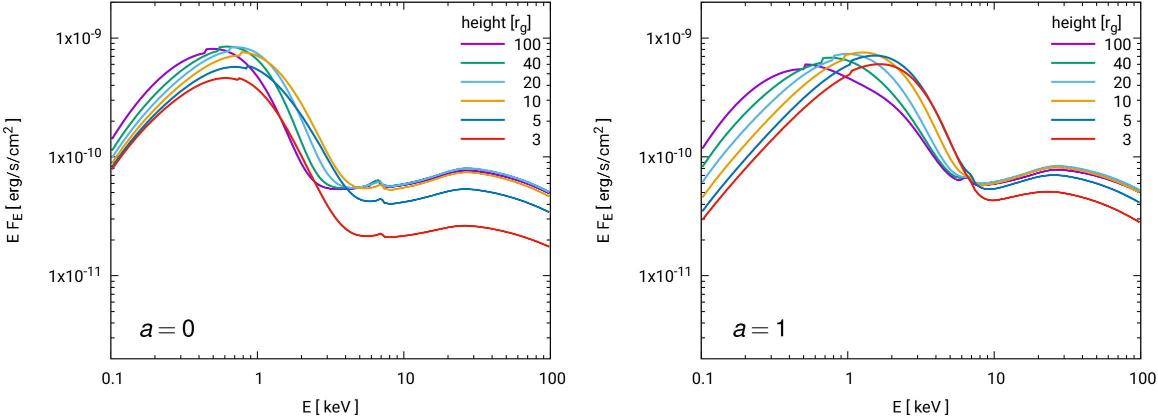


dotted → without reflection

- while the X-ray source is isotropic, the disc emission is a cosine source (*left*)
- due to light bending, close to BH even disc emission increases with inclination (*right*)

Dependence on height

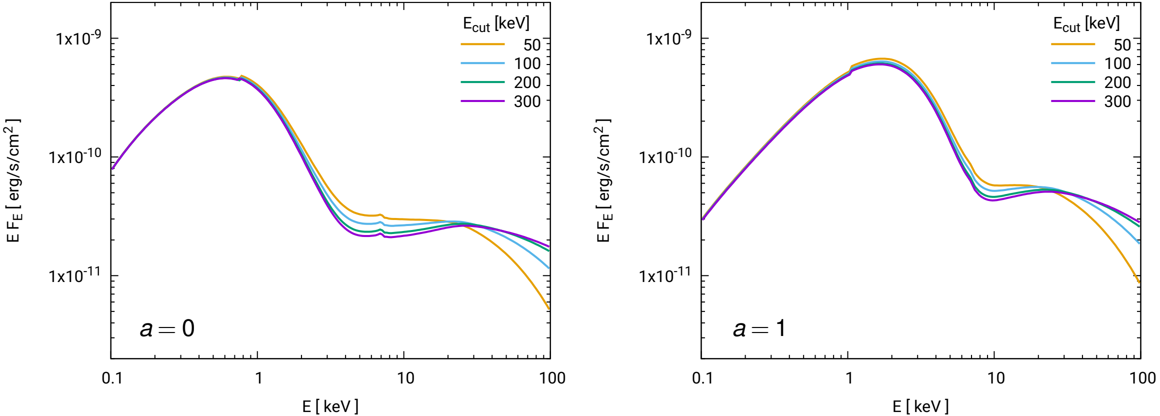
$$M = 10 M_\odot, \dot{M} = 0.01 \dot{M}_{\mathrm{Edd}}, L_{\mathrm{transf}}/L_{\mathrm{disc}} = 0.5, \Gamma = 2, E_{\mathrm{cut}} = 300\,\mathrm{keV}, \theta_o = 45^\circ, D = 10\,\mathrm{kpc}$$



- higher corona illuminates and heats more distant area, lower corona illuminates and heats closer regions
- light bending decreases the X-ray emission for low heights of corona

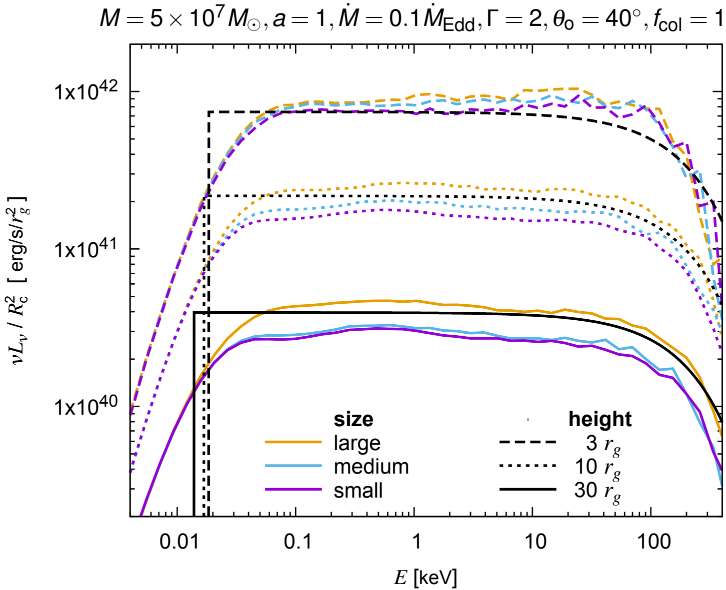
Dependence on high energy cut-off

$$M = 10M_\odot, \dot{M} = 0.01\,\dot{M}_{\rm Edd}, L_{\rm transf}/L_{\rm disc} = 0.5, h = 3\,r_{\rm g}, \Gamma = 2, \theta_{\rm o} = 45^\circ, D = 10\,{\rm kpc}$$



- high energy cut-off changes the primary X-ray normalisation and reflection component

Comparison with 3D corona



height	small	medium	large
$3\,r_{\rm g}$	$0.5\,r_{\rm g}$	$1.5\,r_{\rm g}$	$2\,r_{\rm g}$
$10\,r_{\rm g}$	$1\,r_{\rm g}$	$6\,r_{\rm g}$	$9\,r_{\rm g}$
$30\,r_{\rm g}$	$5\,r_{\rm g}$	$15\,r_{\rm g}$	$29\,r_{\rm g}$

We used MONK code by Zhang et al. (2019):

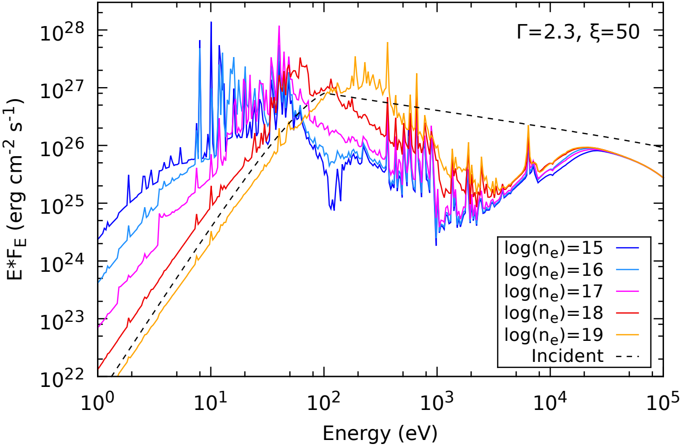
- with different sizes of corona, $R_{\rm c}$
- NT disc assumed down to ISCO
- τ used to produce approx. $\Gamma = 2$
- $T_{\rm e} = 100\,{\rm keV}$
- we scale results to $R_{\rm c} = 1\,r_{\rm g}$

For KYNSED we used:

- external power source, $L_{\rm ext}$, so that the radius of corona is $R_{\rm c} = 1\,r_{\rm g}$
- $E_{\rm cut} = 250\,{\rm keV}$ (POP et al., 2001)

Difference in normalisation equivalent to 20% error in corona radius.

XILLVER and thermal radiation

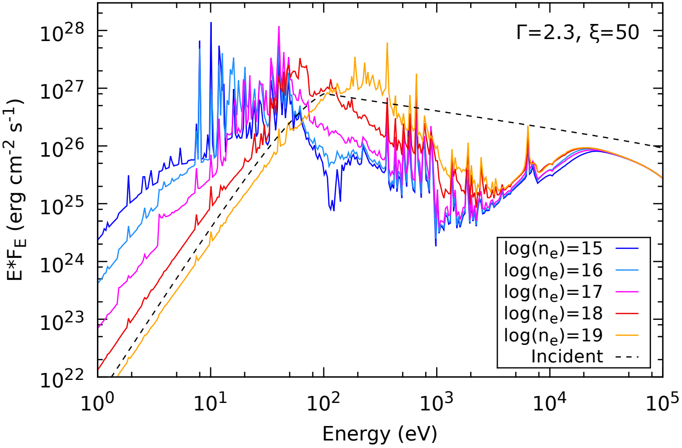


Garcia (2016)

XILLVER tables:

- computed for AGN
- high density tables available
- no internal disc energy included
- thermal radiation contribution from upper heated layers present (soft excess in AGN)
- constant low energy cut-off at 0.1 keV

XILLVER and thermal radiation

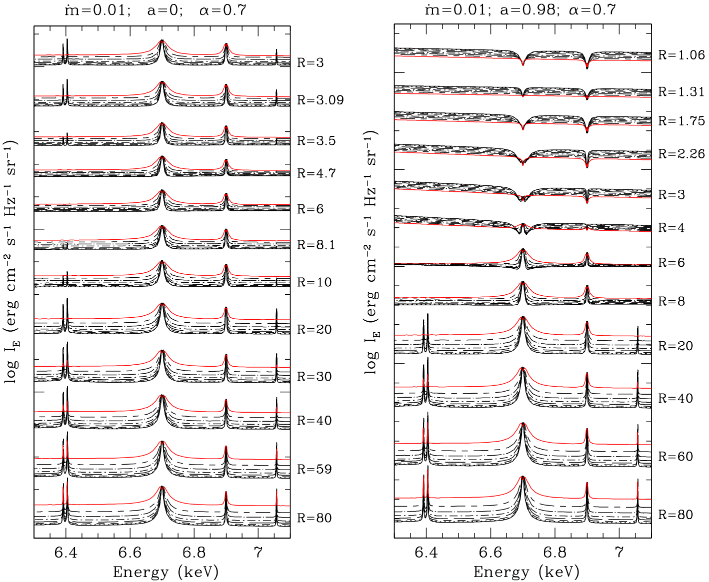


Garcia (2016)

KYNSED:

- we have to exclude the thermal contribution to add it to internal disc energy → low density tables should be used
- in XRBs the seed photon energy may be larger than 0.1 keV → reflection below seed photon energy, E_0, is removed
- we scale ionisation parameter and reflection normalisation to disc density in XRBs ($\xi \equiv 4\pi L/n$)
- regarding thermalisation there is an option to set $F_{\rm abs}$ as a constant fraction of $F_{\rm inc}$ (independent of disc ionisation or radius)

Internal disc energy



Rozanska et al. (2011)

- new reflection tables for XRBs that include internal disc energy should be computed, e.g. with TITAN code
- better estimate of the thermal component for illuminated discs
- different shape of reflection, see Rozanska et al. (2011)
  → iron line may be in absorption instead of emission, e.g. for high spin and innermost regions
- on the other hand the innermost regions are intrinsically cold
  → all released power is transferred to corona,
  thus this applies only above r_{trans}

Colour correction factor for illuminated discs

Ross et al. (1992) for AGN: $f_{\rm col} = 2.4$

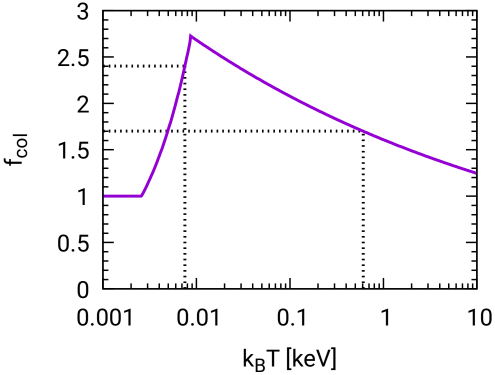
Shimura & Takahara (1995) for XRBs: $f_{\rm col} = 1.7$

Done et al. (2012):

$f_{\rm col} = 1$ for $T_{\rm d}(r) < 3 \times 10^4 K$

$f_{\rm col} = \left[\frac{T_{\rm d}(r)}{3\times 10^4 K}\right]^{0.82}$ for $3 \times 10^4 K < T_{\rm d}(r) < 10^5 K$

$f_{\rm col} = \left[\frac{72 {\rm keV}}{k_{\rm B} T_{\rm d}(r)}\right]^{1/9}$ for $T_{\rm d}(r) > 10^5 K$



→ but is this true also for illuminated discs?

Other effects changing the Comptonised/thermal flux ratio

- Disc geometrical thickness
  → probably important for optical/UV thermal emission in AGN case
- Corona motion – beaming of X-ray emission of corona
  → lower X-ray illumination, reflection and absorption
- Energy extraction from below ISCO or from an external power source
  (e.g. from spinning black hole – Blandford & Znajek 1977)

Summary

- new KYNSED model presented
- lamp-post model in point-source approximation with simplified Comptonisation treatment (isotropic cut-off power-law)
- 100% efficiency assumed in transfer of power from disc to corona
- inactive disc from ISCO to transition radius
- thermalisation of the absorbed incident flux included
- reflection component included
- energy and photon number conservation
- all relativistic effects included
- paper: `https://doi.org/10.1051/0004-6361/202142358`, `https://arxiv.org/abs/2110.01249`
- model available at: `https://projects.asu.cas.cz/dovciak/kynsed`