Relativistic reflection models

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X-ray data modelling of accreting black holes
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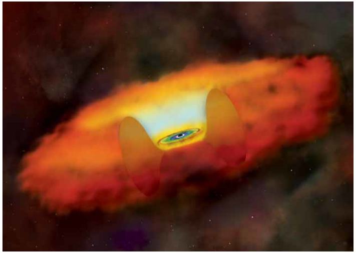
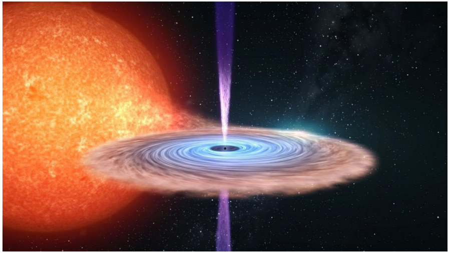
Plan of the talk

- Overview of the physical and spectral system components
- Origin of the reflection spectra
- Relativistic effects
- Relativistically broadened line and reflection spectra
- KYN package of models

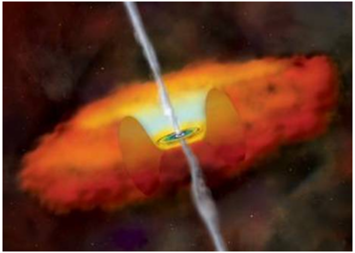
Physical components



Radio quiet AGN



X-ray binary system

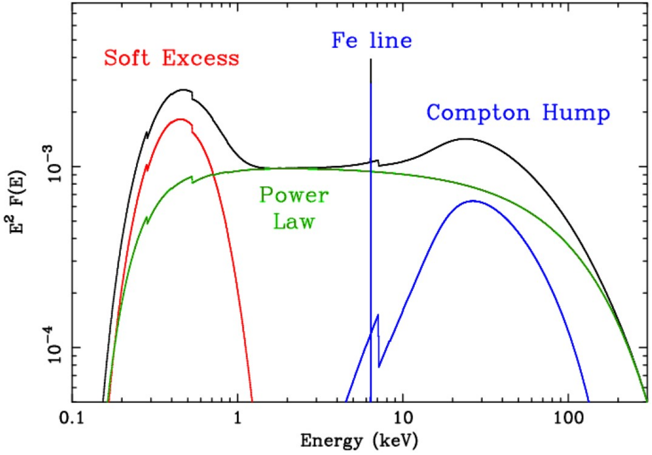


Radio loud AGN

Basic system components:

- **black hole** $\rightarrow$ curves the space-time
- **accretion disc** $\rightarrow$ thermal radiation and relativistic reflection
- **corona** $\rightarrow$ primary X-ray radiation
- **torus** $\rightarrow$ distant reflection
- **others – clouds, warm absorber, winds**
  $\rightarrow$ obscuration, absorption, reflection
- **jet** $\rightarrow$ in radio loud AGN and hard state of XRBs

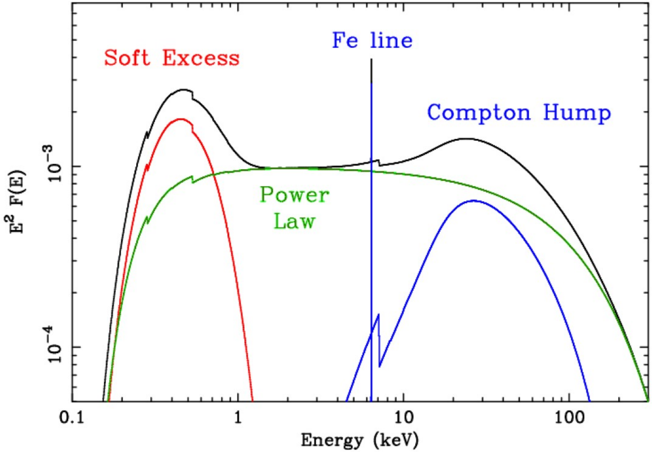
Spectral components



Spectral components in radio quiet AGN:

- multicolour black body (not shown)
  - → thermal disc emission
  - → optical/UV big blue bump
  - → `diskBB`, `kerrd`, `kerrBB`, `KYNBB`
- primary X-ray power-law emission
  - → corona emission
  - → index Γ, energy cut-offs E_0 and E_{cut}
  - → optical depth τ, seed photon energy T_{bb}, electron temperature T_{e}
  - → `cutoffpl`, `compTT`, `compPS`, `nthComp`, `MONK`
- distant reflection
  - → e.g. by torus
  - → `gauss`, `pexrav`, `pexriv`, `MYTorus`
- relativistically blurred reflection
  - → reflection from the accretion disc
  - → `diskline`, `laor`, `KYNrline`, `kerrdisk`
  - → `KYNlpcr`, `relxil`, `KYNxillver`, `KYNstokes`

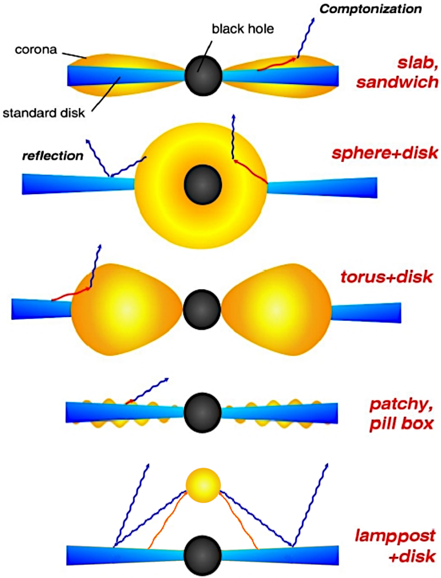
Spectral components



Spectral components in radio quiet AGN:

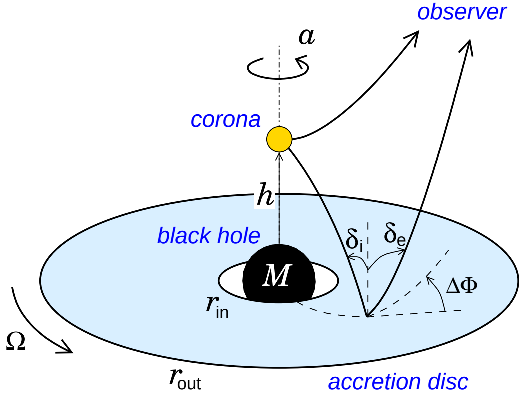
- soft excess
  $\rightarrow$ comptonisation by warm corona?
  $\rightarrow$ blurred spectral lines due to ionised reflection?
- absorption
  $\rightarrow$ `tbabs`, `wabs`, `wndabs`

Corona geometry and disc illumination



Muller (2004)

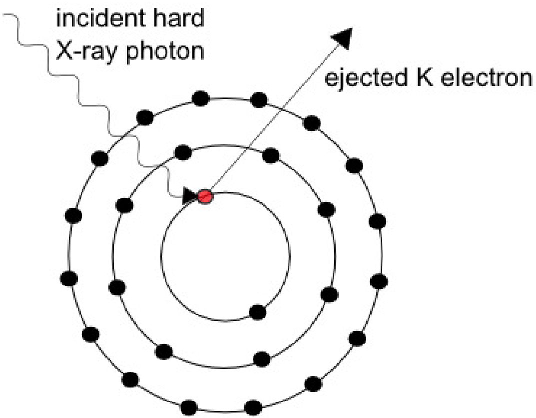
Lamp-post geometry:



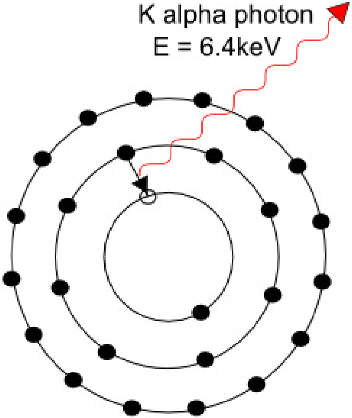
Matt (1993)

Dovčiak, Muleri, Goosmann, Karas & Matt (2011)

Auger effect and fluorescent Kα iron line

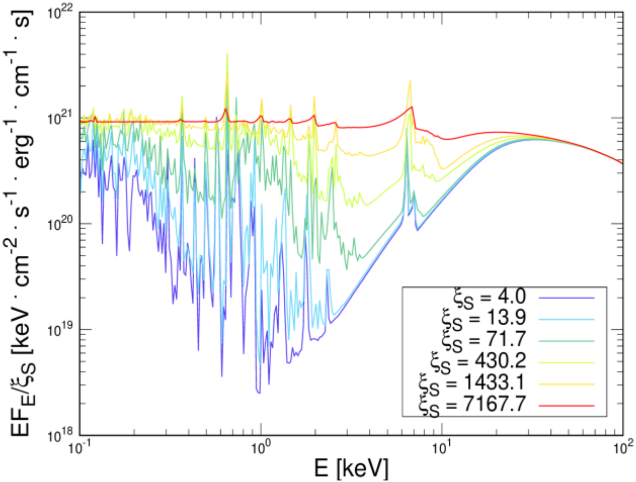


iron atom before photo-ionization



iron atom after photo-ionization

Local re-processed disc emission



Spectral features:

- **fluorescent emission and absorption lines** and spectral edges
  $\rightarrow$ e.g. Fe Kα and Kβ lines at
  6.4 keV and 7.1 keV for neutral Fe
- **Compton hump** due to Compton recoil
  $\rightarrow$ 20 – 50 keV
- **absorption**
- soft excess at soft energies
  $\rightarrow$ forest of ionised spectral lines
  $\rightarrow$ below 1 keV
- dependence on ionisation
  $\rightarrow$ fully ionised disc resembles the original power-law radiation – perfect reflector

Special relativistic effects

- due to **high velocity** of the matter moving close to the black hole

  – orbiting, falling into or being ejected from the centre

  $\rightarrow$ depend on: **direction of motion** with respect to the observer

- observed effects:
  - **Doppler shift** – **shifts energy** dependence of emitted radiation properties
  - **aberration** – **changes angles**
    – emission angle, important if emission depends on direction
    – polarization angle

    $\rightarrow$ **beaming** – **changes intensity** of radiation
  - **time delay** – important for variable emission, e.g. orbiting hot spots

General relativistic effects

- due to **high gravity** of the compact central body

  $\rightarrow$ depend on: system **inclination angle**, black hole **mass** and **spin**
- observed effects:
  - **gravitational redshift** – **shifts energy** dependence of emitted radiation properties and **changes intensity** of radiation
  - **light bending** – photon trajectory is heavily bent close to the BH due to strong gravity and dragging of space-time due to the BH rotation
    – observer can see behind the black hole
    – source of radiation illuminates regions “behind the corner”
    – **changes emission angle**, important if emission depends on direction
    $\rightarrow$ **lensing effect** – **changes intensity** of radiation
  - **rotation of polarization angle**
  - **time delay** – important for variable emission
    – orbiting hot spots
    – reverberation, i.e. “reflection” from different parts of the system

Relativistic broadening

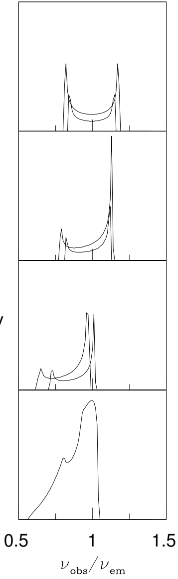
$$G(g) = \sqrt{\frac{g_+ g_-}{(g_+ - g)(g - g_-)}}\, g^2 \cos\left[\theta_e(g)\right] \ell(g) \left[\frac{\partial \psi}{\partial \varphi}(g)\right]^{-1}$$

Newtonian

Special relativity

General relativity

Line profile



Transverse Doppler shift

Beaming

Gravitational redshift

Fabian et al. (2000)

$$g = 1 - \frac{v_k}{c} \sin\theta_o \sin\varphi$$

$$\theta_e = \theta_o \quad \ell = 1 \quad \psi = \varphi$$

$$g = \left[\gamma\left(1 + \frac{v_k}{c}\sin\theta_o \sin\varphi\right)\right]^{-1}$$

$$\theta_e = \theta_o \quad \ell = 1 \quad \psi = \varphi$$

$$g = \left[U^t_k\left(1 - \Omega_k \sin\theta_o\, \alpha\right)\right]^{-1}$$

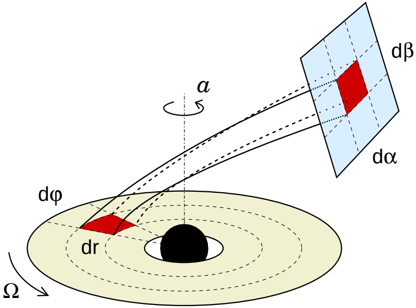
$$\cos\theta_e = \sqrt{\beta^2 + (\alpha^2 - a^2)\cos^2\theta_o}/r$$

$$\ell = \frac{dS_o}{dS_{loc}}$$

$$\sin\psi = \frac{2(\alpha - \overline{\alpha})}{\alpha_+ - \alpha_-}$$

$$F(g) = \int_{r_{in}}^{r_{out}} dr\, r\, R(r) \sum_{j=1}^{2} G_j(g)\, M_j(\mu_i, \mu_e)$$

Transfer function



$$\Delta I = \int_{\Sigma_{\alpha,\beta}} \mathrm{d}\alpha\,\mathrm{d}\beta\; \underbrace{g^{\gamma}}\; I_{\mathrm{loc}}(\alpha,\beta)$$

$$\Delta I = \int_{\Sigma_{r,\varphi}} r\,\mathrm{d}r\,\mathrm{d}\varphi\; \underbrace{g^{\gamma-1}\mu_{\mathrm{e}}\,\ell}\; I_{\mathrm{loc}}(r,\varphi)$$

transfer function G

$$g = \frac{E}{E_{\mathrm{loc}}}$$

$$\mu_{\mathrm{e}} = \cos\theta_{\mathrm{e}}$$

$$\ell = \frac{\mathrm{d}S_{\mathrm{o}}}{\mathrm{d}S^{\perp}_{\mathrm{loc}}}$$

$\gamma = 4$ for $\frac{\mathrm{d}E}{\mathrm{d}t\,\mathrm{d}\Omega\,\mathrm{d}S^{\perp}}$

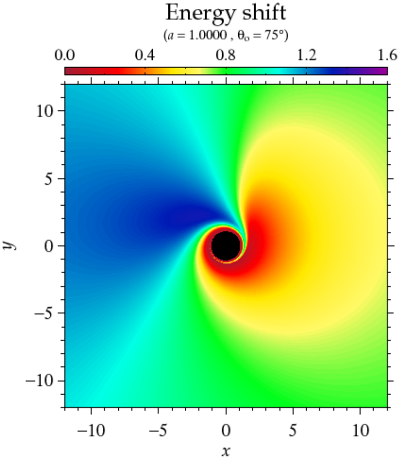
$\gamma = 3$ for $\frac{\mathrm{d}E}{\mathrm{d}t\,\mathrm{d}\Omega\,\mathrm{d}S^{\perp}\mathrm{d}\nu}$ or $\frac{\mathrm{d}N}{\mathrm{d}t\,\mathrm{d}\Omega\,\mathrm{d}S^{\perp}}$

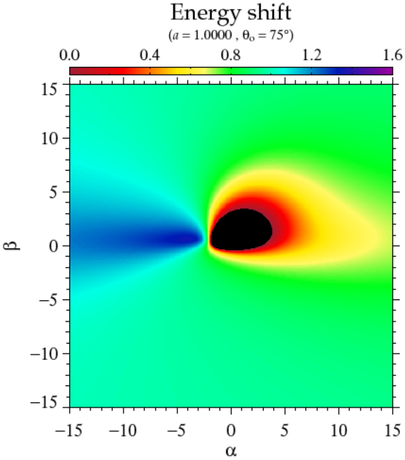
$\gamma = 2$ for $\frac{\mathrm{d}N}{\mathrm{d}t\,\mathrm{d}\Omega\,\mathrm{d}S^{\perp}\mathrm{d}\nu}$

$$\frac{\mathrm{d}\alpha\,\mathrm{d}\beta}{r\,\mathrm{d}r\,\mathrm{d}\varphi} = \frac{\mathrm{d}S_{\mathrm{o}}}{\mathrm{d}S^{\perp}_{\mathrm{loc}}} \times \frac{\mathrm{d}S^{\perp}_{\mathrm{loc}}}{\mathrm{d}S_{\mathrm{loc}}} \times \frac{\mathrm{d}S_{\mathrm{loc}}}{\mathrm{d}S} = \frac{\ell\,\mu_{\mathrm{e}}}{g}$$

Energy shift

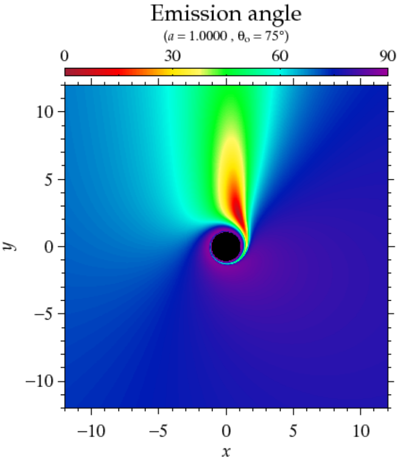
- → shifts spectral features among energy bands of interest
- → due to Doppler shift and gravitational redshift
- → disc (x, y-coordinates) versus detector (α, β-coordinates)
- → bending and dragging of photon path by rotation

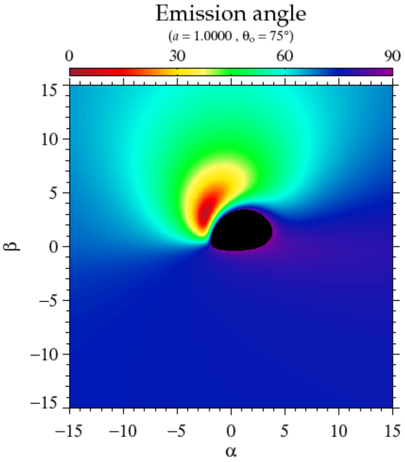




Emission angle

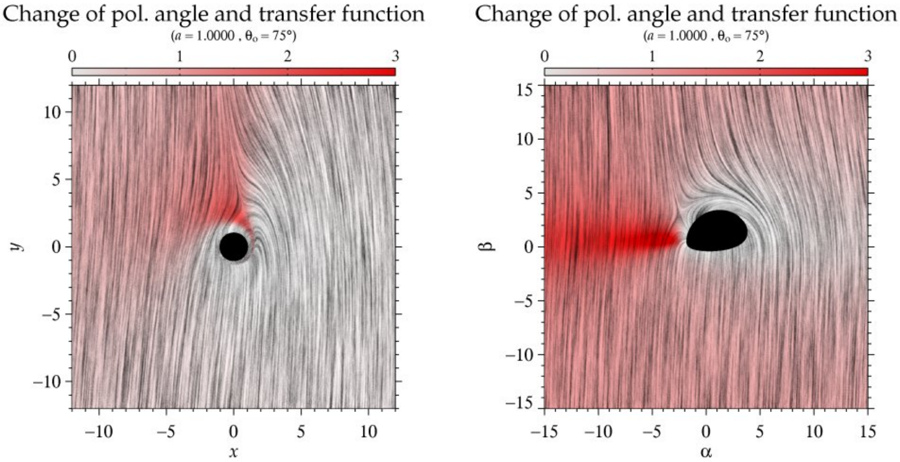
- → important for non-isotropic emission
- → due to aberration and light bending
- → critical point - photons emitted perpendicularly to the dics
- → photons emitted parallelly with the dics close to the black hole





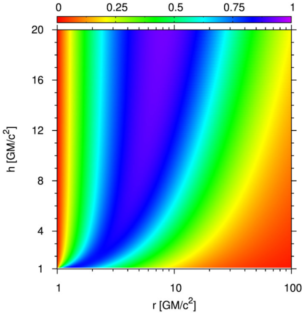
Change of polarization angle and transfer function

- → important for the total observed radiation from the whole disc surface
- → polarization angle changes due to aberration and light bending
- → emission is amplified due to beaming and lensing
- → depolarization around the critical point

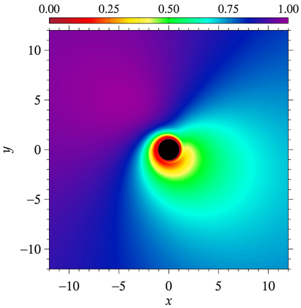


Emission directionality

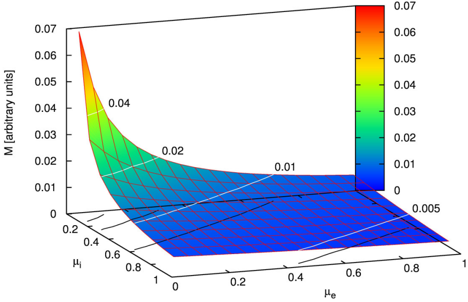
Cosine of the incident angle



Cosine of the emission angle

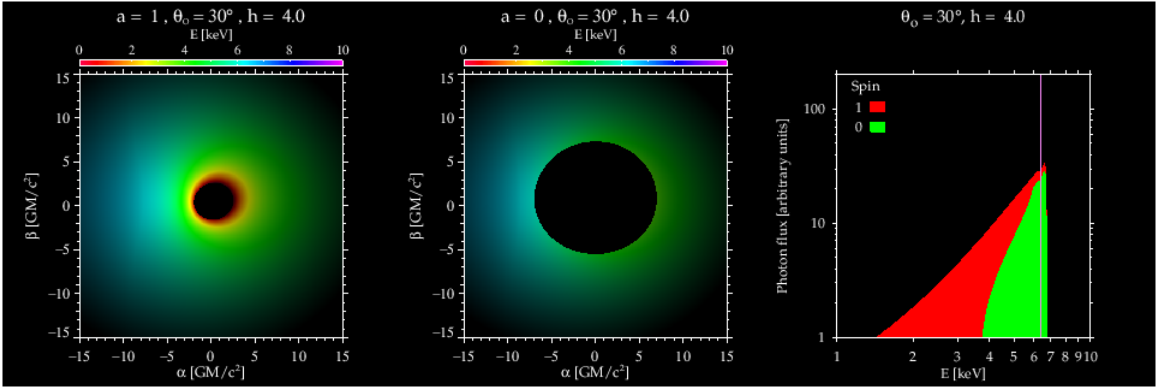


Emission directionality



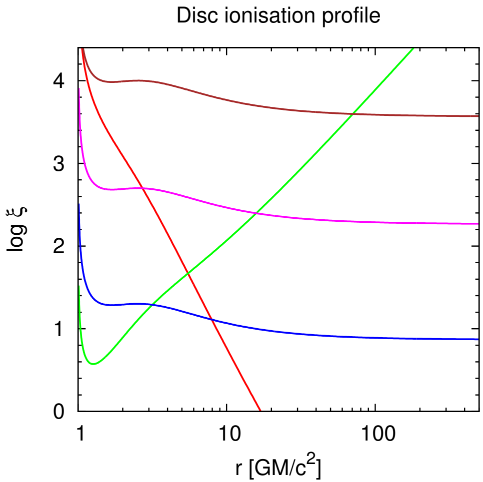
- Kα line emission directionality re-processing numerically computed for neutral disc with Monte Carlo multi-scattering code `NOAR` (Dumont, Abrassart & Collin, 2000)
- enhanced emission close to the black hole due to limb brightening and small incident and emission angles near the horizon – another reason for steeper emissivity
- Svoboda et al (2009), García et al (2014)

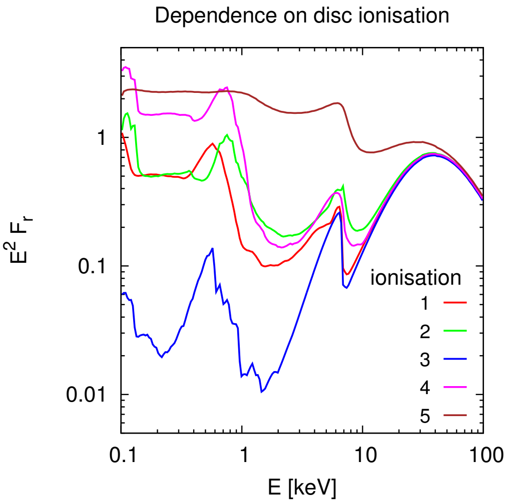
Spin measurements



- spin measurements possible only for a very compact corona situated very close to the black hole

Spectrum dependence on radial ionisation profile





- example spectra for different radial ionisation profiles

KYN package of models

https://projects.asu.cas.cz/stronggravity/kyn

- relativistic fluorescent line models:
  - KYNrline – broken power-law emissivity
  - KYNrlpli – lamp-post geometry
- relativistic convolution models:
  - KYNconv – broken power-law emissivity
  - KYNconvlp – lamp-post geometry
- relativistic reflection models:
  - KYNlpcr – lamp-post geometry, neutral disc (local emissivity computed by NOAR)
  - KYNrefionx – lamp-post geometry, ionised disc (based on REFLIONX)
  - KYNxillver – lamp-post geometry, ionised disc (based on XILLVER)
- relativistic thermal radiation models:
  - KYNrefionx – lamp-post geometry, ionised disc (based on REFLIONX)
  - KYNxillver – lamp-post geometry, ionised disc (based on XILLVER)

KYN parameters

Model kynrefionx<1> Source No.: 1 Active/Off

Model par	Model comp	Component	Parameter	Unit	Value	
1	1	kynrefionx	a/M	GM/c	1.00000	+/- 0.0
2	1	kynrefionx	theta_o	deg	30.0000	+/- 0.0
3	1	kynrefionx	rin	GM/c^2	1.00000	frozen
4	1	kynrefionx	ms		1	frozen
5	1	kynrefionx	rout	GM/c^2	400.000	frozen
6	1	kynrefionx	phi	deg	0.0	frozen
7	1	kynrefionx	dphi	deg	360.000	frozen
8	1	kynrefionx	M/M8		1.00000	+/- 0.0
9	1	kynrefionx	height	GM/c^2	3.00000	frozen
10	1	kynrefionx	PhoIndex		2.00000	frozen
11	1	kynrefionx	L/Ledd		1.00000E-03	+/- 0.0
12	1	kynrefionx	Np:Nr		0.0	frozen
13	1	kynrefionx	density		1.00000	+/- 0.0
14	1	kynrefionx	den_prof		0.0	+/- 0.0
15	1	kynrefionx	abun		1.00000	+/- 0.0
16	1	kynrefionx	alpha	GM/c^2	-6.00000	+/- 0.0
17	1	kynrefionx	beta	GM/c^2	0.0	+/- 0.0
18	1	kynrefionx	rcloud	GM/c^2	0.0	+/- 0.0
19	1	kynrefionx	zshift		0.0	frozen
20	1	kynrefionx	limb		0.0	frozen
21	1	kynrefionx	tab		2	frozen
22	1	kynrefionx	sw		2	frozen
23	1	kynrefionx	ntable		80.0000	frozen
24	1	kynrefionx	nrad		500.000	frozen
25	1	kynrefionx	division		1.00000	frozen
26	1	kynrefionx	nphi		360.000	frozen
27	1	kynrefionx	smooth		1.00000	frozen
28	1	kynrefionx	nthreads		2.00000	frozen
29	1	kynrefionx	norm		1.00000	+/- 0.0

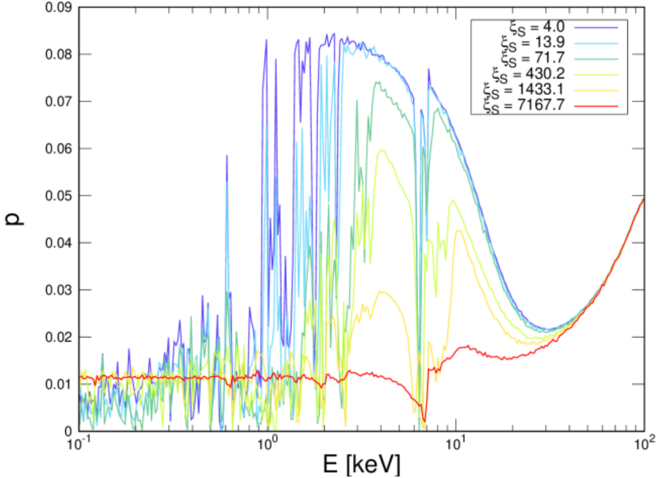
- physical parameters describing the system (spin, inclination, etc.)
- emission from a spot (section of the accretion disc)
- obscuration by a spherical cloud
- numerical parameters setting the computational grid for the integration (influences the speed of the code)

KYNreverb models

https://projects.asu.cas.cz/stronggravity/kynreverb

- X-ray reverberation models in the lamp-post geometry:
  - KYNrefrev – based on REFLIONX tables
  - KYNxilrev – based on XILLVER tables

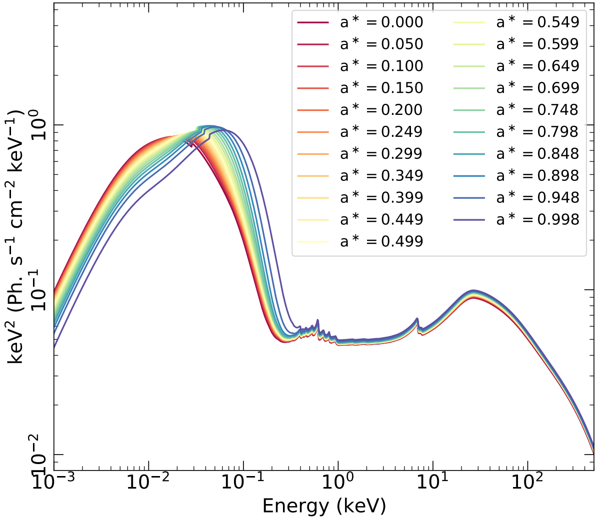
New model for polarisation by reflection for AGN – KYNSTOKES



Local polarisation degree:

- **emission spectral lines** are unpolarised
- **absorption spectral lines** are polarised
- **Compton hump** is mildly polarised due to scattering
- **absorption** increases polarisation
- soft excess at soft energies has very low polarisation
- higher ionisation induces low polarisation degree

Spectral energy distribution model for AGN – KYNSED



Spectral energy distribution model:

- thermal emission of the accretion disc
- primary X-ray emission from the corona
- reflection from the accretion disc
- includes interaction of the disc with the corona
  - $\rightarrow$ disc provides seed photons to corona (corona cooling via Compton scattering)
  - $\rightarrow$ disc provides energy to corona (corona heating)
  - $\rightarrow$ corona illuminates the disc
  - $\rightarrow$ disc reflects
  - $\rightarrow$ disc partly absorbs (disc heating)

- $M_{\rm BH} = 5 \times 10^7\, M_\odot$, $\theta_{\rm o} = 40^\circ$, $\dot{m}_{\rm Edd} = 0.1$, $L_{\rm ext}/L_{\rm acc} = 0.5$, $h = 10\, r_{\rm g}$, $\Gamma = 2$ and $E_{\rm cut,obs} = 300\,\mathrm{keV}$

How to install and use the models

Required files:

- **source files** in the main repository directory.
- **KY tables** – KBHtables80.fits and KBHlamp80.fits
- other **FITS tables** for re-processing in the accretion disc, e.g. REFLIONX, XILLVER

Installation in XSPEC:

- the code is compiled inside XSPEC with the following command:
  initpackage kyn lmodel-kyn.dat /path/to/KYN

To use the KYN models inside XSPEC:

- the package needs to be loaded:
  lmod kyn /path/to/KYN
- the directory including the KYN package needs to be set:
  xset KYDIR /path/to/KYN
- then any model from KYN package may be used, e.g.:
  mo kynxillver

Note: One may need to increase the stack size by one of the following commands (in case of segmentation fault):

- `ulimit -s unlimited`
- `ulimit -s 65532`