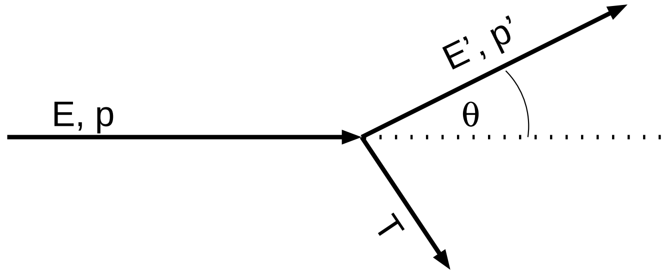
Compton Scattering



Thomson scattering: initial and final wavelength identical.
But: in reality: light consists of photons
$\Longrightarrow$ Scattering: photon changes direction
$\Longrightarrow$ Momentum change
$\Longrightarrow$ Energy change!
This is quantum picture $\Longrightarrow$ Compton scattering.

Energy/wavelength change (see handout):

$$E' = \frac{E}{1 + \frac{E}{m_e c^2}(1-\cos\theta)} \sim E\left(1 - \frac{E}{m_e c^2}(1-\cos\theta)\right) \quad (8.14)$$

$$\lambda' - \lambda = \frac{h}{m_e c}(1-\cos\theta) \quad (8.15)$$

where $h/m_e c = 2.426 \times 10^{-12}$ m (Compton wavelength).
Averaging over θ, for $E \ll m_e c$:

$$\frac{\Delta E}{E} \approx -\frac{E}{m_e c^2} \quad (8.16)$$

E.g., at 6.4 keV, $\Delta E \approx 0.2$ keV.

Amplification factor, I

In electron frame of rest,

$$\frac{\Delta E}{E} = -\frac{E}{m_e c^2} \quad (8.16)$$

Assuming a thermal (Maxwell) distribution of electrons (i.e., they're not at rest), one can show that the relative energy change is given by

$$\frac{\Delta E}{E} = \frac{4kT - E}{m_e c^2} = A \quad (8.48)$$

where A is the Compton amplification factor.
Thus:

$E \lesssim 4kT_e \Longrightarrow$ Photons gain energy, gas cools down.
$E \gtrsim 4kT_e \Longrightarrow$ Photons loose energy, gas heats up.

Amplification factor, II

In reality, photons will scatter more than once before leaving the hot electron medium.

The *total* relative energy change of photons by traversal of a hot ($E \ll kT_\mathrm{e}$) medium with electron density n_e and size ℓ is then approximately

$$\big(\text{rel. energy change } y\big) = \frac{\text{rel. energy change}}{\text{scattering}} \times \big(\#\,\text{scatterings}\big) \qquad (8.49)$$

The number of scatterings is $\max(\tau_\mathrm{e}, \tau_\mathrm{e}^2)$, where $\tau_\mathrm{e} = n_\mathrm{e}\sigma_\mathrm{T}\ell$ ("optical depth"), such that

$$y = \frac{4kT_\mathrm{e}}{m_\mathrm{e}c^2}\max(\tau_\mathrm{e}, \tau_\mathrm{e}^2) \qquad (8.50)$$

"Compton y-Parameter"

Spectral shape

Photon spectra can be found by analytically solving the "Kompaneets equation", but this is very difficult.

Approximate spectral shape from the following arguments:
After k scatterings, the energy of a photon with initial energy E_i is approximately

$$E_k = E_\mathrm{i}A^k \qquad (8.51)$$

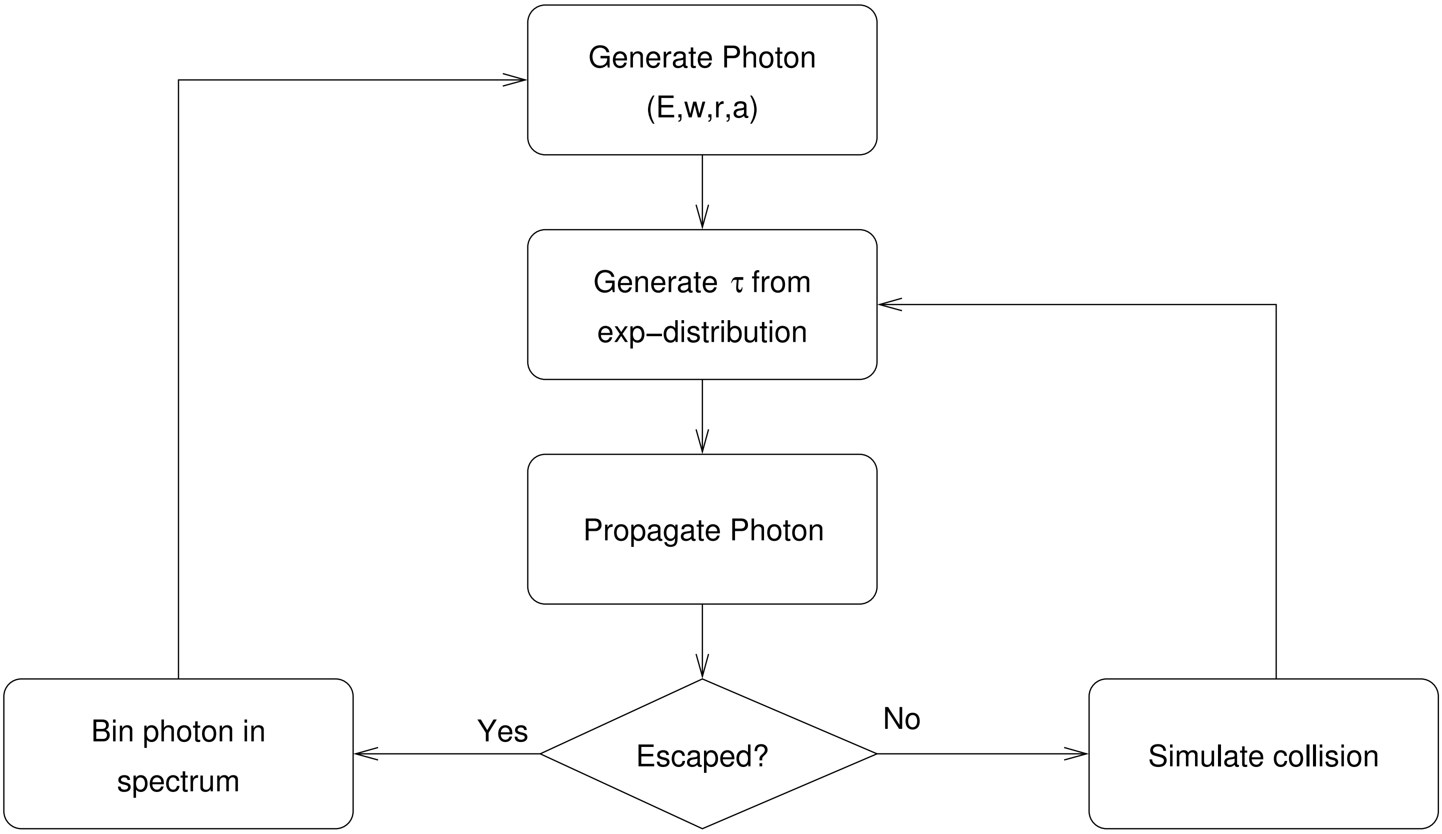
But the probability to undergo k scatterings in a cloud with optical depth τ_e is $p_k(\tau_\mathrm{e}) = \tau_\mathrm{e}^k$ (follows from theory of random walks, note that the mean free path is $\ell = 1/\tau_\mathrm{e}$).

Therefore, if there are $N(E_\mathrm{i})$ photons initially, then the number of photons emerging at energy E_k is

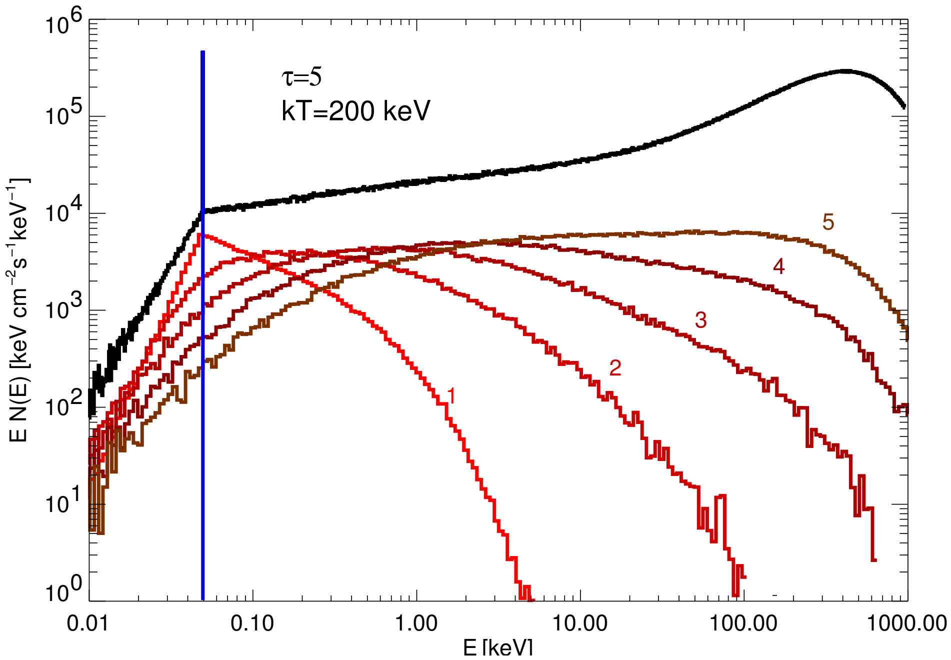
$$N(E_k) \sim N(E_\mathrm{i})A^k \sim N(E_\mathrm{i})\left(\frac{E_k}{E_i}\right)^{-\alpha} \quad \text{with} \quad \alpha = -\frac{\ln \tau_e}{\ln A} \qquad (8.52)$$

Comptonization produces power-law spectra.

General solution: Possible via the Monte Carlo method.

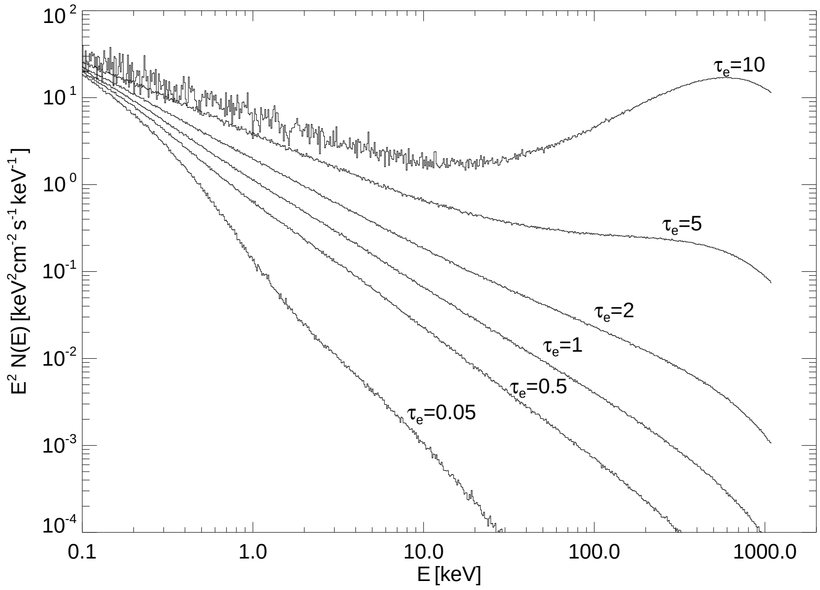


Spectral shape



Monte Carlo simulation shows: Spectrum is $\Longrightarrow$ Power law with exponential cutoff (here: with additional "Wien hump", see next slide)

Spectral shape



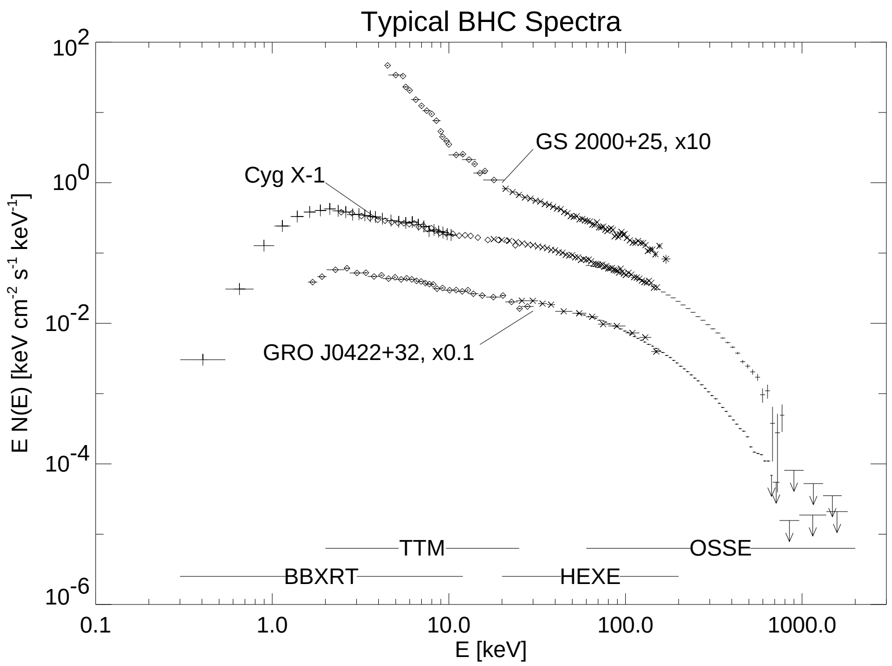
Sphere with $kT_e = 0.7 m_e c^2$ ($\sim$ 360 keV), seed photons come from center of sphere.

$y \ll 1$: pure power-law.
$y < 1$: power-law with exponential cut-off
$y \gg 1$: "Saturated Comptonization".

Saturated Comptonization has never been observed.

Application of Comptonization

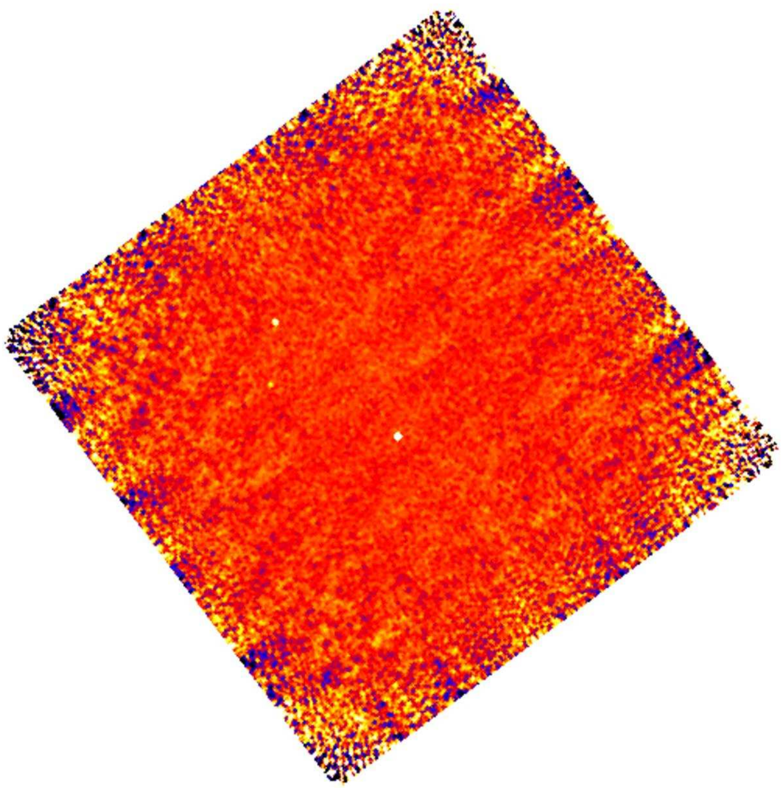
Galactic Black Holes



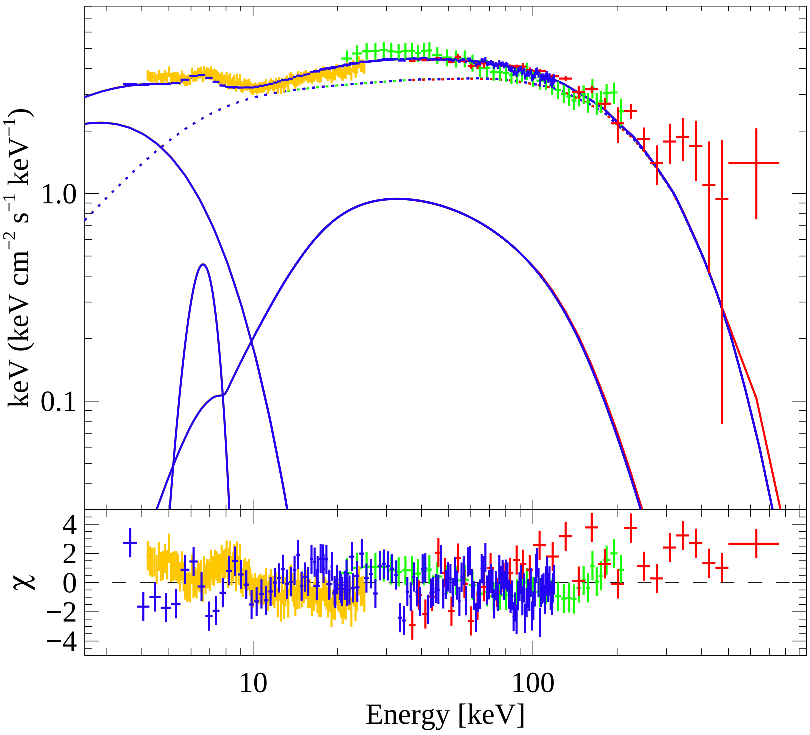
(Cyg X-1: Wilms et al., 1996, ; GRO J0422+32, GS2000+25: Sunyaev et al., 1993, Kroeger [priv. comm.])

X-ray spectra of galactic black hole candidates can be well explained by thermal Comptonization in a plasma with $kT \sim 150$ keV and with $y \sim 1$.

INTEGRAL/RXTE, I



INTEGRAL/RXTE, III



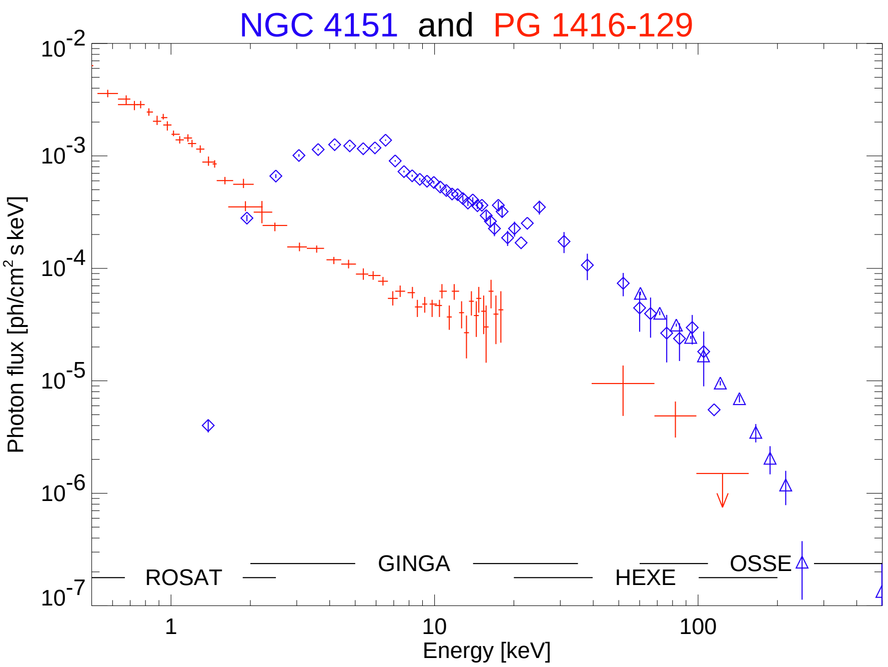
Fritz, et al., 2005, in prep.

Fit of a `Comptonization` model to *RXTE*/*INTEGRAL* data from the galactic black hole Cygnus X-1

$kT_{\text{soft}} = 1.21$ keV,
$\tau_{\text{e}} = 1.09$,
$kT_{\text{e}} \sim 100$ keV

Note presence of a Compton reflection hump (evidence of close vicinity of hot electrons and only mildly ionised material)

AGN



(PG 1416−129: de Kool et al., 1994, Williams et al., 1992, Staubert & Maisack, 1996; NGC 4151: Maisack 1991, 1993)

Note: NGC 4151 not corrected for interstellar absorption.

Spectral shape of AGN very similar to galactic Black Holes $\Longrightarrow$ Same physical mechanism (=Comptonization) responsible!