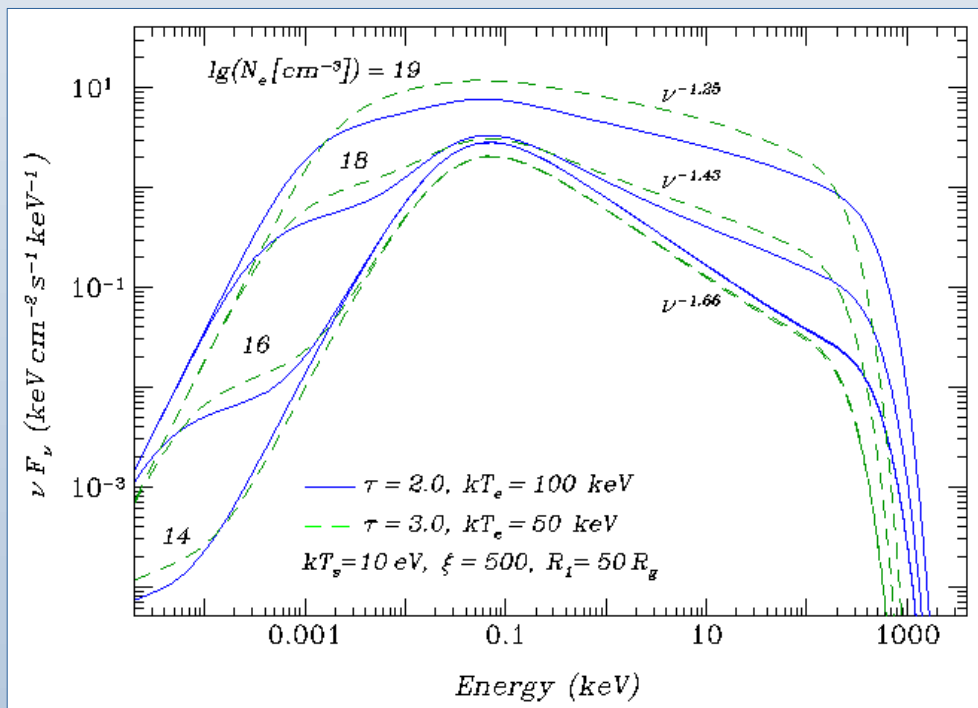
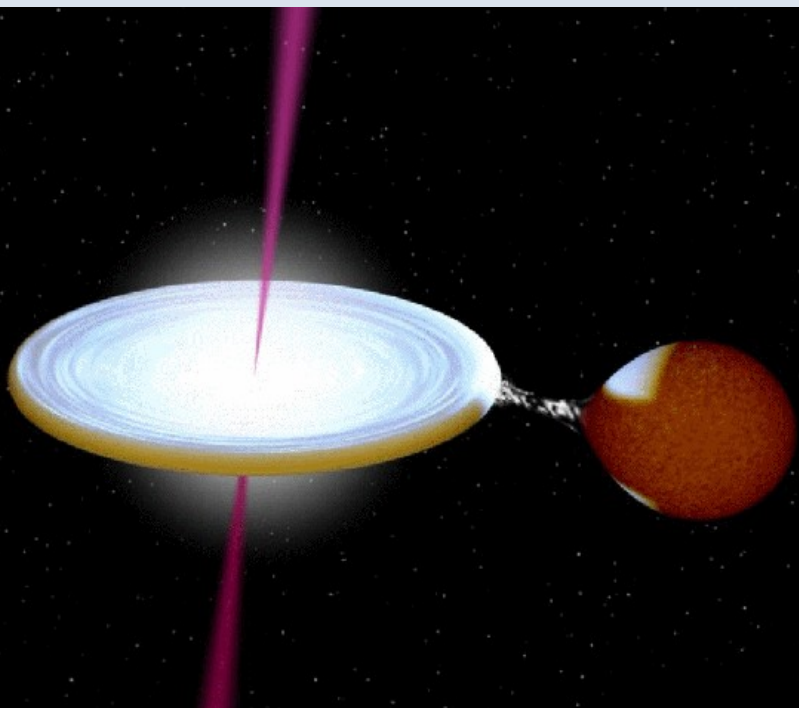


X- and gamma-ray radiation from the high-temperature plasma and spectra of accreting black holes

Sergei A. Grebenev

Space Research Institute, Moscow

Comptonized spectra of the plasma depend not only on its optical depth and electron temperature but also on its density. They can explain observed hard spectra of black holes without any external (seed) photons.



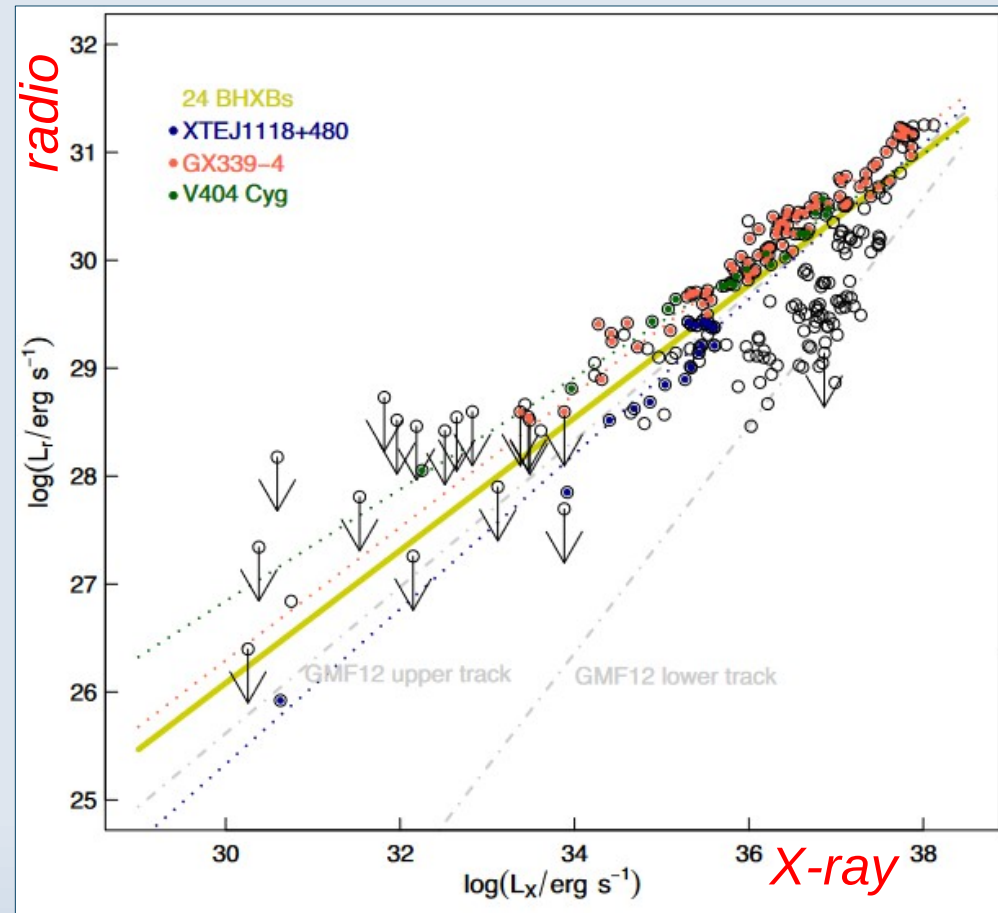
Origin of hard X-rays from accreting black holes

Two opinions:

- *Hard radiation correlates with the radio flux and thus it is formed in relativistic jets*
- *Hard X-ray and optical radiation is emitted by an accreting disk*

The latter options is based mainly on the observed characteristic hard X-ray spectrum, power law one with an exponential cut off at high energies that points on its thermal origin.

Eardley et al. (1975), Shapiro et al. (1976), Sunyaev, Truemper (1979), Sunyaev, Titarchuk (1980) have shown that Comptonization of soft external photons can be responsible for its formation and found an analytical solution describing it.



Gallo, Miller-Jones, Russell (2014)

Black hole spectra and Comptonization

First comparison with the observations was given by Sunyaev-Truemper (1979). Grebenev et al. (1993) showed that the data of better quality disagree with the found solution but Comptonization of seed photons still works if the spectrum is computed by the fully relativistic Monte Carlo method.

Letter | Published: 01 June 1979

Hard X-ray spectrum of Cyg X-1

[R. A. SUNYAEV](#) & [J. TRÜMPER](#)

[Nature](#) **279**, 506–508 (1979) | [Cite this article](#)

587 Accesses | **221** Citations | [Metrics](#)

ASTRONOMY & ASTROPHYSICS

SUPPLEMENT SERIES

Astron. Astrophys. Suppl. Ser. **97**, 281-287 (1993)

Observations of black hole candidates with GRANAT

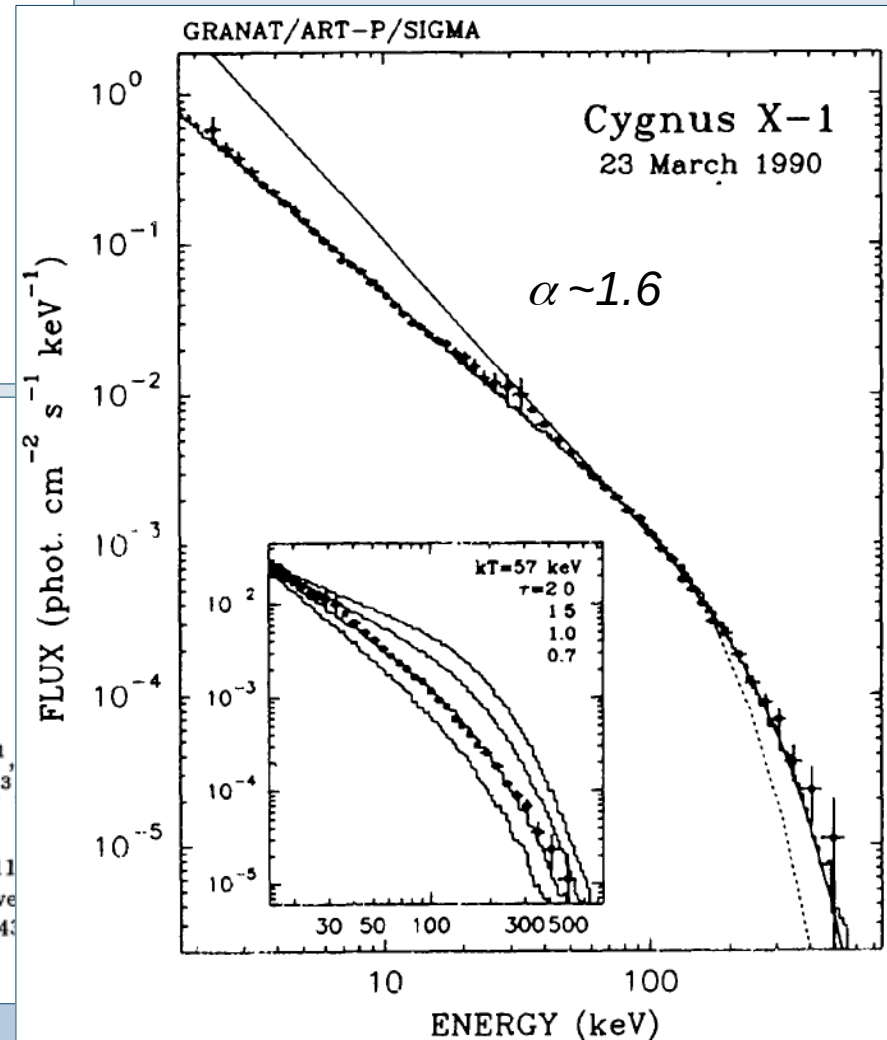
S.Grebenev¹, R.Sunyaev¹, M.Pavlinisky¹, E.Churazov¹, M.Gilfanov¹,
K.Sukhanov¹, P.Laurent², J.Ballet², A.Claret², B.Cordier², E.Jourdain³
Schmitz-Fraysse³

¹ Space Research Institute, Russian Academy of Sciences, Profsovnaya 84/32, 11

² Service d'Astrophysique, Centre d'Etude Nucleaire de Saclay, 91191 Gif-sur-Yve

³ Centre d'Etude Spatiale des Rayonnements, 9, Avenue du Colonel Roche, BP 43

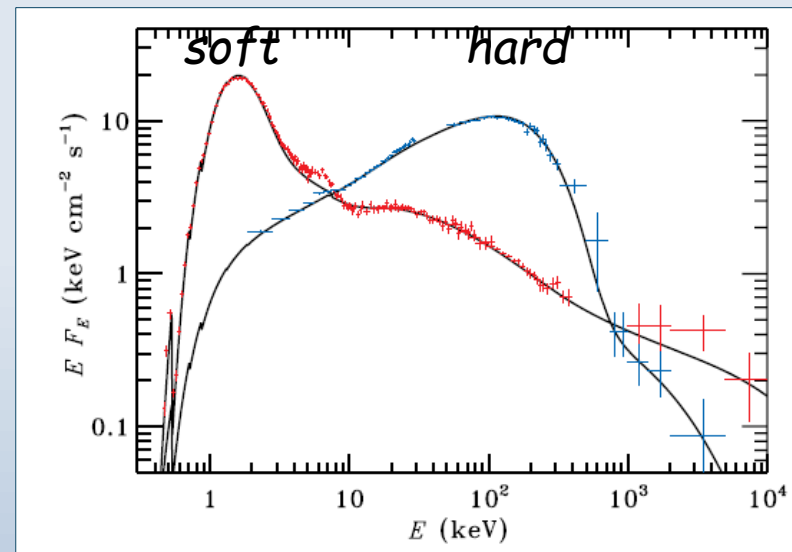
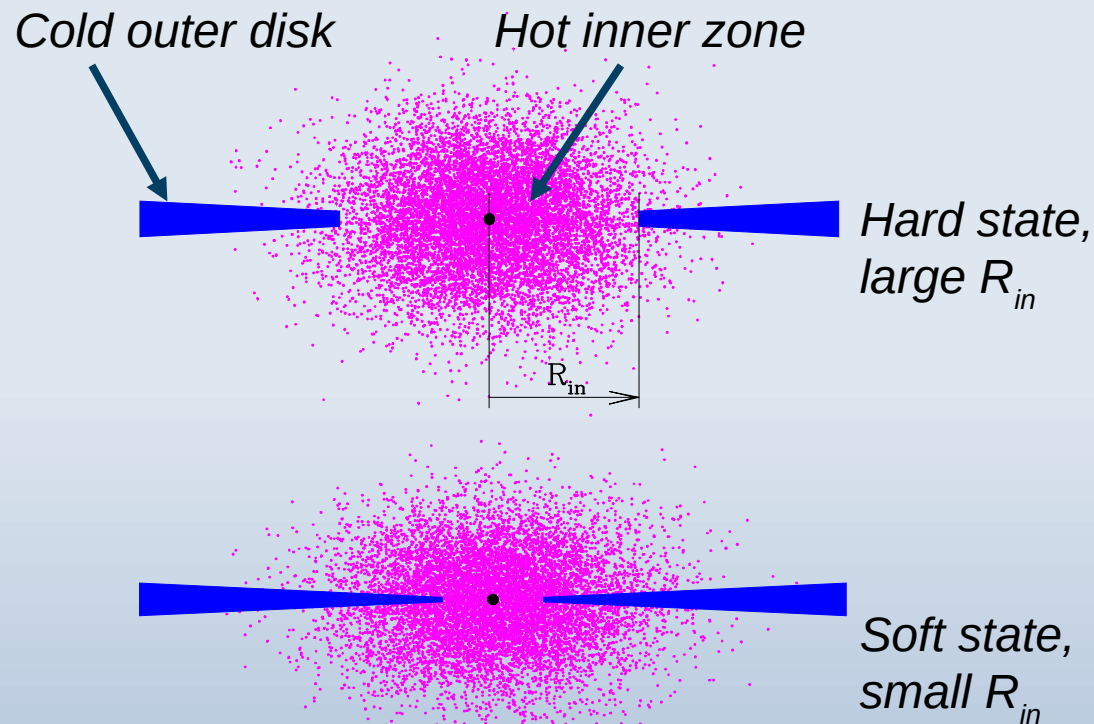
Received September 14; accepted September 21, 1992



Origin of seed photons

Soft seed photons via multiple Compton scatterings produce the characteristic hard X-ray spectrum

- *Photons from the outer cold disk regions illuminating the inner zone (truncated disk)*
- *Corona model* where soft photons are produced by underlying cold disk surface (Galeev et al. 1979; Haardt, Maraschi 1993)
- *Synchrotron or cyclotron photons* from hot thermal or relativistic nonthermal electrons (Wardzinski, Zdziarski 2000; Poutanen et al. 2009, 2014; Veledina et al. 2011; Dexter et al. 2021)



Comptonized spectrum of the hot layer

We solve the Kompaneets (1957) equation to compute broadband spectra of the intrinsic radiation from a semi opaque high-temperature plasma layer (the inner zone of an accretion disk) and compare them with the X-ray spectra observed from several well known accreting black holes in their hard (low) state.

Normalization suggests that a circular region between the radii $R_0 = 3 R_g$ and $R_1 = 50 R_g$ is observed in perpendicular direction at a distance $d = 2.5$ kpc.

The estimates show that the electron density should be high:

$$N_e \simeq 2.3 \times 10^{18} \tau_T r^{-3/2} kT_*^{-1/2} m_*^{-1}, \text{ cm}^{-3}$$

$$r = R/R_0 \quad (R_0 = 3 R_g), \quad m_* = M/10 M_\odot, \quad \text{and} \quad kT_* = kT_e/50 \text{ keV}$$

$$\frac{1}{3} \frac{\partial}{\partial \tau} \left(\frac{\alpha_T}{\alpha_T + \alpha_{\text{ff}}} \frac{\partial U_\nu}{\partial \tau} \right) = \frac{\alpha_{\text{ff}}}{\alpha_T} (U_\nu - B_\nu) - \frac{kT_e}{m_e c^2} x \frac{\partial}{\partial x} \left(x \frac{\partial U_\nu}{\partial x} - 3U_\nu + xU_\nu \right).$$

The computations are based on the computer code developed by Grebenev, Sunyaev (2002) to investigate the radiation spectra forming in a spreading layer of accreting matter over the surface of a neutron star. The code was adapted for the current problem.

The spectra are formed under the combined action of bremsstrahlung processes (emission and absorption) and Compton scattering.

Comptonized photon spectrum of the hot layer

Comptonization of *low-frequency photons created in free-free electron-ion interactions* is the leading process responsible for the hard X-ray spectrum formation in accreting black holes (in their low/hard states).

Blue solid curve — computed spectrum.

Blue dotted curve — Planck spectrum.

Green dashed curve — bremsstrahlung spectrum, arising in the hot layer under assumption of its small optical thickness at all energies.

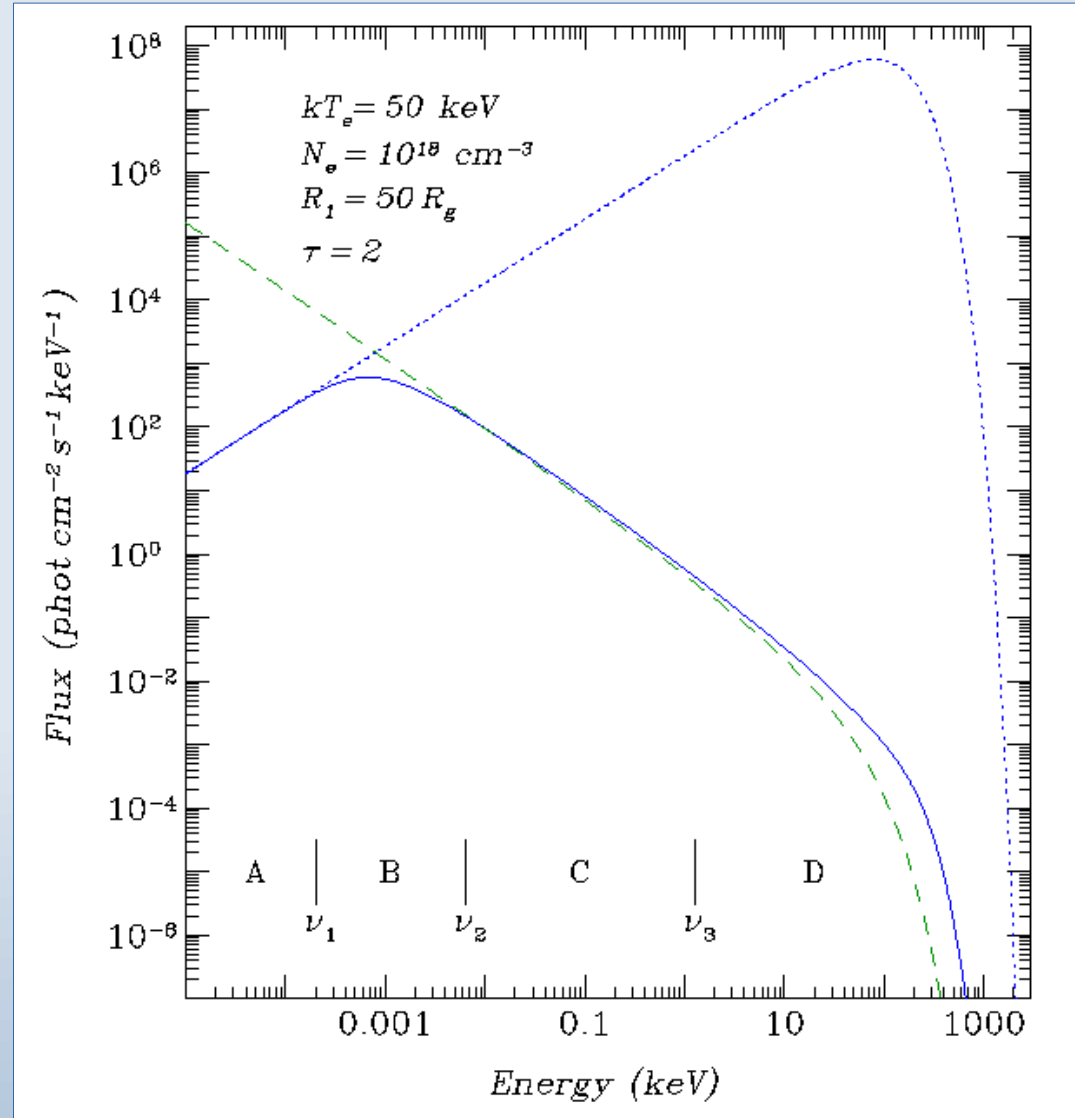
Radiation spectra in different ranges:

A - black-body (Rayleigh-Jeans)

B - RJ spectrum distorted due to scattering and free-free absorption (scattering lengthens the path of photons and enhances the probability of absorption)

C - bremsstrahlung

D - Comptonized spectrum

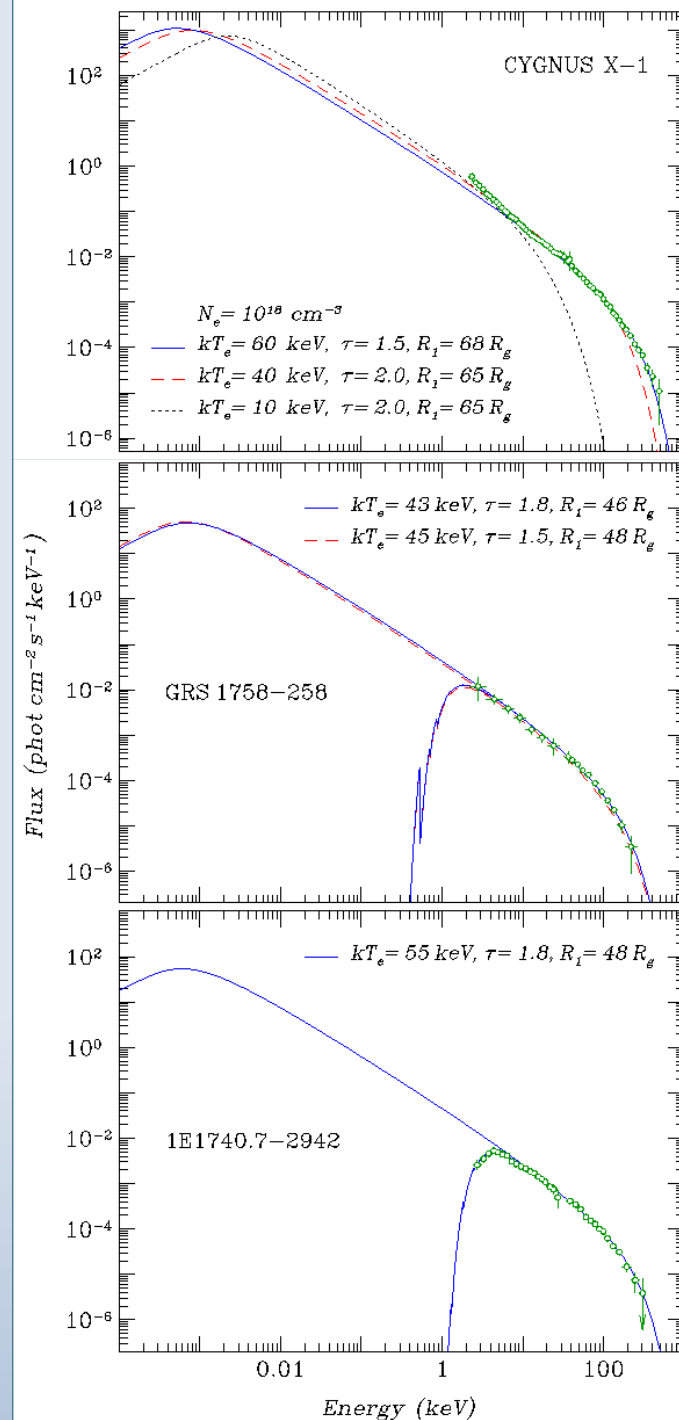


Comparison with observations

Comparison of our computations with the broad-band X-ray (2-600 keV) spectra of three black holes: Cygnus X-1, GRS 1758-258, and 1E 1740.7-2942, measured with the GRANAT observatory (Grebenev et al. 1993, 1995, 1997).

Nice agreement with nearly the same parameters kT_e , R_1 and τ_T for the same electron density $N_e = 10^{18} \text{ cm}^{-3}$

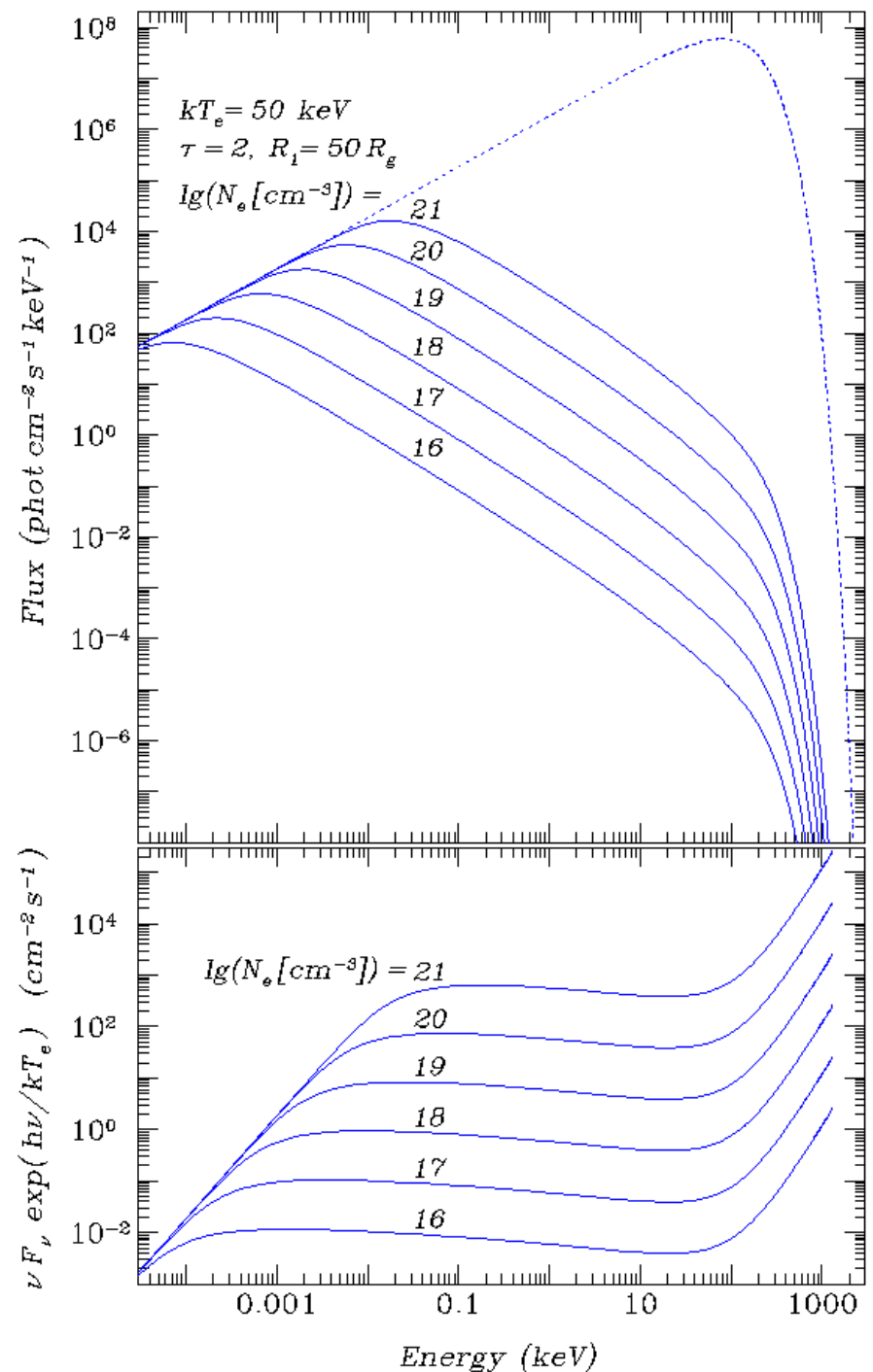
The computed spectra extend with the same slope ($\alpha \sim 1.2-1.6$) to the UV and OIR bands and transform to the Rayleigh-Jeans spectrum below $\sim 1 \text{ eV}$.



Comptonized spectrum of the hot layer

Dependence on the electron number density — the shape of the spectrum changes slightly, the normalization is proportional to N_e .

Photon flux $\times \nu \exp(h\nu / kT_e)$

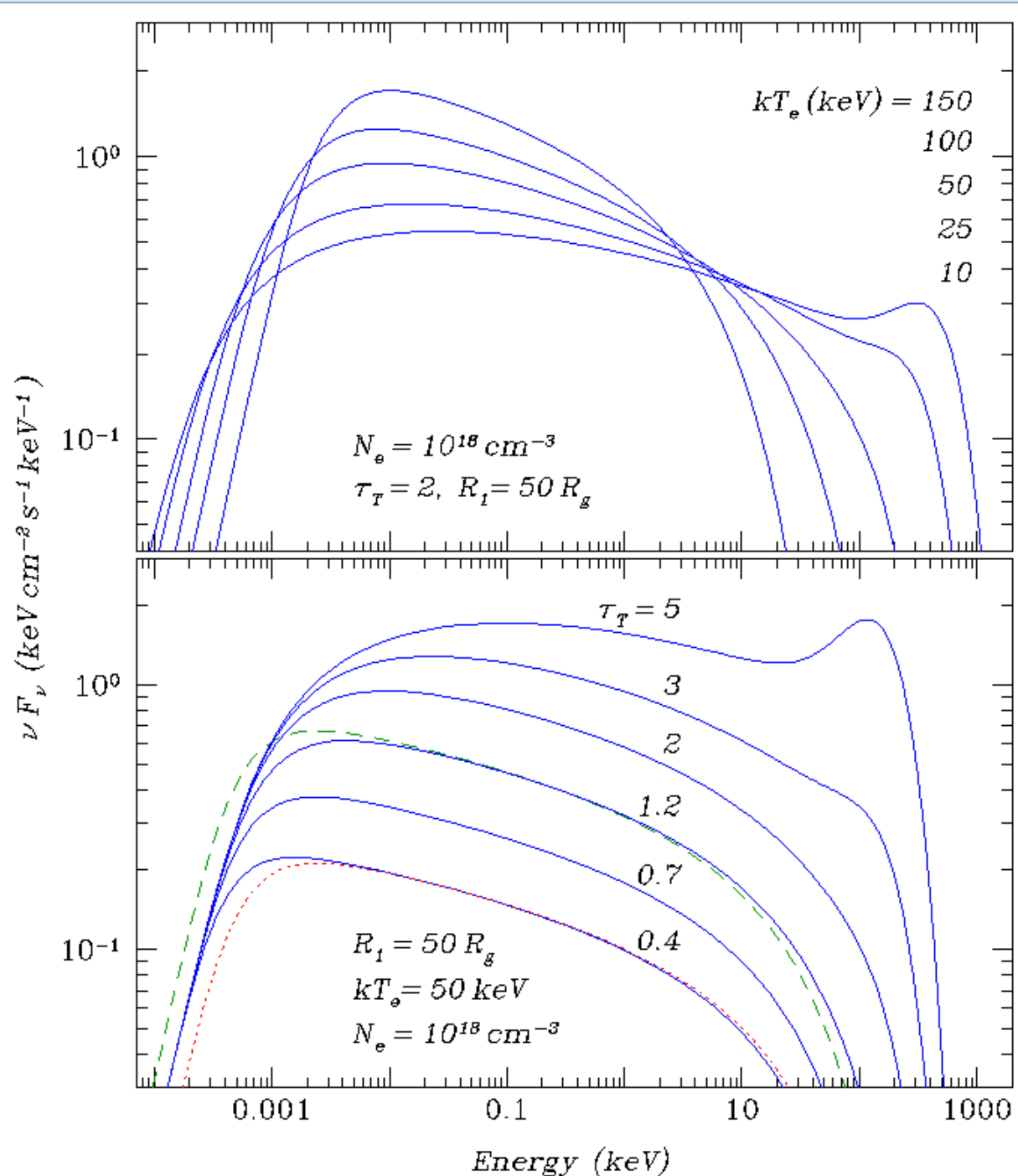


Radiation spectrum of the hot layer

Dependence on the electron temperature and the Thomson transverse optical thickness of the layer.

Increase in kT_e leads to the more extended and flate spectrum. At the highest kT_e considered, saturation of the spectrum is observed.

Dependence on τ_T is not so strong but exists. And again we see saturation of the spectrum for the largest thickness $\tau_T \sim 5$.



Comptonized spectrum of the hot layer

The analytical solution can be reproduced from the Sunyaev, Titarchuk (1980) solution for the spectral formation in the layer from soft photons with energy $x' = h\nu'/kT_e$

$$F_\nu(x', x) = F_0 (x')^{\alpha-1} x^{-\alpha} e^{-x} \times \\ \times \int_0^\infty t^{\alpha-2} (x+t)^{\alpha+2} e^{-t} dt$$

$$\alpha = (9/4 + \gamma)^{1/2} - 1/2,$$

where

$$\gamma = \beta m_e c^2 / kT_e = \pi^2 m_e c^2 / 3kT_e (\tau_T + 4/3)^2$$

and

$$F_0 = \frac{(\alpha - 1)(\alpha + 2)}{\Gamma(2\alpha + 2) kT_e},$$

by its convolution with the bremsstrahlung spectrum

$$F_\nu(x) = \int_{x_s}^x B_{\text{ff}}(x') F_\nu(x', x) dx' = \\ = F_1(x_s, x) x^{-\alpha} e^{-x} \int_0^\infty t^{\alpha-2} (x+t)^{\alpha+2} e^{-t} dt.$$

Here

$$F_1(x_s, x) = F_0 B_0 \left(\frac{S}{d^2} \right) \int_{x_s}^x t^{\alpha-2} g(t) e^{-t} dt,$$

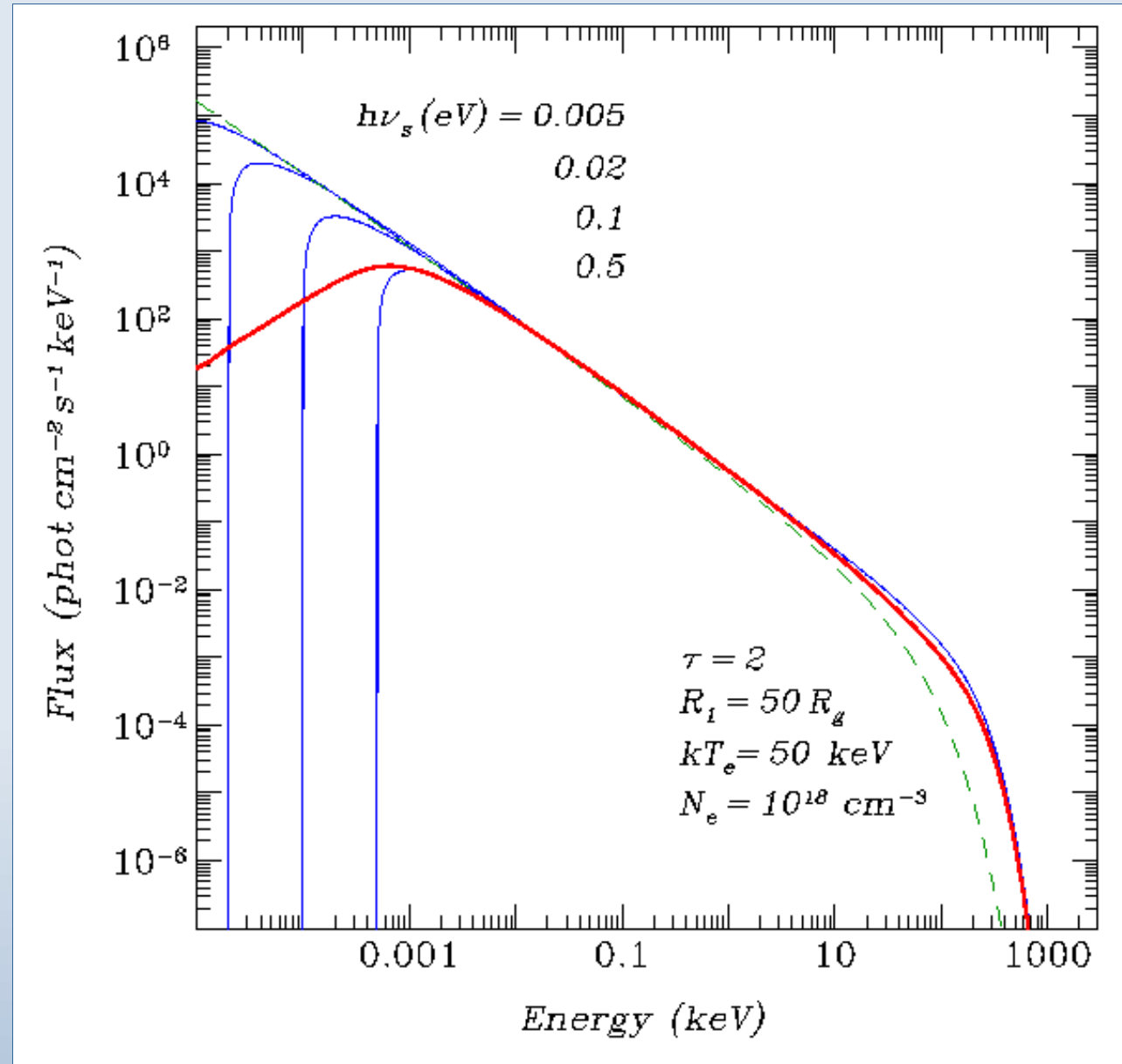
and α is the photon spectral index

Comptonized spectrum of the hot layer

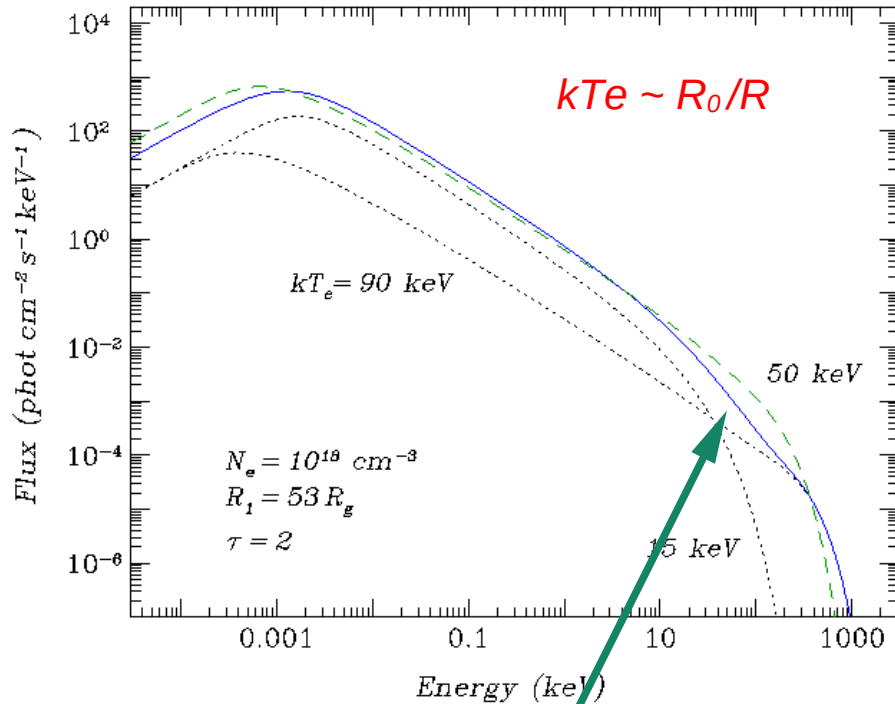
The comparison of our analytical solution (blue curves) with the computed photon spectrum of the internal radiation from the hot layer (red curve).

Energies $h\nu_s$ indicate the smallest energies of the bremsstrahlung spectrum considered.

The slight visible deviation at ~ 100 keV is probably due to different assumptions on the distribution of the initial soft photons over the hot layer depth.



A hot layer with real kT_e , N_e and τ_T radial distributions

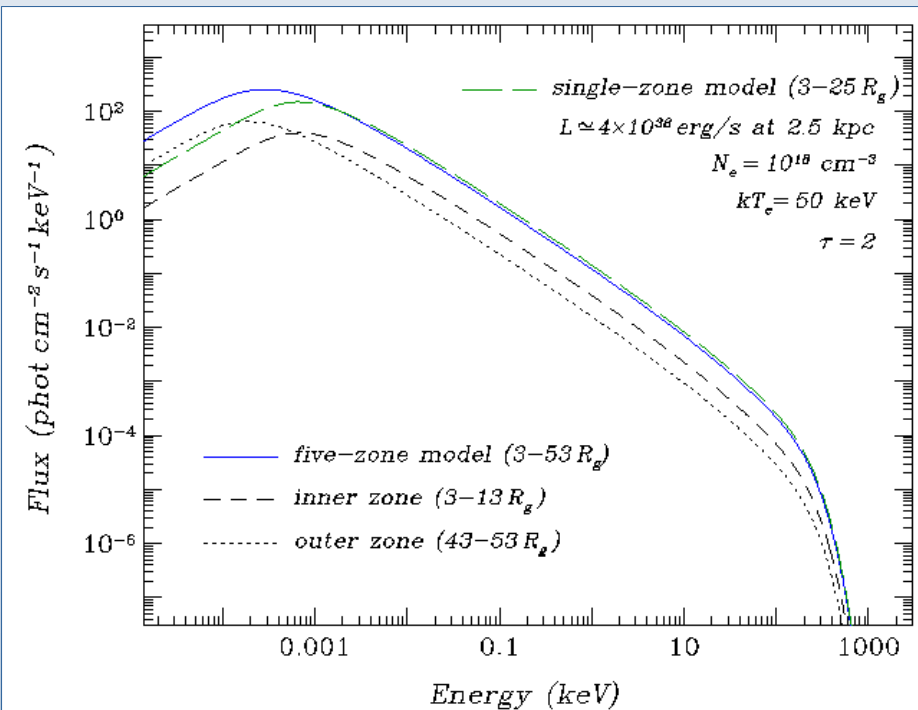


Dotted curves show the spectra for the inner and outer circular zones, green dashed line — the spectrum for a single-temperature model.

Note the quasi power law part of the spectrum in the hard X-ray band.

It is difficult to believe that the whole hot inner zone of the disk is isothermal and homogeneous taking into account a strong dependence of the energy release in a viscous disk on the radius $\sim R^{-3}$ (Shakura & Sunyaev 1973).

The shown are integral spectra for more realistic assumptions on kT_e (left) and N_e (bottom) radial distribution. They are similar the model with the uniform distributions.



$$N_e \simeq 2.3 \times 10^{18} \tau_T r^{-3/2} kT_*^{-1/2} m_*^{-1}, \text{ cm}^{-3}$$

A hot layer with real kT_e , Ne and τ_T radial distributions

$$N_e = 1.6 \times 10^{18} (m_*/\alpha)^{-3/4} \dot{m}_*^{-1/4} \phi^{-1/4} r^{-9/8} \text{ cm}^{-3}$$

Two-temperature model by Shapiro et al. (1976).

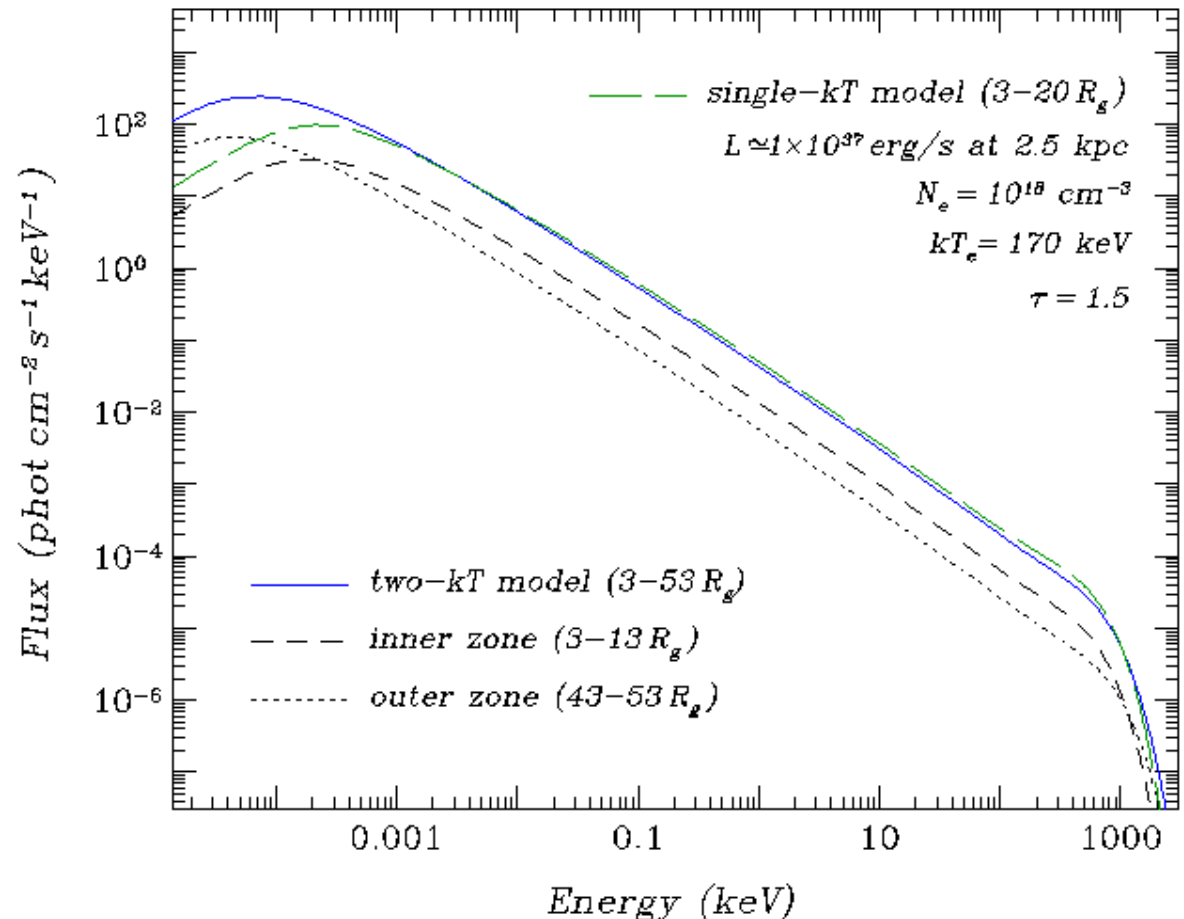
$$kT_e = 110 (m_*/\alpha)^{1/6} \dot{m}_*^{-1/6} \phi^{-1/6} r^{1/4}, \text{ keV}$$

$$\tau_T = 2.2 (m_*/\alpha)^{-1/6} \dot{m}_*^{1/6} \phi^{1/6} r^{-1/4}$$

The spectra of different circular zones are similar to the total spectrum (blue curve) with the exception of its low-energy and high-energy parts.

It can be reproduced by a single-temperature (uniform) model (long-dashed green curve).

Luminosity of the layer increases 10 times due to Comptonization.



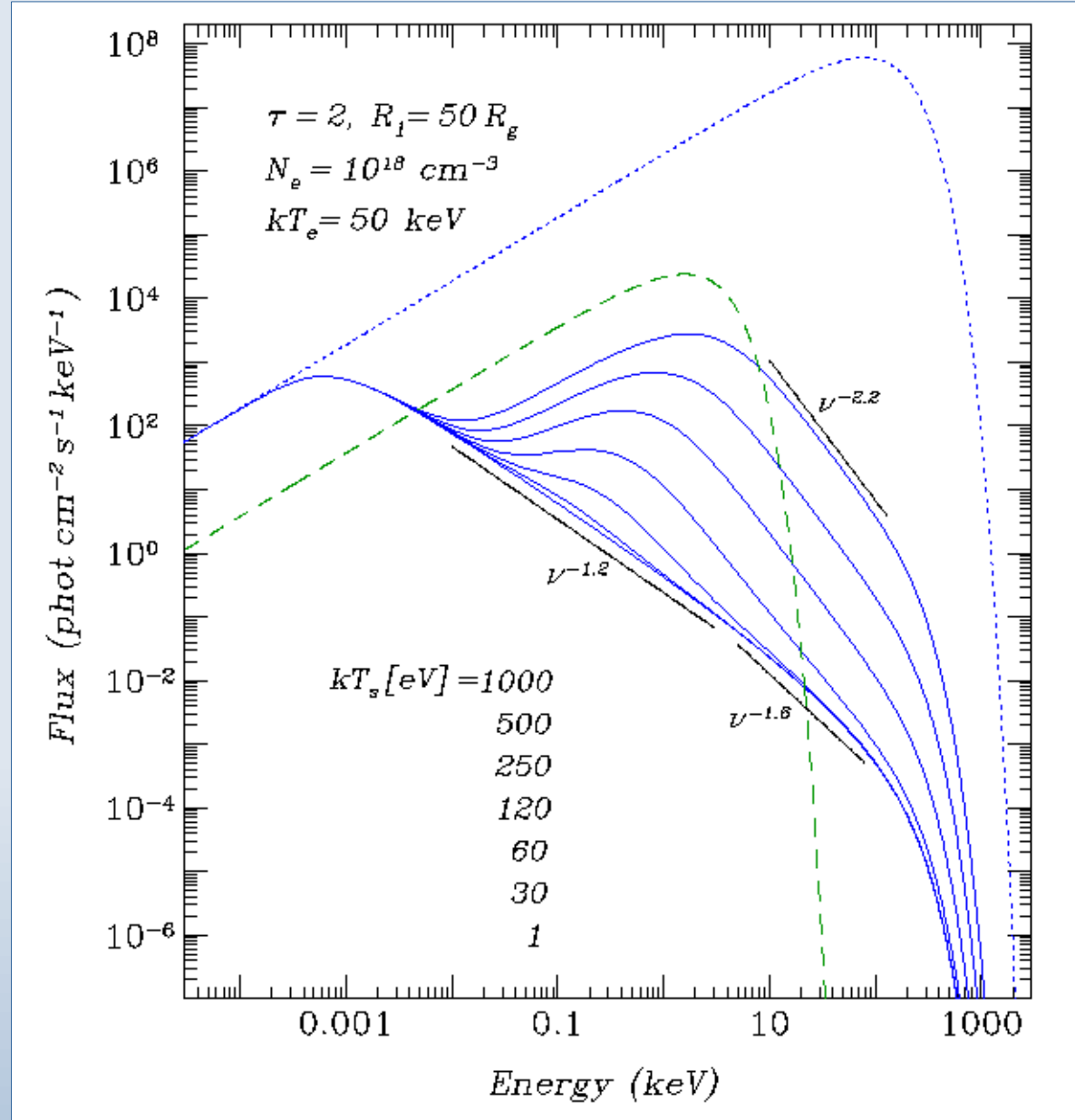
Comptonized spectrum of the hot layer (corona)

Model of a corona suggesting that a cold layer of the dense plasma with a black body temperature kT_s is located under a hot optically thin layer responsible for Comptonization.

The cold bottom layer supplies soft black body photons to the upper hot layer. The spectrum of the cold layer with $kT_s = 1$ keV is shown by green dashed line.

The model drastically changes a slope of the X-ray spectrum but does not affect the OIR emission.

The external soft photons with $kT_s \leq 50$ eV do not affect the shape and normalization of the whole spectrum (at all energies).

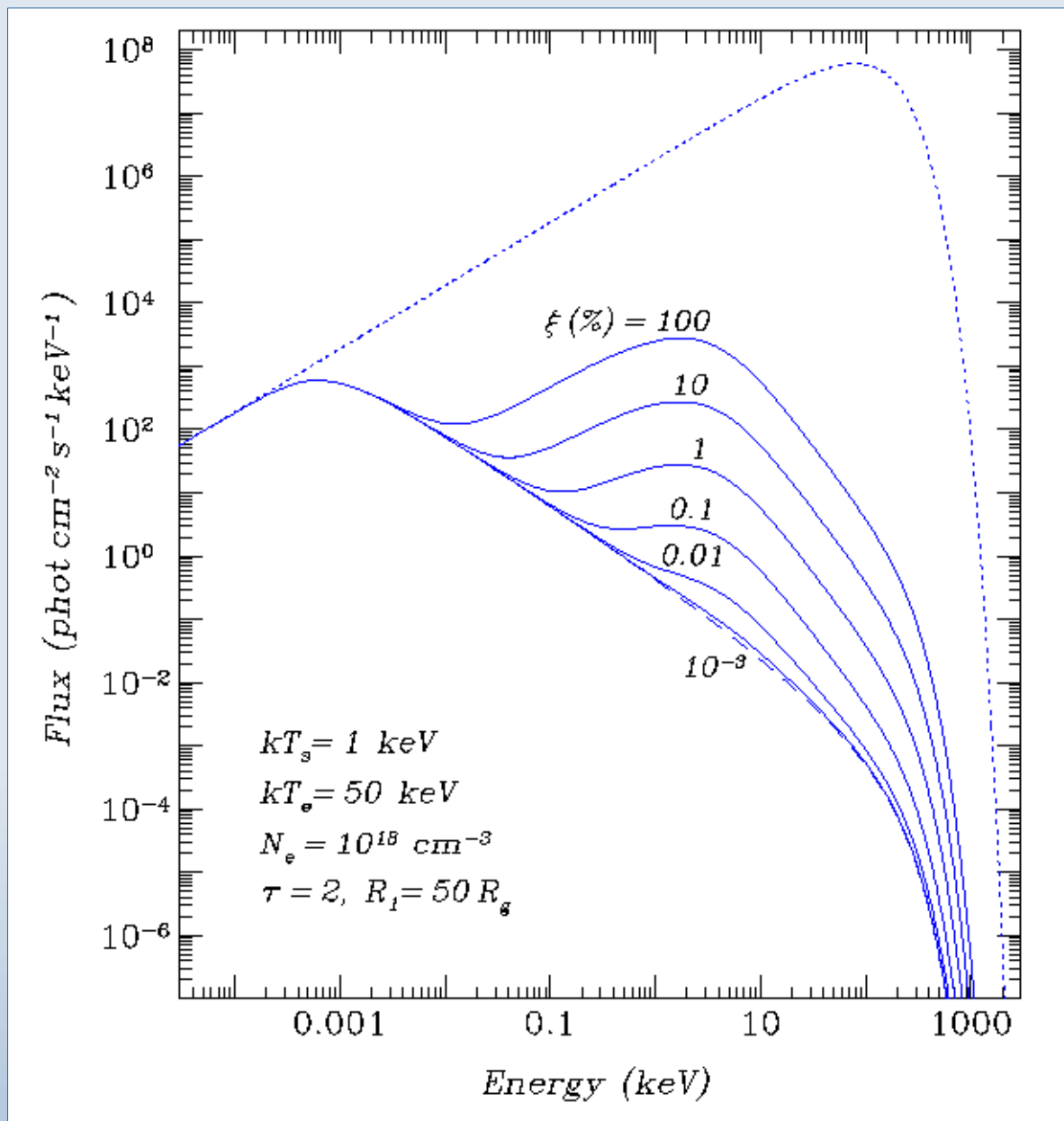


Comptonized spectrum of the hot layer (corona)

The same but for $kT_s = 1$ keV and assuming that only some fraction ξ (in percent) of the soft black body photons enter the hot layer.

This is because the total number of photons emitted by the underlying surface is unreally huge.

But even very small number of such photons ($\xi \sim 10^{-4}$) entering the hot layer affect the spectrum and change its slope.

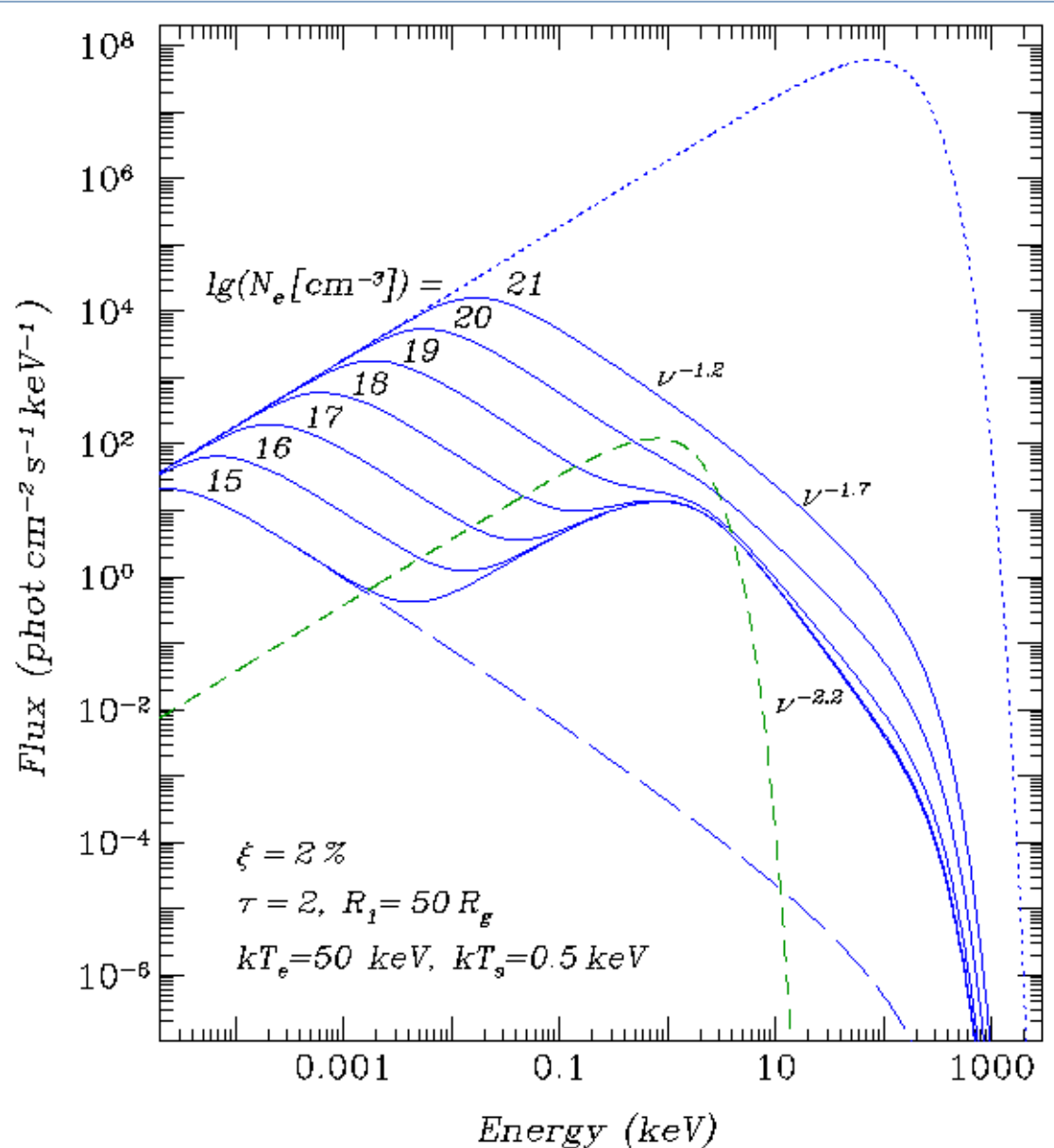


Comptonized spectrum of the hot layer (corona)

Changes in the forming spectrum of the corona vs. the plasma number density.

The temperature of soft photons from the underlying surface $kT_s = 0.5$ keV, their fraction entering the hot layer is 2% ($\xi = 0.02$).

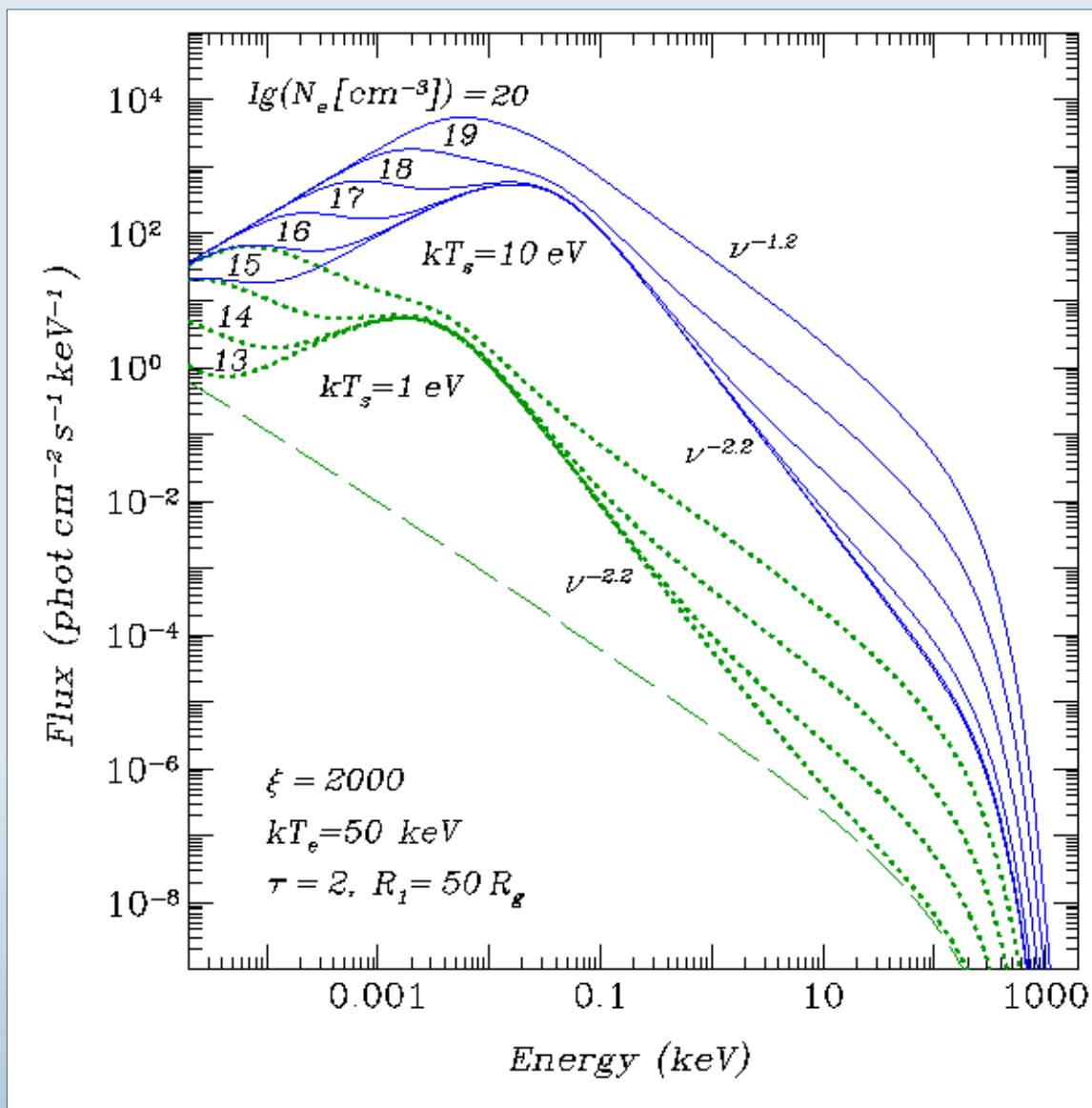
Comptonization of these external photons strongly affects the shape and normalization of the intrinsic plasma X-ray spectrum at $N_e \leq 10^{19} \text{ cm}^{-3}$.



Comptonized spectrum of the hot layer (corona)

The same but for $kT_s = 1$ or 10 eV, the fraction of soft photons entering the hot layer is $\xi = 2000$.

Comptonization of these soft photons affects the shape and normalization of the intrinsic plasma X-ray spectrum at $N_e \leq 10^{17} \text{ cm}^{-3}$ (for $kT_s = 10$ eV) or $N_e \leq 10^{14} \text{ cm}^{-3}$ ($kT_s = 1$ eV).



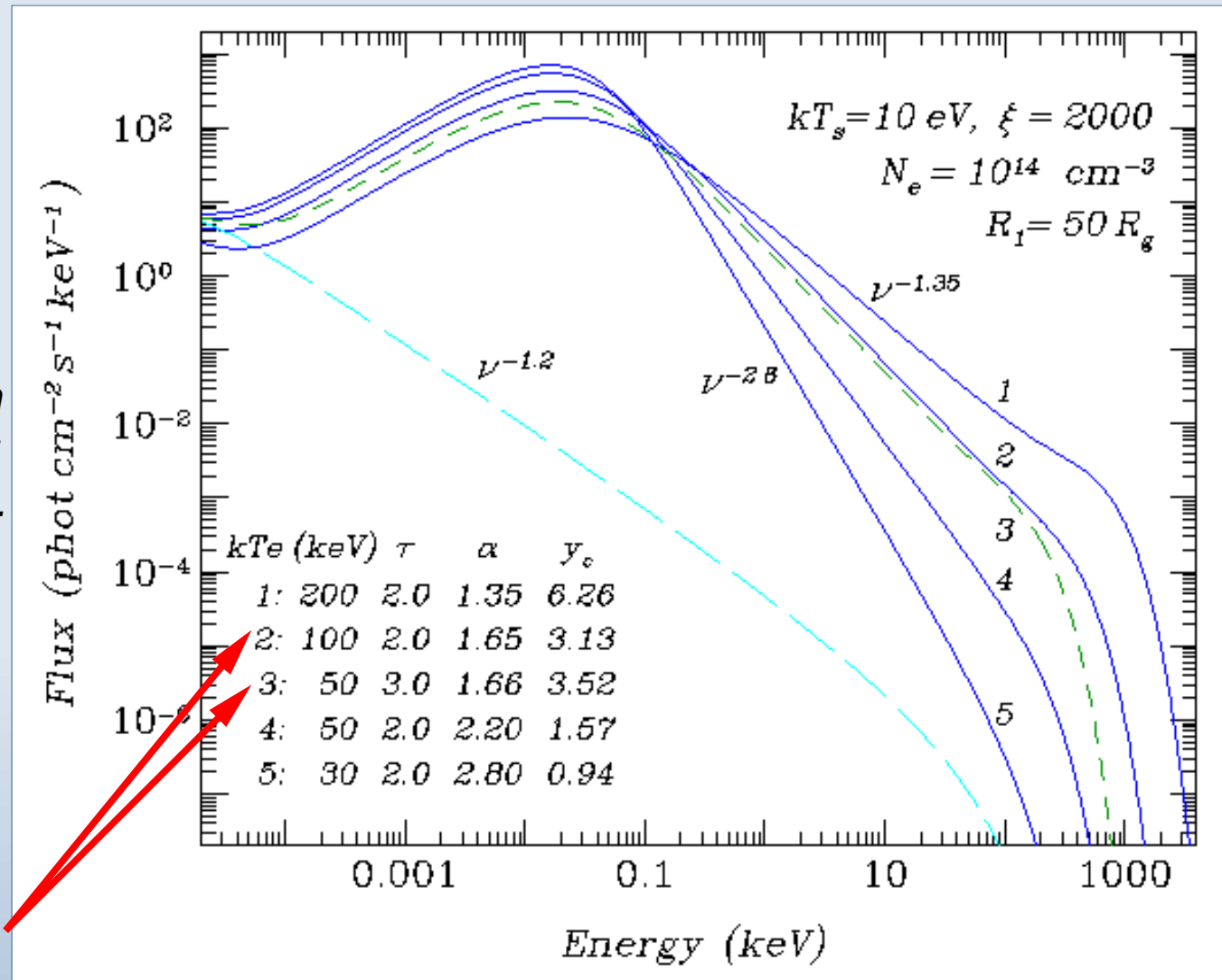
Comptonized spectrum of the hot layer (corona)

The case of the low density plasma $N_e \sim 10^{14} \text{ cm}^{-3}$

In fact this is just usual Comptonization of seed photons.

The temperature of the underlying surface is $kT_s=10 \text{ eV}$, the fraction of the photons entering the hot layer is $\xi=2000$.

It is easy to fit the plasma parameters and obtain the canonical spectrum of black holes in the low (hard) state with the photon index $\alpha = 1.65$.



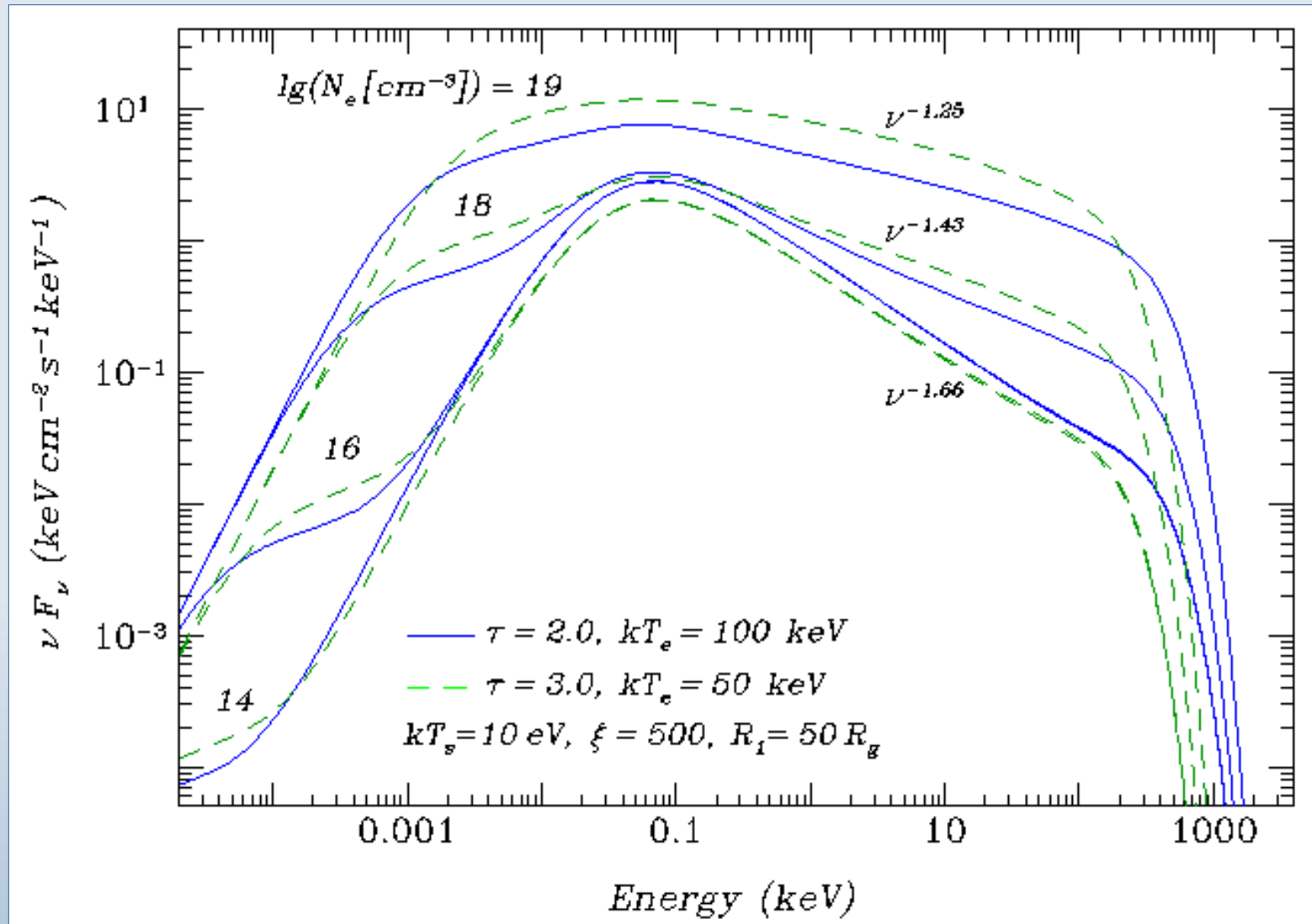
Comptonized spectrum of the hot layer (corona)

Now we see the drastic evolution of the selected (canonical) spectra with increasing the electron density

Green curves are the spectra for $kT_e = 50$ keV and $\tau_T = 3.0$.

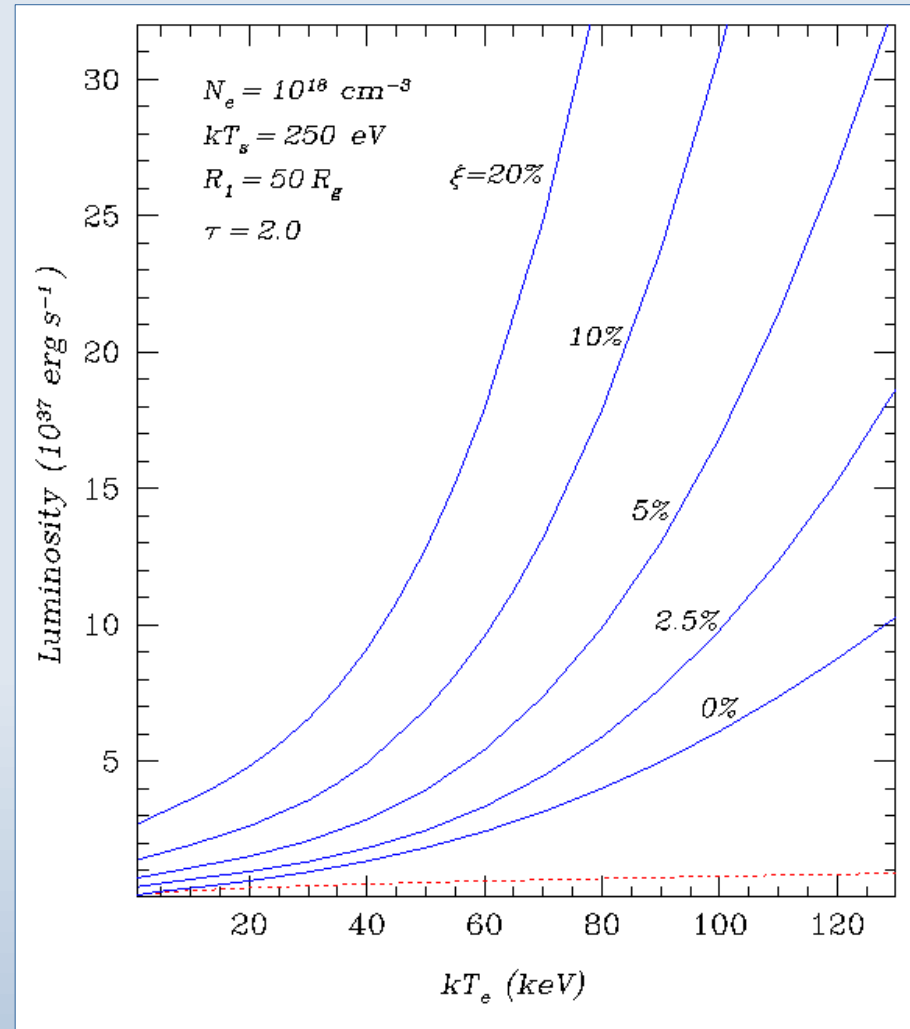
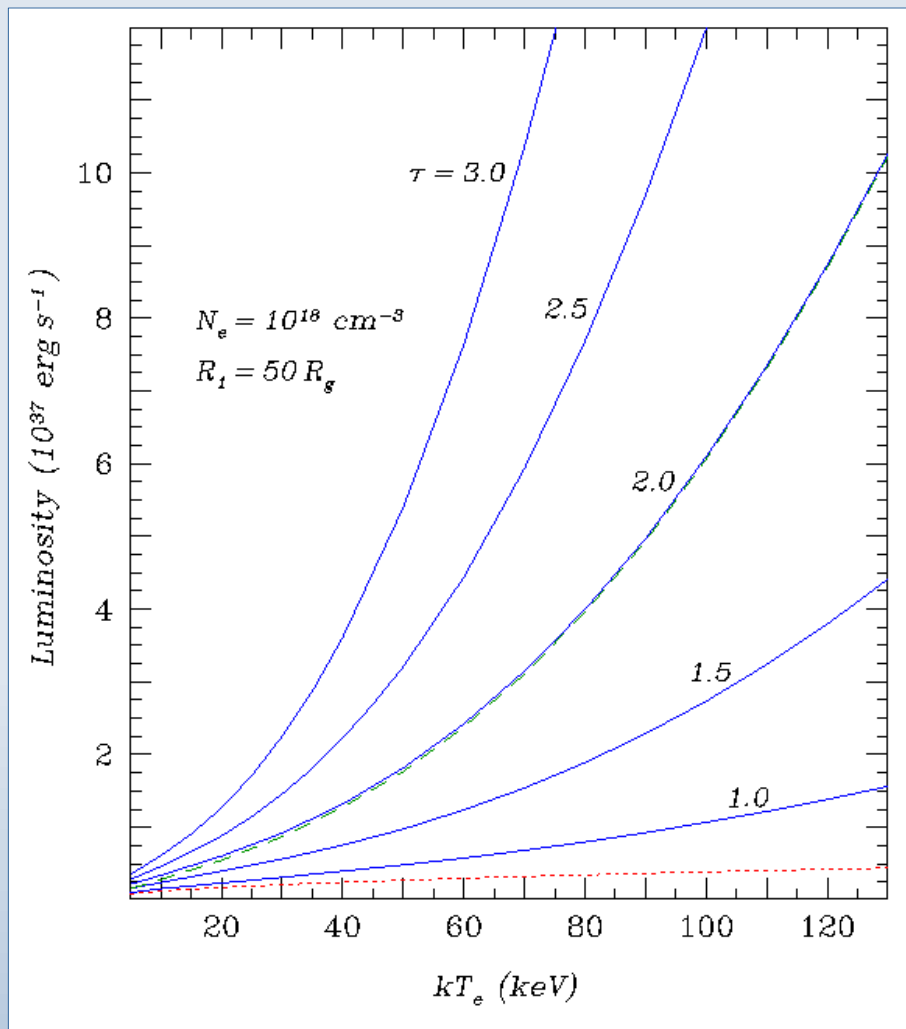
Blue curves are the spectra for $kT_e = 100$ keV and $\tau_T = 2.0$.

The photon index changes from $\alpha = 1.66$ to $\alpha = 1.25$ while the density increases from $N_e = 10^{14}$ to 10^{19} cm^{-3} .



Comptonized spectrum of the hot layer

Luminosity of the plasma layer increases strongly due to Comptonization (rising with the temperature, optical thickness and fraction of the seed photons entering the layer).



UV-OIR radiation

Our computations predict that the hard X-ray spectrum observed from accreting black holes and formed in the high-temperature plasma of the central zone of their accretion disk extends as a power law to the near-infrared, optical, and long-wavelength ultraviolet ranges. The spectral shape changes only below $h\nu \leq 0.3$ eV, where it transforms into the Rayleigh-Jeans spectrum corresponding to the plasma temperature in this zone.

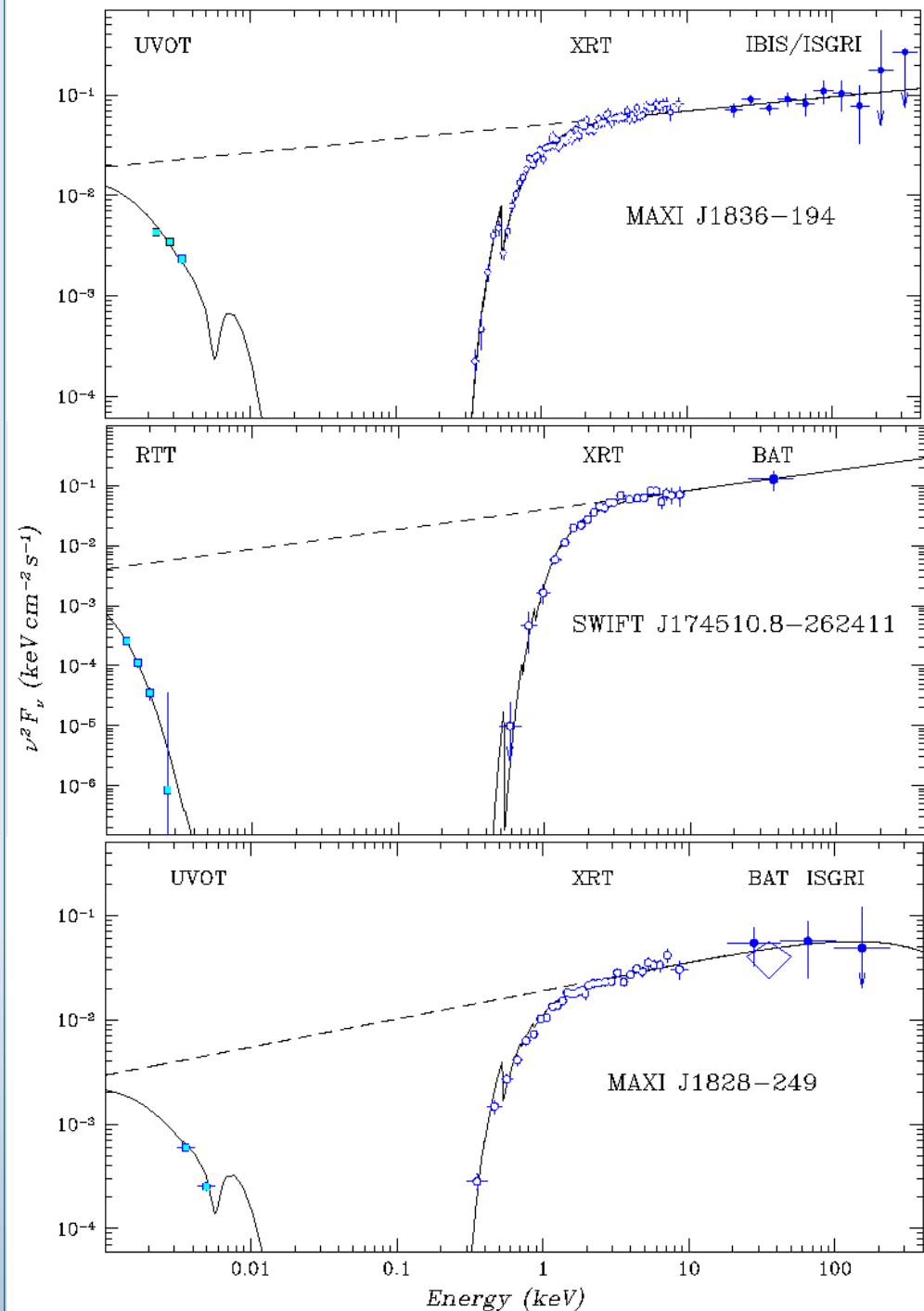
This conclusion coincides with observations.

Source	α^a	N_H^b	Reference ^c
MAXI J1836-194	1.86	0.29	2013
SWIFT J174510.8-262411	1.67	1.21	2014
MAXI J1828-249	1.73	0.23	2016

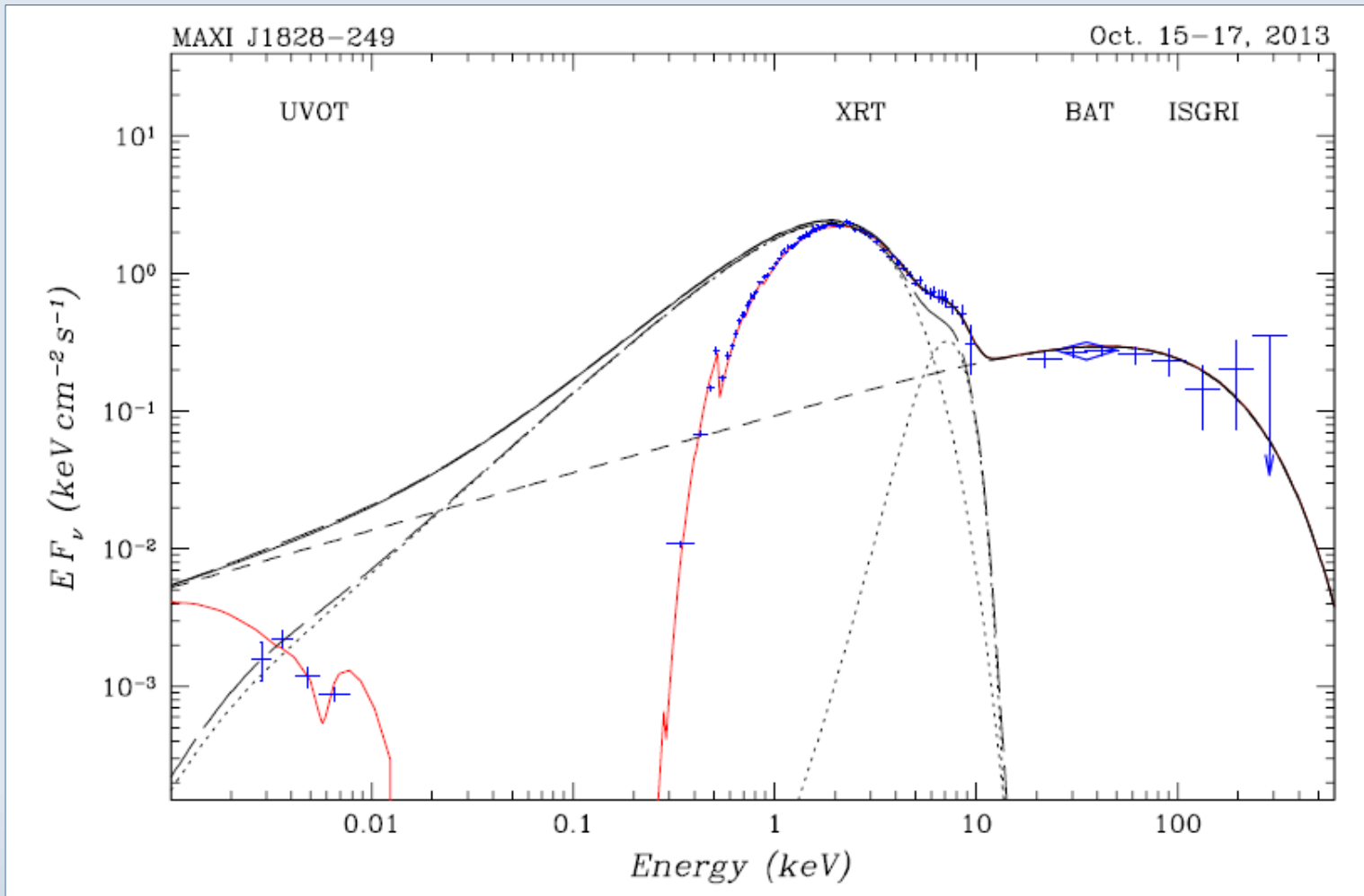
^a The photon index.

^b The hydrogen column density, 10^{22} cm⁻².

^c Grebenev et al. (2013, 2014, 2016).



MAXI J1828-249

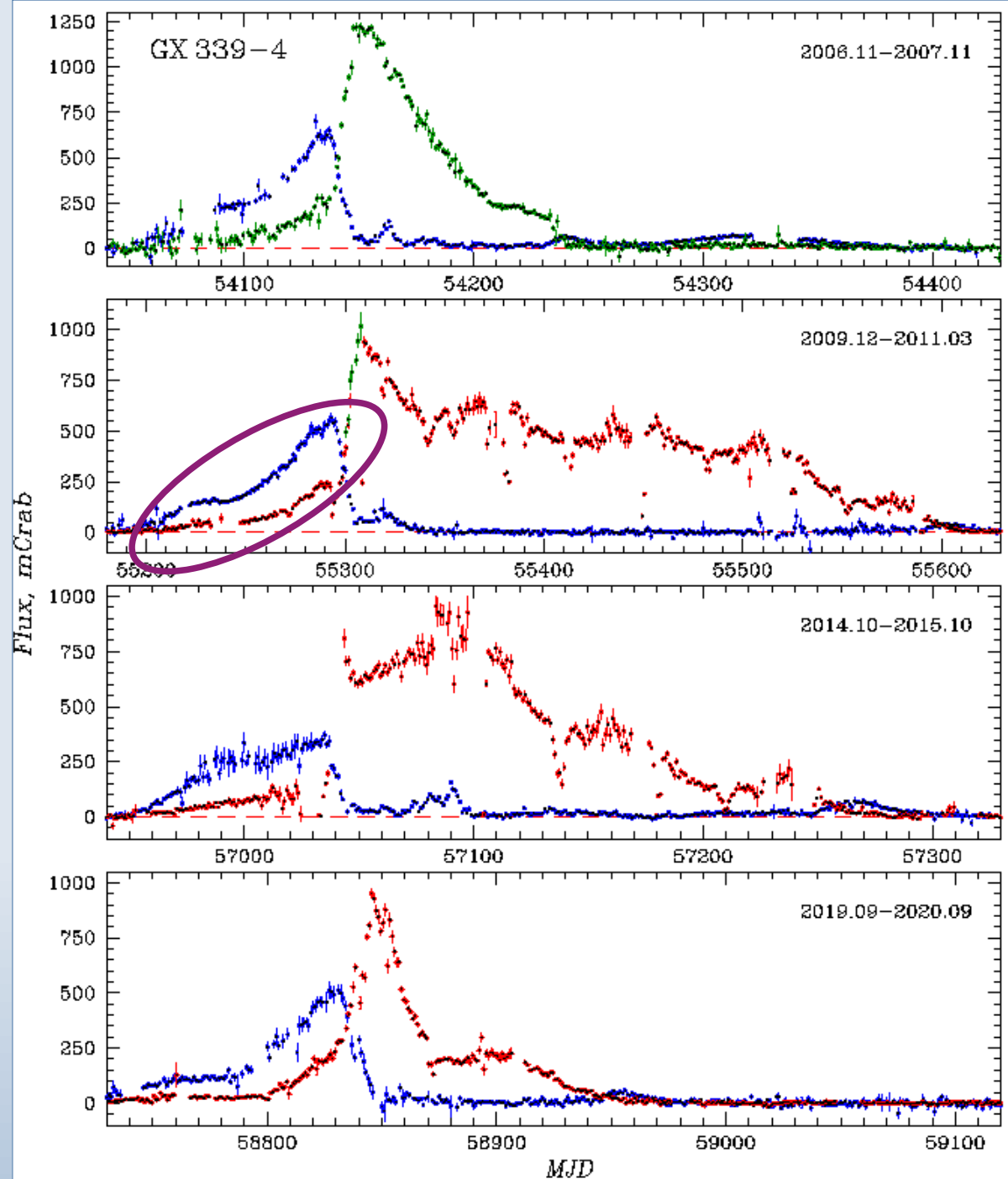


Even when the spectrum had a bright soft X-ray component (high state) its OIR emission was likely produced in the hot region of the disk (it follows the same power law as that describing the hard X-rays, the contribution of the black body component was negligible at these energies (Grebenev et al. 2016).

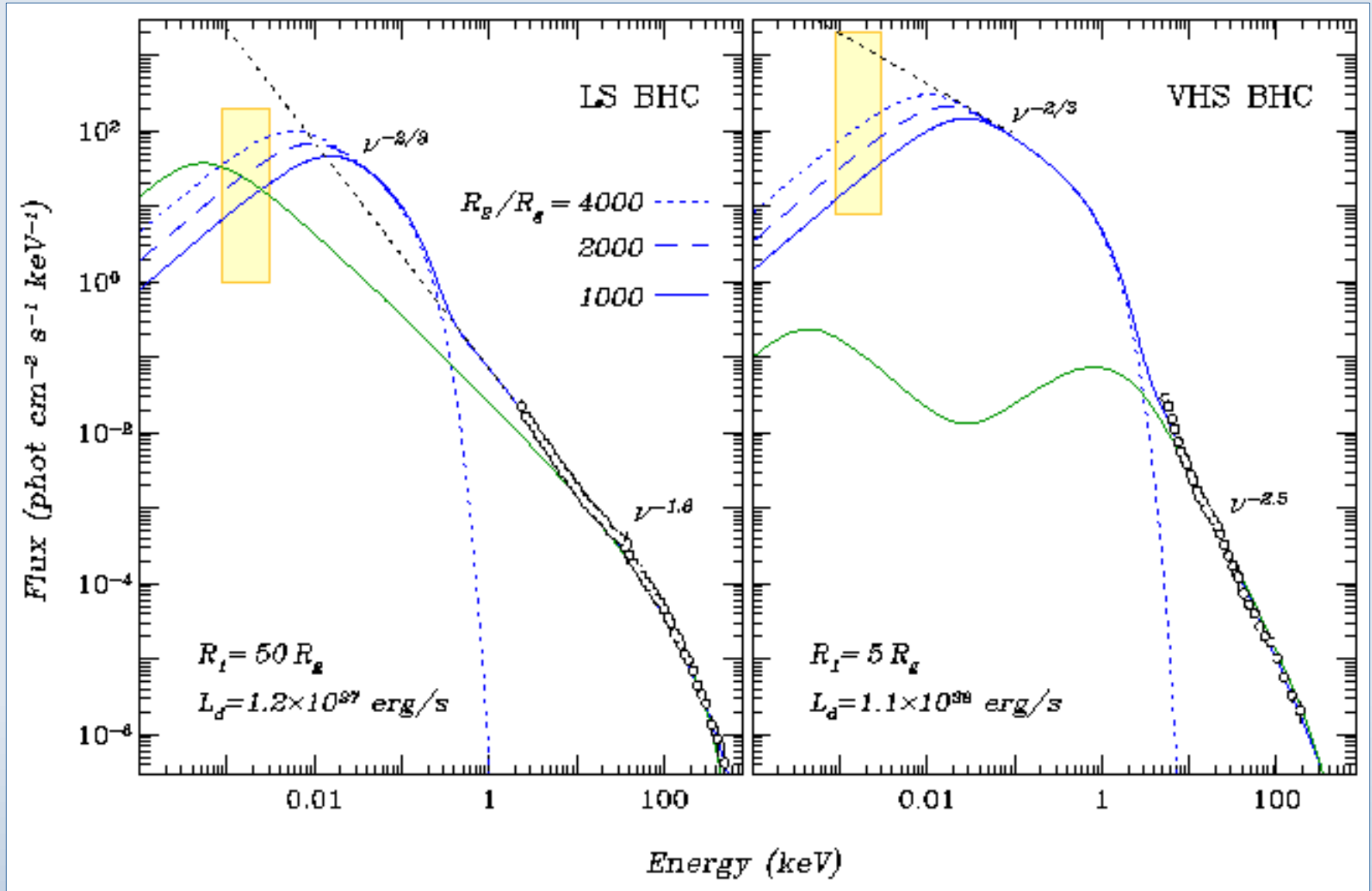
GX 339-4

All the soft outbursts observed in 2005-2019 (blue points — the hard band, others — soft band).

The obvious correlation of the hard and soft light curves in the beginning of the outbursts (at the stage of rising the flux) indicates that the soft X-ray emission was produced in the same inner hot region of the disk where the hard radiation was formed.

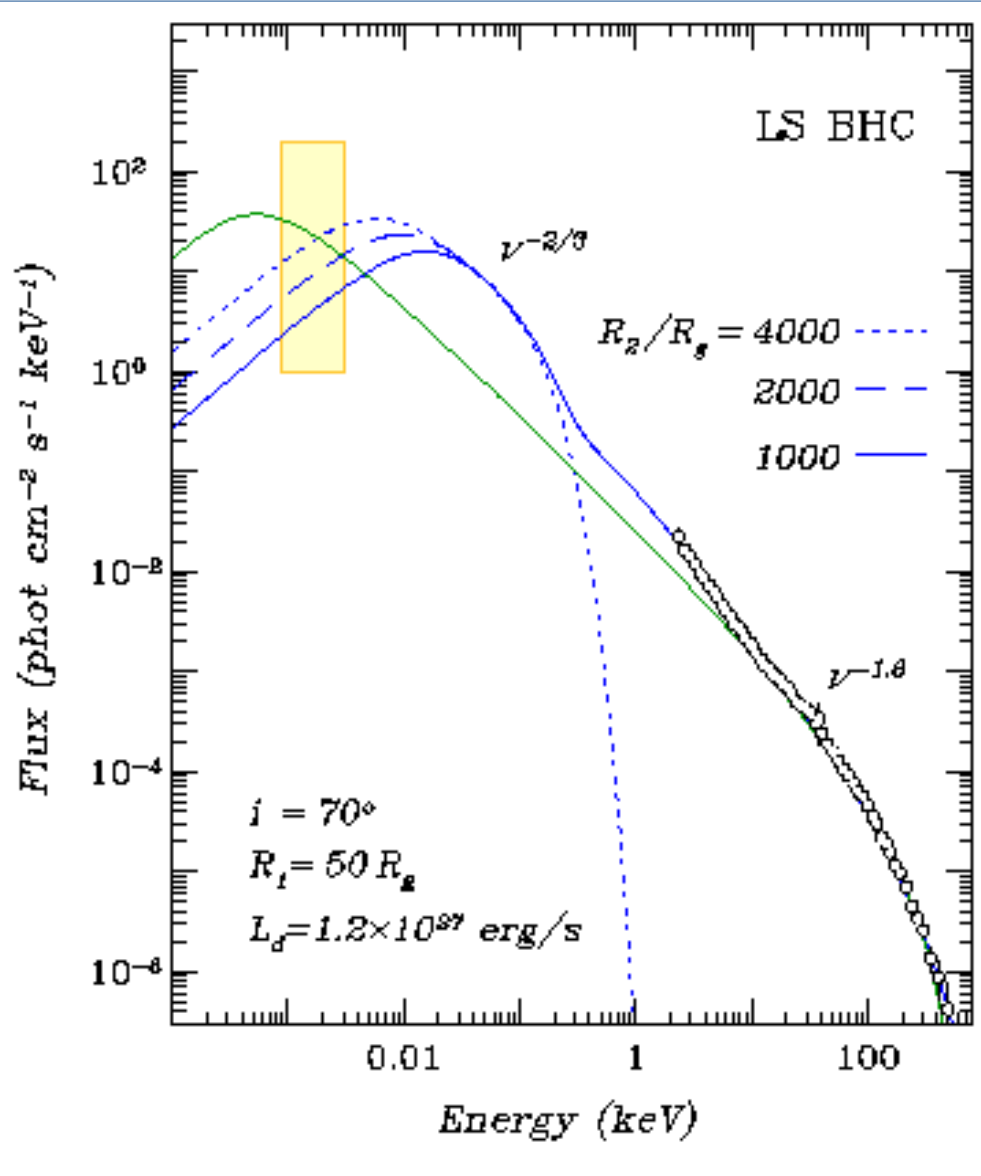


Broad-band accretion disk spectrum for two states



These are computed spectra at 10 kpc. In the X-ray band they are compared with the observations of Cygnus X-1 and Nova Musca 1991 (GRS 1124-68) properly normalized for distance.

Broad-band accretion disk spectrum for two states



The same low state spectrum but observed with a large inclination $i=70^\circ$. The green curve shows the spectrum of the inner hot zone of the disk. In the OIR band it dominates over the black body spectrum of the outer disk regions.

Выводы

- *Intrinsic radiation of a hot plasma layer can completely explain the observed X-ray spectra of accreting black hole in their hard state without involving external soft photons.*
- *Shape of the spectrum depends not only on the plasma temperature and optical depth but also on its electron number density. All of the previous computations of the Comptonization of seed photons in a plasma cloud can be incorrect, since they completely ignore the plasma bremsstrahlung.*
- *The intrinsic hard X-ray spectra of the hot plasma in the central accretion disk zone extend in an invariable form (with the same power law) to the optical and infrared ranges, transforming at $h\nu \leq 1$ eV into the Rayleigh-Jeans spectrum that falls off toward low energies.*
- *When the hot zone is extended (source is in the hard state) the direct correlation between soft and hard X-ray radiation appears.*
- *When photons from the outer cold accretion disk regions enter the hot region, its X-ray spectrum usually softens and becomes similar to the spectrum observed from accreting black holes during their soft or two-component states (with a photon index $\alpha \sim 2.2-2.5$). An increase in the flux of external photons is most likely caused by the fact that the inner edge of the cold disk region approaches the black hole maximally closely.*

Выводы

- *External photons of sufficiently low energies, even when entering the hot disk zone, do not affect noticeably the forming spectrum of its radiation. Otherwise, we could have observed these sources in their canonical hard state much more rarely, since it is impossible to completely rule out the penetration of external photons into the high-temperature region.*
- *Obviously the transition between the spectral states of accreting black holes is determined by the change in the accretion rate and the corresponding approach or recession of the boundary between the central hot and outer cold accretion disk regions (the truncated disk model). But the surface temperature of the outer disk near this boundary plays an important role in whether a change in the shape and type of the X-ray spectrum will be observed in this case.*
- *In many cases, the OIR and UV radiation observed from accreting black holes during their hard state is precisely the radiation from the high-temperature plasma in the central disk region rather than the “multicolor” blackbody radiation from its extended cold regions (as is commonly assumed). During the soft state of such sources the “multicolor” radiation from the outer disk regions almost always dominates in these ranges.*

X-ray and Gamma-ray Emission from a High-Temperature Plasma and the Spectra of Accreting Black Holes

S. A. Grebenev*

Space Research Institute, Russian Academy of Sciences, Moscow, 117997 Russia

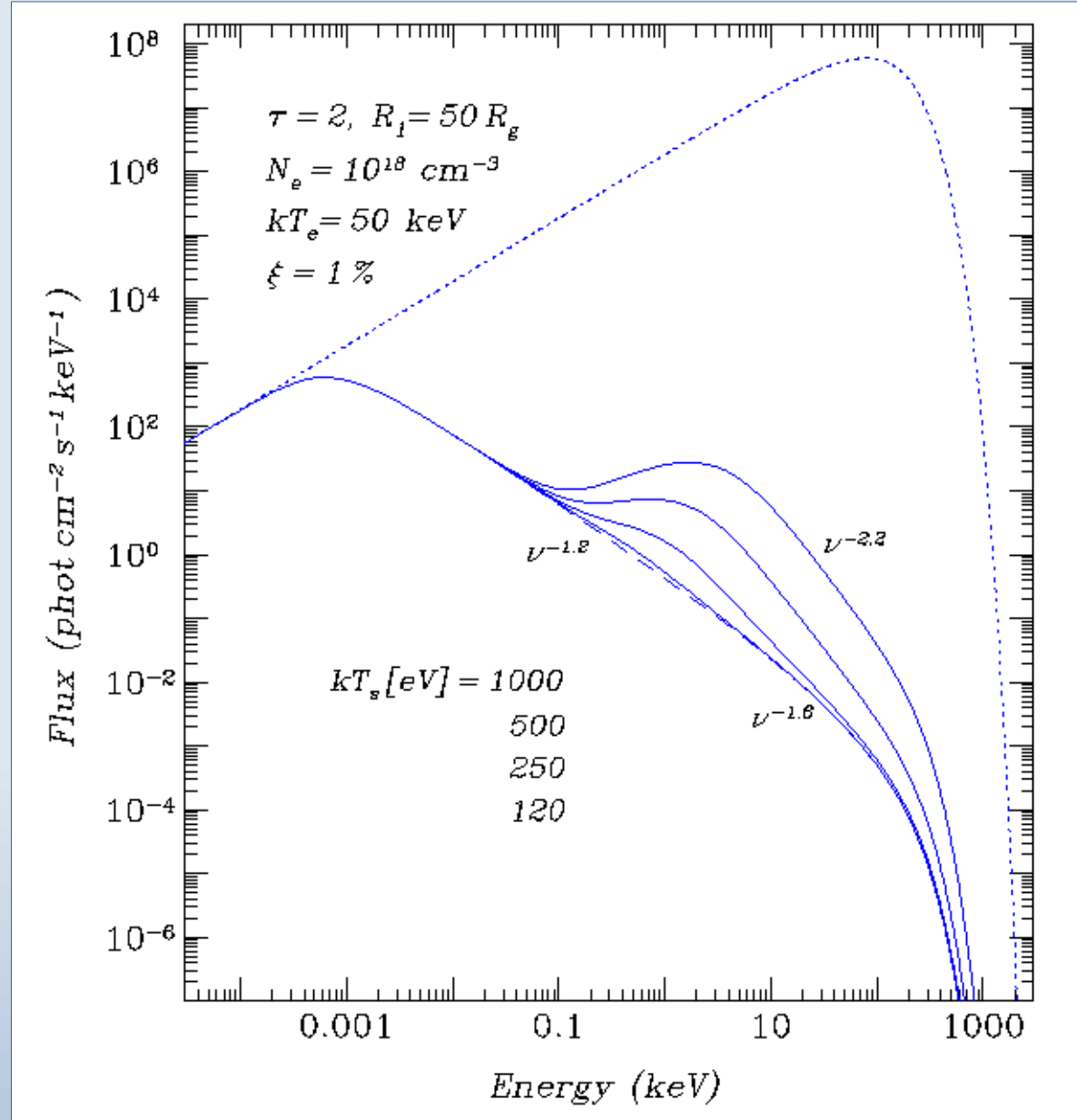
Received January 21, 2025; revised April 22, 2025; accepted August 19, 2025

Thank you !

Comptonized spectrum of the hot layer (corona)

The same but for different kT_s and assuming that only 1% ($\xi = 0.01$) of the soft black body photons enter the hot layer.

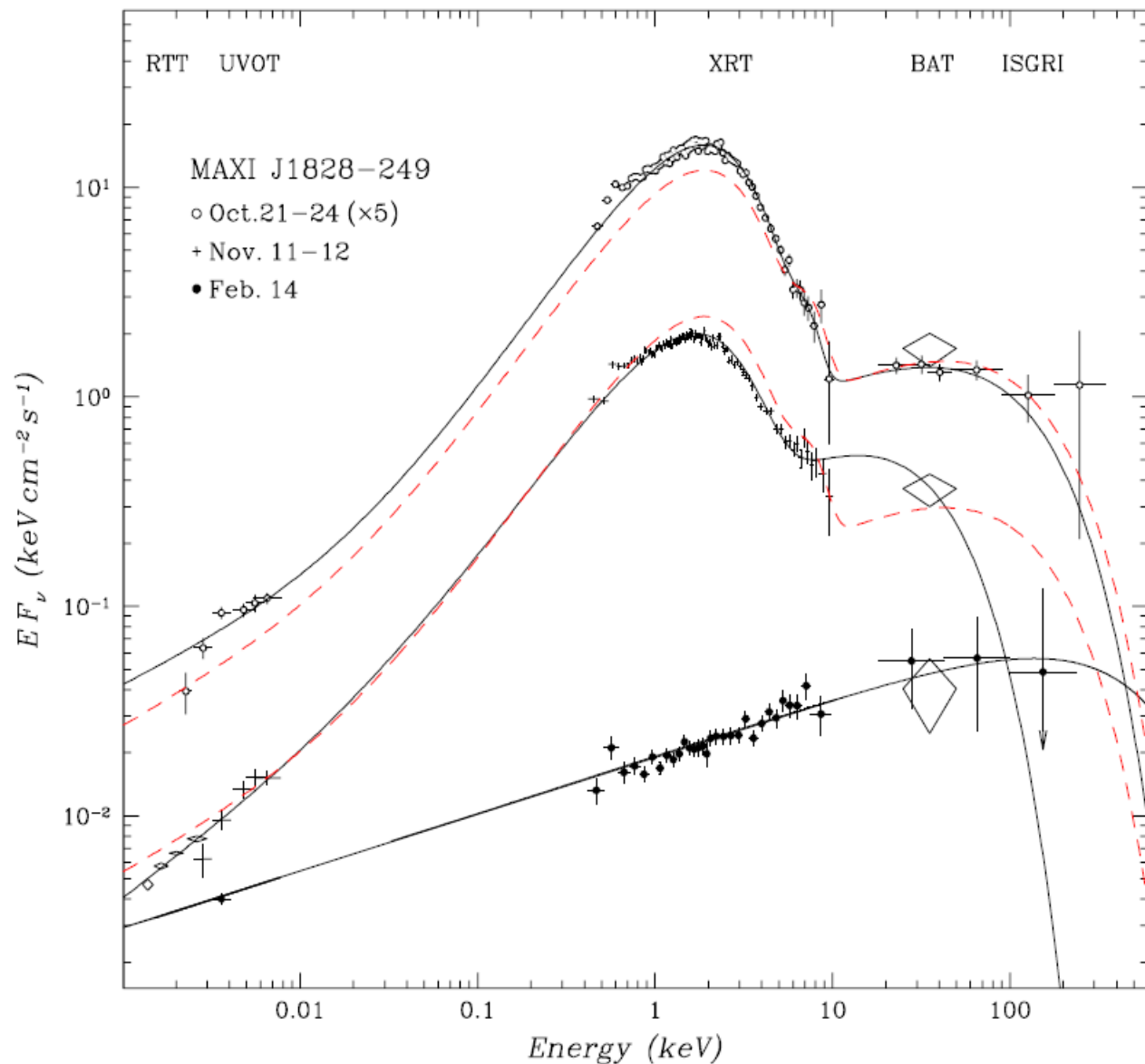
The external photons with $kT_s \leq 120$ eV do not really affect the shape and normalization of the spectrum.



MAXI J1828-249

Степенная экстраполяция жесткого рентгеновского спектра в оптическую область дает доминирующий вклад в наблюдаемый оптический поток не только в жестком состоянии, но и в мягком.

(Гребенев и др., *AstL*, 2016, 42, 69-81)



Комptonизованный спектр горячего слоя

Модель с короной для диска - холодный слой плазмы температуры kT_s , расположенный ниже горячего оптически тонкого слоя, ответственного за комптонизацию. Холодный слой поставляет в горячий мягкие чернотельные фотоны.

Эта модель показывает, что **ранние Монте-Карловские** расчеты не верны, т. к. не учитывают естественное тормозное излучение.

Модель кардинально изменяет наклон рентгеновского спектра, но не затрагивает оптический и инфракрасный поток.

