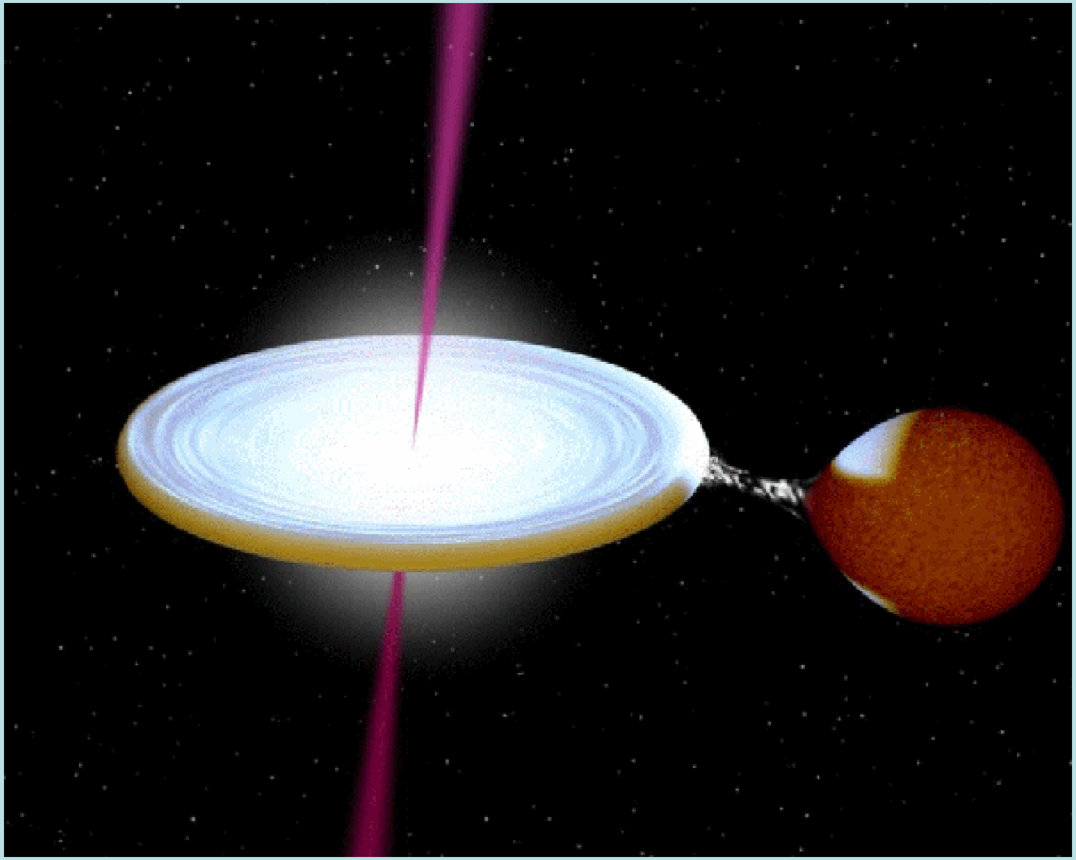
New findings from the broad-band spectra of X-ray novae observed with INTEGRAL



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Black Holes

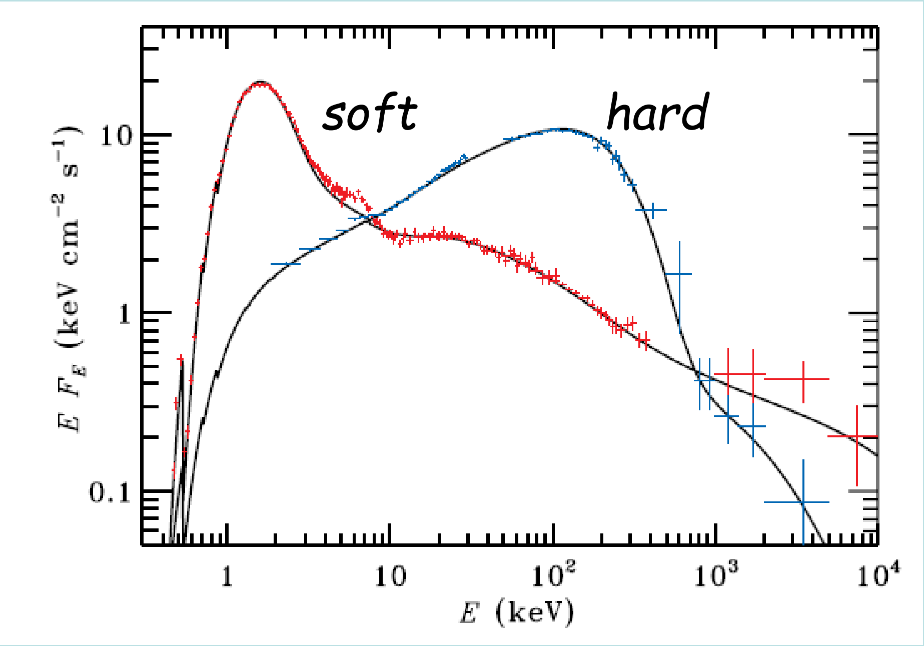
We can not understand the origin of X-rays in accreting BHs using X-ray data only (V.Grinberg)

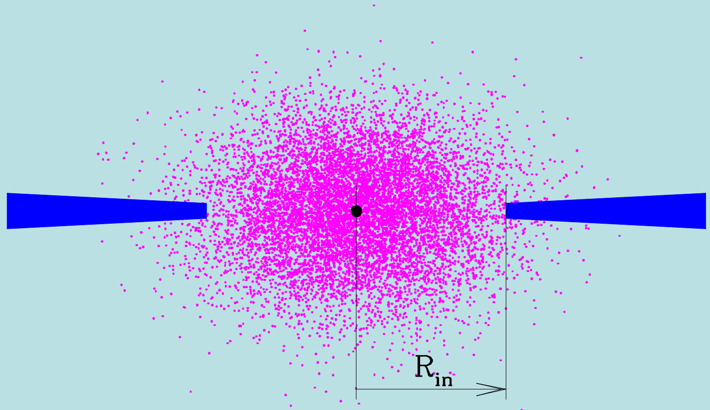
But we can get some understanding from their broad-band (OIR-hard X-ray) spectra (SED)

X-ray novae

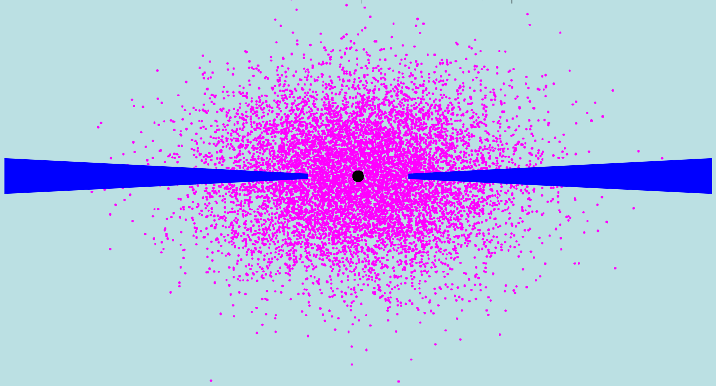
- Long-term (months) X-ray transients containing a black hole (or a neutron star with low magnetic field)
- LMXB $\longrightarrow$ optical and infrared emission comes from the accretion disk (not from the normal star)
- They demonstrate different spectral states vs accretion rate $\longrightarrow$ allow X-ray-optical correlations to be studied for different regimes of accretion

Truncated disk



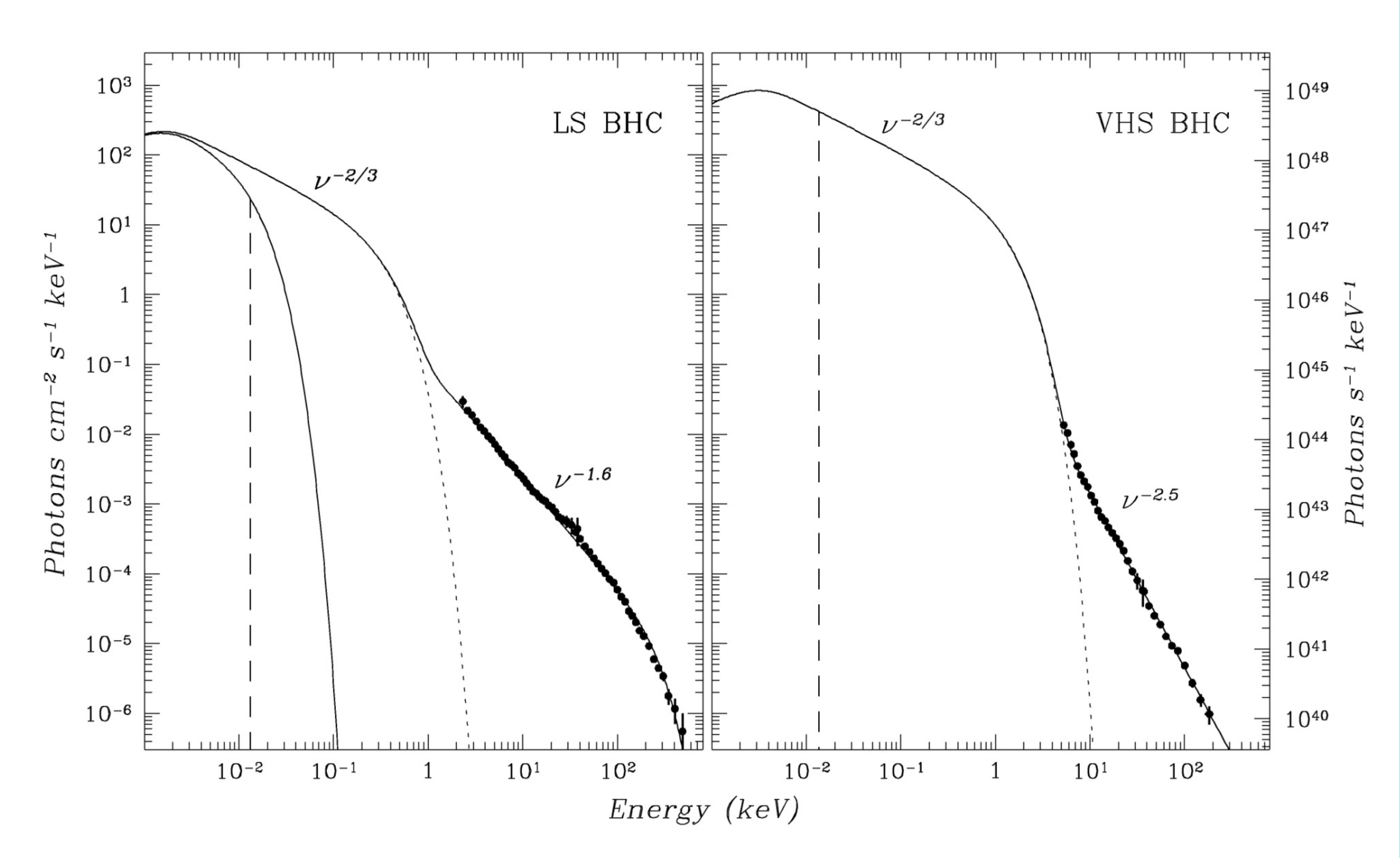


hard state, R_{in} is large



soft state, R_{in} is small

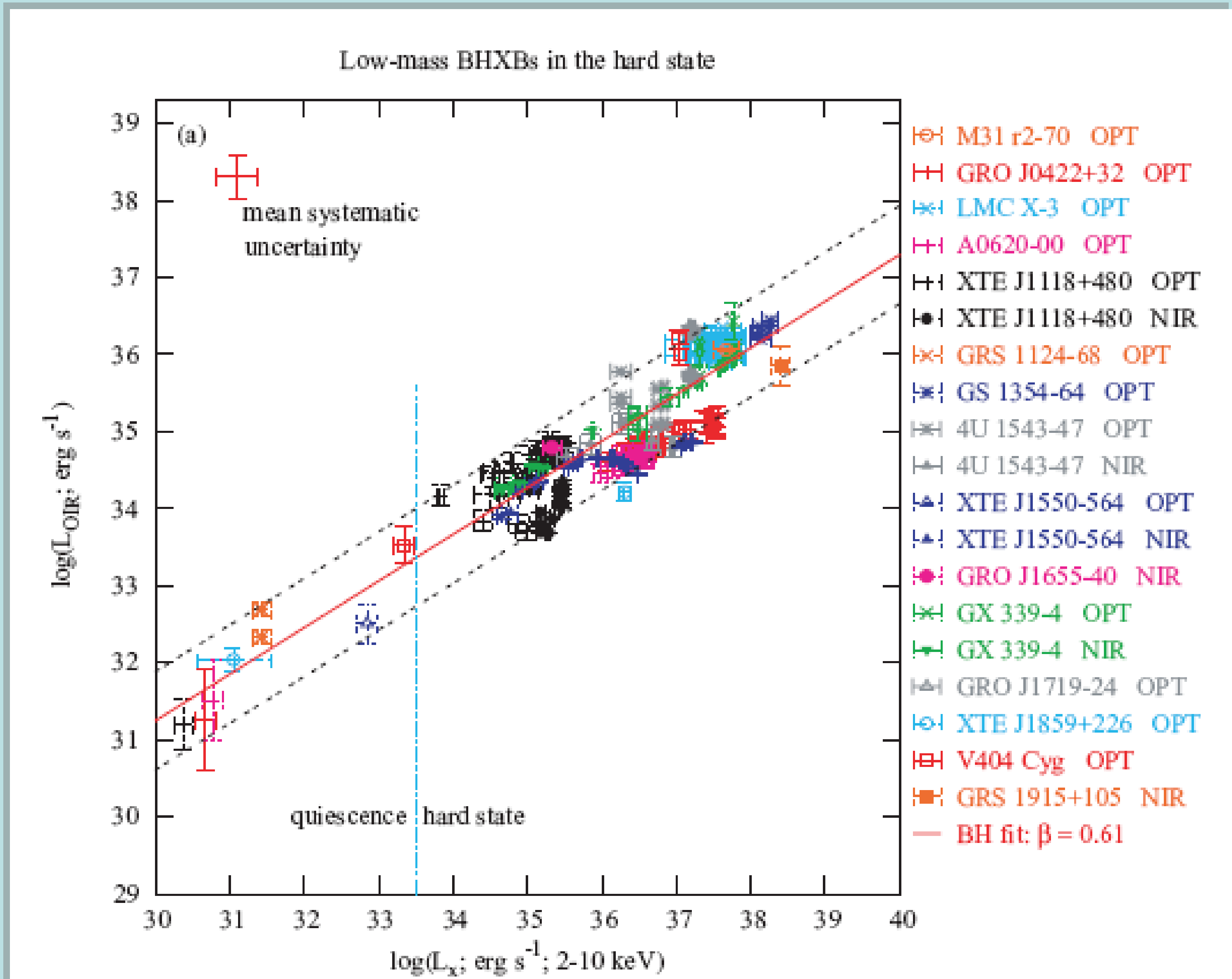
Model broad-band spectra of black holes



Optical and infrared emission of X-ray novae

- *originates from the cold outer regions of an accretion disk*
- *is powered by viscosity inside the disk and illumination of its surface by hard X-rays from the central region*

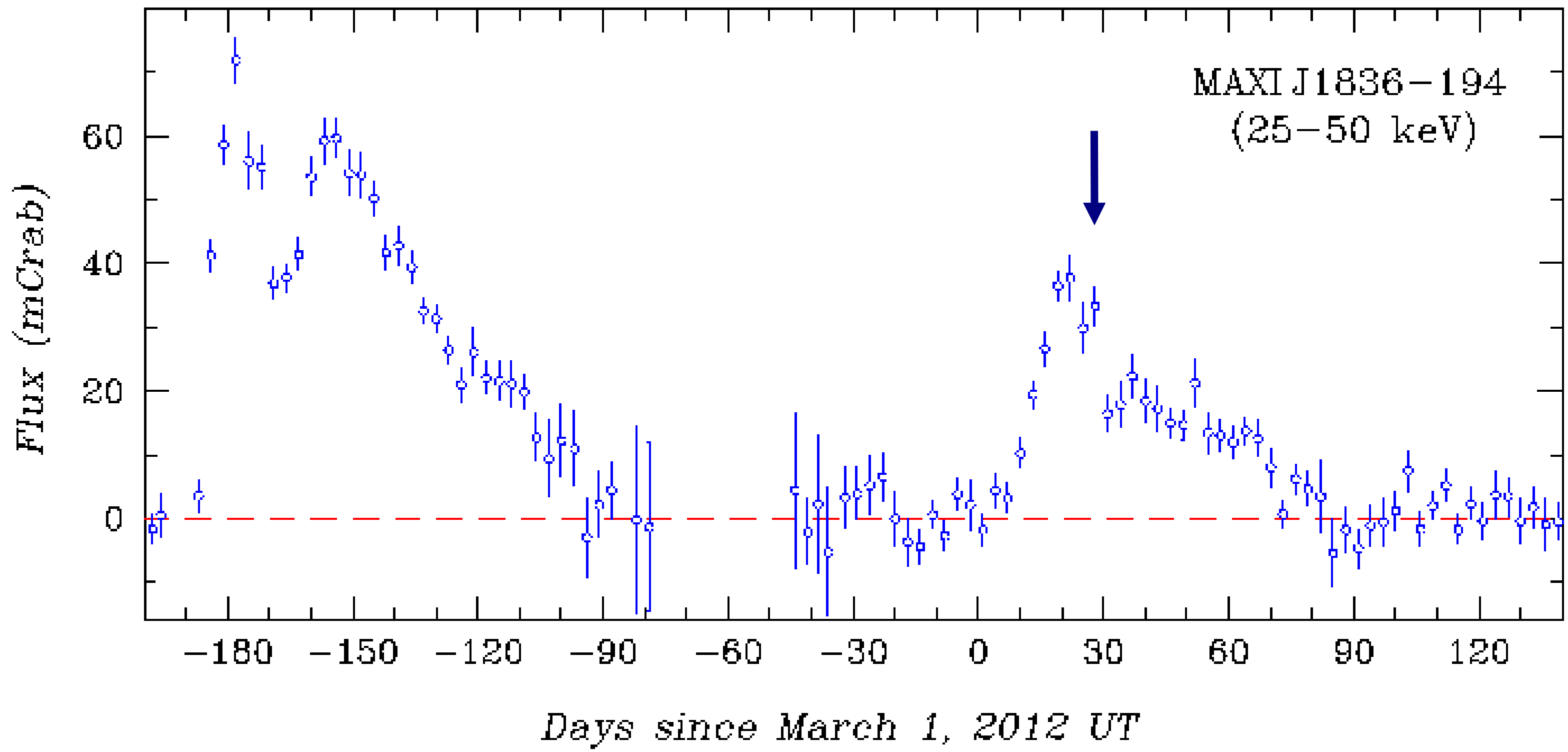
L_X-L_{OIR} correlation for black hole binaries



$$L_{\rm OIR} \propto L_{\rm X}^{0.6}$$

(Russell et al. 2006)

MAXI J1836-194



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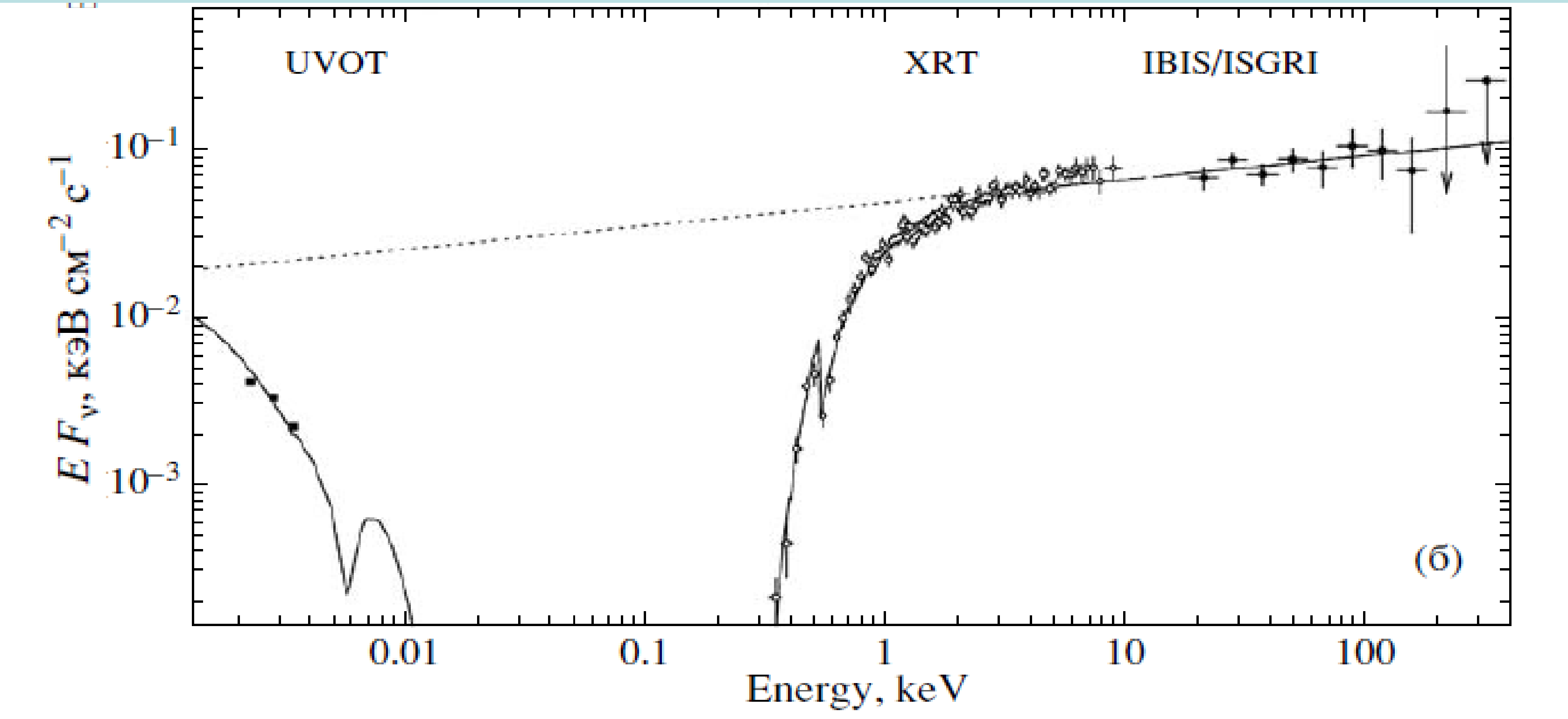
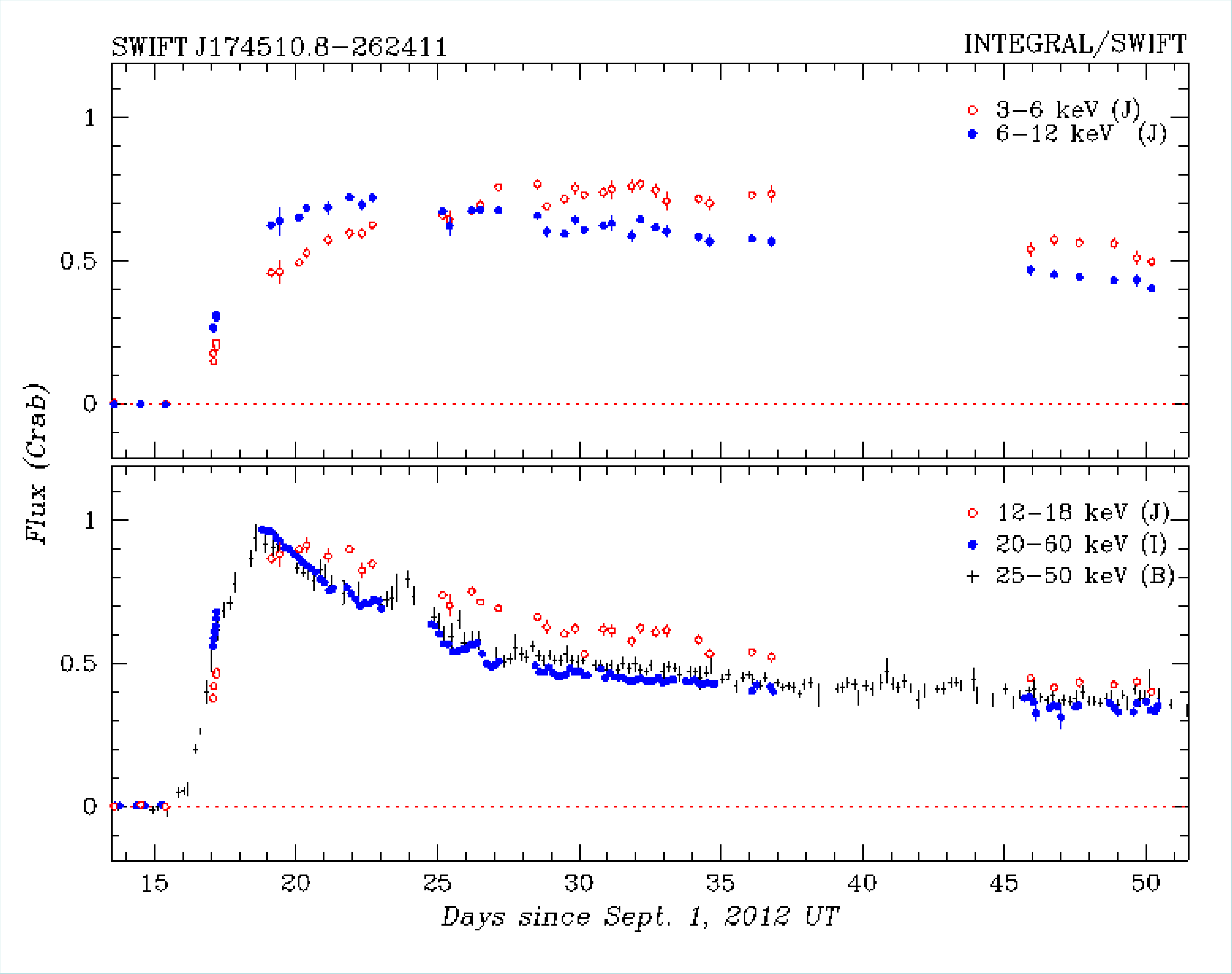
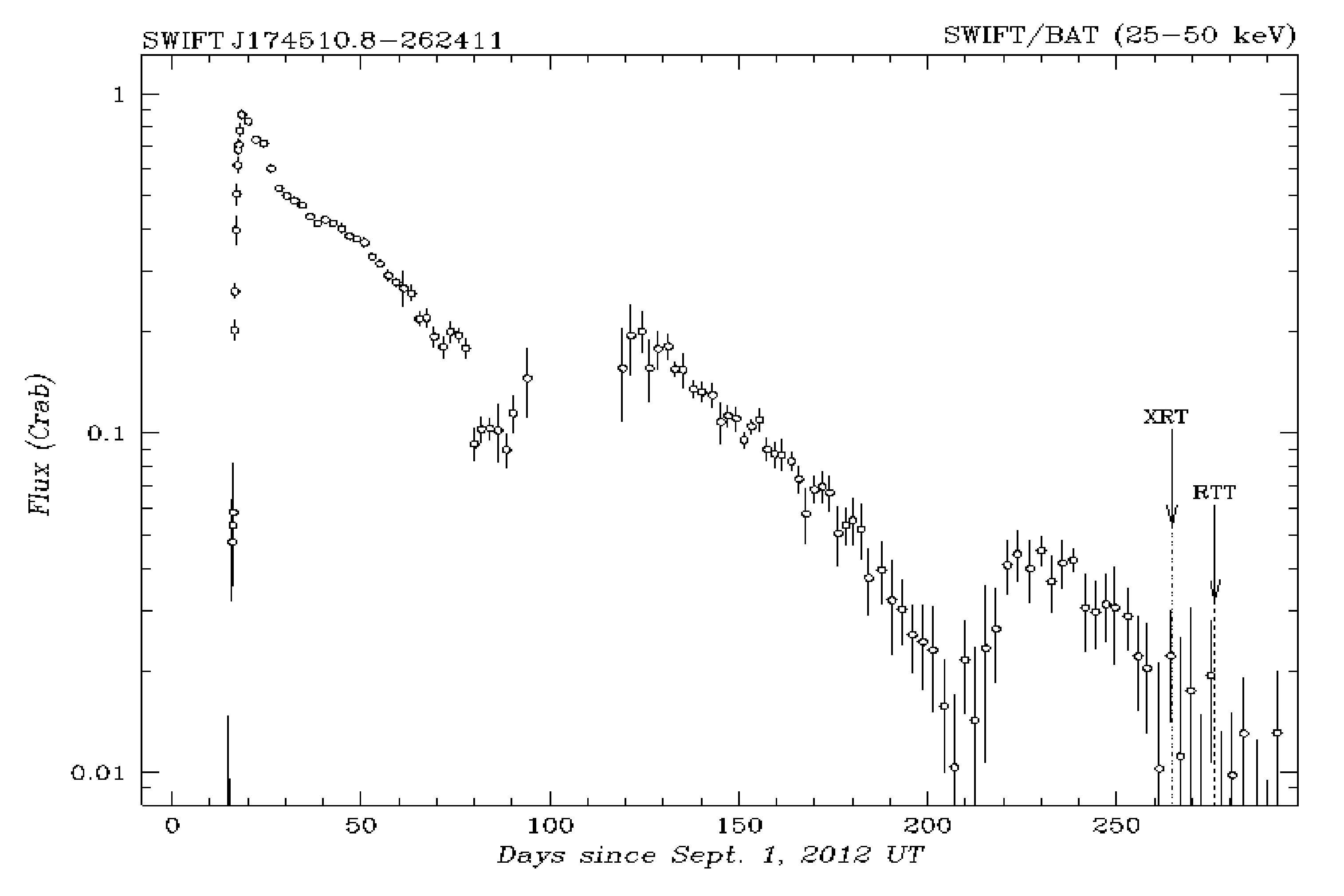


Broad-band spectrum measured on March 27-28, 2012 and its power-law approximation (S.G., Prosvetov, Sunyaev, AstL, 2013, 39, 367-374).

SWIFT J174510.8-262411

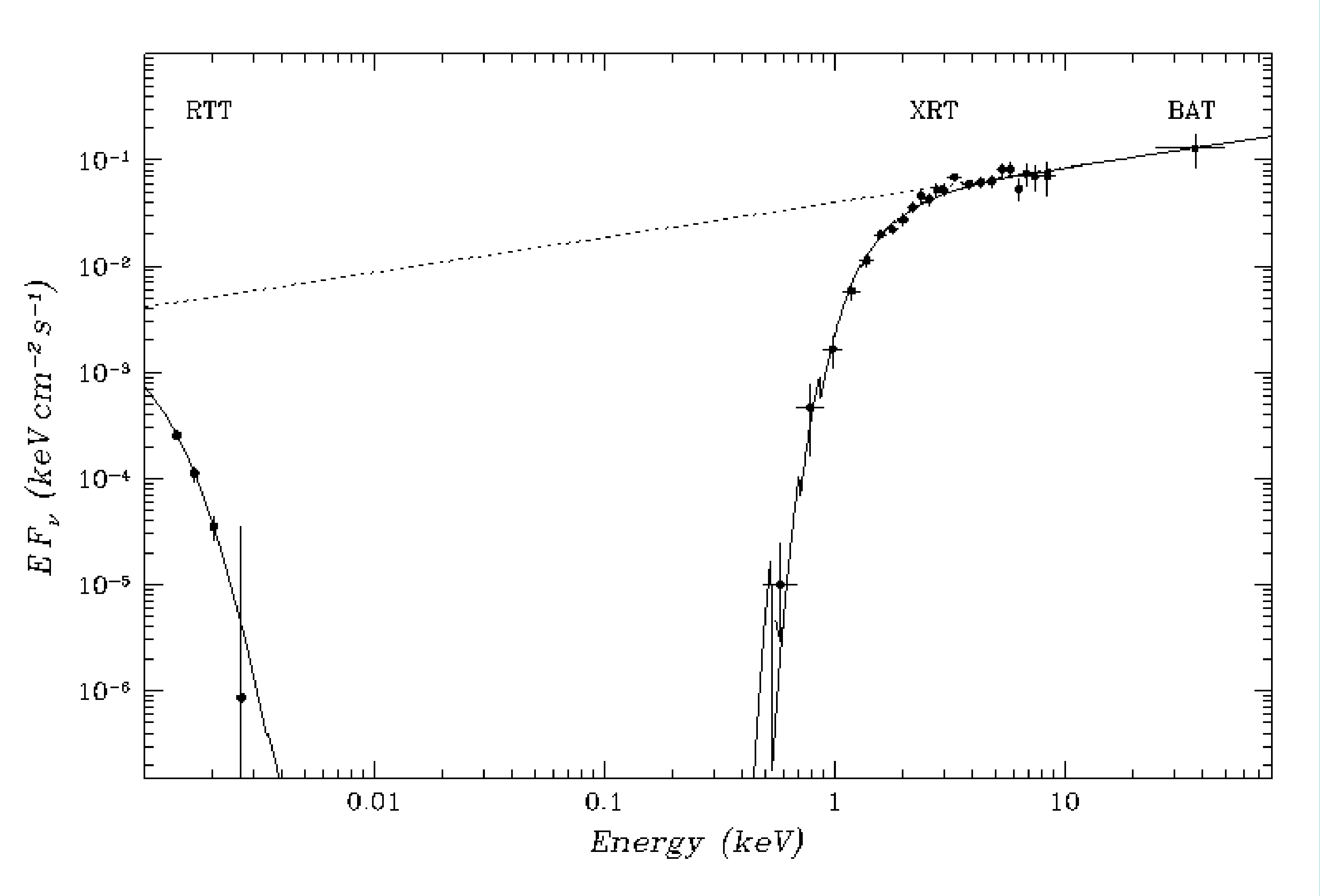


SWIFT J174510.8-262411

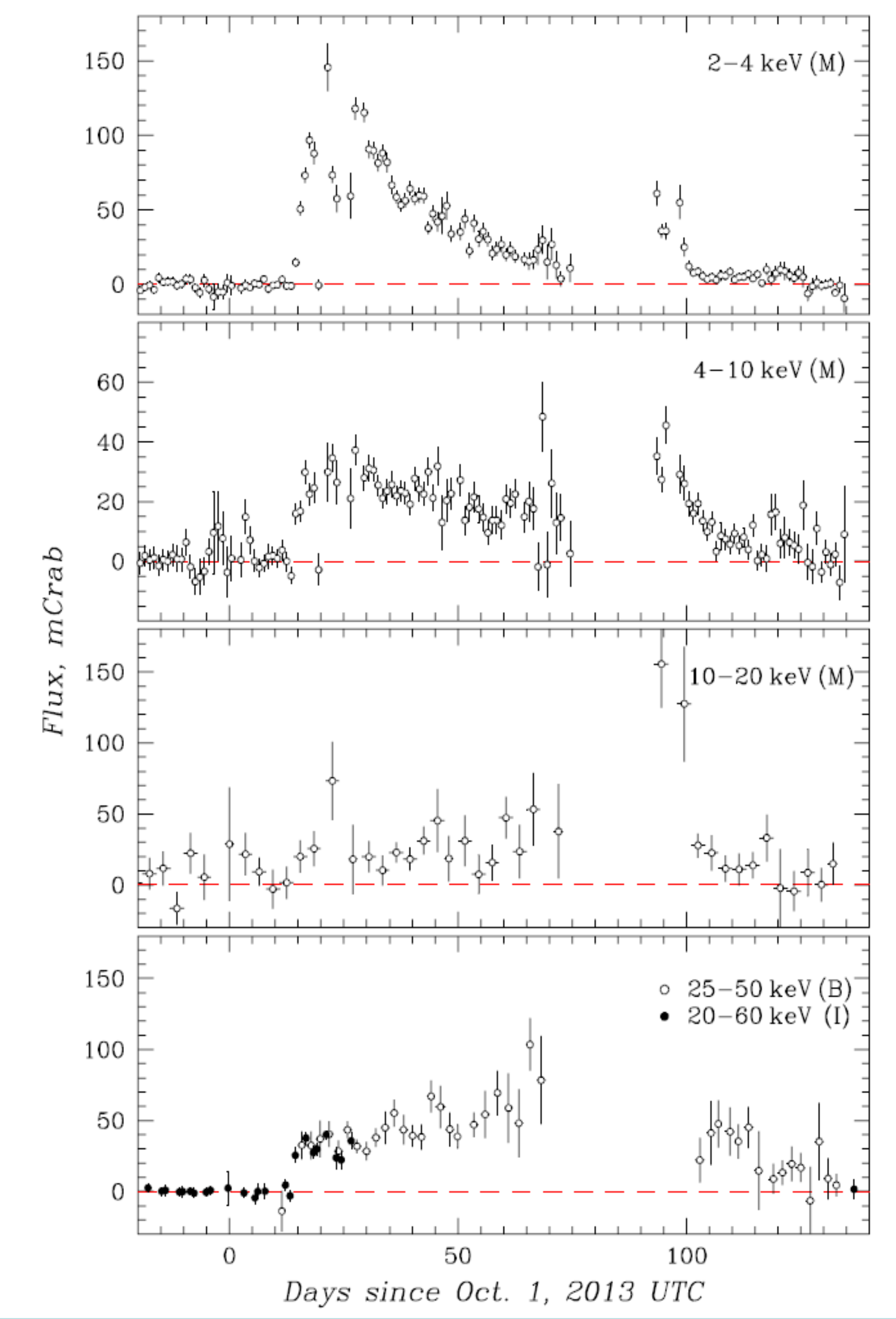


Long-term light curve (since September 2012 till June 2013)

SWIFT J174510.8-262411



Broad-band spectrum and its power-law approximation (S.G., Prosvetov, Burenin, AstL, 2014, 40, 171-176).



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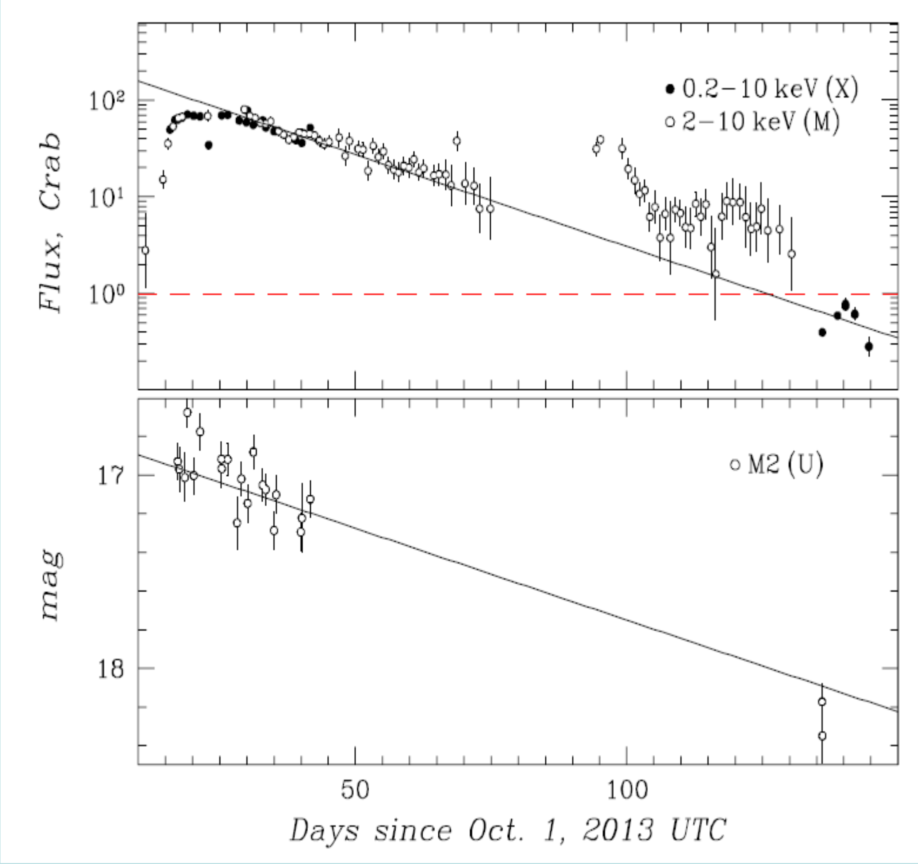
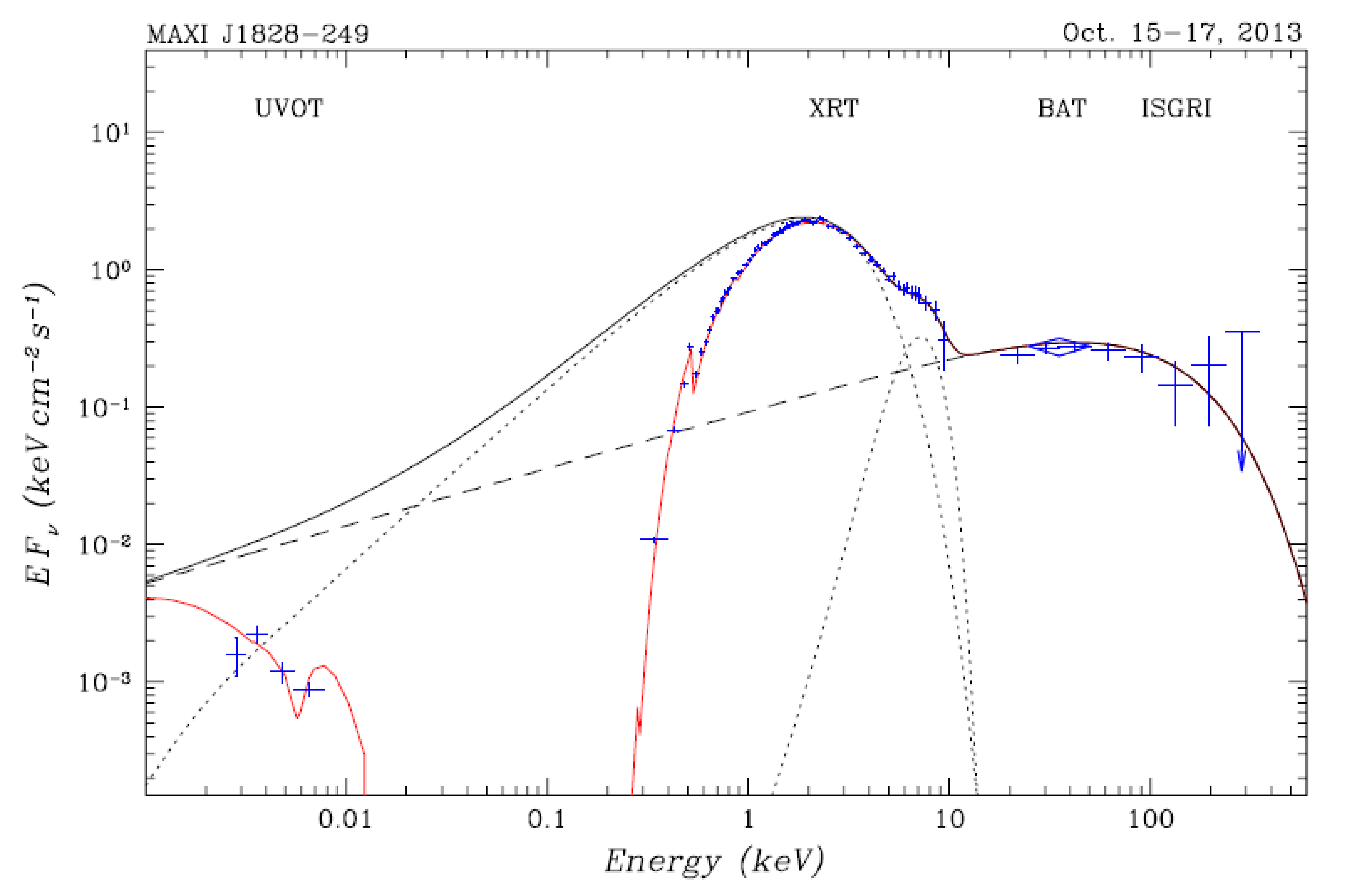
Optical emission correlates with the X-ray one on a time scale of months



MAXI J1828-249



Power-law extrapolation of the hard X-ray spectrum gives the dominant contribution to the observed optical flux

Take into account irradiation by X-rays

$$Q_{\rm vis} = \frac{3}{8\,\pi}\,\frac{GM\dot{M}}{R^3}\,\left[1-\left(\frac{R_0}{R}\right)^{1/2}\right] \simeq \frac{3\,L_d}{4\pi\,R^2}\left(\frac{R_0}{R}\right)$$

$$Q_{\rm irr} = \frac{L_{\rm X}\,(1-\beta_d)}{4\,\pi\,R^2}\,\left(\frac{H}{R}\right)^m\,\left(\frac{d\ln H}{d\ln R}-1\right)$$

(Shakura & Sunyaev 1973; Lyutyi & Sunyaev 1976)

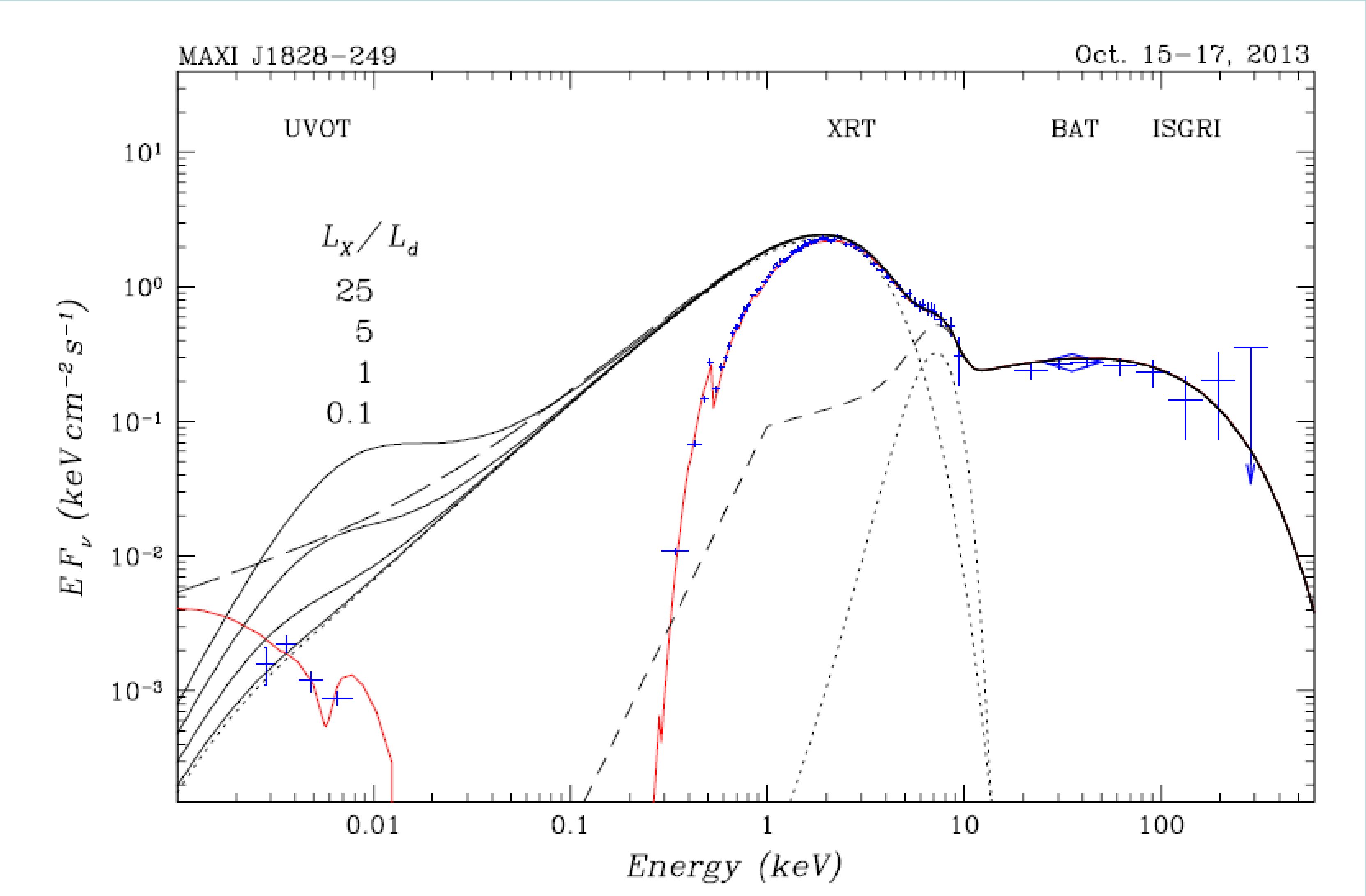
$$T_{\rm s} = (Q_{\rm irr}/\sigma + Q_{\rm vis}/\sigma)^{1/4} \simeq (Q_{\rm irr}/\sigma)^{1/4}$$

$$H/R \simeq 6.7\times 10^{-3}(R/R_0)^{1/8}\;\;(\gamma\,=\,9/8\;)$$

$T_{\rm s} \sim R^{-3/4}$ *standard disk*

$\sim R^{-15/32}$ *irradiated disk, temperature decreases slowly with R*

MAXI J1828-249



X-ray luminosity must exceed the total disk luminosity (0.08 $\dot{M}c^2$) by a factor of 5-10 to provide the observed optical flux by irradiation.

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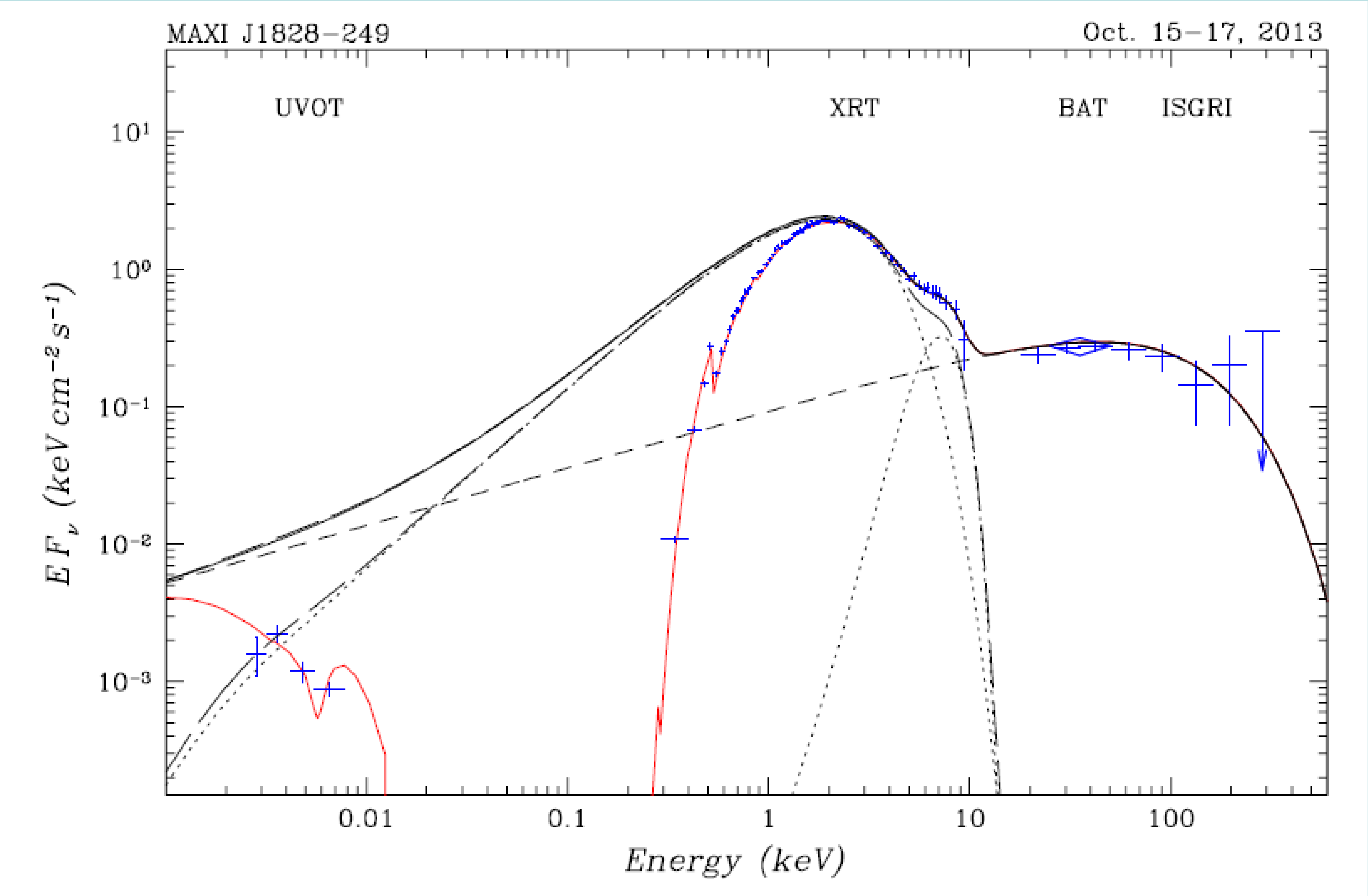


Realistic case of the disk irradiation (X-ray luminosity is only 25% of the total disk luminosity) (S.G. et al., AstL, 2016, 42, 69-81)

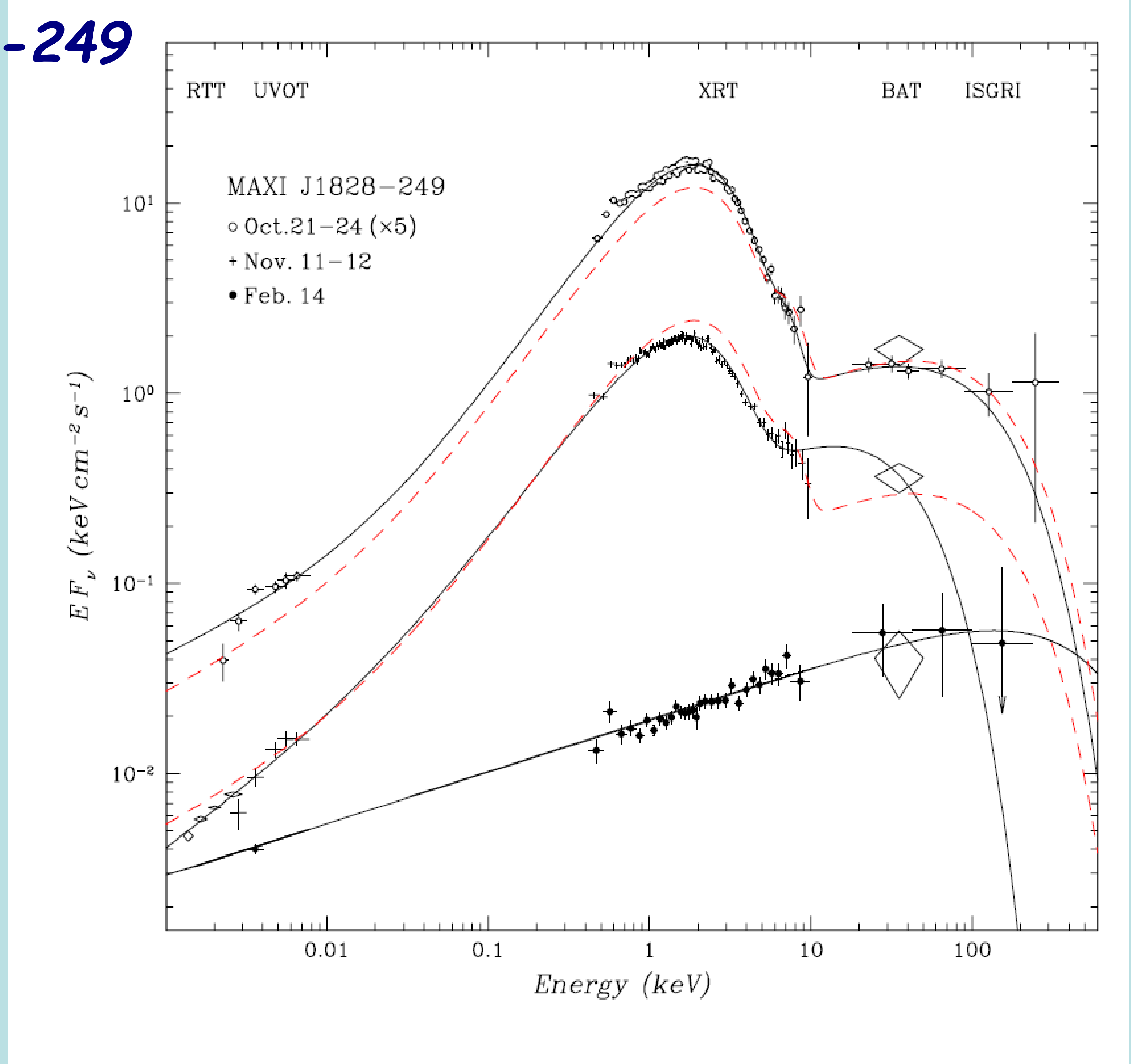
X-ray irradiation

- *Imposibility to heat the outer disk in LMXBs by X-ray irradiation was first recognized by Vrtilek et al. (1990) and van Paradijs (1996) and pushed them to propose an isothermal (in z-direction) disk model. It is well known however (Lyutyi, Sunyaev 1976) that X-ray irradiation can not heats the inner parts of the disk.*

- *Recently Shakura & Mesheryakov (2012) considered X-ray scattering in the corona above the disk as a mechanism capable to enhanced X-ray irradiation. However it is difficult to believe that the dense corona can still exist above the far optically emitting regions of the disk.*

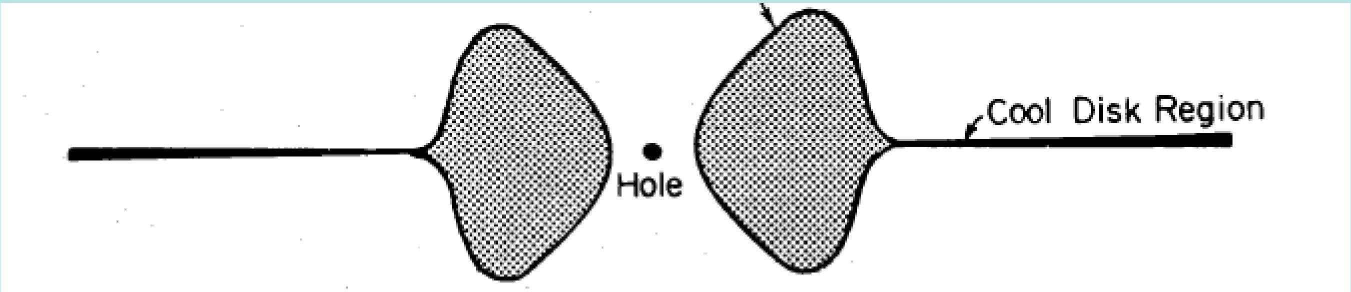
MAXI J1828-249

Power-law extrapolation of the hard X-ray spectrum to the optical band always gives the dominant contribution to the observed optical flux (S.G. et al., AstL, 2016, 42, 69-81).



How we can explain these observations ?

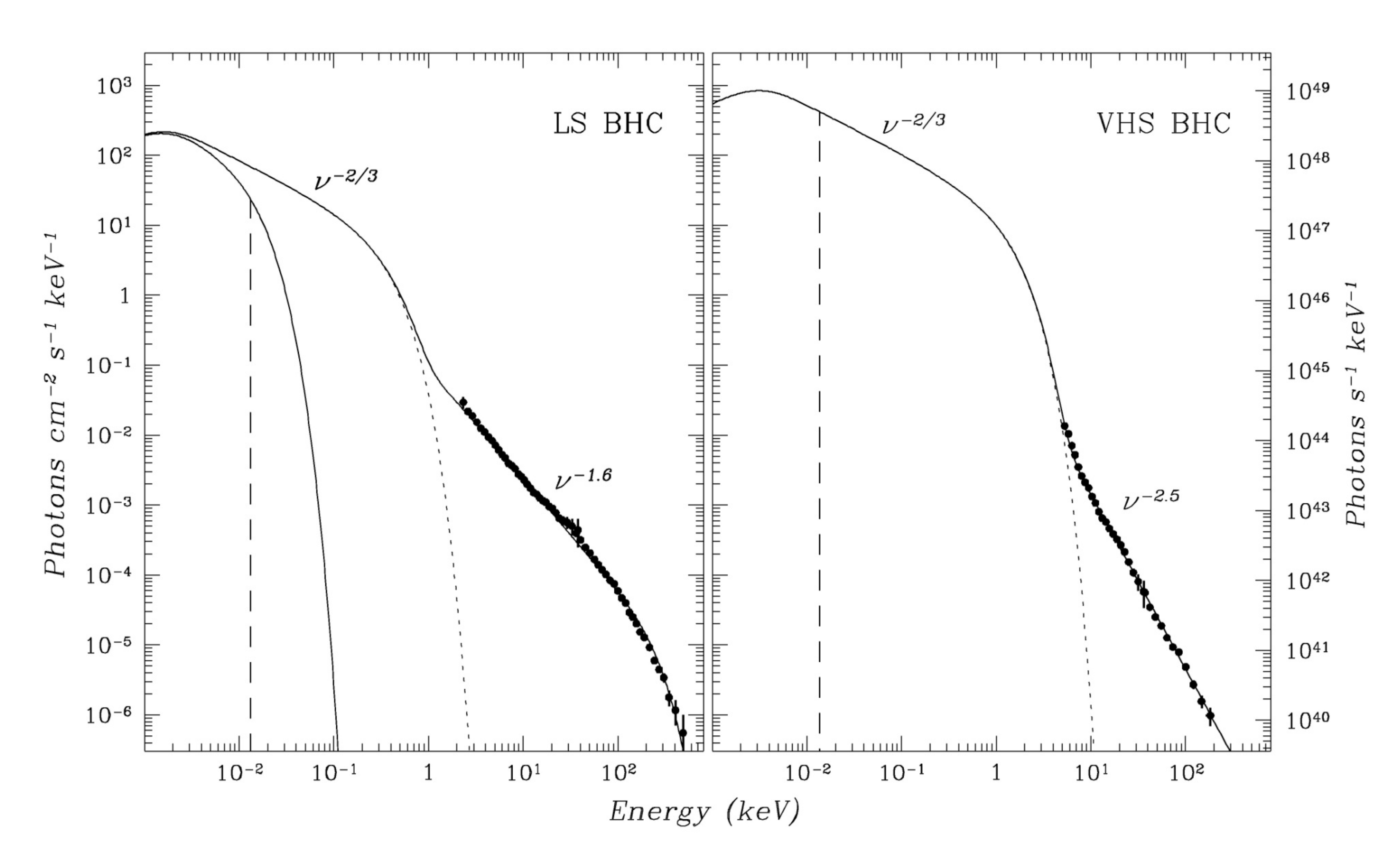
- Synhrotron emission from jets
- Synhro-Compton from disk (Veledina et al)
- Comptonization from disk ✓



OIR and soft X-ray photons from the cold disk

- *illuminate the inner hot region and participate in Comptonization*
- *are responsible for normalization and shape of the hard X-ray spectrum*
- *Intrinsic plasma emission is too weak to explain observed spectra*

Black hole spectra (standard view)



Seed photons could have energies of about 1 keV and be emitted at ~50 R_G.

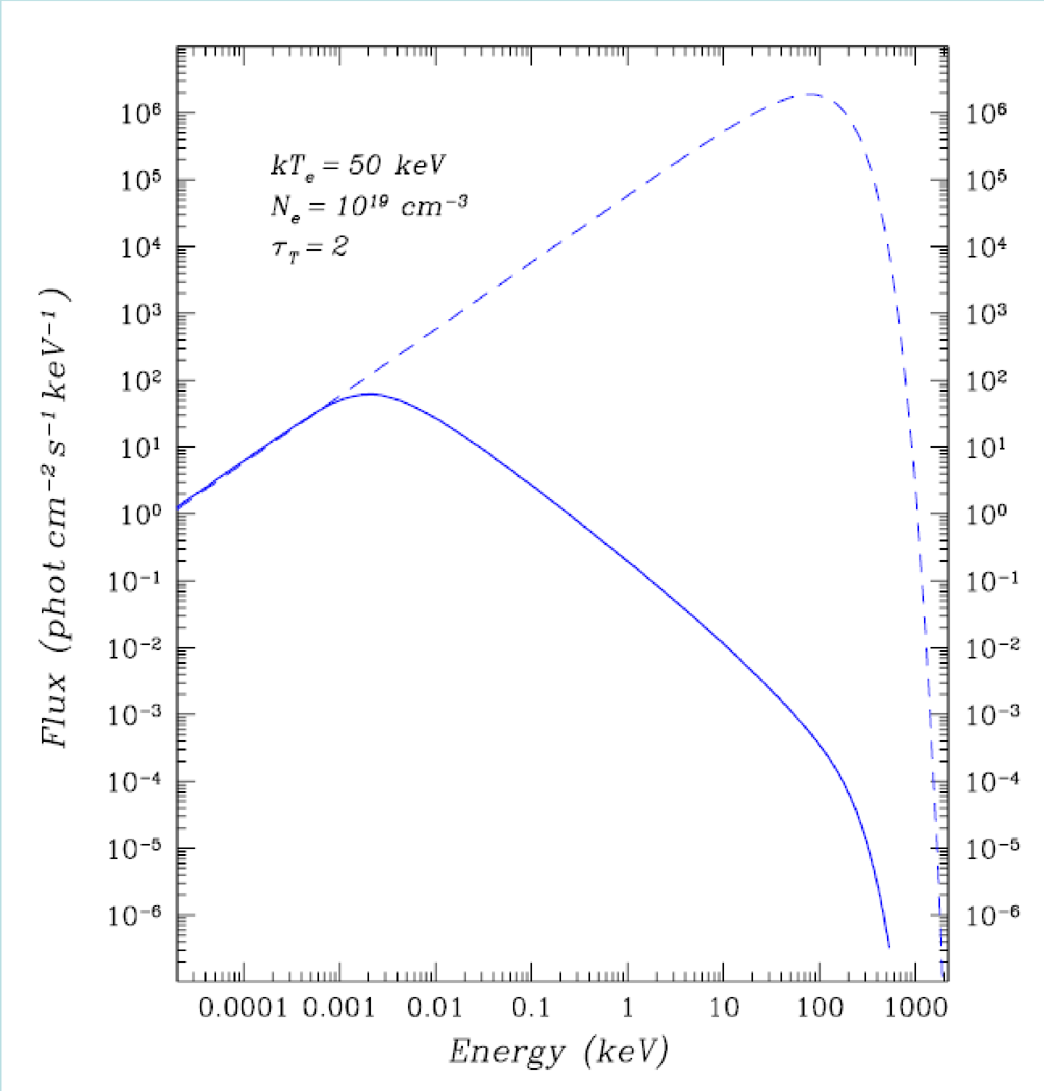
Comptonized spectrum of a hot layer

Our realistic computation (Kompaneets equation) of the spectrum emerging from the high temperature optically thin layer (disk) shows that its power law part begins already in the optical and infrared band.

Normalization — a circular inner region of 40 Rg (for a 10 M⊙ black hole) in radius at a distance of 8 kpc.

$$N_e \simeq \frac{2\tau_T}{\sqrt{\pi}\sigma_T H} \simeq 3.7\times10^{19}\, r^{-3/2} \tau_T\, (kT_{100})^{-1/2} \left(\frac{M}{M_\odot}\right)^{-1} \ \mathrm{cm}^{-3}$$

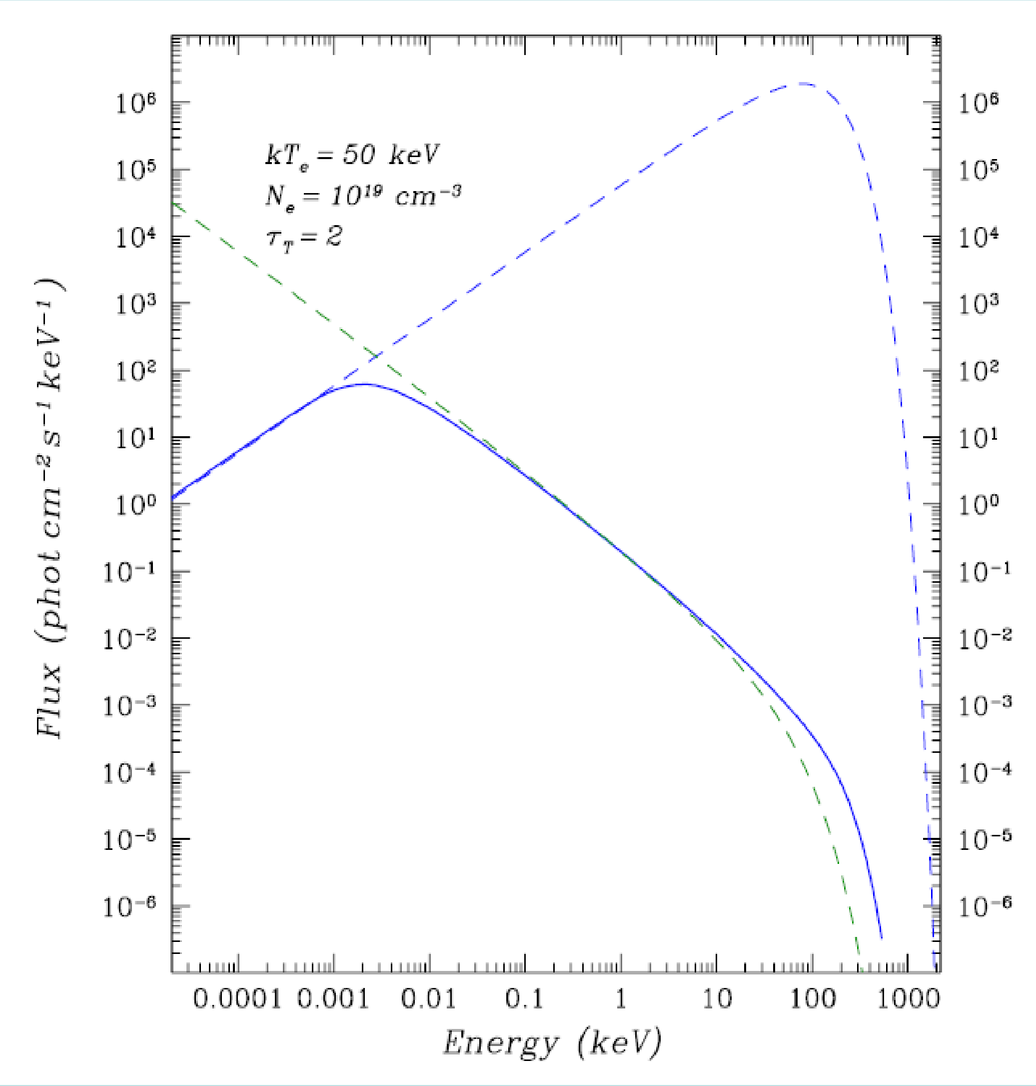
$$H \simeq \left(\frac{4kT_e R^3}{GMm_p}\right)^{1/2} \simeq 1.4\times10^5\, r^{3/2}\, (kT_{100})^{1/2} \left(\frac{M}{M_\odot}\right)\ \mathrm{cm}$$



Comptonized spectrum of a hot layer

Comptonization of low energy photons created in free-free electron-ion interactions is a dominant process responsible for the formation of the hard X-ray spectrum.

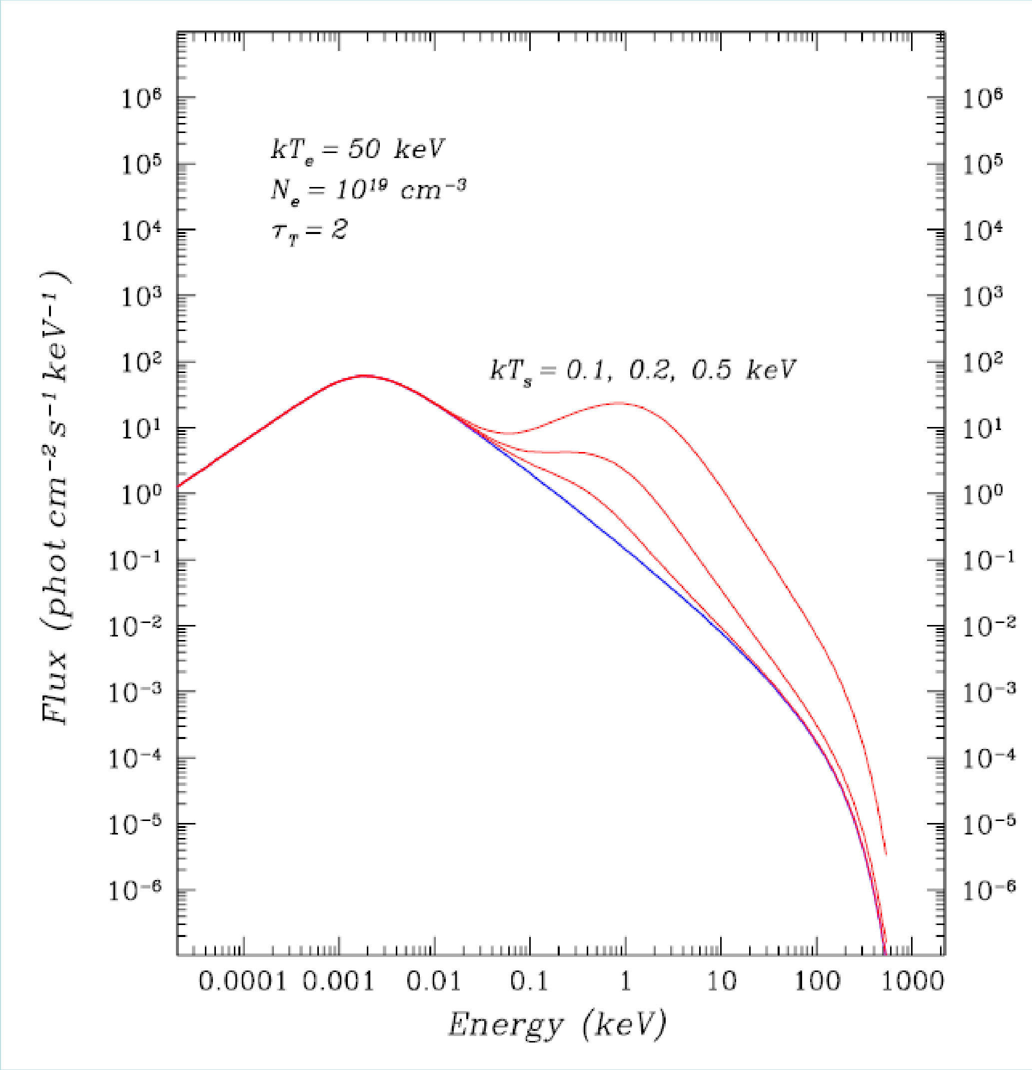
Green curve — bremsstrahlung spectrum assuming that plasma in the hot layer is optically thin at all energies.



Comptonized spectrum of a hot layer

Sandwich model of the disk with a cold layer of plasma of given temperature kTs located below the hot layer and producing seed black-body photons.

This changes a slope of the X-ray spectrum but does not change the optical and infrared flux.

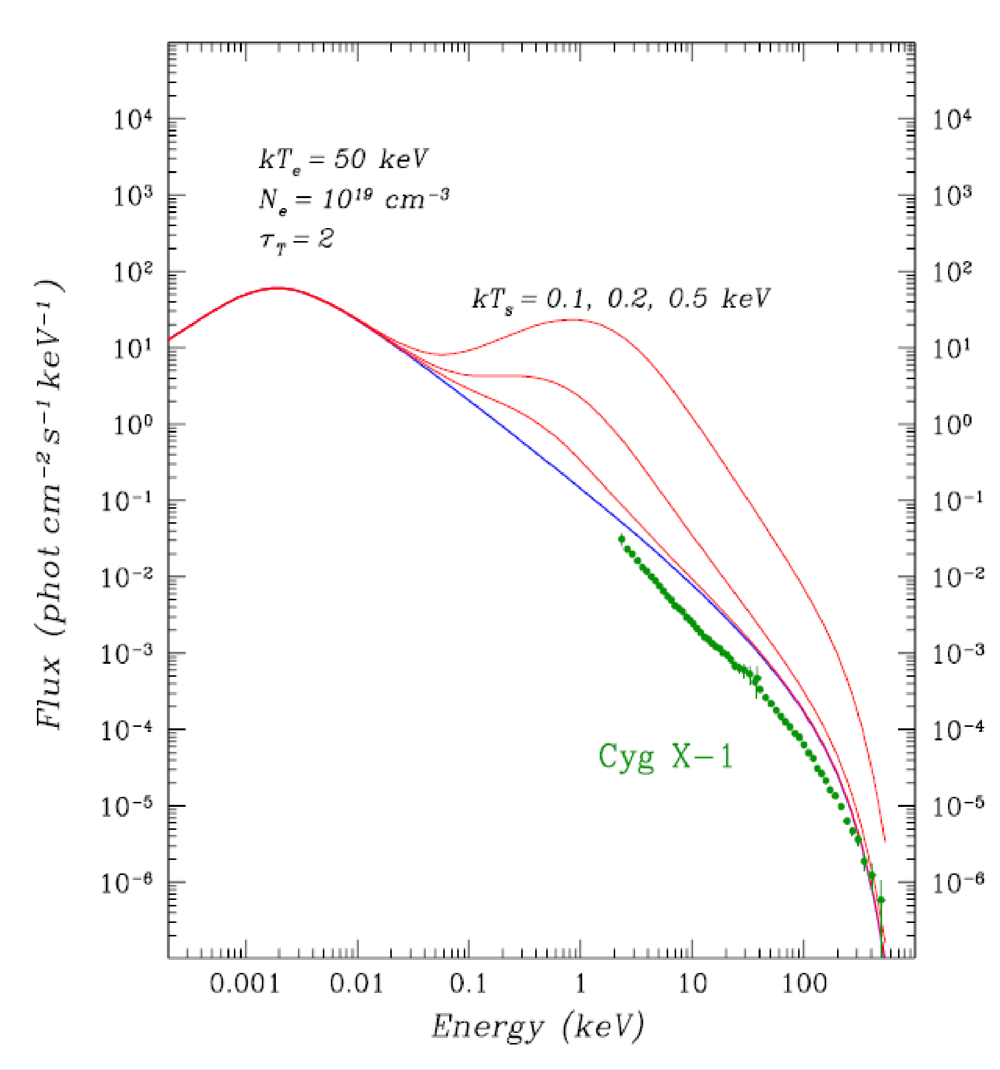


Comptonized spectrum of a hot layer

The same model spectra in comparison with the measured X-ray spectrum of Cyg X-1 (scaled to the 8 kpc distance). We did not fit other model parameters (i.g. area of the hot disk region or its inclination).

The spectrum shows that intrinsic emission of the hot plasma allows the observed spectra of BH in the hard state to be succesfully explained without addition of the seed photons.

But such an addition may be necessary in the soft or intermediate states.



Conclusions

- *Optical and infrared emission of X-ray novae in many cases may be described by power-law approximation of their hard X-ray spectra.*
- *It is likely that this* ***OIR emission is produced in*** *the disk central high-temperature region of the main energy release (****the same region where the hard spectrum is produced****).*
- *The accretion disk and its black-body spectrum gives only a small contribution to the observed flux at the OIR energies.*
- ***The extention of the hard X-ray spectrum to the OIR band is fully consistent with the Comptonization model*** *which takes into account soft photons produced in the free-free (bremssrahlung) process.*
- ***Contribution of seed photons from the cold disk may be small in the BH hard states****. The observed emission is intrinsic emission of the hot plasma.*

During this study we felt something common with the Legendary Myth Destroyers ...

Myth destroyers

Artem Prosvetov   Rodion Burenin

Thank you !