Complex modeling of the radiation spectrum of accreting neutron stars

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24th RAGtime

on Relativistic Astrophysics

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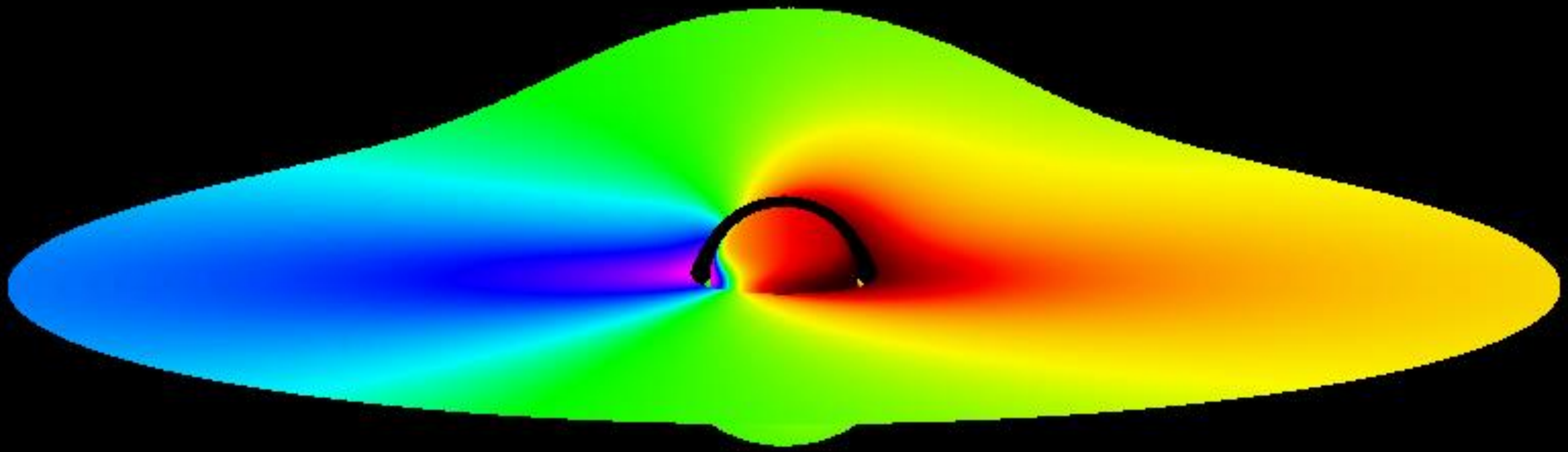
Assumptions / Approximations

- Weak magnetic field $(B \lesssim 10^8\ \mathrm{G})$ ⟶ magnetospheric radius $\leq$ neutron star radius (inner edge of the disk on ISCO) ⟶ accreting material creates boundary layer ⟶ infalling material spinup the neutron star

- Disk – Optically thick, no inner structure, isotropic radiation

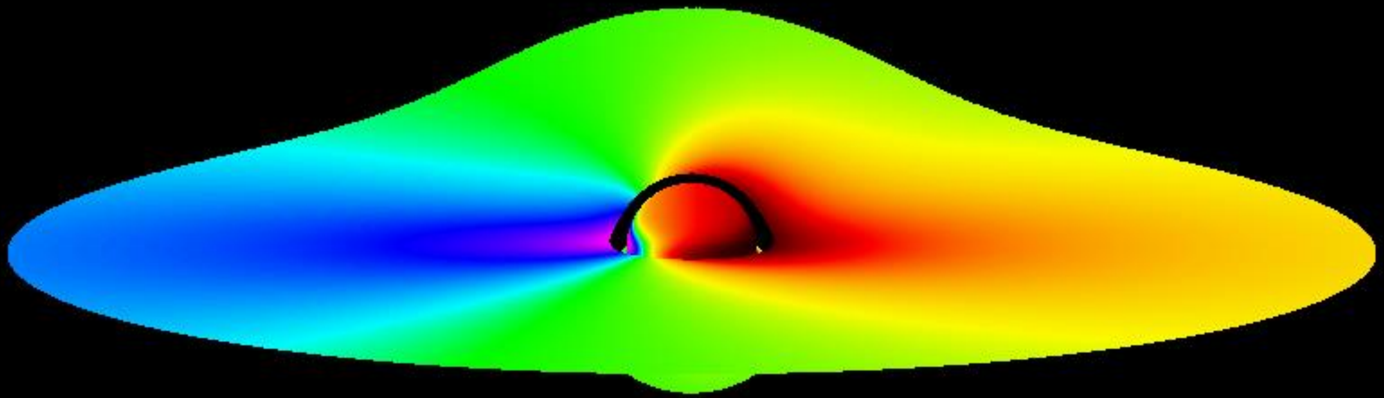
- Schwarzschild metric: $\mathrm{d}s^2 = -\left(1 - \frac{2M}{r}\right)\mathrm{d}t^2 + \left(1 - \frac{2M}{r}\right)^{-1}\mathrm{d}r^2 + r^2\left(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\varphi^2\right)$

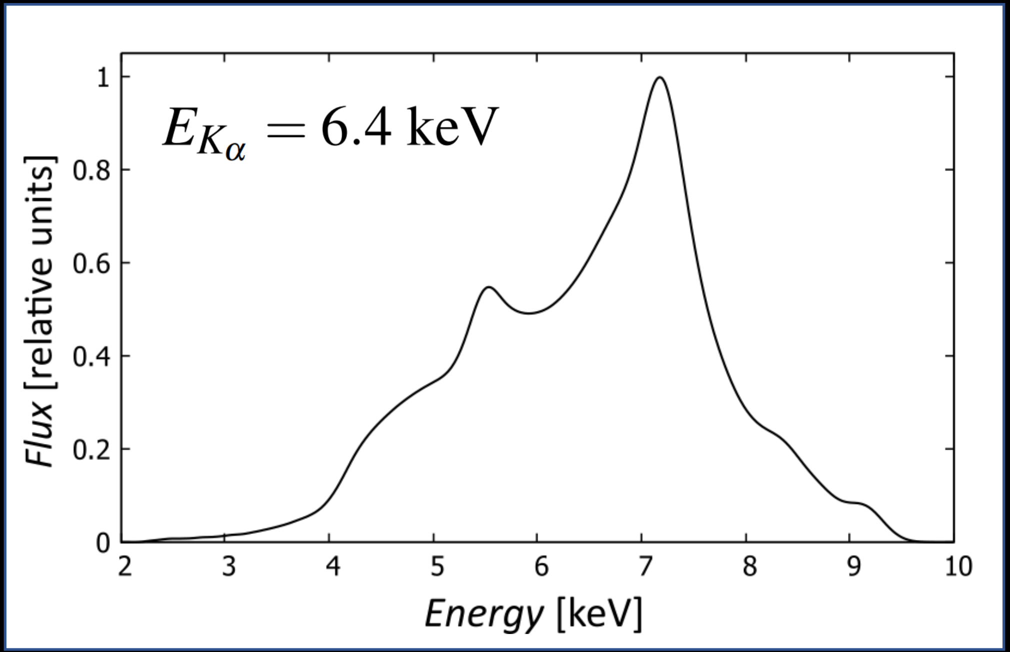
Frequency shift (g-factor) map



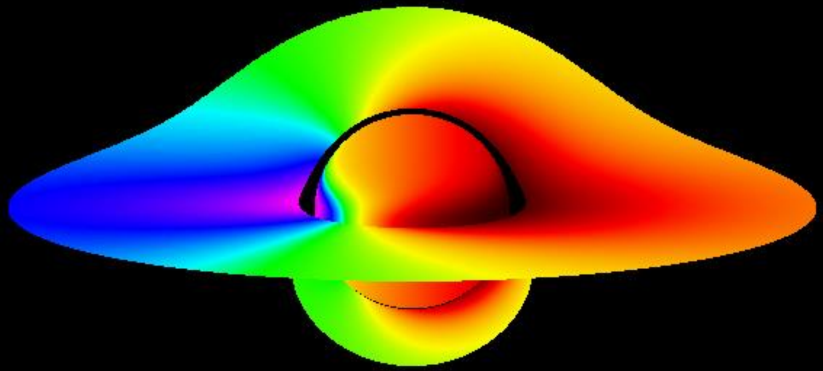
$$frequency\ shift = \frac{observed\ energy}{emitted\ energy}$$

Spectral profile





Components of the system



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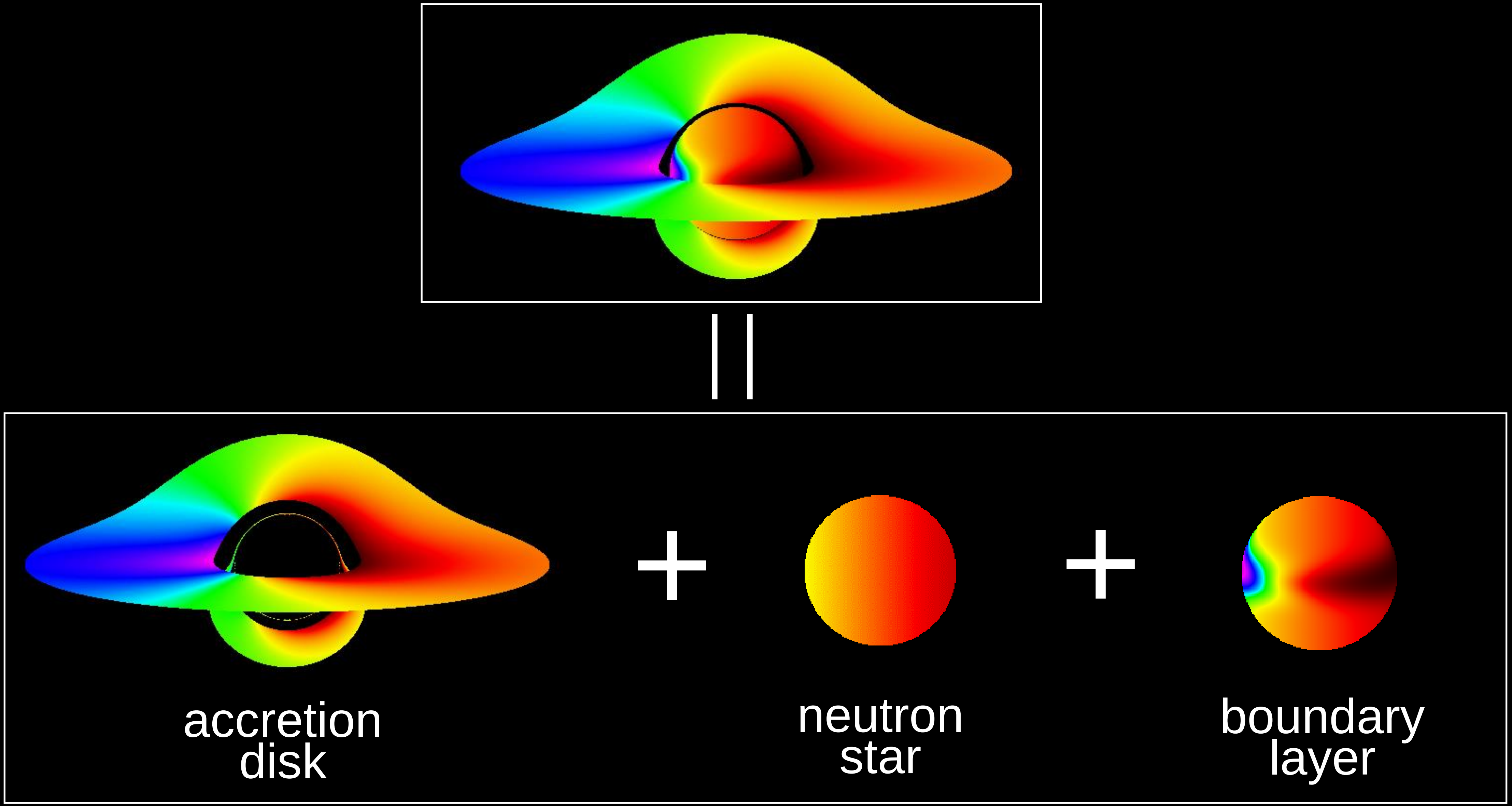


Model – Disk spectrum

Black body

$$F(r) = \frac{3\dot{M}M}{8\pi r^3}\frac{\mathscr{Q}}{\mathscr{B}\mathscr{C}^{1/2}}$$ ← Novikov-Thorne

$$T_{\mathrm{ef}} = \left(\frac{F(r)}{\sigma_{\mathrm{SB}}}\right)^{1/4}$$ ← Stefan-Boltzmann

$$I_{\mathrm{D}}(E) = \frac{2E^3}{(hc)^2}\left(e^{E/k_{\mathrm{B}}T_{\mathrm{ef}}} - 1\right)^{-1}$$

Iron line

$$E_{K_\alpha} = 6.4\ \mathrm{keV}$$ ← rest energy

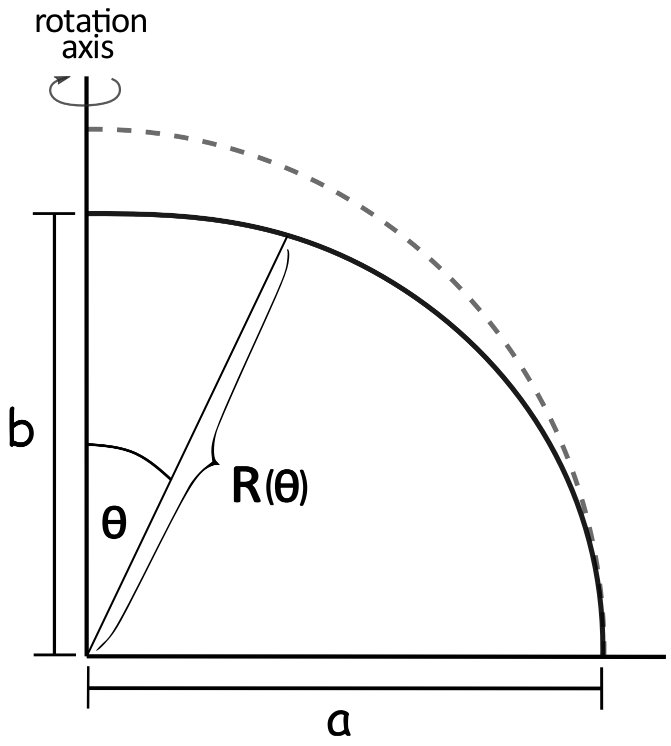
$$f_{\mathrm{D}}(E) = \left(e^{-\frac{(E-E_{K_\alpha})^2}{2\sigma^2}}\right) r^q$$

- Parameters of disk model: $\dot{M}$, r_{i}, r_{o}, q

Model – NS surface

ellipsoid →

$$R(\theta) = \frac{ab}{\sqrt{a^2\cos^2\theta + b^2\sin^2\theta}}$$

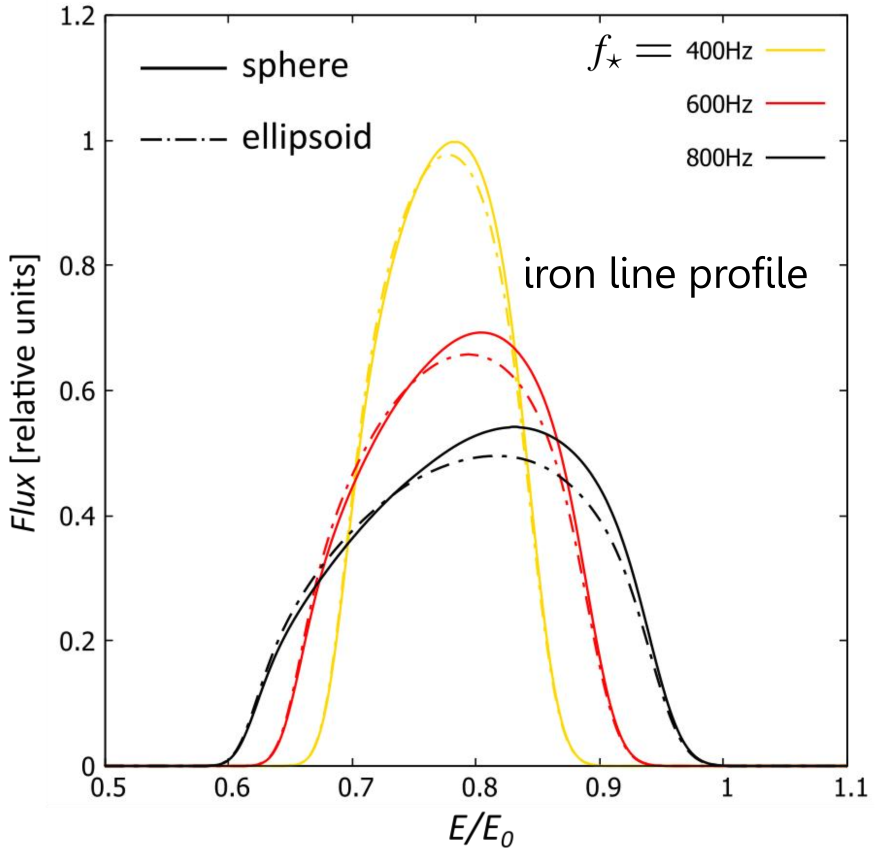


"Oblateness" values for given frequencies based on nummerical modeling

$f_\star$ [Hz]	b/a
400	0.985
600	0.965
800	0.939

MORSINK, S. M.; LEAHY, D. A.; CADEAU, C. & BRAGA, J.
The Astrophysical Journal, **663**(2), p. 1244, 2007.

sphere vs ellipsoid



Model – NS spectrum

Black body

$$I_{\rm NS}(E) = \frac{2E^3}{(hc)^2}\left(e^{\,E/k_{\rm B}T} - 1\right)^{-1}$$

Iron line

$$f_{\rm NS}(E) = e^{-\frac{(E-E_{K_\alpha})^2}{2\sigma^2}}$$

- Parameters of NS model: M, a, b, $f_\star$, T

Model - BL

$$\Omega'_\star = \Omega_\star + e^{-\frac{(\theta-\pi/2)^2}{2\sigma_{\rm BL}^2}}\left(\frac{l(1-2/a)}{a^2} - \Omega_\star\right), \quad \Omega_\star = 2\pi G M f_\star / c^3$$

$$l = 3\sqrt{6}/2$$

angular velocity of the BL ($\Omega'_\star$)

angular velocity of the NS ($\Omega_\star$)

specific angular momentum (in schwarzschild) (l)

Iron line $$f_{\rm BL}(E) = e^{-\frac{(E-E_{K_\alpha})^2}{2\sigma^2}}\left(e^{-\frac{(\theta-\pi/2)^2}{2\sigma_{\rm BL}^2}}\right)$$

- Parameters of BL model: $\sigma_{\rm BL}$

Total intensity

$$\text{Total spectral intensity} = I_{\text{D}}(E) + f_{\text{D}}(E) + I_{\text{NS}}(E) + f_{\text{NS}}(E) + f_{\text{BL}}(E)$$

Total intensity

$$\text{Total spectral intensity} = I_{\mathrm{D}}(E) + f_{\mathrm{D}}(E) + I_{\mathrm{NS}}(E) + f_{\mathrm{NS}}(E) + f_{\mathrm{BL}}(E)$$

(of K_α iron line)

Model – Disk – comparison

When not specified, the other parameters are fixed at:

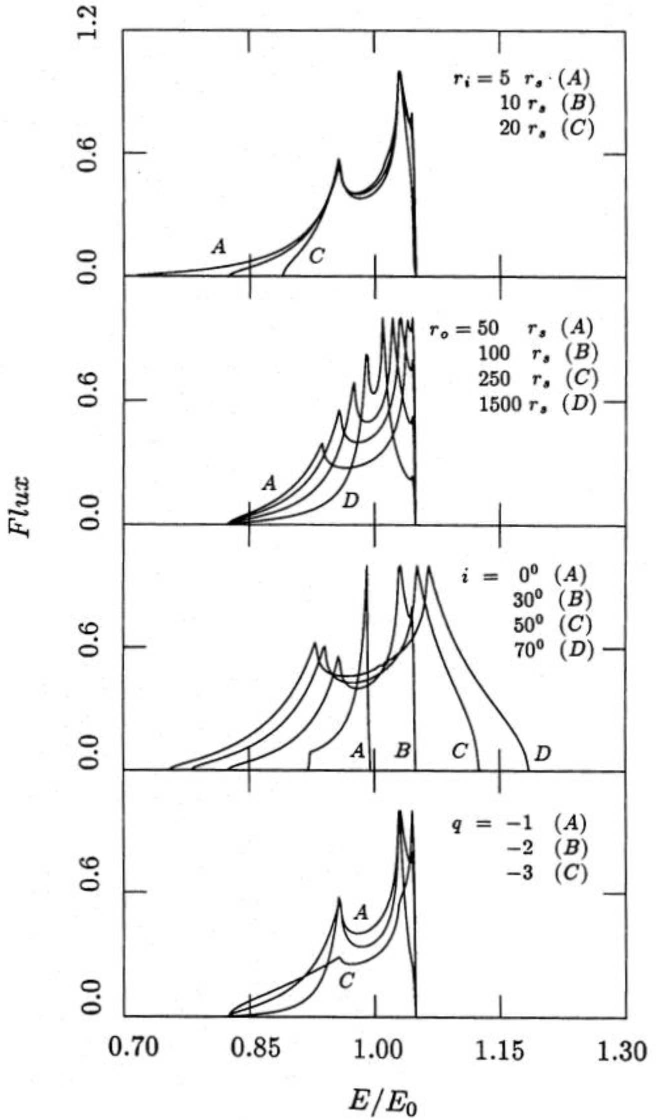
$$i = 30^\circ$$

$$r_i = 10\, r_s$$

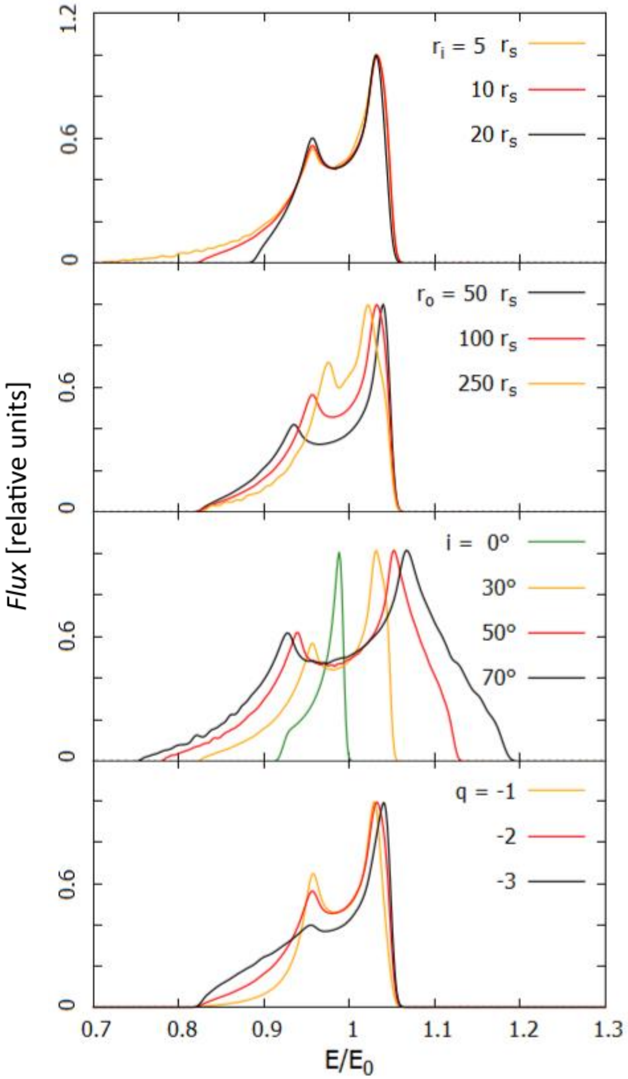
$$r_o = 100\, r_s$$

$$q = -2$$

FABIAN, A.; REES, M.; STELLA, L. & WHITE, N. E.: *Monthly Notices of the Royal Astronomical Society*, **238**(3), pp. 729–736, 1989.



my results



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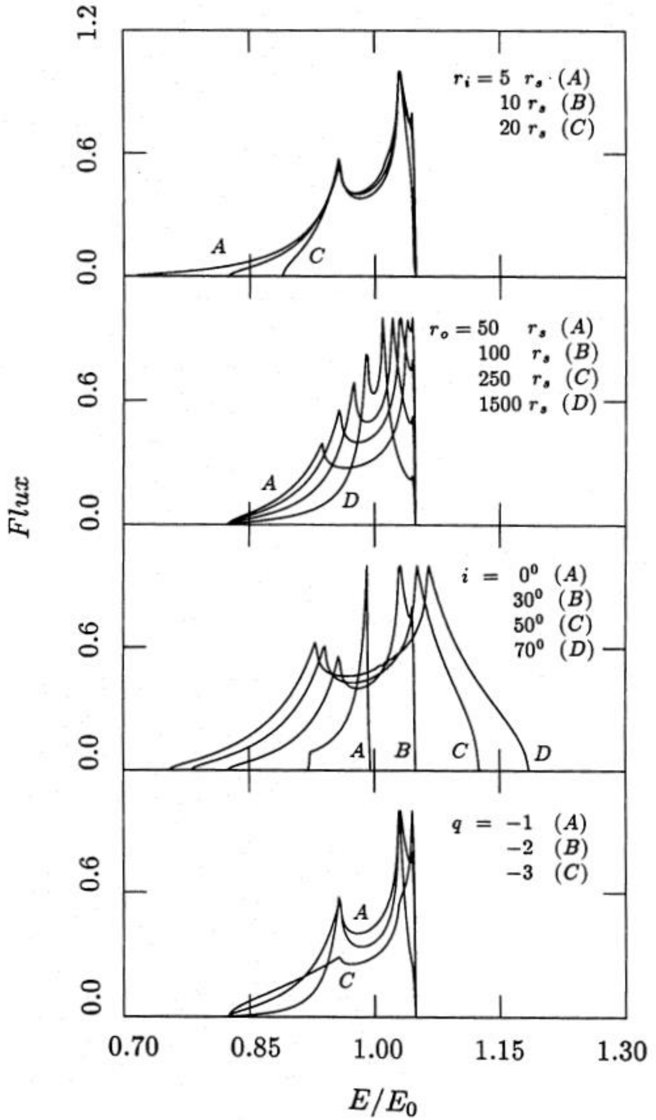

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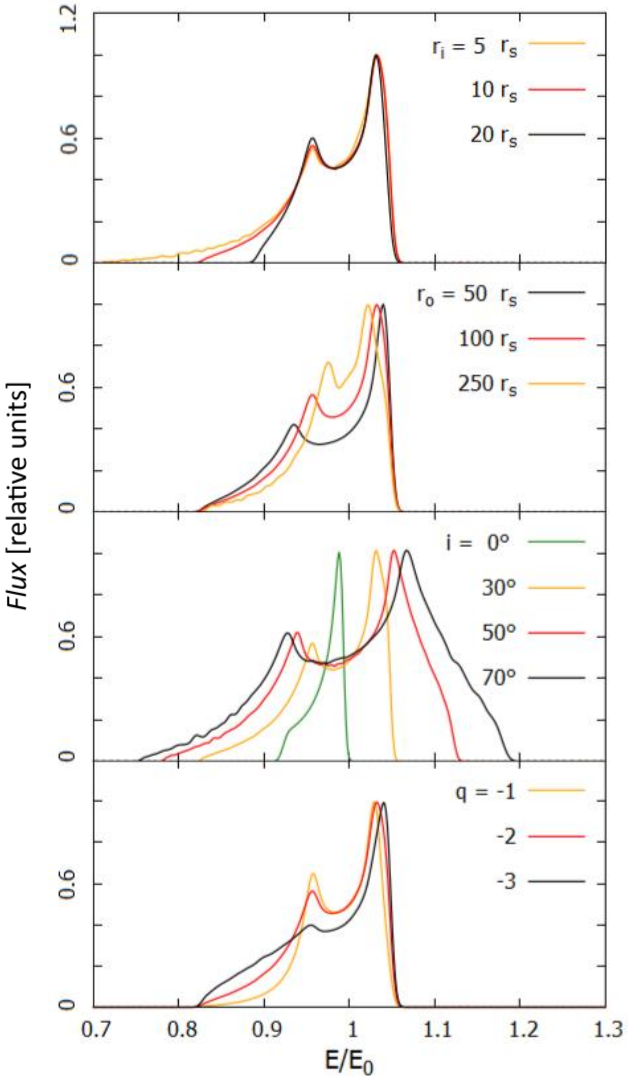
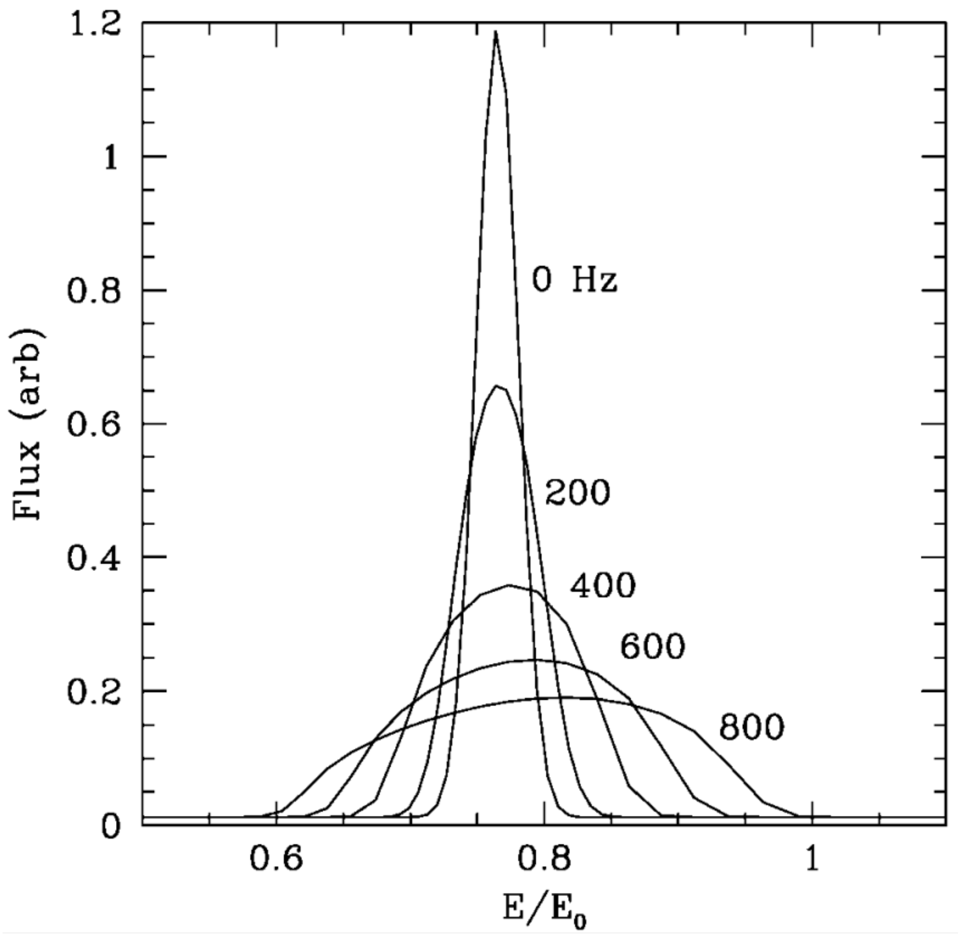


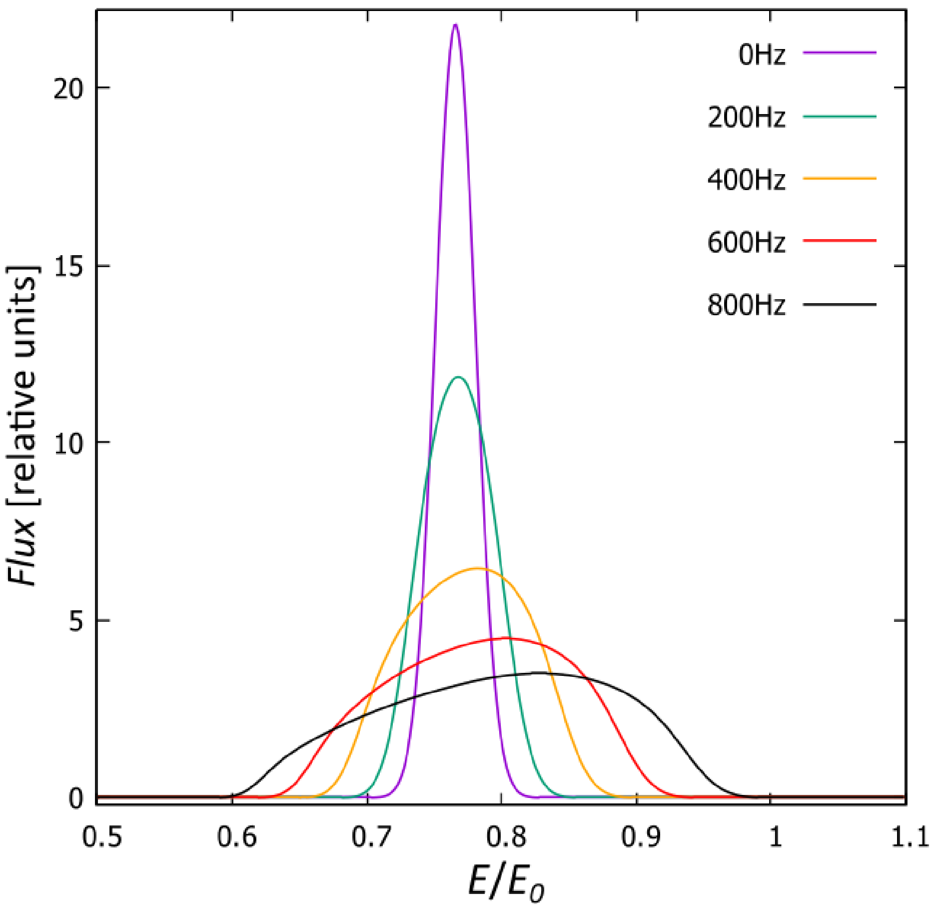
Pretty good

Model – NS – comparison

Özel, F. & Psaltis, D.
Astrophysical Journal, **582**(1), p. L31, 2002.



my results



Model – NS – comparison

✔ Pretty good

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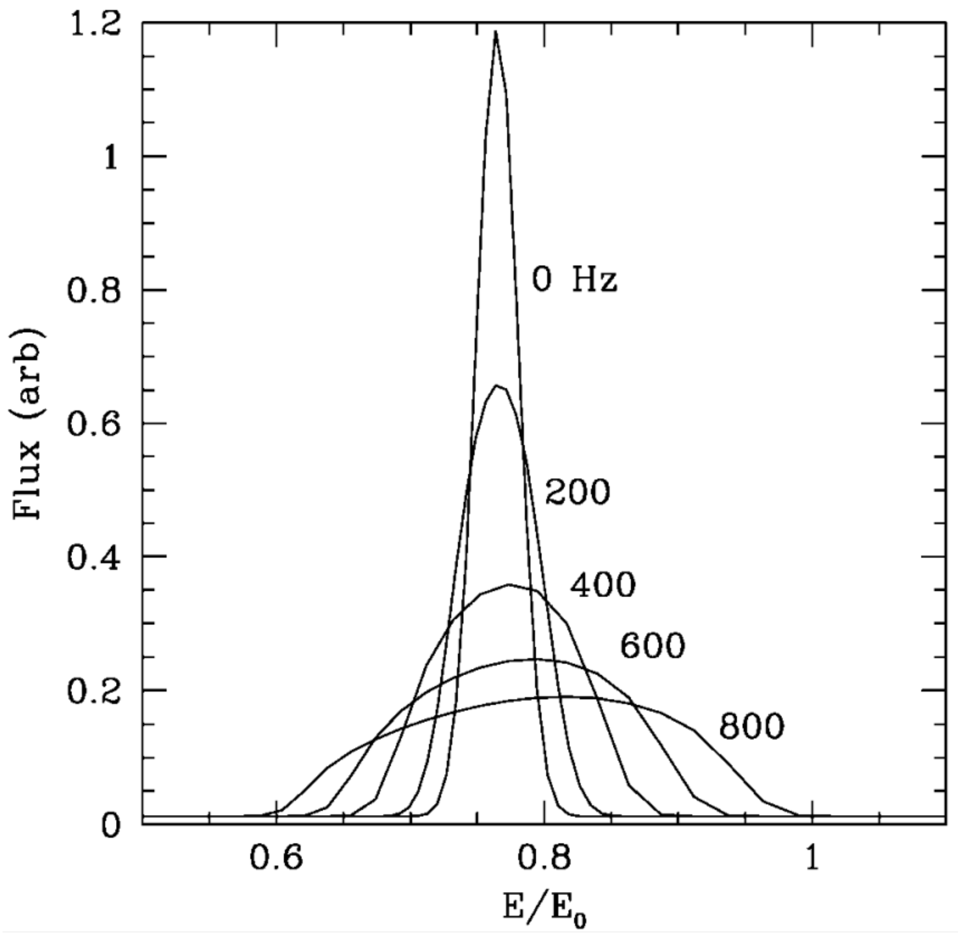
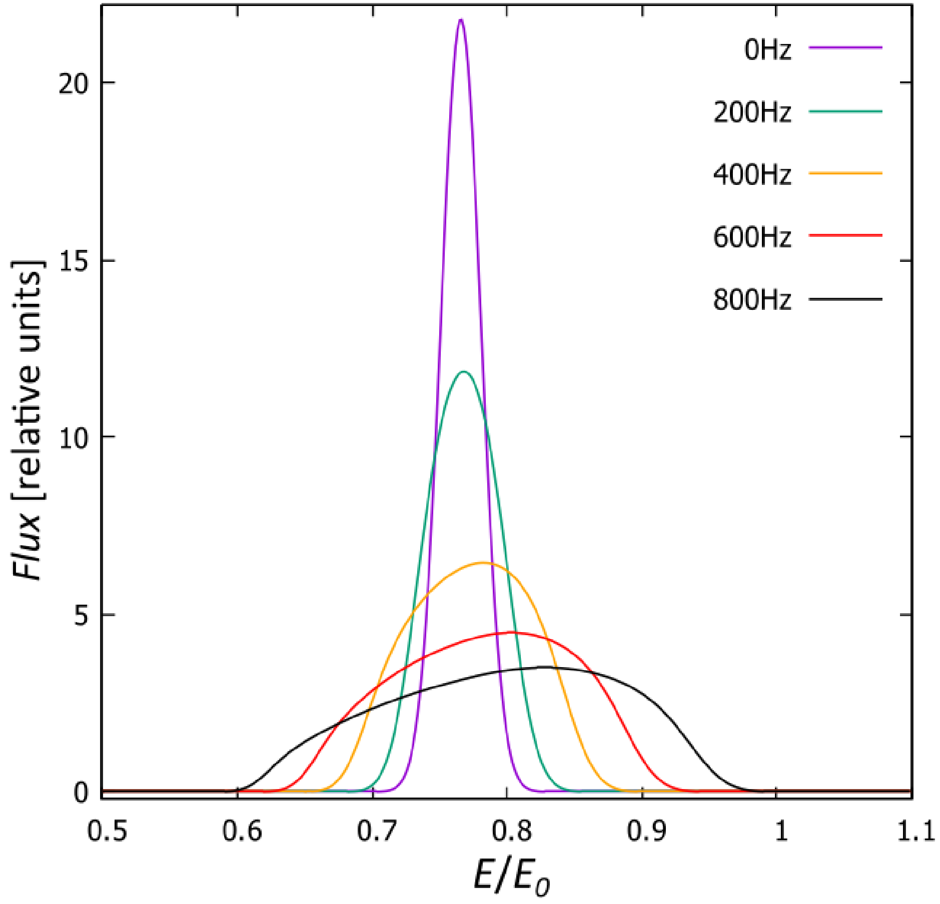
Astrophysical Journal, **582**(1), p. L31, 2002.



my results

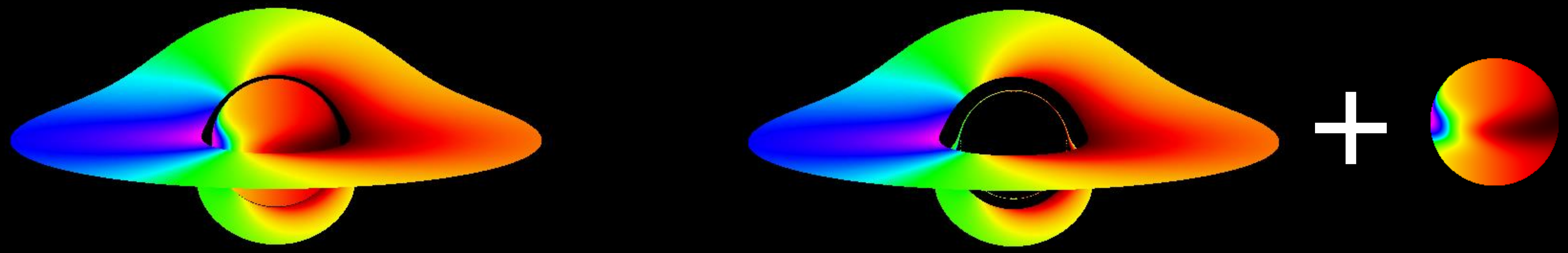


Photon geodesics

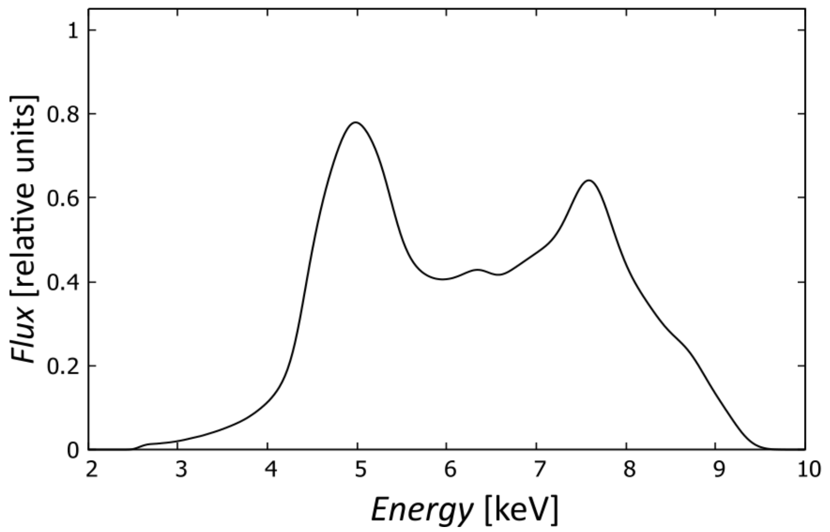
- Numerically calculated using numerical code LSD created by pavel bakala.
- The geodesics are computed for the whole system all at once – all obscuration effects are automatically included.

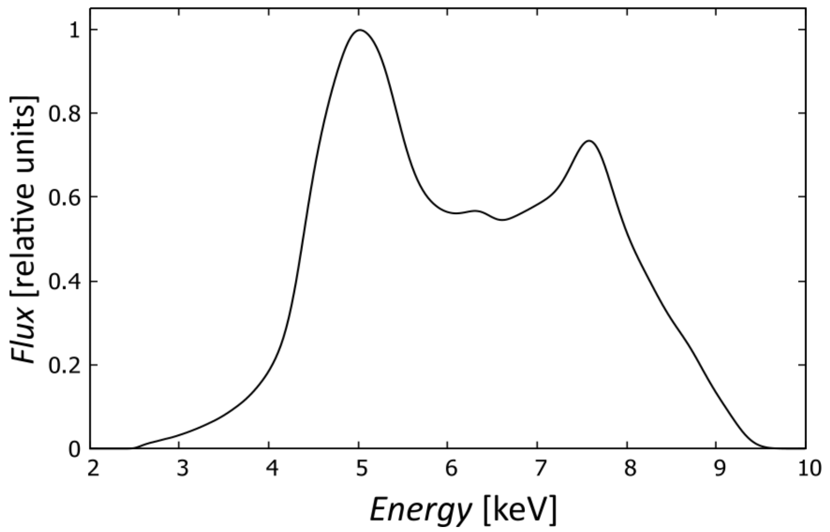
Obscuration effects

- Frequency shift map

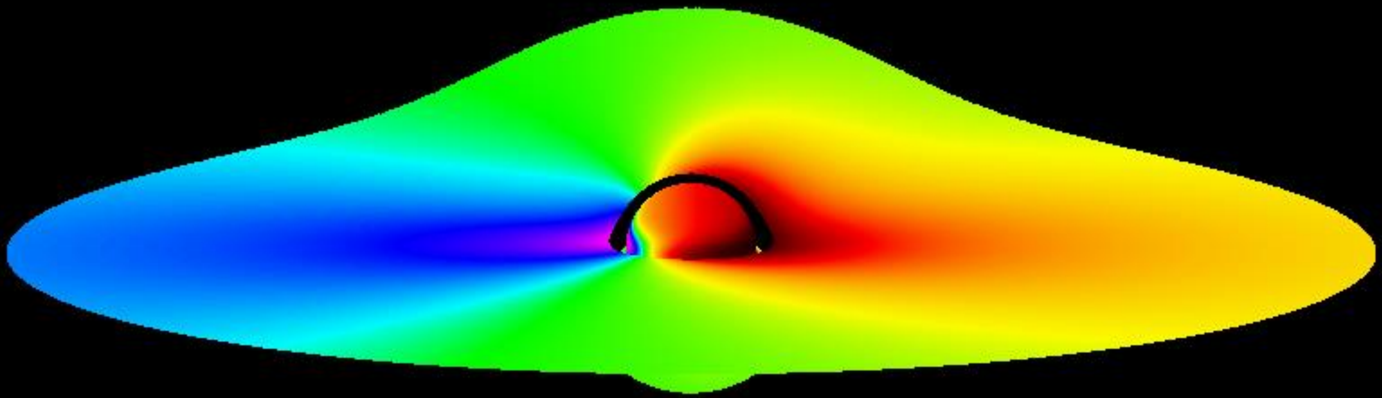


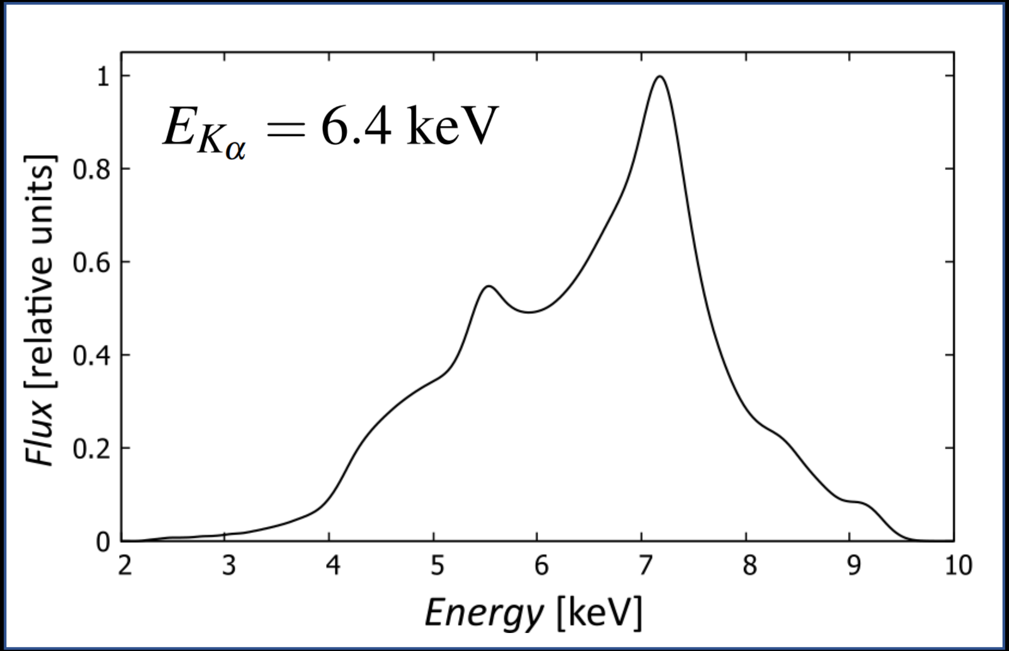
- Spectral profile





Spectral profile





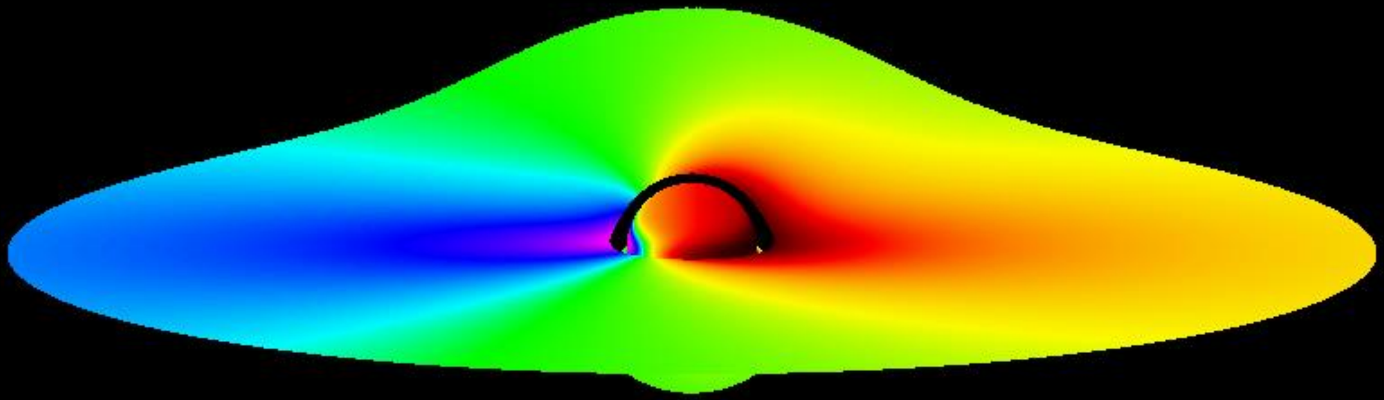
Parameters of this result

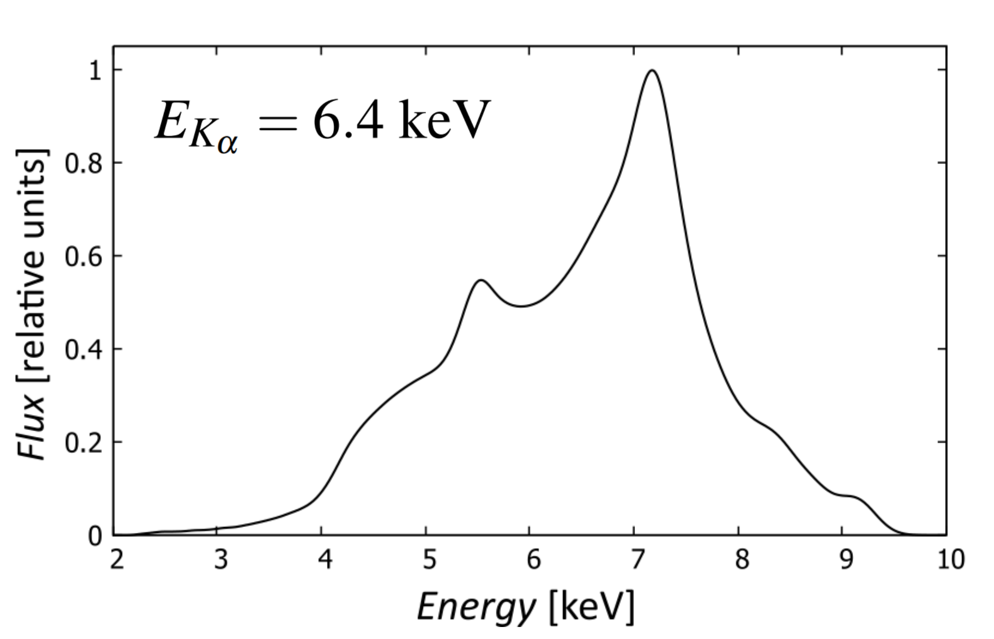
$i = 80°$
$\sigma = 125$ eV

$r_{\rm i} = 6\,M$
$r_{\rm o} = 60\,M$
$q = -1$

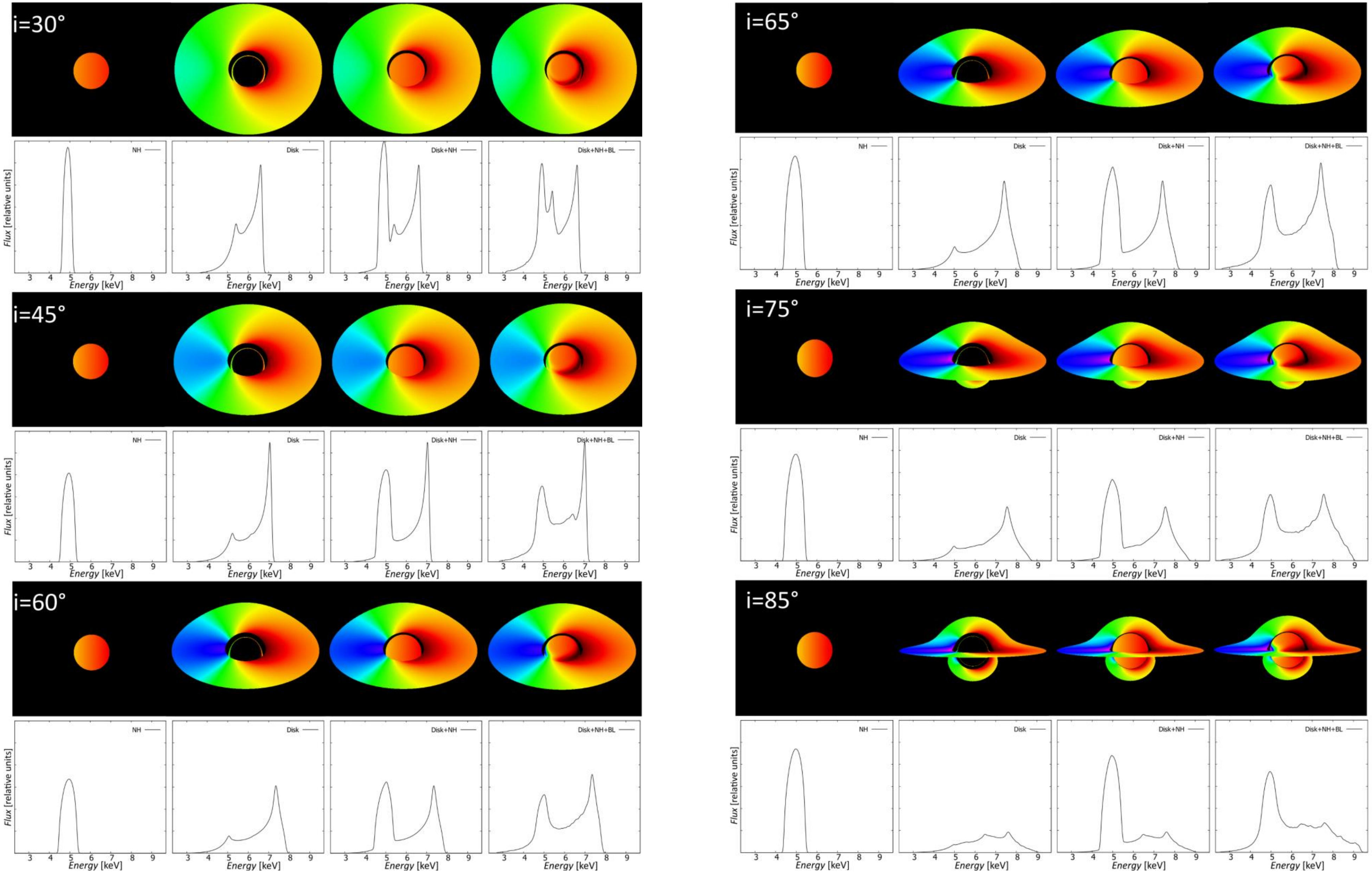
$M = 1.4\,{\rm M}_\odot$
$a = 4.83\,M$ (10 km)
$b = 4.66\,M$ (9.65 km)
$f_\star = 600$ Hz

$\sigma_{\rm BL} = 0.25$



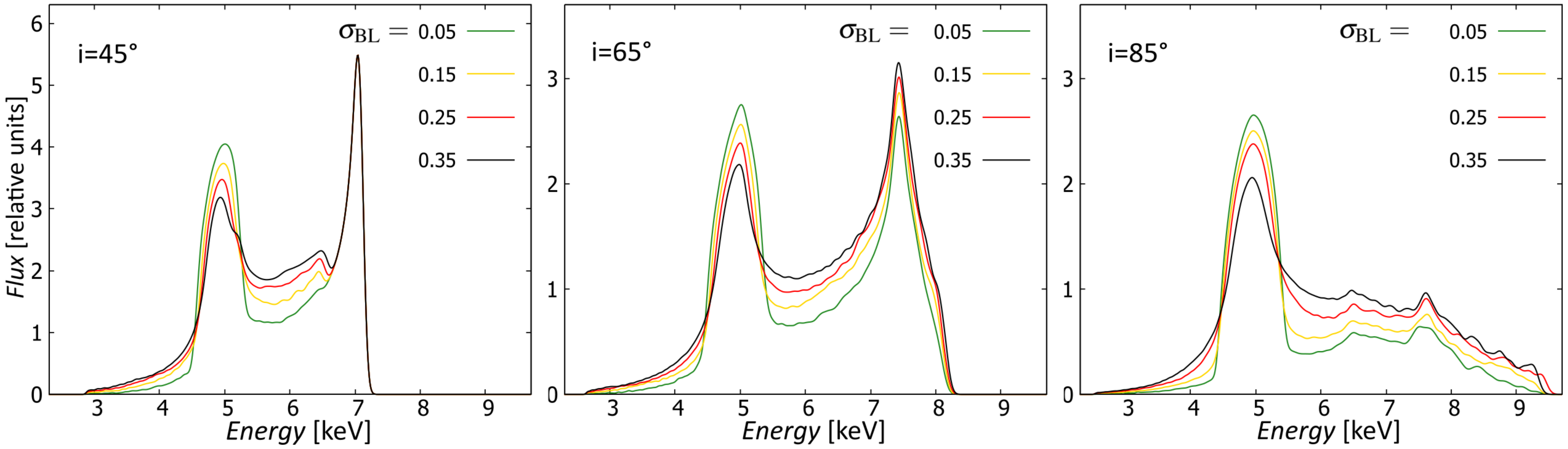


Contribution of components



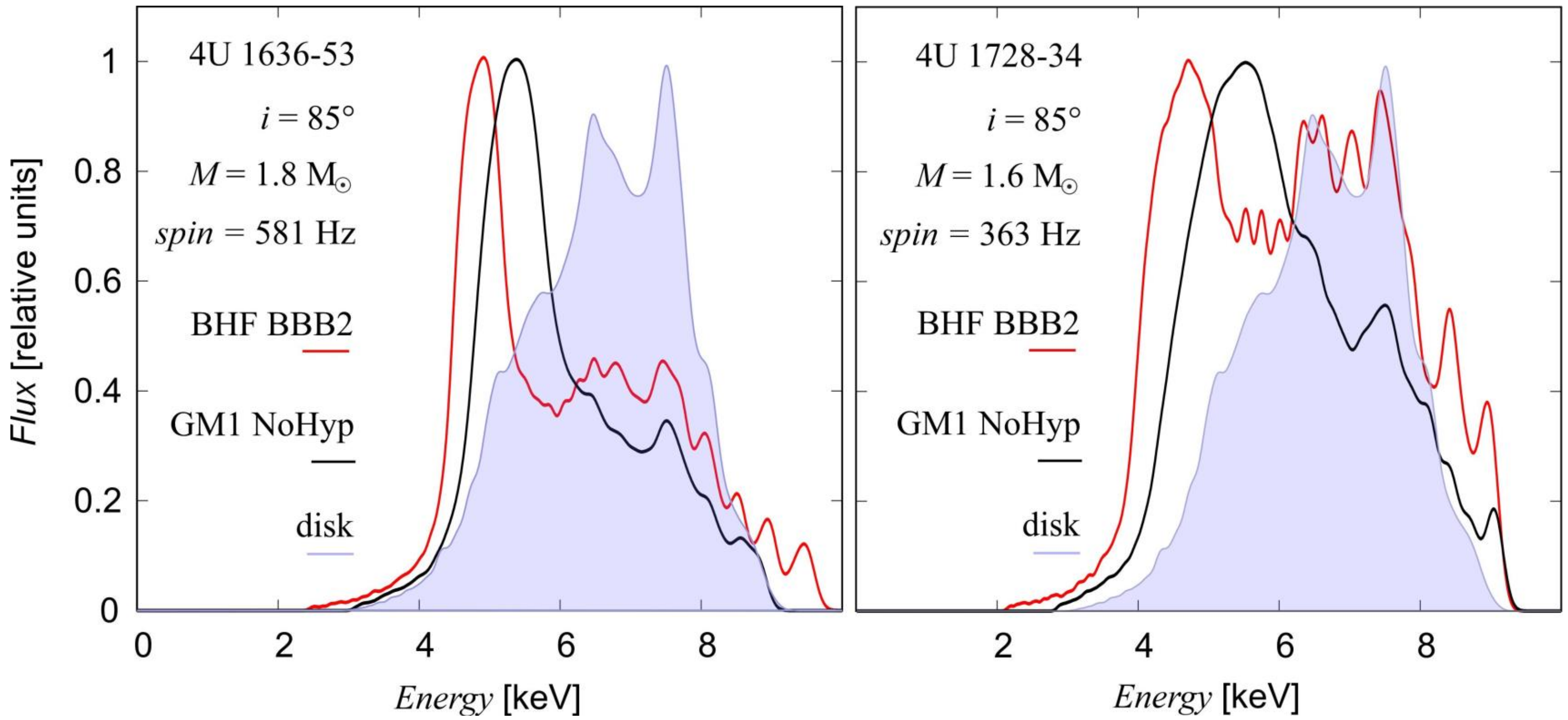
Some more results part 1

- The impact of changing the width of the BL on the overall spectrum of the system for three different observer inclinations.



Some more results part 2

- Iron line profile from accreting neutron star for two different EoS of the NS. The filled region indicates the line from the disk alone.



Summary and conclusions

- We are able to model relativistic spectral profiles from accreting compact object and we can study the influence of individual components of the system on the resulting spectral profiles.

- Modeled spectra can consist of iron line and black body emission.

- Complex model including the radiation of accretion disk, neutron star, boundary layer.

- Consideration of different equation of state for NS with a given mass and spin frequency may result to very different spectral signatures.

Backup slide 1

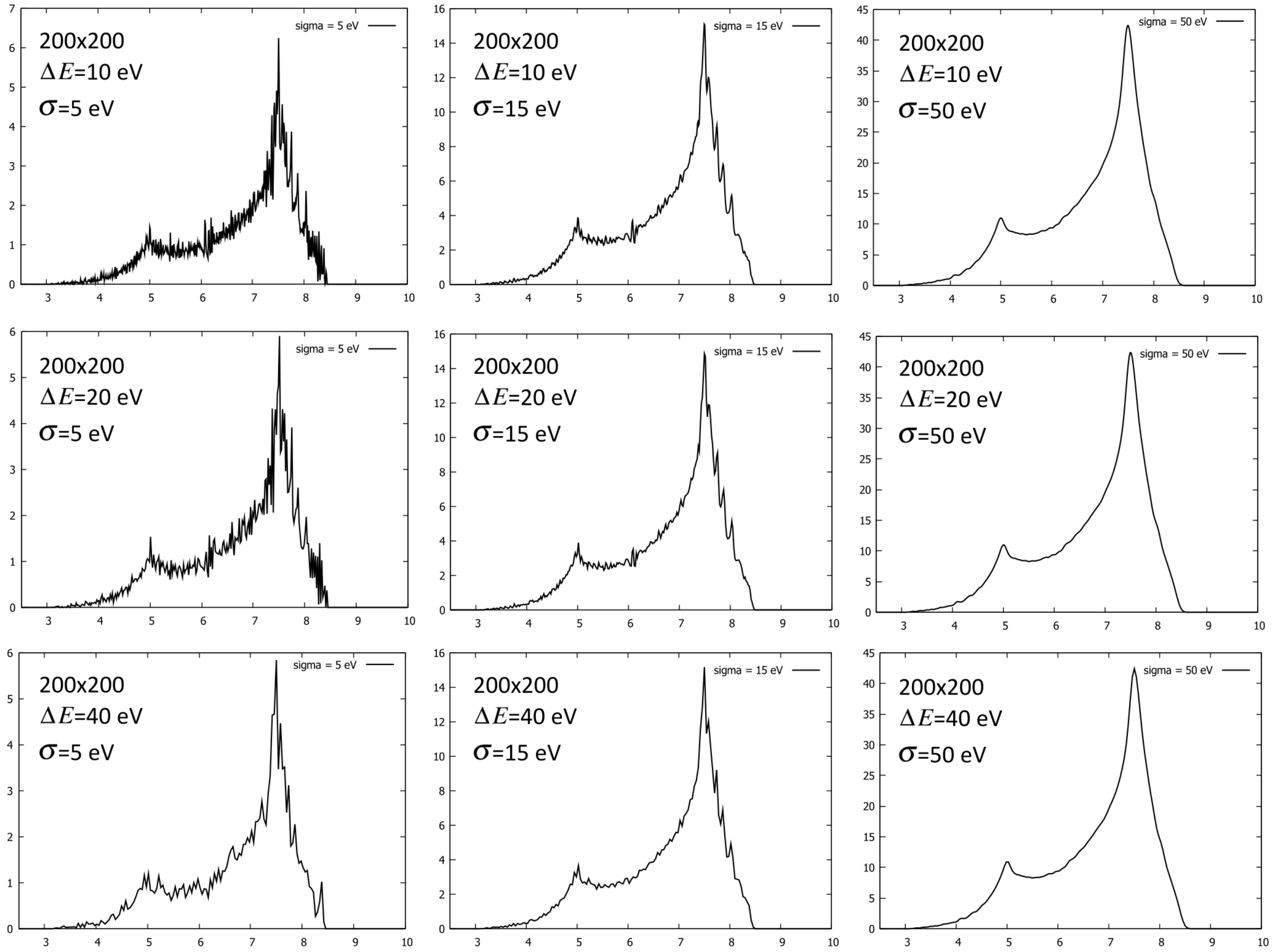
$$e^{-\frac{(E-E_{K\alpha})^2}{2\sigma^2}}$$

$$E_{K\alpha} = 6.4 \text{ keV}$$

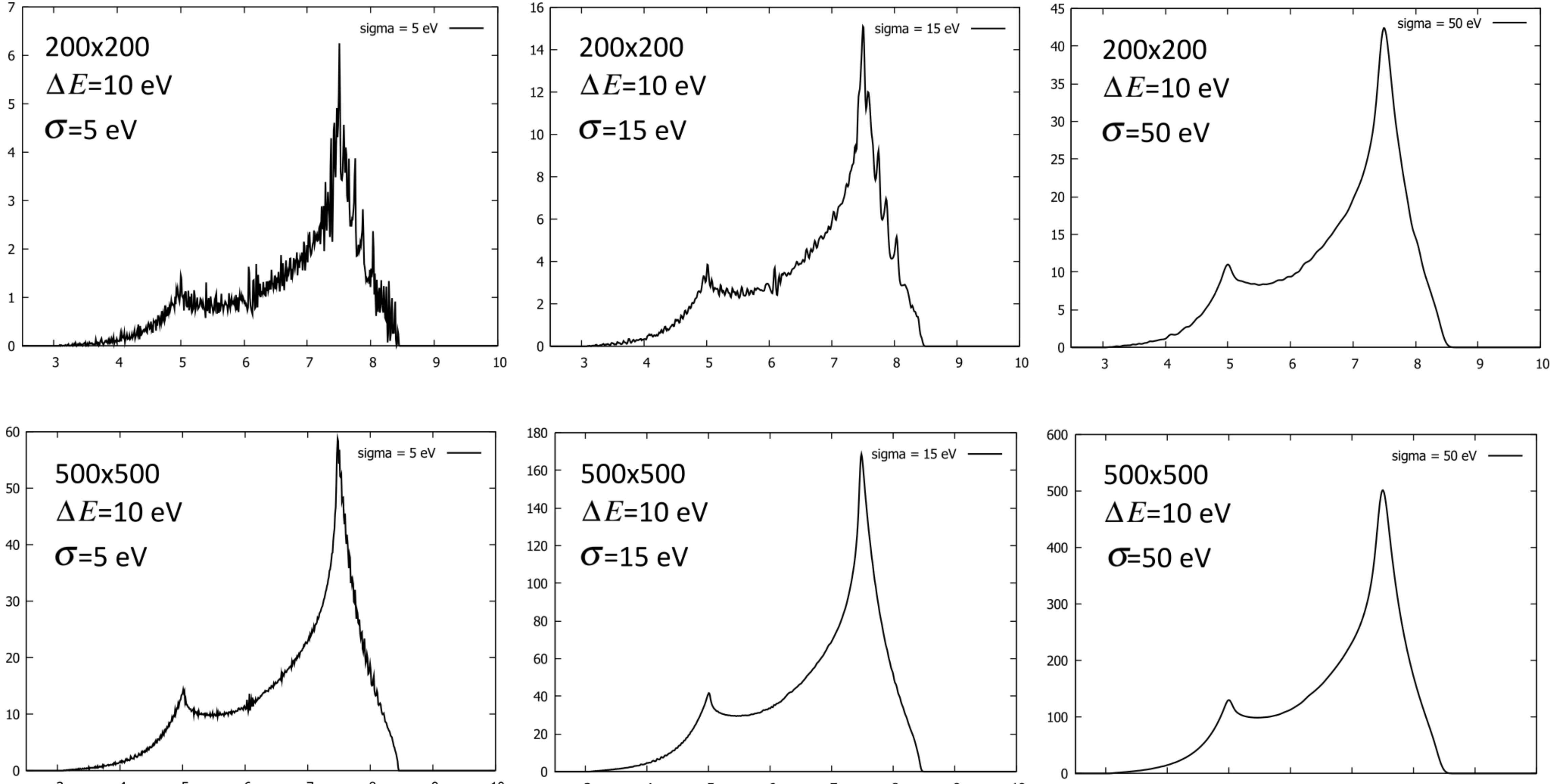
$$E_\mathrm{k} = \mathrm{k}\Delta E + 0.5\Delta E$$

$$\sigma = 15 - 50 \text{ eV}$$

N x N pixels



Backup slide 2



Backup slide 3