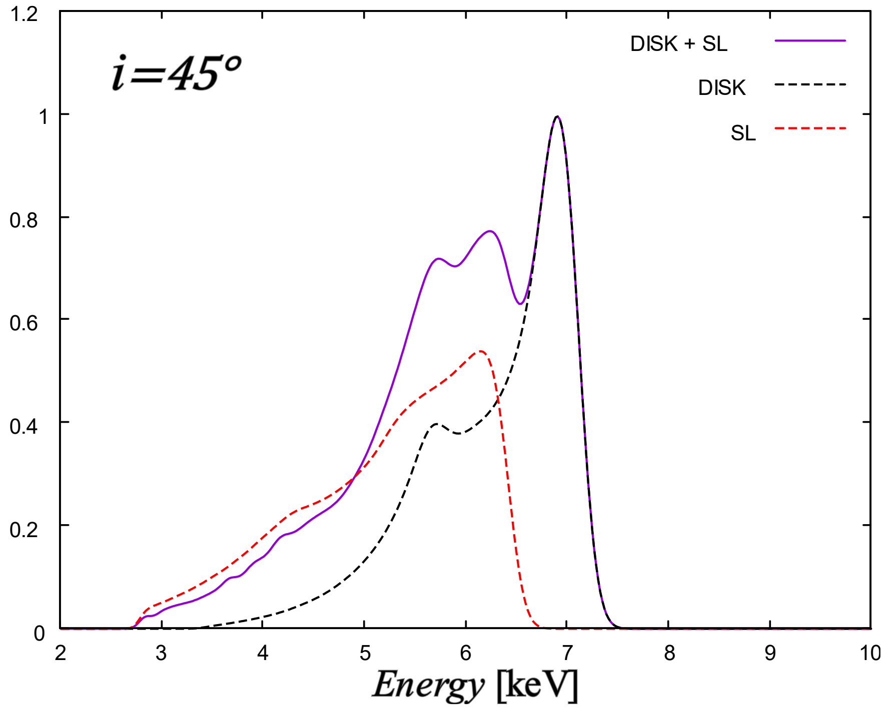
Iron Kα line modeling and possible constraints on EoS of NS

SILESIAN UNIVERSITY
INSTITUTE OF PHYSICS
IN OPAVA

René Šprňa

August 2024, Warsaw

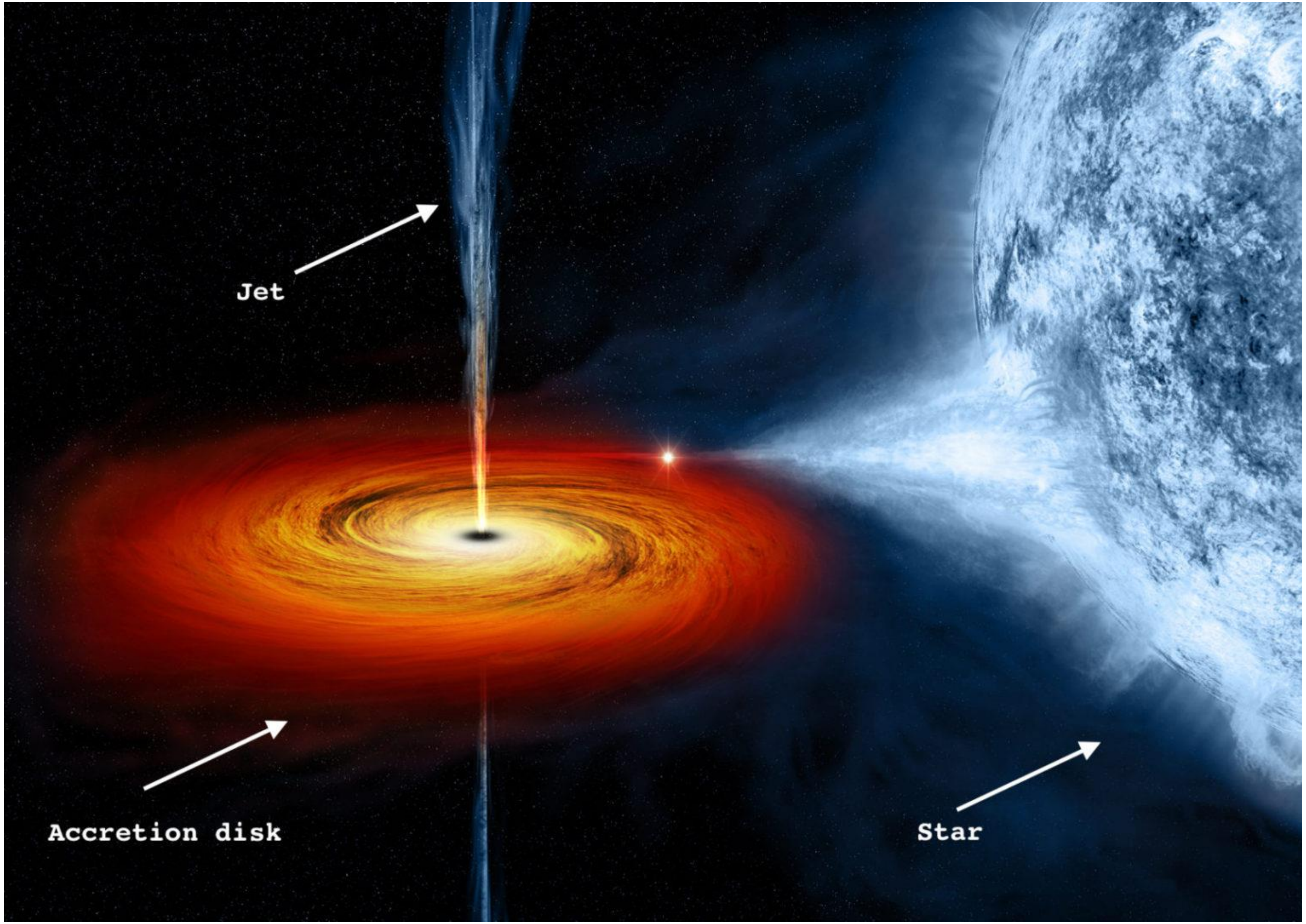
Brainstorming Workshop



Outline

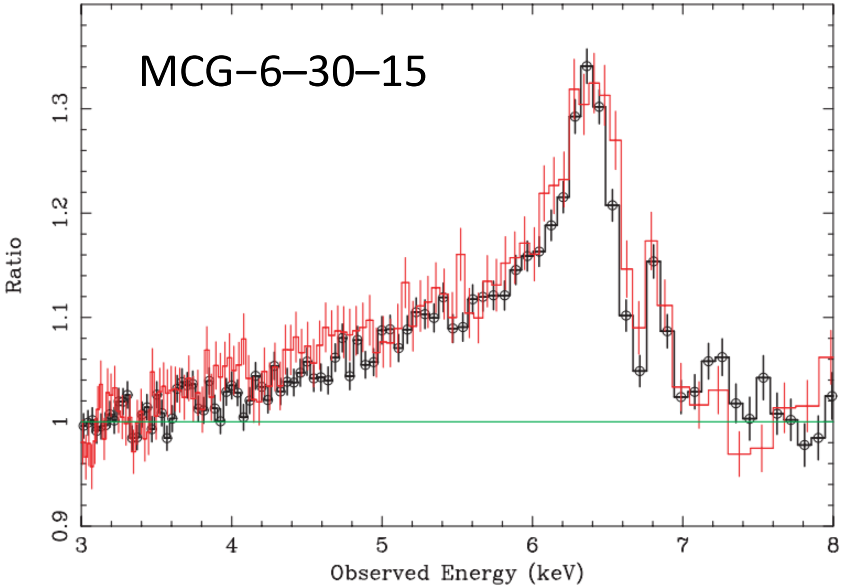
- 1. Iron line observation
- 2. Specifying the source – LMXB with NS
- 3. Iron emission line and the model
- 4. Results and conclusion

Accretion -> iron line



Observed iron lines

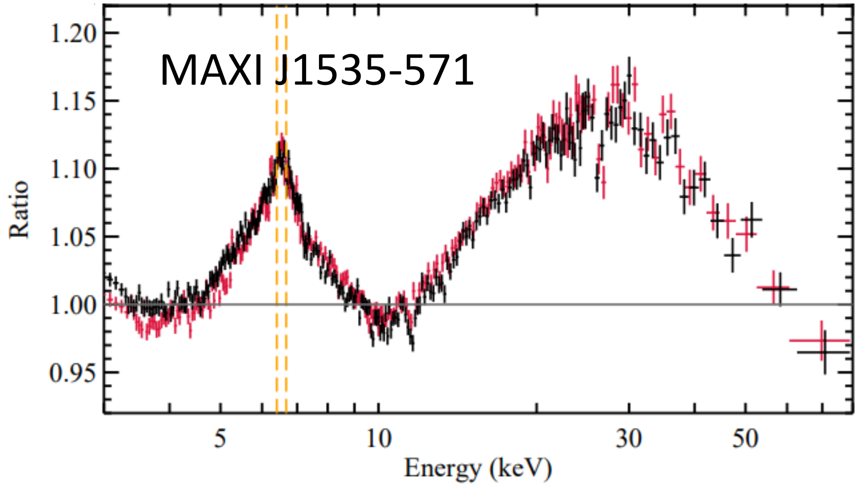
AGN



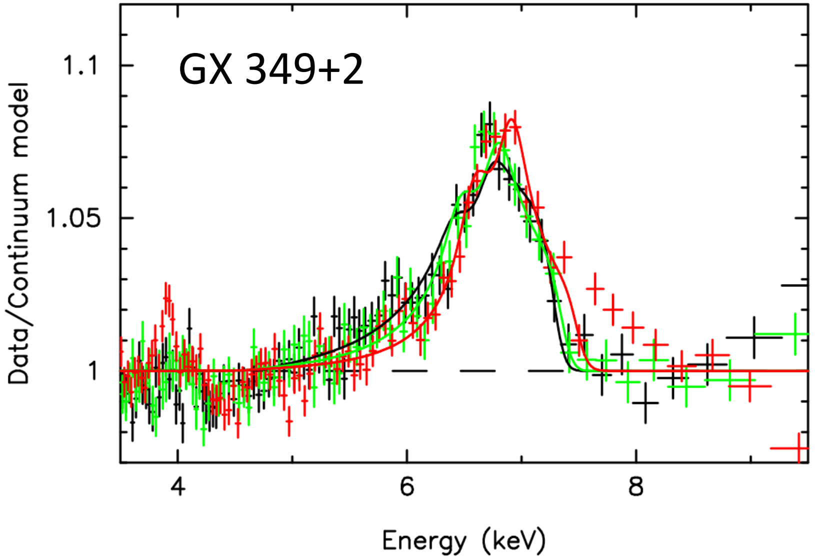
r_{in} -> r_{ms}

To estimate spin and inclinaiton

LMXB with BH

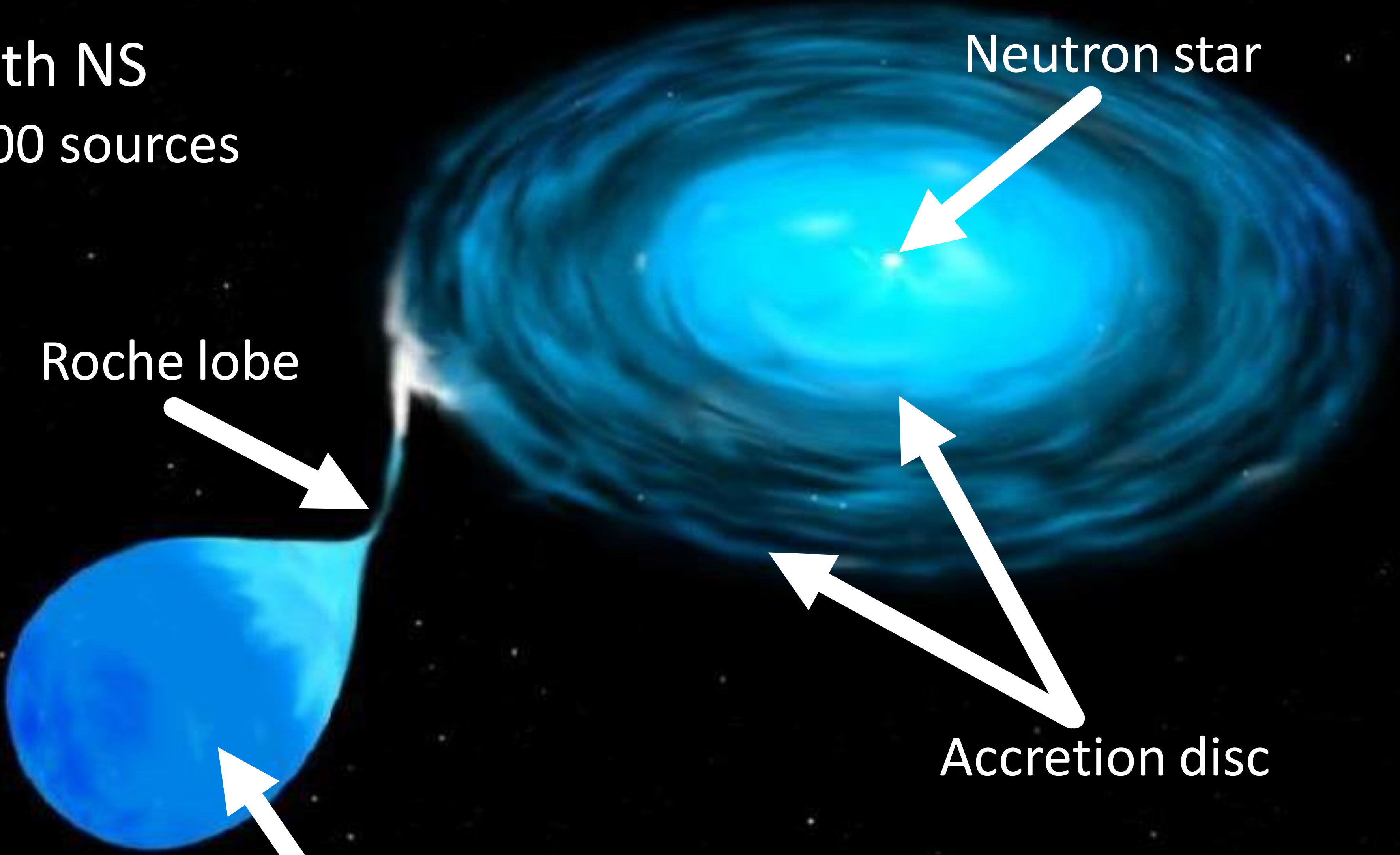


LMXB with NS



LMXB with NS

Around 200 sources



Neutron star

Roche lobe

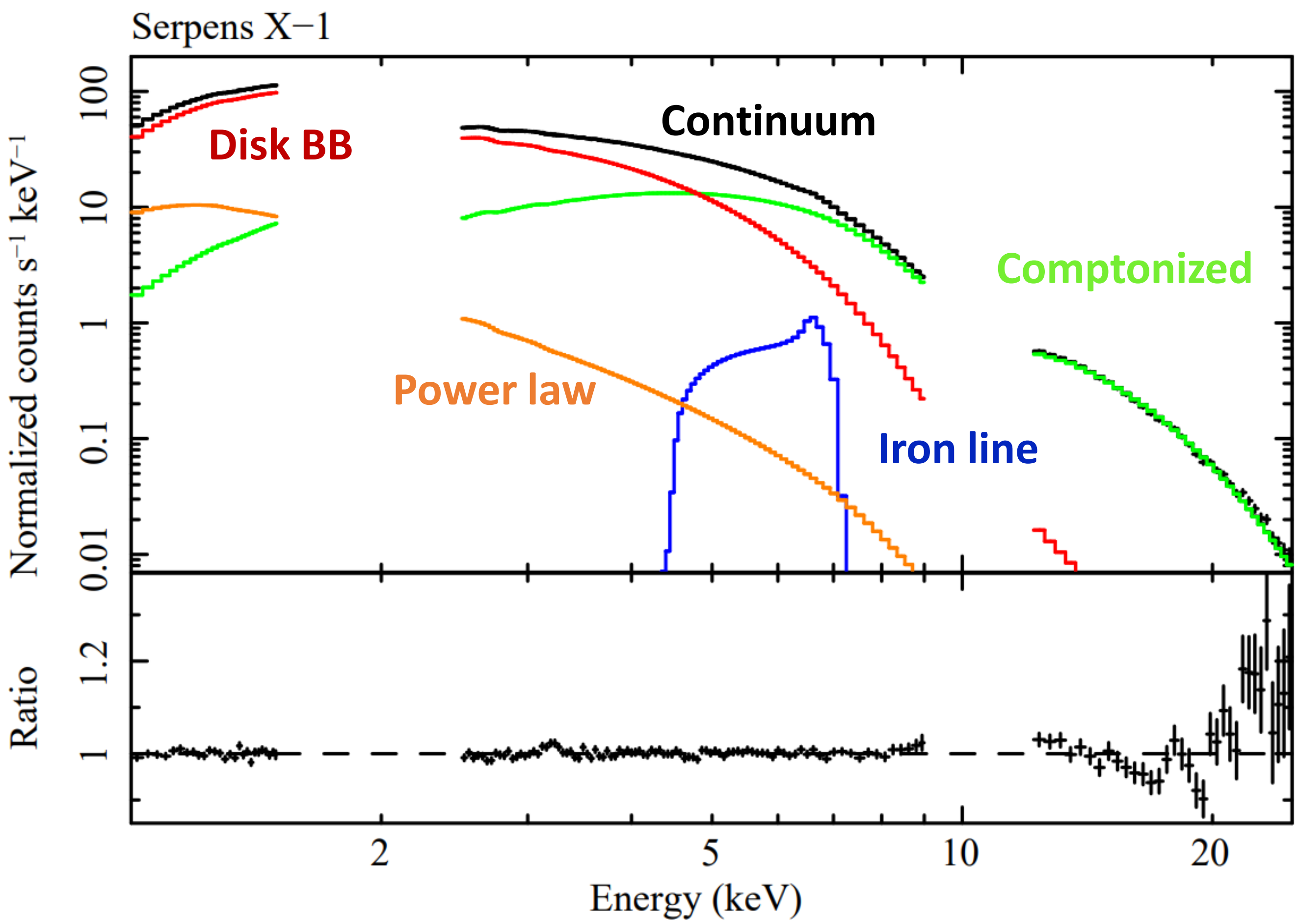
Accretion disc

Donor star (with mass smaller than Sun)

figure taken from the site httpchandra.harvard.edu

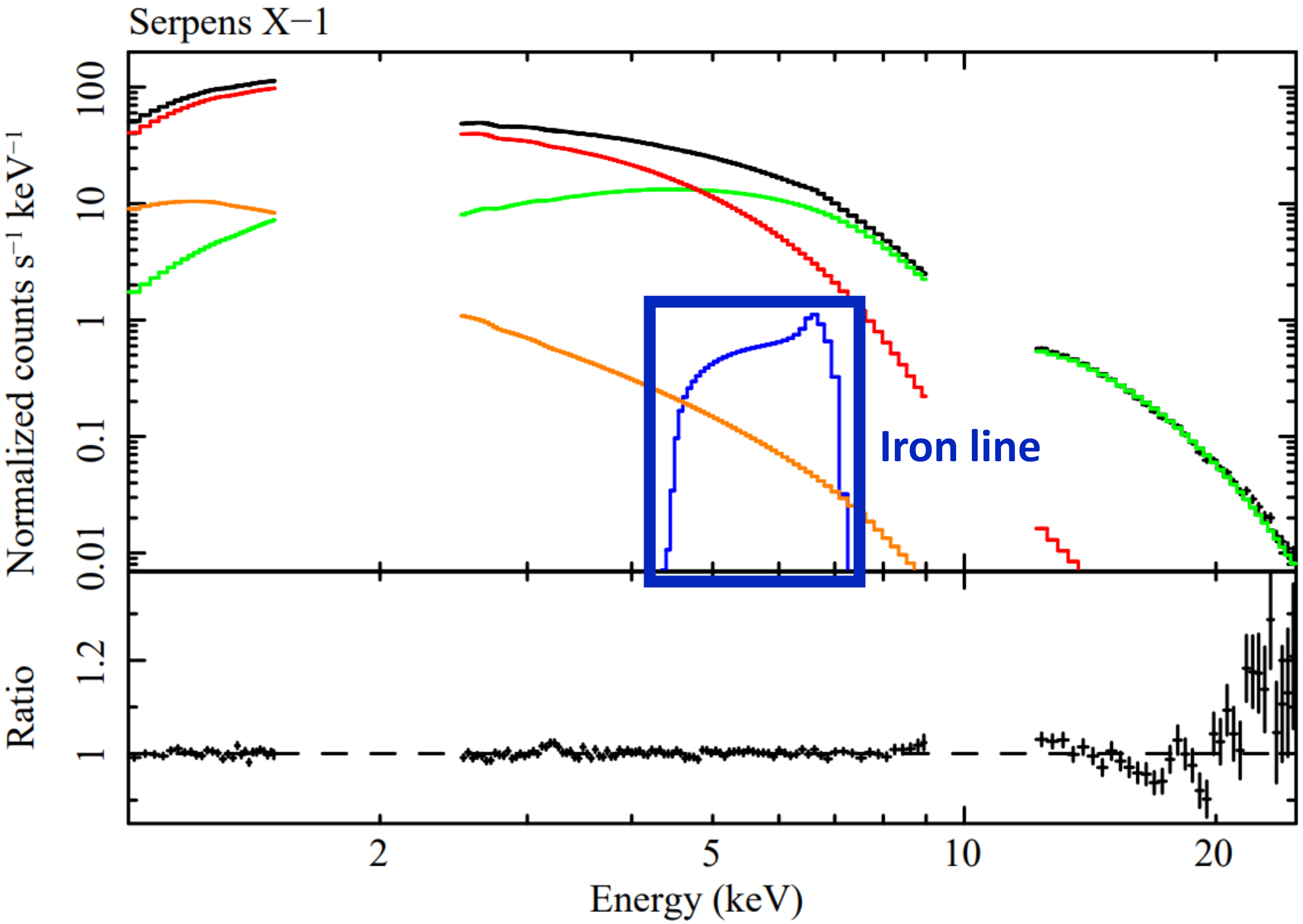
Observed spectrum of LMXB

(Cackett et al. 2008)

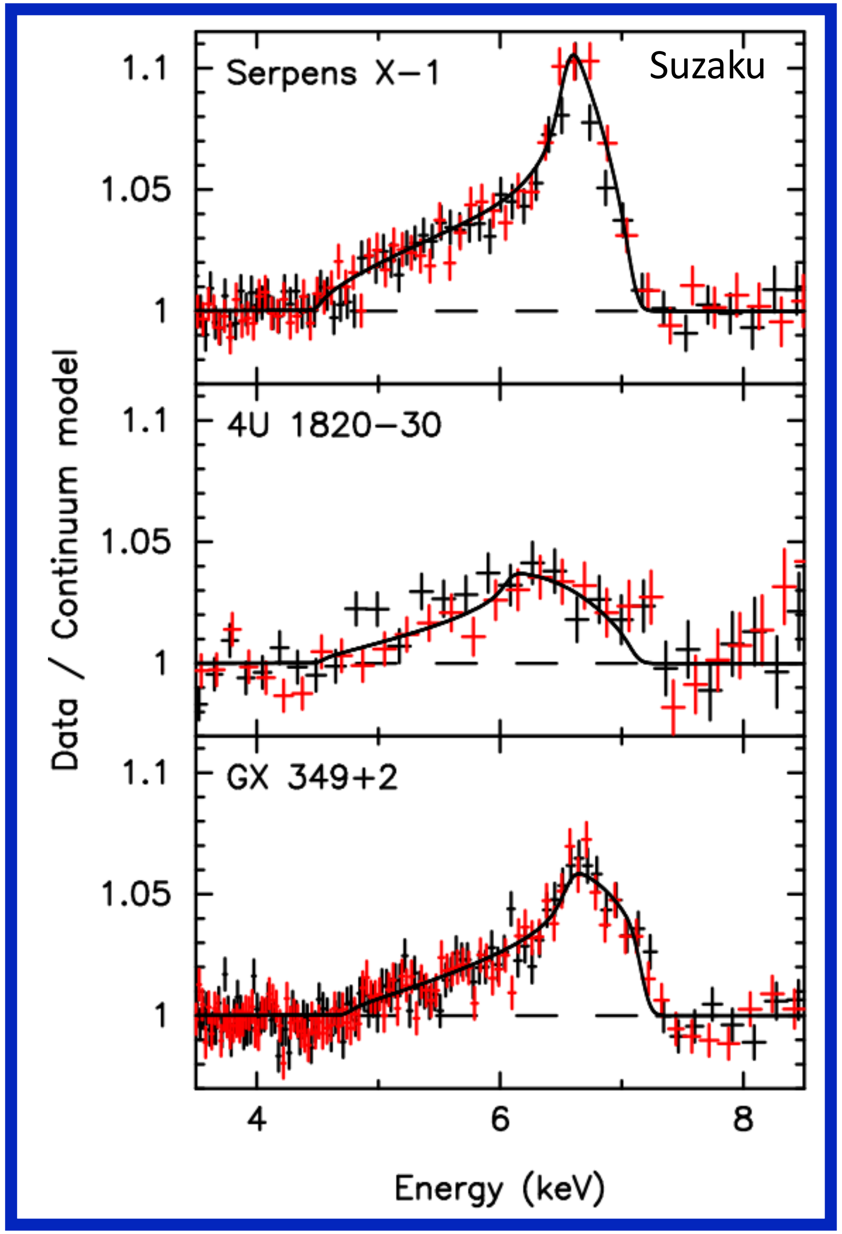


Observed spectrum of LMXB – Iron Kα line

(Cackett et al. 2008)

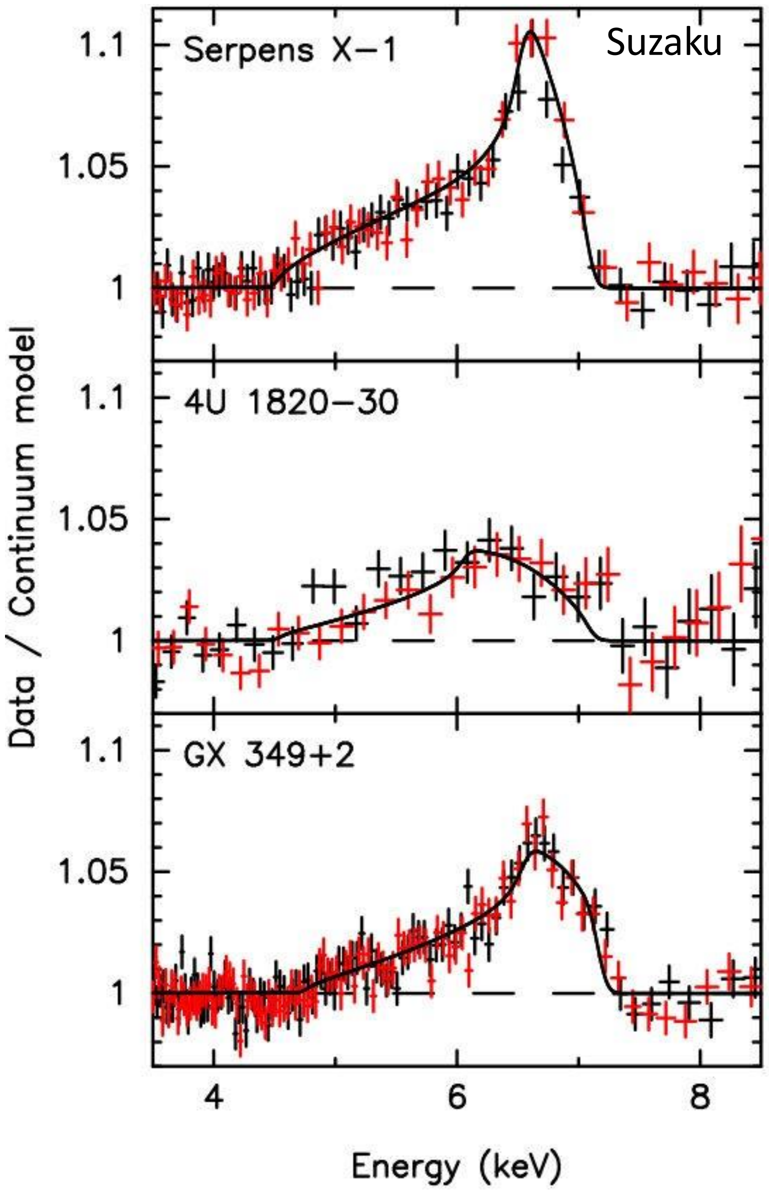


Iron line

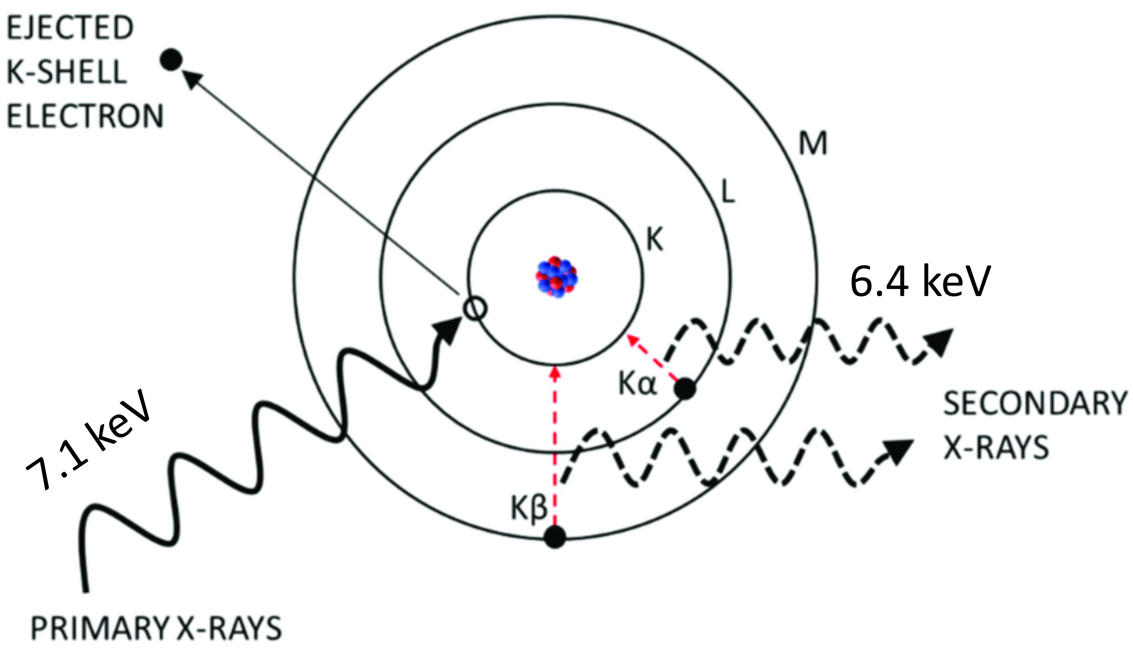

Suzaku

Observed spectrum of LMXB – Iron Kα line

- About 80% of LMXB show iron line signature
- Often broad (3 – 9 keV) asymmetric spectral profile
- Spectral profile fitting is important to estimate inner edge radius of the disc
- Iron line is the most dominant emission line in all x-ray sources

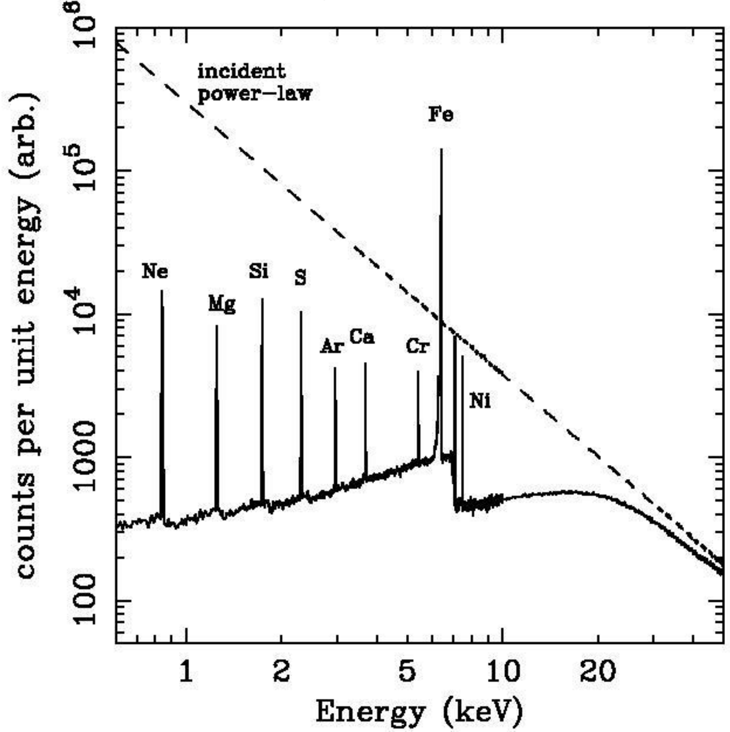


Why iron line?



(34%)

(Reynolds 1996)



- Iron abudance × fluorescence yield = highest among all elements
- The treshold for photoeletric absorbtion by neutral iron is 7.1 keV – high energy (X-ray) seed photons needed – hot corona

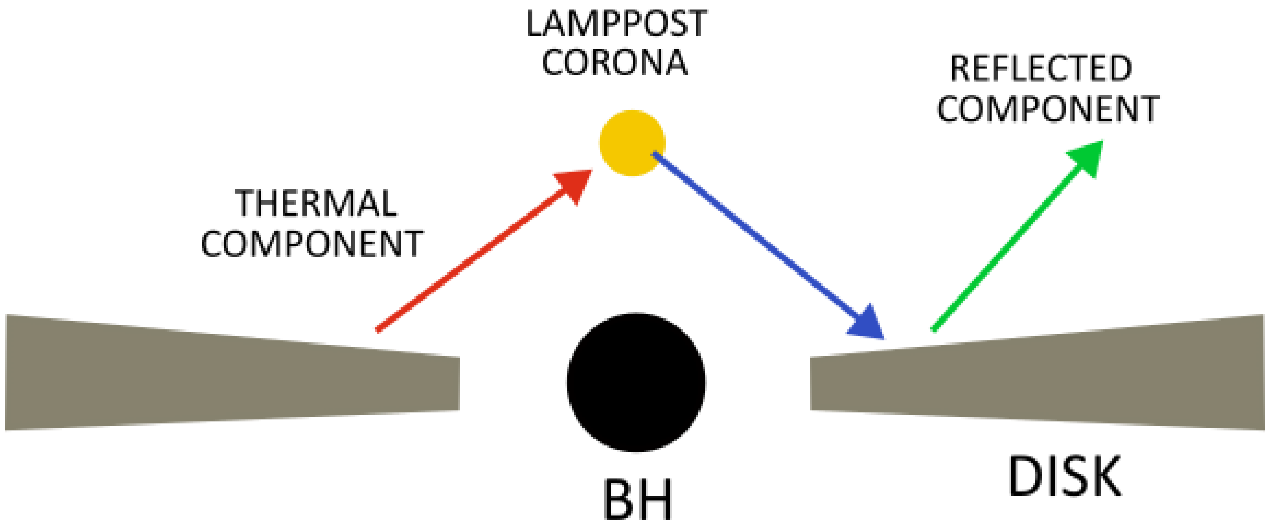
- Fe I-XVI ≈ 6.4 keV
- Fe XXIV-XXV ≈ 6.7 keV
- Fe XXVI ≈ 7 keV

General idea:

– presence of hot corona emitting high energy photons

– corona illuminates cold disc -> iron line emission

– usually the presence of neutron star is ignored

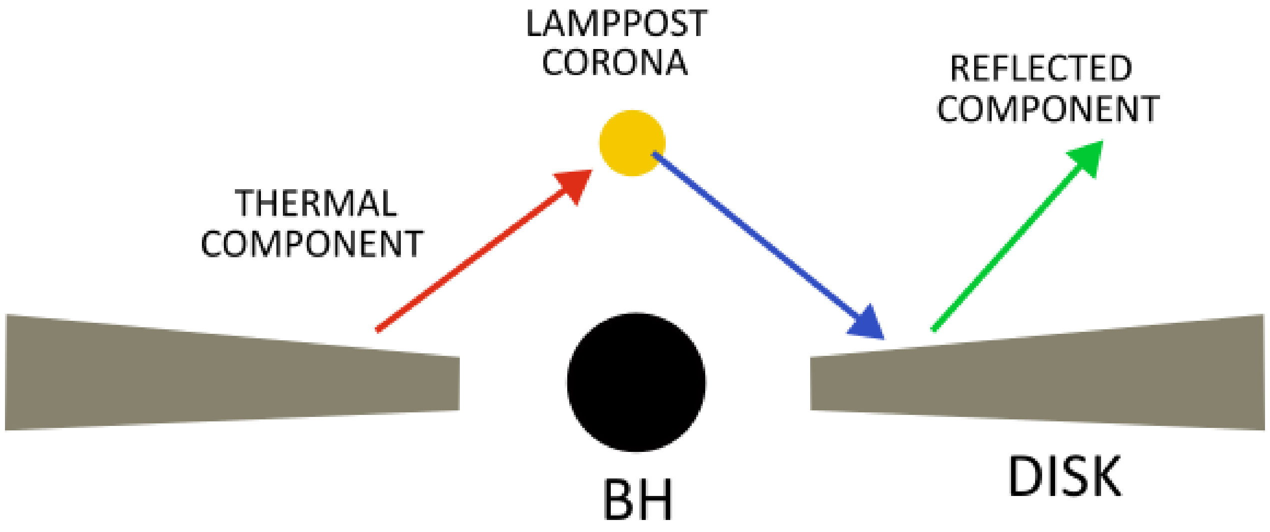


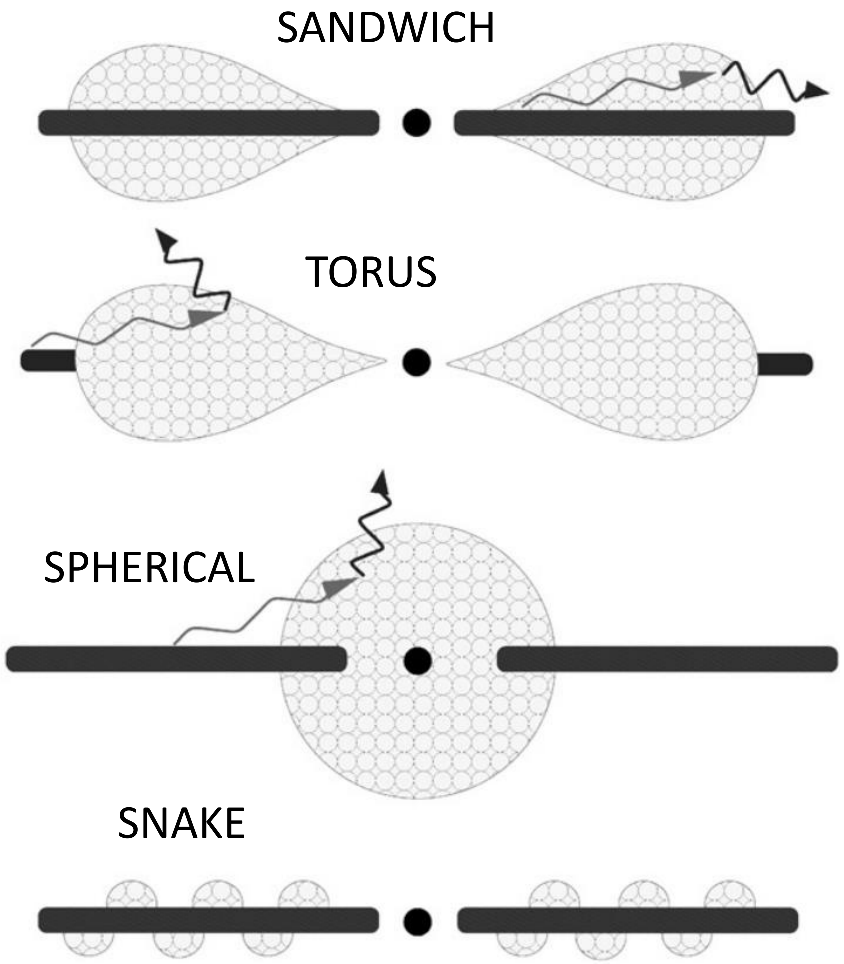
General idea:

– presence of hot corona emitting high energy photons

– corona illuminates cold disc -> iron line emission

– usually the presence of neutron star is ignored



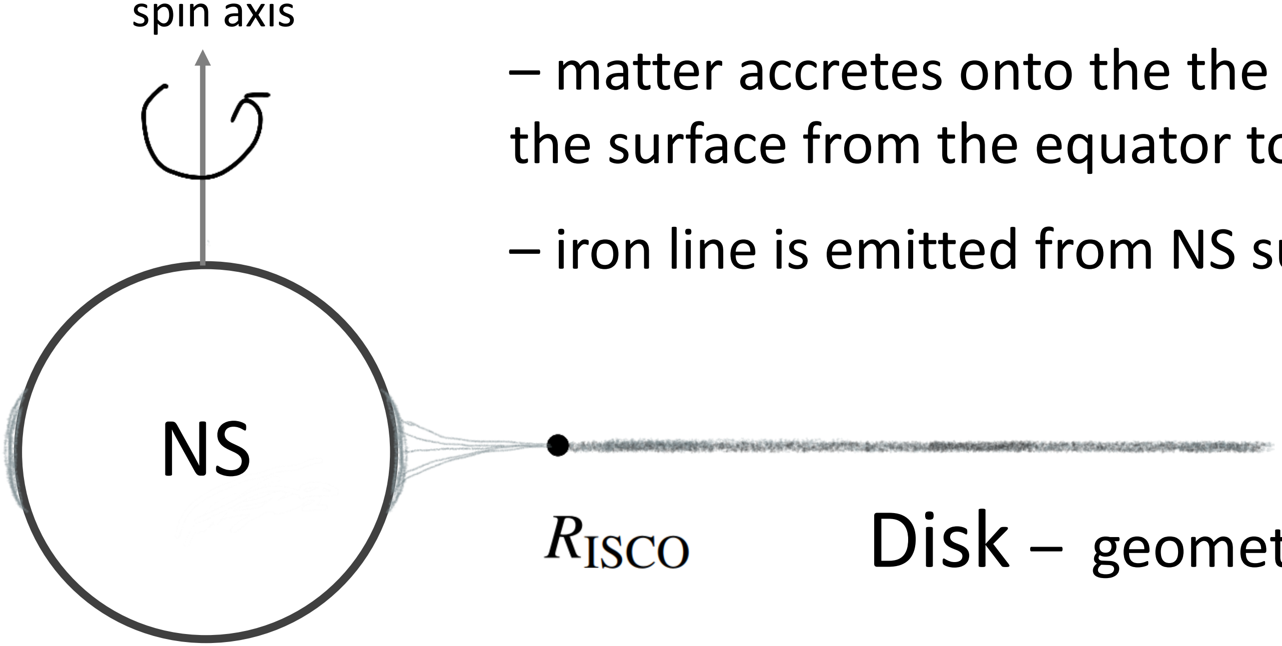


My assumptions:

- weak magnetic field $(B \lesssim 10^8\ \mathrm{G})$

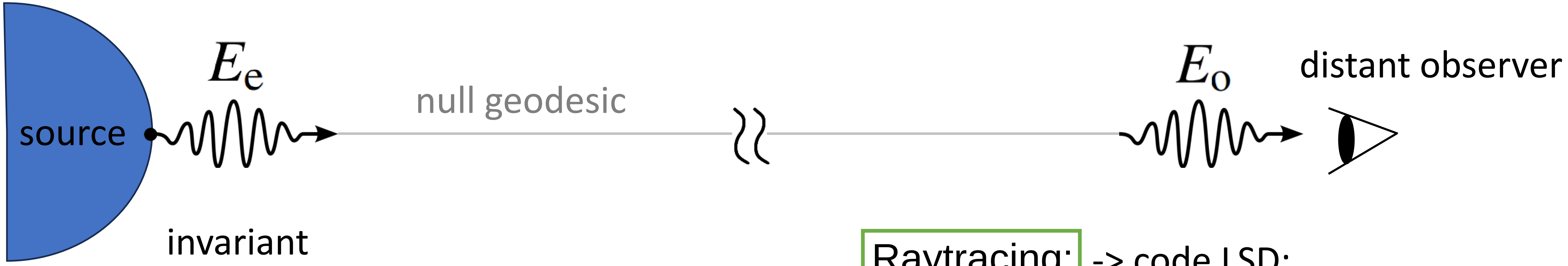
About 30 sources left

- disc ends at marginally stable orbit
- matter accretes onto the the NS and spreads over the surface from the equator toward the poles
- iron line is emitted from NS surface



Disk – geometricly thin, optically thick, $\Omega_{\mathrm{K}} = \sqrt{\frac{M}{r^3}}$

How to model the line



$$\frac{I(E)}{E^3} \Rightarrow I_\mathrm{o}(E_\mathrm{o}) = g^3 I_\mathrm{e}(E_\mathrm{e})$$

$$\Big\downarrow$$

$$g = \frac{E_\mathrm{o}}{E_\mathrm{e}} = \frac{g_{\mu\alpha}u_\mathrm{o}^\mu p^\alpha}{g_{\nu\beta}\boxed{u_\mathrm{e}^\nu}\boxed{p^\beta}}$$

$$\boxed{g_{\mu\nu}u_\mathrm{e}^\mu u_\mathrm{e}^\nu = -1}$$

Raytracing: -> code LSD:

time-reversed integration
of Carter's equations

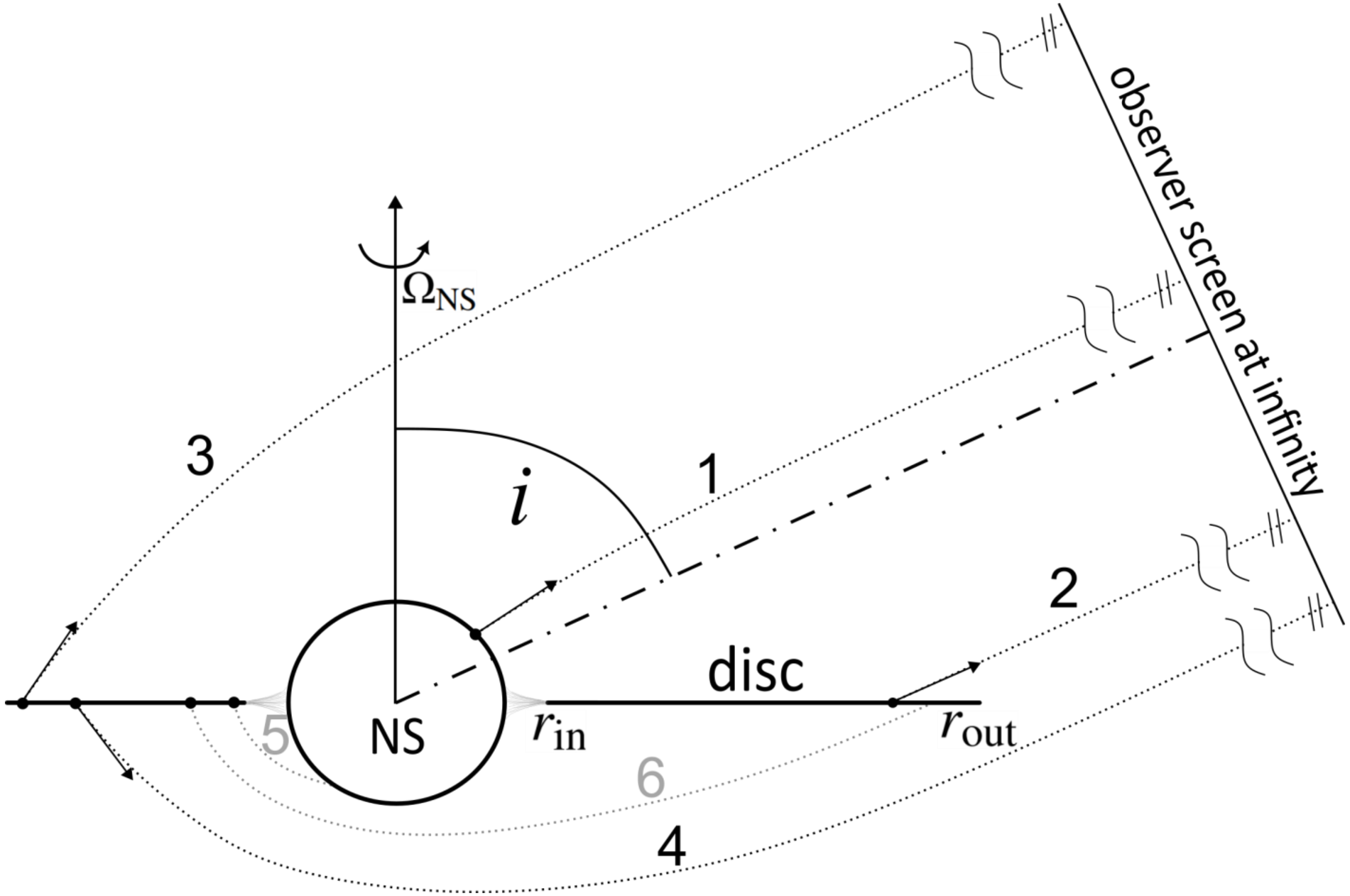
- Schwarzschild
- Kerr

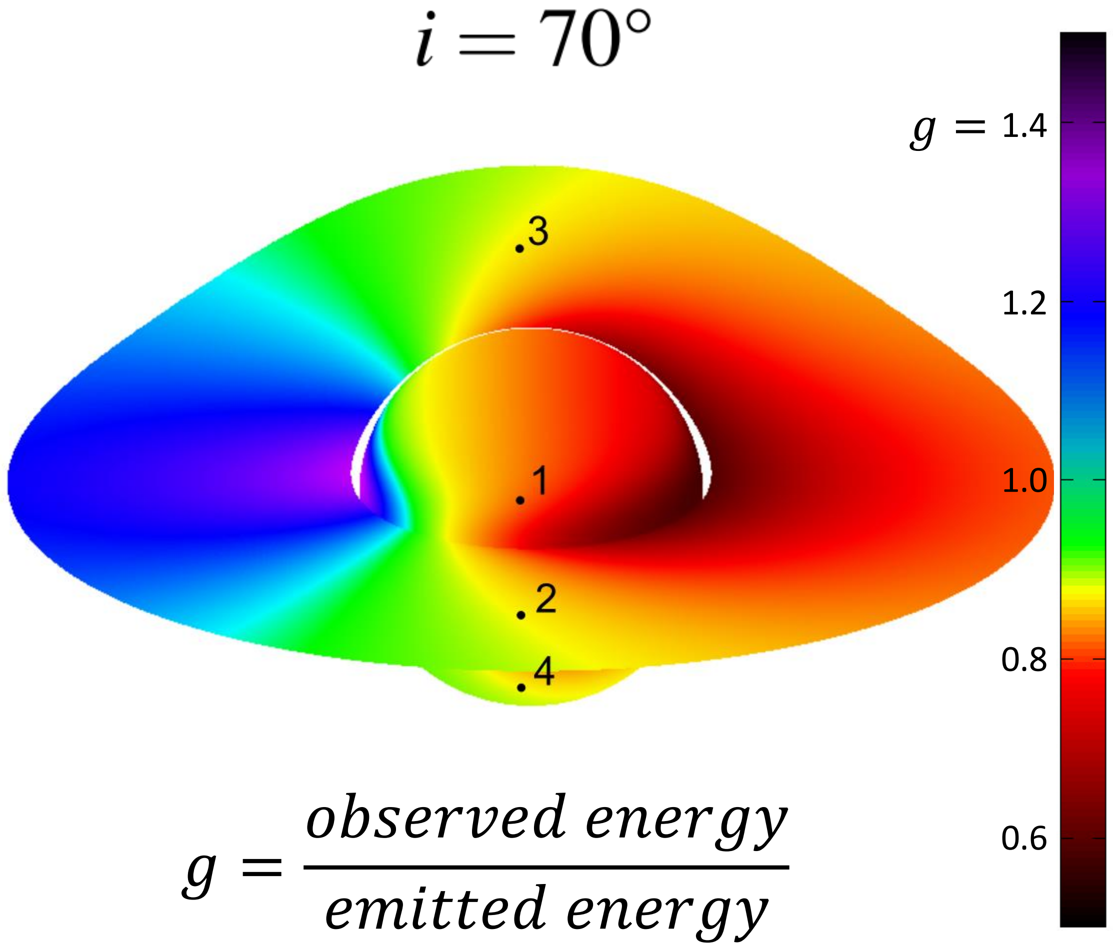
4-velocity and geometry:

- Schwarzschild
- Hartle-Thorne

Example of frequency shift map image

- Ray-tracing done using relativistic numerical code LSD – **all obscuration effects included**





$$g = \frac{observed\ energy}{emitted\ energy}$$

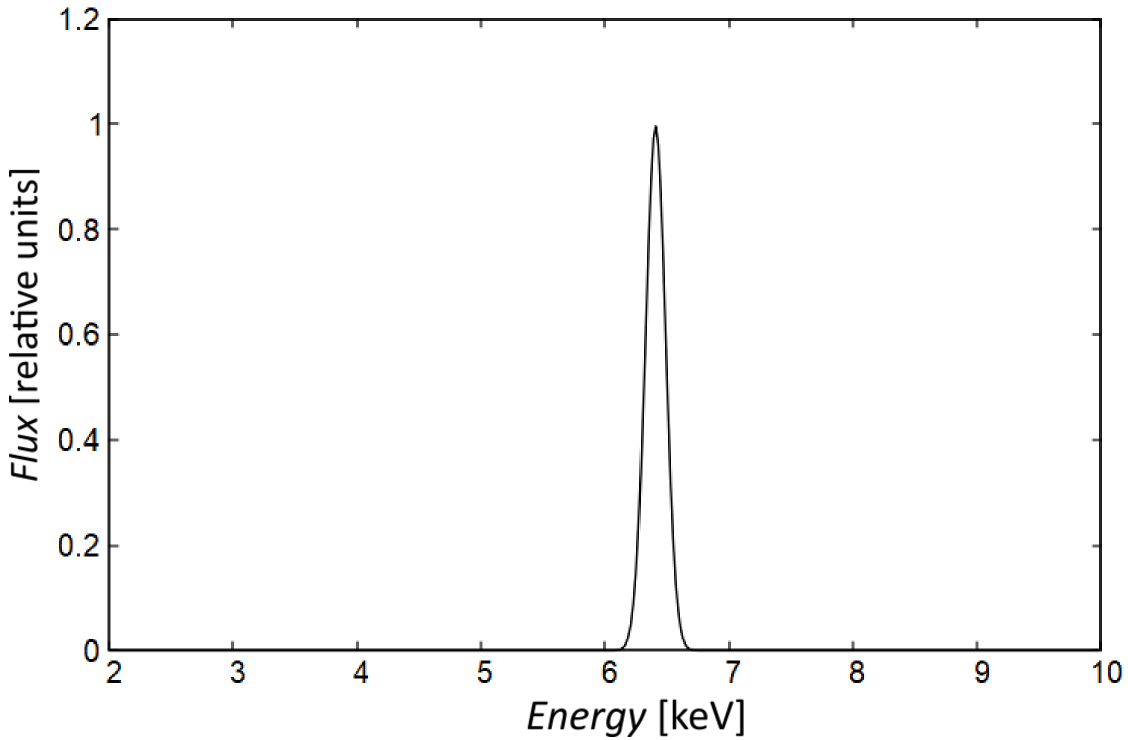
Iron Kα line profile - Gaussian

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

$$f(E_\mathrm{e}, \sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{(E_\mathrm{e} - E_{\mathrm{K}\alpha})^2}{2\sigma^2}}$$

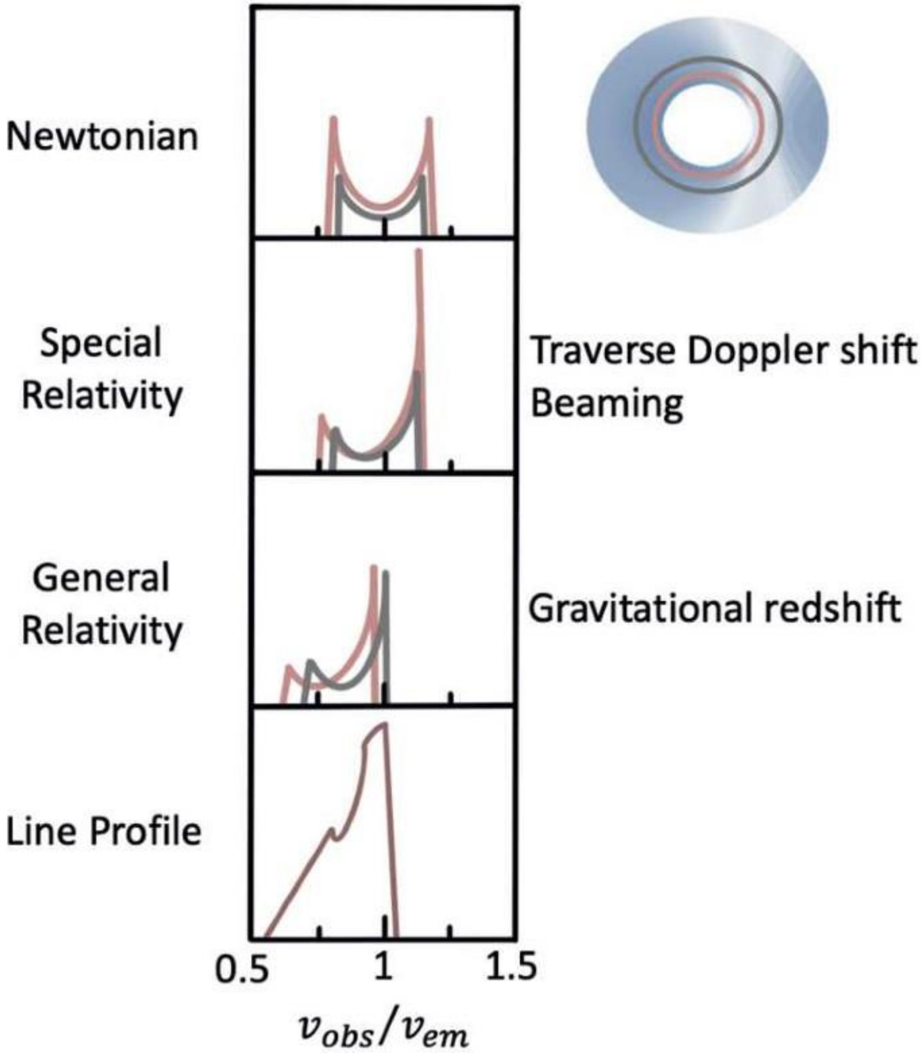
$\sigma = 100\,\mathrm{eV}$ ← standard deviation

$$F_\mathrm{o}(E_\mathrm{o}) = \int_{\Delta\Pi} g^3 I_\mathrm{e}(E_\mathrm{e}) f(E_\mathrm{e}, \sigma)\mathrm{d}\omega$$



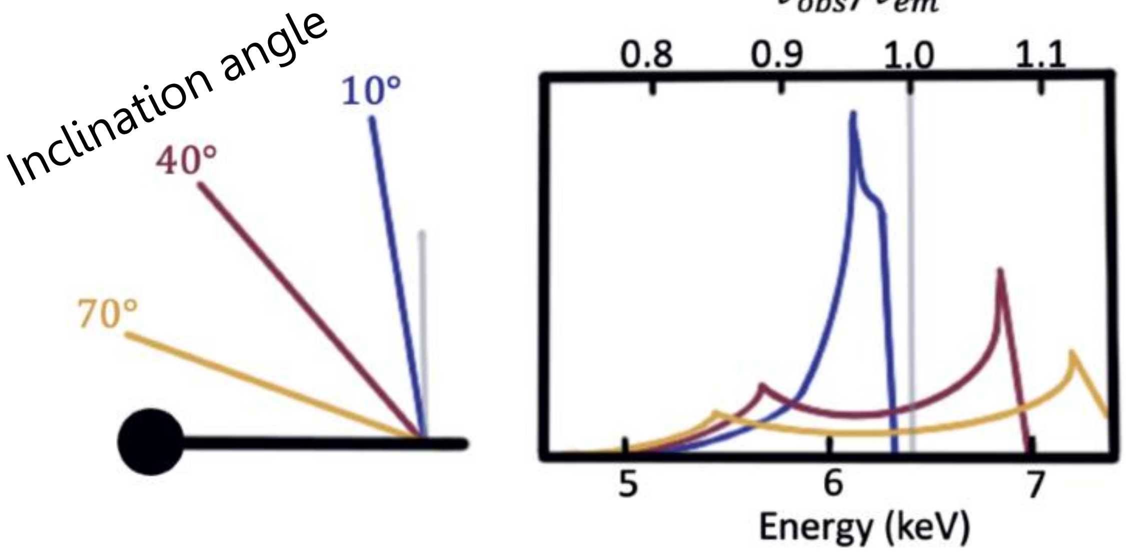
Relativistic effects on line profile

Fabian, 2000

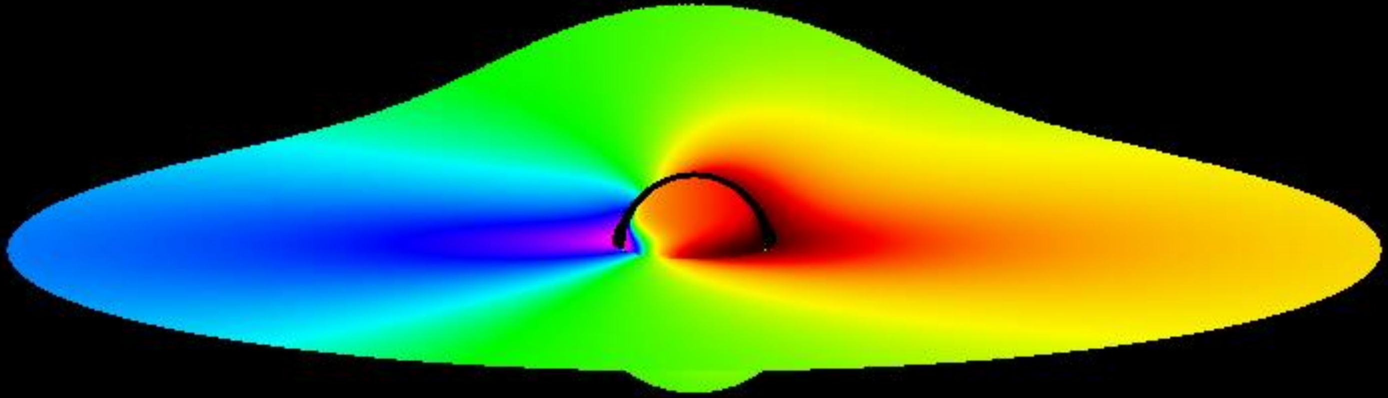


--->Captured by g-factor

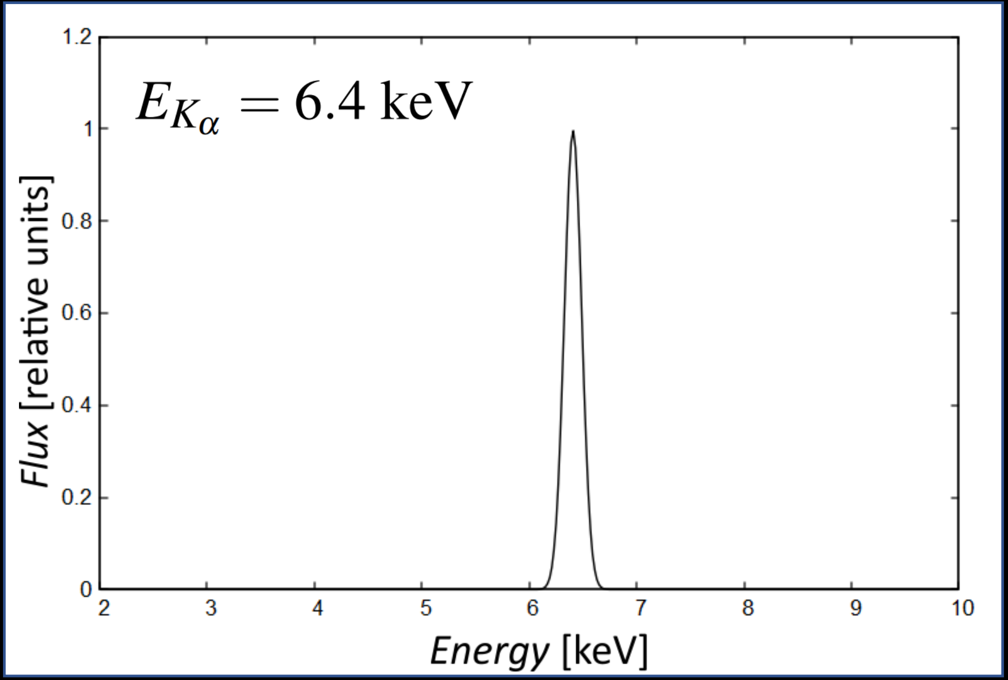
Dauser, 2010



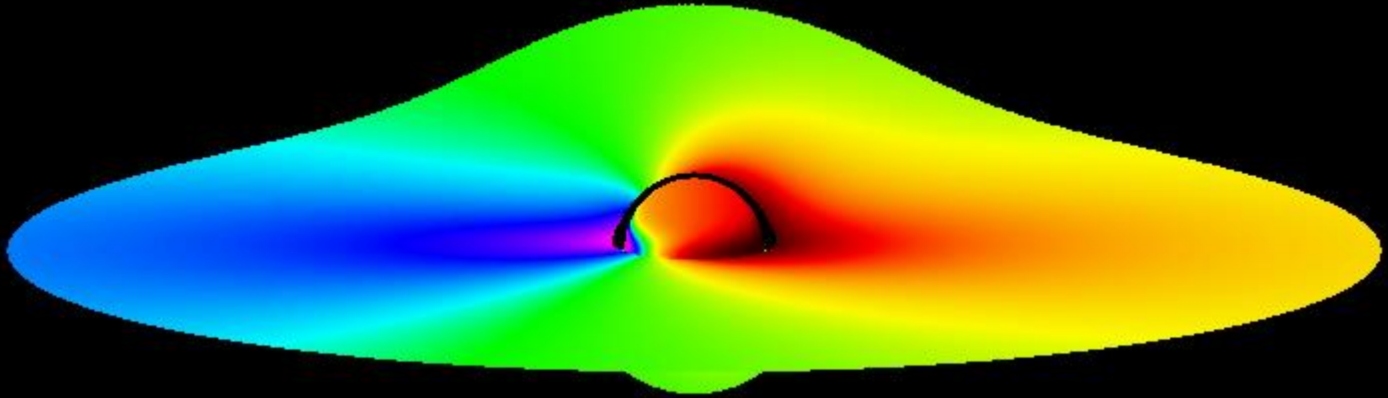
Spectral profile of the iron Kα line



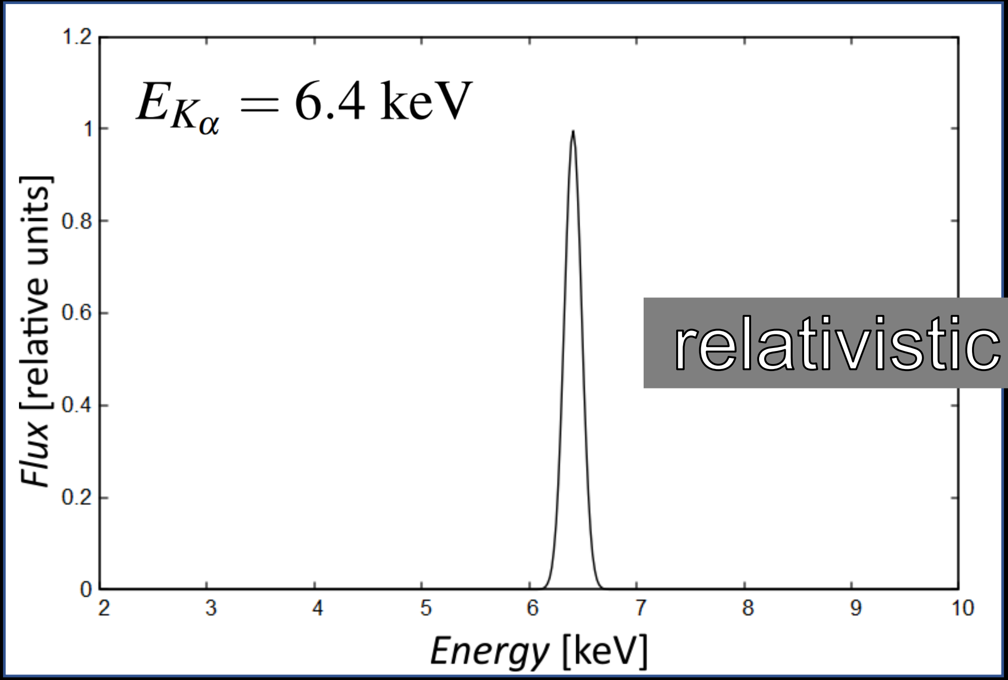
Local



Spectral profile of the iron Kα line

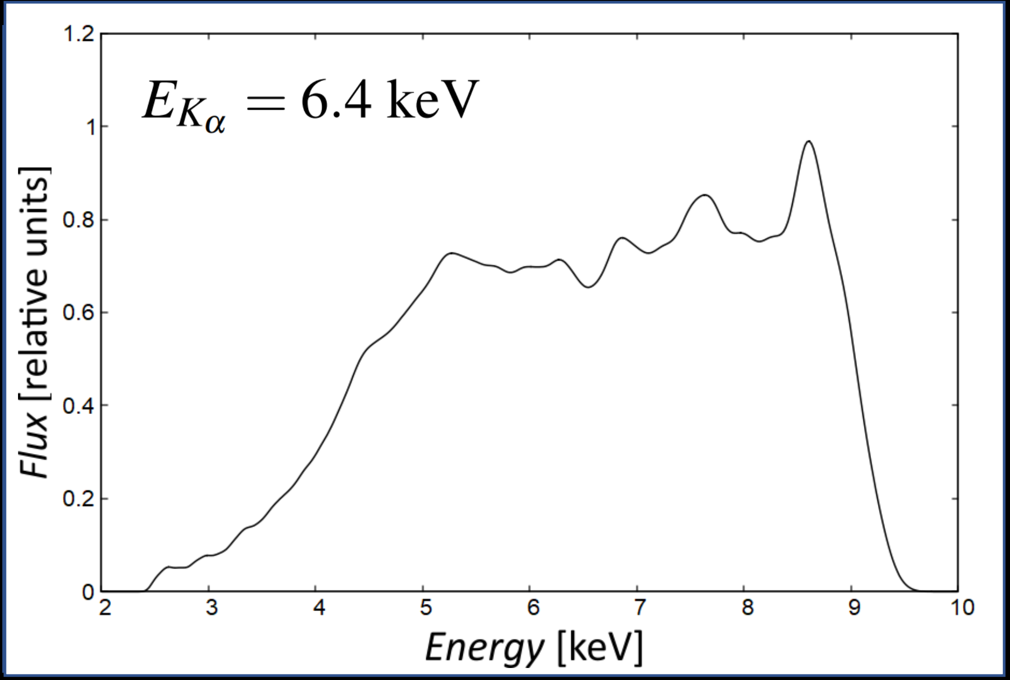


Local

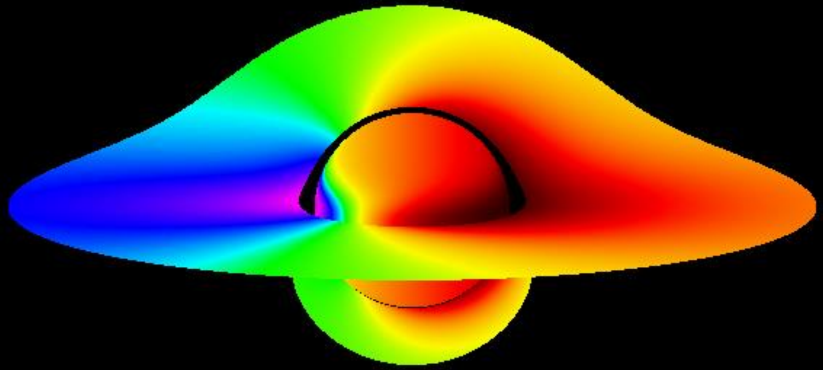


relativistic effects

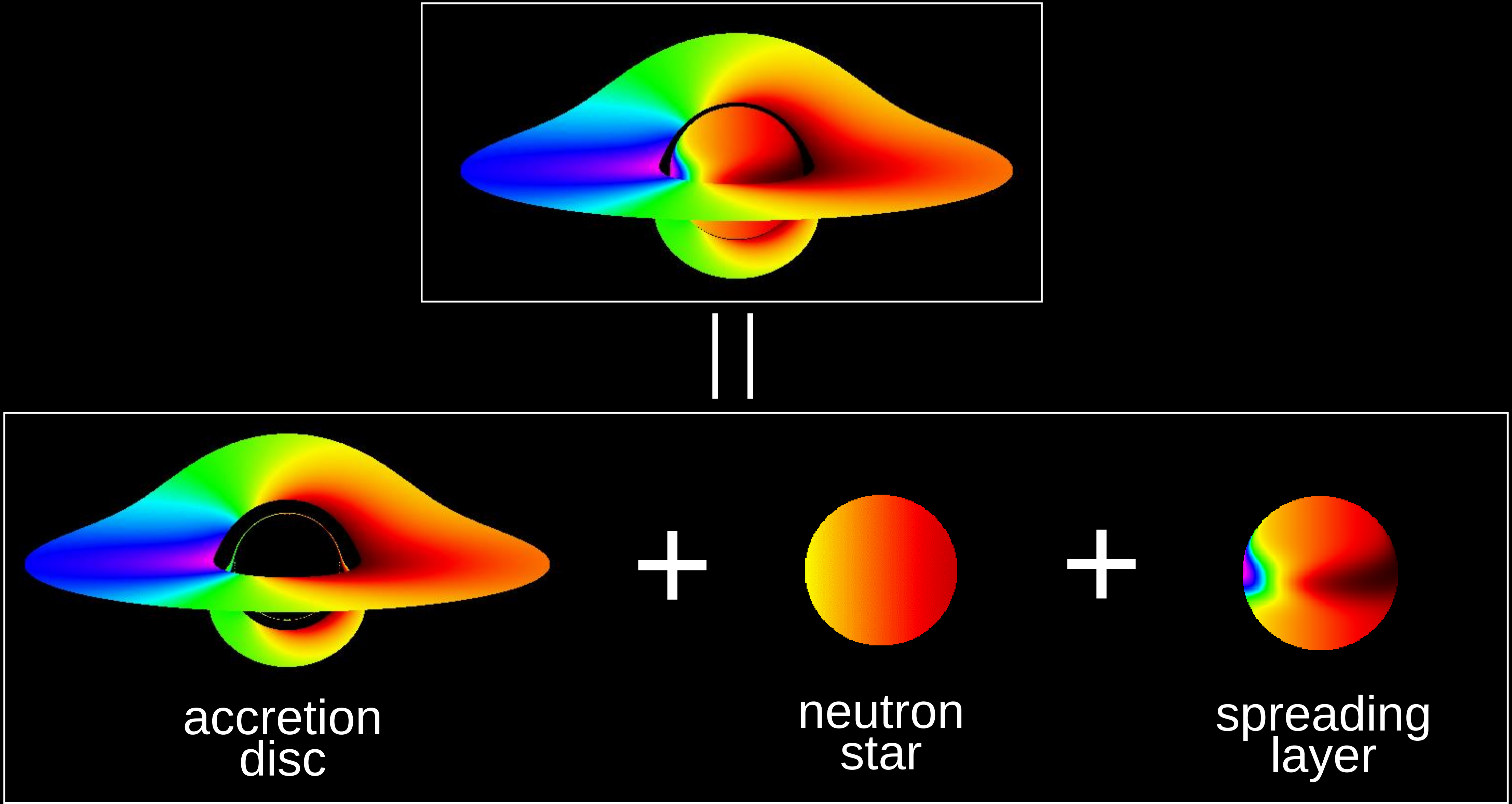
Observed



Components of the system



Components of the system



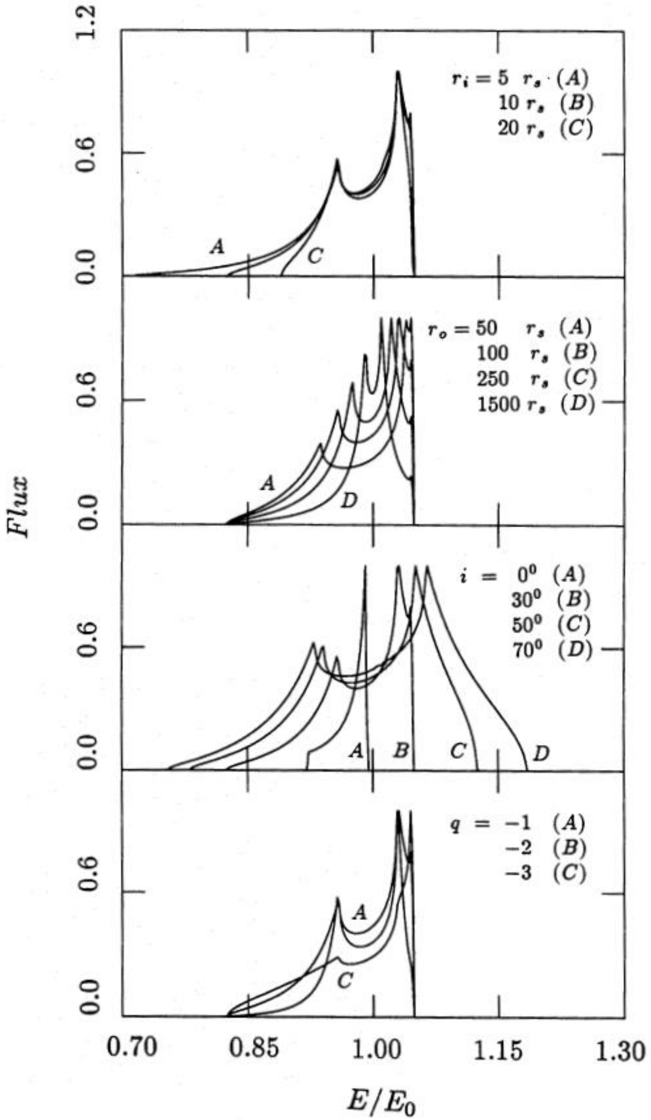
accretion disc

neutron star

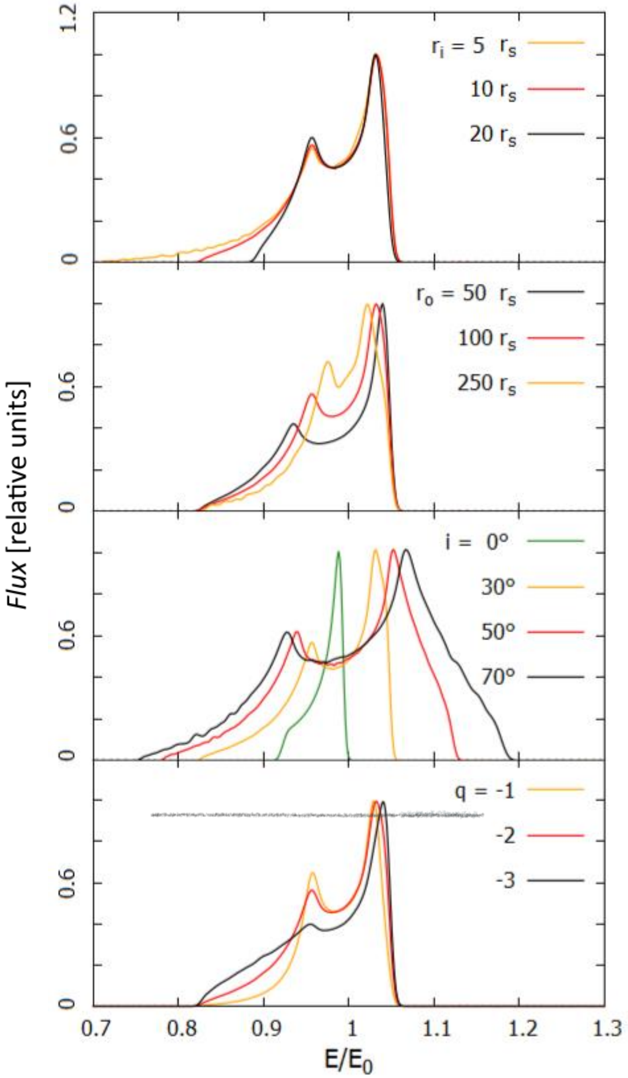
spreading layer

Disc emission – comparison

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



LSD



✓ Pretty good

Disc local emissivity:

$$\boxed{I_e = \alpha_1 r^q}$$

When not specified, the other parameters are fixed at:

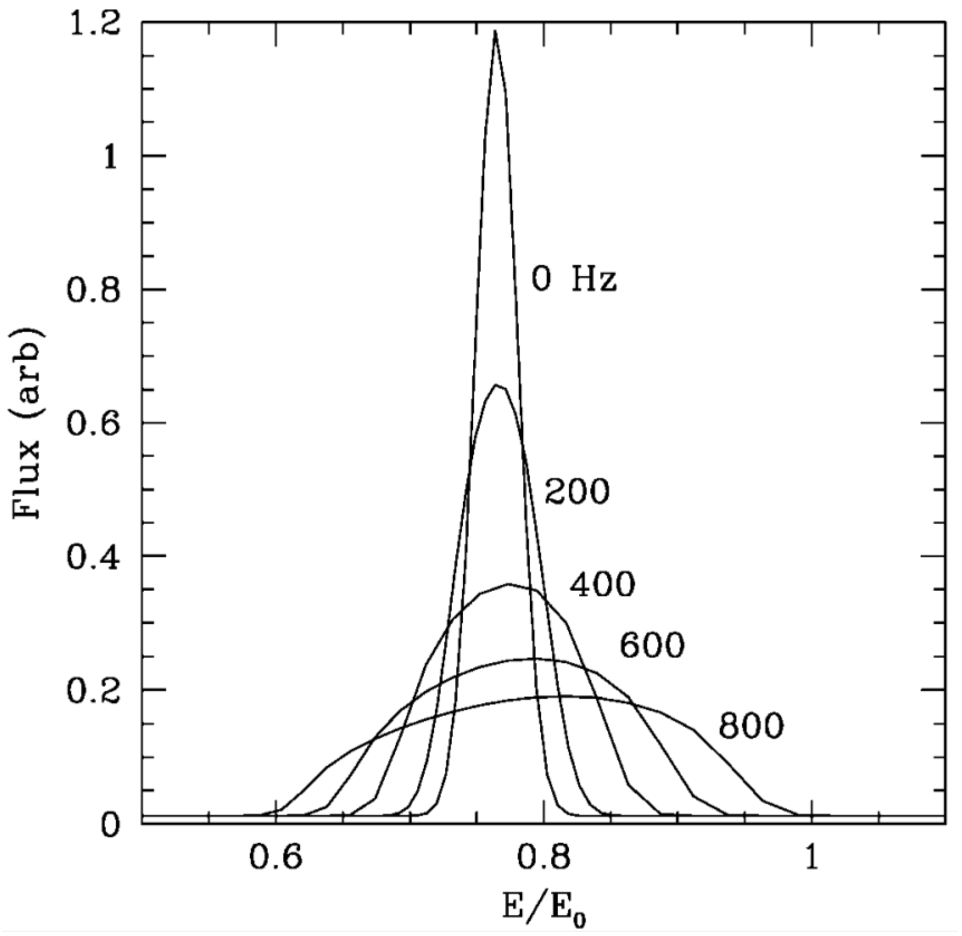
$$r_i = 10\, r_s$$
$$r_o = 100\, r_s$$
$$i = 30^\circ$$
$$q = -2$$

- geometricly thin
- optically thick
- Keplerian

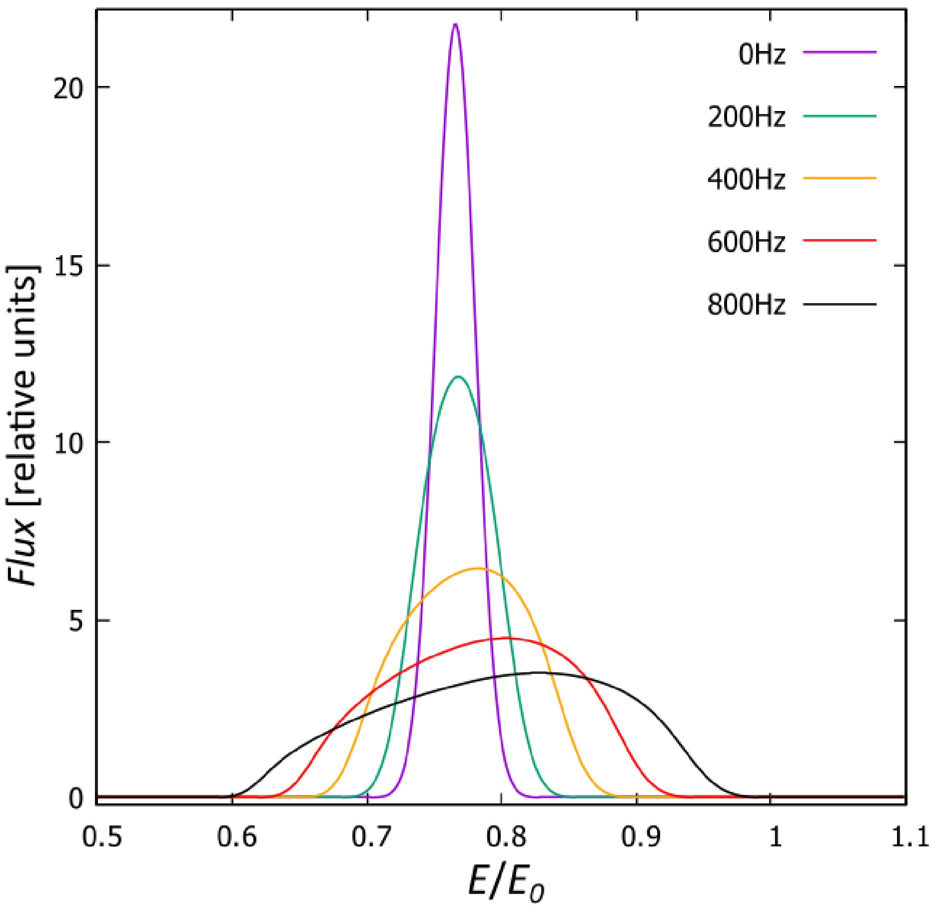
NS emission – comparison

✓ Pretty good

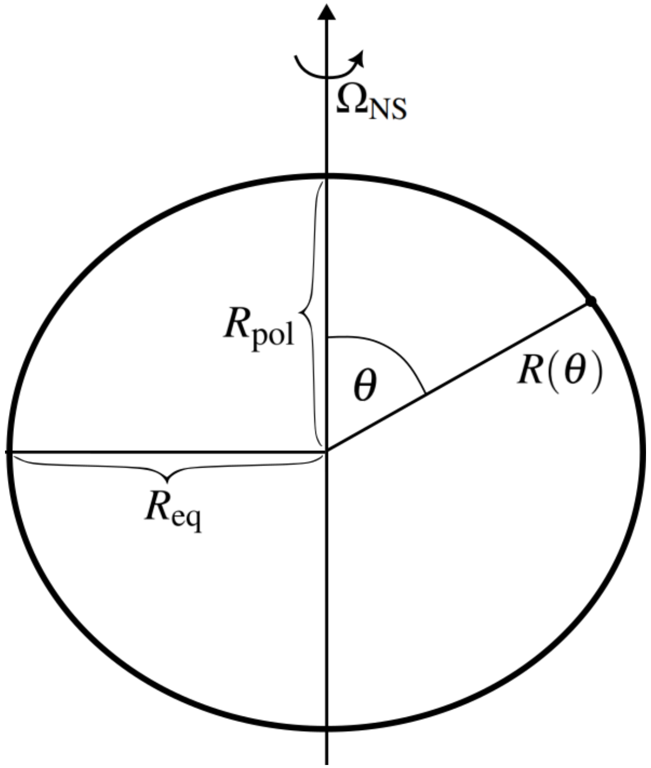
Özel, F. & Psaltis, D.
Astrophysical Journal, **582**(1), p. L31, 2002.



LSD

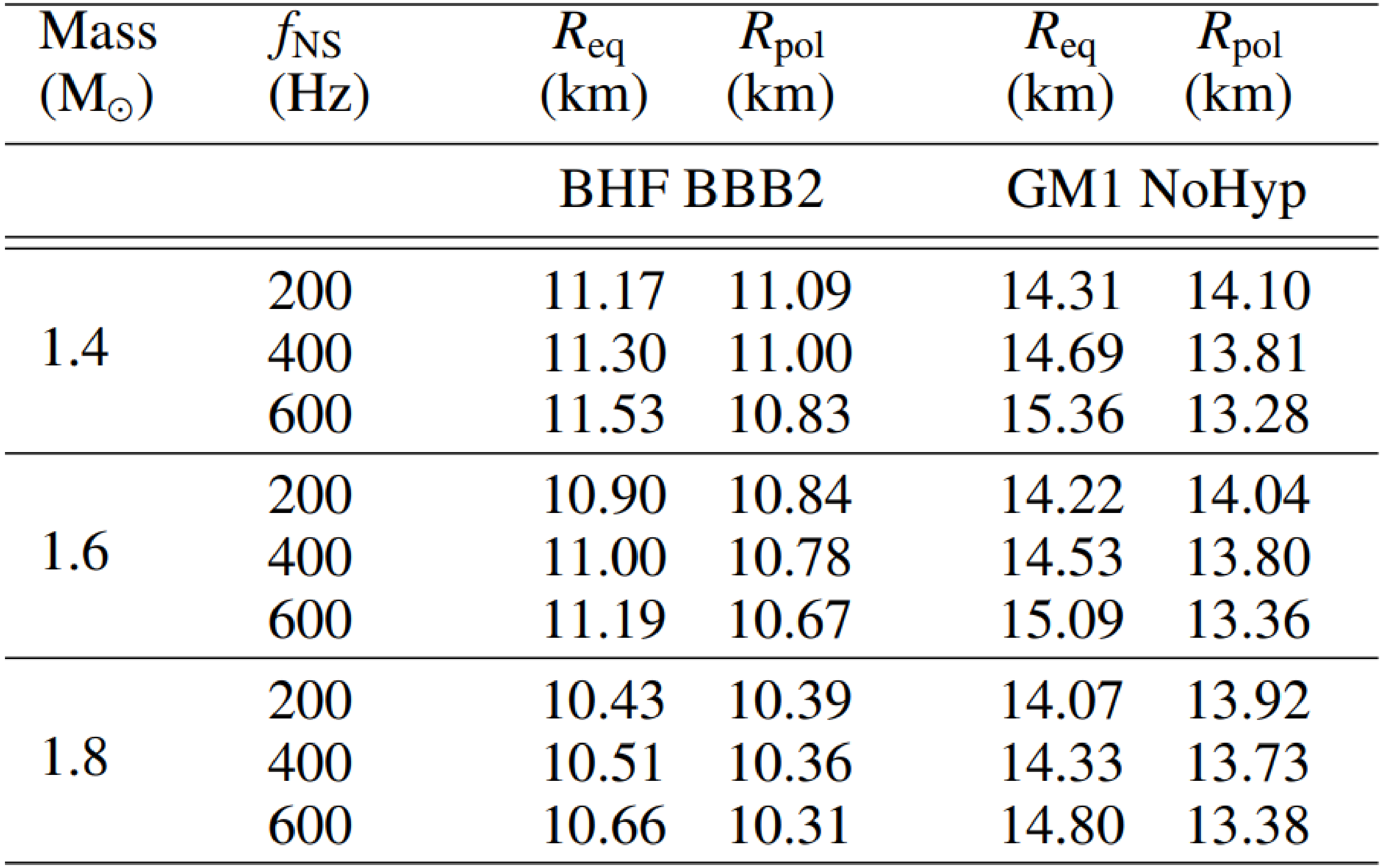


NS surface - spheroid



$$\Omega_{\rm NS} = 2\pi G M f_{\rm NS}/c^3$$

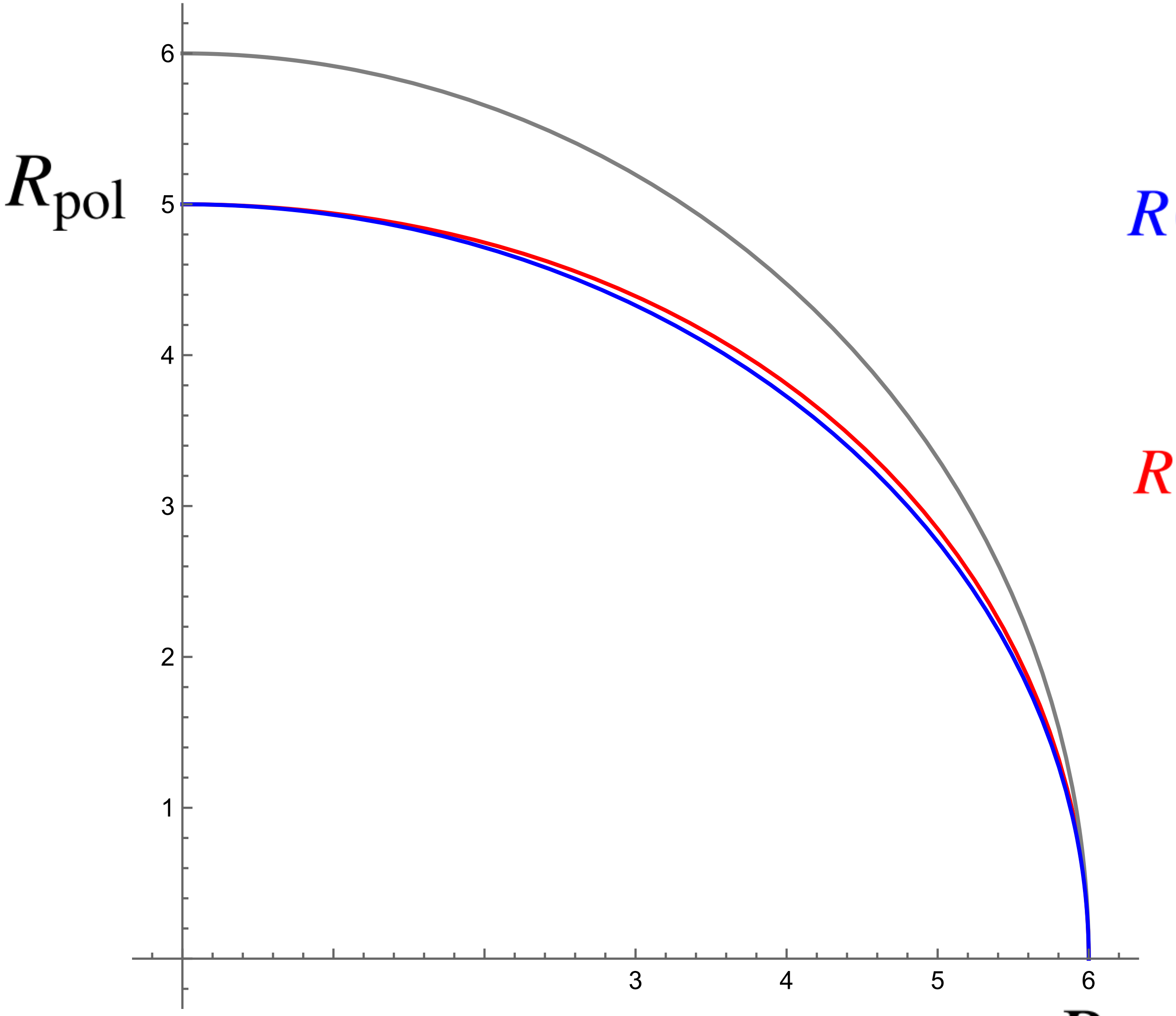
$$R(\theta) = R_{\rm pol} + \alpha \sin^2\theta$$



Mass ($M_\odot$)	$f_{\rm NS}$ (Hz)	$R_{\rm eq}$ (km)	$R_{\rm pol}$ (km)	$R_{\rm eq}$ (km)	$R_{\rm pol}$ (km)
		BHF BBB2		GM1 NoHyp	
1.4	200	11.17	11.09	14.31	14.10
	400	11.30	11.00	14.69	13.81
	600	11.53	10.83	15.36	13.28
1.6	200	10.90	10.84	14.22	14.04
	400	11.00	10.78	14.53	13.80
	600	11.19	10.67	15.09	13.36
1.8	200	10.43	10.39	14.07	13.92
	400	10.51	10.36	14.33	13.73
	600	10.66	10.31	14.80	13.38

Small **Big**

Sphere vs Ellipsoid vs Spheroid

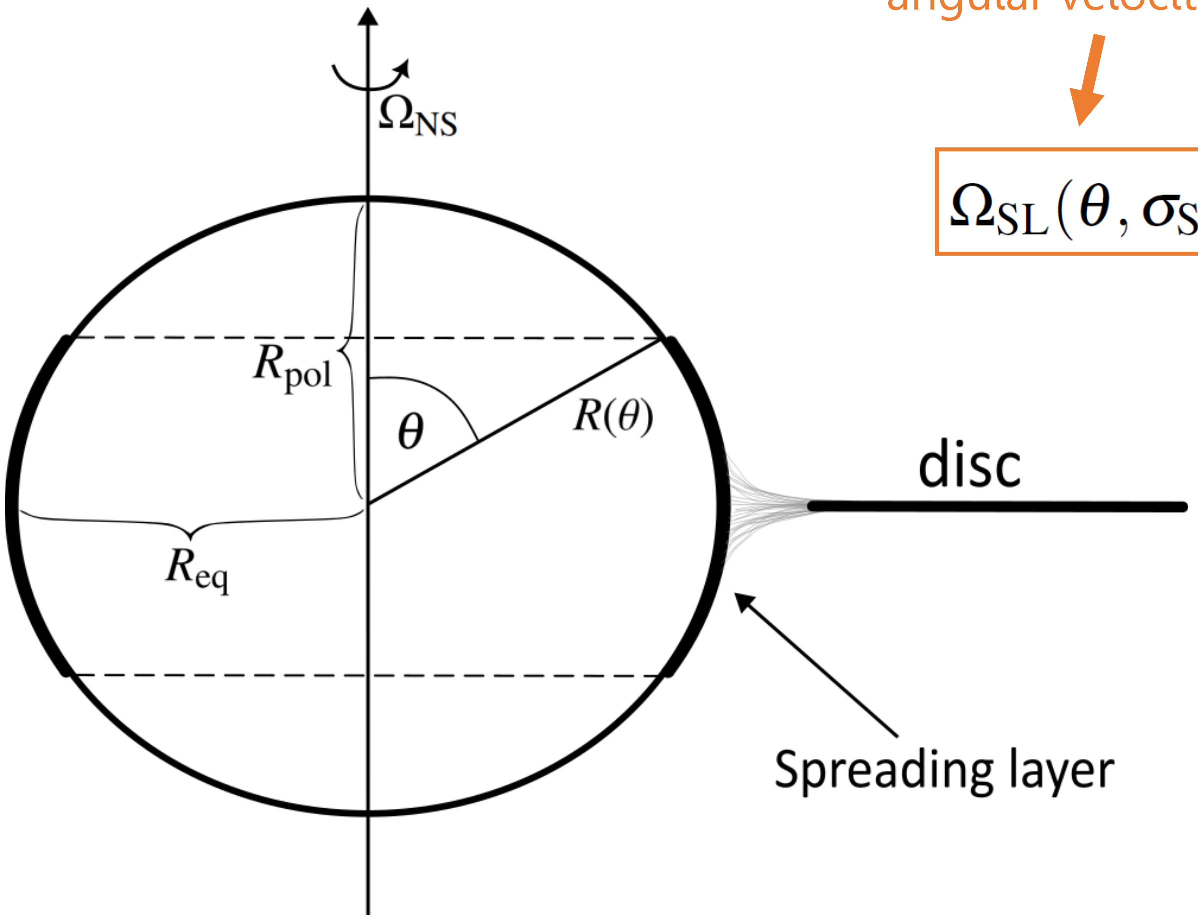


$$R(\theta) = \frac{R_{\text{eq}} R_{\text{pol}}}{\sqrt{R_{\text{eq}}^2 \cos^2\theta + R_{\text{pol}}^2 \sin^2\theta}}$$

$$R(\theta) = R_{\text{pol}} + \alpha \sin^2\theta$$

$R_{\text{eq}} = 1.2 R_{\text{pol}}$

Model - SL



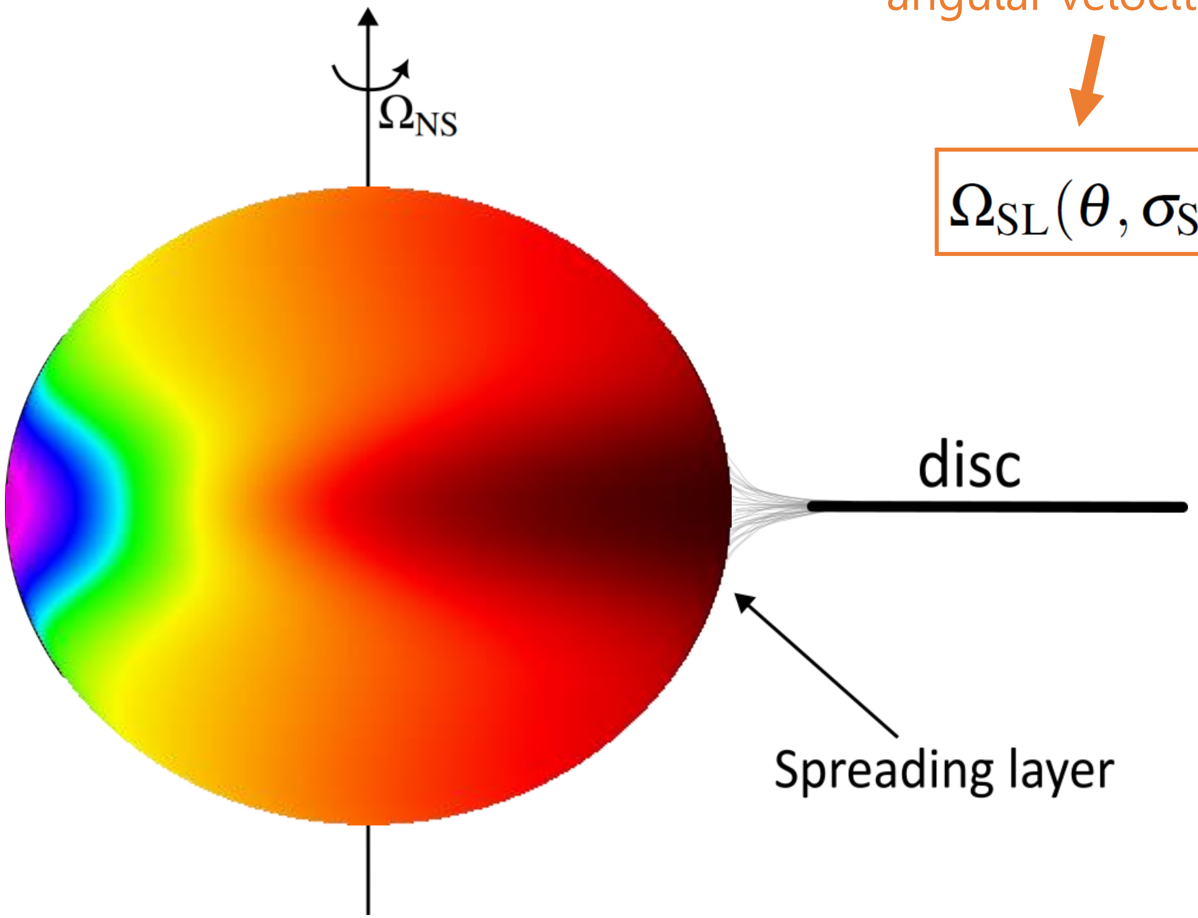
angular velocity of the SL

specific angular momentum
of the inner edge of the disc

$$\boxed{\Omega_{\rm SL}(\theta,\sigma_{\rm SL})} = \Omega_{\rm NS} + f(\theta,\sigma_{\rm SL})\left(\frac{g^{t\varphi} - g^{\varphi\varphi}\boxed{l_{\rm in}}}{g^{tt} - g^{t\varphi}\, l_{\rm in}} - \Omega_{\rm NS}\right)$$

$$f(\theta,\sigma_{\rm SL}) = \frac{1}{\sqrt{2\pi}\sigma_{\rm SL}} e^{\frac{(\theta-\pi/2)^2}{2\sigma_{\rm SL}^2}}$$

Model - SL



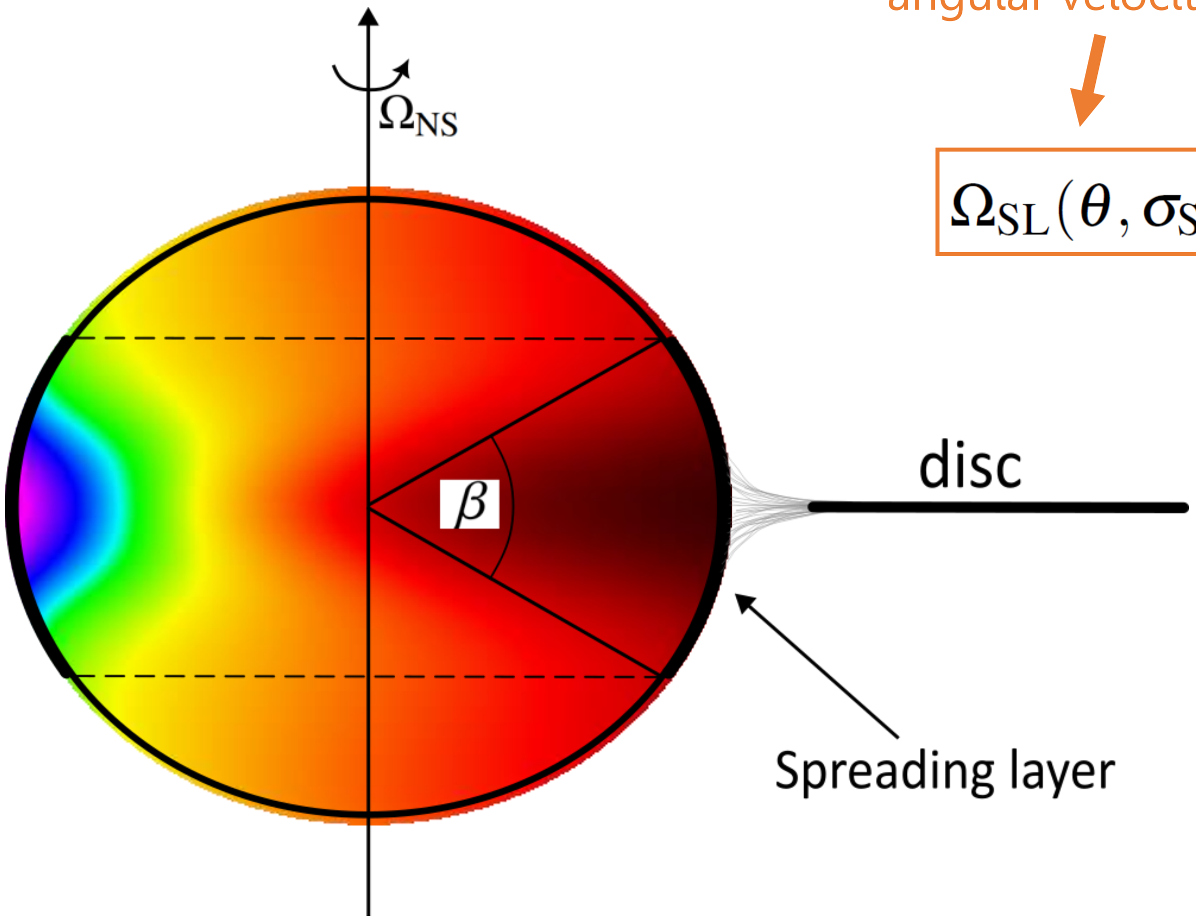
angular velocity of the SL

specific angular momentum of the inner edge of the disc

$$\boxed{\Omega_{\mathrm{SL}}(\theta,\sigma_{\mathrm{SL}})} = \Omega_{\mathrm{NS}} + f(\theta,\sigma_{\mathrm{SL}})\left(\frac{g^{t\varphi} - g^{\varphi\varphi}\boxed{l_{\mathrm{in}}}}{g^{tt} - g^{t\varphi}\, l_{\mathrm{in}}} - \Omega_{\mathrm{NS}}\right)$$

$$f(\theta,\sigma_{\mathrm{SL}}) = \frac{1}{\sqrt{2\pi}\sigma_{\mathrm{SL}}} e^{\frac{(\theta-\pi/2)^2}{2\sigma_{\mathrm{SL}}^2}}$$

Model - SL



angular velocity of the SL

specific angular momentum of the inner edge of the disc

$$\boxed{\Omega_{\rm SL}(\theta,\sigma_{\rm SL})} = \Omega_{\rm NS} + f(\theta,\sigma_{\rm SL})\left(\frac{g^{t\varphi} - g^{\varphi\varphi}\boxed{l_{\rm in}}}{g^{tt} - g^{t\varphi}\,l_{\rm in}} - \Omega_{\rm NS}\right)$$

$$\Big\downarrow$$

$$f(\theta,\sigma_{\rm SL}) = \frac{1}{\sqrt{2\pi}\sigma_{\rm SL}}e^{\frac{(\theta-\pi/2)^2}{2\sigma_{\rm SL}^2}}$$

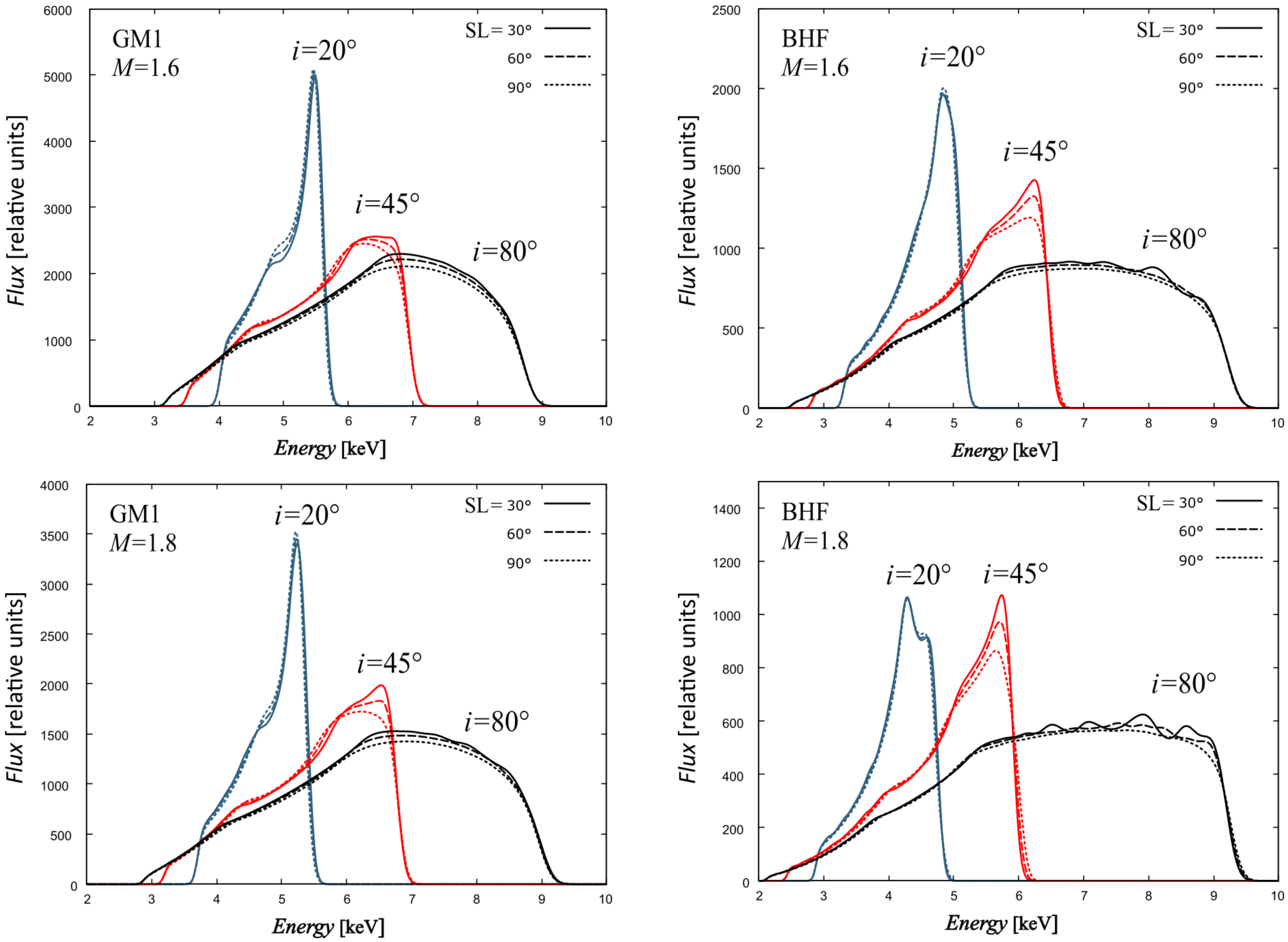
$$\beta = 6\sigma_{\rm SL}\frac{180^\circ}{\pi}$$

full opening angle of SL

$$\beta = \beta(\dot{M})$$

should be like that

Emission form Spreading Layer

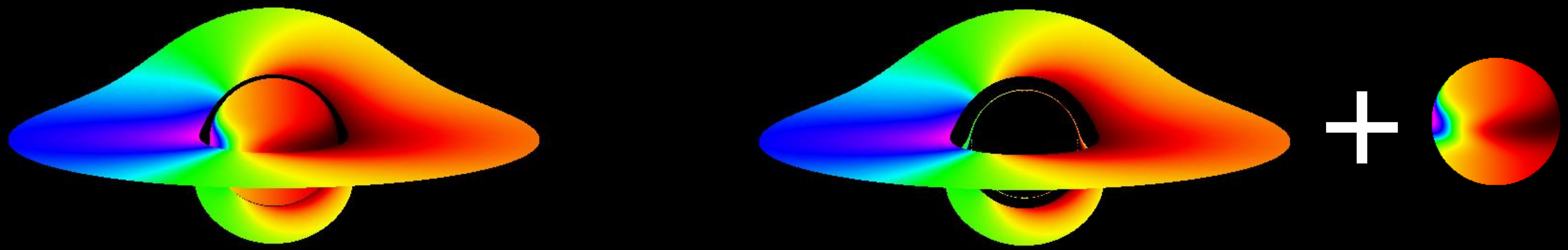


SL local emissivity:

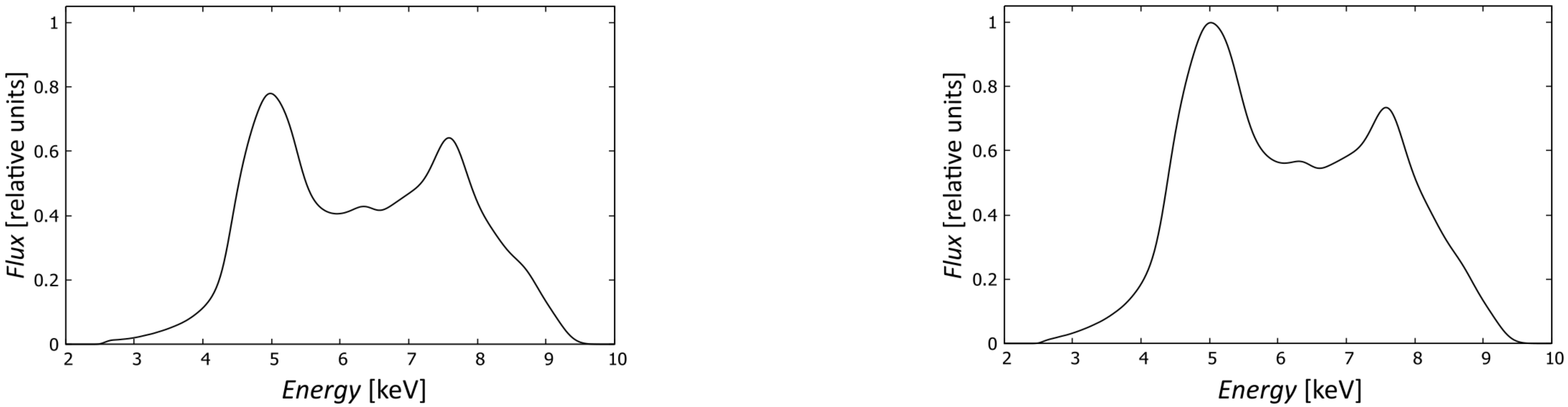
$$\boxed{I_{\mathrm{e}} = \alpha_2 f(\theta, \sigma_{\mathrm{SL}})}$$

Obscuration effects

- ➢ Frequency shift map

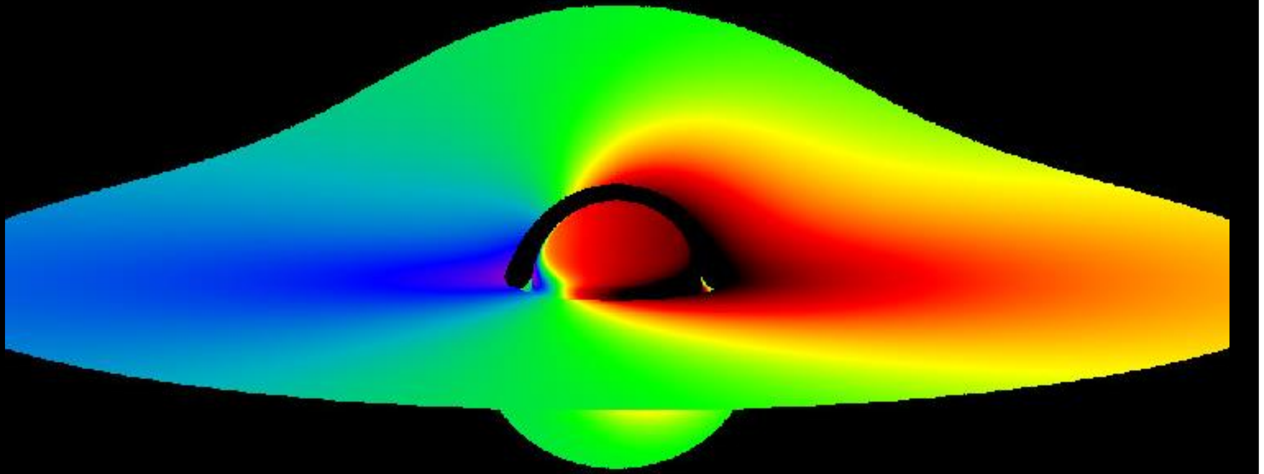


- ➢ Spectral profile

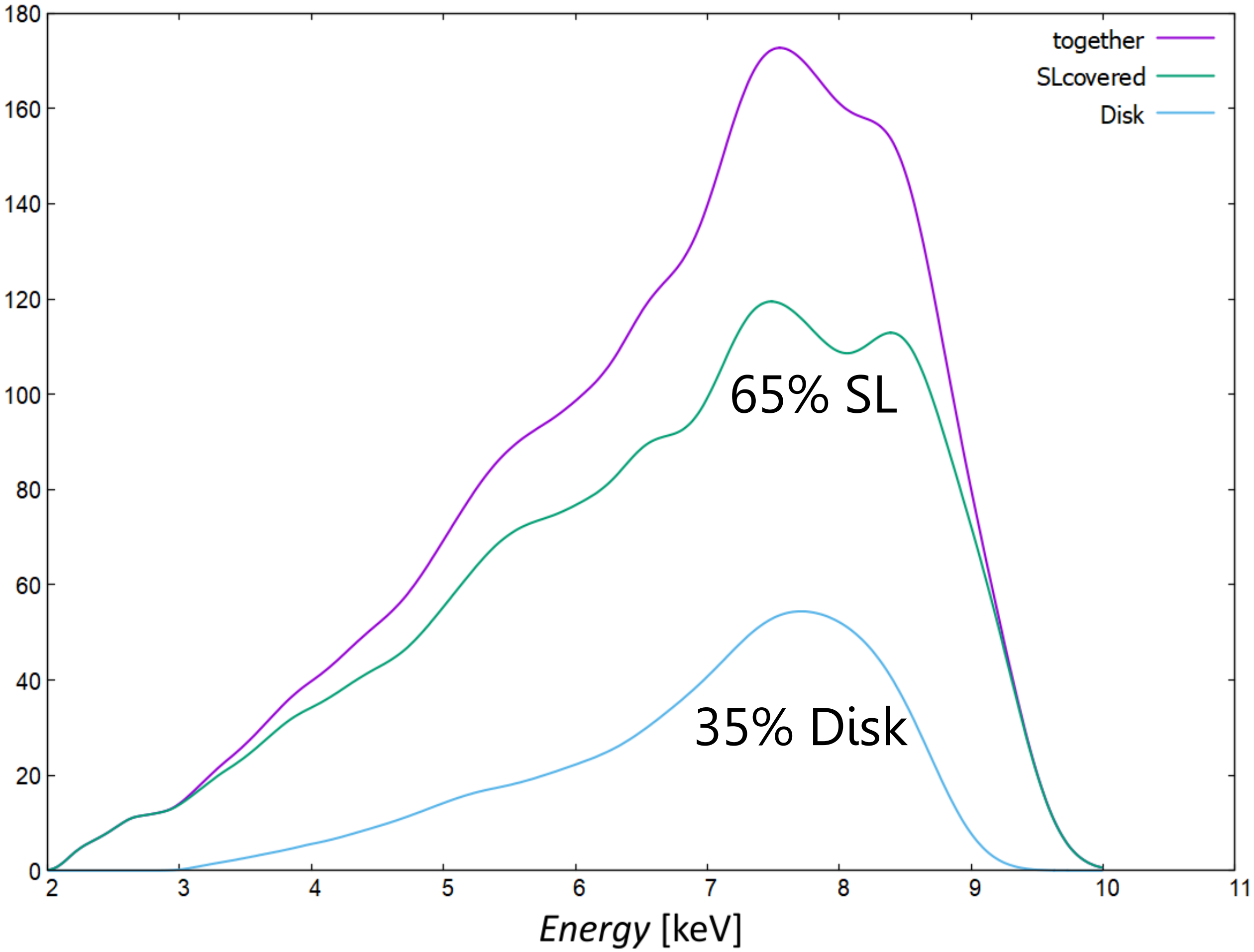


Iron line profile of the system

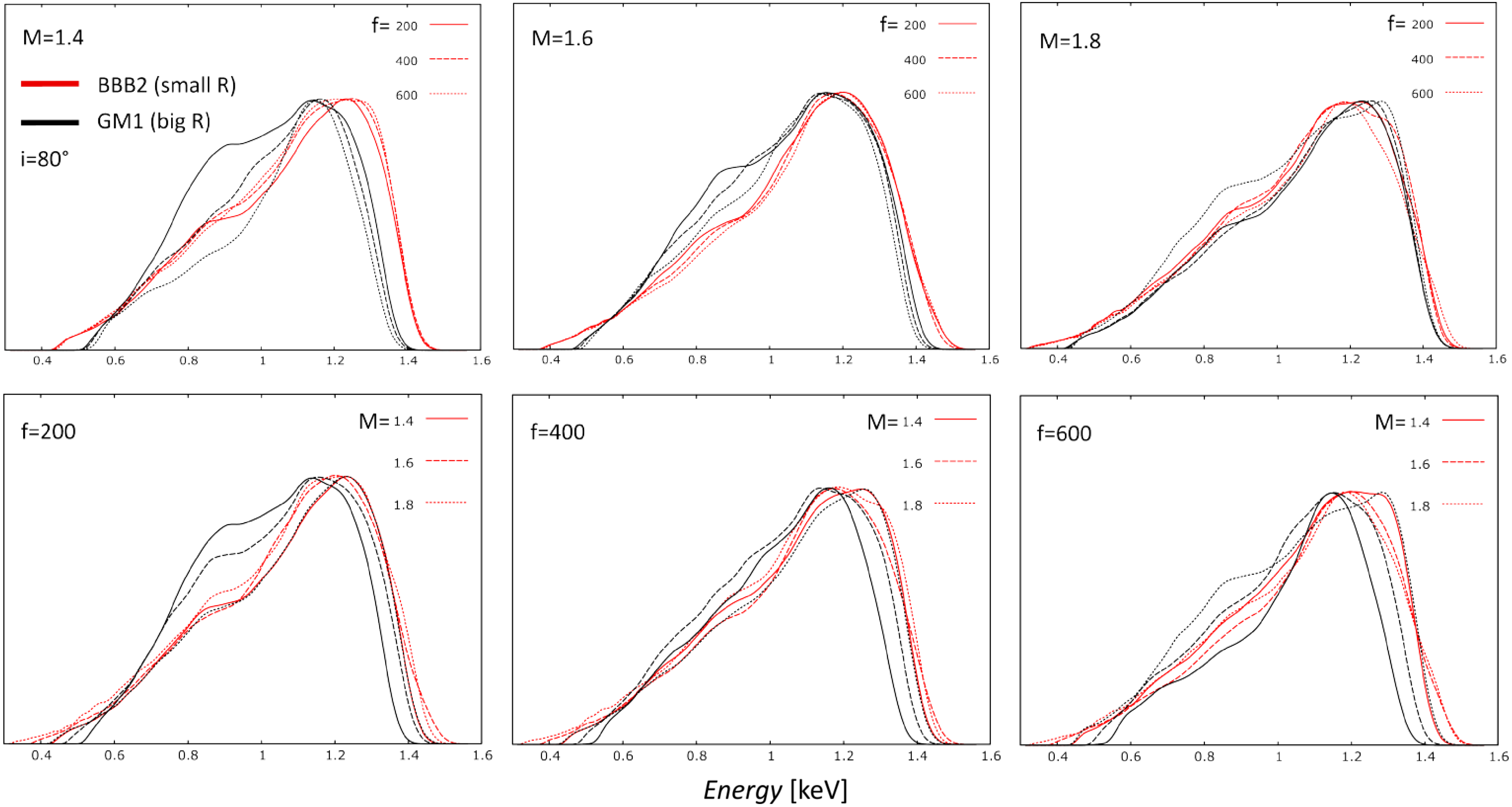
- Frequency shift map



- Spectral profile

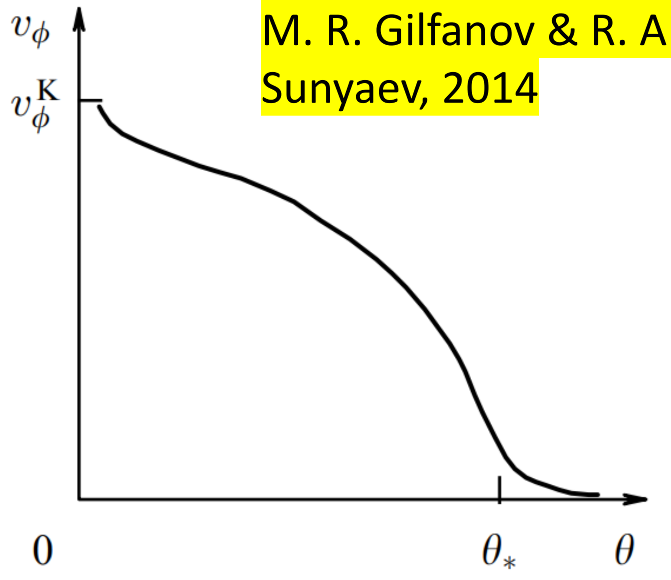


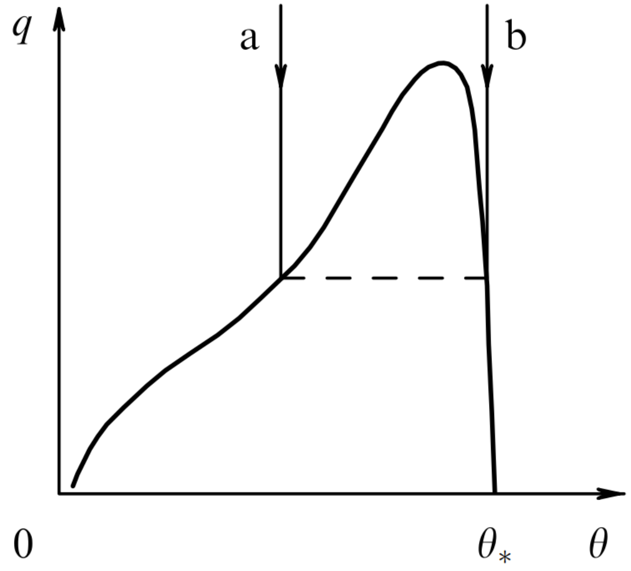
Disk + SL emission: 50% to 50%



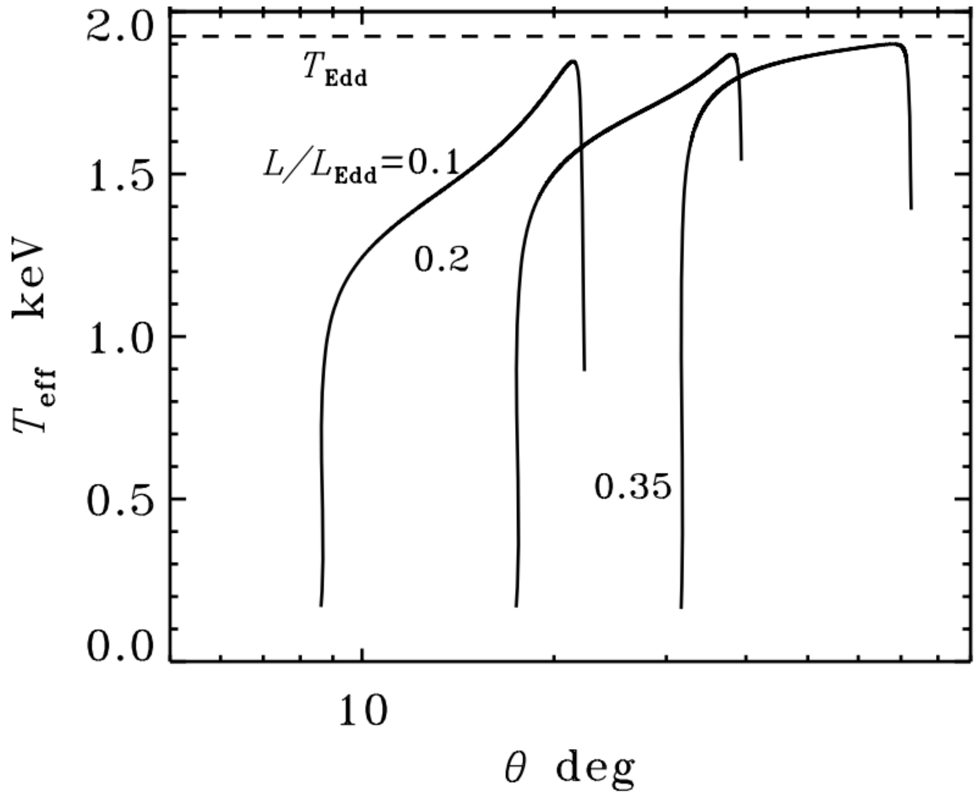
SL simulations

M. R. Gilfanov & R. A. Sunyaev, 2014





V. Suleimanov & J. Poutanen, 2006



$$k_{\rm B}T \approx 2.4\,\mathrm{keV} \qquad \beta = \beta(\dot{M})$$

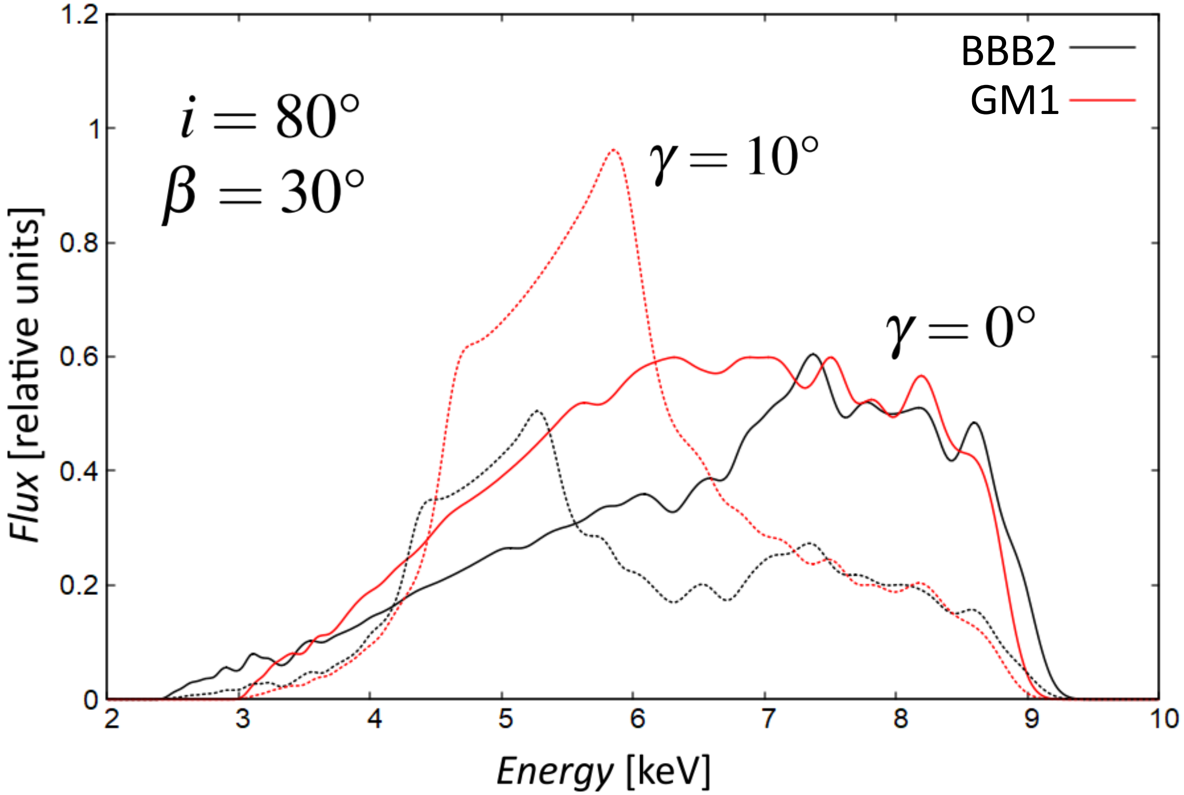
$$\dot{M} \to \dot{M}_{\rm Edd},\ \beta \to 180^\circ$$

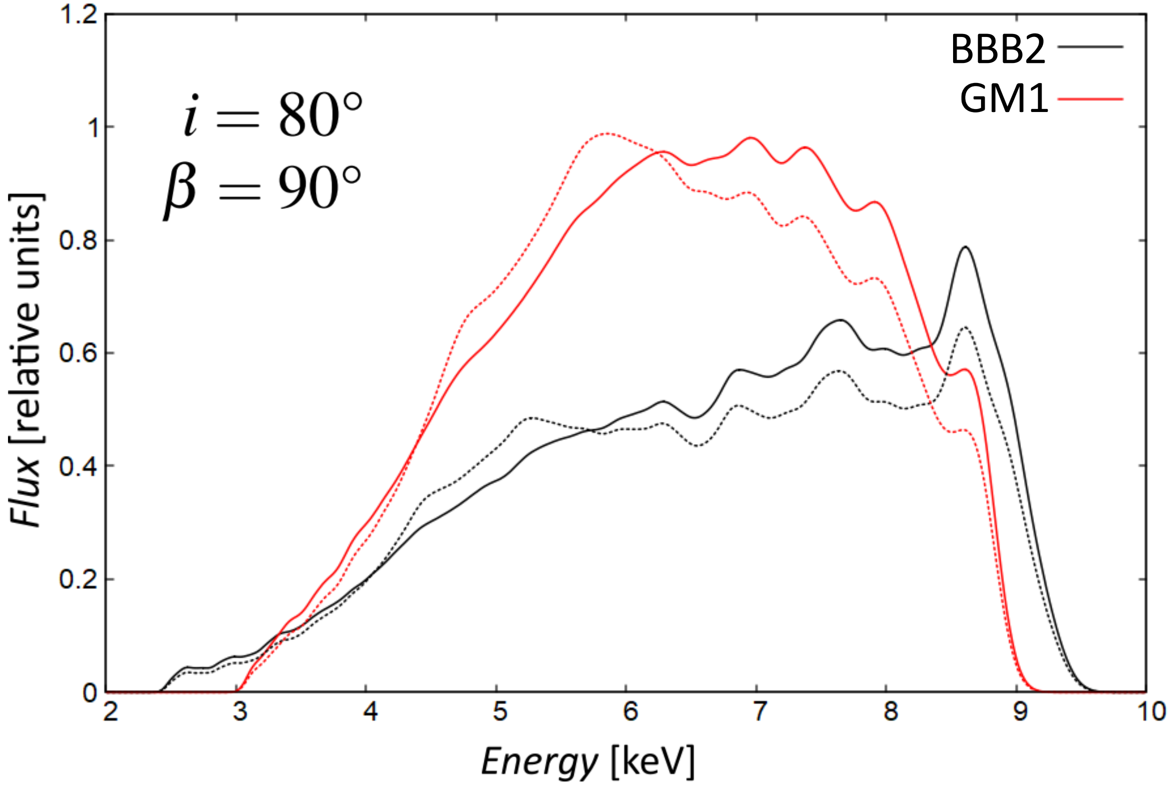
the ionization state of iron might prevent iron line emission

non-equatorial emission from SL

- difference of single peak to double peak local SL intensity

$$f(\theta, \sigma_{\mathrm{SL}}, \gamma) = \frac{N_{\mathrm{SL}}}{2}\left(e^{\frac{(\theta-(\pi/2-\gamma))^2}{2\sigma_{\mathrm{SL}}^2}} + e^{\frac{(\theta-(\pi/2+\gamma))^2}{2\sigma_{\mathrm{SL}}^2}} \right)$$





Summary and conclusions

- ➕ I am able to model relativistic spectral profiles from accreting compact object and study the influence of individual components of the system on the resulting spectral profiles.
- ➕ Complex model including the radiation of accretion disc and neutron star.
- ➕ Consideration of different equation of state of NS with a given mass and spin frequency may result to different spectral signatures.

- ➖ What is the contribution of emission from the NS surface to the overall flux?

Backup slides

Parameters of this result

$$i = 80^\circ$$

$$\sigma = 100\ \mathrm{eV}$$

$$r_{\mathrm{in}} = 6\ M$$

$$r_{\mathrm{out}} = 60\ M$$

$$q = -3$$

$$M = 1.6\ \mathrm{M}_\odot$$

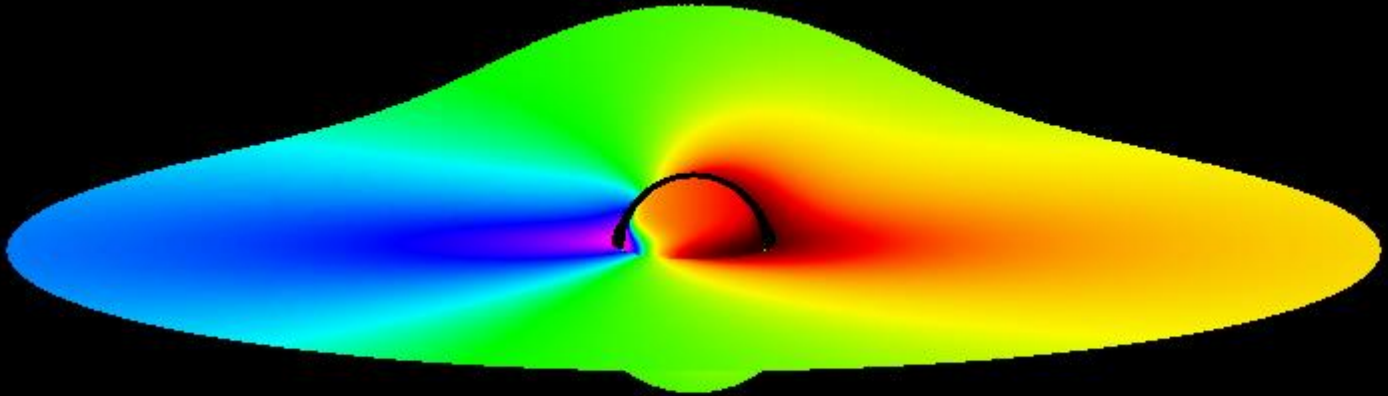
$$R_{\mathrm{eq}} = 11\ \ \mathrm{km}$$

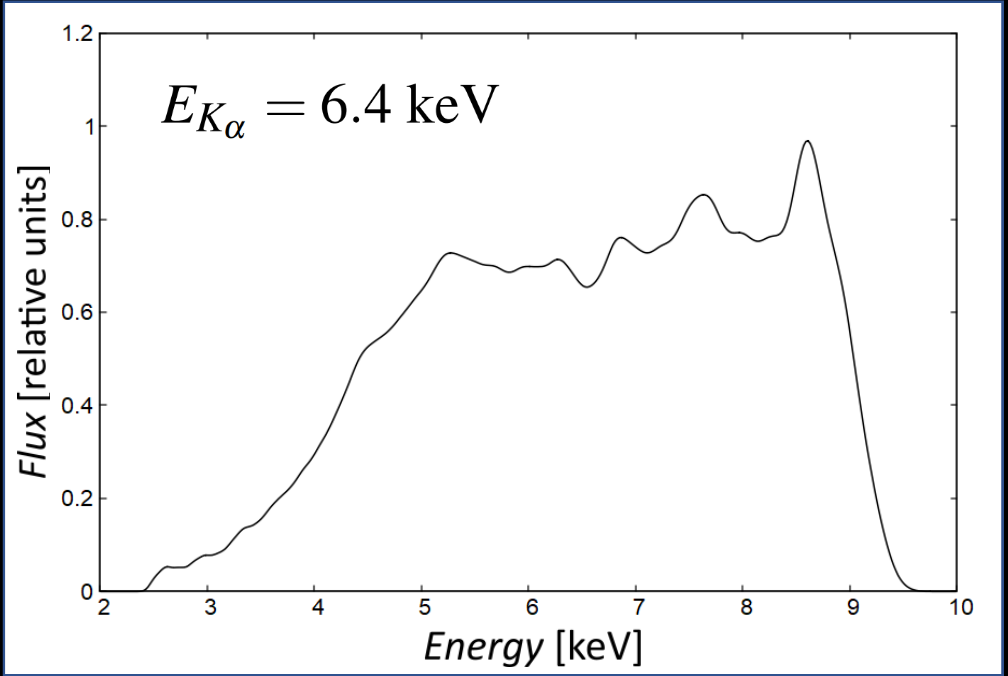
$$R_{\mathrm{pol}} = 10.8\ \ \mathrm{km}$$

$$f_{\mathrm{NS}} = 363\ \mathrm{Hz}$$

$$\beta = 90^\circ$$

$$\gamma = 0^\circ$$





Backup slide 1

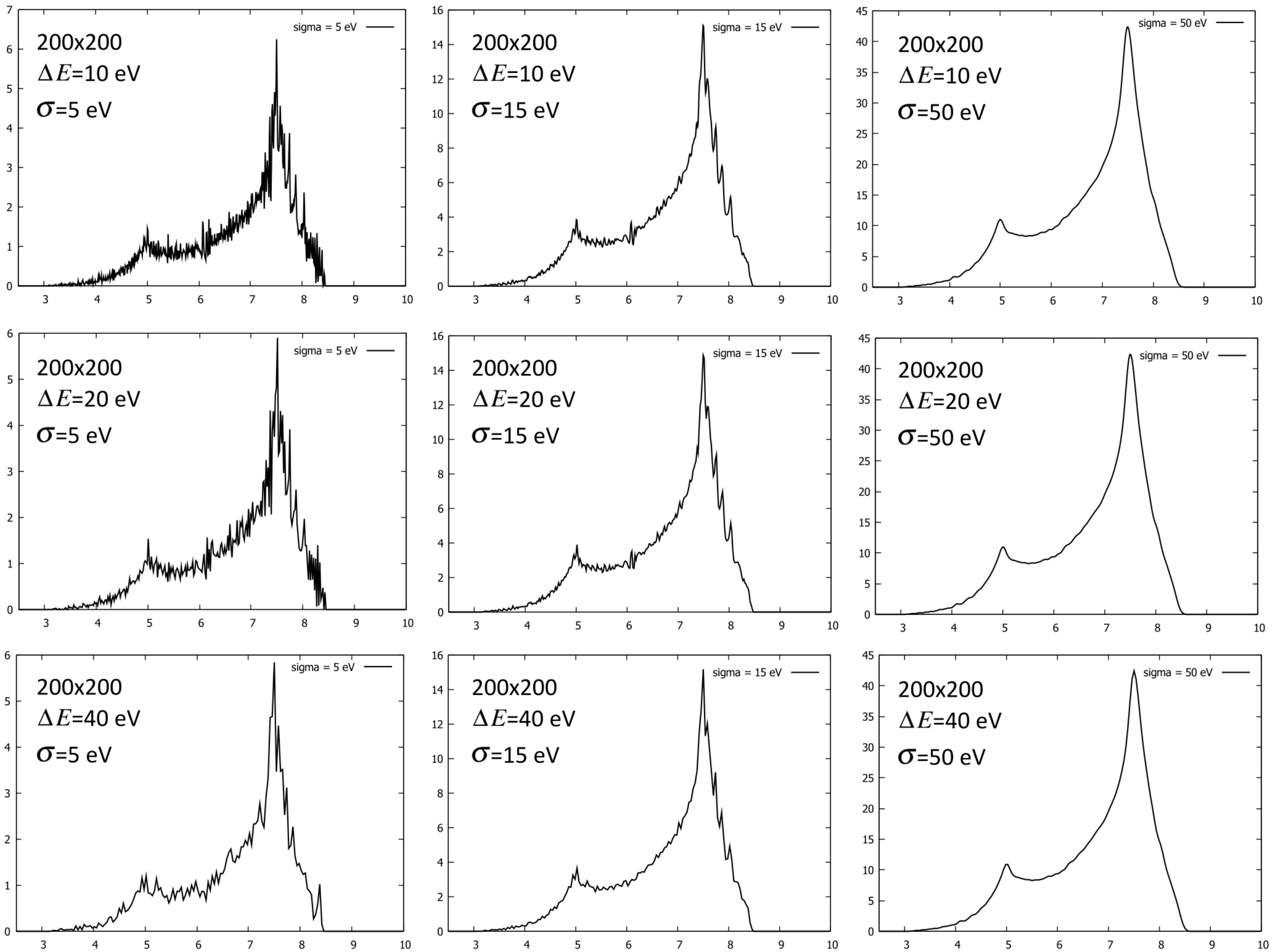
$$e^{-\frac{(E-E_{K\alpha})^2}{2\sigma^2}}$$

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

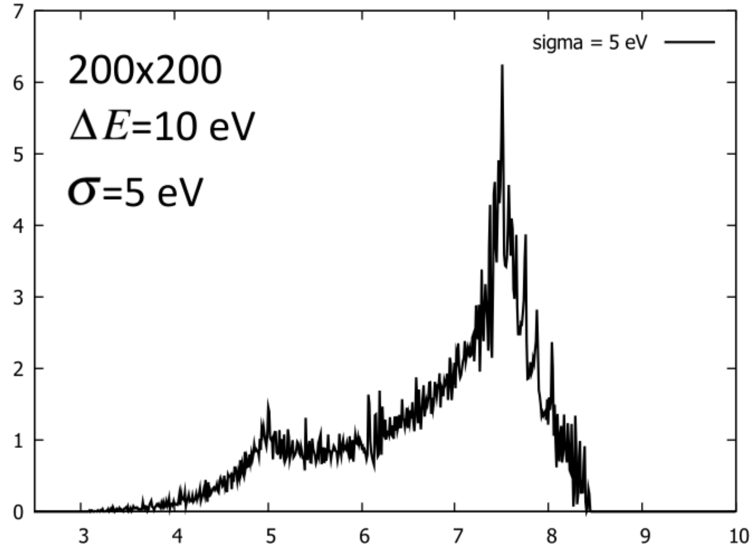
$$E_\mathrm{k} = \mathrm{k}\Delta E + 0.5\Delta E$$

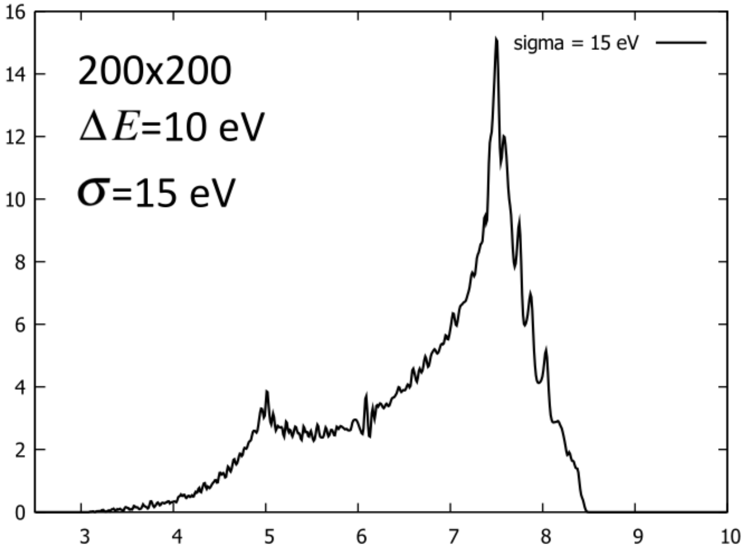
$$\sigma = 15 - 50 \text{ eV}$$

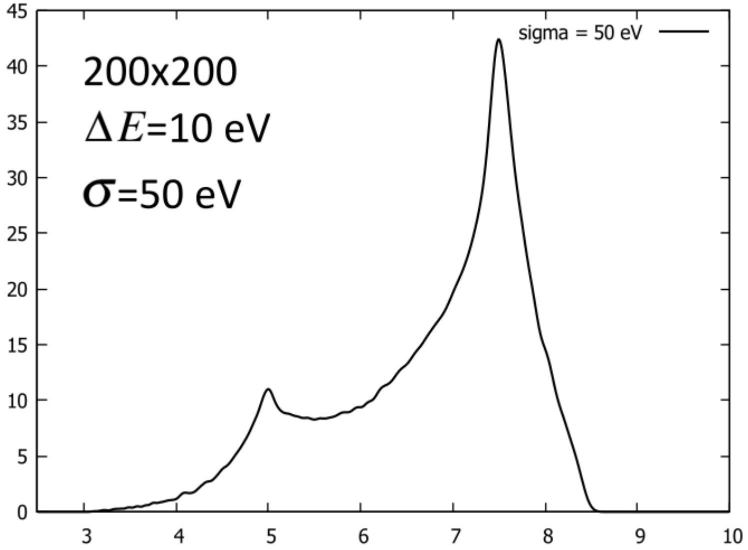
N x N pixels

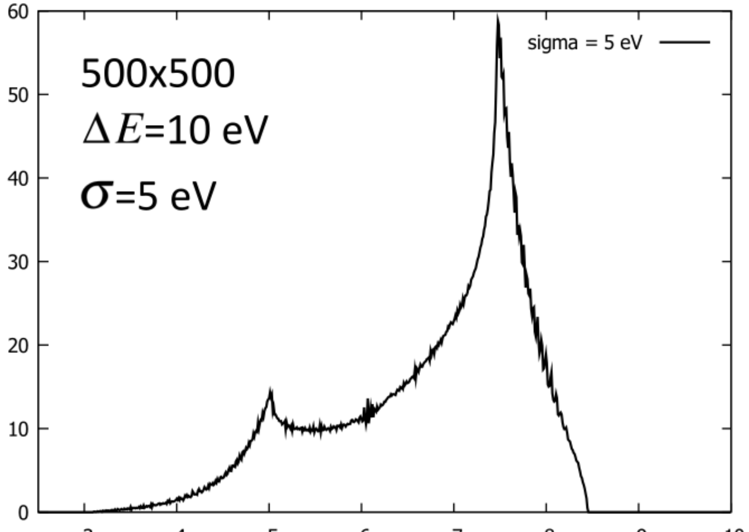


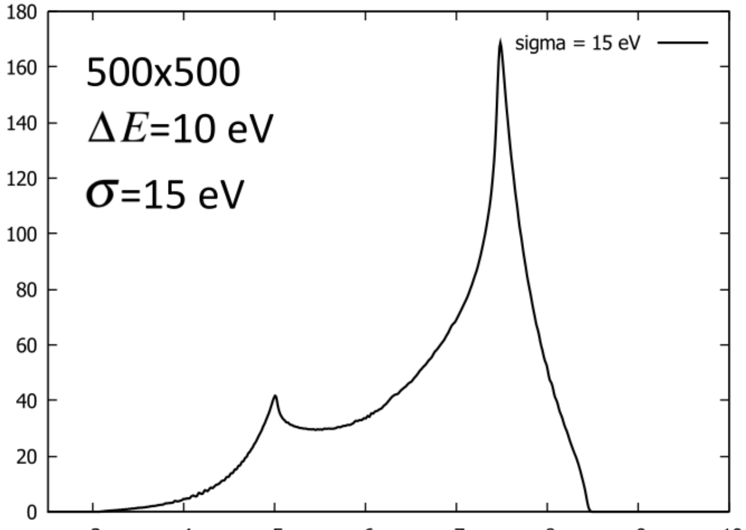
Backup slide 2

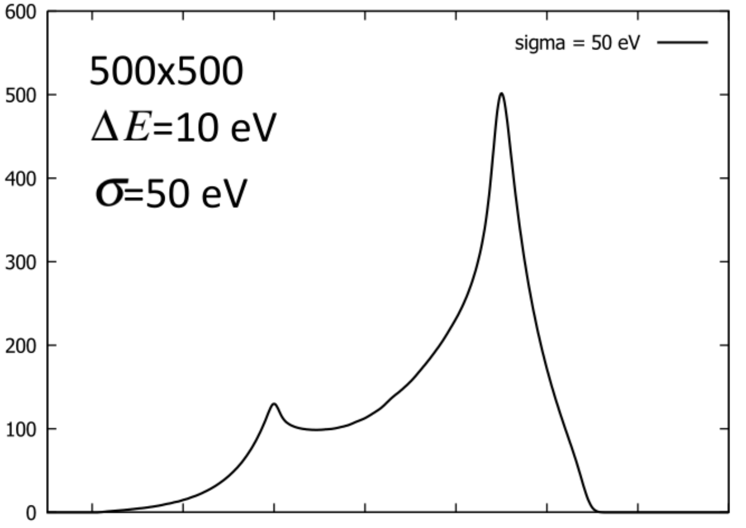




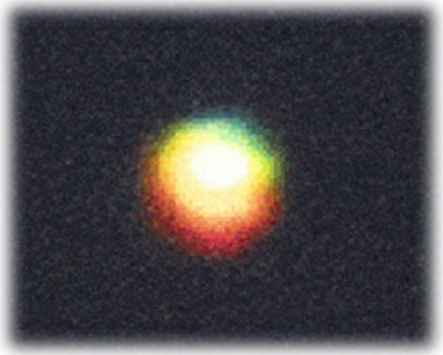


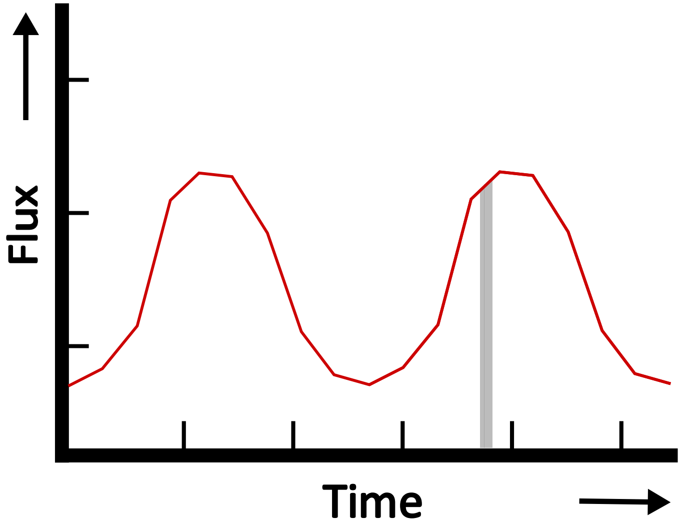


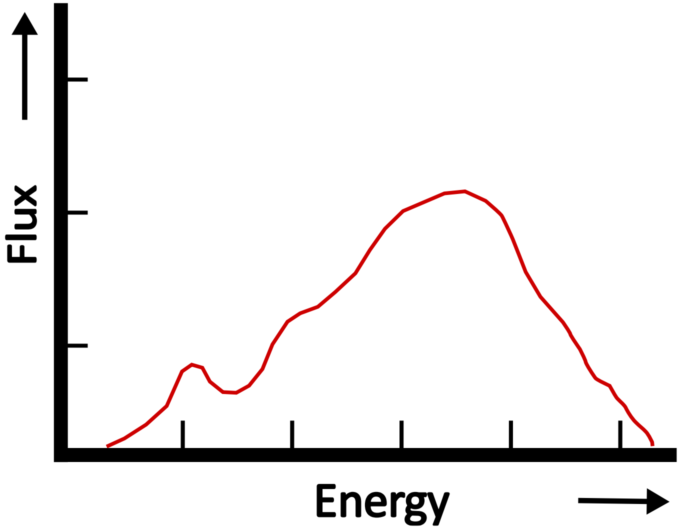




What do we see?
What information it gives us?




light curve


spectrum profile