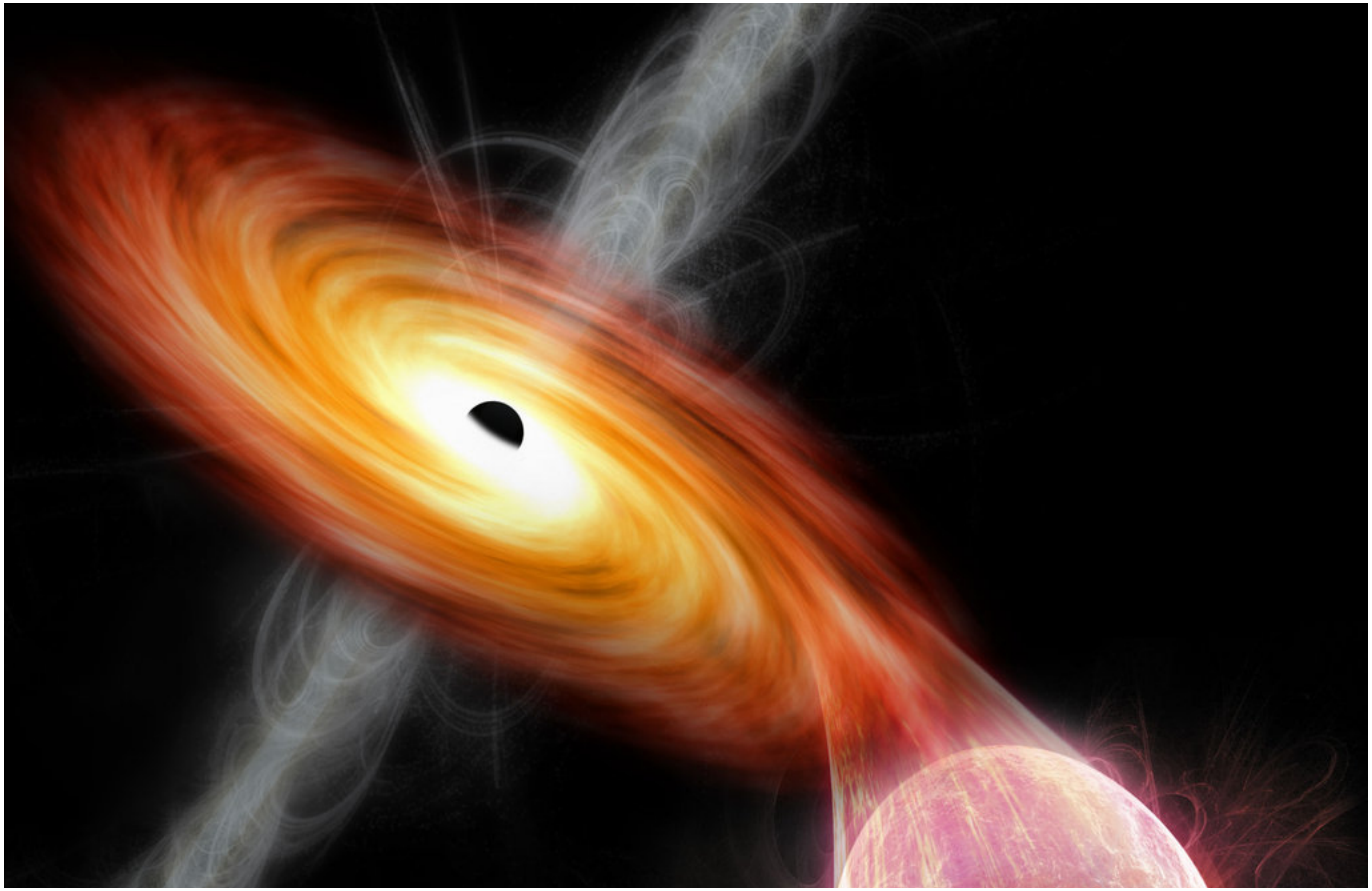
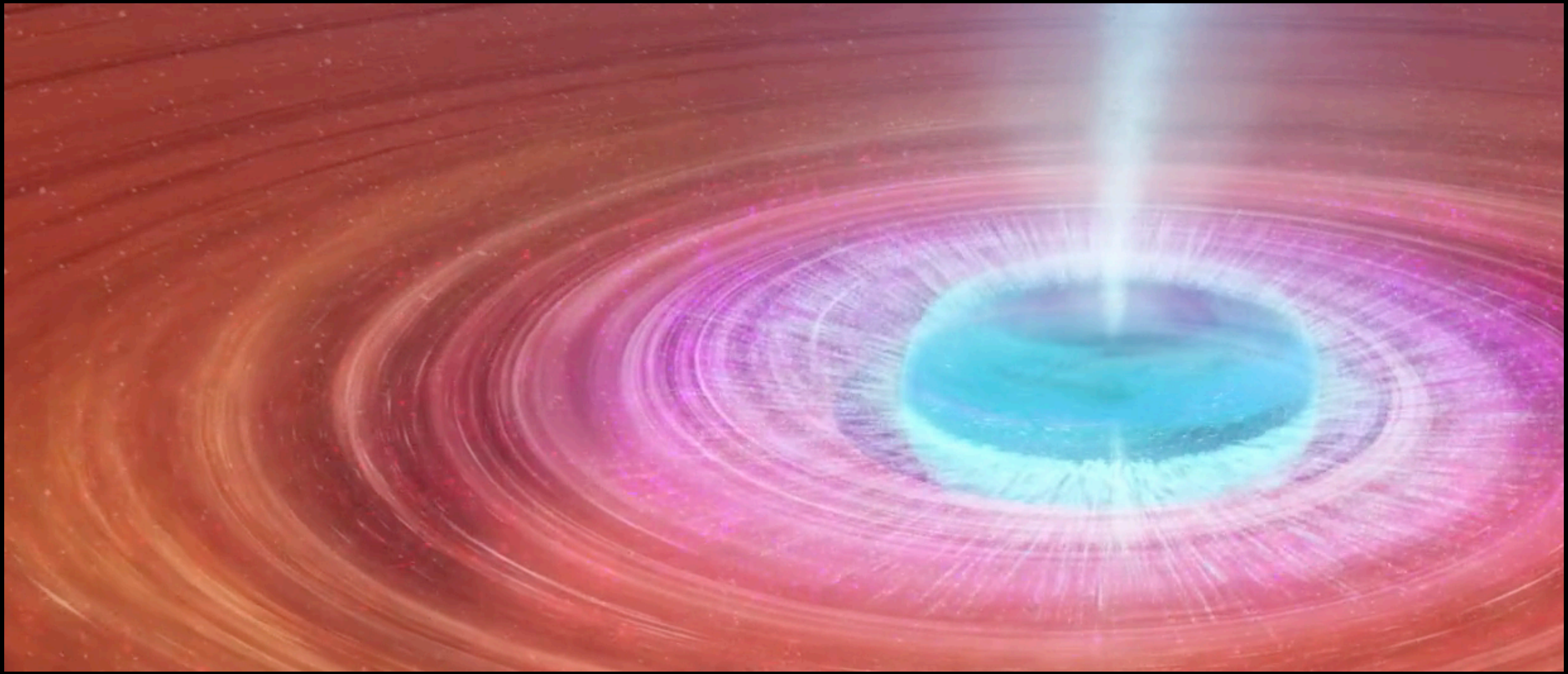
High Energy Astrophysics

Dr. Adam Ingram



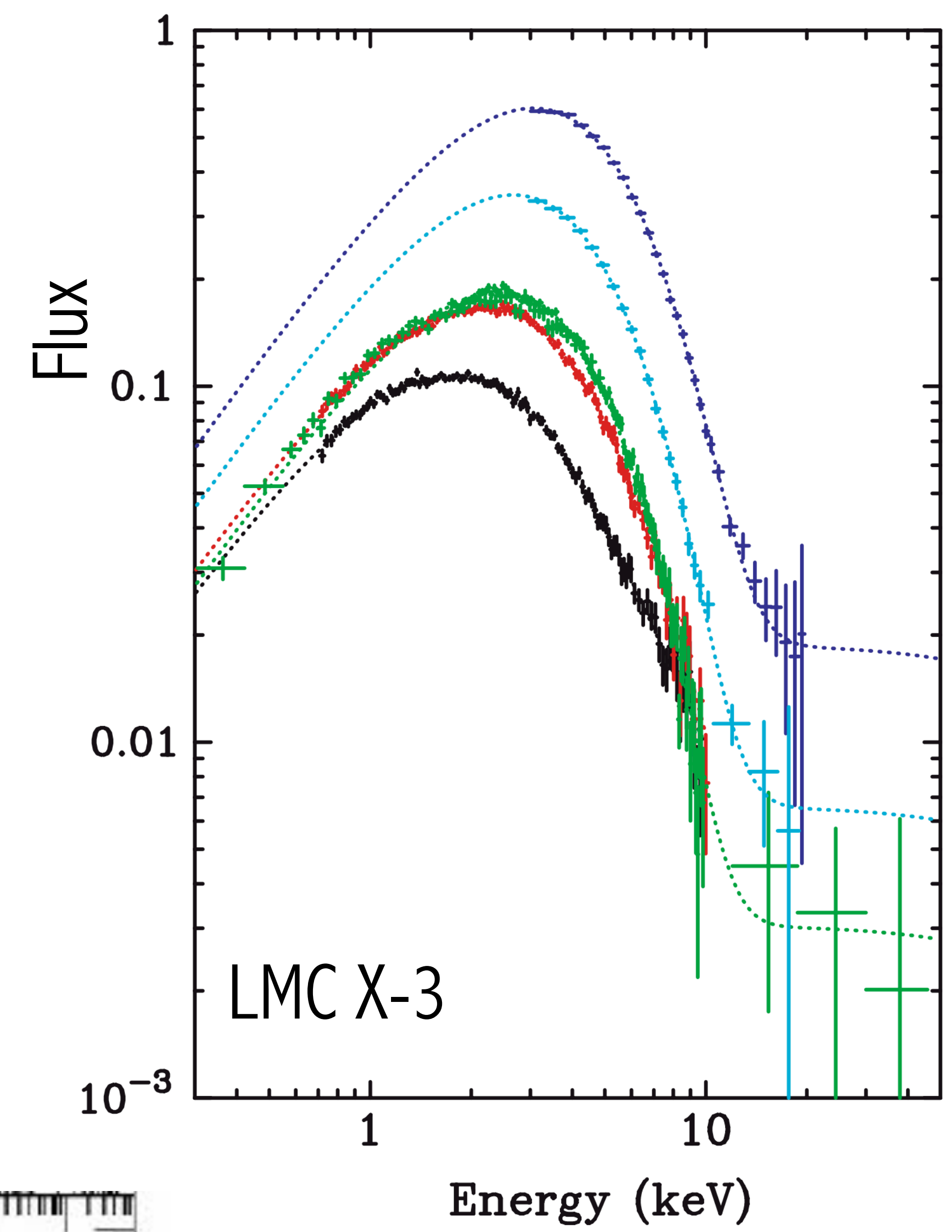
Lecture 6

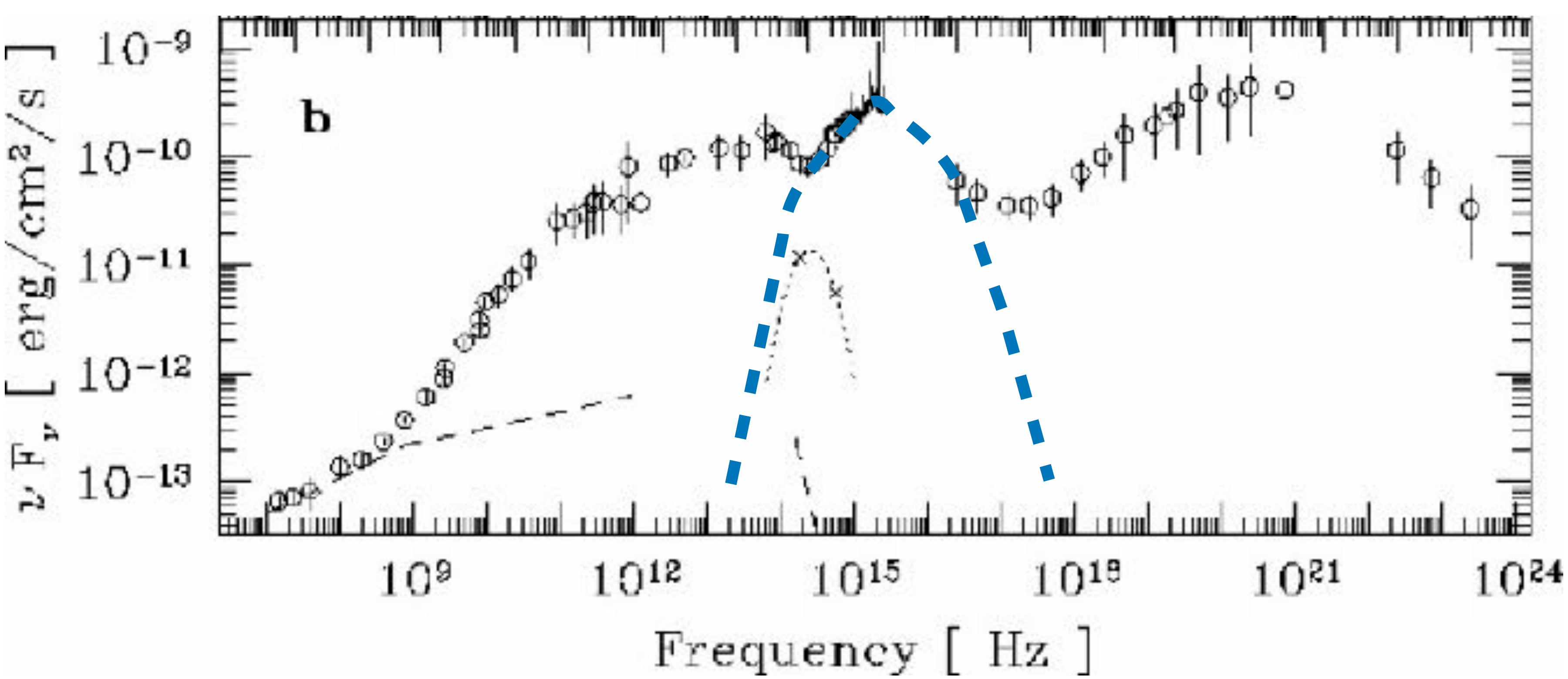
The X-ray Corona



Last time

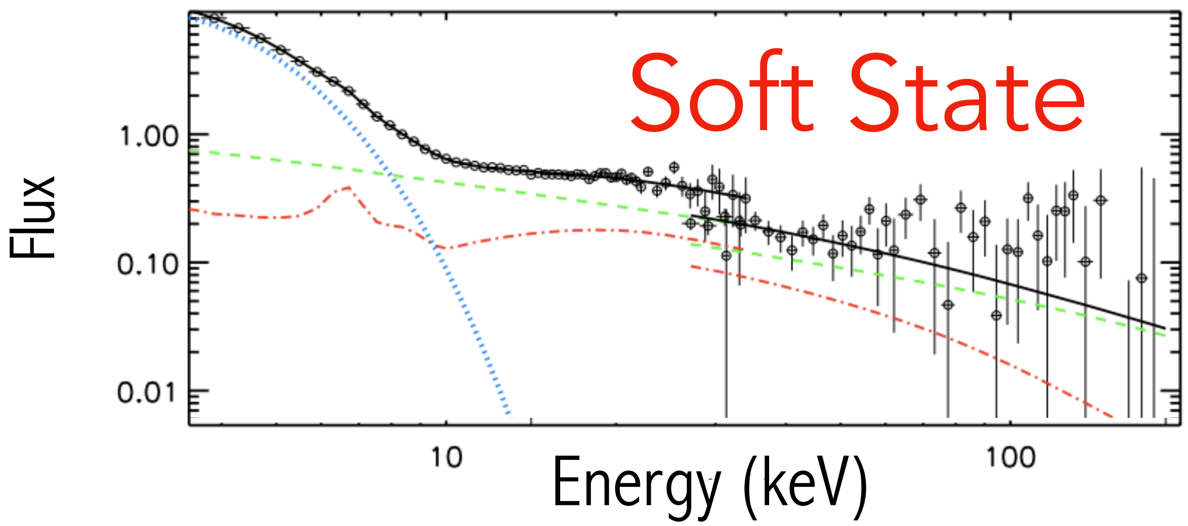
I told you that black hole X-ray binaries _do_ have accretion disc spectra, and AGN _kind of_ have accretion disc spectra (+ other stuff).



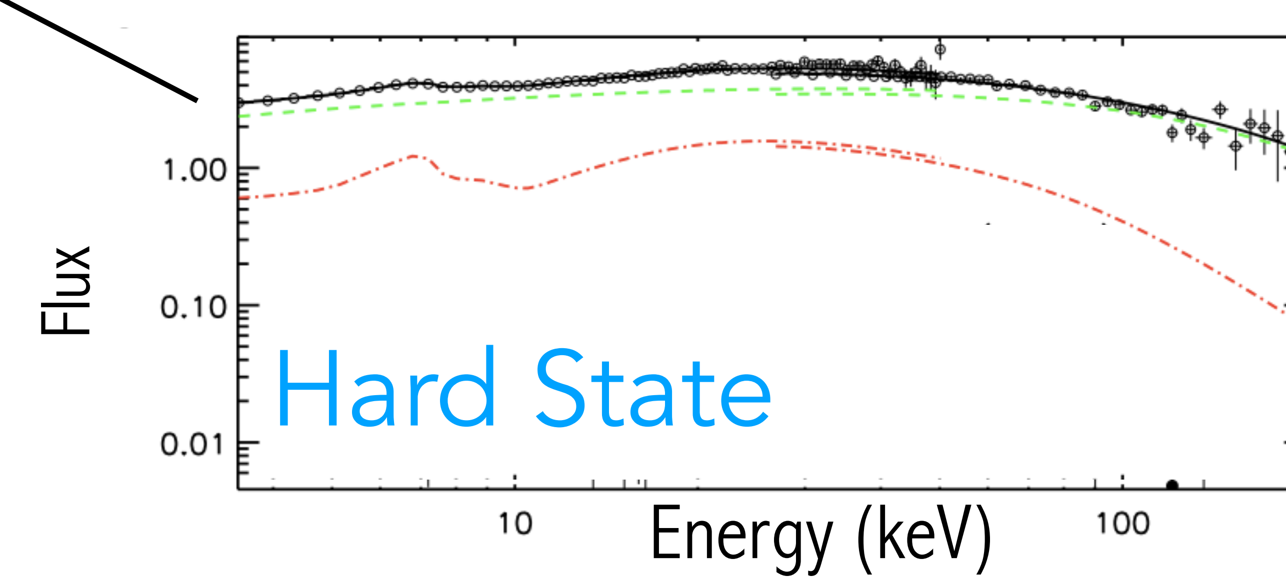


Spectral States

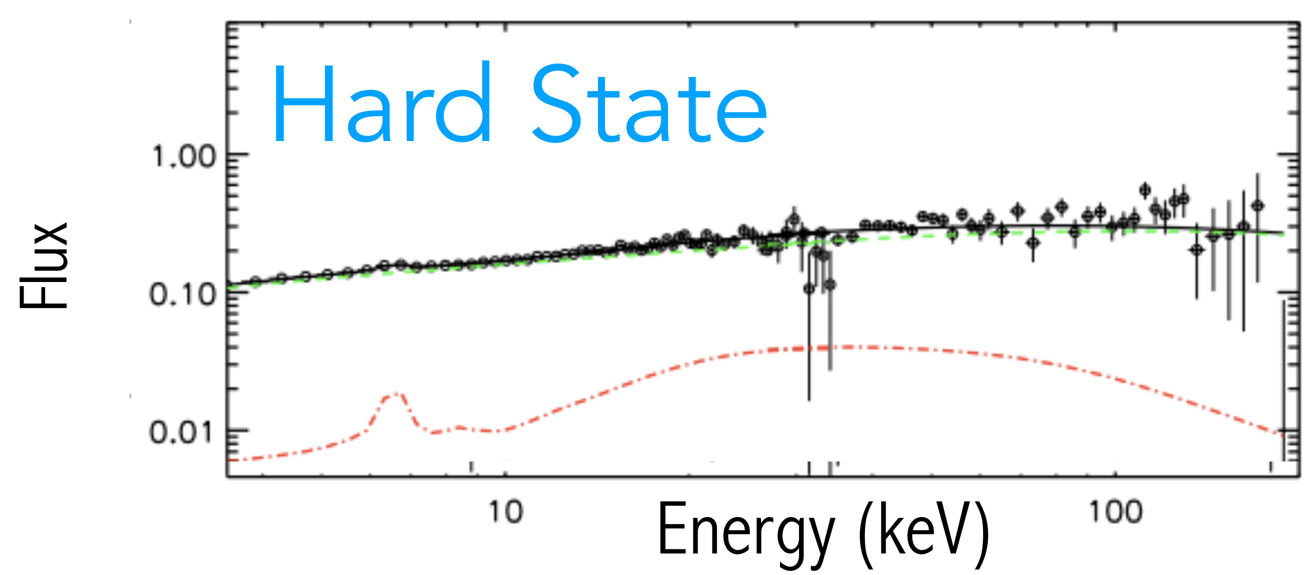
But even XRBs only have ~clean disc spectra *sometimes*: XRBs undergo *state transitions*.



~weeks

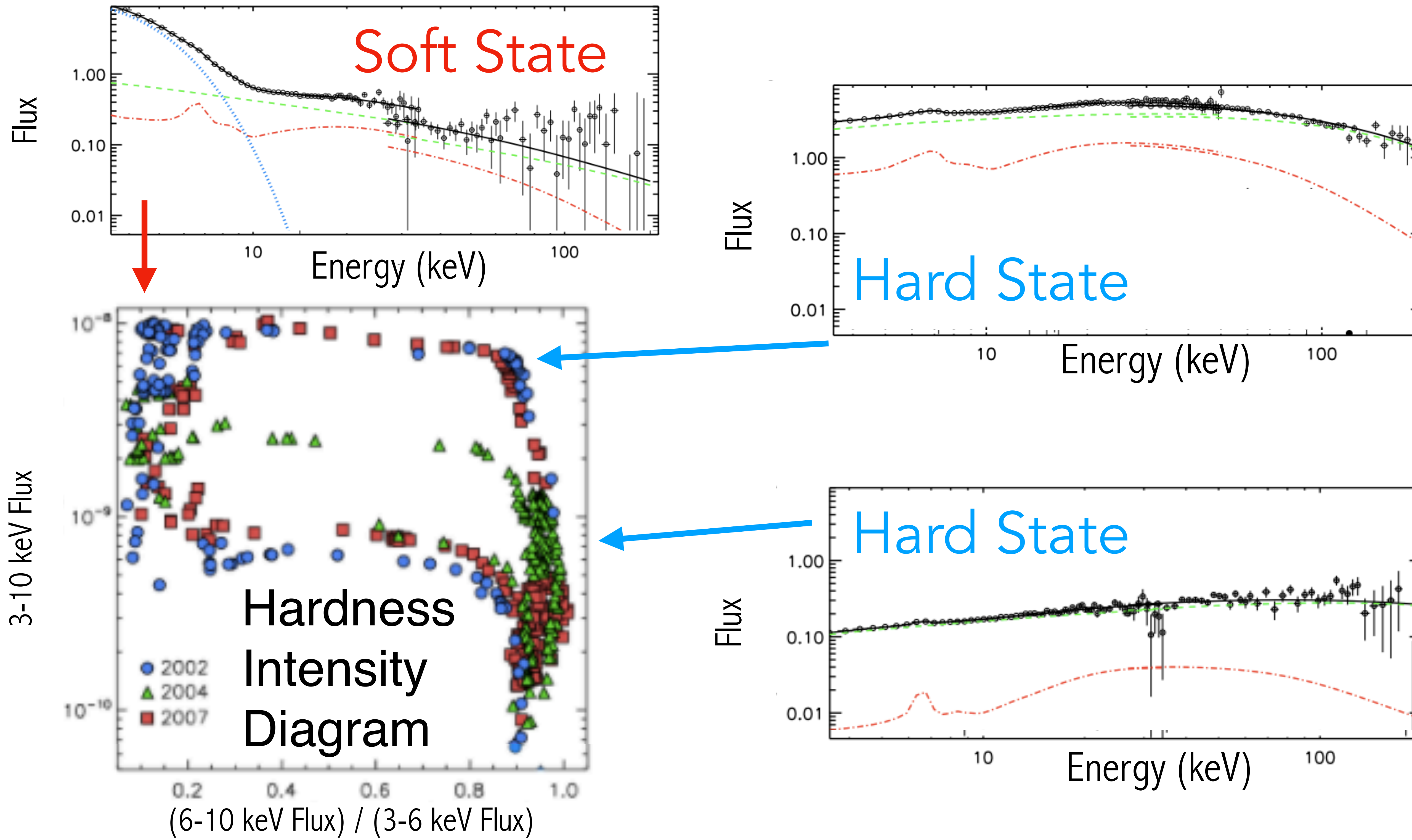


~weeks



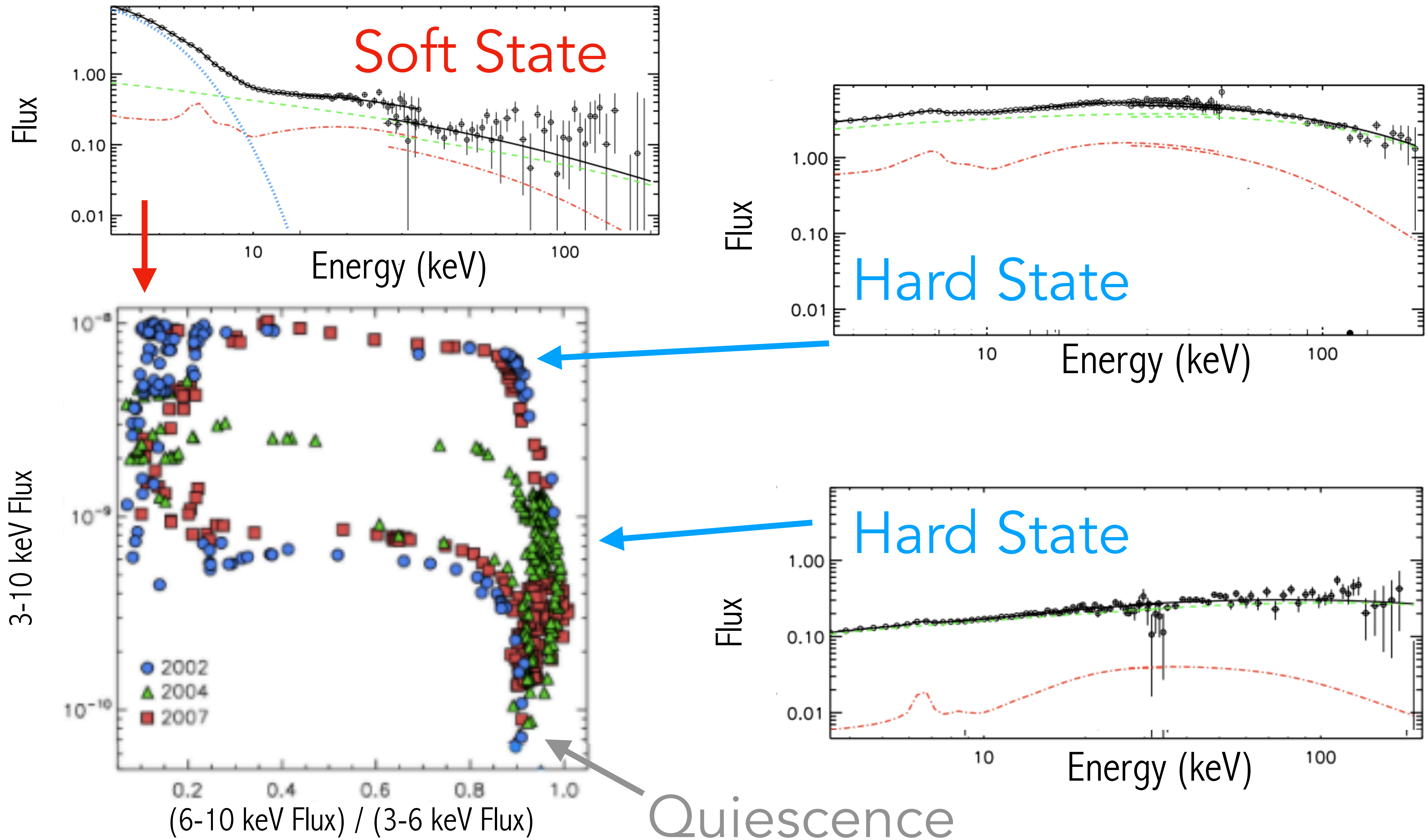
Spectral States

But even XRBs only have ~clean disc spectra *sometimes*: XRBs undergo *state transitions*.



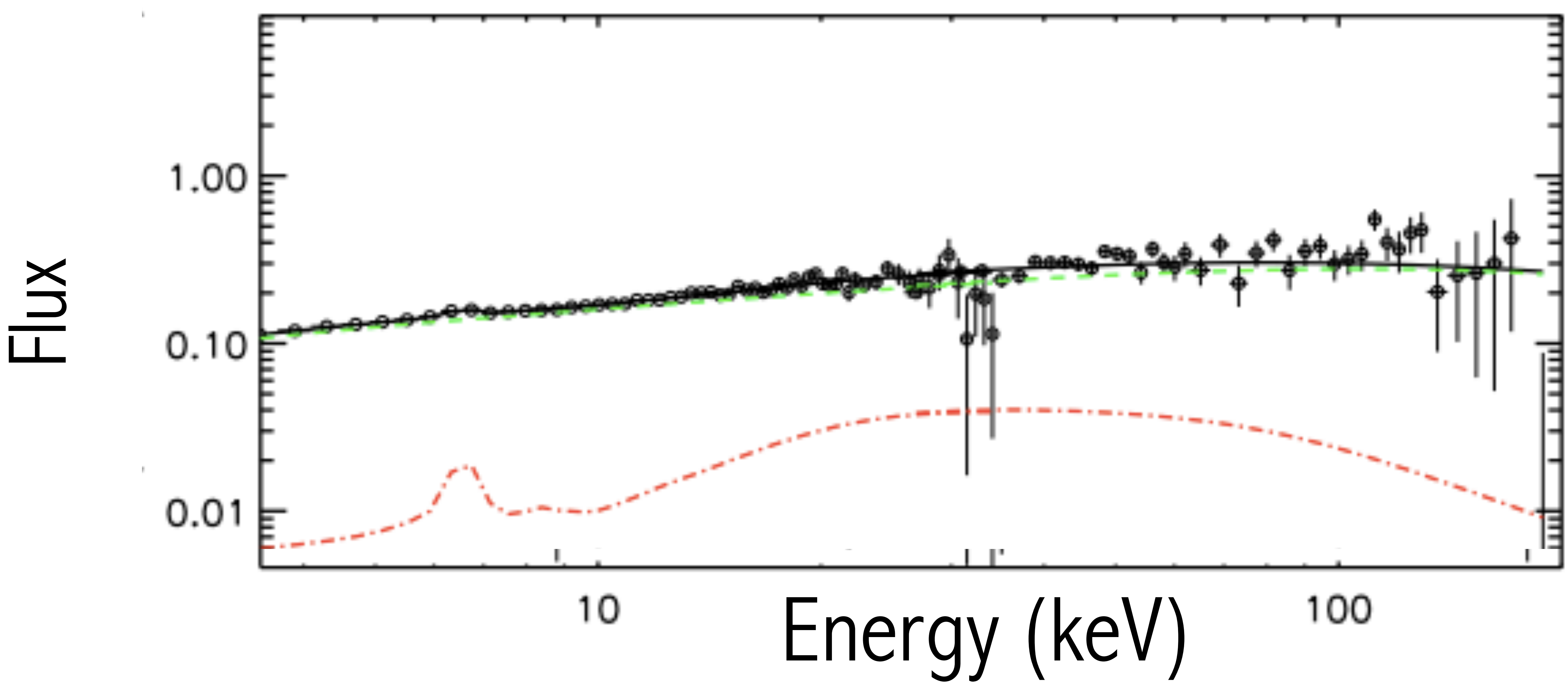
Spectral States

But even XRBs only have ~clean disc spectra *sometimes*: XRBs undergo *state transitions*.



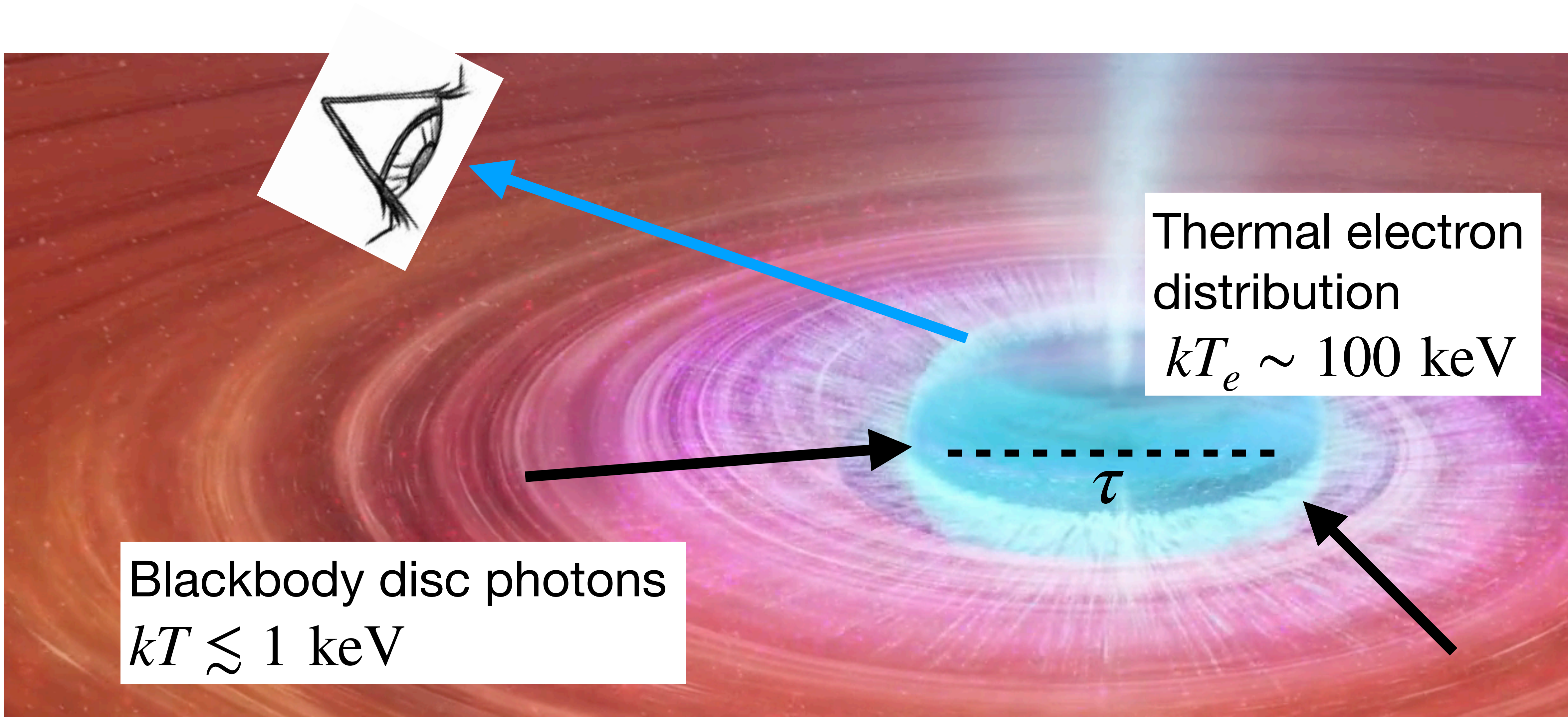
Spectral States

Hard state X-ray binary spectrum and AGN X-ray spectrum dominated by a ~power-law component (green). What is this?



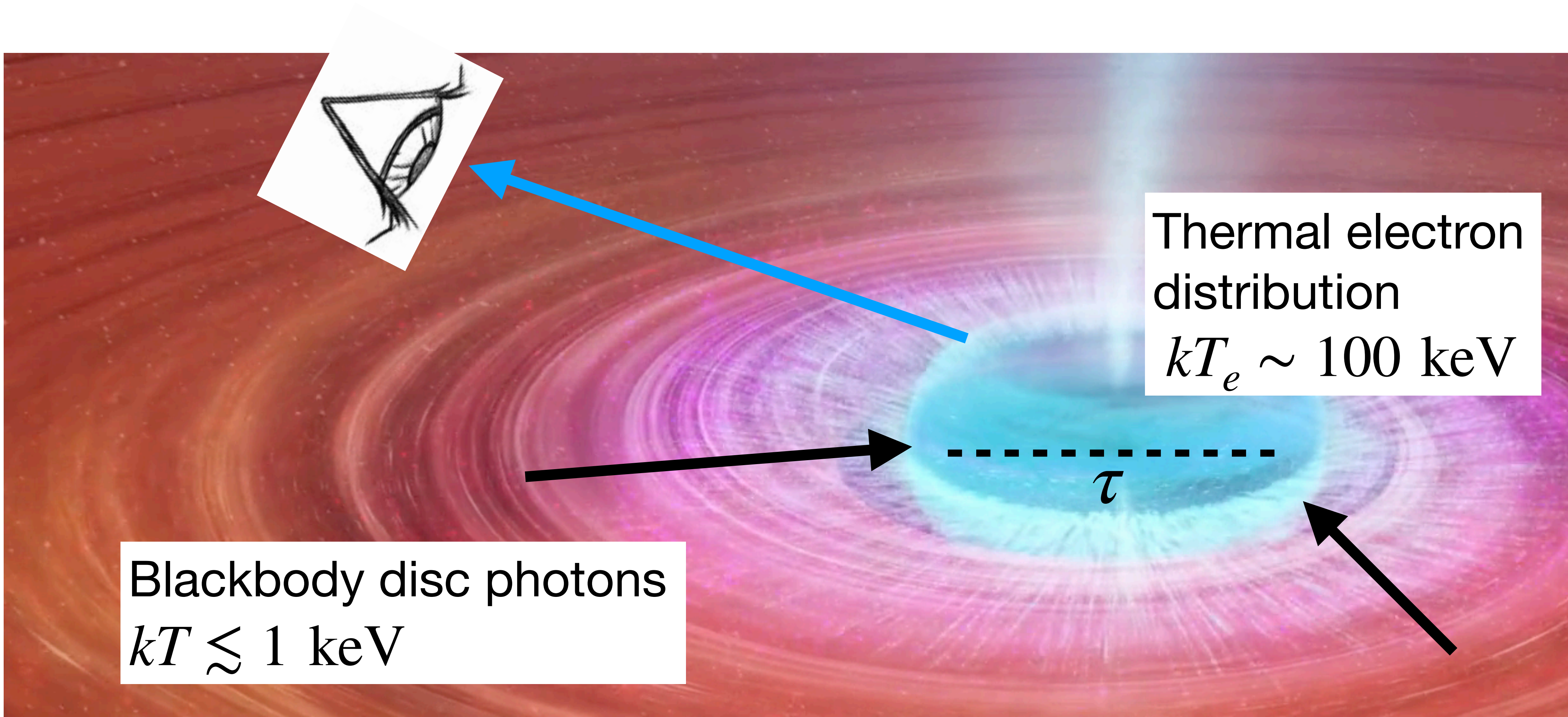
The X-ray Corona

- We can reproduce the hard state / AGN X-ray spectrum if there is a hot, τ~1 plasma close to the black hole.



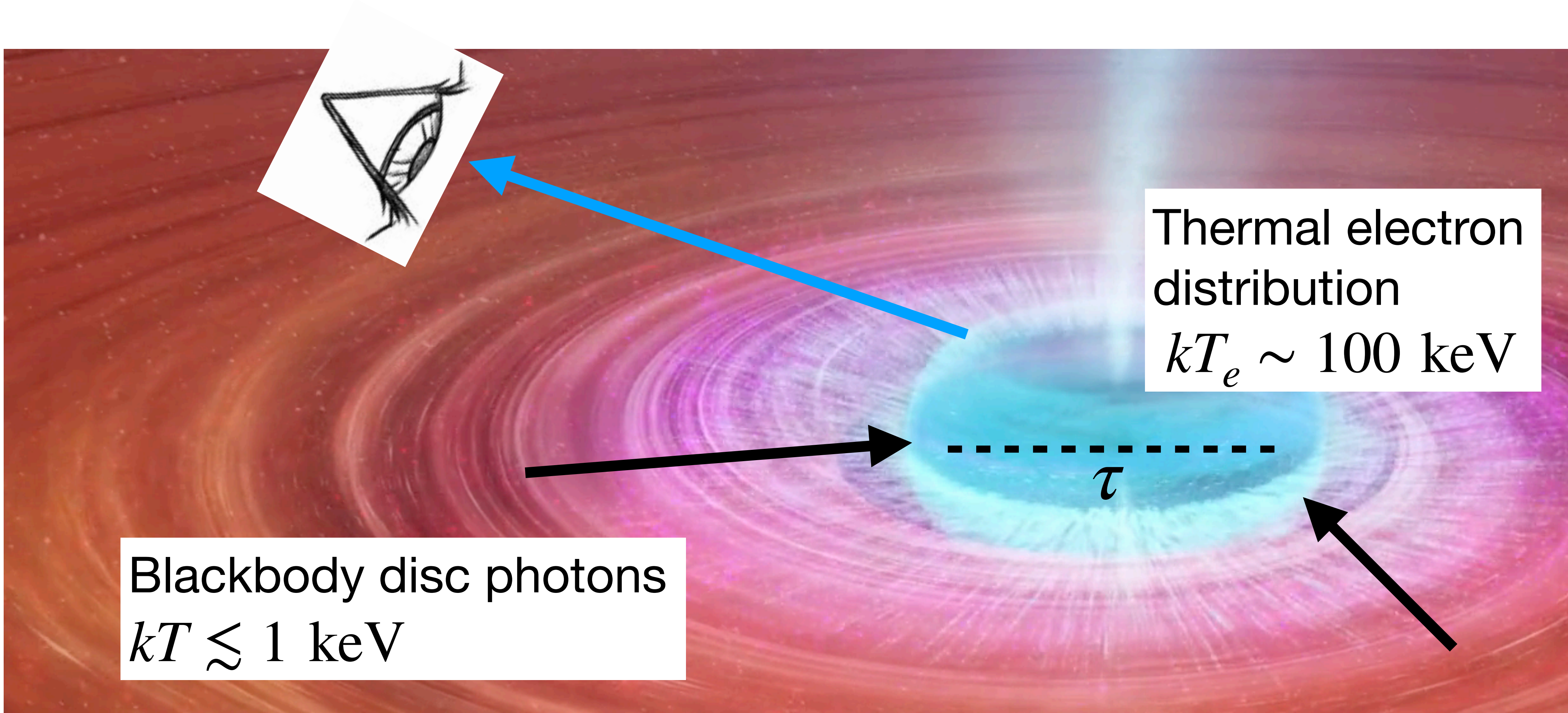
The X-ray Corona

- We can reproduce the hard state / AGN X-ray spectrum if there is a hot, τ~1 plasma close to the black hole.
- Comparatively cool disc photons Compton up-scatter off hot electrons in this plasma, gaining energy.



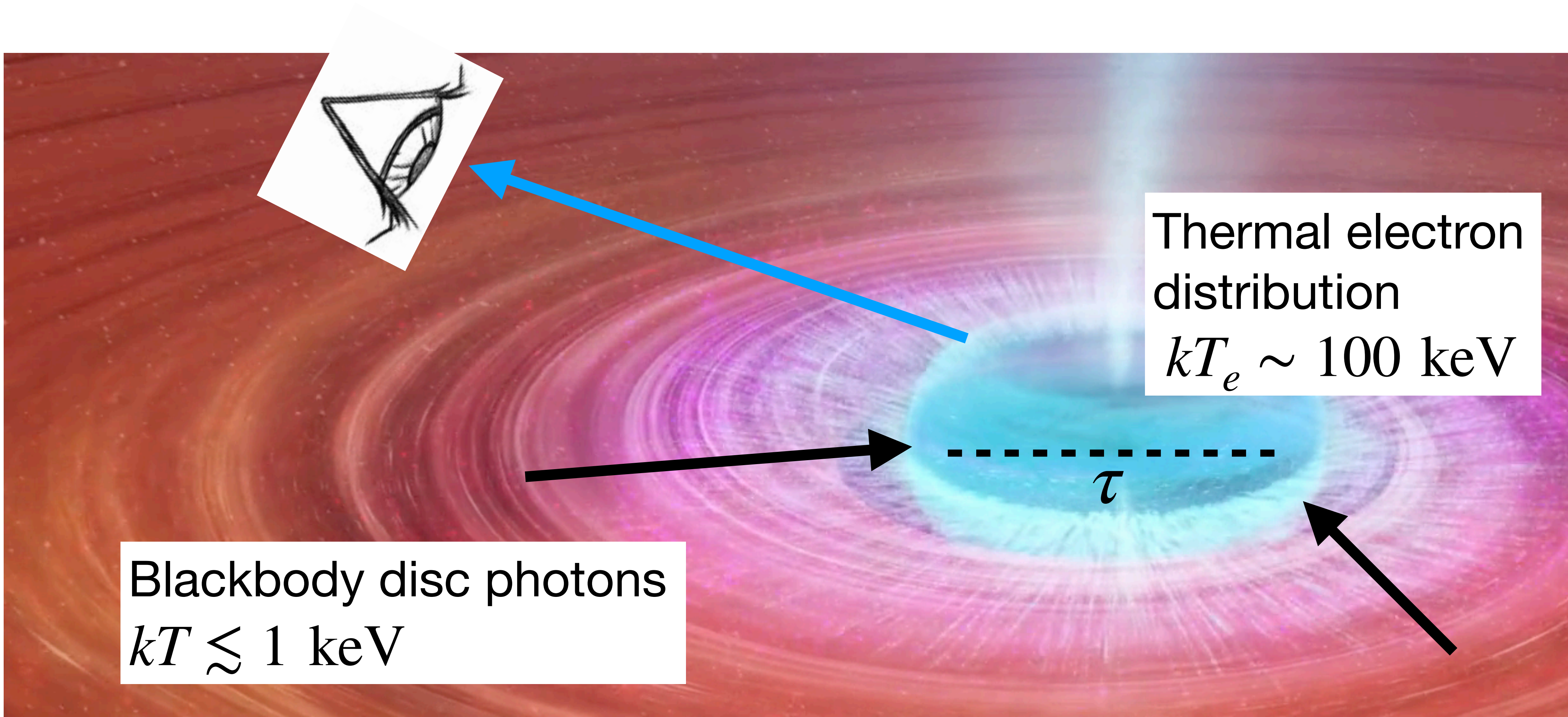
The X-ray Corona

- We can reproduce the hard state / AGN X-ray spectrum if there is a hot, τ~1 plasma close to the black hole.
- Comparatively cool disc photons Compton up-scatter off hot electrons in this plasma, gaining energy.
- We call this plasma the “corona” (in analogy to the Sun’s corona).



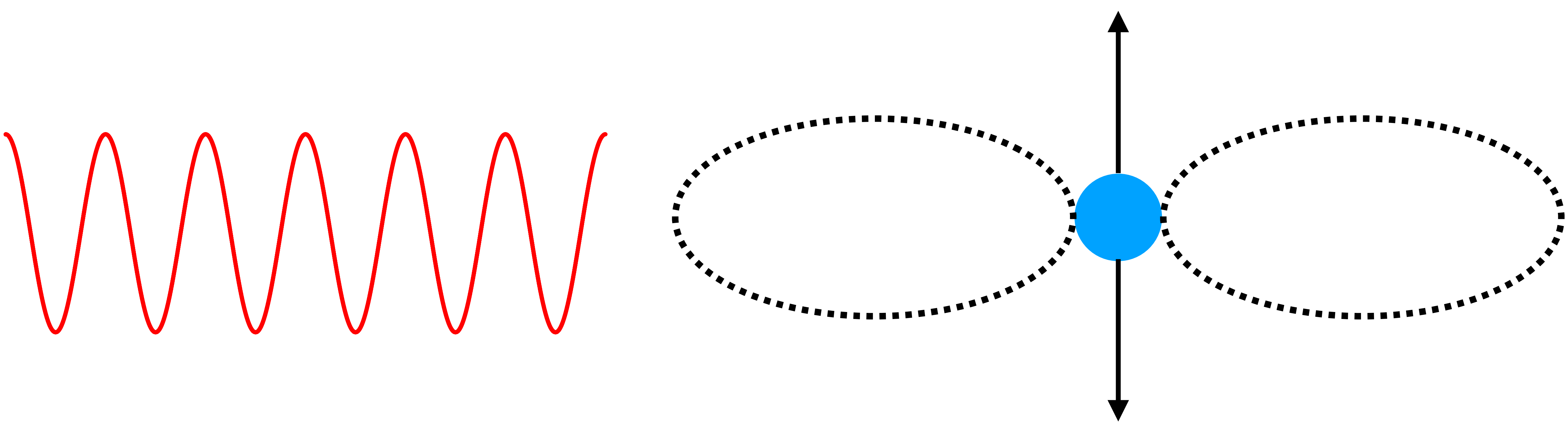
The X-ray Corona

- We can reproduce the hard state / AGN X-ray spectrum if there is a hot, $\tau \sim 1$ plasma close to the black hole.
- Comparatively cool disc photons Compton up-scatter off hot electrons in this plasma, gaining energy.
- We call this plasma the “corona” (in analogy to the Sun’s corona).
- We are still unsure of the actual shape or physical origin of the corona — we just know it needs to be there!



Thomson Scattering

- Incident EM wave drives electron initially at rest to oscillate with it.
- Acceleration of electron causes dipole emission: polarised in the direction of the acceleration.

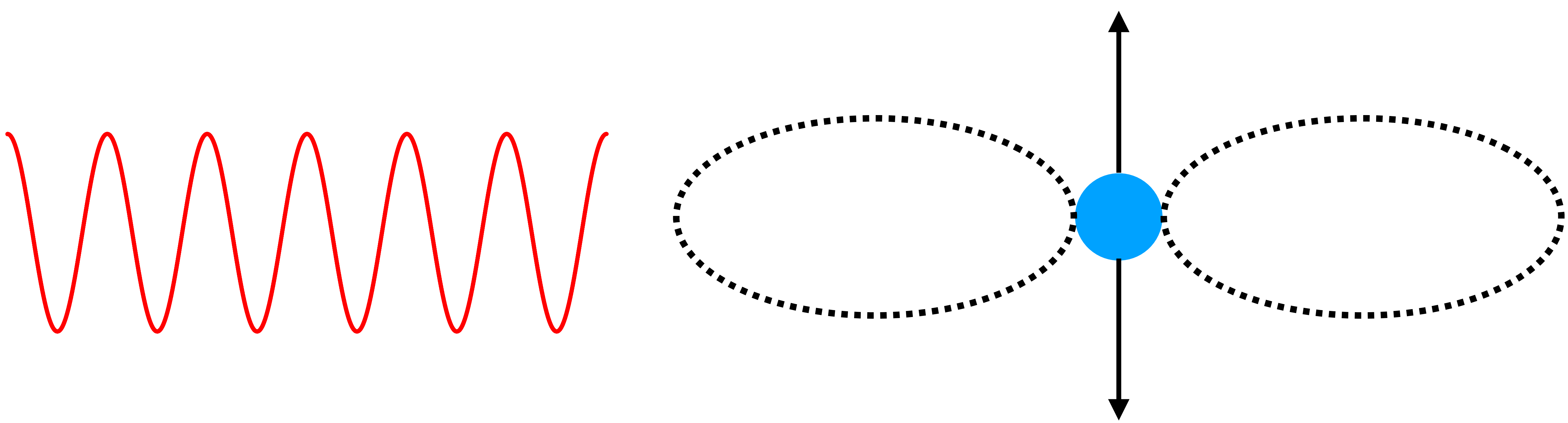


Thomson Scattering

- Incident EM wave drives electron initially at rest to oscillate with it.
- Acceleration of electron causes dipole emission: polarised in the direction of the acceleration.
- Recall that power radiated is:

$$P = \sigma_T c U_{\rm rad}$$

where σ_T is (by definition) the Thomson cross-section and $U_{\rm rad}$ is the energy density of the incoming radiation field.



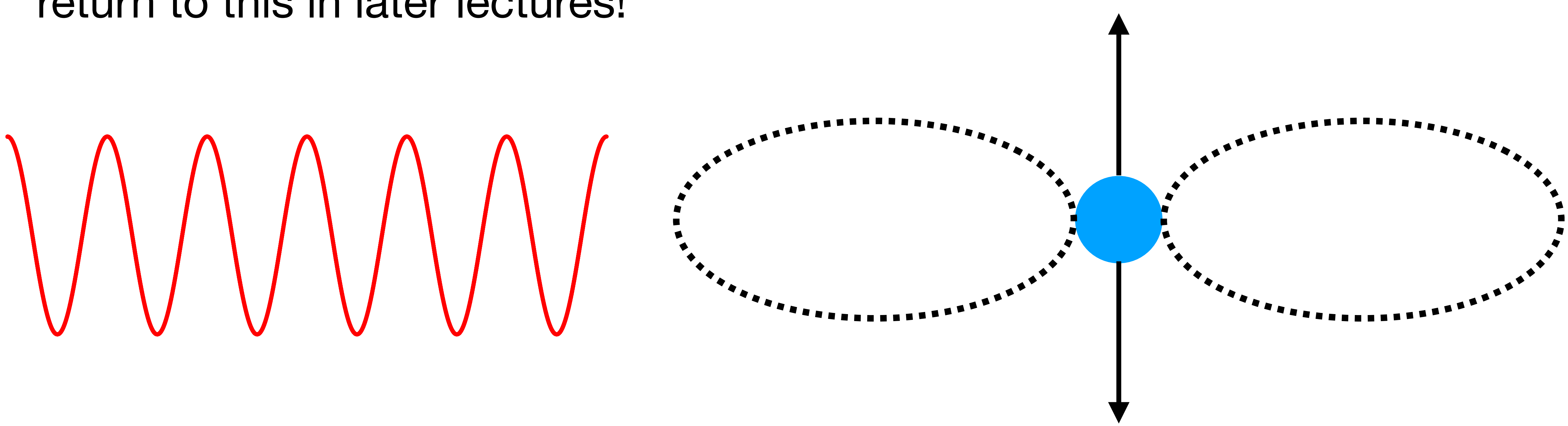
Thomson Scattering

- Incident EM wave drives electron initially at rest to oscillate with it.
- Acceleration of electron causes dipole emission: polarised in the direction of the acceleration.
- Recall that power radiated is:

$$P = \sigma_T c U_{\mathrm{rad}}$$

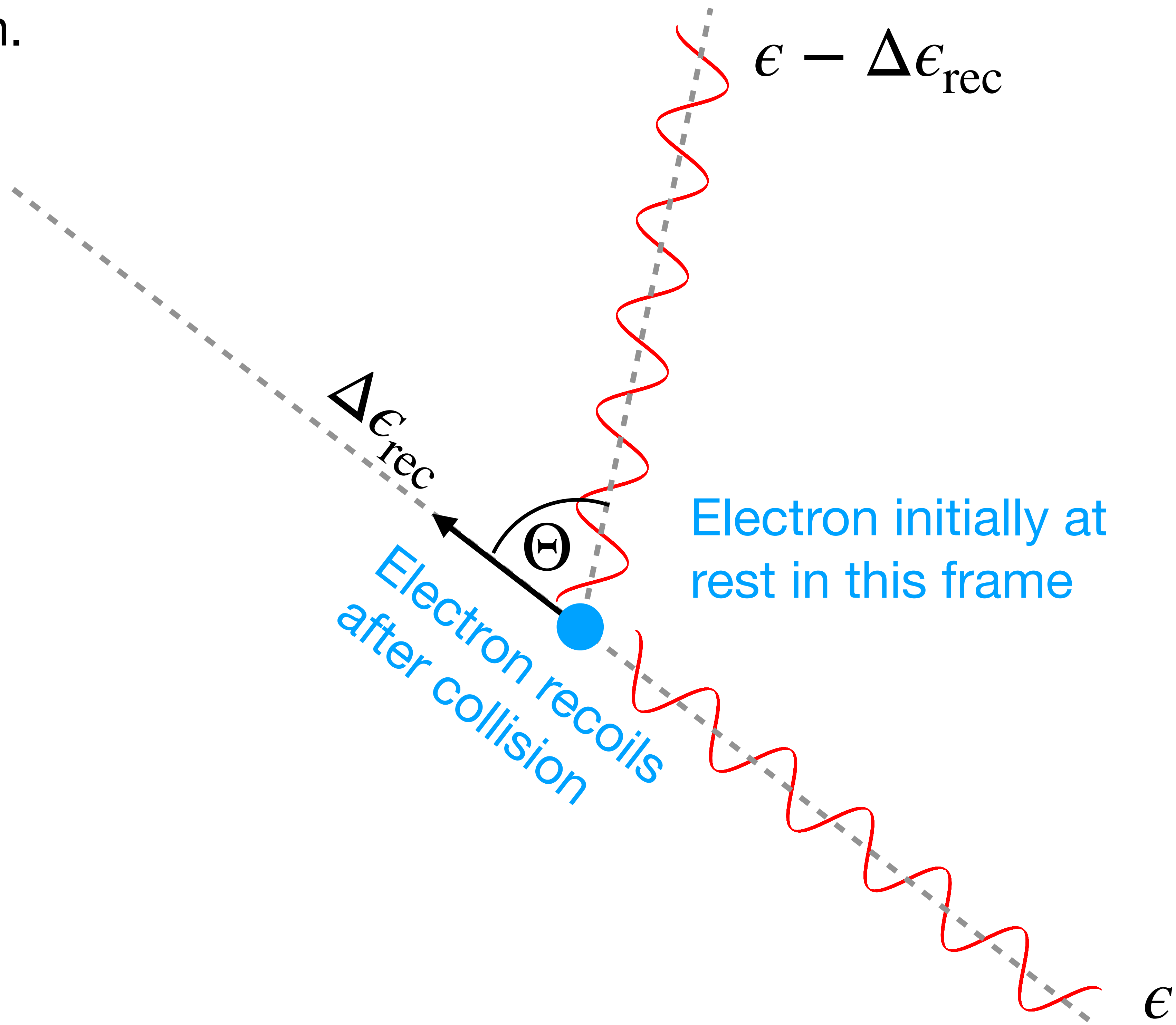
where σ_T is (by definition) the Thomson cross-section and U_{rad} is the energy density of the incoming radiation field.

- Thomson scattering is important in a number of situations in HEA, so will return to this in later lectures!



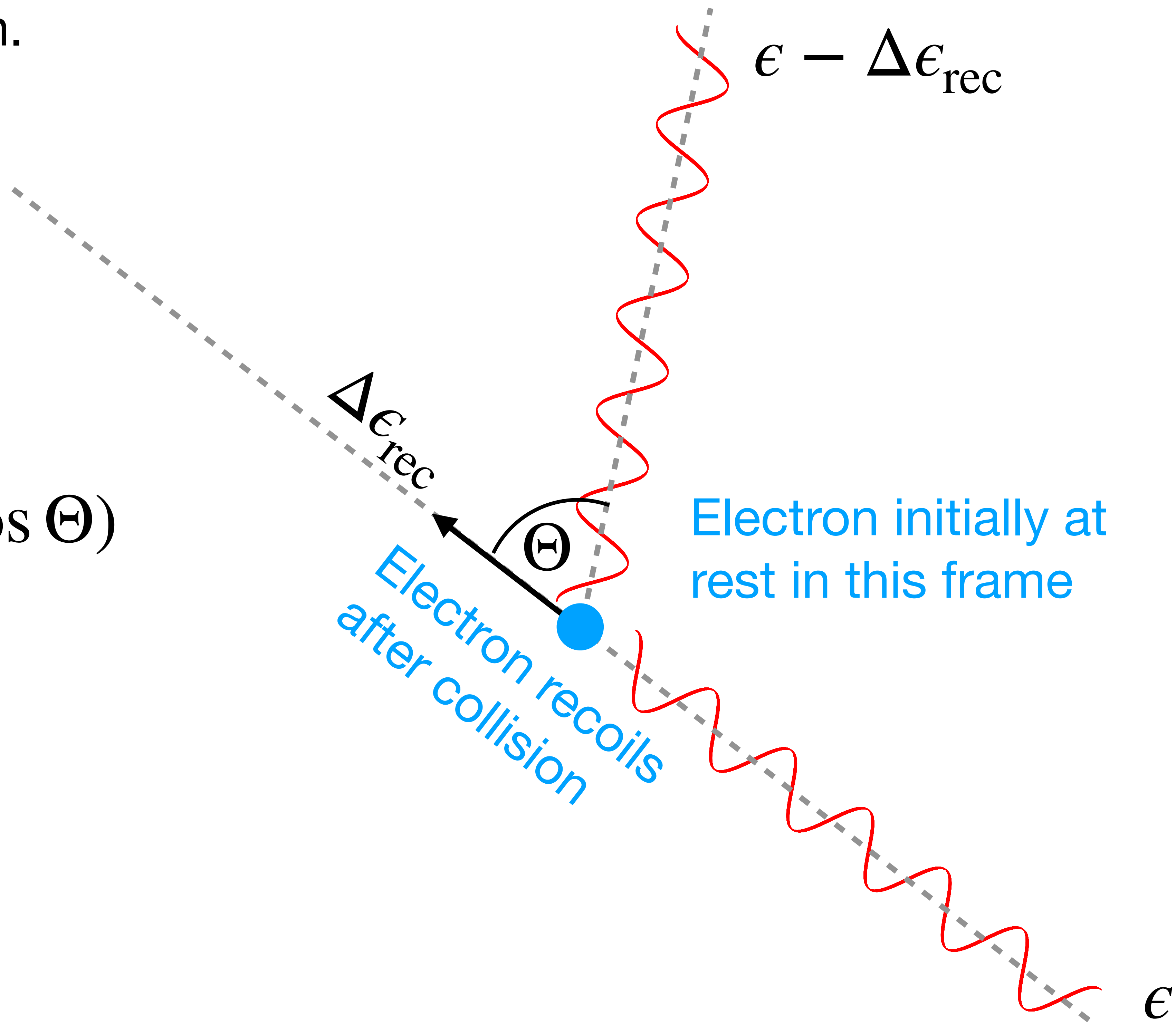
Compton Scattering

Quantum effect: If photon has significant momentum, (i.e. $h\nu \ll m_e c^2$ is *not* met), electron recoils and photon transfers energy to electron.



Compton Scattering

Quantum effect: If photon has significant momentum, (i.e. $h\nu \ll m_e c^2$ is *not* met), electron recoils and photon transfers energy to electron.

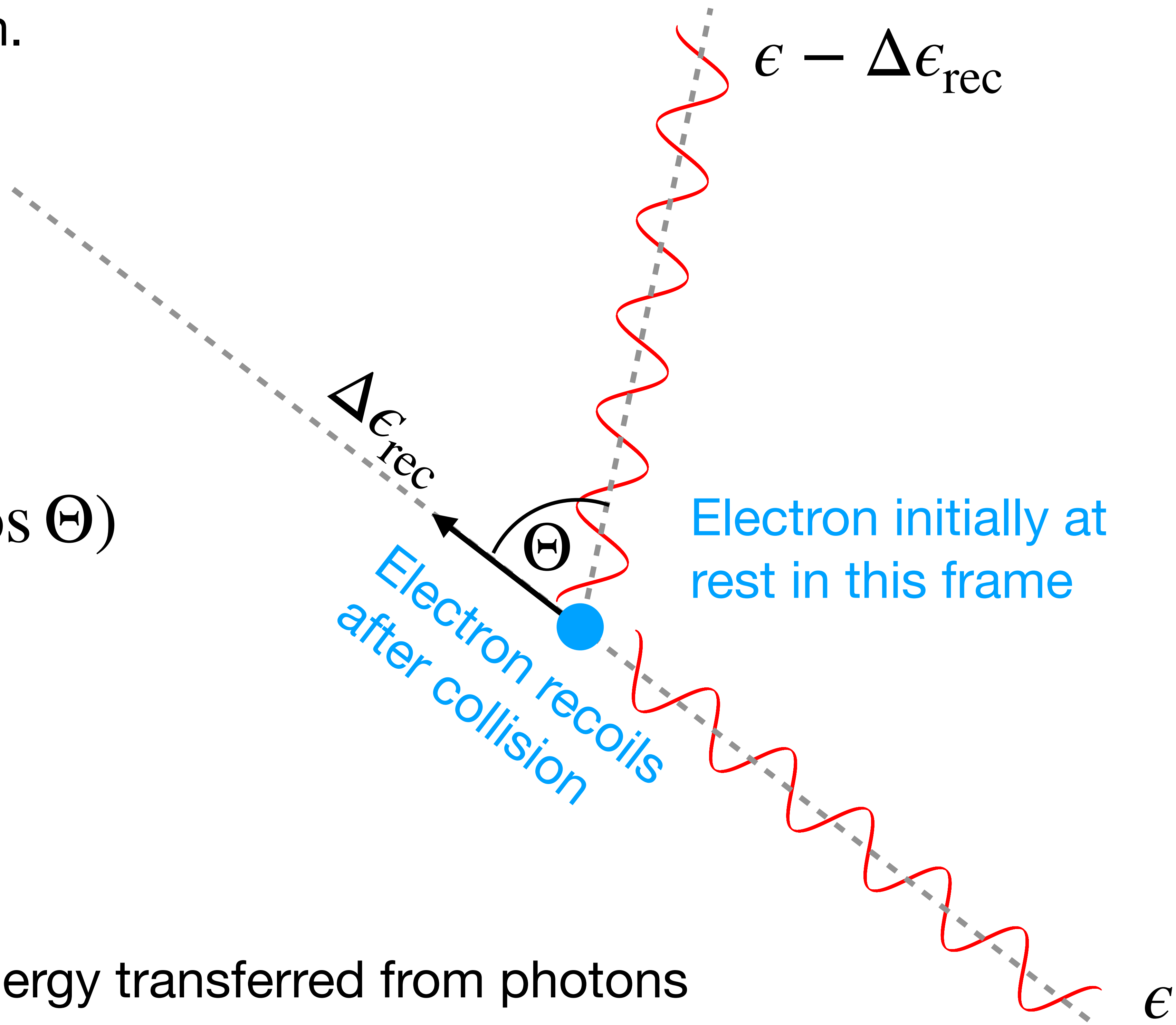


Compton's formula:

$$\frac{\Delta\epsilon_{\rm rec}}{\epsilon} = \frac{\epsilon}{m_e c^2}(1 - \cos\Theta)$$

Compton Scattering

Quantum effect: If photon has significant momentum, (i.e. $h\nu \ll m_e c^2$ is *not* met), electron recoils and photon transfers energy to electron.



Compton's formula:

$$\frac{\Delta\epsilon_{\rm rec}}{\epsilon} = \frac{\epsilon}{m_e c^2}(1 - \cos\Theta)$$

Average over all angles:

$$\left\langle \frac{\Delta\epsilon}{\epsilon} \right\rangle_{\rm rec} = \frac{\epsilon}{m_e c^2}$$

…the average fractional energy transferred from photons to electrons per scattering.

Inverse Compton Scattering

- Net energy transferred from electrons to photons = energy transfer via Thomson scattering ("Inverse Compton") - energy transfer via electron recoil (Compton).

Inverse Compton Scattering

- Net energy transferred from electrons to photons = energy transfer via Thomson scattering ("Inverse Compton") - energy transfer via electron recoil (Compton).
- For electron with non-zero velocity, first calculate Thomson power in the electron rest frame:

$$P' = \sigma_T c U'_{\rm rad}$$

then (trivially) Lorentz transform to the observer frame (P=P').

Inverse Compton Scattering

- Net energy transferred from electrons to photons = energy transfer via Thomson scattering ("Inverse Compton") - energy transfer via electron recoil (Compton).
- For electron with non-zero velocity, first calculate Thomson power in the electron rest frame:

$$P' = \sigma_T c U'_{\rm rad}$$

then (trivially) Lorentz transform to the observer frame (P=P').

- So how do we Lorentz transform $U_{\rm rad}$ (observer frame) to $U_{\rm rad}$' (electron rest frame)?

$U_{\rm rad}$ = energy in radiation field / volume: $$U'_{\rm rad} \propto h\nu' \frac{dN}{dV'}$$

Inverse Compton Scattering

- Net energy transferred from electrons to photons = energy transfer via Thomson scattering (“Inverse Compton”) - energy transfer via electron recoil (Compton).
- For electron with non-zero velocity, first calculate Thomson power in the electron rest frame:

$$P' = \sigma_T c U'_{\mathrm{rad}}$$

then (trivially) Lorentz transform to the observer frame (P=P’).

- So how do we Lorentz transform U_{rad} (observer frame) to U_{rad}’ (electron rest frame)?

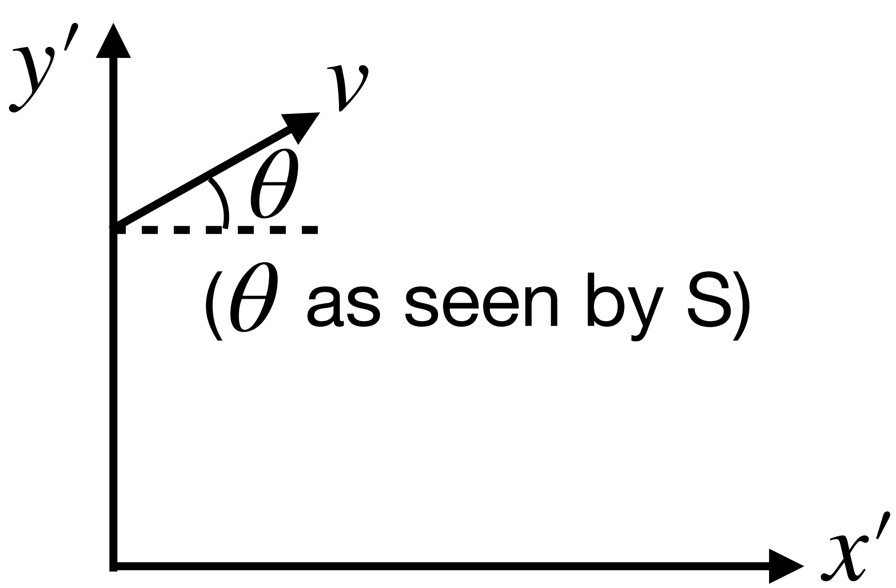
U_{rad} = energy in radiation field / volume: $$U'_{\mathrm{rad}} \propto h\nu' \frac{dN}{dV'}$$

- So we need to transform frequency (relativistic Doppler shift) and the dimension of the volume in the direction of motion of the electron (length contraction)

Inverse Compton Scattering

$$U'_{\mathrm{rad}} \propto h\nu' \frac{dN}{dV'}$$

Electron frame: S’



Observer frame: S

Inverse Compton Scattering

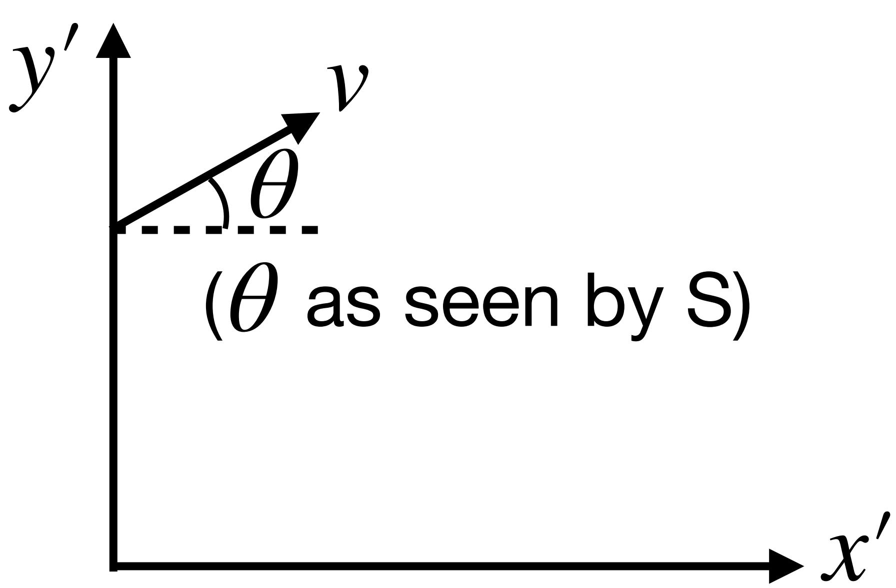
$$U'_{\rm rad} \propto h\nu' \frac{dN}{dV'}$$

- (Special) Relativistic Doppler shift:

$$\nu = \delta \times \nu'$$

Doppler factor
$$\delta = \gamma^{-1}(1 - (v/c)\cos\theta)^{-1}$$

Electron frame: S’



Observer frame: S

Inverse Compton Scattering

$$U'_{\mathrm{rad}} \propto h\nu' \frac{dN}{dV'}$$

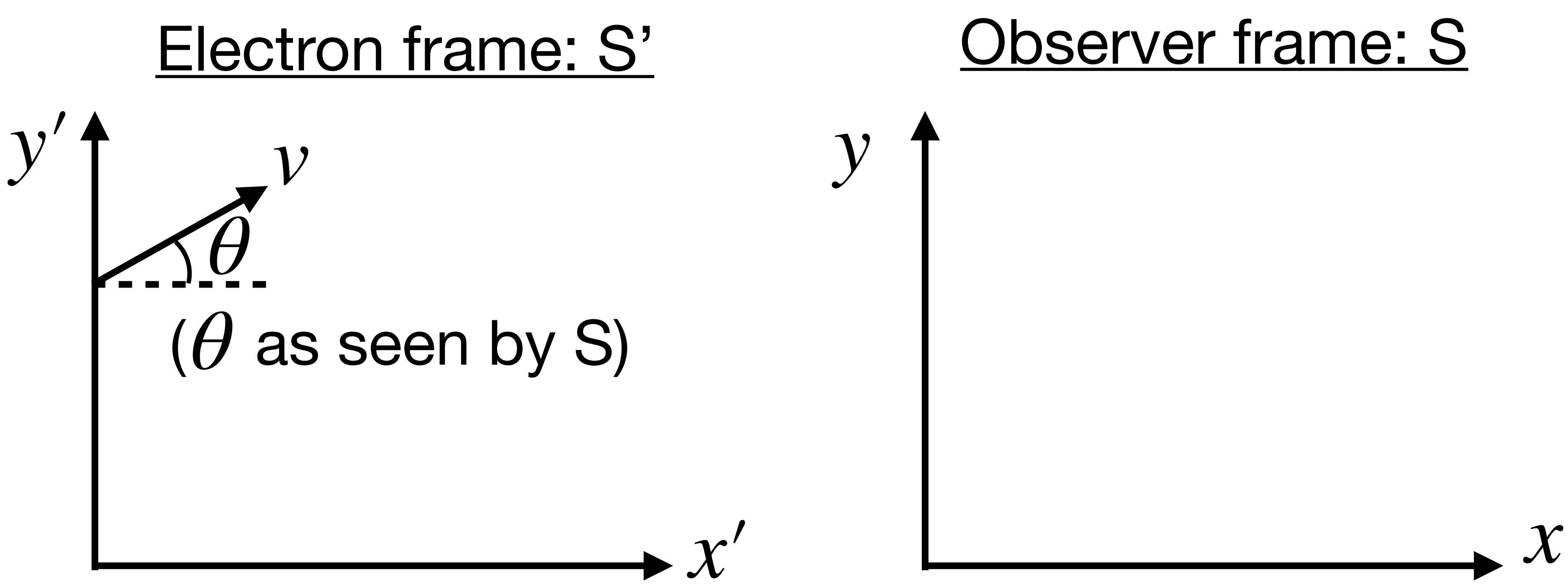
- (Special) Relativistic Doppler shift:

$$\nu = \delta \times \nu'$$

Doppler factor
$$\delta = \gamma^{-1}(1 - (v/c)\cos\theta)^{-1}$$

- Length contraction:

$$dx = dx'/\delta$$



Inverse Compton Scattering

$$U'_{\rm rad} \propto h\nu' \frac{dN}{dV'} = h\frac{\nu}{\delta}\frac{dN}{\delta\ dV}$$

- (Special) Relativistic Doppler shift:

$$\nu = \delta \times \nu'$$

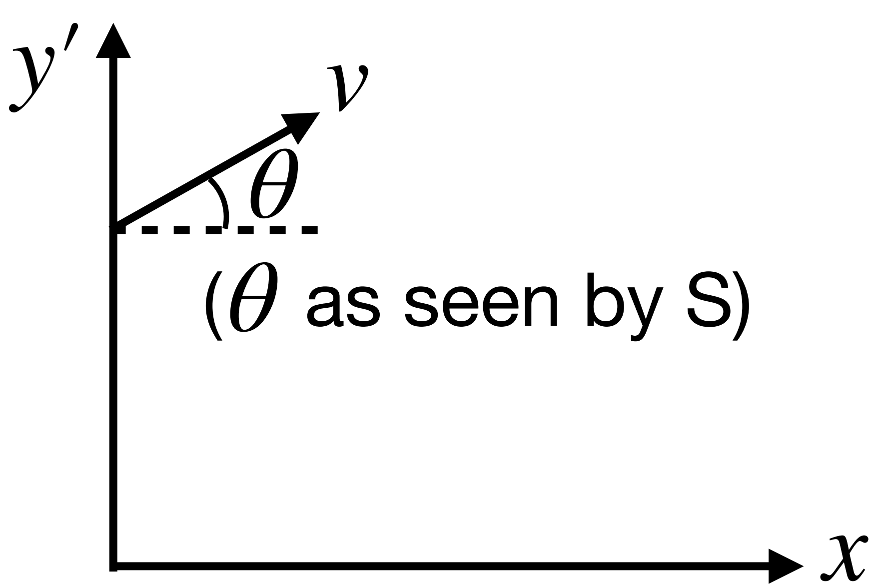
Doppler factor

$$\delta = \gamma^{-1}(1 - (v/c)\cos\theta)^{-1}$$

- Length contraction:

$$dx = dx'/\delta$$

Electron frame: S’



Observer frame: S

Inverse Compton Scattering

$$U'_{\mathrm{rad}} \propto h\nu' \frac{dN}{dV'} = h\frac{\nu}{\delta}\frac{dN}{\delta\; dV} = \frac{U_{\mathrm{rad}}}{\delta^2}$$

- (Special) Relativistic Doppler shift:

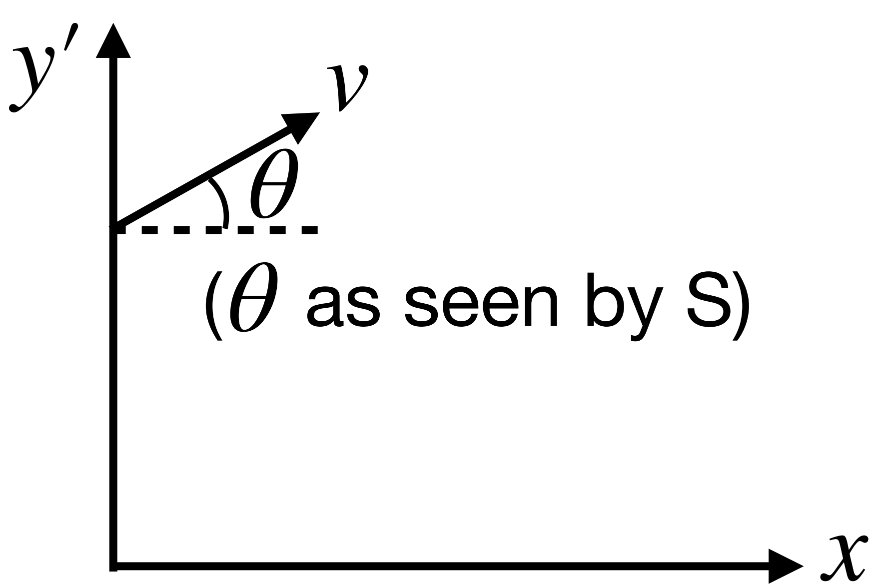
$$\nu = \delta \times \nu'$$

Doppler factor
$$\delta = \gamma^{-1}(1 - (v/c)\cos\theta)^{-1}$$

- Length contraction:

$$dx = dx'/\delta$$

Electron frame: S’



Observer frame: S

Inverse Compton Scattering

$$U'_{\rm rad} \propto h\nu' \frac{dN}{dV'} = h\frac{\nu}{\delta}\frac{dN}{\delta\ dV} = \frac{U_{\rm rad}}{\delta^2}$$

Doppler factor

$$\delta = \gamma^{-1}(1 - (v/c)\cos\theta)^{-1}$$

Therefore:

$$P' = \sigma_T c U'_{\rm rad} = \sigma_T c U_{\rm rad}/\delta^2$$

$$P' = \sigma_T c U_{\rm rad}\gamma^2[1 - (v/c)\cos\theta]^2 = P$$

Inverse Compton Scattering

- Finally, average over all angles:

$$\langle P \rangle = \frac{1}{2}\int_{-1}^{+1} P(\theta) d\cos\theta = \frac{4}{3}\sigma_T c U_{\rm rad}\left(\gamma^2 - \frac{1}{4}\right)$$

Inverse Compton Scattering

- Finally, average over all angles:

$$\langle P \rangle = \frac{1}{2}\int_{-1}^{+1} P(\theta)d\cos\theta = \frac{4}{3}\sigma_T c U_{\rm rad}\left(\gamma^2 - \frac{1}{4}\right)$$

- But this is just the energy radiated, to get the energy *transferred* from the electrons to the photons, we need to subtract off the energy of the photon field pre-scattering:

$$\langle P \rangle_{\rm IC} = \frac{4}{3}\sigma_T c U_{\rm rad}\left(\gamma^2 - \frac{1}{4}\right) - \sigma_T c U_{\rm rad}$$

Inverse Compton Scattering

- Finally, average over all angles:

$$\langle P \rangle = \frac{1}{2}\int_{-1}^{+1} P(\theta) d\cos\theta = \frac{4}{3}\sigma_T c U_{\mathrm{rad}}\left(\gamma^2 - \frac{1}{4}\right)$$

- But this is just the energy radiated, to get the energy ***transferred*** from the electrons to the photons, we need to subtract off the energy of the photon field pre-scattering:

$$\langle P \rangle_{\mathrm{IC}} = \frac{4}{3}\sigma_T c U_{\mathrm{rad}}\left(\gamma^2 - \frac{1}{4}\right) - \sigma_T c U_{\mathrm{rad}}$$

$$\langle P \rangle_{\mathrm{IC}} = \frac{4}{3}\sigma_T c U_{\mathrm{rad}}\left(\gamma^2 - 1\right)$$

Inverse Compton Scattering

- Finally, average over all angles:

$$\langle P \rangle = \frac{1}{2}\int_{-1}^{+1} P(\theta) d\cos\theta = \frac{4}{3}\sigma_T c U_{\rm rad}\left(\gamma^2 - \frac{1}{4}\right)$$

- But this is just the energy radiated, to get the energy *transferred* from the electrons to the photons, we need to subtract off the energy of the photon field pre-scattering:

$$\langle P \rangle_{\rm IC} = \frac{4}{3}\sigma_T c U_{\rm rad}\left(\gamma^2 - \frac{1}{4}\right) - \sigma_T c U_{\rm rad}$$

$$\langle P \rangle_{\rm IC} = \frac{4}{3}\sigma_T c U_{\rm rad}\left(\gamma^2 - 1\right)$$

$$\langle P \rangle_{\rm IC} = \frac{4}{3}\sigma_T c U_{\rm rad}\left(\frac{v}{c}\right)^2 \gamma^2$$

Inverse Compton Scattering

- We have energy per unit time transferred to photon field:

$$\langle P \rangle_{\mathrm{IC}} = \frac{4}{3}\sigma_T c U_{\mathrm{rad}} \left(\frac{v}{c}\right)^2 \gamma^2$$

Inverse Compton Scattering

- We have energy per unit time transferred to photon field:

$$\langle P \rangle_{\mathrm{IC}} = \frac{4}{3}\sigma_T c U_{\mathrm{rad}} \left(\frac{v}{c}\right)^2 \gamma^2$$

- Number of scatterings per second is:

$$\sigma_T N_{\mathrm{phot}} c = \sigma_T (U_{\mathrm{rad}}/h\nu) c$$

N_{phot} = photons / volume

Inverse Compton Scattering

- We have energy per unit time transferred to photon field:

$$\langle P \rangle_{\mathrm{IC}} = \frac{4}{3}\sigma_T c U_{\mathrm{rad}} \left(\frac{v}{c}\right)^2 \gamma^2$$

- Number of scatterings per second is:

$$\sigma_T N_{\mathrm{phot}} c = \sigma_T (U_{\mathrm{rad}}/h\nu) c$$

- Therefore average energy transferred per scattering:

$$\langle \Delta\epsilon \rangle_{\mathrm{IC}} = P_{\mathrm{IC}} h\nu / (\sigma_T U_{\mathrm{rad}} c)$$

Inverse Compton Scattering

- We have energy per unit time transferred to photon field:

$$\langle P \rangle_{\mathrm{IC}} = \frac{4}{3}\sigma_T c U_{\mathrm{rad}} \left(\frac{v}{c}\right)^2 \gamma^2$$

- Number of scatterings per second is:

$$\sigma_T N_{\mathrm{phot}} c = \sigma_T (U_{\mathrm{rad}}/h\nu) c$$

- Therefore average energy transferred per scattering:

$$\langle \Delta\epsilon \rangle_{\mathrm{IC}} = P_{\mathrm{IC}} h\nu / (\sigma_T U_{\mathrm{rad}} c)$$

$$\left\langle \frac{\Delta\epsilon}{\epsilon} \right\rangle_{\mathrm{IC}} = \frac{4}{3}\left(\frac{v}{c}\right)^2 \gamma^2$$

Thermal Comptonisation

- Assume the velocity distribution of electrons in the corona is Maxwellian with electron temperature T_e. In this case:

$$\frac{1}{2}m\langle v^2\rangle = \frac{3}{2}kT_e \qquad\qquad \therefore \langle v^2\rangle/c^2 = 3kT_e/(m_e c^2)$$

Thermal Comptonisation

- Assume the velocity distribution of electrons in the corona is Maxwellian with electron temperature T_e. In this case:

$$\frac{1}{2}m\langle v^2\rangle = \frac{3}{2}kT_e \qquad \therefore \langle v^2\rangle/c^2 = 3kT_e/(m_e c^2)$$

- Also, since $kT_e < m_e c^2$, can set $\gamma \sim 1$ to get:

$$\left\langle \frac{\Delta\epsilon}{\epsilon} \right\rangle_{\mathrm{IC}} = \frac{4}{3}\left(\frac{v}{c}\right)^2 \gamma^2 = 4\frac{kT_e}{m_e c^2}$$

Thermal Comptonisation

- Assume the velocity distribution of electrons in the corona is Maxwellian with electron temperature T_e. In this case:

$$\frac{1}{2}m\langle v^2\rangle = \frac{3}{2}kT_e$$

- Also, since $kT_e < m_e c^2$, can set $\gamma \sim 1$ to get:

$$\left\langle \frac{\Delta\epsilon}{\epsilon} \right\rangle_{\mathrm{IC}} = \frac{4}{3}\left(\frac{v}{c}\right)^2 \gamma^2 = 4\frac{kT_e}{m_e c^2}$$

- The average fractional energy gained by a photon per collision is the (IC) energy gained *from* the electron minus the (recoil) energy transferred *to* the electron:

$$\left\langle \frac{\Delta\epsilon}{\epsilon} \right\rangle = \left\langle \frac{\Delta\epsilon}{\epsilon} \right\rangle_{\mathrm{IC}} - \left\langle \frac{\Delta\epsilon}{\epsilon} \right\rangle_{\mathrm{rec}} = 4\frac{kT_e}{m_e c^2} - \frac{h\nu}{m_e c^2}$$

Thermal Comptonisation

- Assume the velocity distribution of electrons in the corona is Maxwellian with electron temperature T_e. In this case:

$$\frac{1}{2}m\langle v^2\rangle = \frac{3}{2}kT_e$$

- Also, since $kT_e < m_e c^2$, can set $\gamma \sim 1$ to get:

$$\left\langle \frac{\Delta\epsilon}{\epsilon} \right\rangle_{\mathrm{IC}} = \frac{4}{3}\left(\frac{v}{c}\right)^2 \gamma^2 = 4\frac{kT_e}{m_e c^2}$$

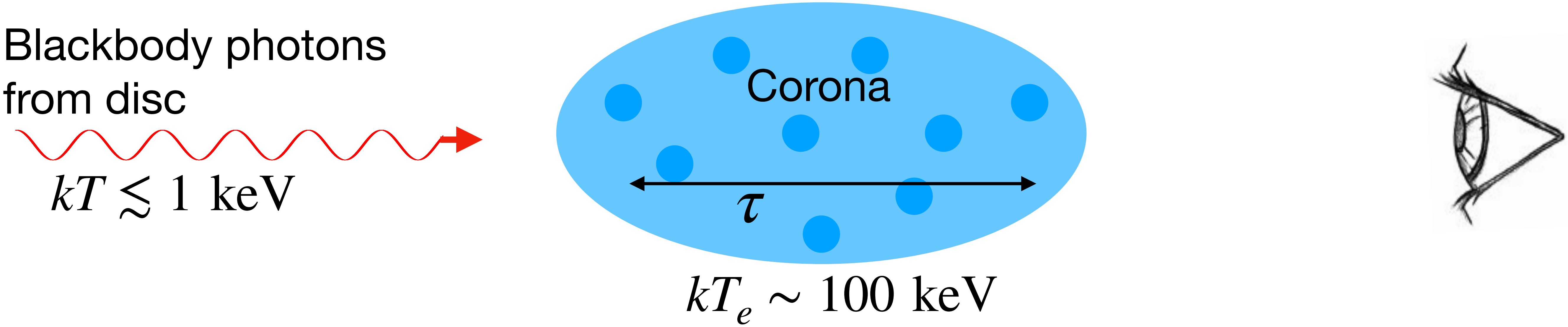
- The average fractional energy gained by a photon per collision is the (IC) energy gained *from* the electron minus the (recoil) energy transferred *to* the electron:

$$\left\langle \frac{\Delta\epsilon}{\epsilon} \right\rangle = \left\langle \frac{\Delta\epsilon}{\epsilon} \right\rangle_{\mathrm{IC}} - \left\langle \frac{\Delta\epsilon}{\epsilon} \right\rangle_{\mathrm{rec}} = 4\frac{kT_e}{m_e c^2} - \frac{h\nu}{m_e c^2}$$

- Therefore photons with $h\nu < 4kT_e$ <u>*gain*</u> energy on average, and photons with $h\nu > 4kT_e$ <u>*lose*</u> energy on average.

Thermal Comptonisation

$$\Delta\epsilon/\epsilon = 4(kT_e/m_ec^2) - h\nu/m_ec^2$$

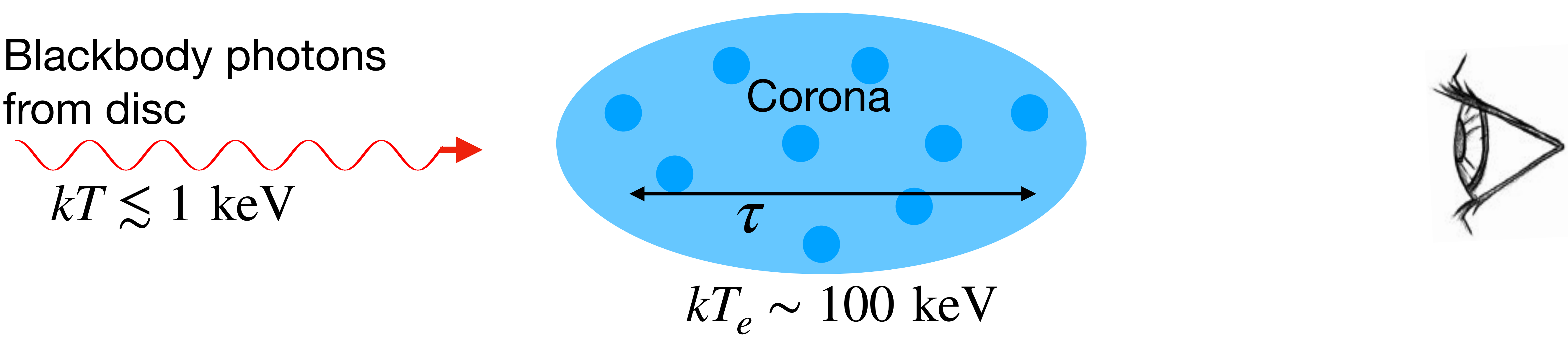


Thermal Comptonisation

$$\Delta\epsilon/\epsilon = 4(kT_e/m_ec^2) - h\nu/m_ec^2$$

- Photons from disc have $h\nu \ll m_ec^2$, therefore:

$$\Delta\epsilon/\epsilon \approx 4(kT_e/m_ec^2)$$



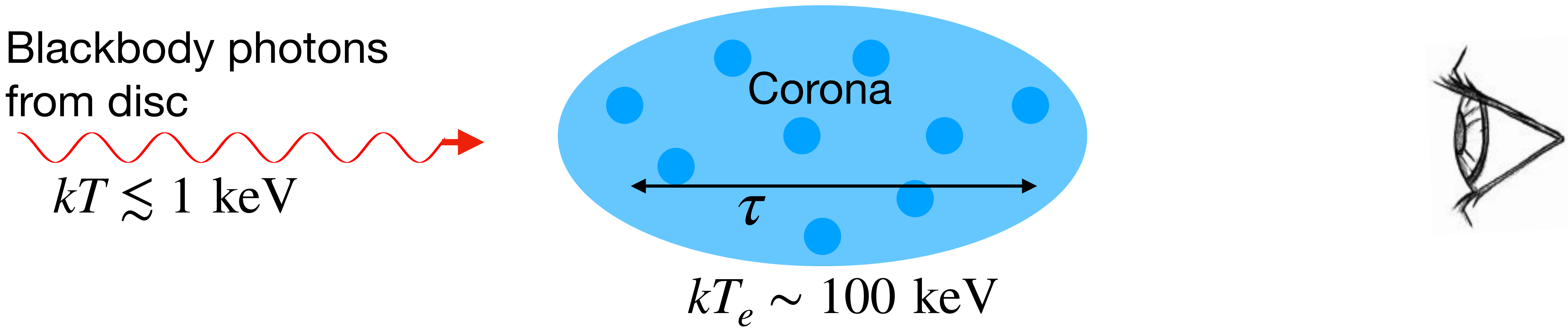
Thermal Comptonisation

$$\Delta\epsilon/\epsilon = 4(kT_e/m_ec^2) - h\nu/m_ec^2$$

- Photons from disc have $h\nu \ll m_ec^2$, therefore:

$$\Delta\epsilon/\epsilon \approx 4(kT_e/m_ec^2)$$

- Same fractional energy gain per scattering, therefore frequency after n scatterings: $\nu = \nu_0(1 + 4kT_e/m_ec^2)^n$



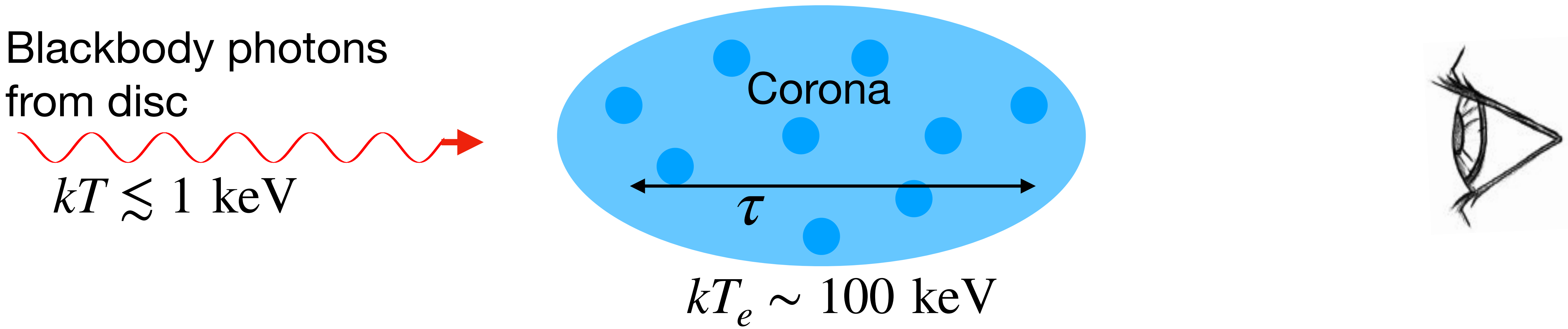
Thermal Comptonisation

$$\Delta\epsilon/\epsilon = 4(kT_e/m_ec^2) - h\nu/m_ec^2$$

- Photons from disc have $h\nu \ll m_ec^2$, therefore:

$$\Delta\epsilon/\epsilon \approx 4(kT_e/m_ec^2)$$

- Same fractional energy gain per scattering, therefore frequency after n scatterings: $\nu = \nu_0(1 + 4kT_e/m_ec^2)^n$
- Probability of staying in corona for n scatterings: $p = (1 - \mathrm{e}^{-\tau})^n \approx \tau^n$



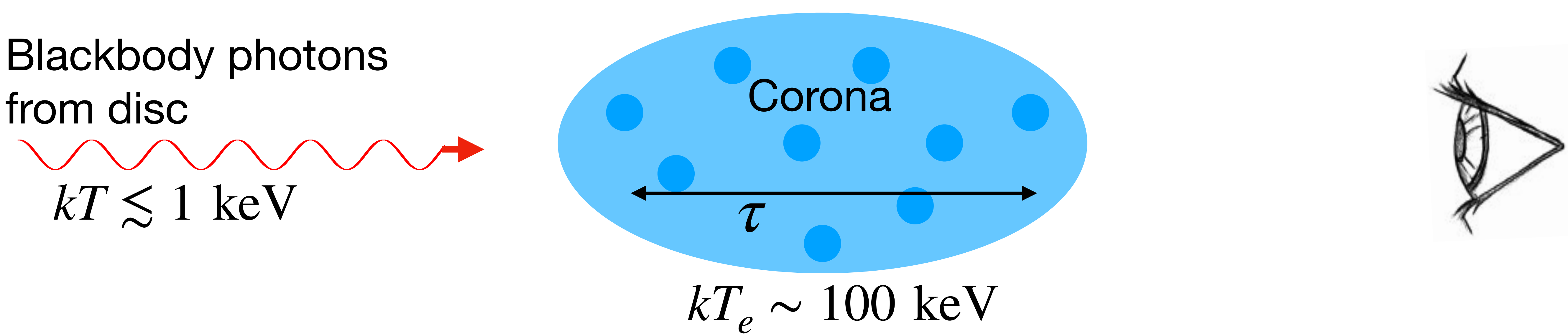
Thermal Comptonisation

$$\Delta\epsilon/\epsilon = 4(kT_e/m_e c^2) - h\nu/m_e c^2$$

- Photons from disc have $h\nu \ll m_e c^2$, therefore:

$$\Delta\epsilon/\epsilon \approx 4(kT_e/m_e c^2)$$

- Same fractional energy gain per scattering, therefore frequency after n scatterings: $\nu = \nu_0(1 + 4kT_e/m_e c^2)^n$
- Probability of staying in corona for n scatterings: $p = (1 - \mathrm{e}^{-\tau})^n \approx \tau^n$
- Number of photons that had n scatterings: $N \approx N_0 \tau^n$



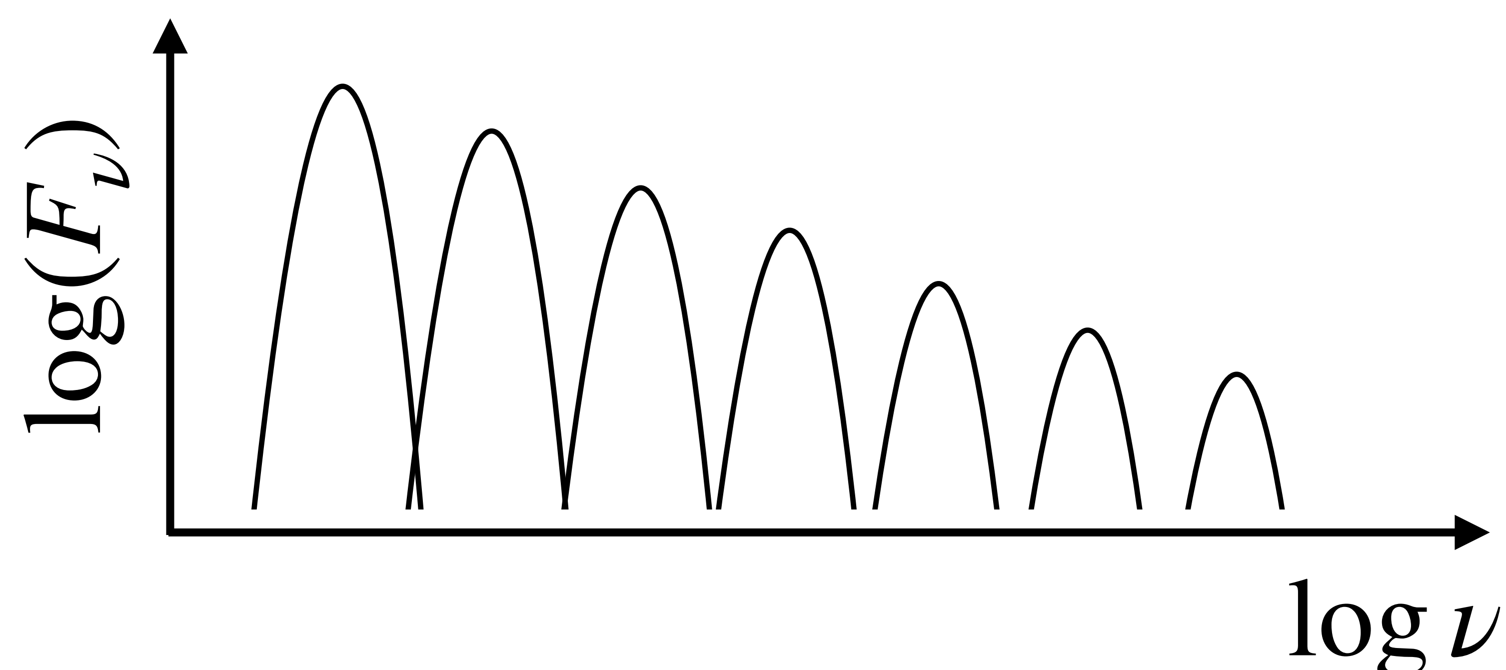
Thermal Comptonisation

Therefore build up power-law spectrum via multiple scatterings

$$\frac{\log(N/N_0)}{\log(\nu/\nu_0)} = \frac{\log \tau}{\log(1 + 4kT_e/m_e c^2)} = -\alpha$$

$$\Longrightarrow$$

Specific flux: $F_\nu \propto \nu^{-\alpha}$ Note that $\log \tau < 0$



Thermal Comptonisation

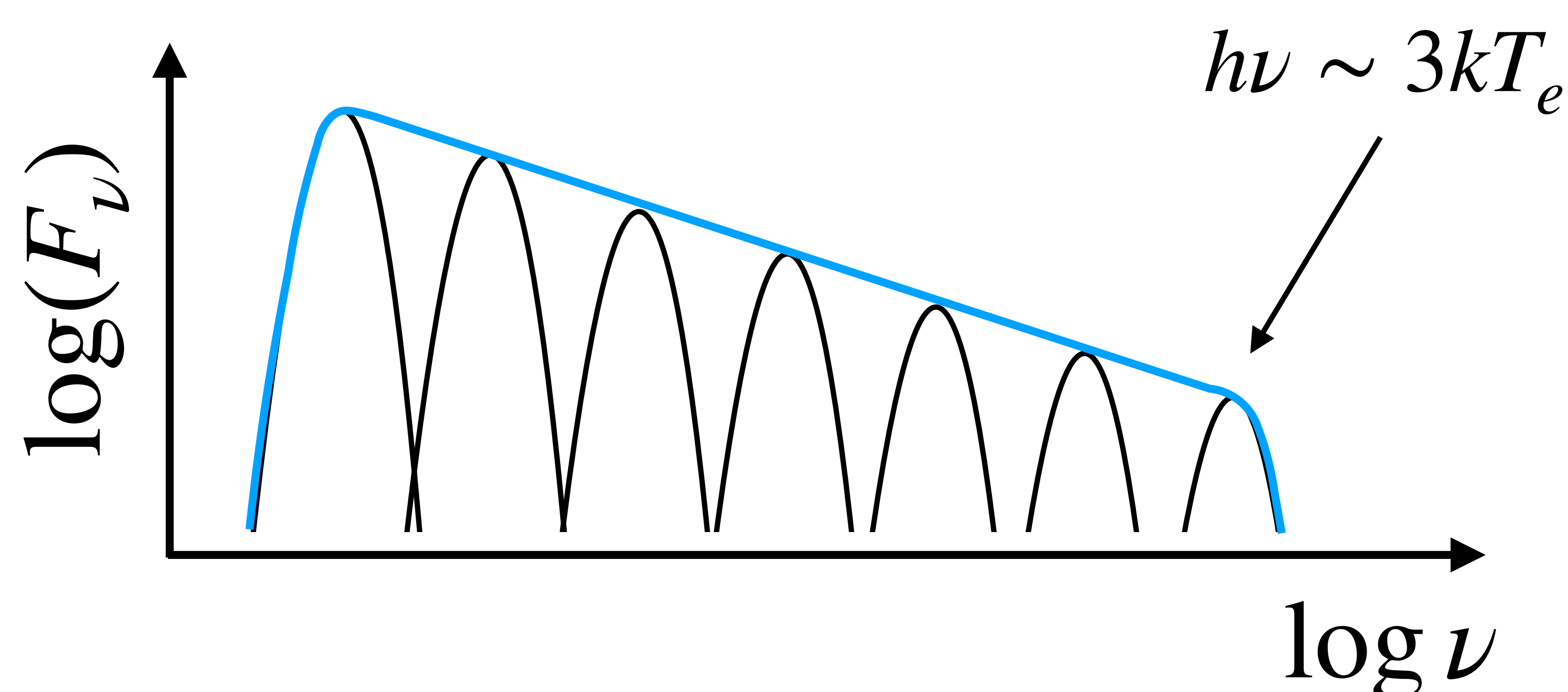
Therefore build up power-law spectrum via multiple scatterings

$$\frac{\log(N/N_0)}{\log(\nu/\nu_0)} = \frac{\log \tau}{\log(1 + 4kT_e/m_e c^2)} = -\alpha$$

$\implies$

Specific flux: $F_\nu \propto \nu^{-\alpha}$ Note that $\log \tau < 0$

- But higher orders will have $h\nu \sim 4kT_e$ and therefore subsequent scatterings don't increase energy further.
- Therefore high frequency break at $h\nu \sim 3kT_e$
- Low frequency break at $h\nu \sim 3kT$

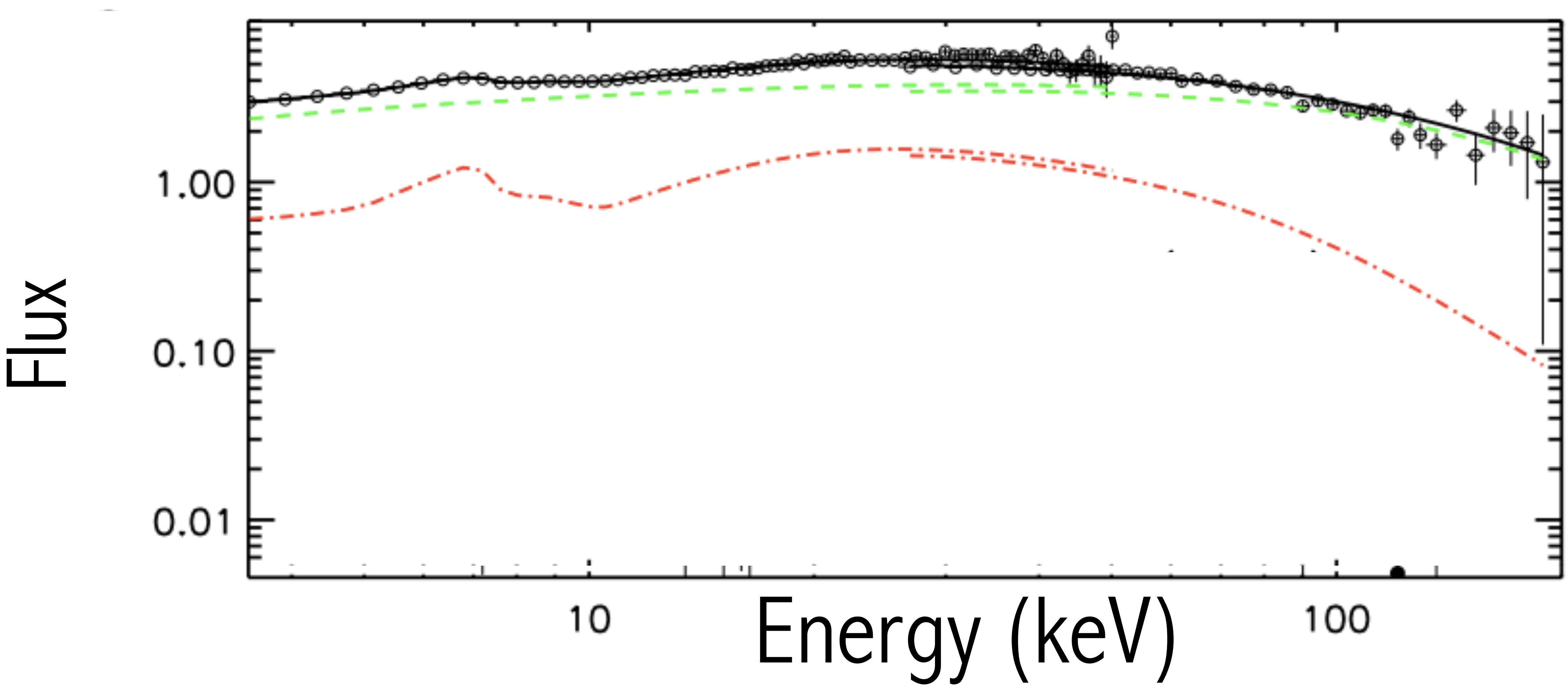


Thermal Comptonisation

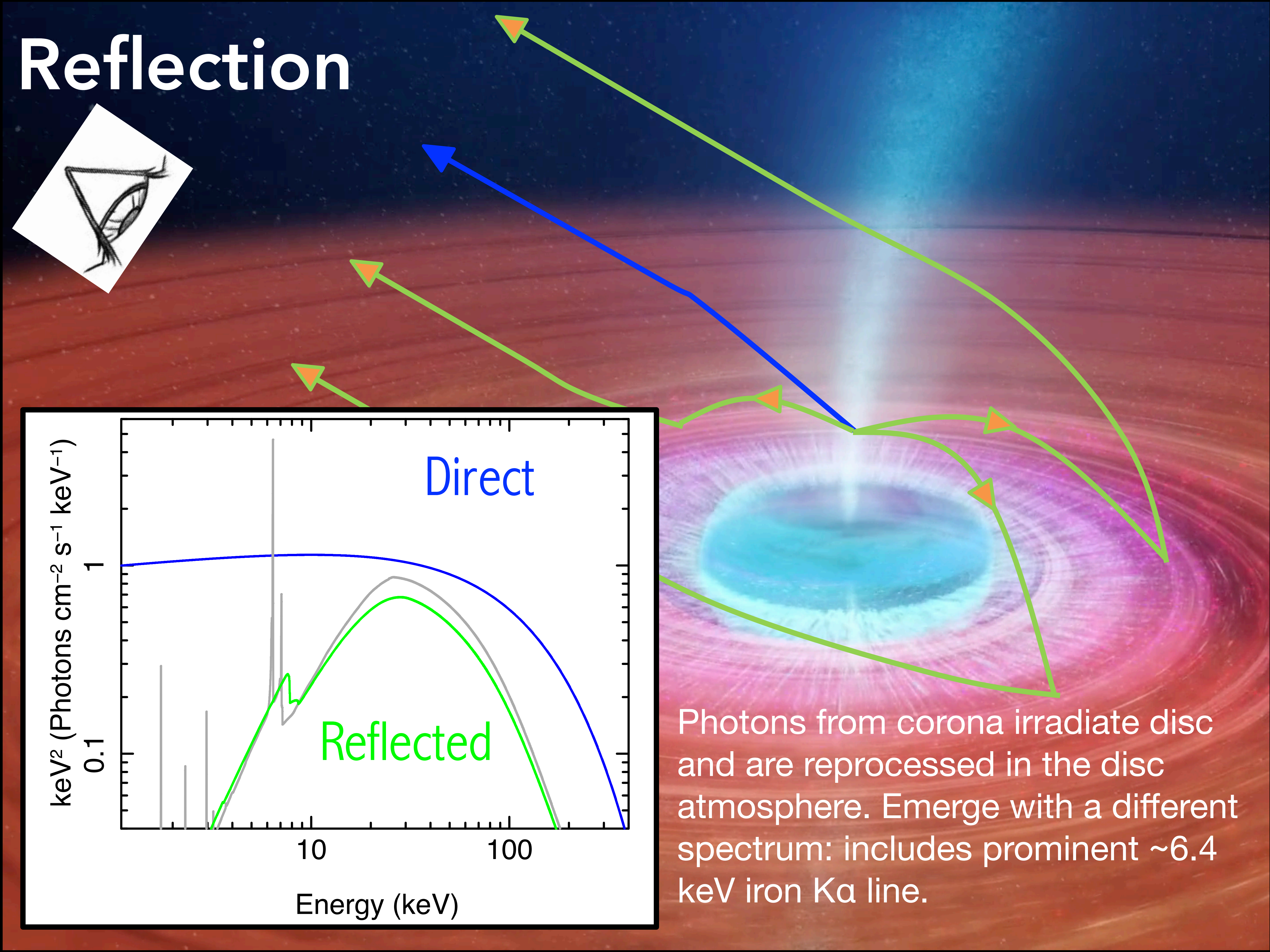
- Thermal Comptonisation can explain hard state XRB spectrum and AGN X-ray spectrum:

$$\tau \sim 1 - 3,\ kT_e \sim 100\ \text{keV}$$

- What about the ~6.4 keV iron line?



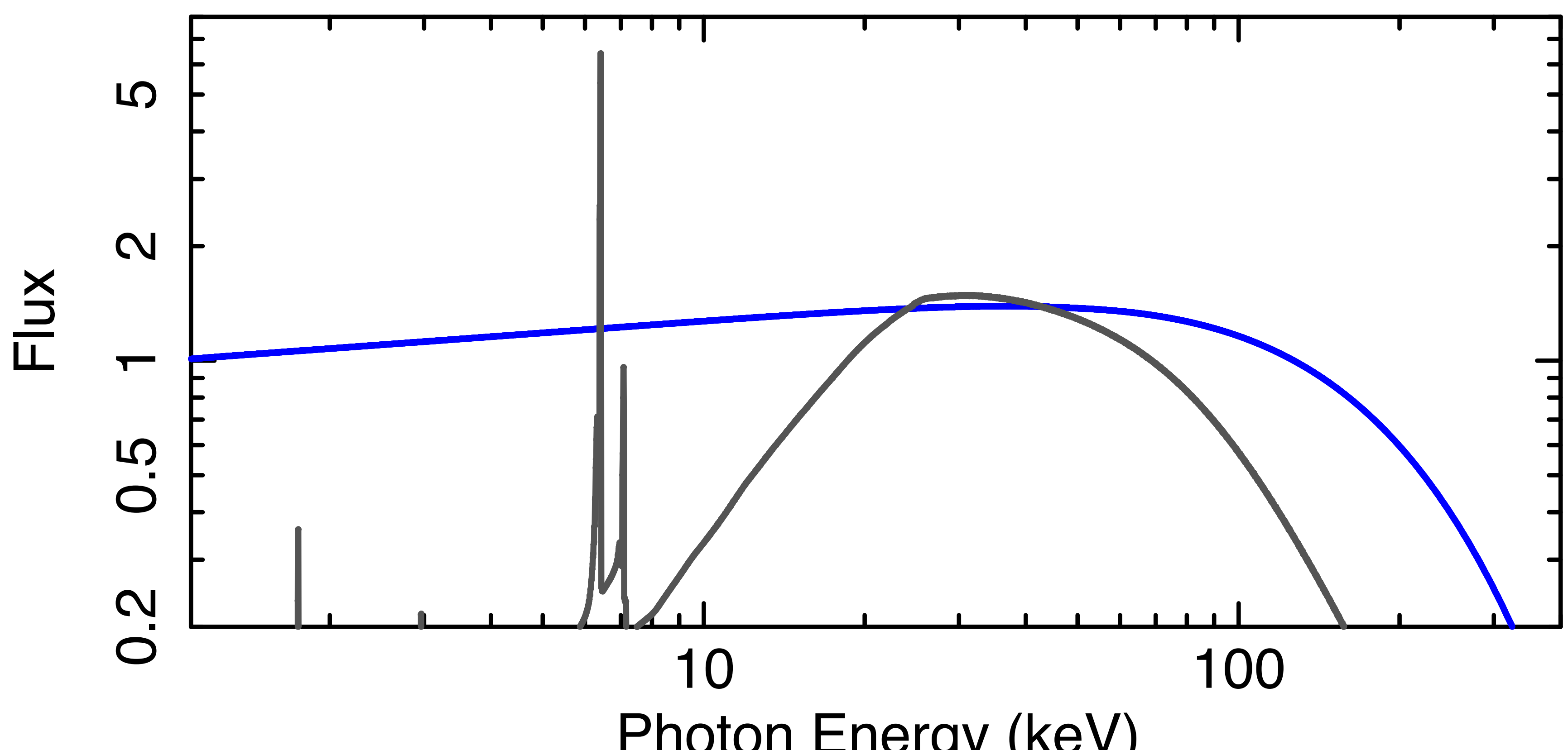
Reflection



Photons from corona irradiate disc and are reprocessed in the disc atmosphere. Emerge with a different spectrum: includes prominent ~6.4 keV iron Kα line.

Reflection spectrum

- In rest frame of disc patch, emergent spectrum includes fluorescence lines, absorption edges and the ~30 keV "Compton hump".
- Absorption cross-section decreases with photon energy, plus iron has highest fluorescence yield of the astrophysical abundant elements.
- Electron scattering dominates at high energies — Compton hump therefore peaks at ~$3kT_e$ of disc electrons, but disc electron temperature set by heating from irradiation.

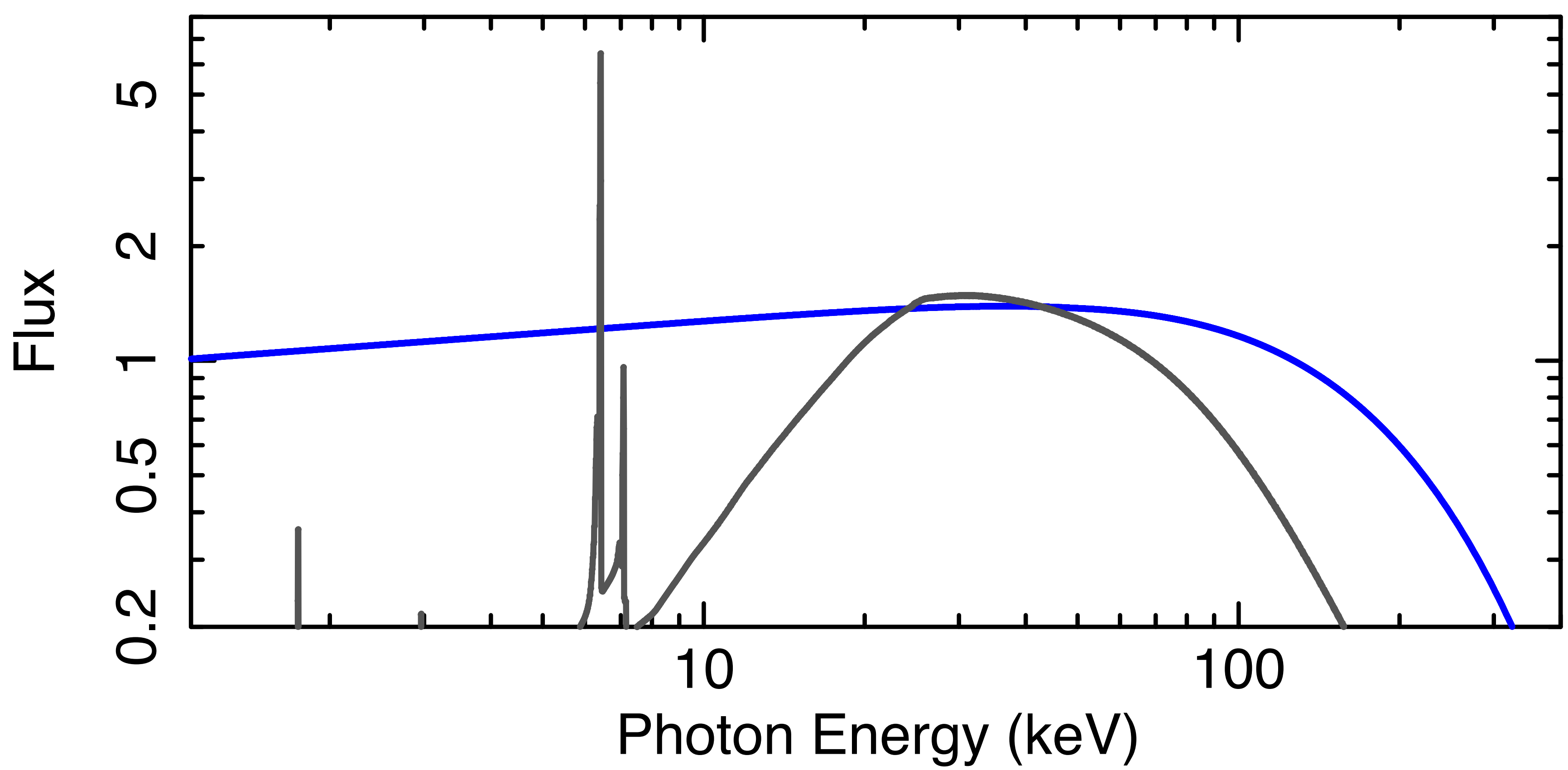


Reflection spectrum

- Ionisation state of the disc important for setting absorption cross-section, fluorescence yields etc

Ionization parameter: $$\xi = \frac{4\pi F_x}{n_e}$$

i.e. more photons shared between less particles => average ionisation state is higher.



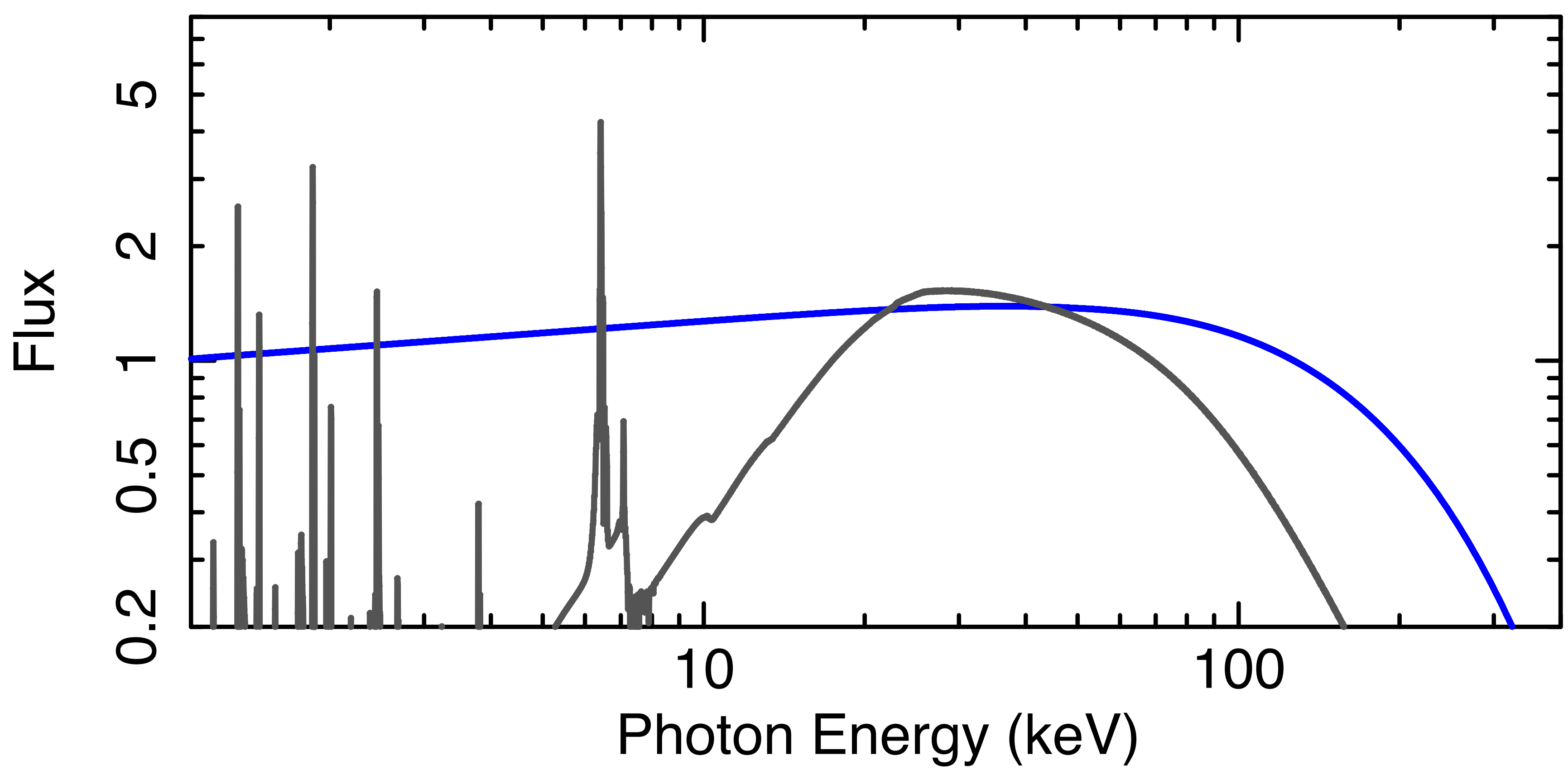
$$\xi = 1$$

Reflection spectrum

- Ionisation state of the disc important for setting absorption cross-section, fluorescence yields etc

Ionization parameter: $$\xi = \frac{4\pi F_x}{n_e}$$

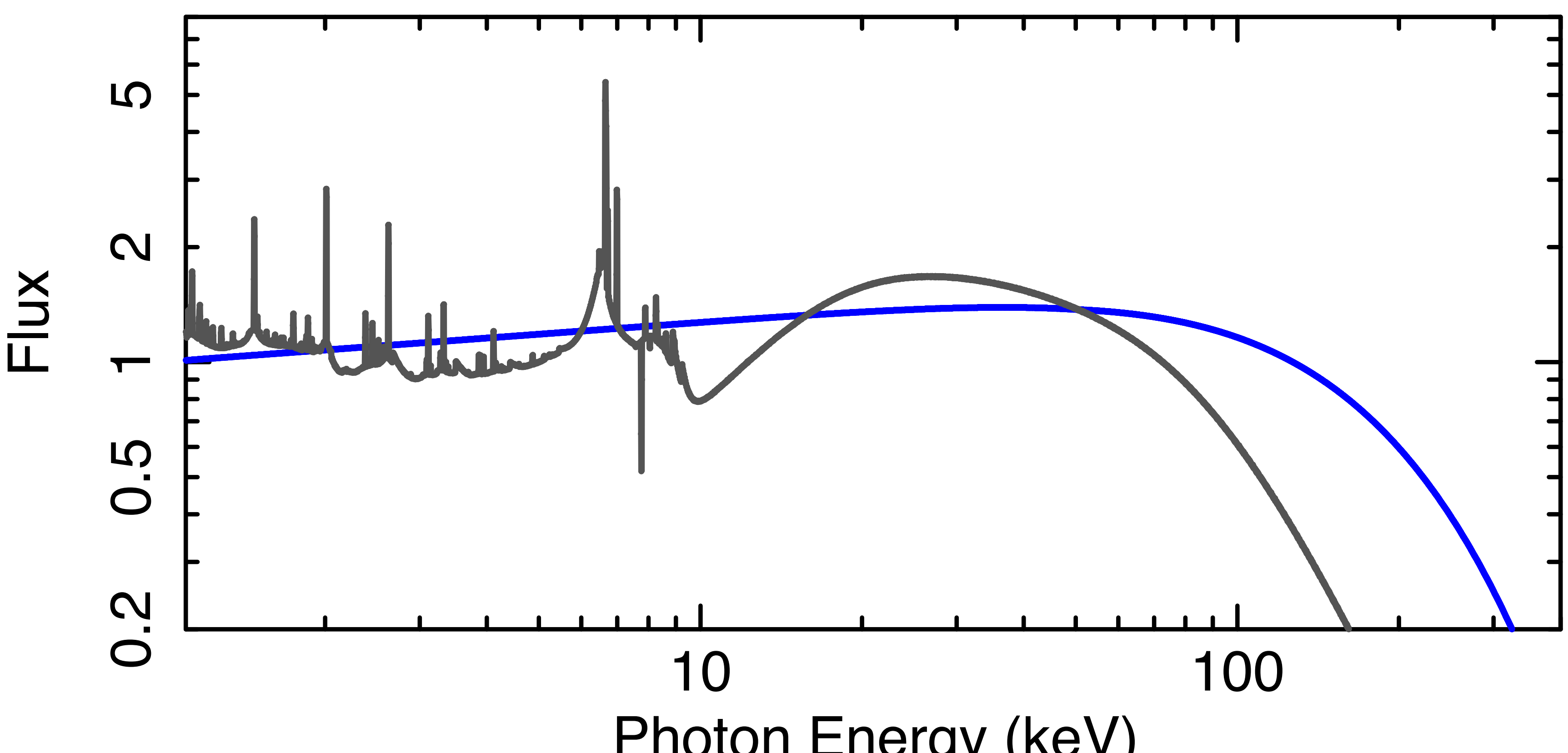
i.e. more photons shared between less particles => average ionisation state is higher.



$$\xi = 100$$

Reflection spectrum

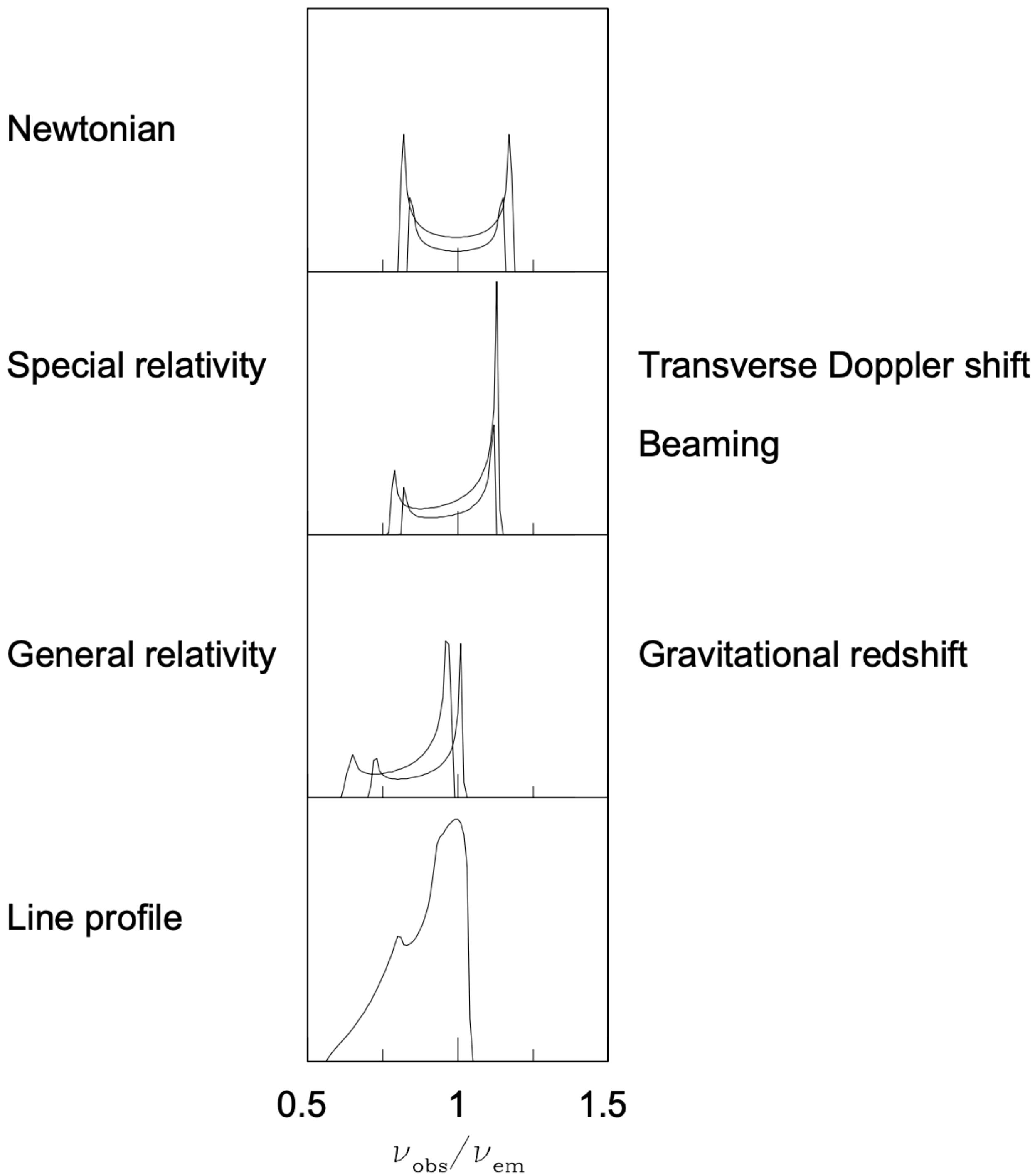
- Ionisation doesn't really affect high energies because they are dominated by electron scattering anyway.

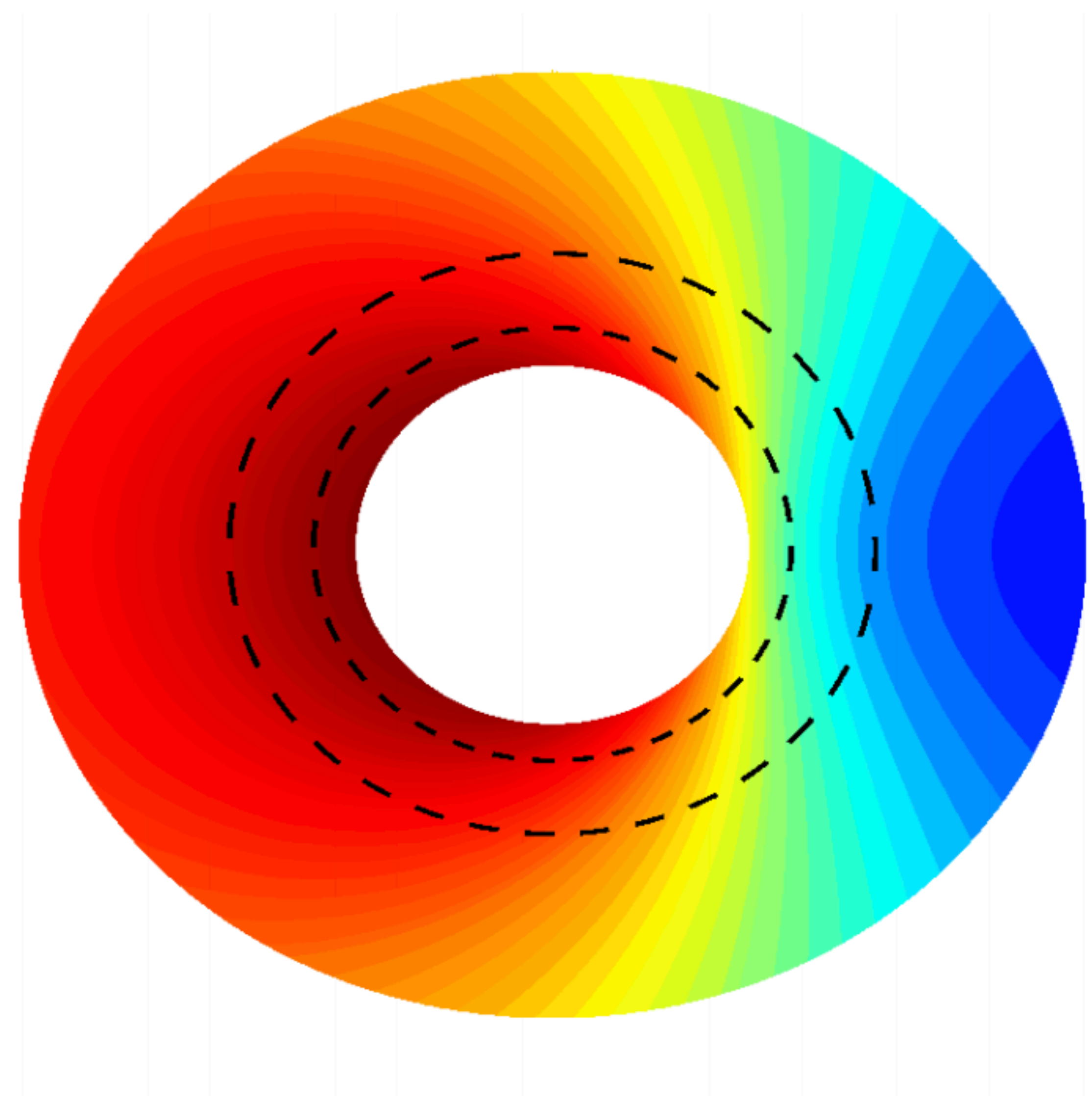


$$\xi = 1000$$

Line profile

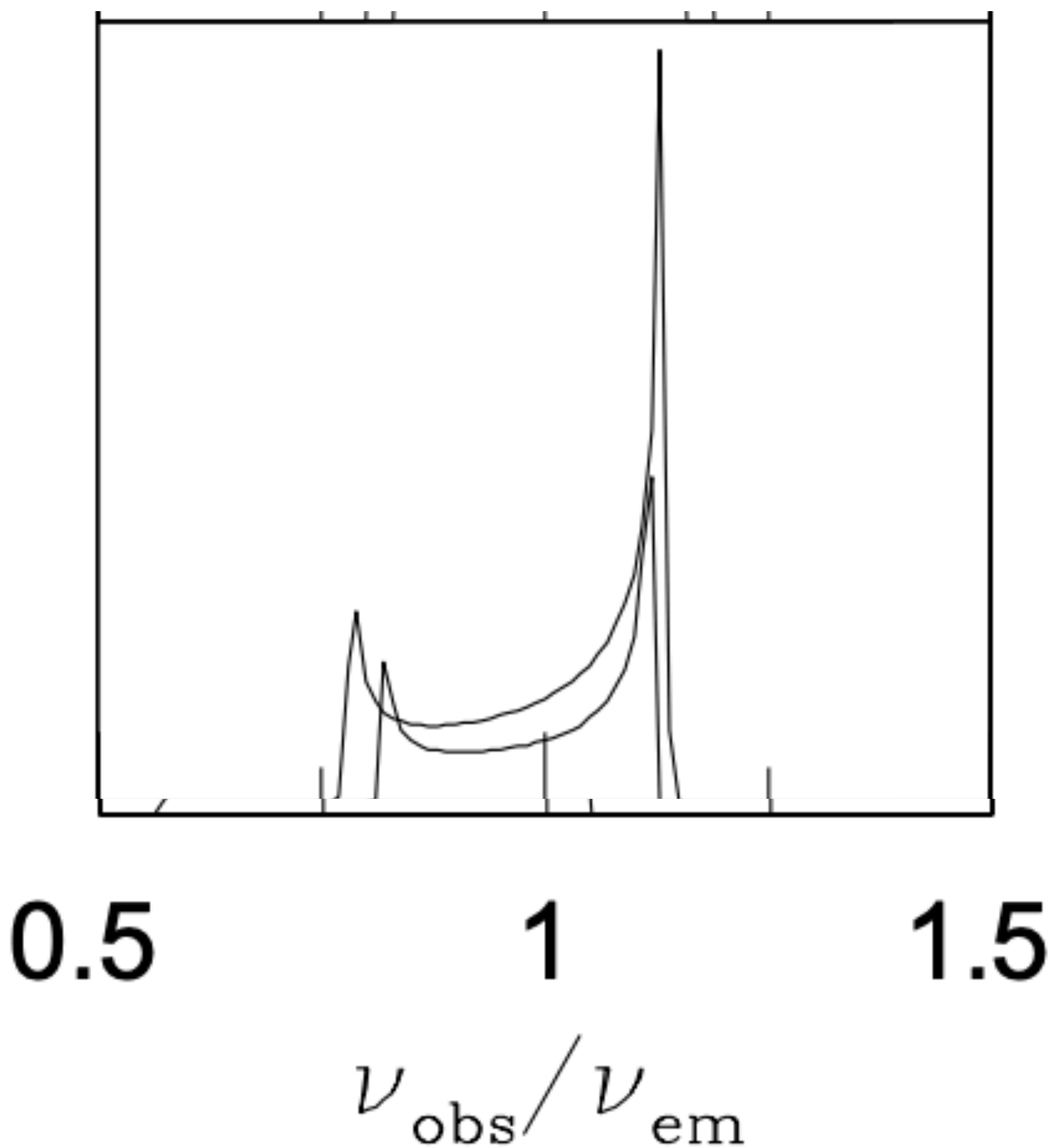
- Spectrum we see is distorted by Doppler shifts and general relativistic effects.
- Iron line narrow, so line profile is diagnostic of disc dynamics.

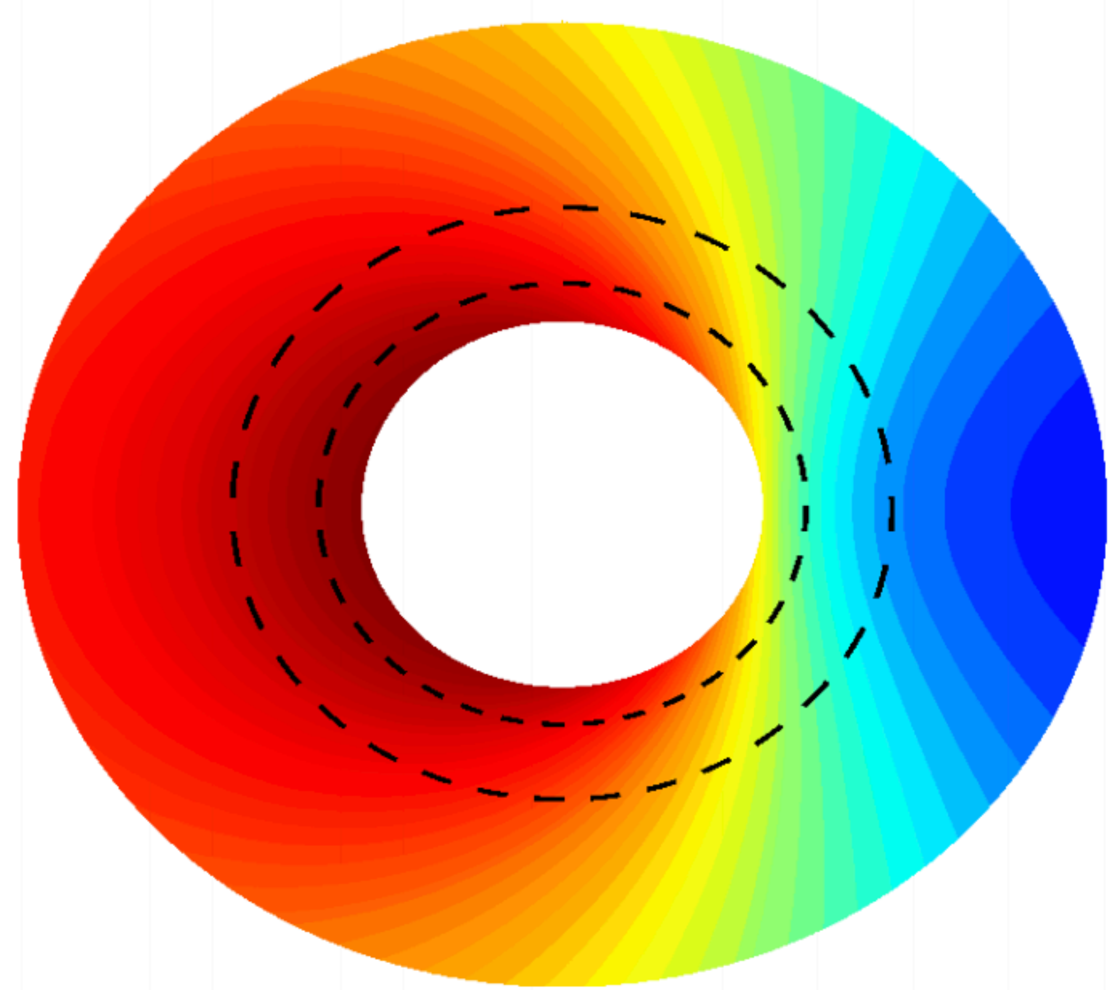




Line profile

- Specific intensity in observer frame: $I_\nu = \delta^3 \, I'_{\nu'}$
- Therefore blue shifted wing of the line is brighter:

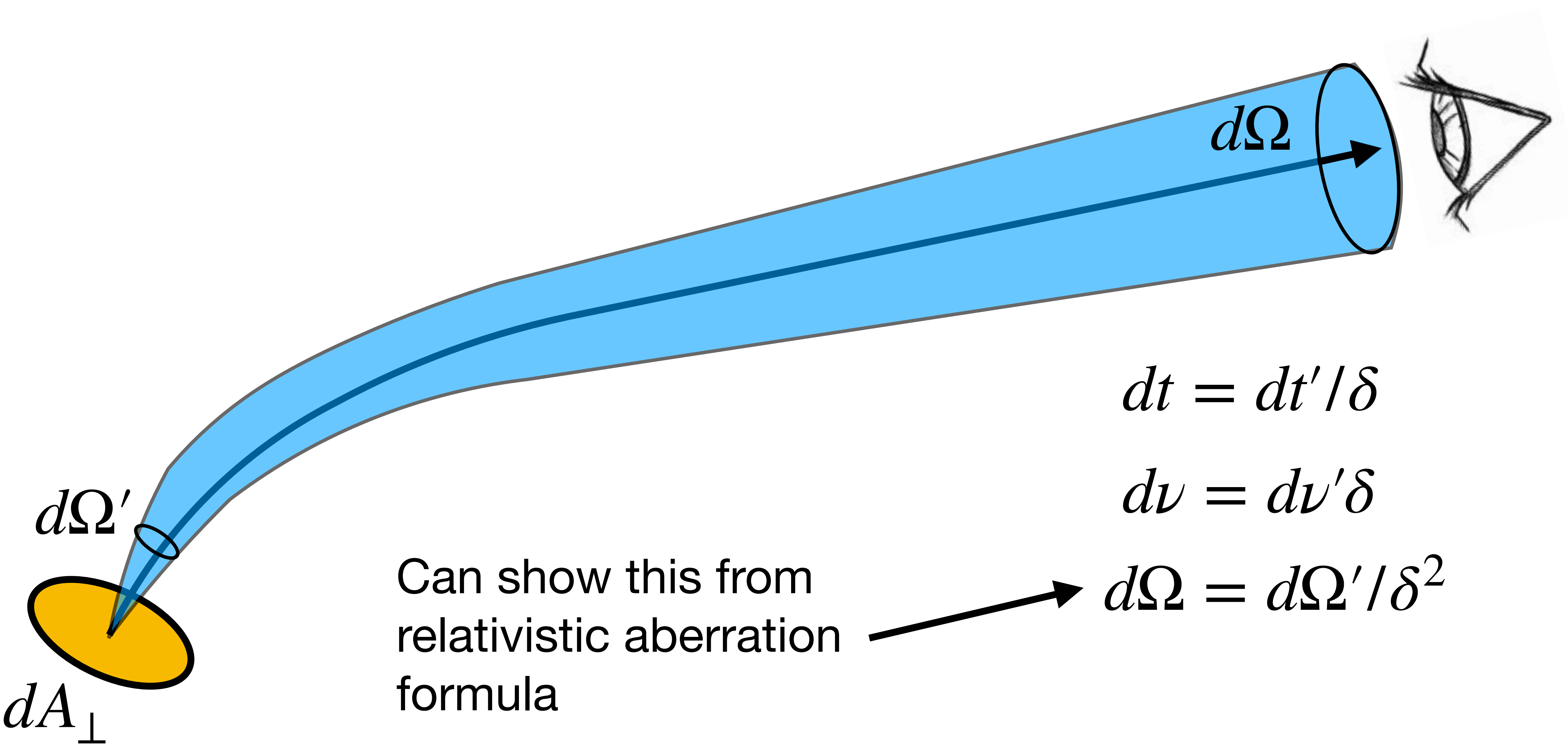




Line profile

- Specific intensity in observer frame: $I_\nu = \delta^3 \ I'_{\nu'}$
- Where do these three factors come from?

$$I_\nu = \frac{h\nu \ dN}{d\nu \ dt \ d\Omega \ dA_\perp}$$



$$dt = dt'/\delta$$

$$d\nu = d\nu'\delta$$

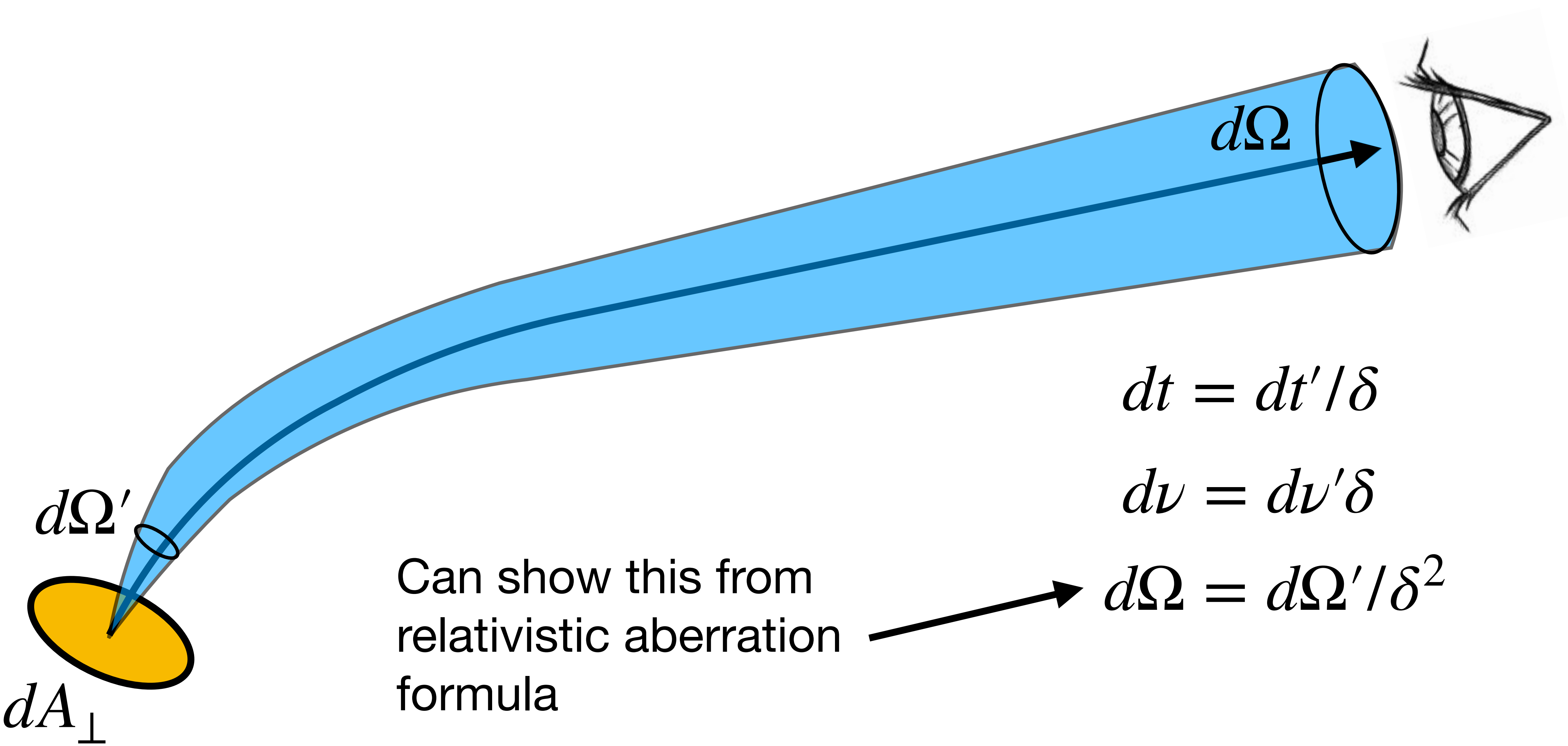
Can show this from relativistic aberration formula

$$d\Omega = d\Omega'/\delta^2$$

Line profile

- Specific intensity in observer frame: $I_\nu = \delta^3 \, I'_{\nu'}$
- Where do these three factors come from?

$$I_\nu = \frac{h\nu \; dN}{d\nu \; dt \; d\Omega \; dA_\perp} = \frac{\delta \; h\nu' \; dN}{\delta \; d\nu' \; dt'/\delta \; d\Omega'/\delta^2 \; dA_\perp} = \delta^3 I'_{\nu'}$$



$$dt = dt'/\delta$$

$$d\nu = d\nu'\delta$$

$$d\Omega = d\Omega'/\delta^2$$

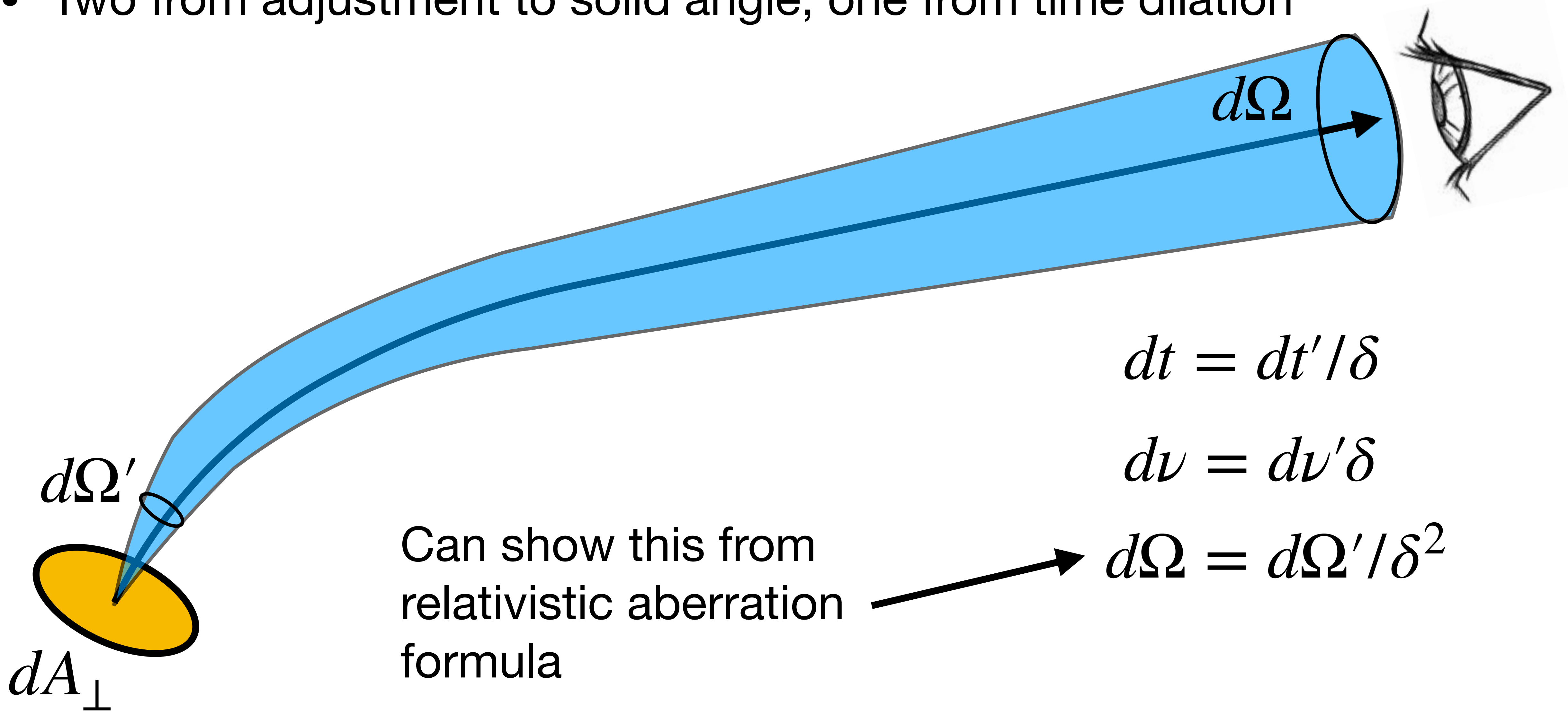
Can show this from relativistic aberration formula

Line profile

- Specific intensity in observer frame: $I_\nu = \delta^3 \; I'_{\nu'}$
- Where do these three factors come from?

$$I_\nu = \frac{h\nu \; dN}{d\nu \; dt \; d\Omega \; dA_\perp} = \frac{\delta \; h\nu' \; dN}{\delta \; d\nu' \; dt'/\delta \; d\Omega'/\delta^2 \; dA_\perp} = \delta^3 I'_{\nu'}$$

- Two from adjustment to solid angle, one from time dilation



$$dt = dt'/\delta$$

$$d\nu = d\nu'\delta$$

Can show this from relativistic aberration formula

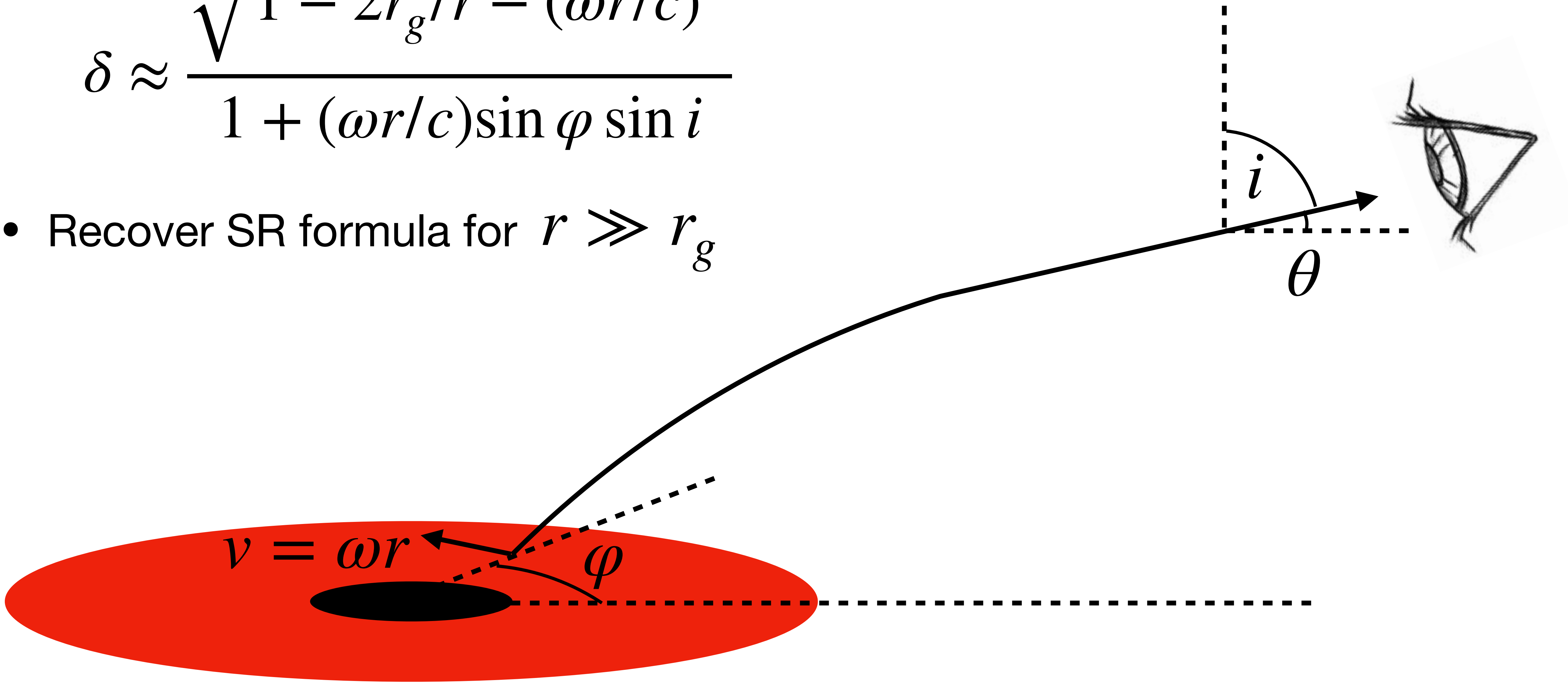
$$d\Omega = d\Omega'/\delta^2$$

Iron Line Profile

- In GR, δ includes gravitational redshift as well as Doppler shifts: photon loses energy leaving the gravitational potential well.
- For orbital angular frequency ω, in the Schwarzschild metric (non-spinning black hole) and ignoring light-bending:

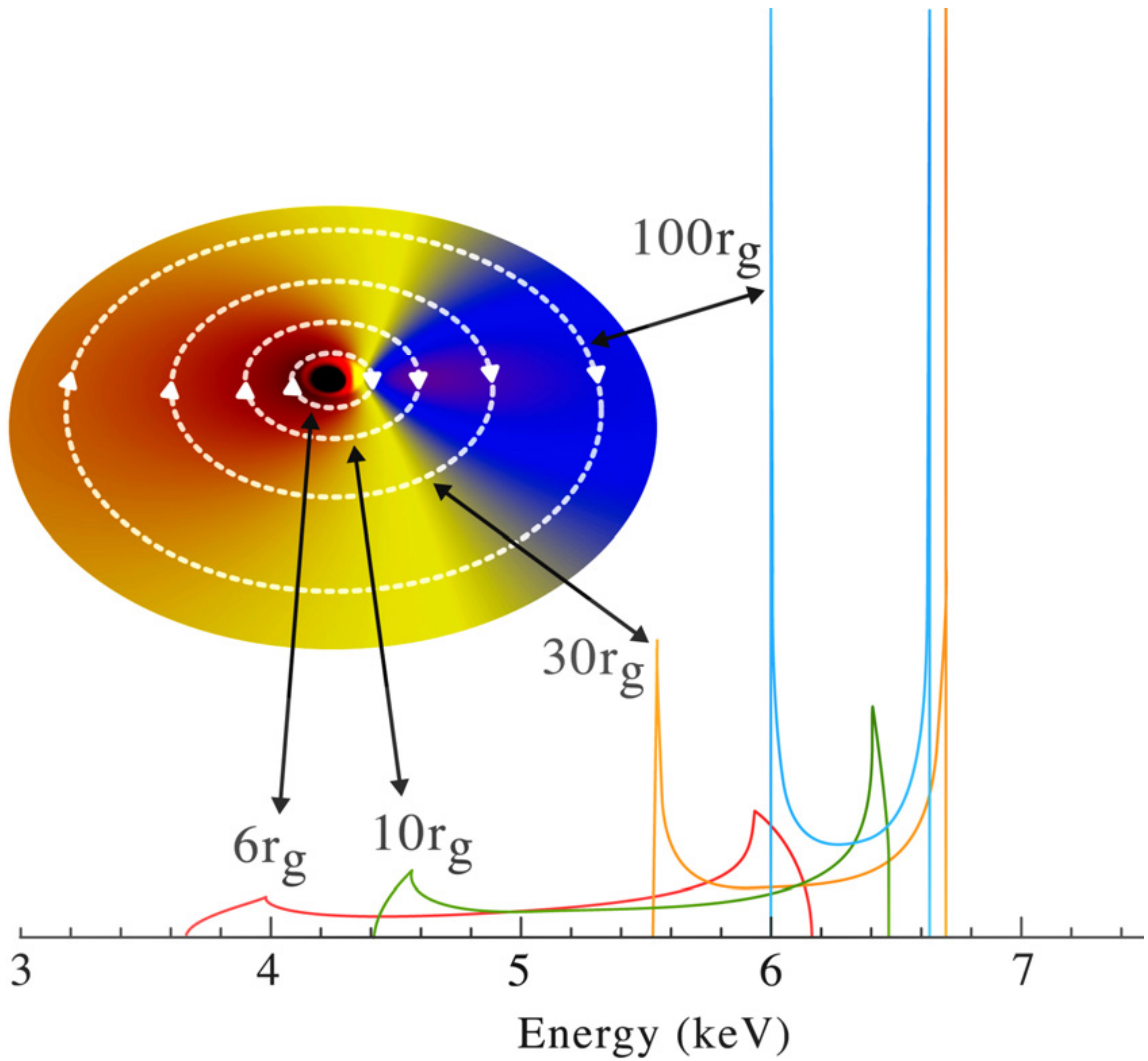
$$\delta \approx \frac{\sqrt{1 - 2r_g/r - (\omega r/c)^2}}{1 + (\omega r/c)\sin\varphi \sin i}$$

- Recover SR formula for $r \gg r_g$



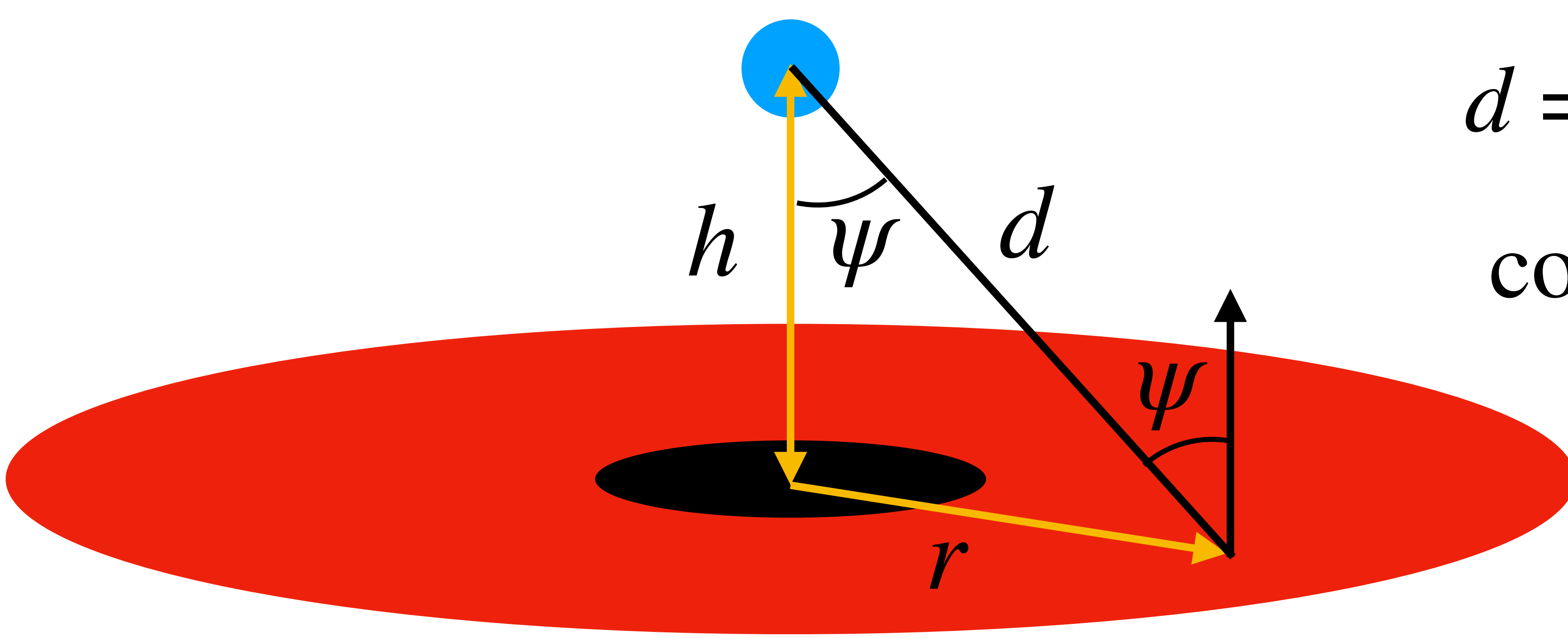
Iron Line Profile

- Integrating flux along φ, obtain line profile from each disc annulus.
- But what is the r-dependence of the reflected flux?
- Can either parameterise (e.g. $I'_{\nu'}(r) \propto r^{-q}$) or make assumption about coronal geometry.



Iron Line Profile

- Simplest possible model is "lamppost" model: isotropically emitting point-like corona with luminosity L_0.
- For illustration, ignore relativistic effects.



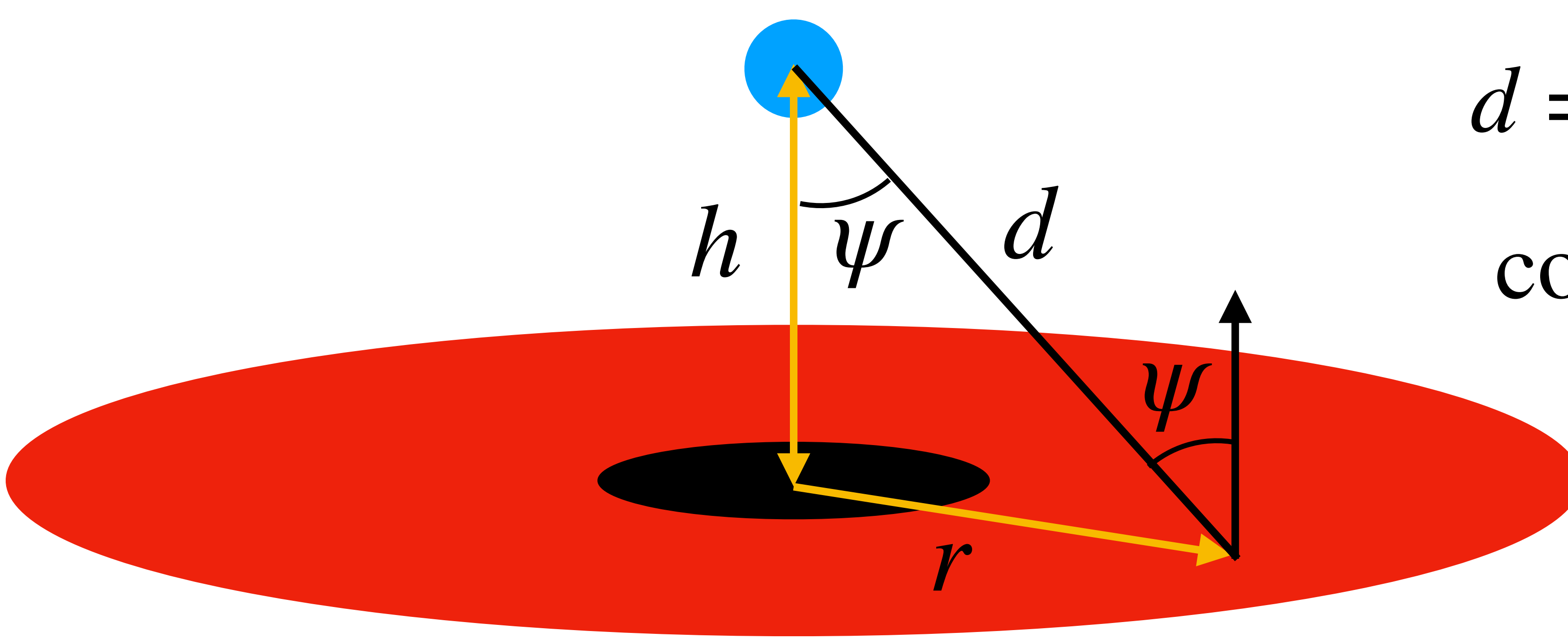
$$d = (h^2 + r^2)^{1/2}$$

$$\cos\psi = h/d$$

Iron Line Profile

- Simplest possible model is “lamppost” model: isotropically emitting point-like corona with luminosity L_0.
- For illustration, ignore relativistic effects.
- Luminosity crossing disc patch at r with area dA:

$$dL = L_0 \frac{dA \cos\psi}{4\pi d^2}$$



$$d = (h^2 + r^2)^{1/2}$$

$$\cos\psi = h/d$$

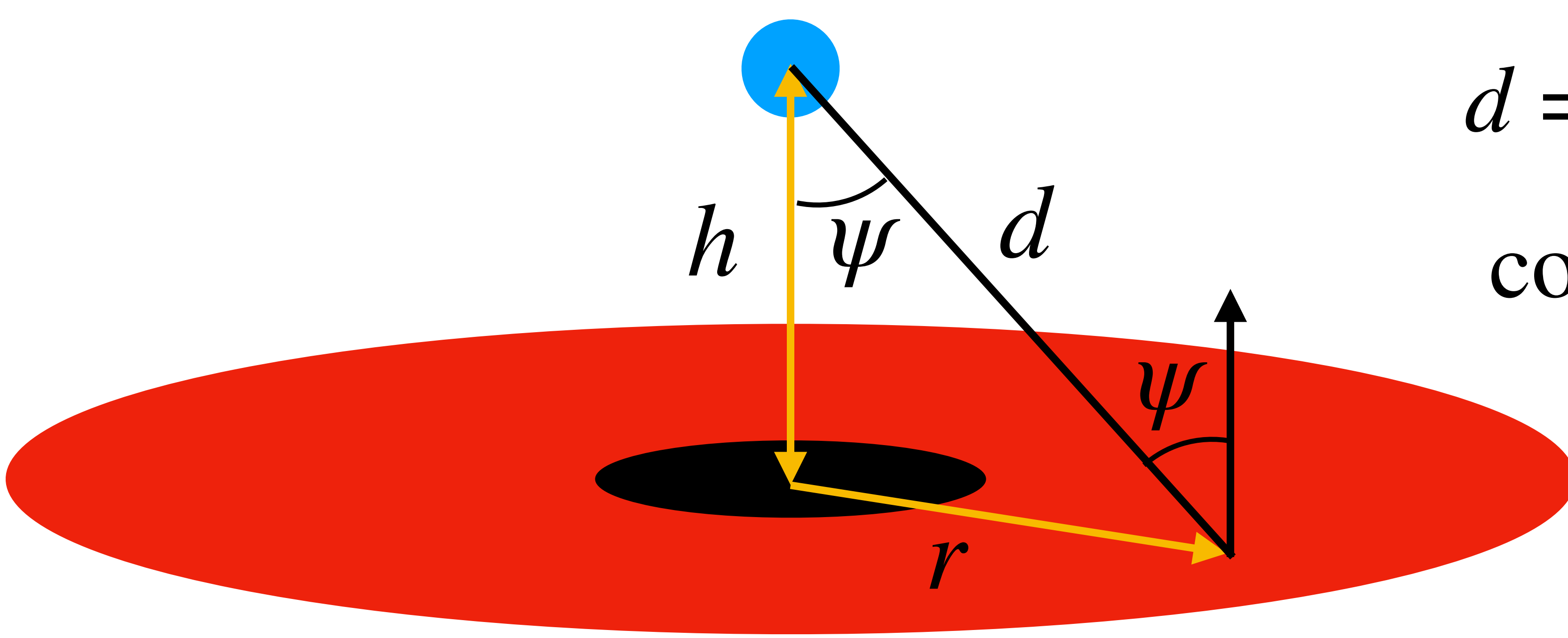
Iron Line Profile

- Simplest possible model is "lamppost" model: isotropically emitting point-like corona with luminosity L_0.
- For illustration, ignore relativistic effects.
- Luminosity crossing disc patch at r with area dA:

$$dL = L_0 \frac{dA \cos\psi}{4\pi d^2}$$

- Flux crossing disc patch through it's upper surface:

$$F(r) = \frac{dL}{dA} = L_0 \frac{\cos\psi}{4\pi d^2} = L_0 \frac{h/(4\pi)}{(h^2 + r^2)^{3/2}}$$

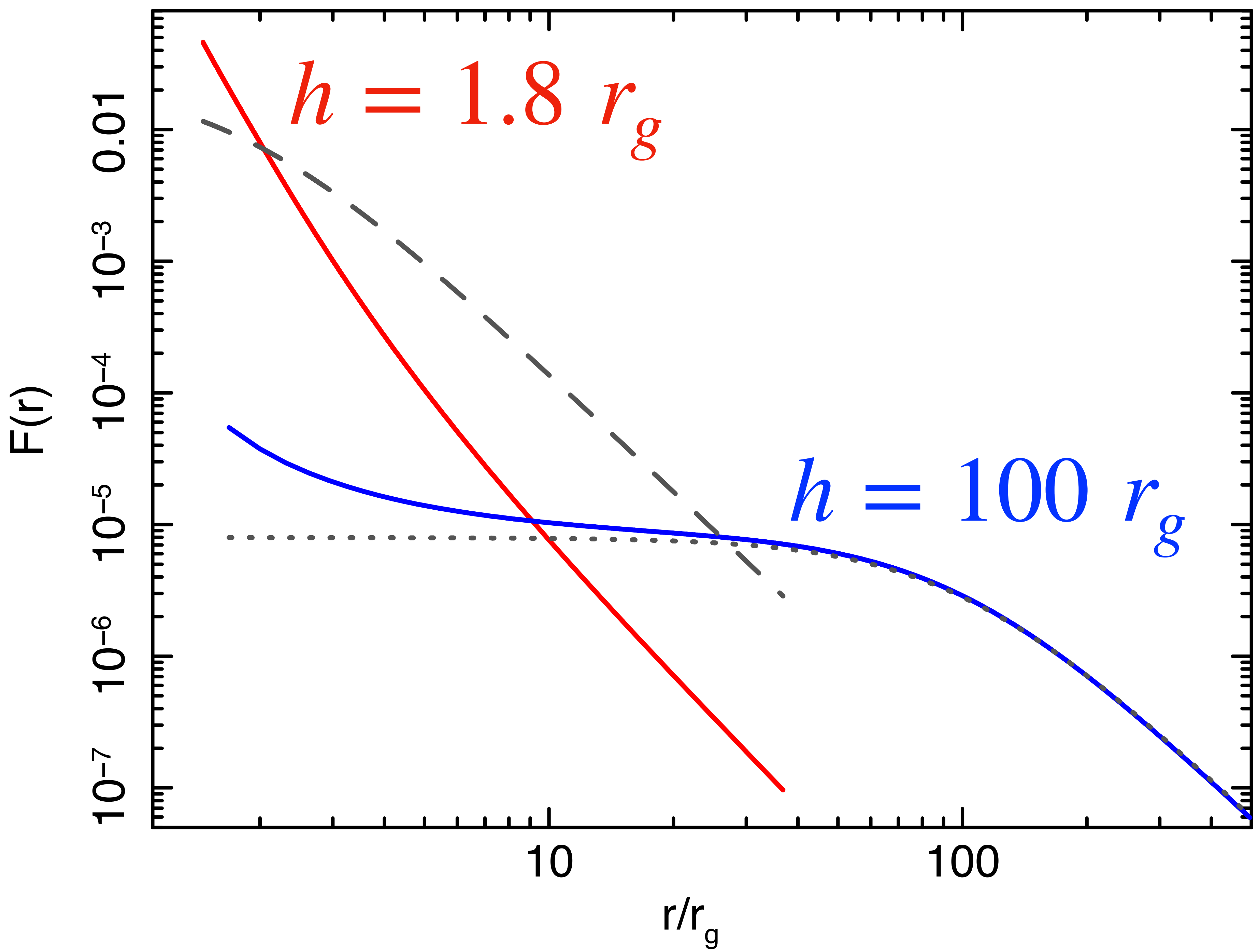


$$d = (h^2 + r^2)^{1/2}$$

$$\cos\psi = h/d$$

Iron Line Profile

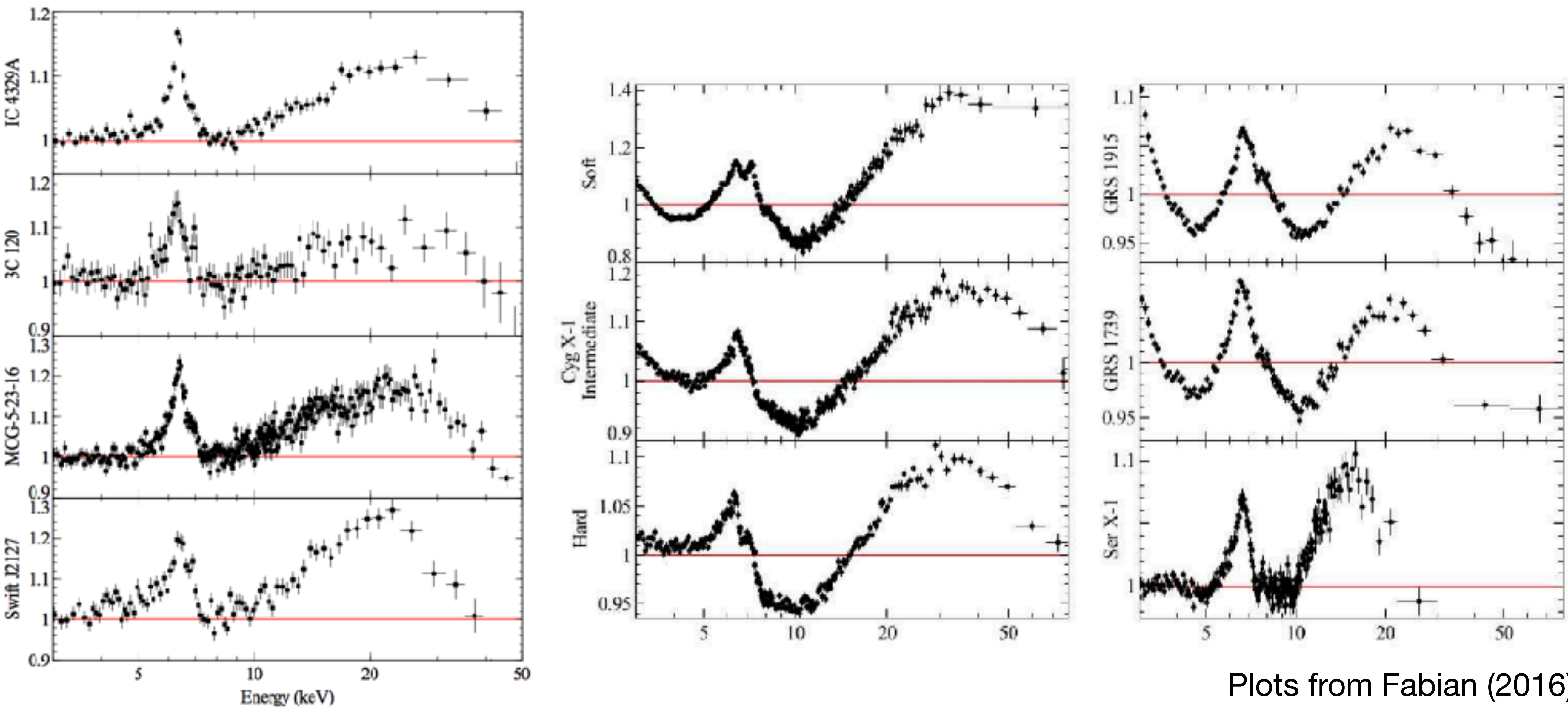
- Light-bending and other GR effects make flux more centrally peaked.
- Most extreme for low source
- Grey lines ignore GR: $h=1.8\ r_g$ (dashed), $h=100\ r_g$ (dotted).



Observations

AGN

X-ray binaries



Plots from Fabian (2016)

We see relativistically blurred reflection features for accreting black holes and neutron stars.

Observations

- Can use observed line profile to measure r_{in}/r_g, and therefore get estimate of black hole spin if r_{in}=ISCO!
- Lots of systematics though, particularly for AGN!

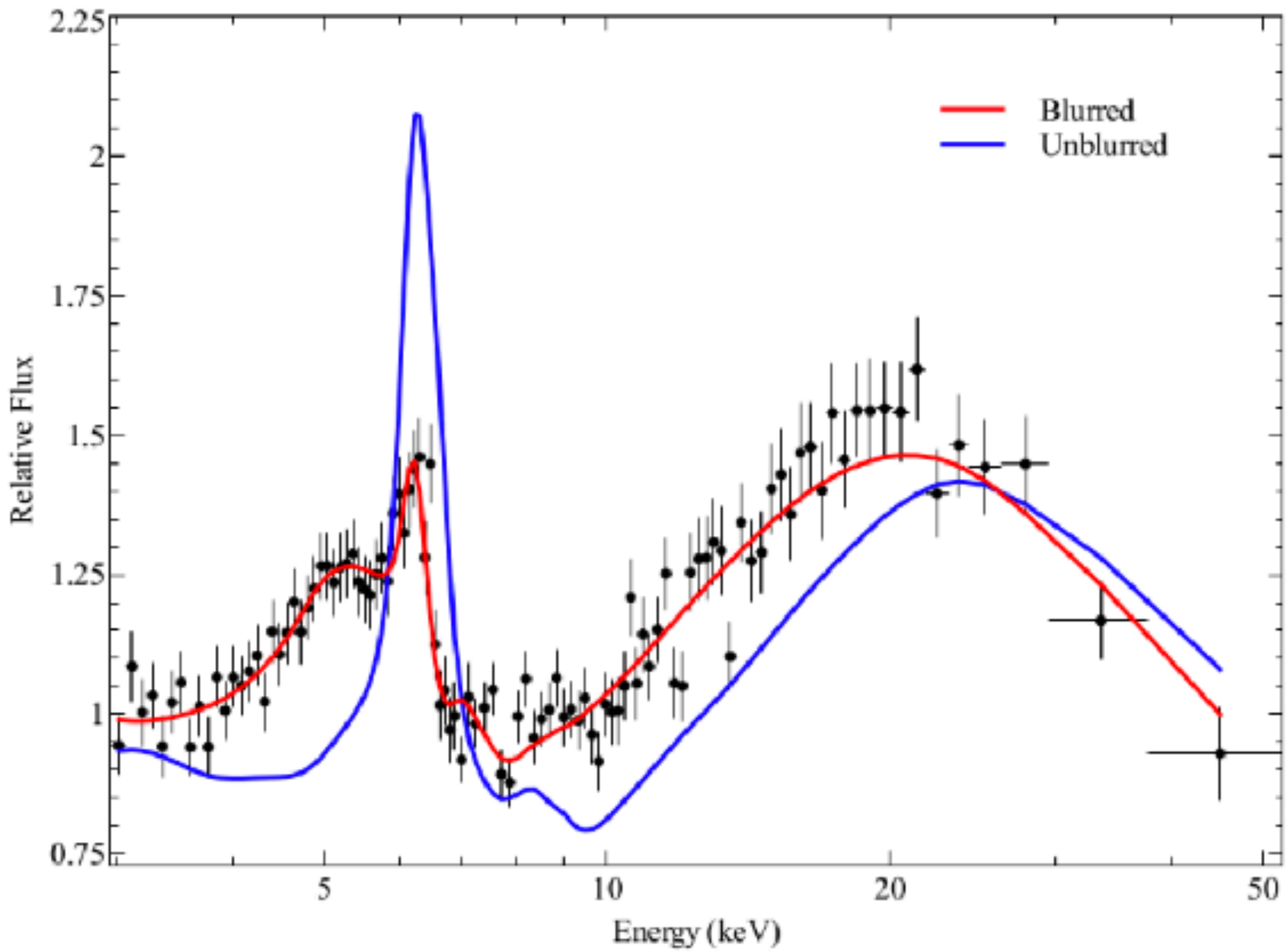
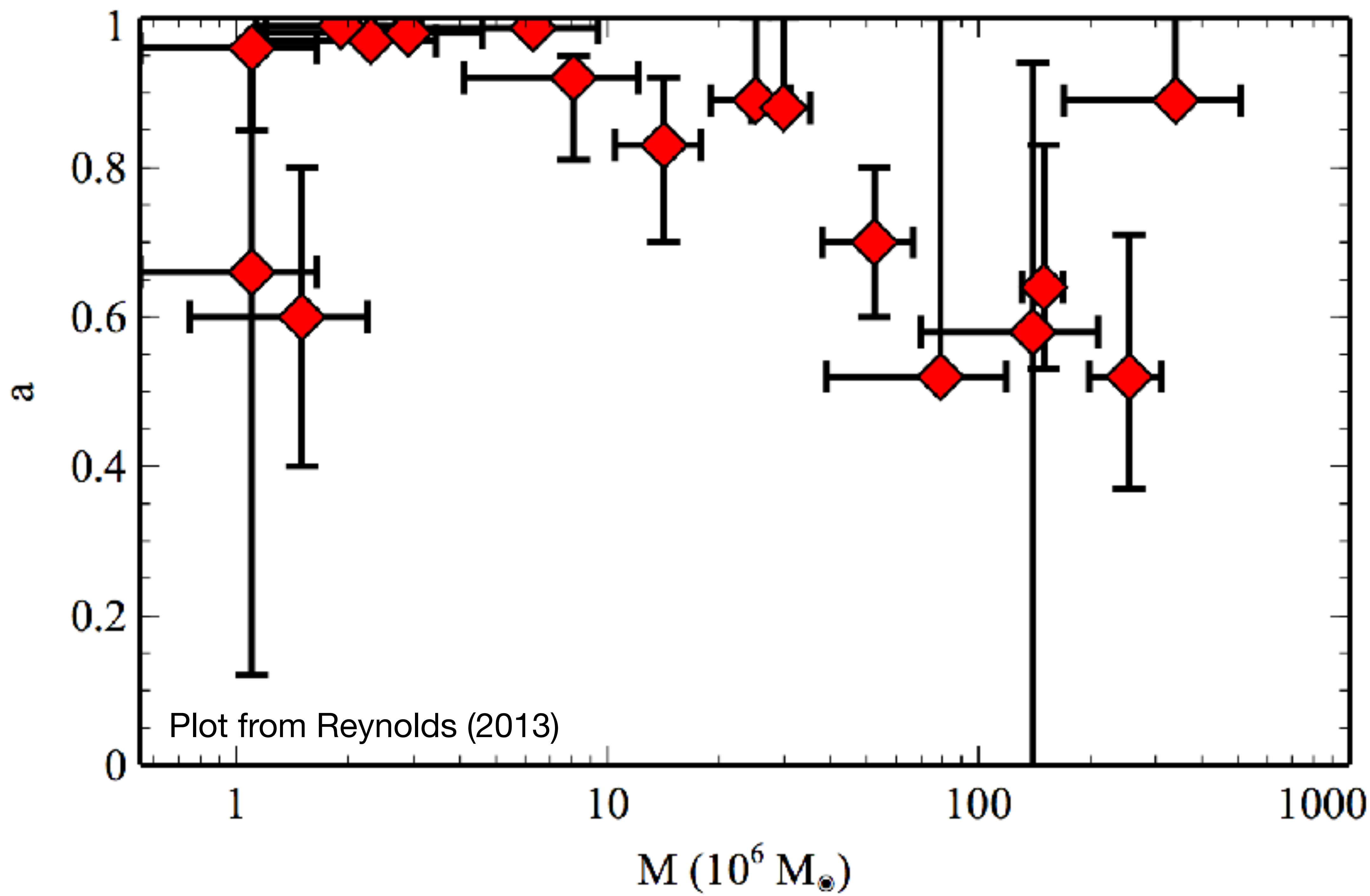


Fig. 5 Blurred and unblurred model spectra overplotted on NuSTAR data from the low state of Mkn335 (Parker et al 2014).

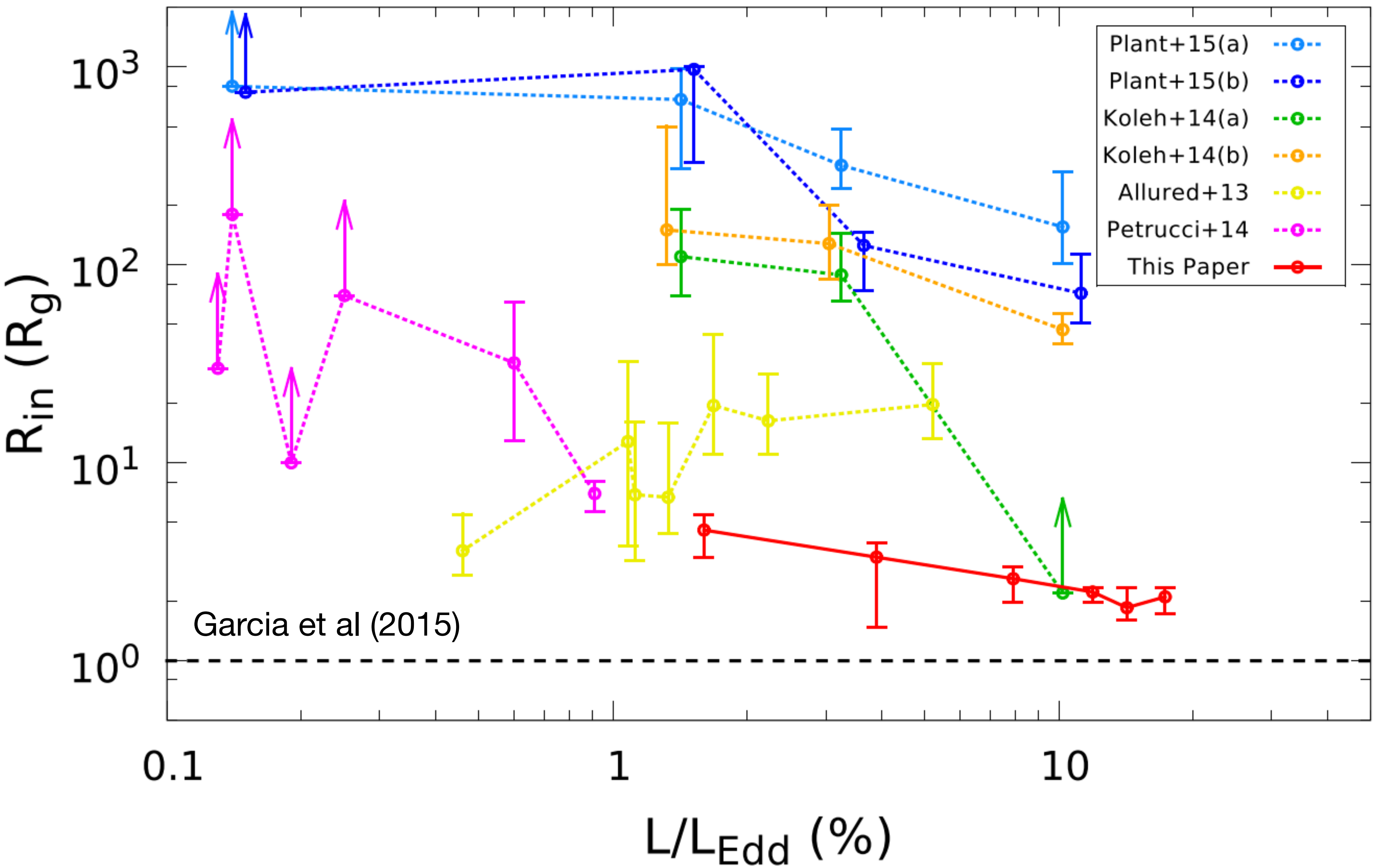
Observations

- Most AGN studies infer high spin — but higher spin black holes lead to brighter AGN, so there is a selection effect!



Observations

- In X-ray binaries, the disc seems to move in from the lowest hard states to the soft state, but lots of systematics so we don't know when the disc inner radius hits the ISCO.



Truncated Disc Model