Ionized winds driven away from black holes

(SPEX/PION exercise)

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Context

This document is used to learn the `SPEX` and `pion` (photoionization equilibrium) plasma model. The `pion` model can be used to measure the physical properties (e.g., hydrogen column density, ionization parameter, wind velocity) of the ionized winds.

The thread used to guide this exercise and the data files are in the cloud drive. Besides, The progressing and resulting files of this exercise are stored in SPEX-exercise.

Read and plot the spectrum

This thread is used to explore the different x- and y-axis units. The useful information to draw the figures: plotting reference, especially axis units and scales and asciidump file format.

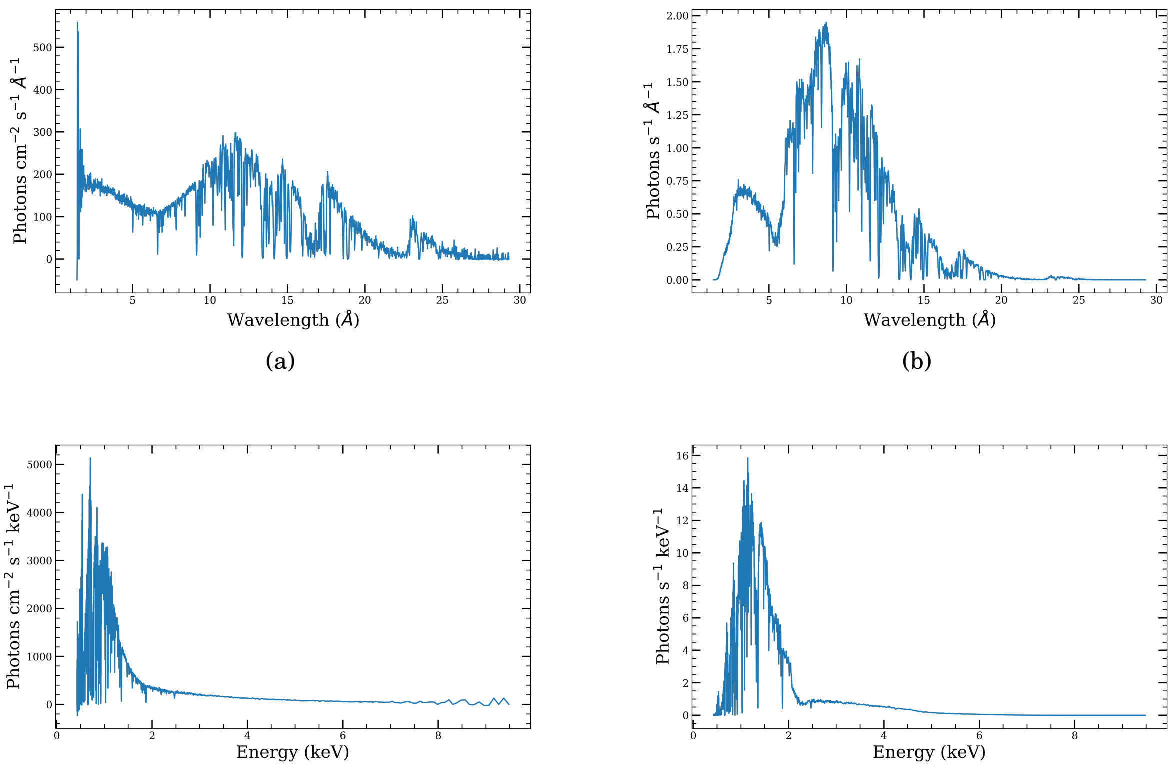


Figure 1: The data figure is shown in different x- and y-axis units. (a) The x-axis unit is $\mathrm{\AA}$ and the y-axis unit is $\mathrm{counts\ m^{-2}\ s^{-1}\ \AA^{-1}}$; (b) The x-axis unit is $\mathrm{\AA}$ and the y-axis unit is $\mathrm{counts\ s^{-1}\ \AA^{-1}}$; (c) The x-axis unit is keV and the y-axis unit is $\mathrm{counts\ m^{-2}\ s^{-1}\ keV^{-1}}$; (d) The x-axis unit is keV and the y-axis unit is $\mathrm{counts\ s^{-1}\ keV^{-1}}$.

Question: What are the disadvantages of plotting the spectrum in units of counts s^{-1} $\mathrm{\AA}^{-1}$ or counts s^{-1} keV^{-1}?

When the unit of the y-axis is counts s^{-1} $\mathrm{\AA}^{-1}$ or counts s^{-1} keV^{-1}, we should take care of the effective area of the specific telescope. It is inconvenient to compare the data from different telescopes.
JMAO: There might be more ...

Continuum model set-up

For this spectrum, we want to use a model including `pow`, `reds`, and `hot` components:

$$\text{model} = \texttt{hot} \times \texttt{reds} \times \texttt{pow} \tag{1}$$

hot

`hot` is a collisional ionization equilibrium (CIE) absorption model component, which can be used to calculate the transmission of plasma in CIE with cosmic abundances. It may be useful in situations where photoionization is relatively unimportant but the source has a non-negligible optical depth. By default, this component mimics the transmission of a neutral plasma by setting the default temperature to 10^{-3} eV (10^{-6} keV).

The main parameters:

`nh`: Hydrogen column density in 10^{28} m^{-2}. Default value: 10^{-4} (corresponding to 10^{24} m^{-2}, a typical value at low Galactic latitudes).

`t`: The electron temperature T_{e} in keV. Default value: 10^{-6} keV. Other parameters can be seen in hot.

reds

`reds` is a redshift model component. This multiplicative model applies a redshift z to an arbitrary additive component. The parameters are shown in reds. `z` is the redshift. Redshifts are positive, blueshifts are negative. It can be used to set the cosmological redshift or velocity redshift

pow

`pow` is a power-law model component that forms part of the continuum. the formula is:

$$F(E) = AE^{-\Gamma}e^{\eta(E)} \tag{2}$$

`norm`, one of the parameters in this component, corresponds to A, in units of 10^{44} ph s^{-1} keV^{-1} at 1 keV. Default value: 1.

`gamm` corresponds to Γ. Default value: 2. Other parameters can be seen in pow.

Fit the hard X-ray data with the power-law model

```
bash > cat 5-2-1.com
data inst_amo1 bhiw_amo1
plot device xs

ignore 5:30 unit ang # ignore the data above 5 angstroms.
dist 0.01158 z # set the distance
comp reds
par 1 1 z value 0.01158
par 1 1 z status f
comp hot
par 1 2 nh value 8.5e-3
par 1 2 nh status f
par 1 2 t s f
```

```
comp pow
par 1 3 norm val 5e8
com rel 3 1,2
cal
plot type data
plot ux ang
plot uy fang
pl
fit
pl

SPEX > log exe 5-2-1
```

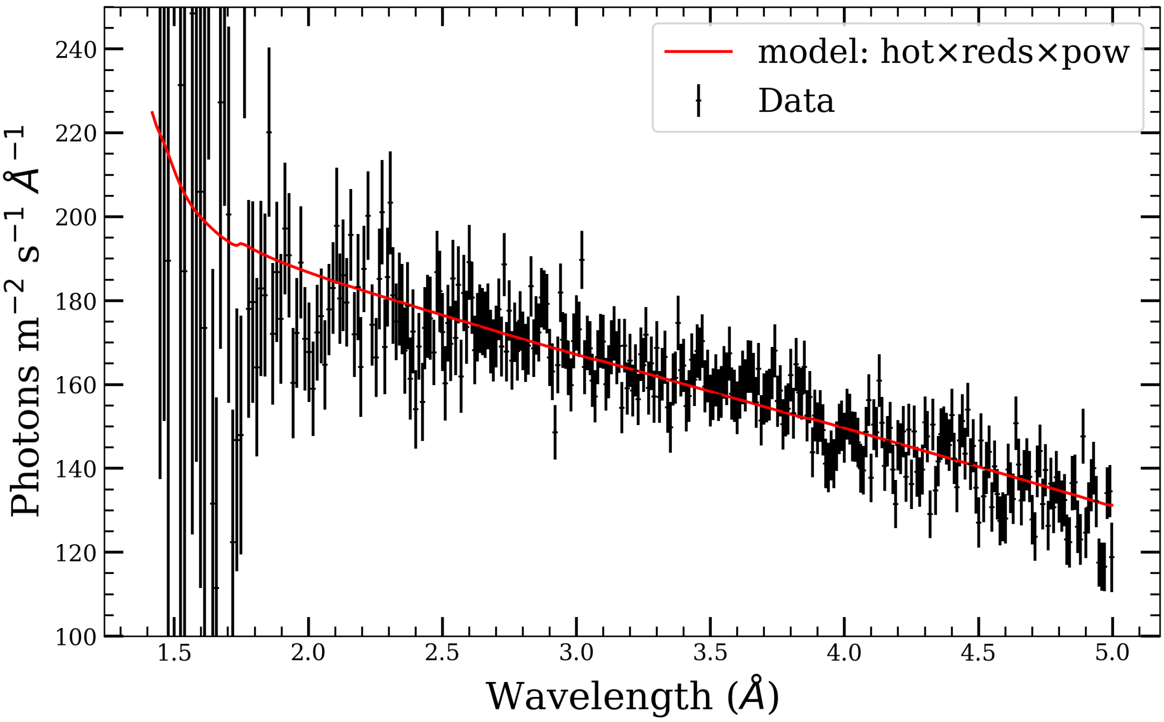


Figure 2: The data and model figure fitting the hard X-ray data.

```
com rel 3 2,1
cal
pl
fit
pl
```

When I change the order of `hot` and `reds`, the fitting result changes. The order of multiplicative components shows the path how the emission lines and continuum from the source to the earth. When I put `hot` in front of `reds`, it means `hot` is not our Galactic absorption, but the absorption close to the source. The absorption will experience the redshift. To fit the spectrum better, the pow-law continuum should change.

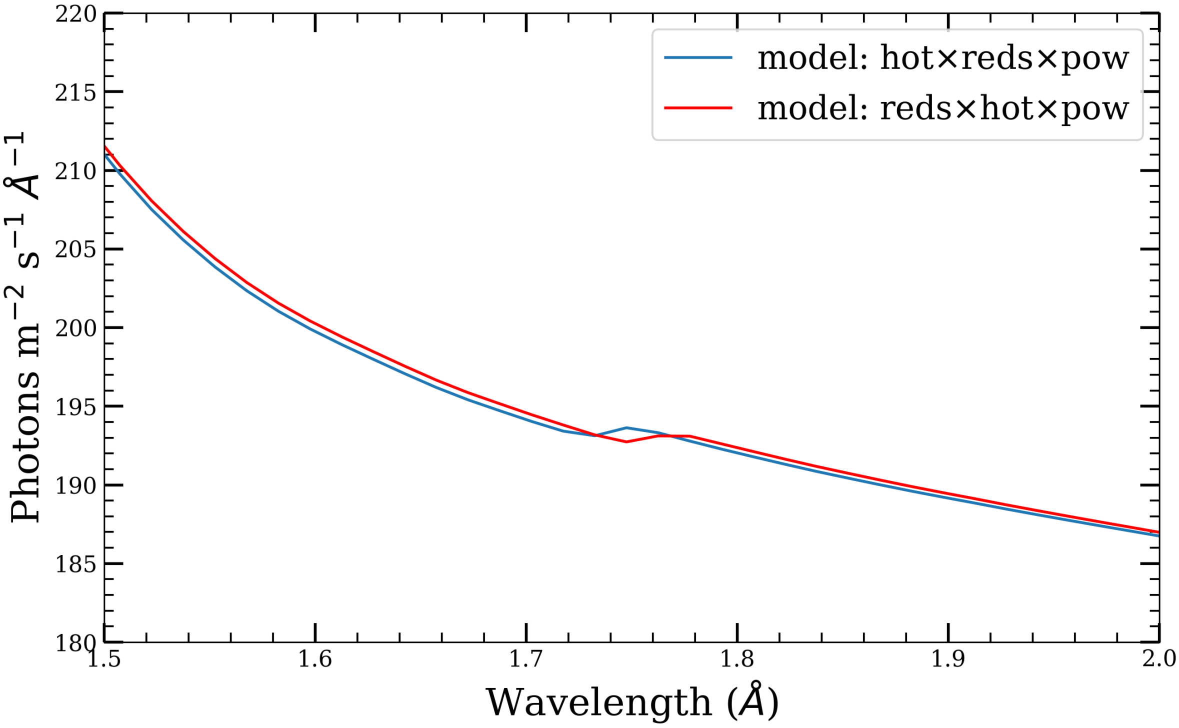


Figure 3: The model figure fitting the hard X-ray data with different order of `hot` and `reds`. The blue line means the initial model spectrum and the red line means the model spectrum changing the order of `hot` and `reds`. The difference is the latter's absorption line moves to the longer wavelength, which is because the line is redshifted.

Fit the broad (soft and hard) X-ray spectrum with the model set up as Eq. 3

Change Eq. 2 to Eq. 3. The difference is the model adds a mbb component.

$$\text{model} = \texttt{hot} \times \texttt{reds} \times (\texttt{mbb} + \texttt{pow}) \tag{3}$$

mbb

mbb is a modified blackbody model component, which describes the spectrum of a black body modified by coherent Compton scattering

$$N(E) = 1358 \frac{AE^{0.25}}{e^{E/T}\left(e^{E/T}-1\right)} \tag{4}$$

norm: Normalization A, in units of $10^{26}\ \mathrm{m}^{0.5}$. Default value: 1.
t: The temperature T in keV. Default value: 1 keV. The detail can be seen in mbb.

```
bash > cat 5-2-2.com
data inst_amo1 bhiw_amo1
plot device xs

dist 0.01158 z
comp reds
comp hot
comp pow
com rel 3 1,2
log exe 5-2-1result
cal
plot type data
pl ux ang
pl uy fang
pl

com mbb
par 1 3 norm val 7.66e7
par 1 3 gamm val 0.57
par 1 4 norm val 2.89e6
par 1 4 t val 0.49
com rel 3:4 1,2
cal
fit
pl

SPEX > log exe 5-2-2
```

There is another method, use ignore and use commands. However, pay attention to whether the data has been binned, because the ignore command will discard bin together, and use will not recover it.

Explore the Galactic absorption model

List the top three absorption lines (incl., wavelength)

See Fig. 5 and Tab. 1.

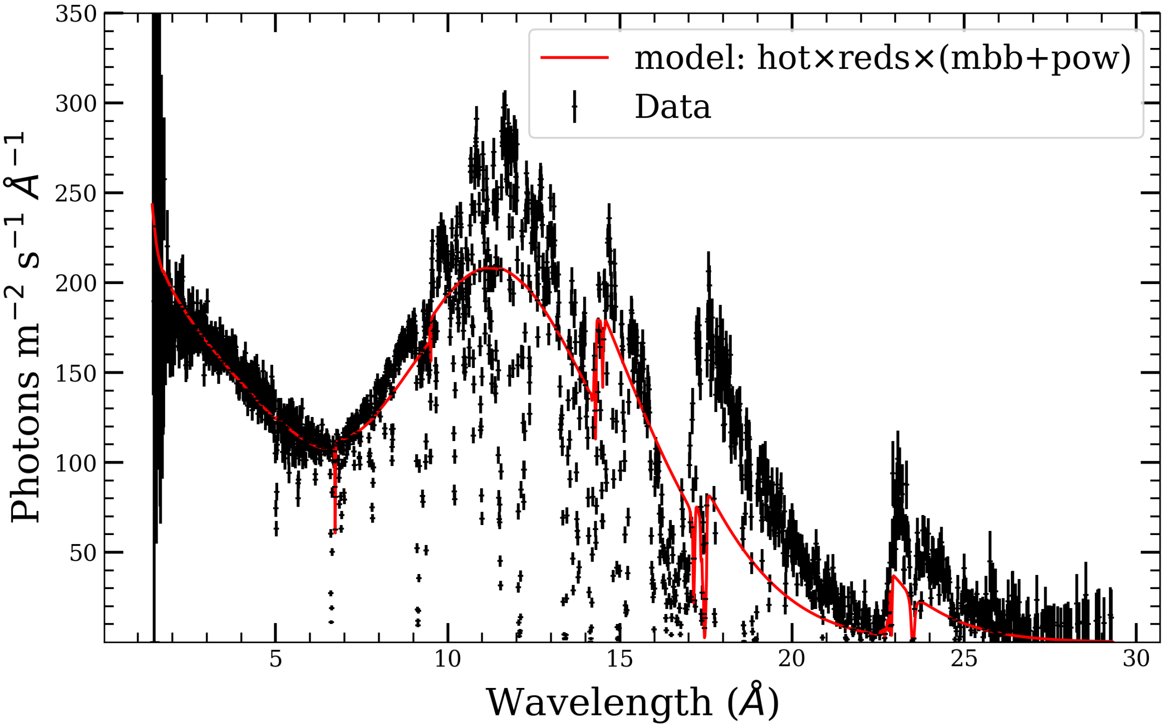


Figure 4: The data and model figure fitting the broad (soft and hard) X-ray data.

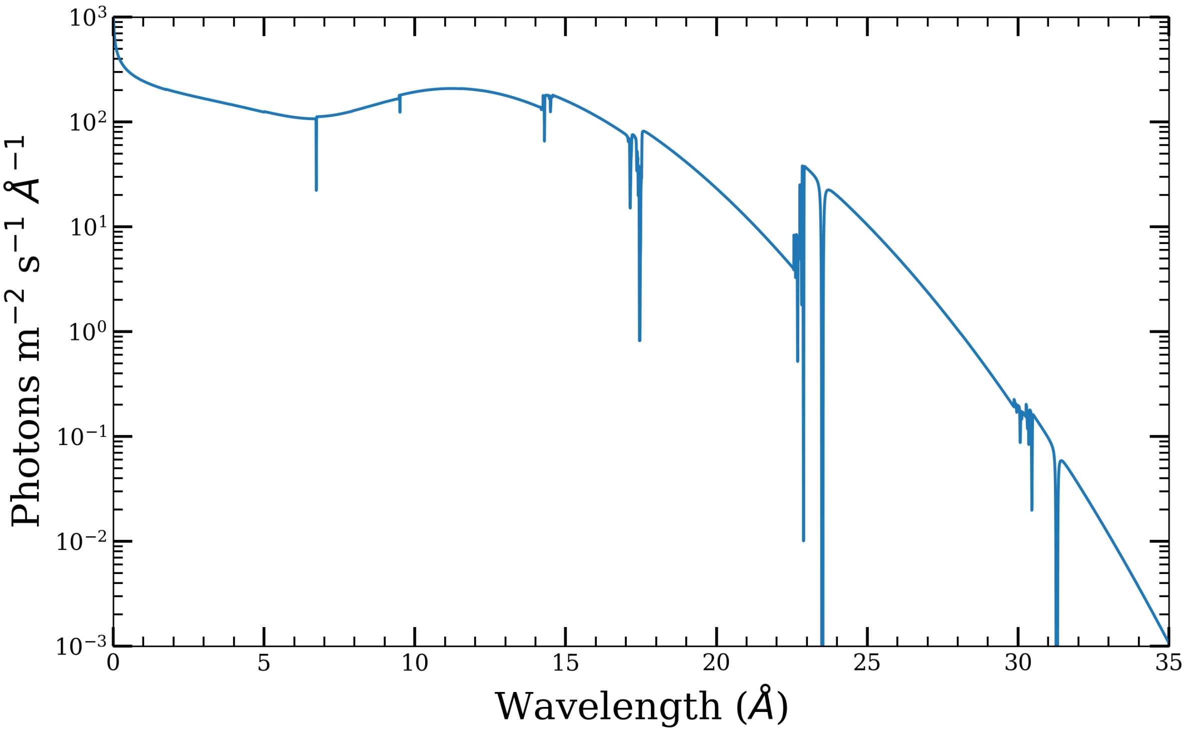


Figure 5: The model figure fitting the broad (soft and hard) X-ray data.

	1	2	3
Å	31.29	23.5	17.45
line	N I	O I	Fe XVI

Table 1: The top three absorption lines. The prediction of lines is from ZZ-weekly-report-06-25.pdf and NIST.

Question: How to interpret the difference between the two sets of component relations?

See Tab. 2 and Fig. 6.

z	0.2	0.1	0.01158	0.001
`hot`× `reds`×(`mbb`+ `pow`)		6.735		
`reds`× `hot`×(`mbb`+ `pow`)	8.08	7.41	6.81	6.74
$\Delta\lambda$	1.345	0.675	0.075	0.005

Table 2: The wavelength difference of the absorption line whose initial wavelength is 6.735 Å by changing the order of `hot` and `reds`.

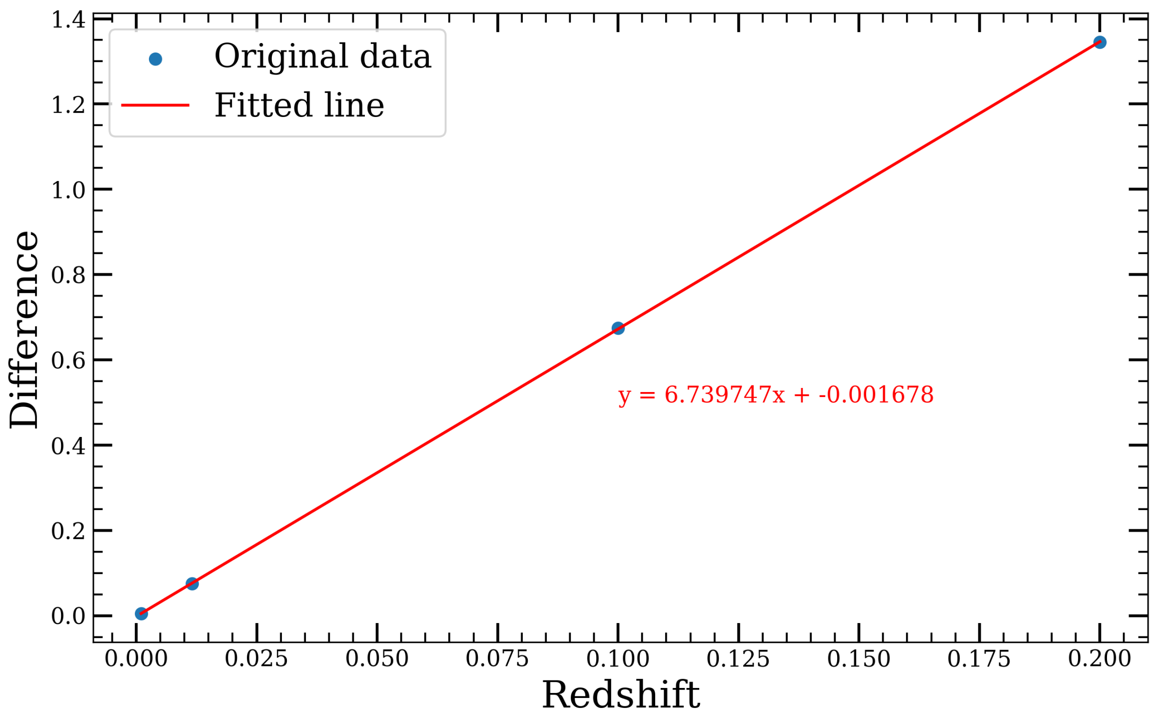


Figure 6: The redshift-$\Delta\lambda$ figure. This figure nearly follows the relation: $z = \frac{\Delta\lambda}{\lambda}$, $\Delta\lambda = \lambda z$.

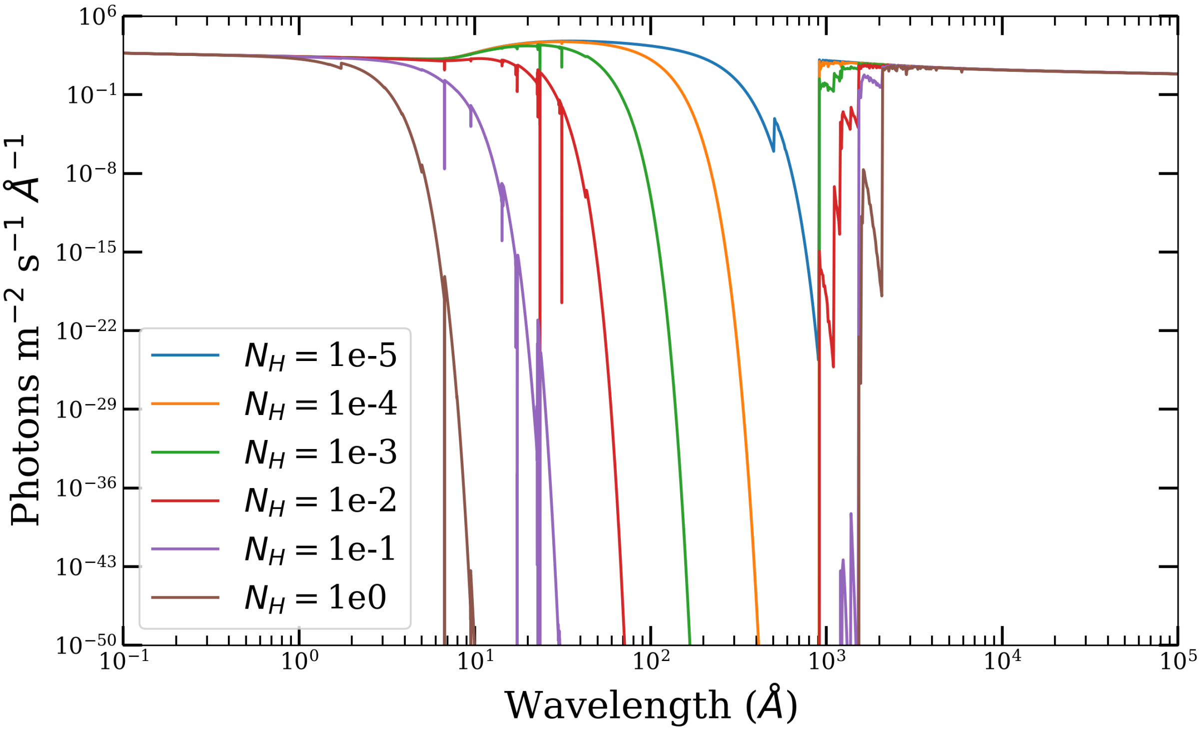


Figure 7: The Wavelength-Flux figure in different N_H settings. N_H is in units of $10^{28}\ \mathrm{m}^{-2}$. `t` in `hot` component is always set in 10^{-6} keV.

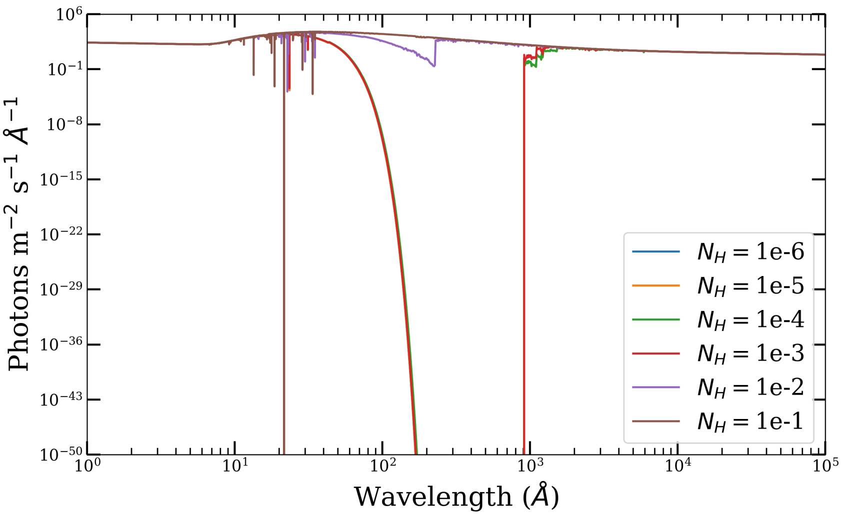
Plot and compare the absorbed power-law model spectra in the wavelength-flux space (1) with $t = 10^{-3}$ eV but different Galactic column densities ($N_\mathrm{H} = 10^{19}, 10^{20}, 10^{21}, ..., 10^{24}\ \mathrm{cm}^{-2}$); (2) with $N_\mathrm{H} = 10^{22}\ \mathrm{cm}^{-2}$ (frozen) but different temperatures ($t = 10^{-3}, 10^{-2}, ..., 10, 100$ eV). Summarize the trends of the absorption feature with increasing N_H or t.

From Fig. 7, we can see that:

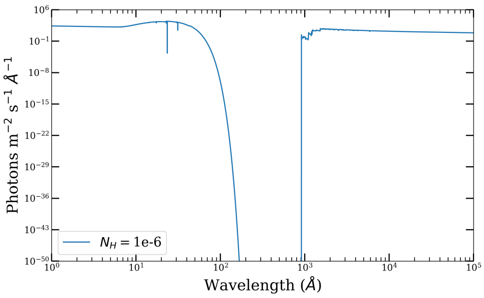
1. In the range that the wavelength $\lambda < 1$ Å and $\lambda > 10^4$ Å, the spectrum is the same as each other.
2. If N_H is larger, the spectrum will earlier decrease. It means the spectrum will decrease in smaller wavelengths, in higher energy.
3. Excluding the range above mentioned, if N_H is larger, the absorption lines have larger depth.

From Fig. 8, we can see that:

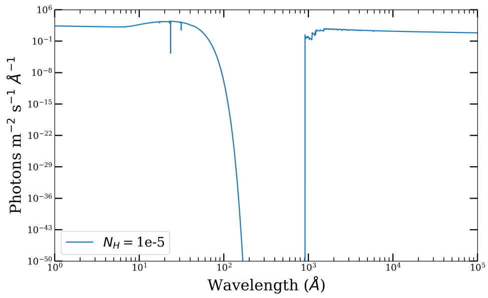
1. When t is smaller than 10^{-4} keV, it will not influence the spectrum.
2. In the range that the wavelength $\lambda < 6$ Å and $\lambda > 10^4$ Å, the spectrum is the same as each other.
3. Excluding the range mentioned above, if t is larger, the continuum absorption is smaller.



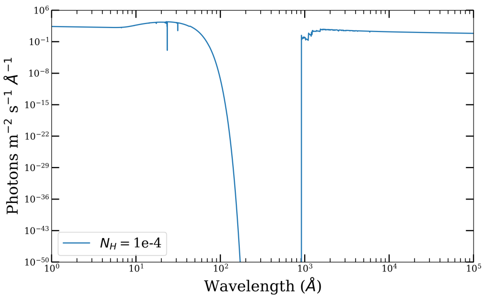
(a)



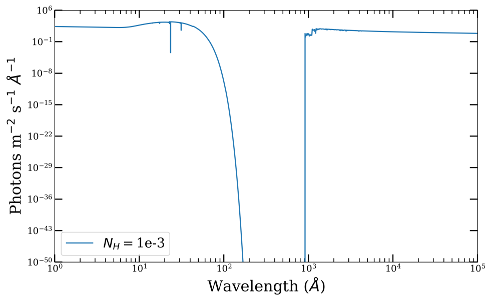
(b)



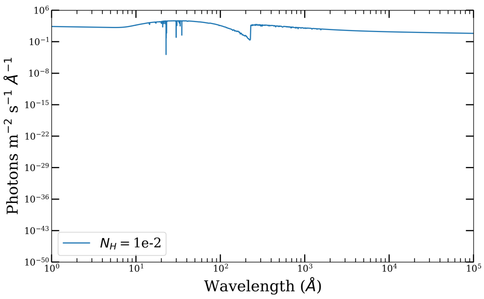
(c)



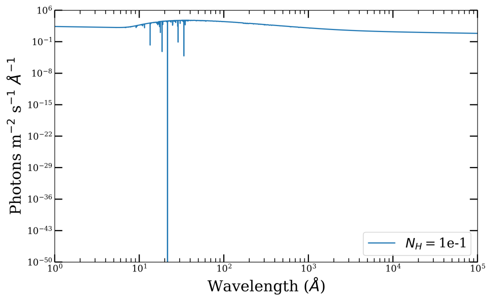
(d)



(e)



(f)



(g)

Figure 8: The Wavelength-Flux figure in different t settings. t is in units of keV. `nh` in `hot` component is always set in 10^{22} cm^{-2}.

Question: How did the $0.5-10$ keV flux and luminosity change before and after setting the distance properly? Calculate the flux and luminosity relation, does it follow the inverse distance-square relation exactly? If not, why?

dist

This command is used to set the source distance. One of the main principles of SPEX is that spectral models are in principle calculated at the location of the X-ray source. Once the distance is set, the flux received at Earth can be calculated. Default: 10^{22} m. The detail is in dist.

elim

This command is used to set flux energy limits. Default: $2-10$ keV. The detail is in elim.

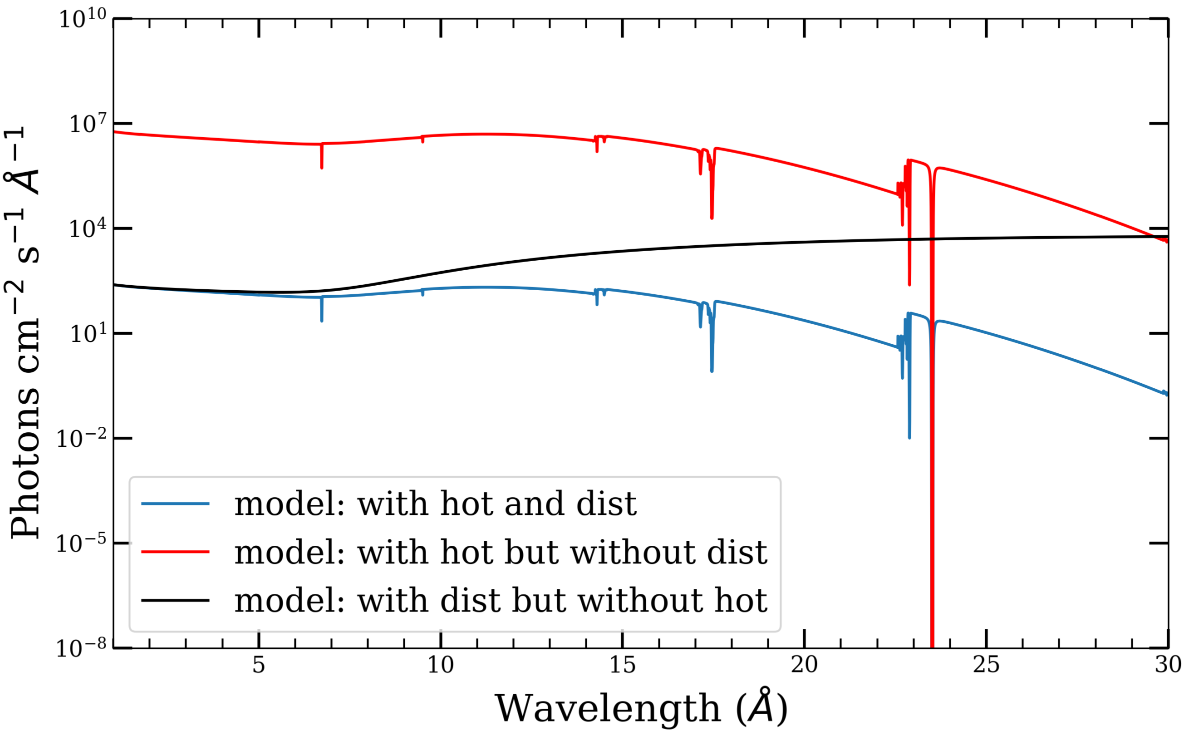


Figure 9: The Wavelength-Flux figure. The blue line shows the model which sets the distance. The red line shows the model without setting the distance. The black line shows the model without considering the Galactic absorption.

	flux (W m^{-2})		luminosity (W)	
without dist	pow	mbb	pow	mbb
	1.502814×10^{-8}	5.803337×10^{-7}	2.670189×10^{37}	1.456384×10^{38}
with dist	pow	mbb	pow	mbb
	6.303949×10^{-13}	2.434362×10^{-13}	2.670189×10^{37}	1.456384×10^{38}
without hot	pow	mbb	pow	mbb
	8.944934×10^{-13}	4.743579×10^{-12}	2.670189×10^{37}	1.456384×10^{38}

Table 3: The flux and luminosity in different models.

When we set the distance, the flux becomes smaller, and the luminosity does not change. From the flux and luminosity relation:

$$L = 4\pi d^2 f \tag{5}$$

L is the intrinsic luminosity, f is the intrinsic flux, and d is the distance from the source to us.

If we do not set the distance, the value should be the defaulted value: 10^{22} m. The flux calculated by the relation above should be larger than the flux we get from SPEX because the flux is absorbed flux.

For pow:

$$d = \sqrt{\frac{L}{4\pi f}} = \sqrt{\frac{2.670189 \times 10^{37}\ \mathrm{W}}{4\pi \times 1.502814 \times 10^{-8}\ \mathrm{W\ m^{-2}}}} = 1.189 \times 10^{22} > 1.000 \times 10^{22}\ \ (\mathrm{m}) \tag{6}$$

For mbb:

$$f = \frac{L}{4\pi d^2} = \frac{1.456384 \times 10^{38}\ \mathrm{W}}{4\pi \times (10^{22}\ \mathrm{m})^2} = 1.159 \times 10^{-7} > 5.803337 \times 10^{-7}\ \ \left(\mathrm{W\ m^{-2}}\right) \tag{7}$$

If we set the distance, the value should be what we set $z = 0.01158$ corresponds to $d = 1.544 \times 10^{24}$ m. However, the inequity still exists.

For pow:

$$d = \sqrt{\frac{L}{4\pi f}} = \frac{2.670189 \times 10^{37}\ \mathrm{W}}{4\pi \times 6.303949 \times 10^{-13}\ \mathrm{W\ m^{-2}}} = 1.836 \times 10^{24} > 1.544 \times 10^{24}\ \ (\mathrm{m}) \tag{8}$$

For mbb:

$$f = \frac{L}{4\pi d^2} = \frac{1.456384 \times 10^{38}\ \mathrm{W}}{4\pi \times (1.544 \times 10^{24}\ \mathrm{m})^2} = 4.861 \times 10^{-12} > 2.434362 \times 10^{-13}\ \ \left(\mathrm{W\ m^{-2}}\right) \tag{9}$$

We try to delete the component hot, which represents the absorptions from the Galaxy. From Tab. 3, we can see that the flux is much closer to the flux calculated by the inverse distance-square relation, but still has an error, I guess that it is because of the measure error.

Intrinsic Spectral Energy Distribution (SED)

Plot the intrinsic SED model in the energy-flux space. Set the X-axis to $0.1\ \mathrm{eV} - 10^4\ \mathrm{keV}$ and Y-axis units to $\mathrm{W\ m}^2$. Describe the intrinsic SED in the infrared, optical, and gamma-ray bands.

```
bash > cat 5-4-1.com
data inst_amo1 bhiw_amo1
plot device xs

dist 0.01158 z
comp reds
comp hot
comp pow
com mbb
com rel 3:4 1,2
log exe 5-2-2result

com del 2
```

```
    cal
    pl ty model
    pl ux kev
    pl uy iw
    pl fill disp f
    pl rx 1e-4:1e4
    pl x log
    pl y log
    pl

    SPEX > log exe 5-4-1
```

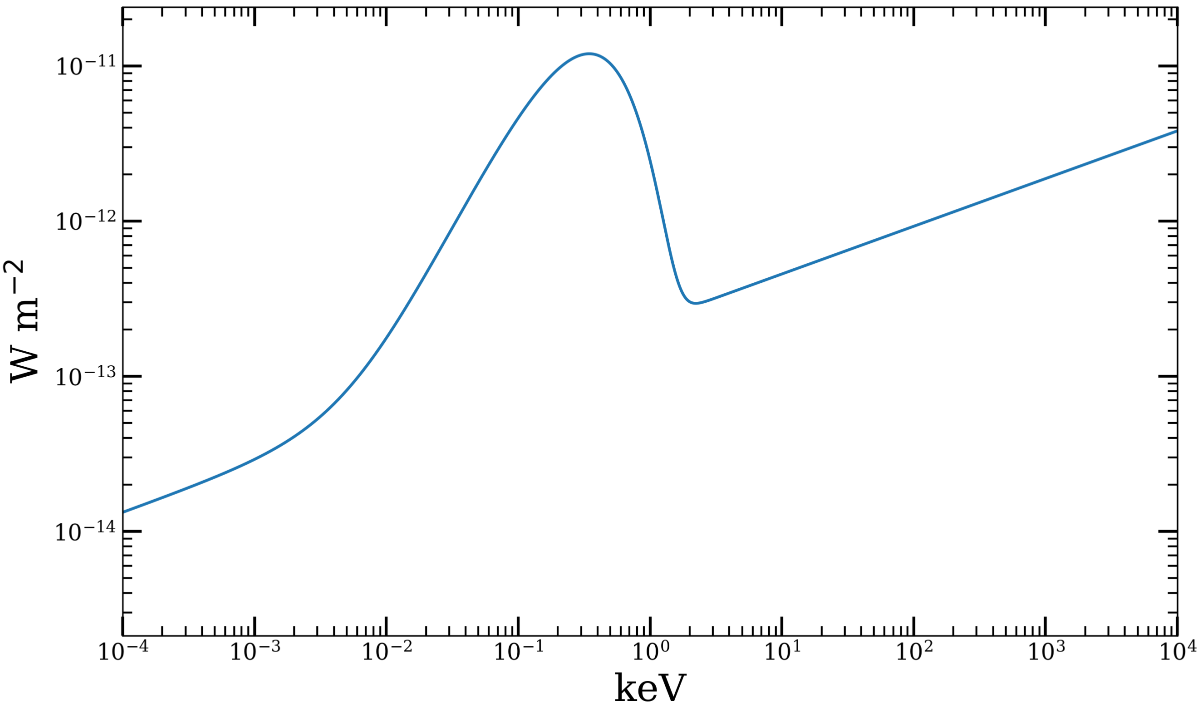


Figure 10: The Wavelength-Flux figure. The x-axis unit is keV and the y-axis unit is $\mathrm{W\ m^{-2}}$. The model is `reds`$\times$(`mbb`+`pow`).

The energy band in units of keV:

Infrared: $4 \times 10^{-6} : 1.6 \times 10^{-3}$

Optical: $1.6 \times 10^{-3} : 3.3 \times 10^{-3}$

Gamma-ray: $1.2 \times 10^{2} : 1.2 \times 10^{6}$

See Fig. 10, the slope of the continuum in infrared, optical, and gamma-ray bands is approximately unchanged. The `pow` spectrum should mainly contribute to their morphology.

Use two etau models to exponentially cut off the pow continuum below 1 Rydberg and above 10^3 Rydberg. Plot and compare the intrinsic SED models (including mbb) in the energy-flux space before and after the cut-off. Set the X-axis to 0.1 eV $-$ 10^4 keV and Y-axis units to W m^2.

etau

etau is a simple transmission model component. The formula is:

$$T(E) = e^{-\tau(E)} \tag{10}$$

with the optical depth $\tau(E)$ given by:

$$\tau(E) = \tau_0 E^a \tag{11}$$

The main parameters:
τ_0: Optical depth τ_0 at $E = 1$ keV. Default value: 1.
a: The index a defined above. Default value: 1. The detail is in etau.

Optical depth $\tau = 1$ is a boundary. $\tau > 1$ is considered as optical-thick, and $\tau < 1$ is considered as optical-thin. Here we use two etau models to exponentially cut off the pow continuum below 0.013605 keV and above 13.605 keV, which means, when $\tau = 1$, the energy should be 0.013605 keV and 13.605 keV. From this formula, for $a > 0$ the spectrum has a high-energy cut-off, for $a < 0$ it has a low-energy cut-off, and for $a = 0$ the transmission is flat. So a is determined to be -1 and 1, separately.

For a=-1:

$$1 = \tau_0 \times 0.013605^{-1} \tag{12}$$

$$\tau_0 = 0.013605 \tag{13}$$

For a=1:

$$1 = \tau_0 \times 13.605^1 \tag{14}$$

$$\tau_0 = \frac{1}{13.605} \tag{15}$$

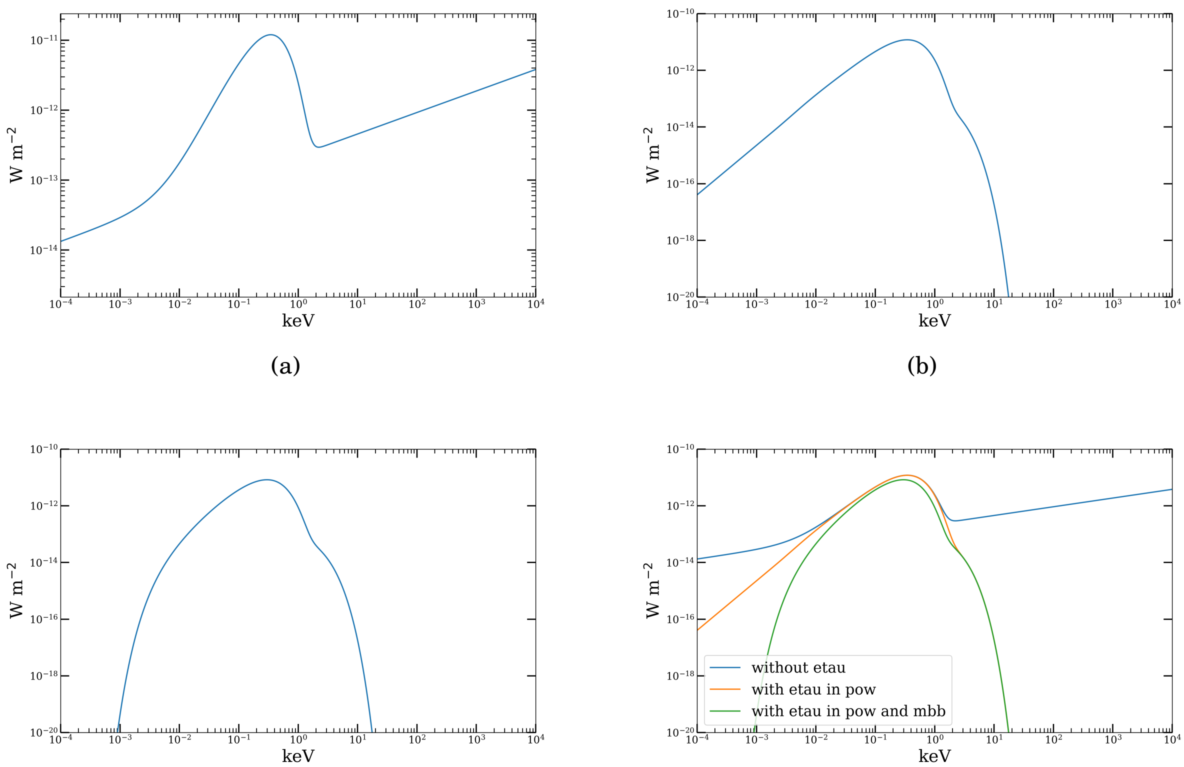
```
bash > cat 5-4-2.com
data inst_amo1 bhiw_amo1
plot device xs

dist 0.01158 z
comp reds
comp pow
com mbb
log exe 5-4-1result

com etau
com etau
com rel 2 5,4,1
com rel 3 1
par 1 4 a val -1
par 1 4 a s f
par 1 4 tau0 val 1.3605E-2
```

```
    par 1 4 tau0 s f
    par 1 5 a val 1
    par 1 5 a s f
    par 1 5 tau0 val 1/13.605
    par 1 5 tau0 s f
    cal
    pl ty model
    pl ux kev
    pl uy iw
    pl fill disp f
    pl rx 1e-4:1e4
    pl x log
    pl y log
    pl

    SPEX > log exe 5-4-2
```



(a) (b) (c) (d)

Figure 11: The Wavelength-Flux figure. The x-axis unit is keV and the y-axis unit is W m^{-2}. (a): The model is `reds`×(`mbb`+`pow`). (b): The model is `reds`×(`mbb`+`etau1`×`etau2`×`pow`). (c): The model is `reds`×`etau1`×`etau2`×(`mbb`+`pow`).

Using `etau` models to `mbb` will influence the soft X-ray spectra, which is incorrect. So we should just use `etau` cut-off to `pow` model. I think this method is helpful when we focus on soft X-ray spectra.