

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](#).

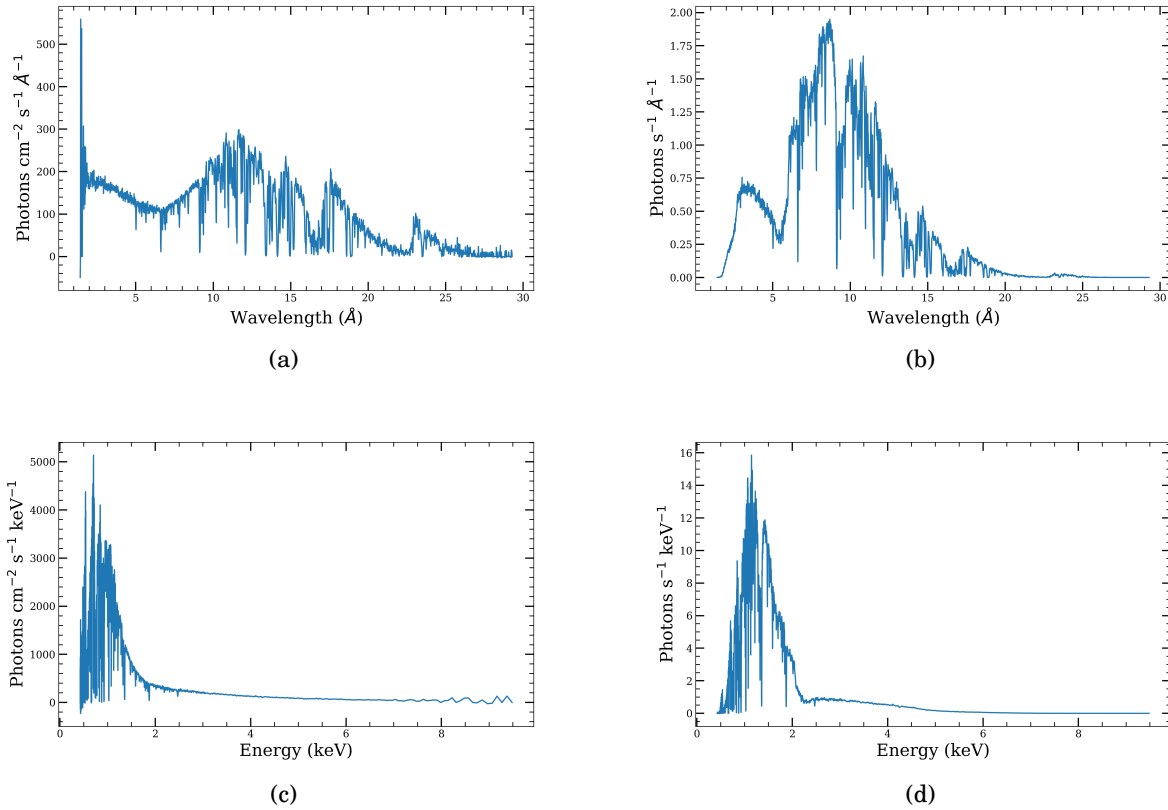


Figure 1: The data figure is shown in different x- and y-axis units. (a) The x-axis unit is \AA and the y-axis unit is $\text{counts cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$; (b) The x-axis unit is \AA and the y-axis unit is $\text{counts s}^{-1} \text{\AA}^{-1}$; (c) The x-axis unit is keV and the y-axis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

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

When the unit of the y-axis is $\text{counts s}^{-1} \text{ \AA}^{-1}$ or $\text{counts s}^{-1} \text{ keV}^{-1}$, 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:

$$\text{model} = \text{hot} \times \text{reds} \times \text{pow} \quad (1)$$

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:

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

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

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

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

```
1  bash > cat 5-2-1.com
2  data inst_amo1 bhiw_amo1
3  plot device xs
4
5  ignore 5:30 unit ang # ignore the data above 5 angstroms.
6  dist 0.01158 z # set the distance
7  comp reds
8  par 1 1 z value 0.01158
9  par 1 1 z status f
10 comp hot
11 par 1 2 nh value 8.5e-3
12 par 1 2 nh status f
13 par 1 2 t s f
```

```

14 comp pow
15 par 1 3 norm val 5e8
16 com rel 3 1,2
17 cal
18 plot type data
19 plot ux ang
20 plot uy fang
21 pl
22 fit
23 pl
24
25 SPEX > log exe 5-2-1

```

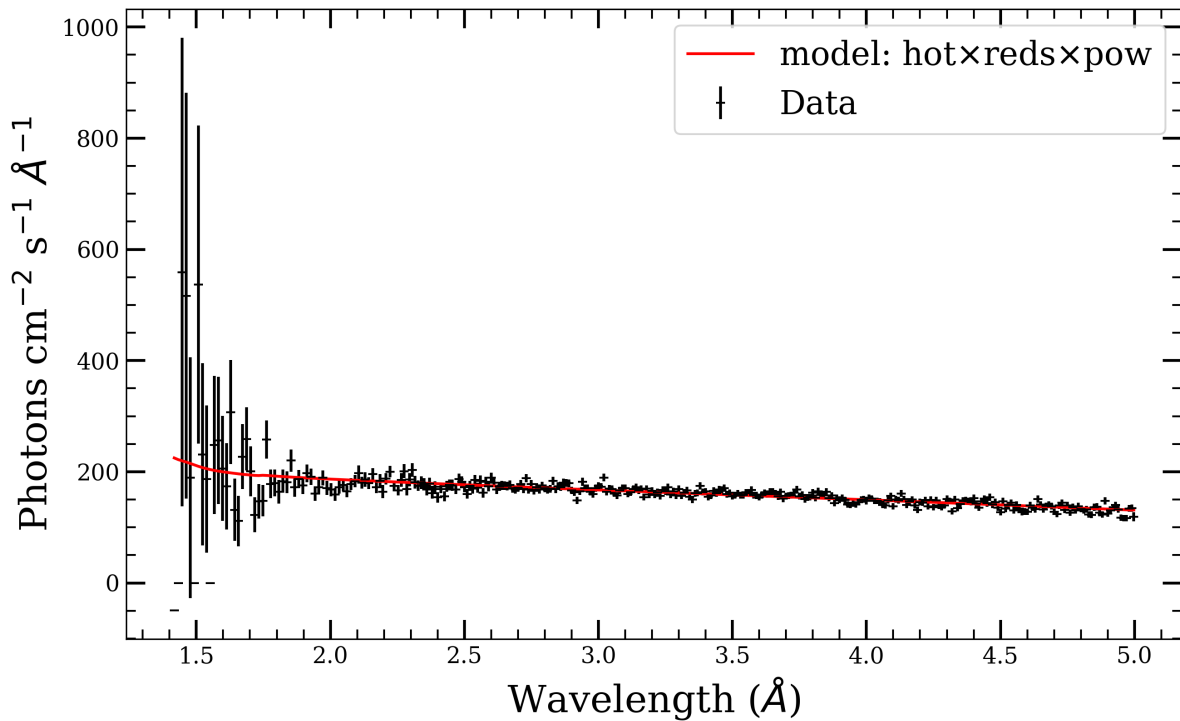


Figure 2: The data and model figure fitting the hard X-ray data.

```

1 com rel 3 2,1
2 cal
3 pl
4 fit
5 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.

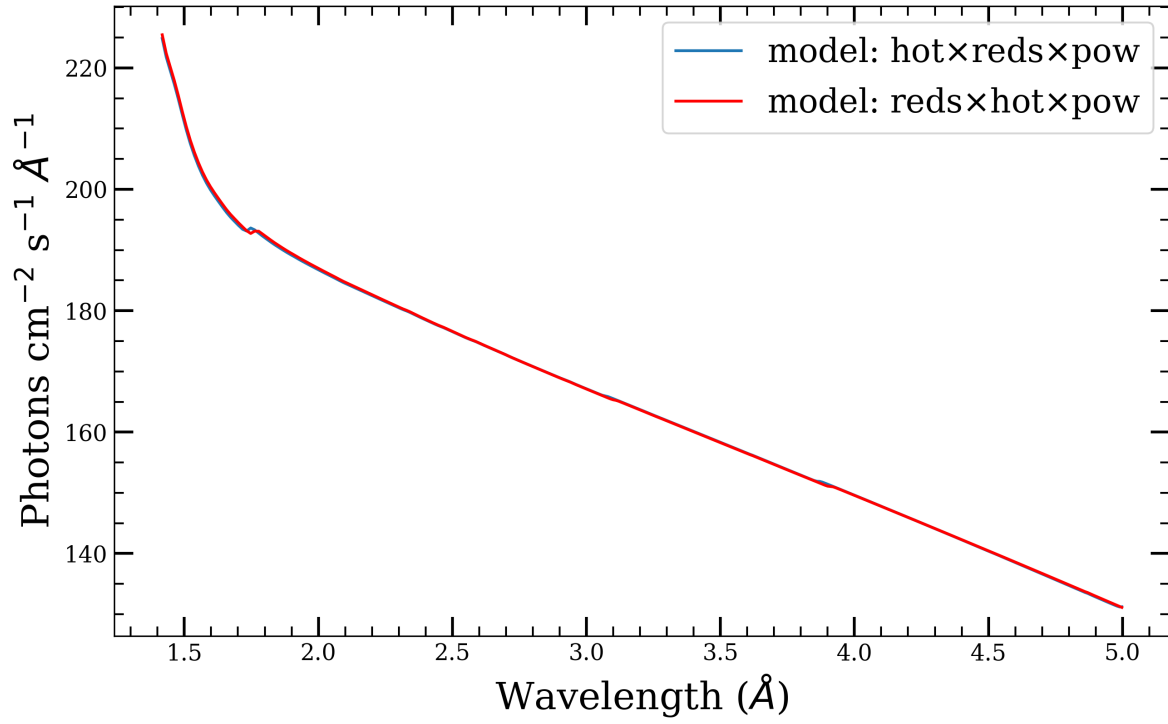


Figure 3: The model figure fitting the hard X-ray data with different order of `hot` and `reds`. The blue line means the initial model spectrum and the red line means the model spectrum changing the order of `hot` and `reds`. The difference is the latter's absorption line moves to the longer wavelength,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

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

mbb

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

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

`norm`: Normalization A , in units of $10^{26} \text{ m}^{0.5}$. Default value: 1.

`t`: The temperature T in keV. Default value: 1 keV. The detail can be seen in `mbb`.

```

1  bash > cat 5-2-2.com
2  data inst_amo1 bhiw_amo1
3  plot device xs
4
5  dist 0.01158 z
6  comp reds
7  comp hot
8  comp pow
9  com rel 3 1,2
10 log exe 5-2-1result
11 cal
12 plot type data
13 pl ux ang
14 pl uy fang
15 pl
16
17 com mbb
18 par 1 3 norm val 7.66e7
19 par 1 3 gamm val 0.57
20 par 1 4 norm val 2.89e6
21 par 1 4 t val 0.49
22 com rel 3:4 1,2
23 cal
24 fit
25 pl
26
27 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.

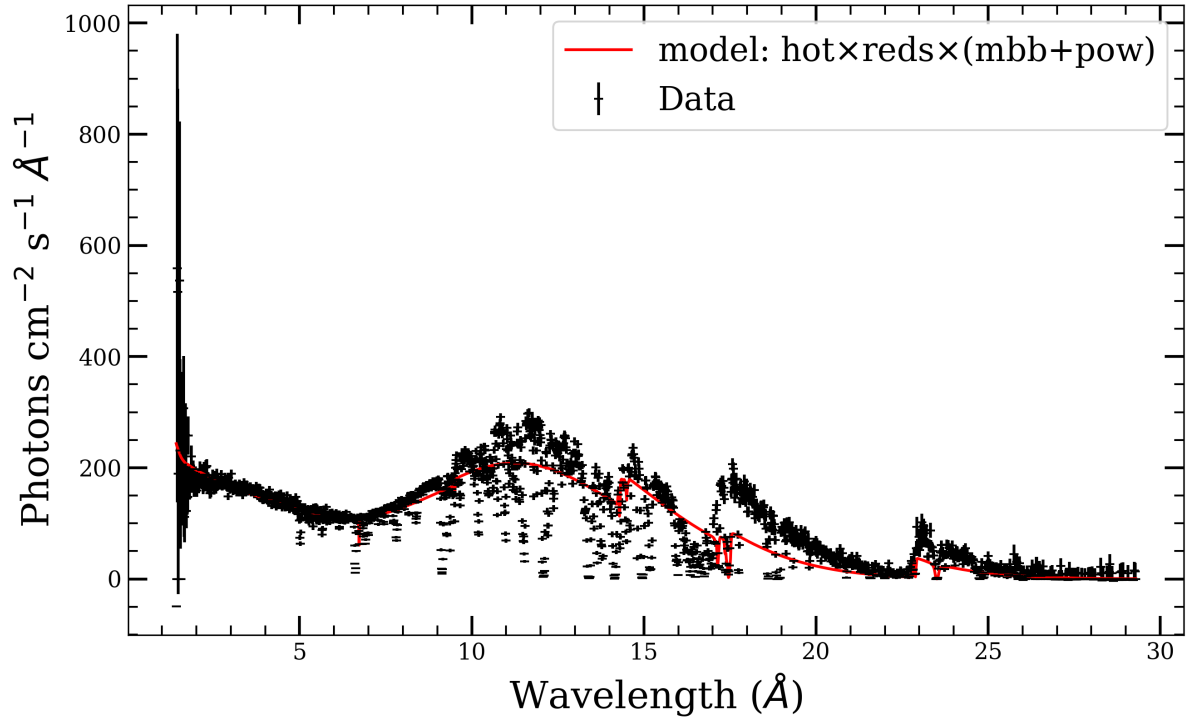


Figure 4: The data and model figure fitting the broad (soft and hard) X-ray data.

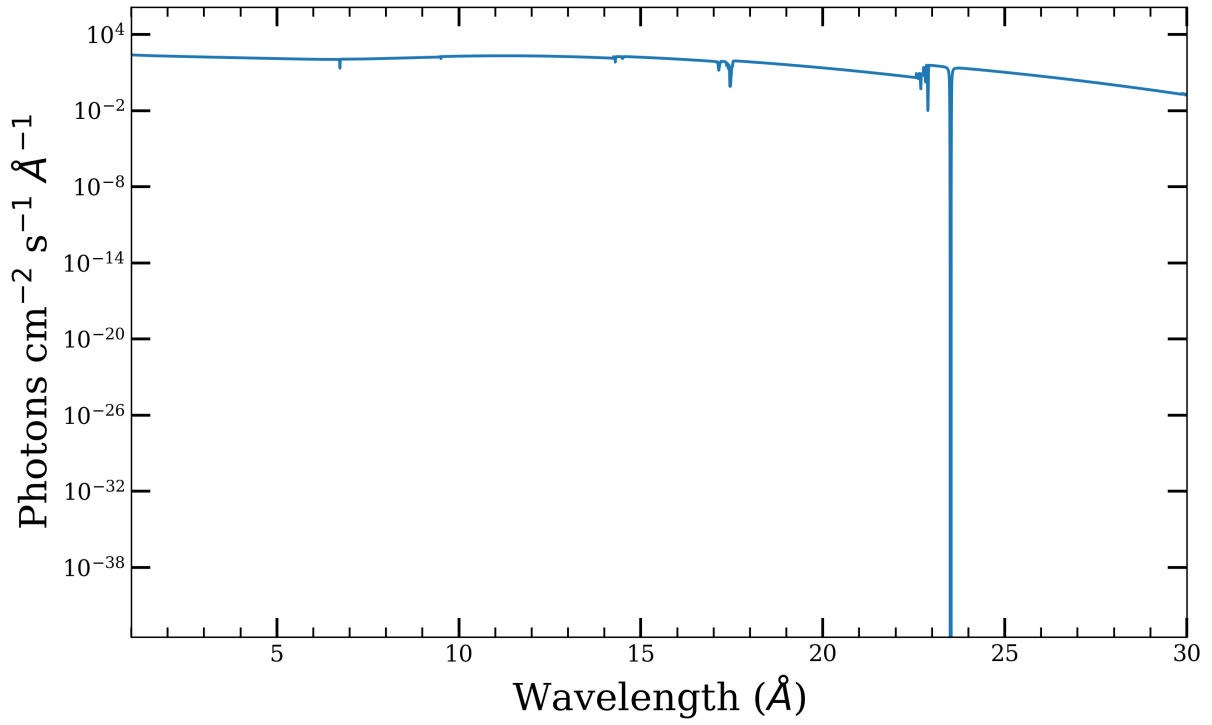


Figure 5: The model figure fitting the broad (soft and hard) X-ray data.

	1	2	3
Å	23.5	22.9	22.7
line	Cu XIX	Sc XIV	Cl XVII
	Ar XVI		Sc XIV

Table 1: The top three absorption lines. The prediction of lines is from **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.

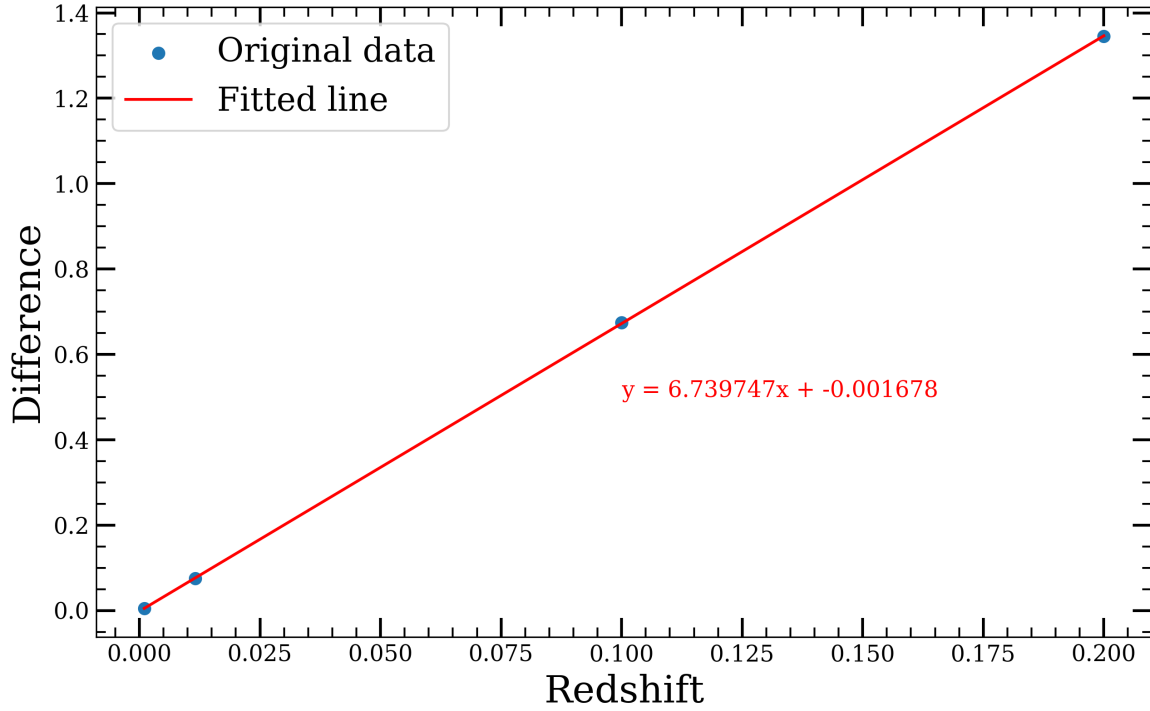


Figure 6: The redshift- $\Delta\lambda$ figure. This figure nearly follows the relation: $z = \frac{\Delta\lambda}{\lambda}$, $\Delta\lambda = \lambda z$.

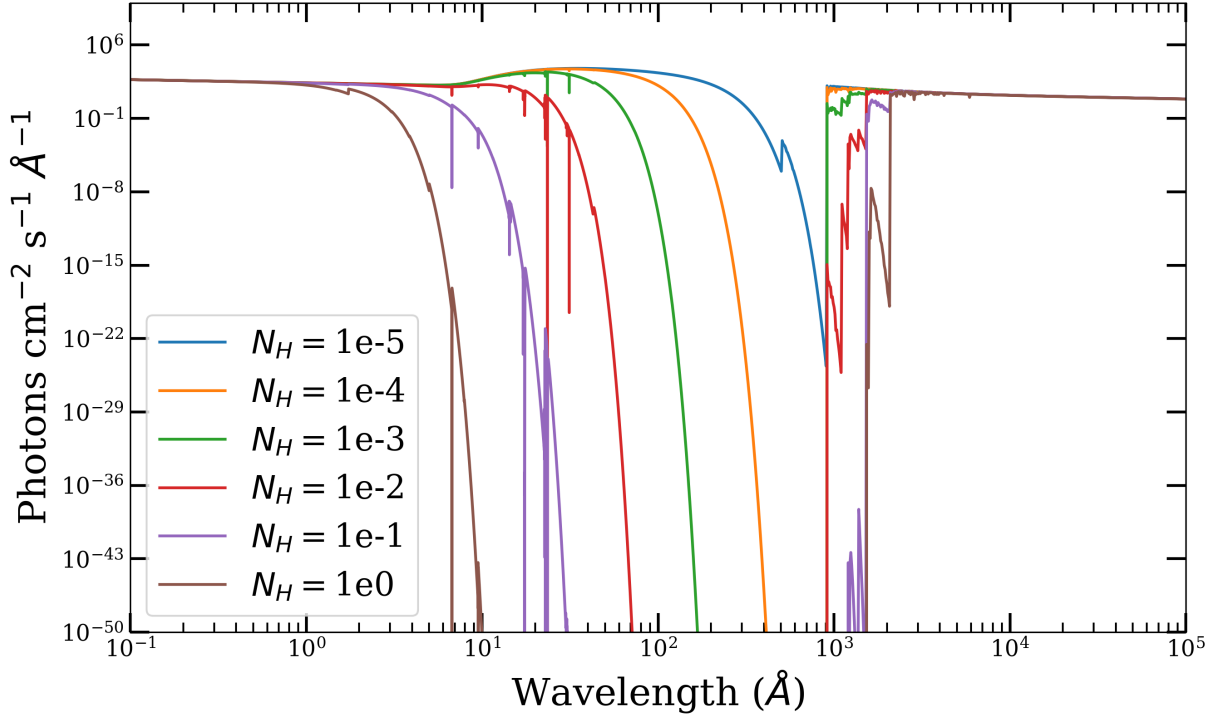


Figure 7: The Wavelength-Flux figure in different N_H settings. N_H is in units of 10^{28} m^{-2} . t in hot component is always set in 10^{-6} keV .

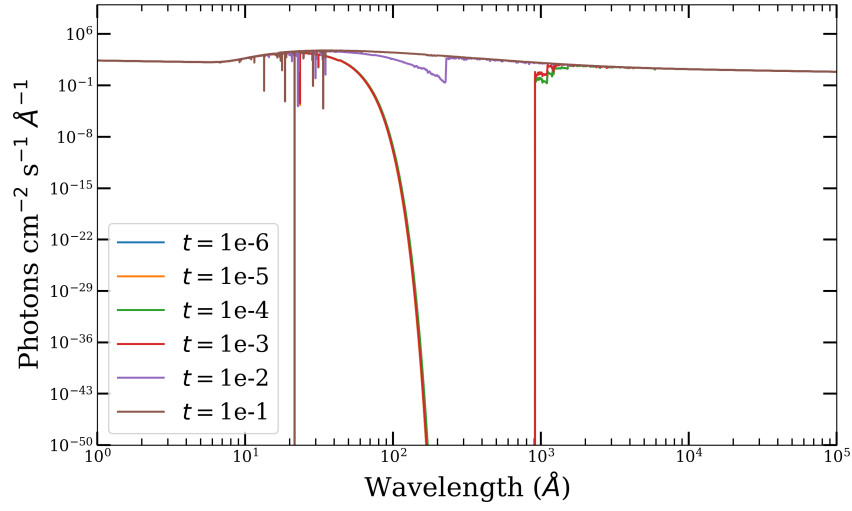
Plot and compare the absorbed power-law model spectra in the wavelength-flux space (1) with $t = 10^{-3} \text{ eV}$ but different Galactic column densities ($N_H = 10^{19}, 10^{20}, 10^{21}, \dots, 10^{24} \text{ cm}^{-2}$); (2) with $N_H = 10^{22} \text{ cm}^{-2}$ (frozen) but different temperatures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

From Fig. 7, we can see that:

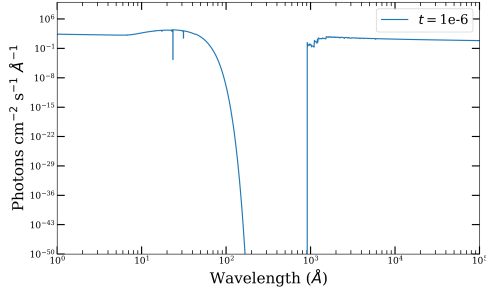
1. In the range that the wavelength is smaller than 1 Å , the spectrum is the same as each other. So do the range that the wavelength is larger than 10^4 Å .
2. If N_H is larger, the spectrum will earlier decrease. It means the spectrum will decrease in smaller wavelengths, in higher energy.
3. Excluding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

From Fig. 8, we can see that:

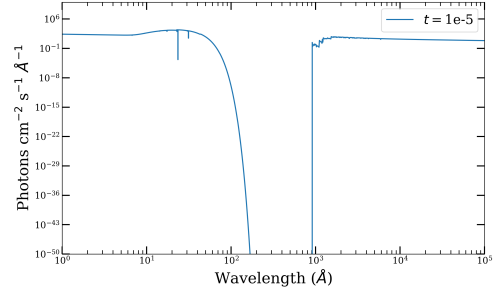
1. When t is smaller than 10^{-3} keV , it will not influence the spectrum.
2. In the range that the wavelength is smaller than 6 Å , the spectrum is the same as each other. So do the range that the wavelength is larger than 10^4 Å .
3. Excluding the range mentioned above, if t is larger, the continuum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



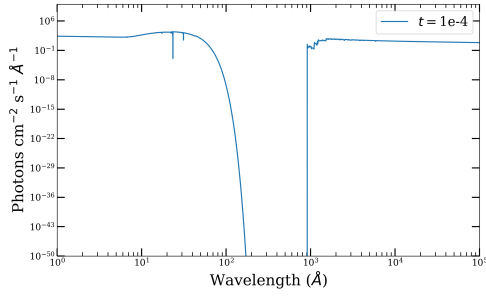
(a)



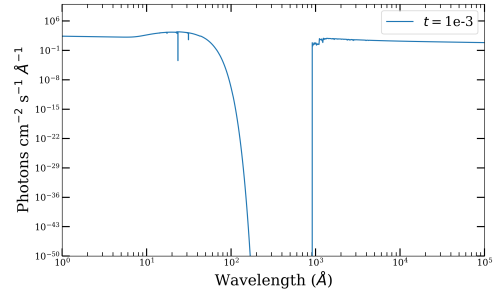
(b)



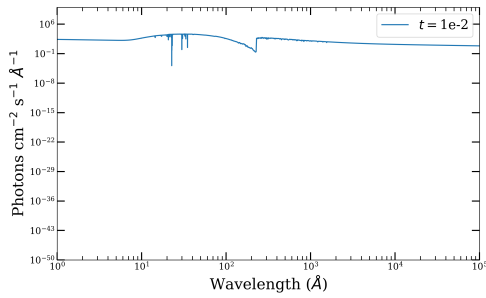
(c)



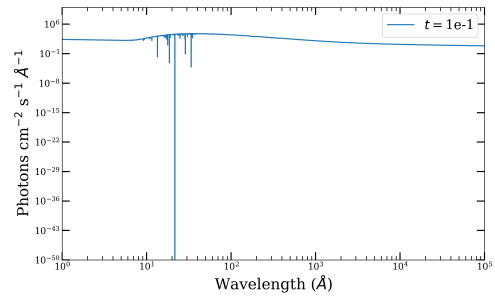
(d)



(e)



(f)



(g)

Figure 8: The Wavelength-Flux figure in different t settings. t is in units of keV. n_h 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](#).

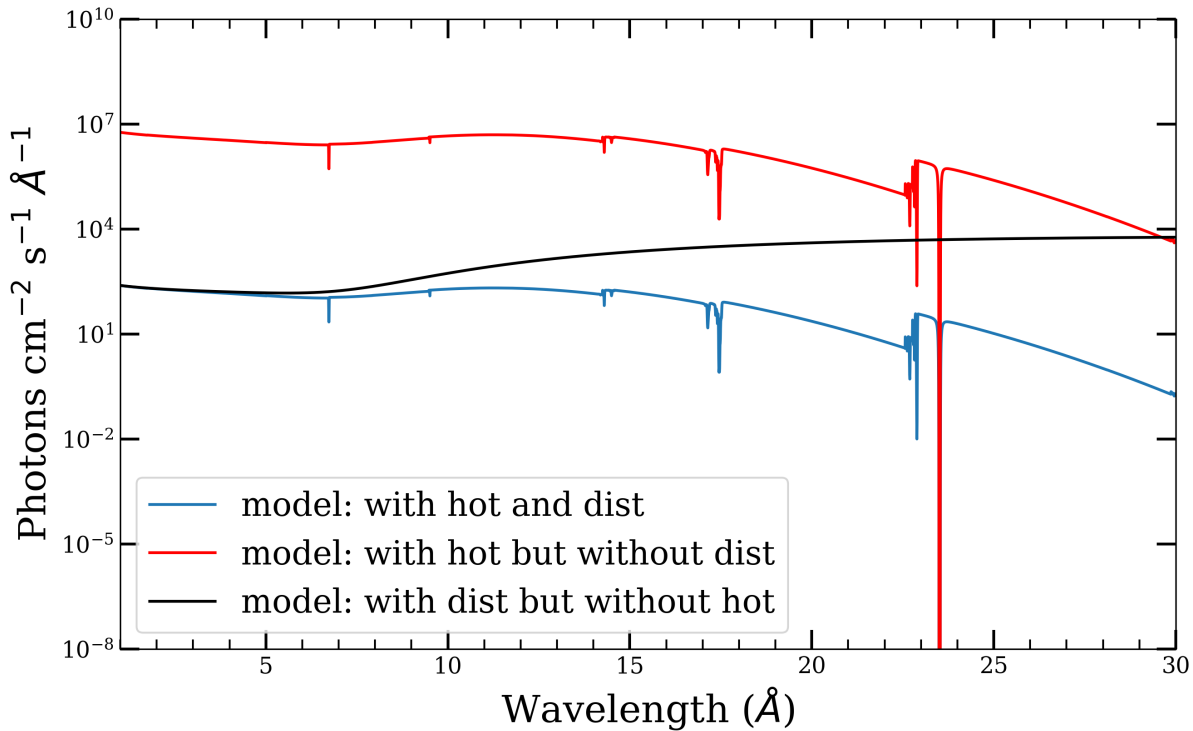


Figure 9: The Wavelength-Flux figure. The blue line shows the model which sets the distance. The red line shows the model without setting the distance. The black line shows the model without considering the Galactic absorption.

flux (W m ⁻²)			luminosity (W)	
without dist	pow	mbb	pow	mbb
	2.05×10^{-8}	1.00×10^{-7}	2.67×10^{37}	1.46×10^{38}
with dist	pow	mbb	pow	mbb
	8.62×10^{-13}	4.21×10^{-12}	2.67×10^{37}	1.46×10^{38}
without hot	pow	mbb	pow	mbb
	8.94×10^{-13}	4.74×10^{-12}	2.67×10^{37}	1.46×10^{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:

$$L = 4\pi d^2 f \quad (5)$$

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`:

$$f = \frac{L}{4\pi d^2} = \frac{2.67 \times 10^{37} \text{ W}}{4\pi \times (10^{22} \text{ m})^2} = 2.12 \times 10^{-8} > 2.05 \times 10^{-8} \text{ (W m}^{-2}\text{)} \quad (6)$$

For `mbb`:

$$f = \frac{L}{4\pi d^2} = \frac{1.46 \times 10^{38} \text{ W}}{4\pi \times (10^{22} \text{ m})^2} = 1.16 \times 10^{-7} > 1.00 \times 10^{-7} \text{ (W m}^{-2}\text{)} \quad (7)$$

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`:

$$f = \frac{L}{4\pi d^2} = \frac{2.67 \times 10^{37} \text{ W}}{4\pi \times (1.544 \times 10^{24} \text{ m})^2} = 8.91 \times 10^{-13} > 8.62 \times 10^{-13} \text{ (W m}^{-2}\text{)} \quad (8)$$

For `mbb`:

$$f = \frac{L}{4\pi d^2} = \frac{1.46 \times 10^{38} \text{ W}}{4\pi \times (1.544 \times 10^{24} \text{ m})^2} = 4.87 \times 10^{-12} > 4.21 \times 10^{-12} \text{ (W m}^{-2}\text{)} \quad (9)$$

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 $0.1 \text{ eV} - 10^4 \text{ keV}$ and Y-axis units to W m^2 . Describe the intrinsic SED in the infrared, optical, and gamma-ray bands.

```
1 data inst_amo1 bhiw_amo1
2 plot device xs
3
4 dist 0.01158 z
5 comp reds
6 comp hot
7 comp pow
8 com mbb
9 com rel 3:4 1,2
10 log exe 5-2-2result
11
12 com del 2
13 cal
14 pl ty model
```

```

15   pl ux kev
16   pl uy iw
17   pl fill disp f
18   pl rx 1e-4:1e4
19   pl x log
20   pl y log
21   pl

```

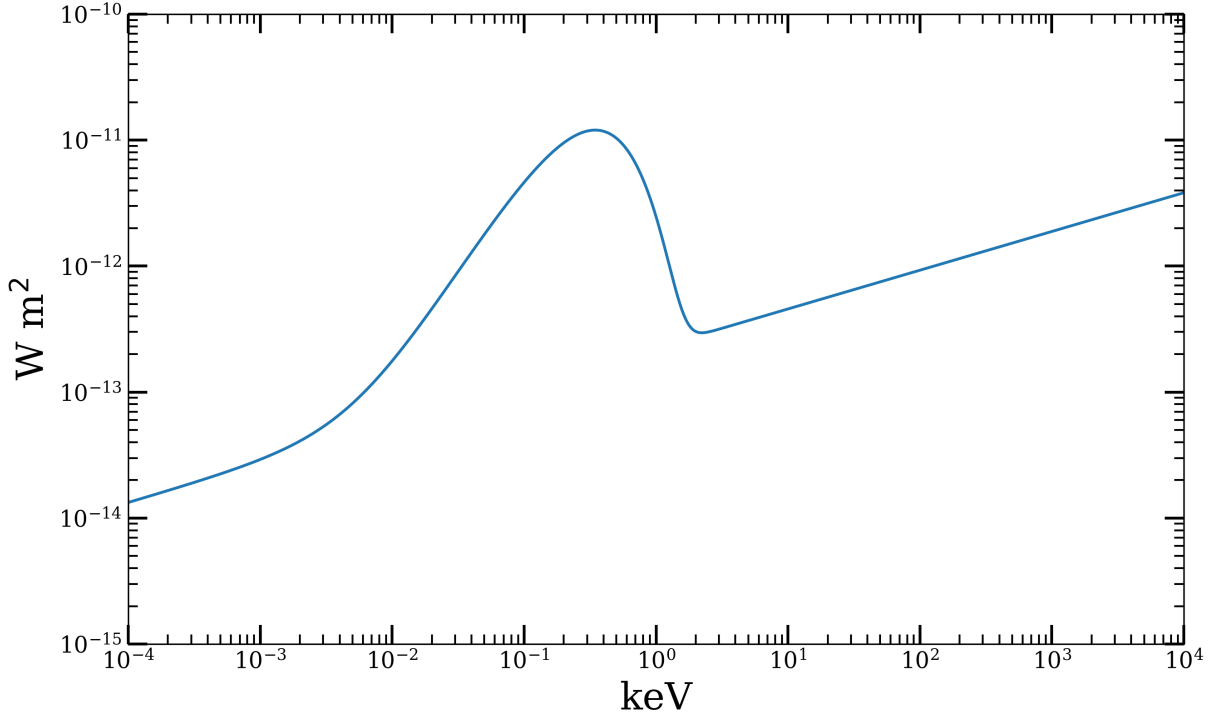


Figure 10: The Wavelength-Flux figure. The x-axis unit is keV and the y-axis unit is W m^2 . The model is `reds×(mbb+pow)`.

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 $0.1 \text{ eV} - 10^4 \text{ keV}$ and Y-axis units to W m^2 .

etau

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

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

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

$$\tau(E) = \tau_0 E^a \quad (11)$$

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**.

```

1    data inst_amo1 bhiw_amo1
2    plot device xs
3
4    dist 0.01158 z
5    comp reds
6    comp pow
7    com mbb
8    log exe 5-4-1result
9
10   com etau
11   com etau
12   com rel 2 5,4,1
13   com rel 3 1
14   par 1 4 a val -1
15   par 1 4 a s f
16   par 1 4 tau0 val 1.3605E-2
17   par 1 4 tau0 s f
18   par 1 5 a val 1
19   par 1 5 a s f
20   par 1 5 tau0 val 13.605
21   par 1 5 tau0 s f
22   cal
23   pl ty model
24   pl ux kev
25   pl uy iw
26   pl fill disp f
27   pl rx 1e-4:1e4
28   pl x log
29   pl y log
30   pl

```

There is one thing that confused me, should a be set to -1 or 1? 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. But from **Pion example**, the setting of a is the opposite. I try to make a comparison.

The first case, etau1 has $\tau_0 = 0.013605$ (1 Ryd) and $a = -1$, and etau2 has $\tau_0 = 13.605$ (10^3 Ryd) and $a = 1$.

The second case, etau1 has $\tau_0 = 0.013605$ (1 Ryd) and $a = 1$, and etau2 has $\tau_0 = 13.605$ (10^3 Ryd) and $a = -1$.

The results are shown in Fig. 11. The influencing factor of mbb is temperature, etau can not and should not affect it. However, The right panel of Fig. 11 shows that etau could not really cut off the pow component and affect the mbb component. I think the left panel of Fig. 11 is more reasonable. It means that the first case is right. Besides, etau should not act on mbb. Fig. 11(b) is correct.

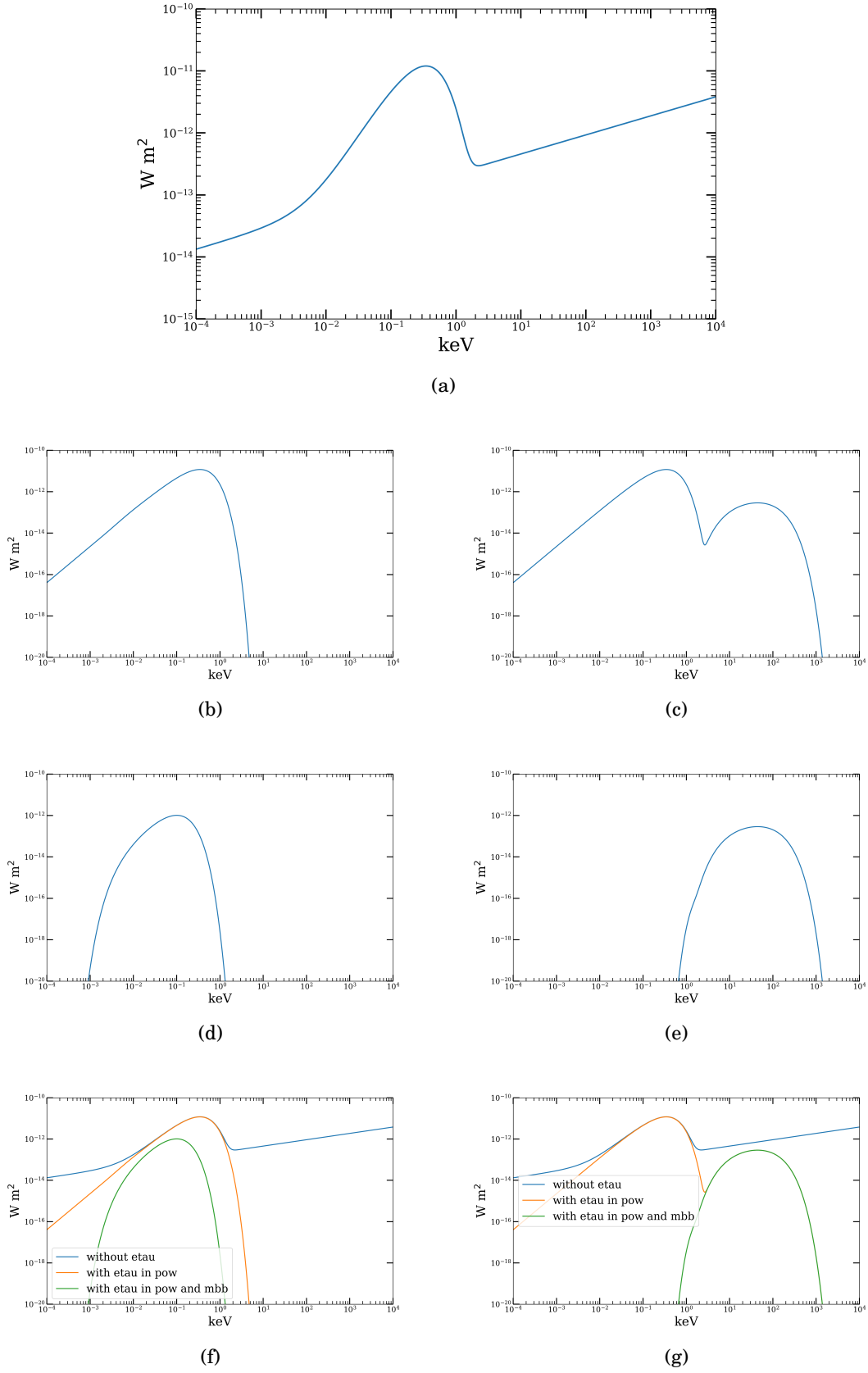


Figure 11: The Wavelength-Flux figure. The x-axis unit is keV and the y-axis unit is W m^2 . (a): The model is $\text{reds} \times (\text{mbb} + \text{pow})$. (b) and (c): The model is $\text{reds} \times (\text{mbb} + \text{etau1} \times \text{etau2} \times \text{pow})$. (d) and (e): The model is $\text{reds} \times \text{etau1} \times \text{etau2} \times (\text{mbb} + \text{pow})$. The left panels are in the first case, and the right panels are in the second case.

Explore the PION absorption model

Plot and compare the model spectra with $\log \xi = 2.0$ (frozen) but different column densities ($N_{\text{H}} = 10^{19}, 10^{20}, 10^{21} \dots, 10^{24} \text{ cm}^{-2}$); Summarize the trends of the absorption feature with increasing N_{H} .