High Intensity Optical Sources Calculations

APHC

U.S. ARMY PUBLIC HEALTH CENTER

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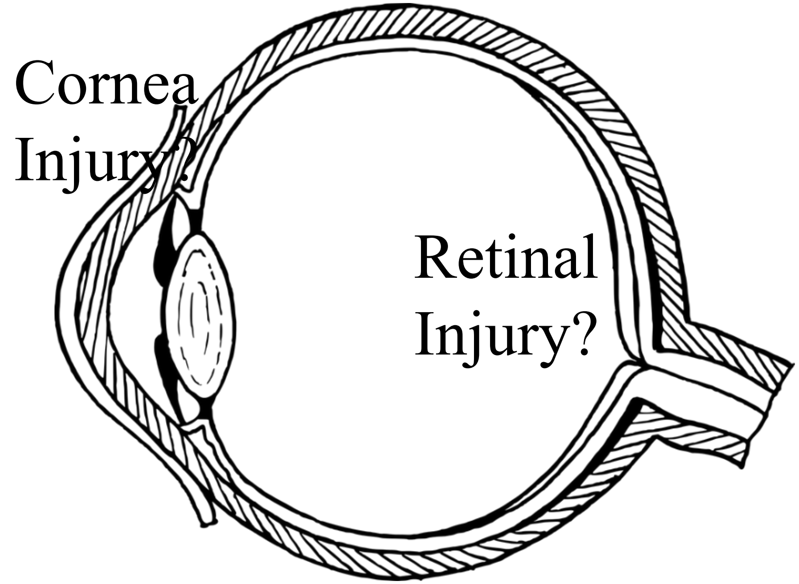
What is a High Intensity Optical Source?

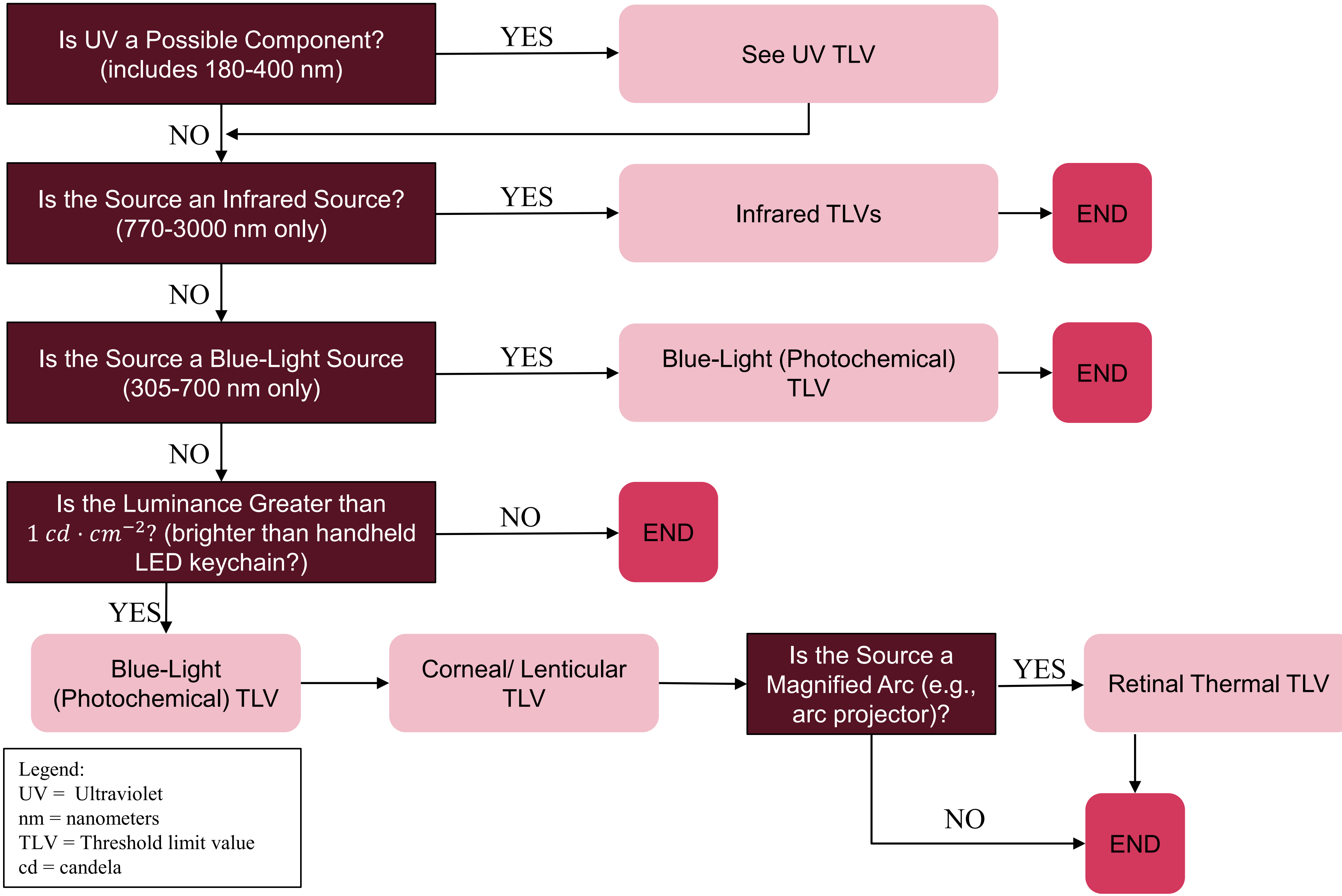
- Non-laser source of ultraviolet, visible, and/or IR radiation.
  - Welding and cutting arcs, high intensity lamps, flash events
- Like lasers, damage mechanisms are thermal & photochemical
- Formerly, guidance was in AR 40-46 with lasers (AR phased out)
  - HIOS guidance became “scattered,” harder to find

- Acute effects (short-term high exposure)
  - Possible damage to eyes and skin
  - Photochemical and thermal damage possible, just like lasers
- Chronic effects (long-term with years of exposure)
  - IR in hot environments (e.g., glass blowing factories, foundries) - cataract
  - UV - photoaging, skin cancer
  - Visible, especially blue – increased risk for eye diseases? Data inconclusive

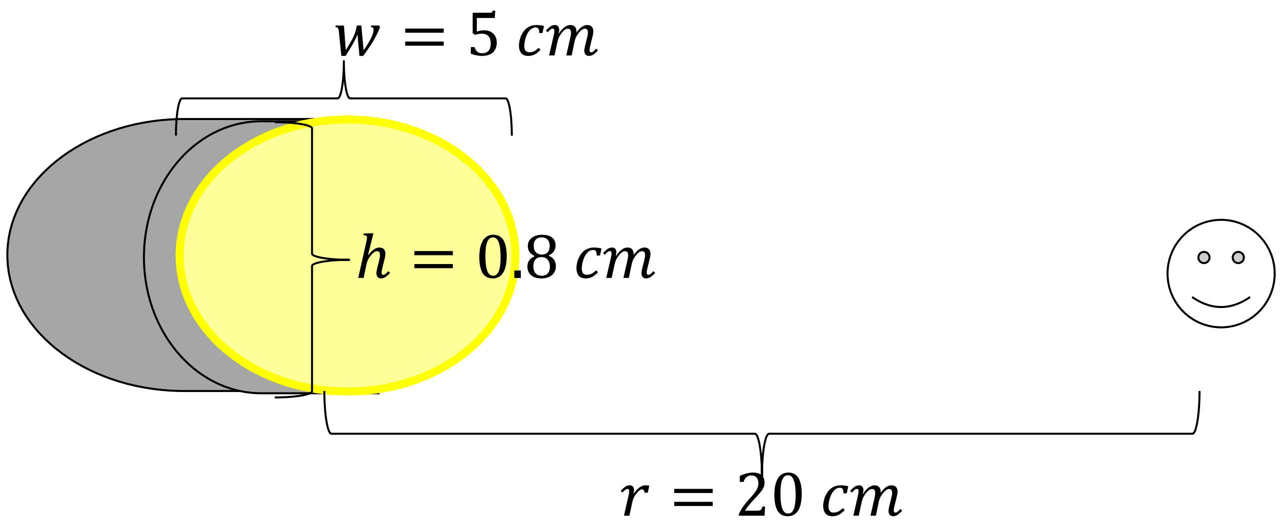


Skin Injury?

Optical (Non-laser) Source

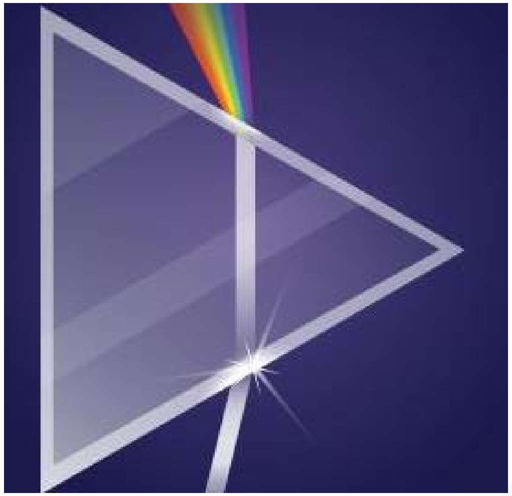


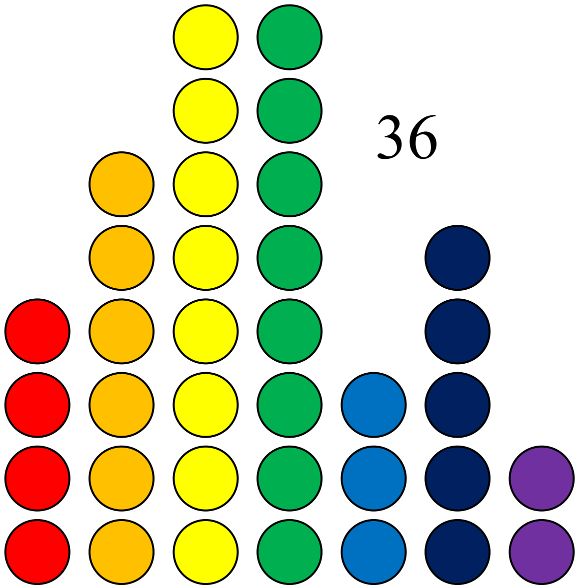
Example Parameters



Example is going to be looking at the spot light hazard for a Xenon Arc Lamp. It is oblong in shape, so it has a width of $h = 0.8\ cm$ and a length of $w = 5\ cm$. We will evaluate the hazard as if it is $r = 20\ cm$ away. The exposure time is only going to be for a quarter of a second $t = 0.25\ s$. The spectrum for the lamp is on the next slide.

Image Source: APHC NRD





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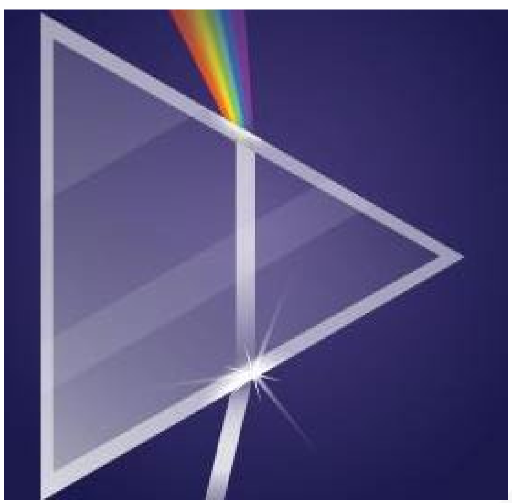

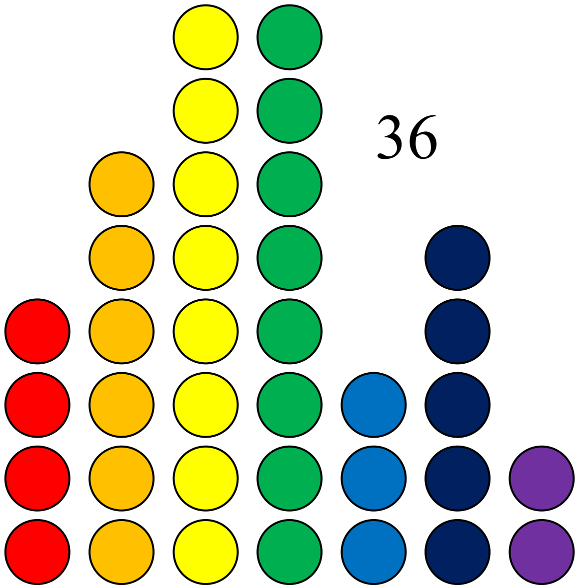

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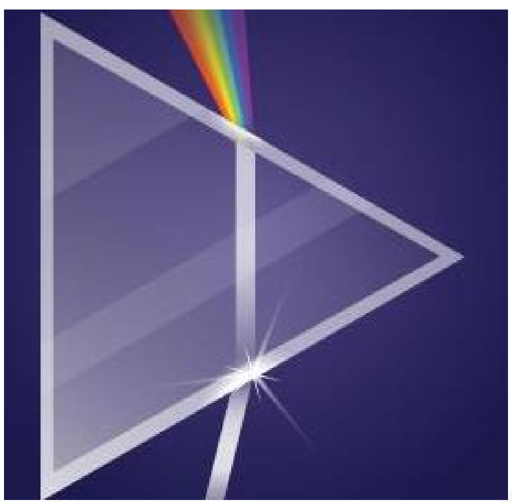

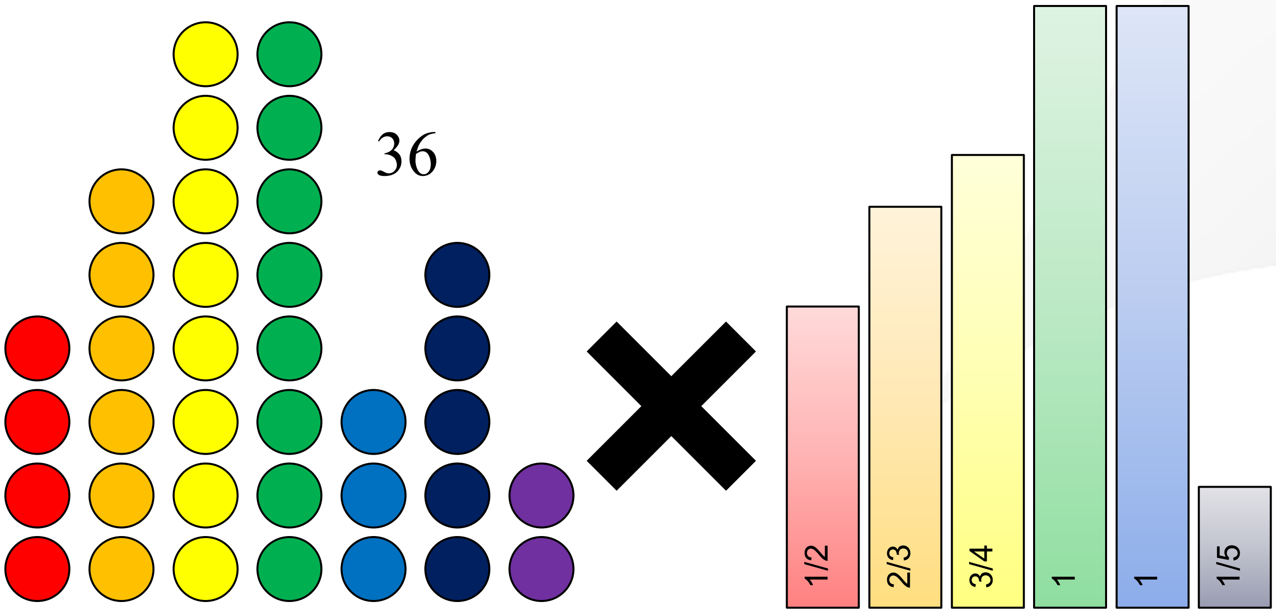
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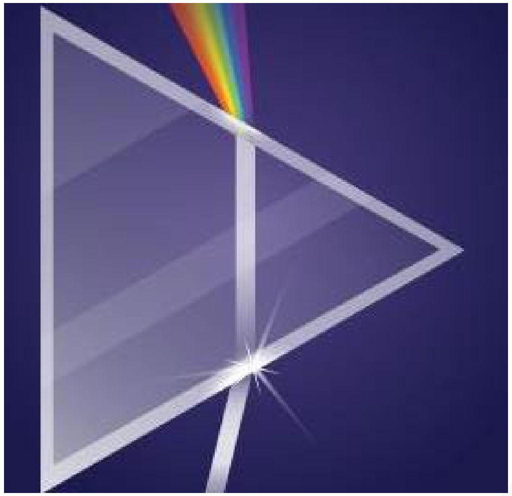
1/2
2/3
3/4
1
1
1/5

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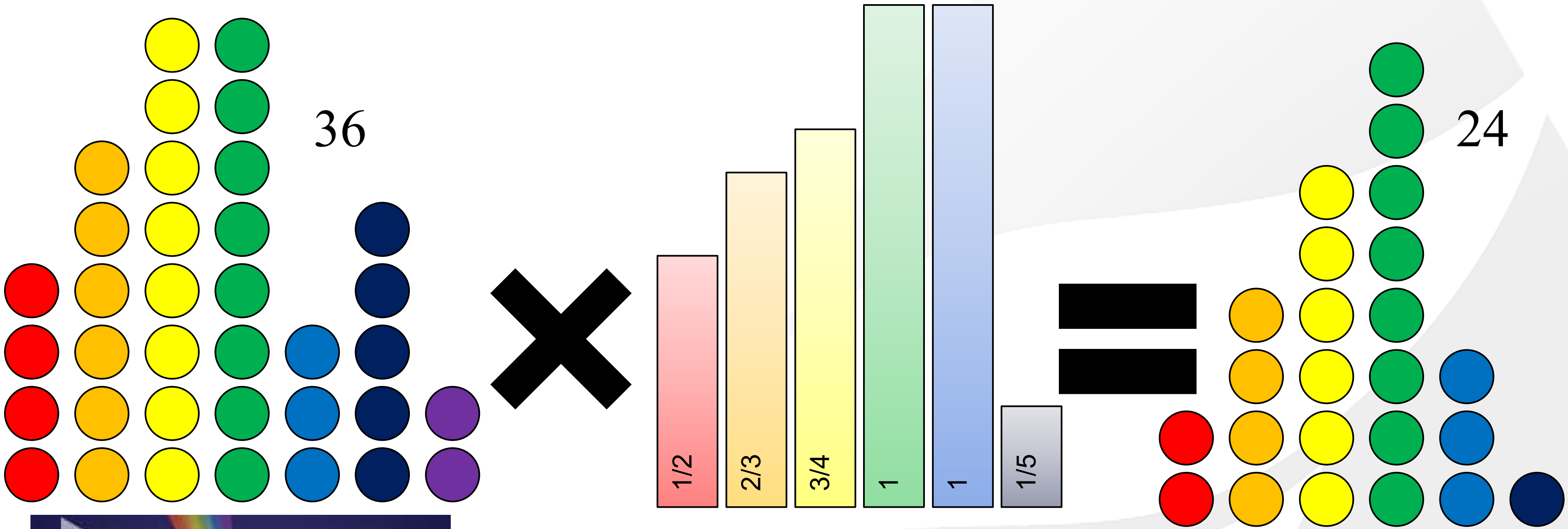
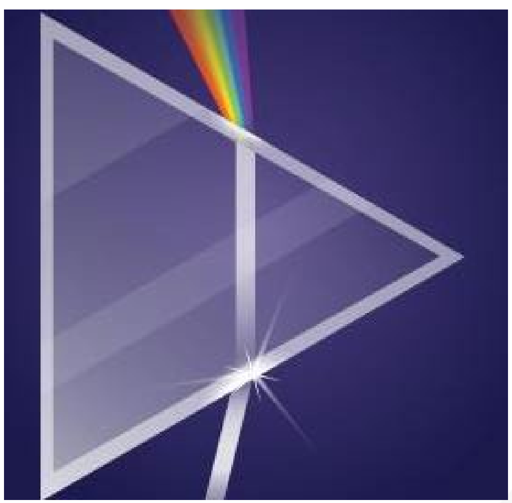

36
1/2
2/3
3/4
1
1
1/5
24

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Lamp Spectrum

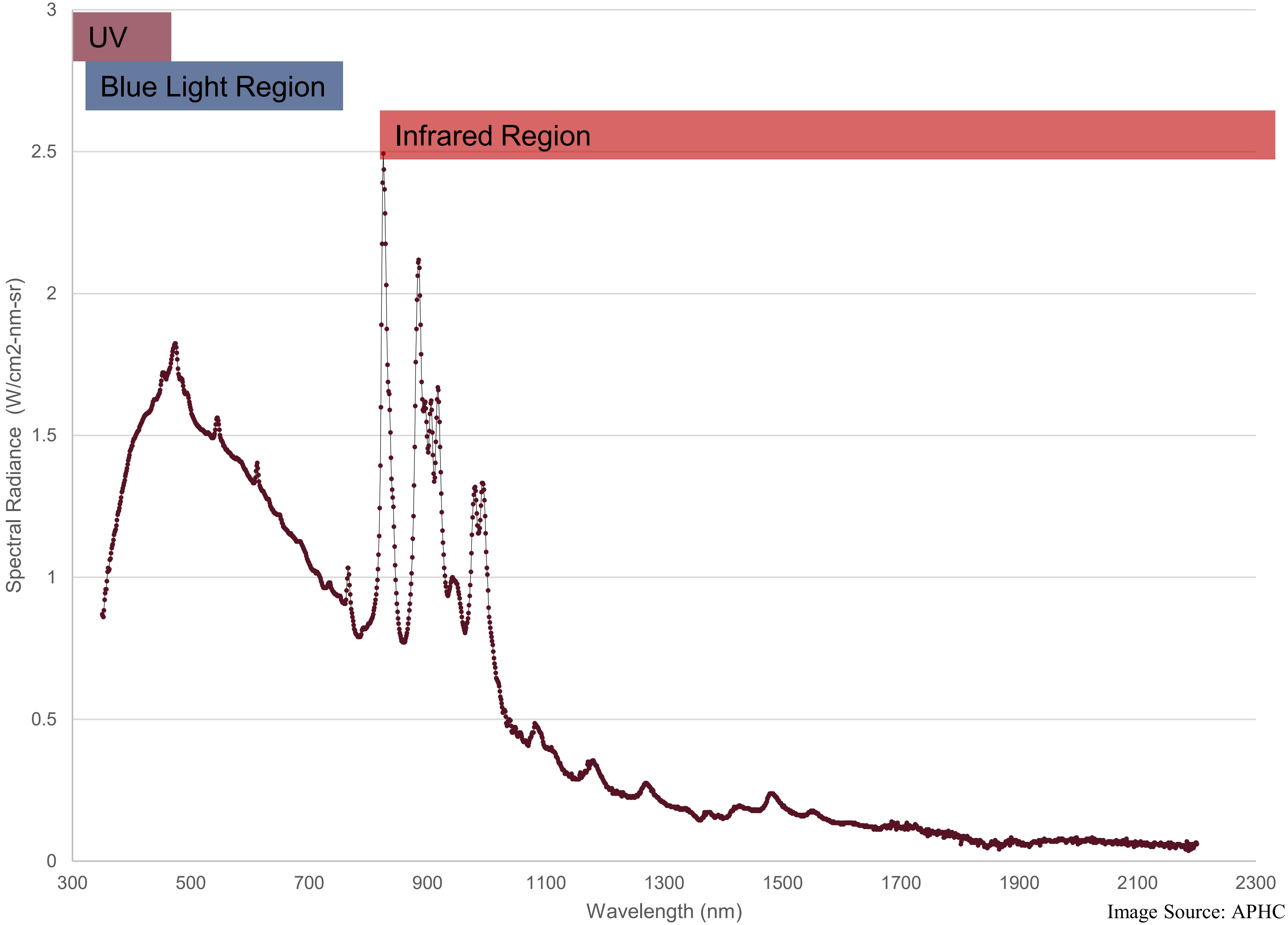
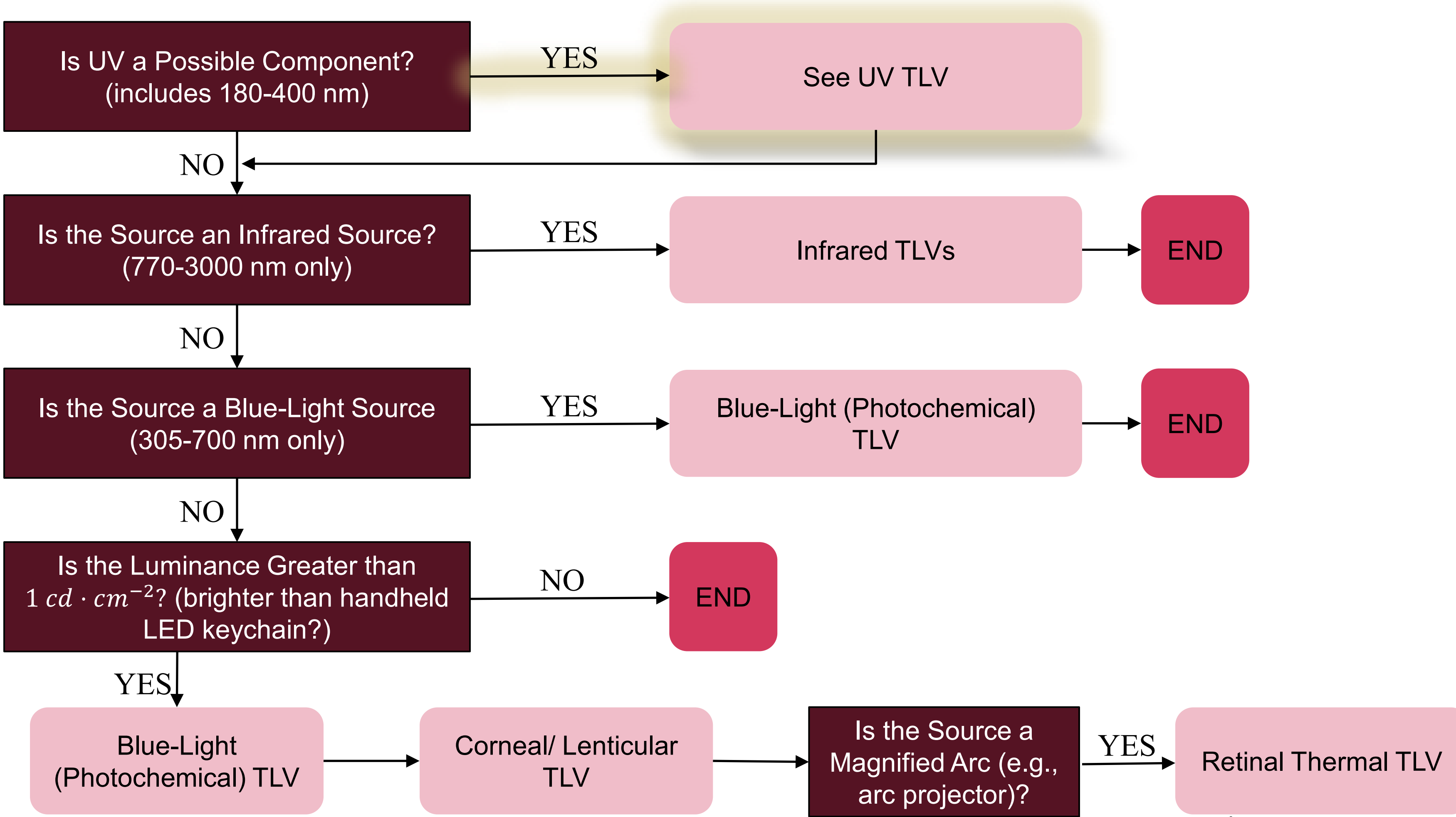


Image Source: APHC NRD

Optical (non-laser) Source



Legend:
UV = Ultraviolet
nm = nanometers
TLV = Threshold limit value
cd = candela

Lamp Spectrum

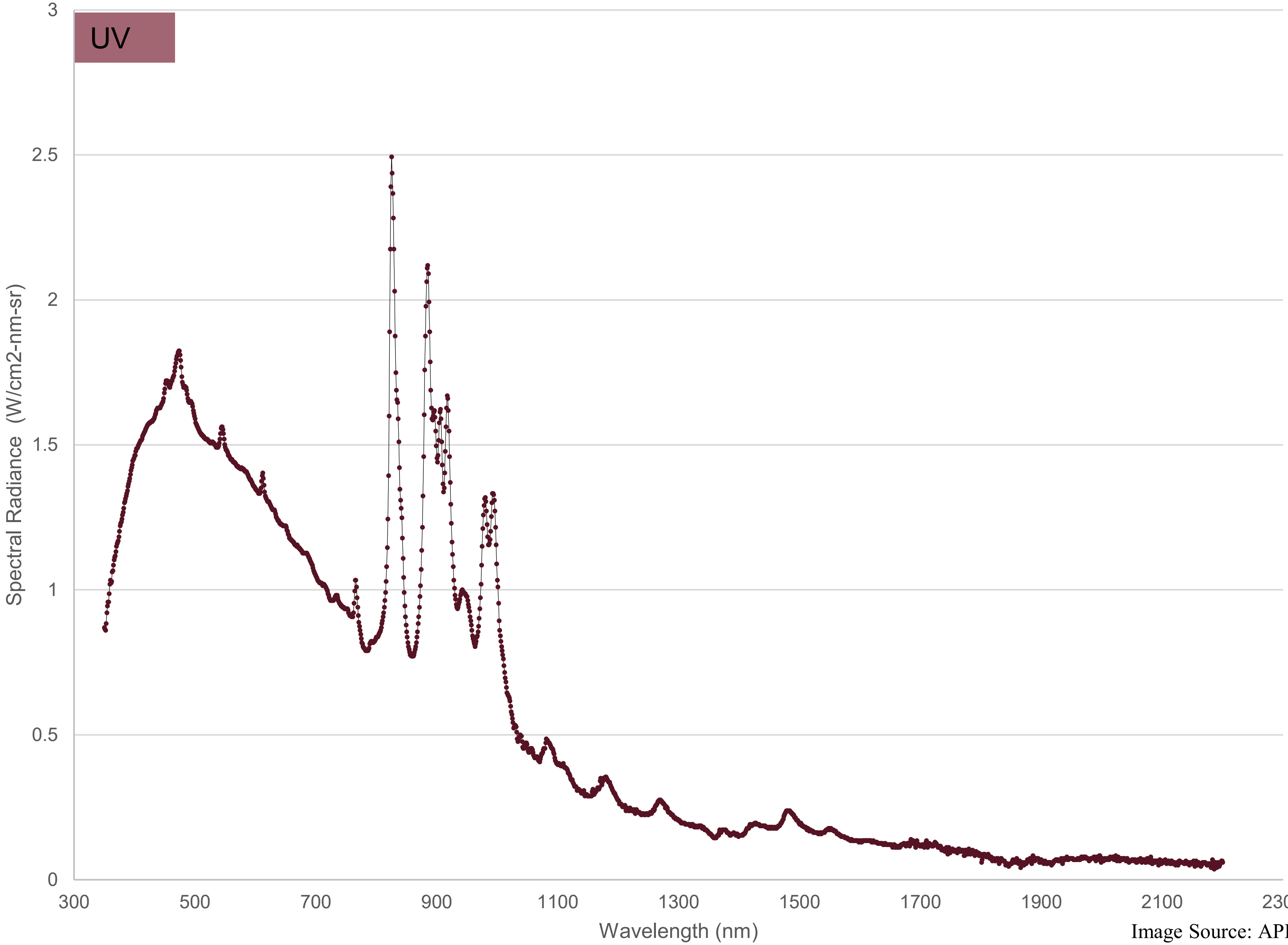


Image Source: APHC NRD

UV Hazard Function

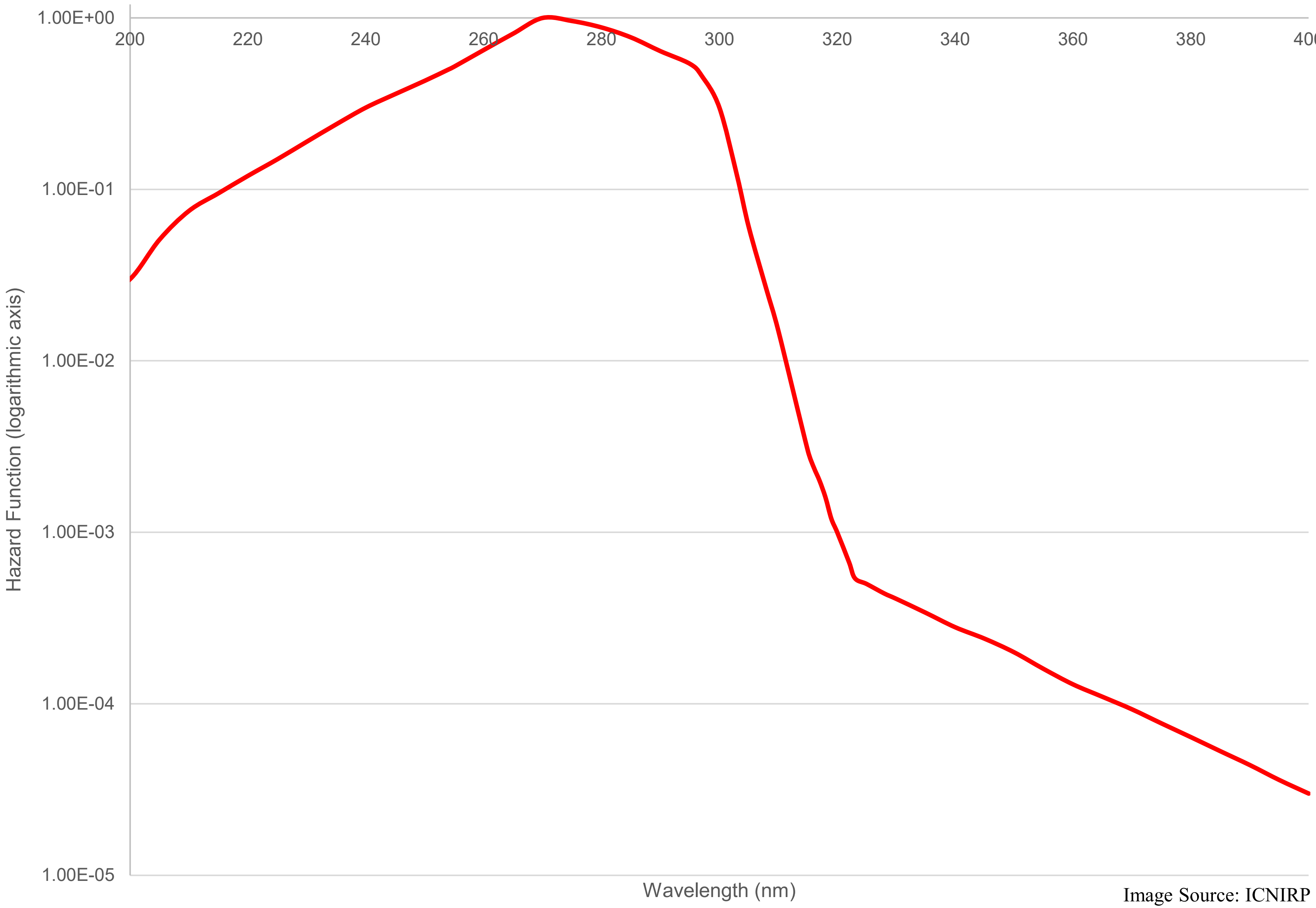
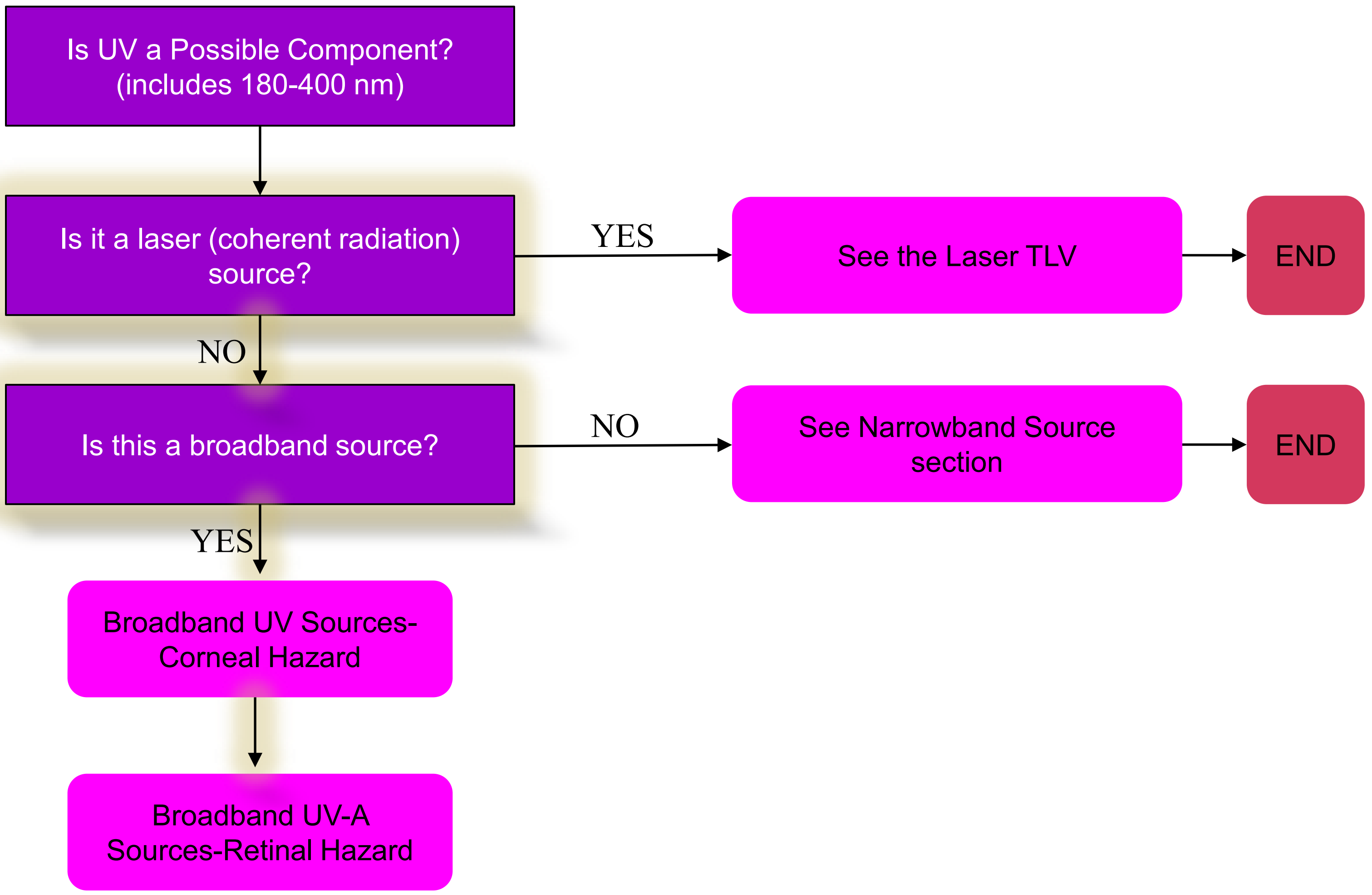


Image Source: ICNIRP 2013

UV Source


Is UV a Possible Component? (includes 180-400 nm)
Is it a laser (coherent radiation) source?
YES
See the Laser TLV
END
NO
Is this a broadband source?
NO
See Narrowband Source section
END
YES
Broadband UV Sources-Corneal Hazard
Broadband UV-A Sources-Retinal Hazard

Protect Against Cataractogenesis

$$E_{eff} = \Sigma_{180}^{400} E_\lambda \cdot S(\lambda) \cdot \Delta\lambda$$

Where:

$E_{eff} =$ Effective Irradiance $\left(\frac{W}{cm^2}\right)$ relative to a monochromatic source at $270\ nm$

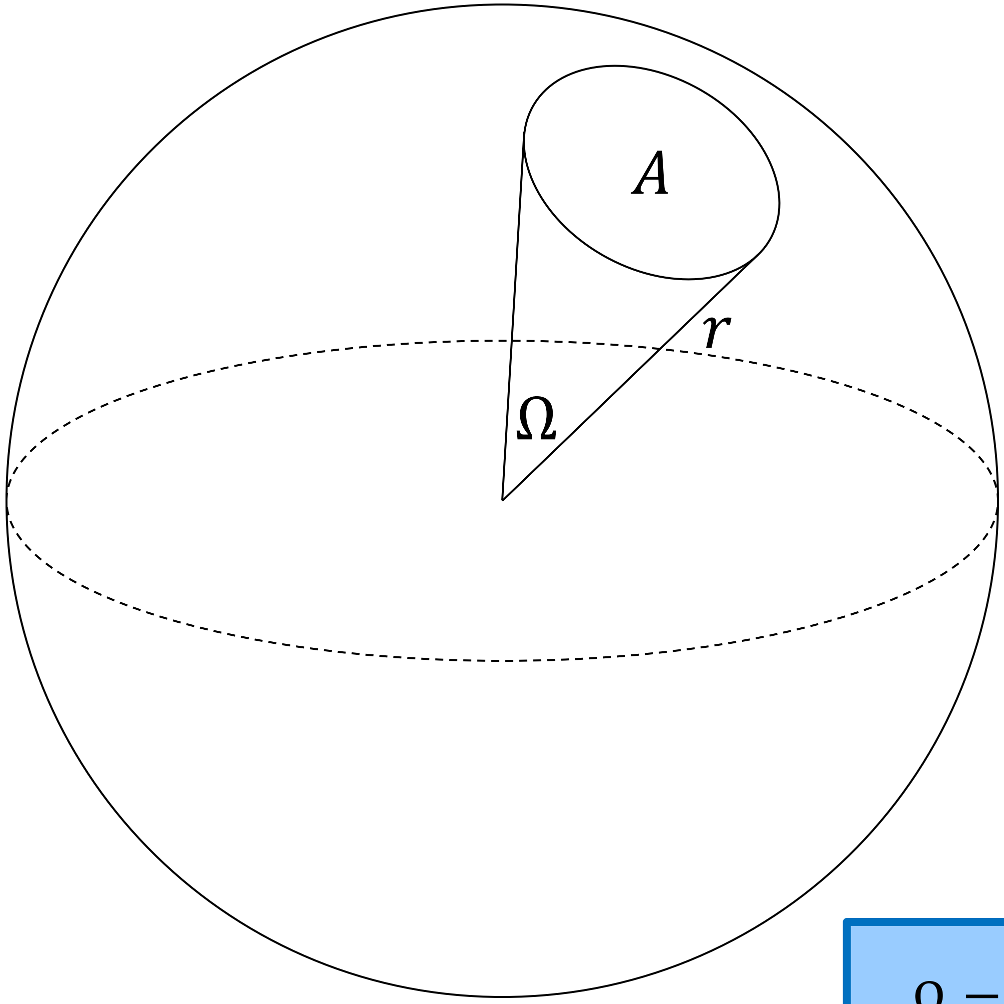
E_λ = Spectral Irradiance $\left(\frac{W}{cm^2 \cdot nm}\right)$

$S(\lambda)$ = Relative Spectral Effectiveness $(unitless)$ at the center wavelength

$\Delta\lambda$ = “bucket size” (nm)

NOTE: This equation is talking about the Irradiance $\left(\frac{W}{cm^2}\right)$, where as our data is in Radiance $\left(\frac{W}{cm^2 \cdot sr}\right)$. When dealing with this stuff be extremely careful with the units. The difference between Irradiance and Radiance is the unit of steradians (sr) in the denominator. To convert between the two we need to calculate the solid angle.

Solid Angle



Basically, the Solid Angle is the area of the source divided by the square of the distance from the source.

$$\Omega = \frac{A}{r^2}$$

Where:

Ω = Solid Angle (sr)

A = Area of source (cm^2)

For circle $A = \pi r^2$

For ellipse $A = \pi(\frac{h}{2} \cdot \frac{w}{2})$

r = distance from source (cm), if not specified then use $20\ cm$ as closest distance.

$$\Omega = \frac{A}{r^2} = \frac{\pi(5 \times 0.8)}{4 \cdot 20^2} = 0.0078\ sr$$

Image Source: APHC NRD

UV Hazard

	A	B	C	D	E
1	Wavelength	Radiance of Lamp	S Lambda	Scaling Factor (\Delta	Weighted Radiance
2	180		1.20E-02	5	0.00
3	185		1.55E-02	5	0.00
4	190		1.90E-02	5	0.00
5	195		2.45E-02	5	0.00
6	200		3.00E-02	5	0.00
7	205		5.10E-02	5	0.00
8	210		7.50E-02	5	0.00
9	215		9.50E-02	5	0.00
10					
14	340		2.80E-04	5	0.00
15	345		2.40E-04	5	0.00
16	350	0.870351178	0.0002	5	0.000870
17	355	0.945220096	0.00016	5	0.000756
18	360	1.034126937	0.00013	5	0.000672
19	365	1.085599319	0.00011	5	0.000597
20	370	1.151109622	0.000093	5	0.000535
21	375	1.202582004	0.000077	5	0.000463
22	380	1.258733693	0.000064	5	0.000403
23	385	1.314885382	0.000053	5	0.000348
24	390	1.366357763	0.000044	5	0.000301
25	395	1.422509452	0.000036	5	0.000256
26	400	1.464623219	0.00003	1	0.000044
27					
28					SUM
29					0.00524588

$$E_{eff} = \Sigma_{180}^{400} E_\lambda \cdot S(\lambda) \cdot \Delta\lambda$$

Where:

E_{eff} = Effective Irradiance $\left(\frac{W}{cm^2}\right)$ relative to a monochromatic source at $270\ nm$

E_λ = Spectral Irradiance $\left(\frac{W}{cm^2 \cdot nm}\right)$

$S(\lambda)$ = Relative Spectral Effectiveness $(unitless)$ at the center wavelength

$\Delta\lambda$ = “bucket size” (nm)

$$E_{eff} = 0.00525 \left(\frac{W}{cm^2 \cdot sr}\right) \cdot 0.0078\ sr$$

$$E_{eff} = 4.12 \times 10^{-5} \left(\frac{W}{cm^2}\right)$$

Multiply your Spectral data by the weighting function by how many wavelengths it represents.

To find E_{eff} simply use a spreadsheet to add all the values of the weighted data from $(180\ nm < \lambda < 400\ nm)$, and multiply by the solid angle to get the Radiance.

Exposure Limits

The exposure limit really depends on the viewing duration. The longer the viewing duration, the less light a person should be exposed to.

Is viewing duration (t) less than $1000\ s$ ($17\ mins$)

YES: Use $E_{UV-A}\left(\frac{mW}{cm^2}\right) t_{exposure} \leq 1000 \left(\frac{mJ}{cm}\right)$

NO: Use $E_{UV-A}\left(\frac{mW}{cm^2}\right) \leq 1.0 \left(\frac{mW}{cm^2}\right)$

$$E_{UV-A}\left(\frac{mW}{cm^2}\right) t_{exposure} \leq 1000 \left(\frac{mJ}{cm^2}\right)$$

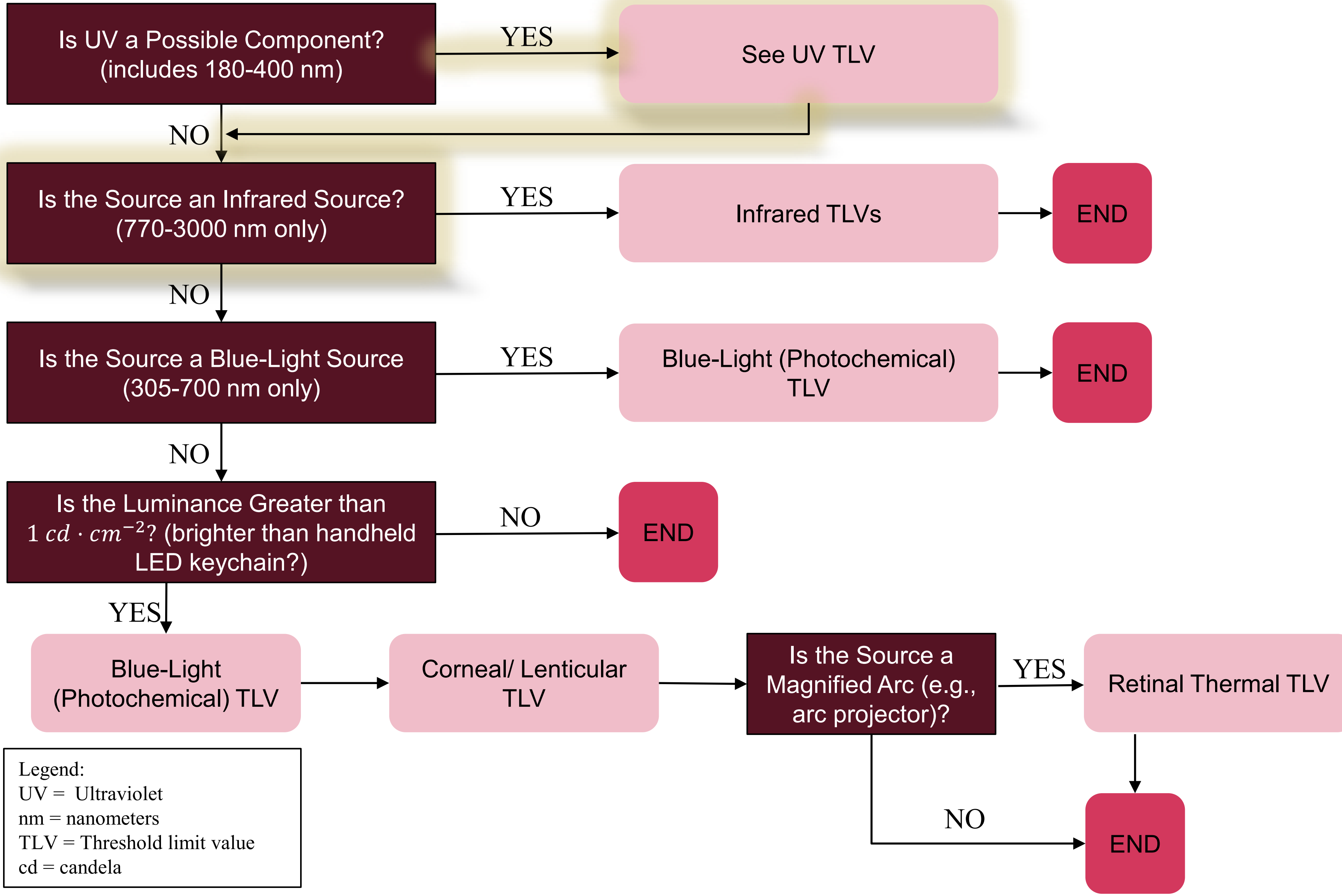
$$t = 0.25\ s$$

$$4.12 \times 10^{-5}\left(\frac{W}{cm^2}\right) \cdot \left(\frac{1000mW}{1W}\right) \cdot 0.25\ s \leq 1000 \left(\frac{mJ}{cm^2}\right)$$

$$0.0103\left(\frac{mJ}{cm^2}\right) \leq 1000 \left(\frac{mJ}{cm^2}\right)$$

It is very important to note that UV exposure is **cumulative**. Also be careful with the units of this, notice how I had to convert Watts to milliwatts to make sure that the units match.

Optical (Non-laser) Source



Lamp Spectrum

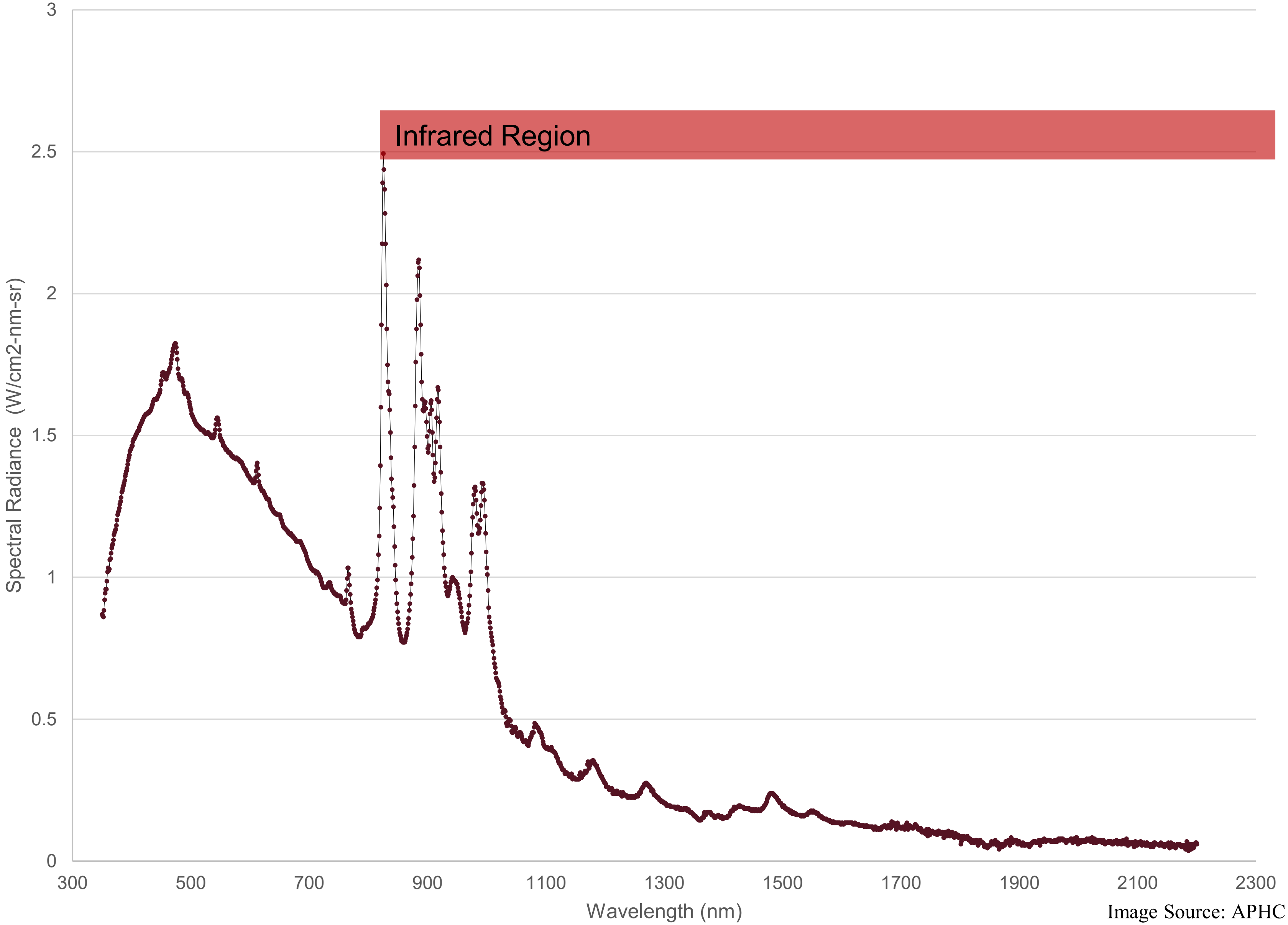
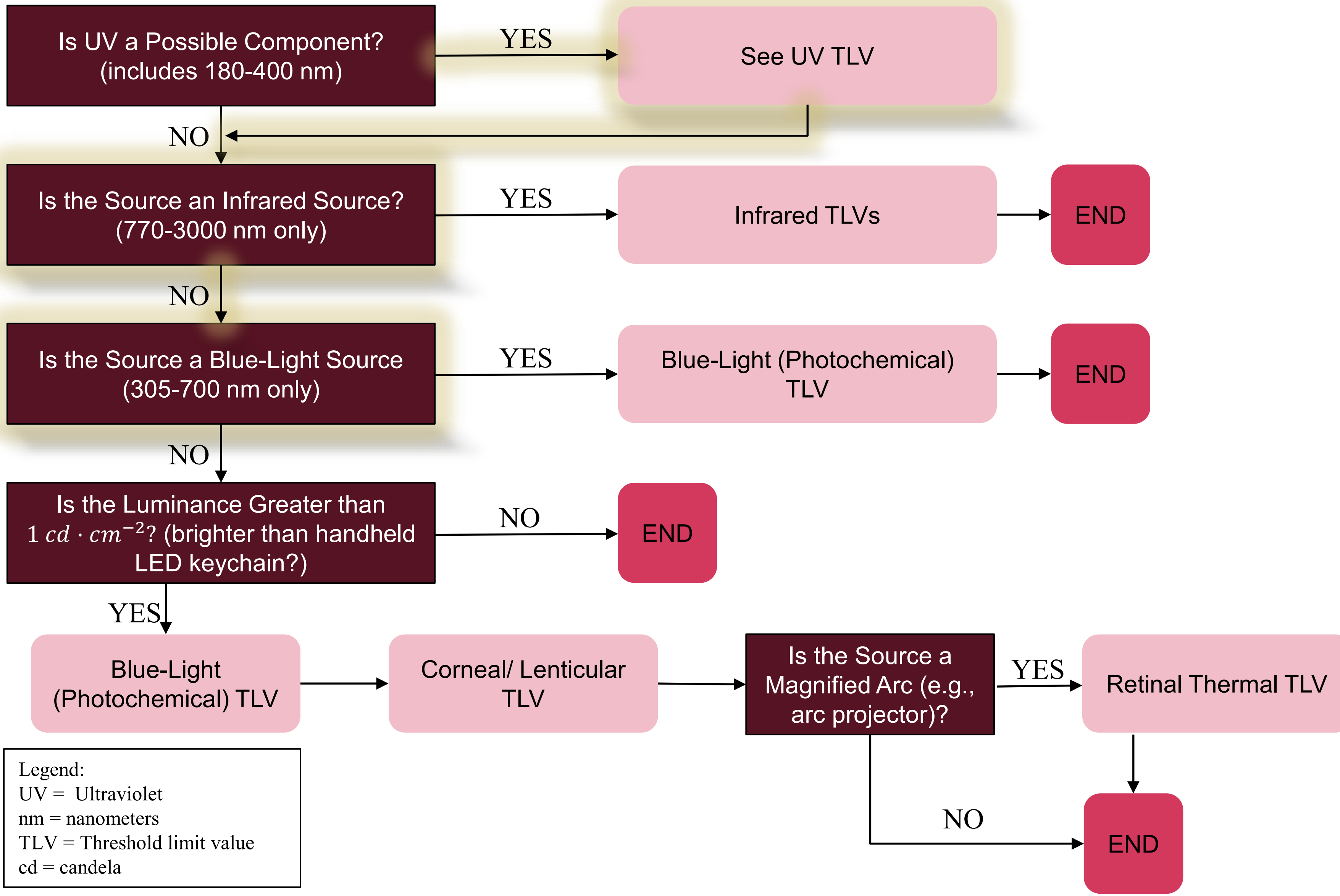
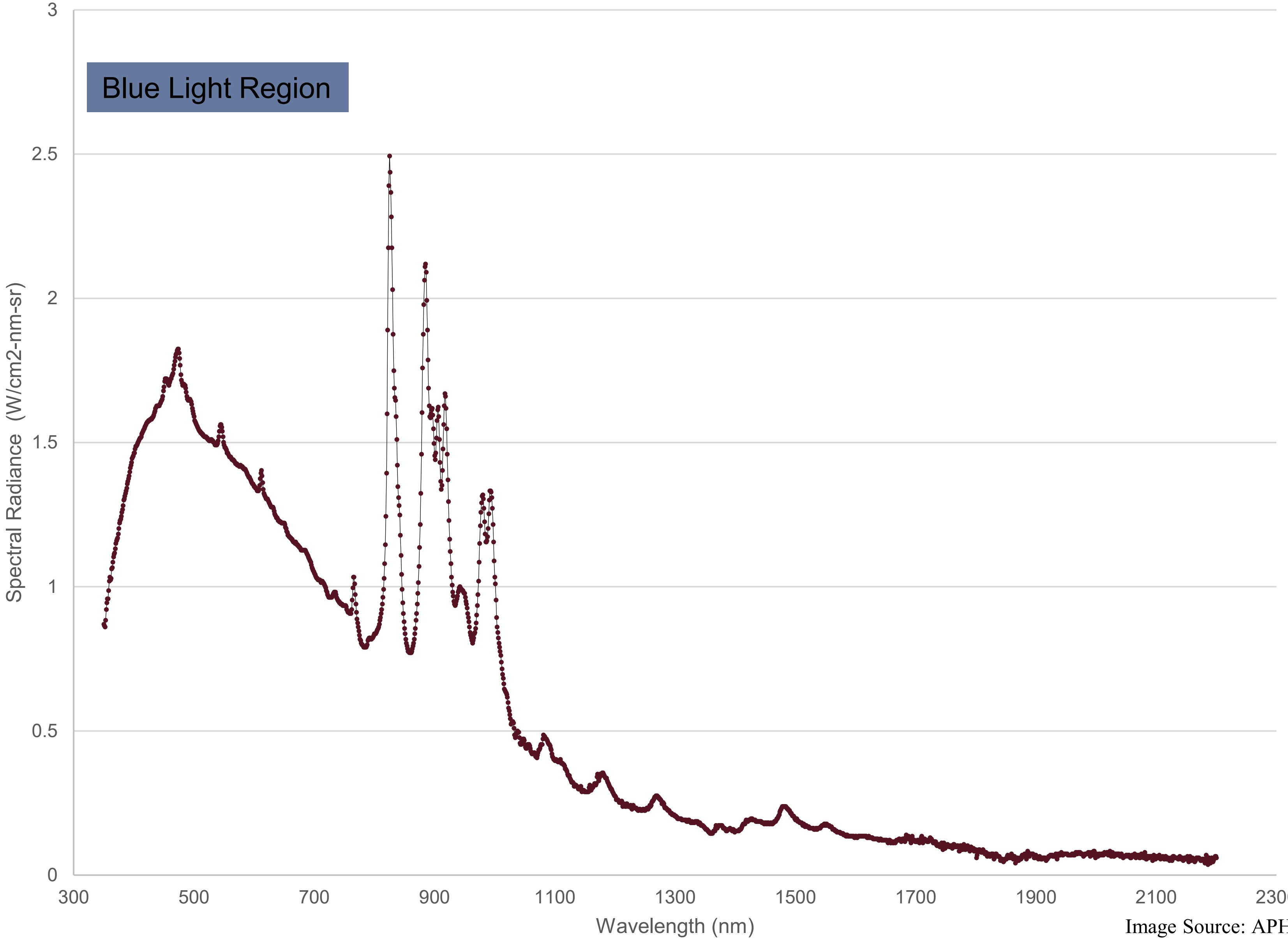


Image Source: APHC NRD

Optical (Non-laser) Source



Lamp Spectrum



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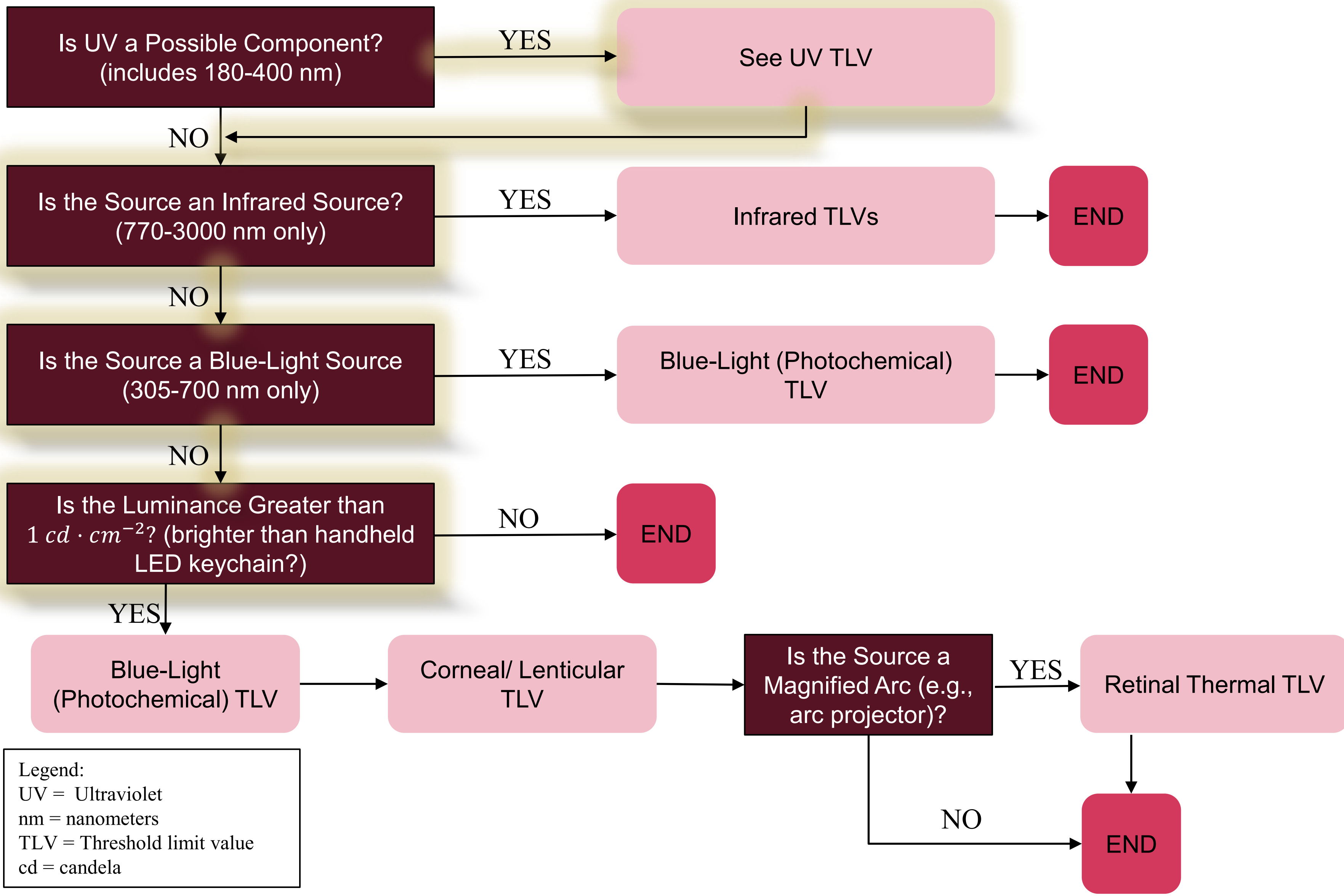
Optical (Non-laser) Source



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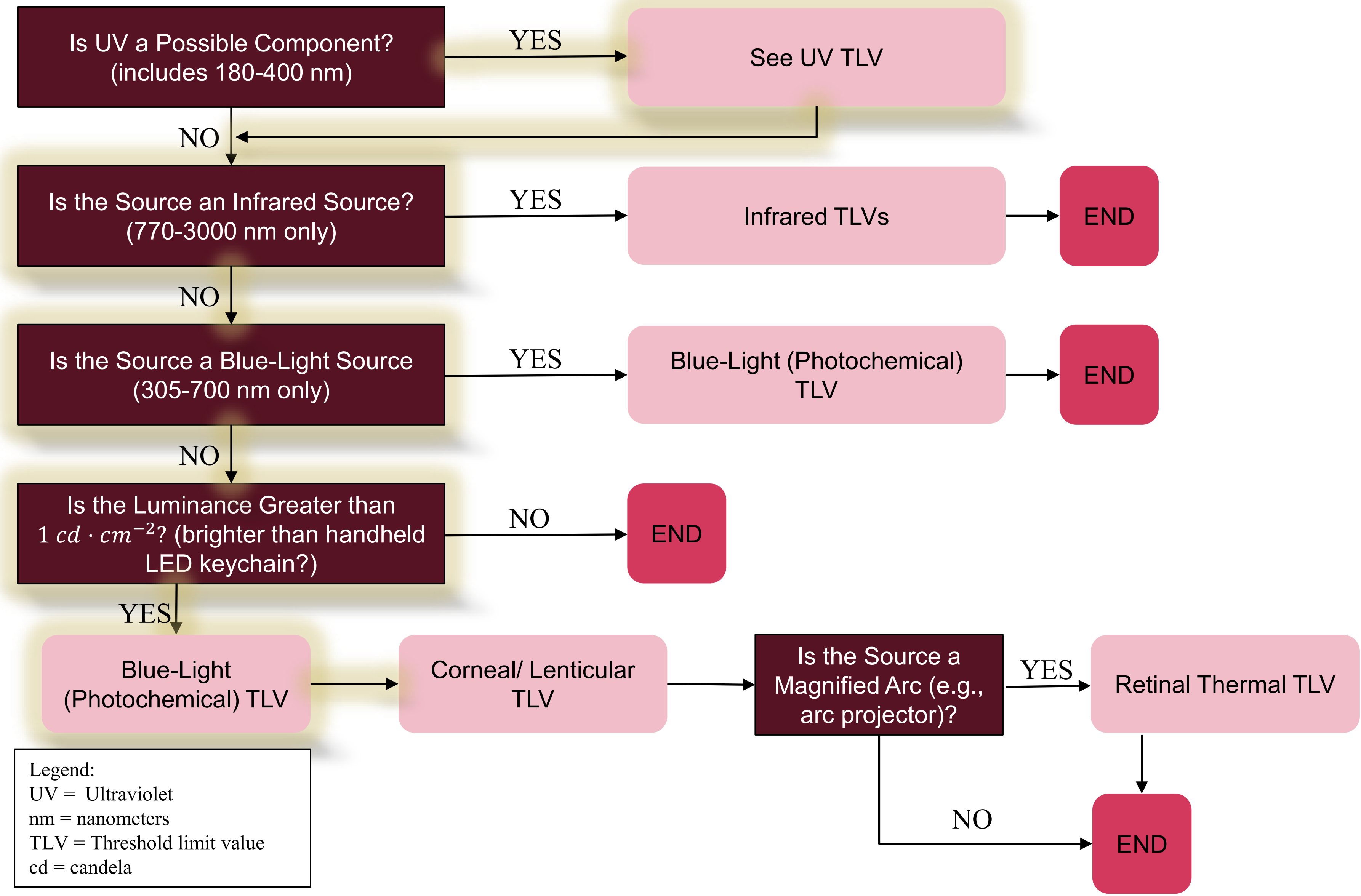
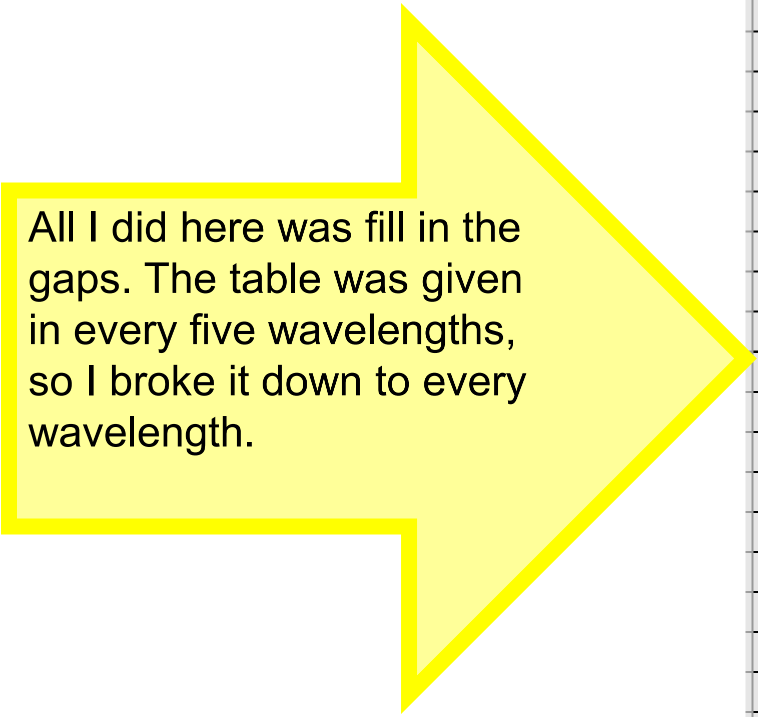


Weighting Functions

Wavelent	Aphakic H	Blue-Light	Retinal Ther
310	6.000	0.01	
315	6.000	0.01	
320	6.000	0.01	
325	6.000	0.01	
330	6.000	0.01	
335	6.000	0.01	
340	5.880	0.01	
345	5.710	0.01	
350	5.460	0.01	
355	5.220	0.01	
360	4.620	0.01	
365	4.290	0.01	
370	3.750	0.01	
375	3.560	0.01	
380	3.190	0.01	0.01
385	2.310	0.0125	0.0125
390	1.880	0.025	0.025
395	1.580	0.050	0.050
400	1.430	0.100	0.100
405	1.300	0.200	0.200
410	1.250	0.400	0.400
415	1.200	0.800	0.800
420	1.150	0.900	0.900
425	1.110	0.950	0.950
430	1.070	0.980	0.980
435	1.030	1.000	1.00



A	B	C	D
Waveleng	Aphakic H	Blue-Light	Retinal The
305	6.000	0.01	
306	6.000	0.01	
307	6.000	0.01	
308	6.000	0.01	
309	6.000	0.01	
310	6.000	0.01	
311	6.000	0.01	
312	6.000	0.01	
313	6.000	0.01	
314	6.000	0.01	
315	6.000	0.01	
316	6.000	0.01	
317	6.000	0.01	
318	6.000	0.01	
319	6.000	0.01	
320	6.000	0.01	
321	6.000	0.01	
322	6.000	0.01	
323	6.000	0.01	
324	6.000	0.01	
325	6.000	0.01	
326	6.000	0.01	
327	6.000	0.01	
328	6.000	0.01	
329	6.000	0.01	
330	6.000	0.01	

Blue Light Hazard Function

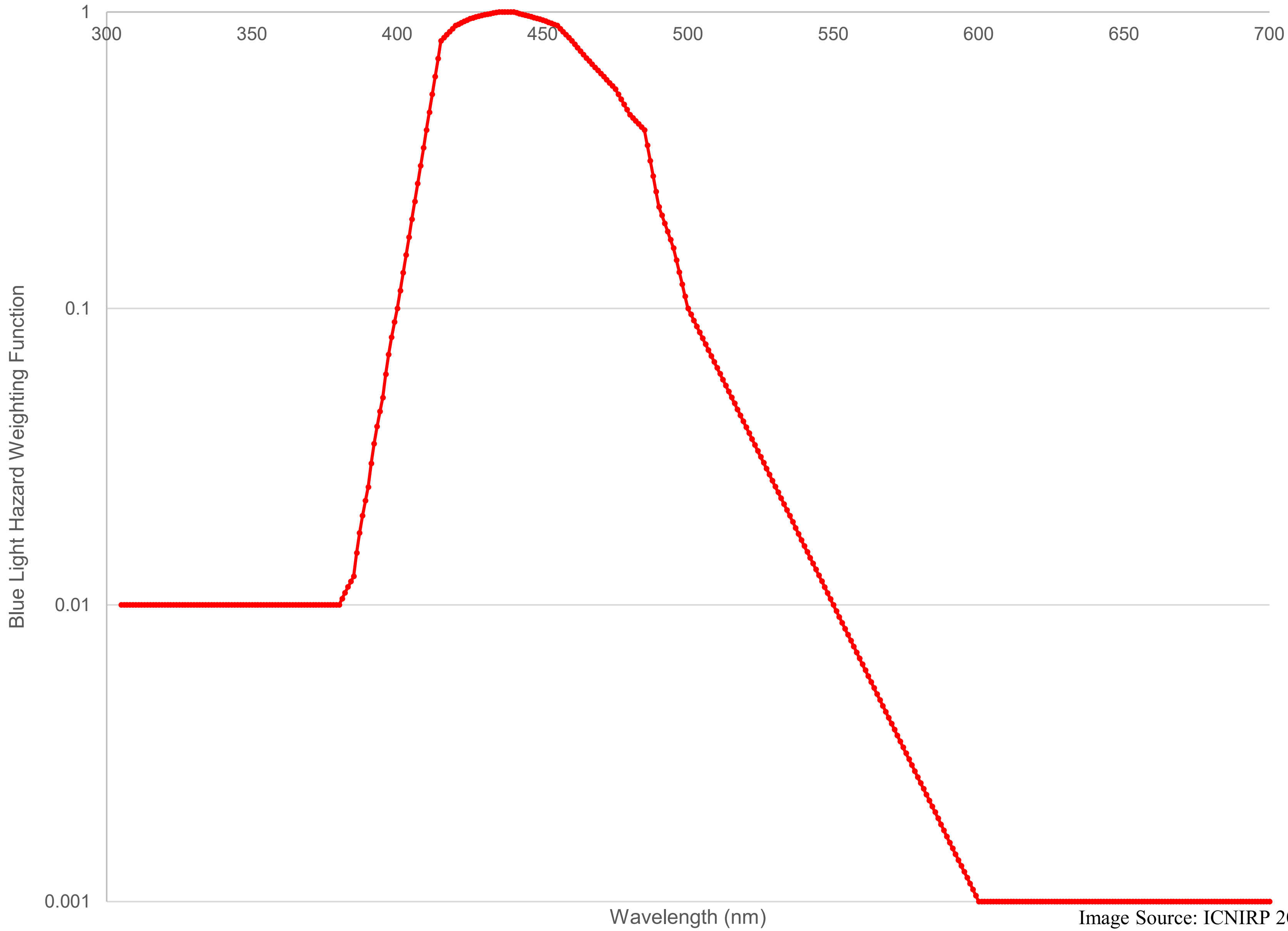


Image Source: ICNIRP 2013

Blue-Light Weighting Function Applied to Our Spectrum

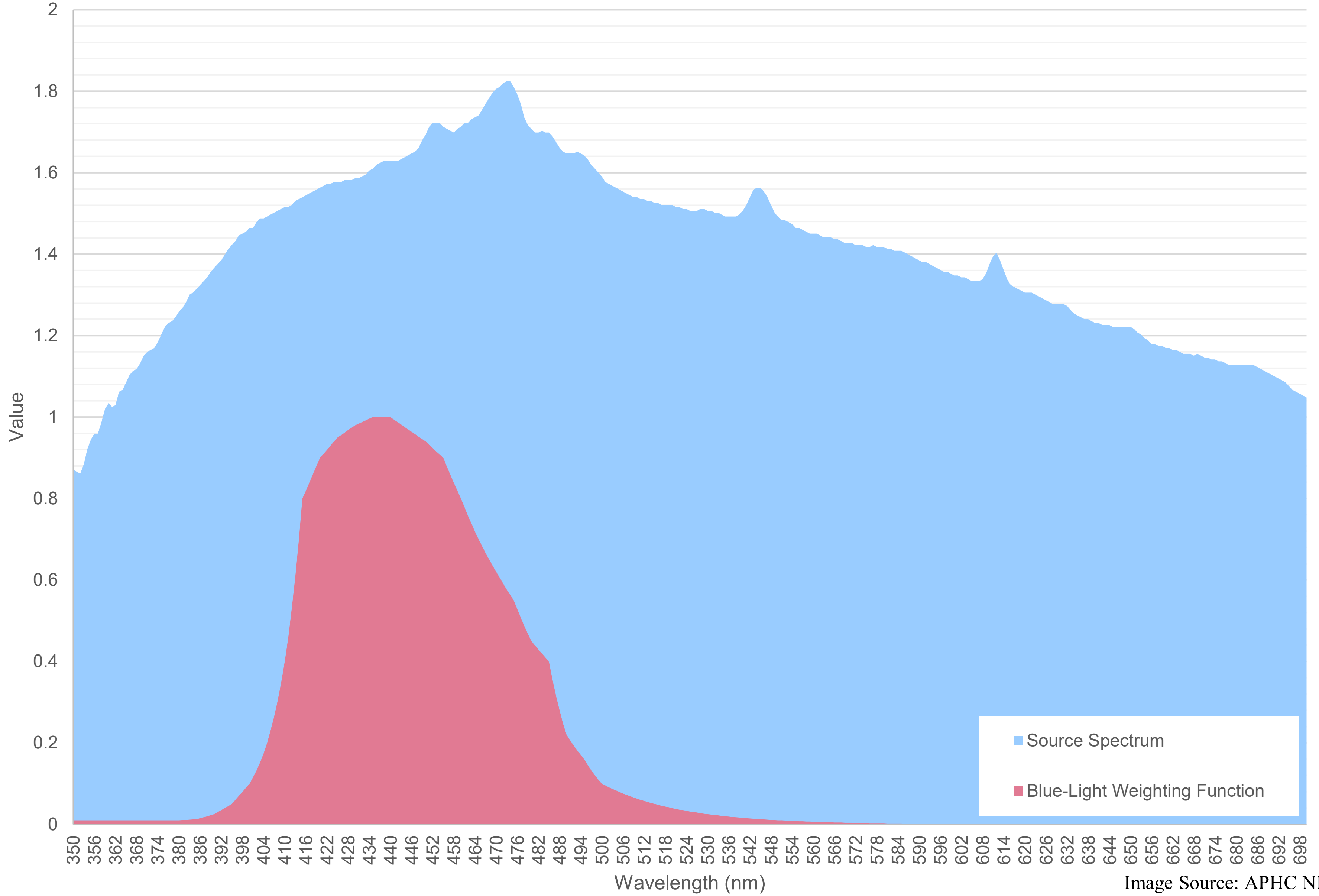


Image Source: APHC NRD

Blue-Light Weighting Function Applied to Our Spectrum

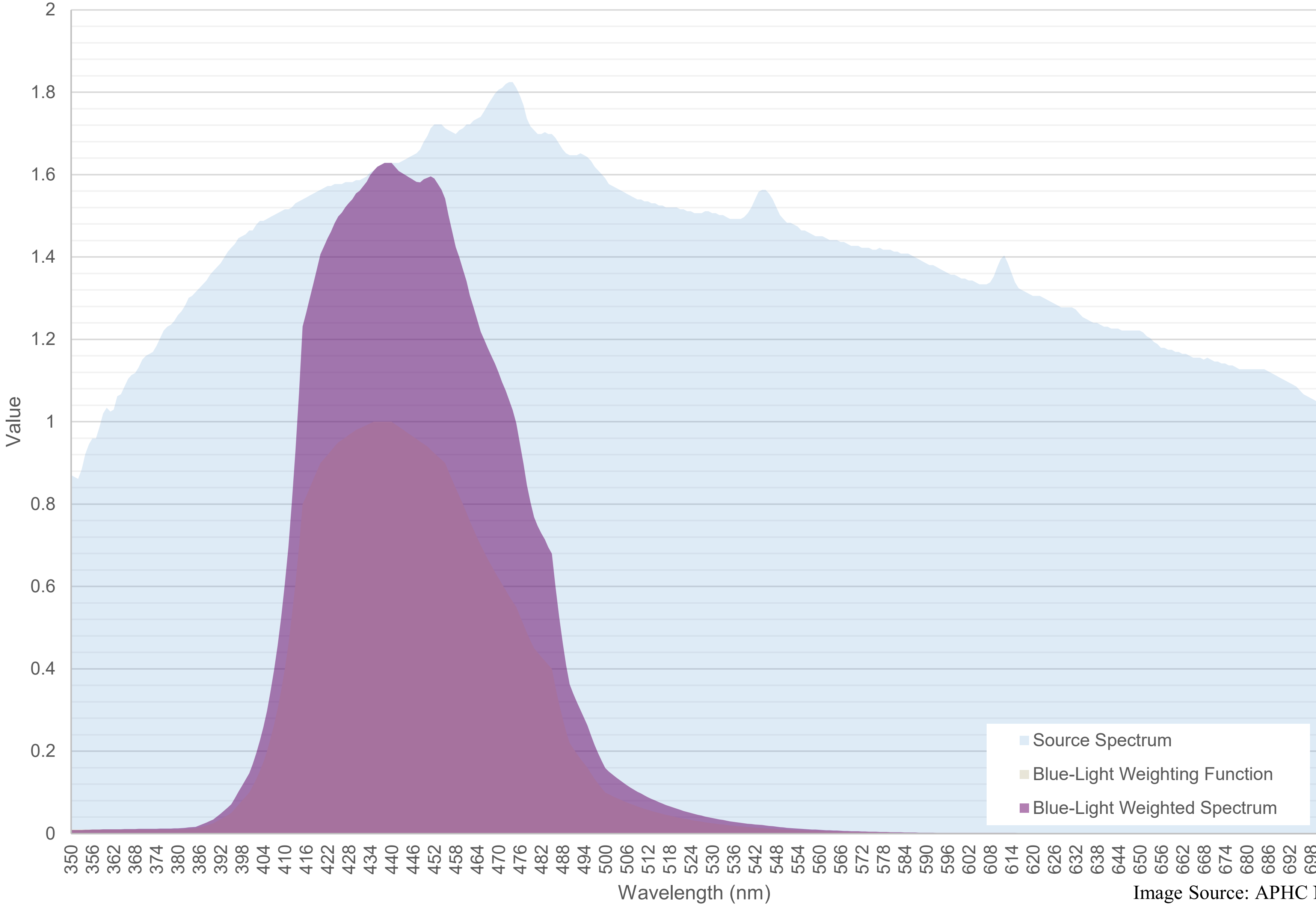


Image Source: APHC NRD

Blue Light Hazard

	A	B	C	D	F	G	I	J
1	Wave-	Spectral		SUM		SUM		SUM
2	length	Radiance		309.3239		111.7254		616.6538
3	nm	W/cm2-nr	Aphakic H	Weighted	Blue-Light	Weighted	Retinal Th	Weighted
4	305		6.000	0	0.01	0		0
5	306		6.000	0	0.01	0		0
6	307		6.000	0	0.01	0		0
7	308		6.000	0	0.01	0		0
8	309		6.000	0	0.01	0		0
9	310		6.000	0	0.01	0		0
10	311		6.000	0	0.01	0		0
11	312		6.000	0	0.01	0		0
12	313		6.000	0	0.01	0		0
13	314		6.000	0	0.01	0		0
14	315		6.000	0	0.01	0		0
15	316		6.000	0	0.01	0		0
16	317		6.000	0	0.01	0		0
17	318		6.000	0	0.01	0		0
91	692	1.094958	0.001	0.001095	0.001	0.001095	1.0	1.094958
92	693	1.090279	0.001	0.00109	0.001	0.00109	1.0	1.090279
93	694	1.085599	0.001	0.001086	0.001	0.001086	1.0	1.085599
94	695	1.076241	0.001	0.001076	0.001	0.001076	1.0	1.076241
95	696	1.066882	0.001	0.001067	0.001	0.001067	1.0	1.066882
96	697	1.062203	0.001	0.001062	0.001	0.001062	1.0	1.062203
97	698	1.057523	0.001	0.001058	0.001	0.001058	1.0	1.057523
98	699	1.052844	0.001	0.001053	0.001	0.001053	1.0	1.052844
99	700	1.048165	0.001	0.001048	0.001	0.001048	1.000	1.048165

$$L_B = \Sigma_{305}^{700} L_\lambda \cdot B(\lambda) \cdot \Delta\lambda$$

Where:

L_B = Effective Radiance of Light Source $\left(\frac{W}{cm^2 \cdot sr}\right)$; To protect against retinal photo-chemical injury from chronic blue-light exposure

L_λ = Spectral Radiance $\left(\frac{W}{cm^2 \cdot sr \cdot nm}\right)$

$B(\lambda)$ = Blue-Light Hazard Function $(unitless)$

$\Delta\lambda$ = "bucket size" (nm)

Multiply your Spectral data by the weighting function to get weighted data (column G).

To find L_B simply use a spreadsheet to add all the values of the weighted data from $(305\ nm < \lambda < 700\ nm)$.

$$L_B = 111.75 \left(\frac{W}{cm^2 \cdot sr}\right)$$

Exposure Limits

The exposure limit really depends on the viewing duration. The longer the viewing duration, the less light a person should be exposed to.

Is viewing duration (t) less than $10^4\ s$ ($167\ mins$ or $\sim 2.8\ hrs$)

YES → Use $L_B\left(\frac{W}{cm^2 \cdot sr}\right) \leq \frac{100}{t(s)}$

NO → Use $L_B\left(\frac{W}{cm^2 \cdot sr}\right) \leq 10^{-2}$

$$L_B \leq \frac{100}{t(s)}$$

$$t = 0.25\ s$$

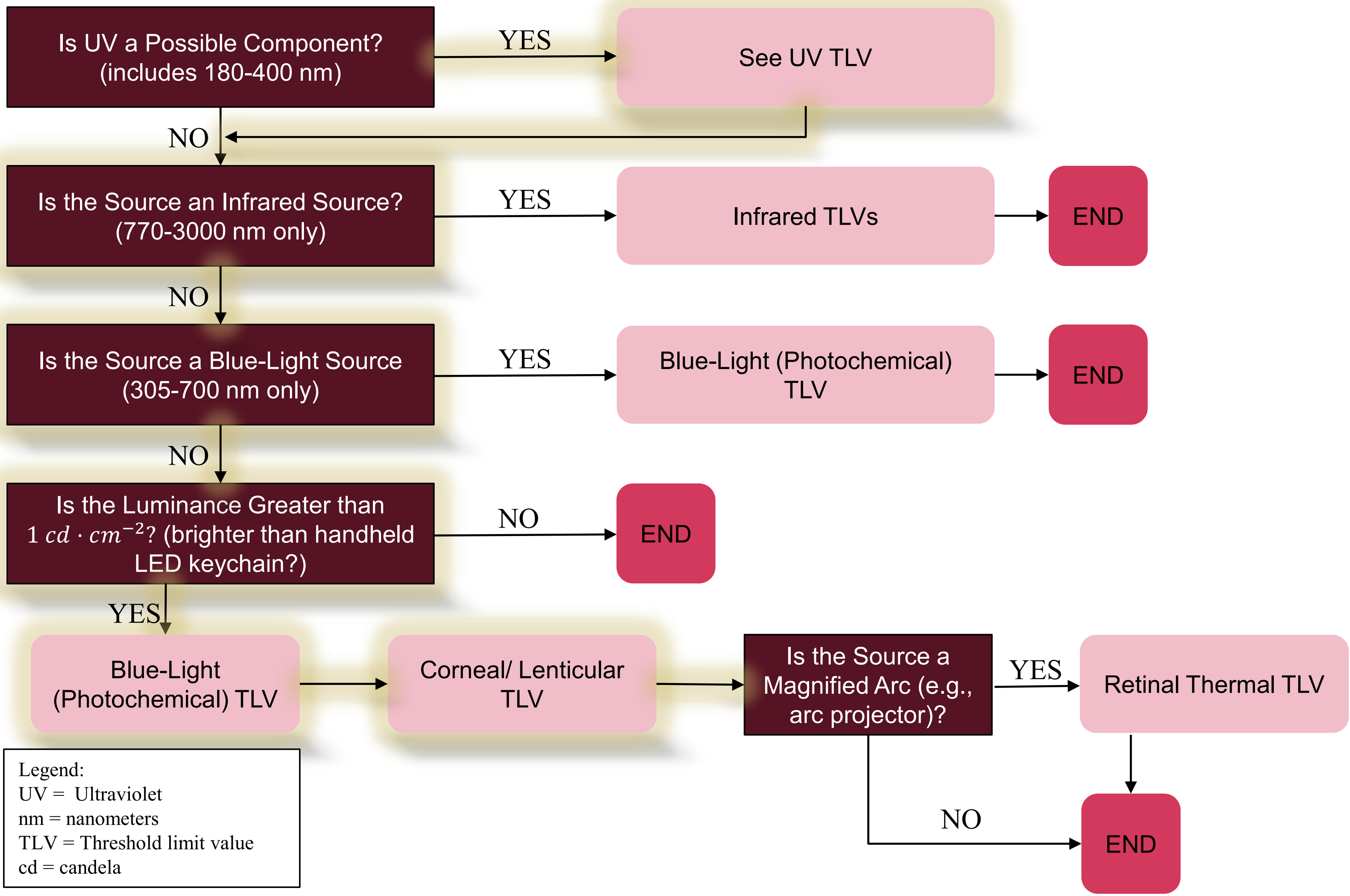
$$111.75 \leq \frac{100}{.25}$$

$$111.75 \leq 400$$

True

It is very important to note that Blue Light Exposure is **cumulative**, so our example says that this person is safe for a 0.25-s exposure, but if they are exposed for longer than 1 s within that working day, then they are over the limit.

Optical (Non-laser) Source



Protect against Cataractogenesis

$$E_{IR-only} = \sum_{770}^{3000} E_\lambda \cdot \Delta\lambda$$

Where:

$E_{IR-only}$ =Total Infrared Irradiance $\left(\frac{W}{cm^2}\right)$; To protect against thermal injury to the cornea and lens from infrared (IR) radiation.

E_λ = Irradiance $\left(\frac{W}{cm^2 \cdot nm}\right)$

$\Delta\lambda$ = "bucket size" (nm)

NOTE: There is no weighting function, which means that all wavelengths between 770-3000 nm contribute equally to the corneal hazard.

NOTE: This equation is talking about the Irradiance $\left(\frac{W}{cm^2}\right)$, where as our data and all the calculations before us is in Radiance $\left(\frac{W}{cm^2 \cdot sr}\right)$. When dealing with this stuff be extremely careful with the units.

Solid Angle

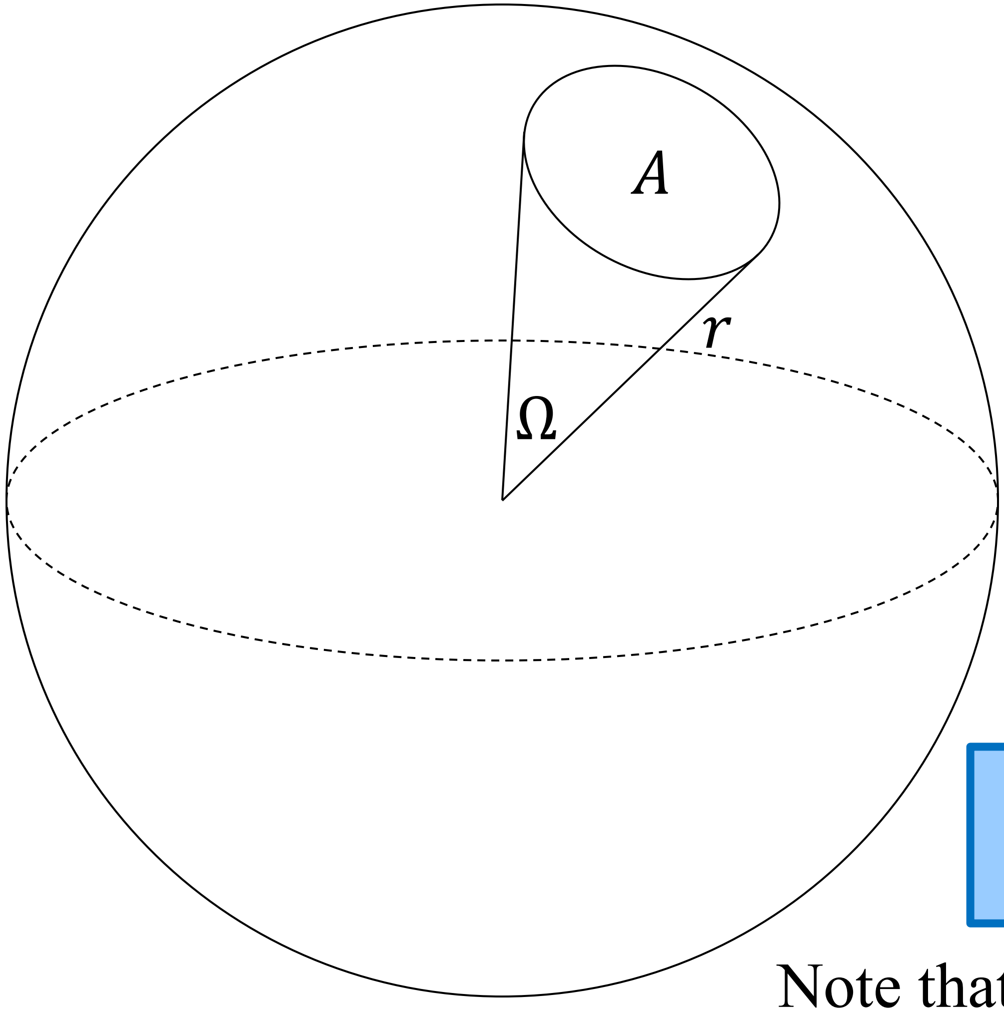


Image Source: APHC NRD

Again I should remind you about Solid Angles

$$\Omega = \frac{A}{r^2}$$

Where:

Ω = Solid Angle (sr)

A = Area of source (cm^2)

For circle $A = \pi r^2$

For ellipse $A = \pi(\frac{l}{2} \cdot \frac{w}{2})$

r = distance from source (cm), if not specified then use $20\ cm$ as closest distance.

$$\Omega = \frac{A}{r^2} = \frac{\pi(5 \times 0.8)}{4 \cdot 20^2} = 0.0078\ sr$$

Note that his Solid Angle is specific to the situation of being 20 cm away. You can adjust this, based on the situation.

Protect against Cataractogenesis

	A	B	C	D	E	F	G	H	I	J
1	Wave-	Spectral		SUM			SUM			SUM
2	length	Radiance		66.9913			0.201096			0.092931
3	nm	W/cm2-nr	Aphakic H	Weighted		Blue-Light	Weighted		Retinal Th	Weighted
4	365	1.085599	3.750	4.070997		0.01	0.010856			0
5	366	1.104317	3.750	4.141187		0.01	0.011043			0
6	367	1.113675	3.750	4.176282		0.01	0.011137			0
7	368	1.118354	3.750	4.193829		0.01	0.011184			0
8	369	1.132392	3.750	4.246471		0.01	0.011324			0
9	370	1.15111	3.560	4.09795		0.01	0.011511			0
10	371	1.160468	3.560	4.131267		0.01	0.011605			0
11	372	1.165148	3.560	4.147925		0.01	0.011651			0
12	373	1.169827	3.560	4.164584		0.01	0.011698			0
13	374	1.183865	3.560	4.214559		0.01	0.011839			0
14	375	1.202582	3.190	3.836237		0.01	0.012026		0.01	0.012026
15	376	1.221299	3.190	3.895945		0.01	0.012213		0.01	0.012213
16	377	1.230658	3.190	3.925799		0.01	0.012307		0.01	0.012307
26	2190	0.042114								0
27	2191	0.051472								
28	2192	0.060831								
29	2193	0.051472								
30	2194	0.046793								
31	2195	0.051472								
32	2196	0.056152								
33	2197	0.060831								
34	2198	0.06551								
35	2199	0.06551								
36	2200	0.060831								

$$E_{IR-only} = \Sigma_{770}^{3000} E_\lambda \cdot \Delta\lambda$$

$$\Omega = \frac{A}{r^2}$$

$$E_{IR-only} = 483.44 \left(\frac{W}{cm^2 \cdot sr}\right) \cdot 0.007854\ sr$$

$$E_{IR-only} = 3.80 \left(\frac{W}{cm^2}\right)$$

Sum the Spectral Radiance directly (column B). You don't need to use any weighting functions for this.

Exposure Limits

The exposure limit really depends on the viewing duration. The longer the viewing duration, the less light a person should be exposed to. This is not cumulative exposures.

Is viewing duration (t) less than $10^3\ s$ ($17\ mins$)

YES → Use $E_{IR-only}\left(\frac{W}{cm^2}\right) \leq 1.8 \cdot t^{-0.75}$

NO → Use $E_{IR-only}\left(\frac{W}{cm^2}\right) \leq 0.01$

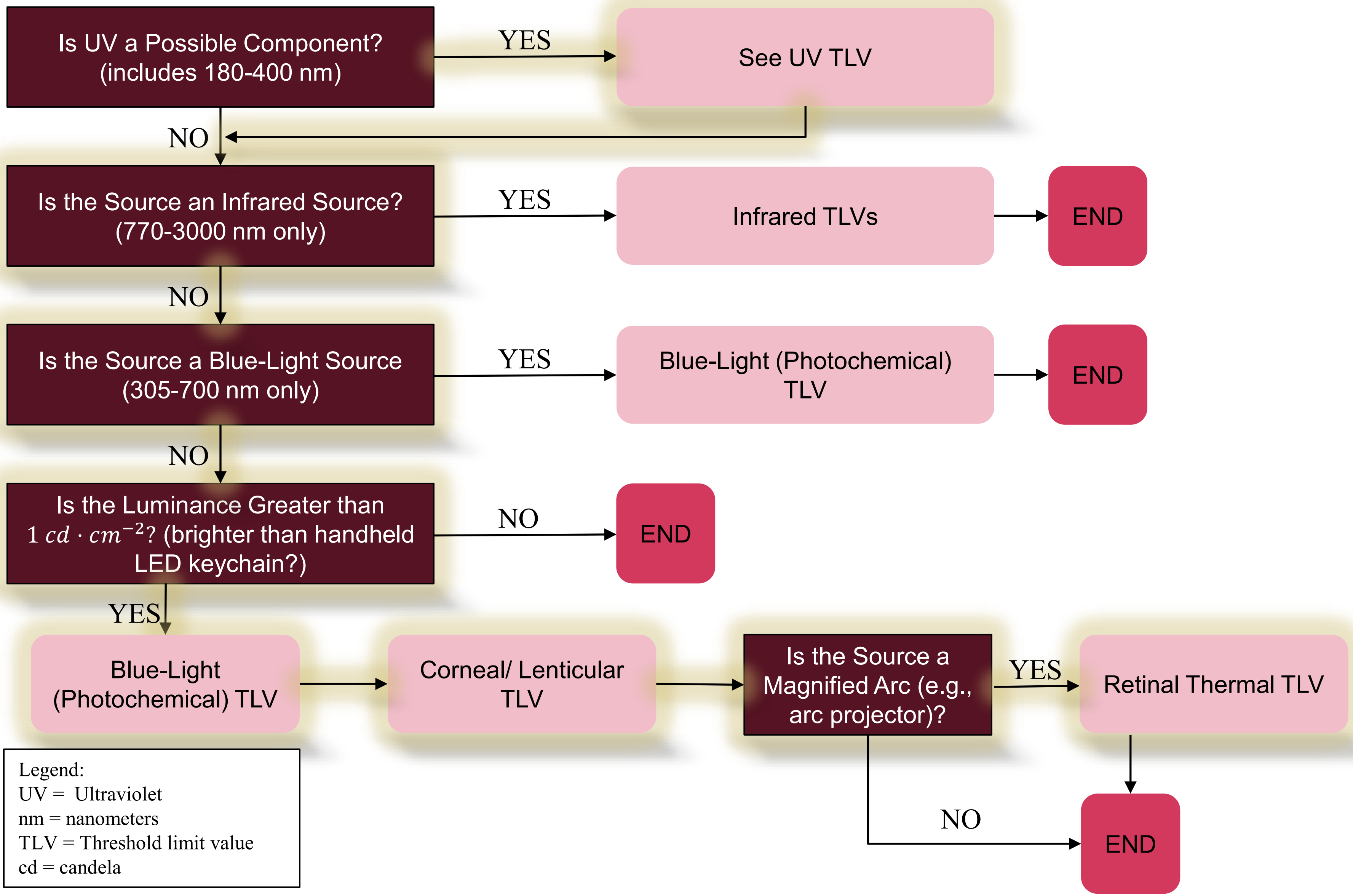
$$E_{IR-only} \leq 1.8 \cdot t^{-0.75}$$

$$3.80 = 1.8 \cdot 0.25^{-0.75}\ s$$

$$3.80\left(\frac{W}{cm^2}\right) \leq 5.09\left(\frac{W}{cm^2}\right)$$

True, the lamp for our example is safe for this Hazard

Optical (Non-laser) Source



Retinal Thermal Hazard Function

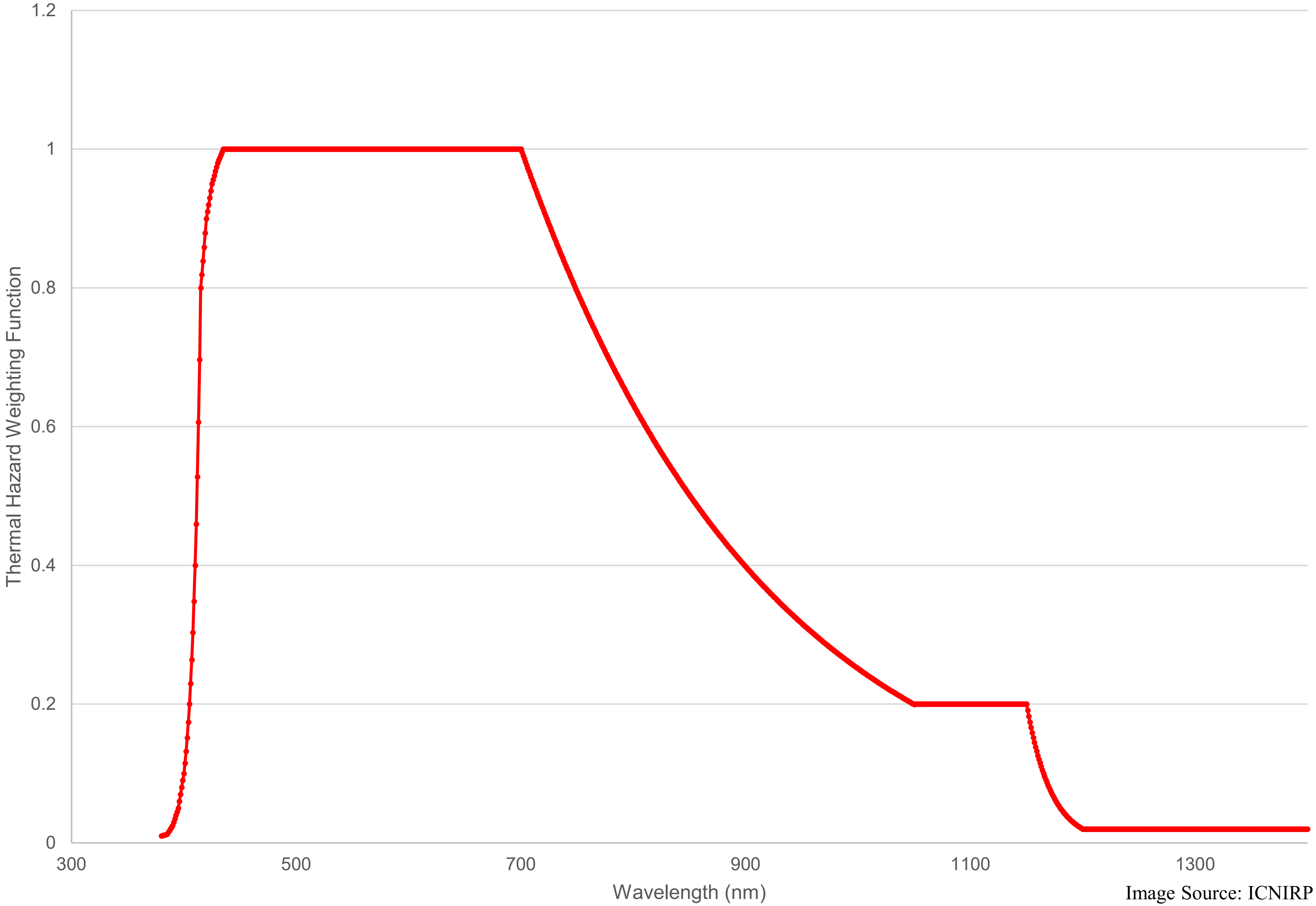


Image Source: ICNIRP 2013

Retinal Thermal Weighting Function Applied to Our Spectrum

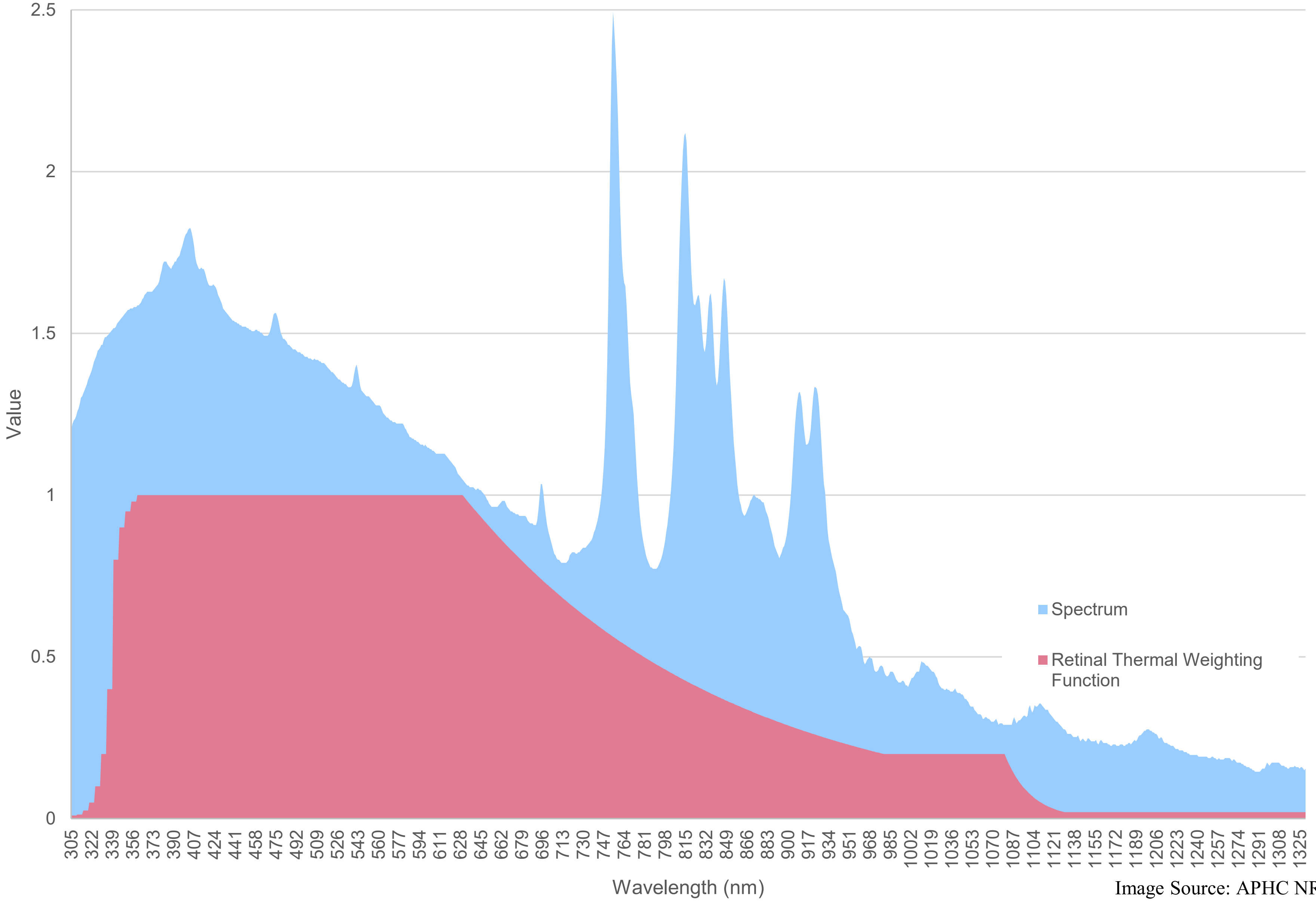


Image Source: APHC NRD

Retinal Thermal Weighting Function Applied to Our Spectrum

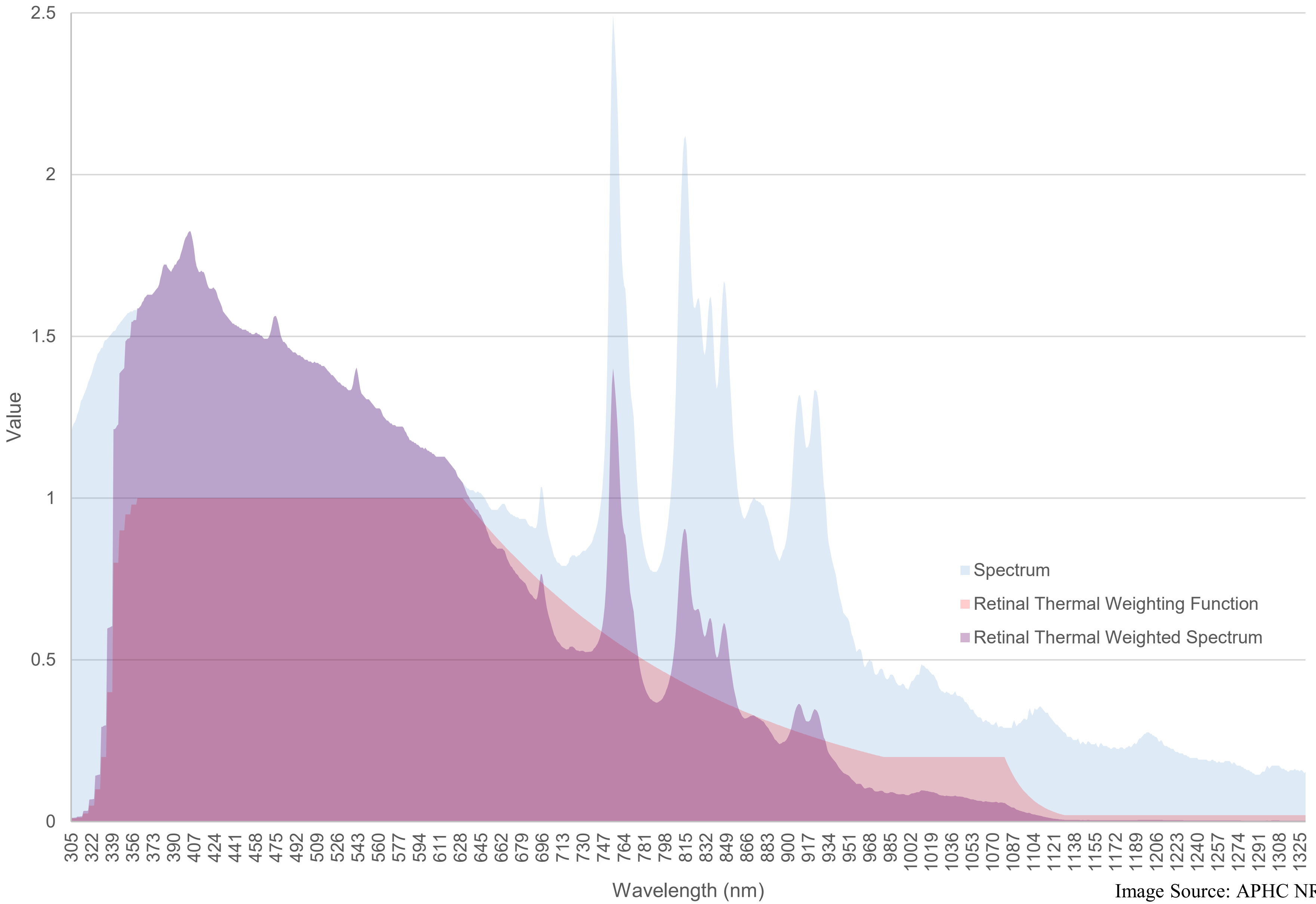


Image Source: APHC NRD

Retinal Thermal

	A	B	C	D	E	F	G	H	I	J
1	Wave-	Spectral		SUM			SUM			SUM
2	length	Radiance		309.3239			111.7254			616.6538
3	nm	W/cm2-nr	Aphakic H	Weighted		Blue-Light	Weighted		Retinal Th	Weighted
4	305		6.000	0		0.01	0			0
5	306		6.000	0		0.01	0			0
6	307		6.000	0		0.01	0			0
7	308		6.000	0		0.01	0			0
8	309		6.000	0		0.01	0			0
9	310		6.000	0		0.01	0			0
10	311		6.000	0		0.01	0			0
11	312		6.000	0		0.01	0			0
12	313		6.000	0		0.01	0			0
13	314		6.000	0		0.01	0			0
14	315		6.000	0		0.01	0			0
15	316		6.000	0		0.01	0			0
16	317		6.000	0		0.01	0			0
91	692	1.094958	0.001	0.001095		0.001	0.001095		1.0	1.094958
92	693	1.090279	0.001	0.00109		0.001	0.00109		1.0	1.090279
93	694	1.085599	0.001	0.001086		0.001	0.001086		1.0	1.085599
94	695	1.076241	0.001	0.001076		0.001	0.001076		1.0	1.076241
95	696	1.066882	0.001	0.001067		0.001	0.001067		1.0	1.066882
96	697	1.062203	0.001	0.001062		0.001	0.001062		1.0	1.062203
97	698	1.057523	0.001	0.001058		0.001	0.001058		1.0	1.057523
98	699	1.052844	0.001	0.001053		0.001	0.001053		1.0	1.052844
99	700	1.048165	0.001	0.001048		0.001	0.001048		1.000	1.048165

$$L_R = \Sigma_{380}^{1400} L_\lambda \cdot R(\lambda) \cdot \Delta\lambda$$

Where:

L_R = Effective Radiance of Lamp $\left(\frac{W}{cm^2 \cdot sr}\right)$; To protect against retinal thermal injury from a visible light source

L_λ = Spectral Radiance $\left(\frac{W}{cm^2 \cdot sr \cdot nm}\right)$

$R(\lambda)$ = Thermal Hazard Function $(unitless)$

$\Delta\lambda$ = “bucket size” (nm)

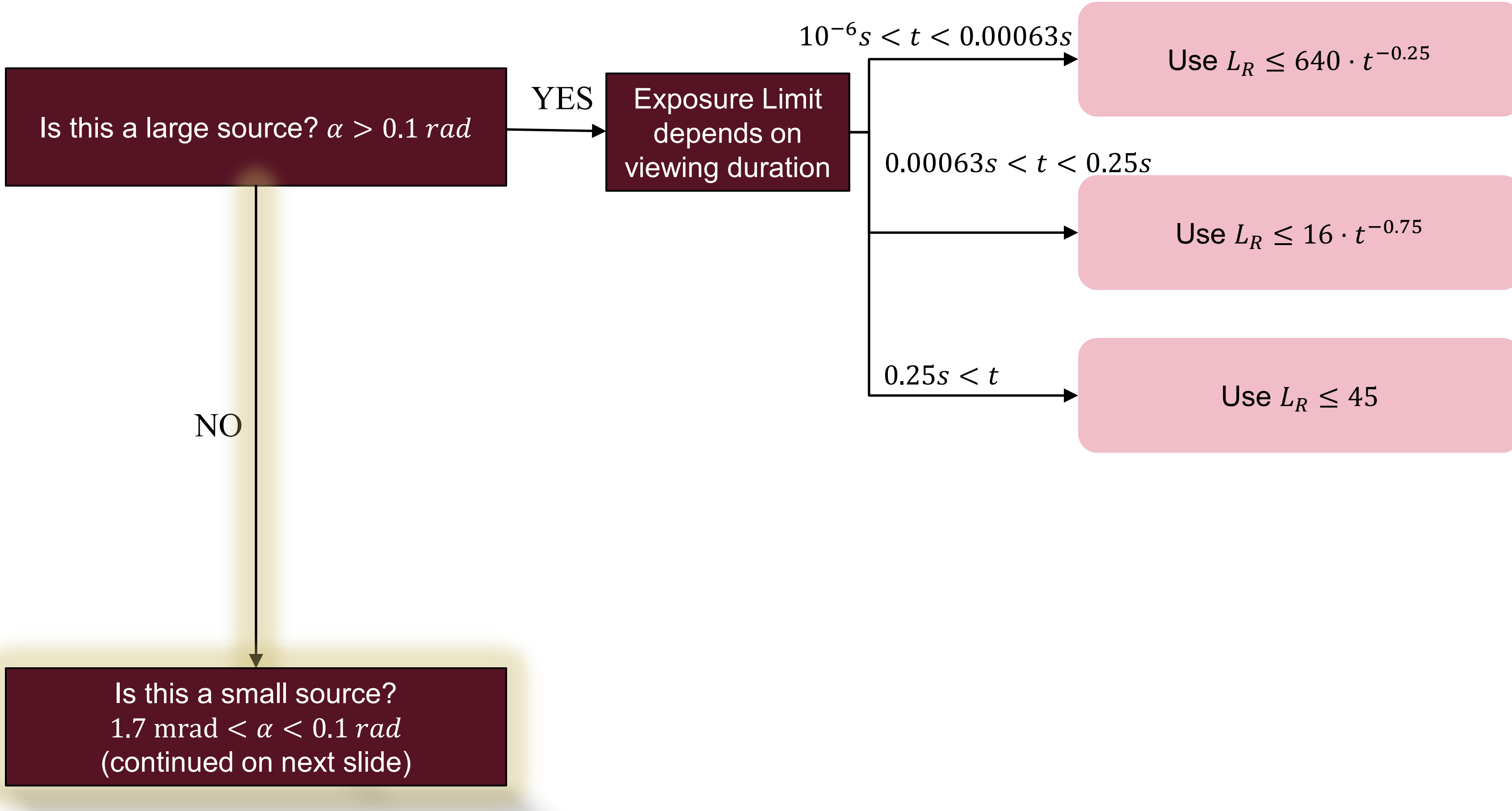
$$L_R = 616.65 \left(\frac{W}{cm^2 \cdot sr}\right)$$

Multiply your Spectral data by the weighting function to get weighted data (column J).

To find L_R simply use a spreadsheet to add all the values of the weighted data from $(380\ nm < \lambda < 1400\ nm)$.

Retinal Thermal Exposure Limits

For protection against retinal thermal injury find, L_R which is measured in $\left(\frac{W}{cm^2 \cdot sr}\right)$, and compare this to the exposure limit which varies based on exposure duration, and angular subtense.

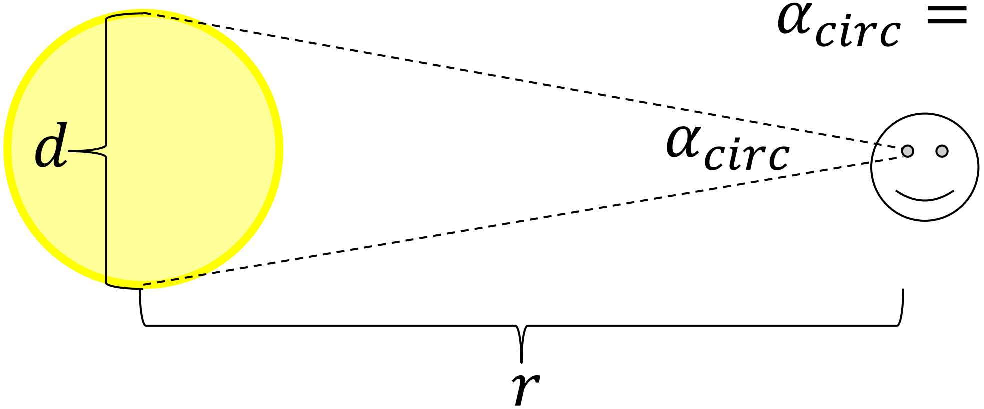


Angular Subtense (α)

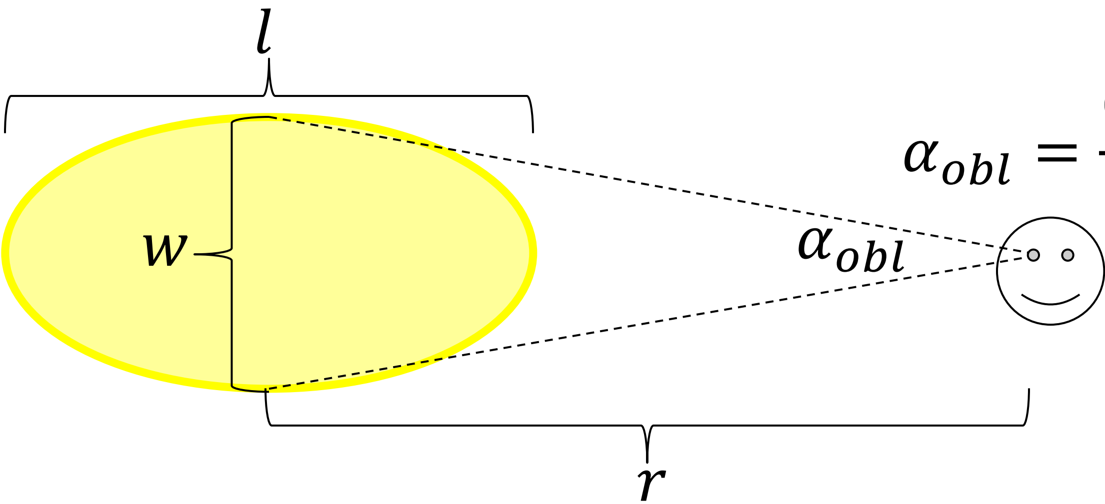
Determine the Angular Subtense (α) of the source in radians (rad).

$$l = 5\ cm$$
$$w = 0.8\ cm$$
$$\alpha_{obl} = \frac{l + w}{2r}$$
$$\alpha_{obl} = 0.029\ radians$$

$$\alpha_{circ} = \frac{d}{r}$$

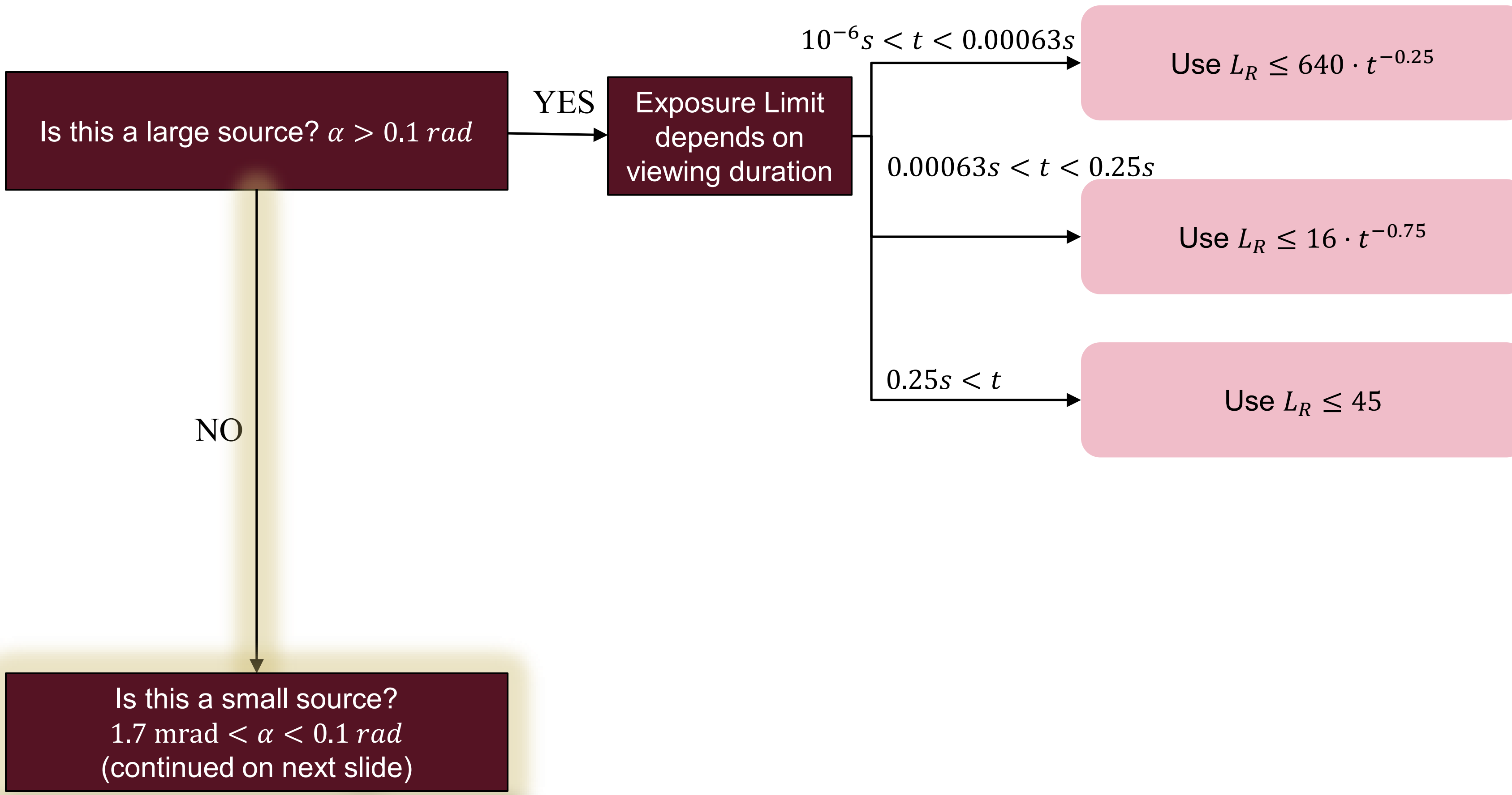


$$\alpha_{obl} = \frac{(l + w)}{2r}$$



Retinal Thermal Exposure Limits

For protection against retinal thermal injury find, L_R which is measured in $\left(\frac{W}{cm^2 \cdot sr}\right)$, and compare this to the exposure limit which varies based on exposure duration, and angular subtense.



Retinal Thermal Exposure Limits (Cont.)

For protection against retinal thermal injury find, L_R which is measured in $\left(\frac{W}{cm^2 \cdot sr}\right)$, and compare this to the exposure limit which varies based on exposure duration, and angular subtense.

(continued from previous slide)
Is this a small source?
$1.7 \text{ mrad} < \alpha < 0.1 \, rad$

YES →

Exposure Limit depends on viewing duration, and limits on angular subtense

- $10^{-6}s < t < 0.00063s$, With $\alpha < 0.2\sqrt{t}$ (radians) → Use $L_R \leq 640 \cdot t^{-0.25}$
- $0.00063s < t < 0.25s$, With $\alpha < 0.1$ (radians) → Use $L_R \leq \frac{4.5}{\alpha}$
- $0.25s < t$, With $\alpha < 0.1$ (radians) → Use $L_R \leq \frac{3.2}{\alpha} t^{-0.25}$

Note: if

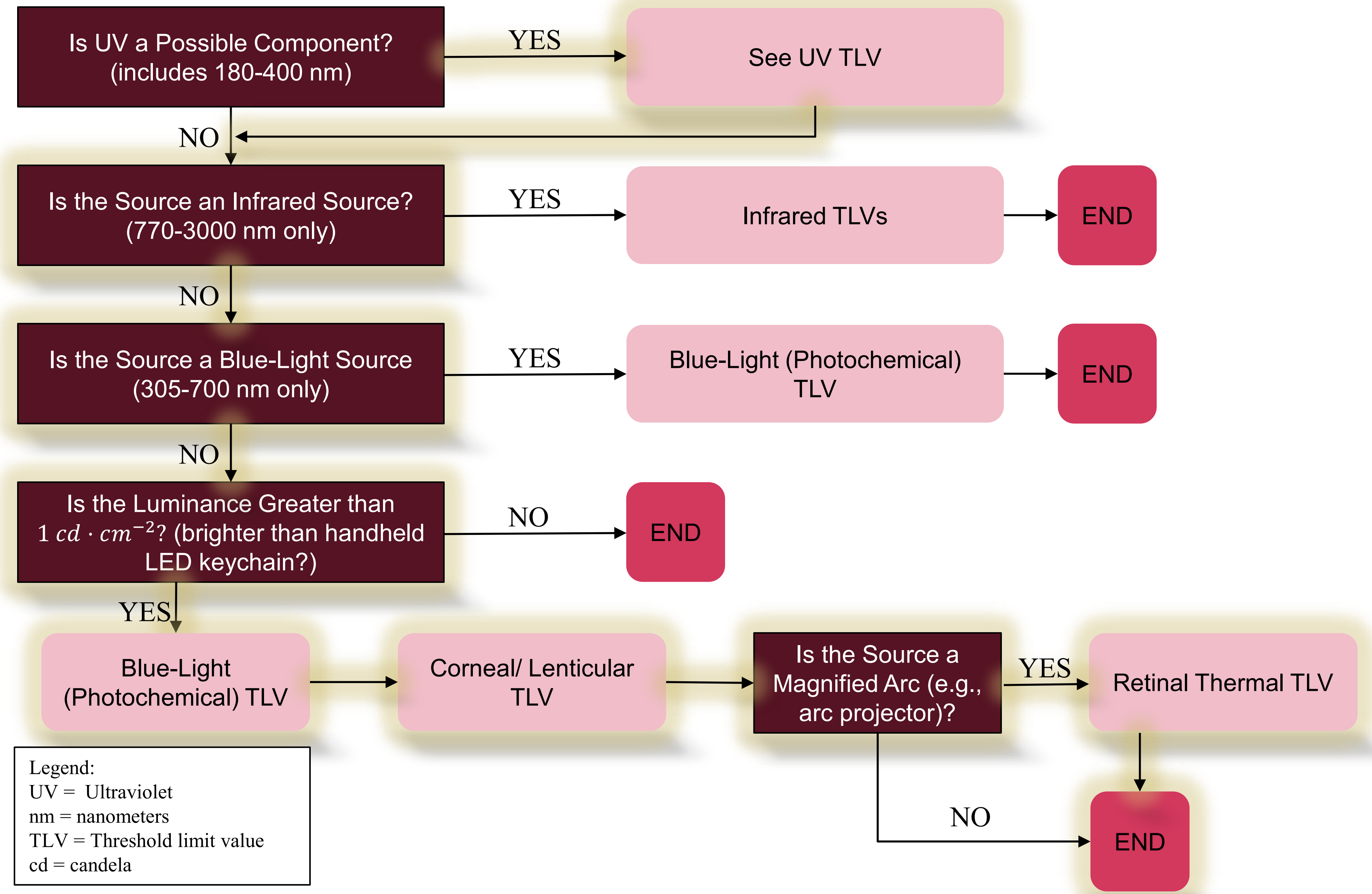
$$L_R \leq \frac{3.2}{\alpha} t^{-0.25}$$

$$616.65 \leq \frac{3.2}{0.029} (0.25)^{-0.25}$$

$$616.65 \leq 156.05$$

This lamp from our example is a Retinal Thermal Hazard

Optical (Non-laser) Source



Aphakic Hazard Function

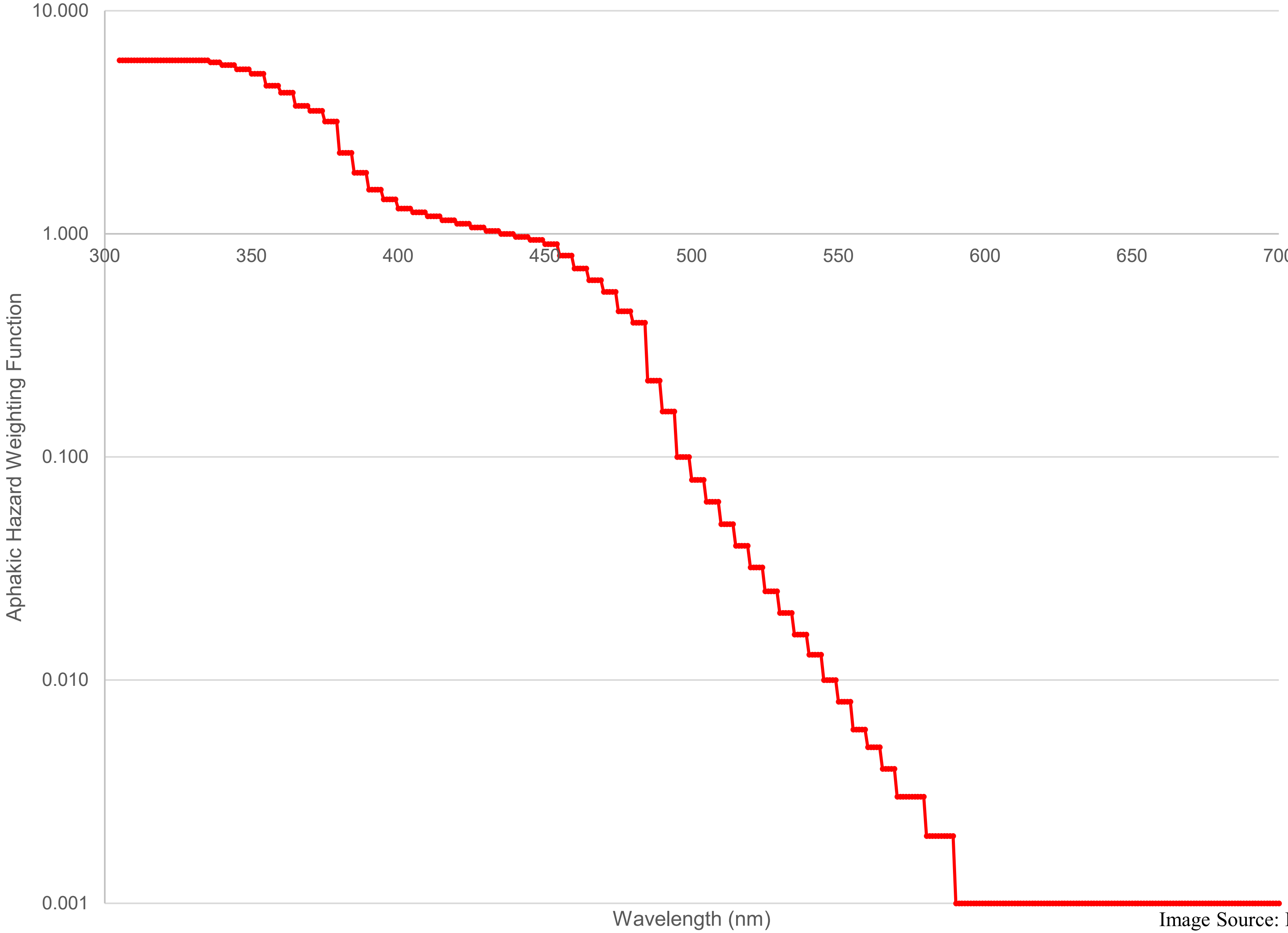


Image Source: ICNIRP 2013