U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

# Spectral Power Distribution
## The Building Block of Applied Lighting

**DOE Technology Development Workshop**

November 16, 2016

**Dr. Michael Royer**

Pacific Northwest National Laboratory

examiner.com

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# Are LED lights ruining Van Gogh's Sunflowers?

EUROPE TRAVEL | JANUARY 20, 2013 | BY: LESLEY PETERSON | + *Subscribe*

SUSTAINABILITY

# The Dark Side of LED Lightbulbs

47

## LIGHTBULB FRENZY IN THE 21ST CENTURY

1. Why My Parents Have a Closet Full of Lightbulbs
2. Blinded by the Light: Wrecked Up by Our Juice, Another Citizen of the Night [Slide Show]
3. Does Turning Fluorescent Lights Off Use More Energy Than Leaving Them On?
4. How to Green Your Office

# LED Lights May Damage Eyes, Researcher Says

By Marc Lallanilla, Live Science Contributor | May 13, 2013 12:02pm ET

The retinas of the eye may be especially sensitive to radiation from LED lights.

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June 14, 2016

# AMA Adopts Community Guidance to Reduce the Harmful Human and Environmental Effects of High Intensity Street Lighting

**For immediate release:**
June 14, 2016

CHICAGO - Strong arguments exist for overhauling the lighting systems on U.S. roadways with light emitting diodes (LED), but conversions to improper LED technology can have adverse consequences. In response, physicians at the Annual Meeting of the American Medical Association (AMA) today adopted guidance for communities on selecting among LED lighting options to minimize potential harmful human and environmental effects.

Converting conventional street light to energy efficient LED lighting leads to cost and energy savings, and a lower reliance on fossil-based fuels. Approximately 10 percent of existing U.S. street lighting has been converted to solid state LED technology, with efforts underway to accelerate this conversion.

"Despite the energy efficiency benefits, some LED lights are harmful when used as street lighting," AMA Board Member Maya A. Babu, M.D., M.B.A. "The new AMA guidance encourages proper attention to optimal design and engineering features when converting to LED lighting that minimize detrimental health and environmental effects."

High-intensity LED lighting designs emit a large amount of blue light that appears white to the naked eye and create worse nighttime glare than conventional lighting. Discomfort and disability from intense, blue-rich LED lighting can decrease visual acuity and safety, resulting in concerns and creating a road hazard.

In addition to its impact on drivers, blue-rich LED streetlights operate at a wavelength that most adversely suppresses melatonin during night. It is estimated that white LED lamps have five times greater impact on circadian sleep rhythms than conventional street lamps. Recent large surveys found that brighter residential nighttime lighting is associated with reduced sleep times, dissatisfaction with sleep quality, excessive sleepiness, impaired daytime functioning and obesity.

The detrimental effects of high-intensity LED lighting are not limited to humans. Excessive outdoor lighting disrupts

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# Doctors issue warning about LED streetlights

THE CONVERSATION

By Richard G. "Bugs" Stevens, The Conversation

Updated 2:00 PM ET, Tue June 21, 2016

**Photos:** Los Angeles LED streetlights

The Sixth Street bridge over the Los Angeles River looks a bit different with old, left, and new streetlights.

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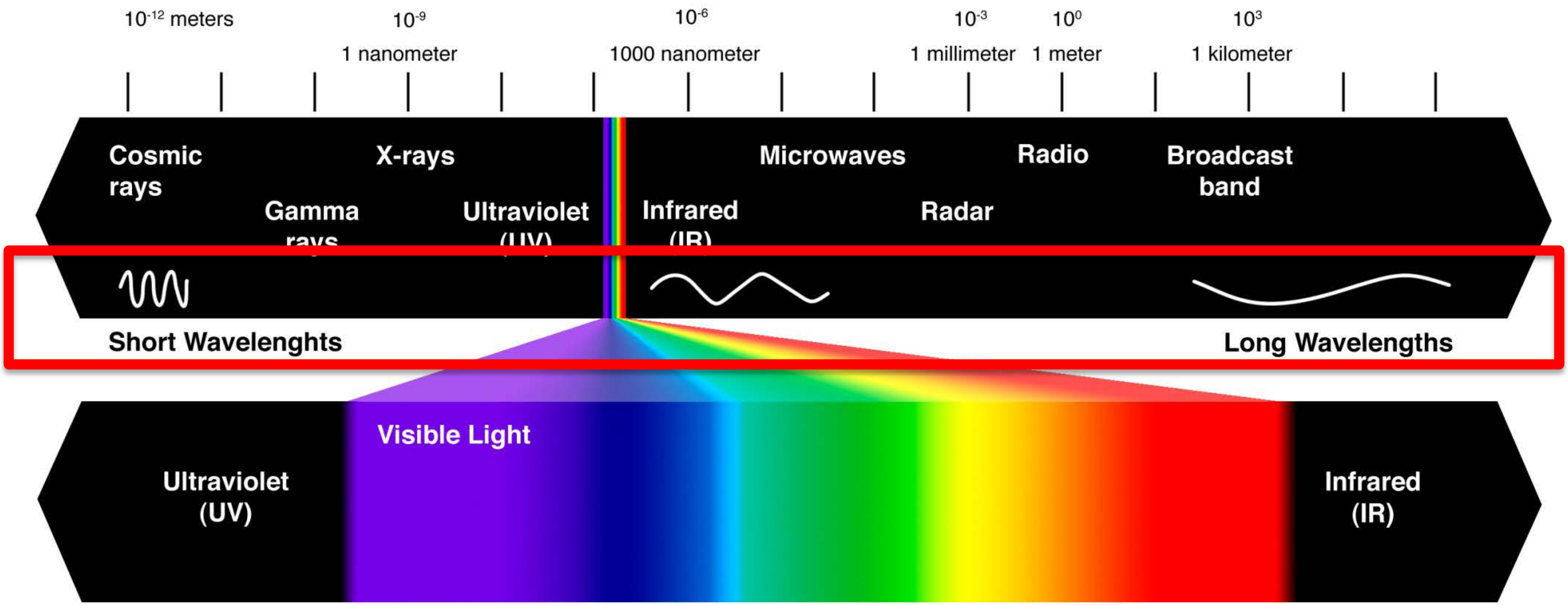
# What is this about?

1. Basics of light and vision
2. Types of light sources
3. Displaying spectral data
4. Weighting functions: use and meaning
5. Spectral tuning

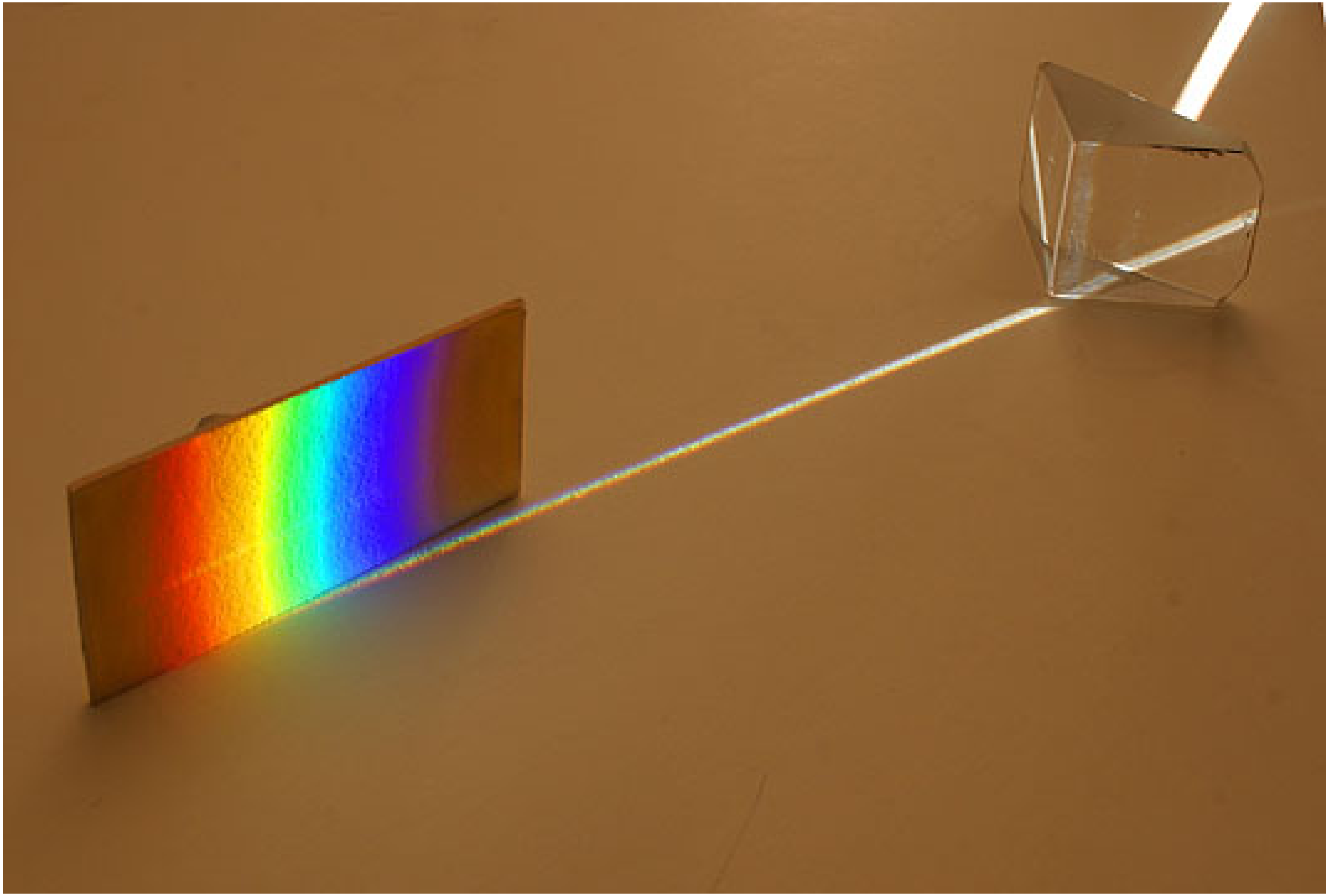
# Electromagnetic Spectrum





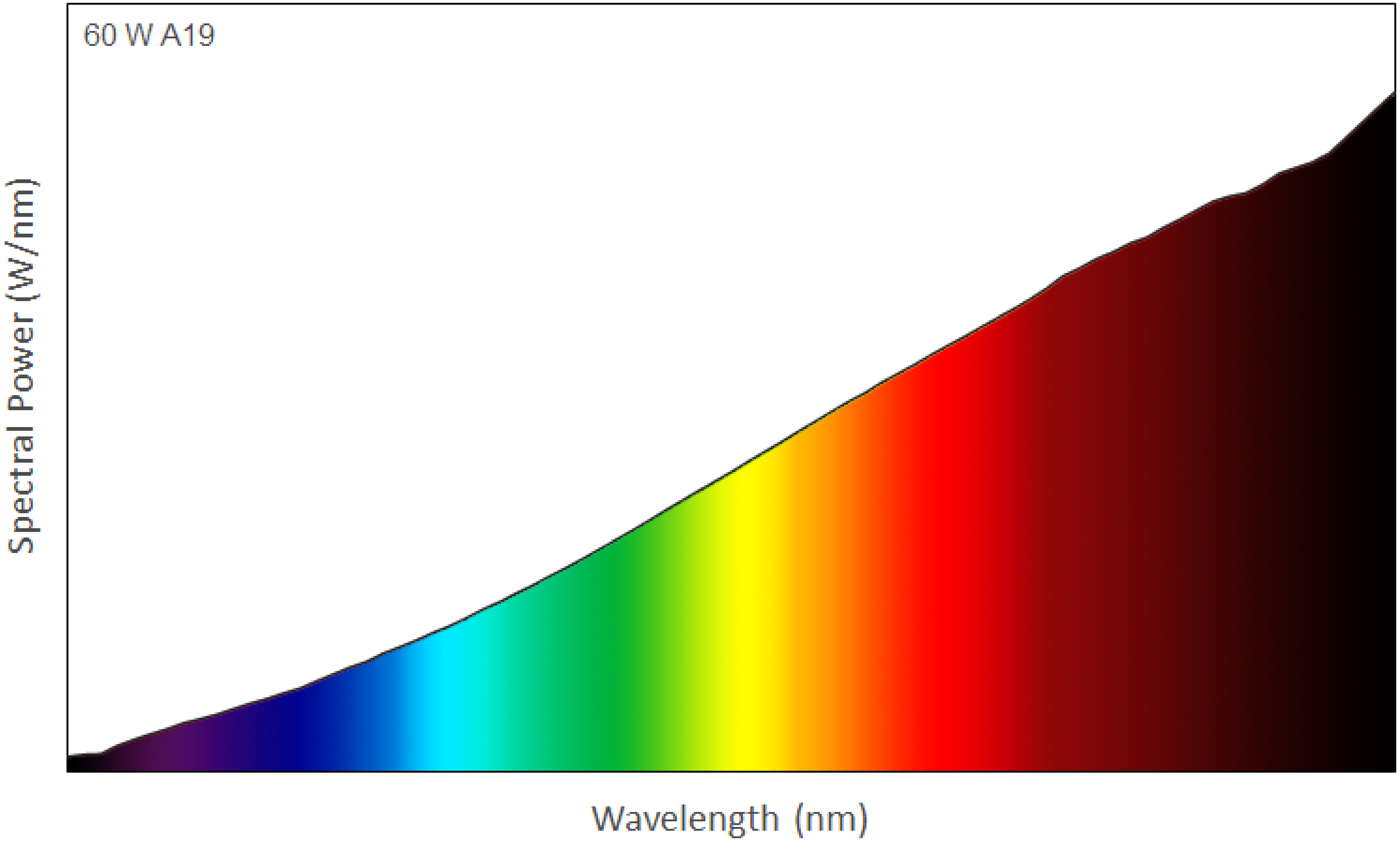
https://sites.google.com/site/mochebiologysite/online-textbook/light

# What is a Spectral Power Distribution?

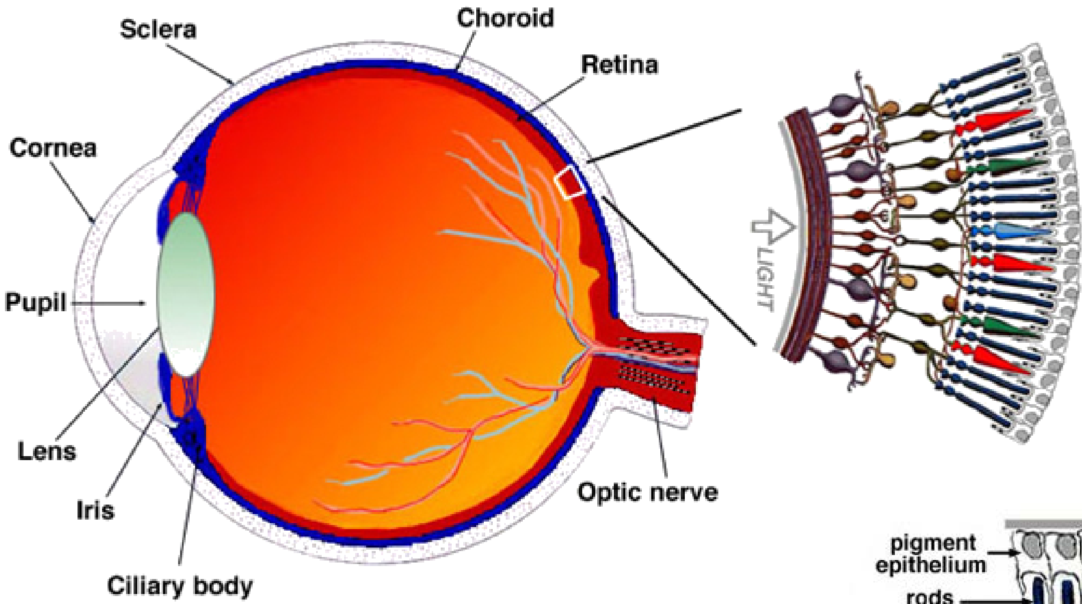


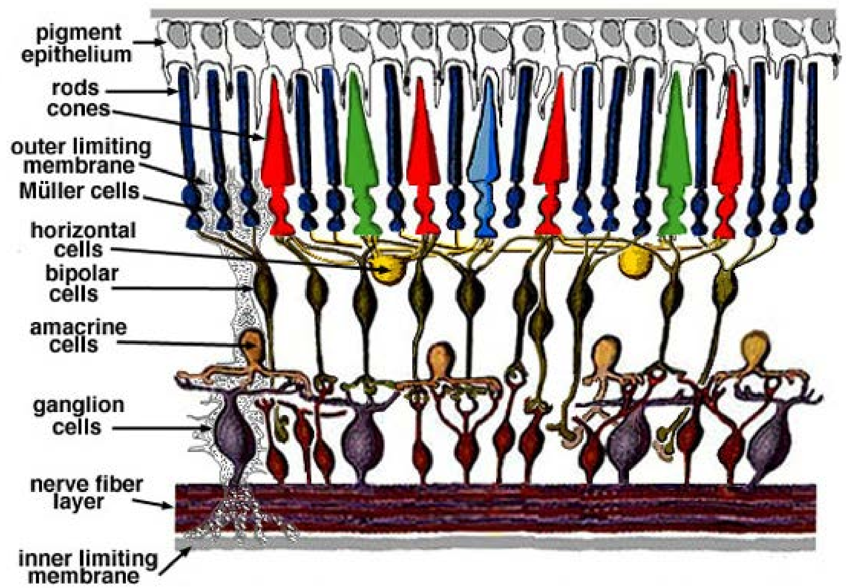
https://people.rit.edu/andpph/photofile-c/spectrum_8664.jpg

# Plotting a Spectral Power Distribution



# Sensing Radiant Energy – The Human Eye

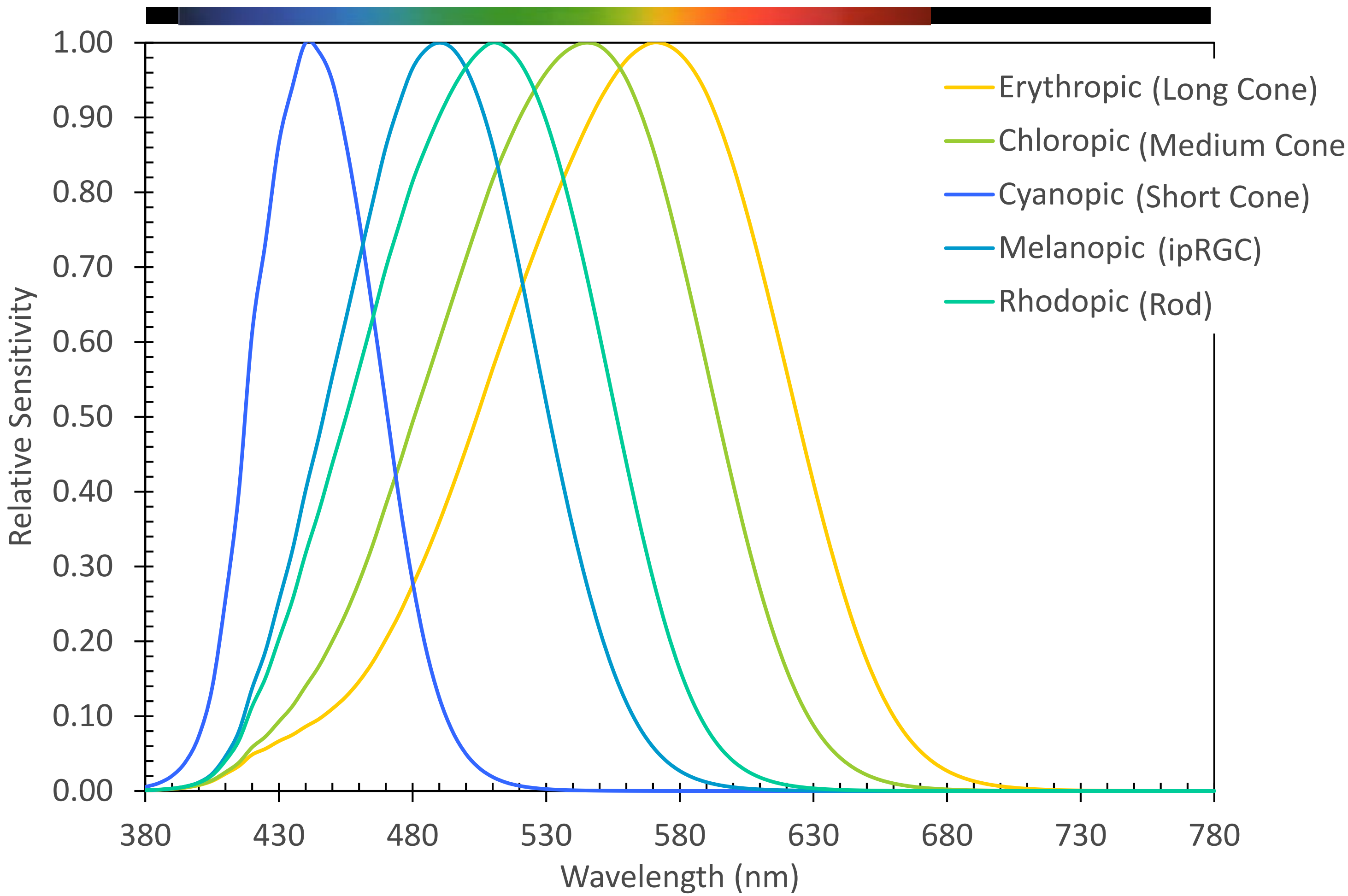


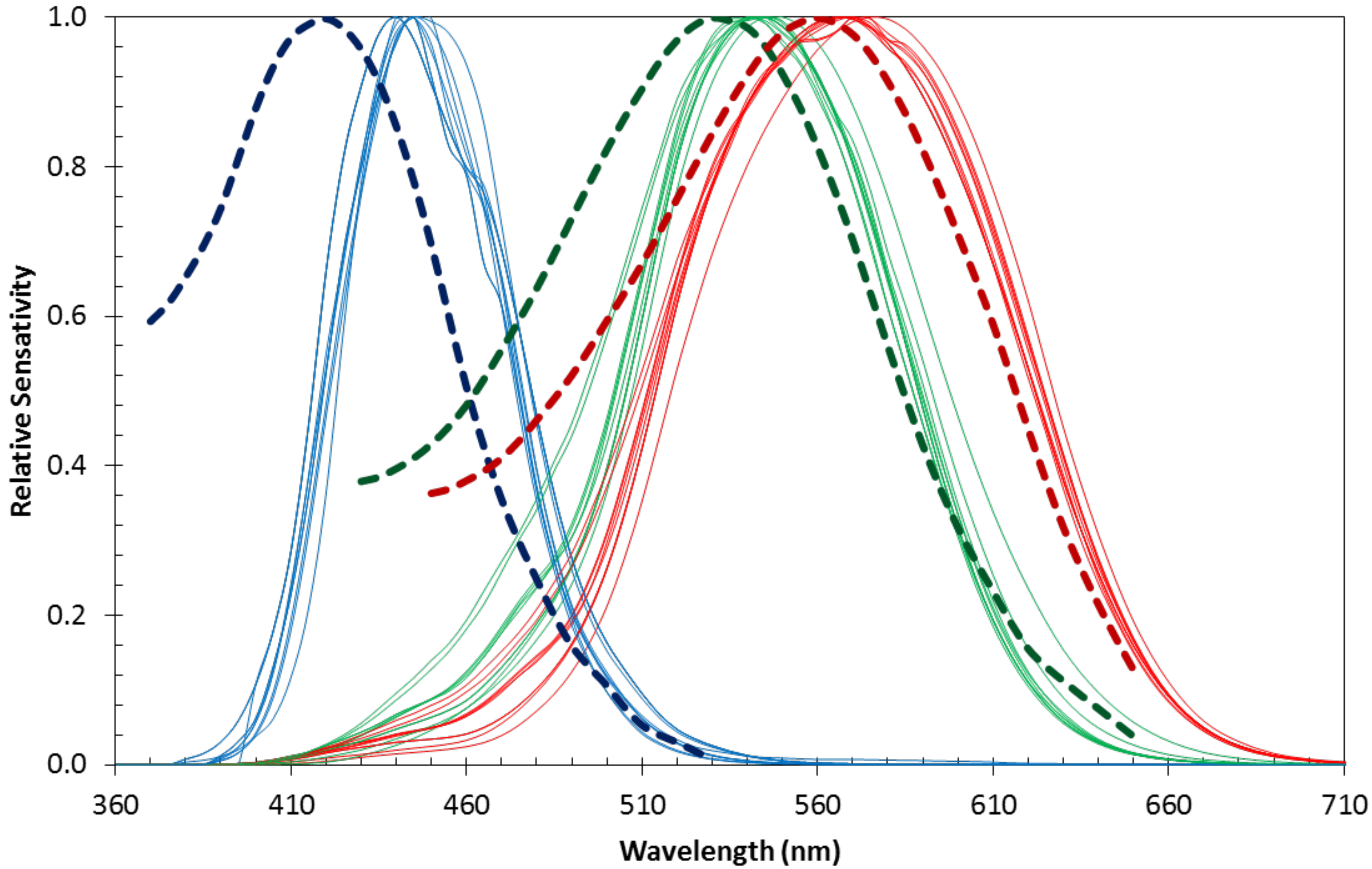



http://webvision.med.utah.edu/book/part-i-foundations/simple-anatomy-of-the-retina/

# Photosensor Sensitivity

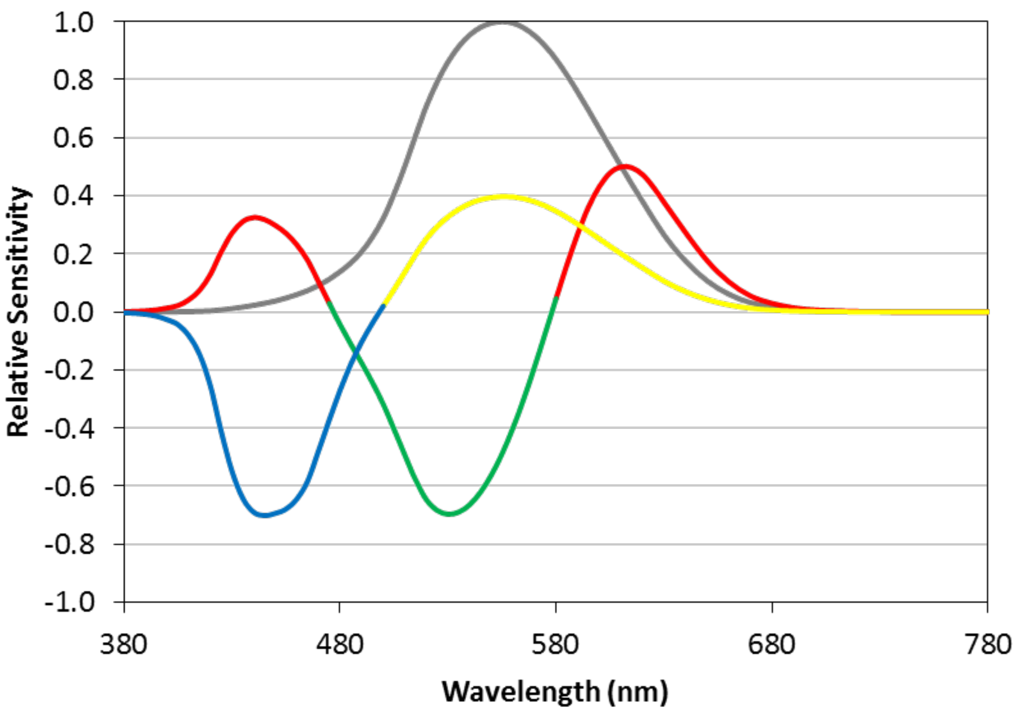


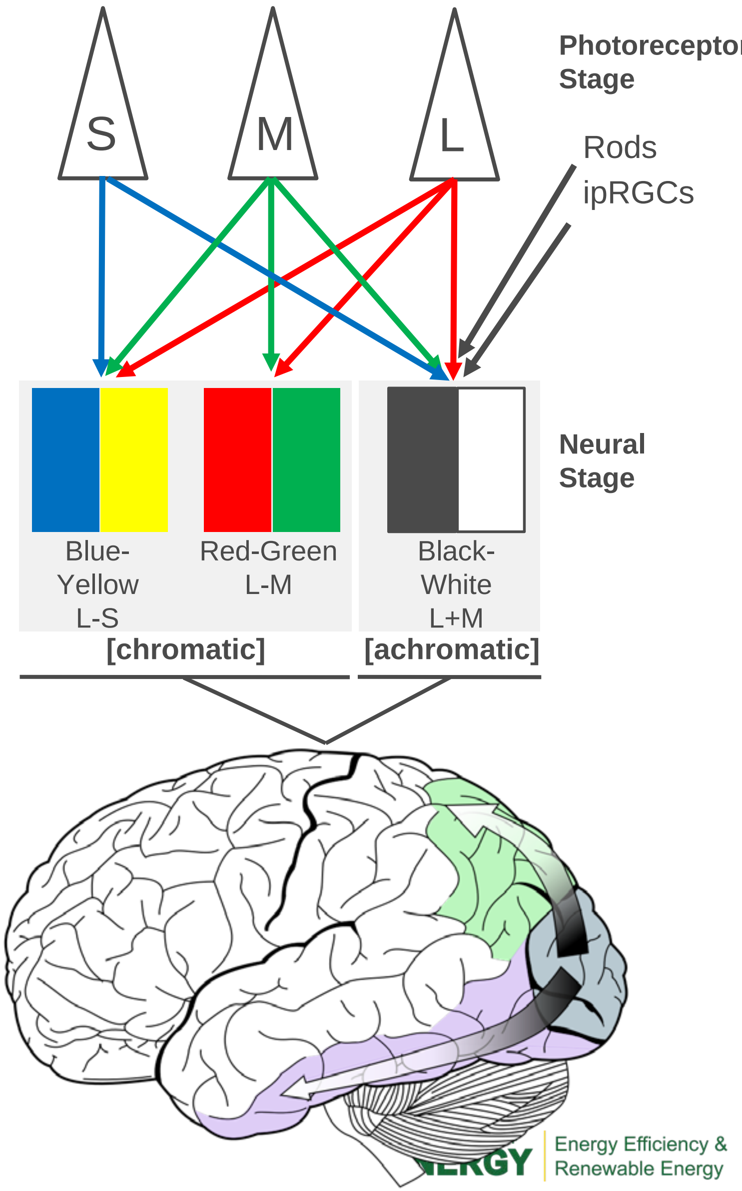
# Photoreceptor Variation



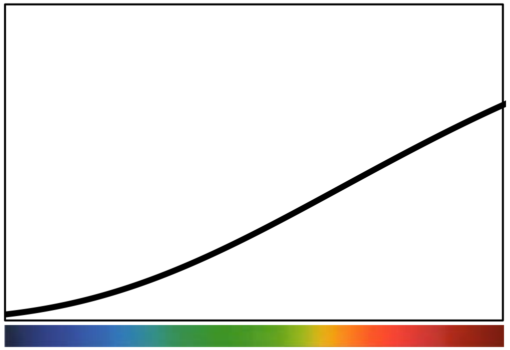
# Visual System: It's Complex!

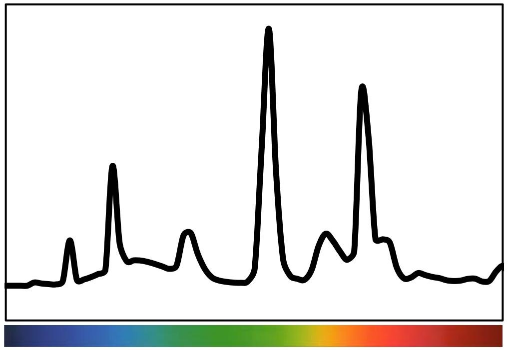
**And that's not even talking about non-visual photoreception.**

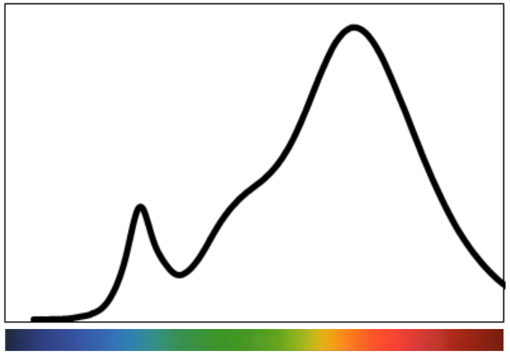


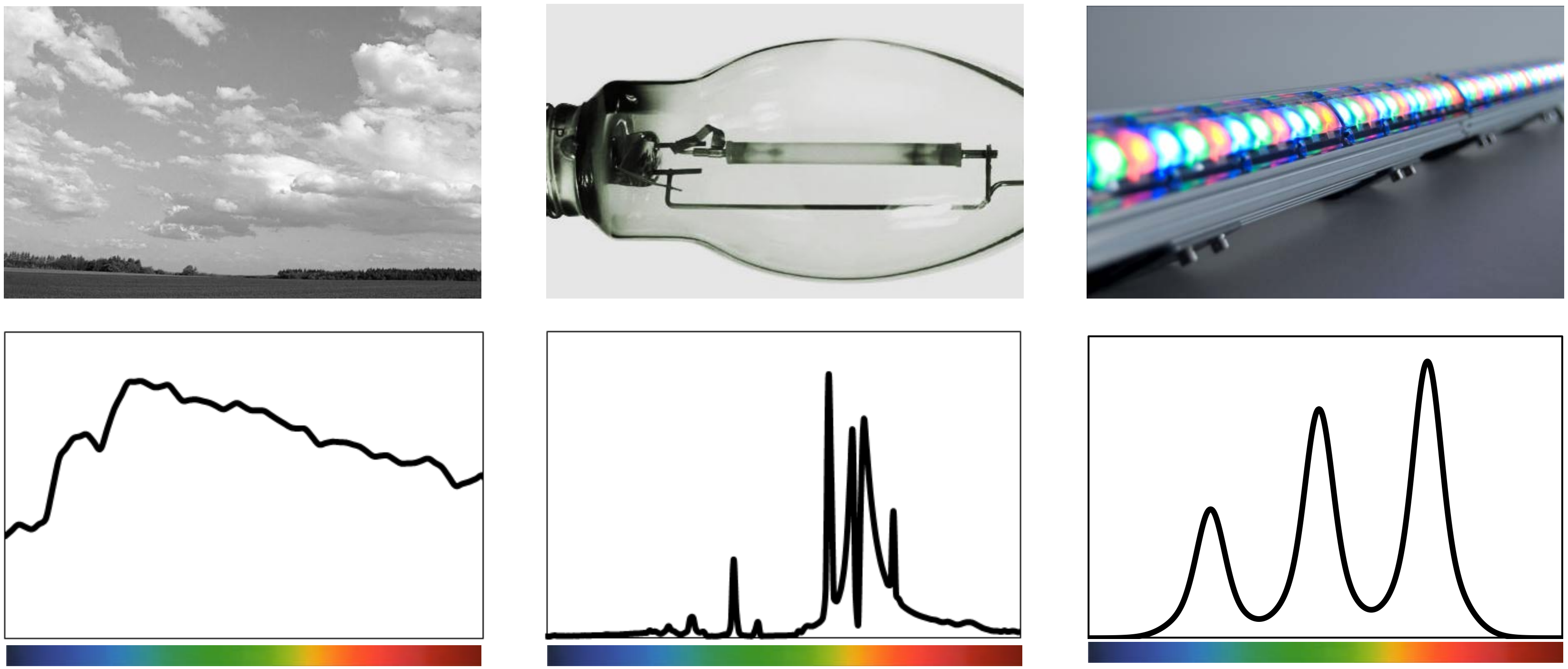
# Spectral Power Distributions





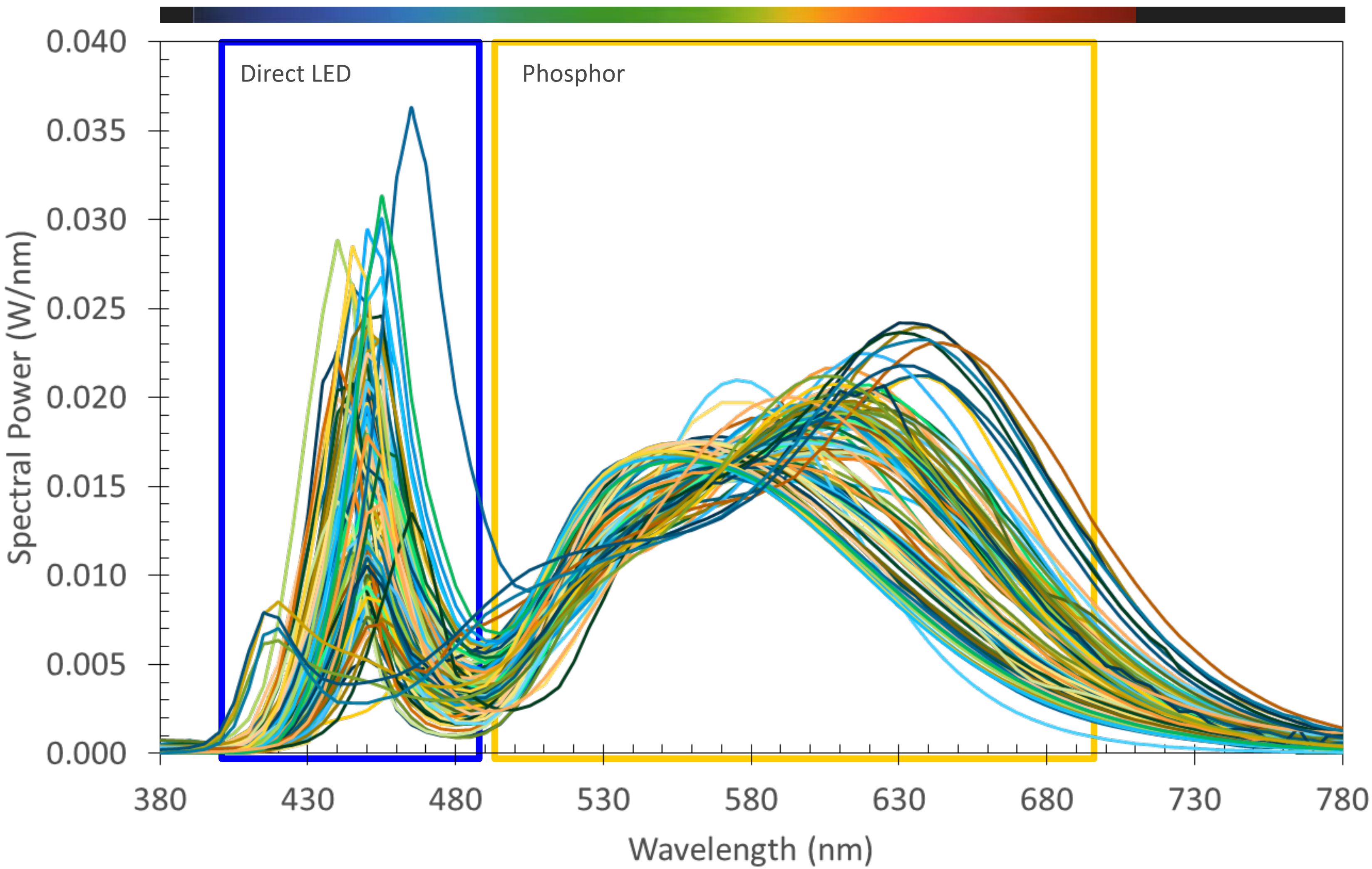


# Spectral Power Distributions

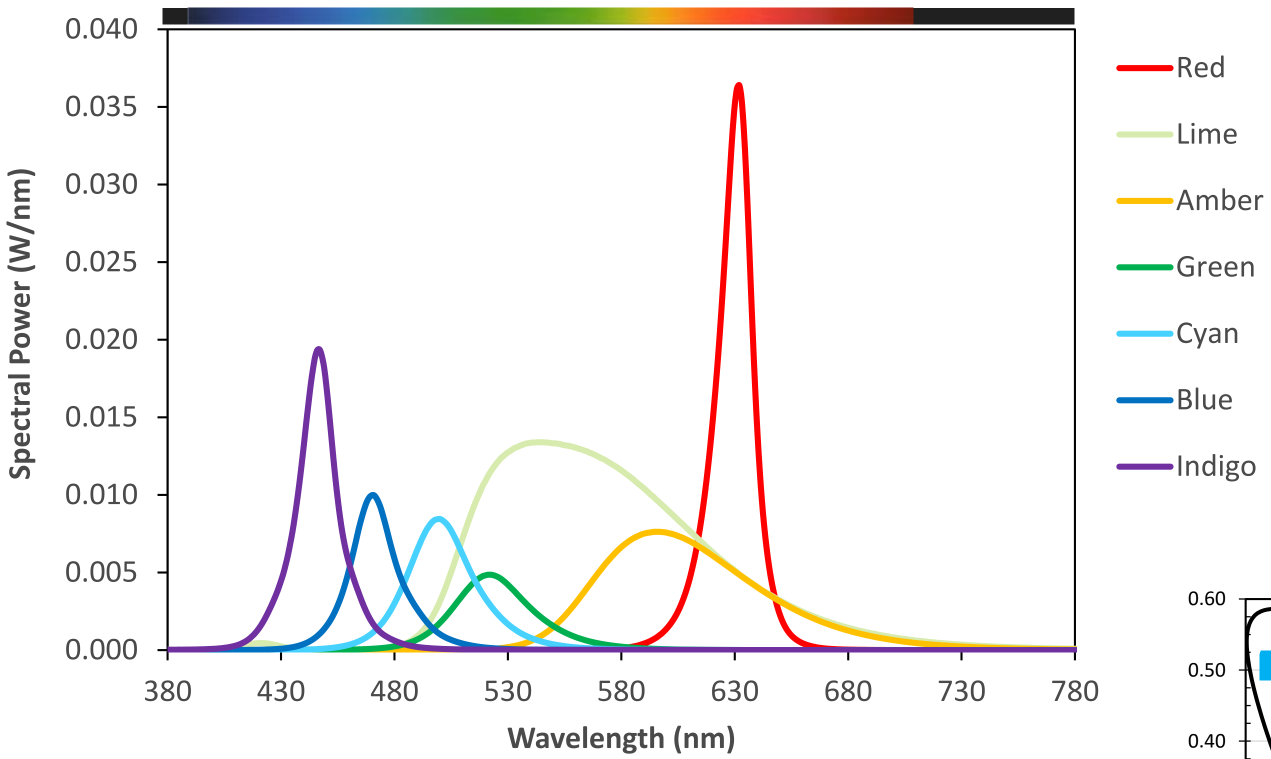


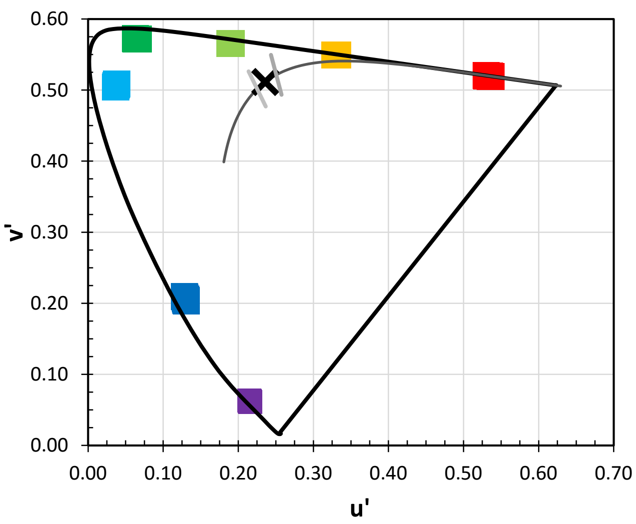
**CAUTION: Light sources technologies are not homogenous!**

# Phosphor-Coated LEDs

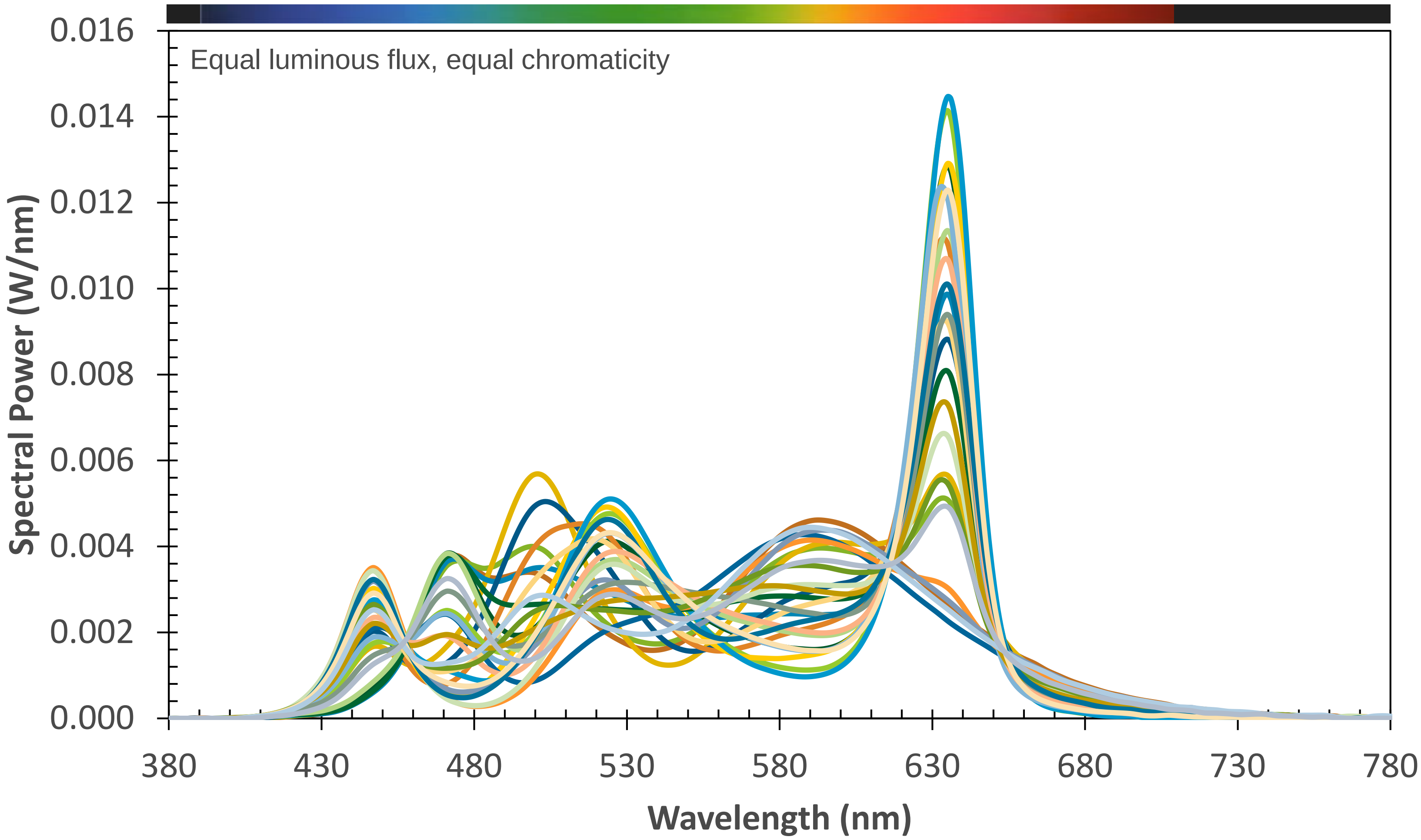


# Color Mixed LEDs



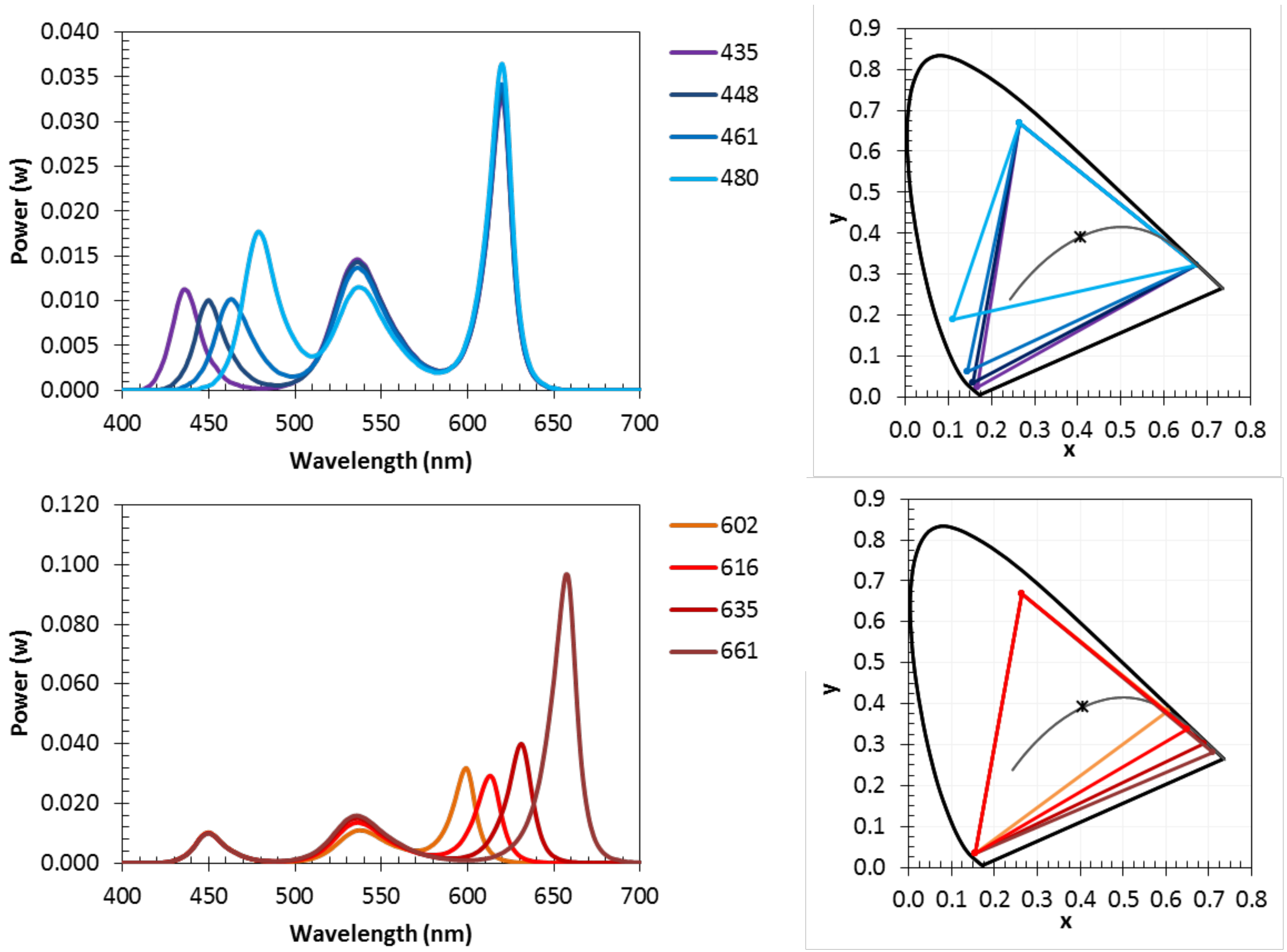



# Color-Mixed LEDs

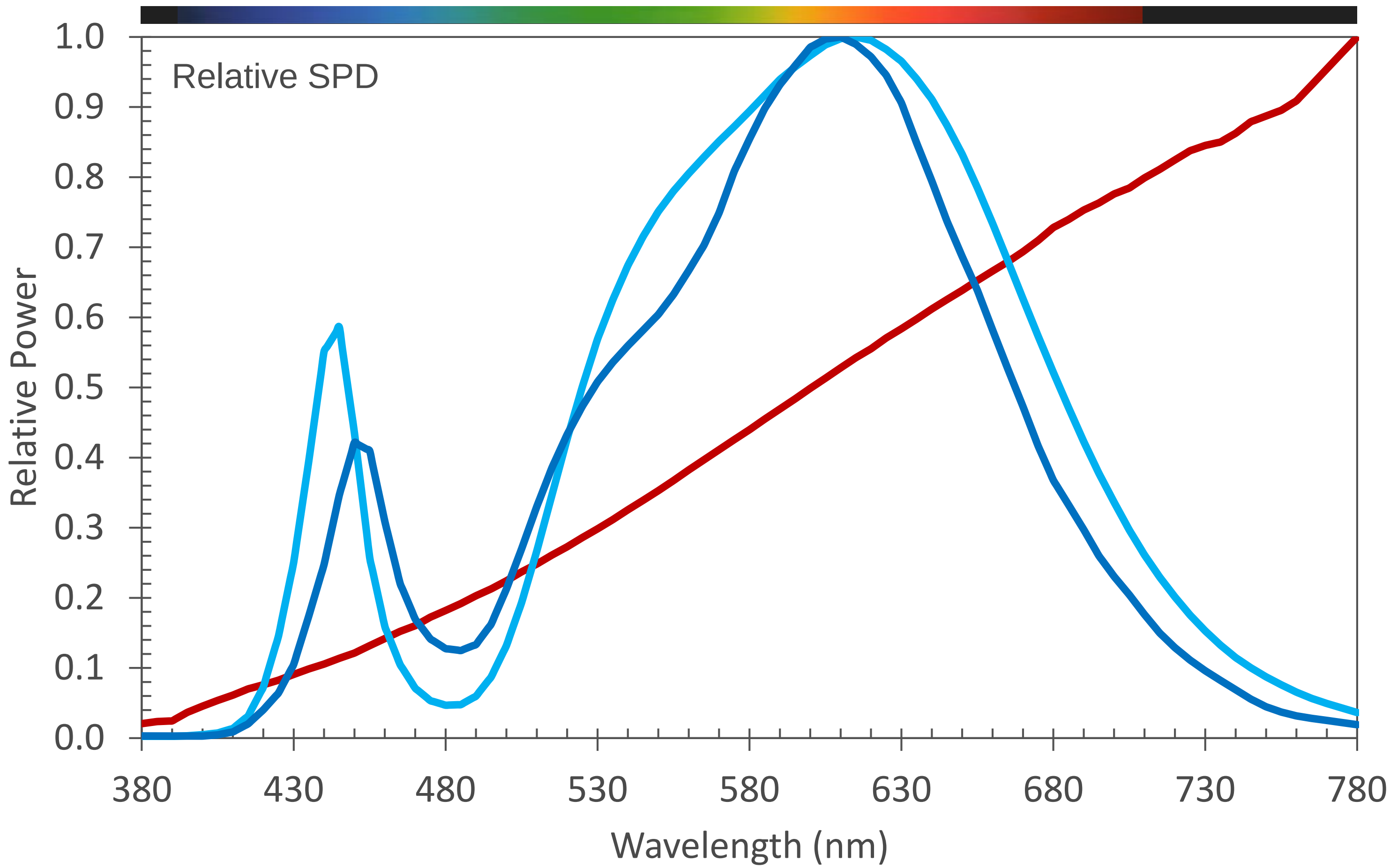



SPDs from: Royer MP, Wilkerson AM, Wei M, Houser KW, Davis RG. 2016. Human Perceptions of Color Rendition Vary with Average Fidelity, Average Gamut, and Gamut Shape. Lighting Research and Technology. Online before print. DOI: 10.1177/1477153516663615

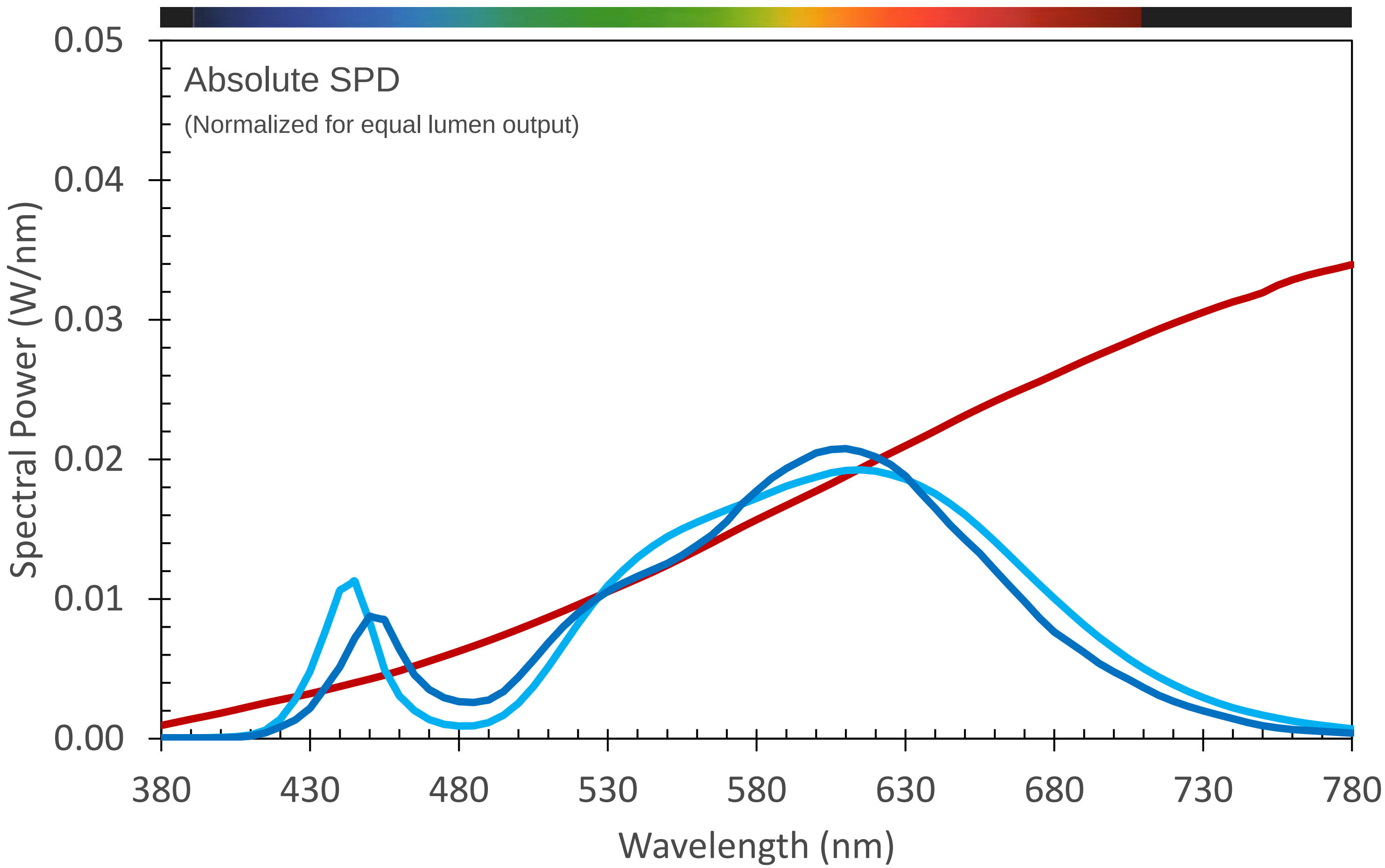
# Color-Mixed LEDs



# Comparing Spectral Power Distributions



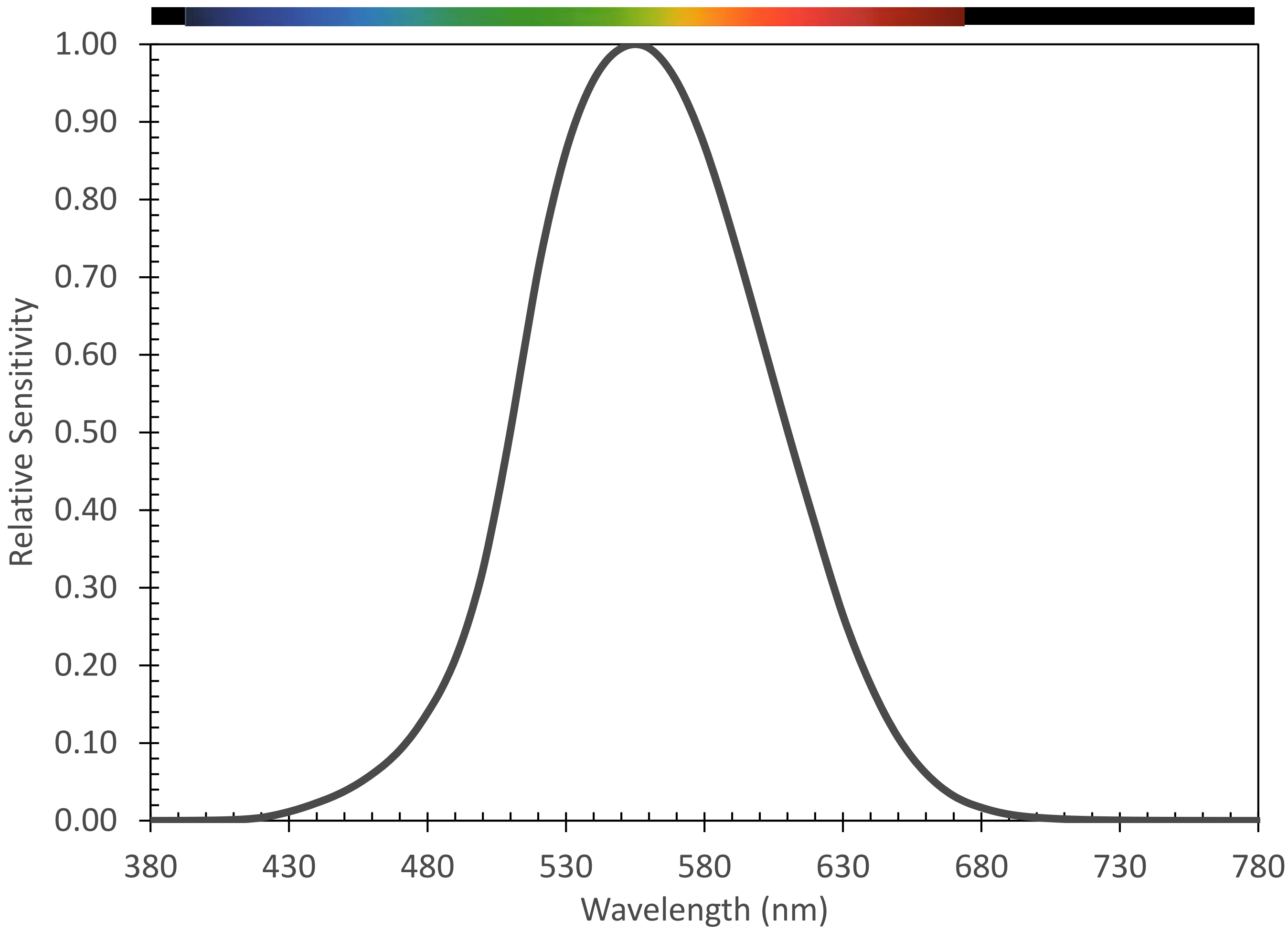
# Comparing Spectral Power Distributions



# Spectral Weighting Functions

- Also known as Action Spectra, (Spectral) Efficiency Functions
- Assign a weight to each wavelength, based on a given effect or perception
- Based on human subjects experiments, then standardized
- Weighting functions are often a simplification
- Effects assumed to be additive
- Various effects:
  - (Relative) Brightness perception
  - Viewing colored light
  - Melatonin suppression/circadian effects
  - Retinal damage
  - Material damage
- Other spectrum-related effects, such as color rendering or CS, are not weighting functions

# Luminous (Visual) Efficiency Function, V(λ)

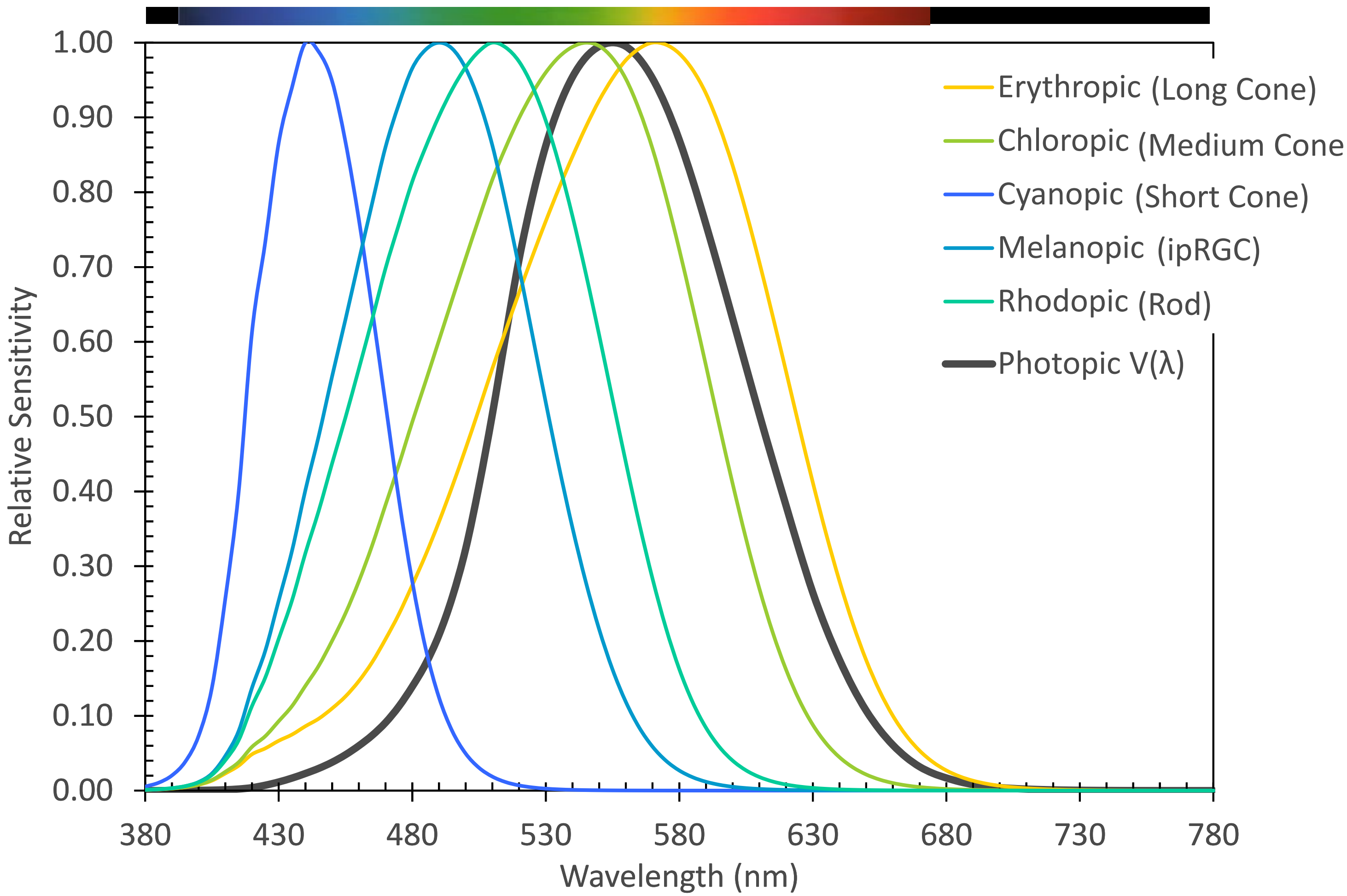



$$\Phi = 683 * \int P_\lambda V_\lambda d\lambda$$

# Luminous (Visual) Efficiency Function, V(λ)

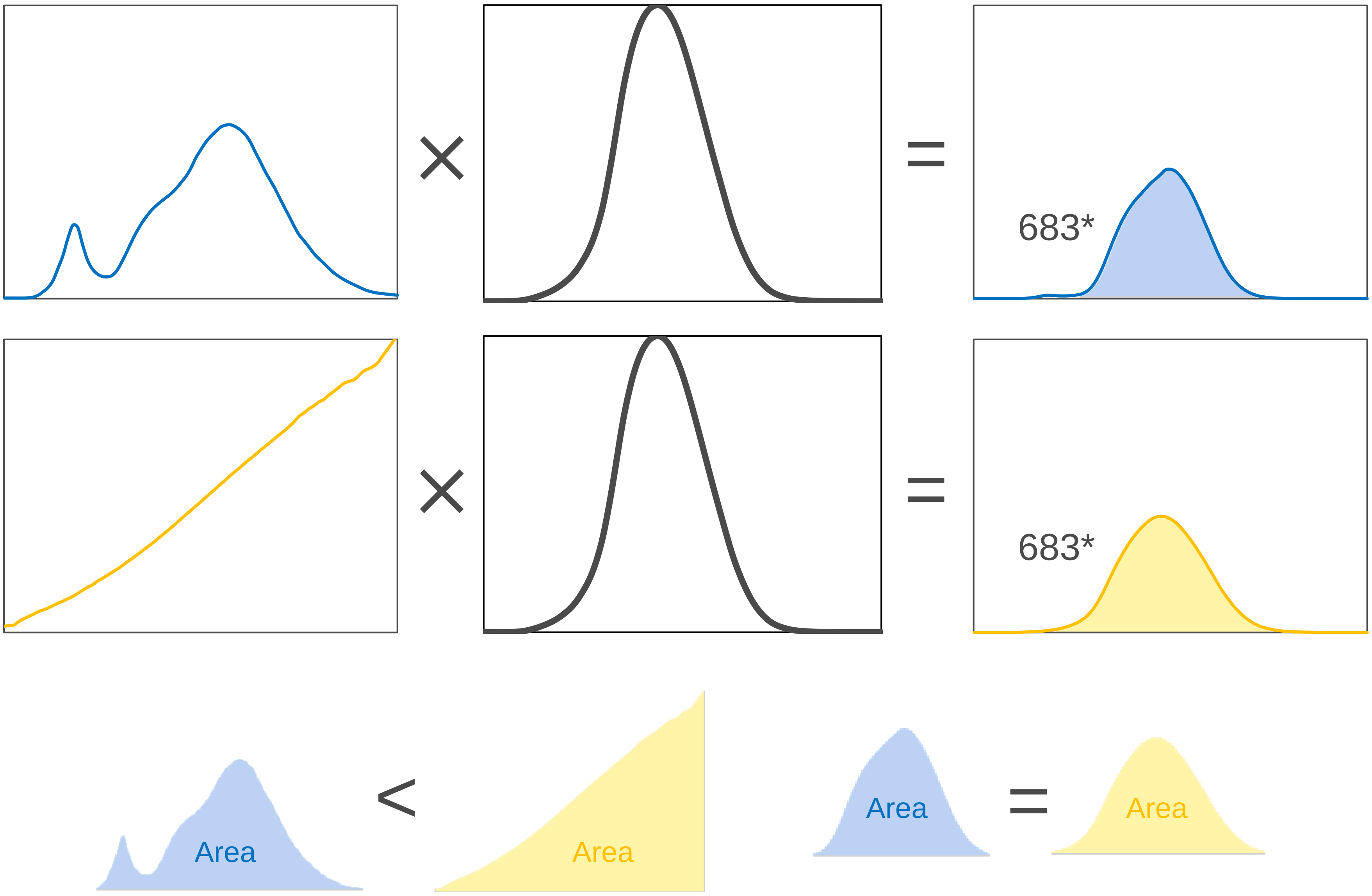
- Adopted by CIE in 1924
- Informed by five experiments using three different methods
  - Minimum flicker
  - Step-by-step brightness matching
  - Direct brightness matching
- All experiments used a 2° field of view, surround of same brightness
- Official version combines three experiments across different parts of the spectrum
- Large individual differences standardized to a single function
- Later refinements made, but change is difficult!
- Relative brightness, or “brightness-based”

# Luminous (Visual) Efficiency Function, V(λ)




Functions from CIE TN 003:2015

# Calculating Weighted Values

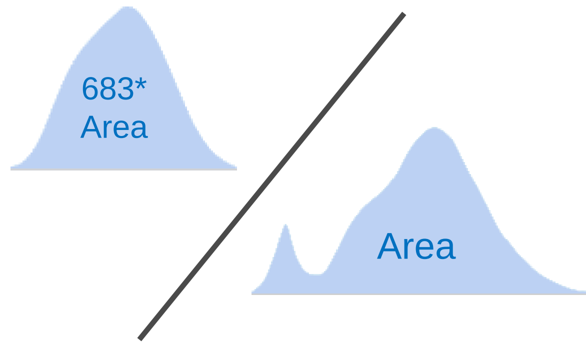


# Luminous Efficacy of Radiation

$$\text{Luminous Efficacy of Radiation (LER)} = \frac{\text{Luminous Flux (lm)}}{\text{Radiant Flux (W)}}$$

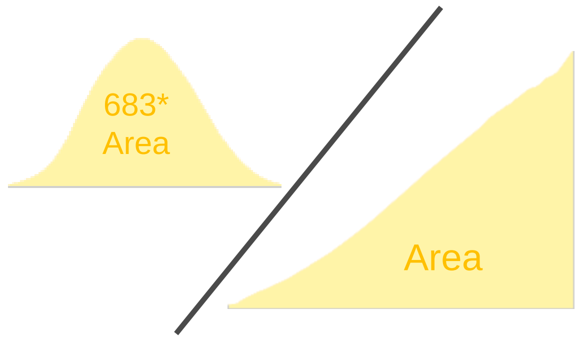
Radiant Watts, Not Electrical Watts

LER =

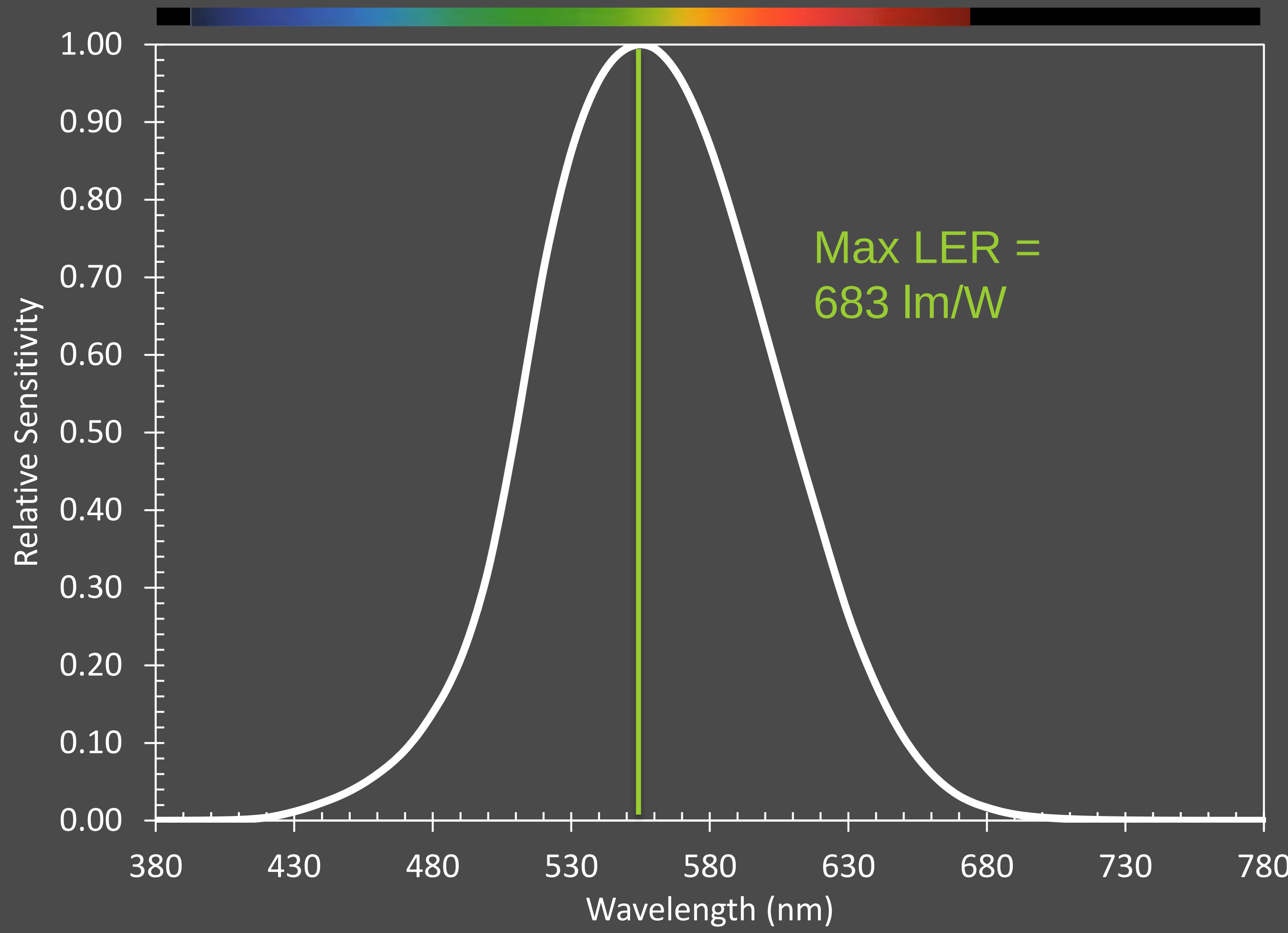



= $315\ \text{lm/W}_{radiant}$

LER =

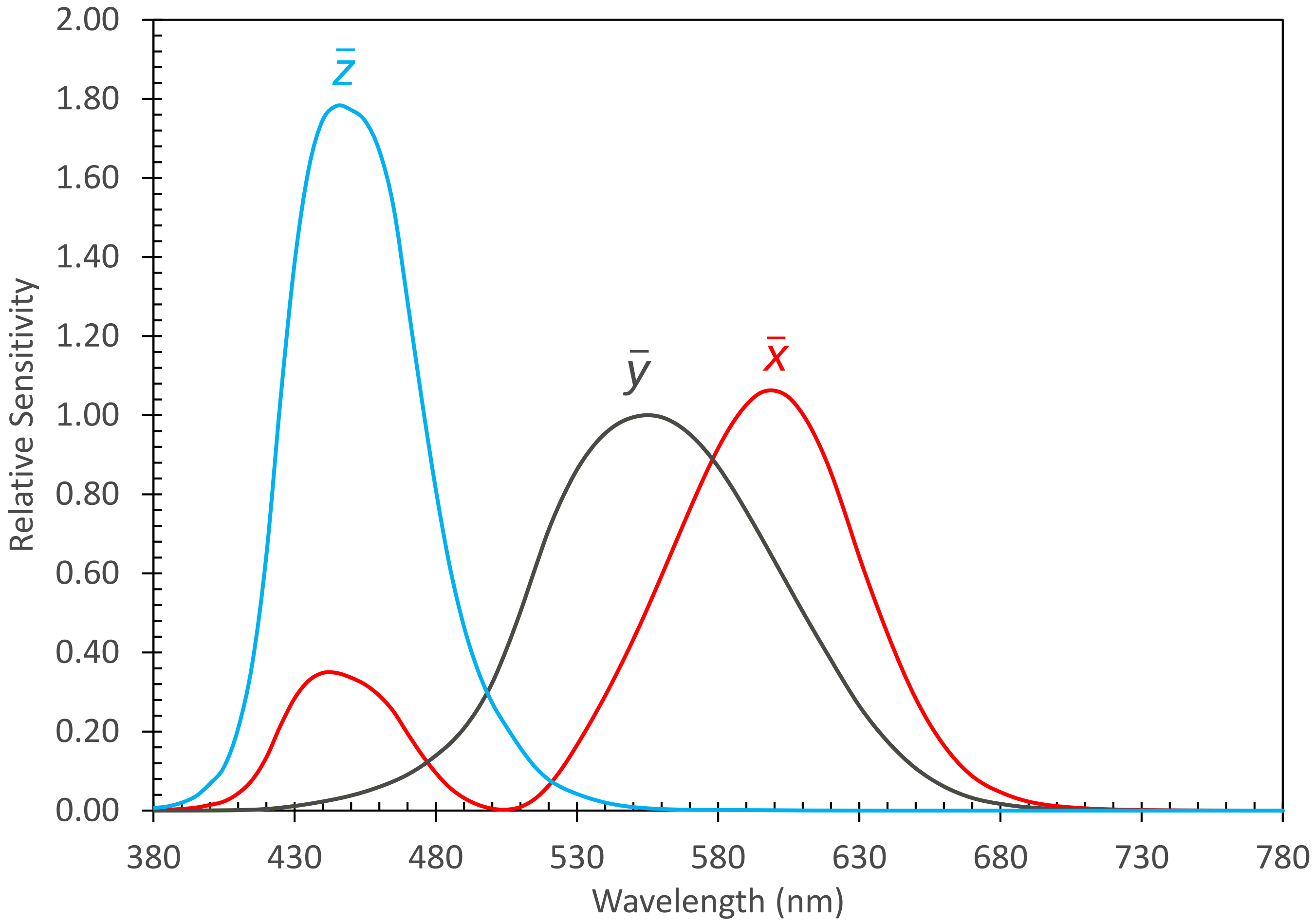



= $154\ \text{lm/W}_{radiant}$

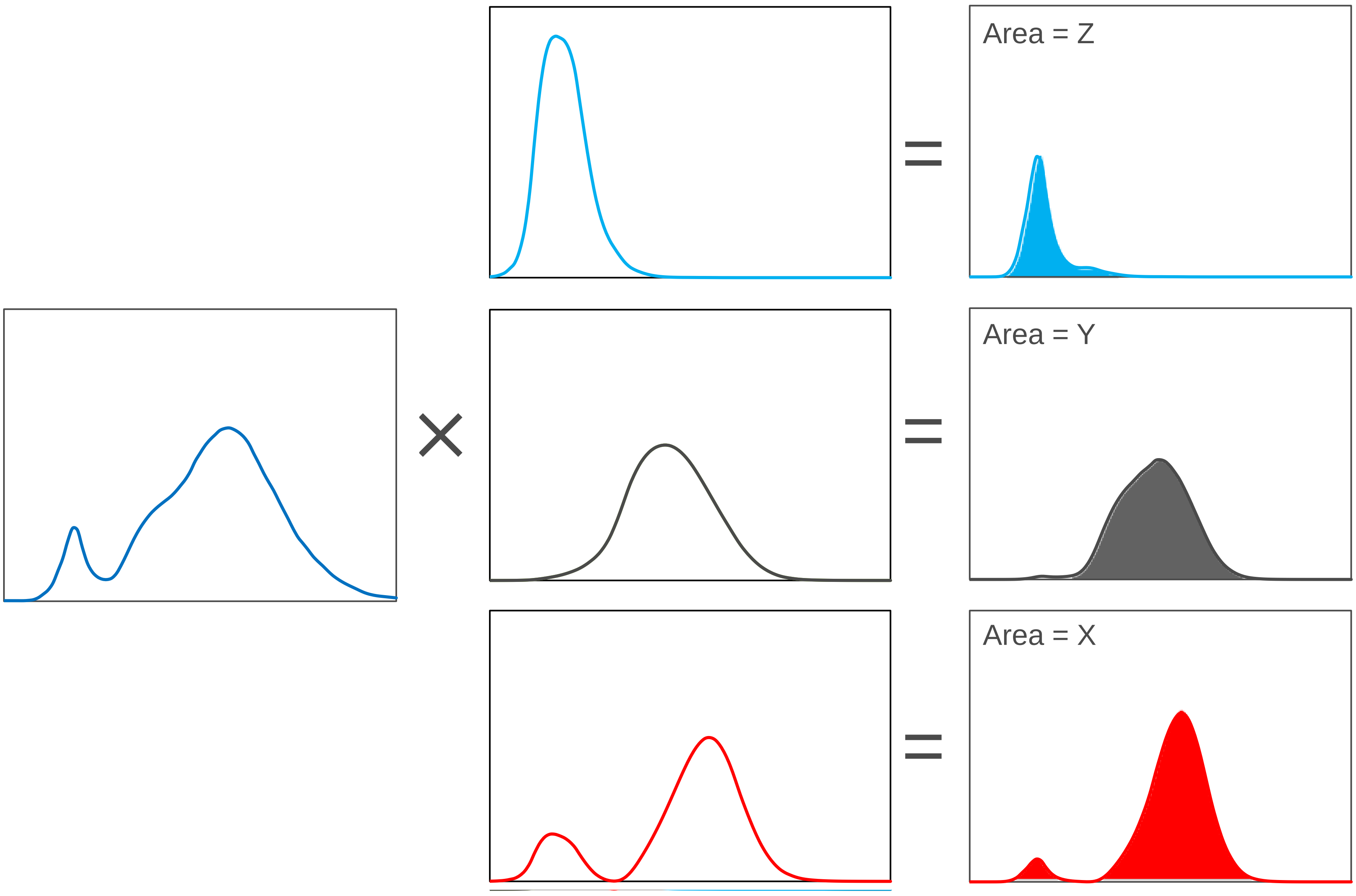



**Maximizing lumens requires tradeoffs with light color, color rendering, nonvisual stimulation, etc.!**

# Color Vision – CIE 1931 Standard Colorimetric Observer



# Metamerism



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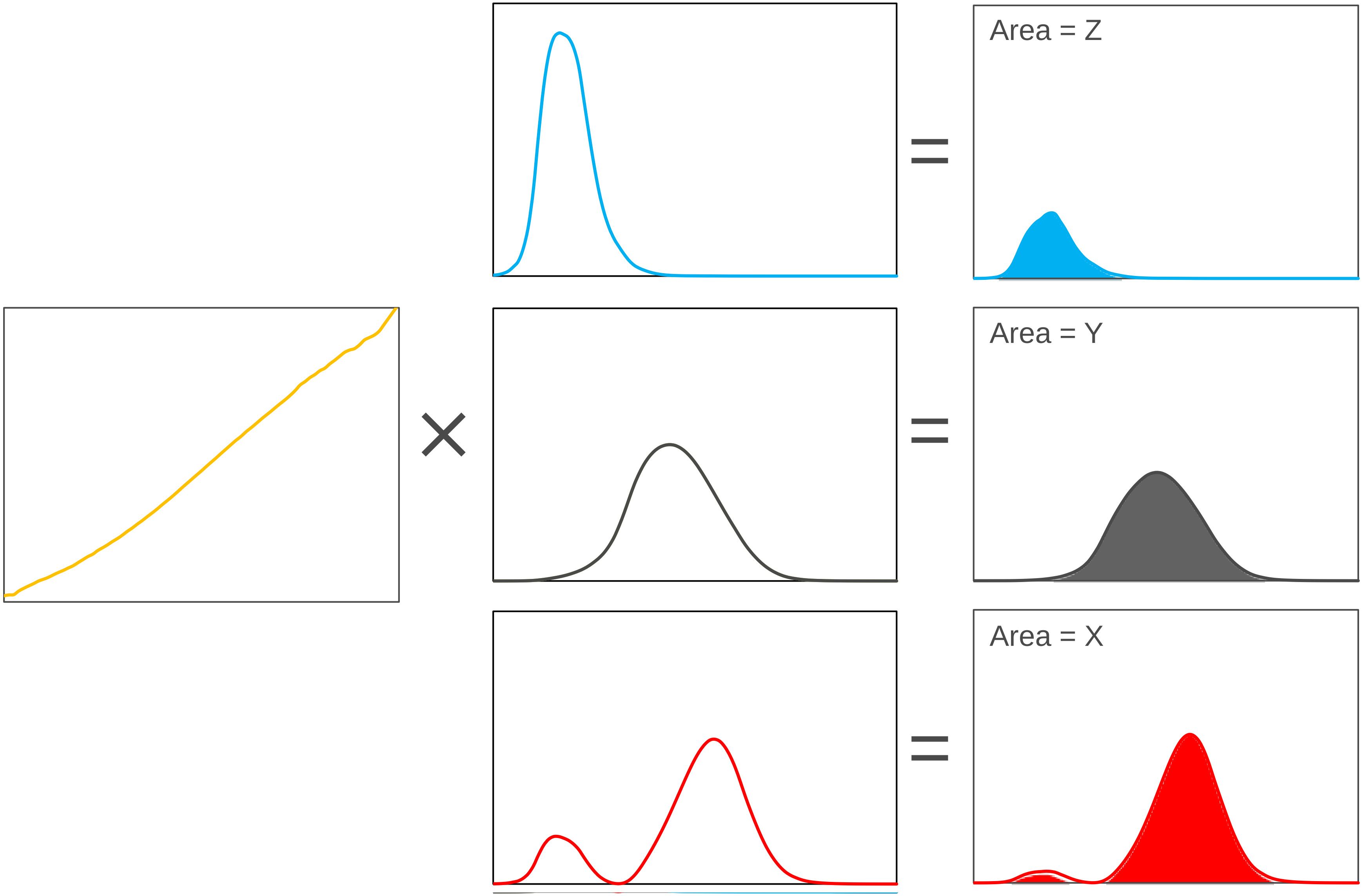




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# Metamerism / Light Color

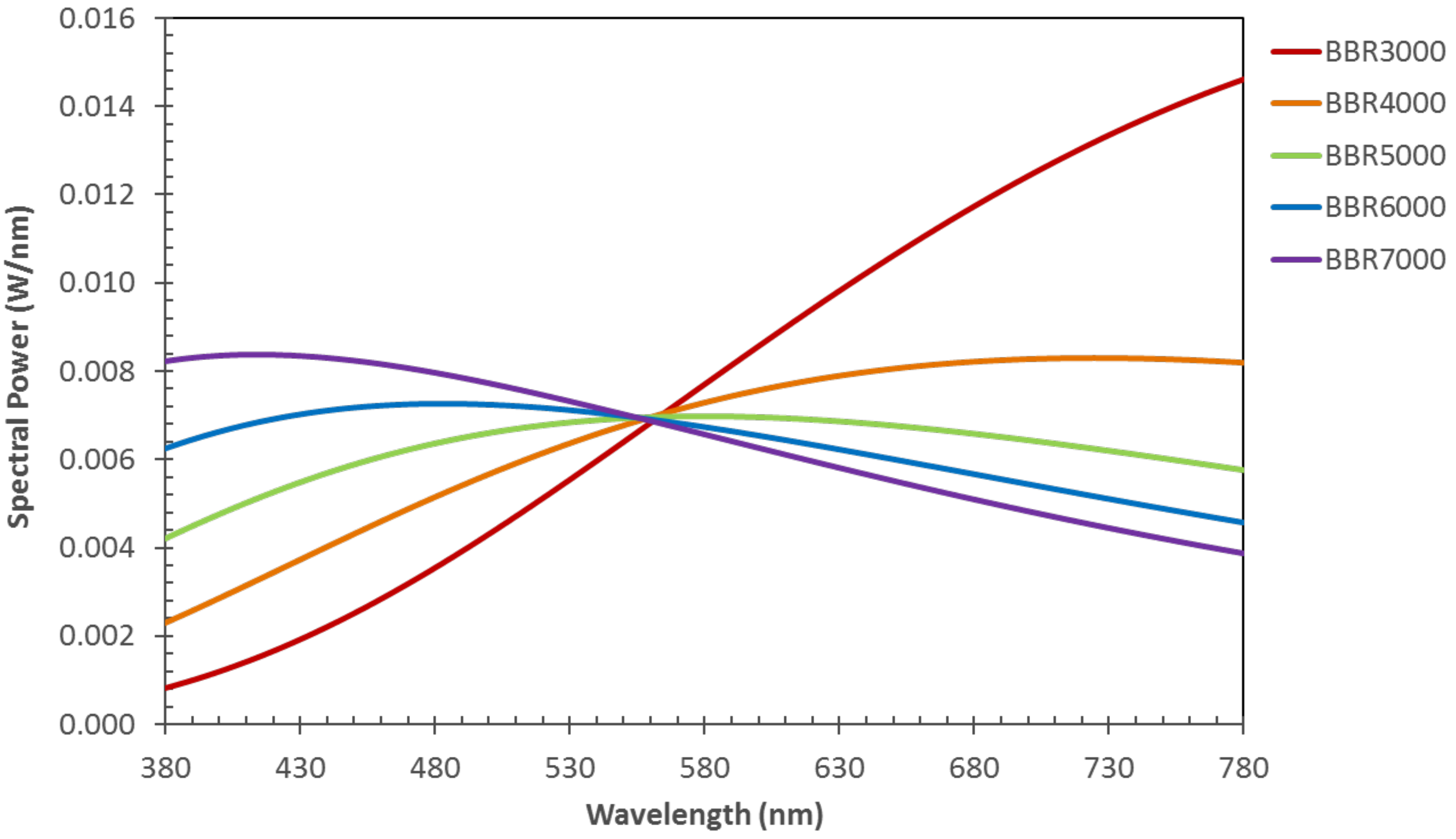
| | LED | Incandescent |
|---|---|---|
| $x = \dfrac{X}{X + Y + Z}$ | 0.4507 | 0.4515 |
| $y = \dfrac{Y}{X + Y + Z}$ | 0.4080 | 0.4067 |

(*u*, *v*) and (*u*′, *v*′) are just linear transformations of (*x*, *y*)

# Metamerism / Light Color

| | LED | Incandescent |
|---|---|---|
| $x = \dfrac{X}{X + Y + Z}$ | 0.4507 | 0.4515 |
| $y = \dfrac{Y}{X + Y + Z}$ | 0.4080 | 0.4067 |
| **Correlated Color Temperature (CCT) = Closest point on the blackbody curve (in CIE 1960 chromaticity diagram)** | 2789 K | 2812 K |

# CCT: An Approximation of Spectral Content



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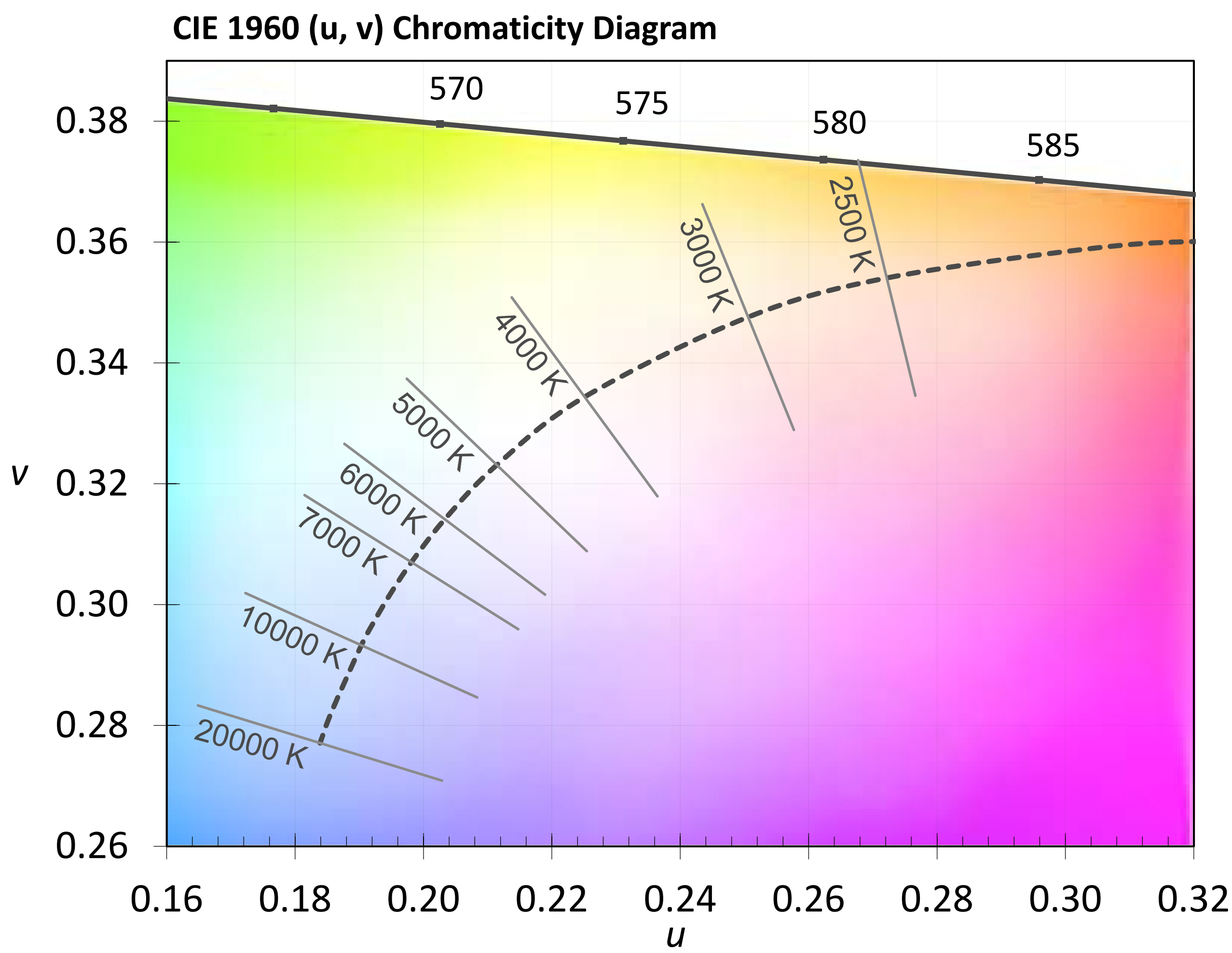

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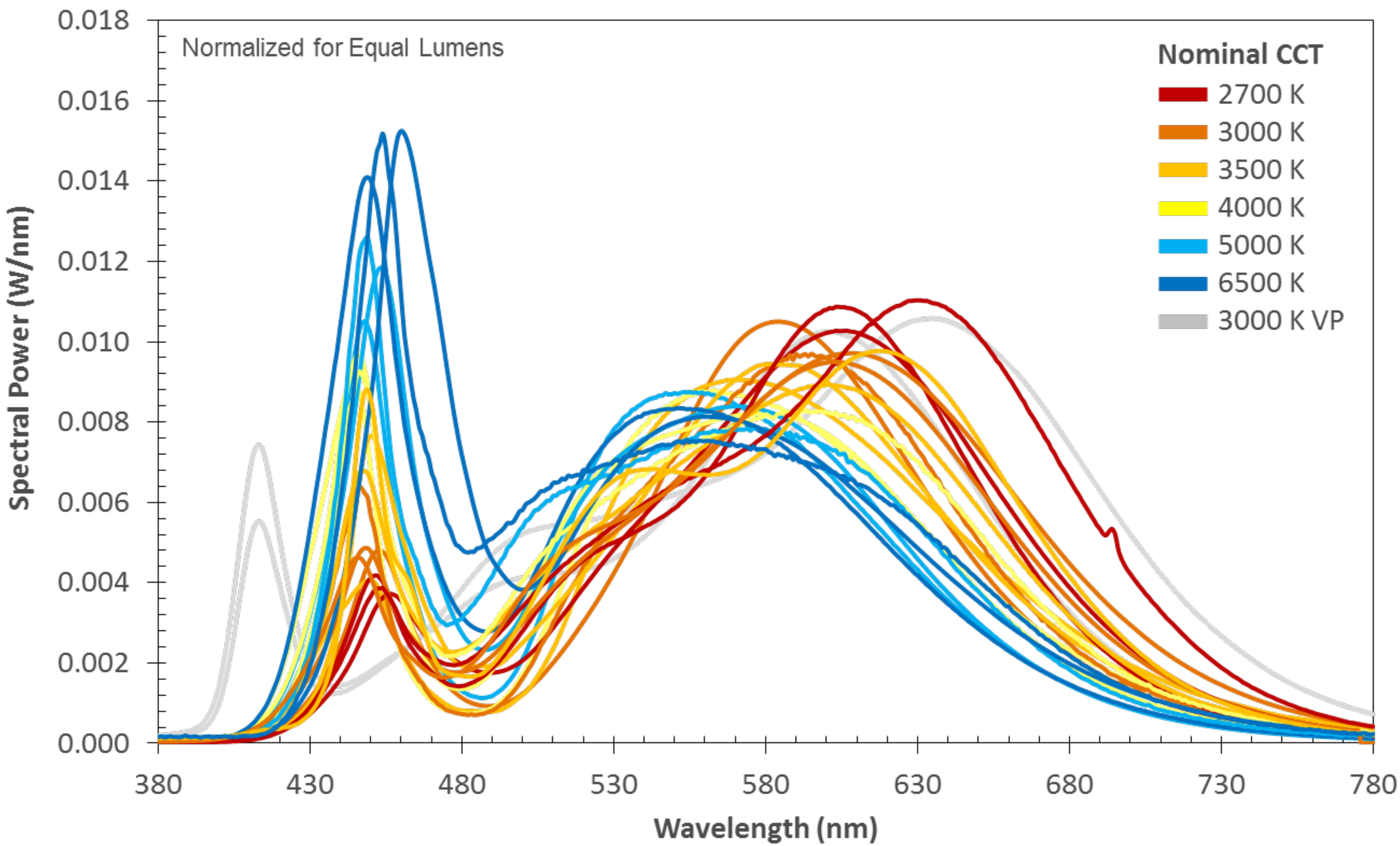

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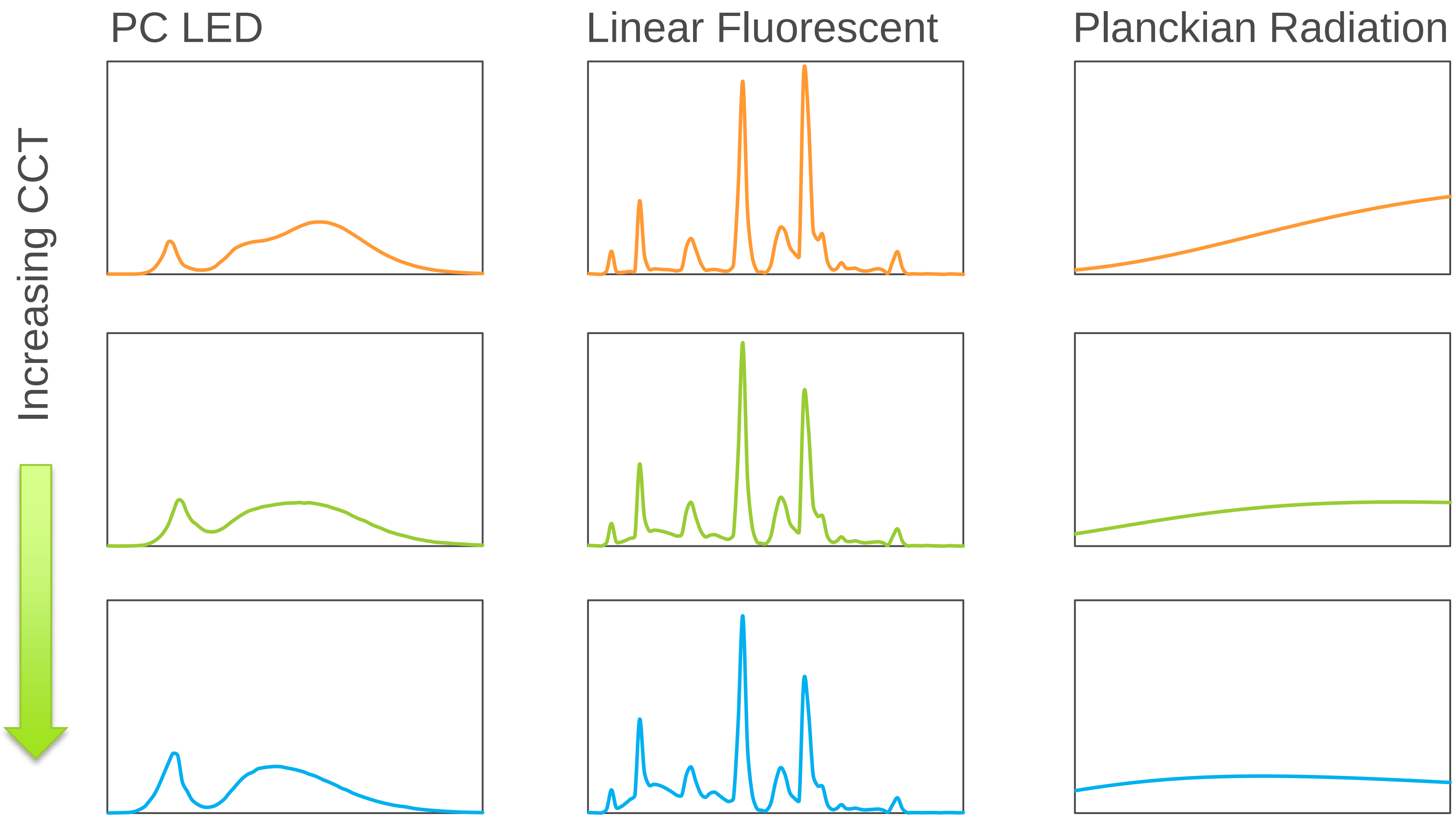
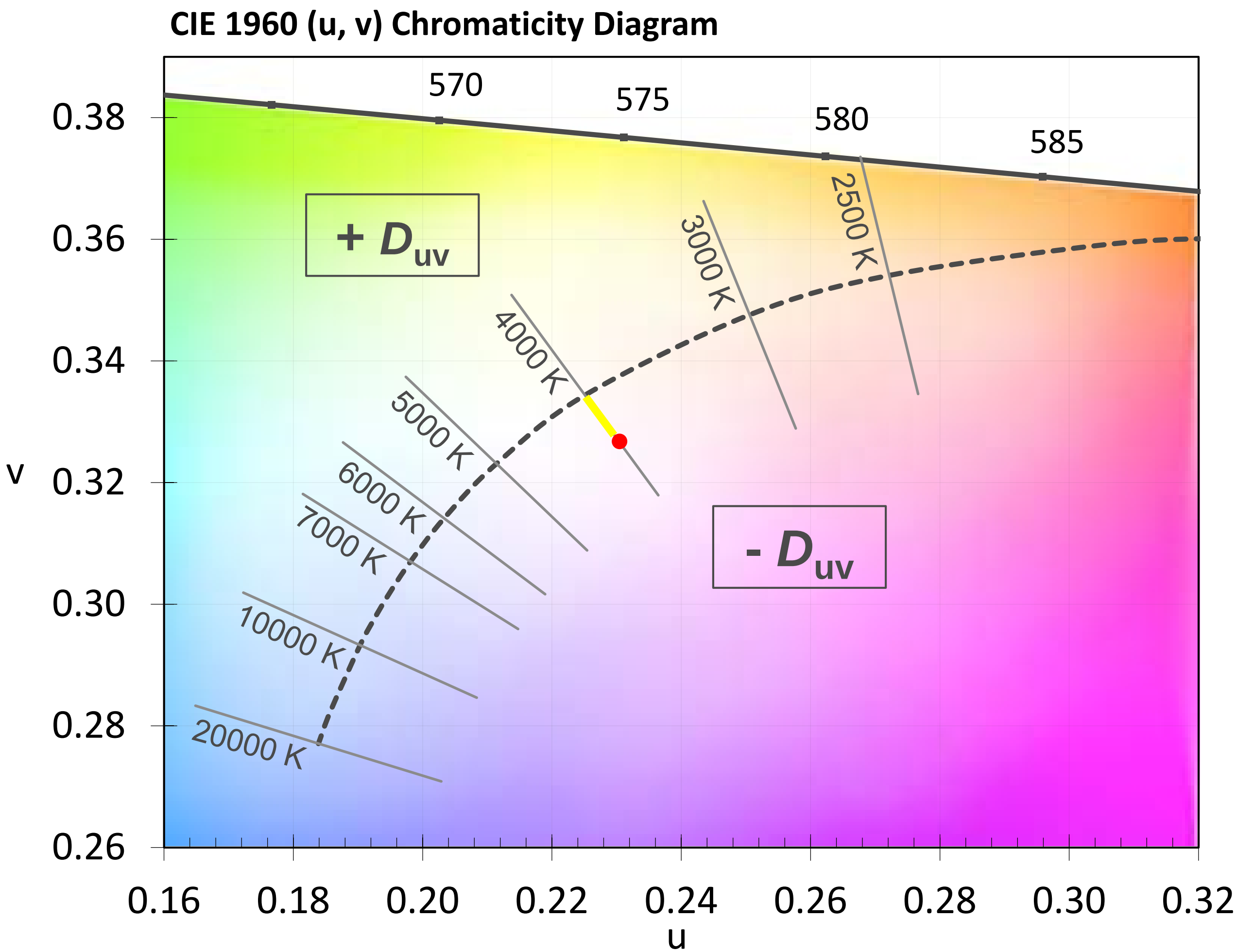


# Metamerism / Light Color

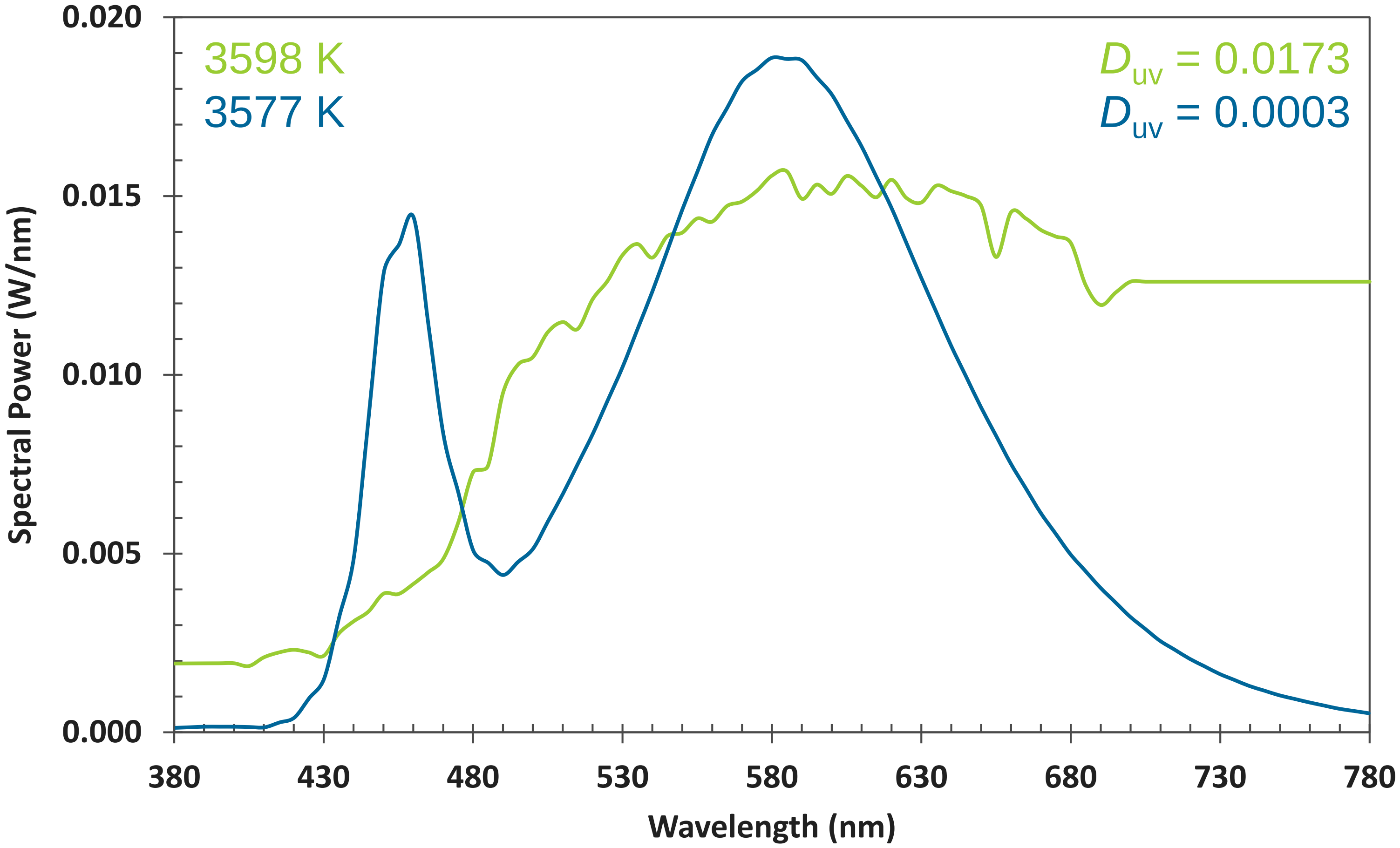
| | LED | Incandescent |
|---|---|---|
| $x = \frac{X}{X + Y + Z}$ | 0.4507 | 0.4515 |
| $y = \frac{Y}{X + Y + Z}$ | 0.4080 | 0.4067 |
| **CCT = Closest point on the blackbody curve (in CIE 1960 chromaticity diagram)** | 2789 K | 2812 K |
| **$D_{uv}$ = Distance between source and blackbody curve (in CIE 1960)** | -0.0007 | -0.0001 |

# CCT and $D_{uv}$

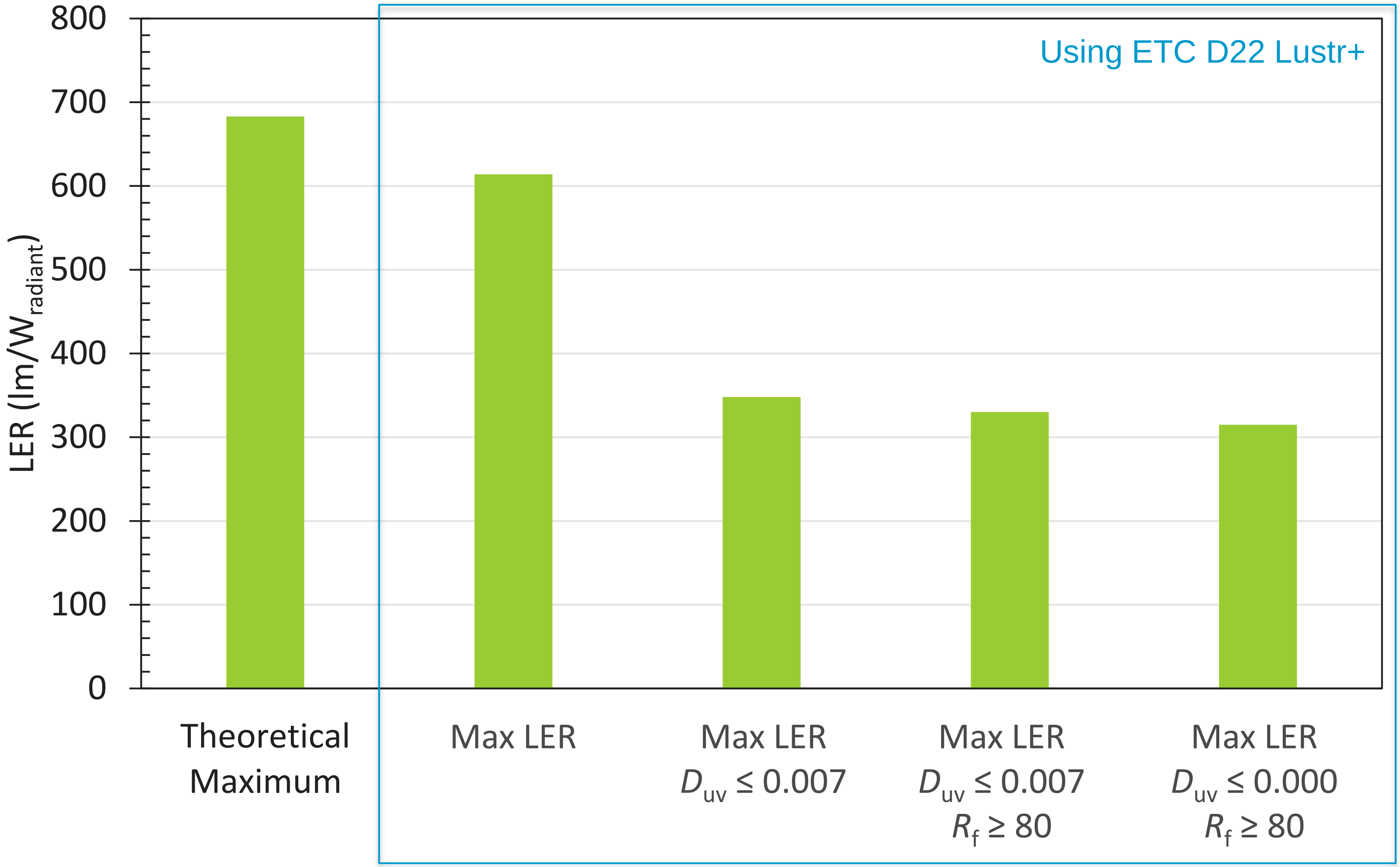


CIE 1960 (u, v) Chromaticity Diagram
570
575
580
585
+ D_uv
- D_uv
2500 K
3000 K
4000 K
5000 K
6000 K
7000 K
10000 K
20000 K
v
0.38
0.36
0.34
0.32
0.30
0.28
0.26
0.16
0.18
0.20
0.22
0.24
0.26
0.28
0.30
0.32
u

# CCT Has Limitations!



# Revisiting LER: Tradeoffs



# “Blue” Light Special!

**ipRGCs and Nonvisual Photoreception (i.e., Light and Health)**

- Big picture, nonvisual photoreception is a new phenomenon
- The photosensitivity of melanopsin is known and agreed upon (peak in the “blue”), but the overall sensitivity of various elements of the human body (e.g., circadian system) are still under investigation.
  - Other photoreceptors likely contribute
  - Response may be non-linear/non-additive
  - Response may change based on other factors

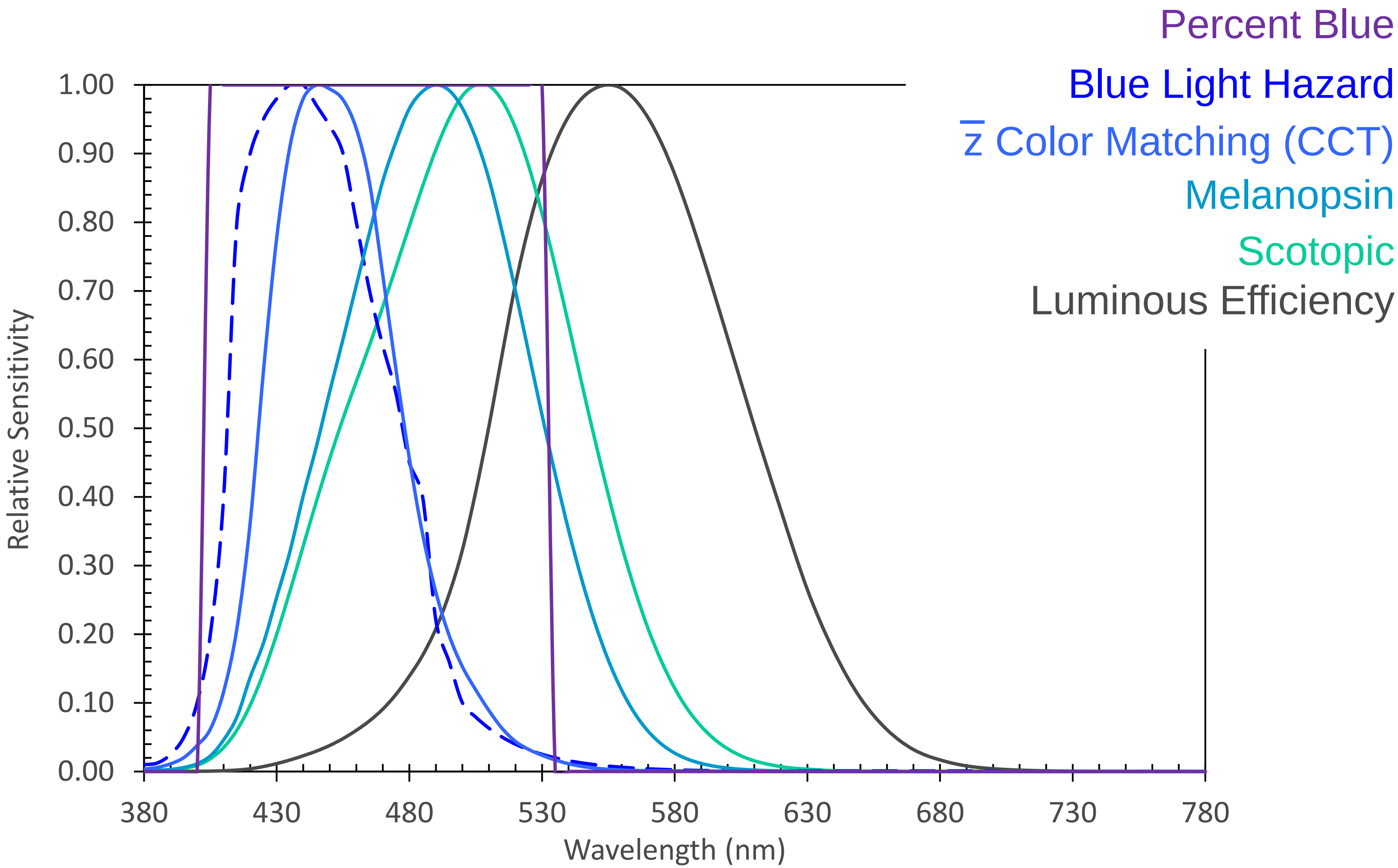
**Blue light Hazard**

- “Blue” light can case damage to the retina under the right circumstances

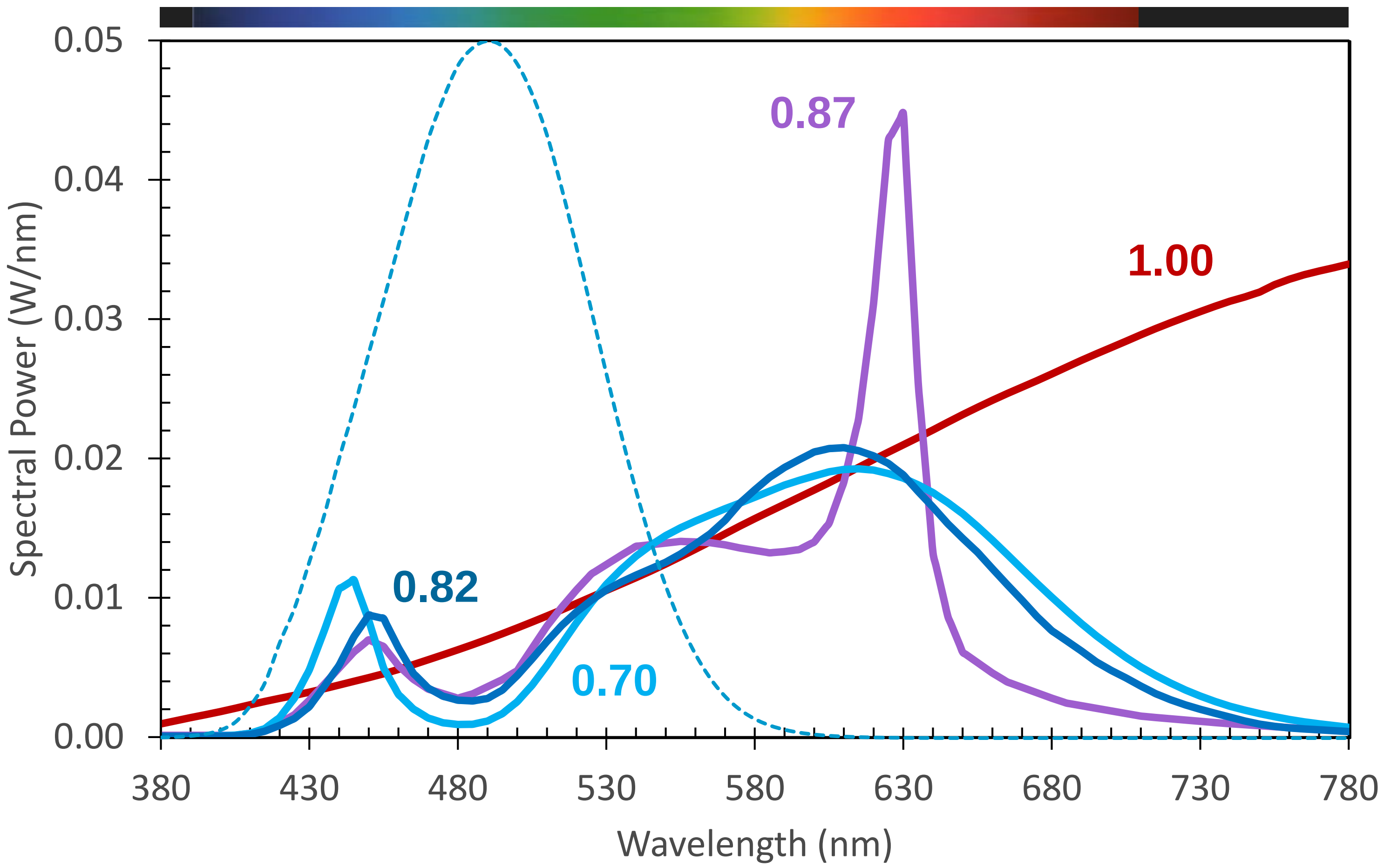
**Material Damage**

- “Blue” light can damage materials, like artwork

# Blue Light Considerations



# Comparing Spectral Power Distributions






(Values shown are relative M/P ratio)

# Compare with numbers!

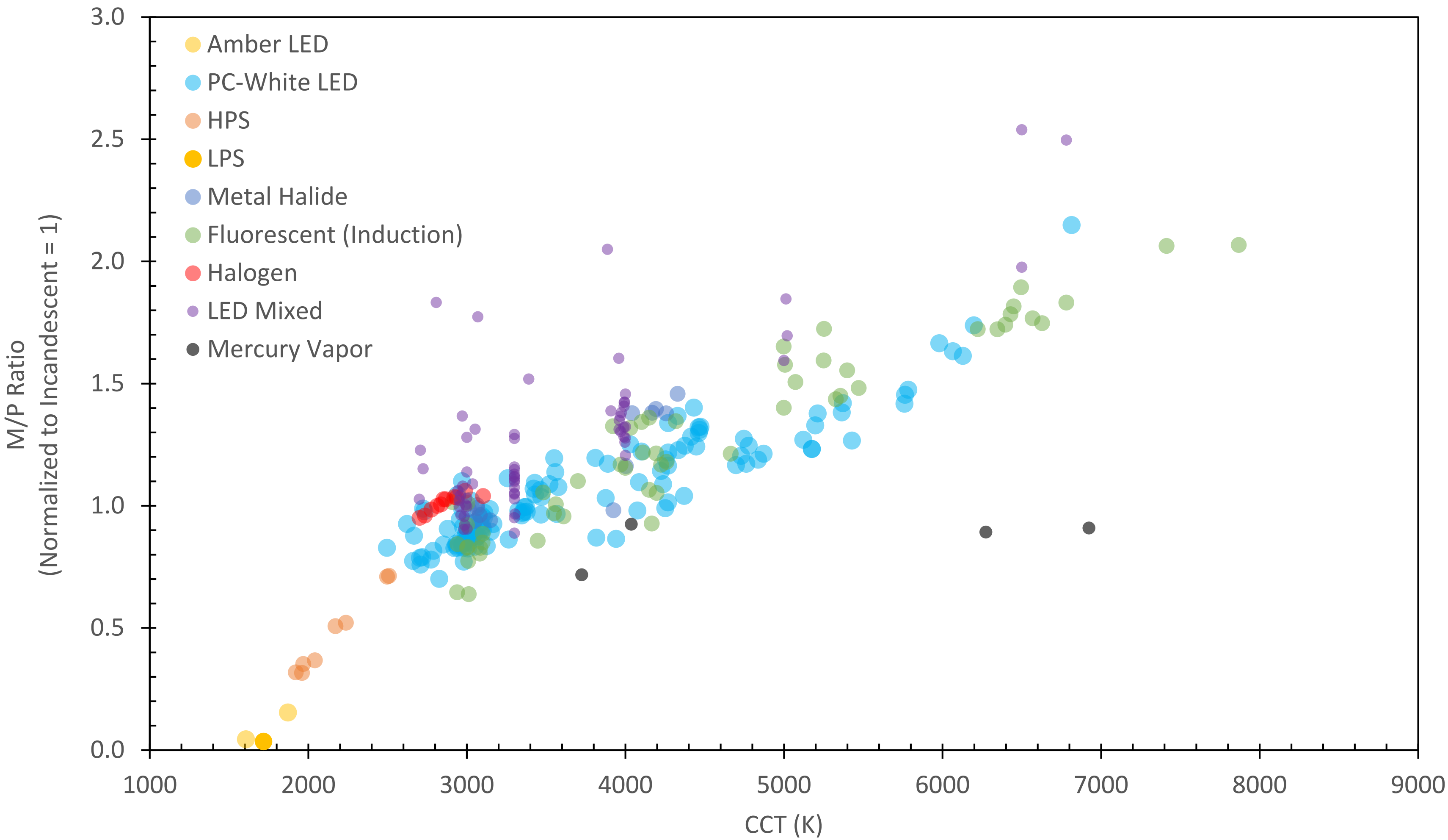
| Row | Light source | Luminous Flux (lm) | CCT (K) | % Blue* | Relative Scotopic Potential | Relative Melanopic Potential** | Relative BLH Potential |
|---|---|---|---|---|---|---|---|
| A | PC White LED | 1000 | 2700 | 17% - 20% | 0.80 - 0.99 | 0.70 - 0.99 | 0.79 - 1.05 |
| B | PC White LED | 1000 | 3000 | 18% - 25% | 0.85 - 1.08 | 0.77 - 1.10 | 0.67 - 1.35 |
| C | PC White LED | 1000 | 3500 | 22% - 27% | 0.92 - 1.24 | 0.86 - 1.31 | 1.21 - 1.70 |
| D | PC White LED | 1000 | 4000 | 27% - 32% | 0.95 - 1.20 | 0.86 - 1.25 | 1.38 - 1.94 |
| E | PC White LED | 1000 | 4500 | 31% - 35% | 1.06 - 1.29 | 1.01 - 1.40 | 1.77 - 2.11 |
| F | PC White LED | 1000 | 5000 | 34% - 39% | 1.17 - 1.31 | 1.17 - 1.38 | 1.91 - 2.46 |
| G | PC White LED | 1000 | 5700 | 39% - 43% | 1.25 - 1.50 | 1.27 - 1.66 | 2.22 - 2.74 |
| H | PC White LED | 1000 | 6500 | 43% - 48% | 1.48 - 1.79 | 1.61 - 2.15 | 2.52 - 2.84 |
| I | Narrowband Amber LED | 1000 | 1606 | 0% | 0.16 | 0.04 | 0.02 |
| J | Low Pressure Sodium | 1000 | 1718 | 0% | 0.16 | 0.04 | 0.01 |
| K | PC Amber LED | 1000 | 1872 | 1% | 0.32 | 0.15 | 0.06 |
| L | High Pressure Sodium | 1000 | 1959 | 9% | 0.40 | 0.32 | 0.36 |
| M | High Pressure Sodium | 1000 | 2041 | 10% | 0.45 | 0.37 | 0.42 |
| N | Mercury Vapor | 1000 | 6924 | 36% | 1.05 | 0.91 | 2.58 |
| O | Mercury Vapor | 1000 | 4037 | 35% | 0.96 | 0.92 | 3.36 |
| P | Metal Halide | 1000 | 3145 | 24% | 0.98 | 0.94 | 1.28 |
| Q | Metal Halide | 1000 | 4002 | 33% | 1.14 | 1.16 | 2.15 |
| R | Metal Halide | 1000 | 4041 | 35% | 1.28 | 1.38 | 2.14 |
| S | Moonlight*** | 1000 | 4681 | 29% | 1.50 | 1.68 | 2.26 |
| **T** | **Incandescent** | **1000** | **2812** | **11%** | **1.00** | **1.00** | **1.00** |
| U | Halogen | 1000 | 2934 | 13% | 1.03 | 1.03 | 1.03 |
| V | F32T8/830 Fluorescent | 1000 | 2940 | 20% | 0.91 | 0.84 | 1.08 |
| W | F32T8/835 Fluorescent | 1000 | 3480 | 26% | 1.07 | 1.05 | 1.50 |
| X | F32T8/841 Fluorescent | 1000 | 3969 | 30% | 1.17 | 1.17 | 1.68 |

* Percent blue calculated according to LSPDD: Light Spectral Power Distribution Database, http://galileo.graphycs.cegepsherbrooke.qc.CA/app/en/home

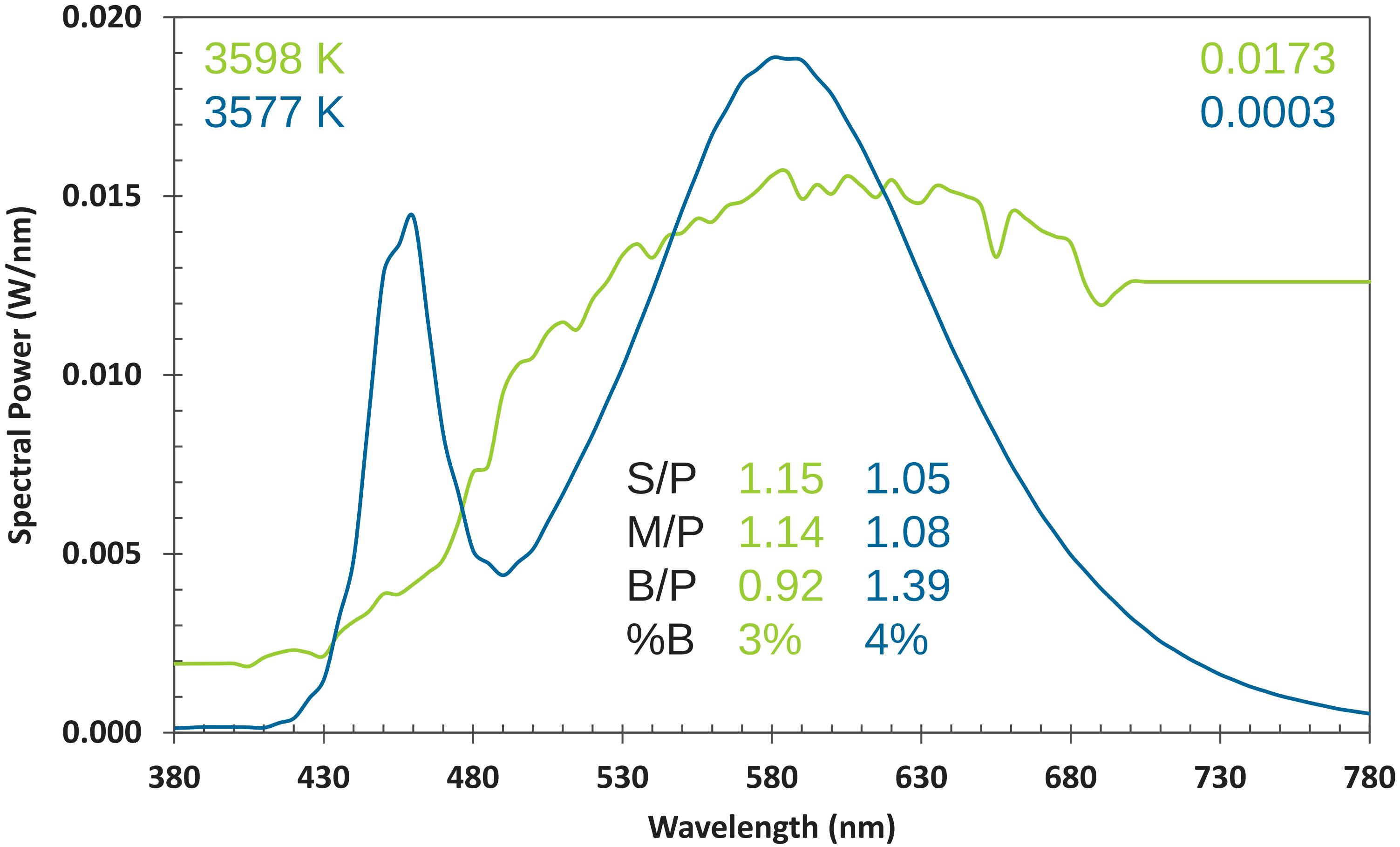
** Melanopic content calculated according to CIE Irradiance Toolbox, http://files.cie.co.at/784_TN003_Toolbox.xls, 2015

*** Measurement by Telelumen. Moonlight does not have a constant CCT.

# Comparing Blue Measures

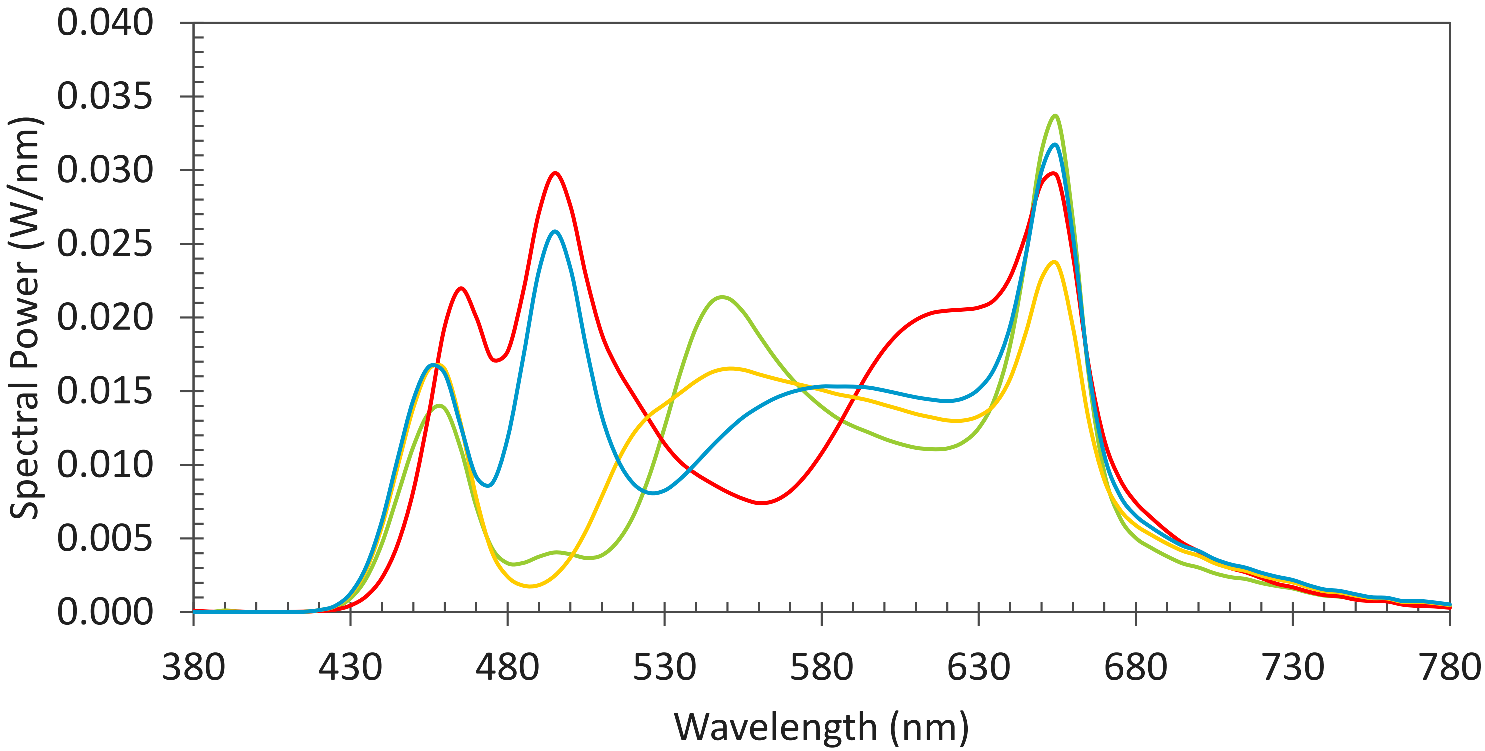


# Compare with numbers!



# Spectral Engineering – Sources of the future

Maximizing and minimizing melanopic content at same chromaticity:

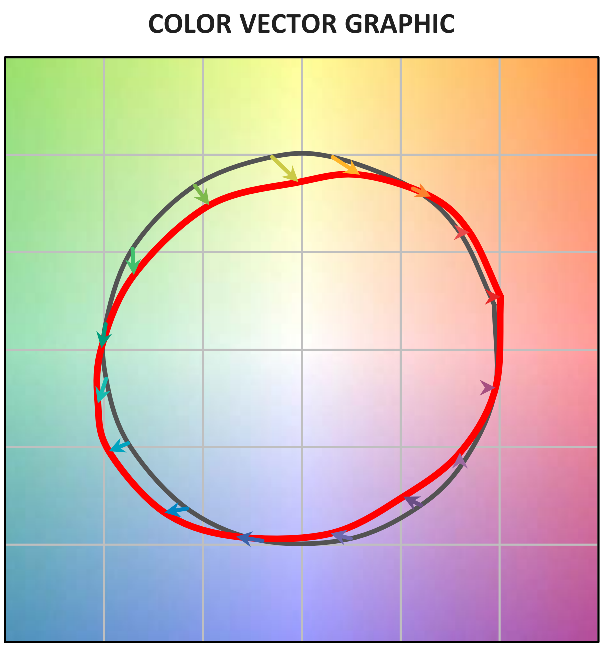


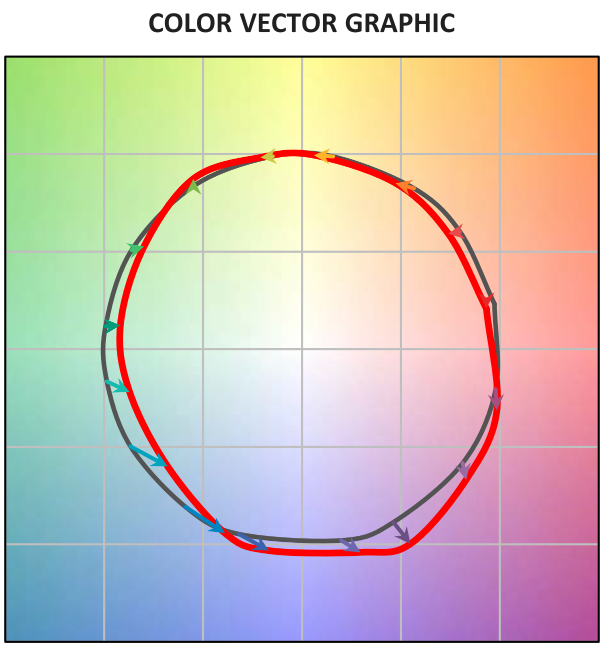

| | | | |
|---|---|---|---|
| CCT = 4133 K | CCT = 3838 K | CCT = 3900 K | CCT = 4101 K |
| $D_{uv}$ = -0.0094 | $D_{uv}$ = 0.01 | $D_{uv}$ = 0.005 | $D_{uv}$ = -0.005 |
| Rf = 57 | Rf = 75 | Rf = 80 | Rf = 80 |
| Rg = 92 | Rg = 96 | Rg = 99 | Rg = 95 |
| **m/p = 2.27** | **m/p = 1.00** | **m/p = 1.11** | **m/p = 1.83** |

m/p normalized to incandescent = 1

# Spectral Engineering – Sources of the future

Maximizing and minimizing melanopic content at same chromaticity:

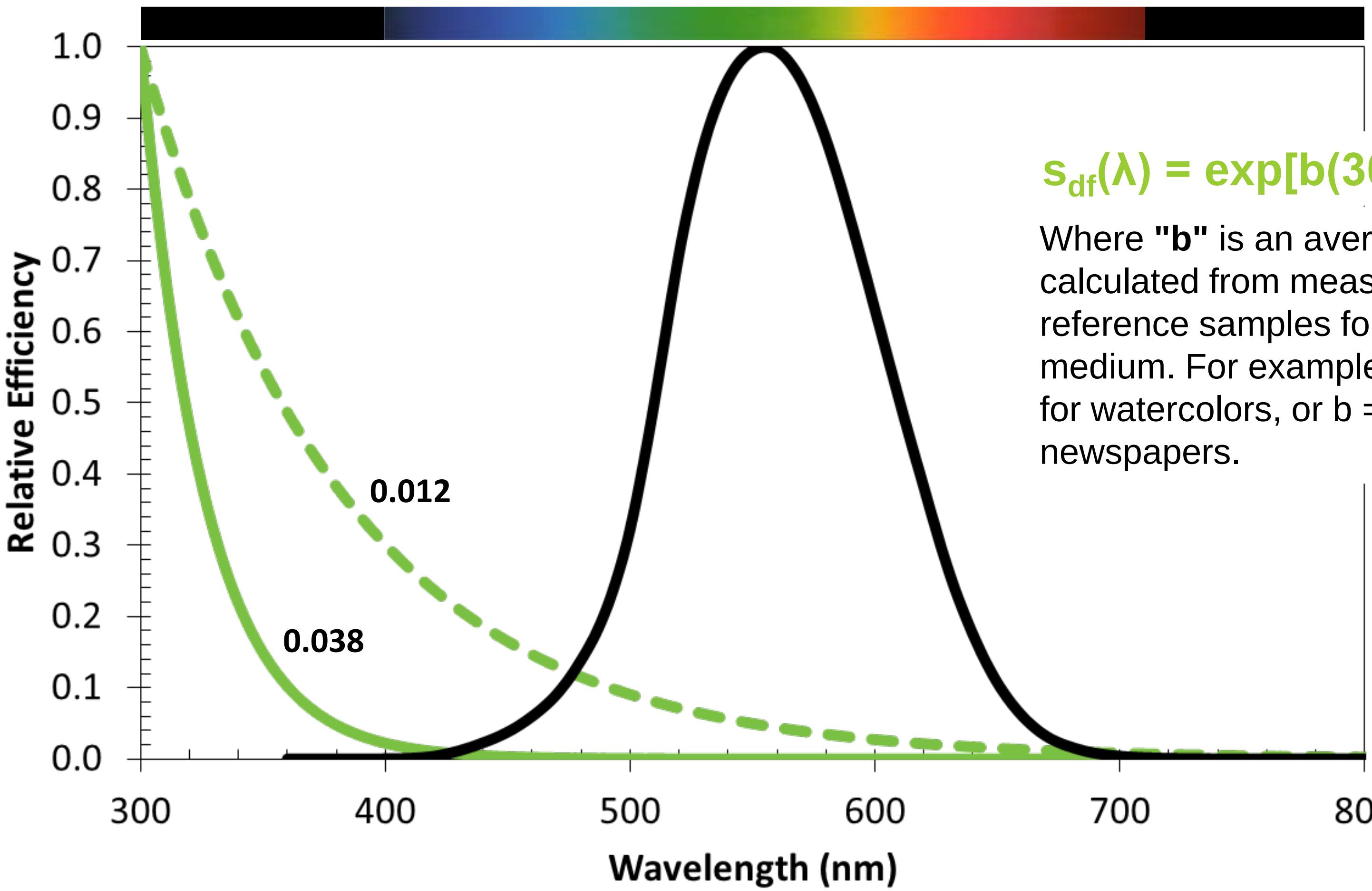



CCT = 3900 K
$D_{uv}$ = 0.005
Rf = 80
Rg = 99
**m/p = 1.11**

CCT = 4101 K
$D_{uv}$ = -0.005
Rf = 80
Rg = 95
**m/p = 1.83**

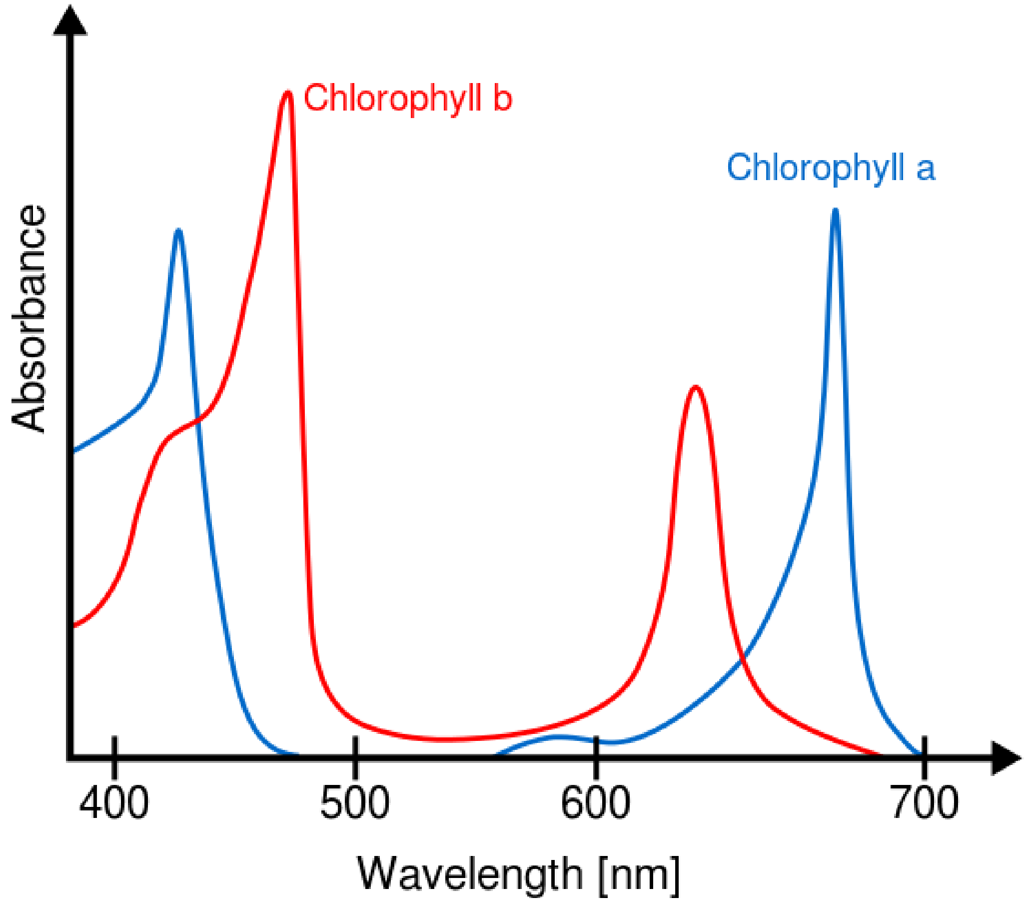
# **Don't Forget!** Material Damage Function, S(λ)



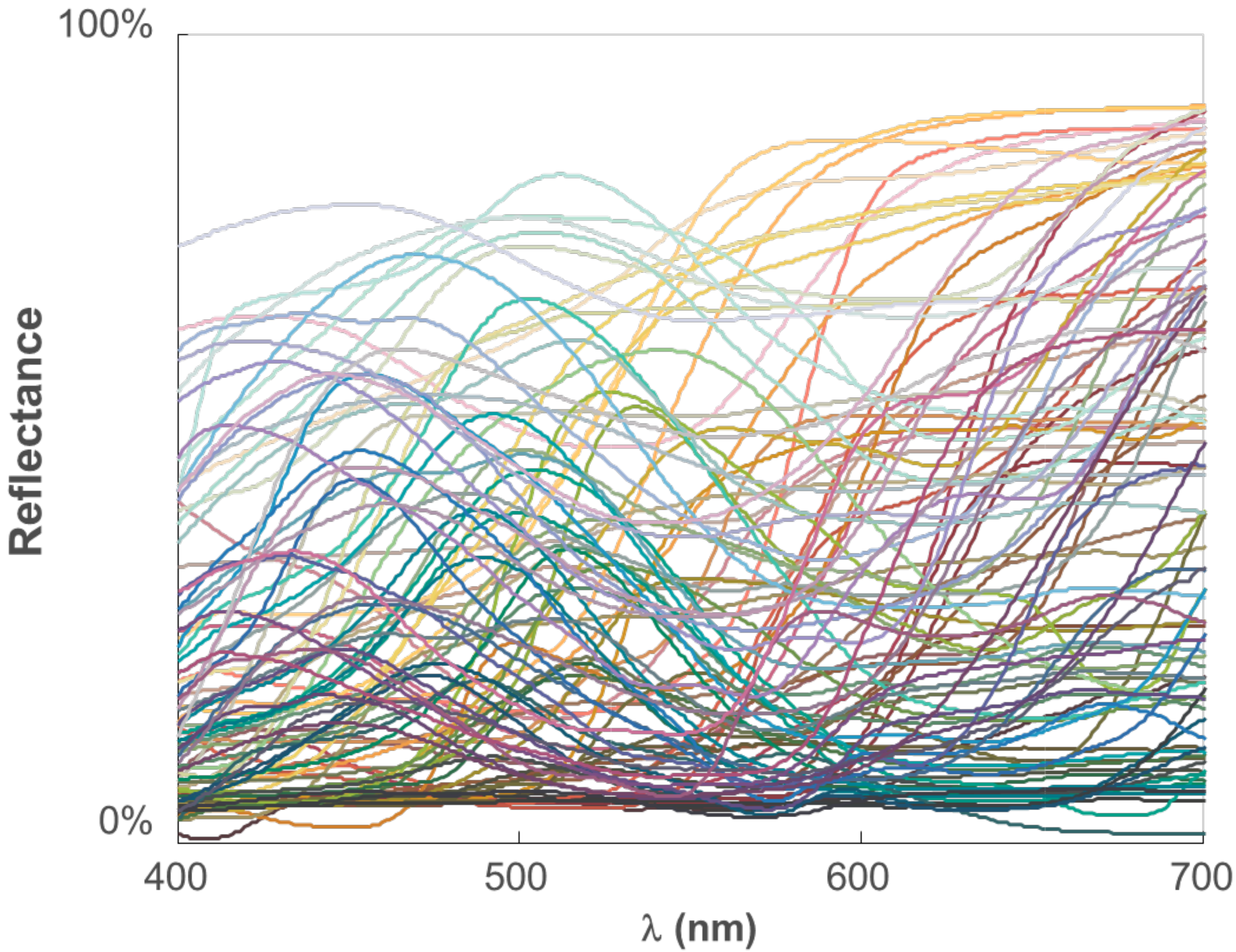

$s_{df}(\lambda) = \exp[b(300-\lambda)]$

Where **"b"** is an average value calculated from measured reference samples for a specific medium. For example, b = 0.012 for watercolors, or b = 0.038 for newspapers.

# **Don't Forget!** Plants and Animals



# **Don't Forget!** Color Rendition



# Conclusions

- LEDs offer unprecedented ability for spectral engineering.
- LED is not a homogenous technology!
- LEDs do not pose an unusual hazard for any undesirable consequence of lighting.
- Measures of blue are correlated, but not substitutes. Sources can be carefully tuned to minimize or maximize various effects.
- One action spectrum can't be used to quantify another. Illuminance doesn't characterize melanopic response.
- When designing a spectrum, there are inevitably tradeoffs.
- Understand how SPDs are measured and reported.
- Understand how SPDs can be represented in charts.
- Use numbers, rather than visual evaluations.

Other warnings:
Never use two weighting functions at once.
Watch out for scaling factors and know when they are/aren't used.
Always use absolute SPDs when calculating weighted values.
Understand the dλ term and how SPDs are measured/reported.