

COL7655 (3-0-2)

Foundations of Visual Computing

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Thanks to Rahul Narain for help with slides

Pre-assignment

- Programming language + image library to use for IP assignments:
 - Python with scikit-image or opencv-python
 - Matlab with the Image Processing Toolkit
 - C++ with OpenCV
- Use your chosen library to load an image, view it at different zoom levels, read values from the underlying pixel array, and save the image to a new PNG file.

Digital Representation of Light

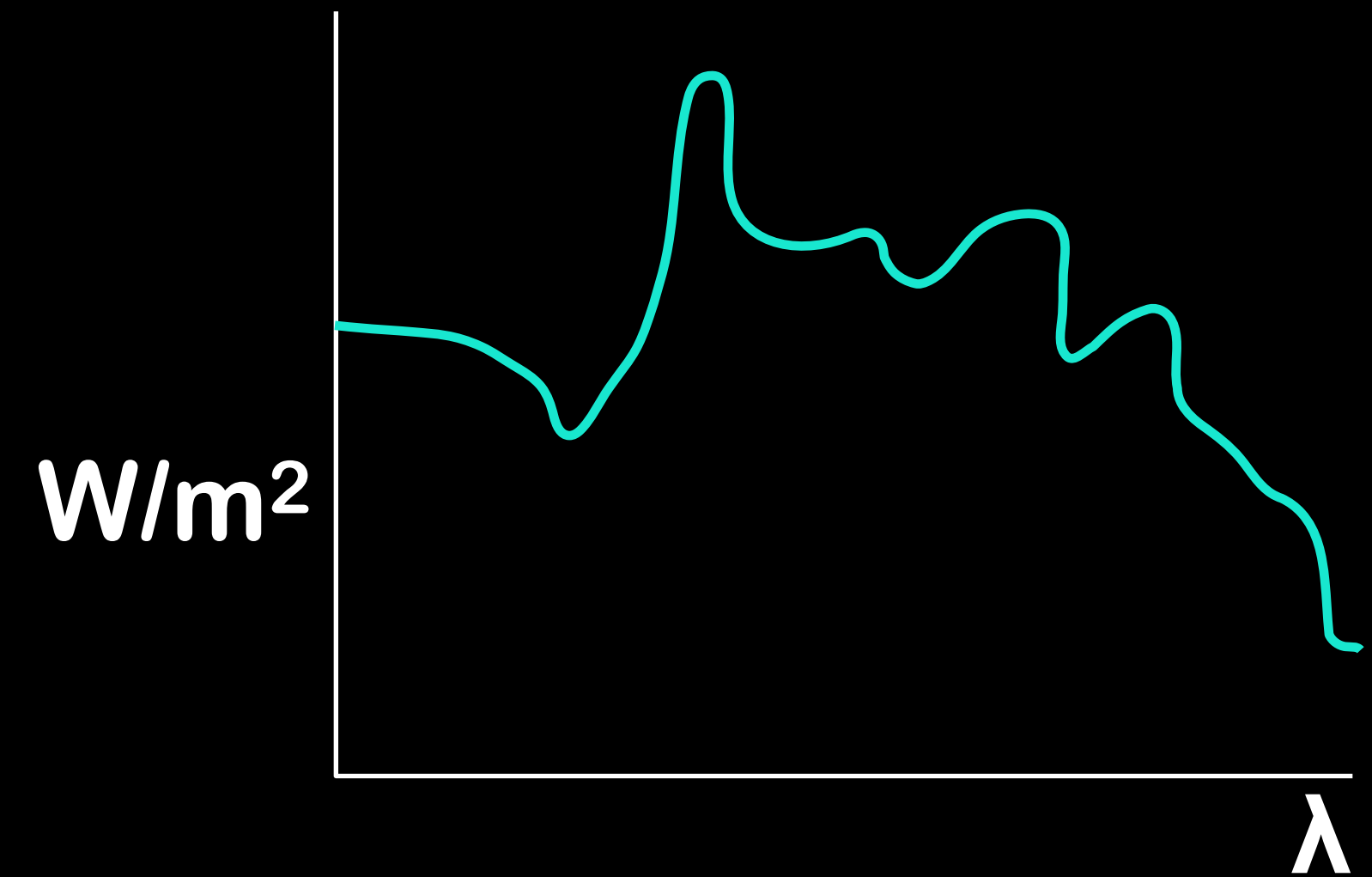
In Bits

- How to model Distribution
 - Continuous function
 - Sample? Uniformly?
 - Represent intensity and “chromaticity”
 - What range of values?
 - How many bits?
 - Account for perception to maximize the information content of bits
- Color is not a physical quantity and cannot be disjointed from intensity

Sensing Light

Brightness and Color

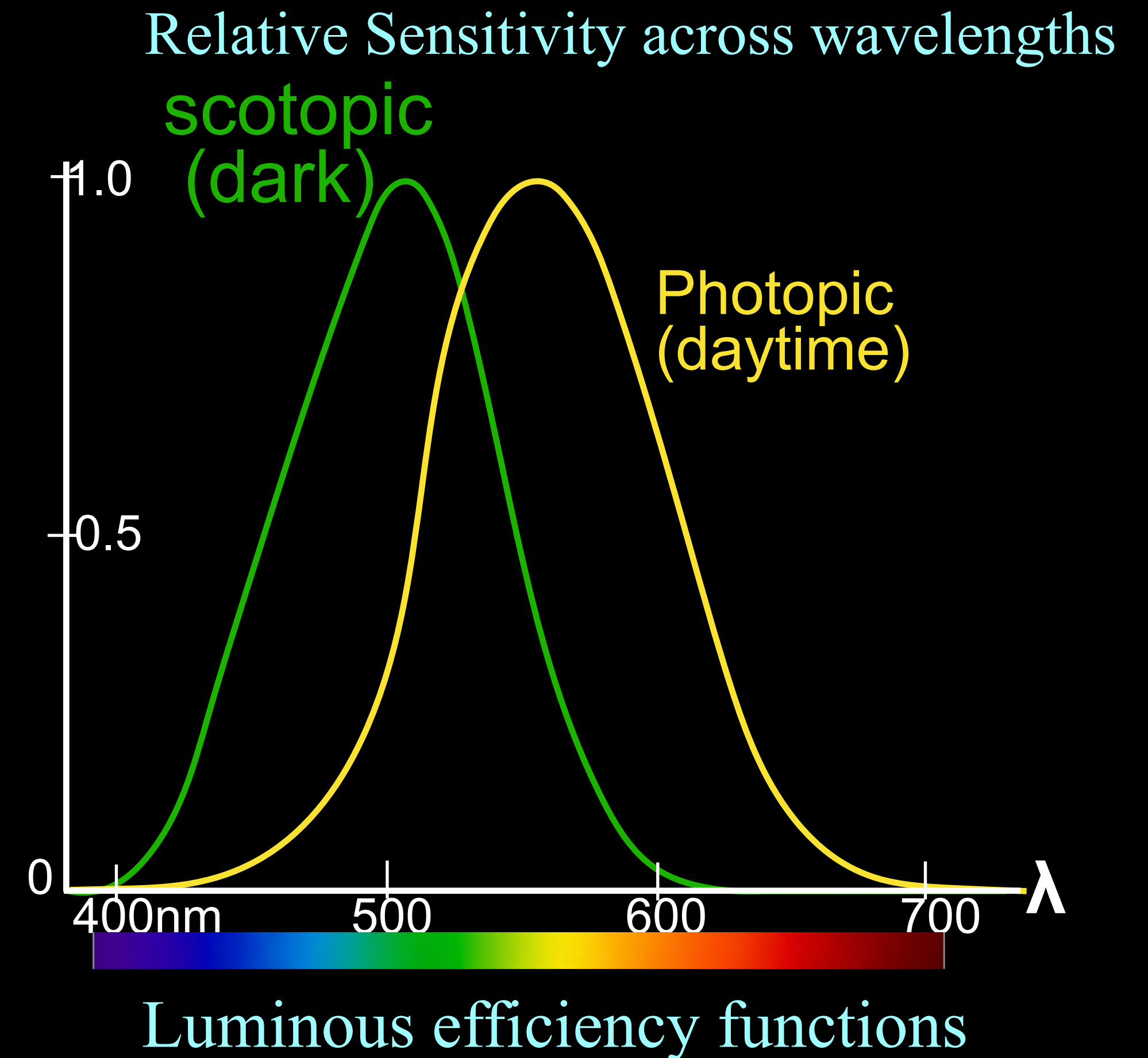
- Eye senses light distribution
 - But light $\neq$ R-G-B (or any other such model)
- Electromagnetic energy (waves or photons)
 - $h\nu == hc/\lambda$ (Joules)
 - c can vary with medium, λ can shift
- Eyes only comprise four types of sensor cells (rods, SML cones)
- Equal W/m^2 with different λ do not appear equally bright



Luminous Efficiency

- ↖ Luminous flux: Perceived power
- Lumens per watt (lm/W)
 - Bright light efficiency < 683 lm/W
 - @ Monochromatic light with $\lambda = 555$ nm
 - Dark light efficiency < 1700 lm/W
 - @ $\lambda = 507$ nm

Perceived brightness is not independent of “color”

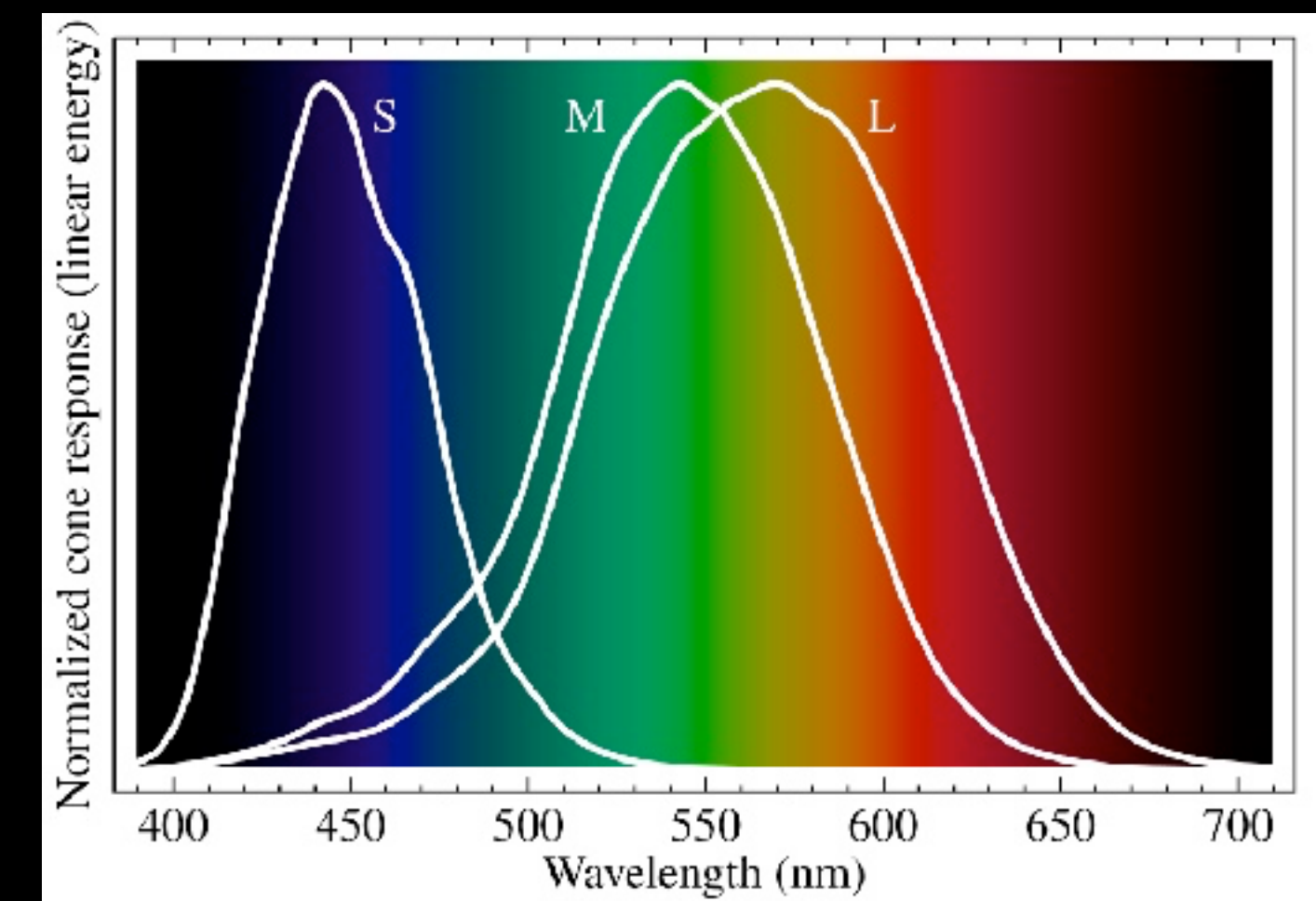
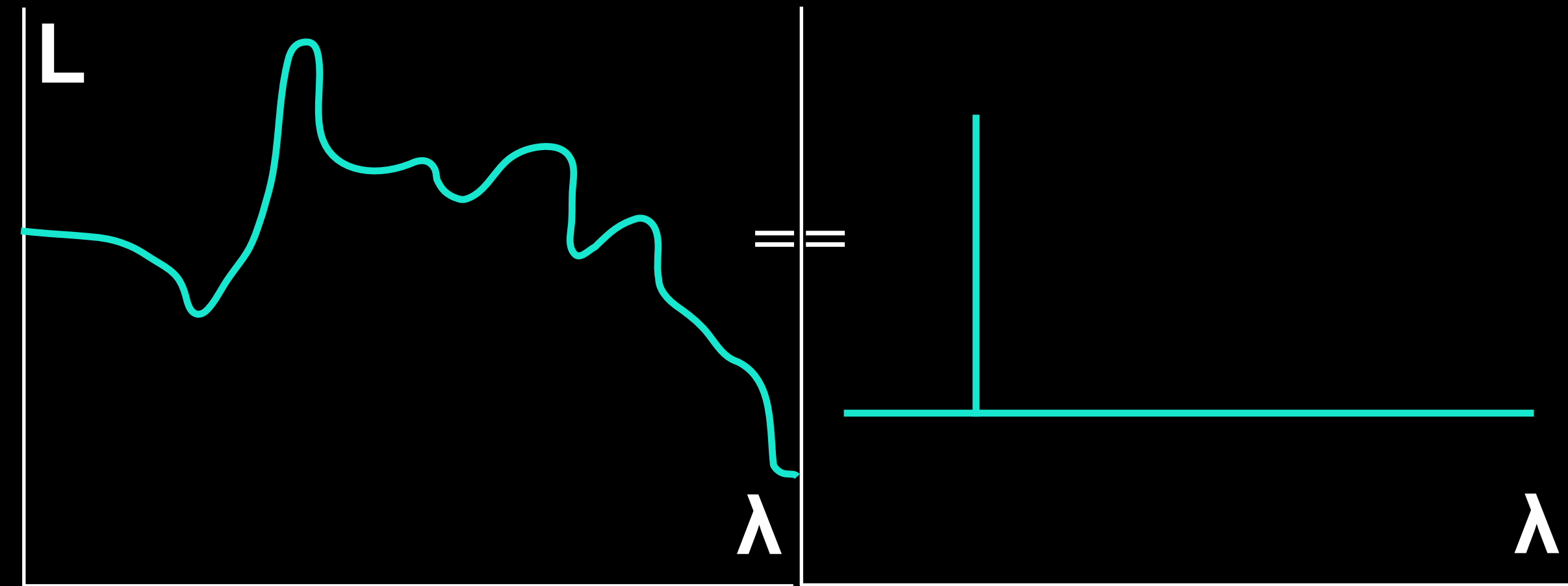


Tri-Stimulus Theory

(aka channels, components)

Just three values can describe every visible color perception

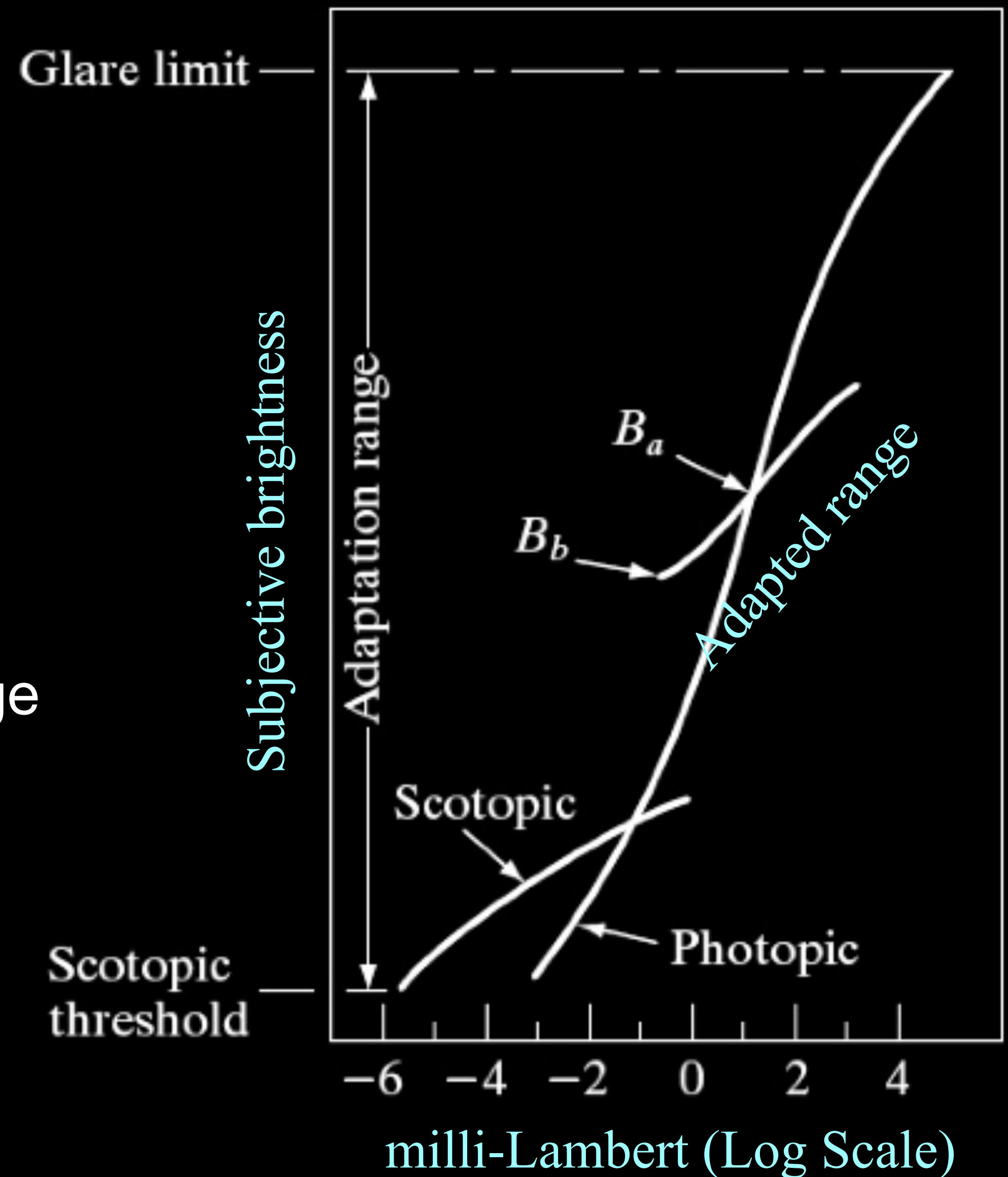
- Metamers appear the same
- Retina has photosensors:
 - Rods (low resolution, Peripheral, Many)
 - Cones (High res, in fovea, few, 3 types)
 - Maximum response at 420 nm (blue)
 - Maximum response at 534 nm (Yellowish-Green)
 - Maximum response at 564 nm (Orangish-Yellow)
- Integrating (Filtering) Sensors



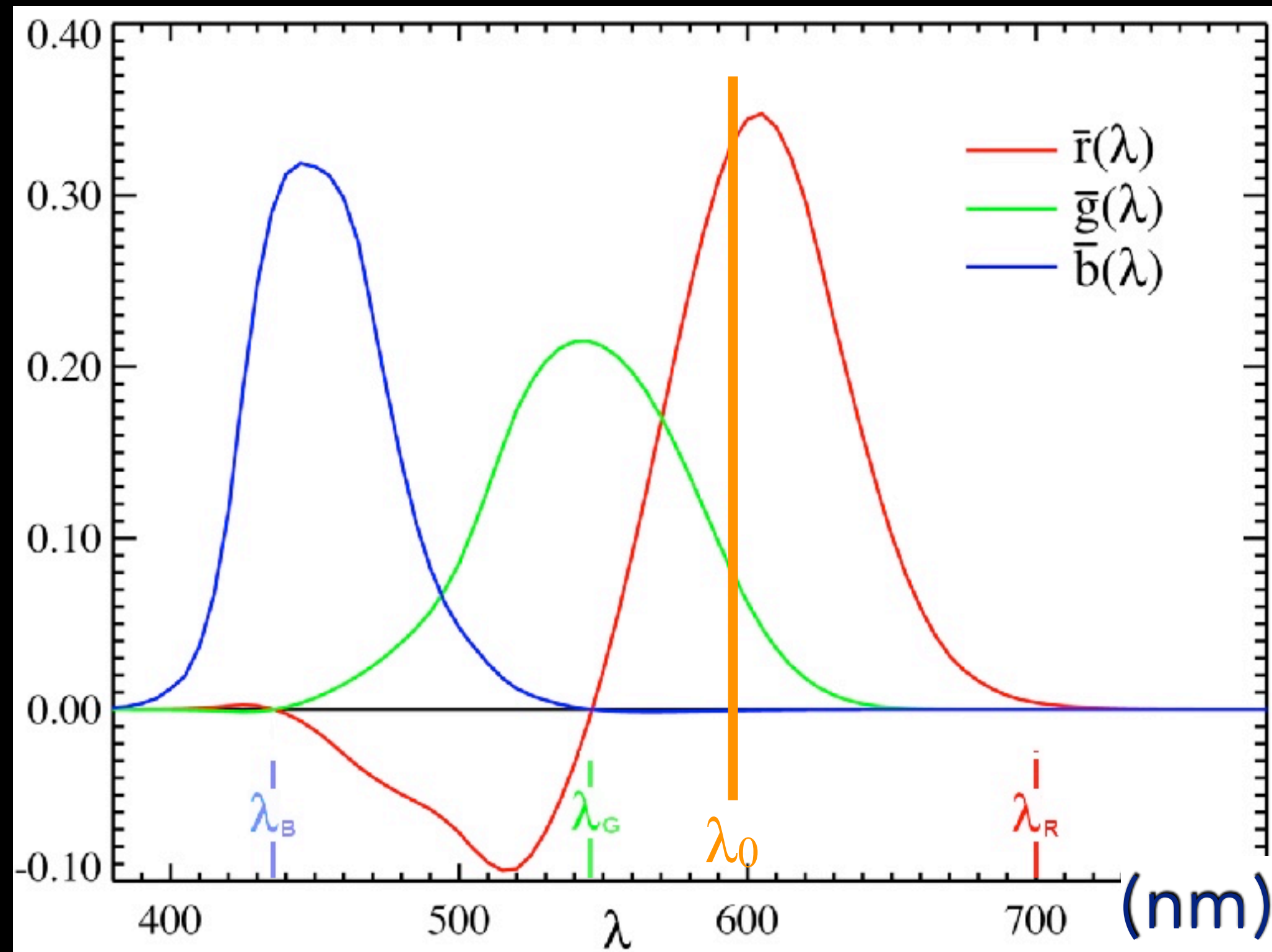
Cone Response Function

Brightness

- Subjective brightness is ~logarithmic in physical light intensity
- Human visual system can adapt to a large range of intensities (billion times)
 - But can discriminate only within a limited range at a time



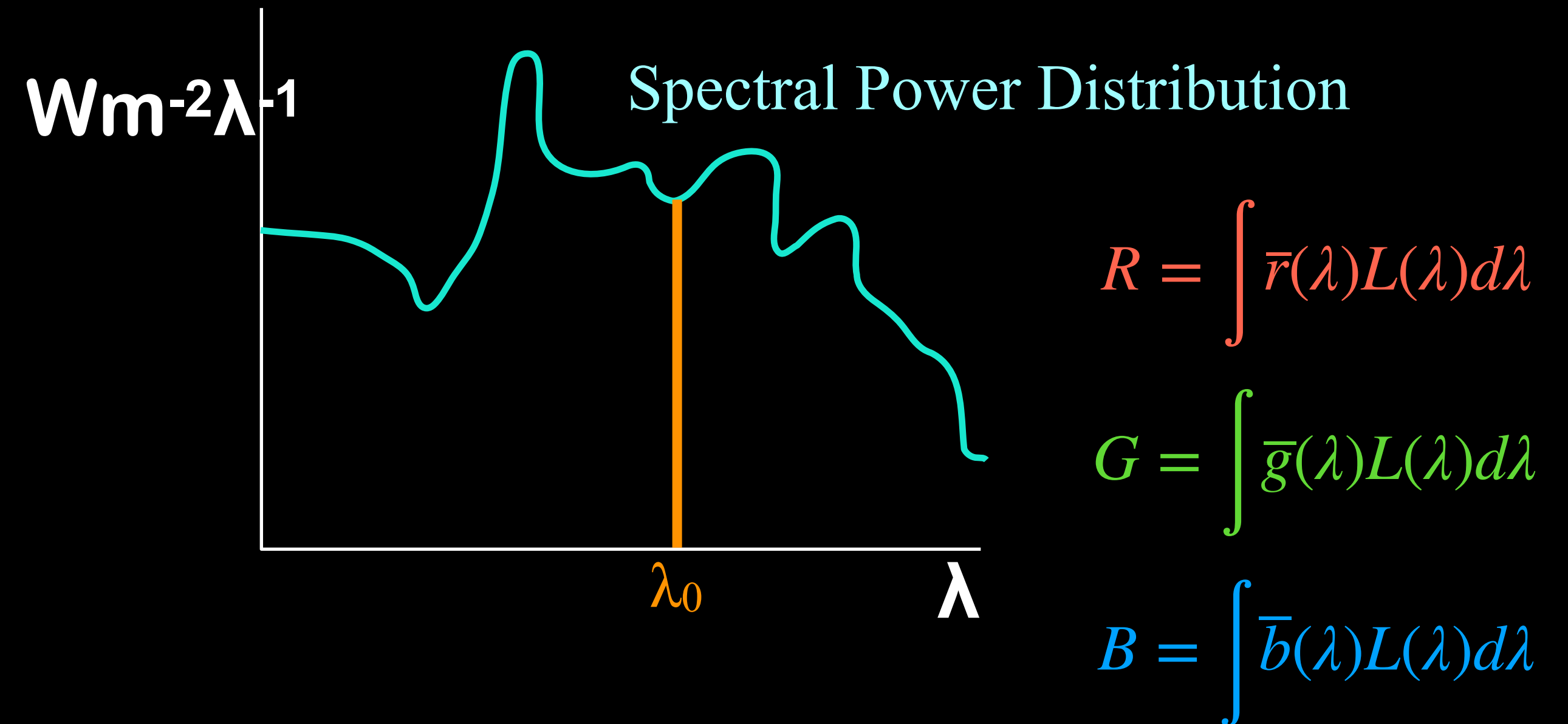
R-G-B Color Matching Functions



Primaries: 435.8, 546.1, 700 nm

Relative Luminosity: .06, 4.59, 1

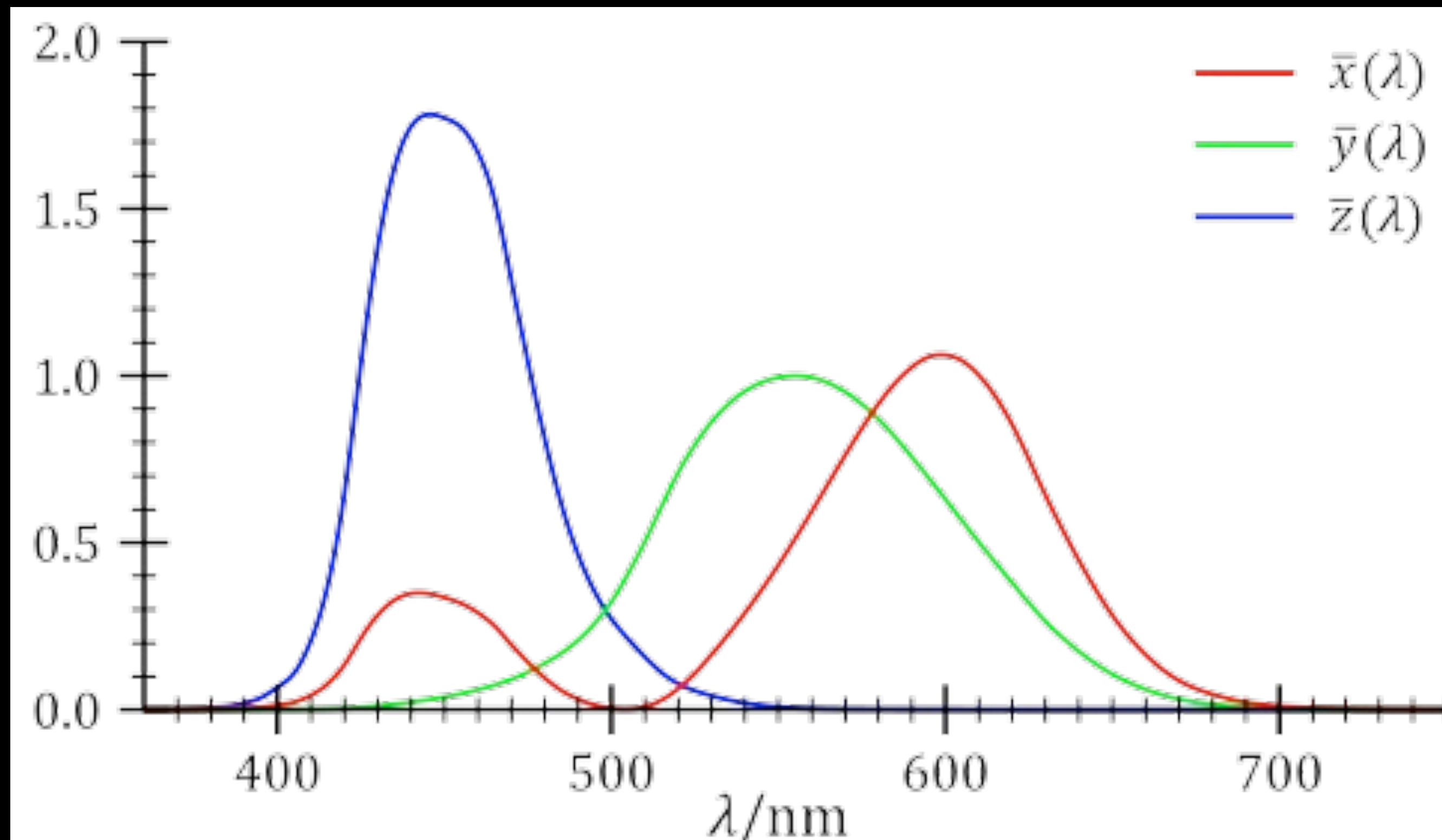
Monochromatic λ of fixed luminance = $\bar{r}(\lambda) + \bar{g}(\lambda) + \bar{b}(\lambda)$ (Additive colors)



$$\text{Color}_{\lambda_0} = L(\lambda_0)d\lambda [\bar{r}(\lambda_0) + \bar{g}(\lambda_0) + \bar{b}(\lambda_0)]$$

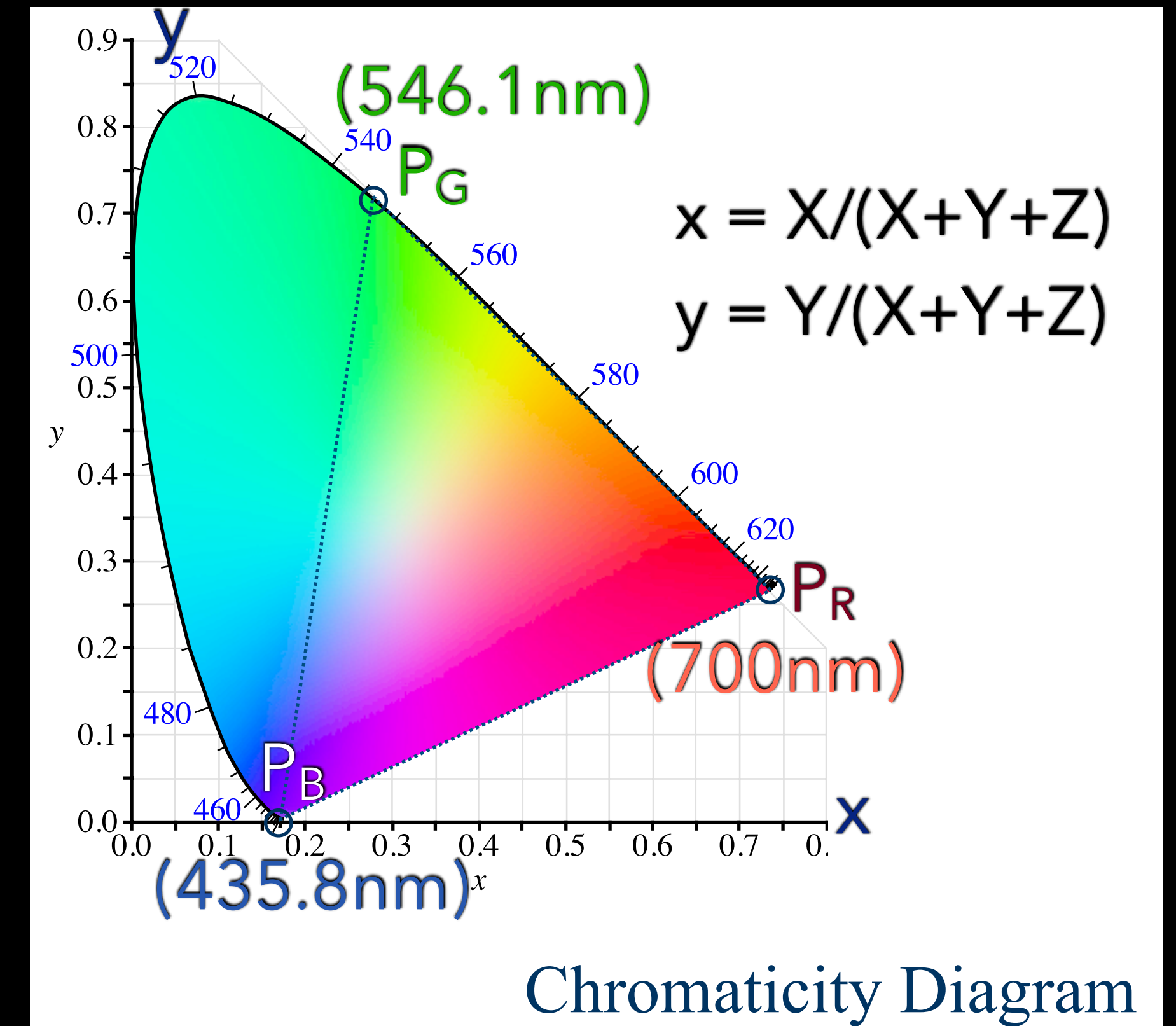
X-Y-Z Positive Color Matching Functions

$$[XYZ] = [M][RGB]^T \text{ (Device independent)}$$



Imagined Primaries s.t. $\bar{y}$ equals photopic luminous efficiency, and $\bar{x}$ and $\bar{z}$ remain +ve

$$\text{Spectrum} = X \bar{x}(\lambda) + Y \bar{y}(\lambda) + Z \bar{z}(\lambda)$$



The diagram depicts all perceptible color tones

Any color gamut (range) can be shown on this diagram

Color Transformation

- $C = X + Y + Z$
- Represented in x-y-Y space as:
 - $x = X/(X+Y+Z)$, $y = Y/(X+Y+Z)$, Y
 - x and y have chromaticity, Y is luminance

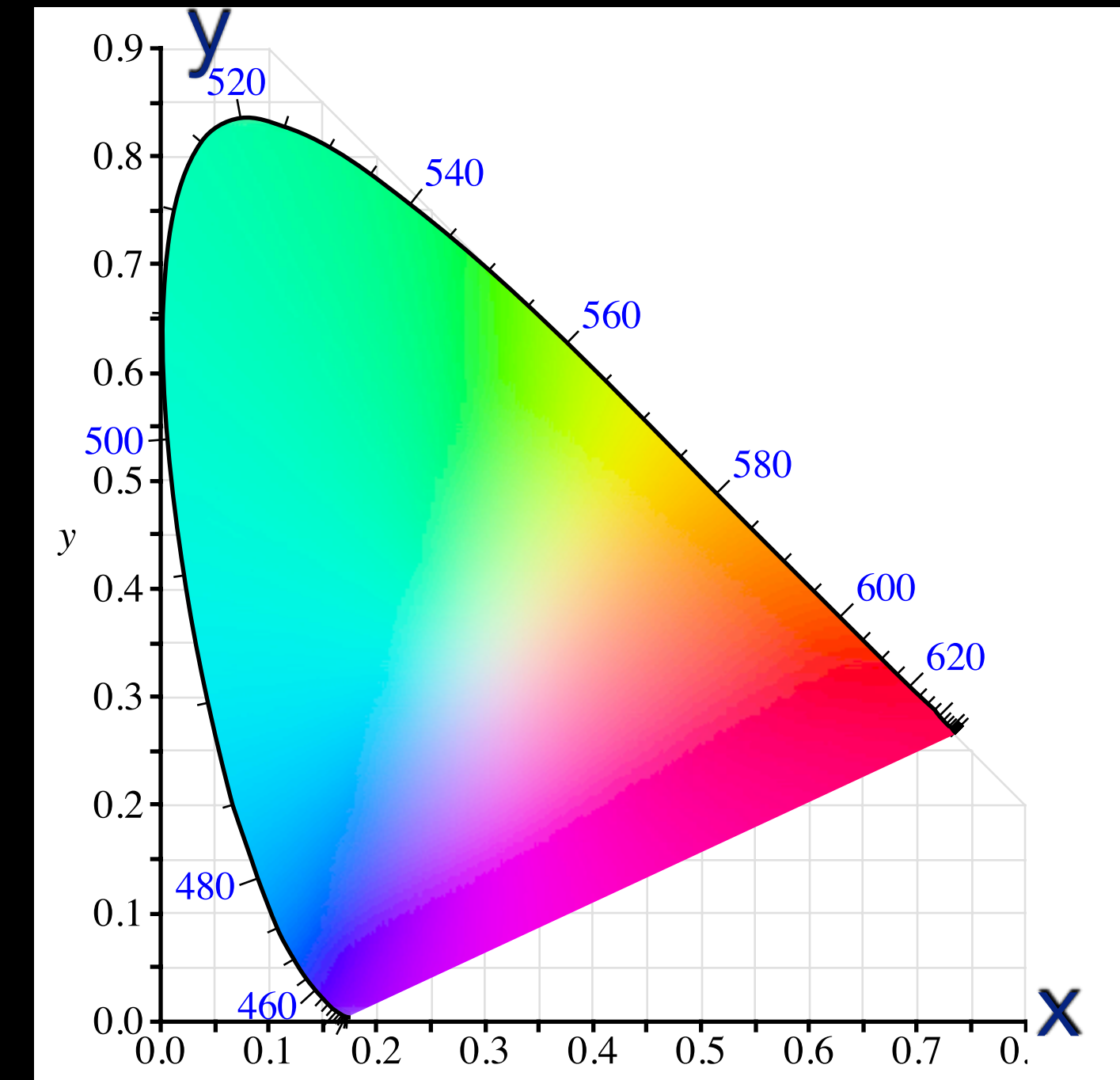
$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \frac{1}{0.17697} \begin{bmatrix} 0.49 & 0.31 & .20 \\ 0.17697 & 0.8124 & 0.01063 \\ 0 & .01 & .99 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Linear Transformation

L*a*b Color Model

CIELAB (Device Independent)

- L (Lightness)
- a: Green-red balance: - $\Rightarrow$ green, + $\Rightarrow$ red
- b: Blue-yellow balance: - $\Rightarrow$ blue, + $\Rightarrow$ red
- Perceptually Uniform: Numerical distance between colors matches human perception
- Easy to maintain color tone while modulating only brightness with L



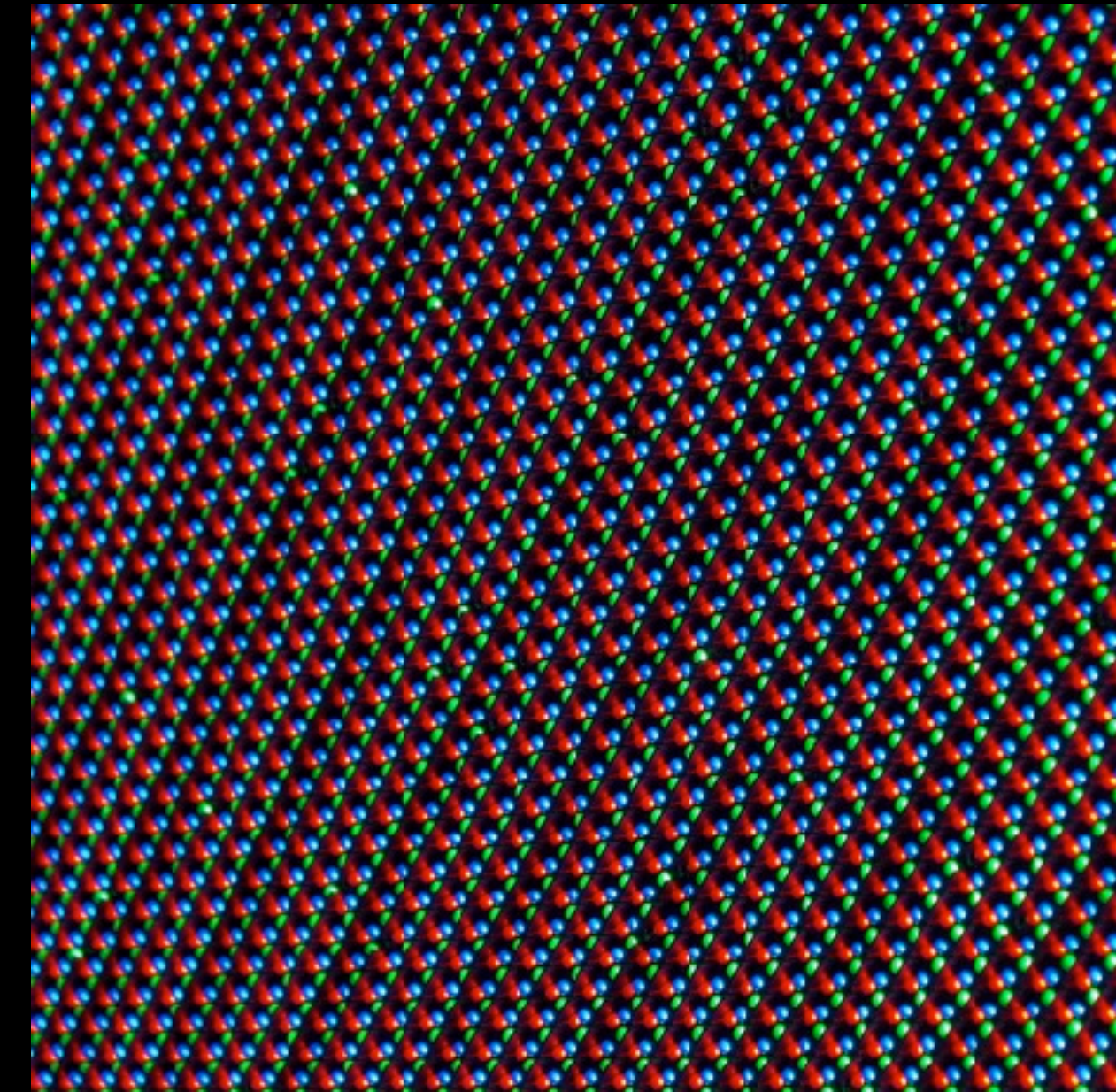
Color Models/Space

Space = Model + Range/Scale to produce actual color values

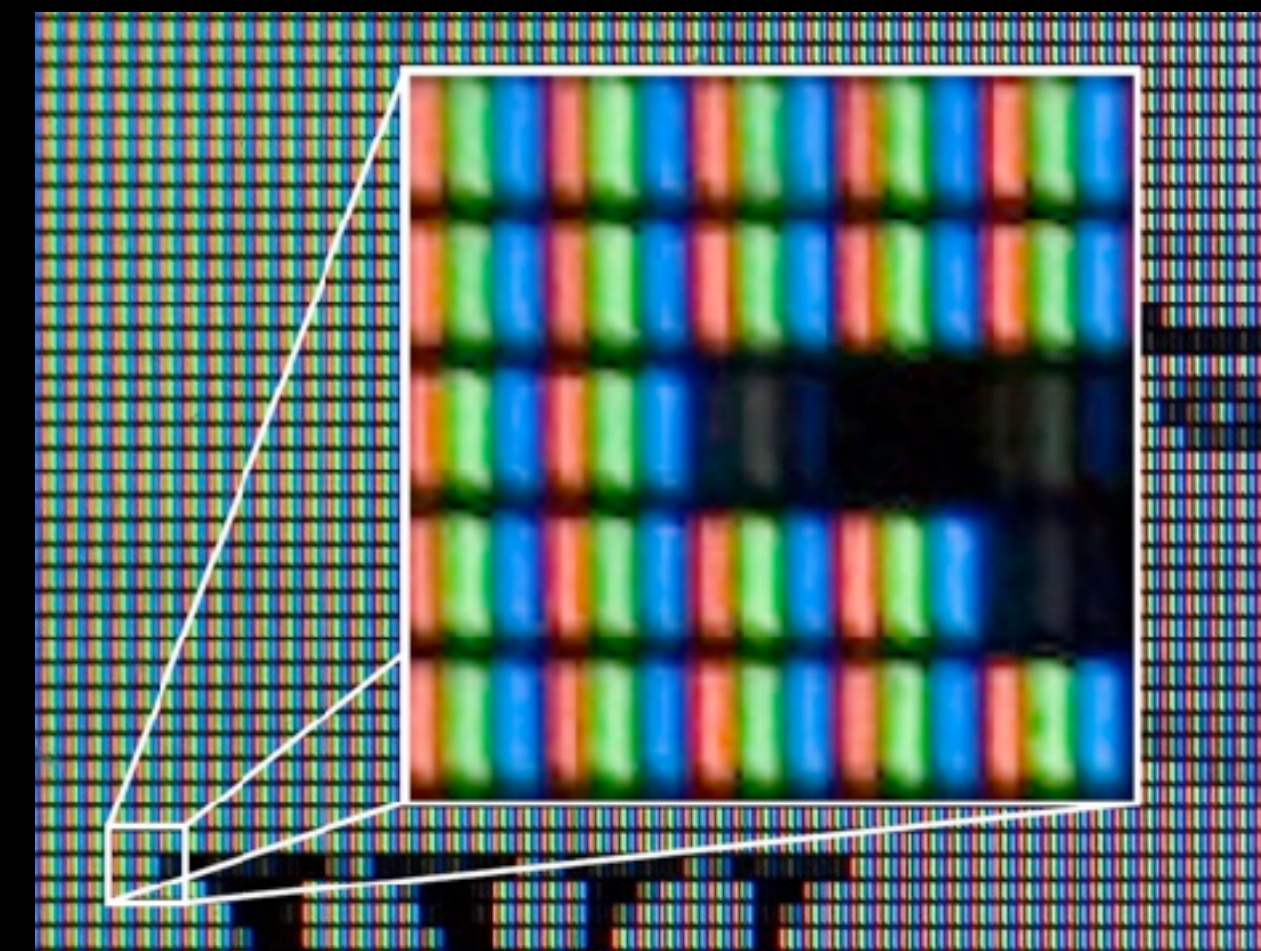
- XYZ, xyY, L*a*b
- HSV/HSB, HSL, HSI
- RGB
 - Different R, G, B primaries in use
- CMYk (Subtractive)
- sRGB (RGB-based space)
- HDR (High Dynamic Range) (Space; may be used for any model)

Color Models/Space

- XYZ, xyY, L^*a^*b
- HSV/HSB, HSL, HSI
- RGB
 - Different R, G, B primaries in use
- CMYk
- sRGB
- HDR (High Dynamic Range)



LED
display



LCD
display

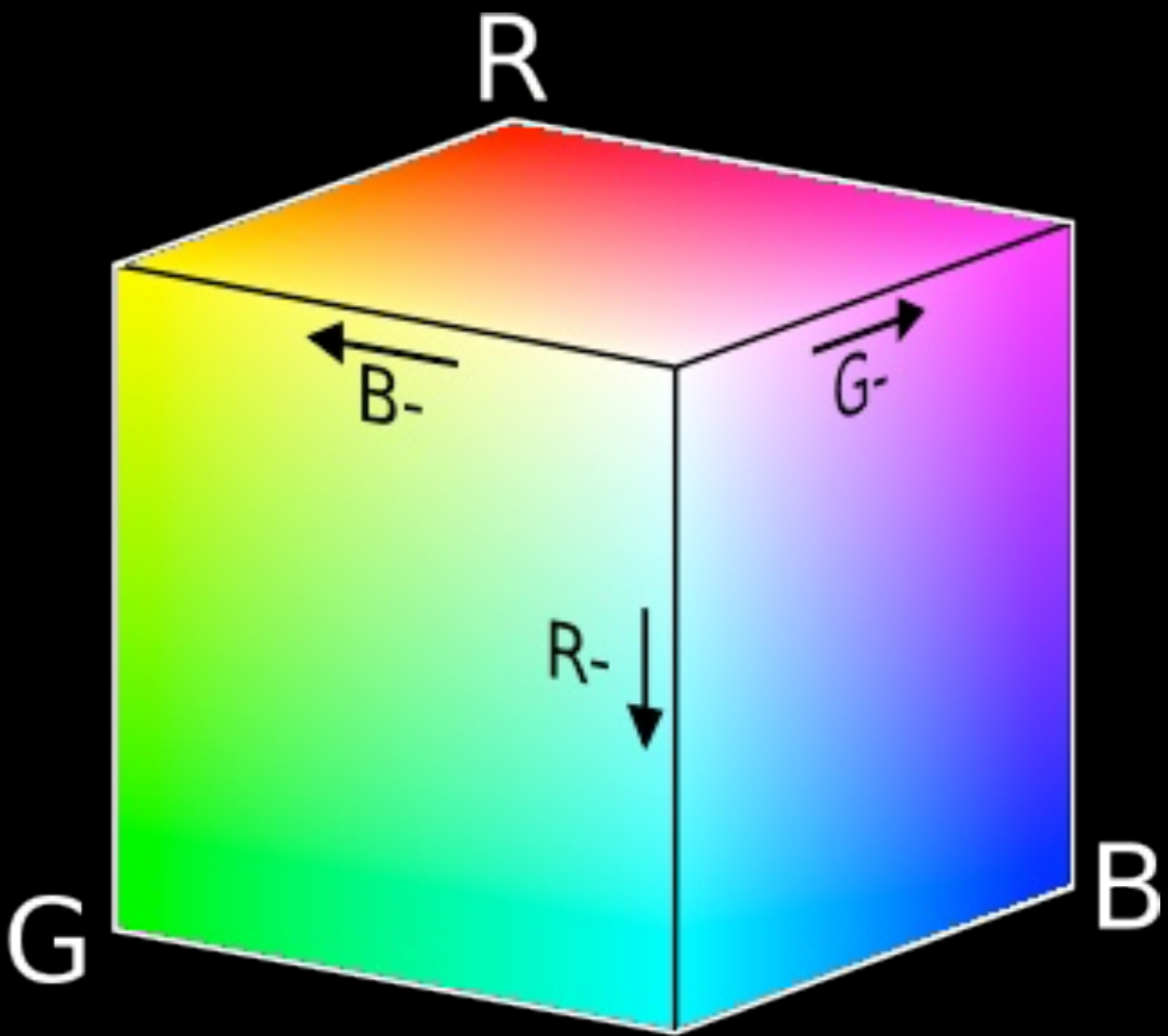
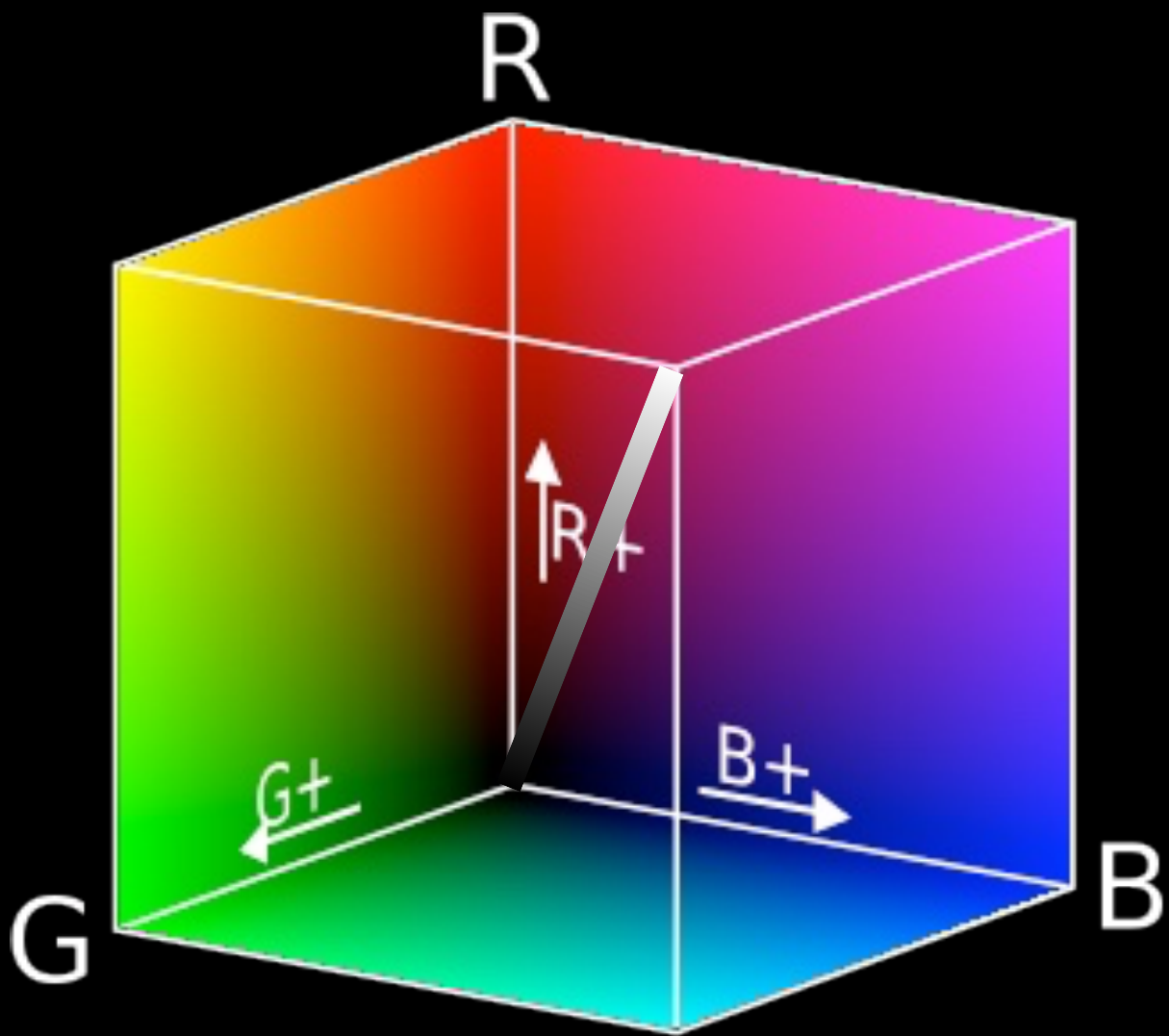
RGB Color Space

Additive: superposition of red, green, blue lights

- In arbitrary range 0-1 ("24-bit colour" = 8 bits/channel = 0-255)
- Grayscale $\Rightarrow R = G = B$
- RGB image = 2D array of 3-vectors
= 3-vector of 2D arrays

143	150	135	106	77	61	45	35	36
3	5	6	5	9	22	31	23	10
29	34	34	39	60	89	110	105	81
139	143	126	97	65	52	41	31	39
7	4	6	3	8	23	28	18	4
30	33	34	40	61	90	107	97	70
134	135	117	88	59	48	37	29	42
12	5	3	1	12	25	26	11	0
33	33	36	44	67	93	102	85	57

(x=407, y=308) ~ R:41 G:29 B:95





Blue

Green

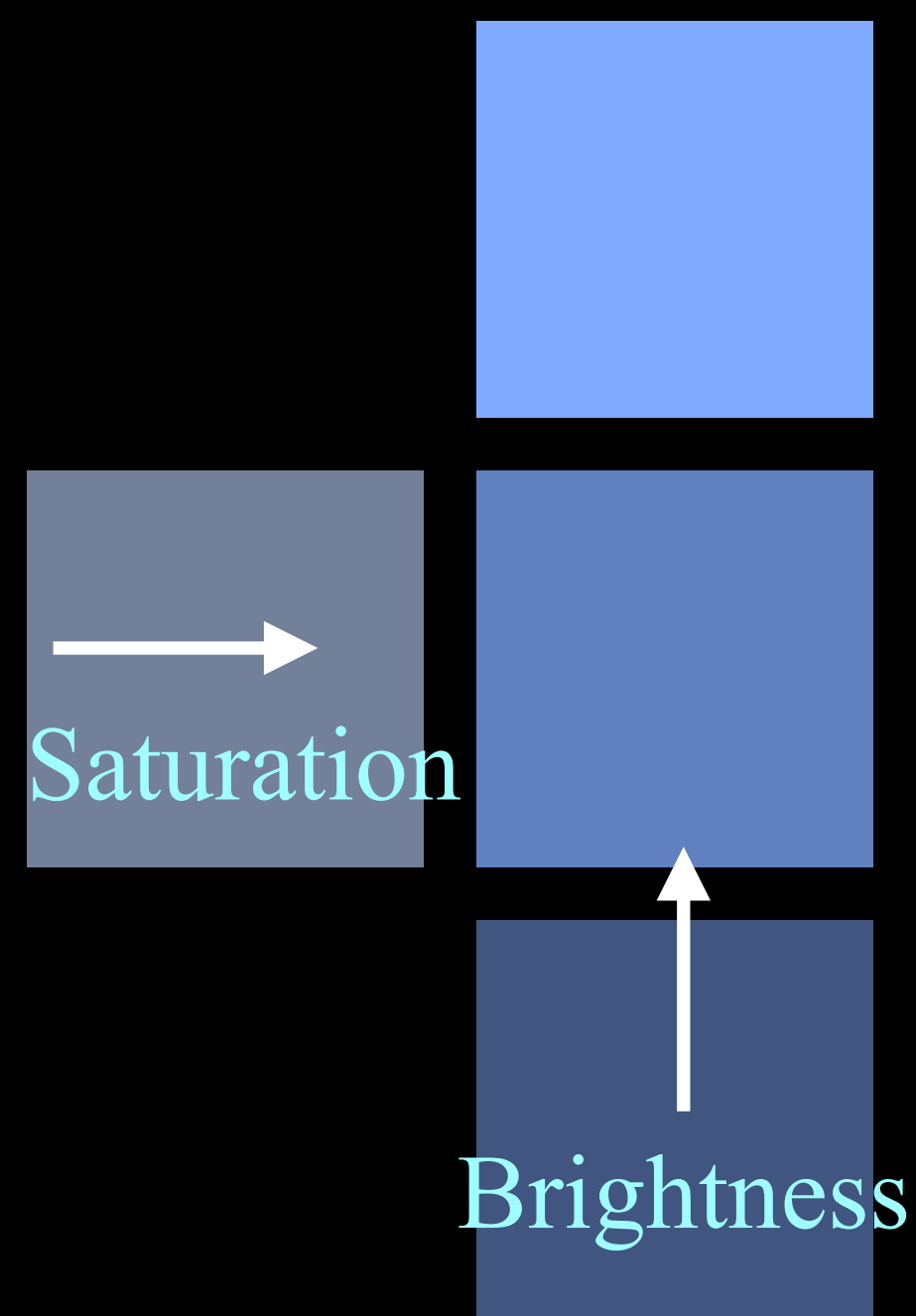
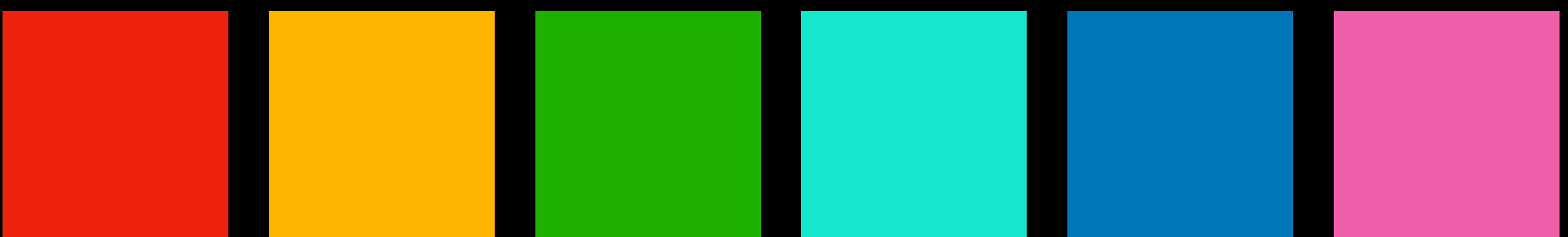
Red

Hue and Saturation

Chromaticity

- Color = Intensity/brightness + chromaticity (hue)

Colors with different hues



Saturation

Brightness

Different colors with the same hue

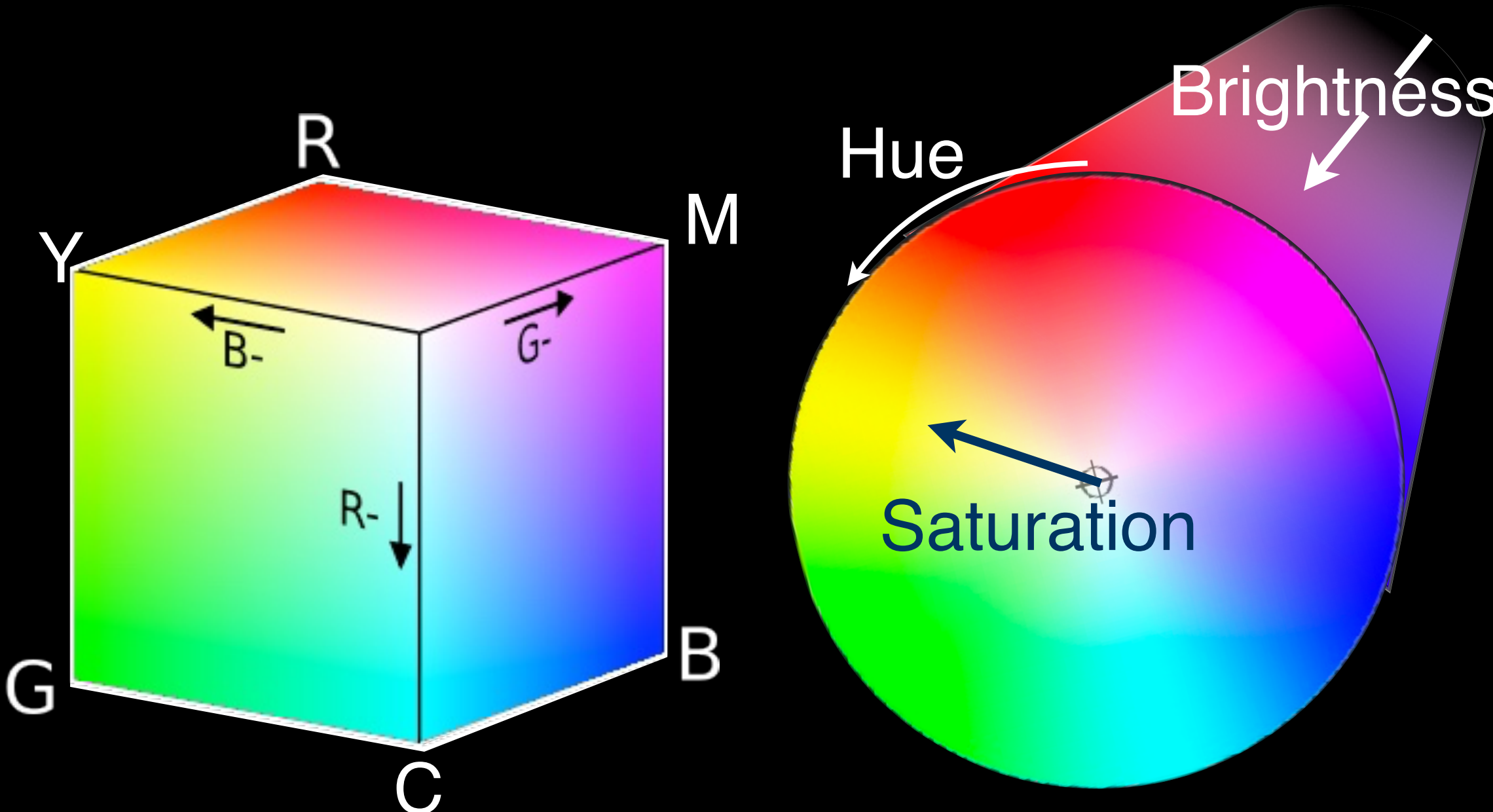
$$S = (1 - \min(R, G, B) / I)$$
$$\text{Intensity} = (R + G + B) / 3$$

Cylindrical Spaces: HSB, HSI, HSL

Brightness
Or, value
= $\max(R, G, B)$

Lightness

$$= [\min(R, G, B) + \max(R, G, B)] / 2$$



R-G-B

vs

H-S-B

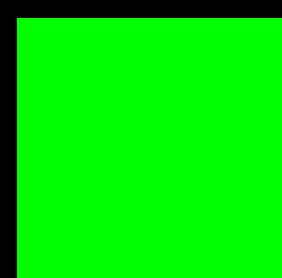
vs

H-S-L

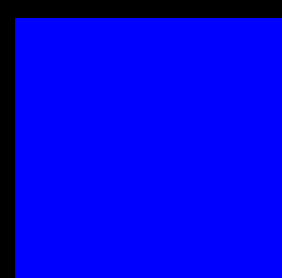
Color Palette



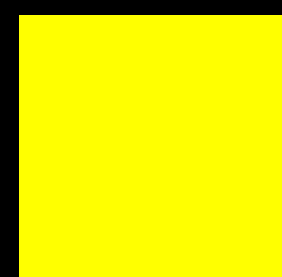
1,0,0



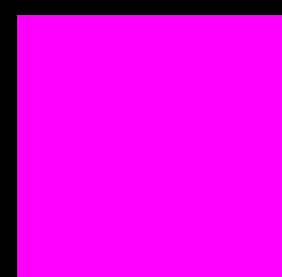
0,1,0



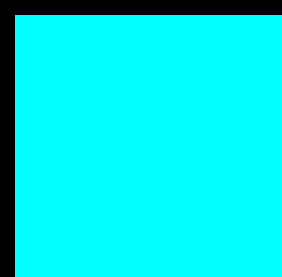
0,0,1



1,1,0



1,0,1



0,1,1



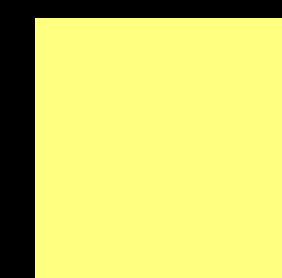
.5,.5,0



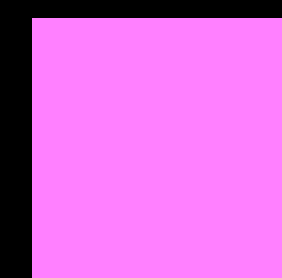
.5,0,.5



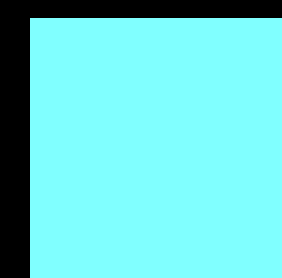
0,.5,.5



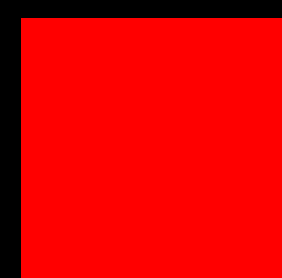
1,1,.5



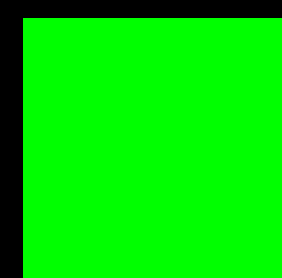
1,.5,1



.5,1,1



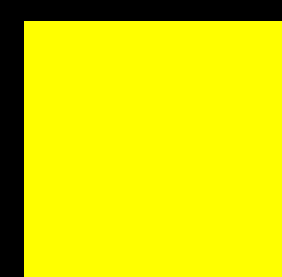
1,1,1



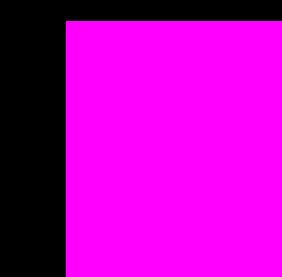
.33,1,1



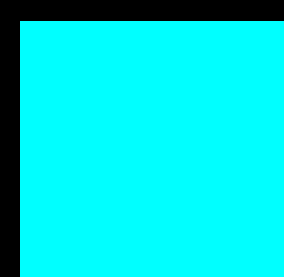
.67,1,1



.167,1,1



.83,1,1



.5,1,1



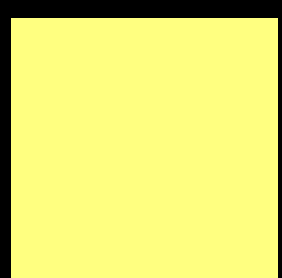
.167,1,.5



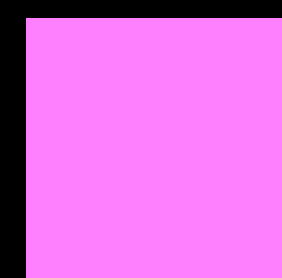
.83,1,.5



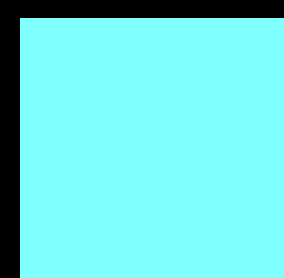
.5,1,.5



.167,.5,1



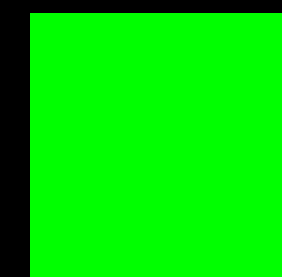
.83,.5,1



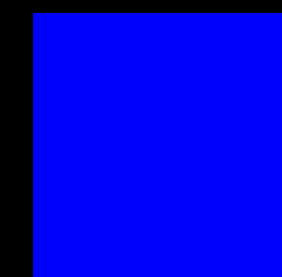
.5,.5,1



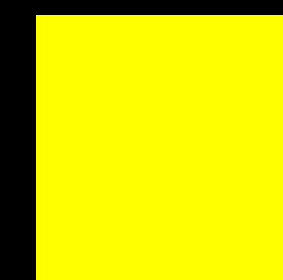
1,1,.5



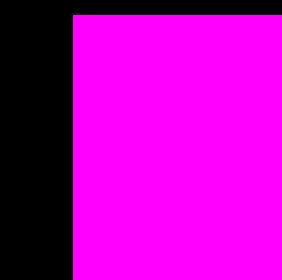
.33,1,.5



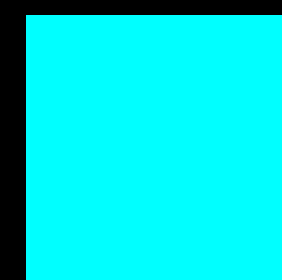
.67,1,.5



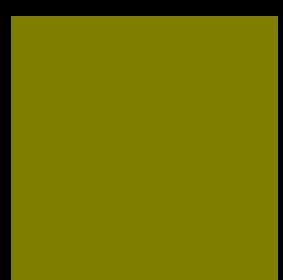
.167,1,.5



.83,1,.5



.5,1,.5



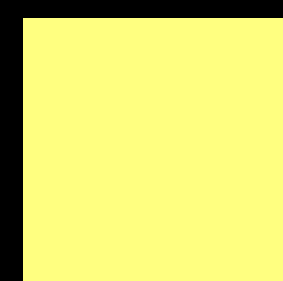
.167,1,.25



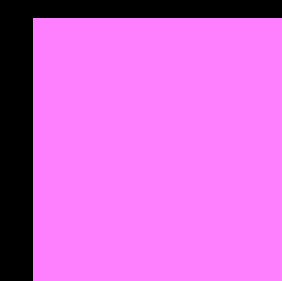
.83,1,.25



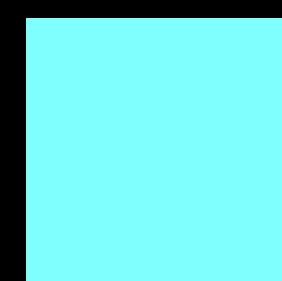
.5,1,.25



.167,1,.75



.83,1,.75



.5,1,.75

Color Spaces, e.g.

Feature	RGB Space	L*a*b Space	HSI Space
Primary Focus	Hardware & displays	Human color perception	Color & lighting separation
Device Dependent?	Yes (Varies by screen/sensor)	No (Universal standard)	Yes (Derived from RGB)
Perceptual Uniformity	Poor (Math distance $\neq$ visual distance)	Excellent (Built for uniform distance)	Moderate (Separates brightness, but not perceptually uniform)
Use case	Web & App Development, Rendering	Image Editing, Color matching	Image processing, Computer Vision

CMY(K) Color Space

Subtractive: Color formed by removing wavelengths

- Primaries: cyan (absorbs red), magenta (absorbs green), yellow (absorbs blue)

- Absorption is nonlinear!

Approximate conversion from RGB:

$$\text{> } C = 1 - R \quad M = 1 - G \quad Y = 1 - B$$

- In practice, absorption is imperfect: $C = M = Y = 1$ doesn't give pure black
⇒ Include black $K = \min(C, M, Y)$ and compensate the rest,

- $C \leftarrow (C - K)/(1 - K)$ etc.

