

Color

Computer Graphics
CMU 15-462/15-662

Why do we need to be able to talk precisely about color?

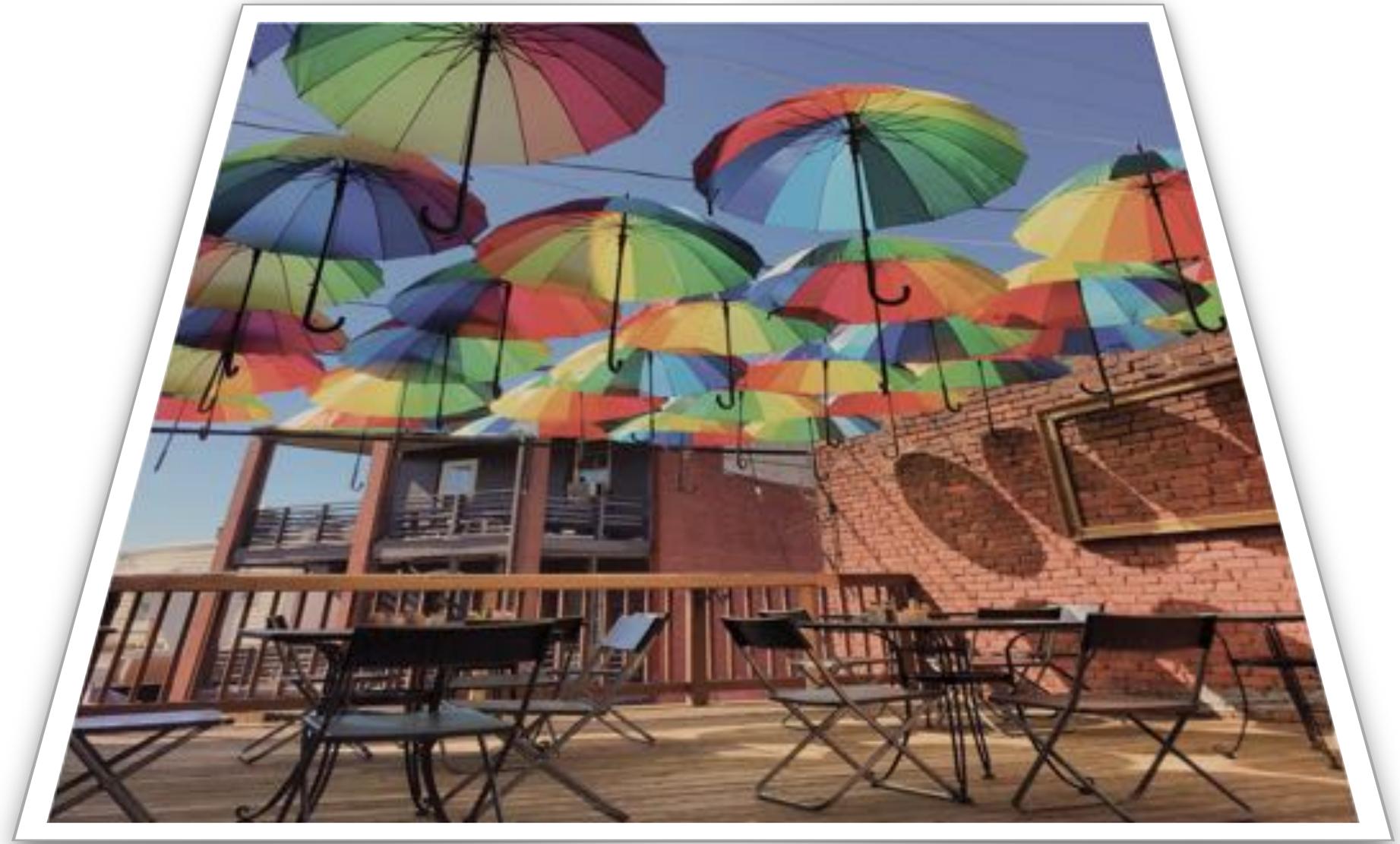








on screen

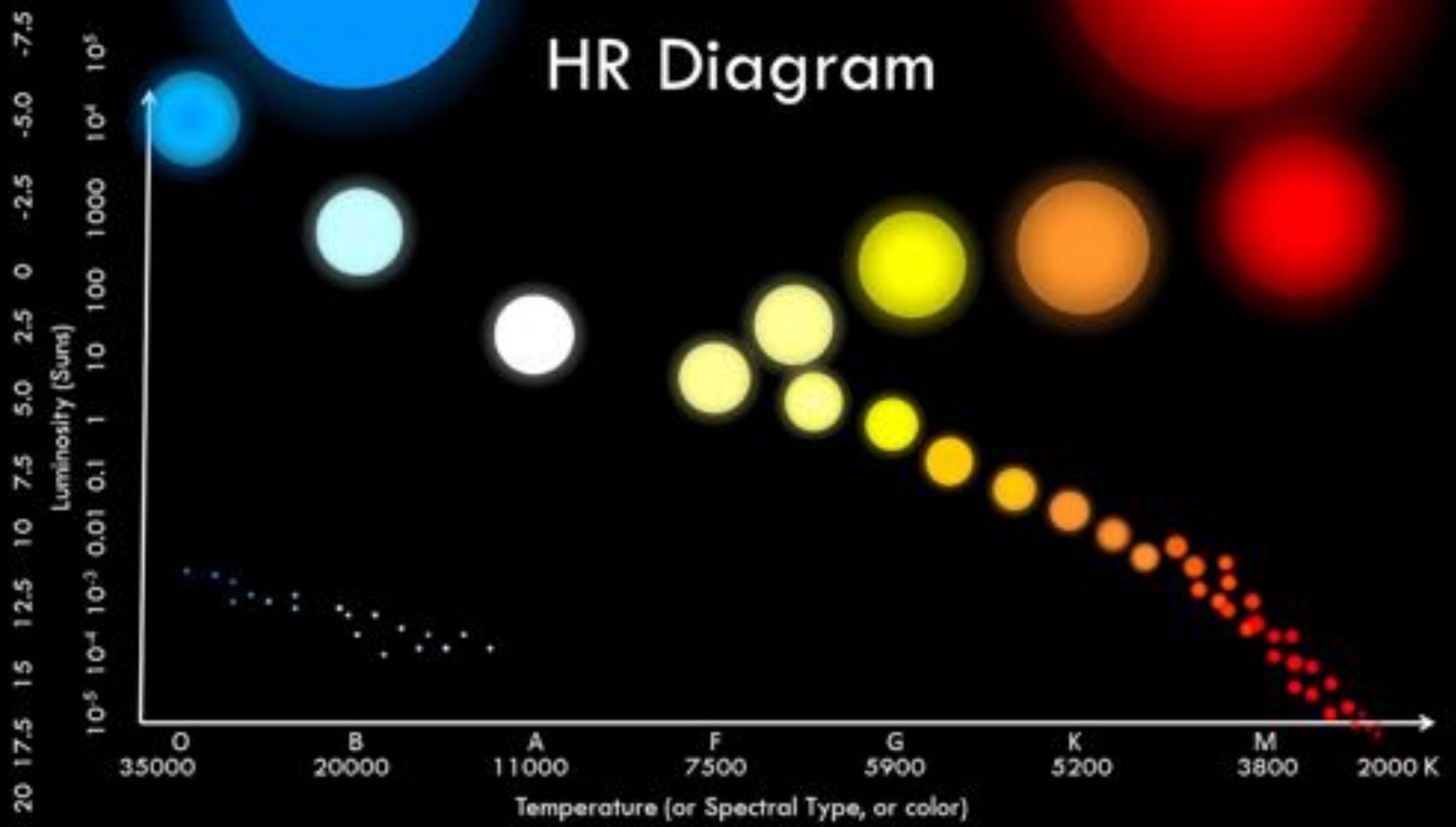


printed



Zhangye Danxia Geological Park, China

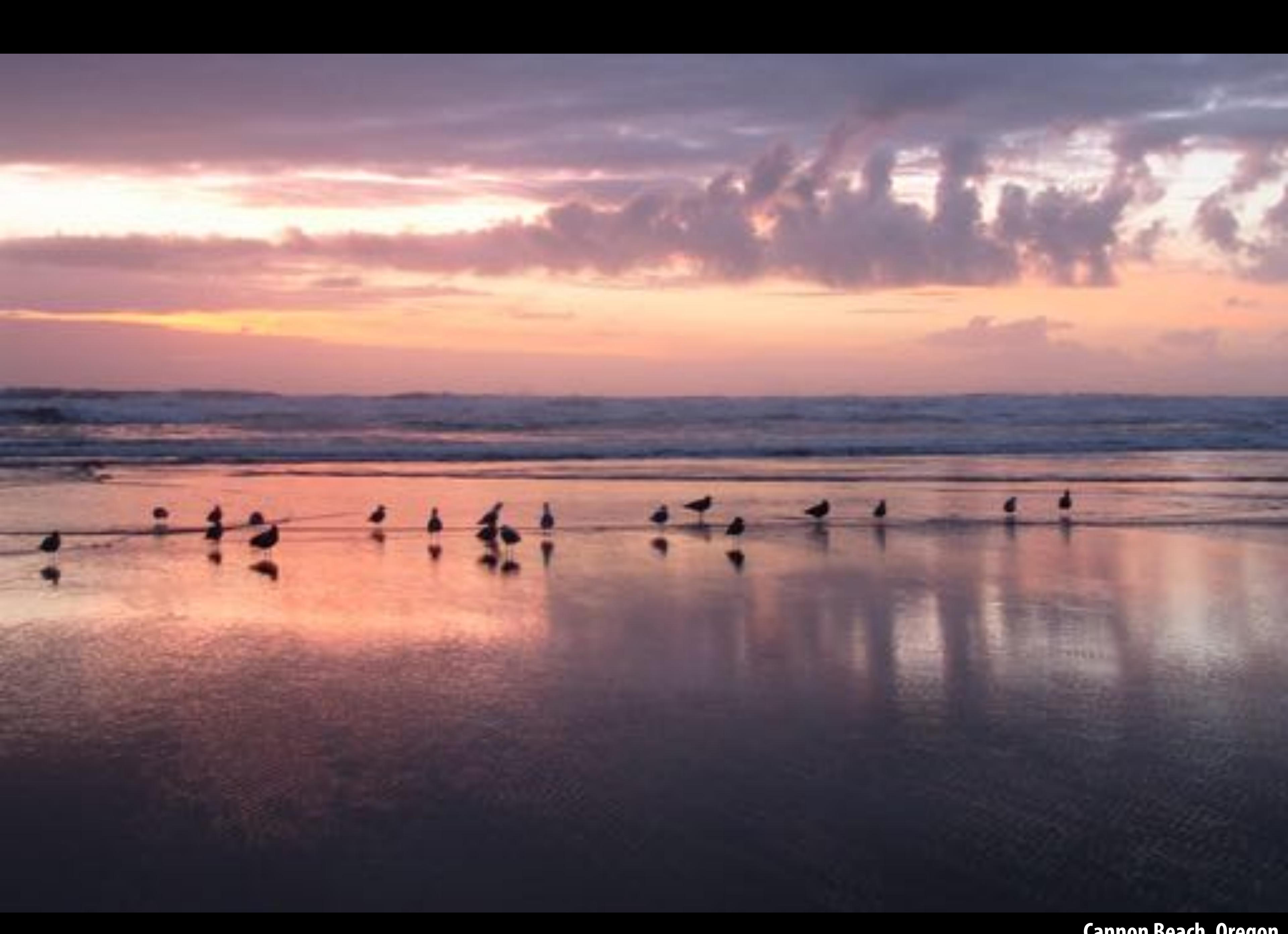
HR Diagram



Hertzsprung-Russell diagram



Starry Night, Van Gogh

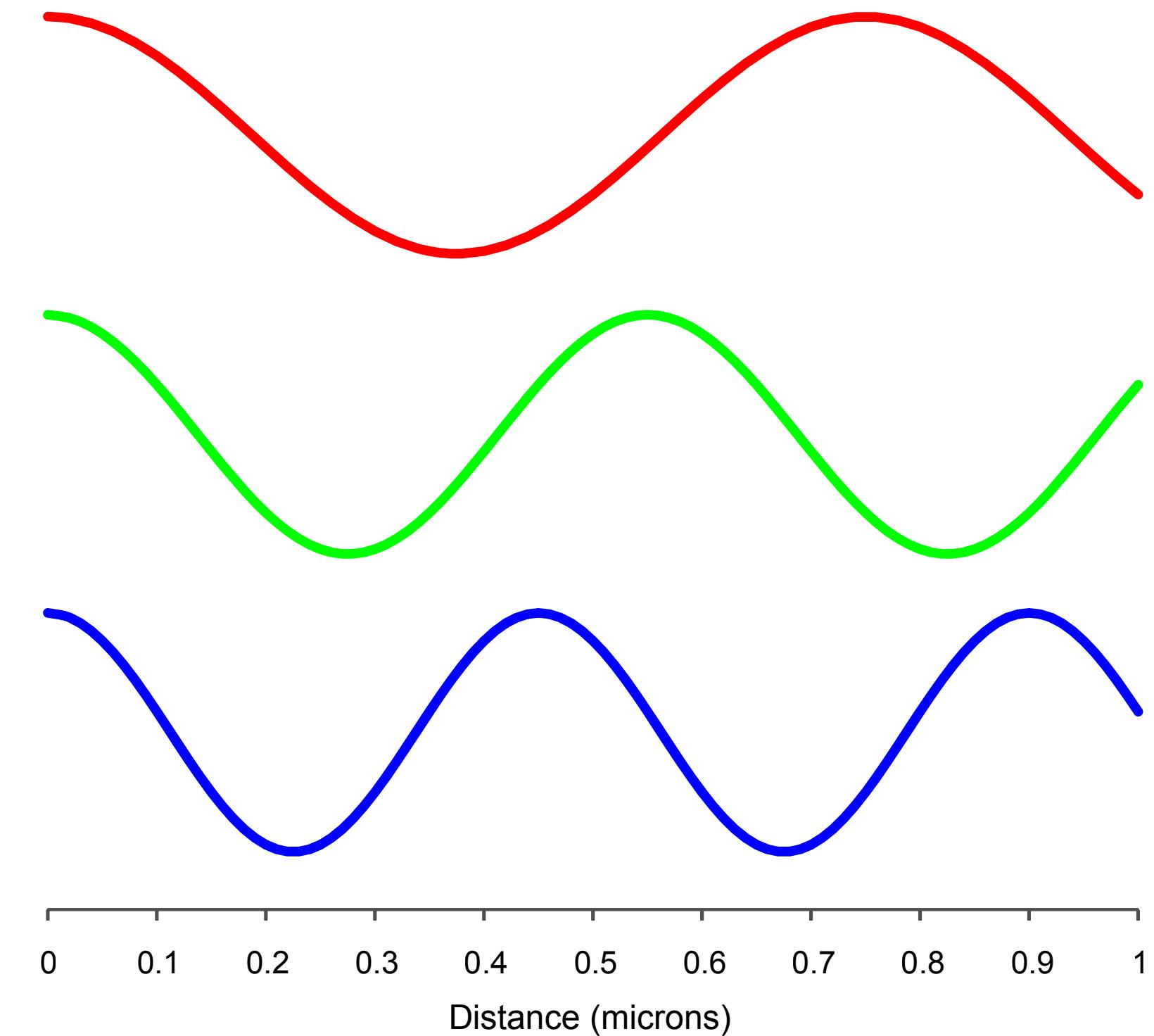
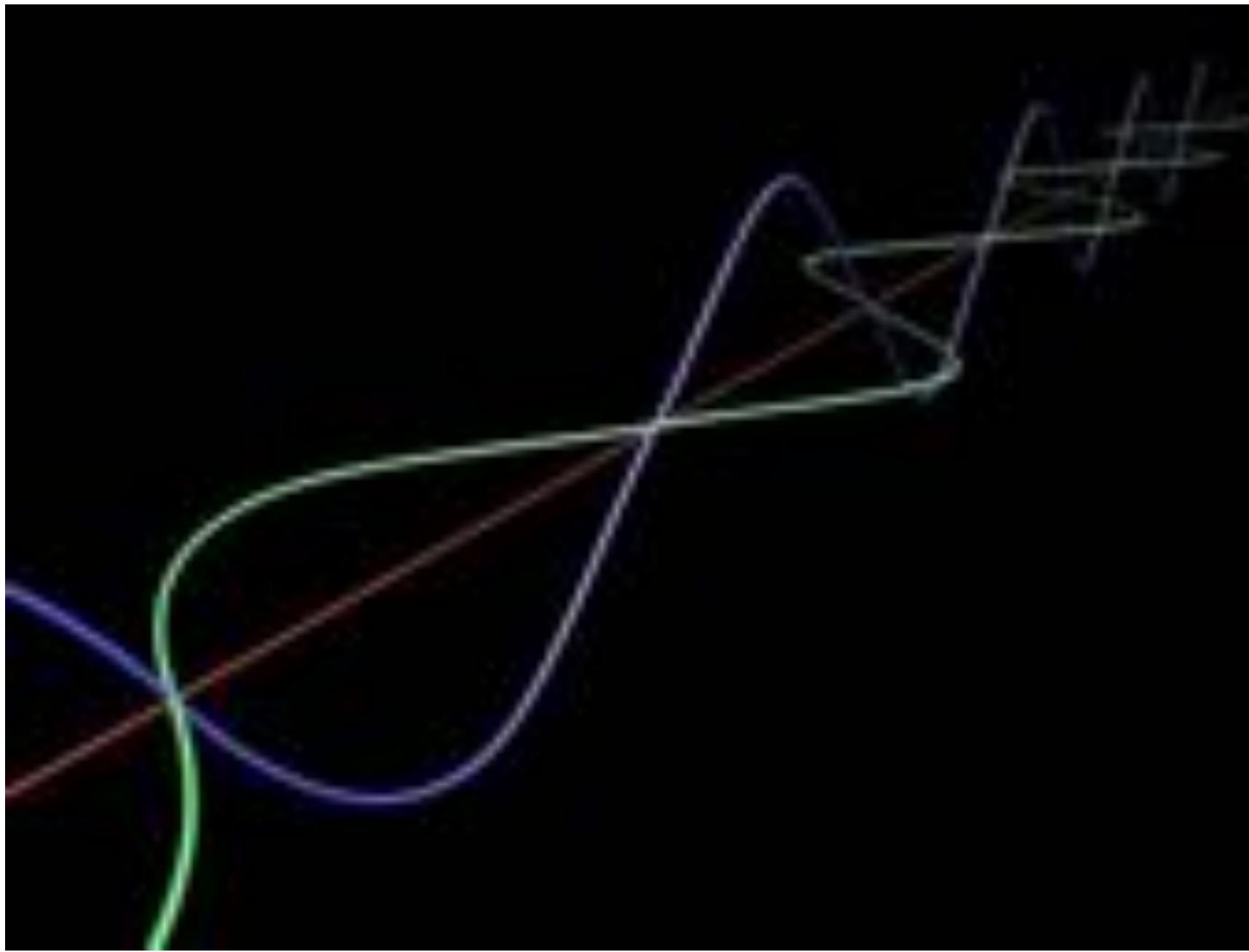


Cannon Beach, Oregon

What is color?

Light is EM Radiation; Color is Frequency

- Light is oscillating electric & magnetic field
- KEY IDEA: frequency determines color of light
- Q: What is the difference between frequency and wavelength?

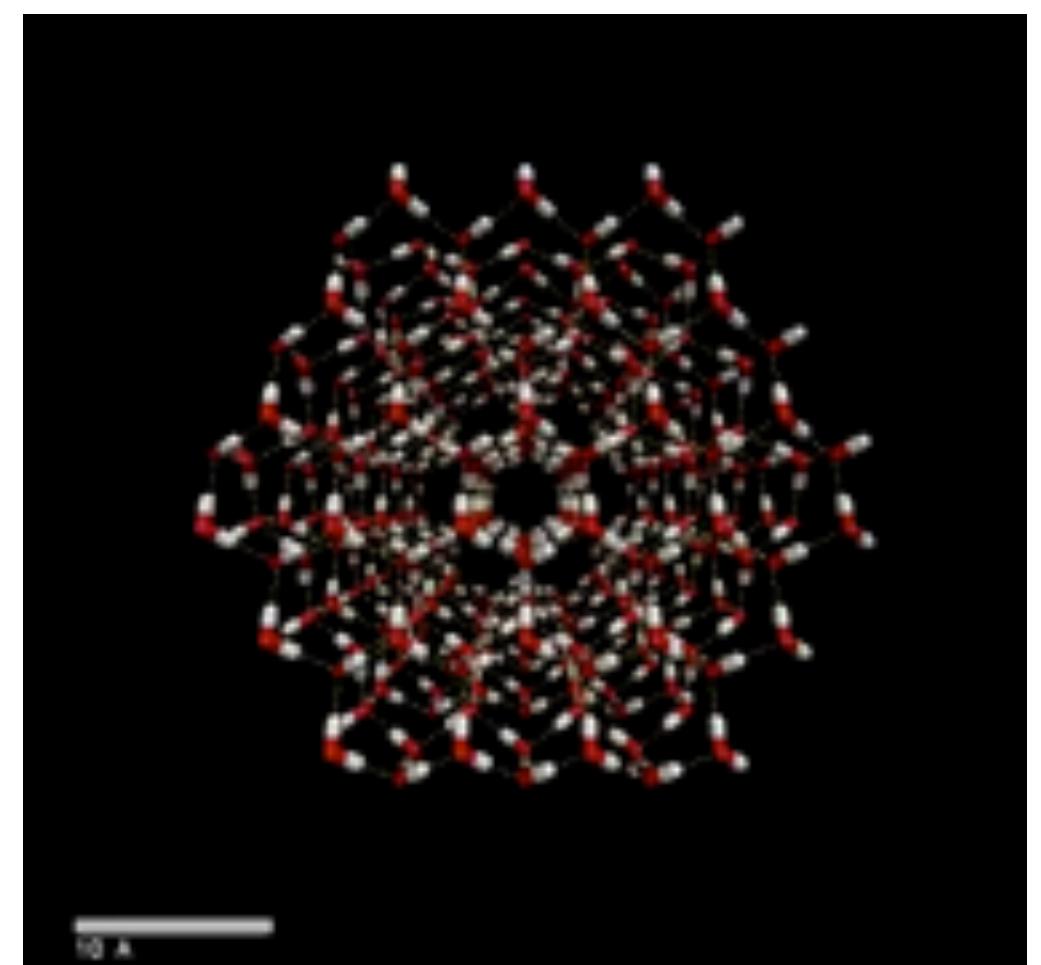
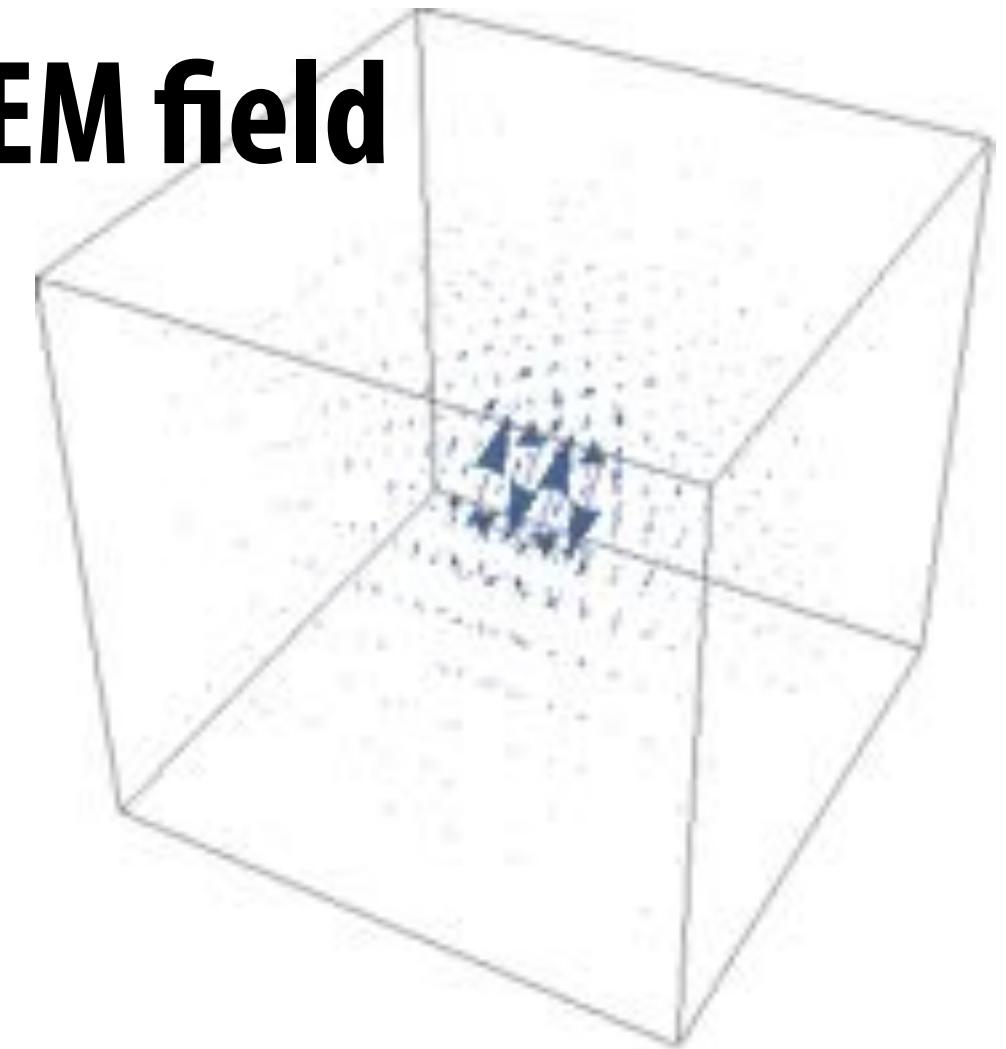




Q: Why does your stove turn **red when it heats up?**

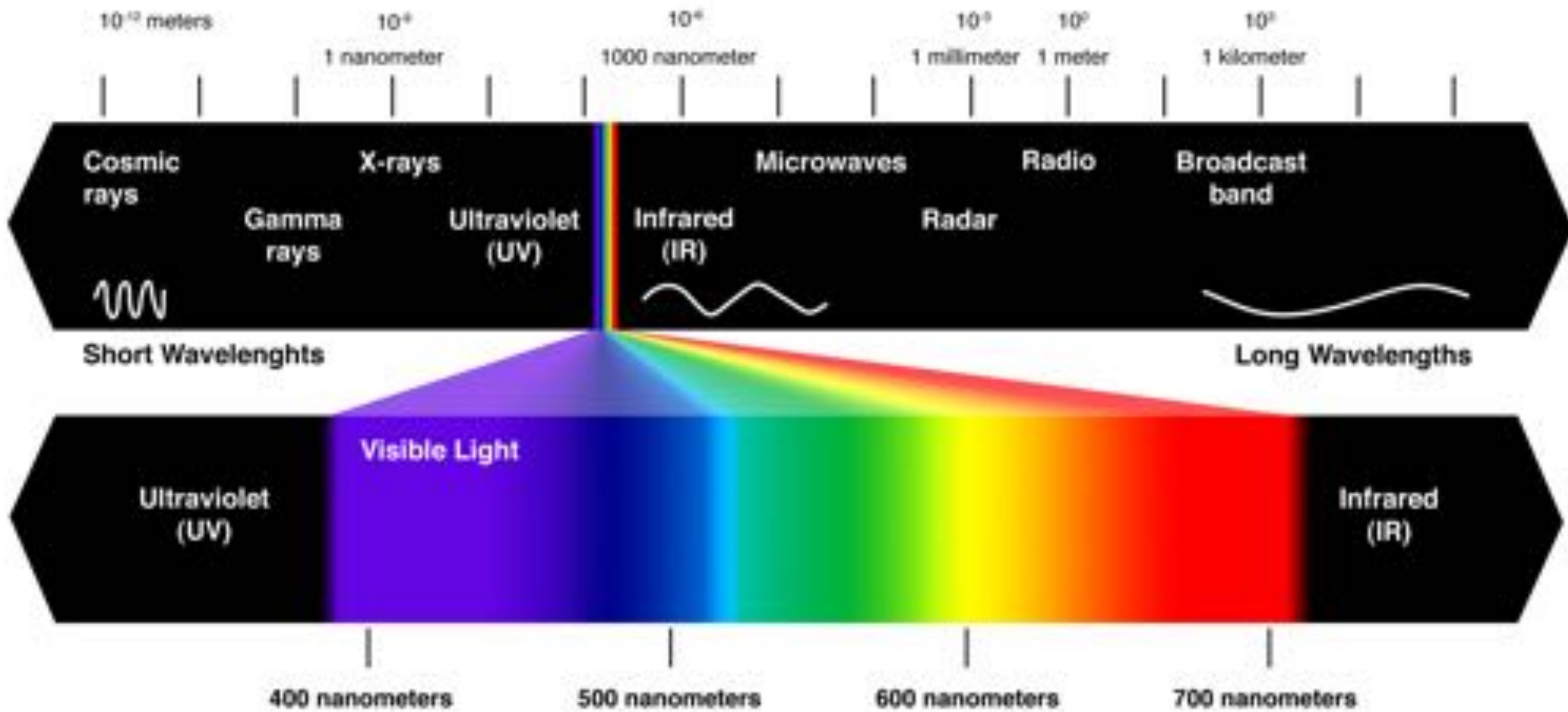
Heat generates light

- One of many ways light is produced:
- Maxwell: motion of charged particles creates EM field
- Thermodynamics: ...particles jiggle around!
- Hence, anything moving generates light
- In other words:
 - every object around you is producing color!
 - frequency determined by temperature



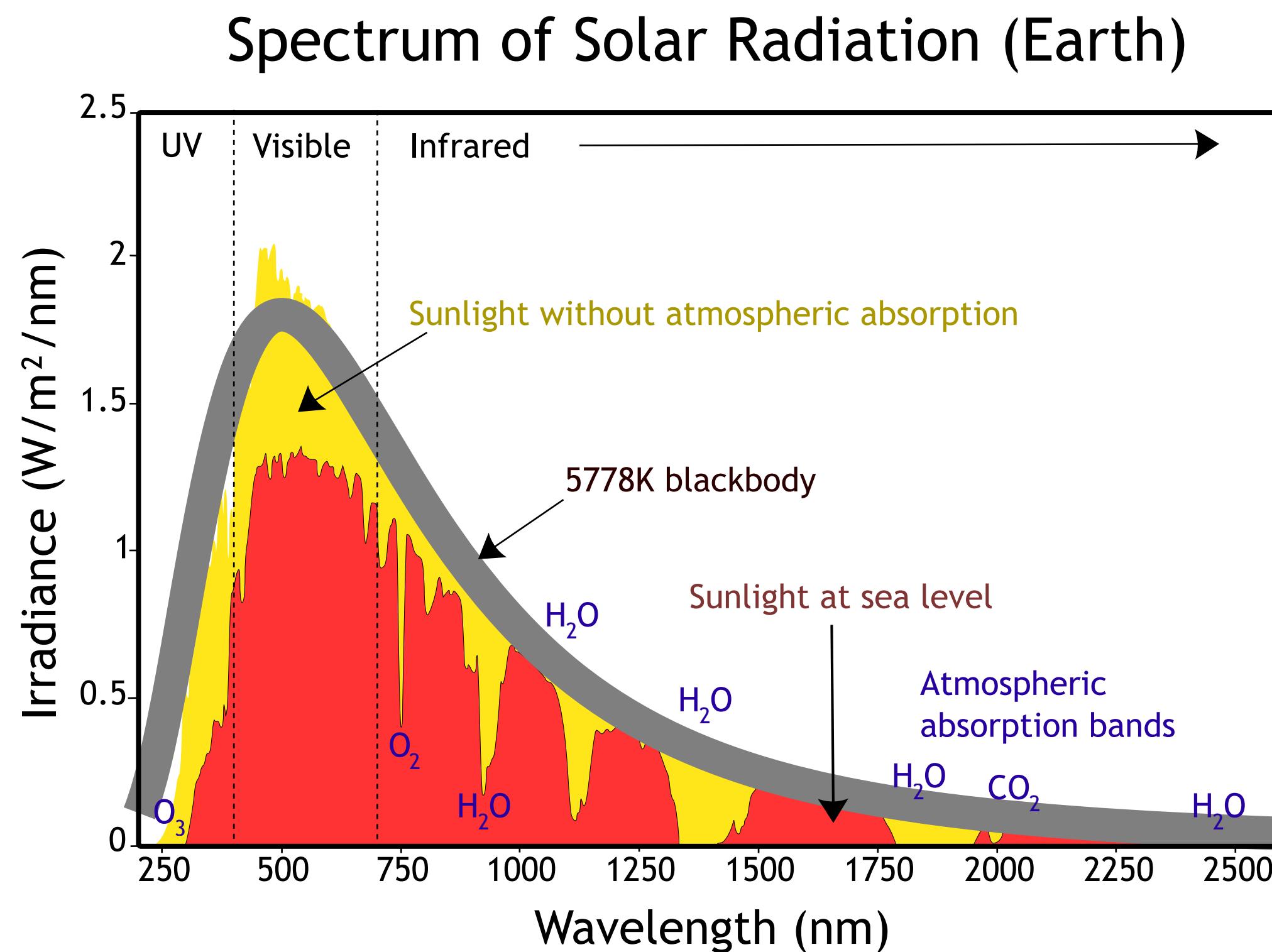
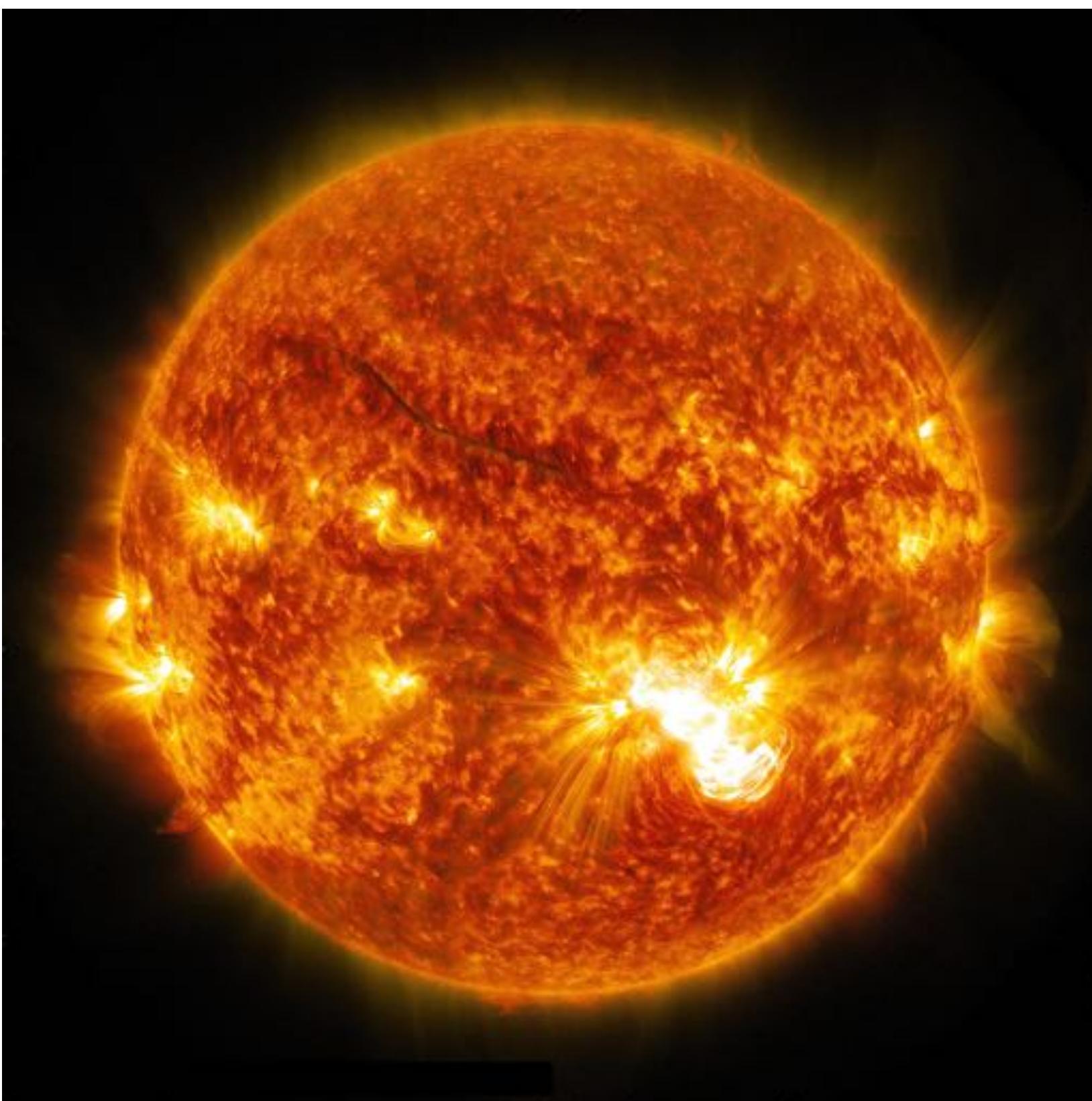
Most light is not visible!

- Frequencies visible by human eyes are called “visible spectrum”
- These frequencies what we normally think of as “color”



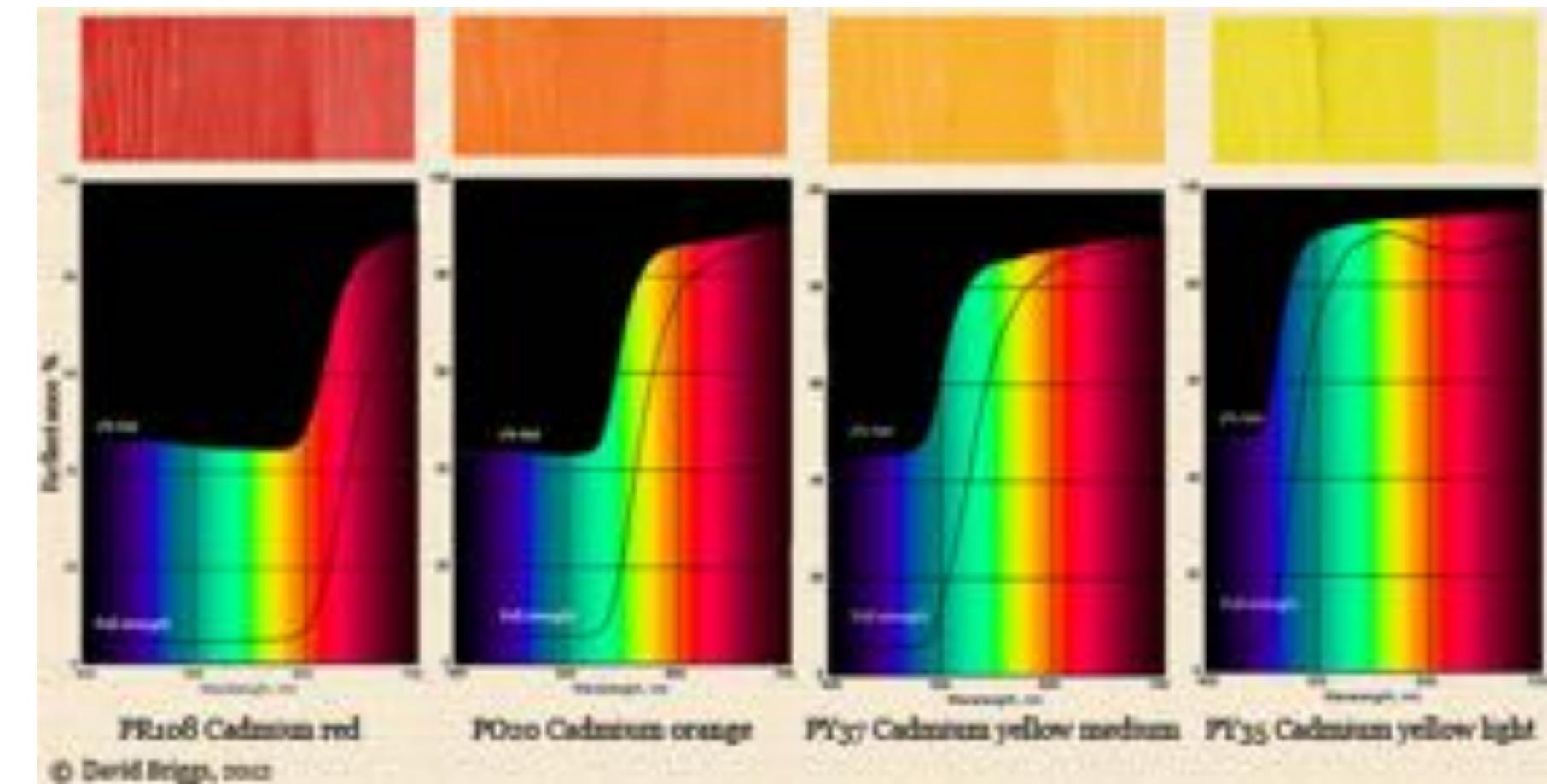
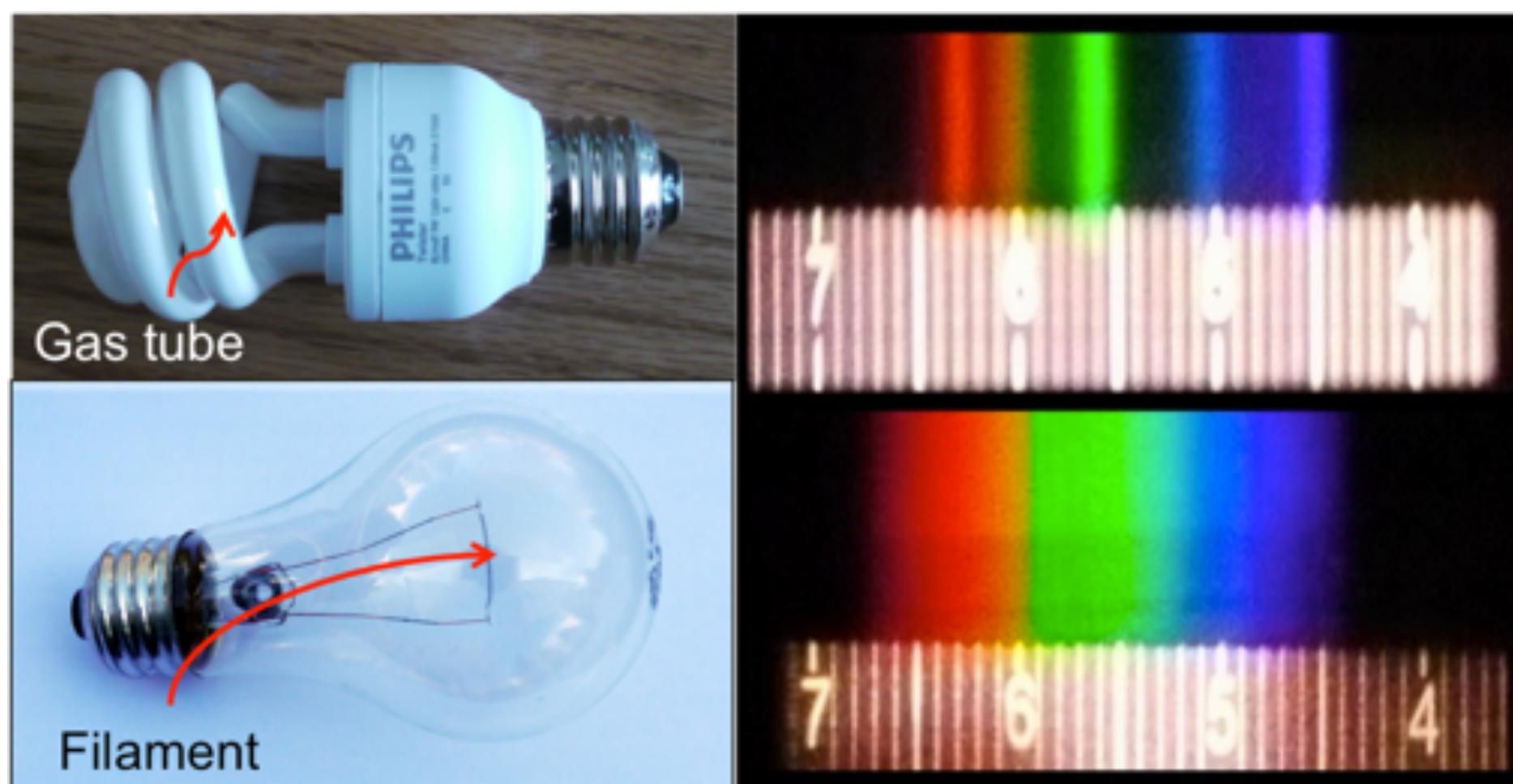
Natural light is a mixture of frequencies

- “White” light is really a mixture of all (visible) frequencies
- E.g., the light from our sun



Additive vs. Subtractive Models of Light

- Spectrum we just saw for the sun “emission spectrum”
 - How much light is produced (by heat, fusion, etc.)
 - Useful for, e.g., characterizing color of a lightbulb
- Another useful description: “absorption spectrum”
 - How much light is absorbed (e.g., turned into heat)
 - Useful for, e.g., characterizing color of paint, ink, etc.



Emission Spectrum

Describes light intensity as a function of frequency

Below: spectrum of various common light sources:

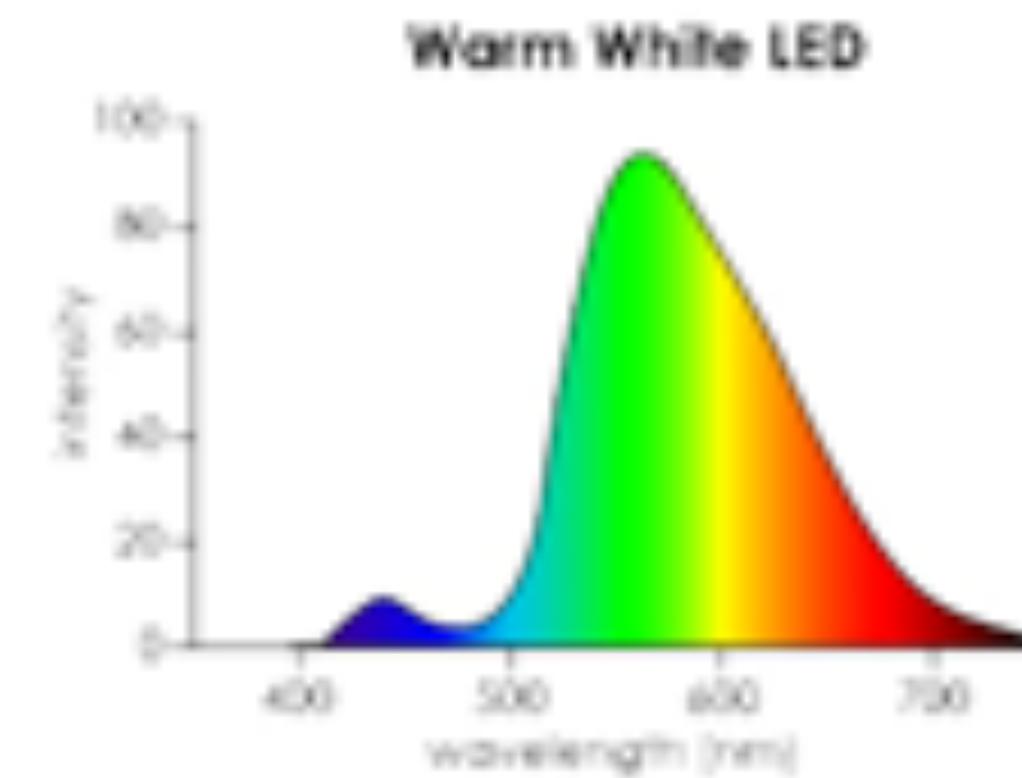
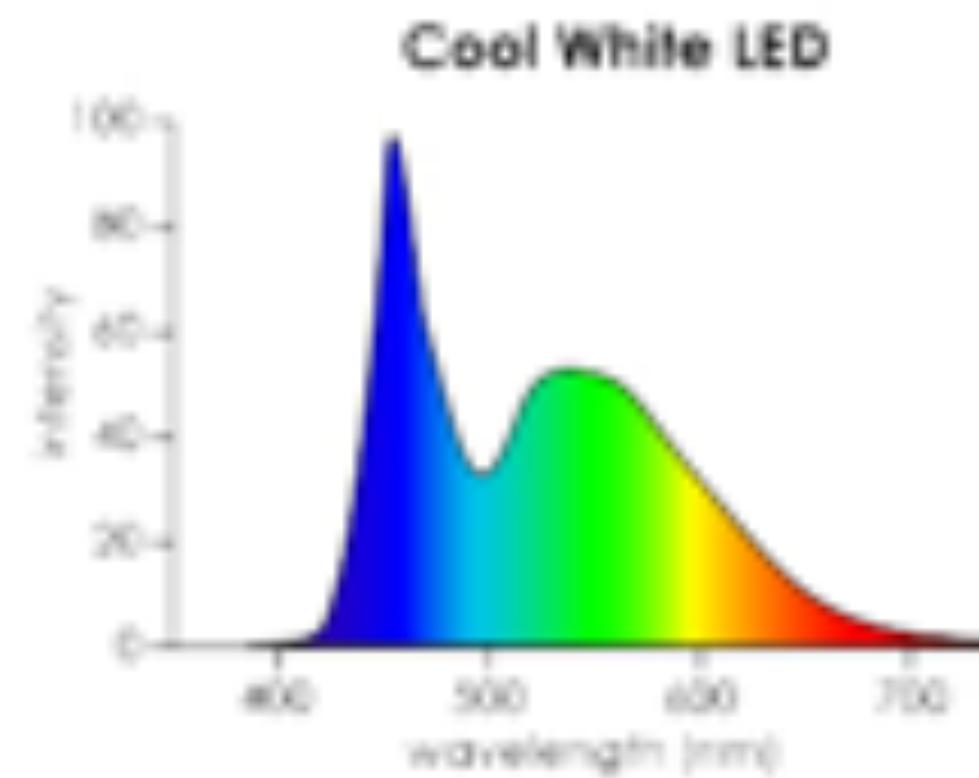
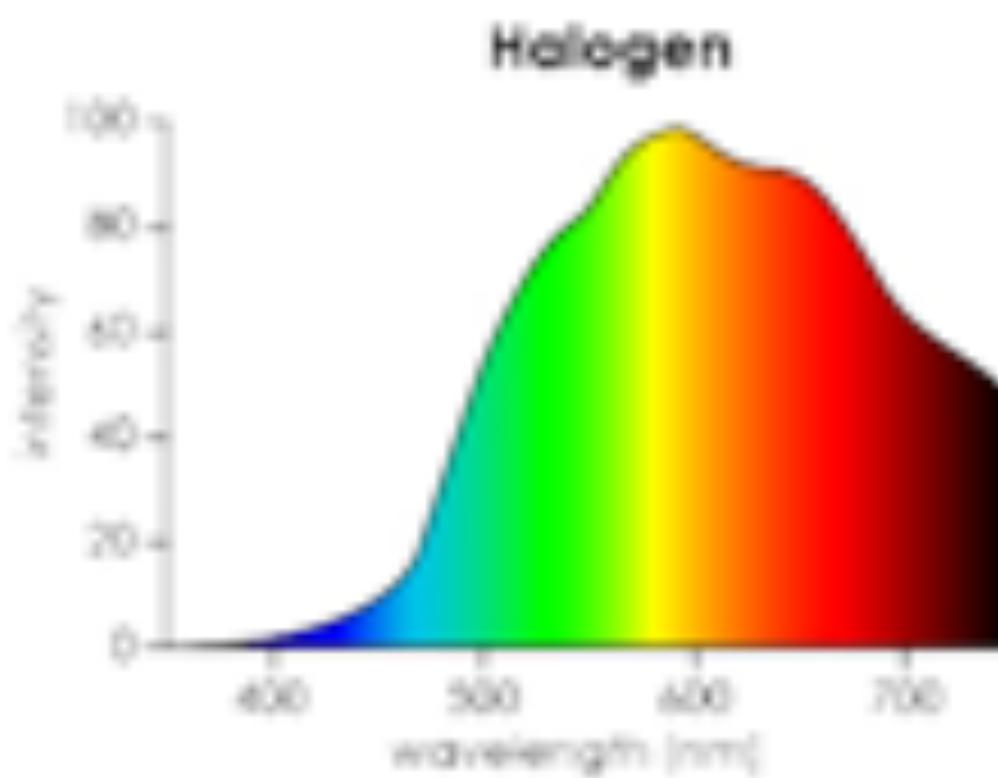
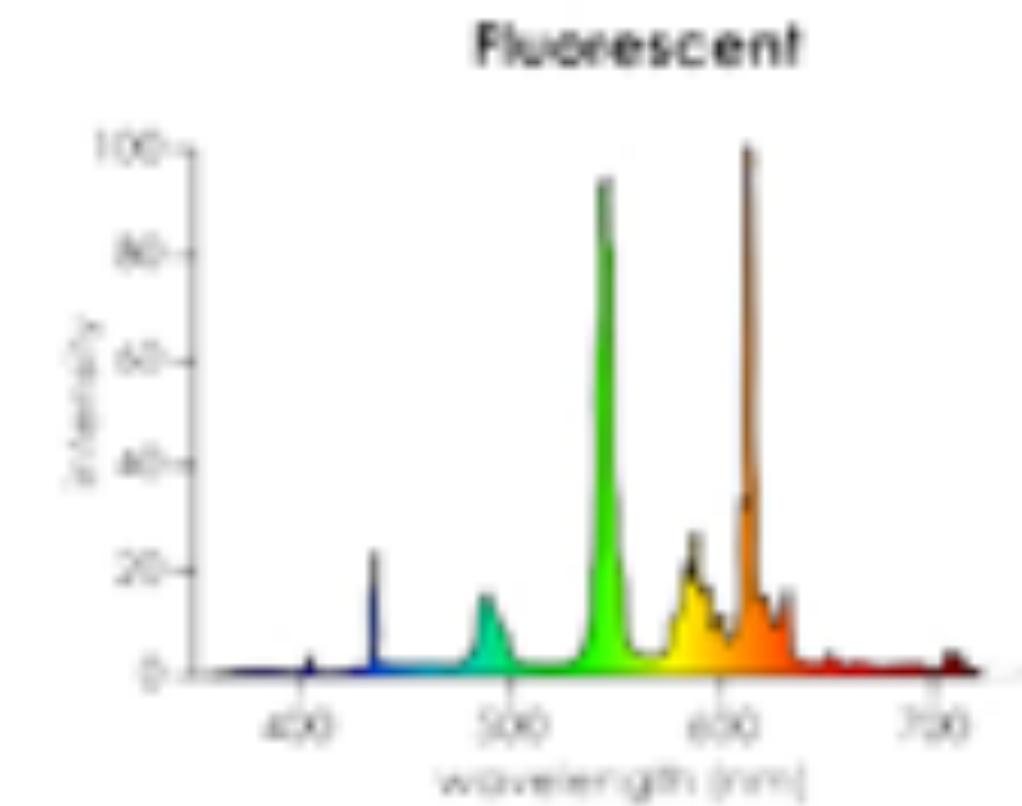
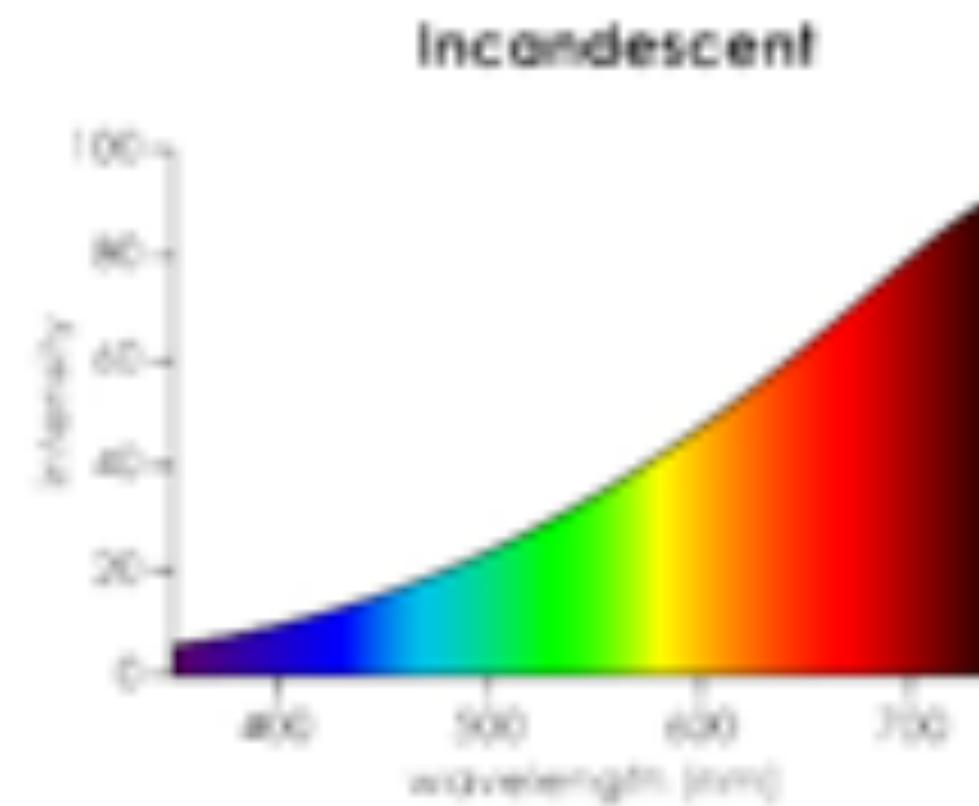
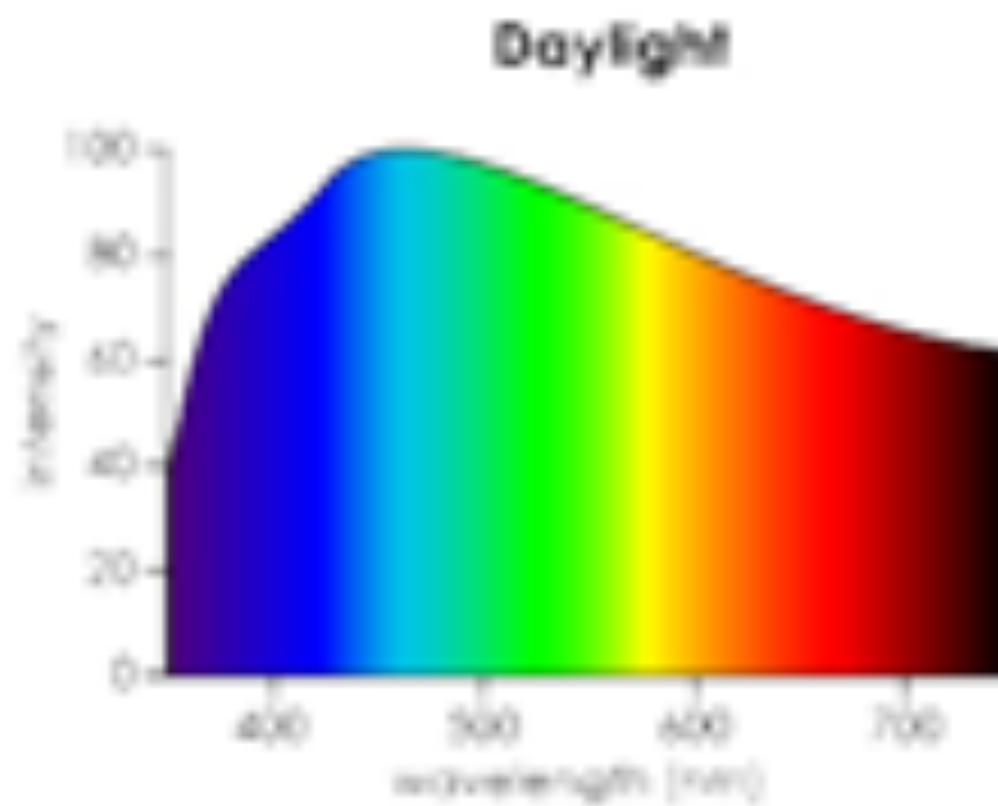


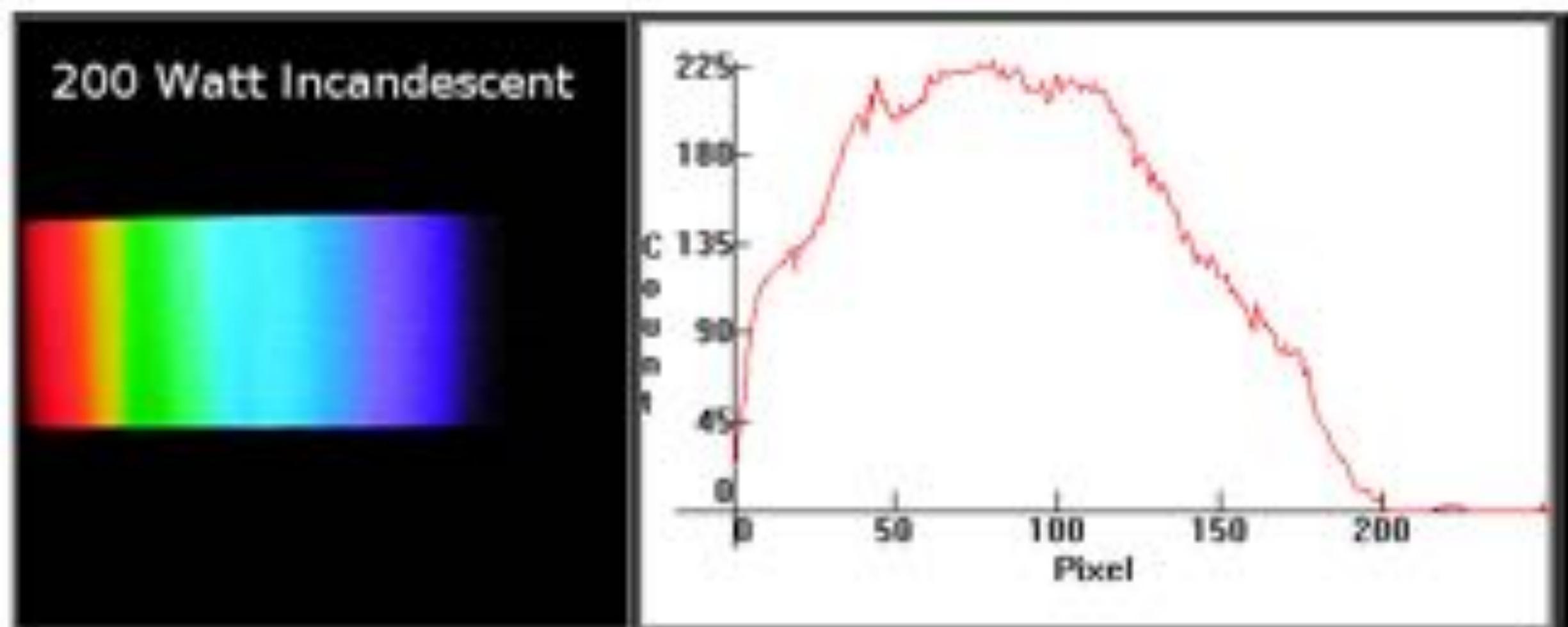
Figure credit:

Emission Spectrum—Example

- Why so many different kinds of lightbulbs on the market?
- “Quality” of light:

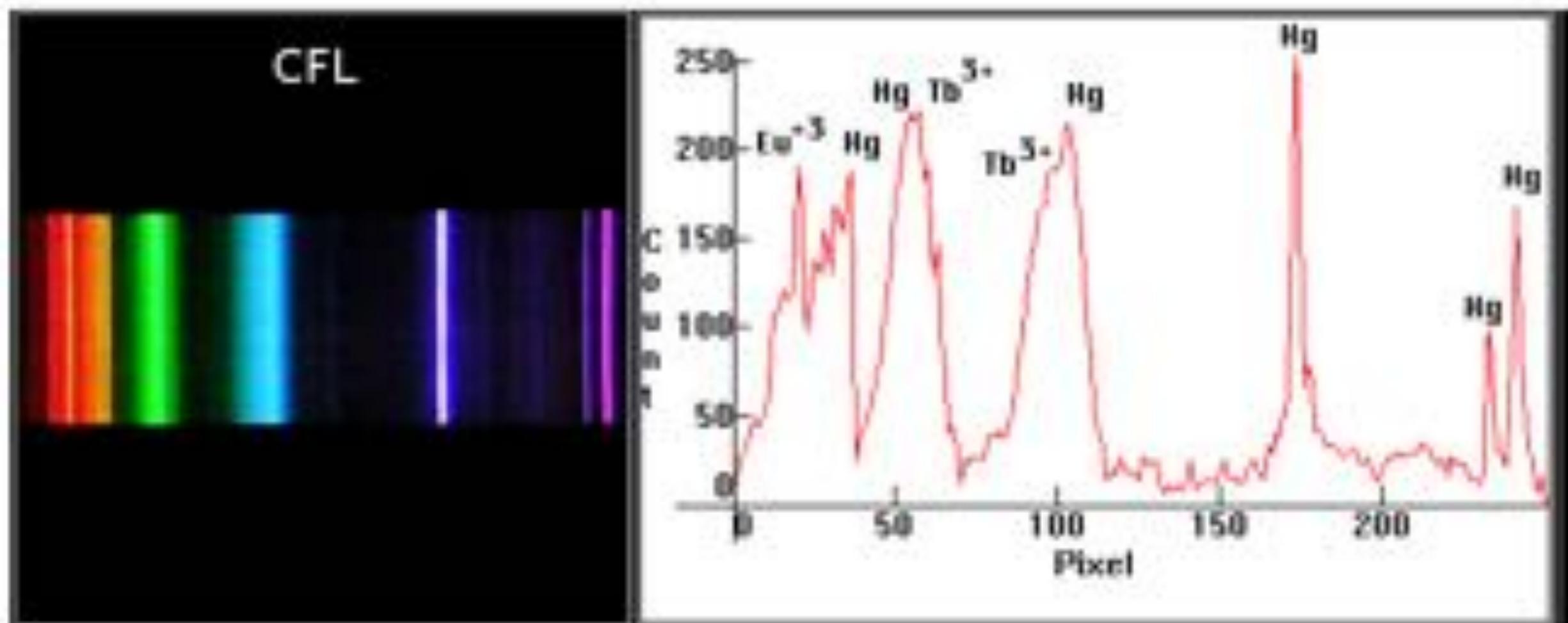
Incandescent:

- +more sun-like
- power-hungry



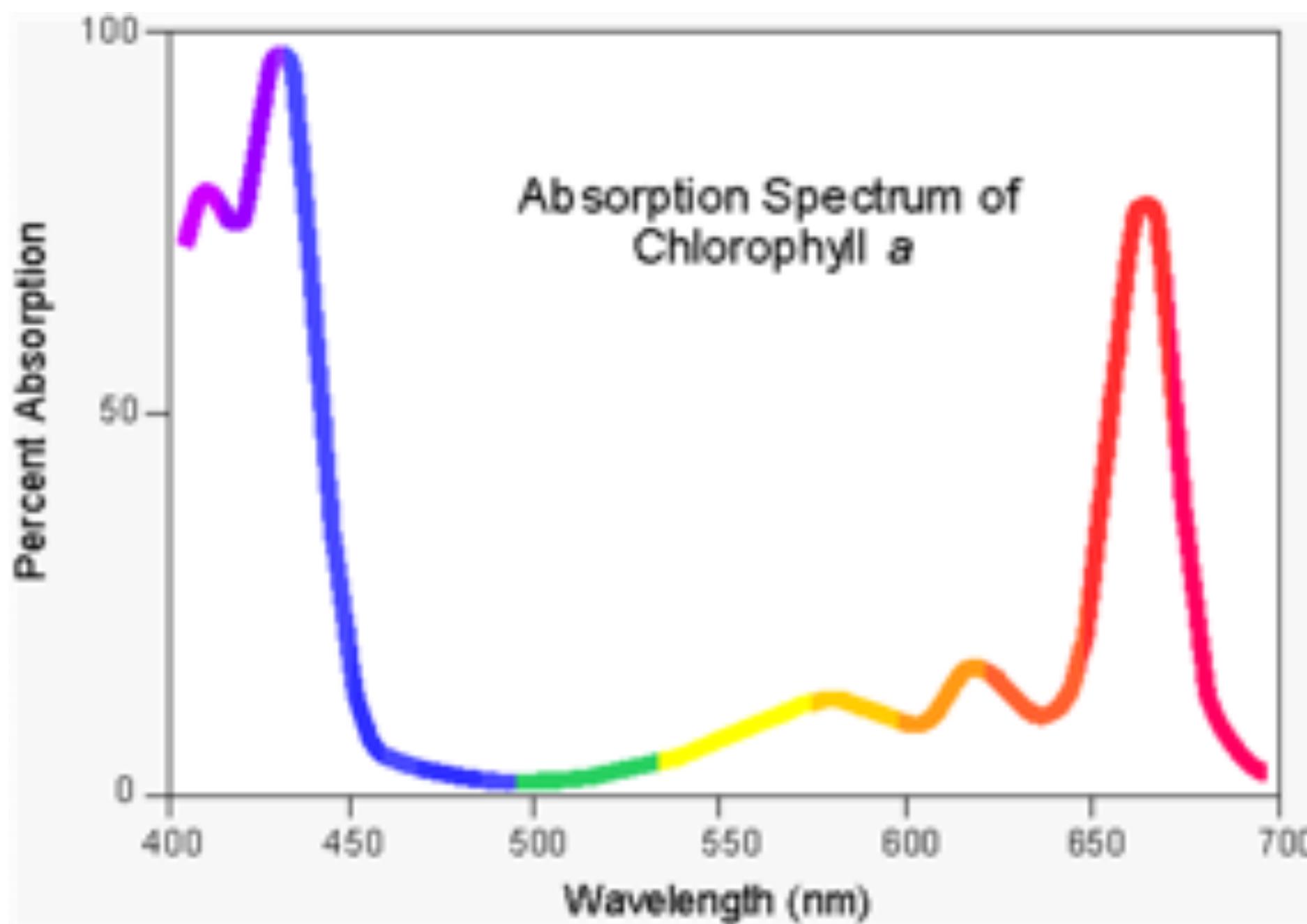
CFL:

- “choppy” spectrum
- +power efficient



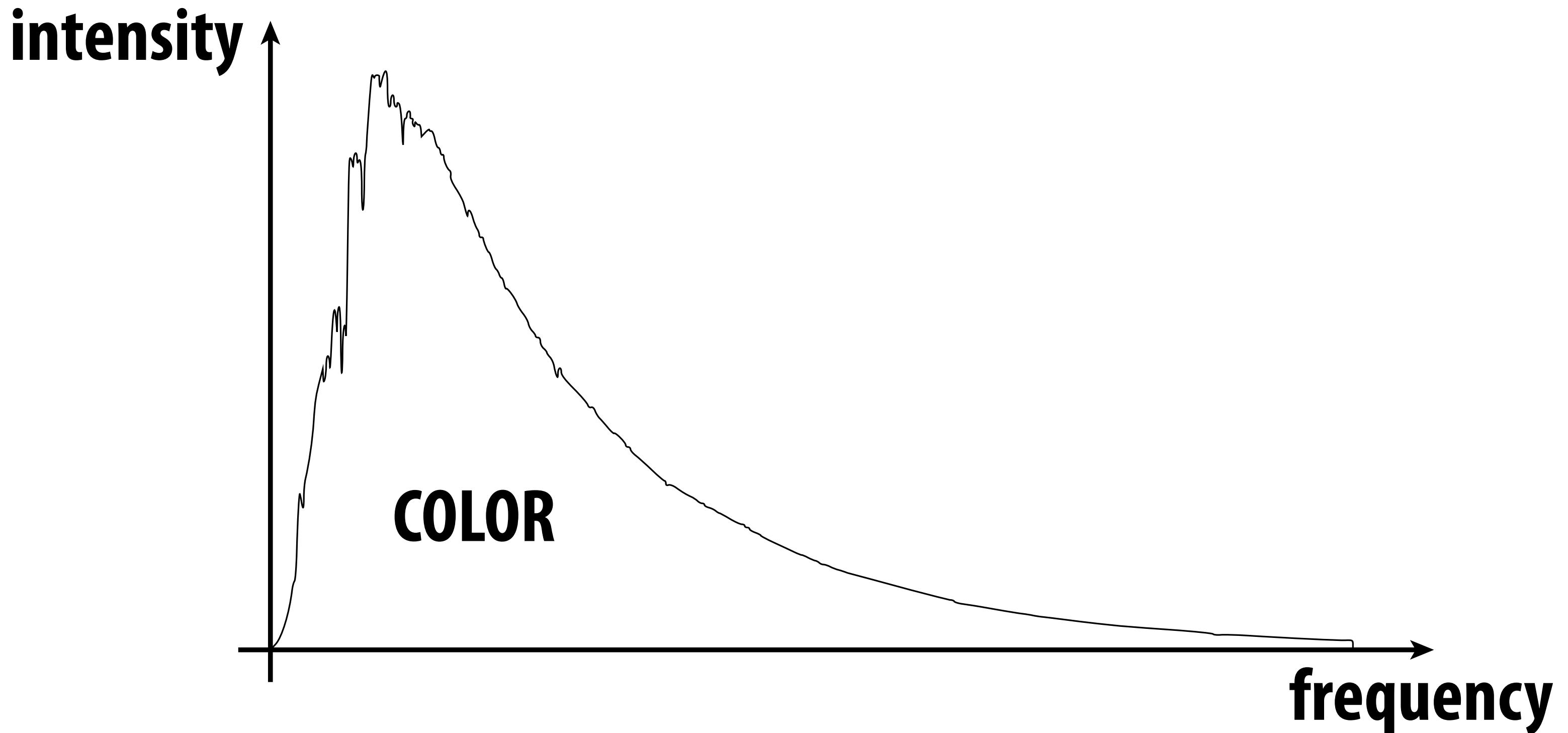
Absorption Spectrum

- Emission spectrum is intensity as a function of frequency
- Absorption spectrum is fraction absorbed as function of frequency



Q: What color is an object with this absorption spectrum?

**This is the fundamental description of color:
intensity or absorption as a function of frequency**



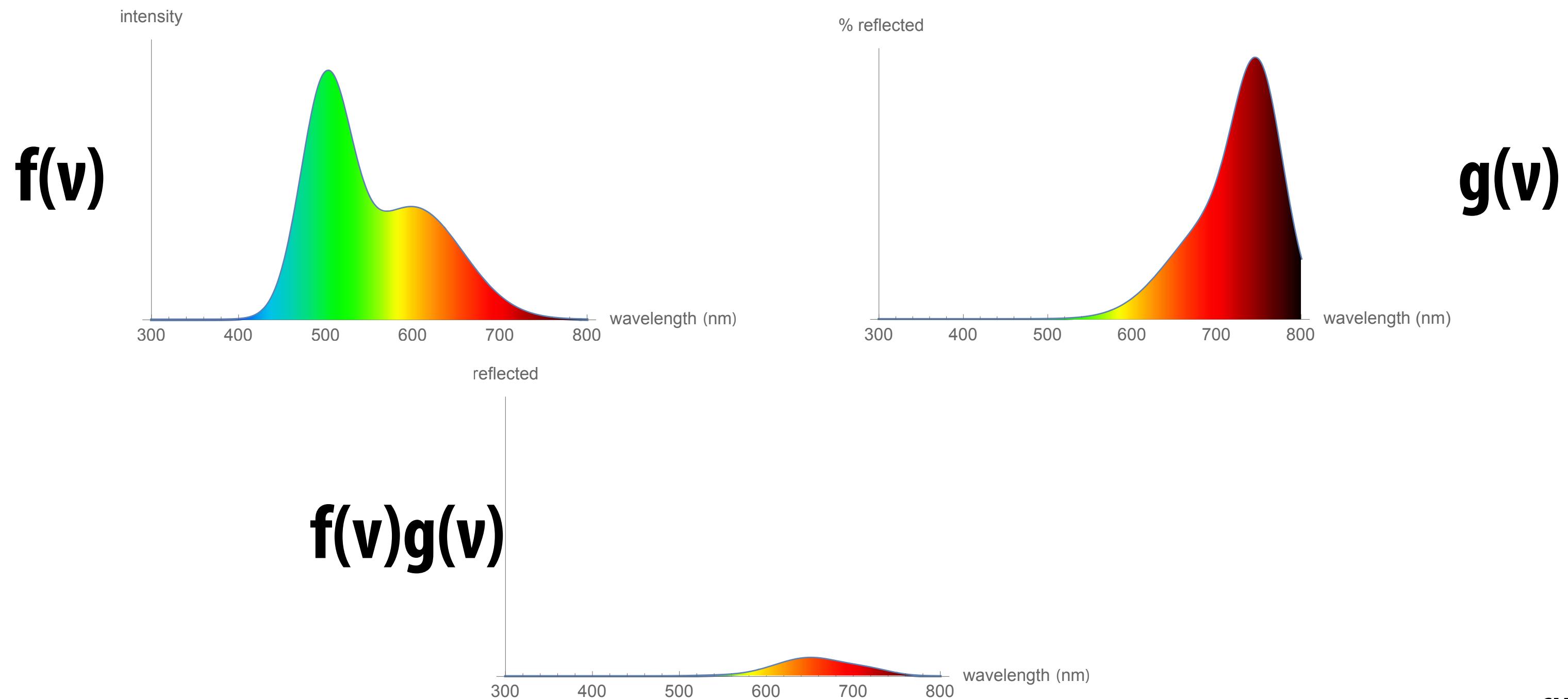
Everything else is merely a convenient approximation!

**If you remember to use spectral
description as a starting point, the
issues surrounding color theory/
practice will make a lot more sense!**

If on the other hand you always think of color in terms of approximate digital encodings (RGB, CMYK) etc., there are certain phenomena you simply cannot explain/understand!

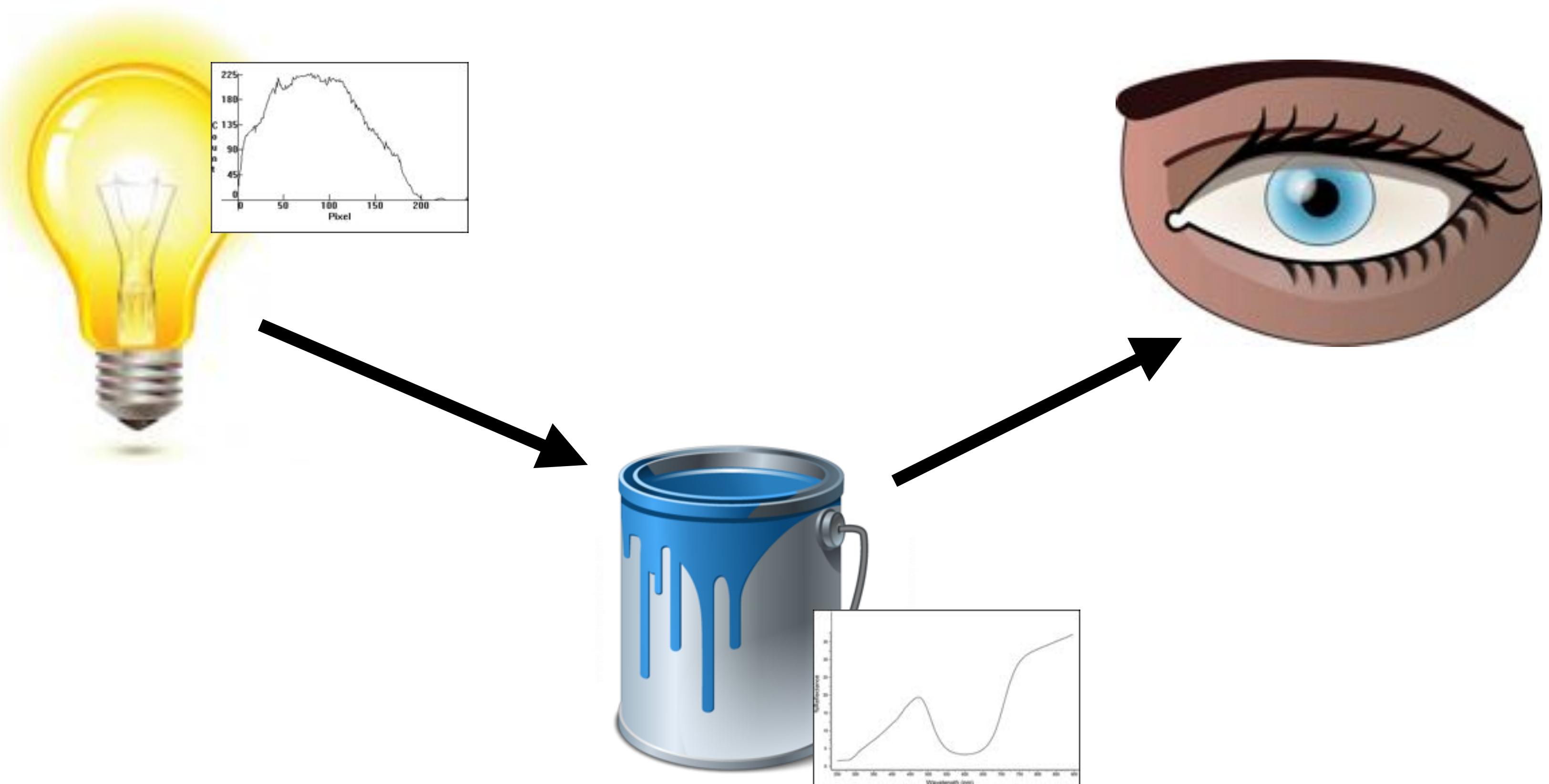
Interaction of emission and reflection

- Toy model for what happens when light gets reflected
 - ν —frequency (Greek “nu”)
 - Light source has emission spectrum $f(\nu)$
 - Surface has reflection spectrum $g(\nu)$
 - Resulting intensity is the product $f(\nu)g(\nu)$



Color reproduction is hard!

- Color clearly starts to get complicated as we start combining emission and absorption/reflection (real-world challenge!)



(What color ink should we use to get the desired appearance?)

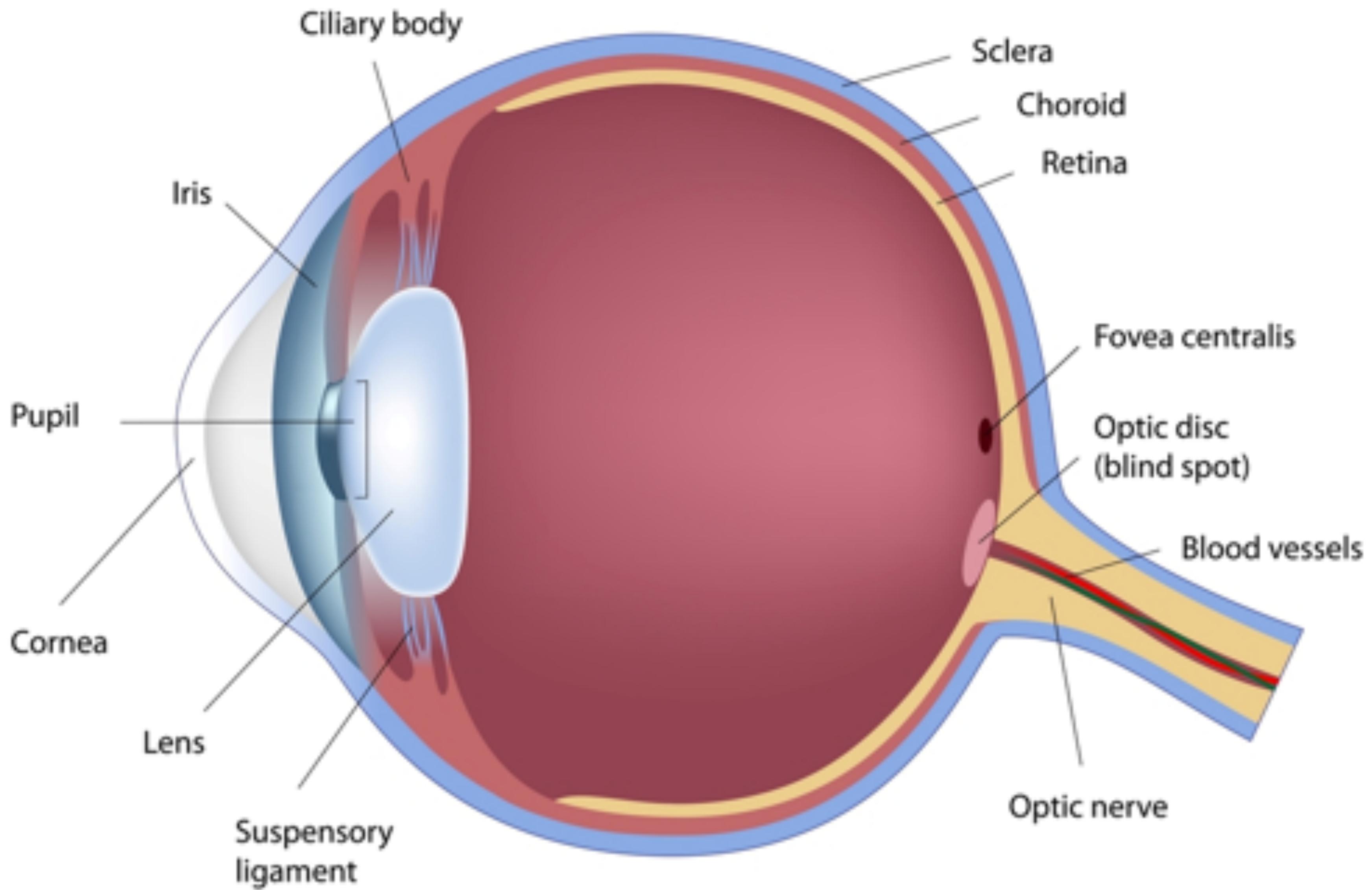
...And what about perception?

Q: What color is this dress?

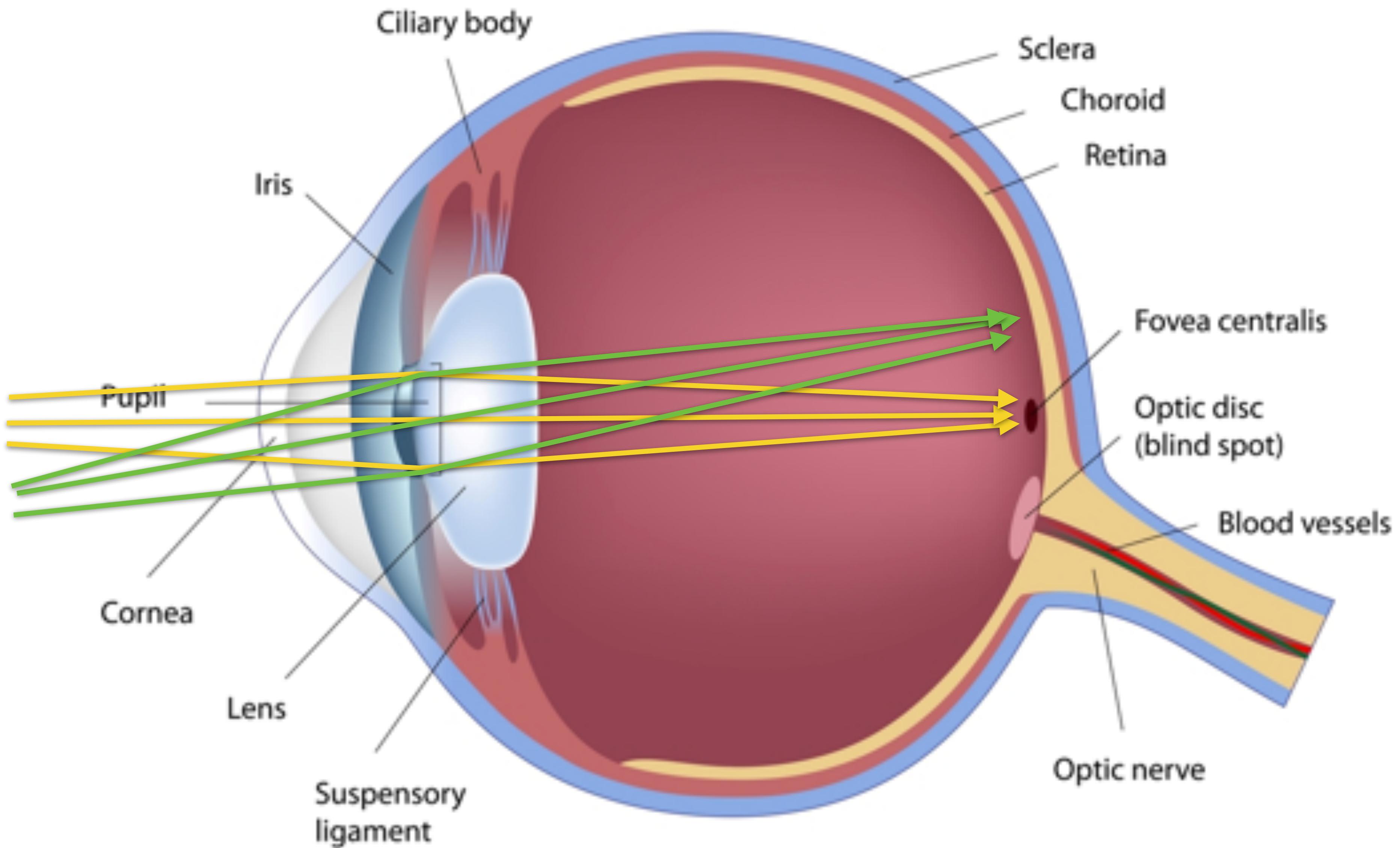


How does electromagnetic radiation (with a given power distribution) end up being perceived by a human as a certain color?

The eye



The eye (optics)



Photosensor response (eye, camera, ...)

- Photosensor input: light

- Electromagnetic power distribution over wavelengths: $\Phi(\lambda)$

- Photosensor output: a “response”... a number

- e.g., encoded in electrical signal

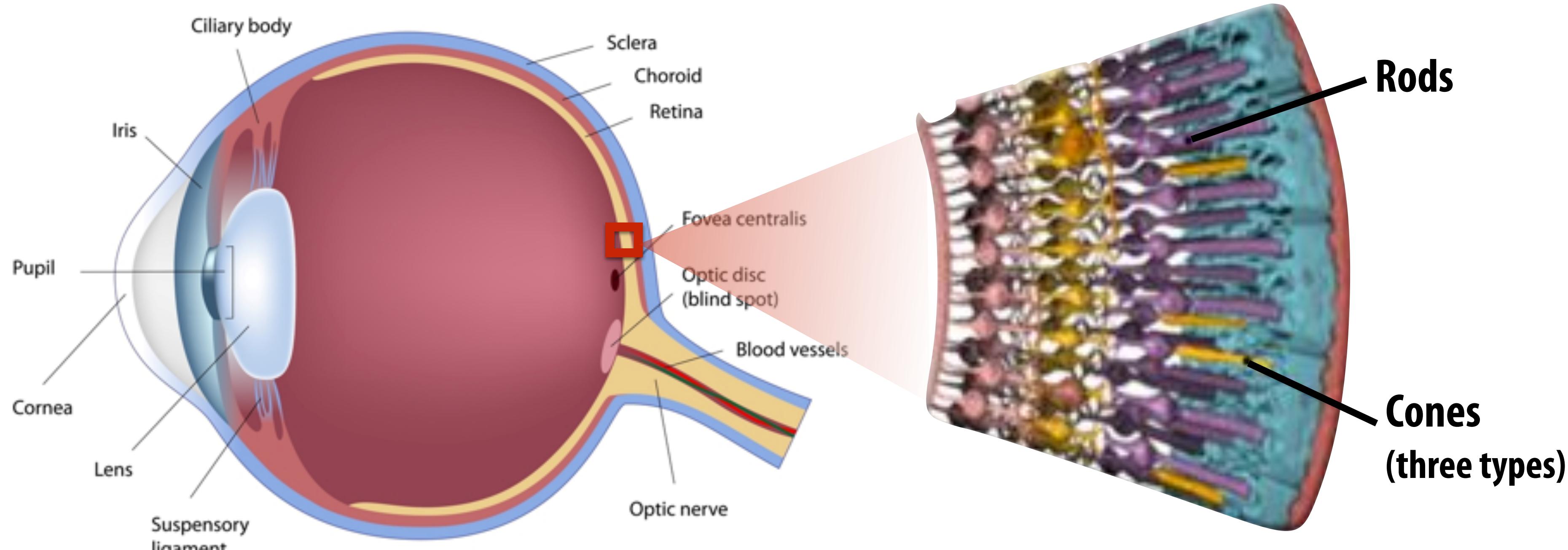
- Spectral response function: $f(\lambda)$

- Sensitivity of sensor to light of a given wavelength
 - Greater $f(\lambda)$ corresponds to more efficient sensor (when $f(\lambda)$ is large, a small amount of light at wavelength λ will trigger a large sensor response)

- Total response of photosensor:

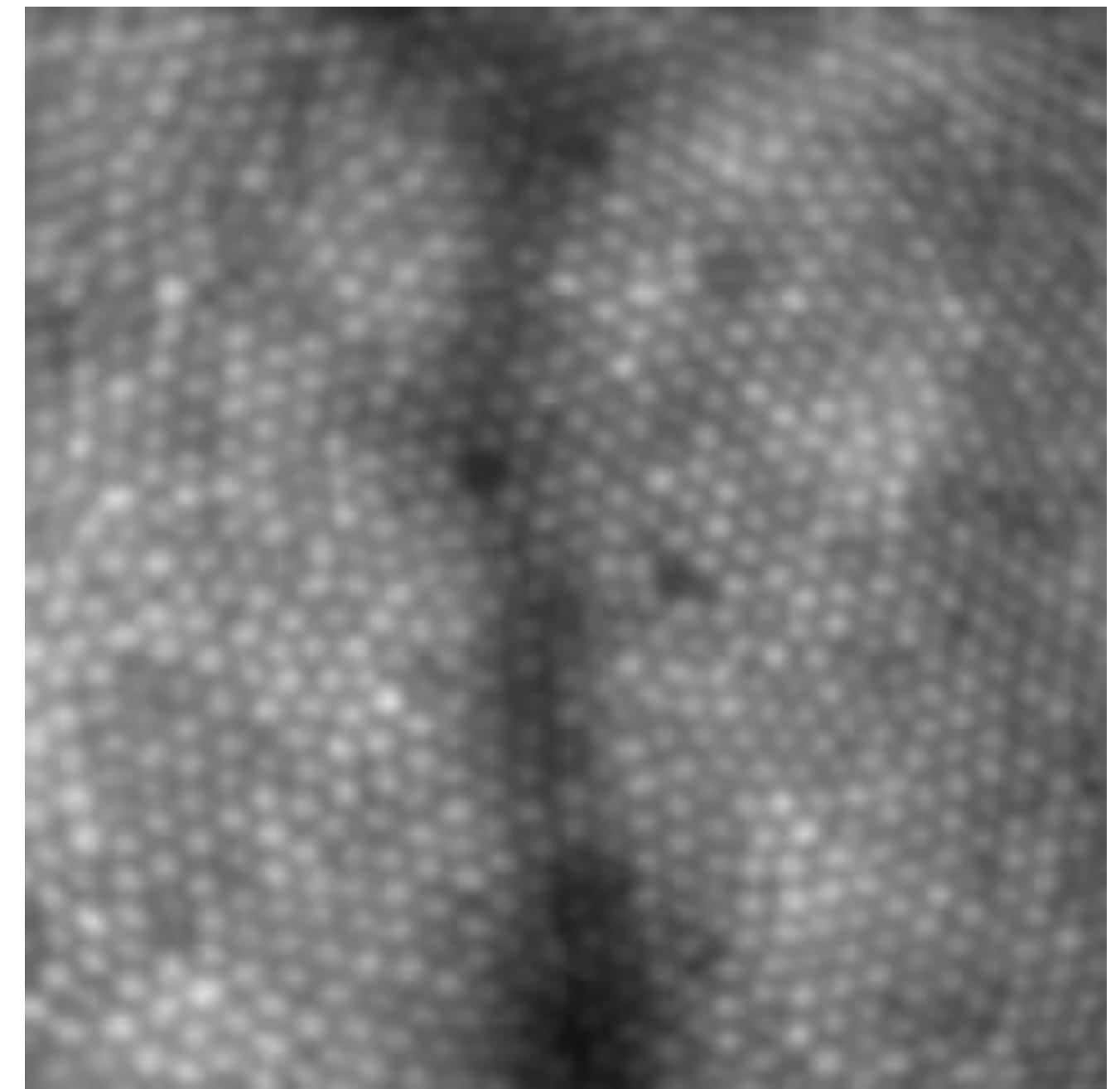
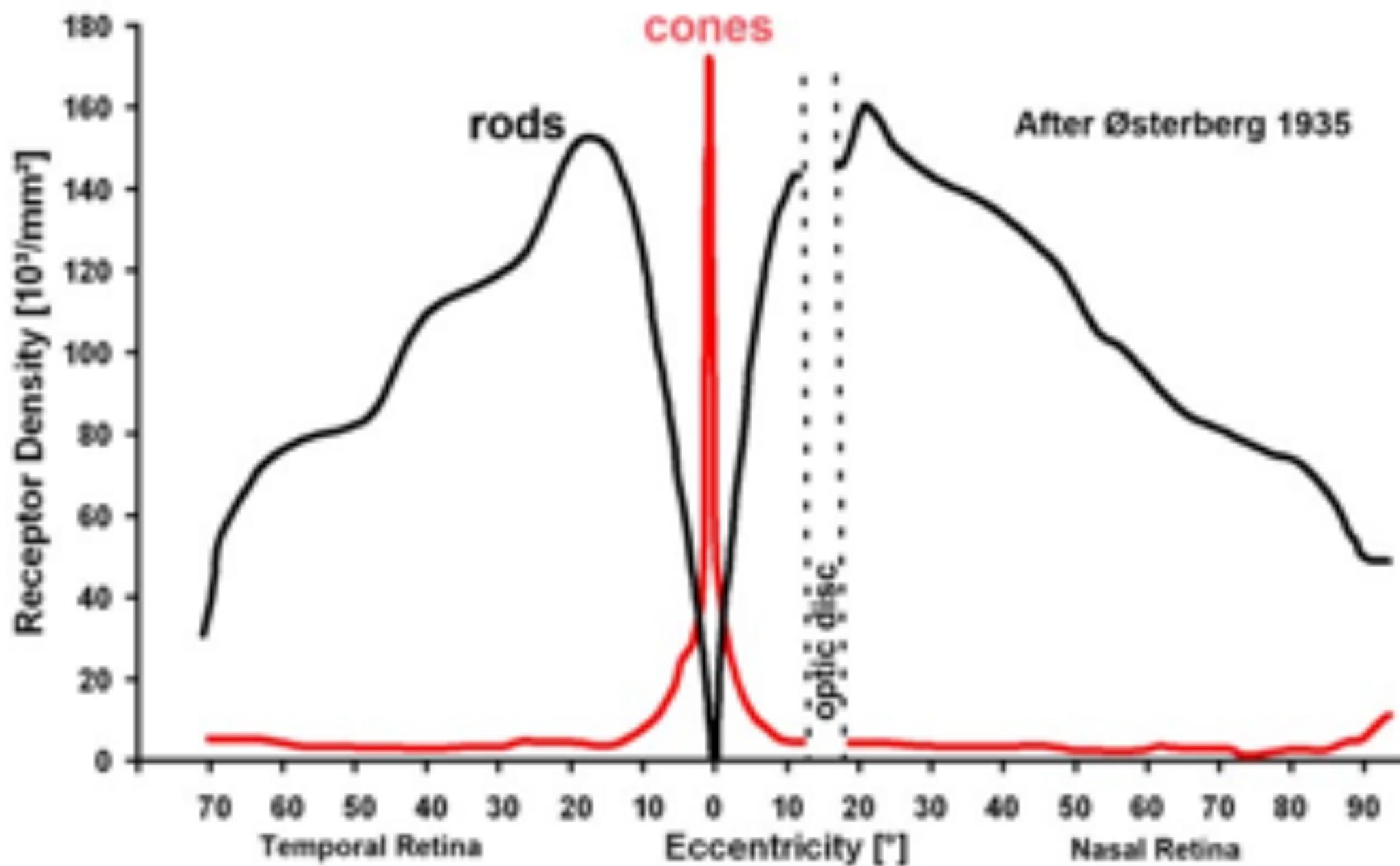
$$R = \int_{\lambda} \Phi(\lambda) f(\lambda) d\lambda$$

The eye's photoreceptor cells: rods & cones



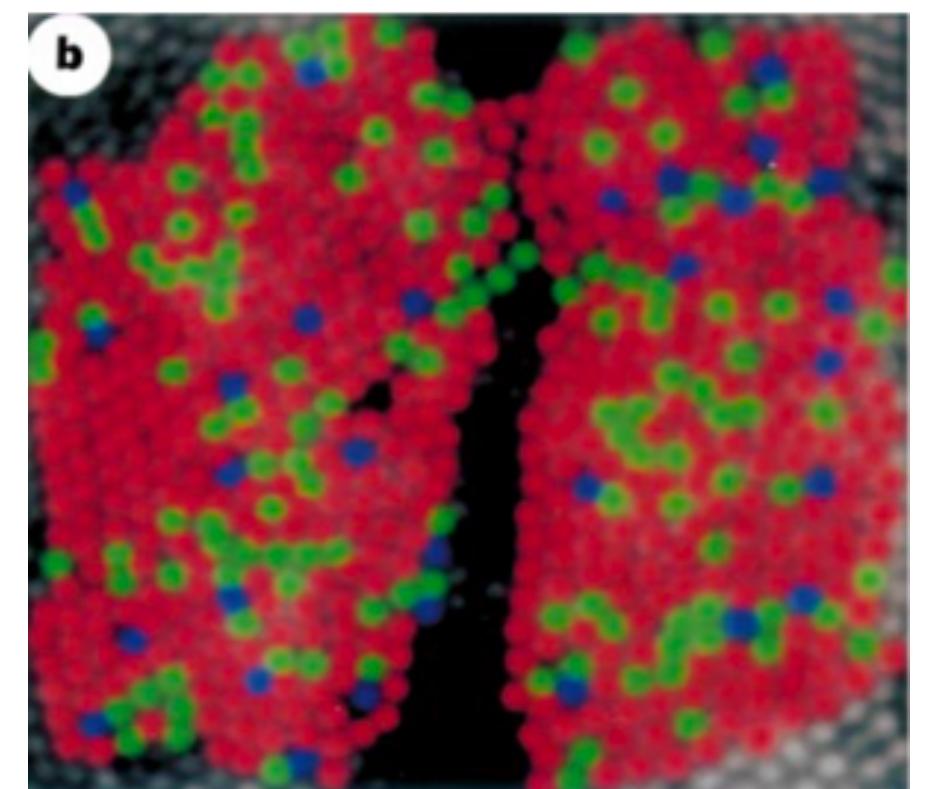
- Rods are primary receptors under dark viewing conditions (scotopic conditions)
 - Approx. 120 million rods in human eye
- Cones are primary receptors under high-light viewing conditions (photopic conditions, e.g., daylight)
 - Approx. 6-7 million cones in the human eye
 - Each of the three types of cone feature a different spectral response. This will be critical to color vision (much more on this in the coming slides)

Density of rods and cones in the retina



[Roorda 1999]

- Highest density of cones is in fovea
(best color vision at center of where human is looking)
- Note “blind spot” due to optic nerve



ACTIVITY: Rods vs. Cones

- Grab someone and try it at home!
 - Have them hold up colored markers in peripheral vision
 - All you have to do is say what color it is (easy!)



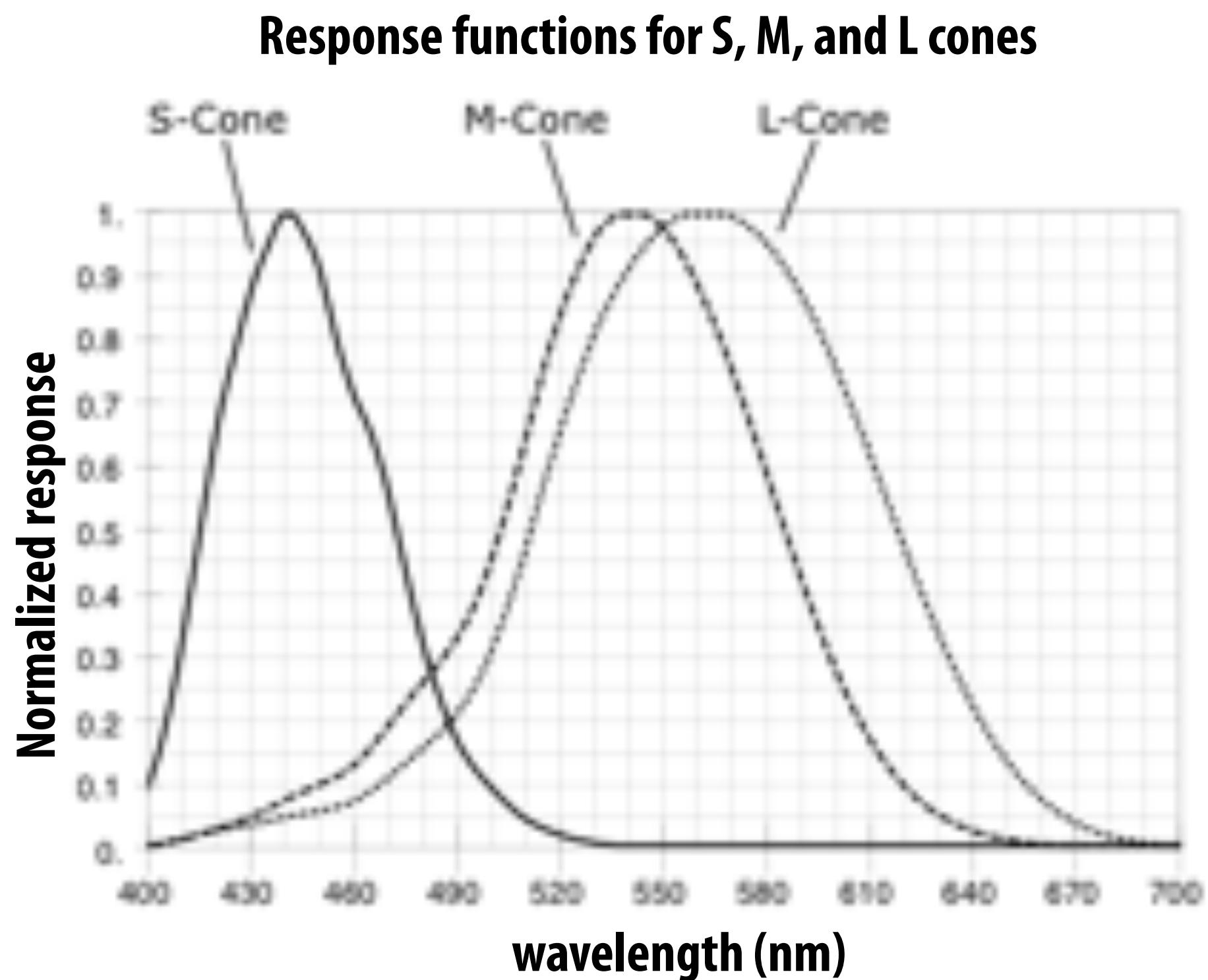
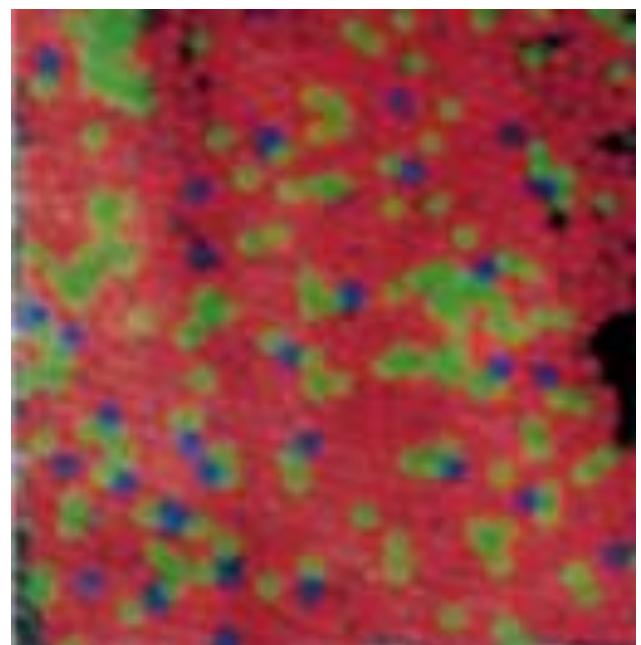
Spectral response of cones

Three types of cones: S, M, and L cones (corresponding to peak response at short, medium, and long wavelengths)

$$S = \int_{\lambda} \Phi(\lambda) S(\lambda) d\lambda$$

$$M = \int_{\lambda} \Phi(\lambda) M(\lambda) d\lambda$$

$$L = \int_{\lambda} \Phi(\lambda) L(\lambda) d\lambda$$

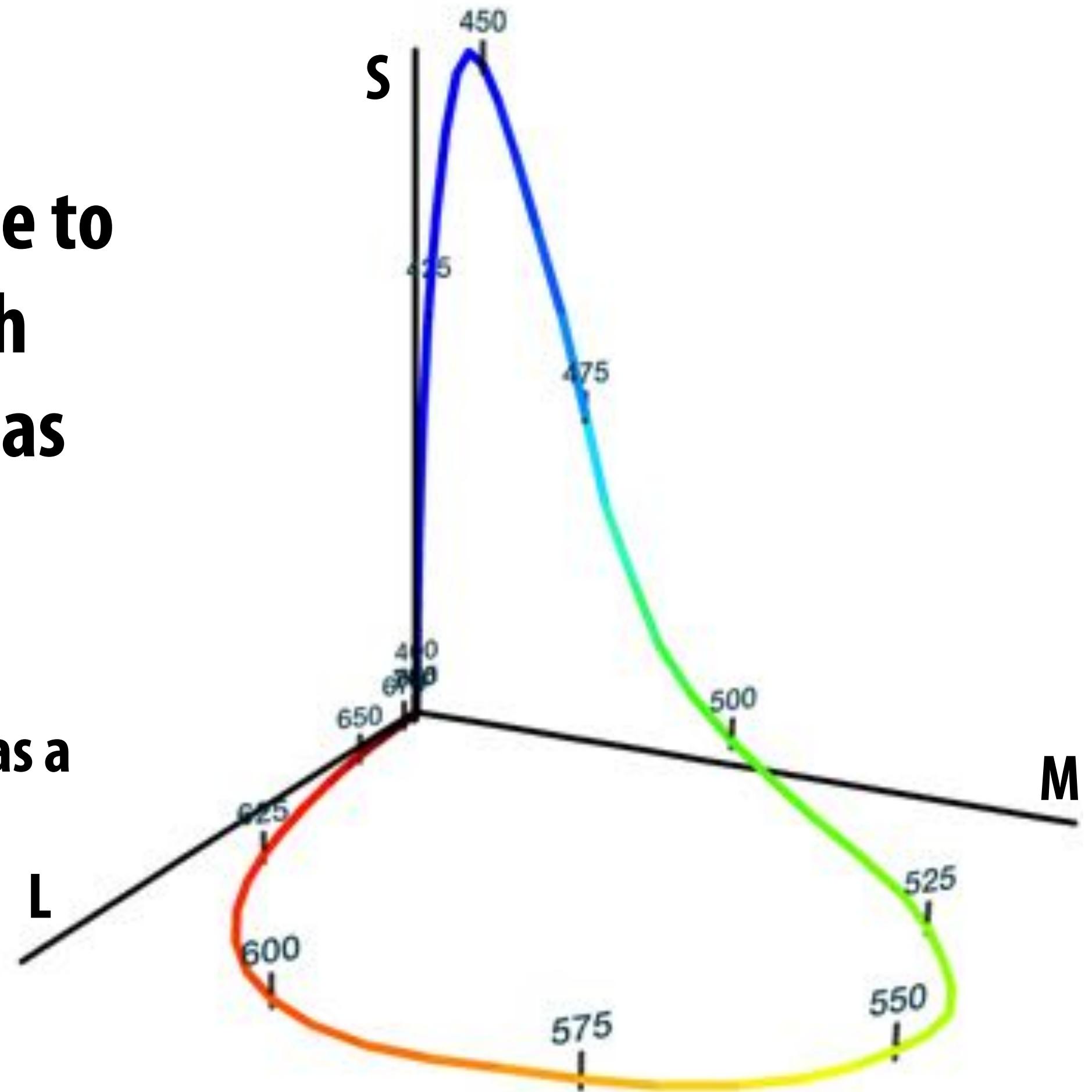


Uneven distribution of cone types in eye
~64% of cones are L cones, ~32% M cones

Response of S,M,L cones to monochromatic light

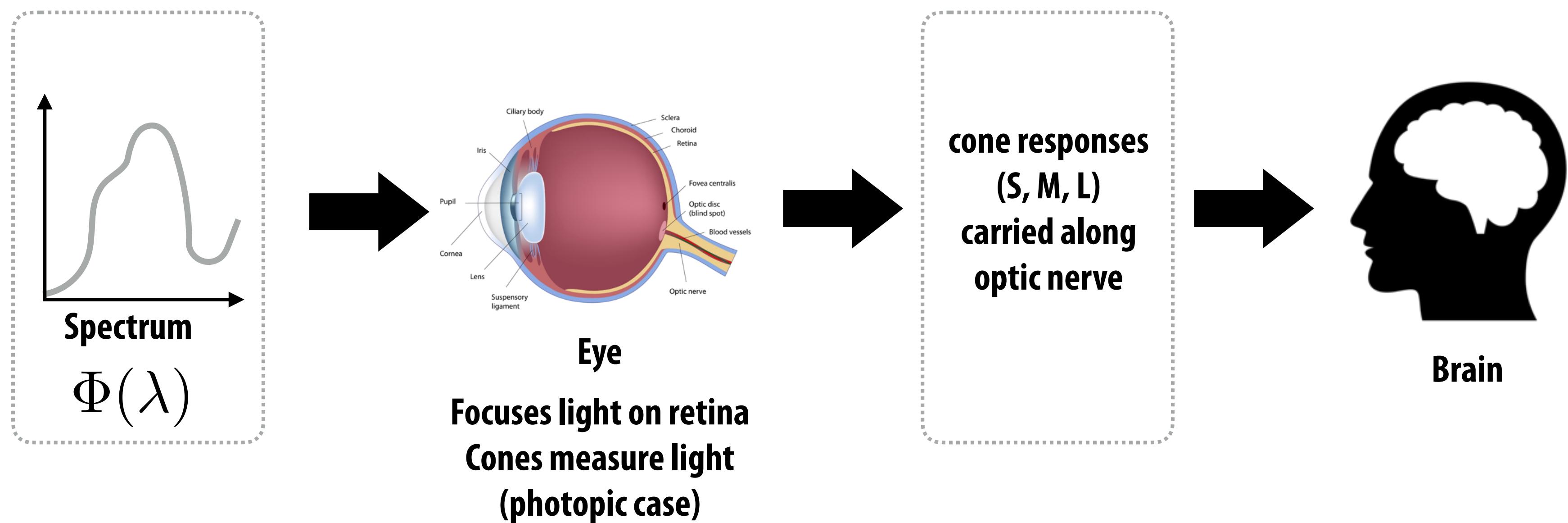
Figure visualizes cone's response to monochromatic light (light with energy in a single wavelength) as points in 3D space

(plots value of S, M, L response functions as a point in 3D space)



The human visual system

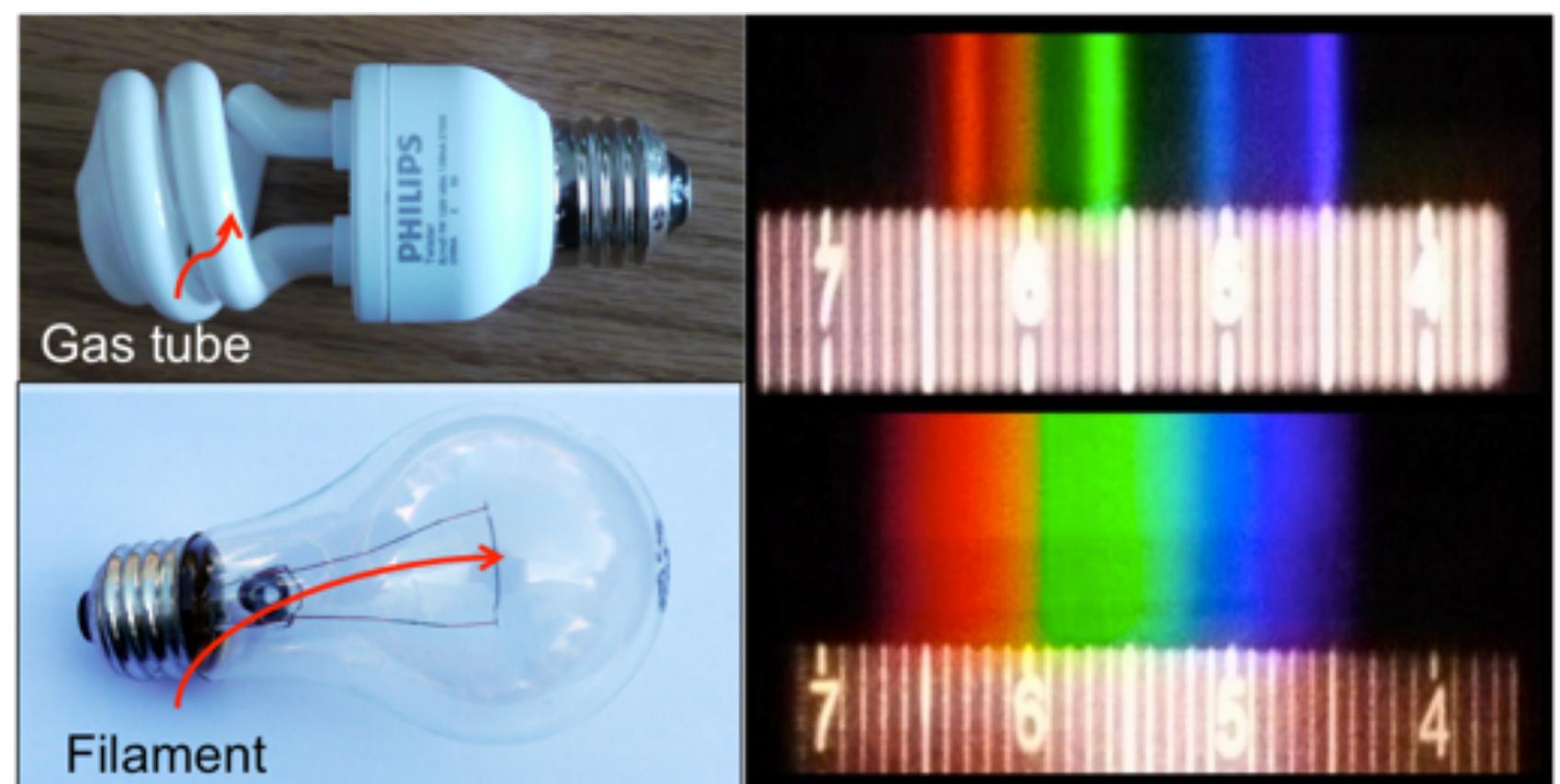
- Human eye does not directly measure the spectrum of incoming light
 - i.e., the brain does not receive “a spectrum” from the eye
- The eye measures three response values = (S, M, L). The result of integrating the incoming spectrum against response functions of S, M, L-cones



**Q: Is it possible for two functions
to integrate to the same value?**

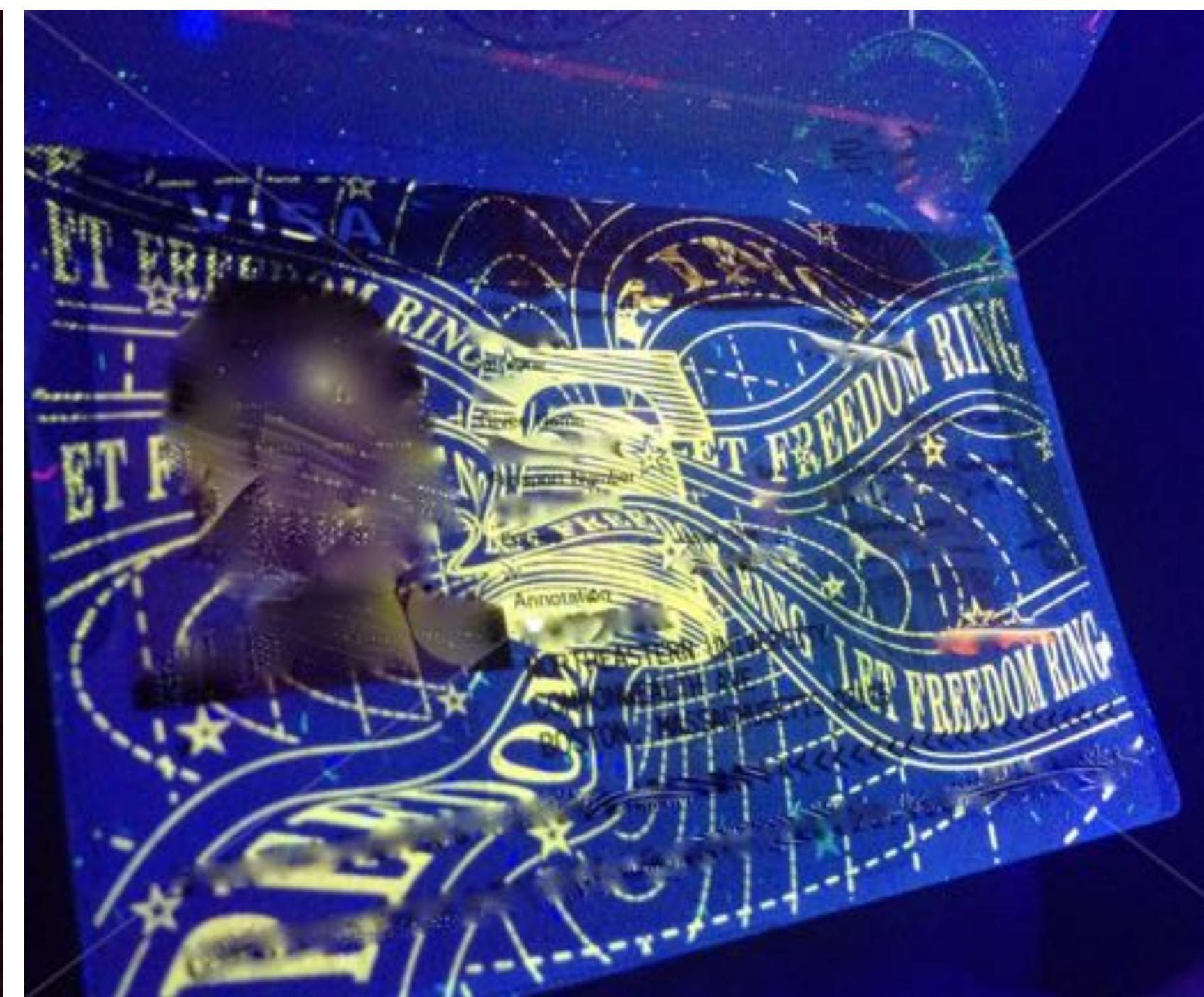
Metamers

- Metamers = two different spectra that integrate to the same (S,M,L) response!
- The fact that metameters exist is critical to color reproduction: we don't have to reproduce the exact same spectrum that was present in a real world scene in order to reproduce the perceived color on a monitor (or piece of paper, or paint on a wall)
- ...On the other hand, combination of light & paint could still cause trouble—different objects appearing “wrong” under different lighting conditions.



Example: Counterfeit Detection

- Many countries print currency, passports, etc., with special inks that yield different appearance under UV light:

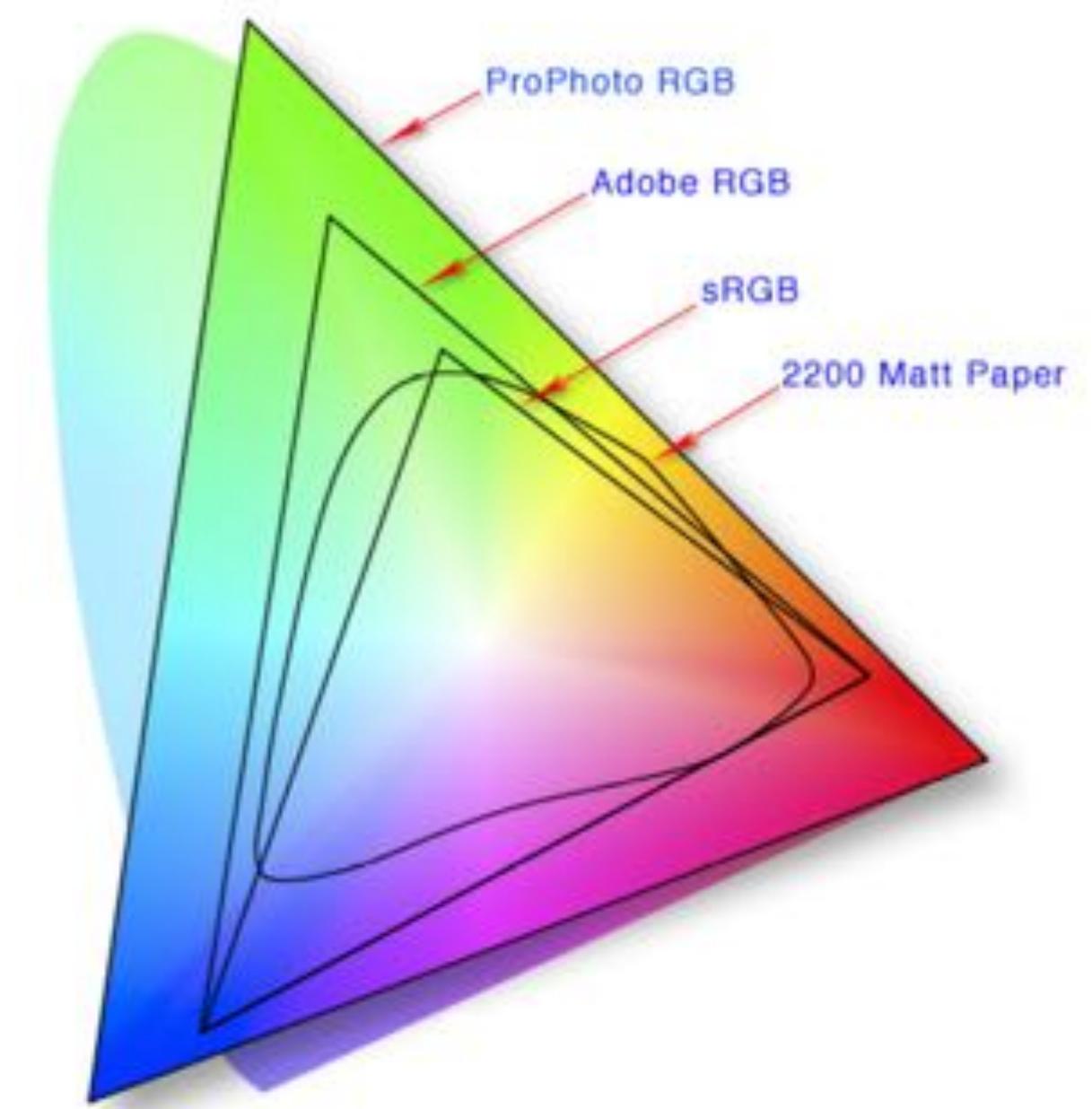


Ok, so color can get pretty complicated!

How do we encode it in a simple(r) way?

Color Spaces and Color Models

- Many ways to specify a color
 - storage
 - convenience
- In general, specify a color from some color space using a color model
- Color space is like artist's palette: full range of colors we can choose from
- Color model is the way a particular color in a color space is specified:
 - artist's palette: "yellow ochre"
 - RGB color model: 204, 119, 34



Additive vs. Subtractive Color Models

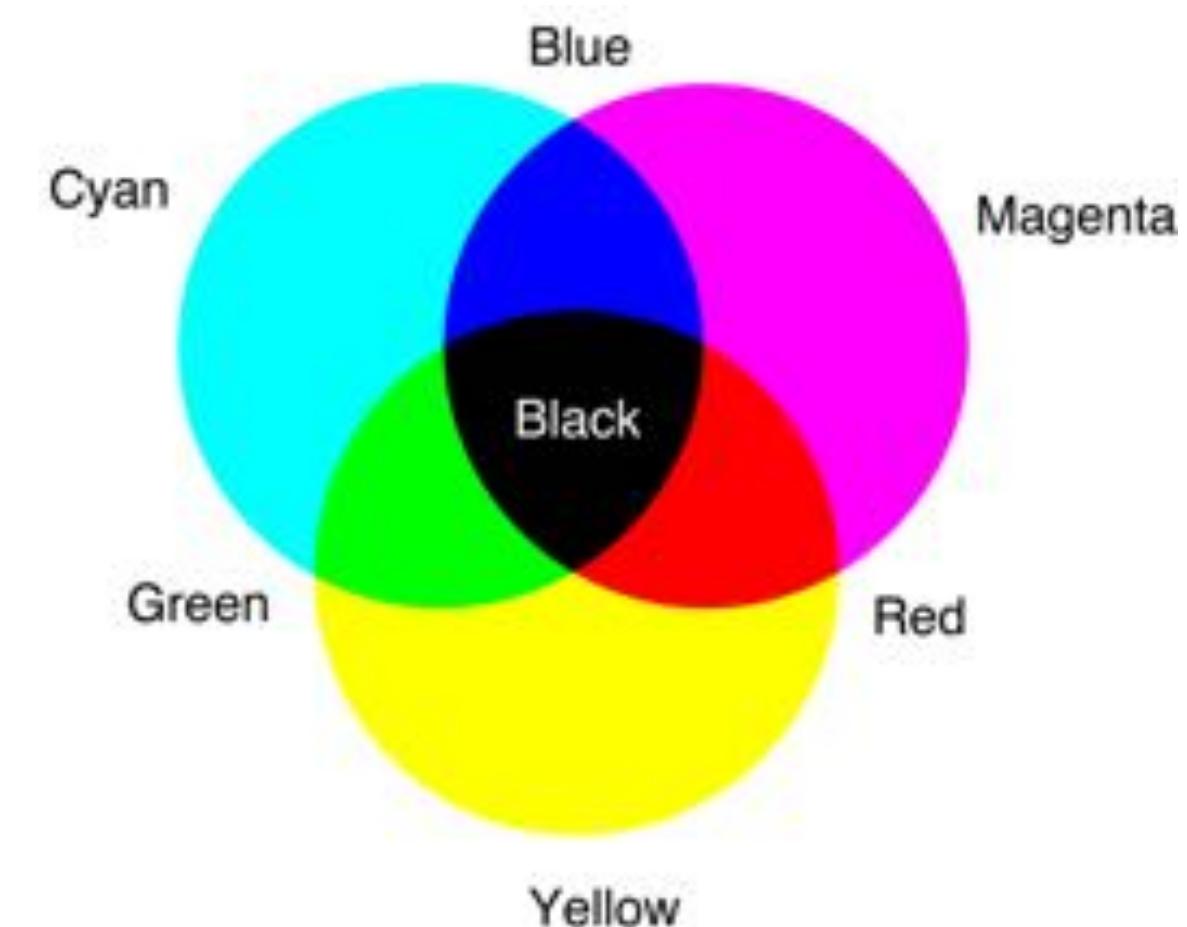
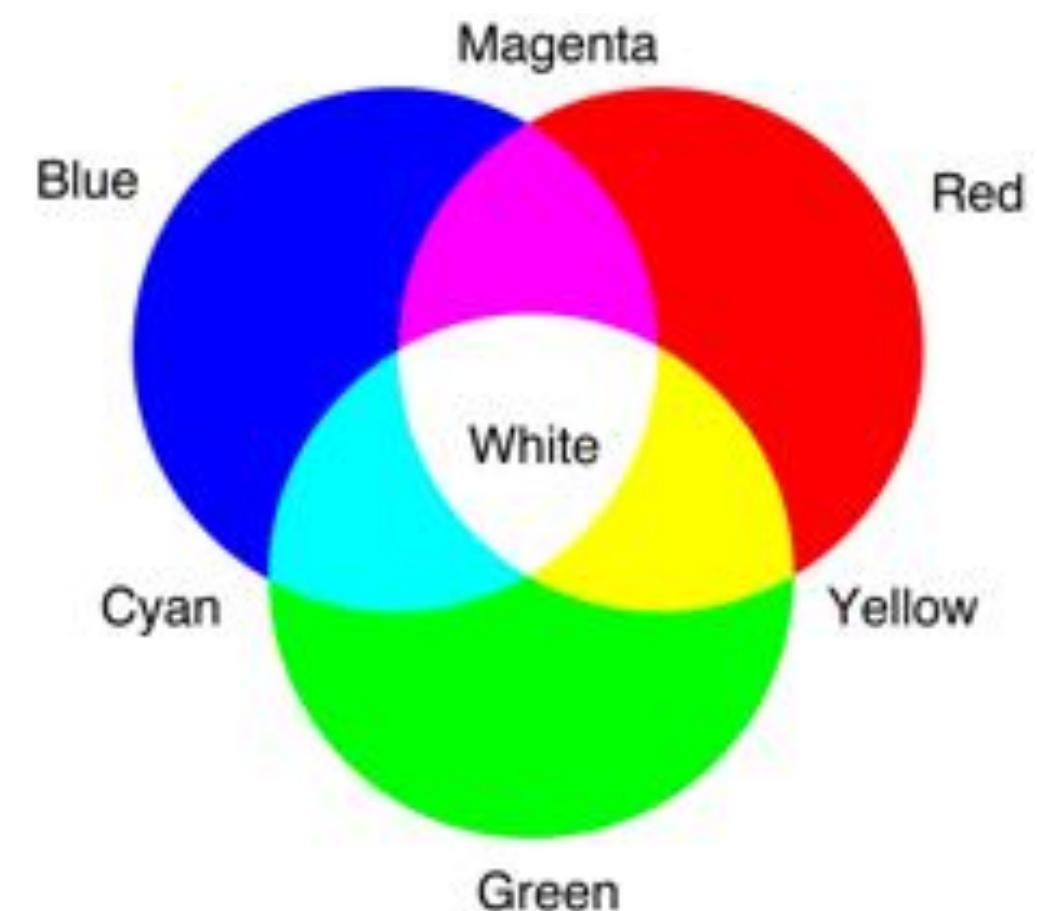
- Just like we had emission & absorption spectra, we have additive and subtractive* color models

- Additive

- Used for, e.g., combining colored lights
 - Prototypical example: RGB

- Subtractive

- Used for, e.g., combining paint colors
 - Prototypical example: CMYK



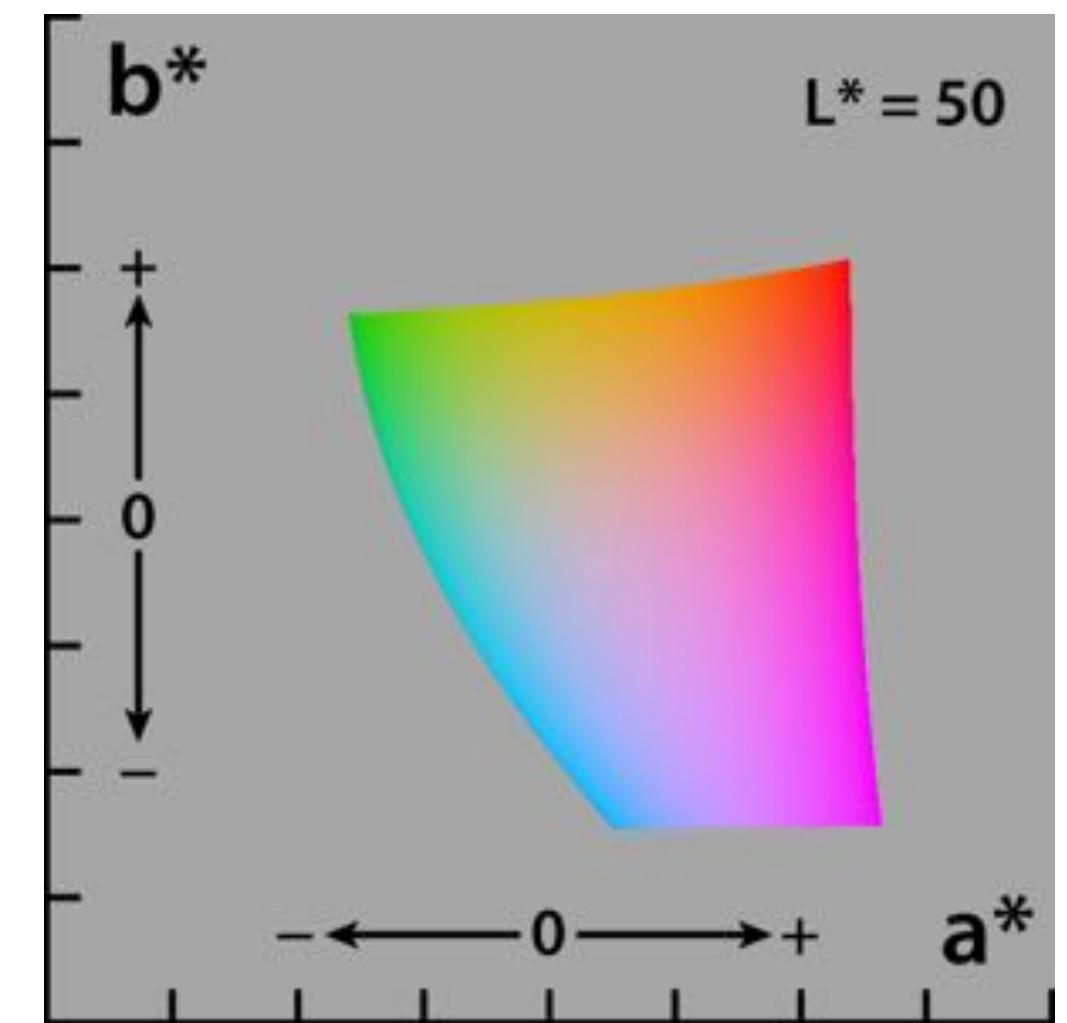
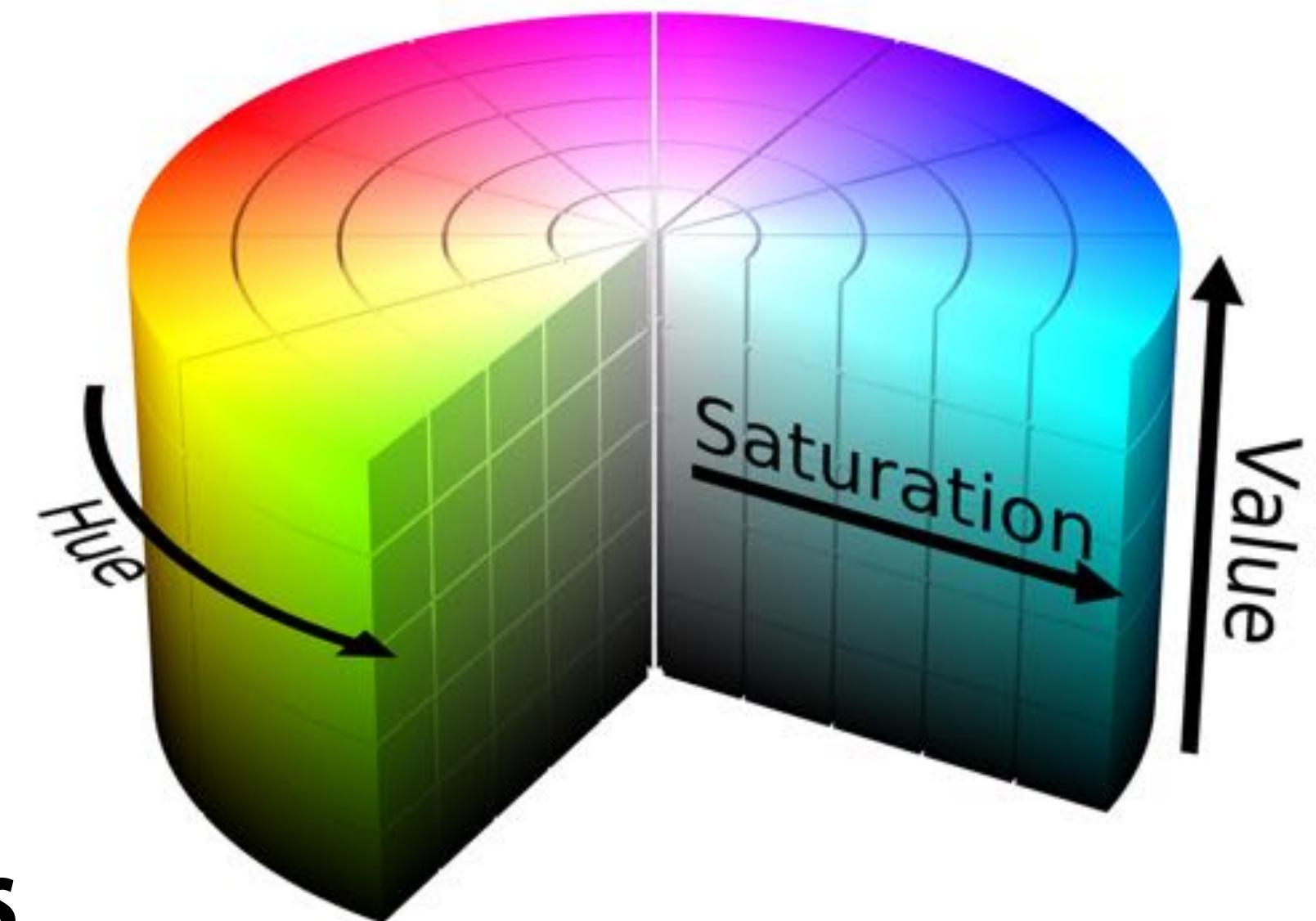
*A better name than subtractive might be multiplicative, since we multiply to get the final color!

Let's shed some light on this picture...



Other Common Color Models

- **HSV**
 - hue, saturation, value
 - more intuitive than RGB/CMYK
- **SML—physiological model**
 - corresponds to stimulus of cones
 - not practical for most color work
- **XYZ—perceptually-driven model**
 - Y captures luminance (intensity)
 - X,Z capture chromaticity (color)
 - related to, but different from, SML
- **Lab—“perceptually uniform” modification of XYZ**



Practical Encoding of Color Values

- How do colors actually get encoded digitally?
- One common encoding (e.g., HTML): 8bpc hexadecimal values*:

1B1F8A

- What does this string mean? Common encoding of RGB.
- Want to store 8-bits per channel (red, green, blue), corresponding to 256 possible values
- Rather than use digits 0-9, use 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E, F
- Single character now encodes 16 values, two characters encode $16 \times 16 = 256$ values
- Q: Roughly what color is # ff6600?



*Upper vs. lowercase letters? Makes absolutely no difference!

Other Ways of Specifying Color?

- Other color specifications not based on continuous color space
- E.g., Pantone Matching System
 - industry standard (proprietary)
 - 1,114 colors
 - Combination of 13 base pigments
- And not to forget...



Why use different color models?

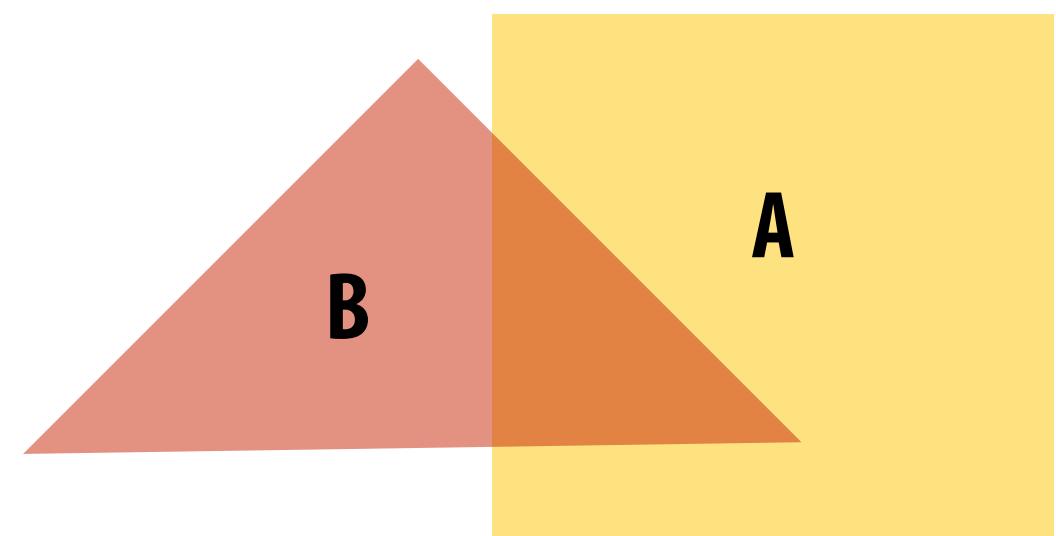
■ Convenience

- Is it easy for a user to choose the color they want?



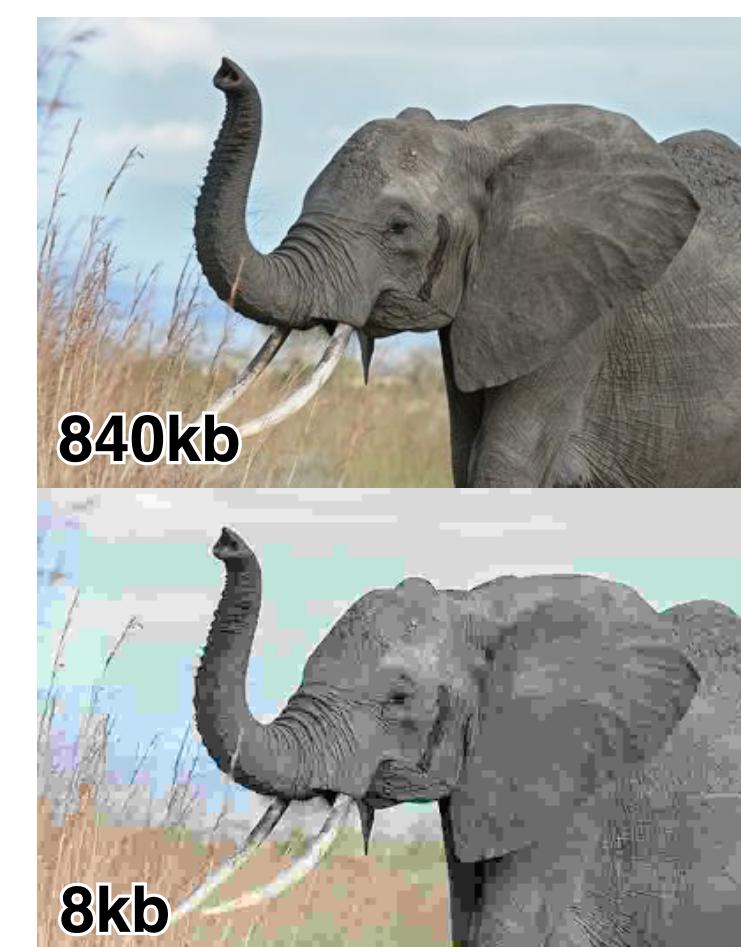
■ Color compositing/processing

- Does it matter what color space we interpolate / blend in?



■ Efficiency of encoding

- E.g., use more of numerical range for perceptually significant colors
- Compression!



Example: Y'CbCr color model

- Common for modern digital video
- Y' = luma: perceived luminance (same as L^* in CIELAB)
- Cb = blue-yellow deviation from gray
- Cr = red-cyan deviation from gray

(input)

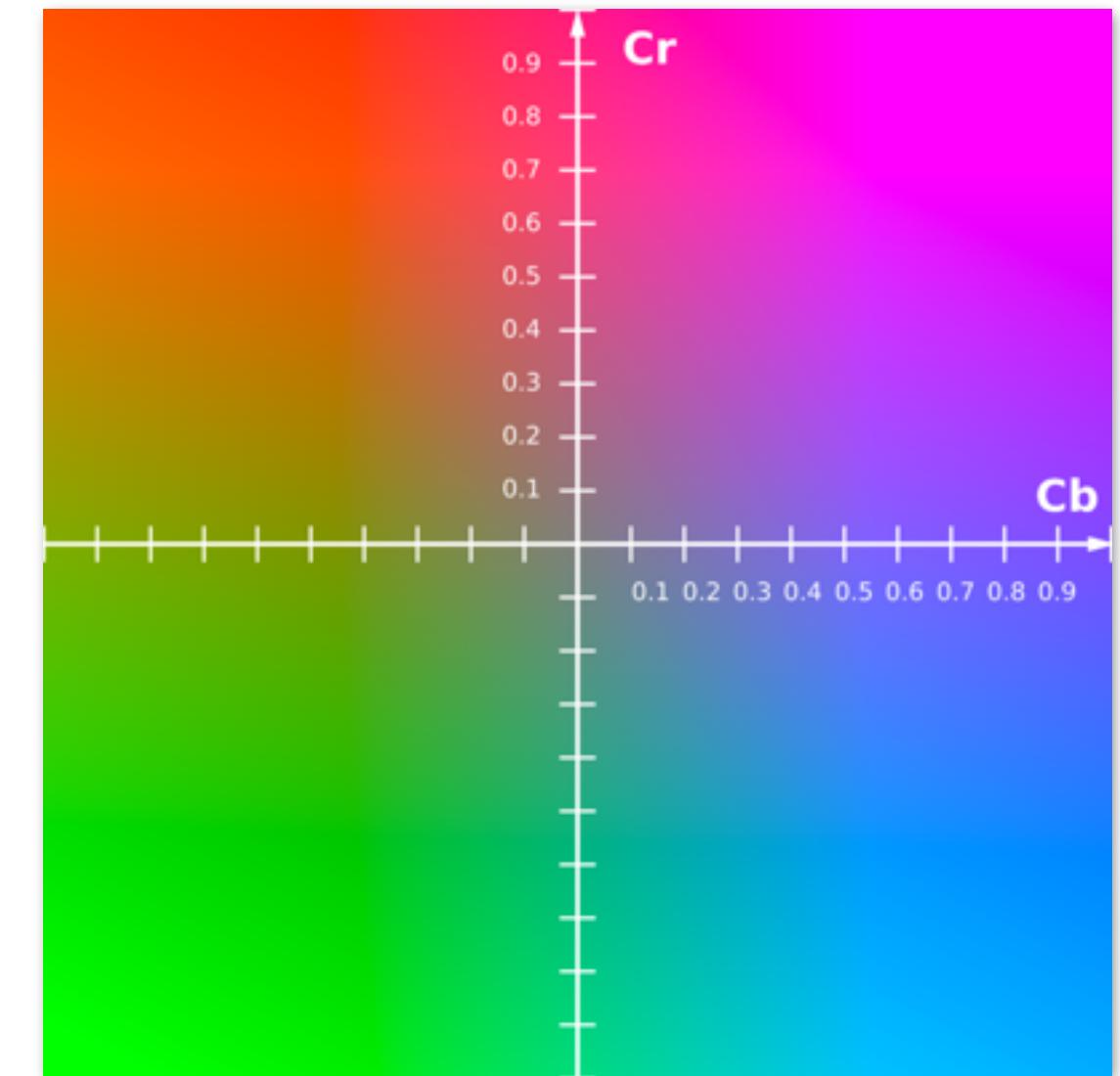


Y'

Cb



Cr





Original picture



**Contents of CbCr color channels downsampled by a factor of 20 in each dimension
(400x reduction in number of samples)**



Full resolution sampling of luma (Y')



**Reconstructed result
(looks pretty good)**



Original picture

By the way, how might we reduce this artifact?



Reconstructed result

Why use different color models? (cont.)

■ Convenience

- Is it easy for a user to choose the color they want?

■ Efficiency of encoding

- E.g., use more of numerical range for perceptually significant colors
- Do color images compress well?

■ Gamut

- Which colors can be expressed using a given model?
- Very different for print vs. display



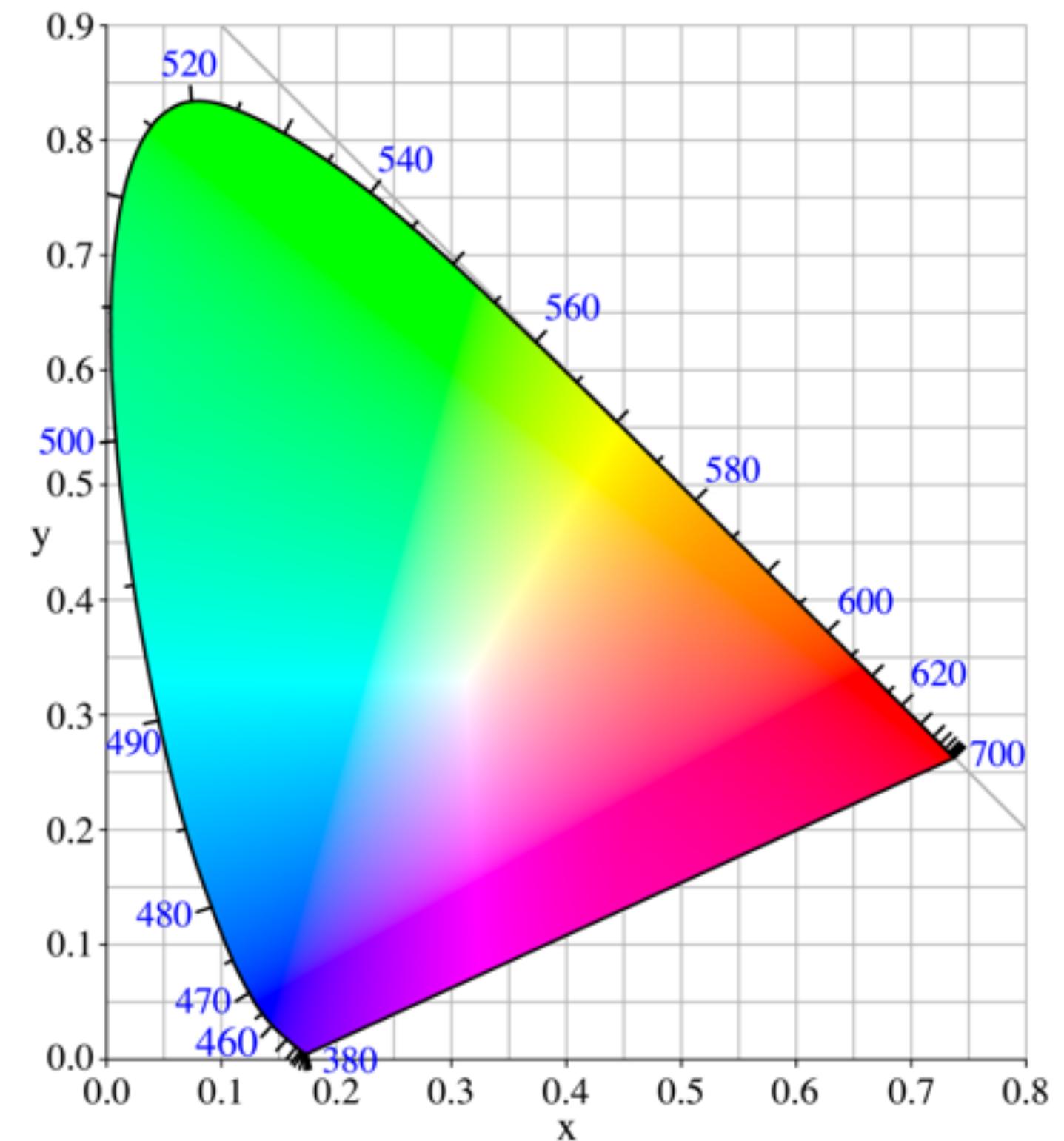
CMYK

Which raises a very important question:

**Which actual colors (i.e., spectra) do
these values get mapped to?**

CIE 1931* Color Space

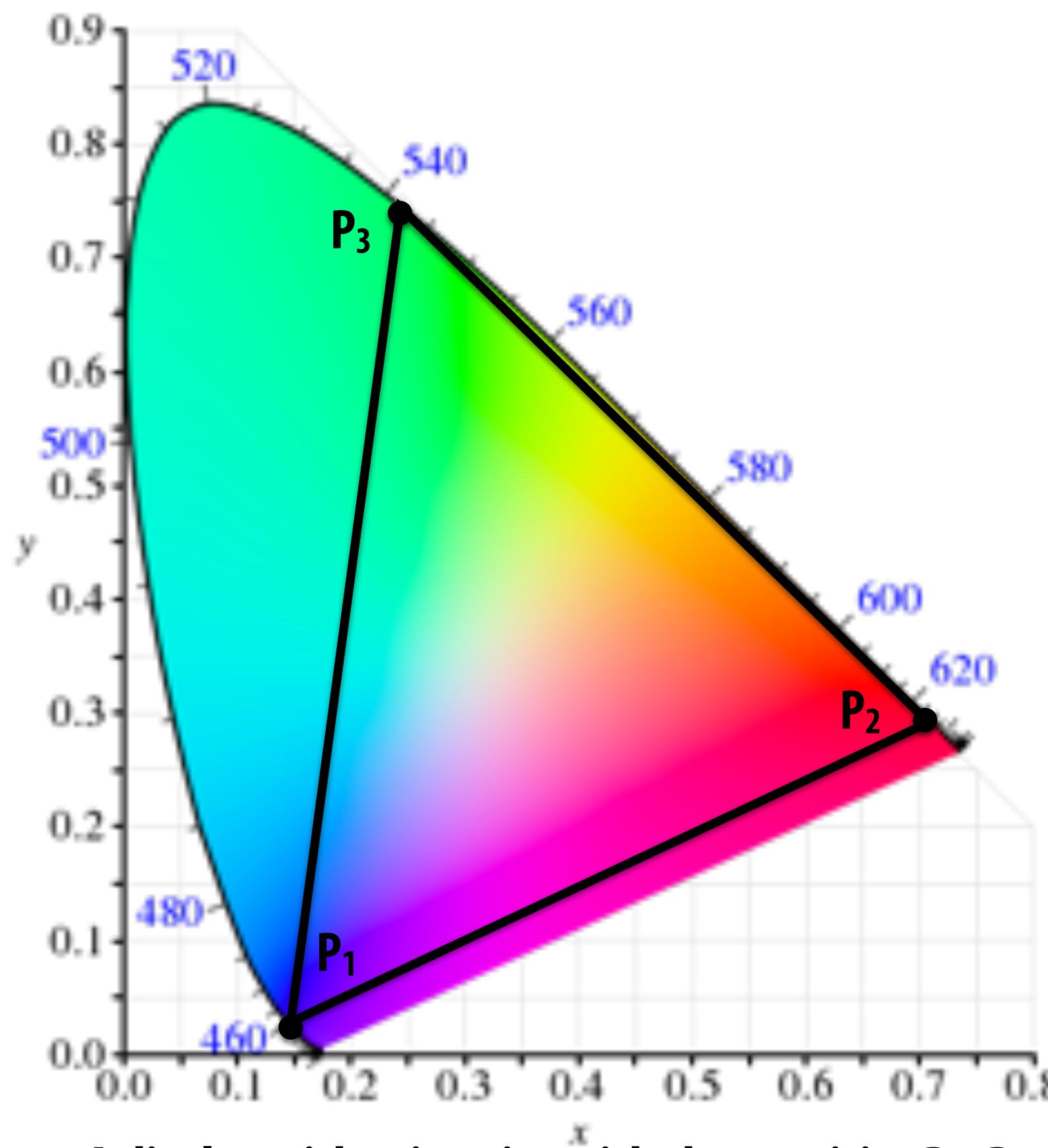
- Standard “reference” color space
- Encompasses all colors visible by “most” human observers
 - associated color model (XYZ) captures perceptual effects
 - e.g., perception of color (“chromaticity”) changes w/ brightness (“luminosity”)
 - different from specifying direct simulation of cones (SML)



*CIE 1931 does not mean anything important: “created in 1931 by the Commission Internationale de l’Éclairage”

Chromaticity Diagrams

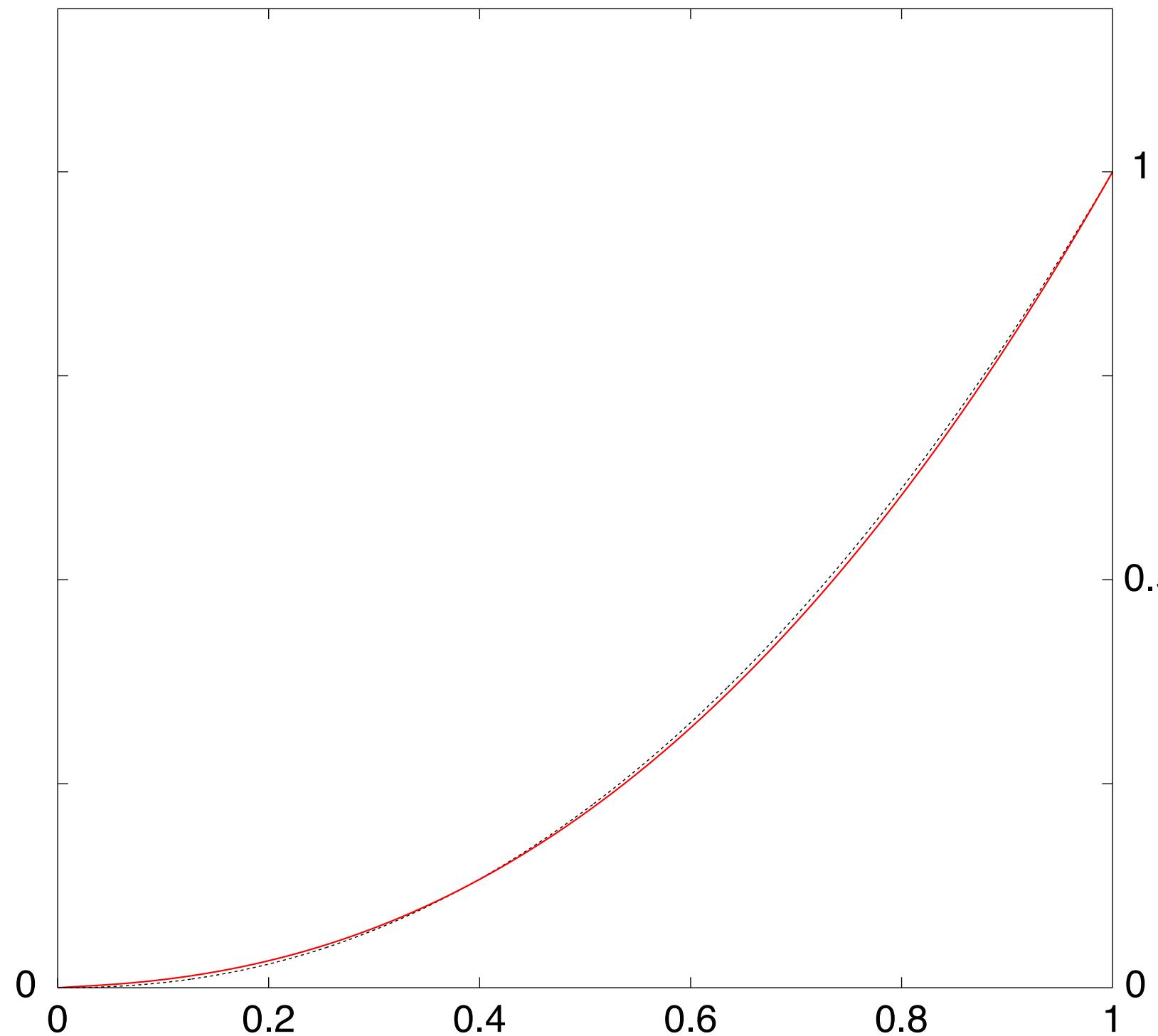
- Chromaticity is the intensity-independent component of a color
- Chromaticity diagram used to visualize extent of a color space



A display with primaries with chromacities P_1 , P_2 , P_3
can create colors that are combinations of these
primaries (colors that fall within the triangle)

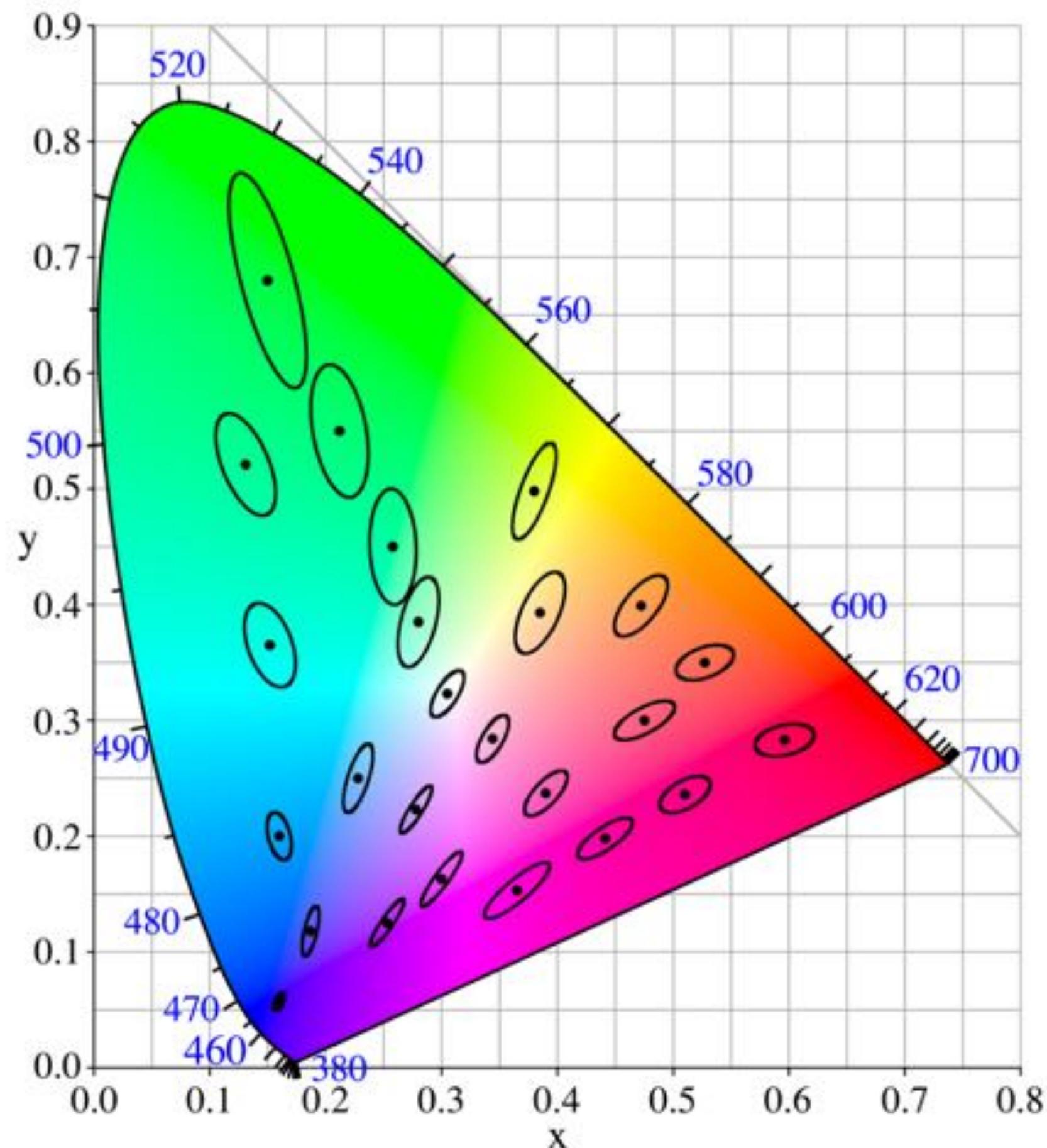
sRGB Color Space

- CIE 1934 captured all possible human-visible colors
- sRGB (roughly) subset of colors available on displays, printers, ...
- Nonlinear relationship between stored RGB values & intensity
 - Makes better use of limited set of numerical values



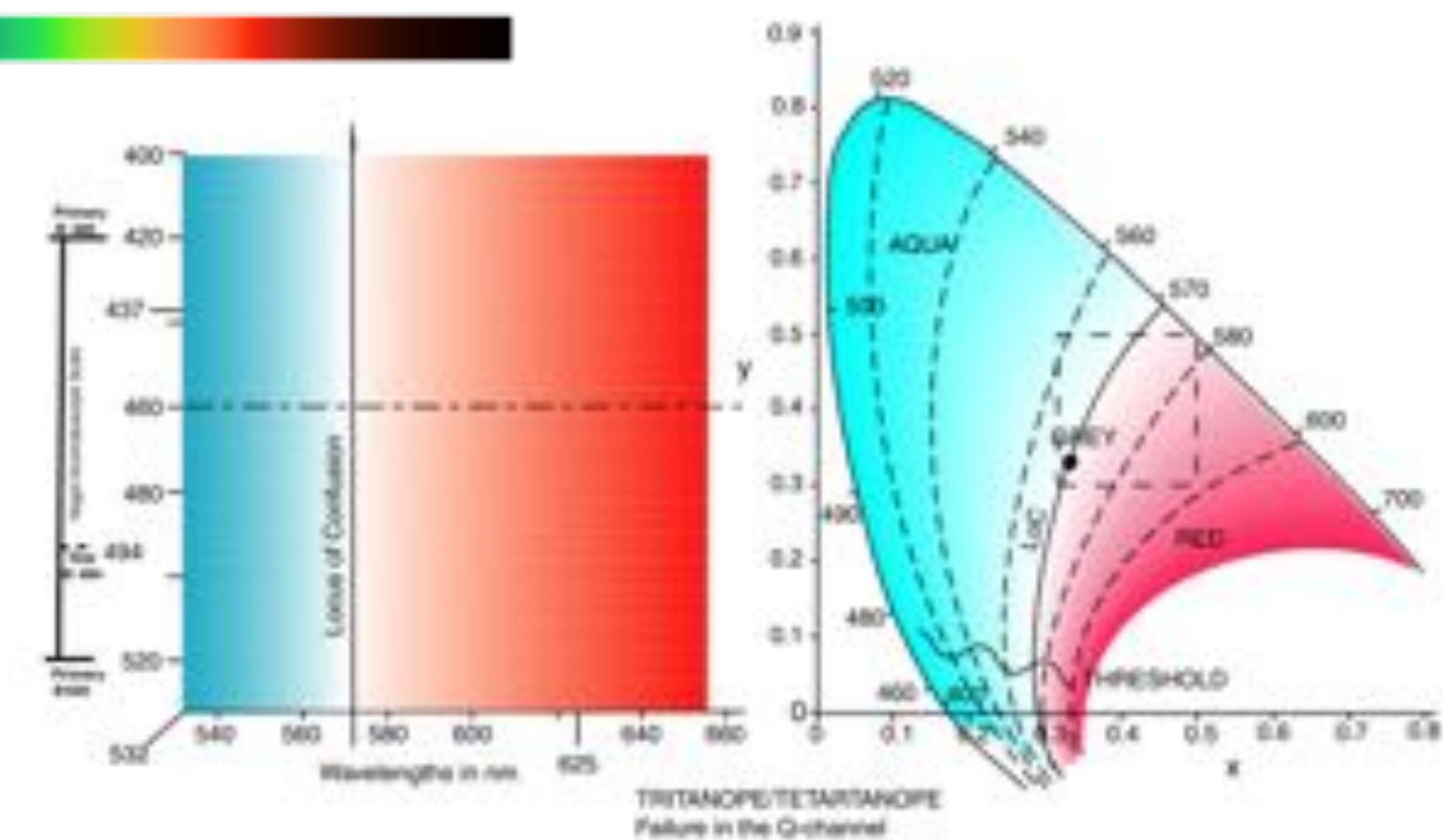
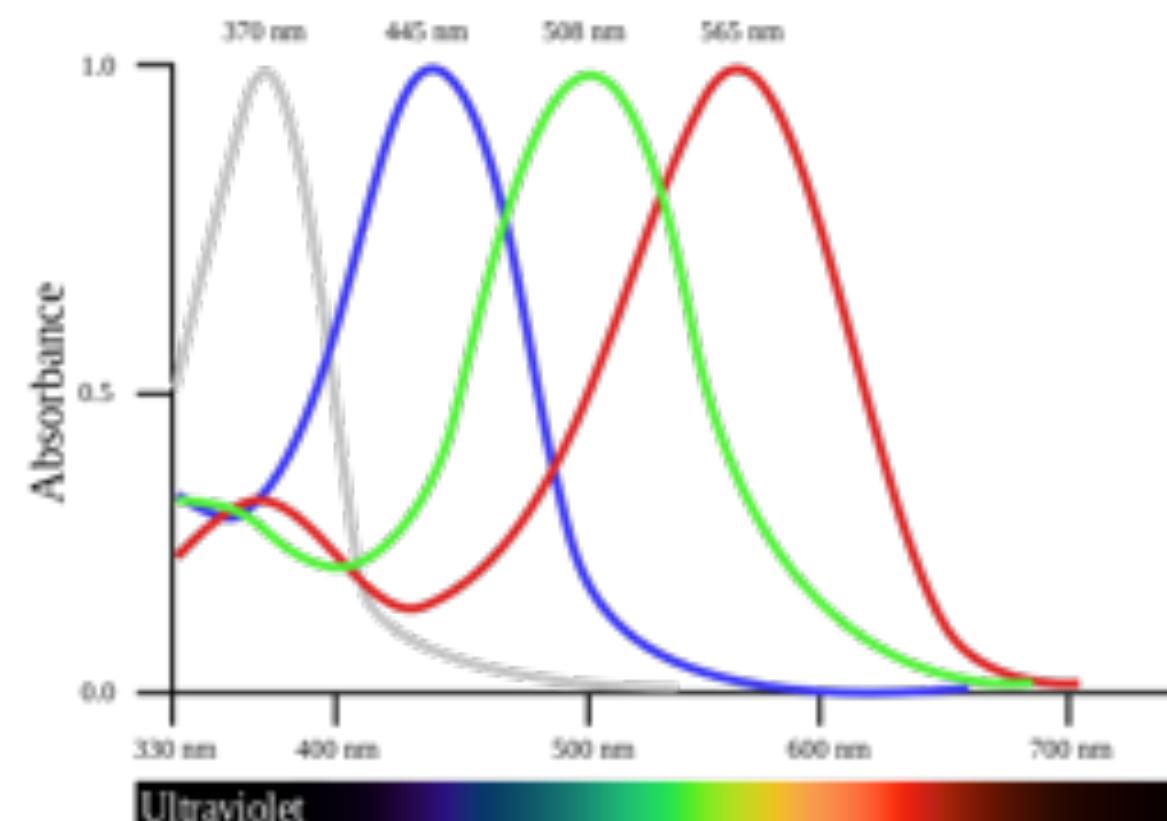
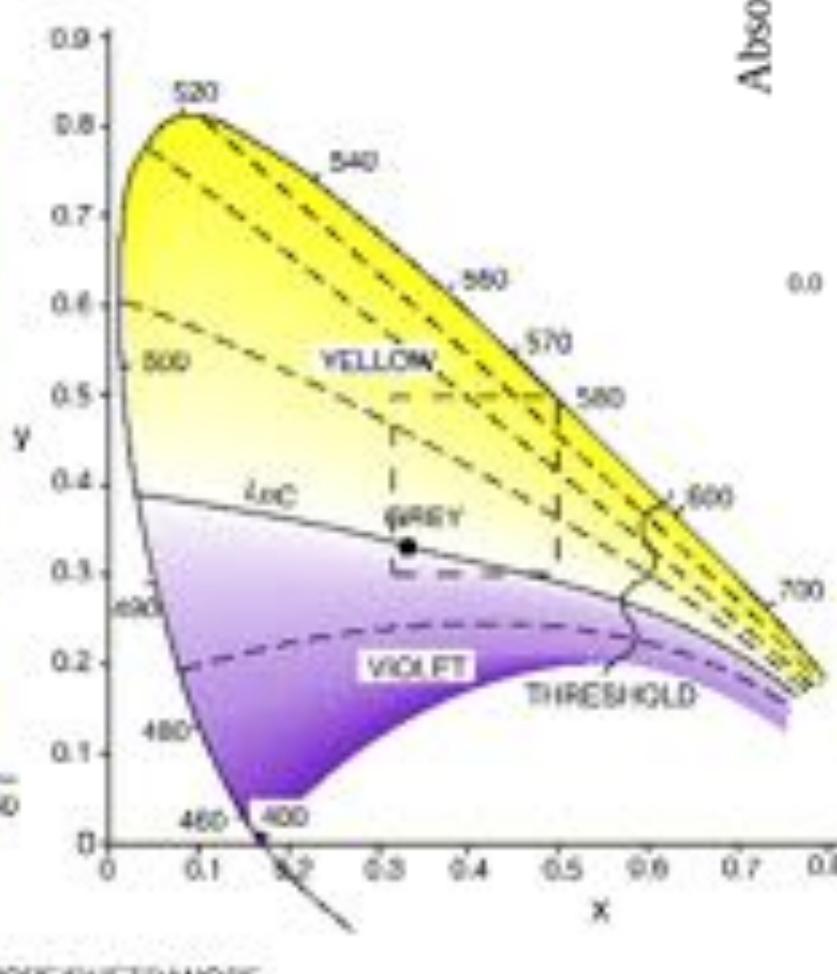
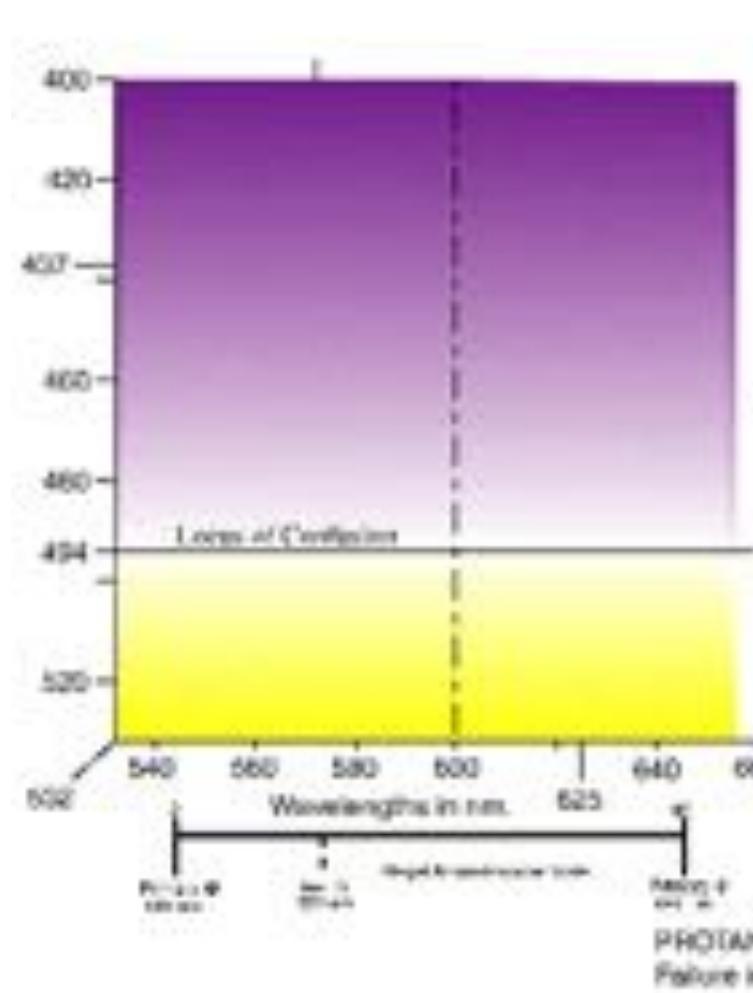
Color Acuity (MacAdam Ellipse)

- In addition to range of colors visible, one might be interested in how sensitive people are to changes in color
- Each ellipse corresponds to a region of “just noticeable differences” of color (chromaticity)
- So, if you want to make two colors distinct, at bare minimum should avoid overlapping ellipses...



Nonstandard Color Vision

- Morphological differences in eye can cause people (& animals) to see different ranges of color (e.g., more/fewer cone types)
- Alternative chromaticity diagrams help visualize color gamut, useful for designing, e.g., widely-accessible interfaces



Color Conversion

- Given a color specified in one model/space (e.g., sRGB), try to find corresponding color in another model (e.g., CMYK)
- In a perfect world: want to match output spectrum
- Even matching perception of color would be terrific (metamers)
- In reality: may not always be possible!
 - Depends on the gamut of the output device
 - E.g., VR headset vs. inkjet printer
- Complicated task!
- Lots of standards & software
 - ICC Profiles



Gamma correction

(non-linear correction for CRT display)

Old CRT display:

1. Image contains value X
2. CRT display converts digital signal to an electron beam voltage $V(x)$ (linear relationship)
3. Electron beam voltage converted to light:
(non-linear relationship)

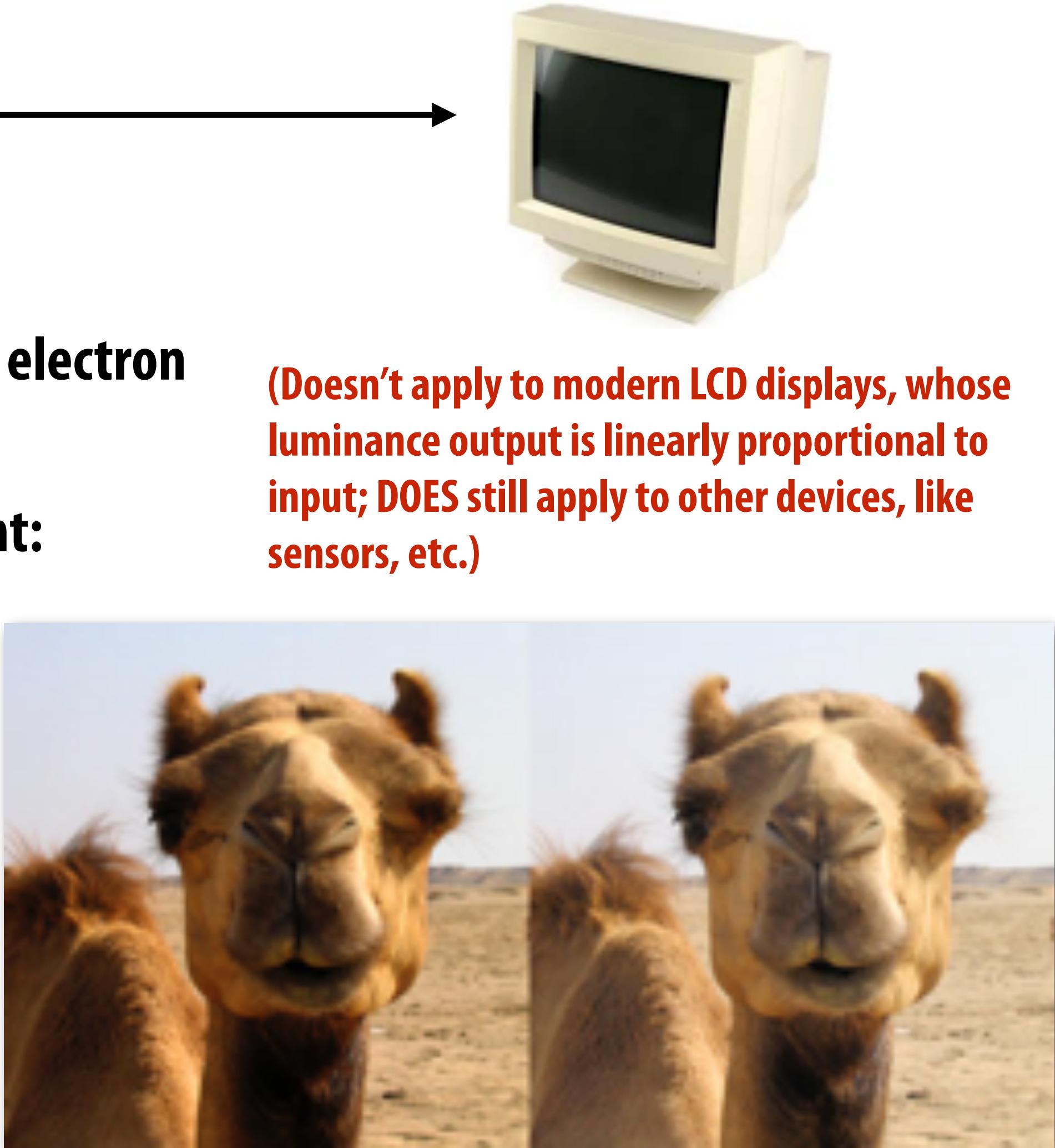
$$Y \propto V^\gamma$$

Where: $\gamma \approx 2.5$

So if pixels store Y, what will the display's output look like?

Fix: pixels sent to display must store:

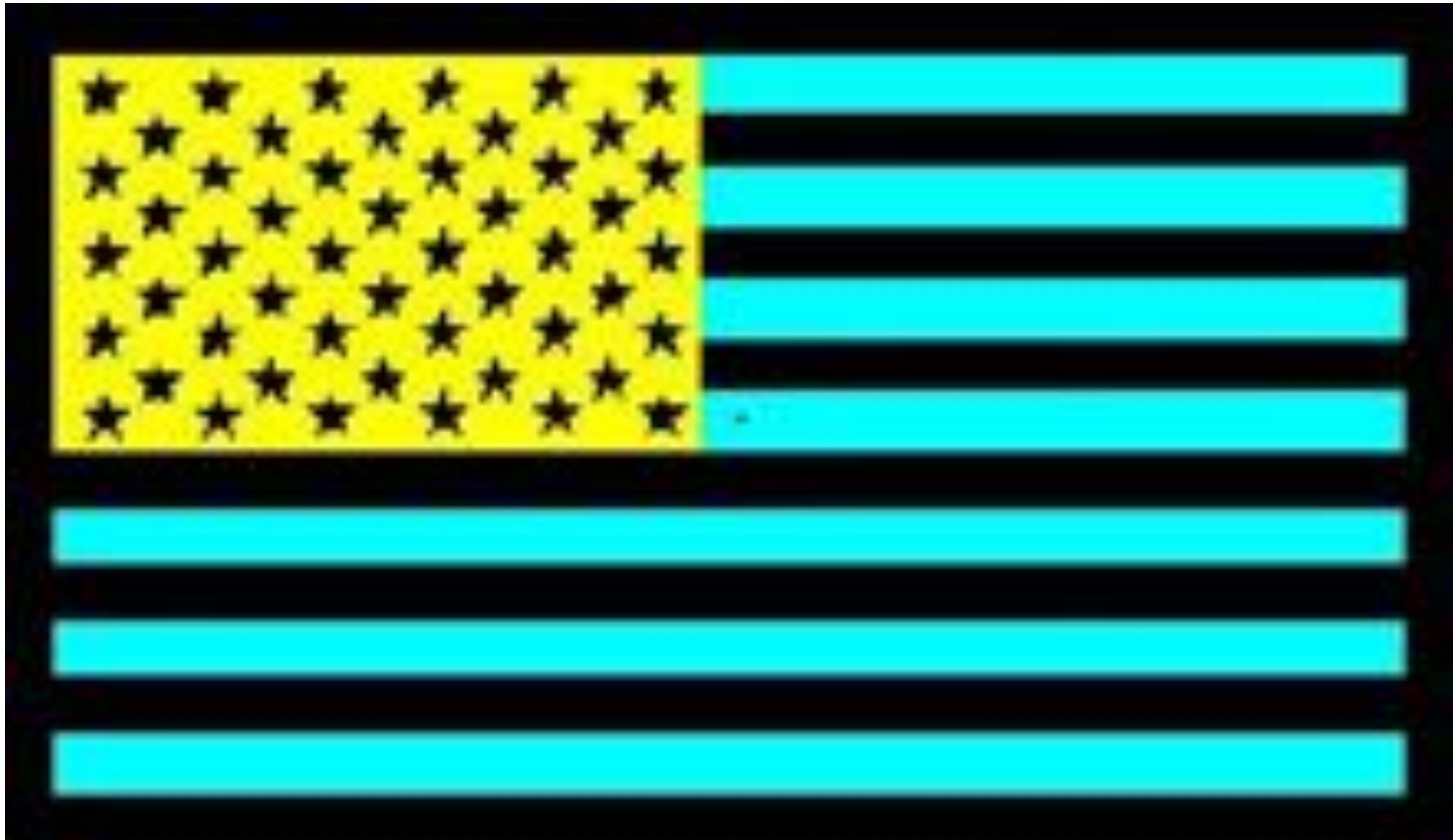
$$Y^{1/2.5} = Y^{0.4}$$



Observed
display output

Desired
display output

Human Perception—Accommodation Effect



Human Perception—A accommodation Effect

Next time...

- A whole spectrum of things to know about light & color
- In the next few lectures we'll talk more about
 - radiometry
 - cameras
 - scattering
 - ...

