

# Lecture 7: Color Sources & Color From Emission: Bioluminescence, Display, Lightning

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CSC 292/572, Fall 2022  
Mobile Visual Computing



# Logistics

Programming assignment 1 is up and is due Sept. 30 11:30 AM.

- Can work in groups of 2.

WA0 grades posted.

WA2/WA1 will be graded soon.

# The Roadmap

Theoretical Preliminaries

Human Visual Systems

**Color in Nature, Arts, Tech**  
(a.k.a., the birth, life, and death of light)

Digital Camera Imaging

Modeling and Rendering

Applications



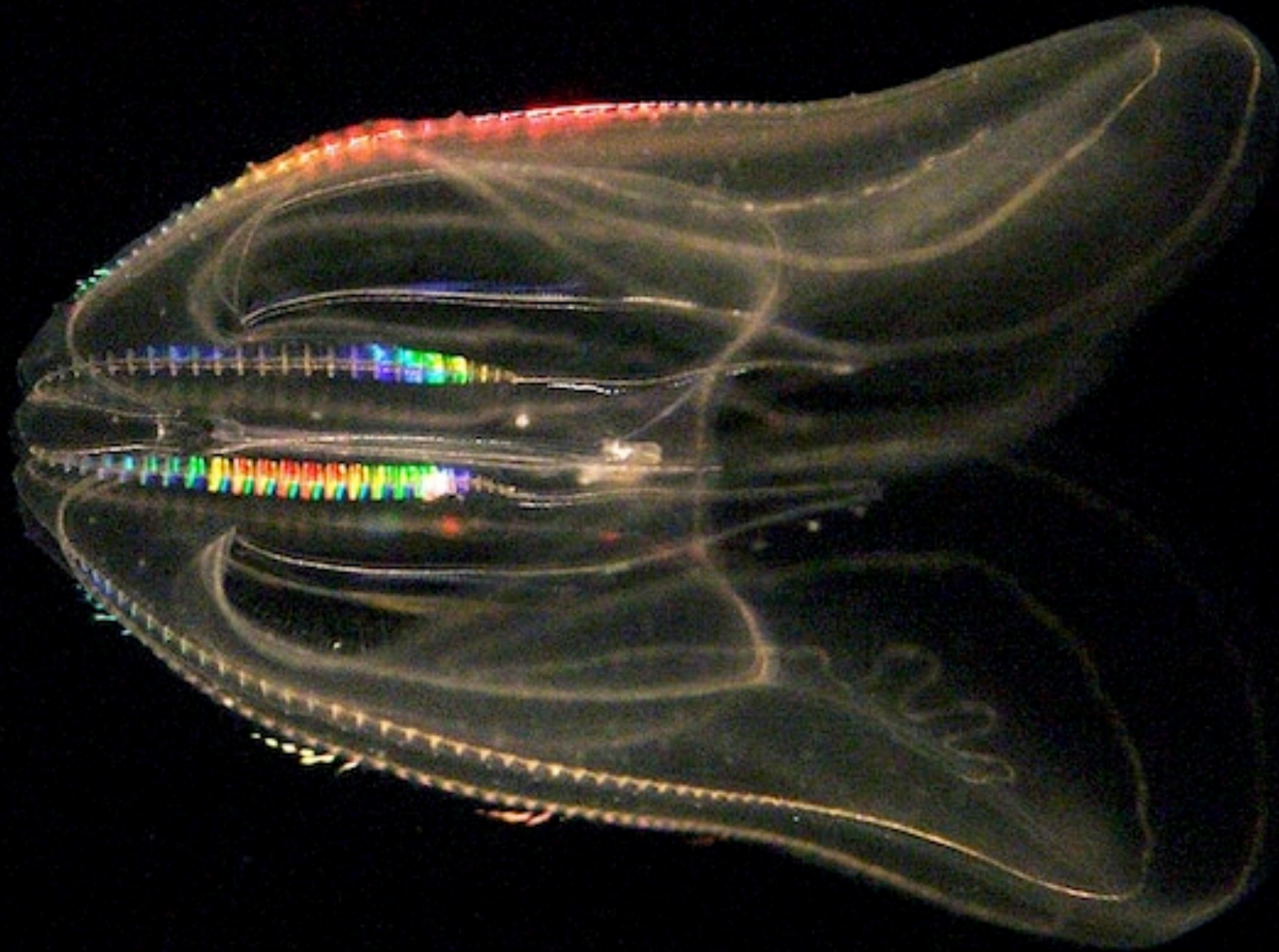
Color Source

Display and Lightning

Material Colors



# Bioluminescence





# Biofluorescence







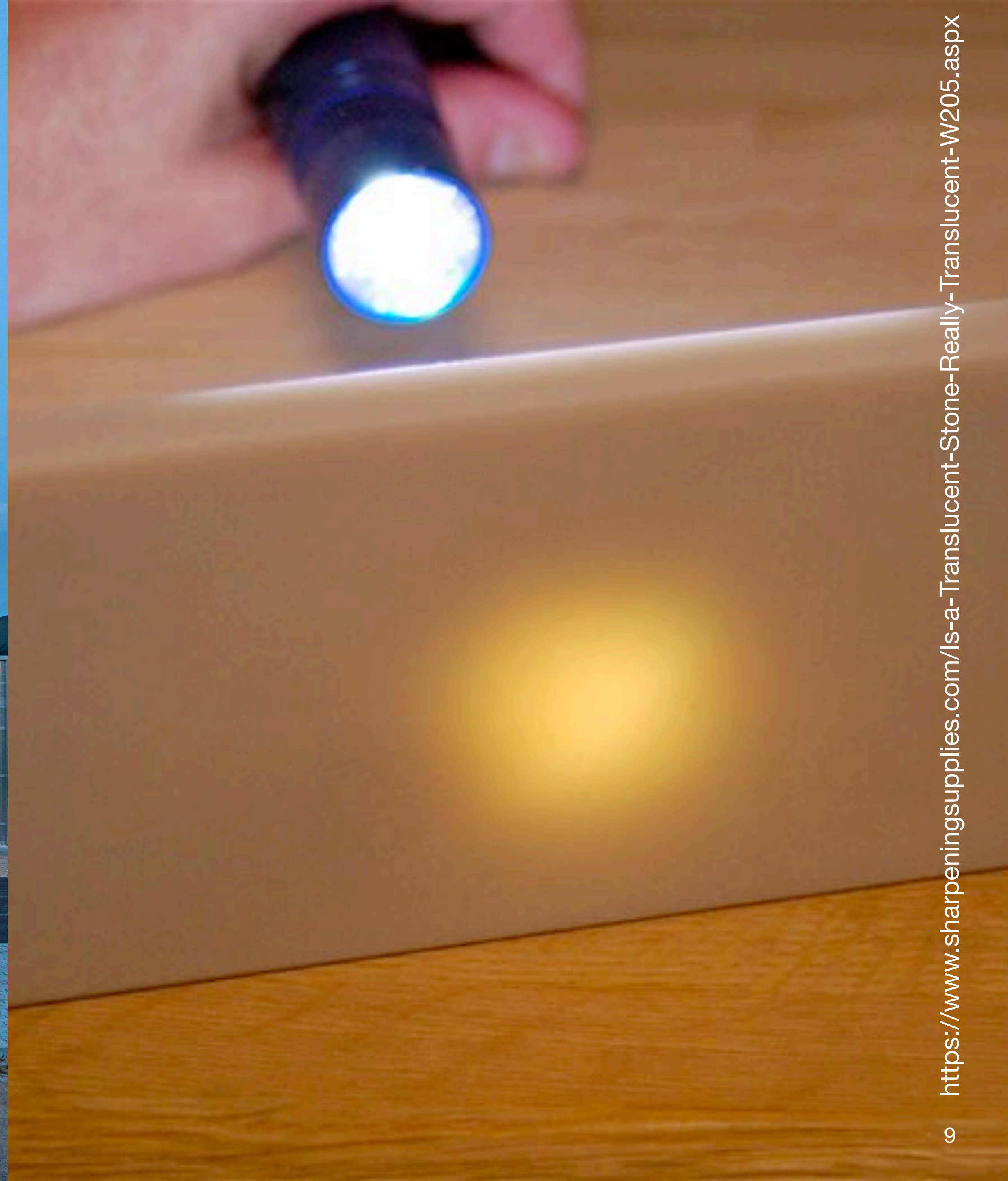














# Sources of Color

# Sources of Colors

Color comes from lights entering our eyes. Lights come either directly from light-emitting objects or from materials that interact and modify light that strikes them.

**Emission:** objects directly generate lights

Light-matter interaction: light interacting with matter and then leaves with a different spectrum than prior to the interaction

- **Absorption:** photons taken away from incident light
- **Scattering:** photons change direction (could also change wavelength)

# Sources of Colors

Emission, absorption, and scattering are all wavelength dependent. That's why things have color.

Reflection, refraction, diffusion, transmission are results of absorption and/or scattering. They are **macroscopic** abstractions, not fundamental forms of light-matter interactions.

**This lecture:** an overview of all sources + color from emission

**Next lecture:** color from absorption + scattering



# Color From Emission (An Incomplete List)

**Thermal radiation** (e.g.,  
Sun, tungsten lights)



**Bioluminescence**  
(e.g., Firefly)



**Electroluminescence**  
(e.g., Displays)





# Thermal Radiation

Everything radiates. You are radiating right now.

Radiation spectrum depends on temperature. An adult with a surface area of  $2\text{m}^2$  and a body temperature of  $33^\circ\text{C}$  emits about 1000 Watt of power.

- You are also absorbing the same amount of power.
- In equilibrium, how much you absorb is exactly the same as how much you emit at each wavelength.

Emission spectrum is very broad.

- So radiation is inefficient way to create specific colors.

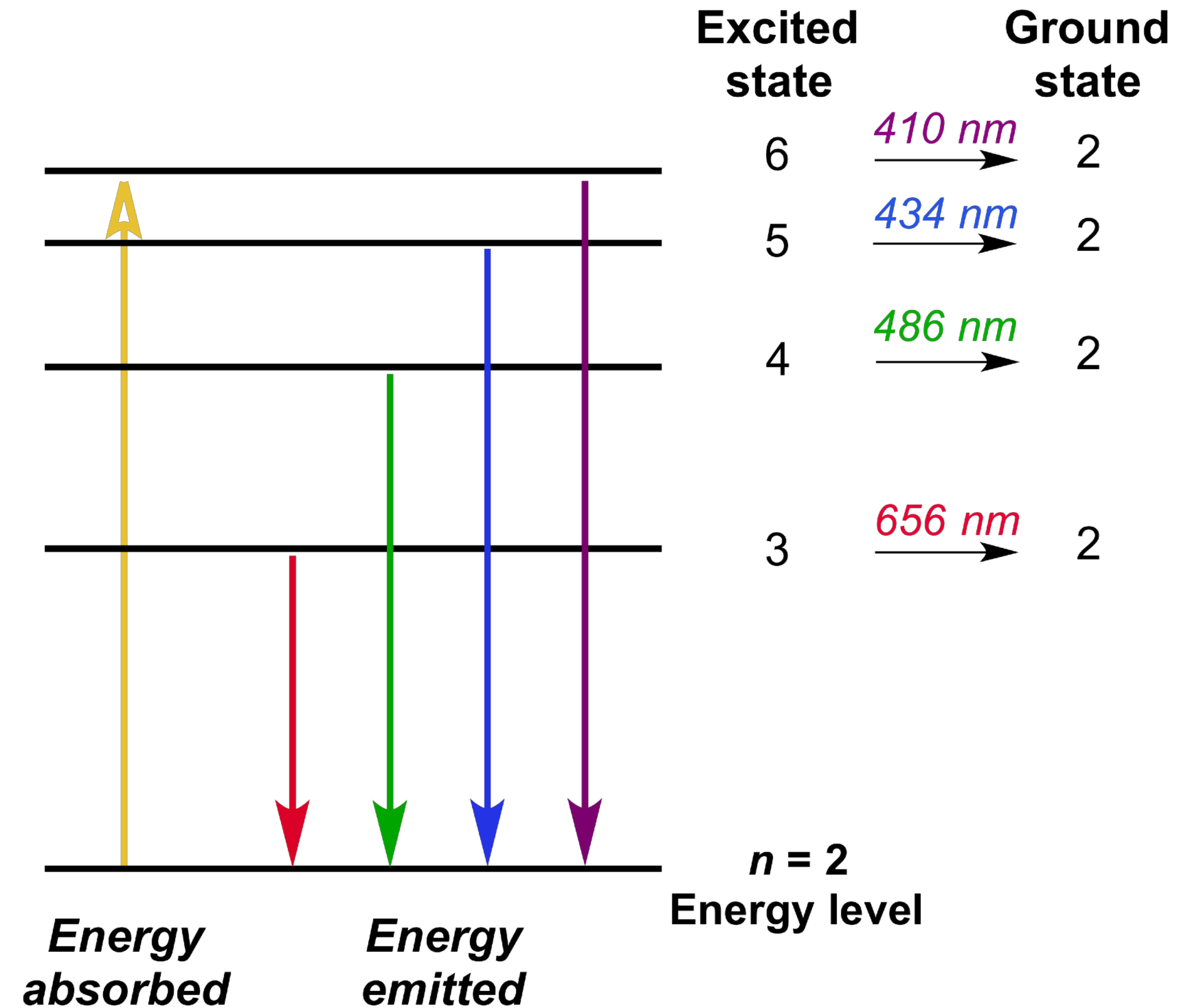
# Bioluminescence

Electron in atoms absorbs energy and its energy state gets increased. Shortly, the energy state drops back to the ground level, emitting a photon.

- The initial energy bump (excitation) comes from a chemical reaction.

Very common in ocean

- 80% of the bioluminescent animals are marine.
- 90% of oceanic life emits lights.



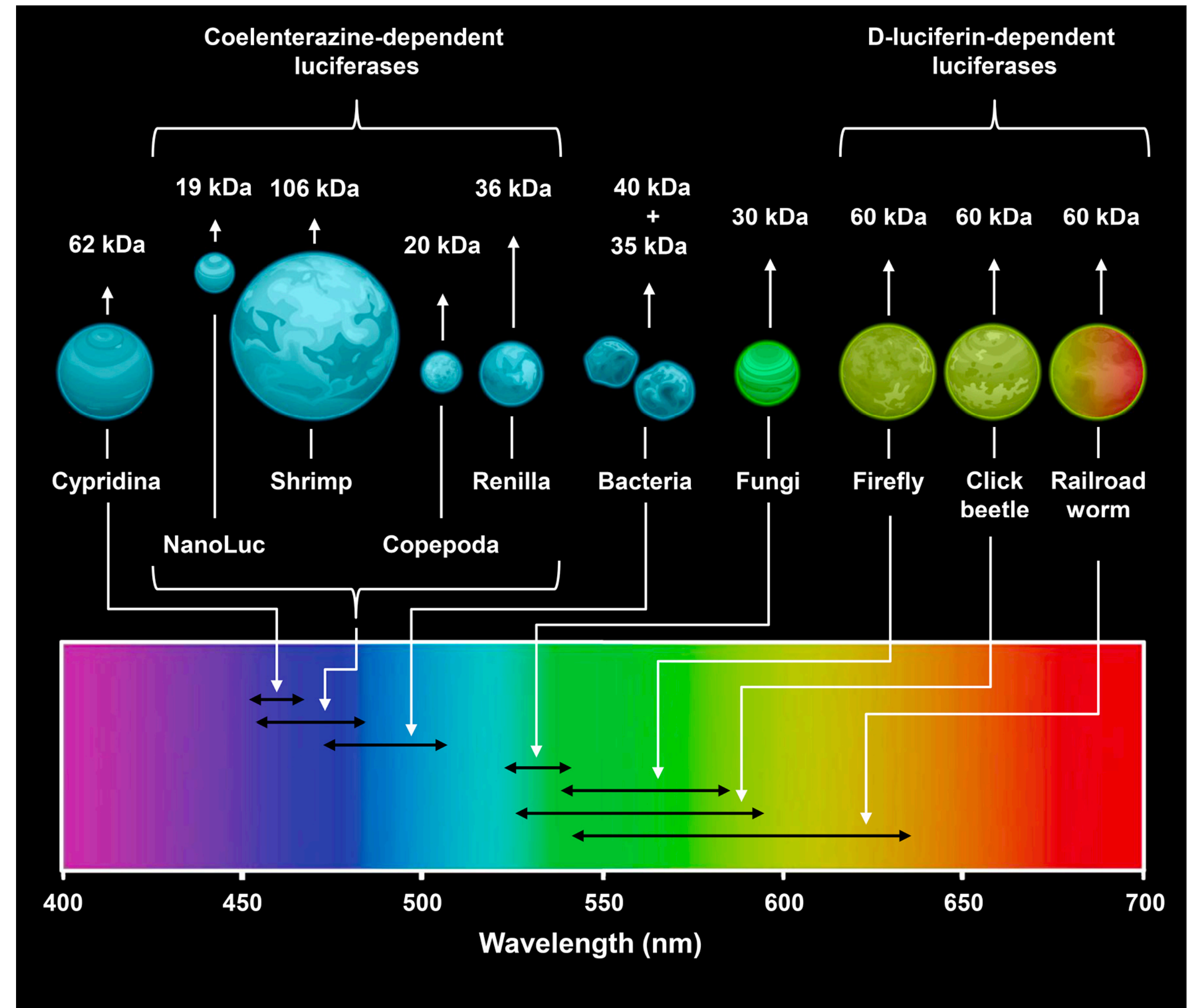
# Bioluminescence

Very weak in power.

- $10^3 - 10^{12}$  photons/s. Assuming 500 nm wavelength  $\Rightarrow 10^{-16} - 10^{-7}$  Watt.

The emission spectra are mostly in the visible range.

- Peak  $\sim 480\text{nm}$ , width  $\sim 80\text{nm}$ .
- C.f., black-body radiation spectrum range much wider; includes UV.
- Imagine bioluminescence spectra are like thermal radiation...



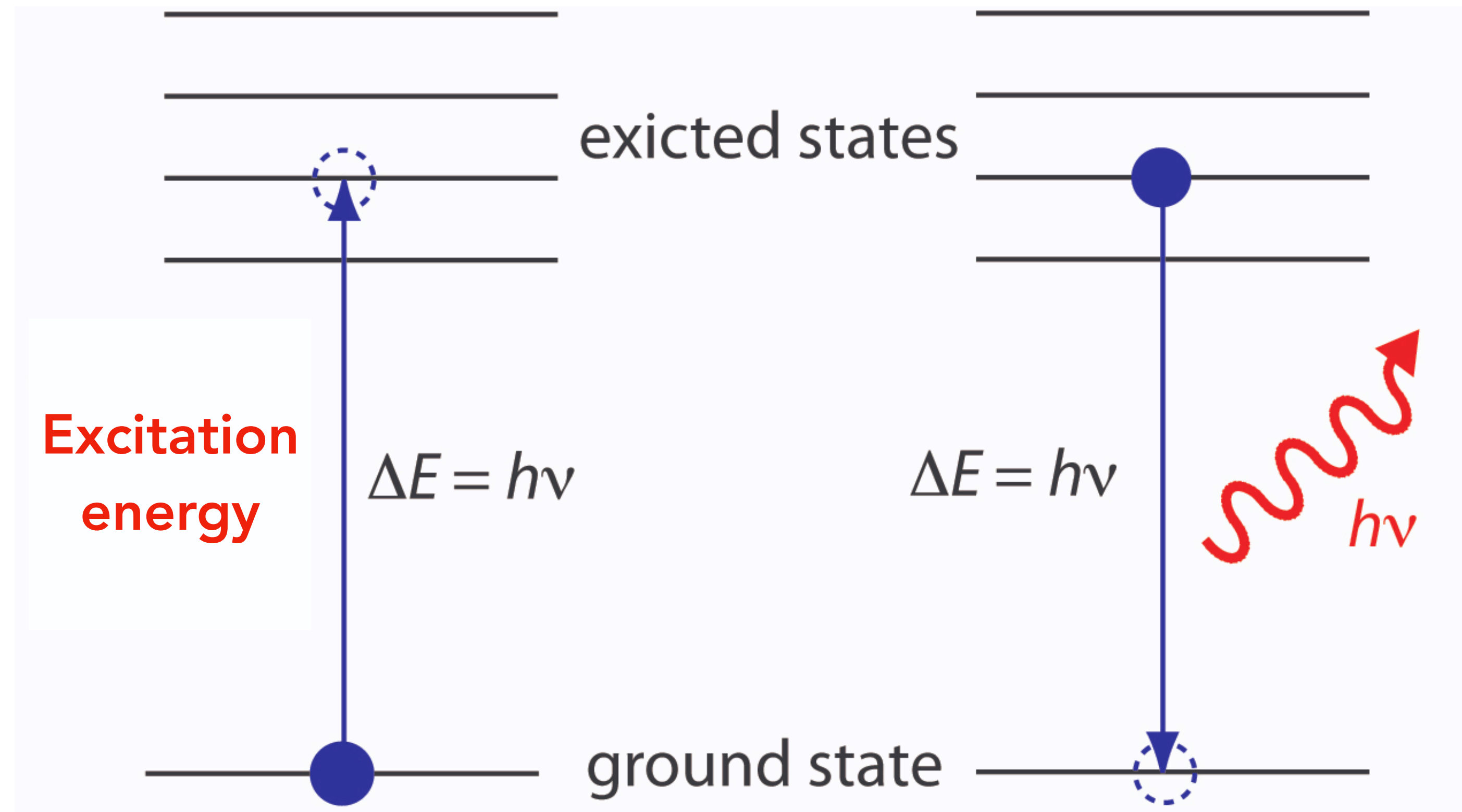
# Luminescence

## Bioluminescence:

- Excitation = chemical reaction

## Electroluminescence:

- Excitation = External current
- Displays operate based on this. More later.





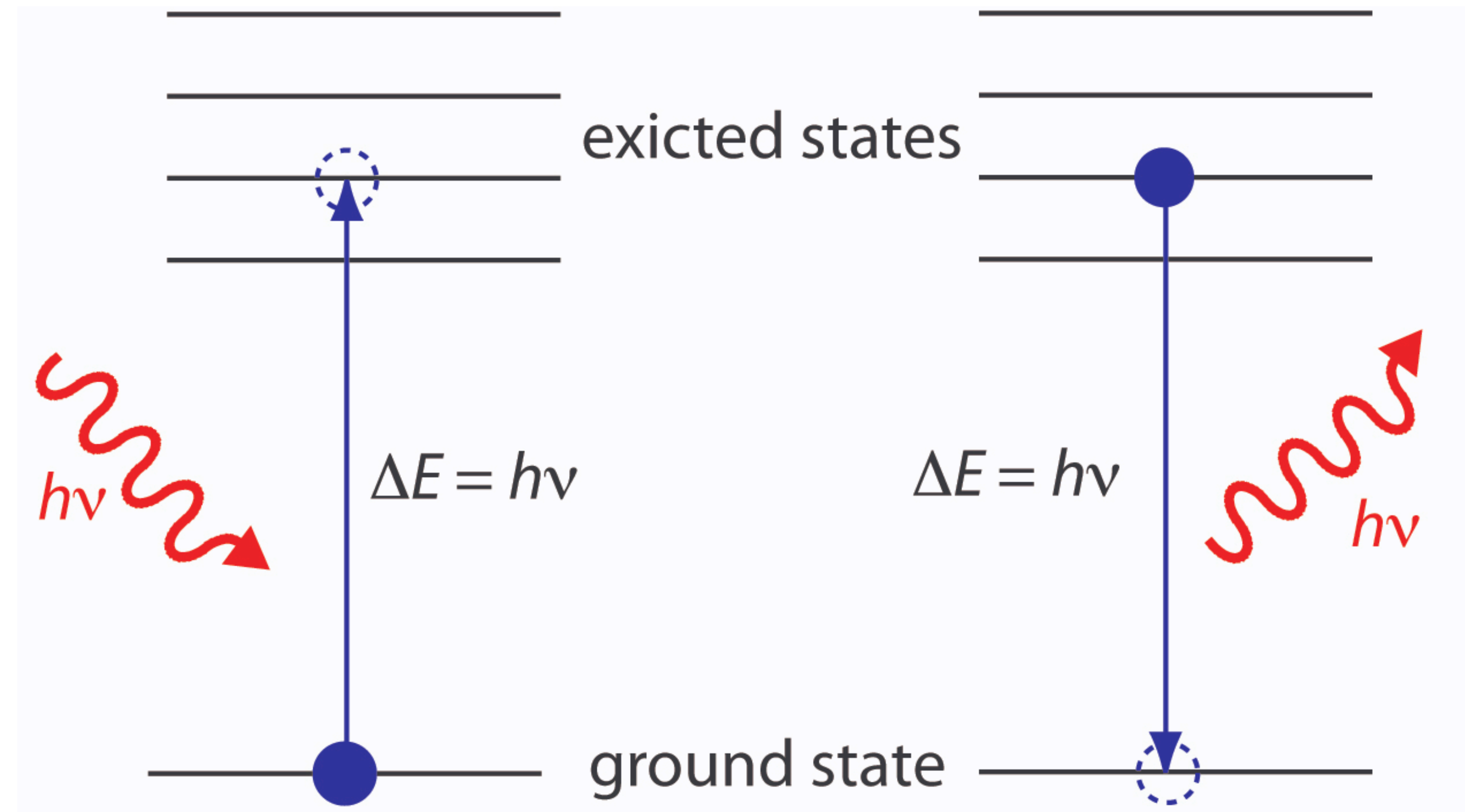
# Absorption and Scattering

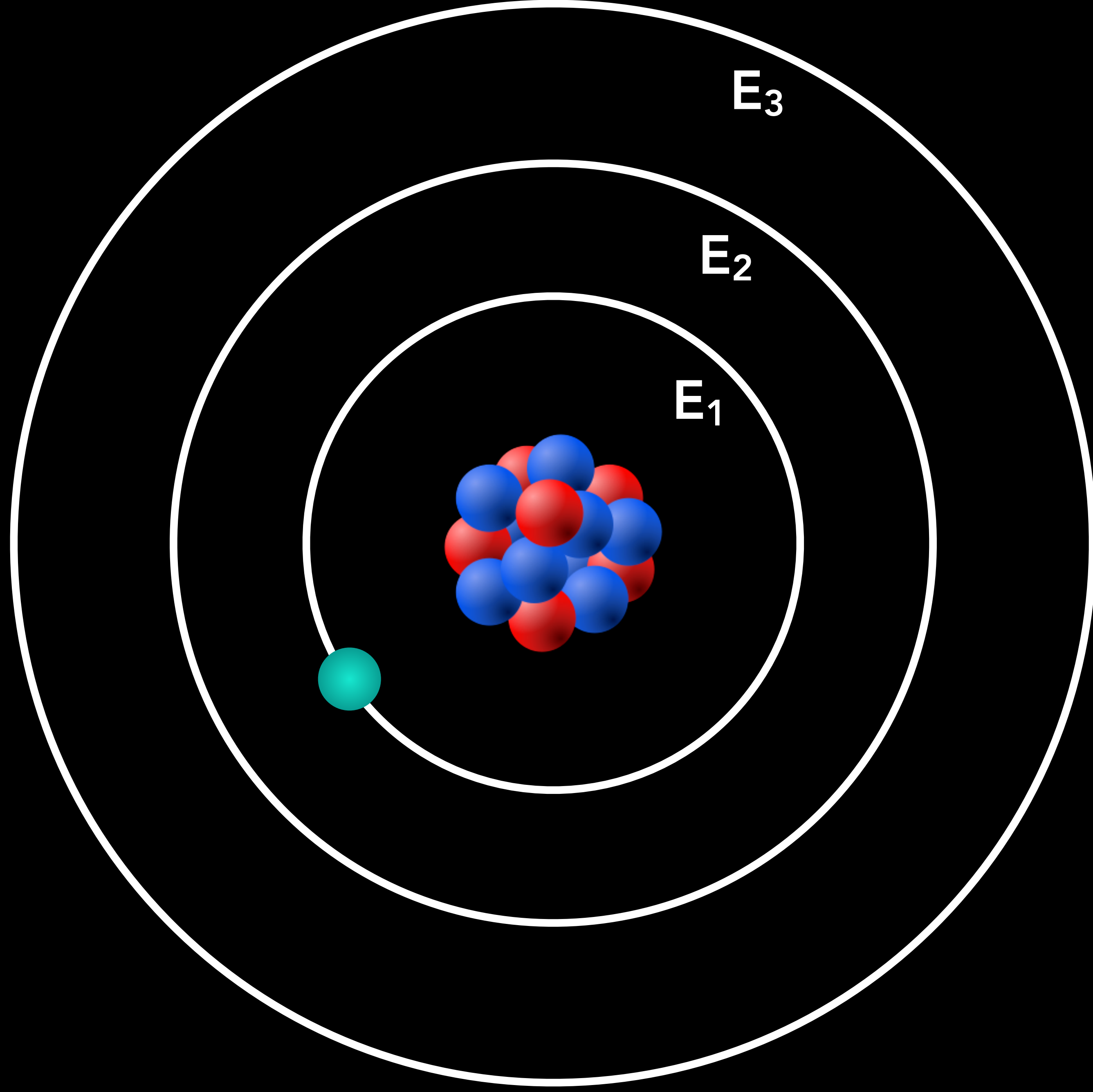
## Absorption:

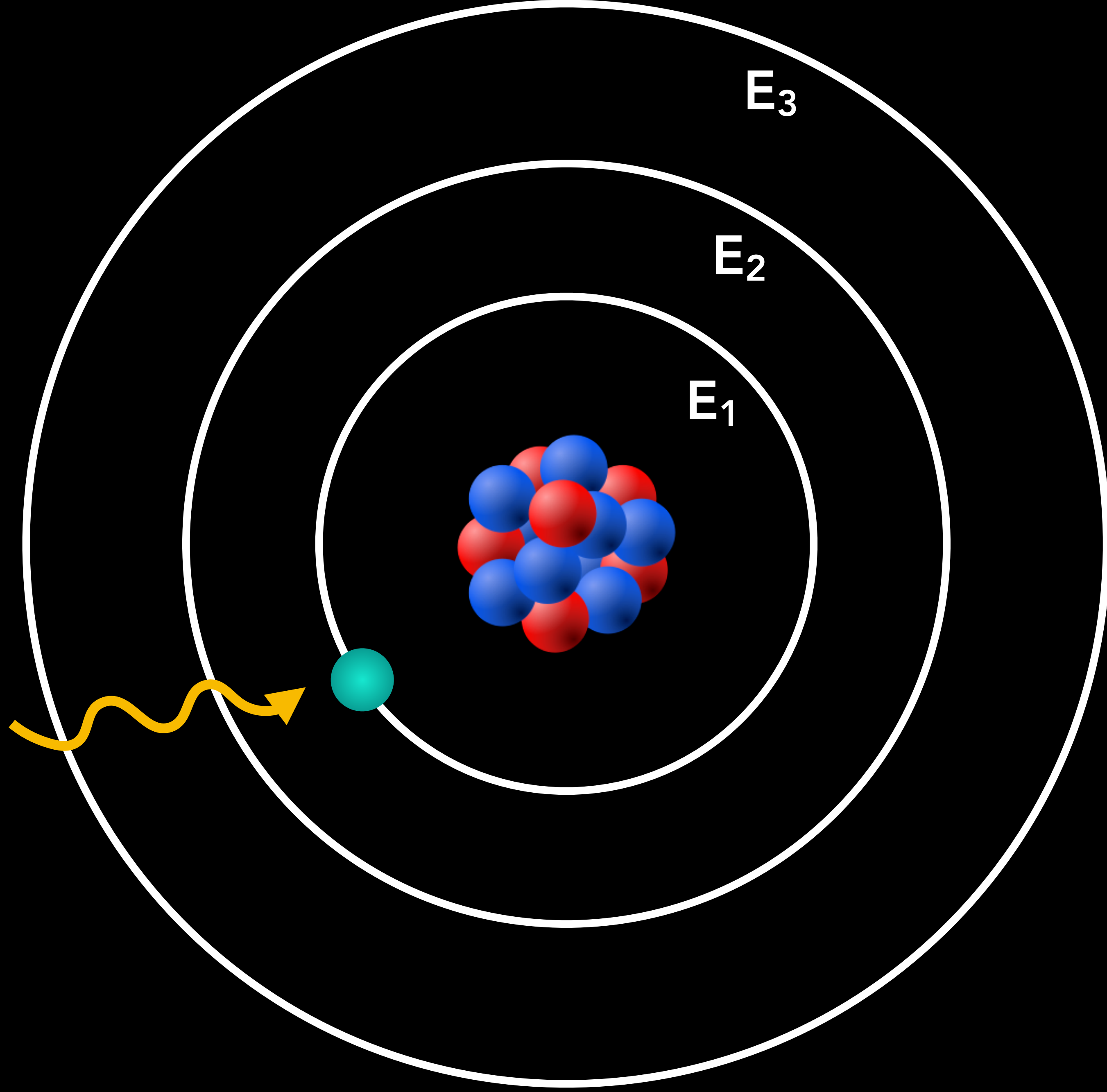
- Excitation energy = another photon
- No photon emission

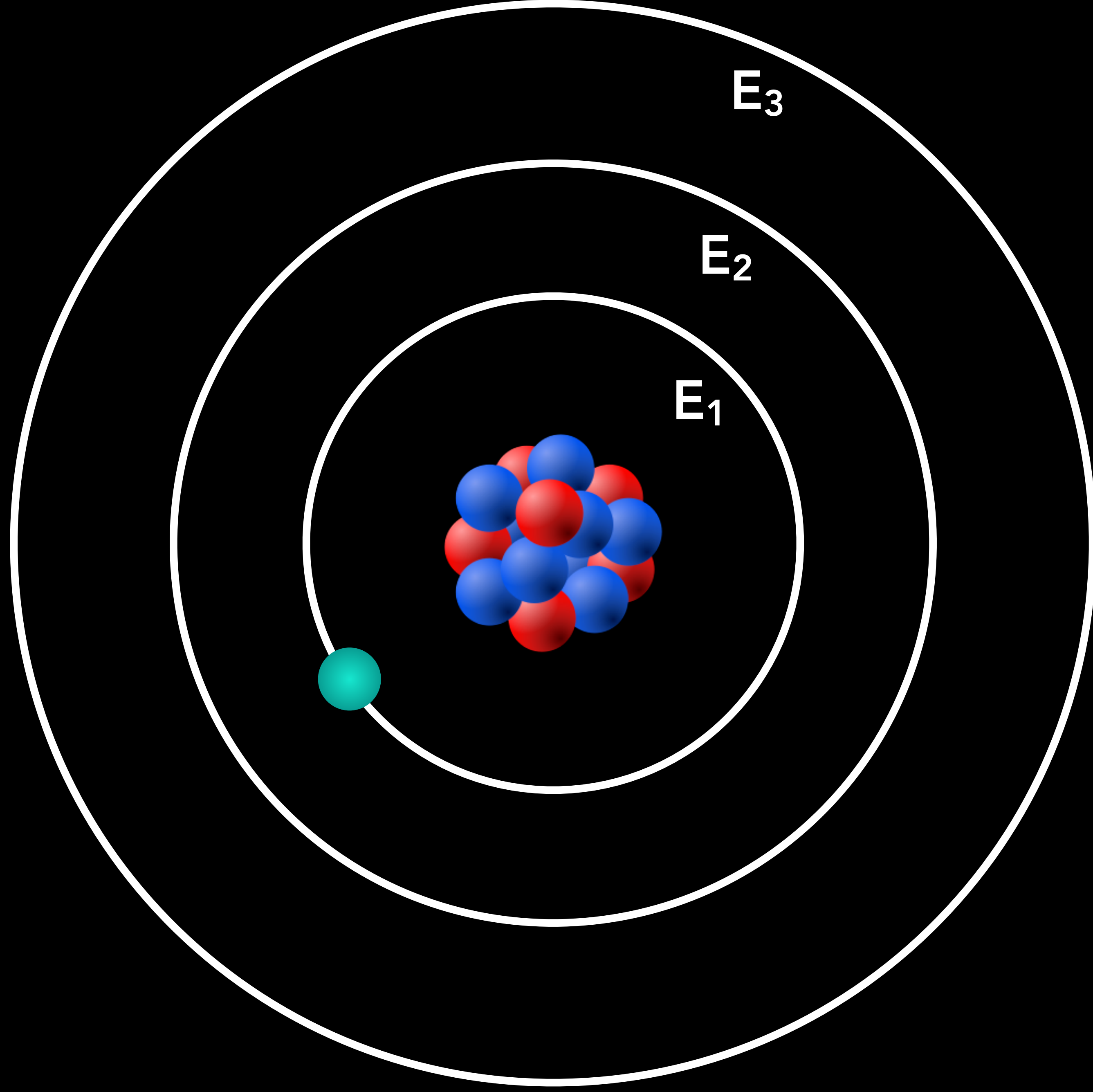
## Scattering:

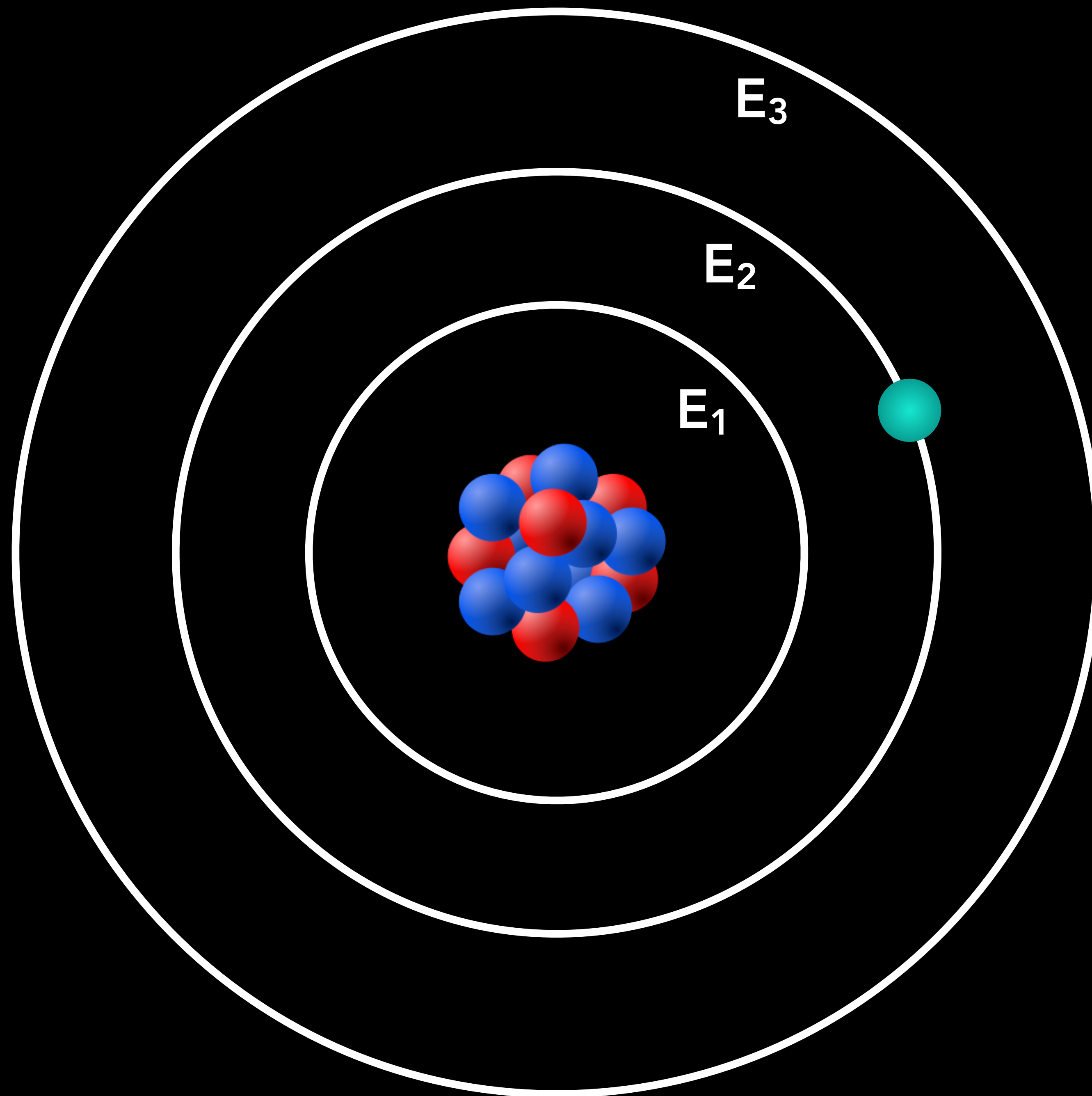
- Excitation energy = another photon
- Emits another photon

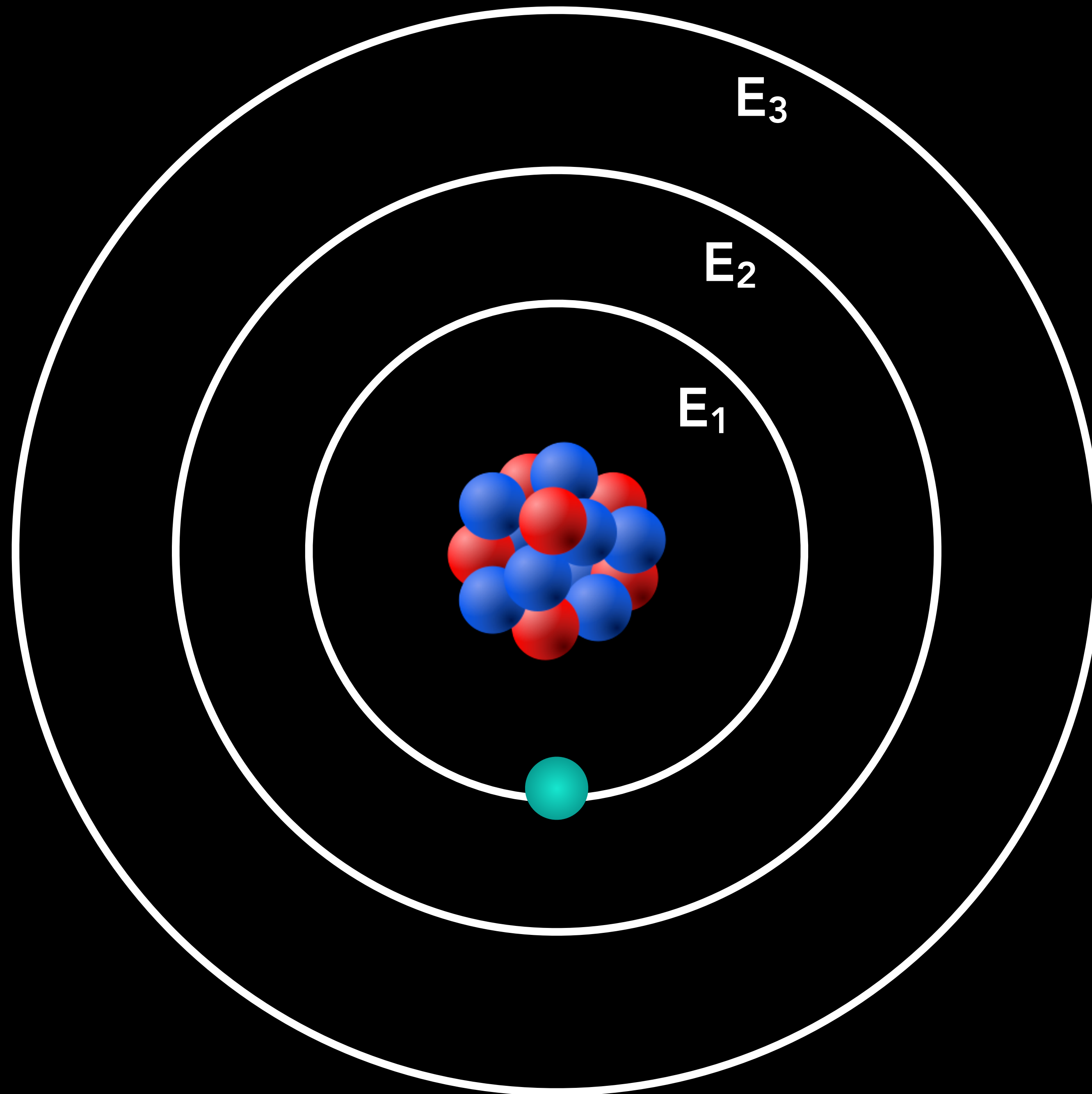


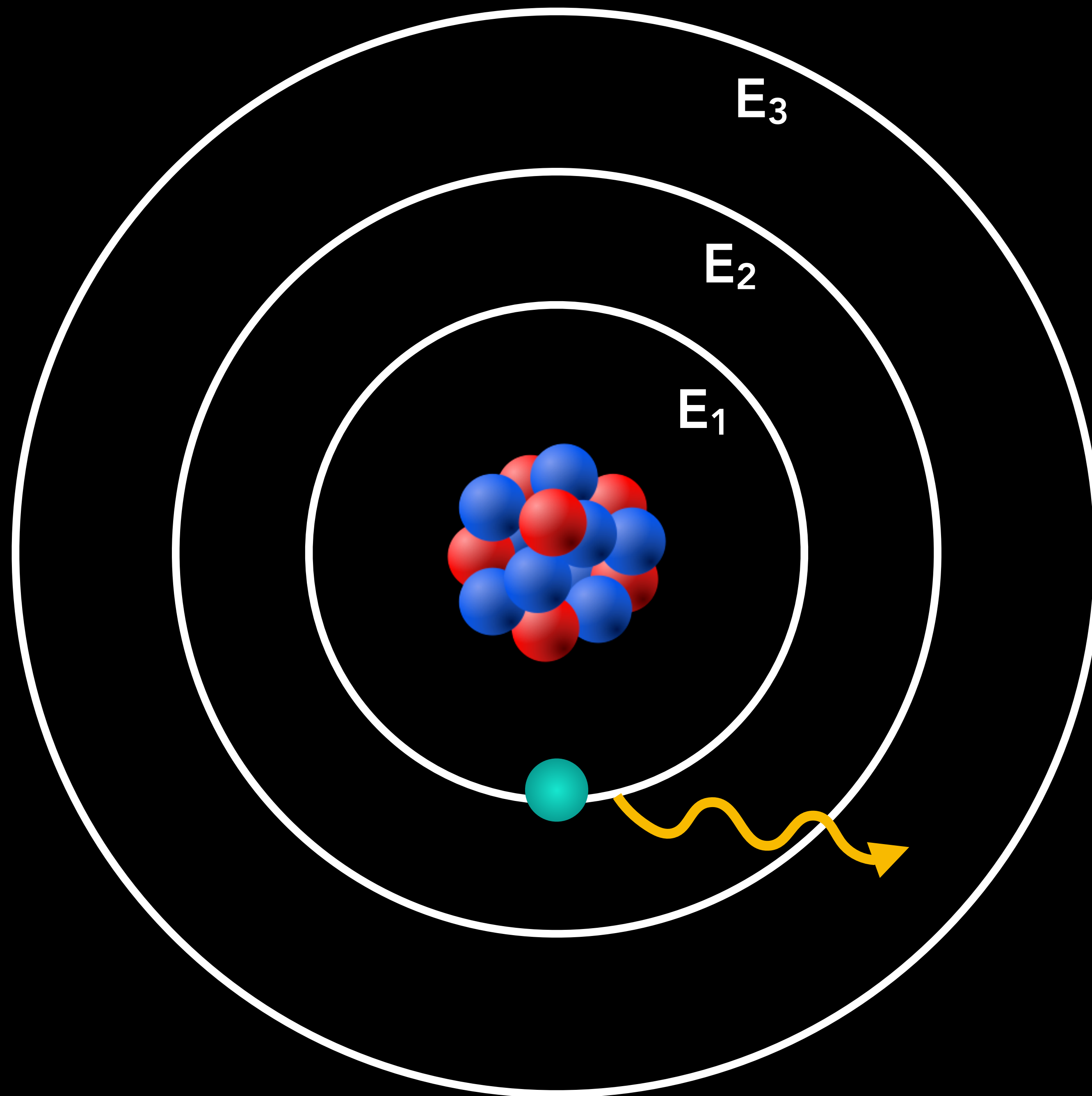










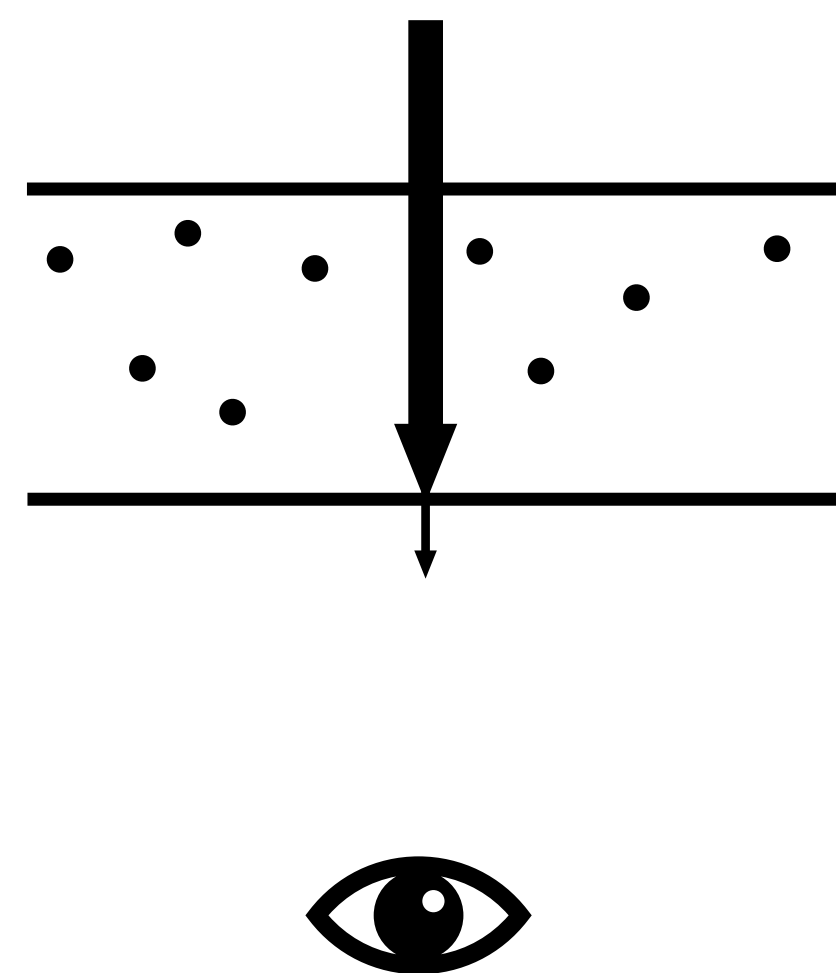


**Scattering is the result of an electron picking up a photon,  
“scratching its head”, and then emitting a new photon.**  
— Richard Feynman

\* The new photon might not have the same energy as the absorbed photon, and the emission can be to any direction. More next lecture.



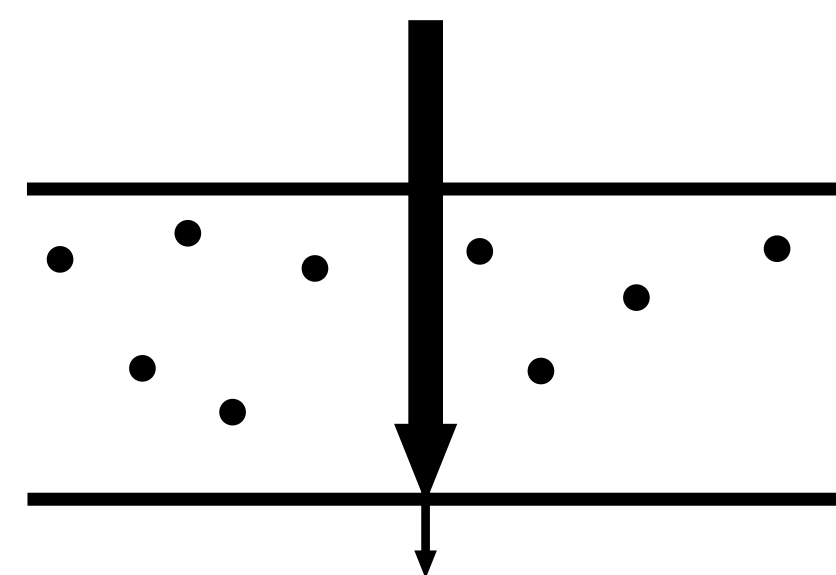
# Pure Absorption: **Transparent**



Some lights are absorbed, but the rest transmits through in one direction.

Absorption (transmission) is wavelength dependent, so the medium looks colored, but we can still "see through" it.

# Pure Absorption: **Transparent**

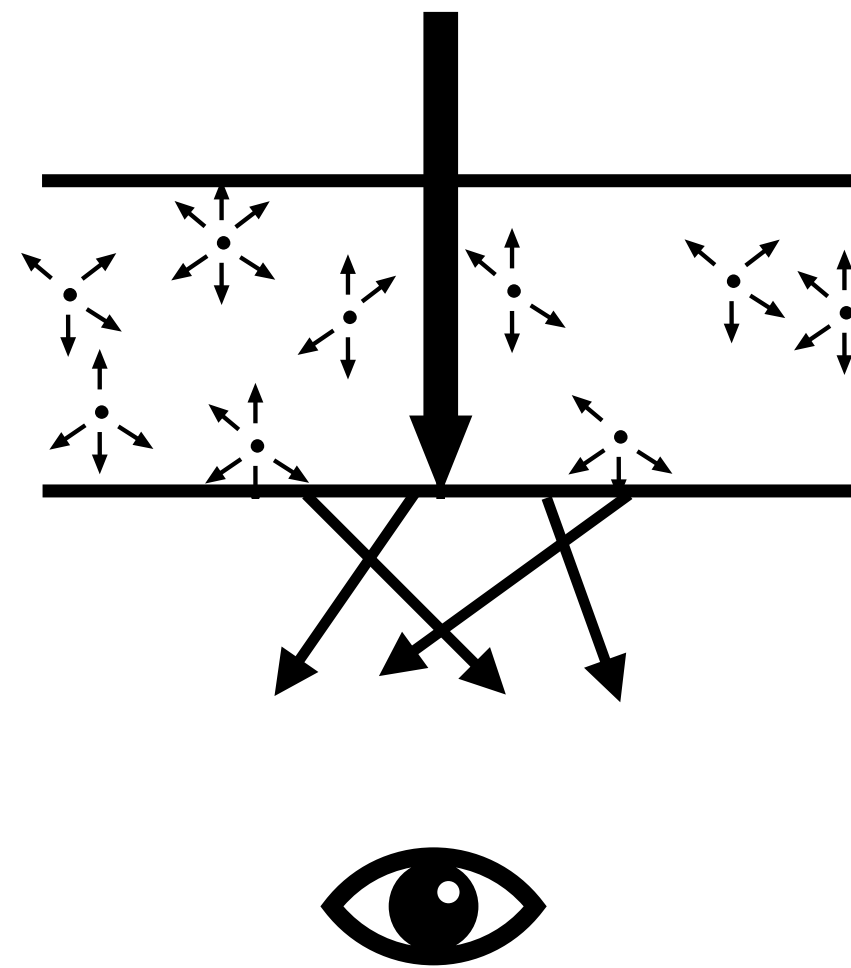


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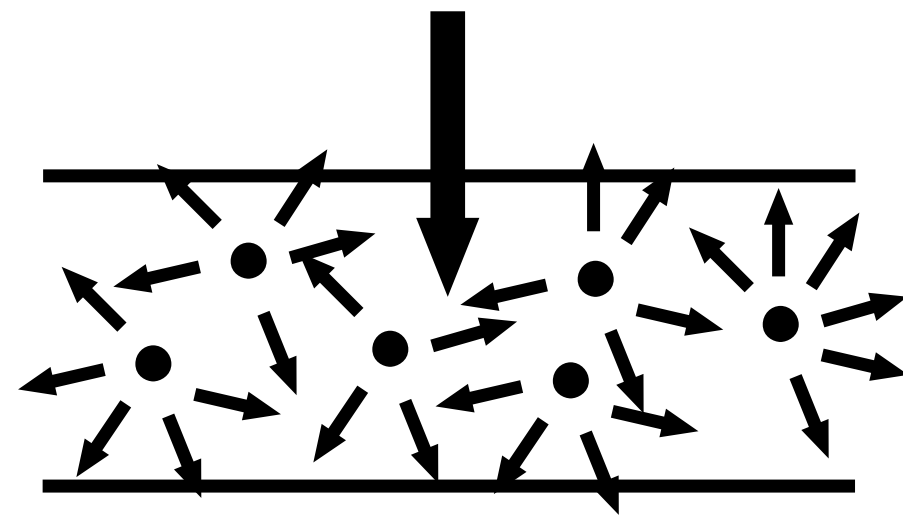
# A Little Scattering + Absorption: **Translucent**



Particles in the medium scatter lights (along with absorption). Some lights still go through but have changed directions.

We can still see light transmitted through (with color) but can't "see through" the medium.

# A Lots of Scattering + Absorption: **Opaque**

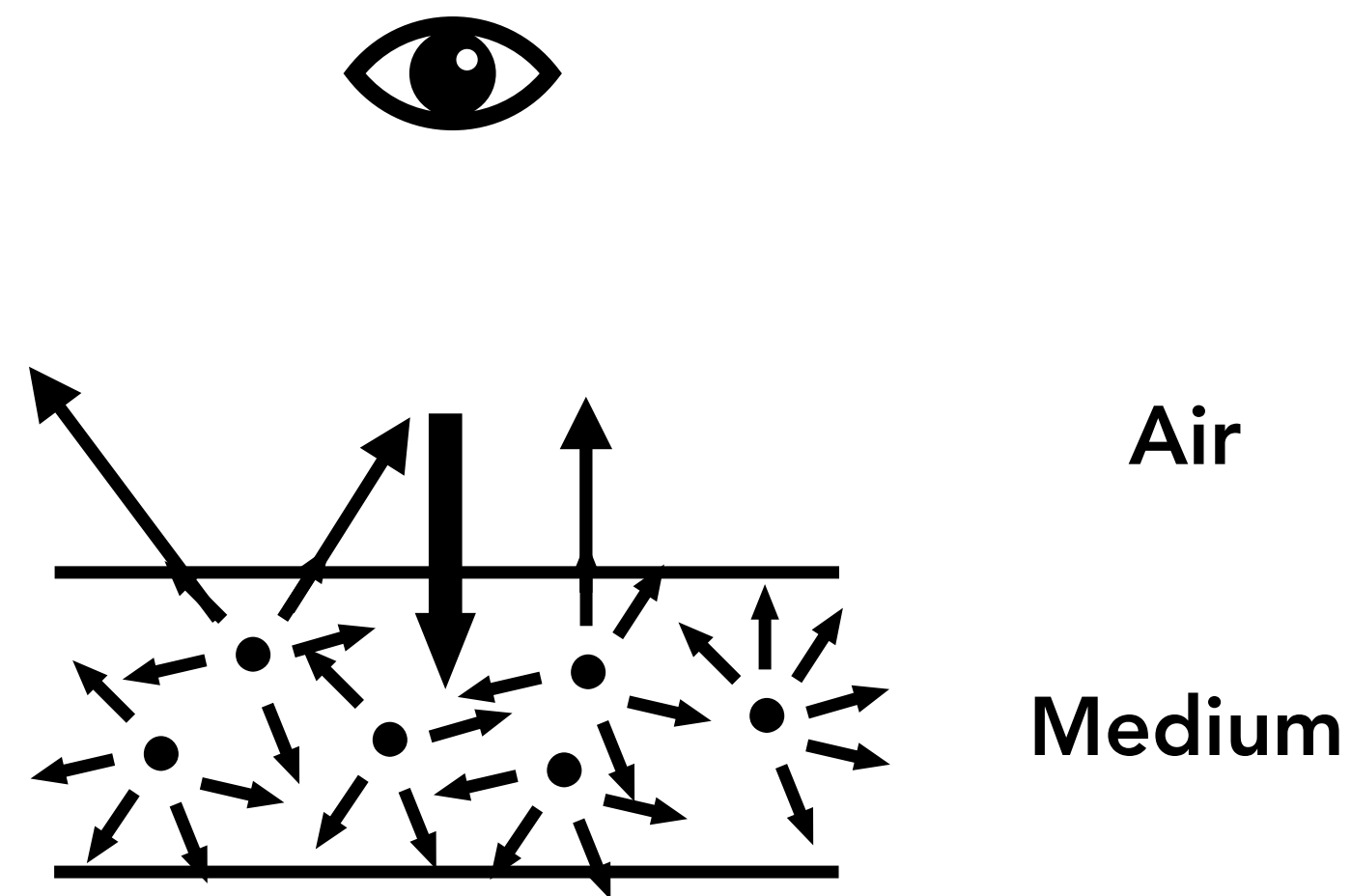


A lot of scattering, which means photons travel a long distance and have a higher chance of being absorbed.

When no light goes through, the medium looks opaque.



# "Color From Reflection"?

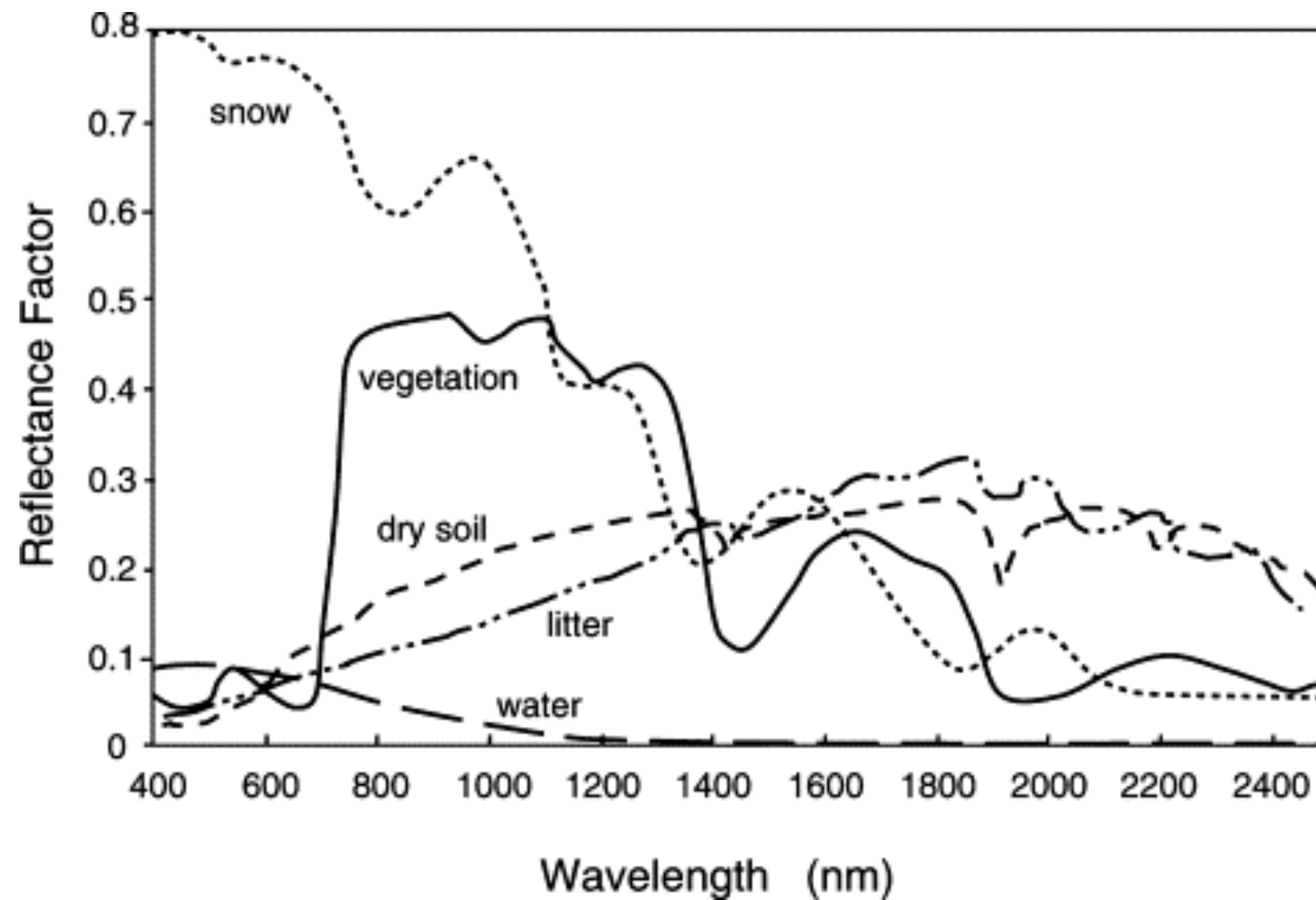


Some scattering are **backwards + surface reflection** (due to air-medium refractive index mismatch). More next lecture.





# Spectral Reflectance

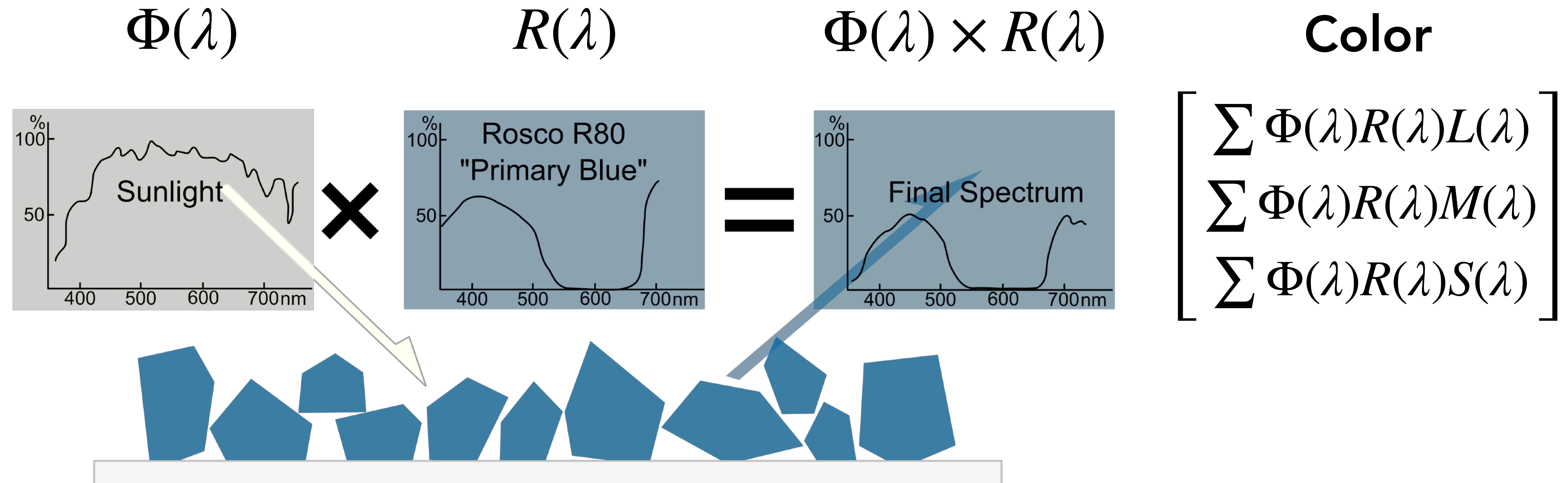


Spectral reflectance is a macroscopic, phenomenological metric: the ratio of reflected and incident light at each wavelength.

- Spectral transmittance is similarly defined.

Material reflectance/transmittance sometimes can be used as a **signature** to identify the material.

# Color of Material Depends on Illumination!!!

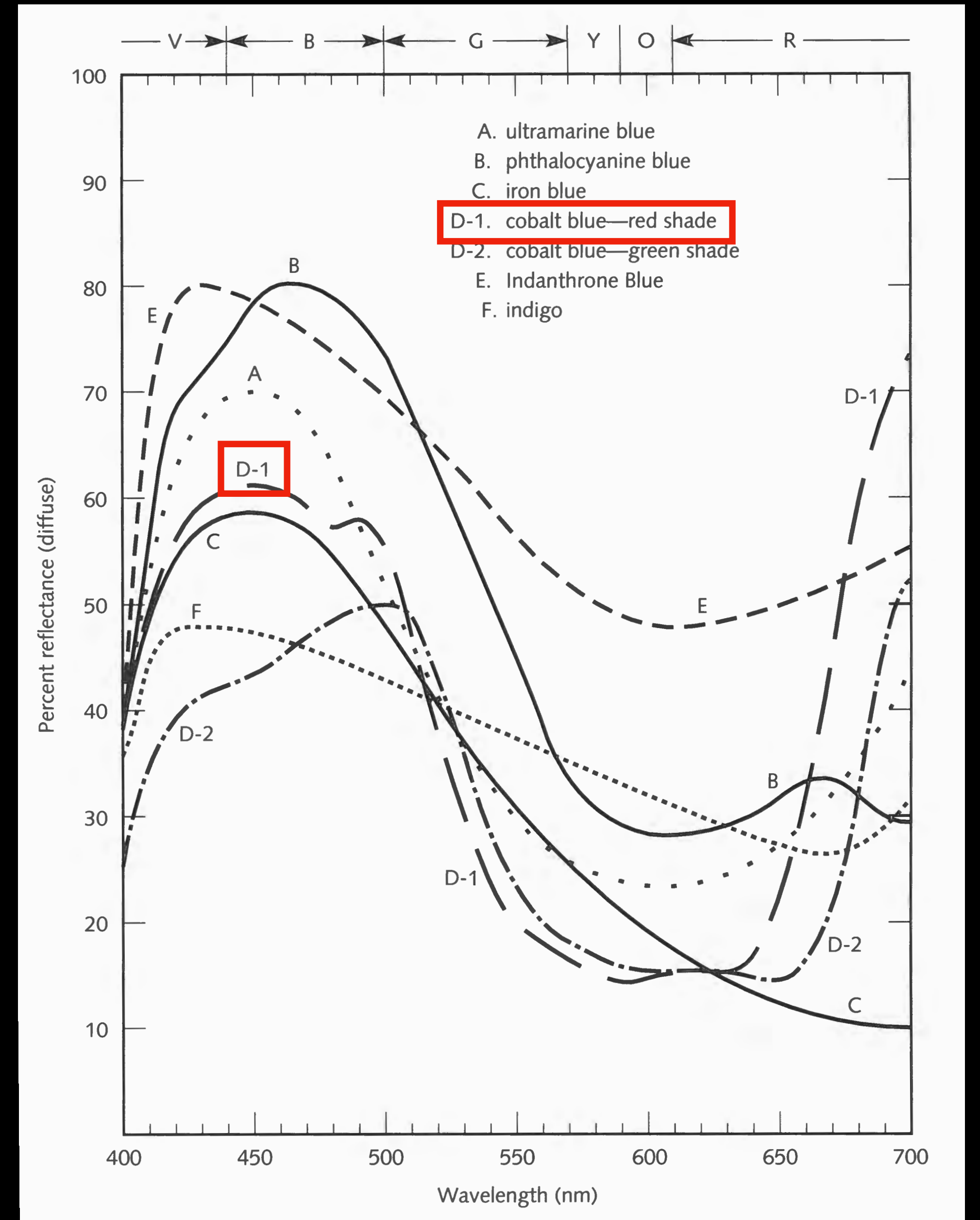




# Bedroom in Arles, Van Gogh, 1888. Post-Impressionism Van Gogh Museum, Amsterdam.

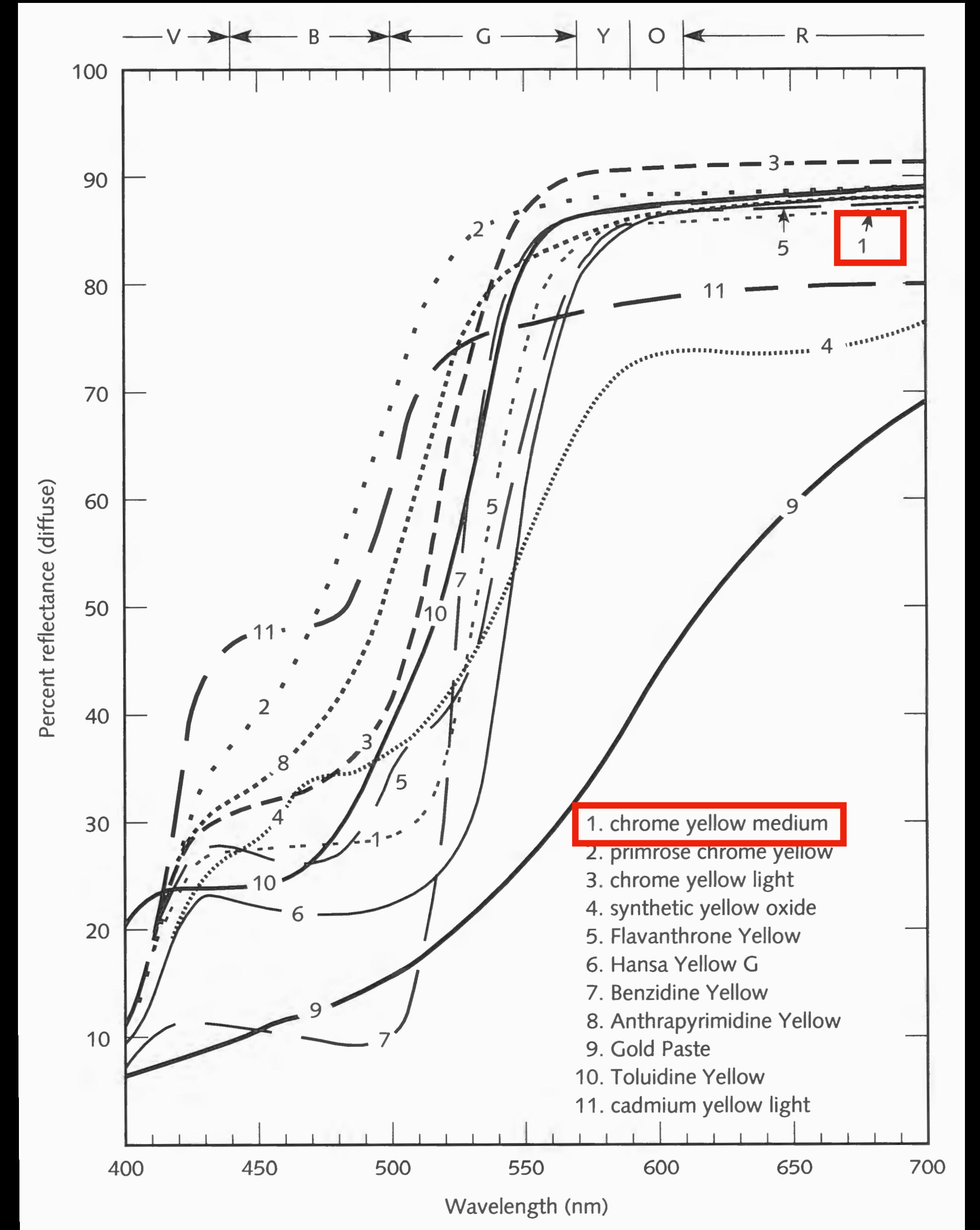


\* Spectra on the right are not the measured spectra from the painting





# Bedroom in Arles, Van Gogh, 1888. Post-Impressionism Van Gogh Museum, Amsterdam.





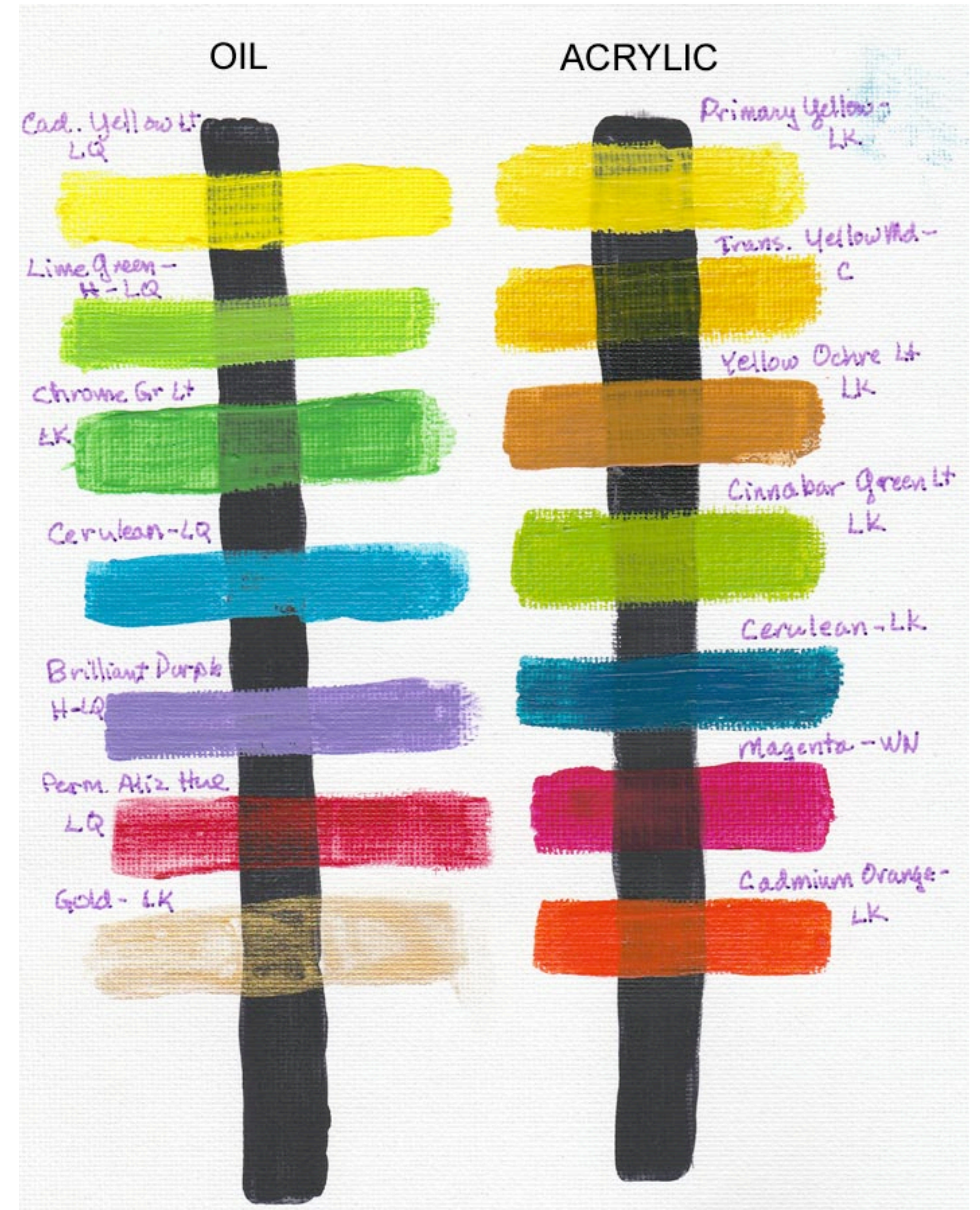
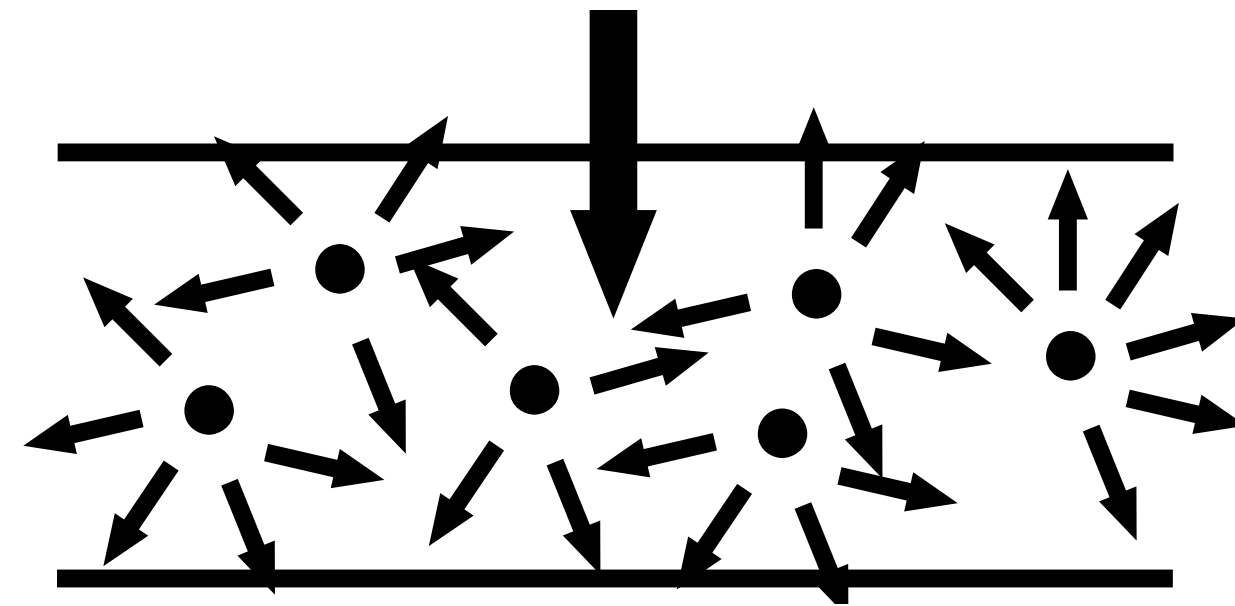
Acadia Redfish looks colorless in deep sea. Second photo taken in the Ripley's Aquarium of Canada.





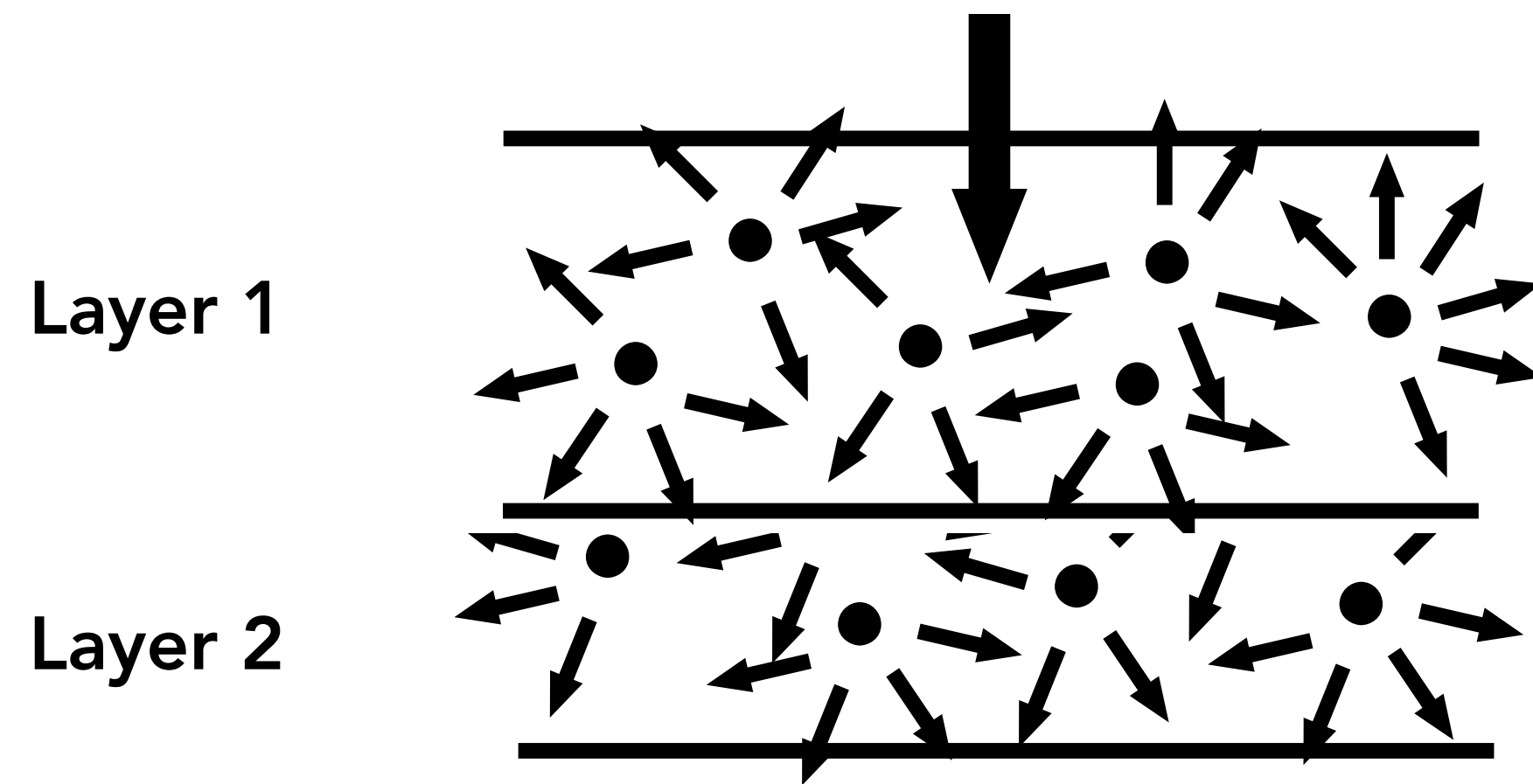
# Layering

Layer 1



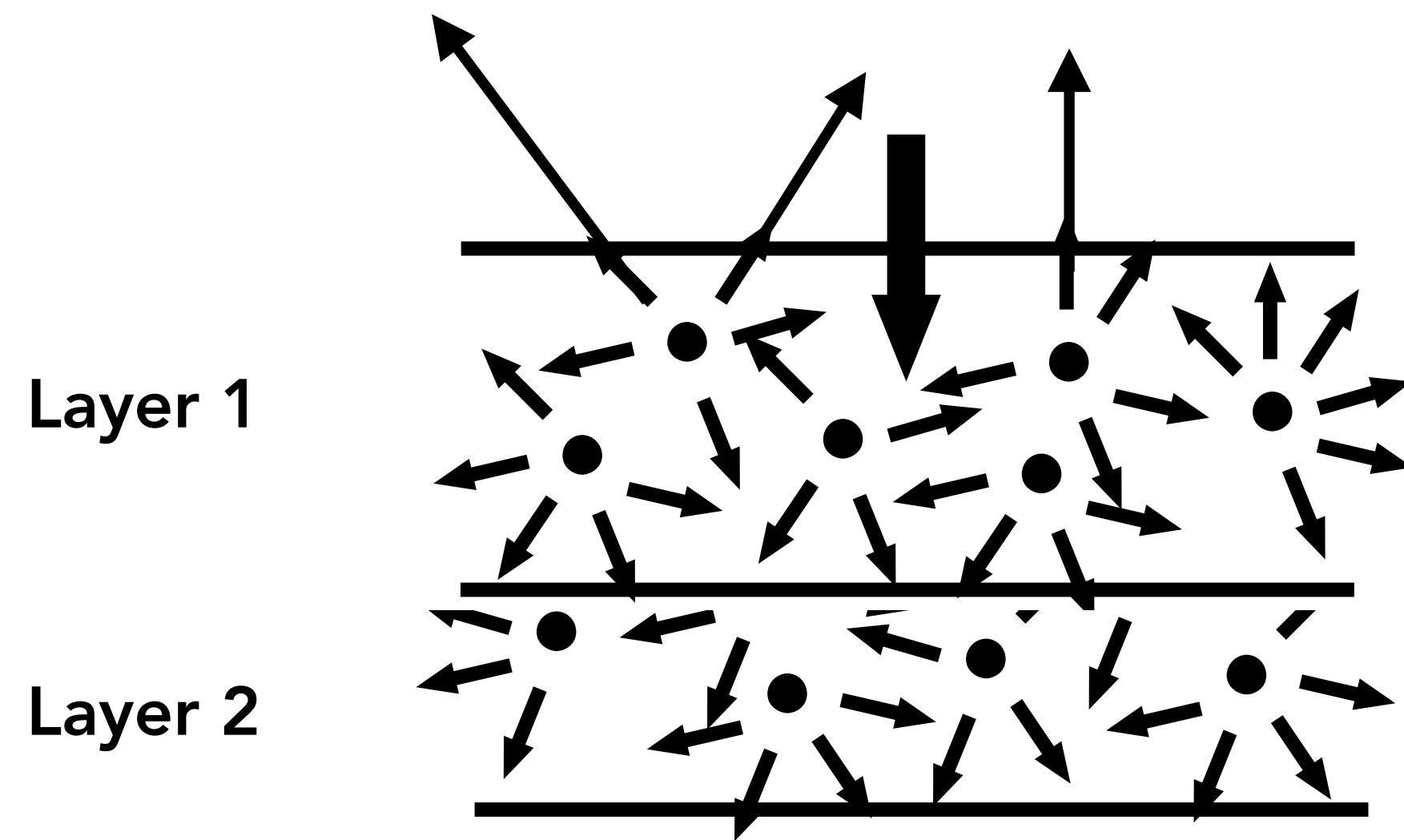


# Layering



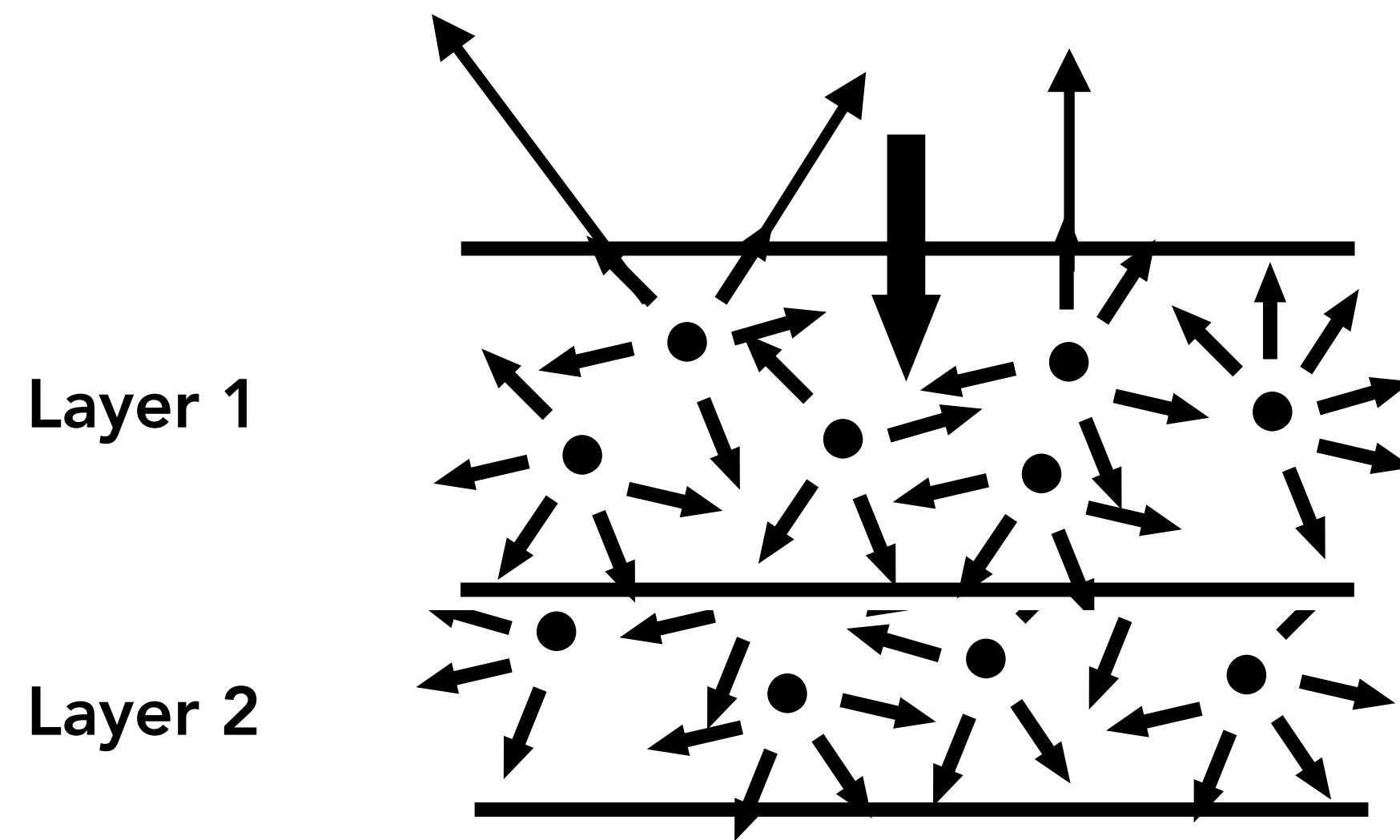


# Layering





# Layering



Some photons transmit through the first layer, interact with the second layer (more absorption and scattering), and make their way back and eventually emerge from layer 1.

We say that layer 1's hiding is incomplete.



# Glazing = Incomplete Hiding





*Holy Women at the Sepulcher*, P. P. Rubens, c 1611-1644. Norton Simon Foundation.





*The Fall of Phaeton*, P. P. Rubens, 1604.  
National Gallery of Art, Washington, D.C





# Vanishing





# Vanishing = High Surface Reflection + Transparency



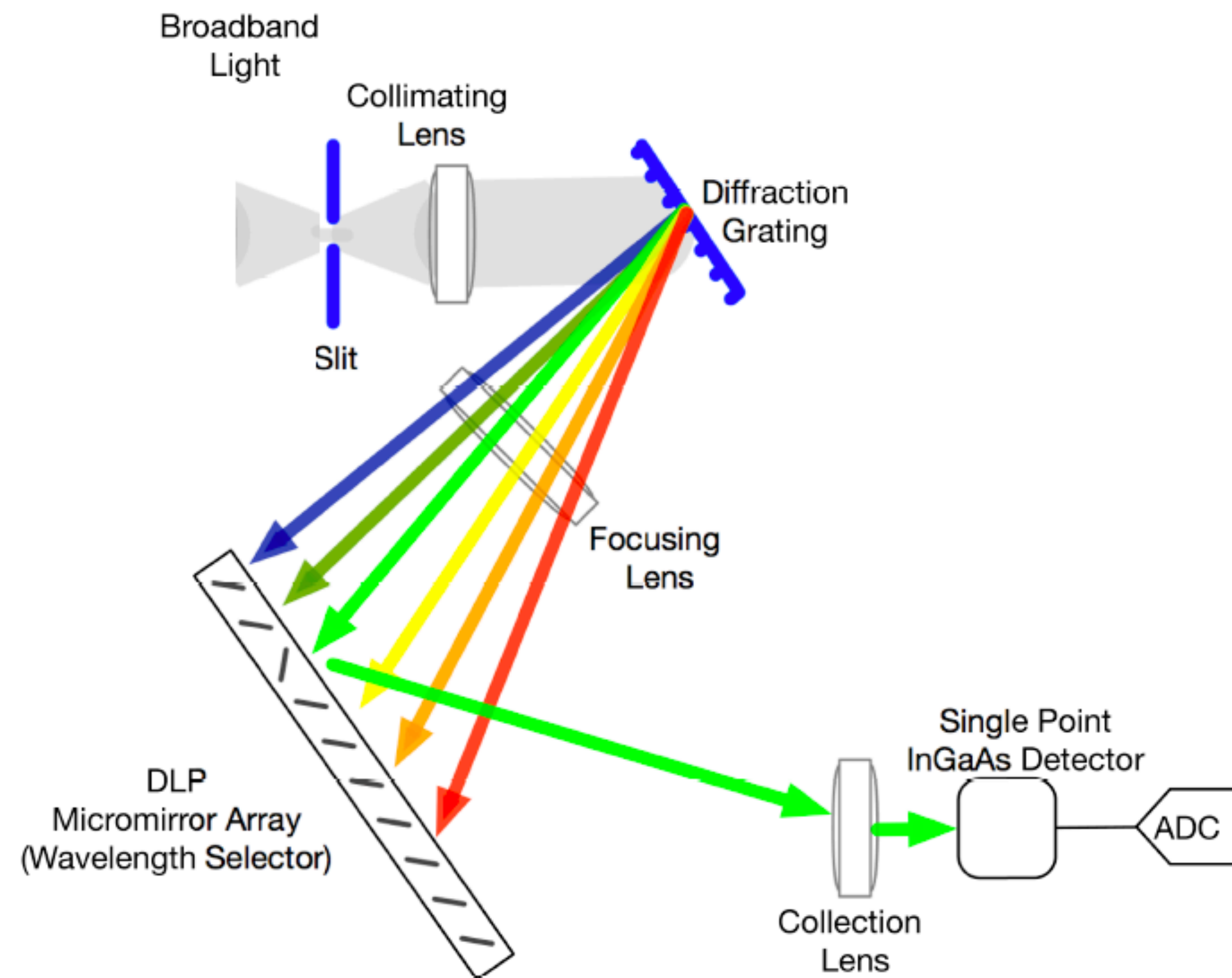
A lot of incident lights are reflected off of the surface, creating the glossy look.

The varnish layer itself is transparent, so photons that do go through the surface layer are not scattered much. So the background is clearly seen.

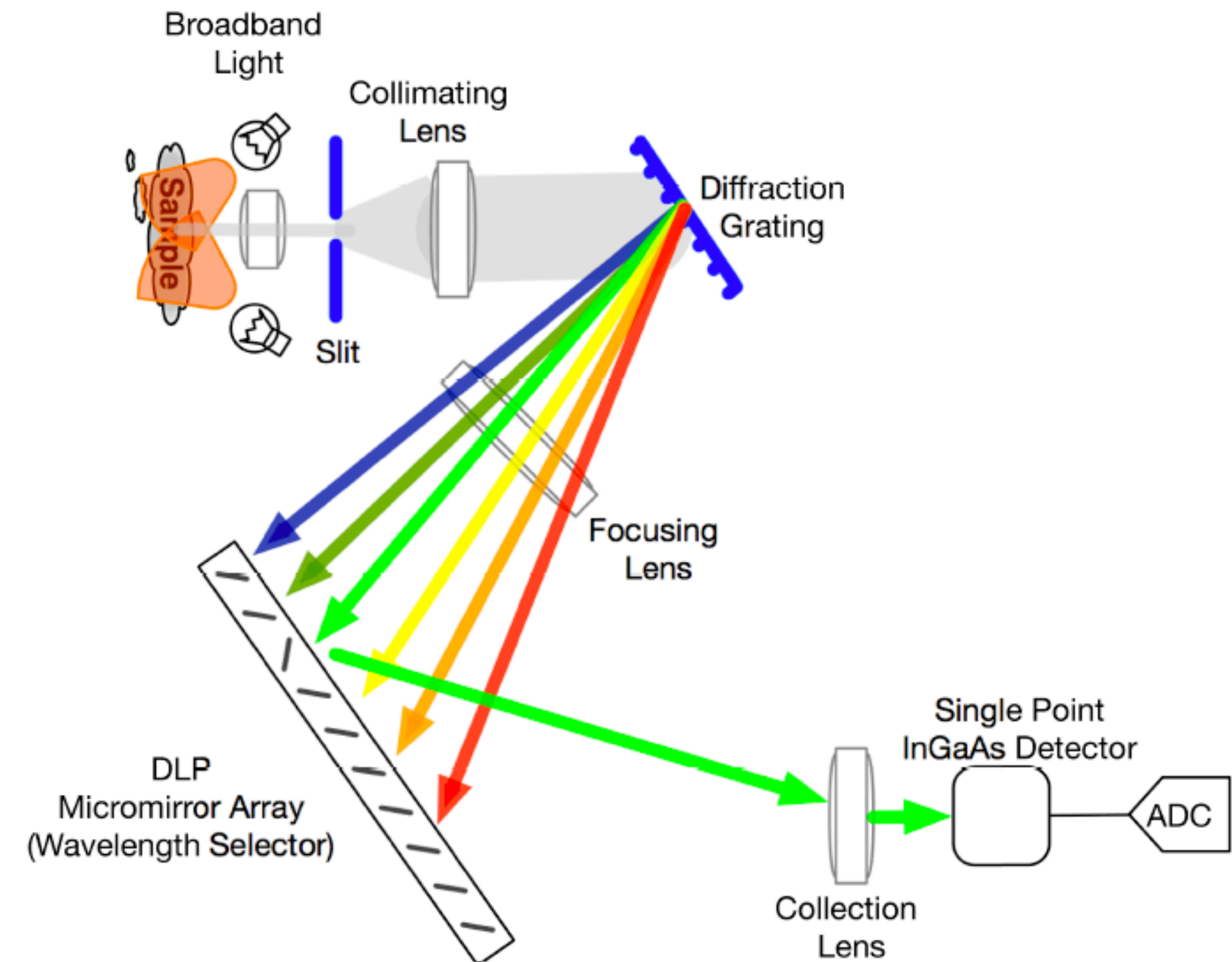


# Measuring Radiation and Reflectance

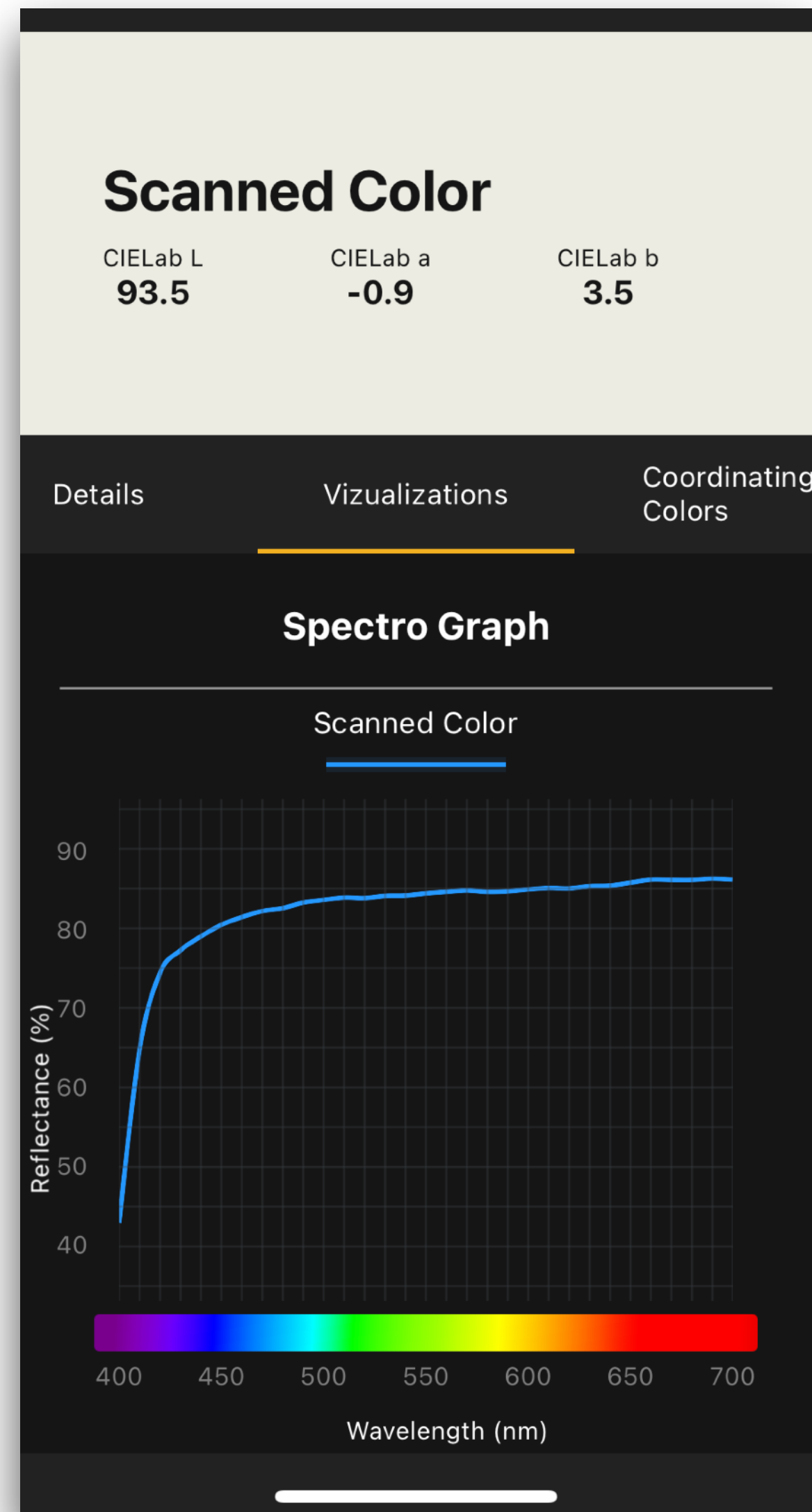
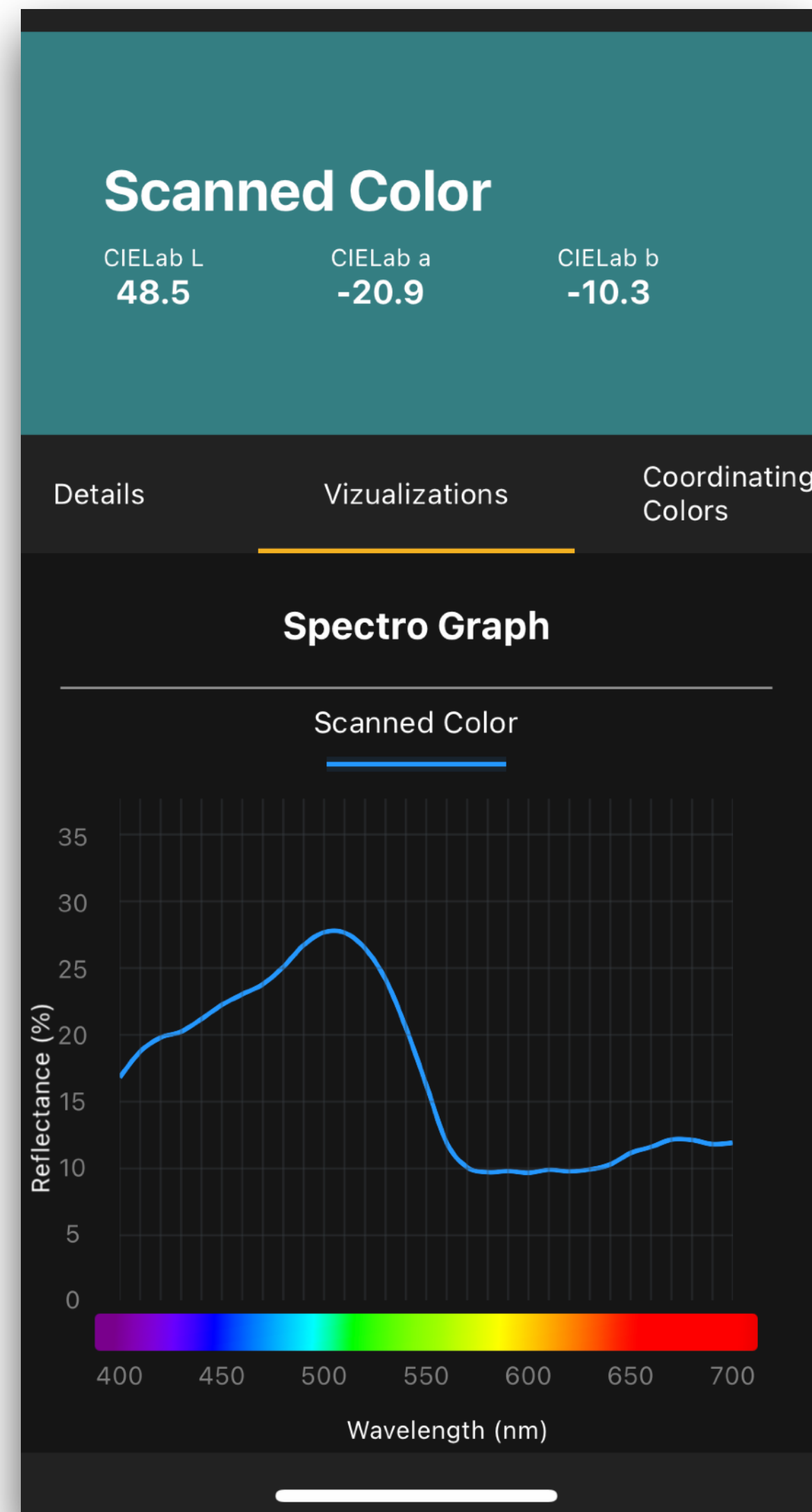
## Spectroradiometer



## Spectrophotometer



# Reflectance Spectra Measured During the Class



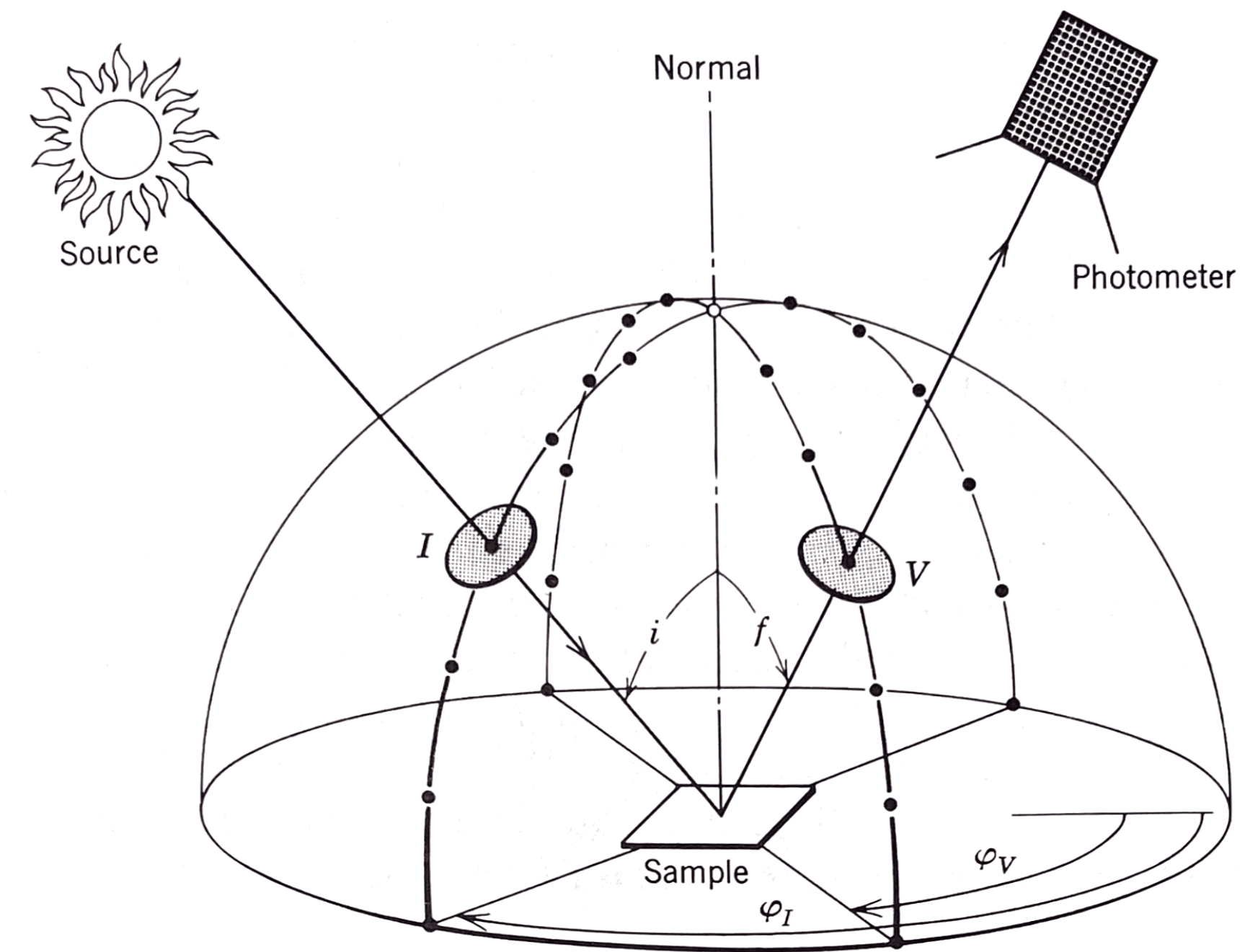
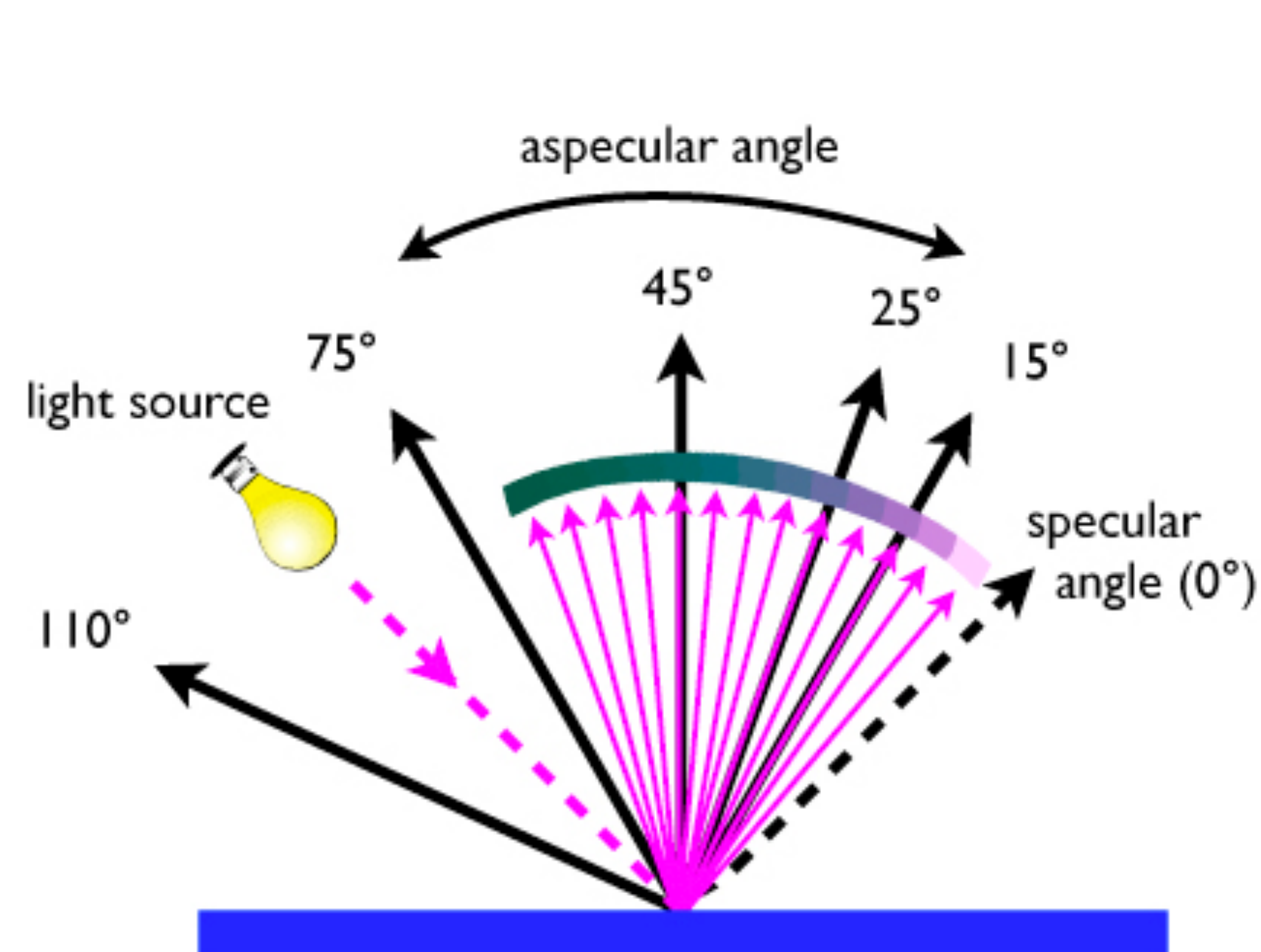
Left: The **cyan** user guide of the device

Right: The **white** table at the front of the classroom

The spectrophotometer I used is from here:  
<https://www.variableinc.com/spectro-1.html>

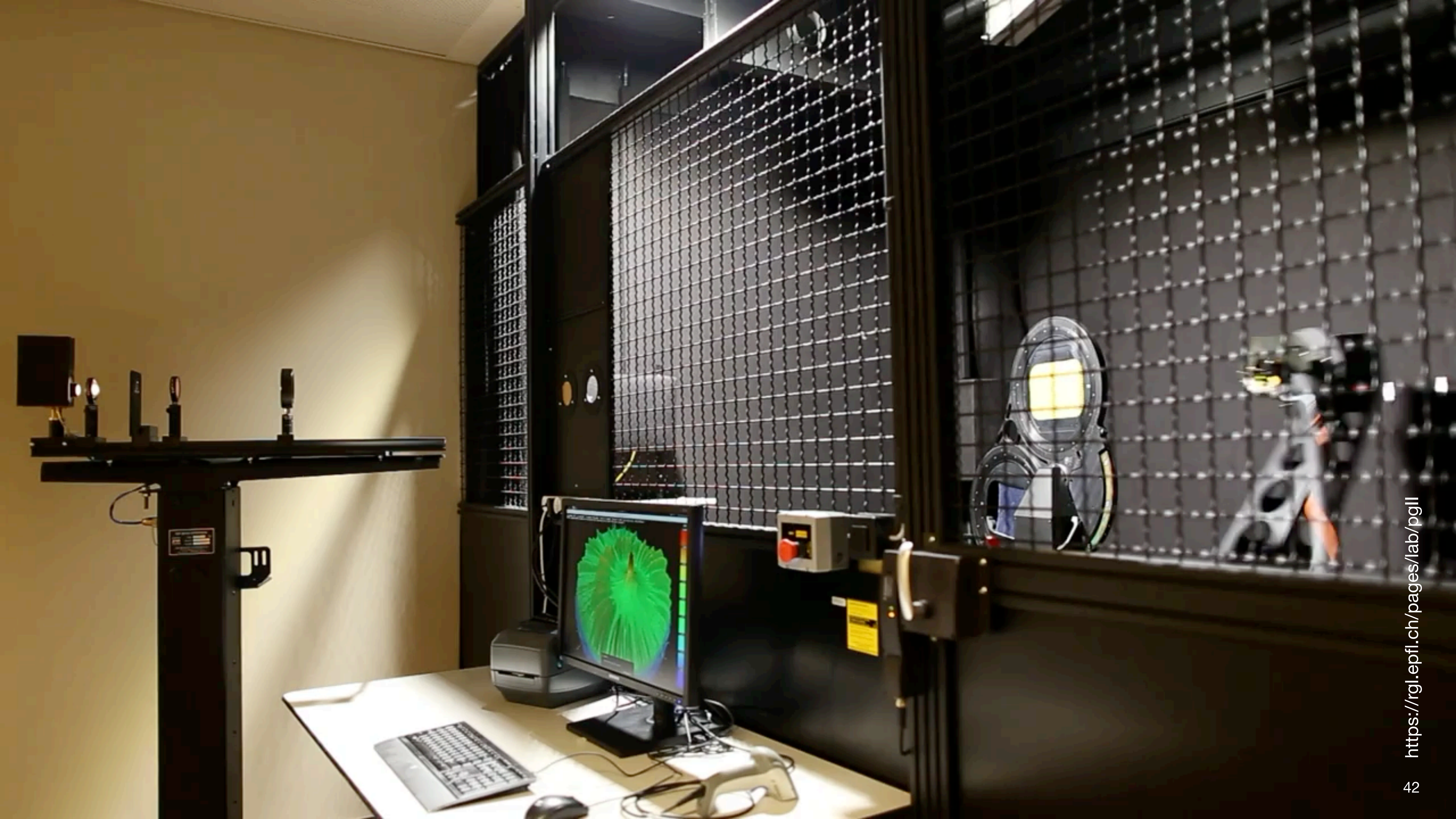


# Gonio Spectrophotometer

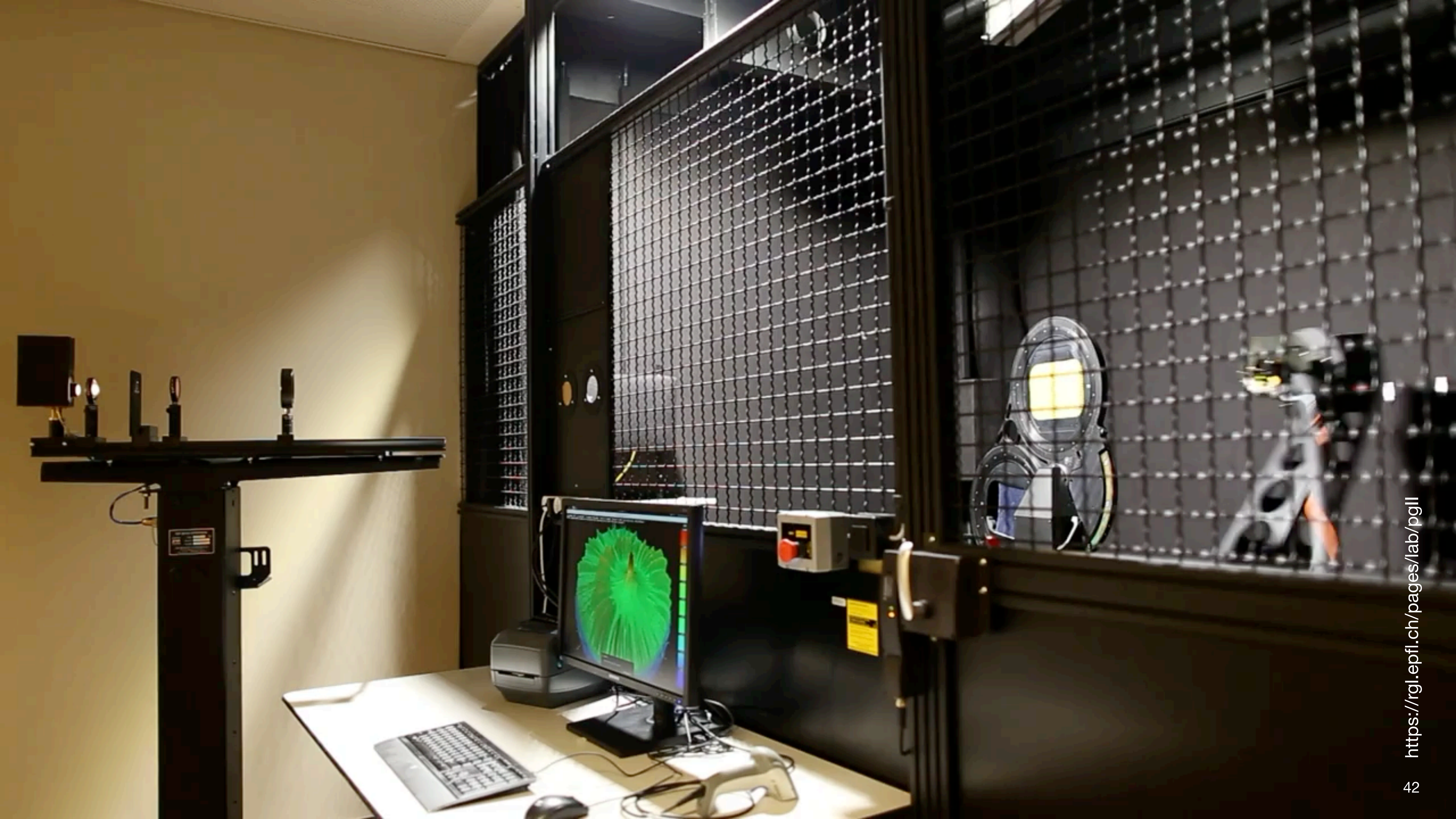


Reflectance depends both incident angle and the viewing angle (called BRDF)  
More on this later.









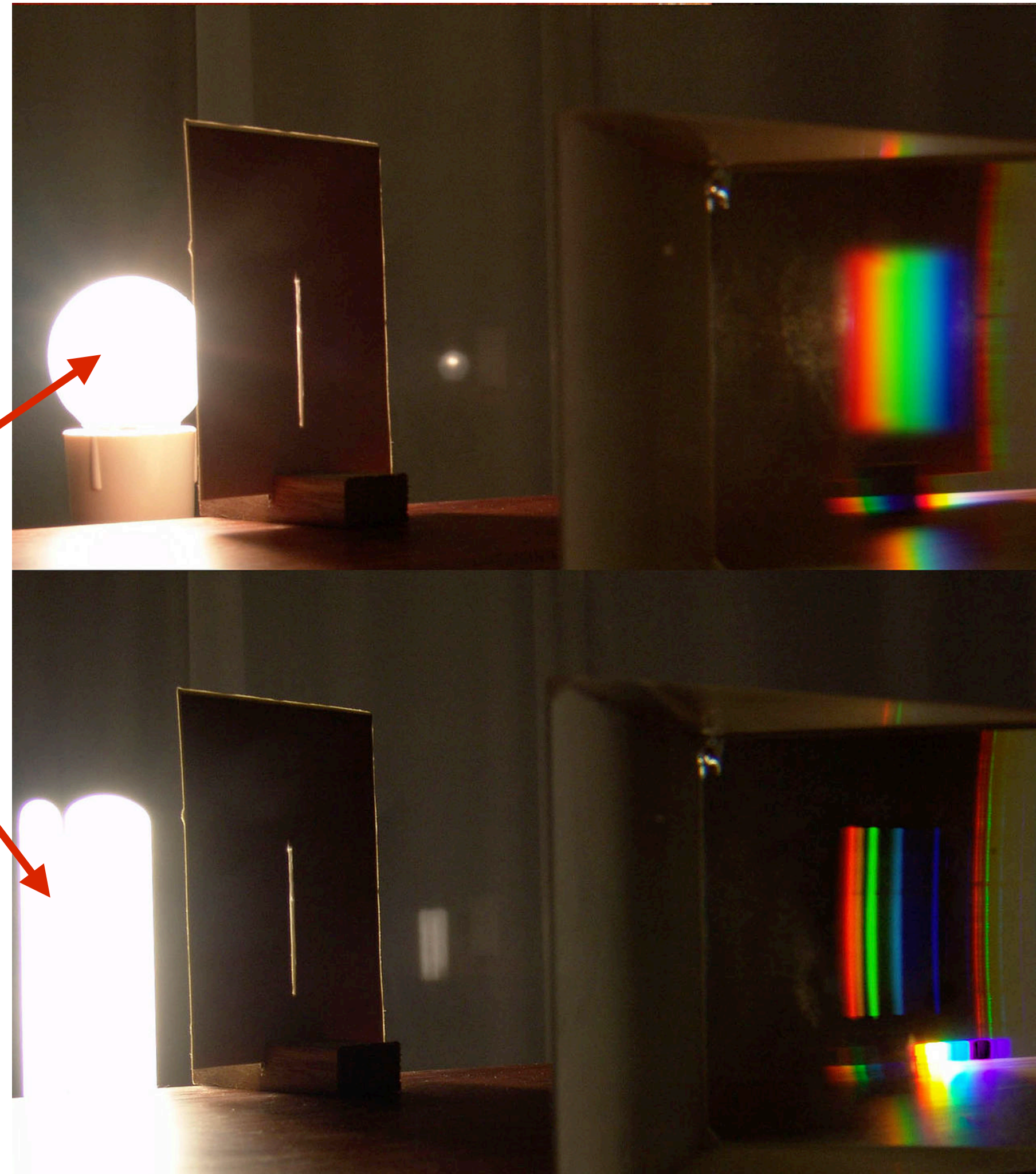


# Display vs. Lighting



# Apparent Color vs. Spectrum

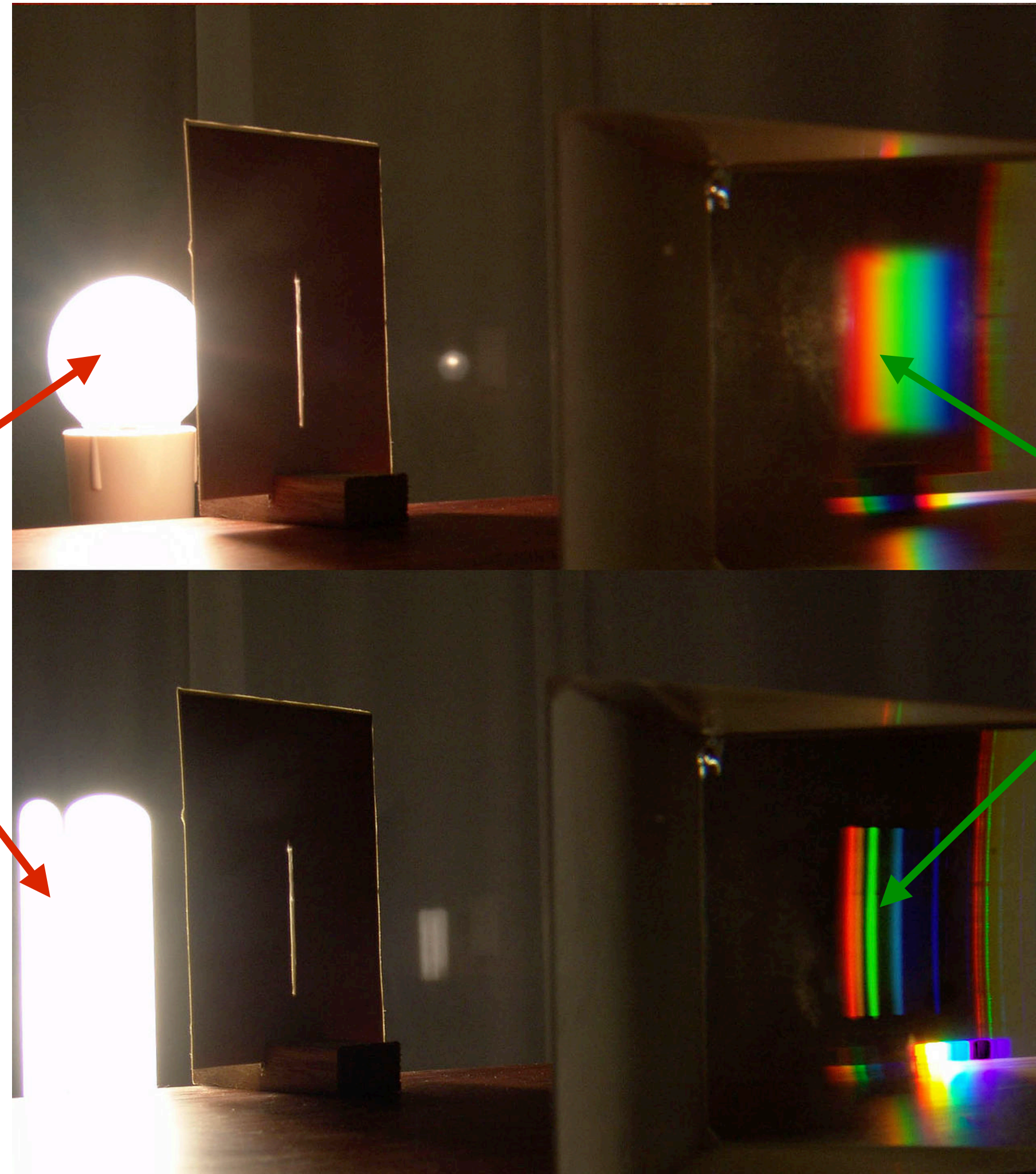
The two lights have similar  
apparent color, but are  
they the same light?





# Apparent Color vs. Spectrum

The two lights have similar  
apparent color, but are  
they the same light?



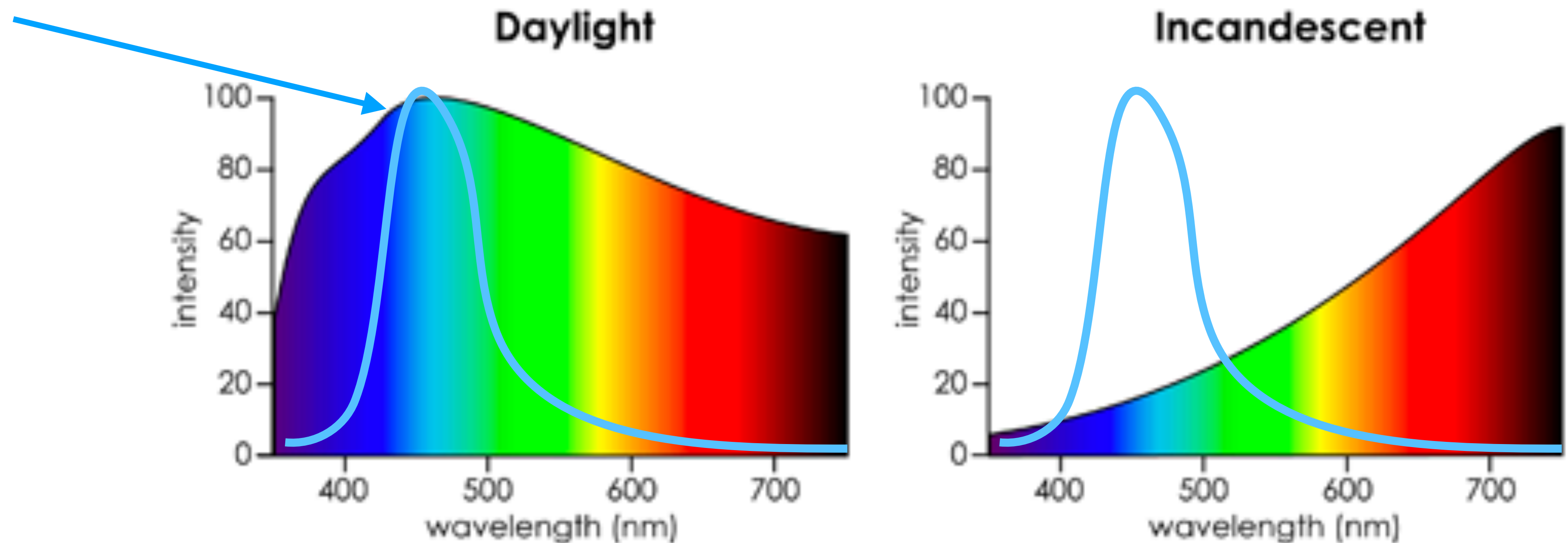
No! Lights with the  
same apparent color  
could have very  
different spectra.



# Do Spectra Ever Matter?

Assuming these two lights are metamers, which one is better at “revealing the color” of the object with the given spectral reflectance?

Reflectance spectrum  
of the object





# Do Spectra Ever Matter?

To reveal the “true color” of an object, the light source needs to emit wavelengths that the object reflects.

Of course there is nothing called “true color”. What’s the objective reality is the reflectance spectrum of the object.

But we do have a common color perception of an object, and that perception is obtained/formed with respect to a typical lighting under which the object is usually viewed.



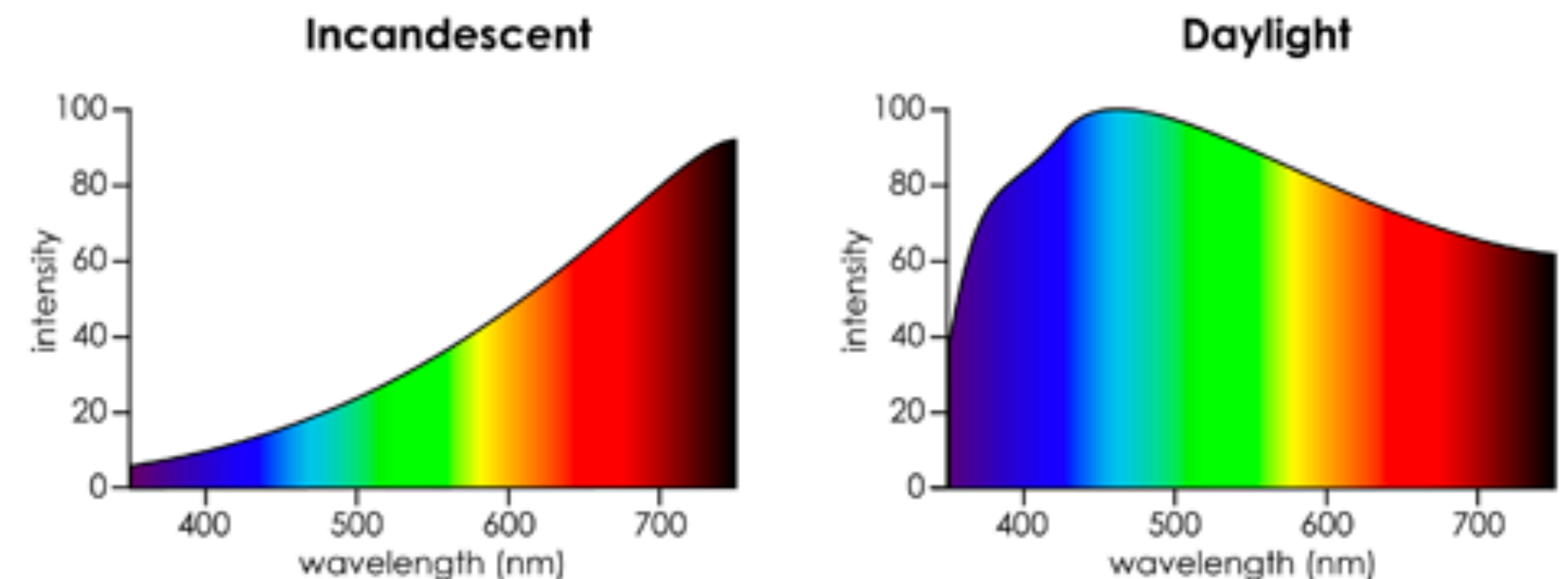
# Color Rendering

**Color rendering** concerns with the ability of a light source to reveal the “true color” of an object, which is the color of an object under a “reference” light.

- The choice of reference light is somewhat arbitrary, but it’s generally white, e.g., daylight.

The reference light is:

- A blackbody radiation (some form of **incandescent** light) when CCT is below 5000K.
- A standard illuminant D (some form of **daylight**) when CCT is above 5000K.



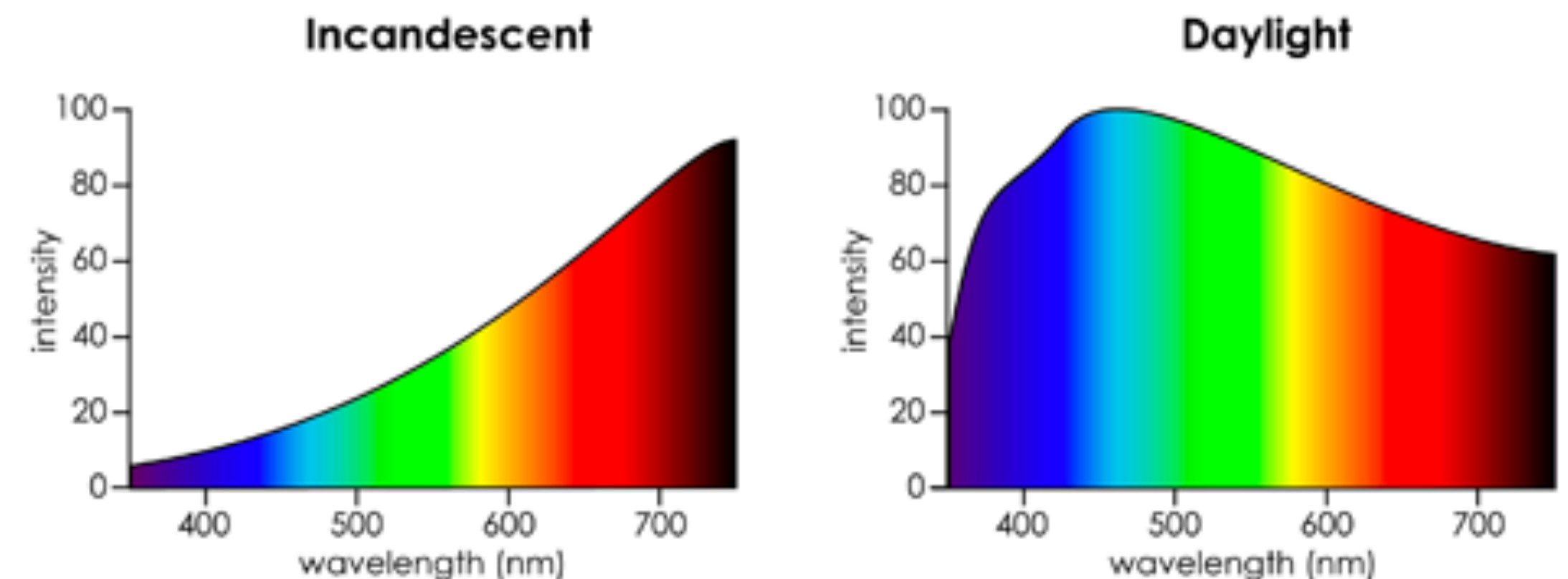


# Color Rendering Index (CRI)

A metric standardized by CIE.

**CRI** quantifies the coloring rendering capability of a given light source w.r.t., a **reference** light under the same correlated color temperature.

- CRI is defined only for light sources that are approximate white, i.e., the chromaticity distance to the Planckian locus is below a threshold.



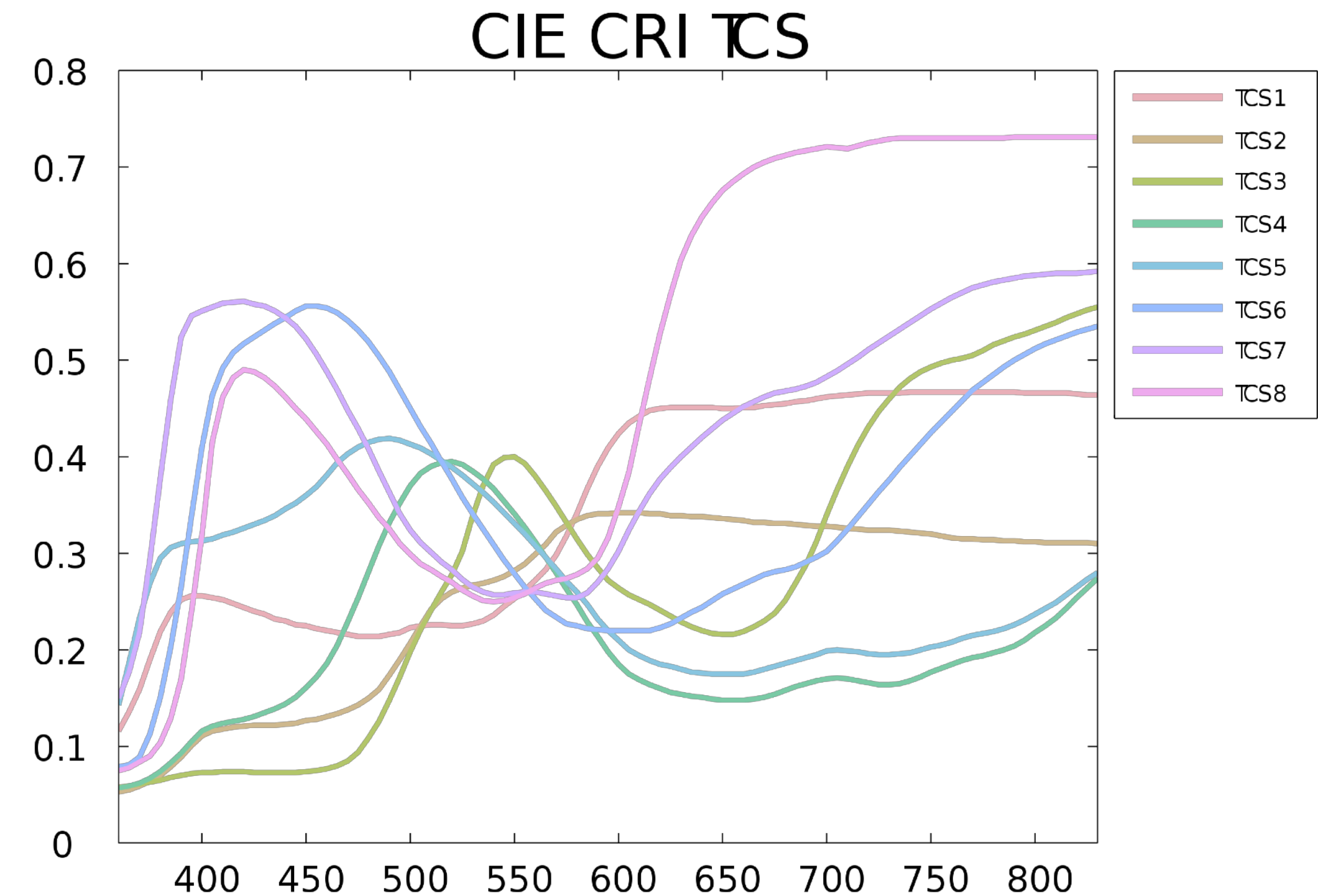


# Calculating Color Rendering Index (CRI)

Pick a set of calibration materials with given spectral reflectance.

For each material, illuminate it with both the test light and the reference light. Calculate the two sets of xy-chromaticities, apply von Kries chromatic adaption, and calculate the distance in the xy diagram.

Take some form of average across the samples and normalize to 100.



Reflectance spectra of the calibration samples (CIE 1995)

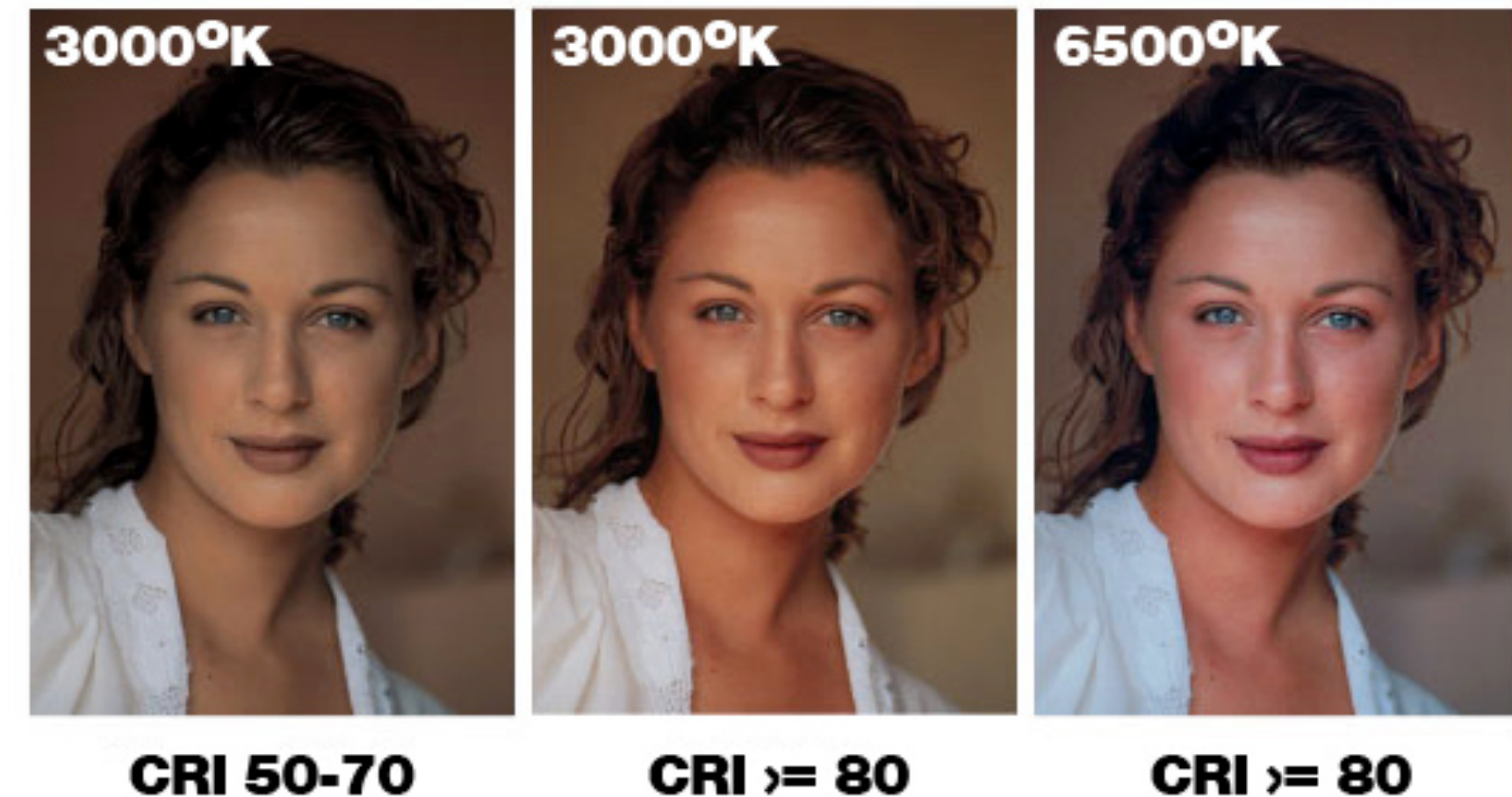


# Interpreting CRI

Lights that are more similar to the reference lights (incandescent or daylight) have higher CRIs. Reference lights have a CRI of 100.

Generally, lights with continuous spectrums have higher CRIs.

- A continuous spectrum better integrates across the entire visible range.





# Display vs. Lighting

We directly look at lights from the display.

- Reproducing the color (using metamerism) is key. Spectrum is not important.

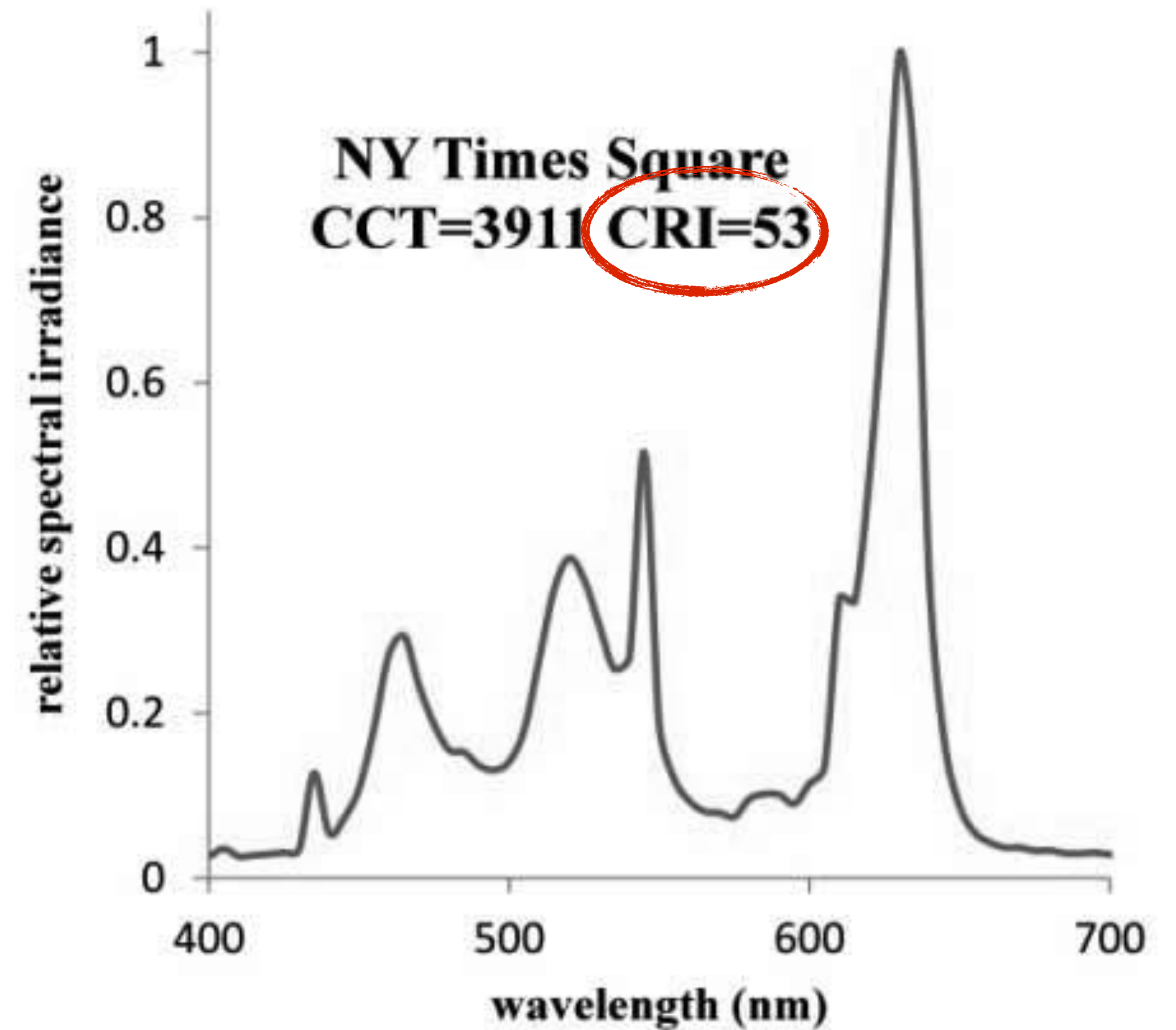
We don't directly look at lights. We use a lighting system mostly to light an object so that we can see the **color of the object**.

- CRI matters the most. Spectrum becomes important.

What happens when we use displays for lighting?



# Display vs. Lighting





# Fluorescence

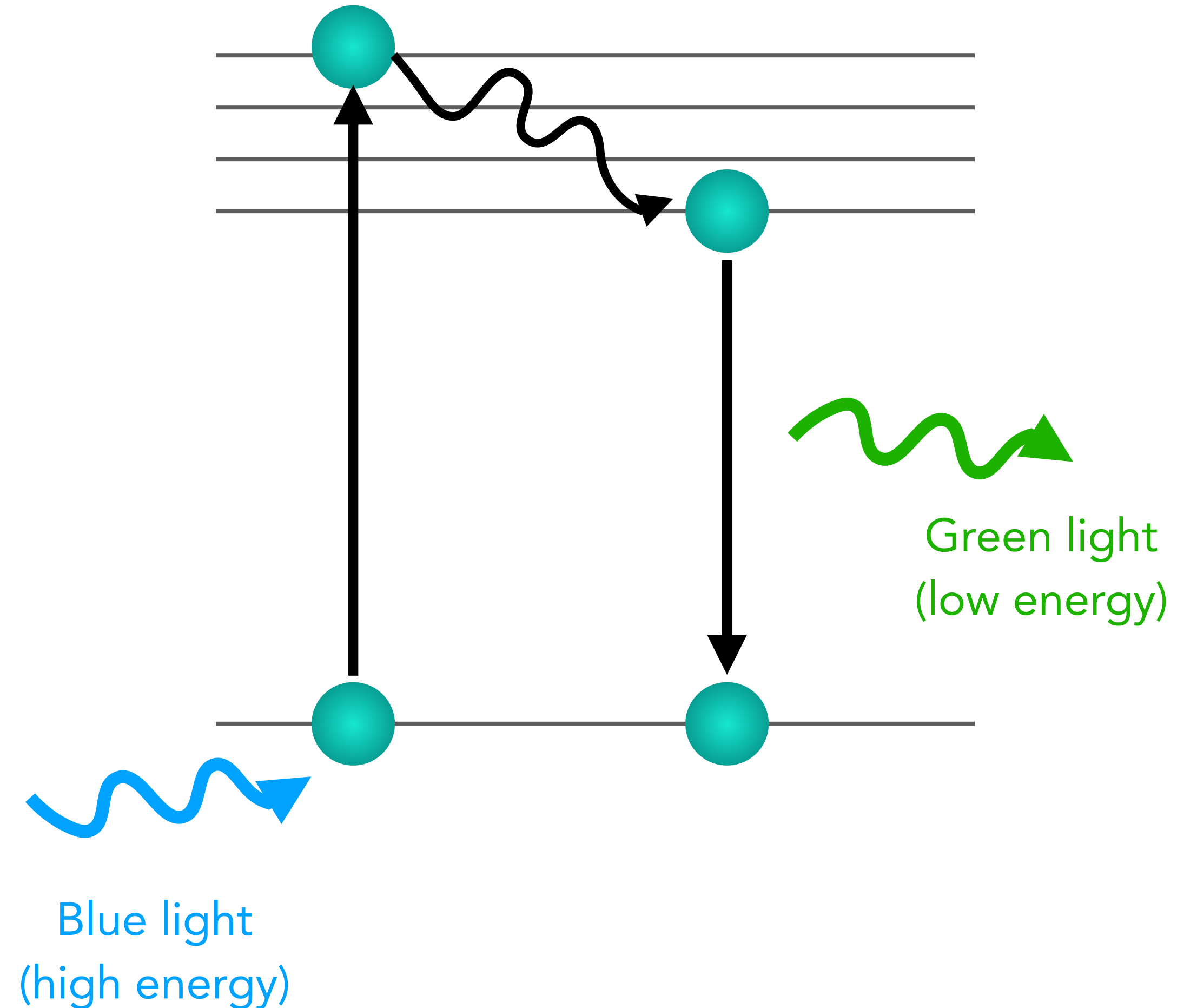


# What is Fluorescence?

High energy photons are absorbed and lower-energy (longer-wavelength) photons are emitted.

- The rest of the energy turns into other forms.

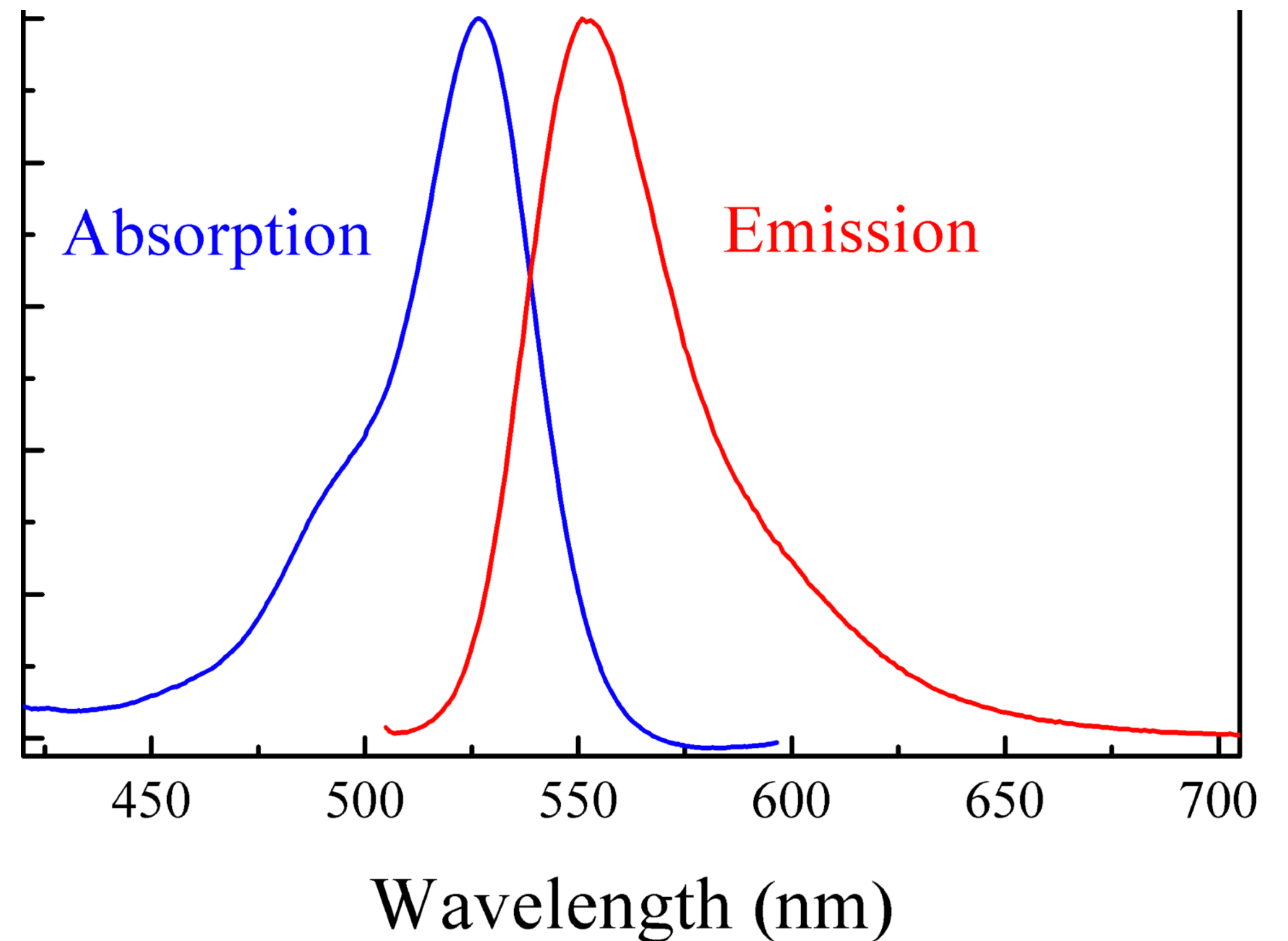
Usually blue/UV lights are absorbed and green lights are emitted — that's why fluorescence is usually green.





# What is Fluorescence?

Absorption and emission spectra of a typical fluorescent material. The spectra show the spectral **probability** of absorption and emission of a particular material.



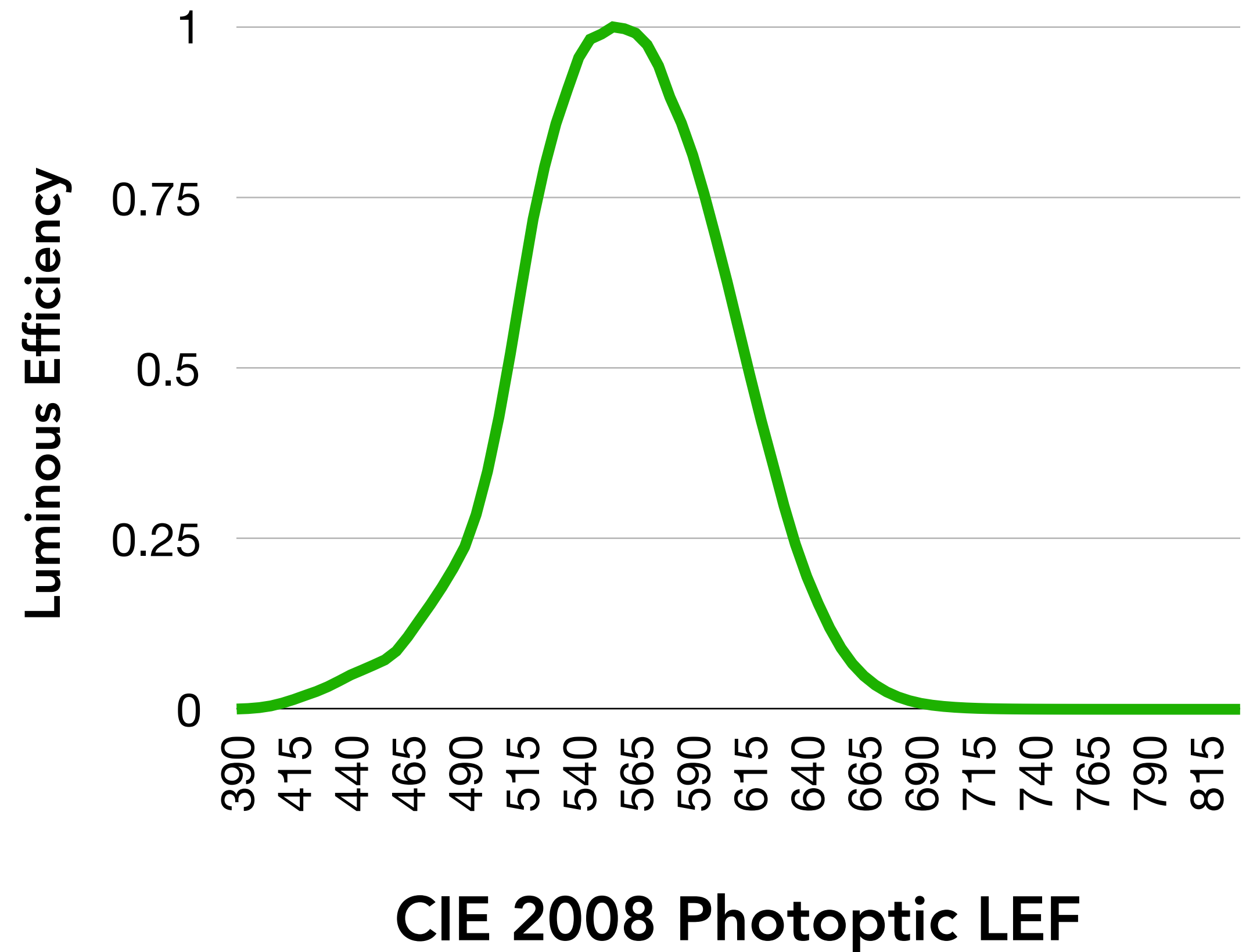


# Fluorescence Makes Things Brighter

Fluorescence can make things appear **brighter**/more conspicuous, even though the emitted **energy** is almost always lower than the incident energy.

This is because human visual system is more sensitive to green-ish lights.

- Recall: the luminous efficiency peaks at 555 nm.





# Fluorescent Light

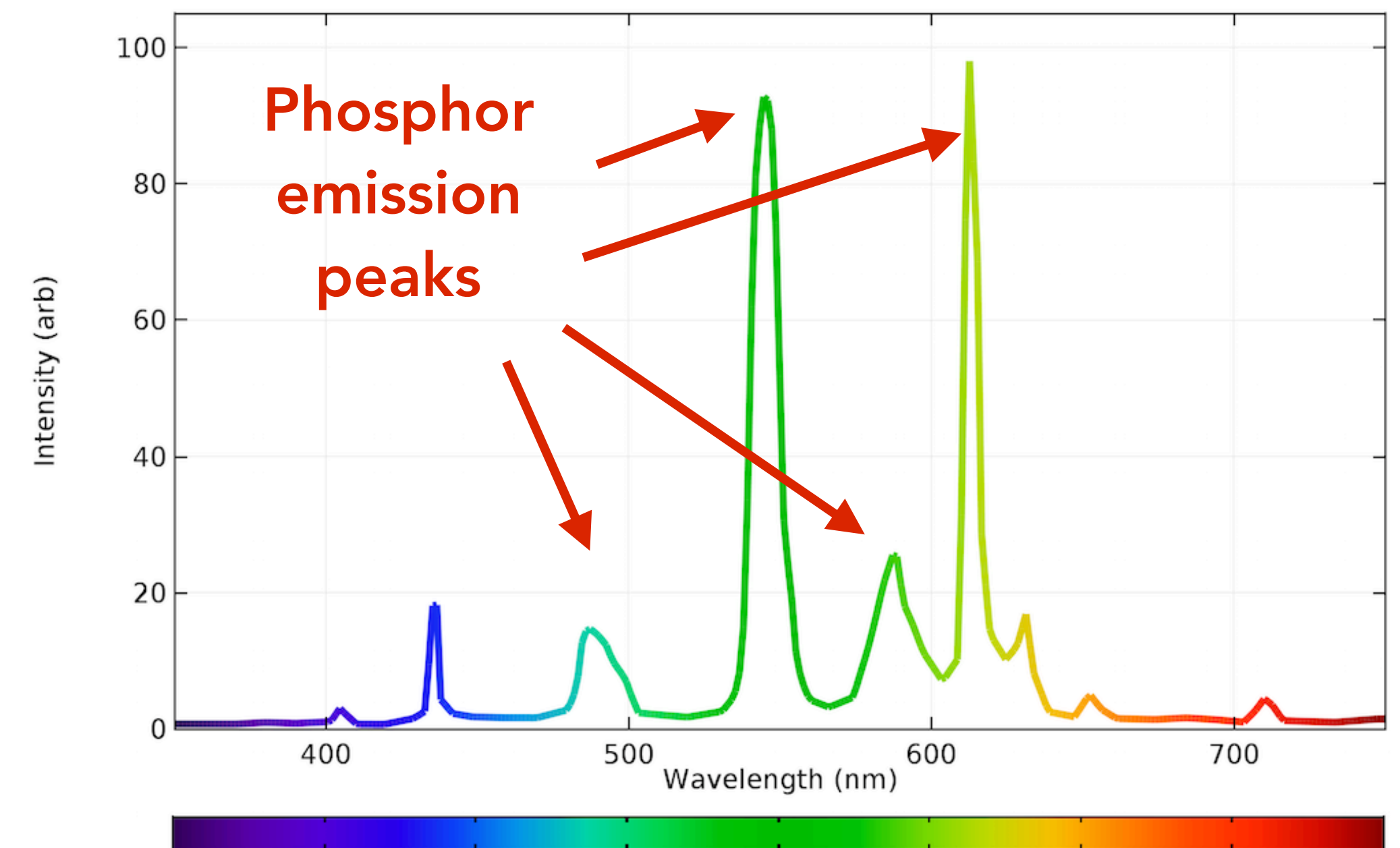
**Phosphors** used as fluorescent material.

Usually use UV light to excite the phosphor coating inside a lamp.

- Could mix phosphors to improve CRI.

The UV light is generated by applying current to excite mercury vapor.

What enters your eyes is the combination of fluorescence and light directly emitted by the mercury vapor.



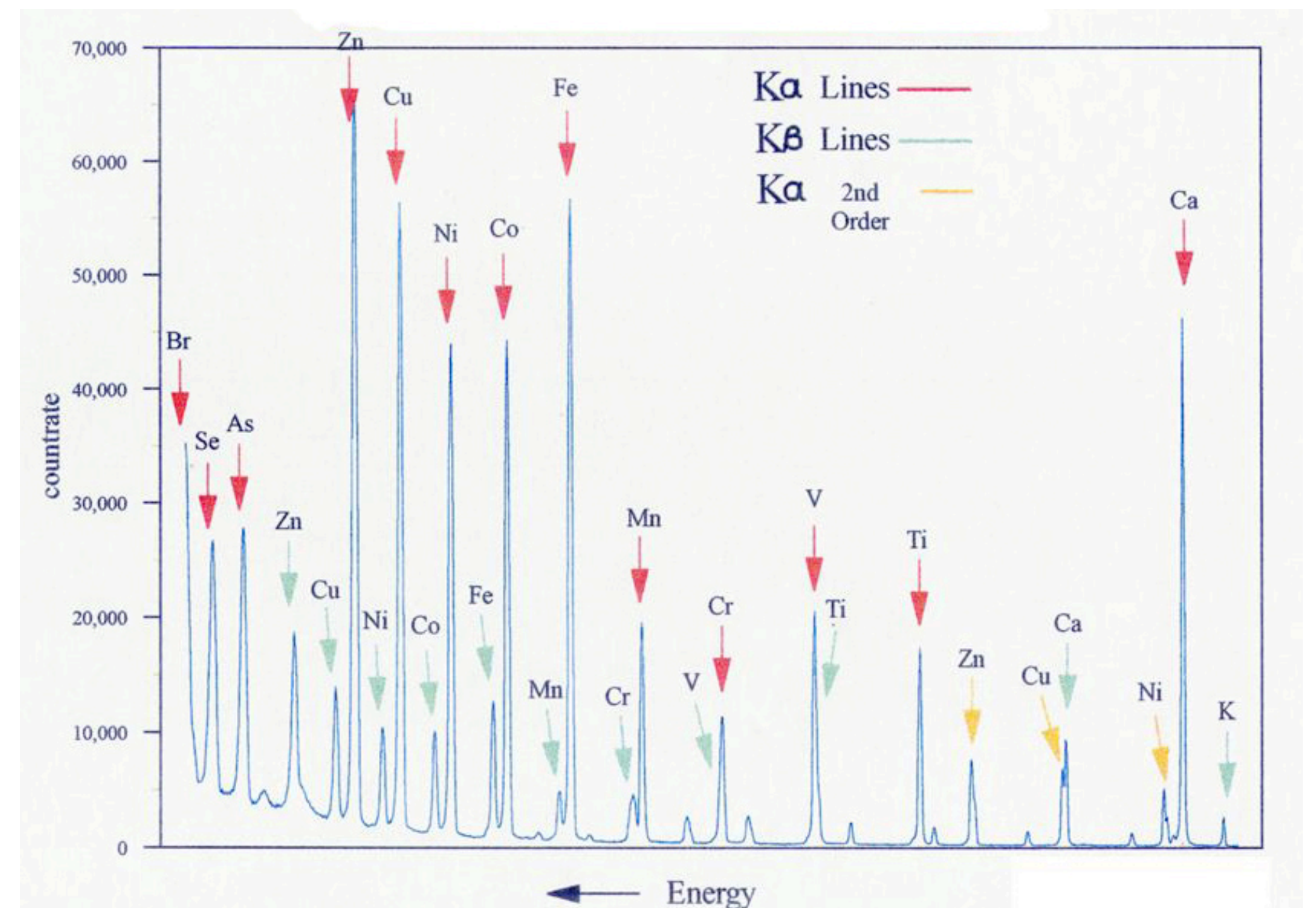


# Fluorescence in Cultural Heritage

The emission spectrum is specific to the material. Analyzing the emission spectrum can tell us a lot about the material.

Fluorescence photography is widely used in cultural heritage for identifying pigments, pentimenti, etc.

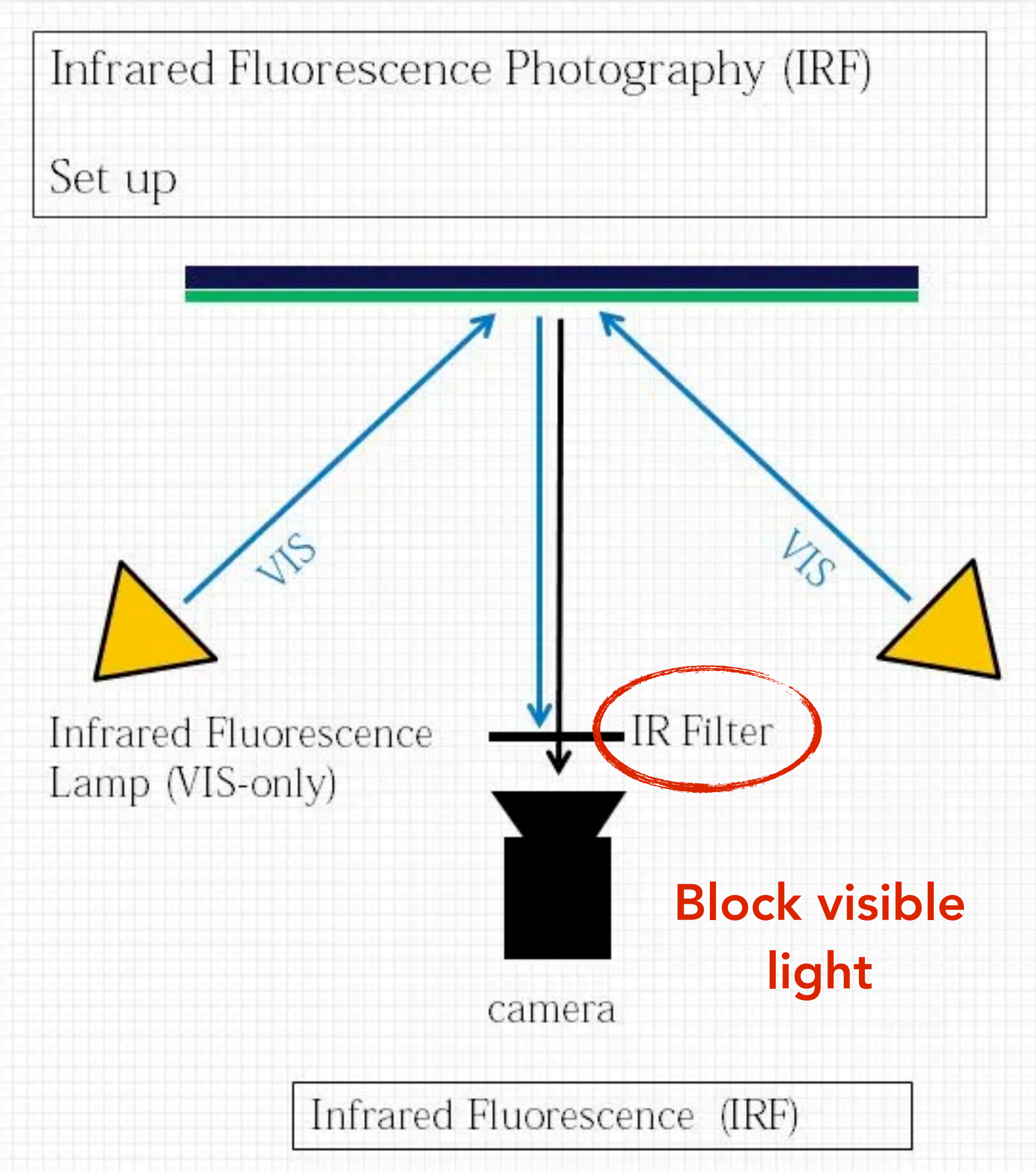
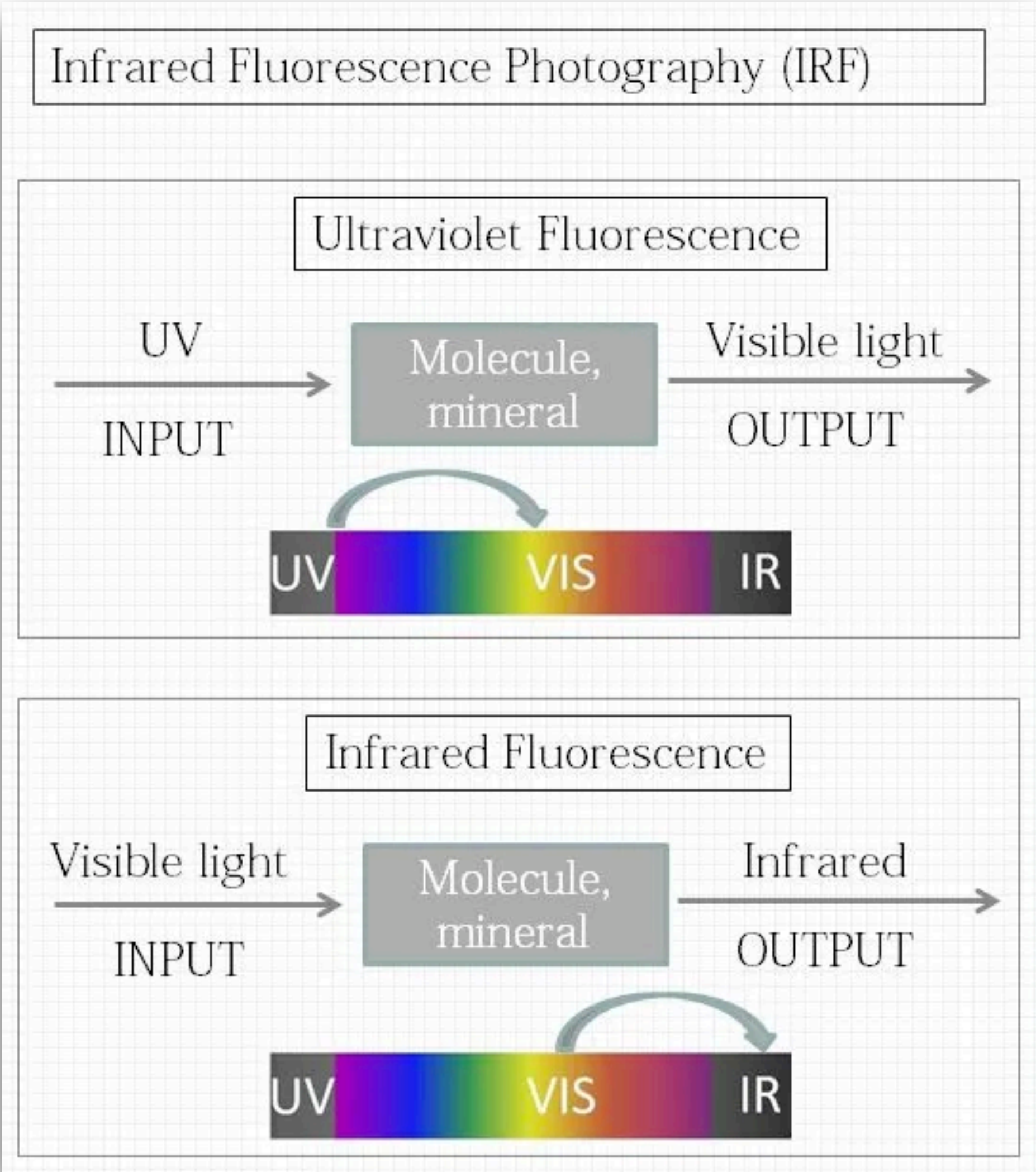
- IR Fluorescence
- UV Fluorescence
- X-Ray Fluorescence



**An XRF emission spectra**

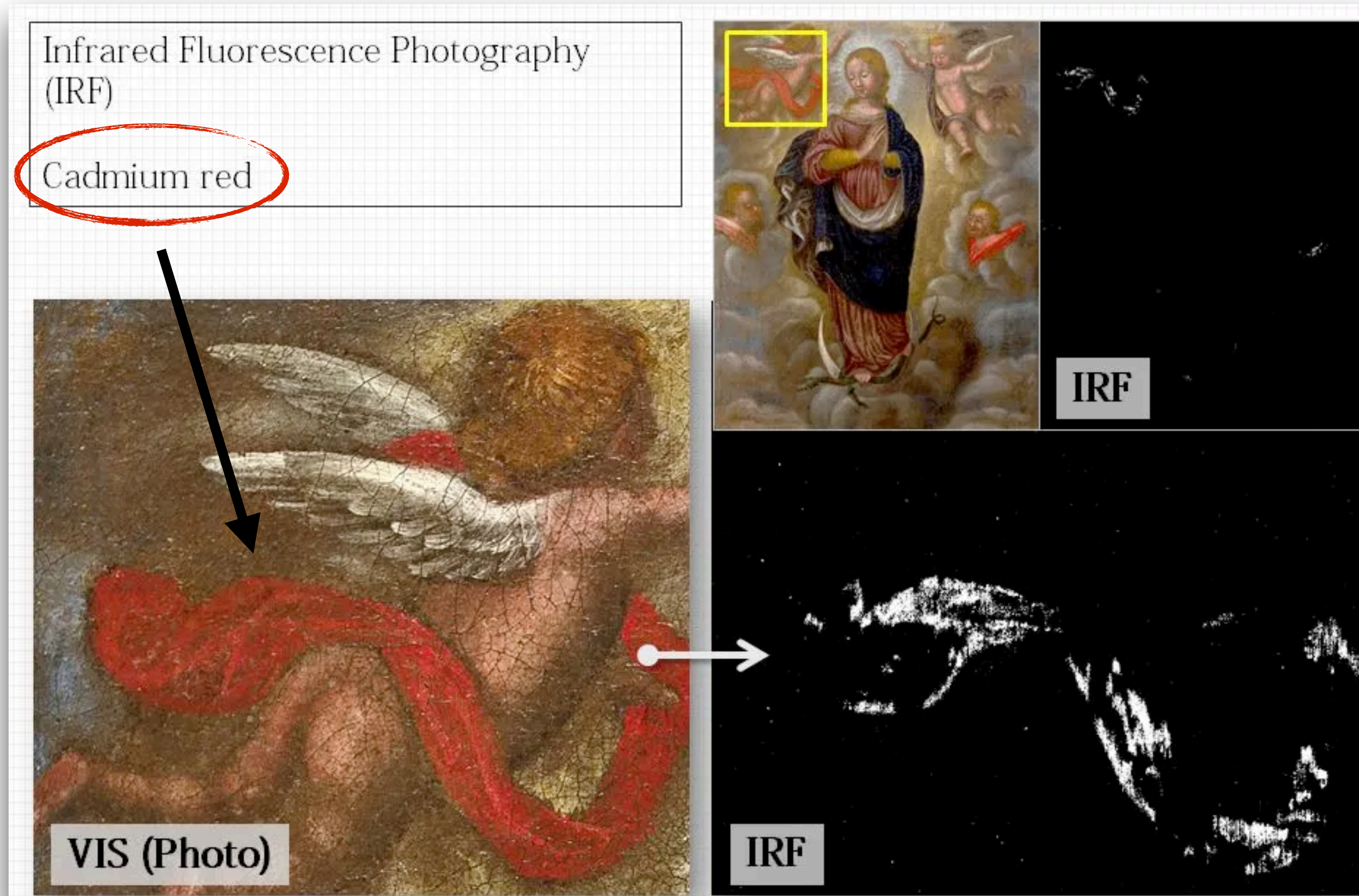


# Fluorescence in Cultural Heritage





# Fluorescence in Cultural Heritage



Egyptian blue, cadmium red, and cadmium yellow exhibit IR fluorescence.

- Of historical significance.

IR fluorescence photography is used to detect even tiny fragments of, e.g., Egyptian blue pigment.



***Gothic Madonna with Child*, Rogier van der Weyden**  
The Paintings Gallery of the Academy of Fine Arts Vienna, Austria

**Under visible light**



**Under UV Fluorescence**



**Later retouches**



# Private postcard

Under visible light

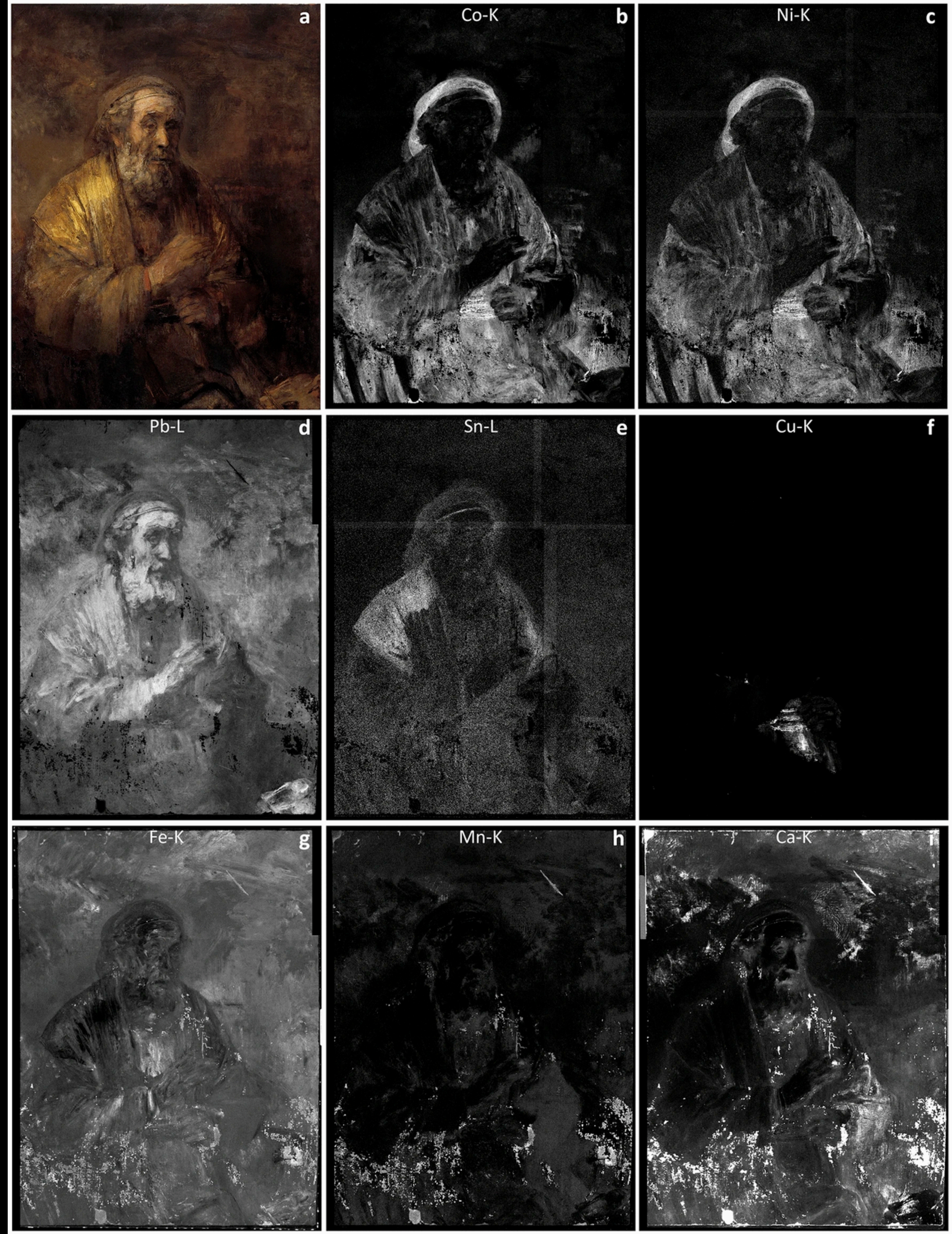


Under UV Fluorescence



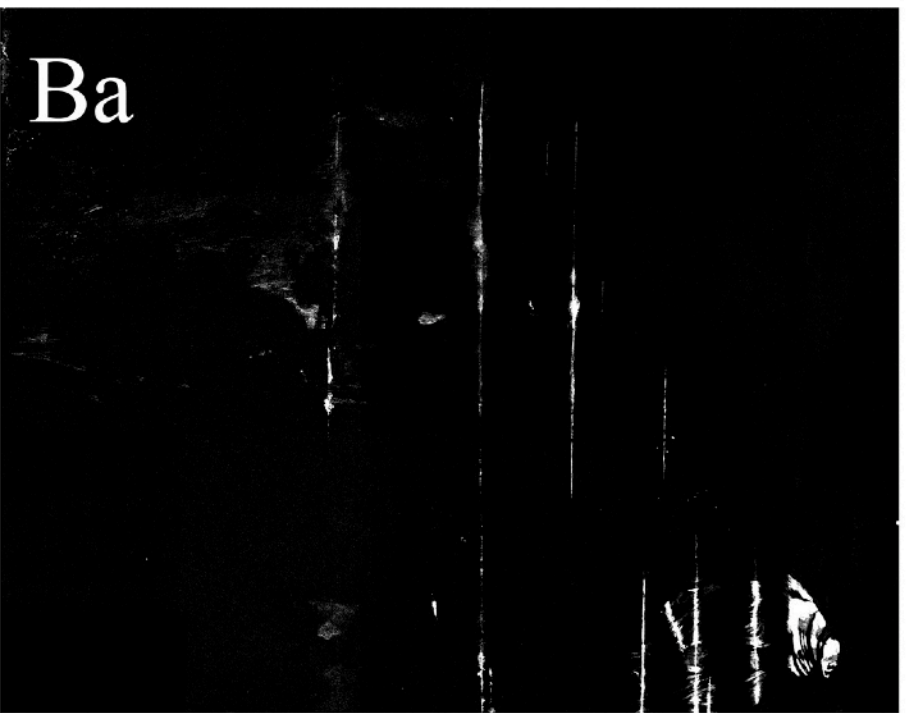
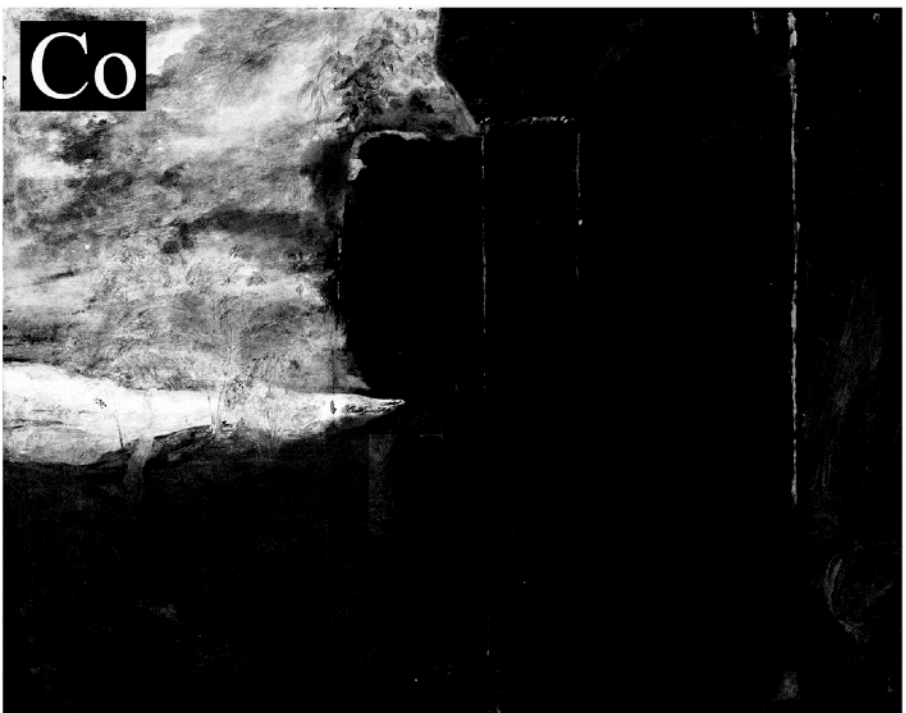
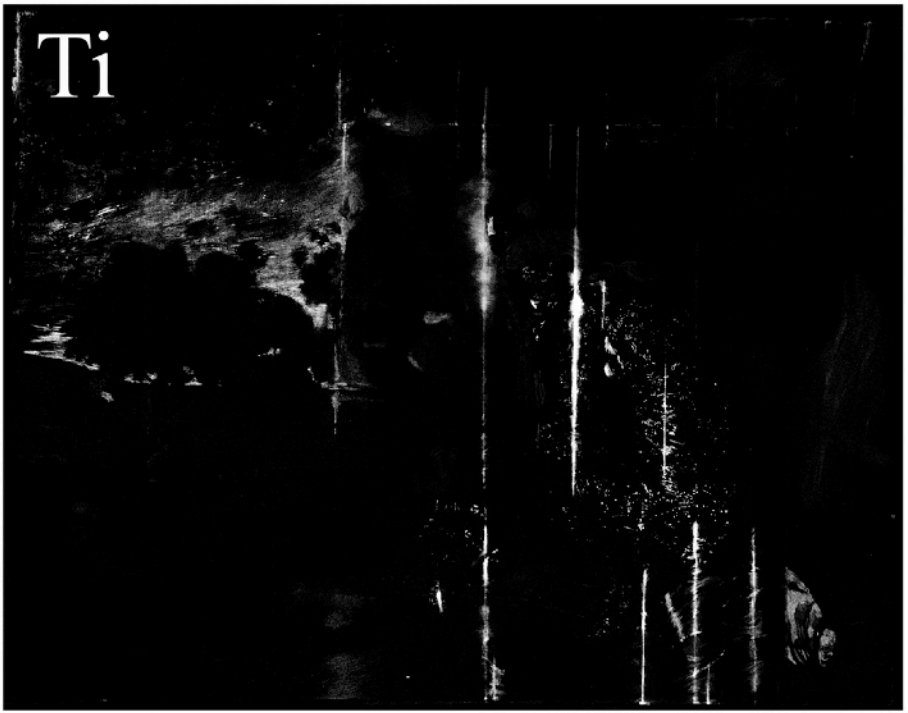
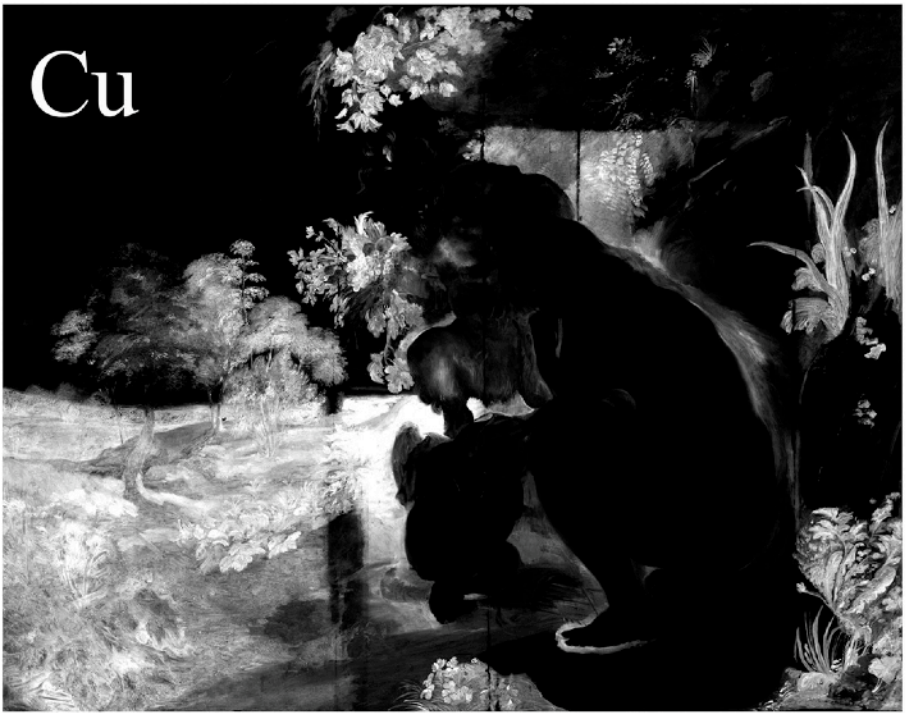
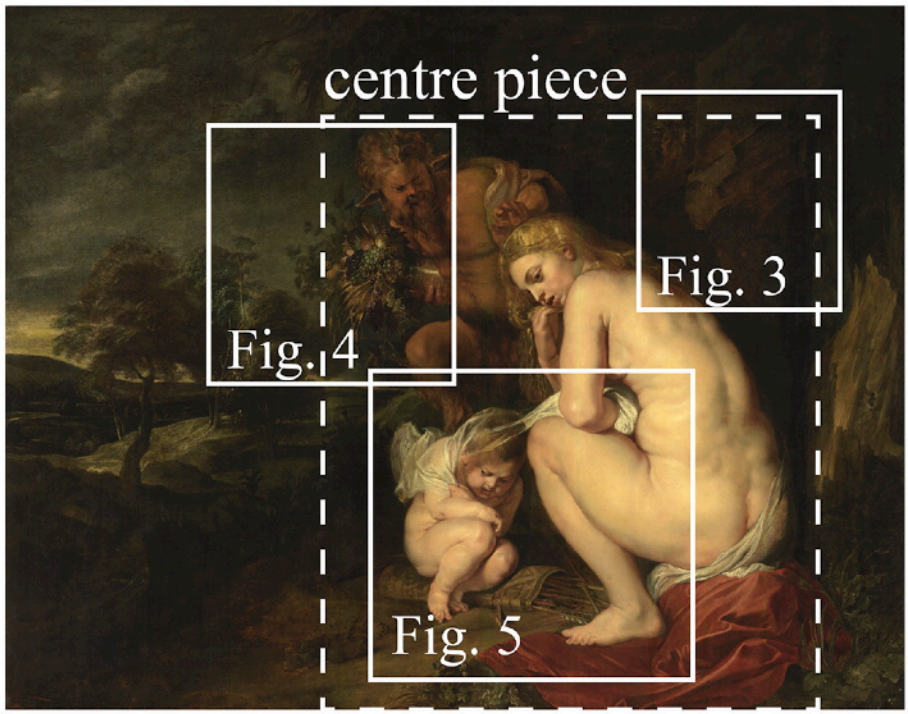


*Homer Dictating his Verses*, Rembrandt,  
1663. Mauritshuis Netherlands





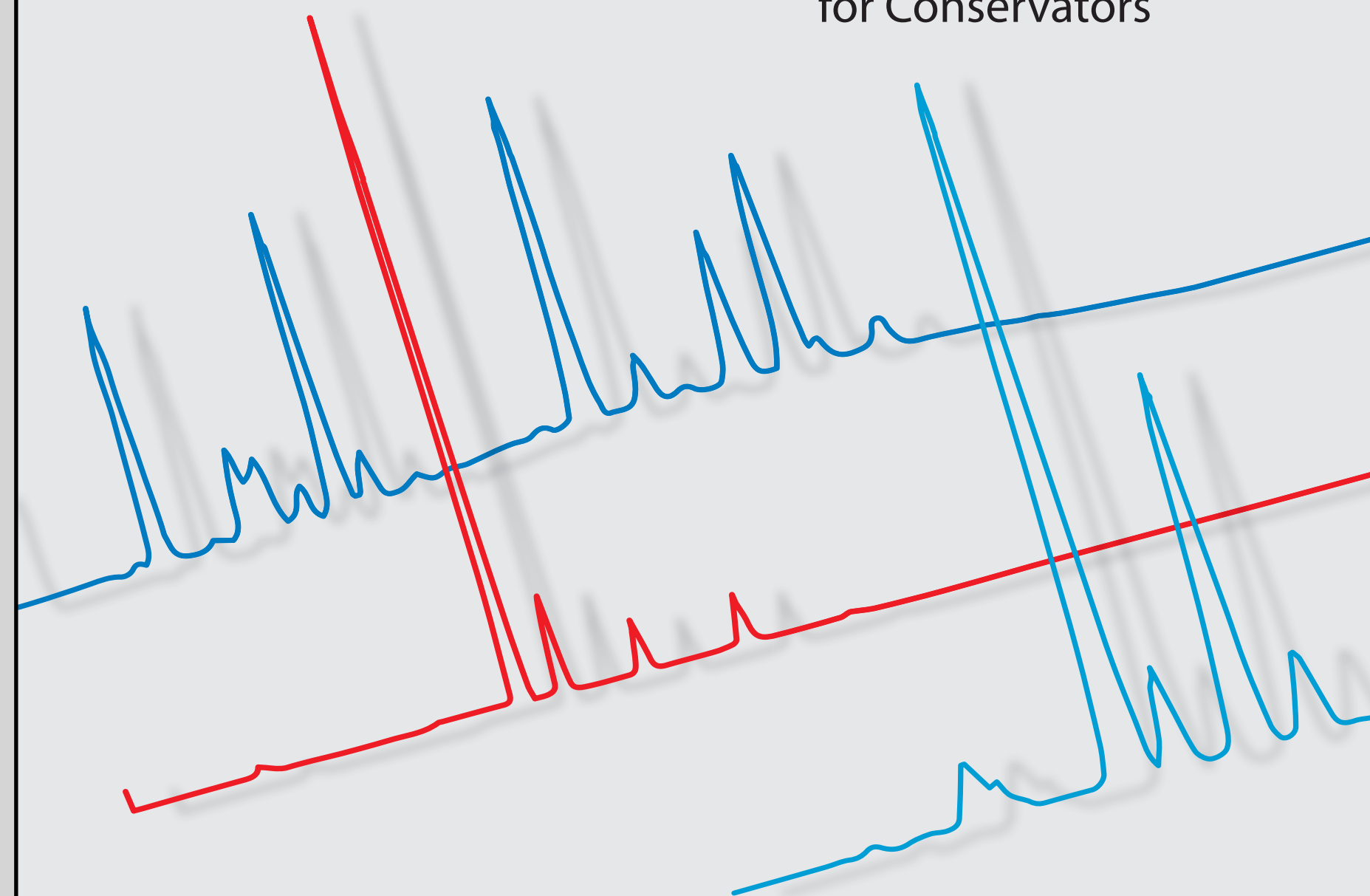
*Venus Frigida*, P. P. Rubens, 1614.  
Royal Museum for Fine Arts Antwerp.





# Handheld XRF In Cultural Heritage

A Practical Workbook  
for Conservators



Anikó Bezur | Lynn Lee | Maggi Loubser | Karen Trentelman

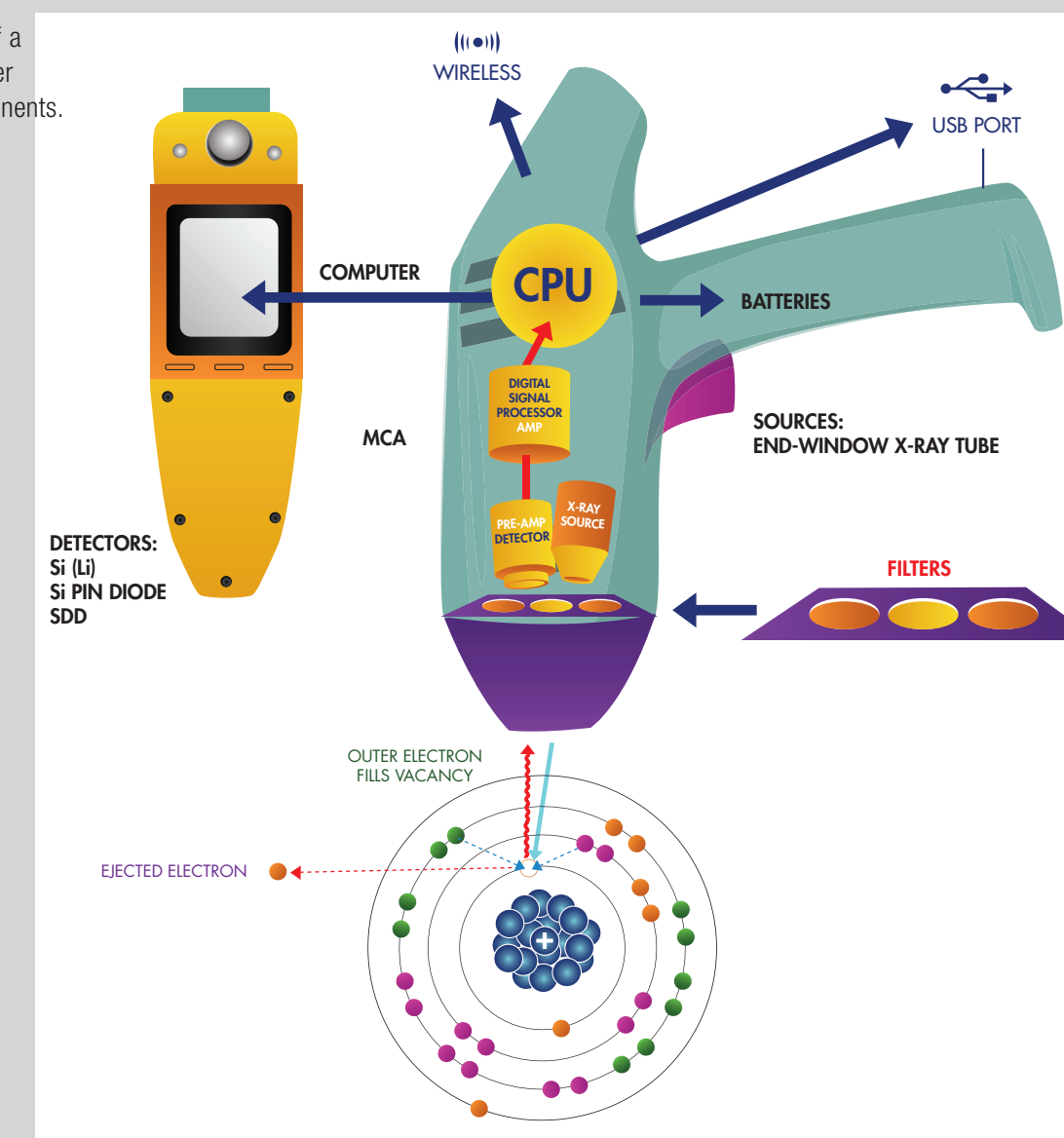
Getty Conservation Institute

In XRF spectroscopy, scattering is usually undesirable, but it can be exploited to get an idea of the output of the X-ray tube. Taking advantage of the fact that scattering is strongest in low Z materials, the spectrum acquired from a “blank” sample (i.e., something with no analyte peaks as would be provided by a material containing only low Z elements such as C, O, and N; e.g., polyethylene foam) consists only of X-rays from the tube that have been scattered from the sample. As discussed below and explored in exercise 2.3a, this approach can help us to understand how the tube output is affected by the choice of target material, voltage, and current.

## 2.2 The XRF Spectrometer

All XRF spectrometers, whether handheld or laboratory based, have the same main components: an X-ray source, filters or other beam modifiers, a detector, signal processors, and a means of recording the data (a computer). A schematic illustration of a spectrometer appears in figure 2.8. Briefly, a low-amperage, high-voltage supply enables X-rays to be generated in the tube. These X-rays leave the tube through a beryllium window and pass through primary beam filters (if any) before irradiating the sample. Fluorescent X-ray photons generated in the sample—as described in the next section—are then detected, preamplified, and processed in the digital signal processor or multichannel analyzer (MCA). From here, data are collected and stored in the central processing unit (CPU) of a computer as an XRF spectrum. Each of these components is discussed in the following sections, with the processes occurring in each component described.

**FIGURE 2.8.** Diagram of a handheld XRF spectrometer illustrating its main components.



Handheld XRF in Cultural Heritage

23



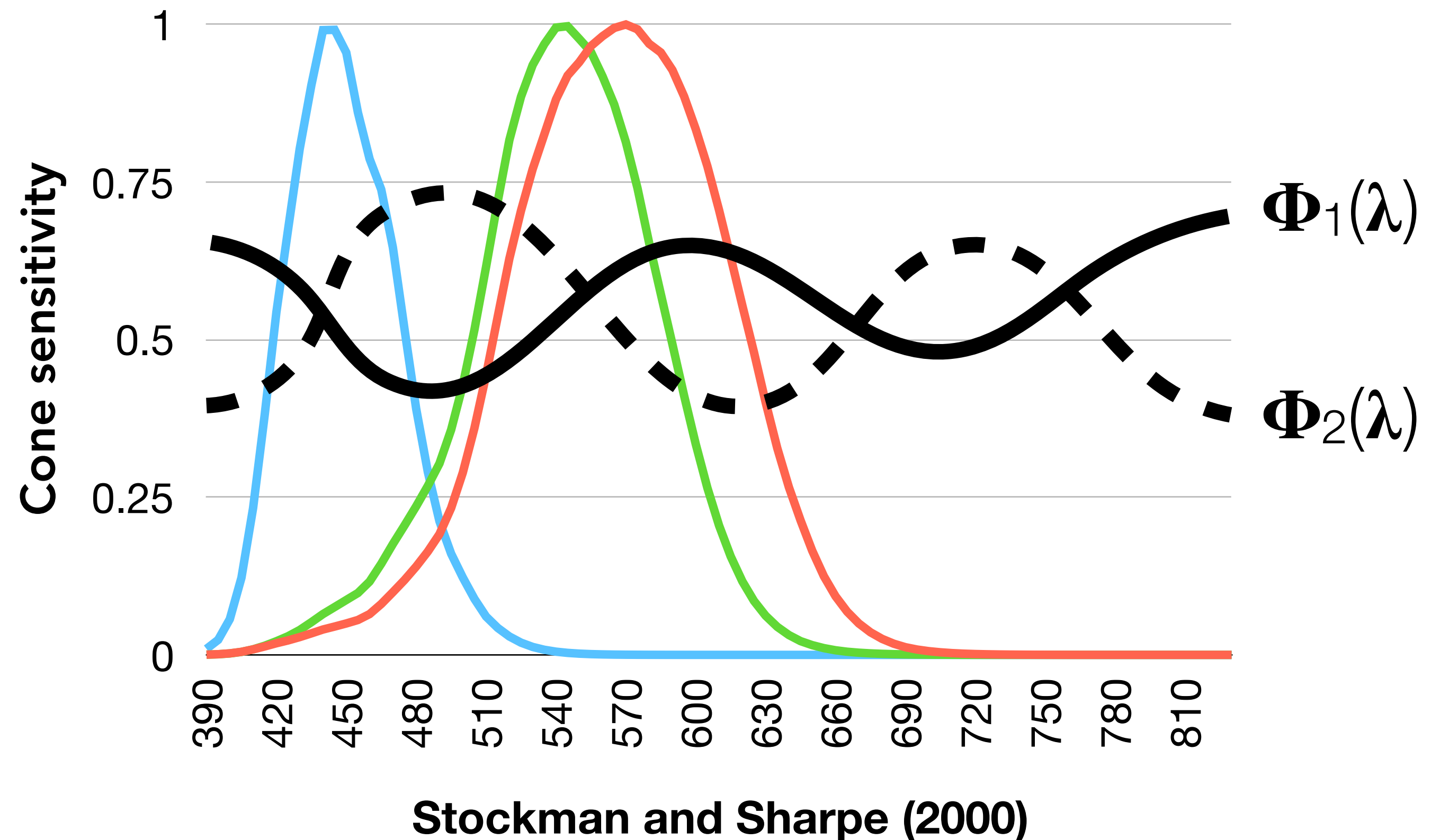
# Displays



# Recall: Metamerism

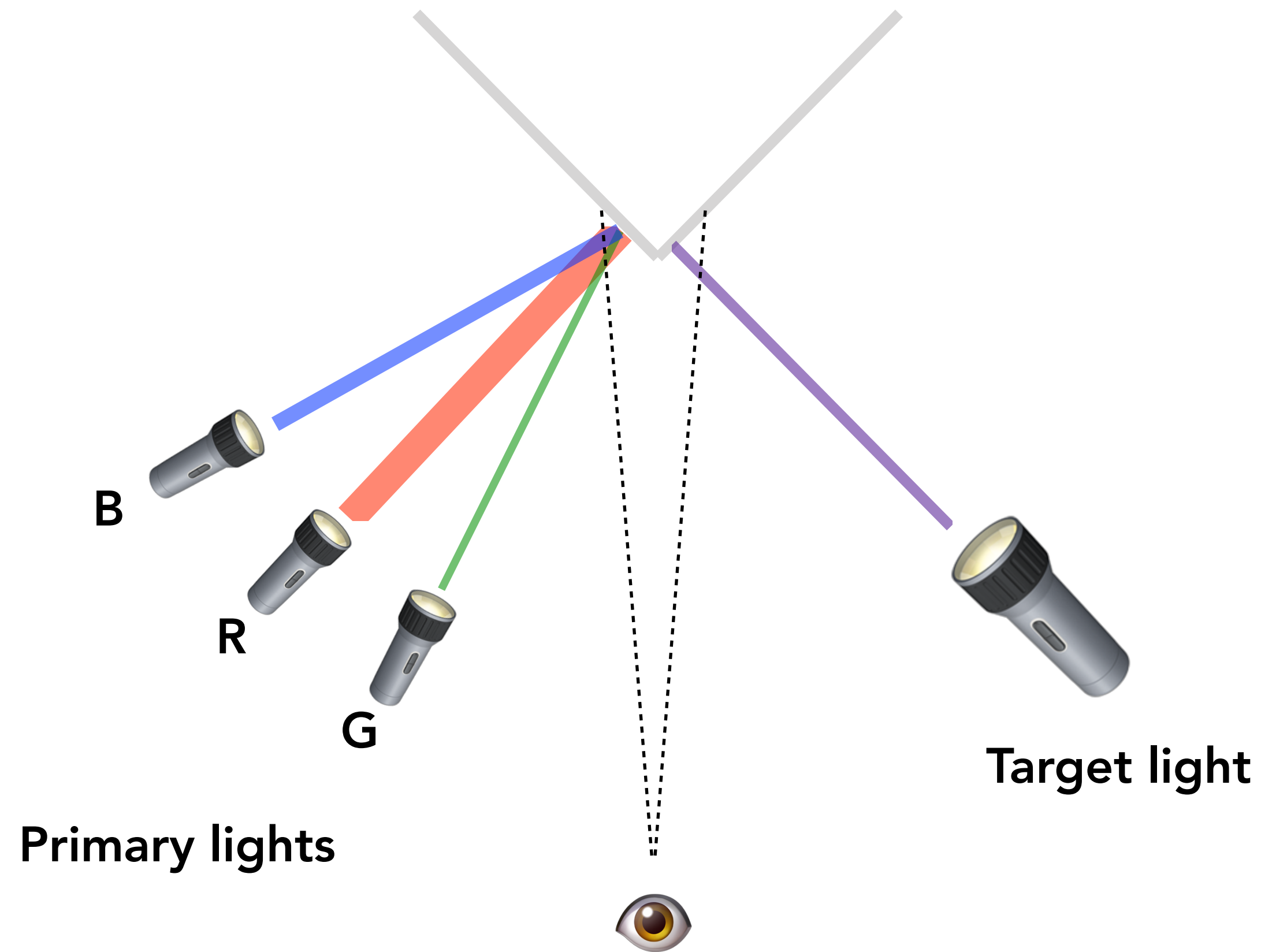
The two lights are metamers of each other if their LMS responses match.

$$\begin{aligned}\sum_{\lambda} \Phi_1(\lambda)L(\lambda) &= \sum_{\lambda} \Phi_2(\lambda)L(\lambda) \\ \sum_{\lambda} \Phi_1(\lambda)M(\lambda) &= \sum_{\lambda} \Phi_2(\lambda)M(\lambda) \\ \sum_{\lambda} \Phi_1(\lambda)S(\lambda) &= \sum_{\lambda} \Phi_2(\lambda)S(\lambda)\end{aligned}$$





# Recall: Trichromatic Theory of Color



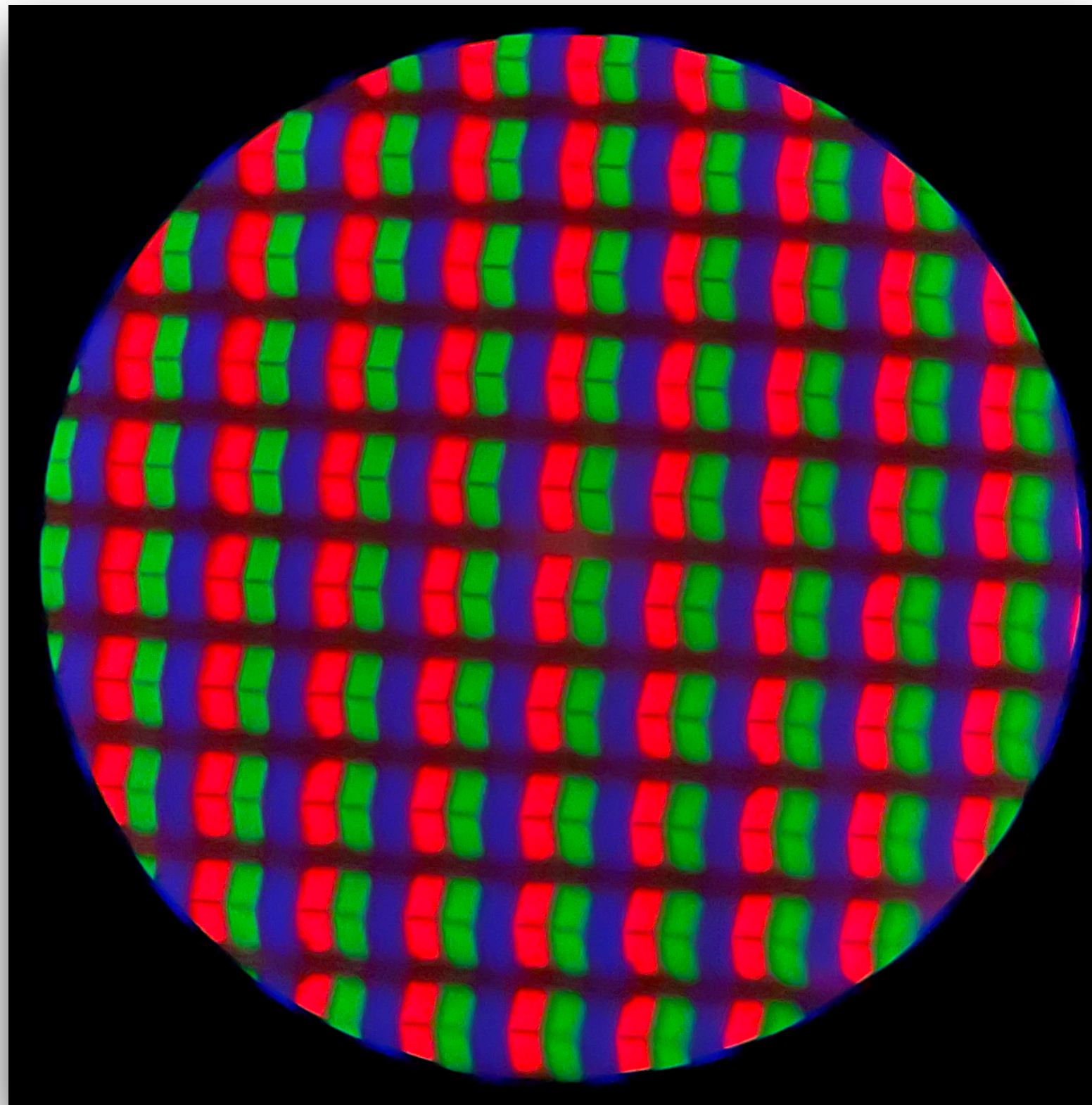
We can match the color of a given light by mixing three primary colors.

- Provided that the primaries are carefully chosen so that the target color falls within the gamut of the color space.

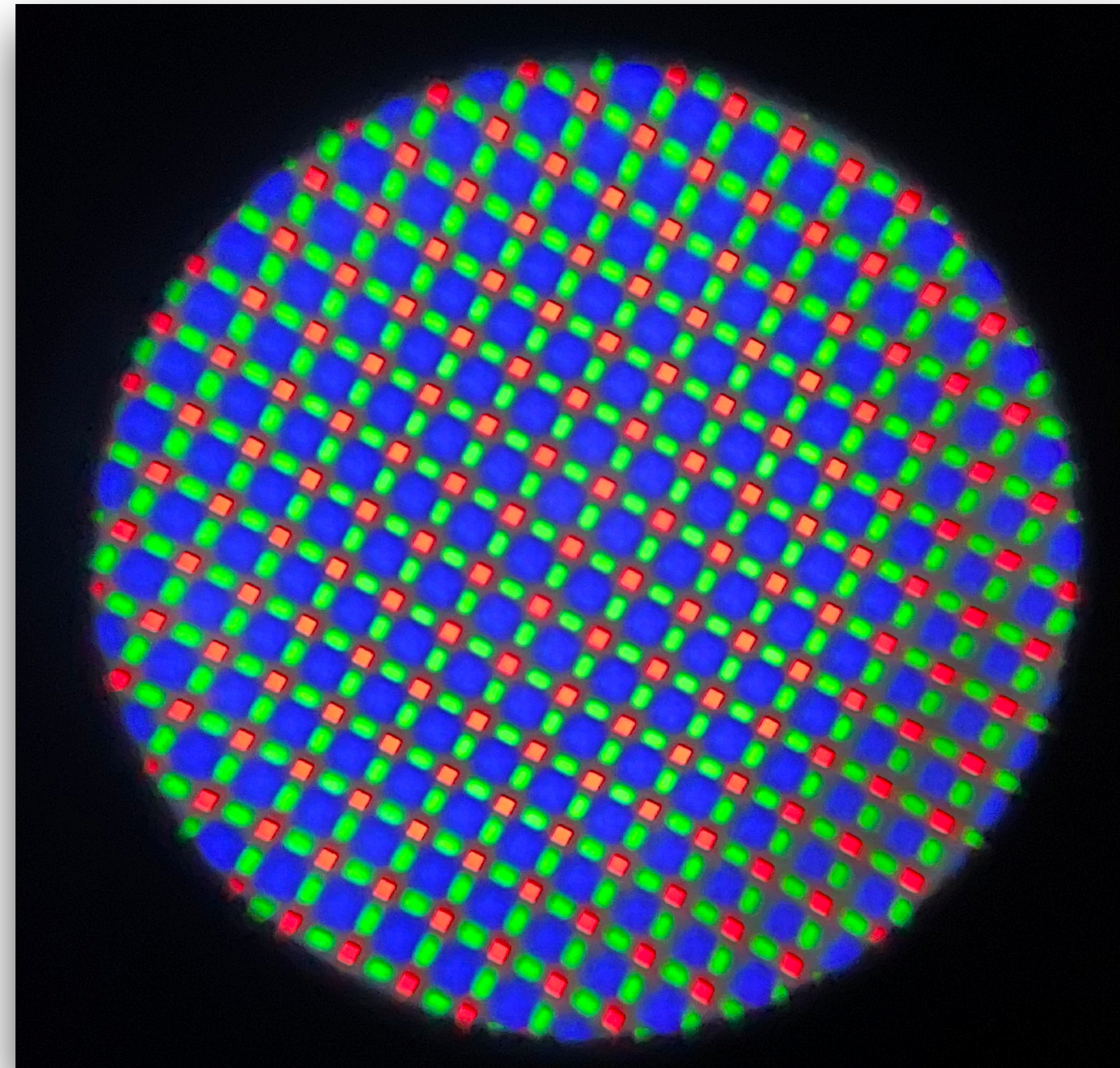
For displays, this means we don't need to produce the exact light **spectrum** if our goal is simply to produce the desired **color**.



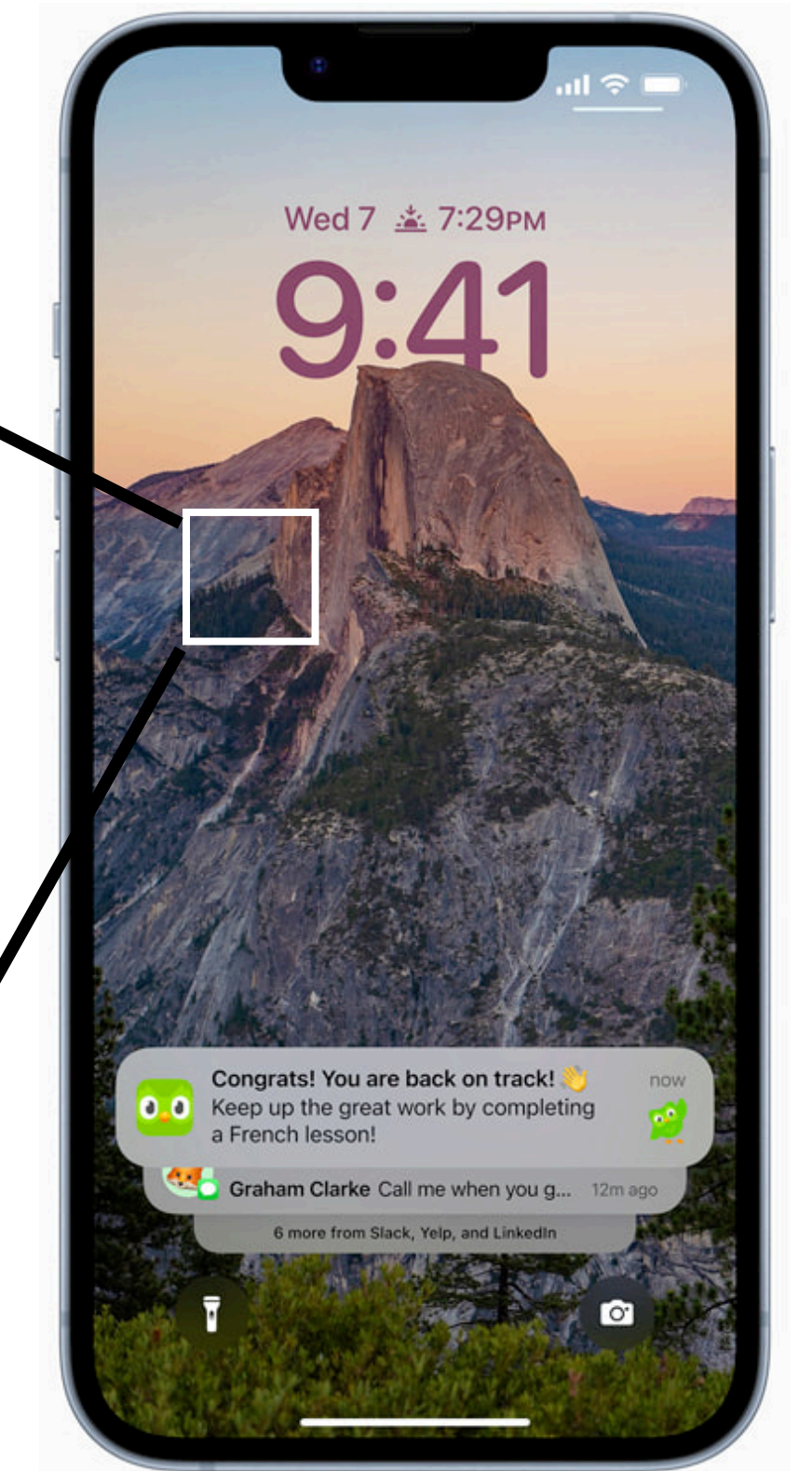
# Basic Principle: Spatial Integration



iPhone 6



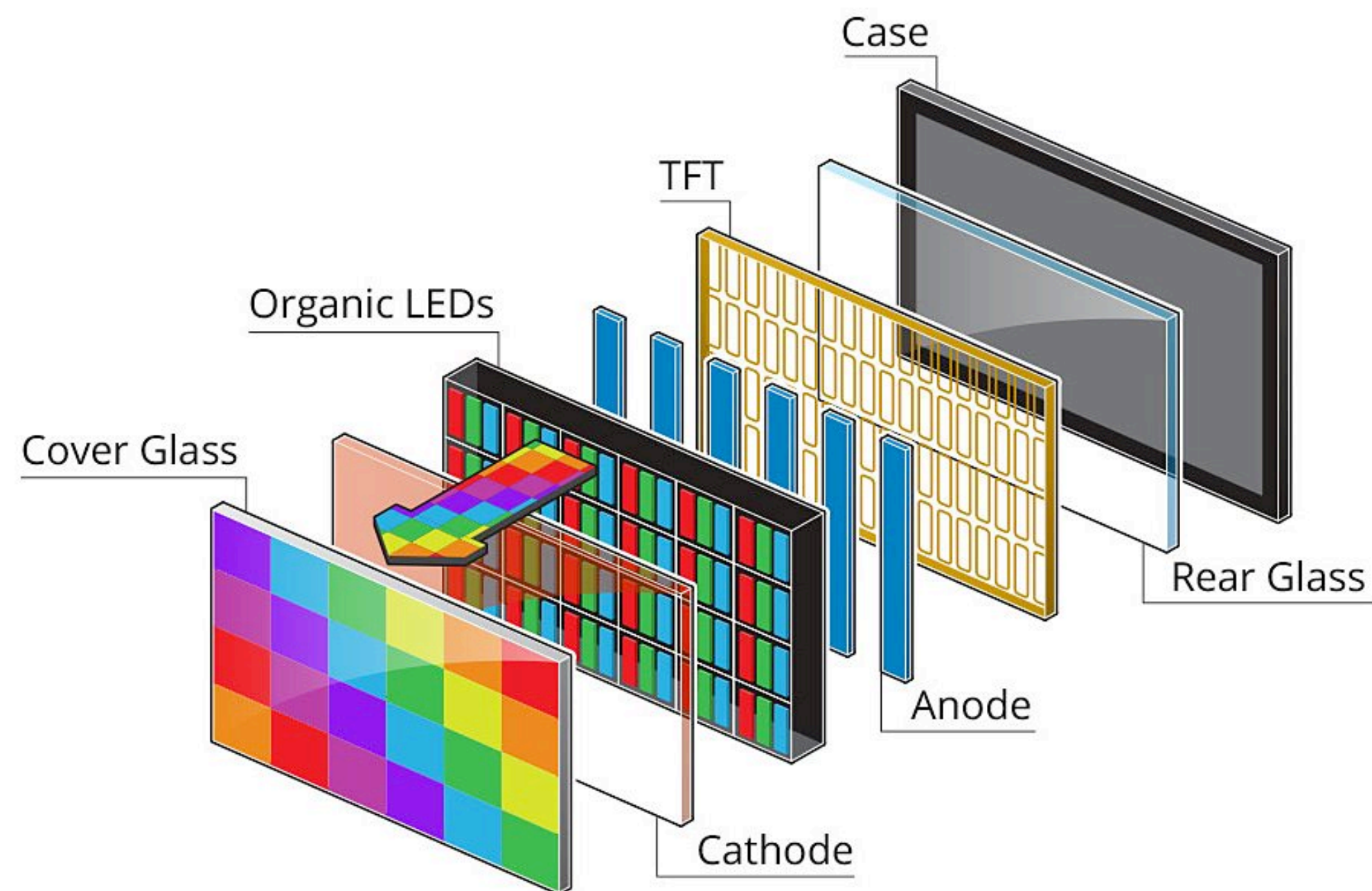
iPhone 14 Pro



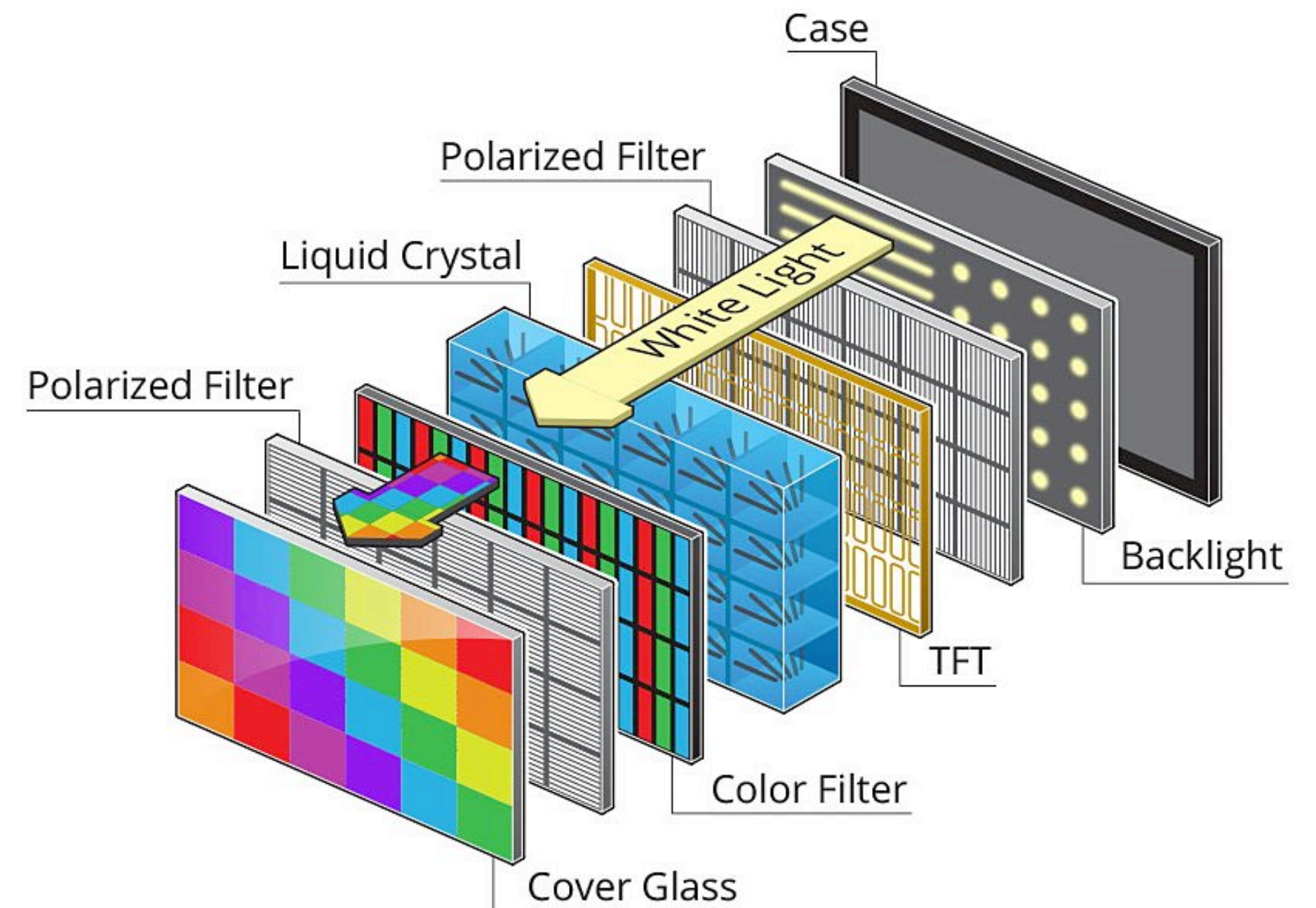


# Two Main Display Mechanisms

## Emissive Displays (e.g., OLED)

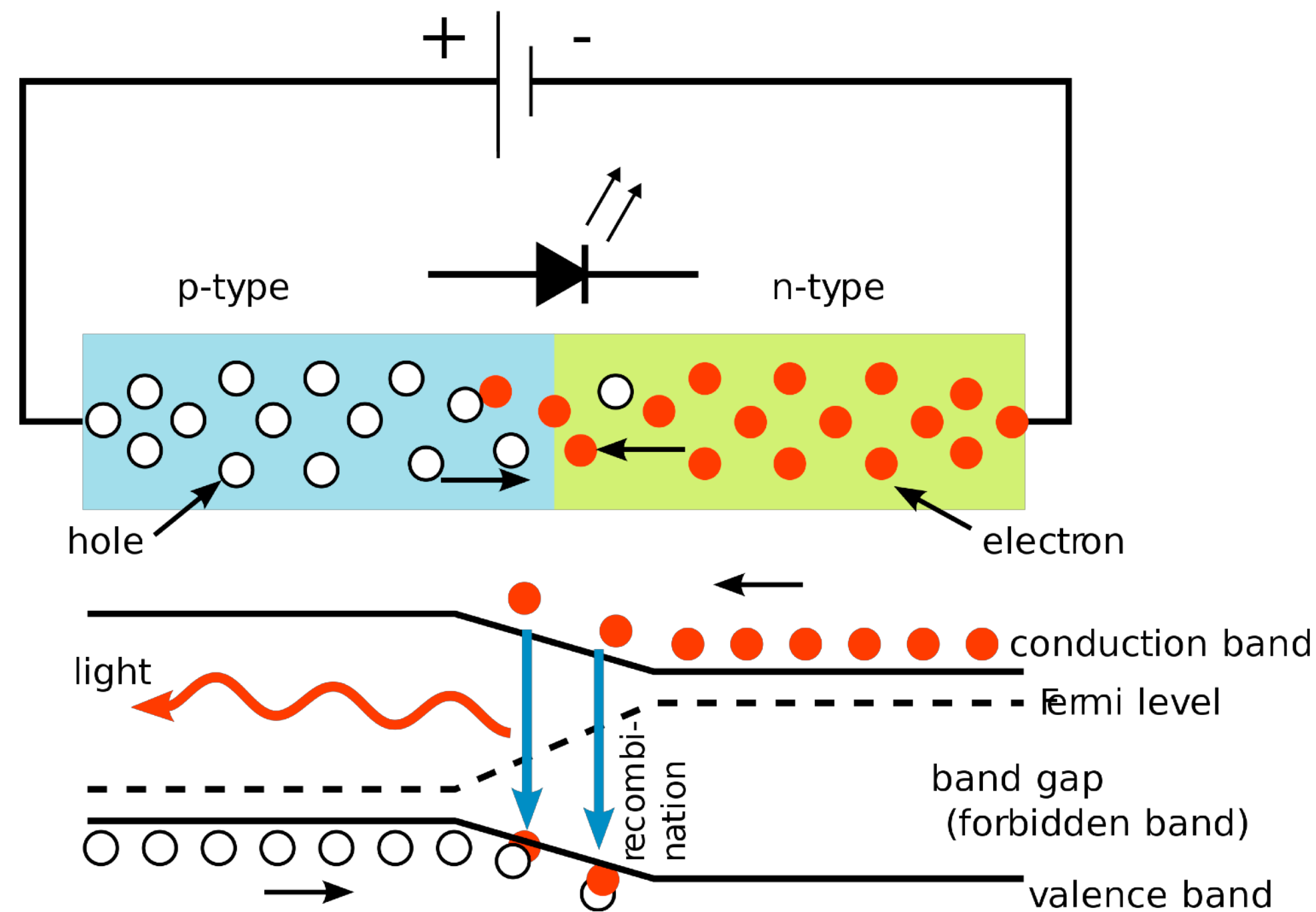


## Light-Filtering Displays (e.g., LCD/Projector)





# Light-Emitting Diodes: Photons From Electrons



External power creates potential differences that move electrons from the n-side (higher energy state) to the p-side (lower energy state), releasing photons.

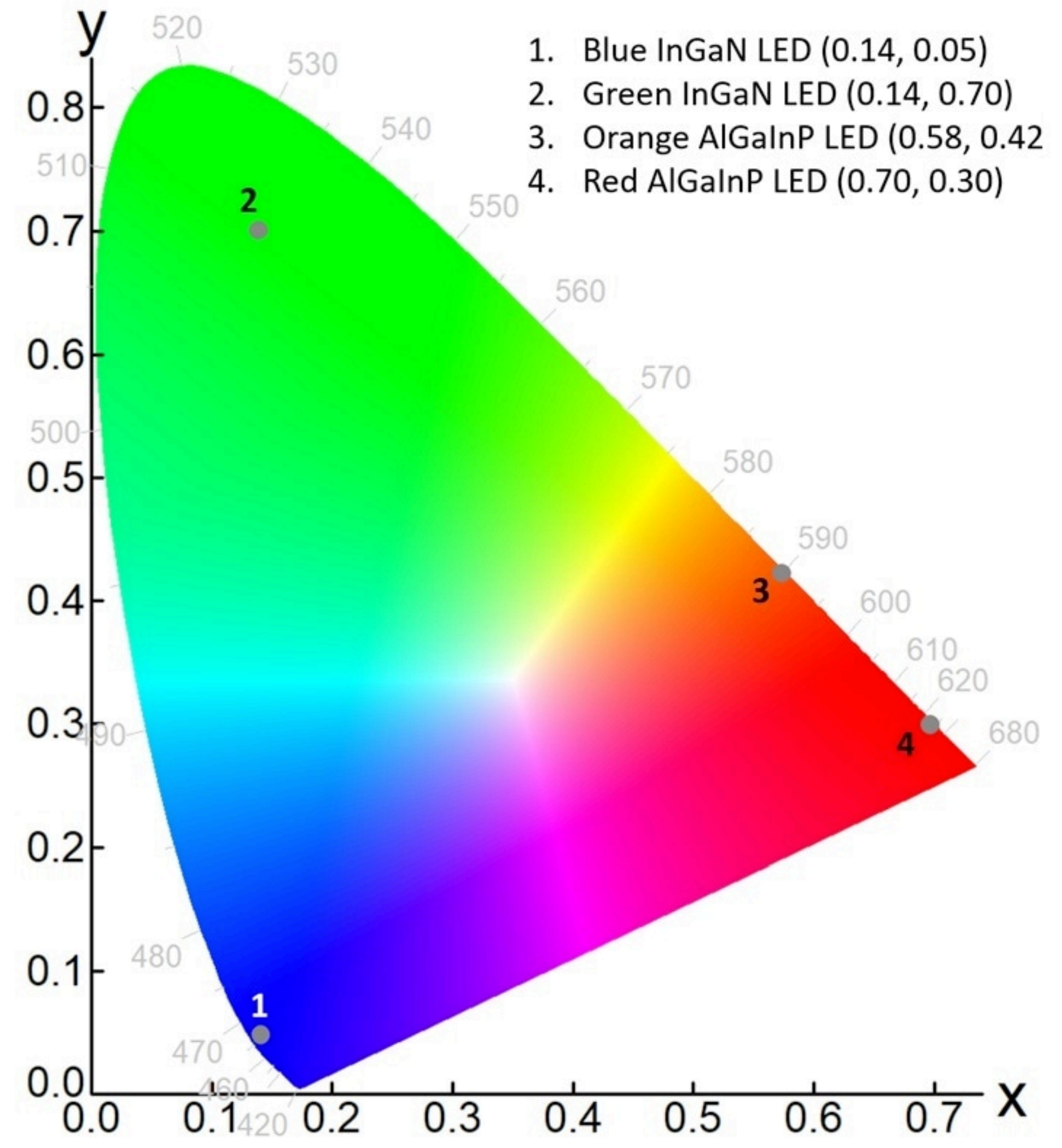
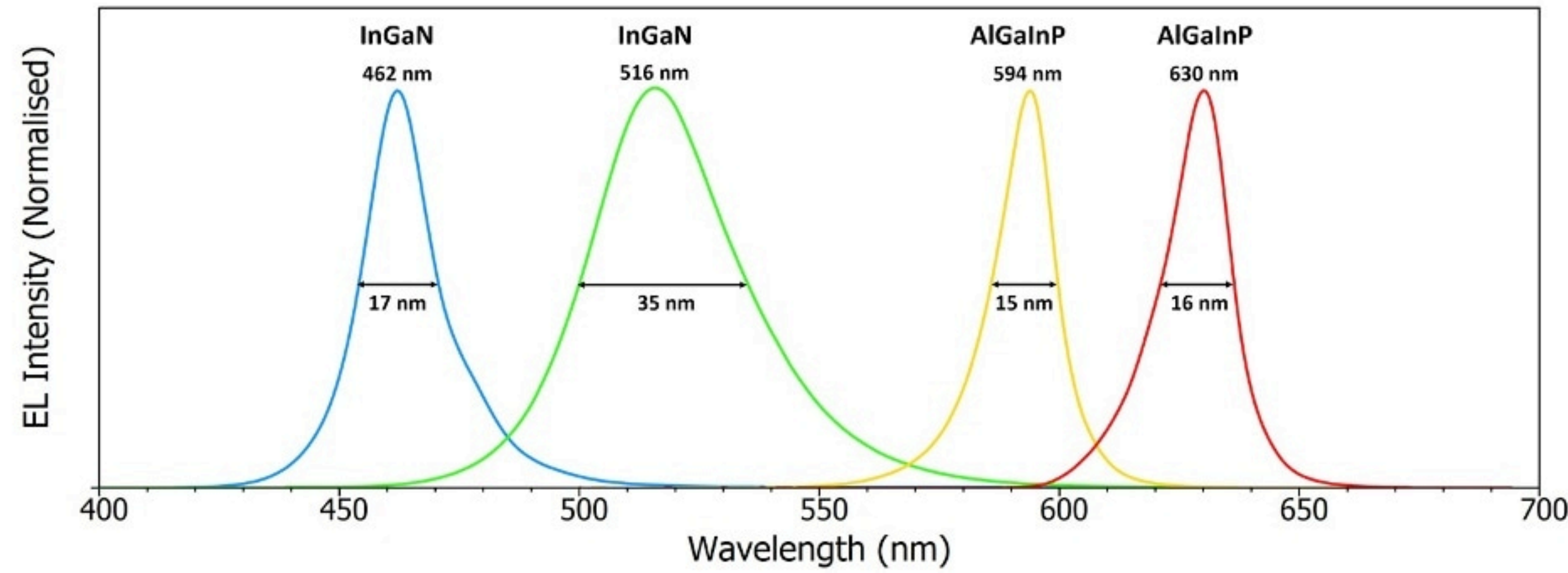
The photon wavelength depends on the energy gap, which depends on material.

A form of electroluminescence.

- Variants: OLED, QLED, AMOLED, etc.
- Two common materials: AlGaInP and InGaN.

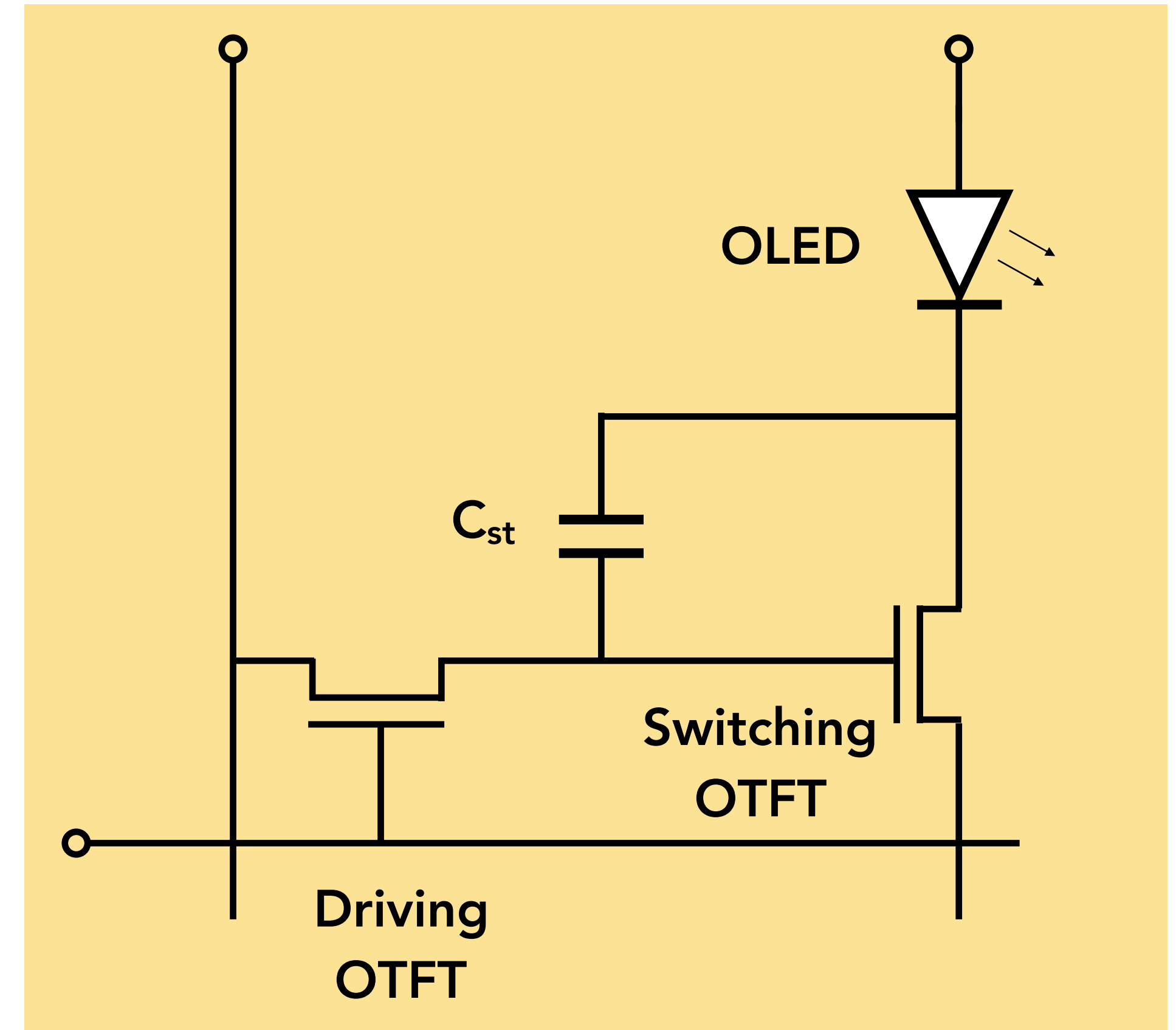
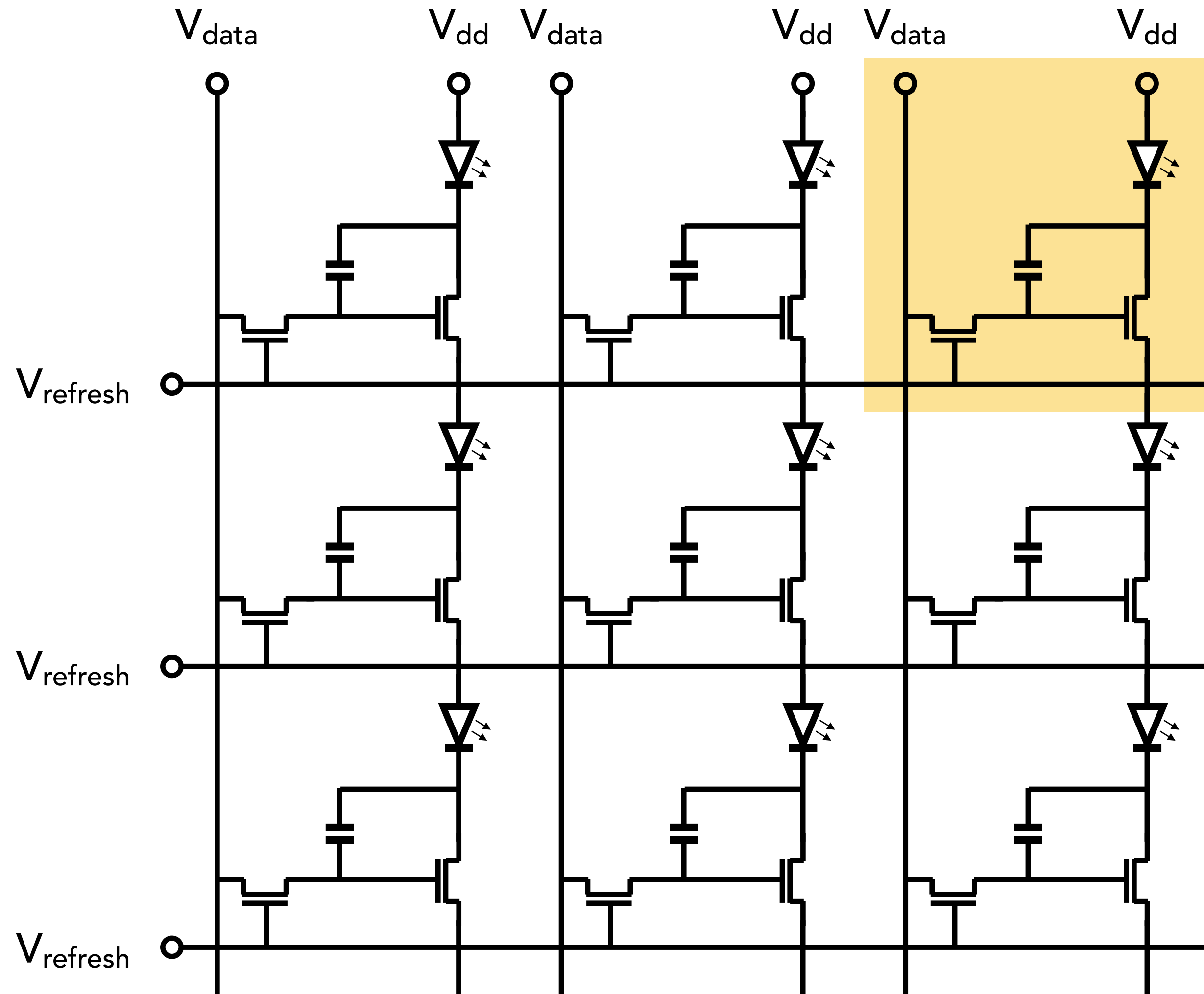


# Light-Emitting Diodes (LED)





# OLED Pixel Circuit





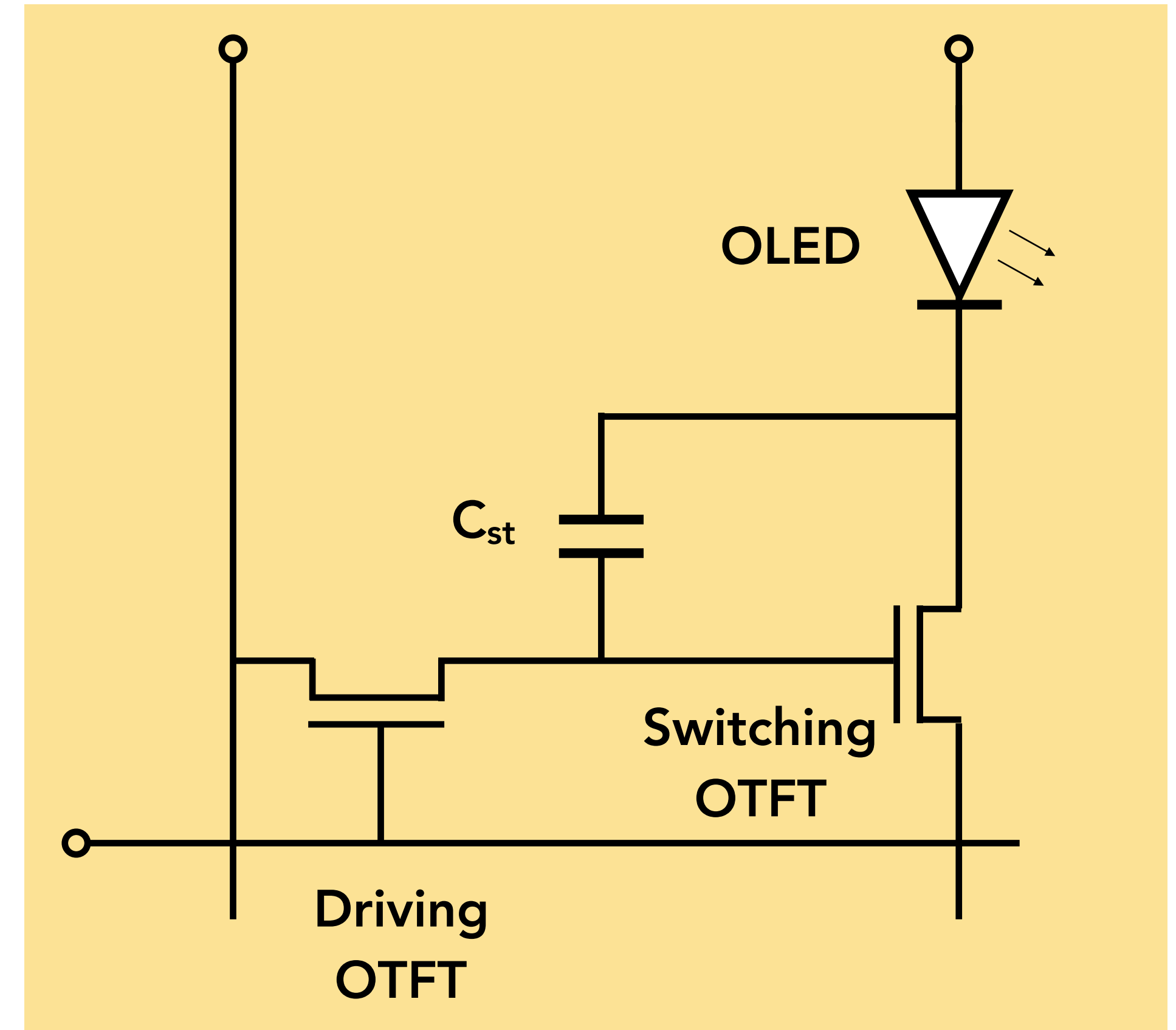
# OLED Pixel Circuit

The array is organized much like a SRAM array.

Each row is refreshed separately.

The capacitor holds the charge before next refresh.

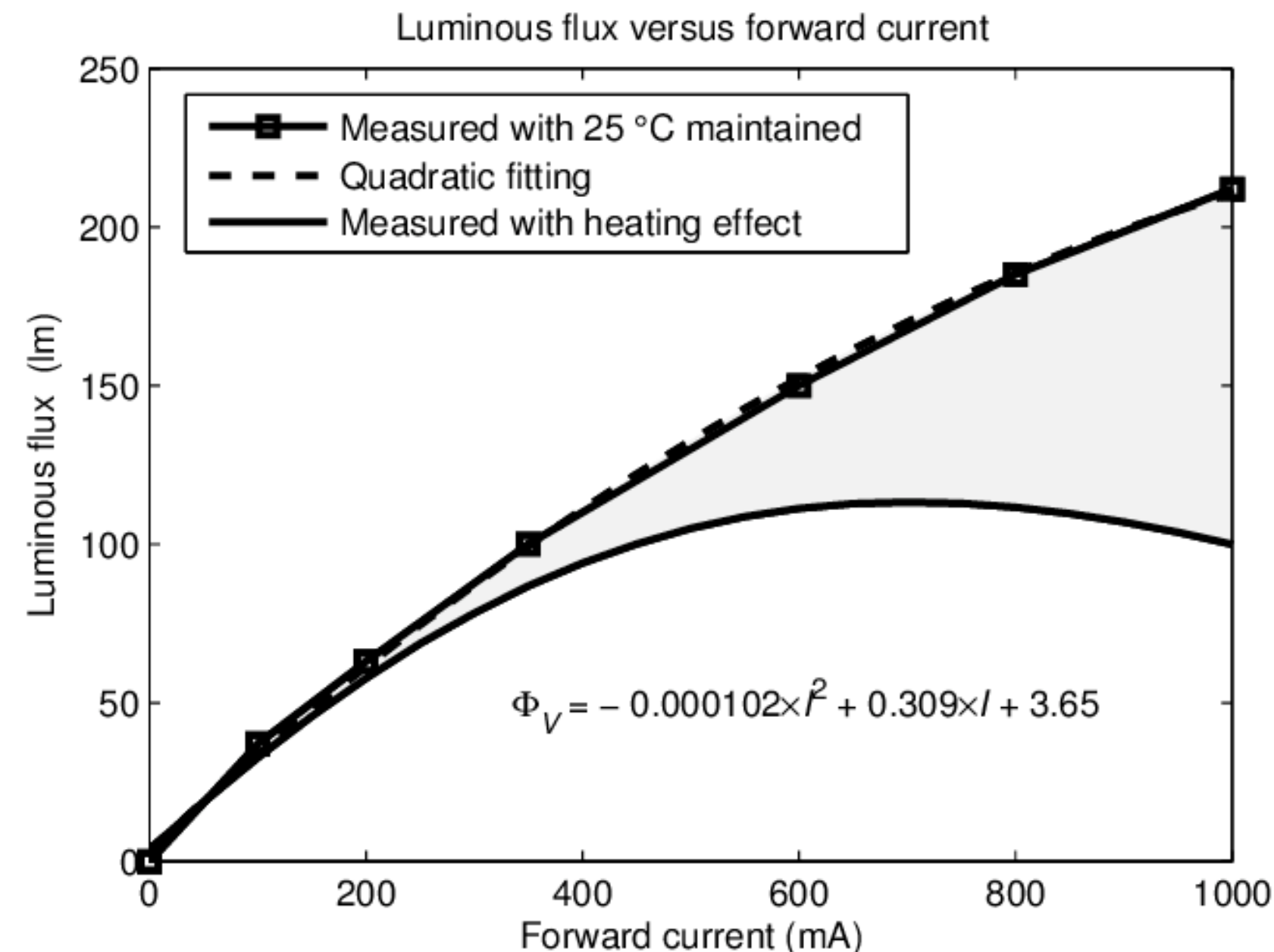
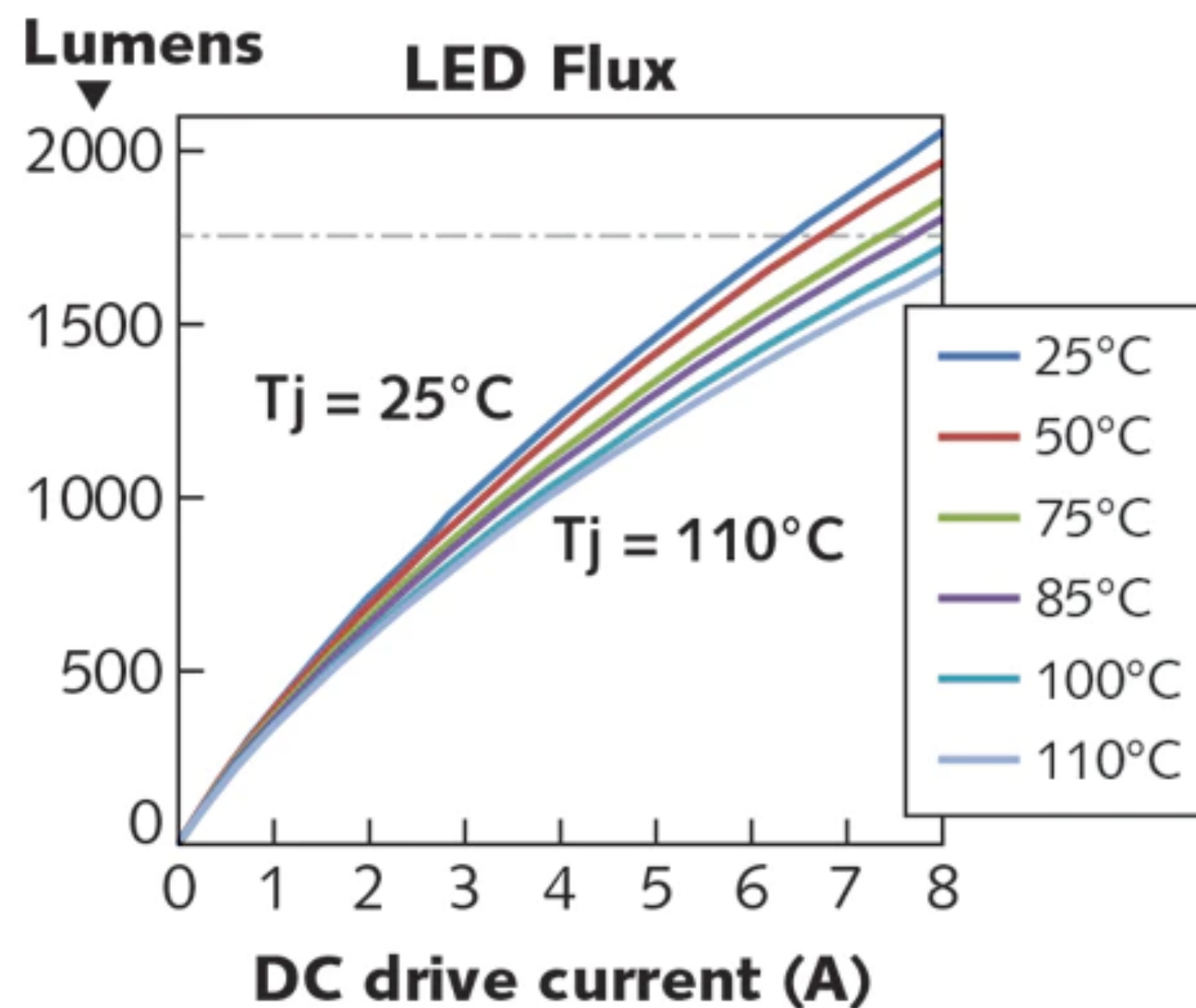
The two thin-film transistors (TFTs) control the charging of the capacitor and driving the OLED.





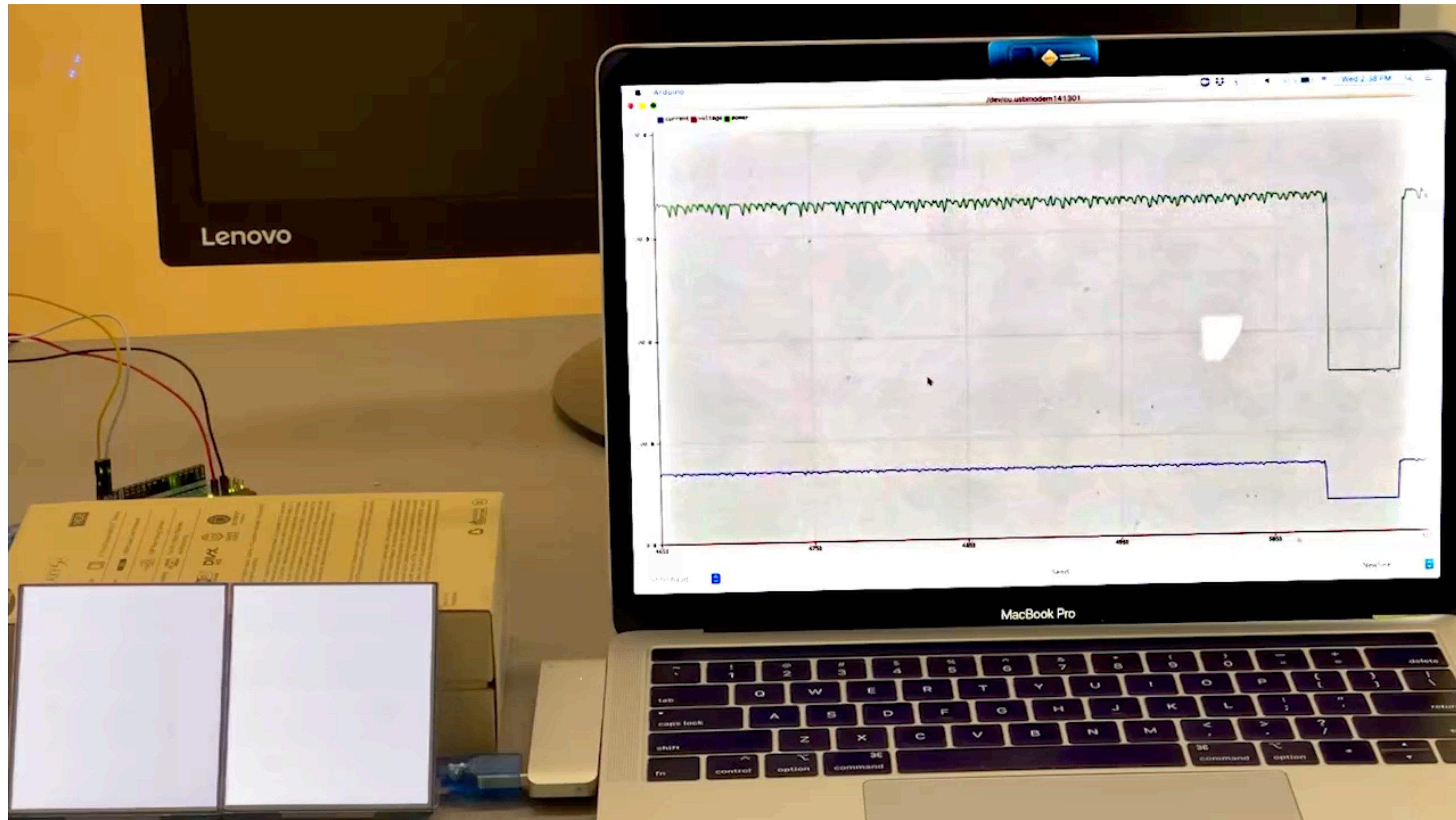
# Controlling Intensity of LEDs

The **higher** is the **current** of the driver circuit and the **lower** is the **temperature**, the higher is the light output intensity (luminous flux).



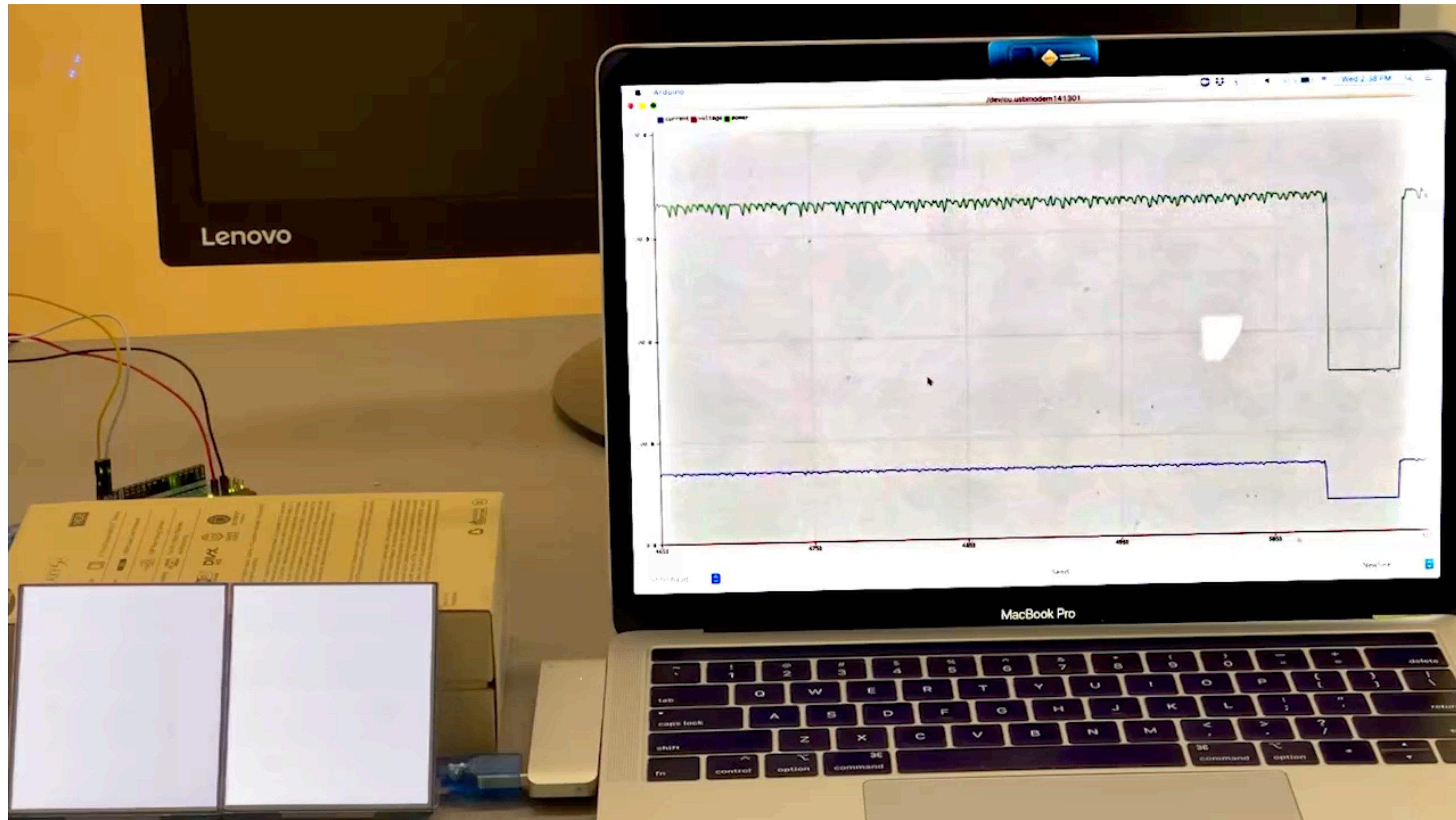


# OLED Display Power vs. Color





# OLED Display Power vs. Color



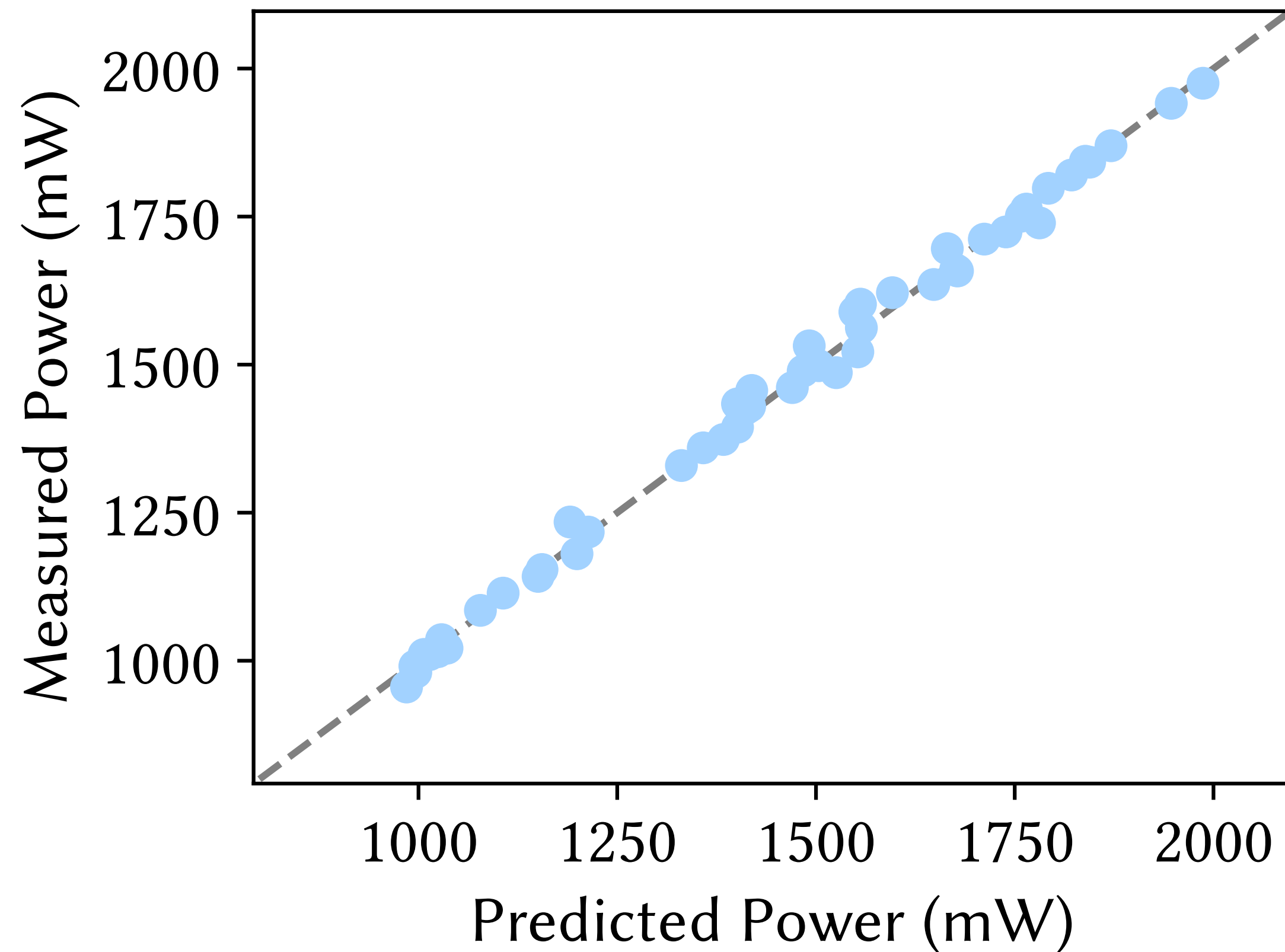
Power

Current



# OLED Display Power vs. Color

$$\text{Power} = 233.5 * \mathbf{R} + 209.6 * \mathbf{G} + 567.7 * \mathbf{B} + 983.8 \text{ (unit is mW)}$$



Wisecoco AMOLED Display (1200x1080)

## Setup:

- All pixels display the same color.
- R, G, B are linear sRGB values (without gamma) and in the [0, 1] range.

The intercept (983.8) represents the circuit power independent of color.



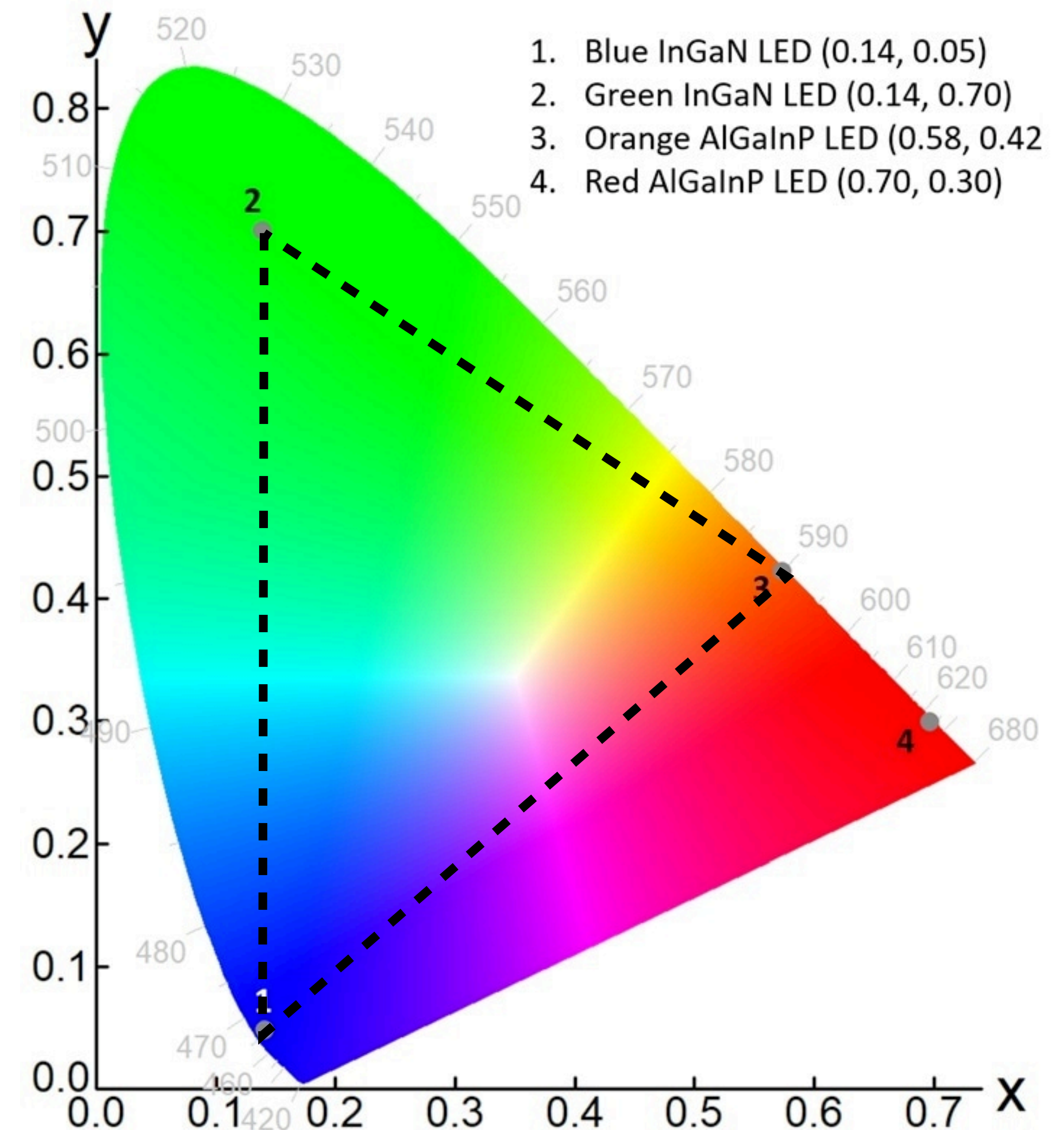
# Producing White in Emissive Display

Mixing different colored LEDs.

Trade-off:

- More primaries means more stable white (one primary being off a little doesn't affect the "whiteness" much).
- More primaries means more LEDs (form factor). The luminance efficacy (lumen/watt) might be lower depending on what LEDs are used.

LEDs age at different rates; adjustment.





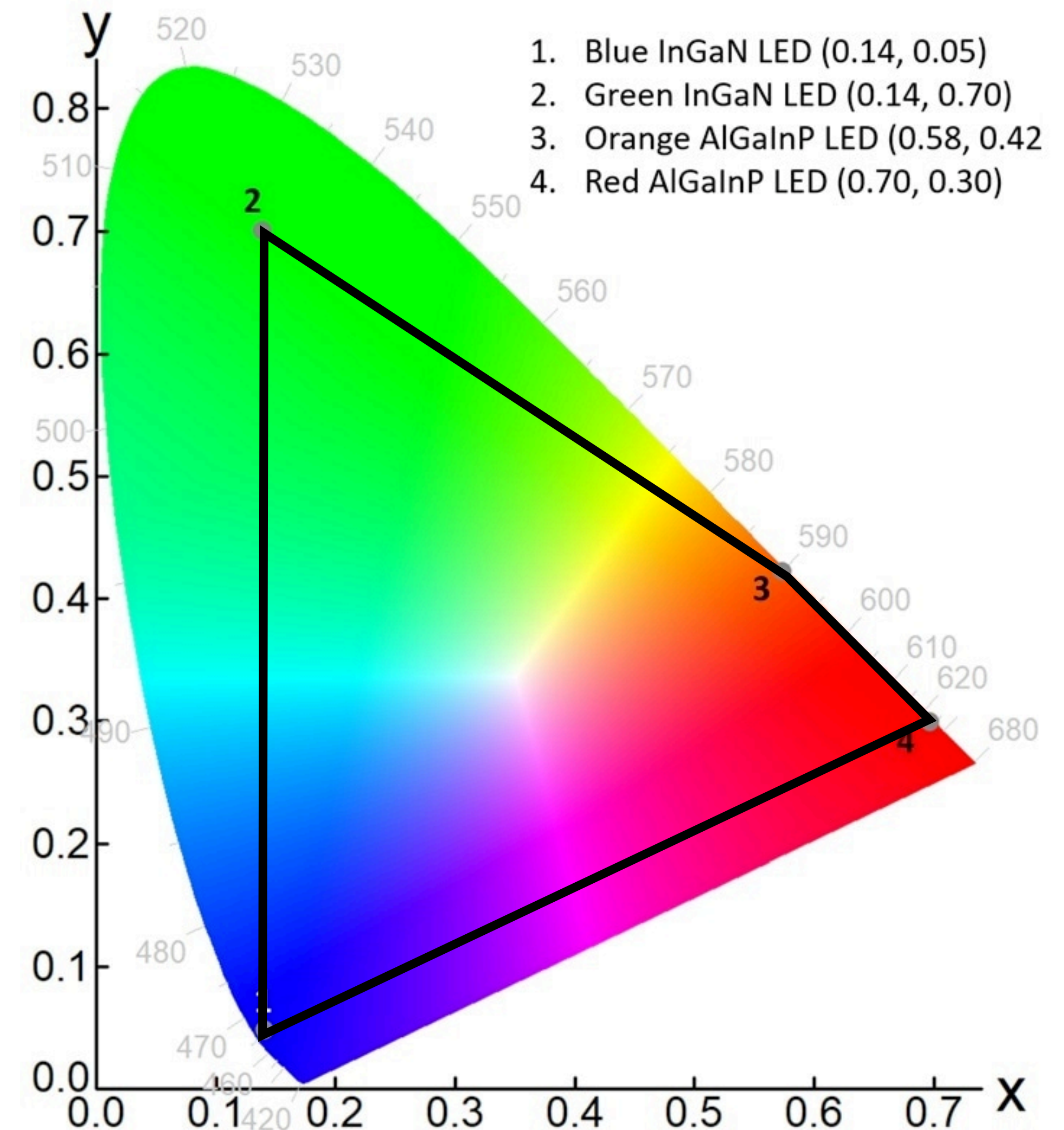
# Producing White in Emissive Display

Mixing different colored LEDs.

Trade-off:

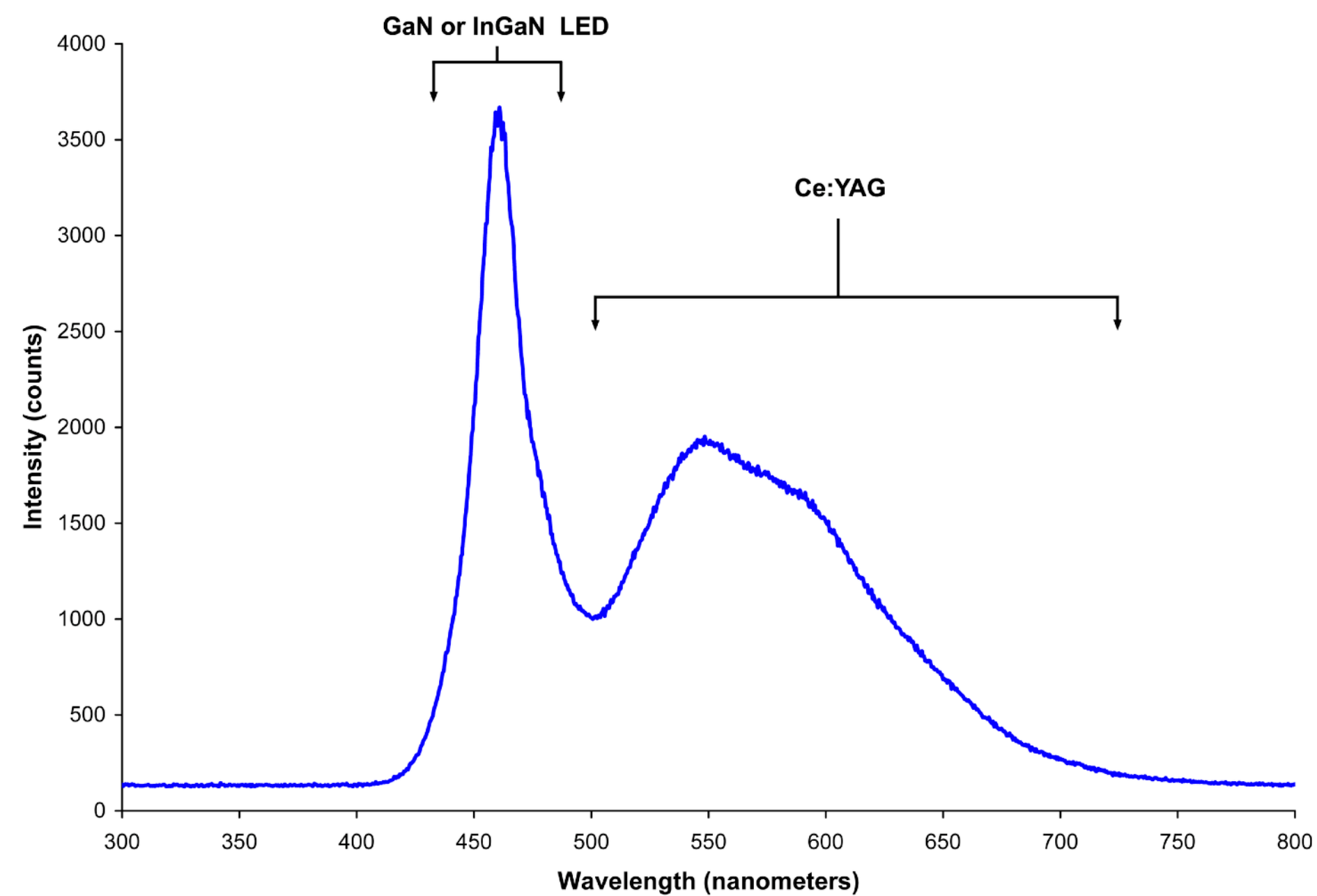
- More primaries means more stable white (one primary being off a little doesn't affect the "whiteness" much).
- More primaries means more LEDs (form factor). The luminance efficacy (lumen/watt) might be lower depending on what LEDs are used.

LEDs age at different rates; adjustment.





# White LED

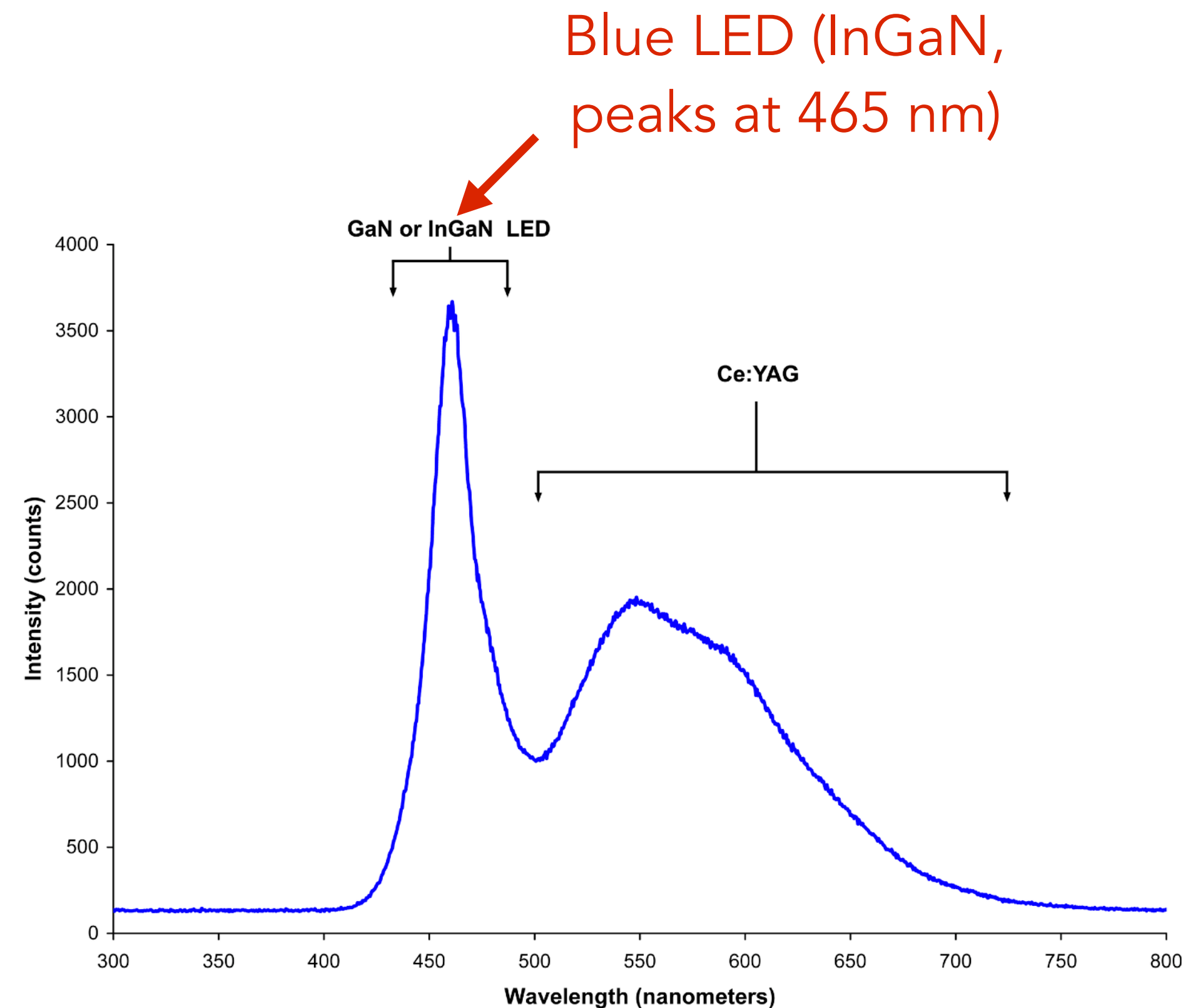


Use a blue LED to light fluorescent materials, which generate (usually) yellow spectrum.

- Also called “phosphor-converted white LED”.



# White LED

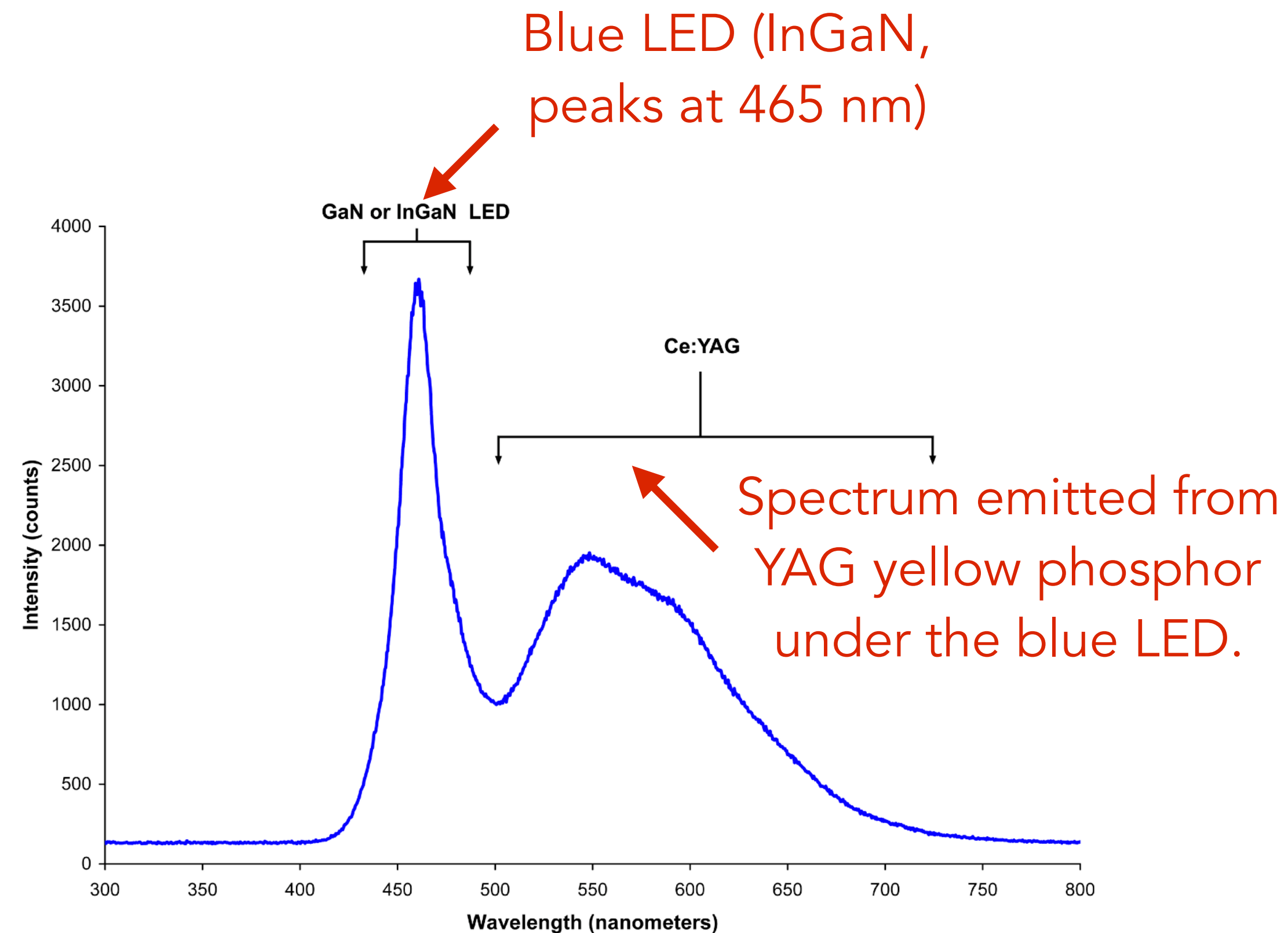


Use a blue LED to light fluorescent materials, which generate (usually) yellow spectrum.

- Also called “phosphor-converted white LED”.



# White LED



Use a blue LED to light fluorescent materials, which generate (usually) yellow spectrum.

- Also called “phosphor-converted white LED”.



# White LED

## Backlight

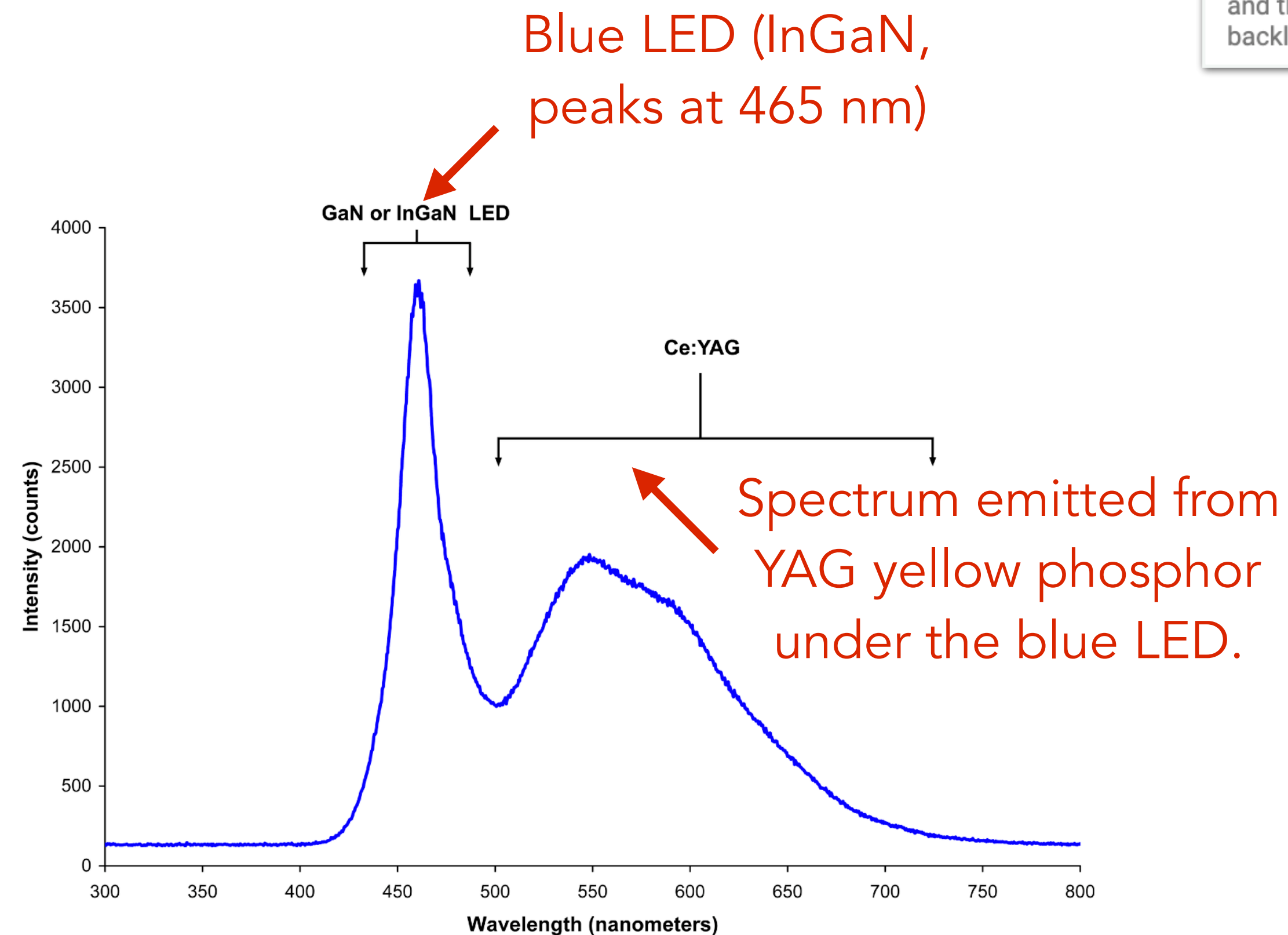
The backlight is the source of light of the LCD display panels. The type of backlight determines the image quality and the color space of the display. There are various backlights such as CCFL, LED, WLED, RGB-LED, and etc.

W-LED

From my LG LCD monitor

Use a blue LED to light fluorescent materials, which generate (usually) yellow spectrum.

- Also called “phosphor-converted white LED”.



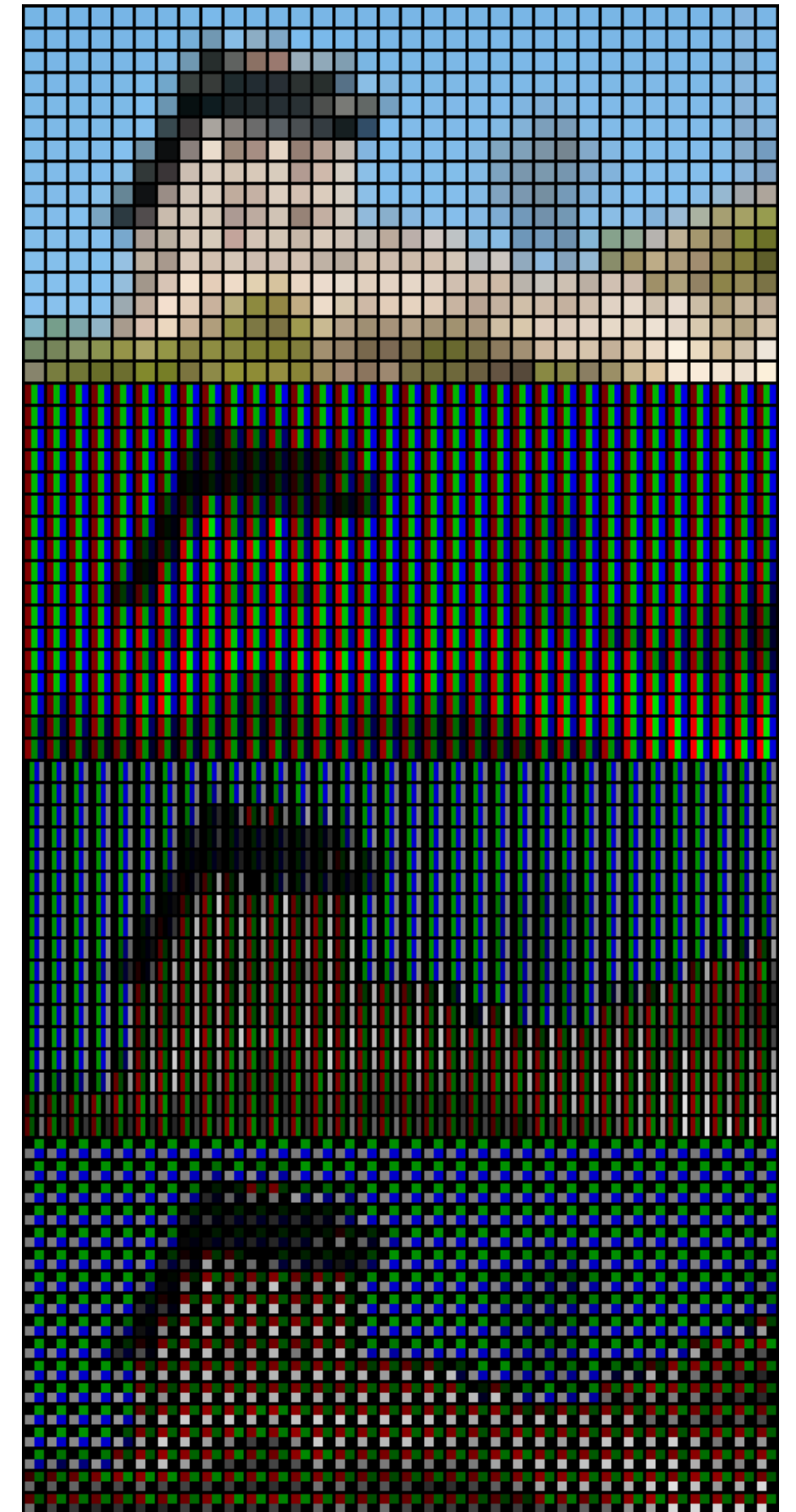
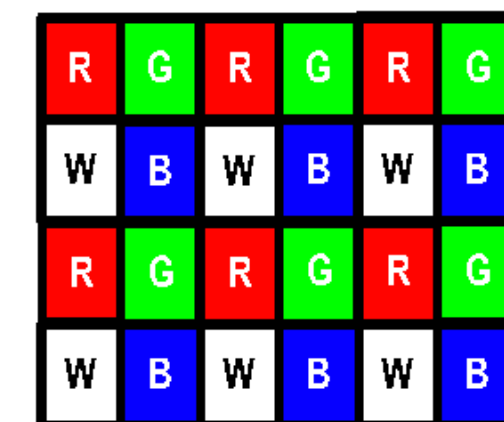
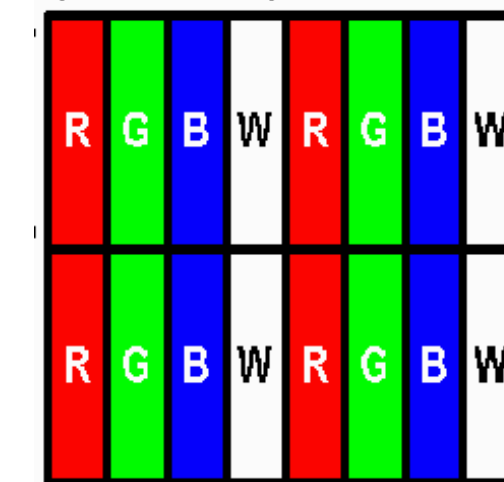
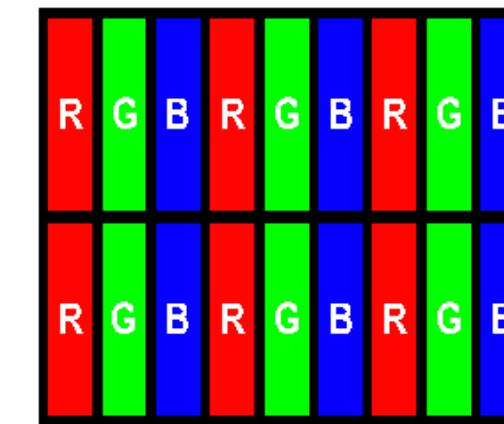


# RGBW Sub-Pixel Structure

Some displays use the RGBW sub-pixel structure, which adds white sub-pixels.

Why?

- Use W in place of R+G+B to improve power efficiency
- Add W to boost brightness (think of it as adding power to each of the RGB sub pixels). Sacrifice color fidelity; common in projectors.





# Light-Filtering Display

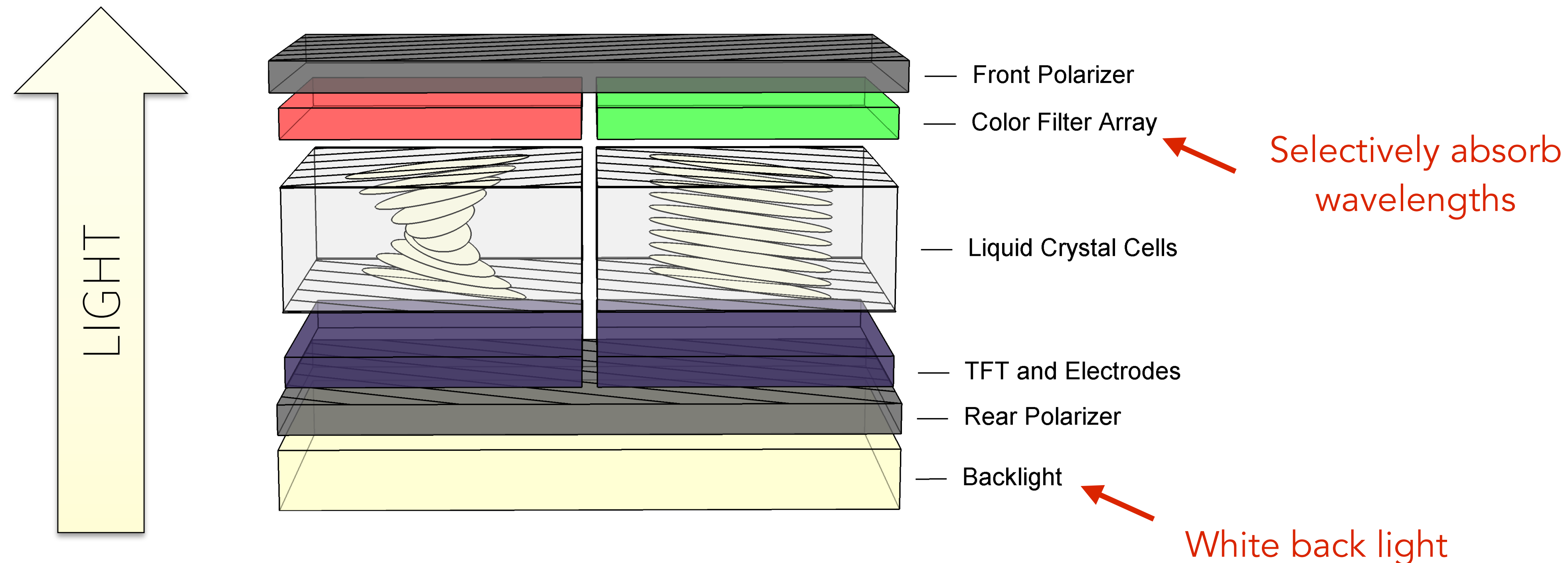
White light source is **filtered** and attenuated at each pixel to control color and light intensity.

Used in Liquid Crystal Displays (LCD) and DLP projectors.



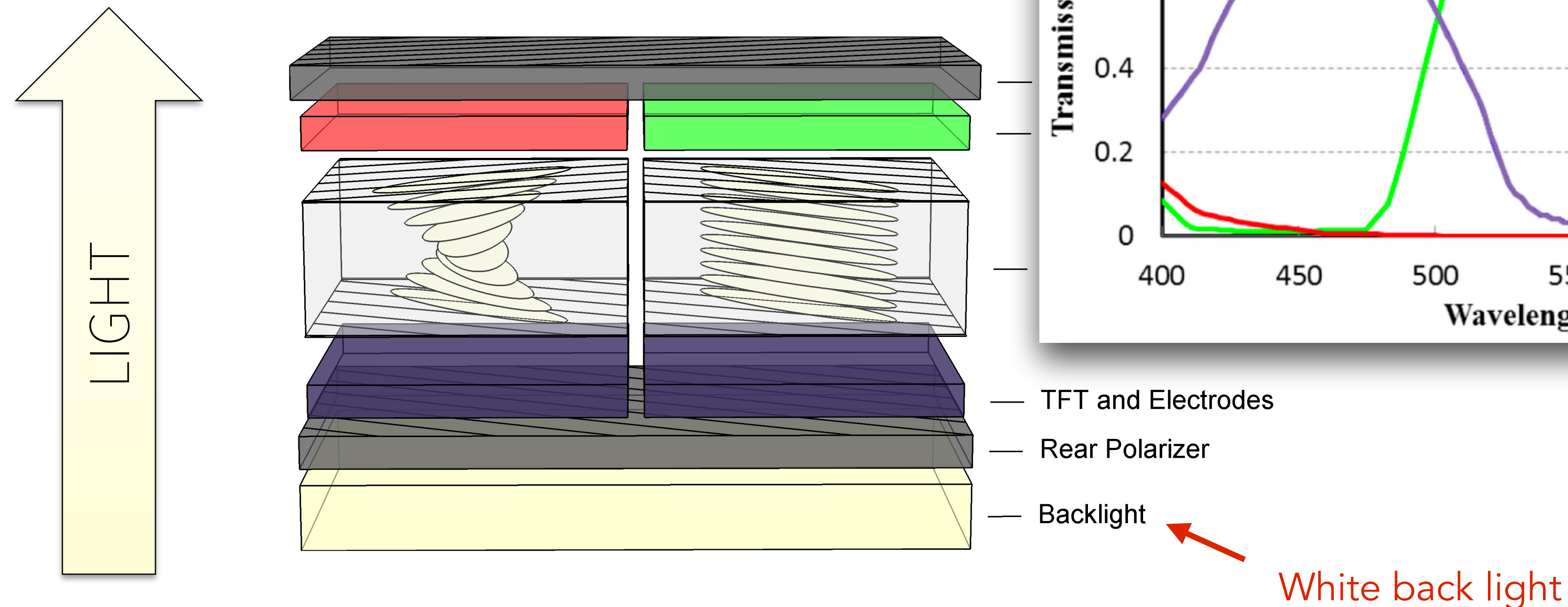


# Controlling Intensity of LCD Pixels





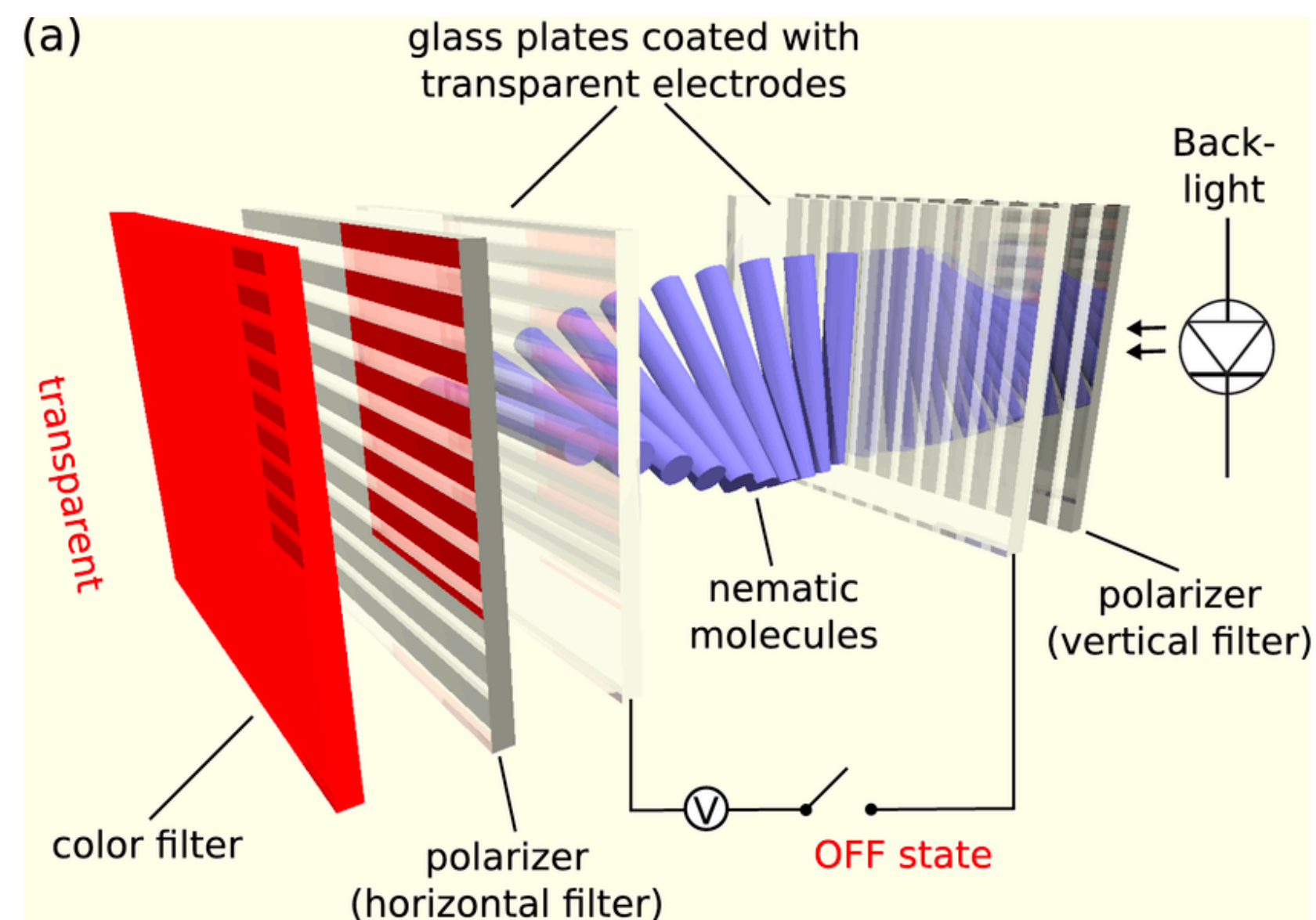
# Controlling Intensity of LCD Pixels



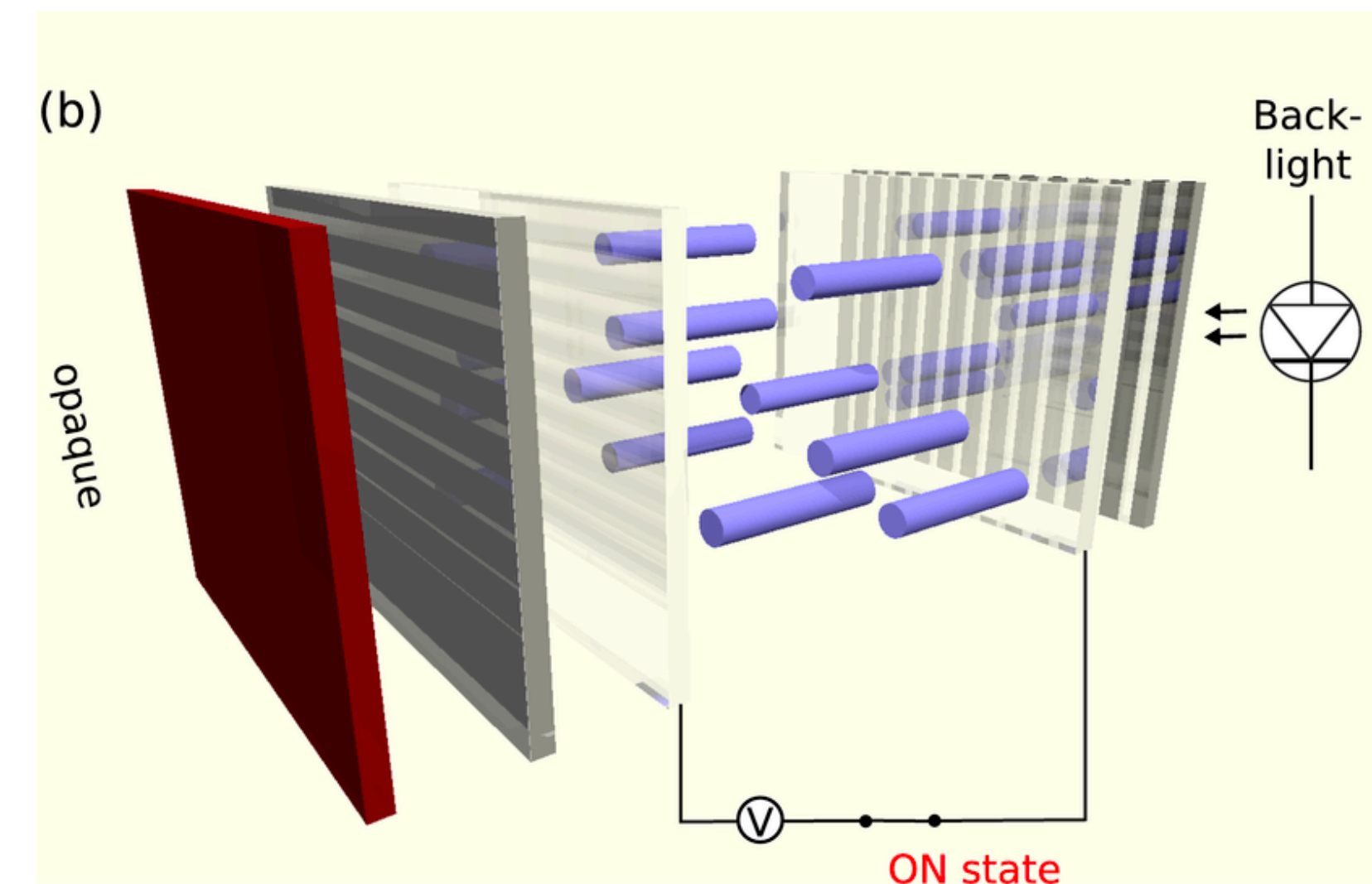


# Controlling Intensity of LCD Pixels

In natural state, the liquid crystal rotates light by  $90^\circ$  so that light passes through the output polarizer.

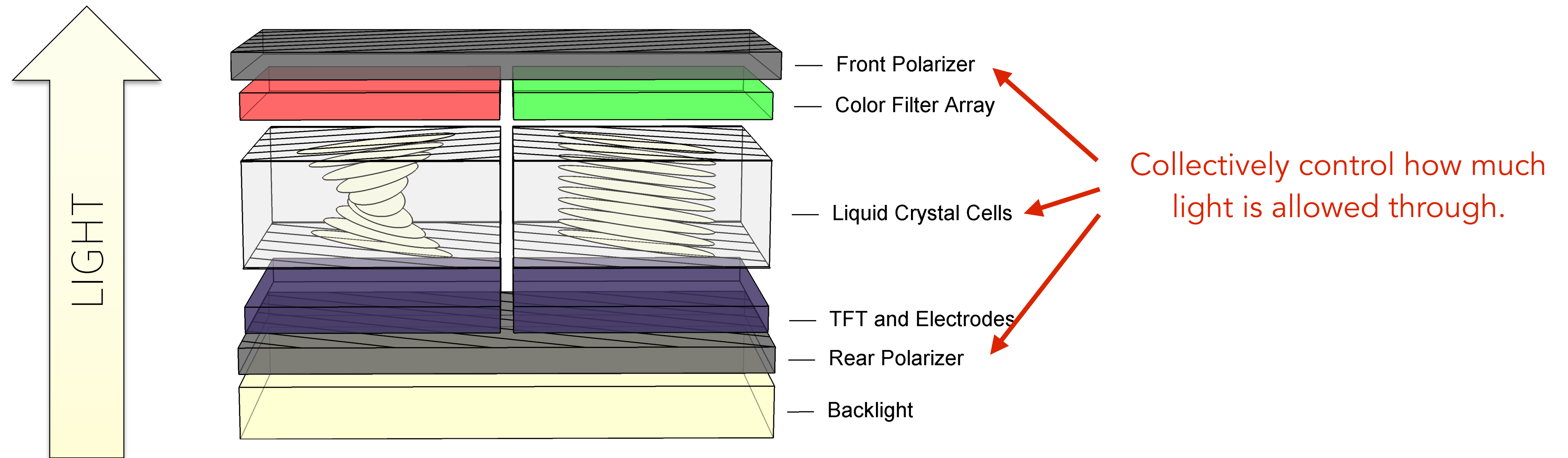


When applied electric field, the liquid crystal causes no change to light, which is blocked by the output polarizer.



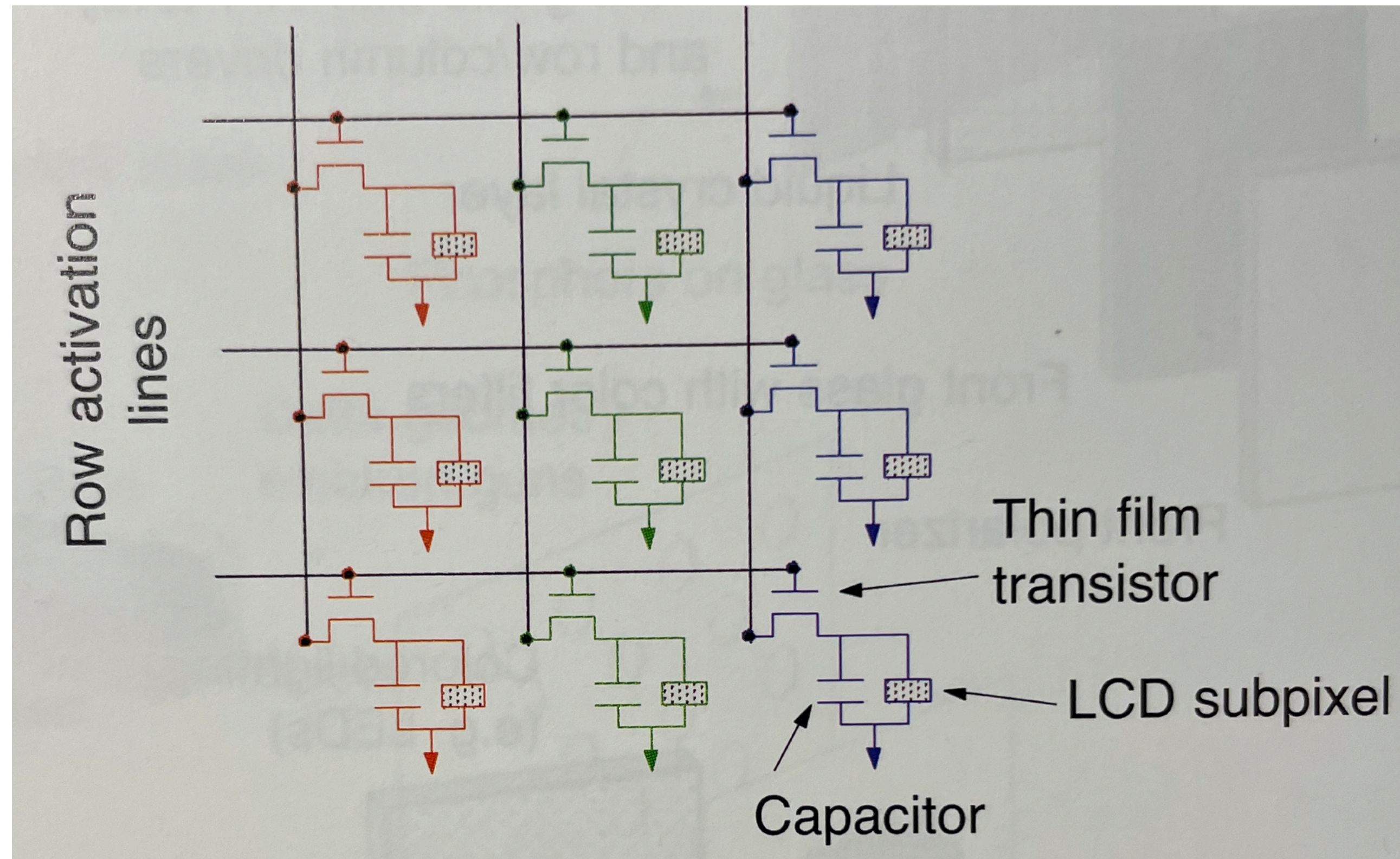


# Controlling Intensity of LCD Pixels





# LCD Pixel Array Circuit



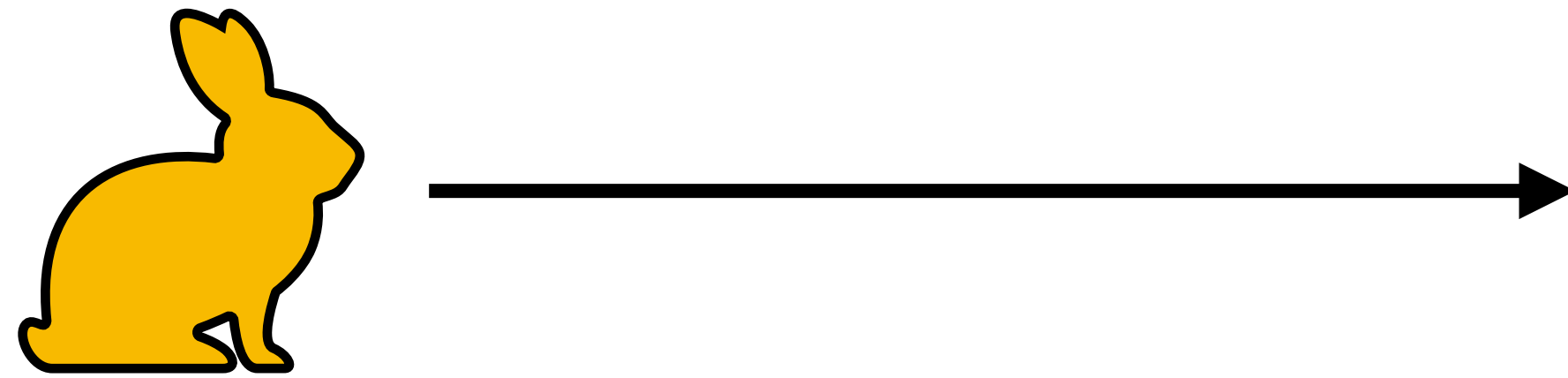
Array-like structure, similar to OLED/SRAM. Each row is refreshed separately.

The thin film transistor acts as an access switch. The capacitor holds the charge before next refresh.

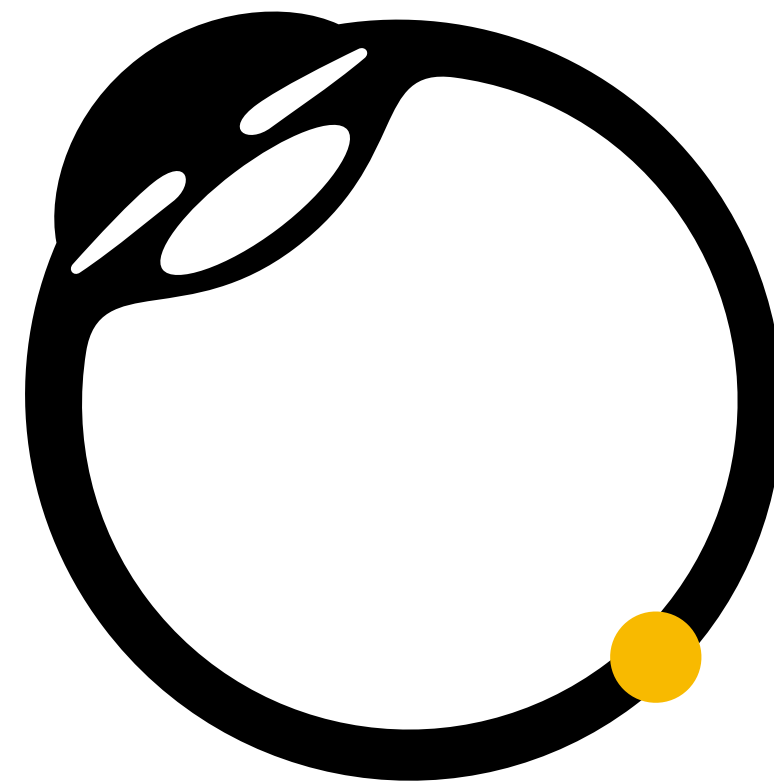


# Refresh Rate and Motion Blur

Actual Object  
Movement  
(Continuous)



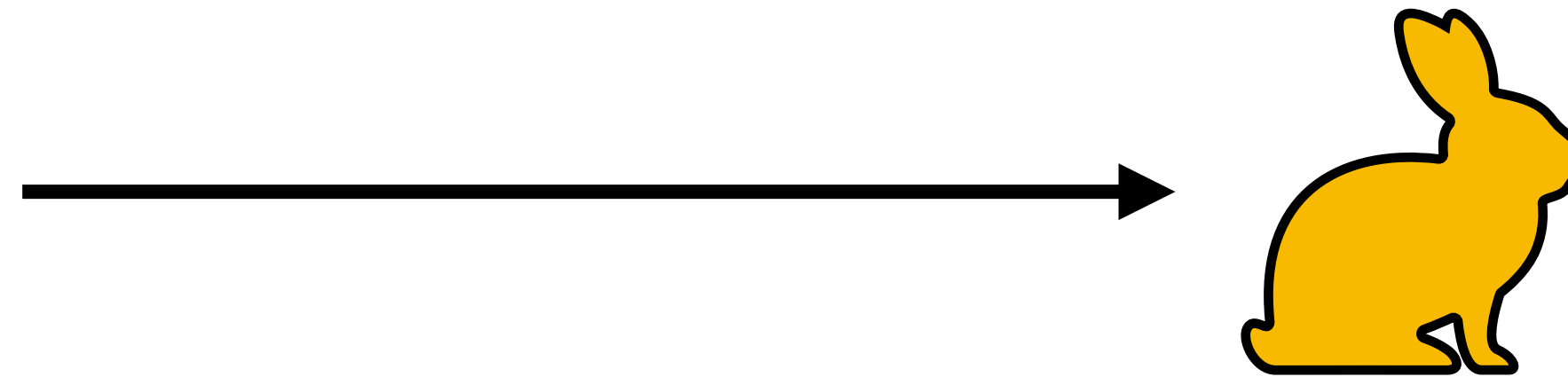
Eye Pursuit  
(Continuous)



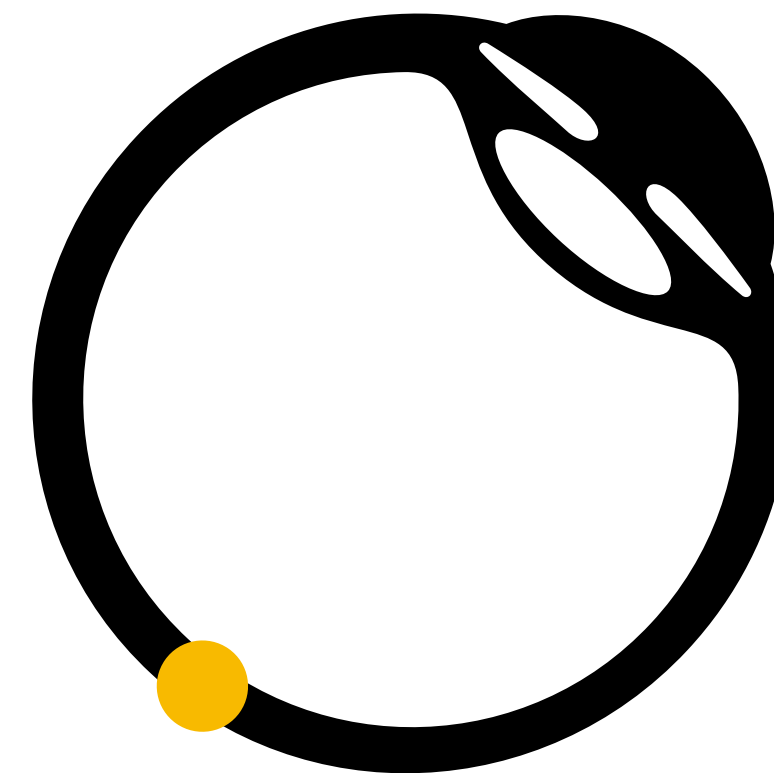


# Refresh Rate and Motion Blur

Actual Object  
Movement  
(Continuous)



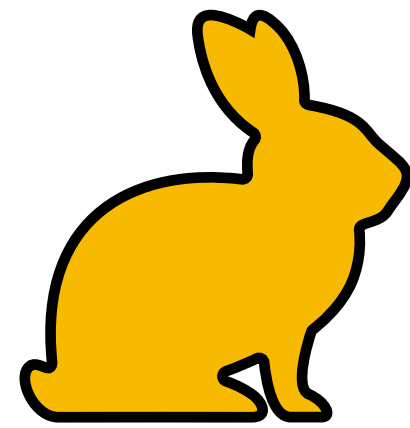
Eye Pursuit  
(Continuous)





# Refresh Rate and Motion Blur

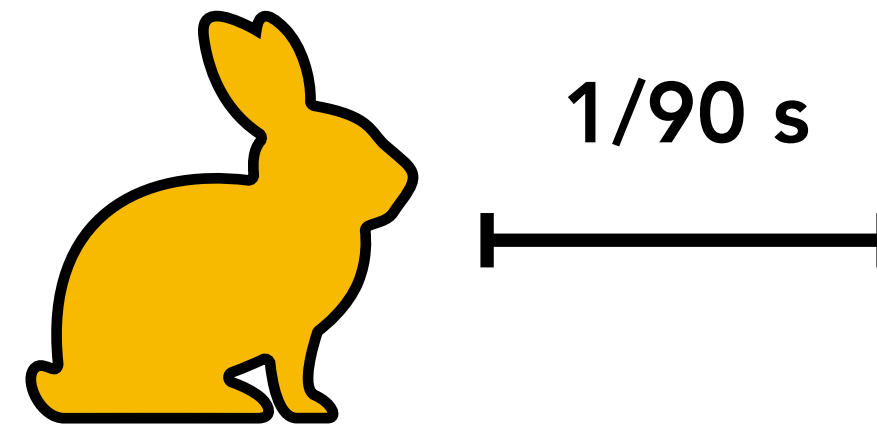
Displayed  
Frames  
(Discrete)





# Refresh Rate and Motion Blur

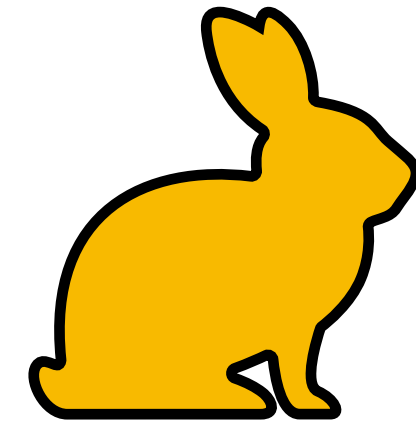
Displayed  
Frames  
(Discrete)





# Refresh Rate and Motion Blur

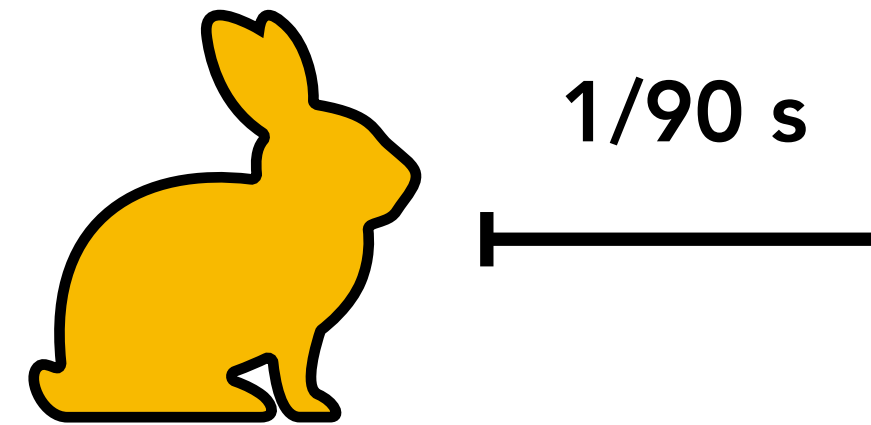
Displayed  
Frames  
(Discrete)





# Refresh Rate and Motion Blur

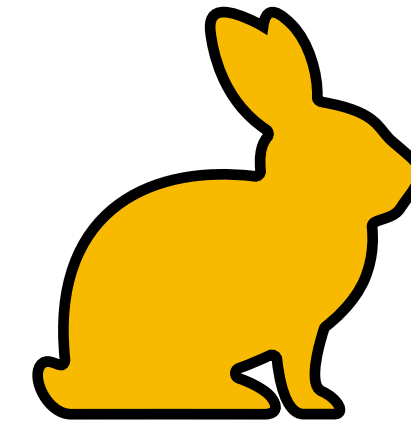
Displayed  
Frames  
(Discrete)





# Refresh Rate and Motion Blur

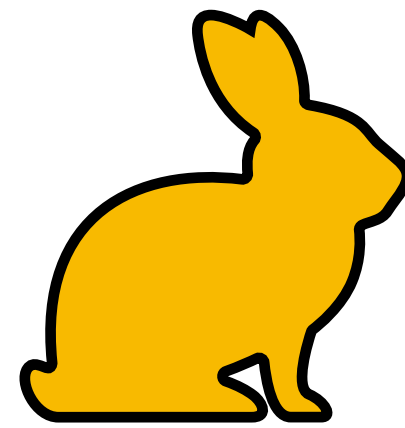
Displayed  
Frames  
(Discrete)



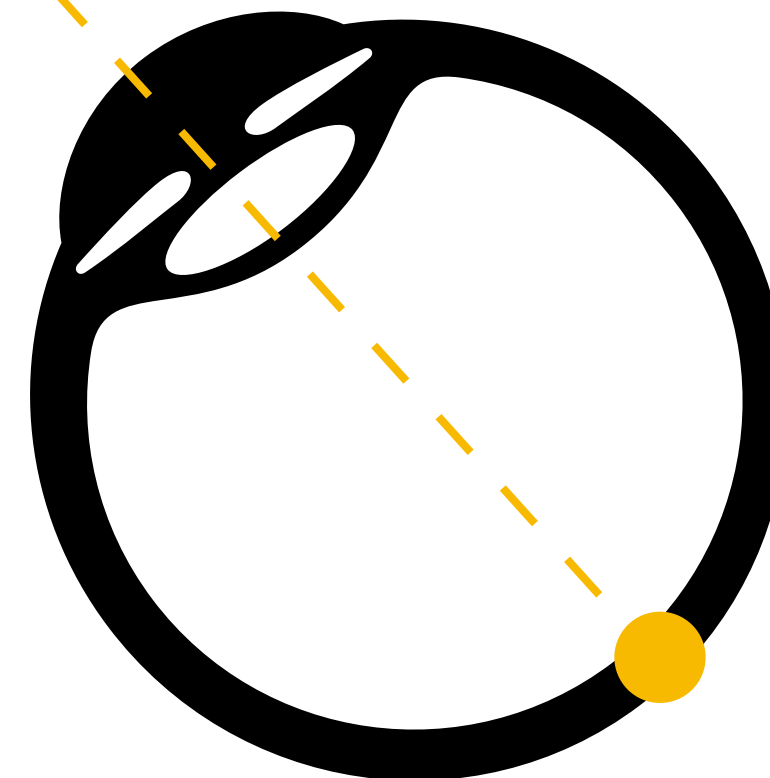


# Refresh Rate and Motion Blur

Displayed  
Frames  
(Discrete)



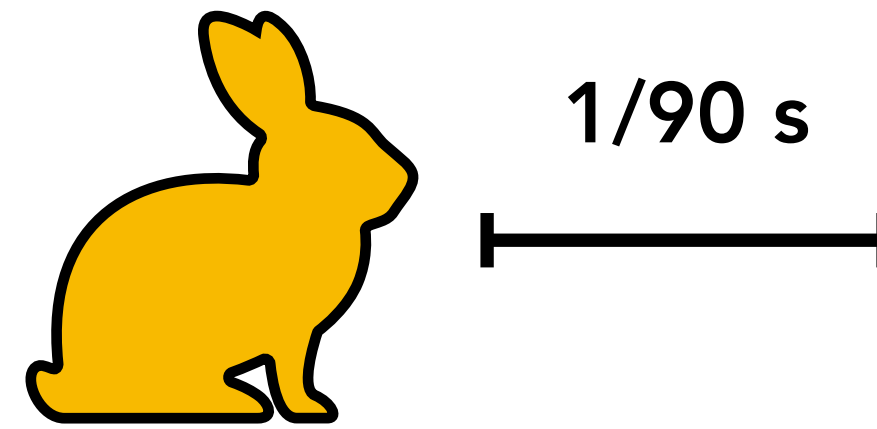
Eye Pursuit  
(Continuous)



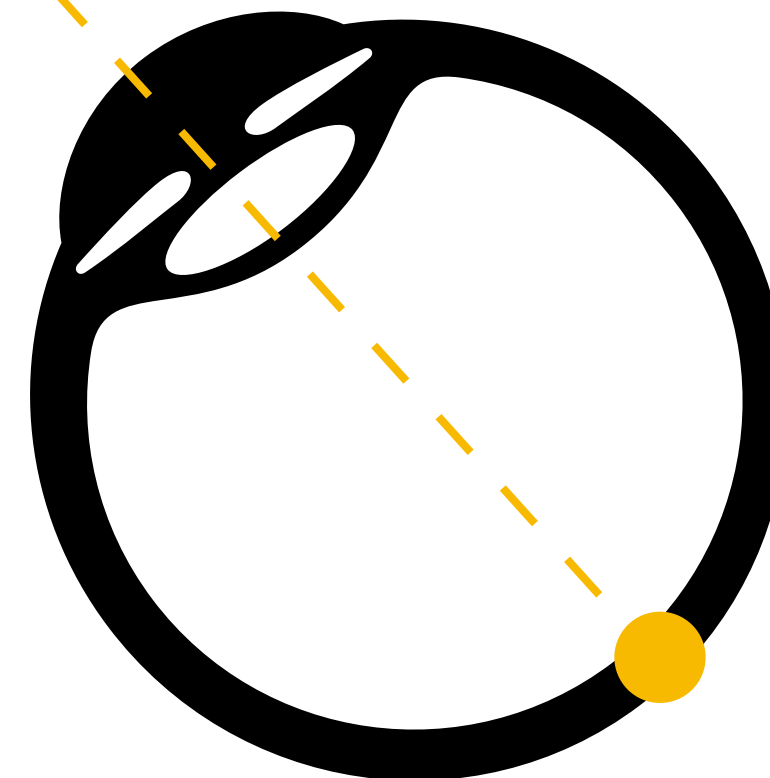


# Refresh Rate and Motion Blur

Displayed  
Frames  
(Discrete)



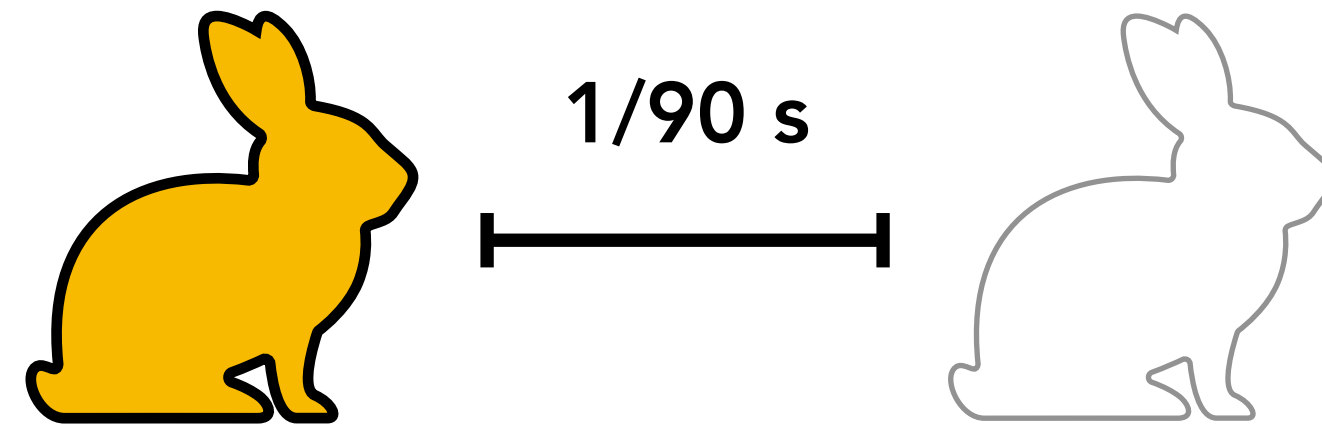
Eye Pursuit  
(Continuous)



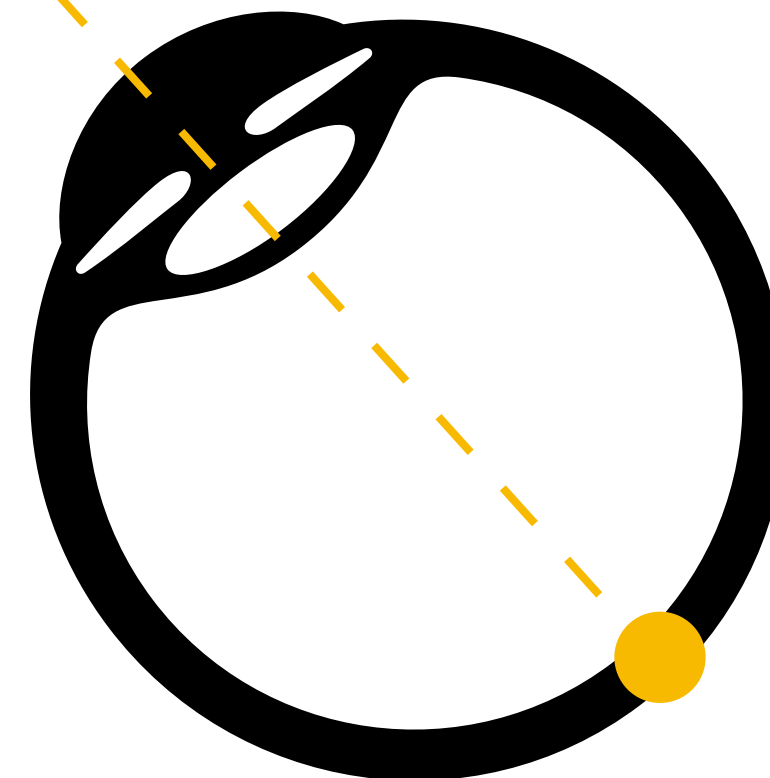


# Refresh Rate and Motion Blur

Displayed  
Frames  
(Discrete)



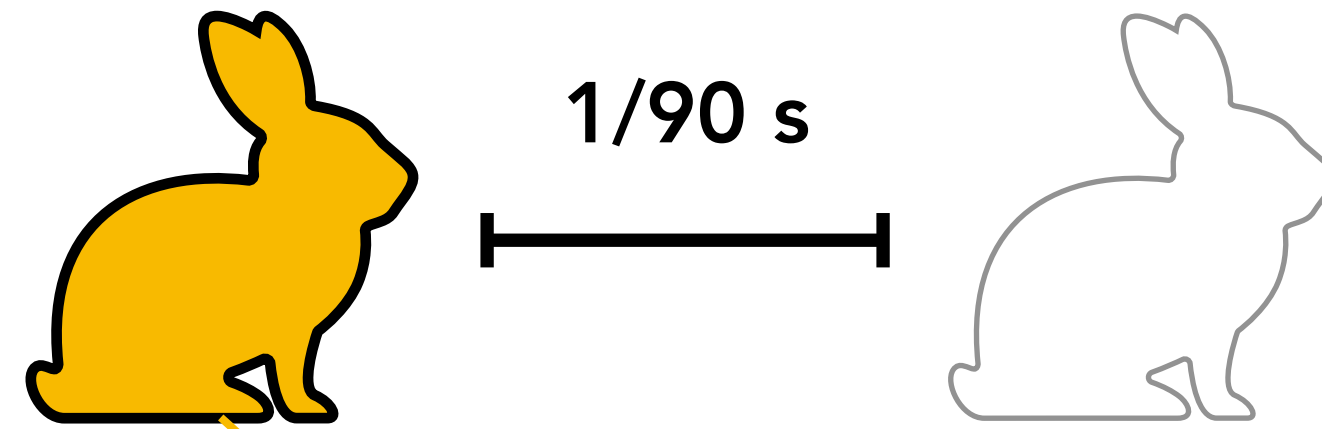
Eye Pursuit  
(Continuous)



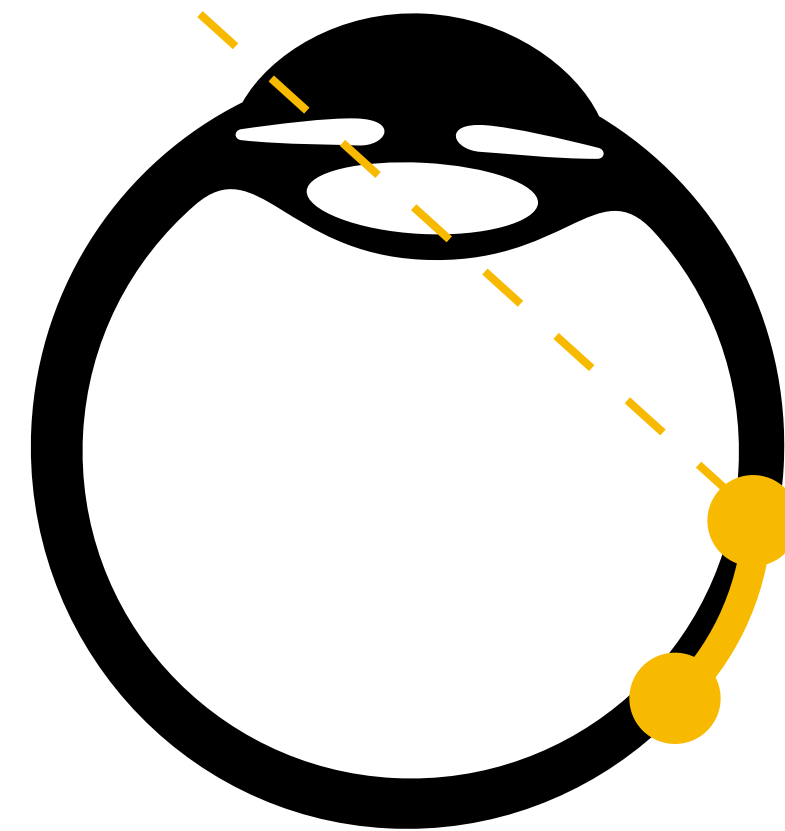


# Refresh Rate and Motion Blur

Displayed  
Frames  
(Discrete)



Eye Pursuit  
(Continuous)





# Refresh Rate and Motion Blur

Caused by the “sample and hold” nature of displays. Your eyes tend to perform smooth pursuit but object appears on display in discrete locations.

The end result is the object smears across your retina — motion blur.

Fixes: reduce the size of the smear

- Increase the refresh rate (cons: power increase)
- Use “low-persistence” mode: for each refresh cycle display the image only for a short period of time with a black screen for the remaining time before next frame arrives (cons: lower brightness)

Variable-refresh-rate displays have been investigated.



# Sequential Color Displays



# Field Sequential Color (FSC)

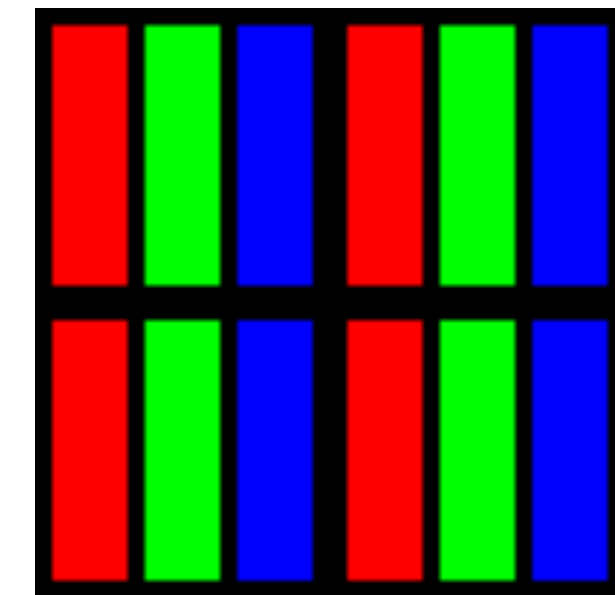
Flash each each primary at a high rate. Relies on **temporal integration** in human visual system, which fuses successive images into a color picture.

Color filtering array **spatially** adds colors; FSC **temporally** adds color.

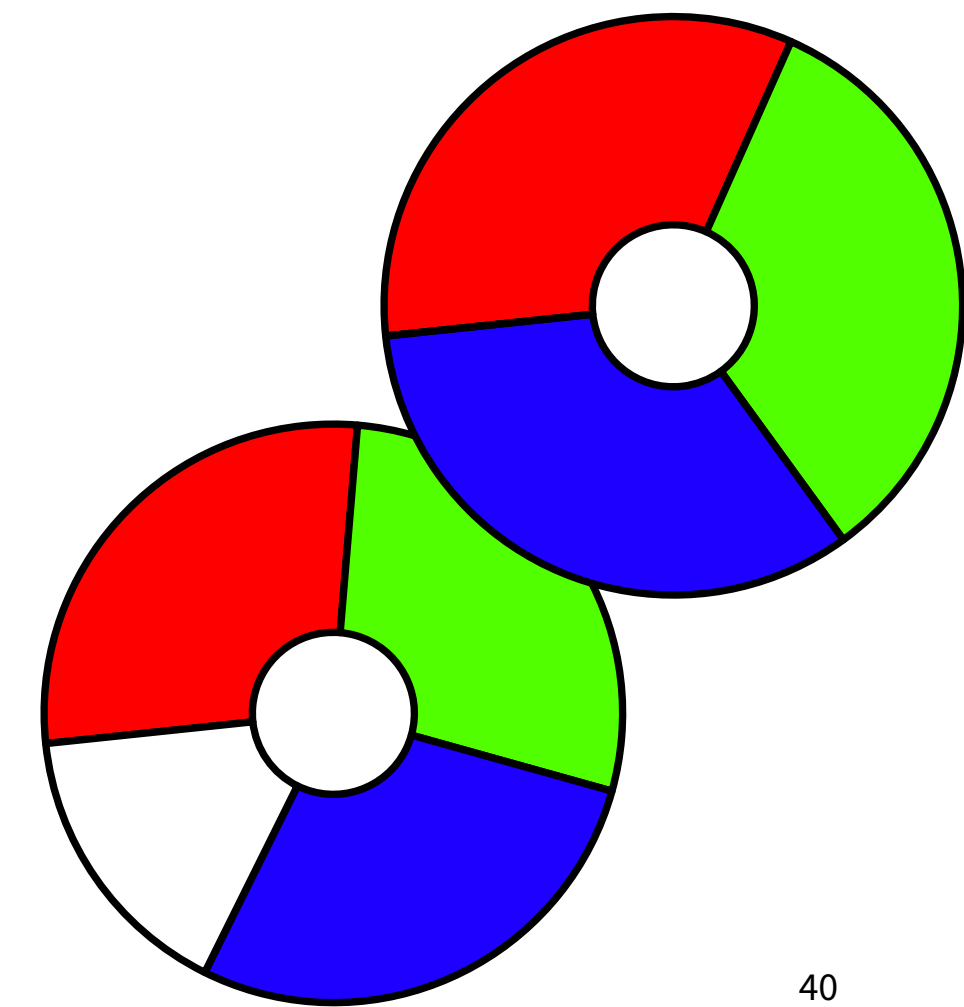
Compared to using color filtering arrays:

- + 3X higher resolution if nothing else changes.
- + higher luminous efficacy (if not using filters).
- + manufacturing cost is lower.

Color  
filter array



Color  
wheel



40



# CBS FSC TV System

CBS debuted the FSC TV system in 1940.

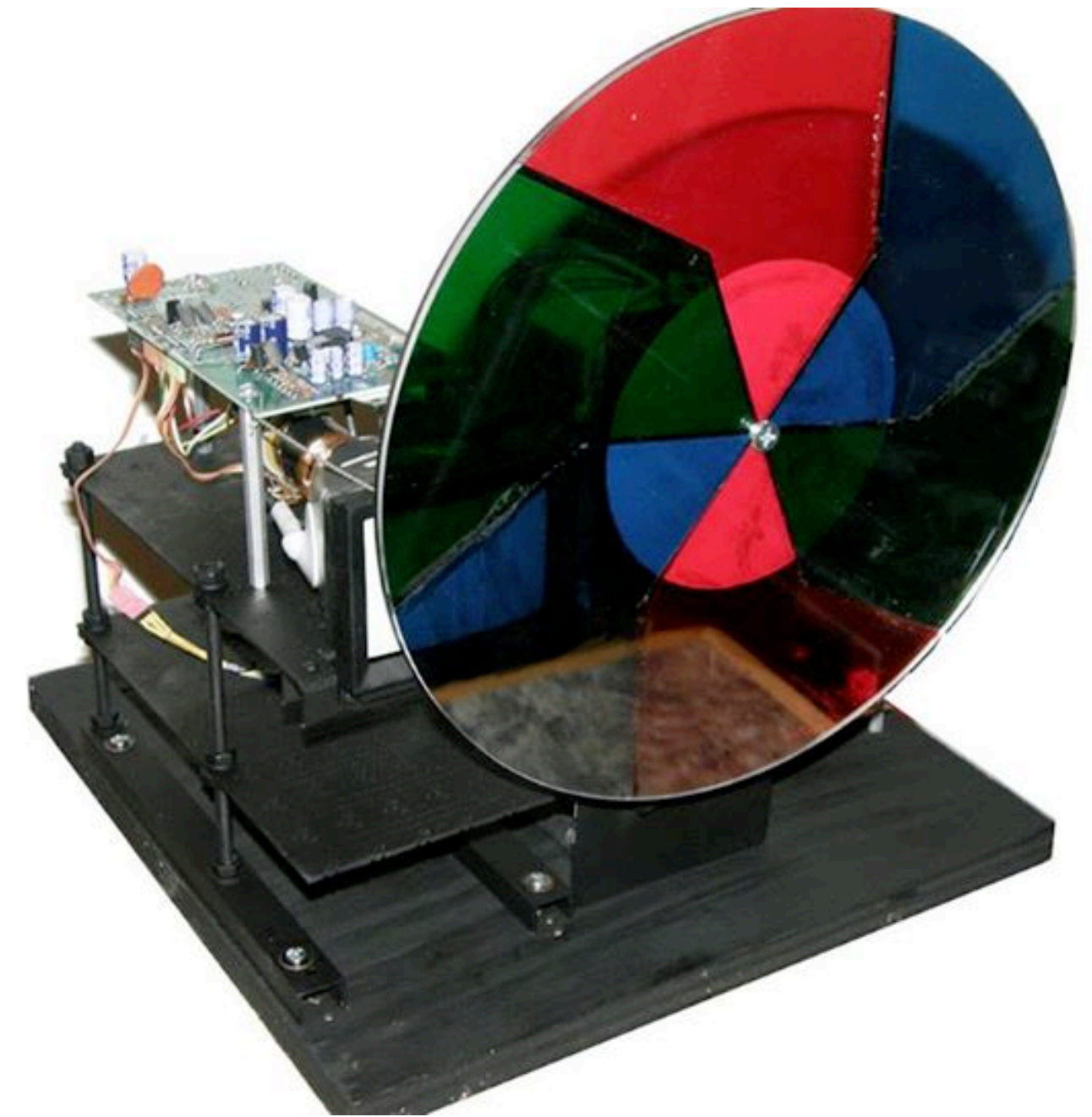
- Obsolete now. Watch a [video](#) demo.

24 rotations per second. Each color is scanned twice per rotation.

Transmitted images are black and white. Each image (also called a field) is unique and is in-sync with the color filter.

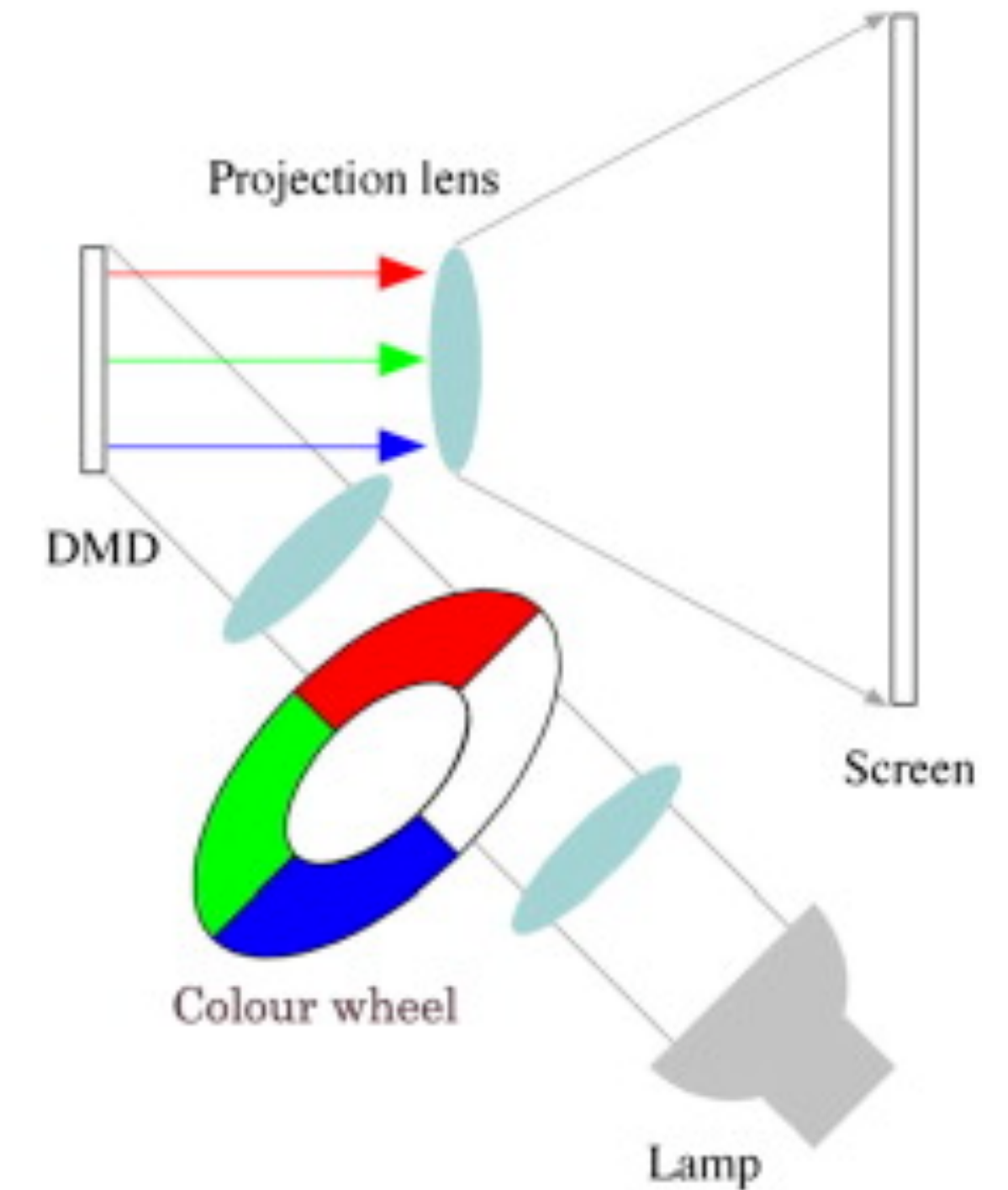
- Each B/W pixel encoded brightness.

$24 \times 6 = 144$  fields/s transmitted.



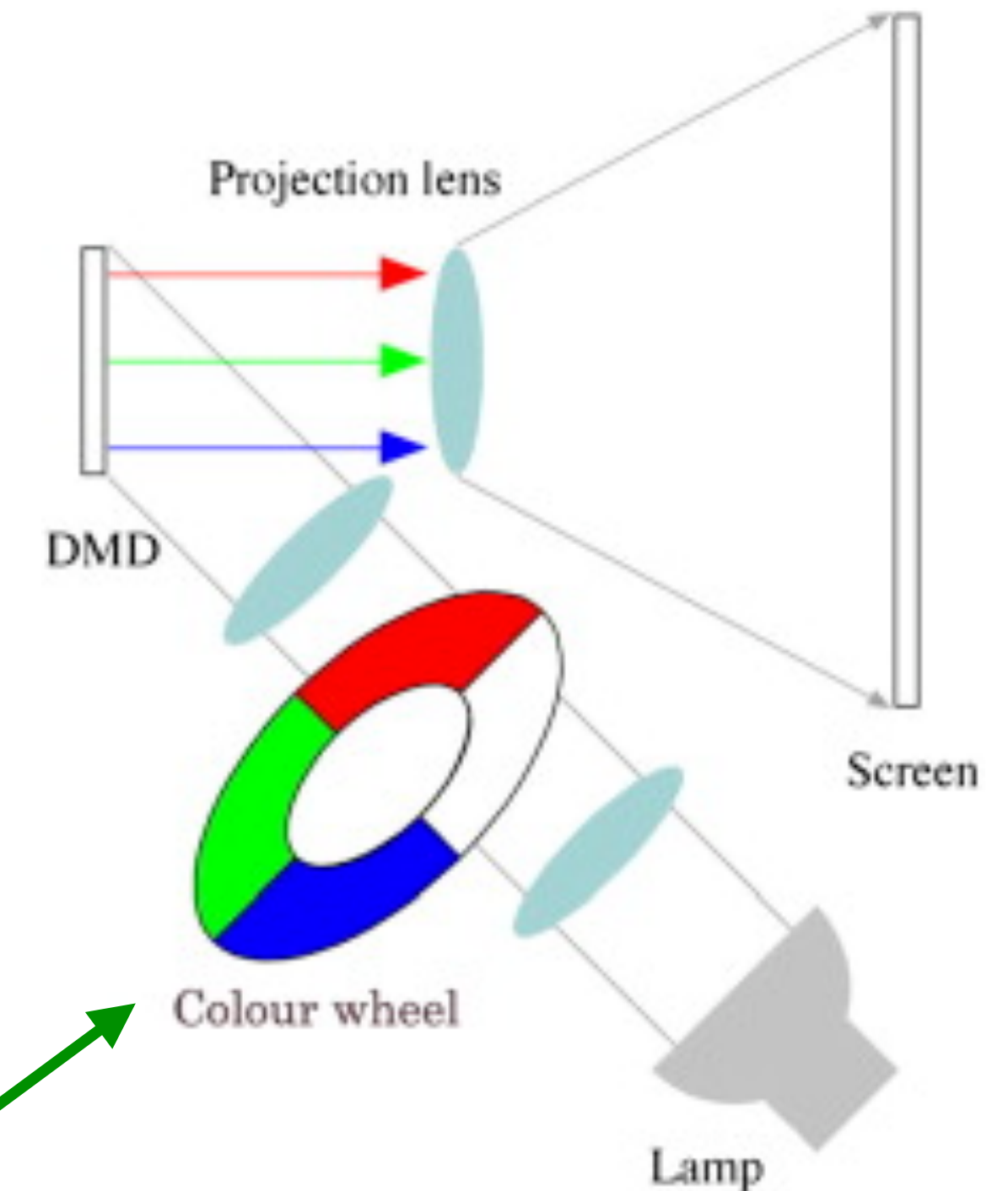


# FSC in Digital Light Processing (DLP) Projectors





# FSC in Digital Light Processing (DLP) Projectors



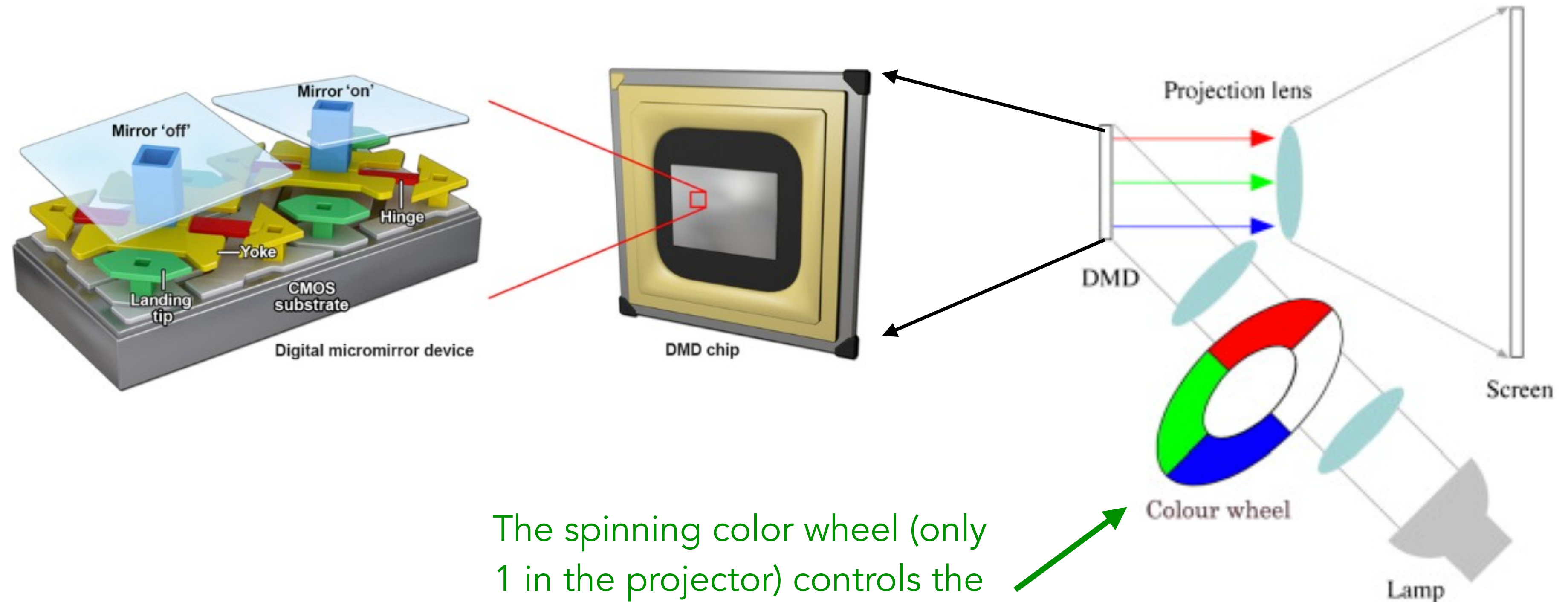
The spinning color wheel (only 1 in the projector) controls the color of each pixel.





# FSC in Digital Light Processing (DLP) Projectors

DMD (created  
by TI at 1987)



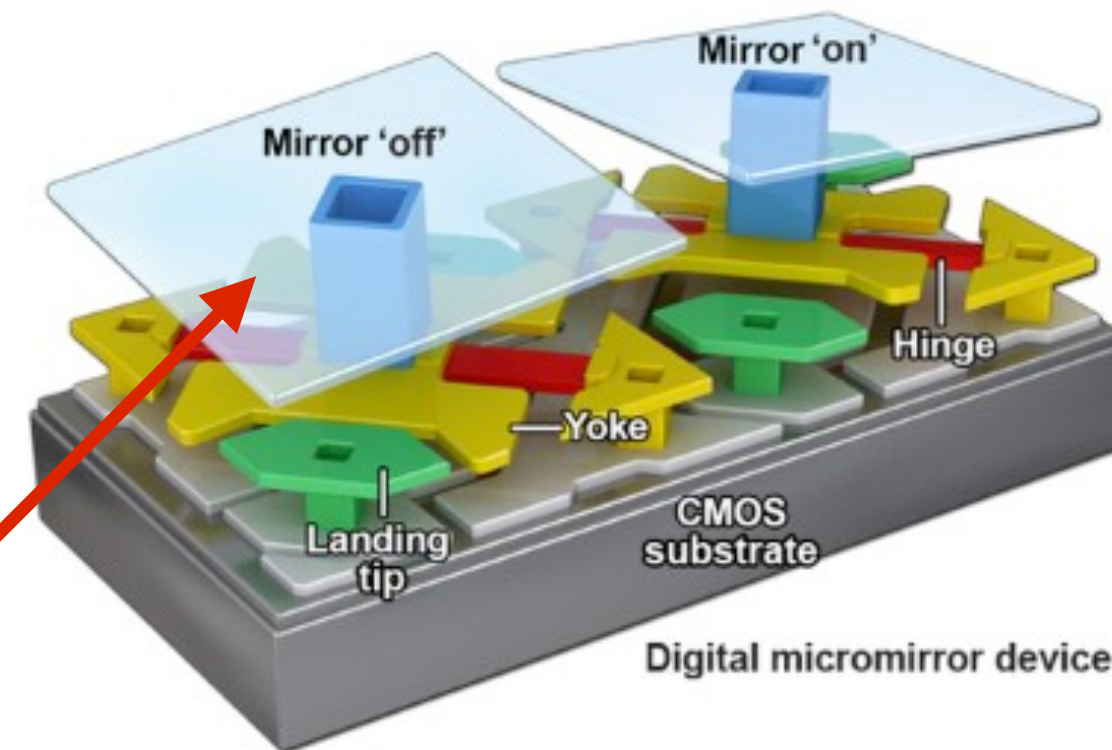
The spinning color wheel (only  
1 in the projector) controls the  
color of each pixel.



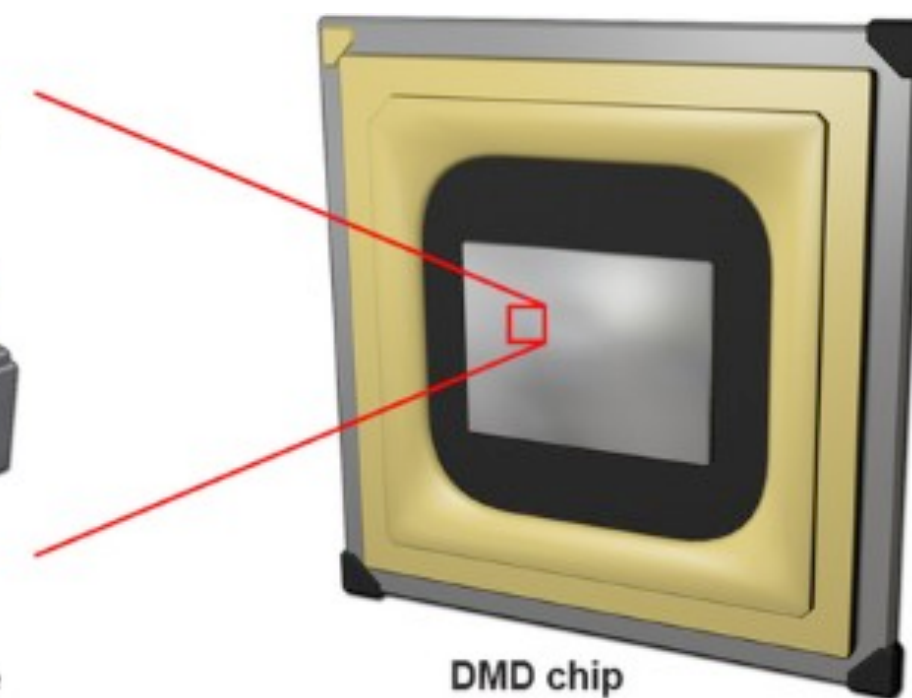


# FSC in Digital Light Processing (DLP) Projectors

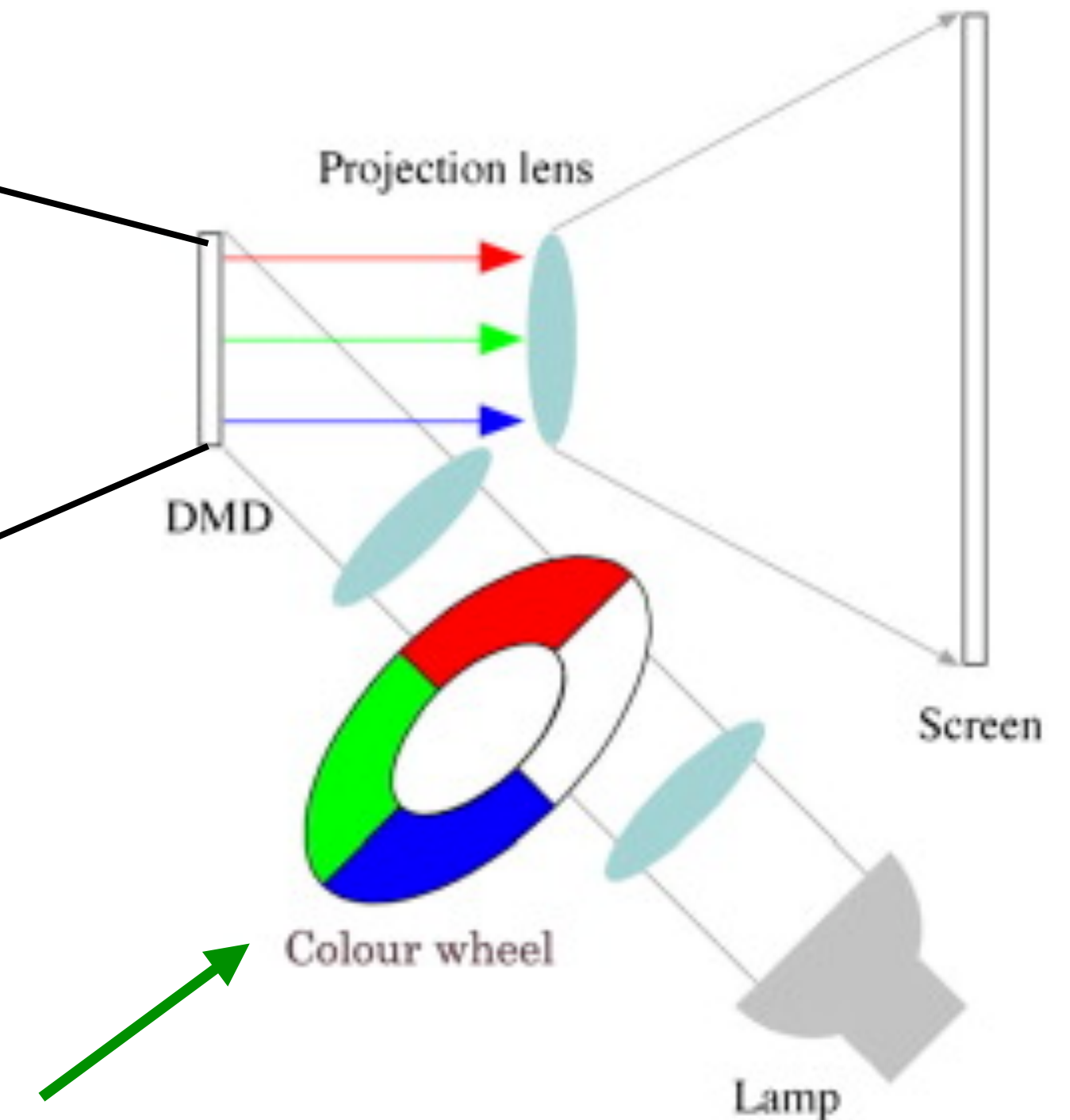
DMD (created by TI at 1987)



Per-pixel mirror controls the brightness of light at each pixel. "Off" means the mirror reflects light away from the lens. A mirror can be switch between on/off thousands of times a second and with ~1024 levels (resolution).



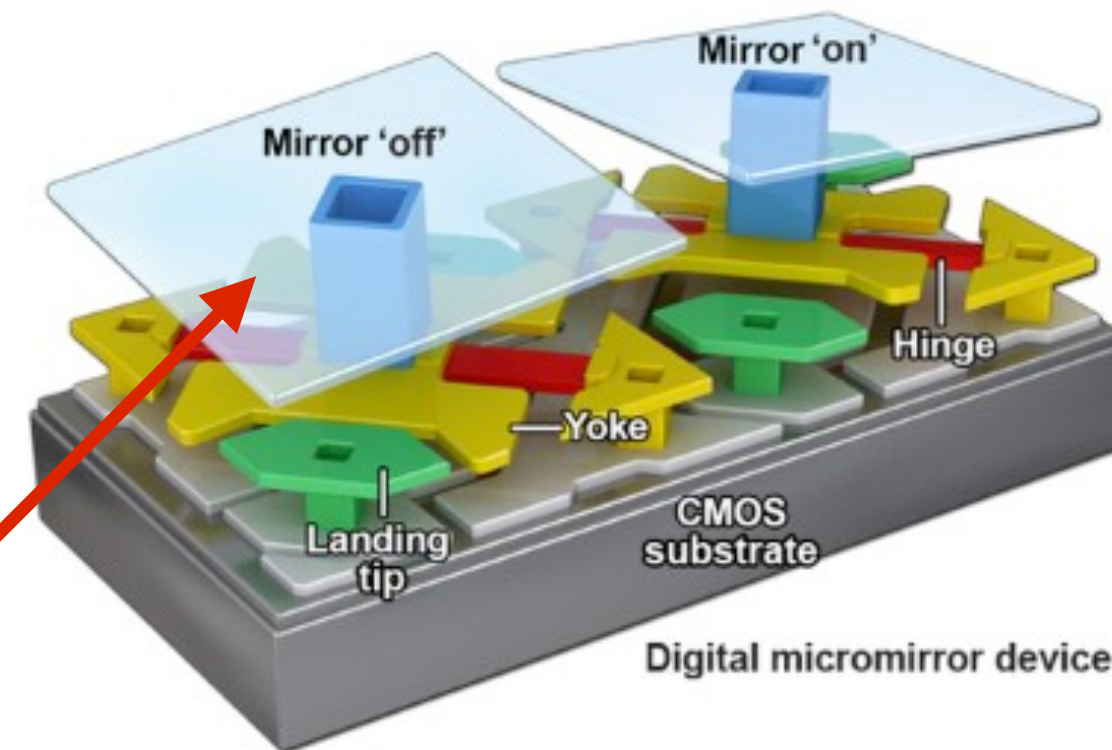
The spinning color wheel (only 1 in the projector) controls the color of each pixel.





# FSC in Digital Light Processing (DLP) Projectors

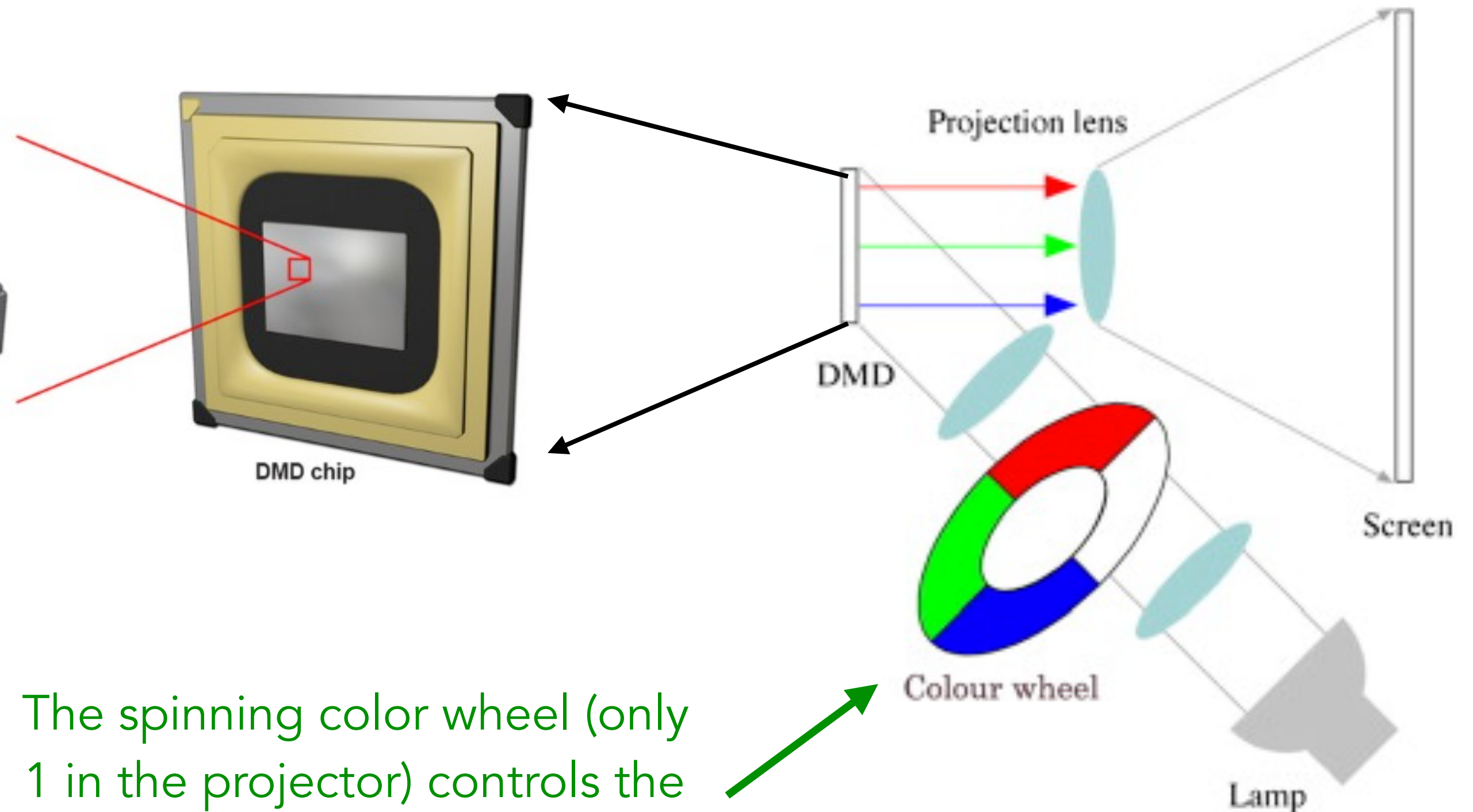
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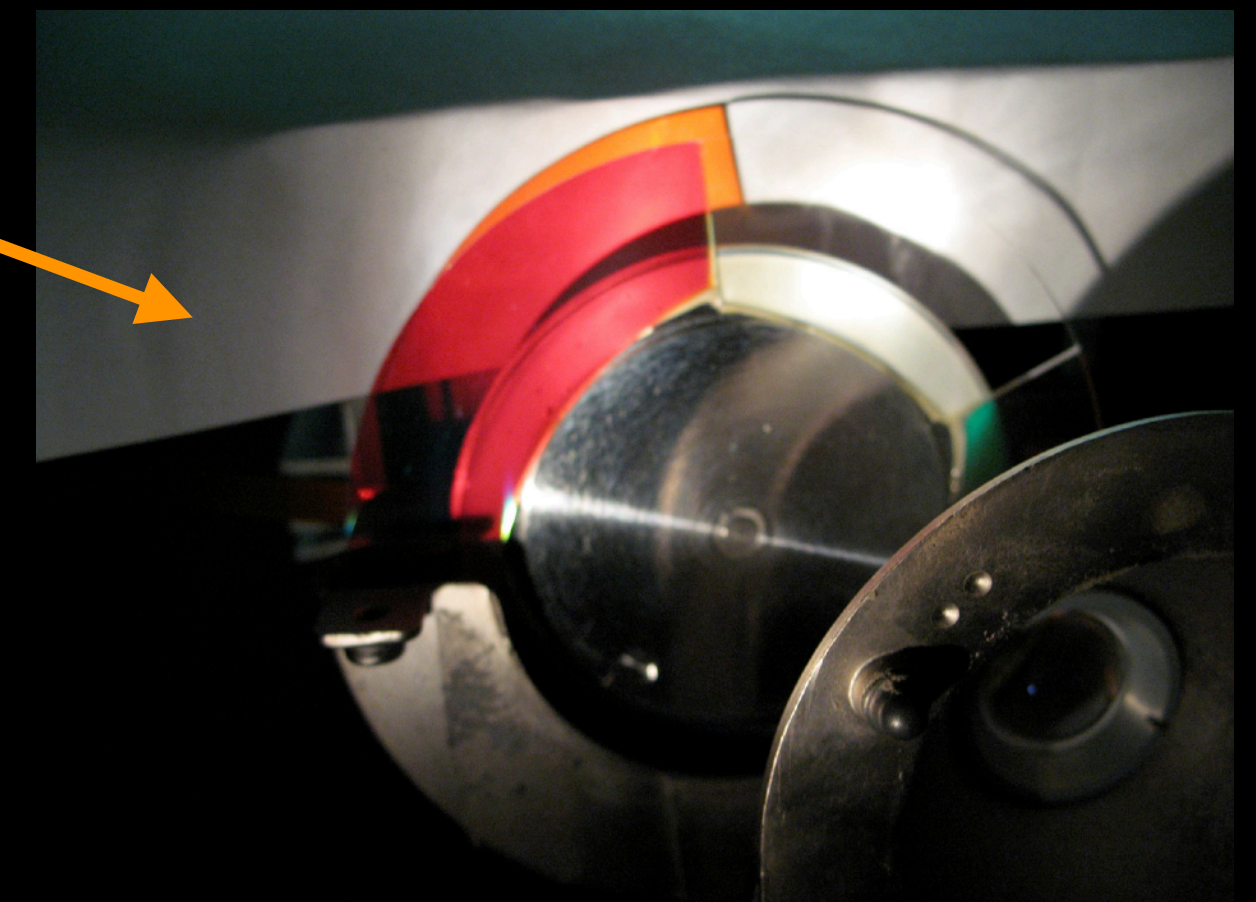
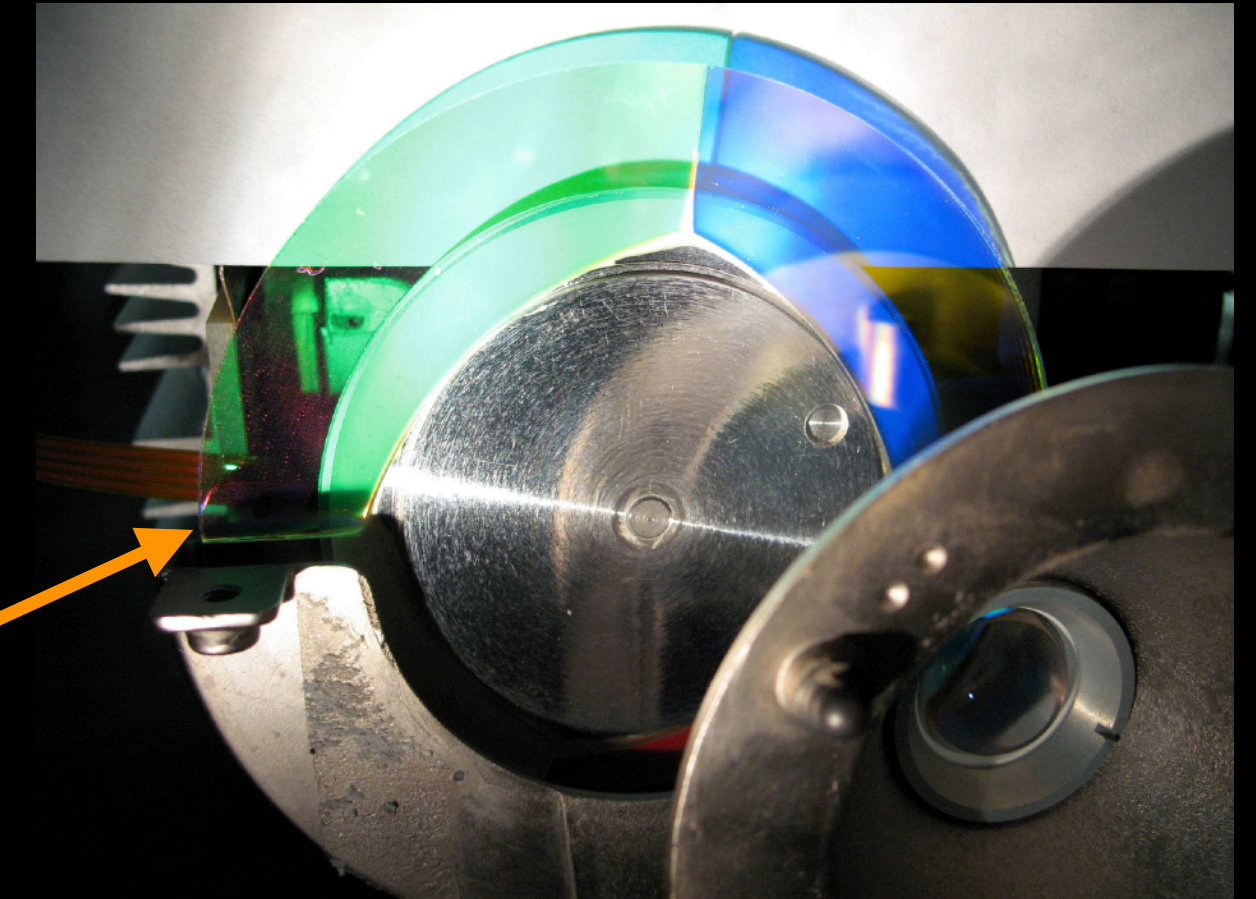
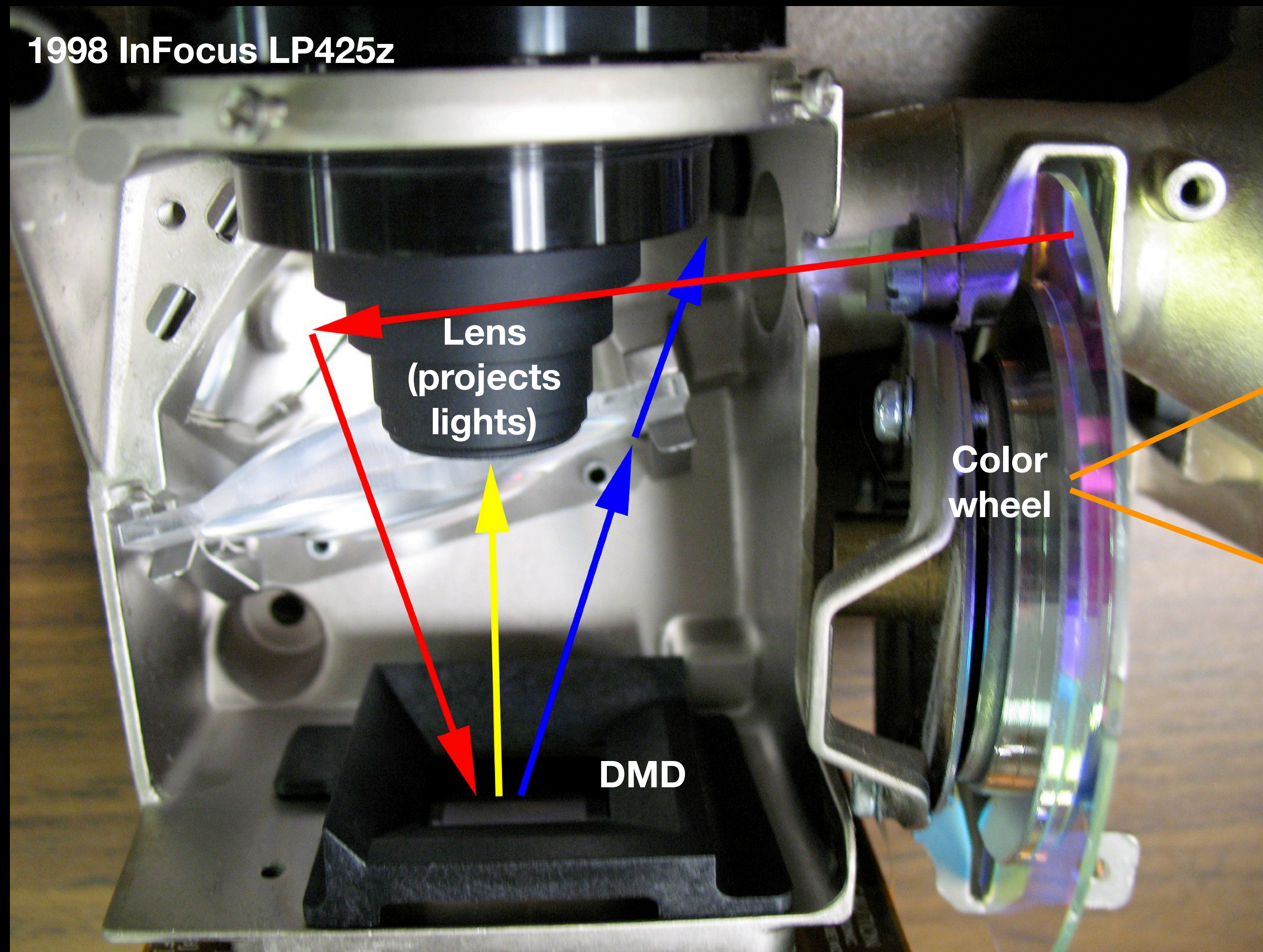
The spinning color wheel (only 1 in the projector) controls the color of each pixel.

The mirror orientation and the color wheel rotation must be perfectly in-sync. ~10 spin/s.





1998 InFocus LP425z



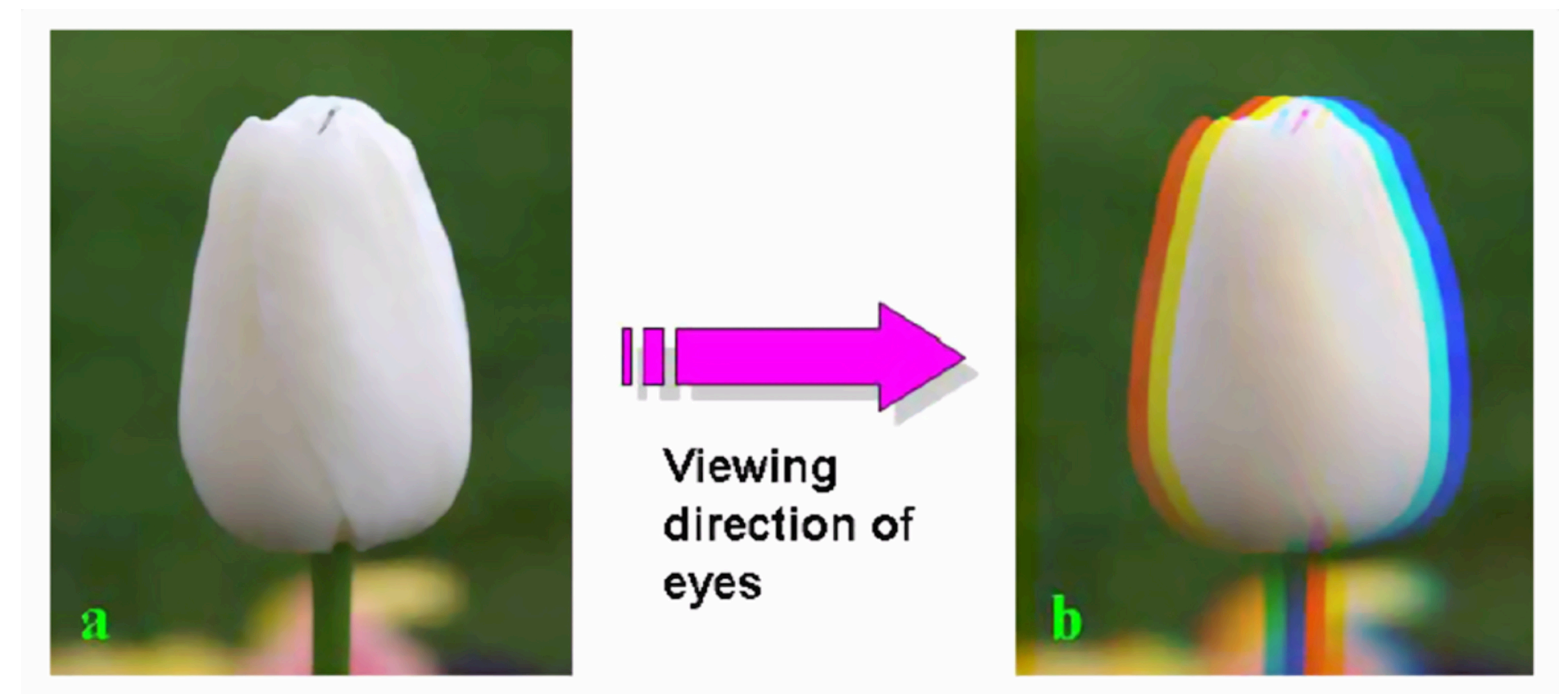
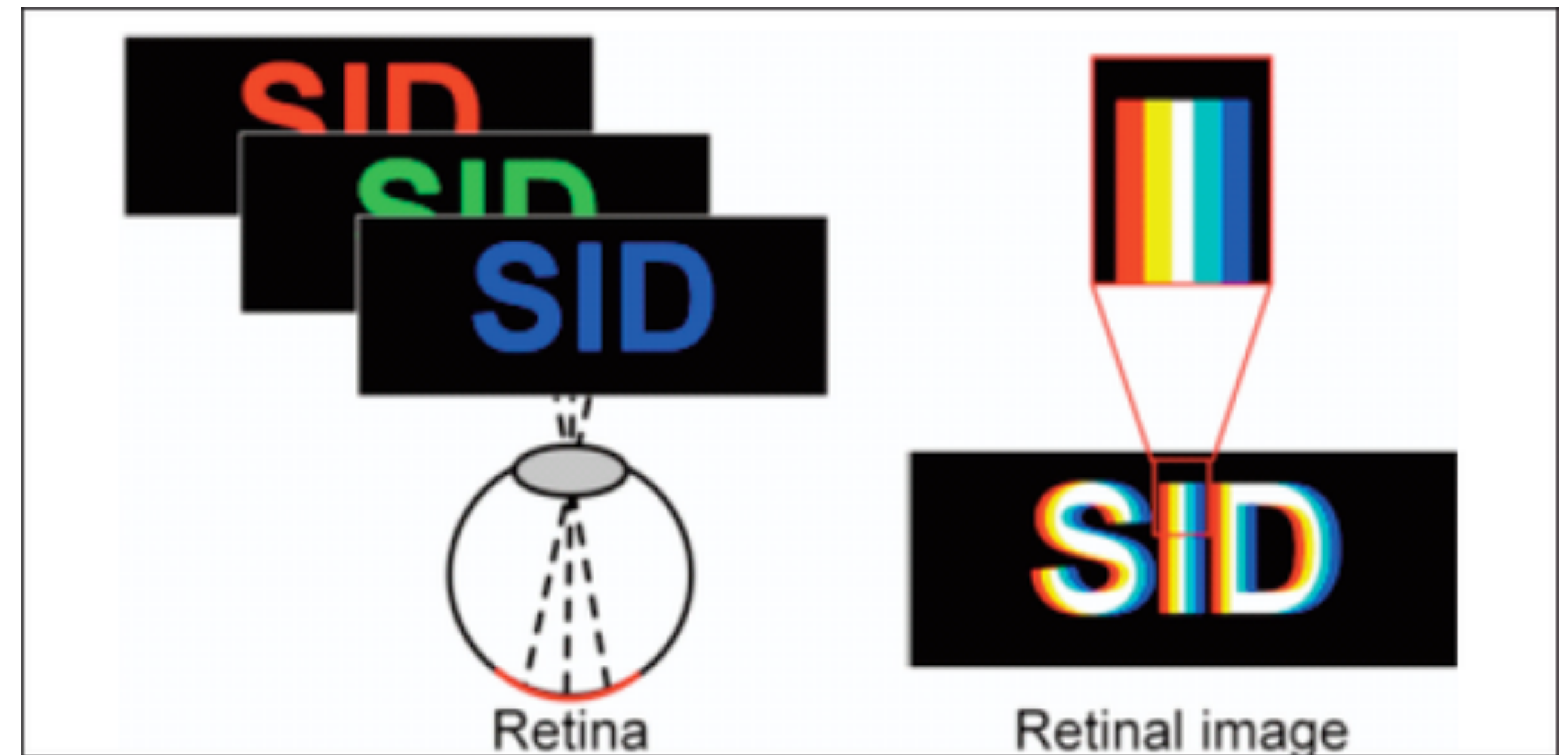


# Color Breakup in FSC

Are your eyes are tracking a moving object the three color channels of the same object are sequentially captured on retina.

- In spirit similar to motion blur from low refresh rate.

A good explanation [here](https://spie.org/news/1254-suppressing-color-breakup-in-lcds?SSO=1).

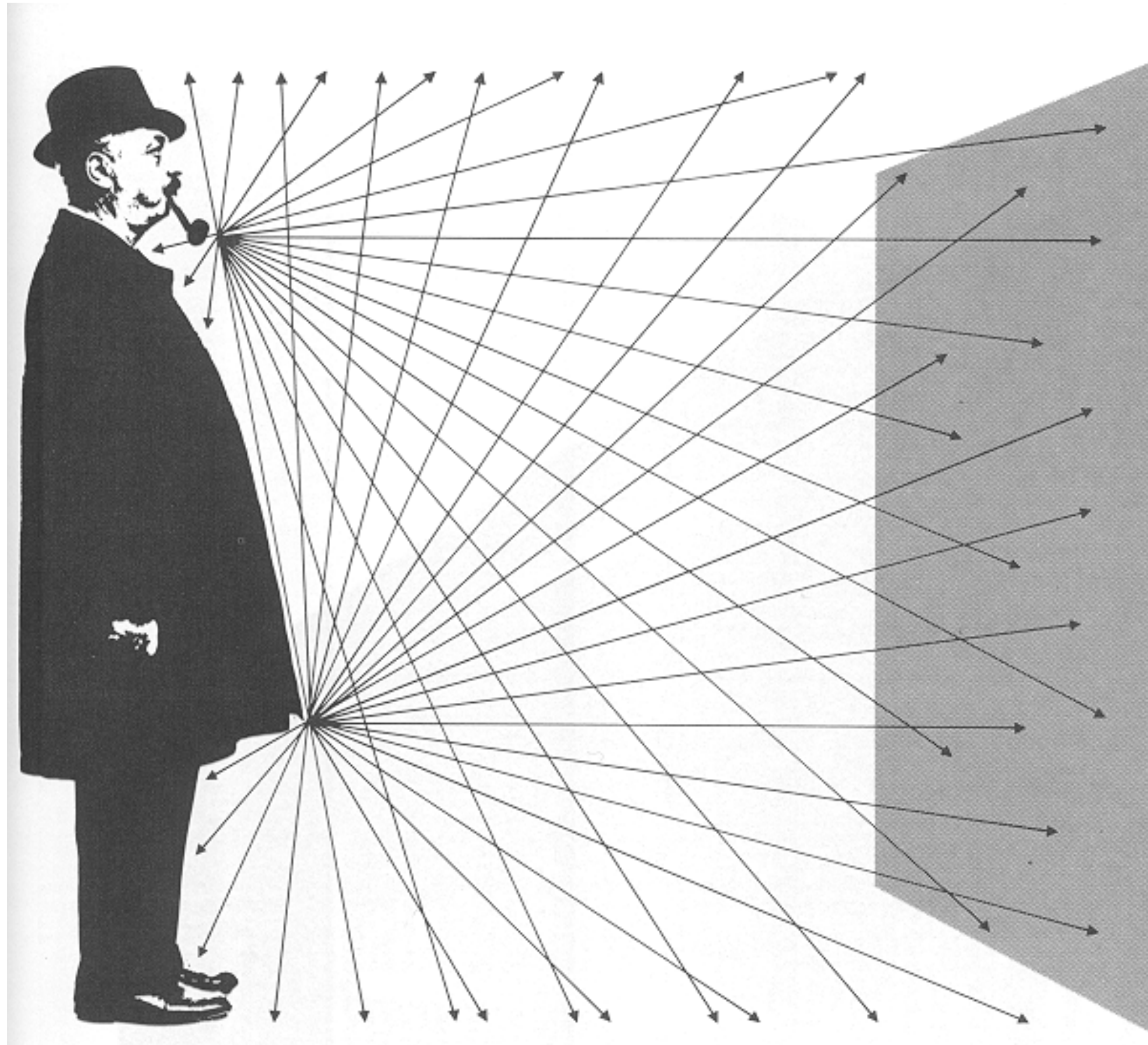




# **“Intensity” and Dynamic Range**



# Intuition



From London and Upton

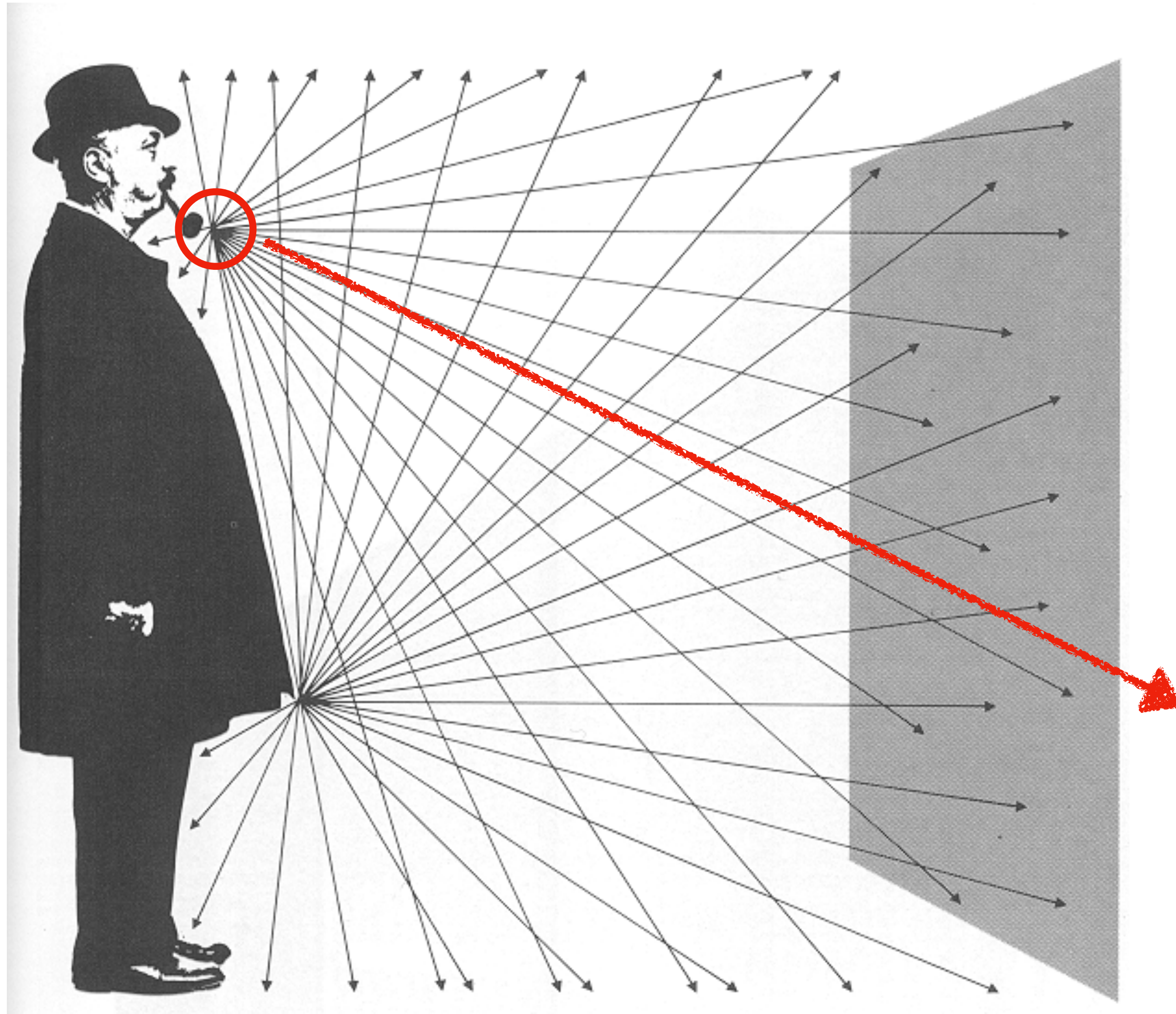
So far we have been using power to describe light's intensity.

- Power is **all** the light energy received/emitted per unit time

But there are other more specific metrics we care about:



# Intuition



From London and Upton

So far we have been using power to describe light's intensity.

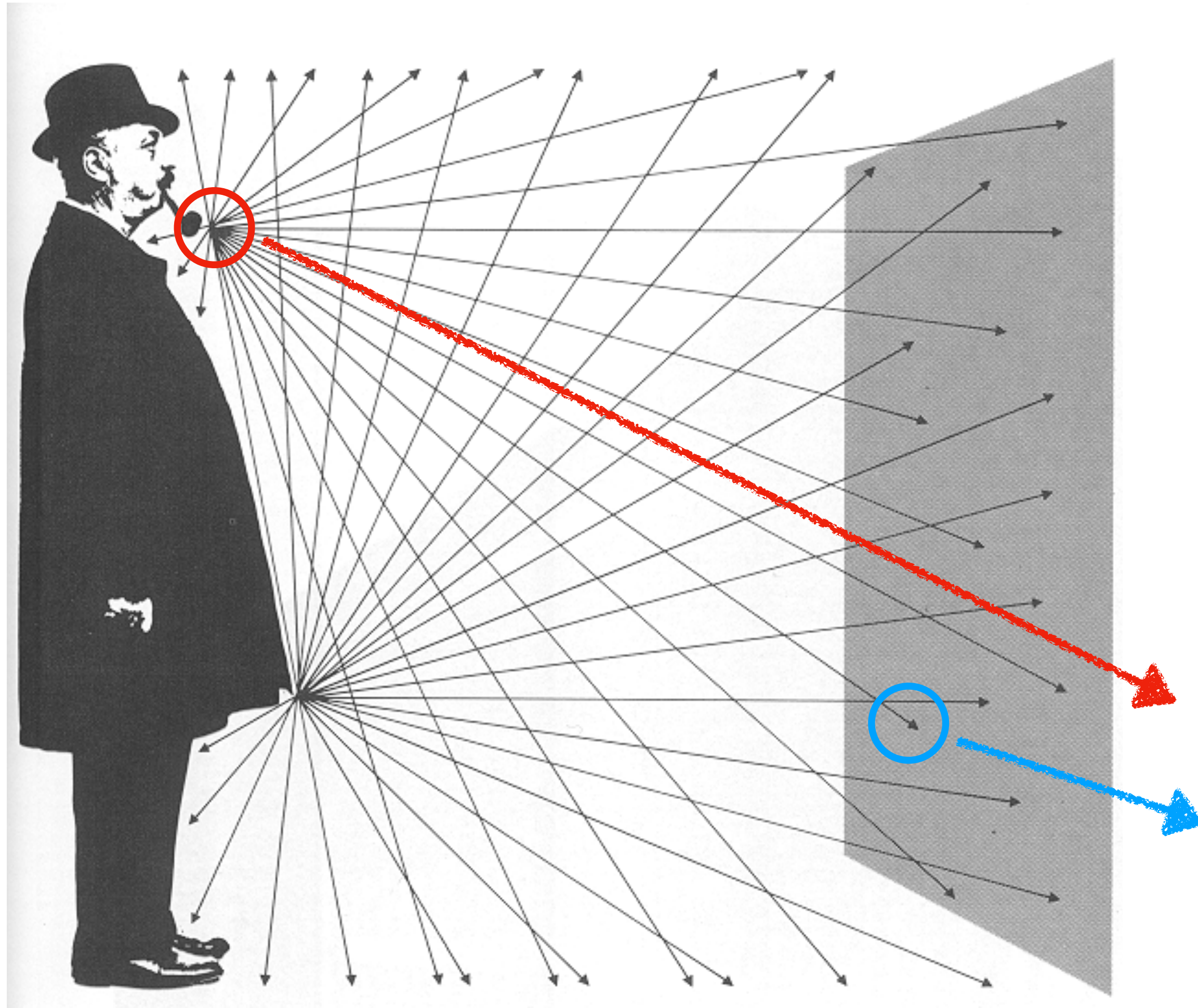
- Power is **all** the light energy received/emitted per unit time

But there are other more specific metrics we care about:

- Light emitted/received at a single point?



# Intuition



From London and Upton

So far we have been using power to describe light's intensity.

- Power is **all** the light energy received/emitted per unit time

But there are other more specific metrics we care about:

- Light emitted/received at a single point?
- Light emitted/received at a single point along a single ray?



# Intuition

\* Note: just like power is wavelength dependent, so are irradiance and radiance. We will generally omit the wavelength symbol for simplicity.

**Irradiance:** power per unit area

**Radiance:** power per unit  
area per "direction"



So far we have been using power to describe light's intensity.

- Power is **all** the light energy received/emitted per unit time

But there are other more specific metrics we care about:

- Light emitted/received at a single point?
- Light emitted/received at a single point along a single ray?



# Recall: Power/Radiant Flux and Luminous Flux

LEF captures the wavelength-dependent sensitivity of human visual system.

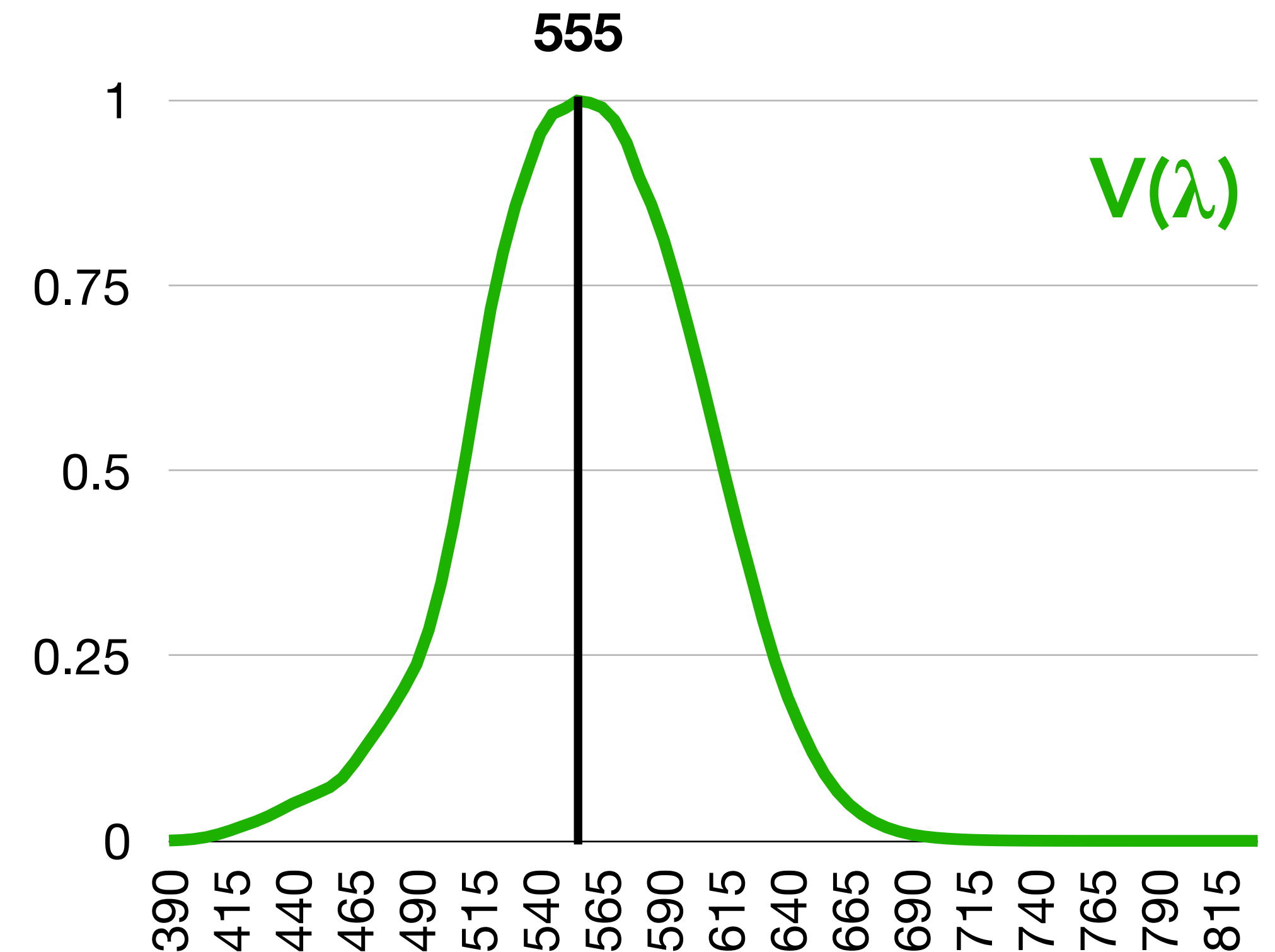
- The constant 683 is to normalize to historical standards.

Power (unit: **watt**) weighted by LEF is called luminous flux (unit: **lumen**).

$$\Phi_v(\lambda) = 683 \frac{\text{lm}}{\text{W}} \Phi_e(\lambda) V(\lambda)$$

Luminous flux  
Unit: **lm**

Power (radiant flux)  
Unit: **W**



CIE 2008 Photopic LEF



# Irradiance = Power Per Unit Area (W/m<sup>2</sup>)



$$E_e = \frac{d\Phi_e}{dA}$$

Irradiance  
Unit: **W/m<sup>2</sup>**

Power (radiant flux)  
Unit: **W**

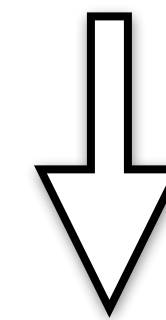


# Irradiance = Power Per Unit Area (W/m<sup>2</sup>)



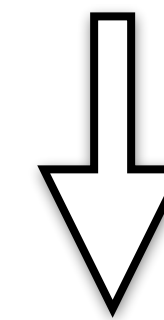
$$E_e = \frac{d\Phi_e}{dA}$$

Irradiance  
Unit: **W/m<sup>2</sup>**



Illuminance  
Unit: **lux = lm/m<sup>2</sup>**

Power (radiant flux)  
Unit: **W**

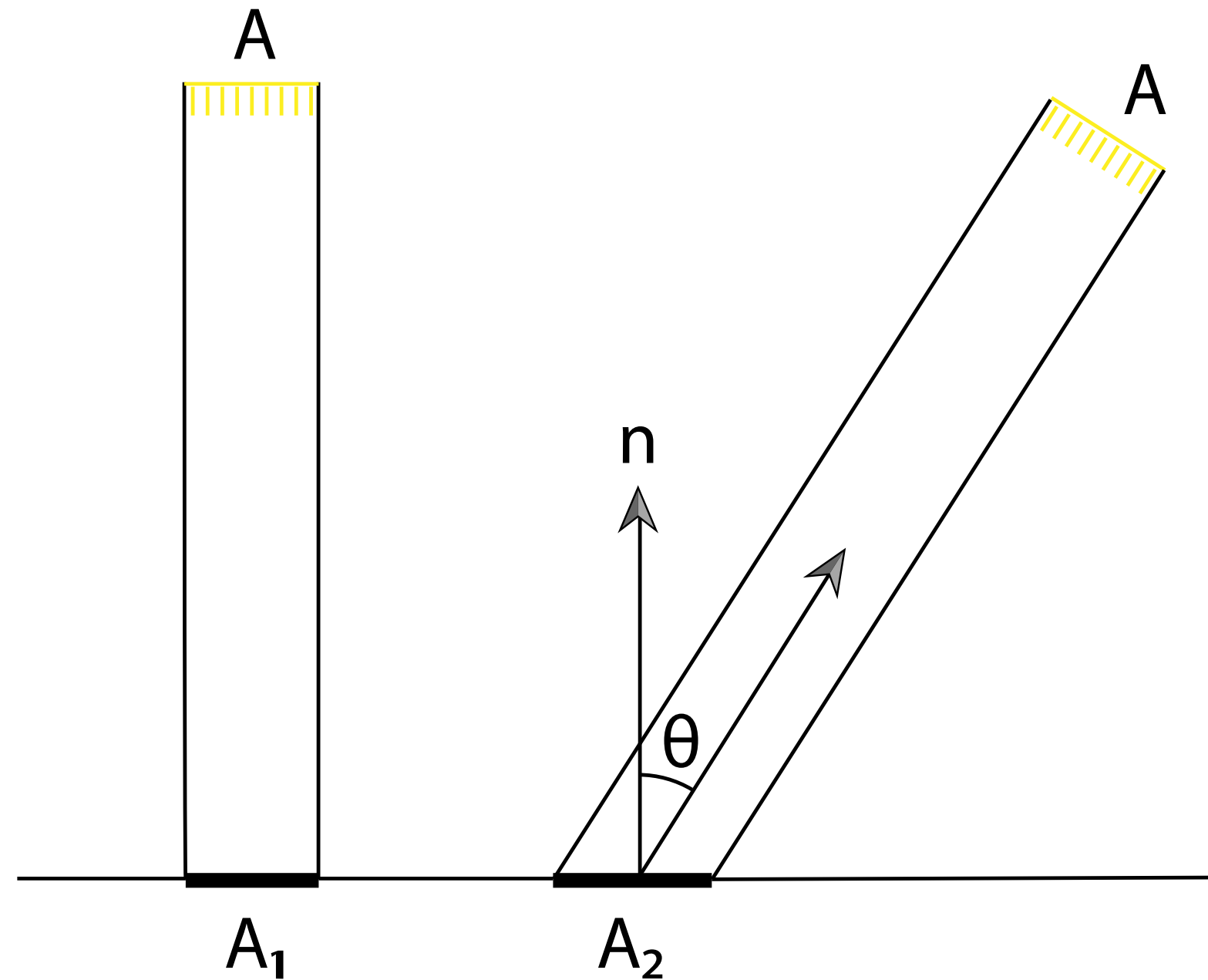


Weighted by LEF

Luminous flux  
Unit: **lm**



# Irradiance Falls Off With Incident Angle



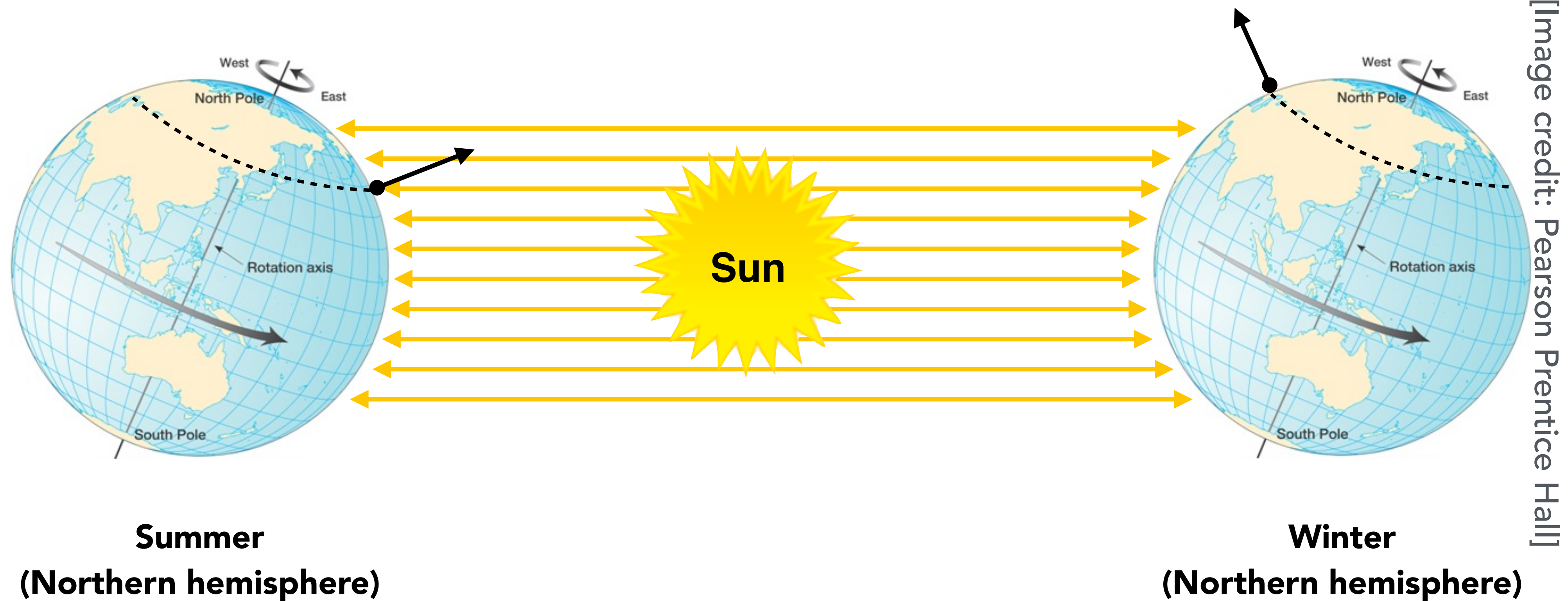
$$E_{e,1} = \frac{d\Phi_e}{dA_1} = \frac{d\Phi_e}{dA}$$

$$E_{e,2} = \frac{d\Phi_e}{dA_2} = \frac{d\Phi_e \cos \theta}{dA}$$

Intuition is that the incident photons get smeared across a larger area as incident angle increases. Extreme case: incident light is parallel to the surface, in which case the surface irradiance is 0.



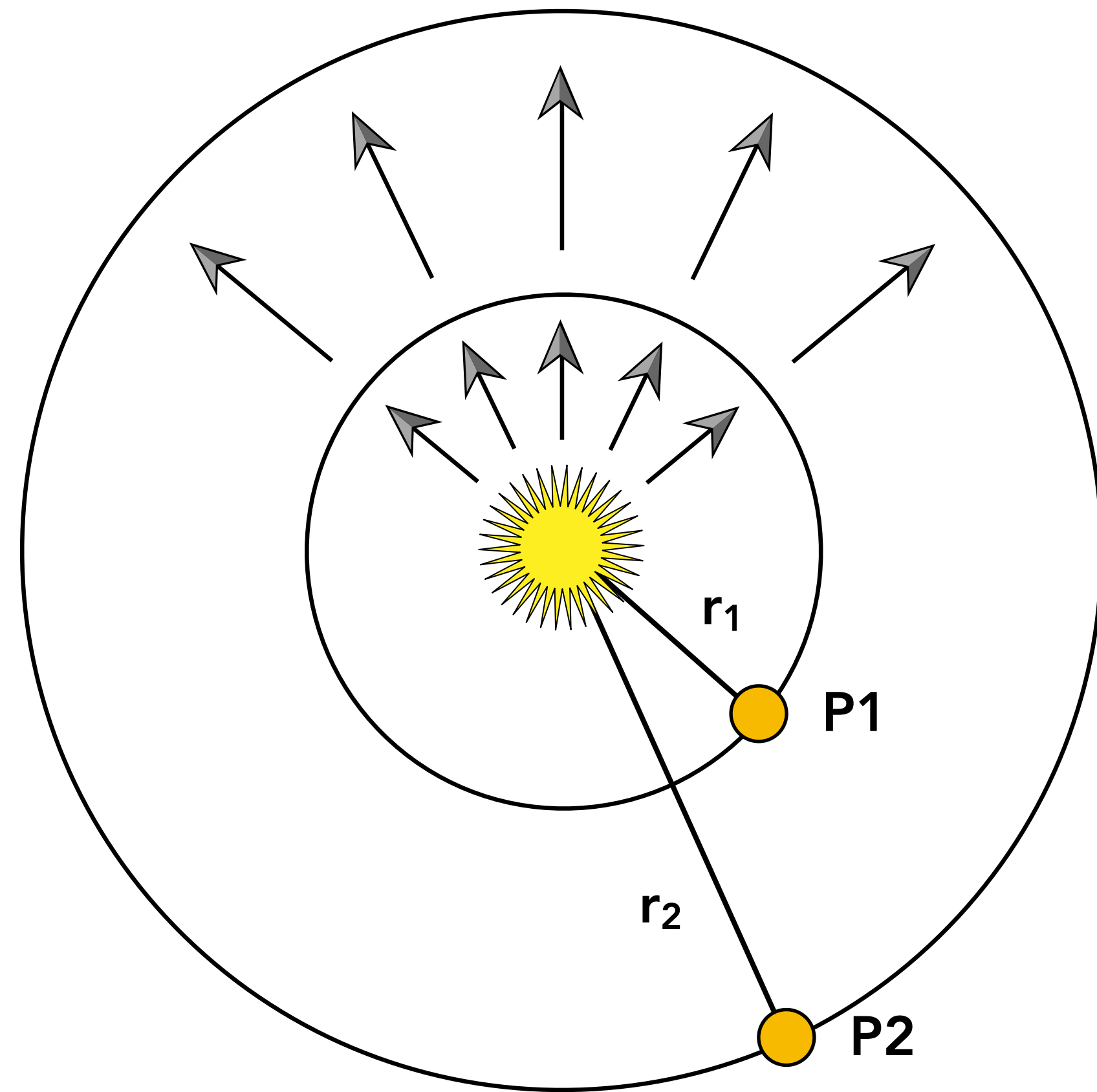
# That's Why We Have Seasons!



Earth's axis of rotation:  $\sim 23.5^\circ$  off axis



# Irradiance Falls Off With Distance



$$E_{e,1} = \frac{\Phi_e}{4\pi r_1^2} \quad E_{e,2} = \frac{\Phi_e}{4\pi r_2^2}$$

Irradiance falls off quadratically with respect to distance.

Intuition: the same amount of photons emitted from the light source gets smeared across a larger surface area as distance increases.

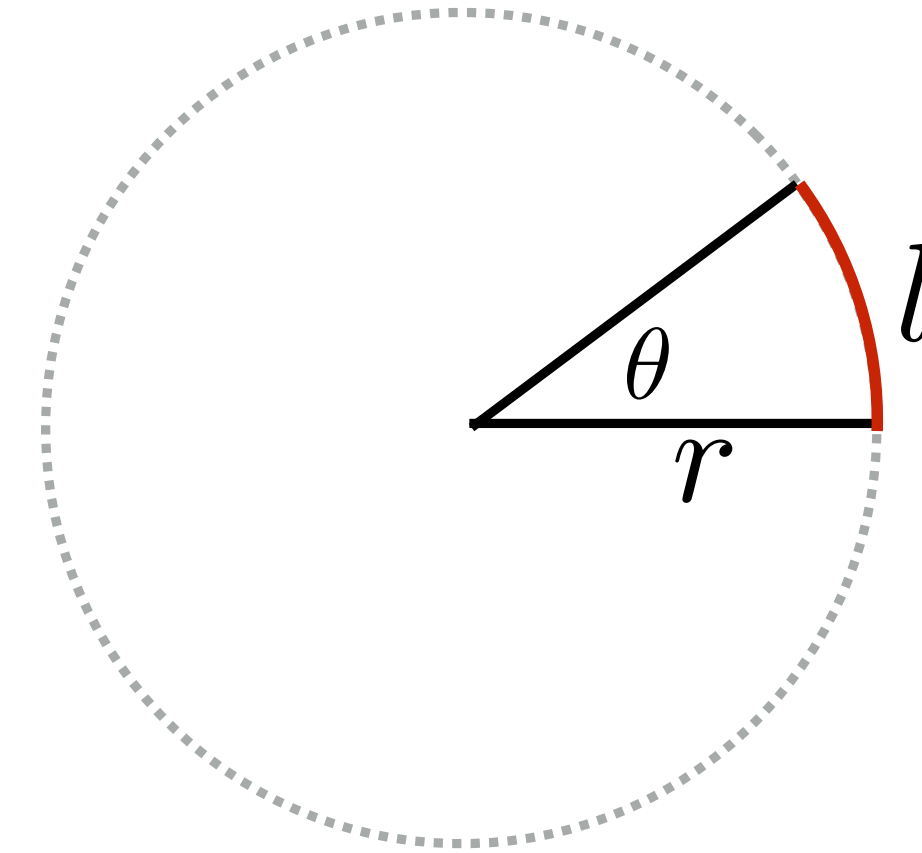


# How to Describe Direction?

## Angles and Solid Angles

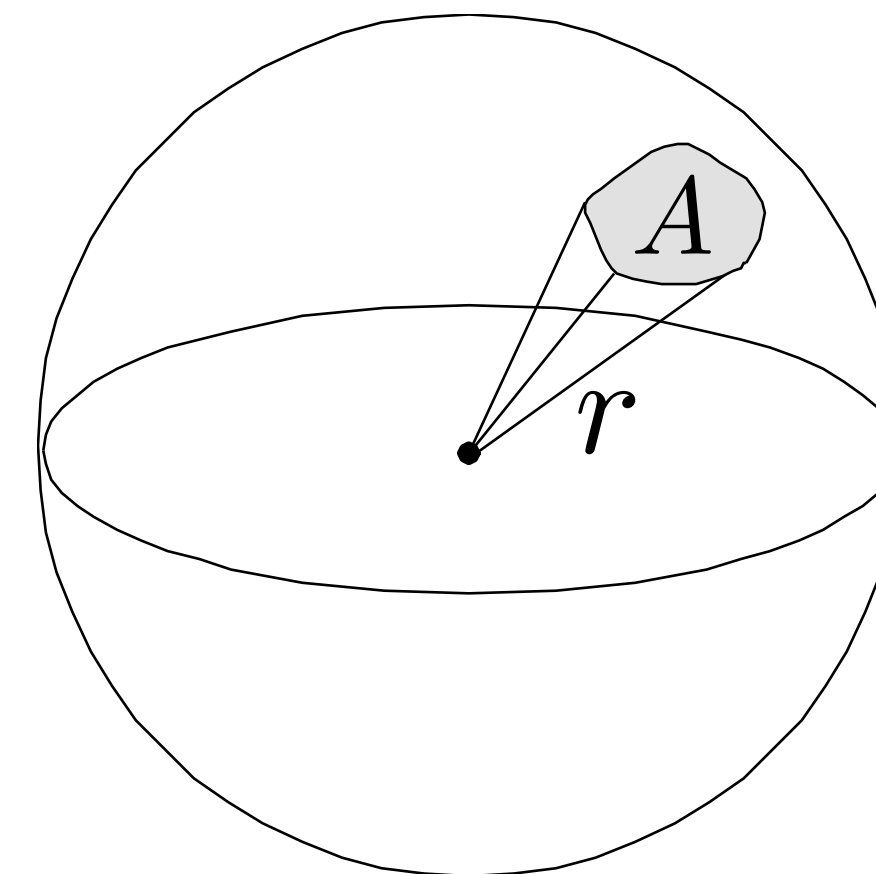
Angle: ratio of subtended arc length on circle to radius

- $\theta = \frac{l}{r}$
- Circle has  $2\pi$  **radians**



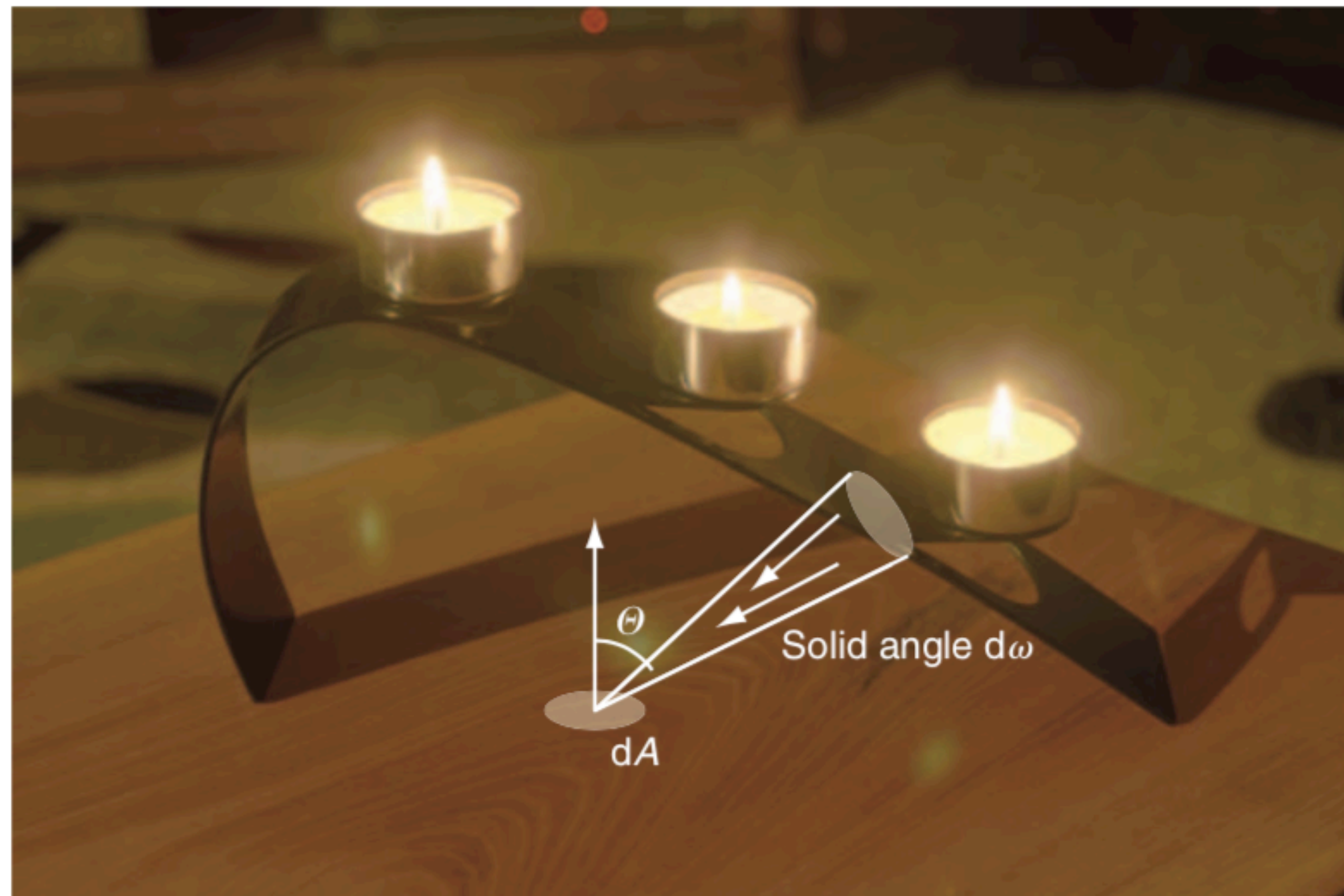
Solid angle: ratio of subtended area on sphere to radius squared

- $\Omega = \frac{A}{r^2}$
- Sphere has  $4\pi$  **steradians**

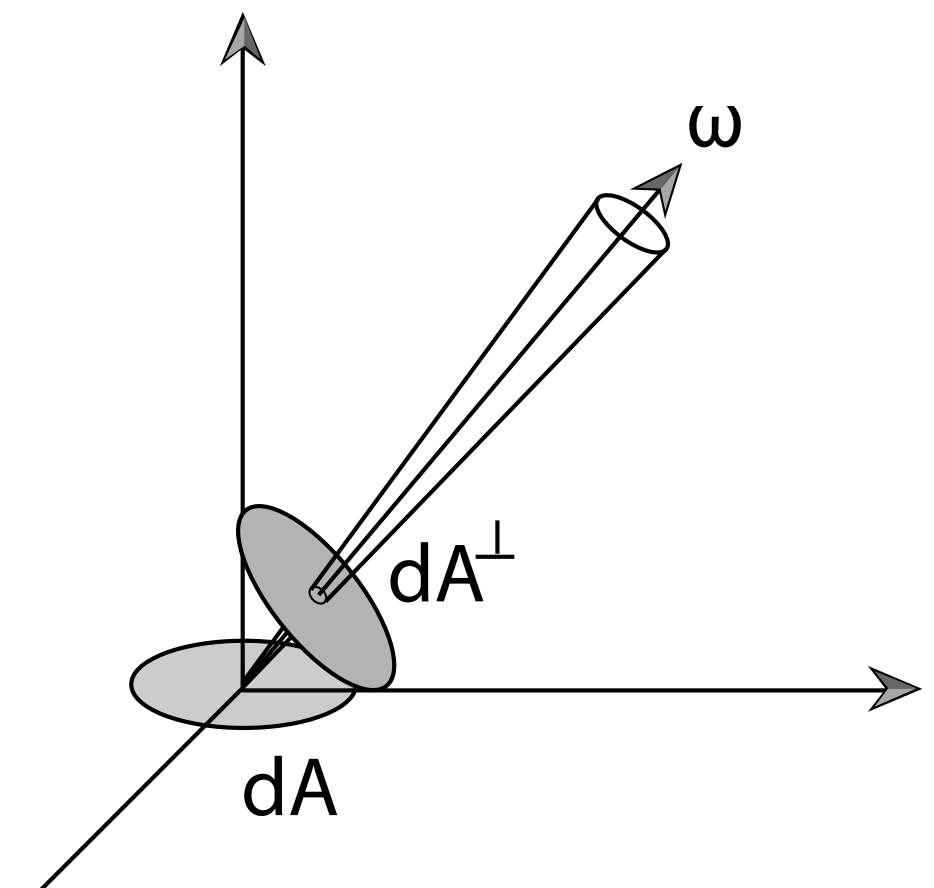




# Radiance = Irradiance Per Unit Solid Angle

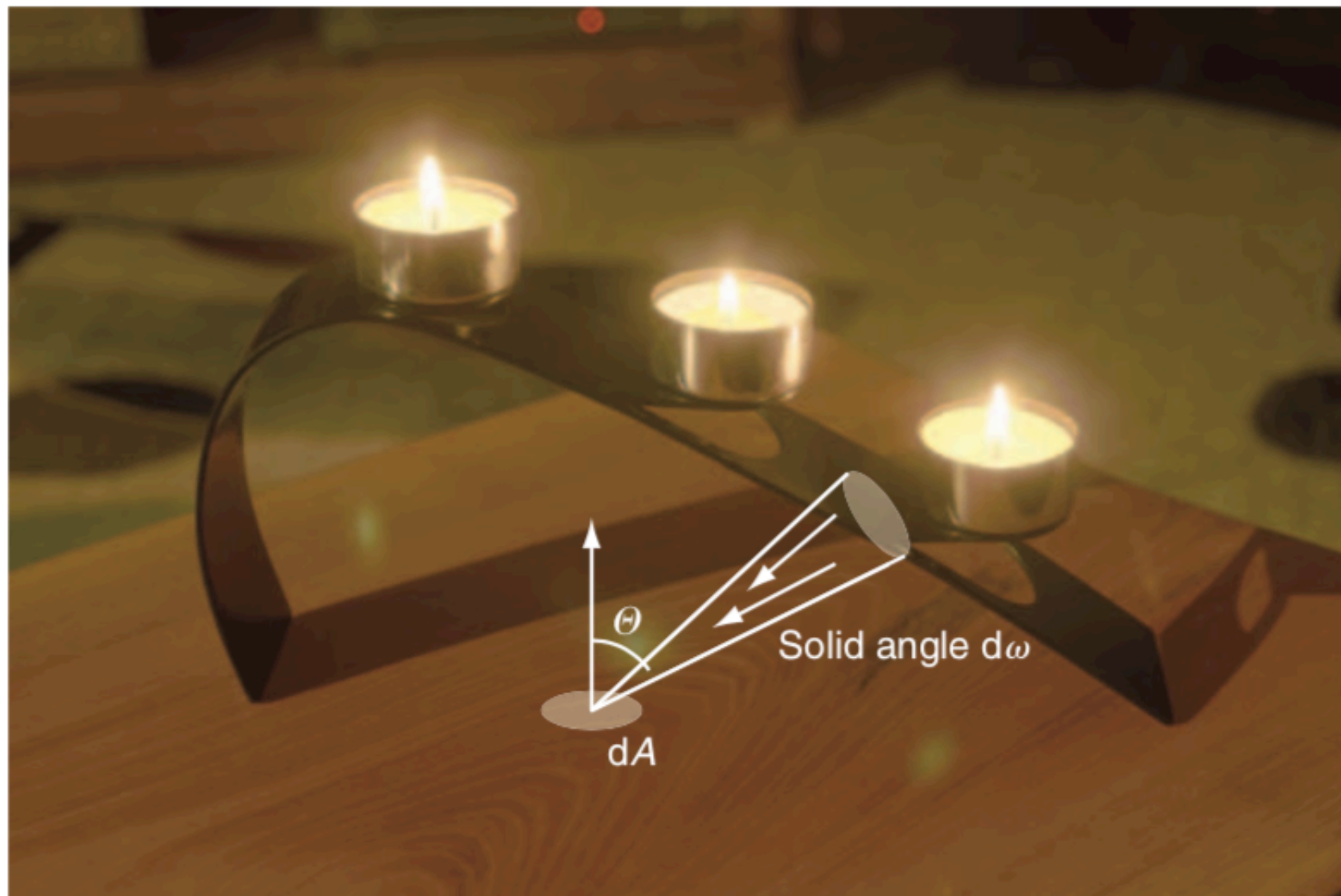


\* radiance is defined at the projected area  $dA^\perp$ , rather than  $dA$ .

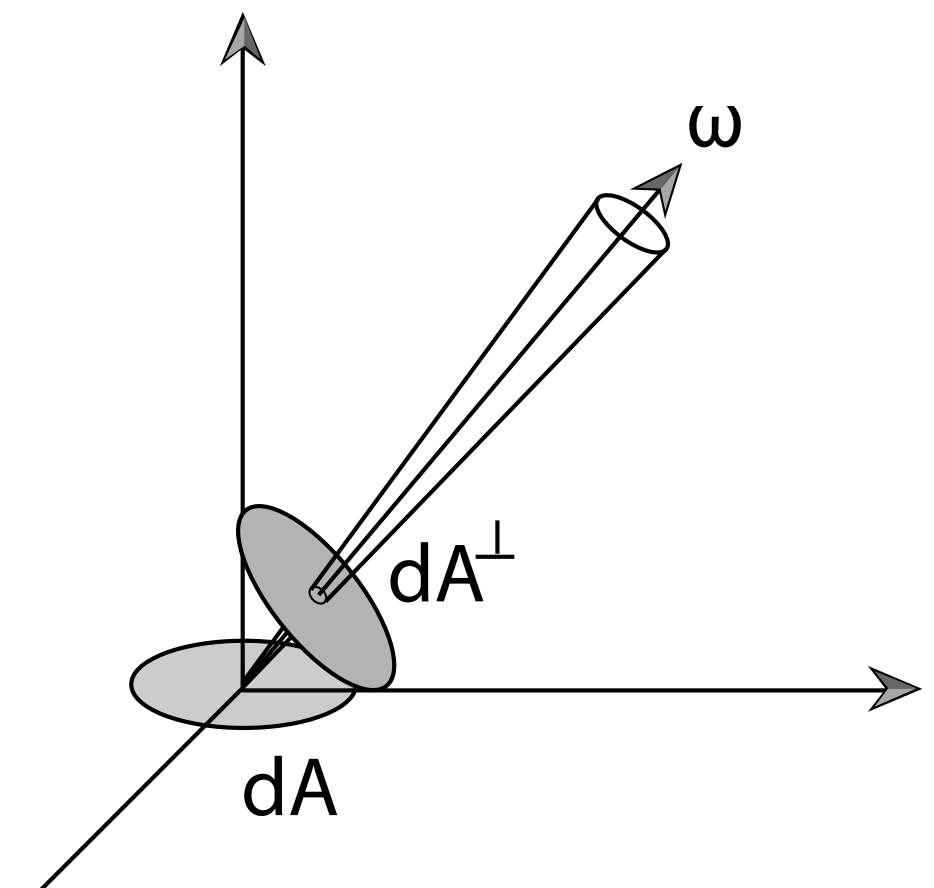




# Radiance = Irradiance Per Unit Solid Angle



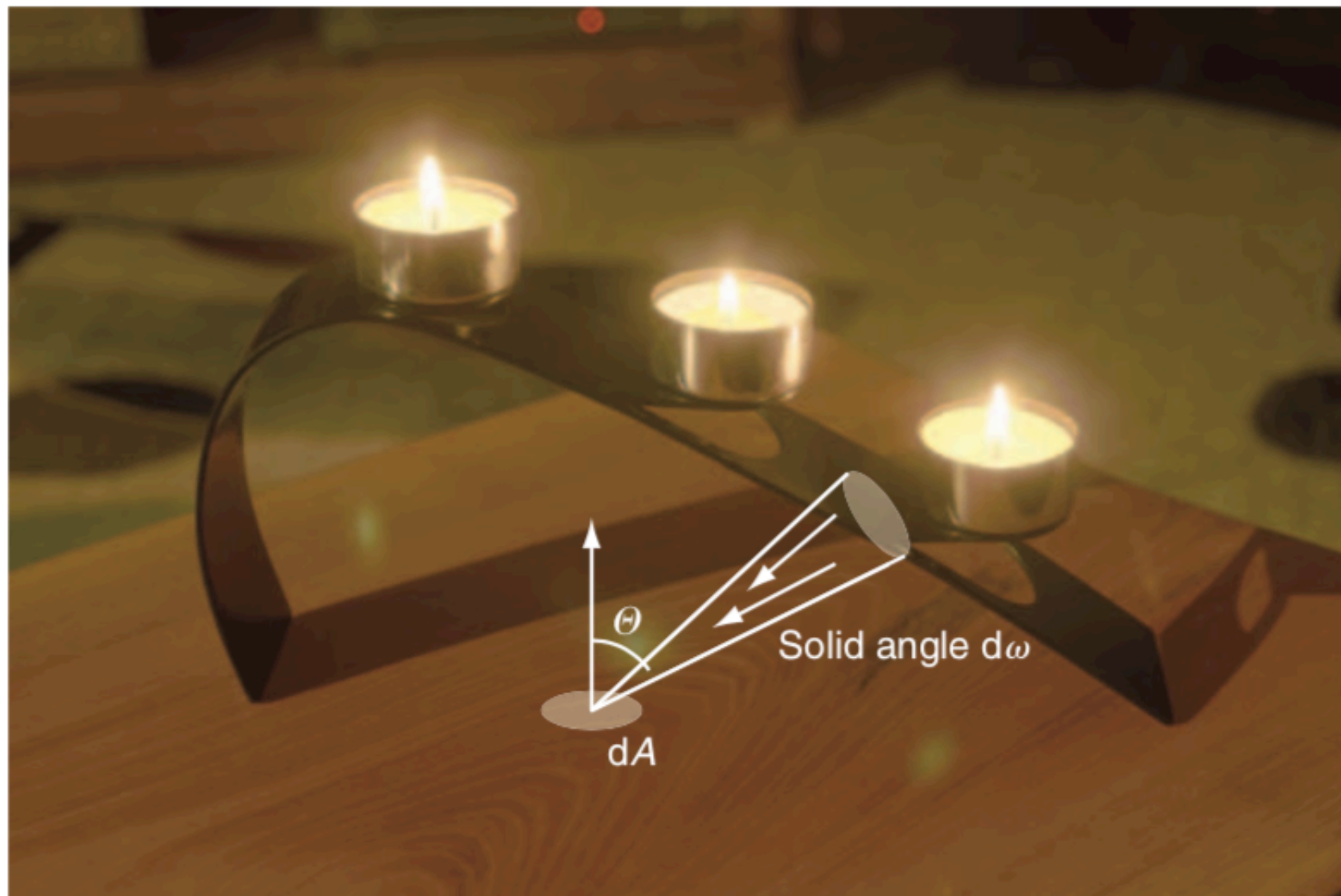
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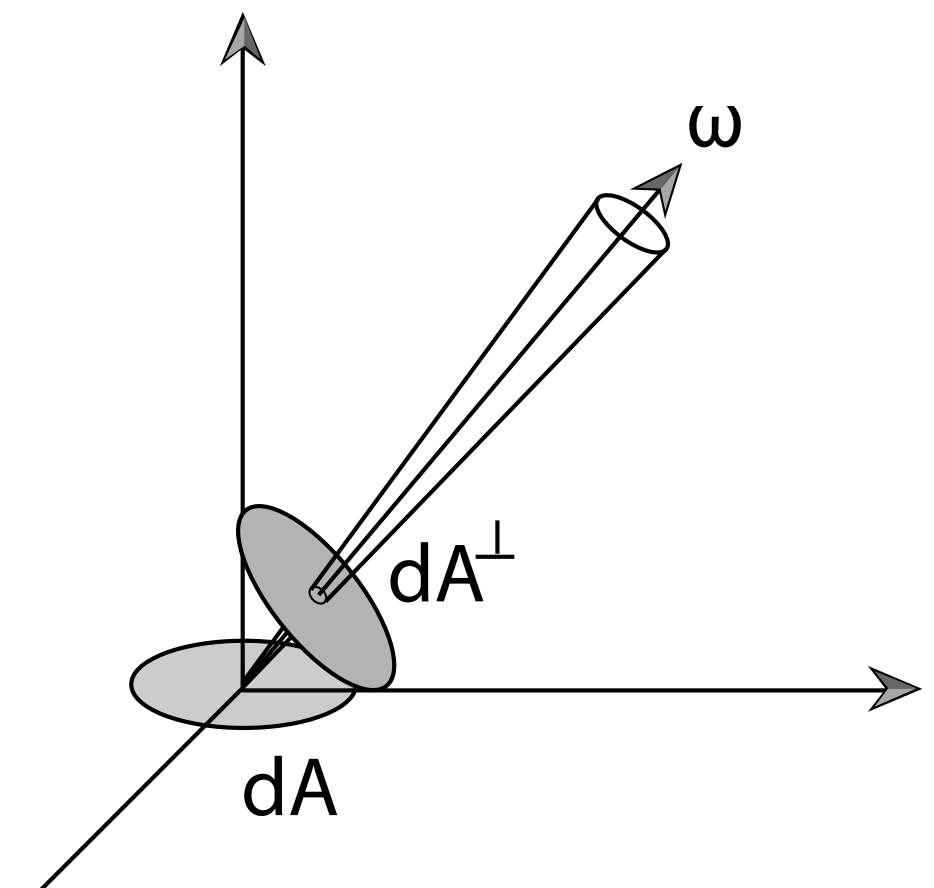
$$L_e = \frac{dE_e}{d\omega} = \frac{d\Phi_e}{d\omega dA^\perp} = \frac{d^2\Phi_e}{d\omega dA \cos \theta}$$



# Radiance = Irradiance Per Unit Solid Angle



\* radiance is defined at the projected area  $dA^\perp$ , rather than  $dA$ .

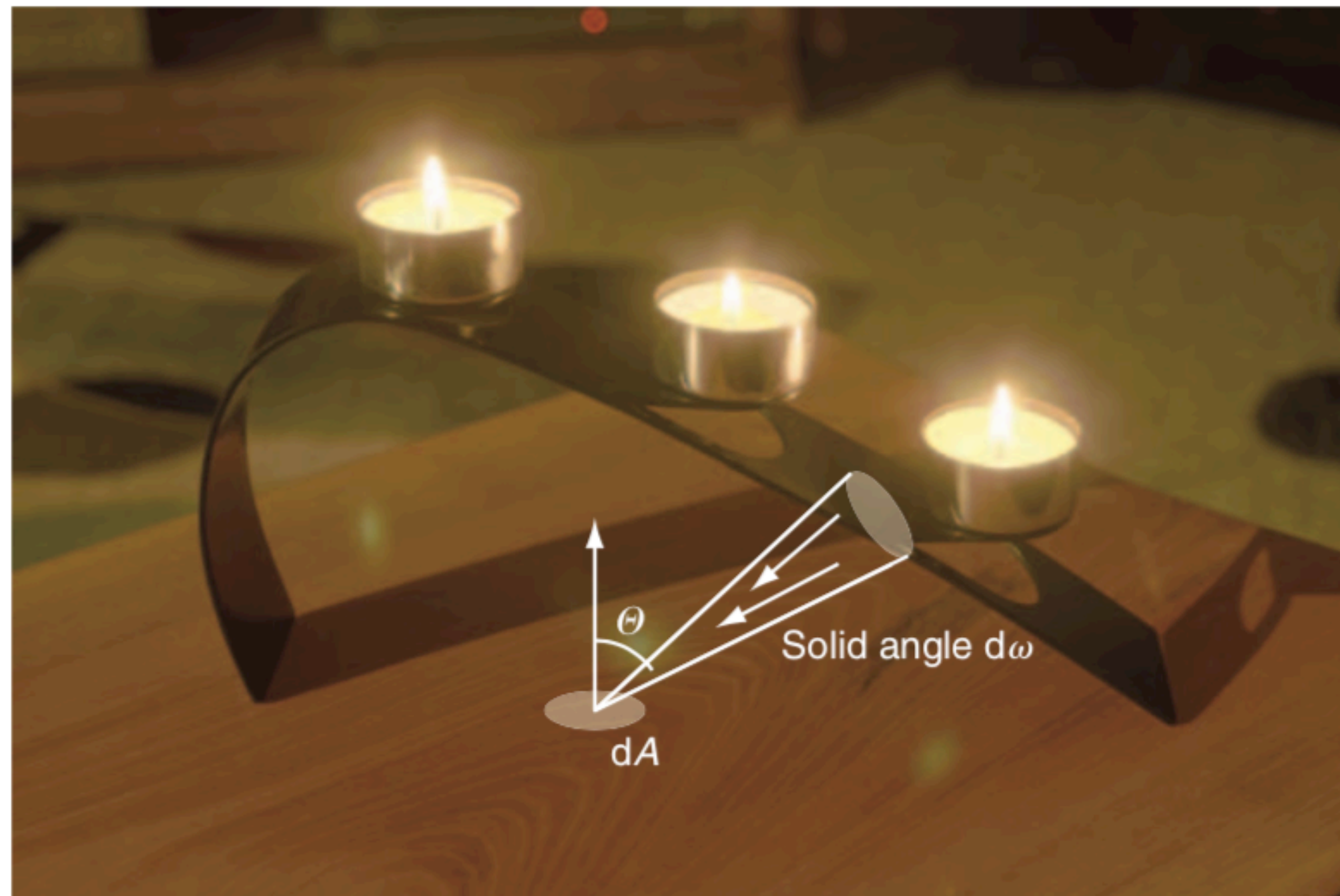


$$L_e = \frac{dE_e}{d\omega} = \frac{d\Phi_e}{d\omega dA^\perp} = \frac{d^2\Phi_e}{d\omega dA \cos \theta}$$

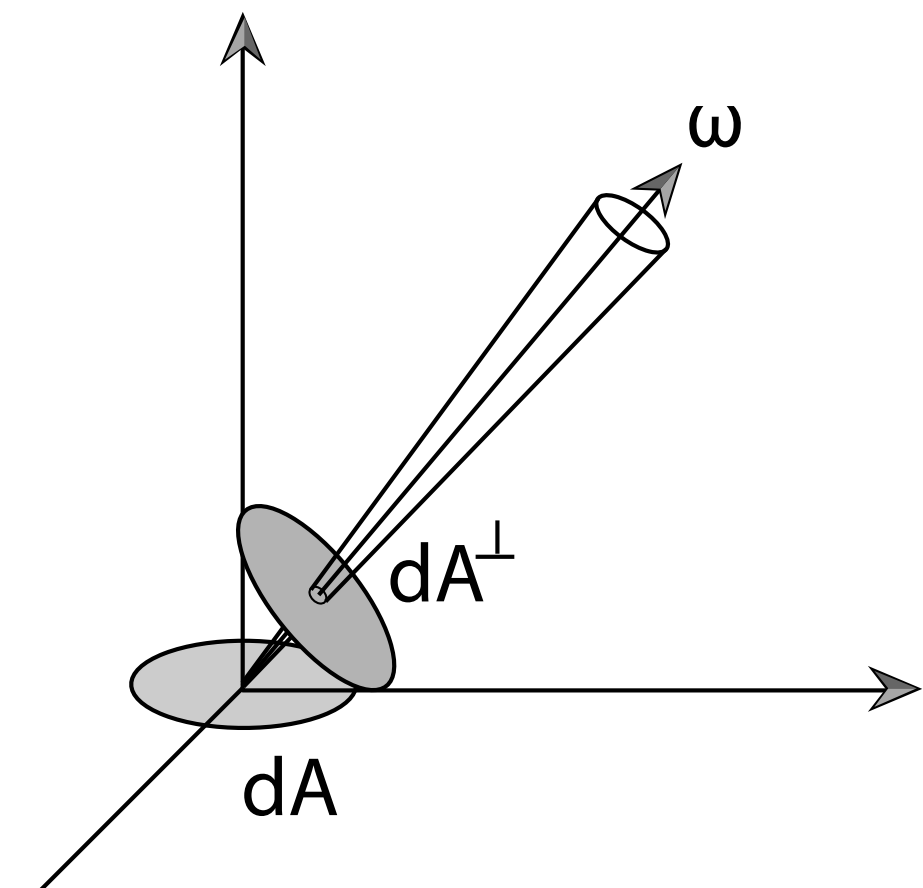
Radiance  
Unit: **W/(sr m<sup>2</sup>)**



# Radiance = Irradiance Per Unit Solid Angle

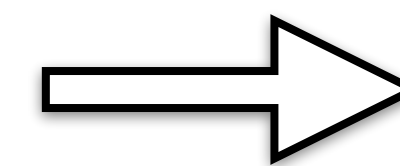


\* radiance is defined at the projected area  $dA^\perp$ , rather than  $dA$ .



$$L_e = \frac{dE_e}{d\omega} = \frac{d\Phi_e}{d\omega dA^\perp} = \frac{d^2\Phi_e}{d\omega dA \cos \theta}$$

Radiance  
Unit: **W/(sr m<sup>2</sup>)**



Luminance  
Unit: **nit = lm/(sr m<sup>2</sup>) = cd/m<sup>2</sup>**

Weighted by LEF



# Radiometry vs. Photometry

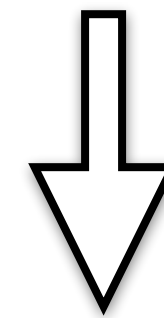
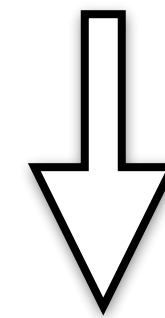
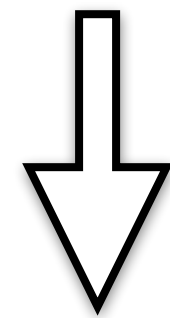
**Radiometry** Units

Power (radiant flux)  
Unit: **W**

Irradiance  
Unit: **W/m<sup>2</sup>**

Radiance  
Unit: **W/(sr m<sup>2</sup>)**

Weighted by LEF



**Photometry** Units

Luminous flux  
Unit: **lm**

Illuminance  
Unit: **lux = lm/m<sup>2</sup>**

Luminance  
Unit: **nit = lm/(sr m<sup>2</sup>) = cd/m<sup>2</sup>**



# Display Luminance



LG 27UK850-W (LCD): **350** nits



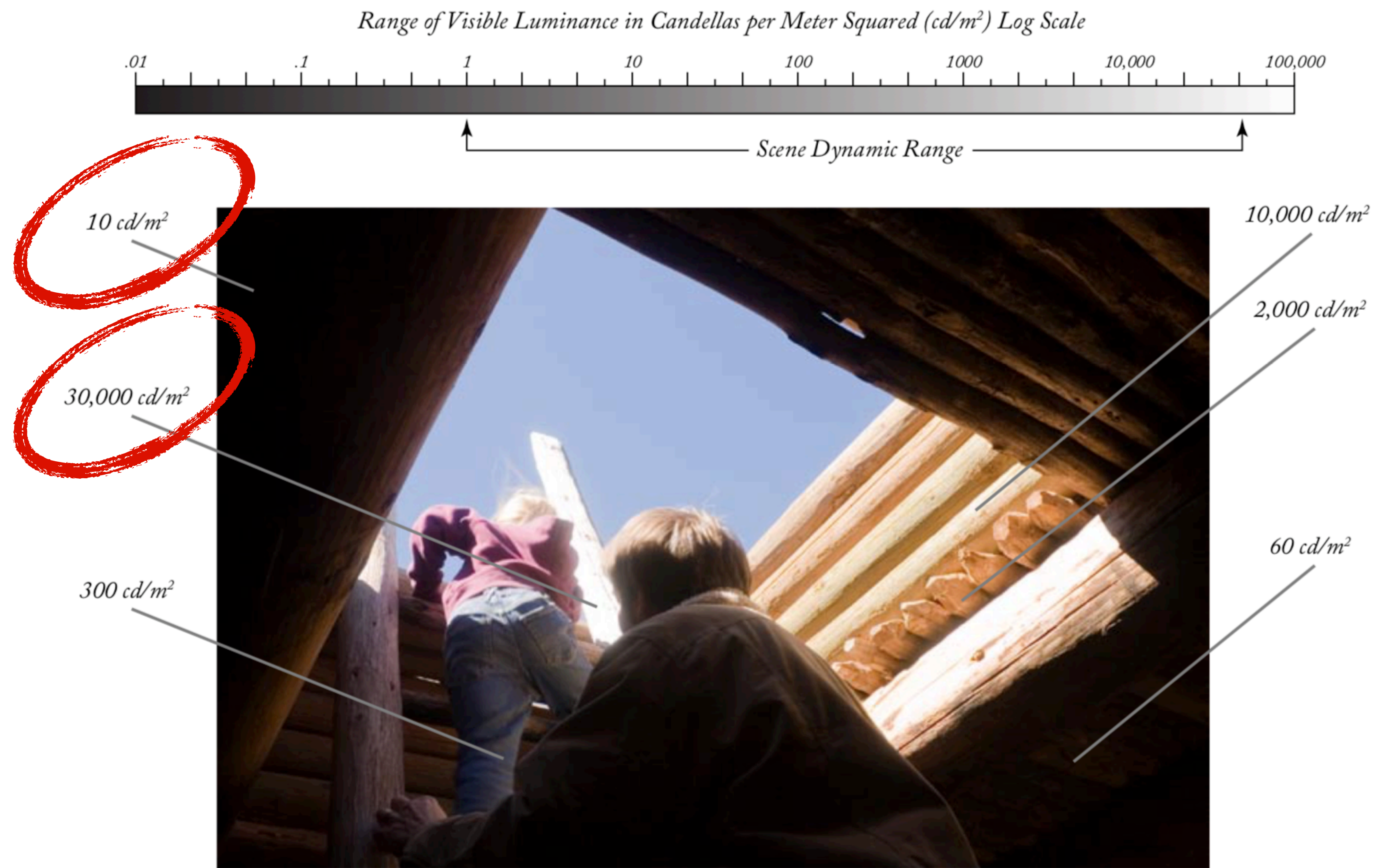
iPhone 14 (OLED): **1000** nits  
(2000 nits max)



Pixel 7 (OLED): **600** nits  
(1,000 nits max)

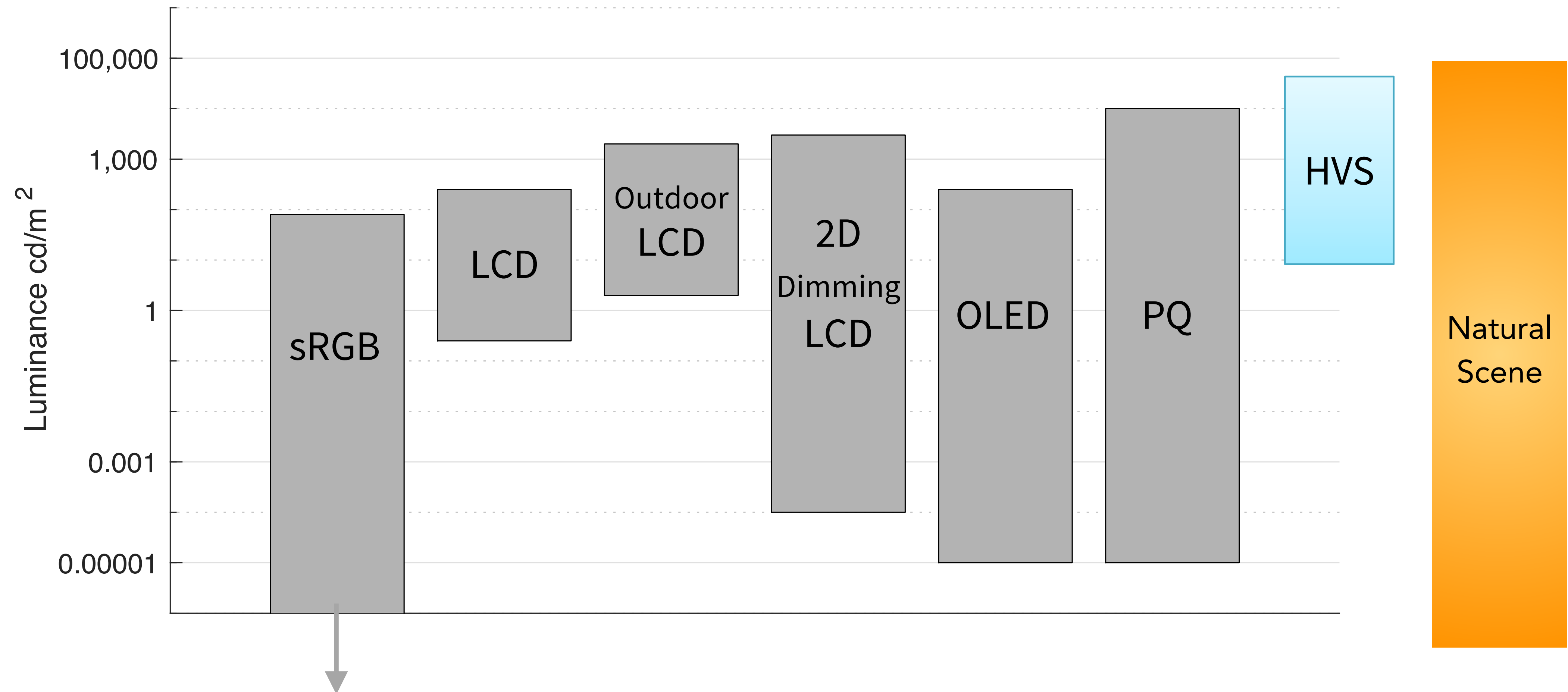


# Luminance in Natural Scenes



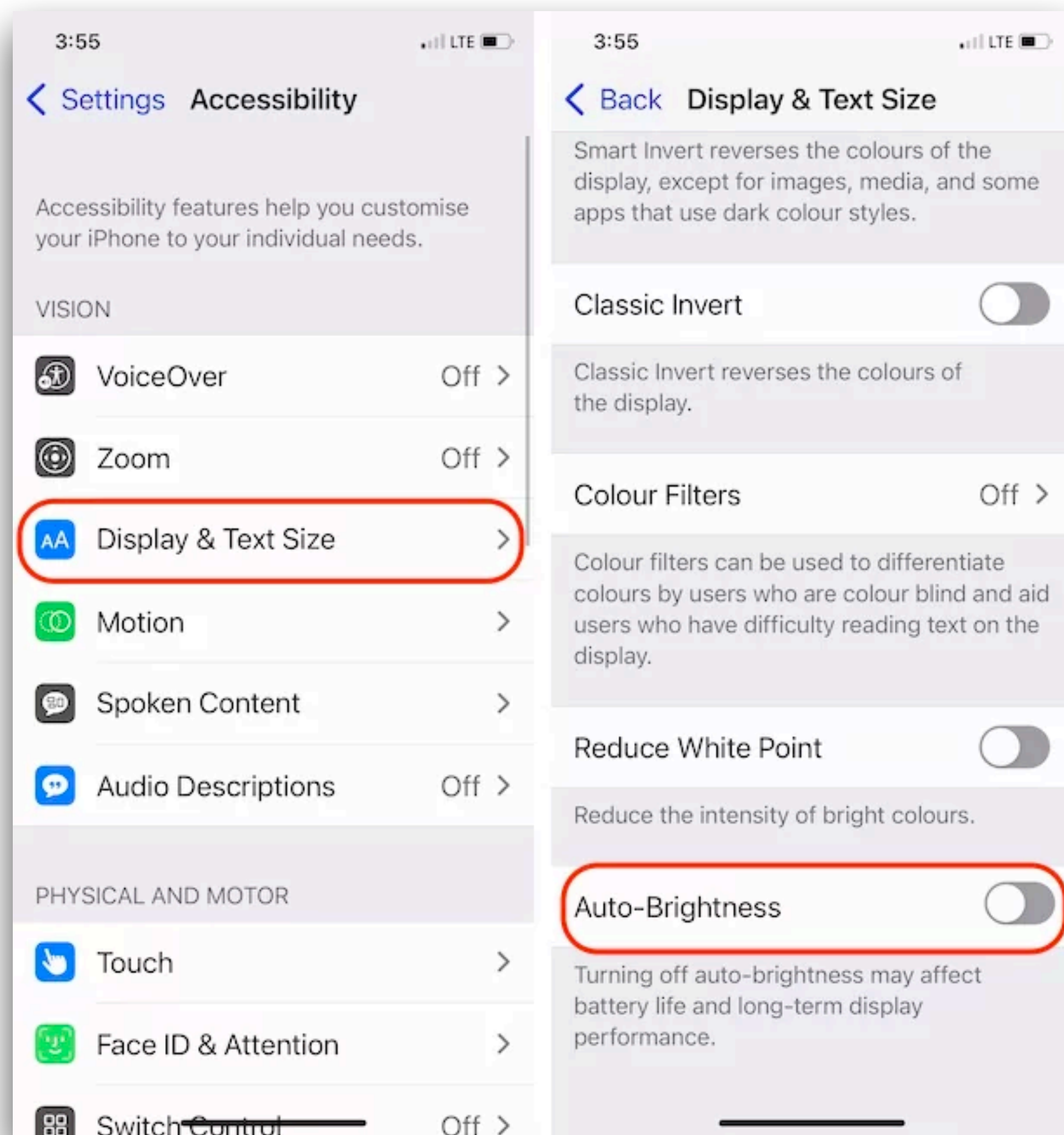


# Dynamic Range = Max Luminance / Min Luminance

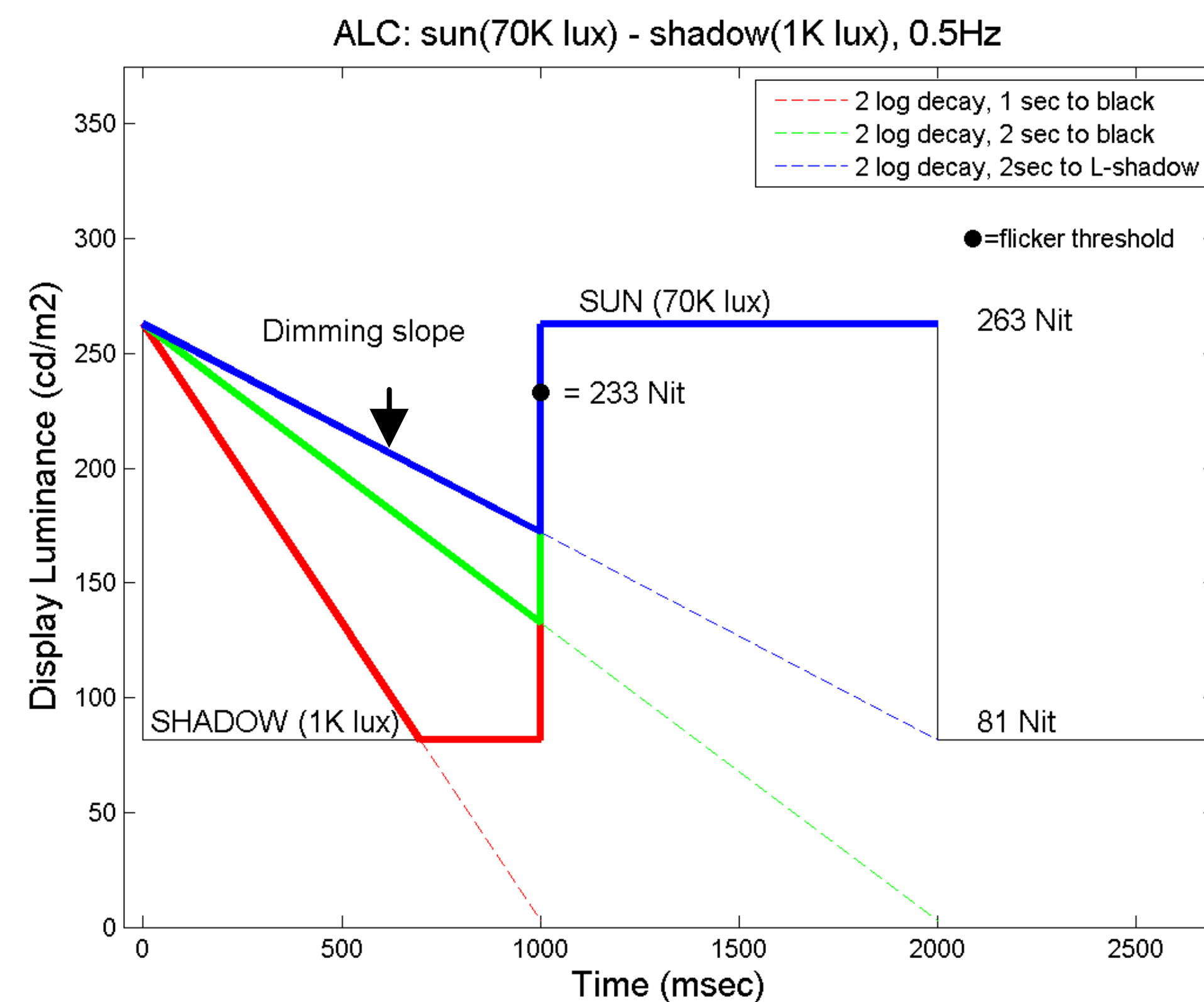




# Automatic Brightness



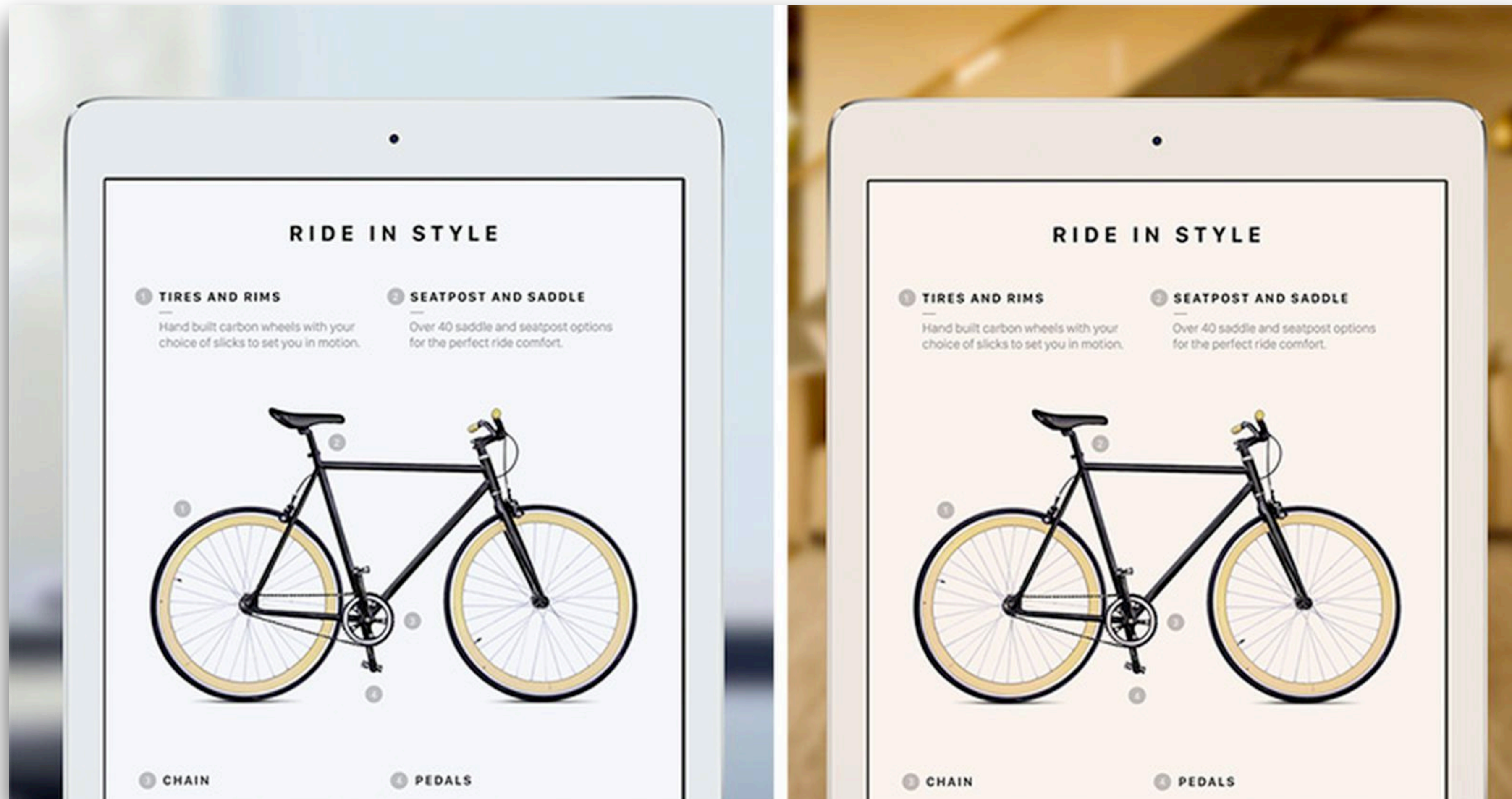
When external illumination is high, increase the display luminance because: 1) unwanted reflectance from display is high and 2) your eye "exposure time" is shorter.





# Related: Apple TrueTone

TrueTone adjusts the white point of the display. It's related to chromatic adaption of human visual system and camera white balance. More later in the camera module.





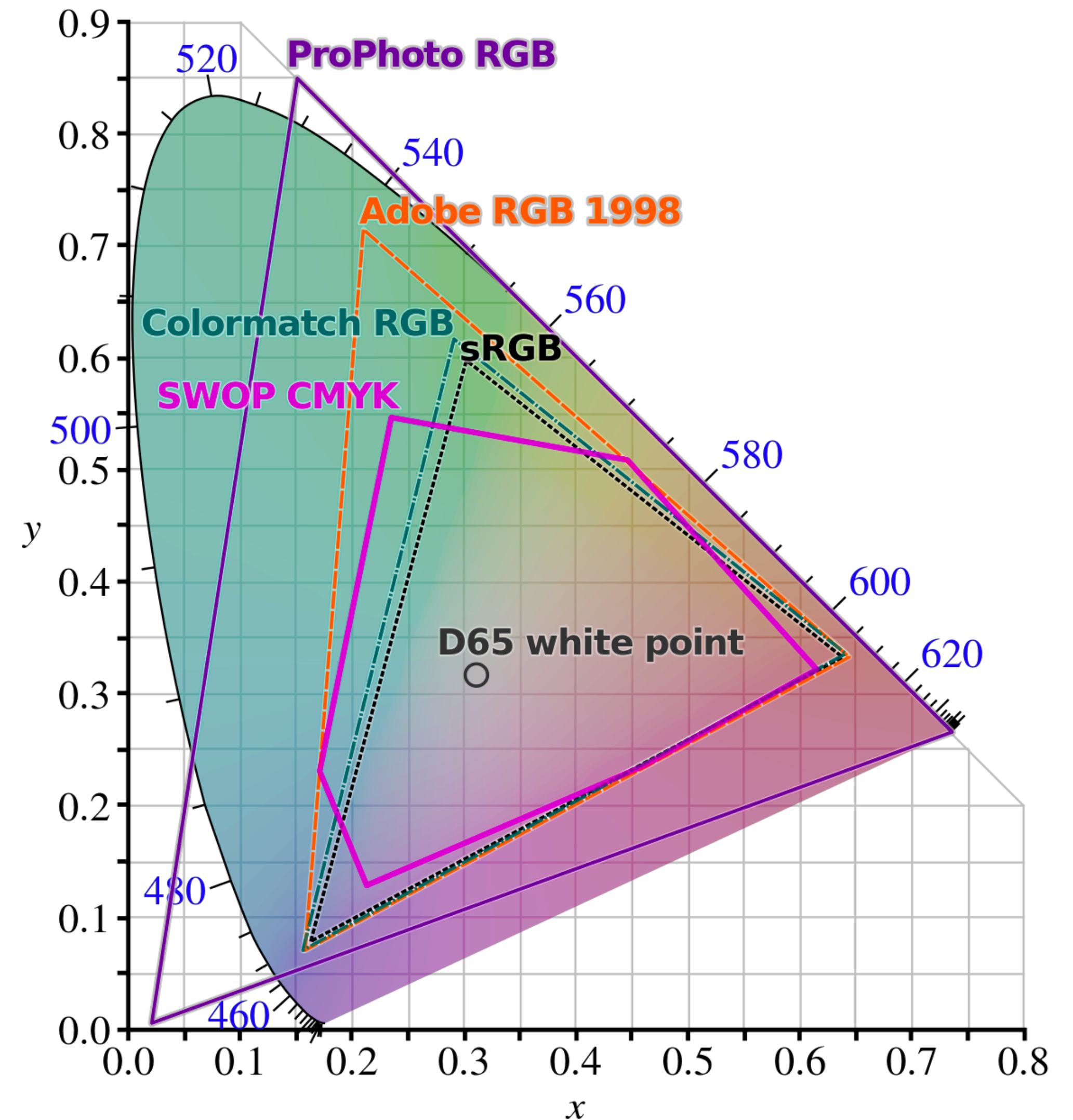
# Gamut Mapping and Color Management



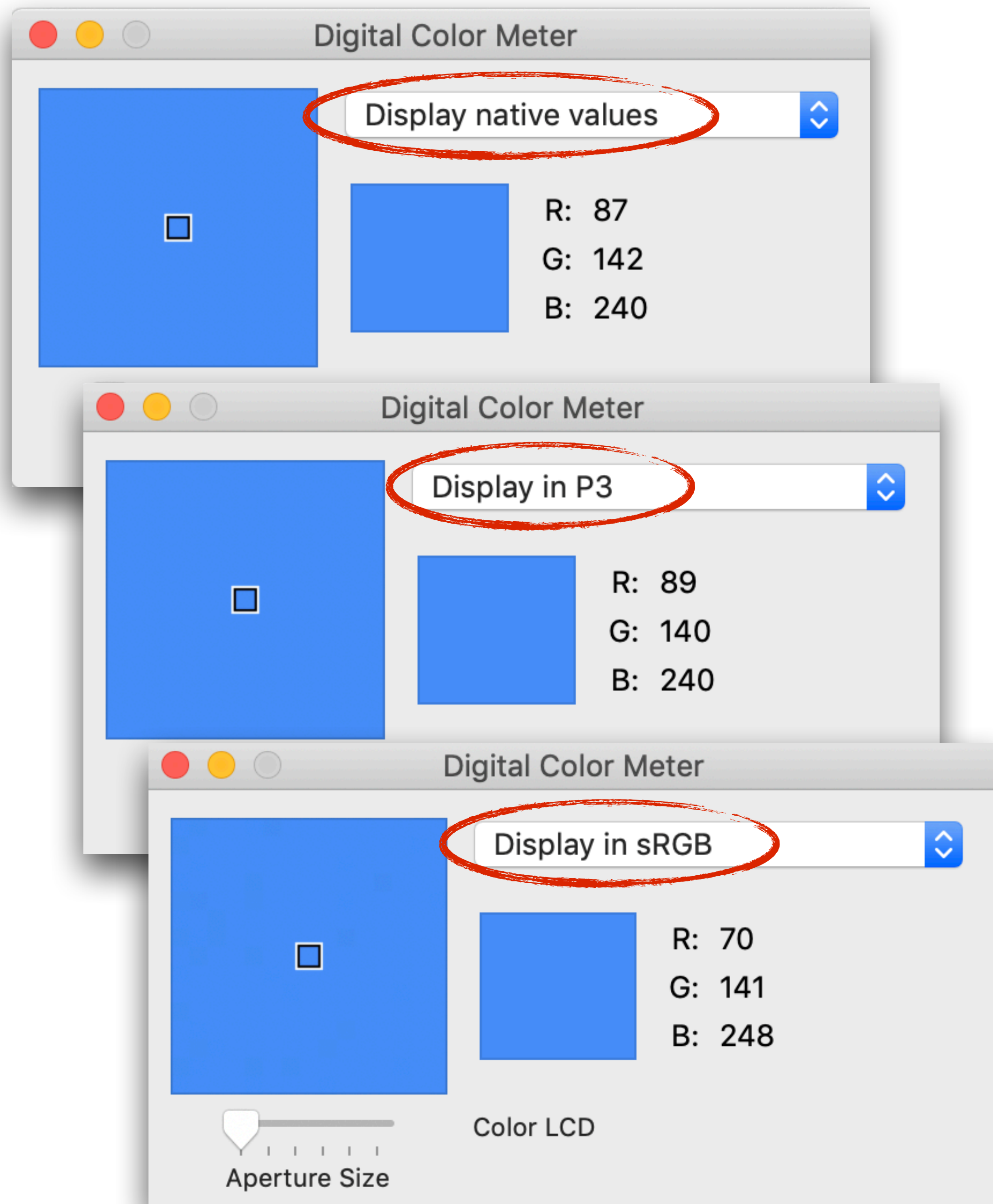
# Issue: Color Spaces Don't Match

Gamuts of different color spaces don't match.

Without care, an image that looks great on one display (with one color space) might look awful when printed or on another display (with a different color space).







Display native color space rarely matches exactly with an existing color space (manufacturing constraints).

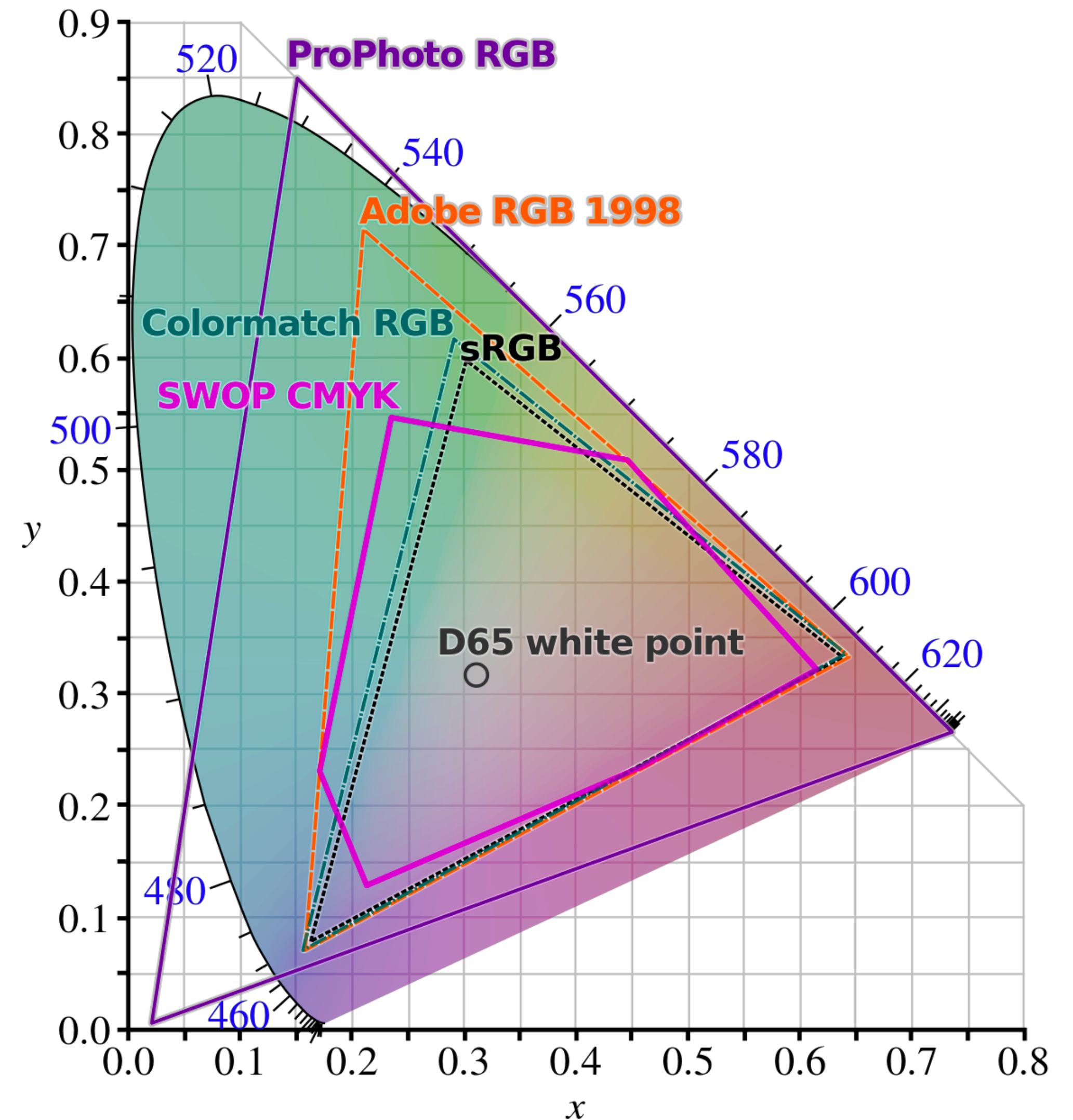
The same pixel shown in three different color spaces. The RGB values in the display native space roughly match the values in the DCI P3 color space, but are very different from the values in the sRGB color space.



# An Example

Consider this workflow:

- Edit a photo using Photoshop on a display that uses **Adobe RGB** color space.
- Save the photo.
- View the photo on another display that uses the **sRGB** color space. It would look horrible. Why?
- The color [10, 20, 30] in AdobeRGB color space and the color [10, 20, 30] in the sRGB space are two different colors! Can't just take the pixel values as is without care.





# An Example

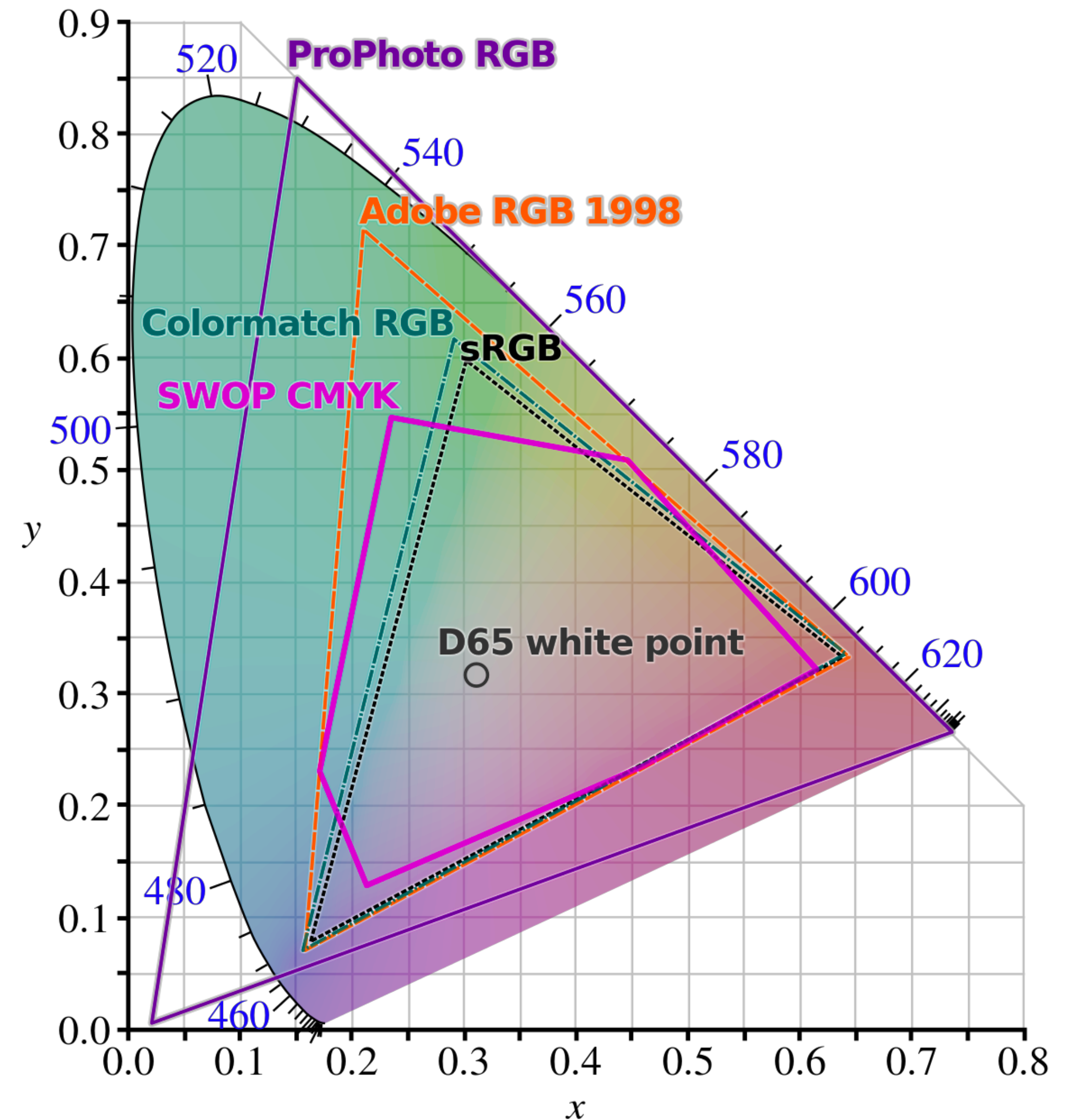
Actually it's even worse. sRGB gamut is a **subset** of the Adobe RGB gamut.

It's guaranteed that there are some colors in Adobe RGB that can't possibly be reproduced in the sRGB space!

Same with printing. Printer gamut is usually even smaller.

and so forth), we strongly suggest you avoid placing color figures in your document. If you do include color figures, you must (1) use the CMYK (not RGB) colorspace and (2)

**Paper formatting instructions of AAAI 2020.**





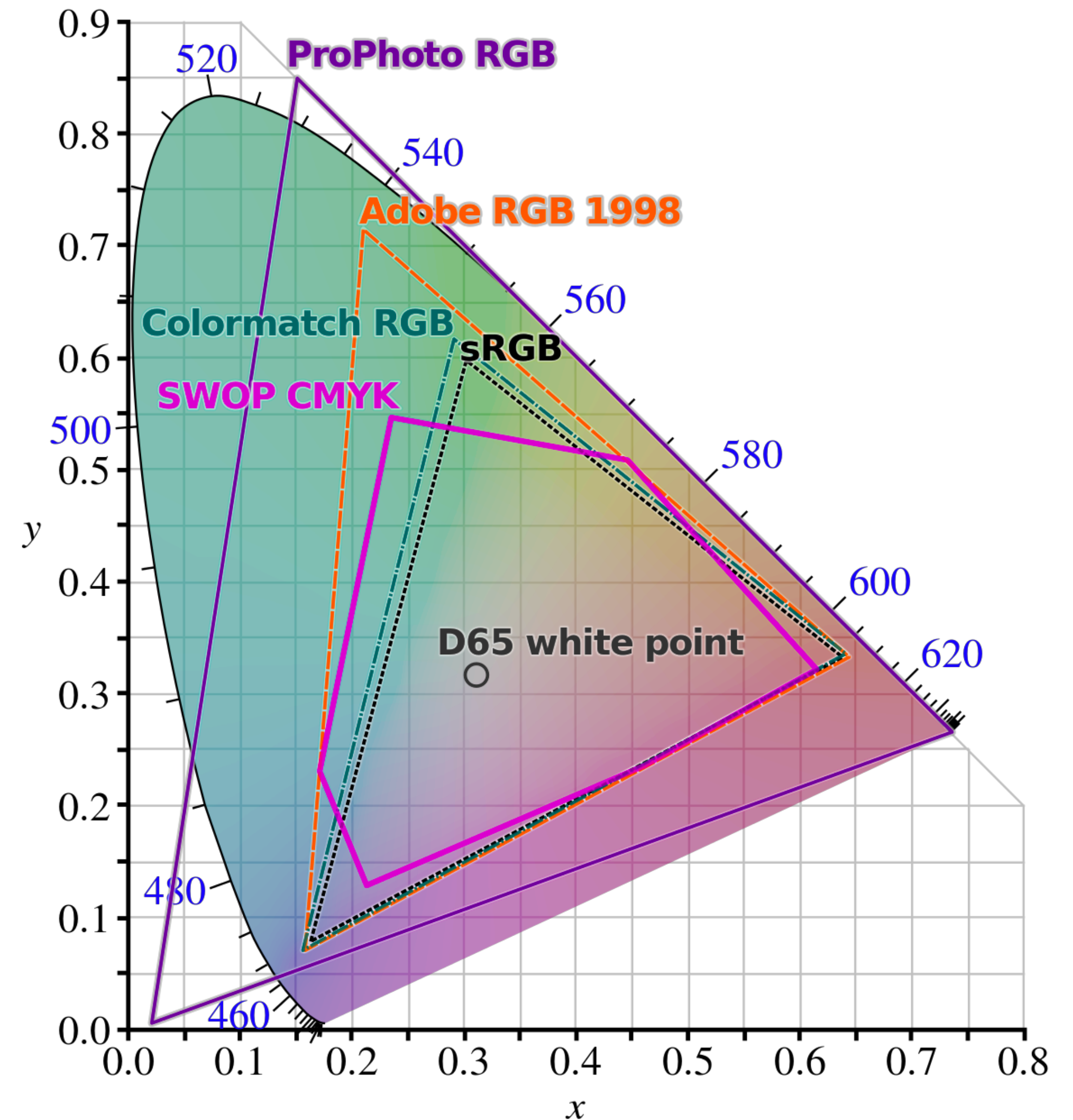
# Color Management

Solution: every media needs to have a **color profile** associated with it.

- A photo must have metadata showing in what color space are the RGB pixels interpreted?
- A display must reveal its native color space.

Using color profiles, a **color management** software will properly re-interpret RGB values from one color space to another.

What about colors that are outside the gamut of the display/paper?



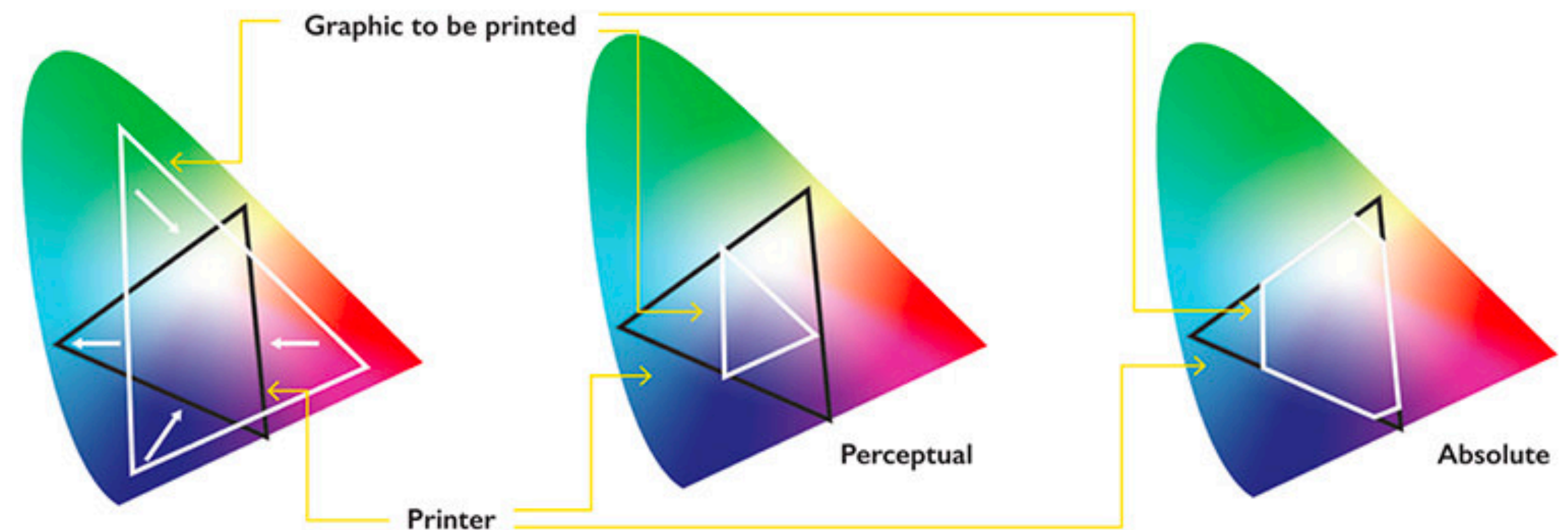
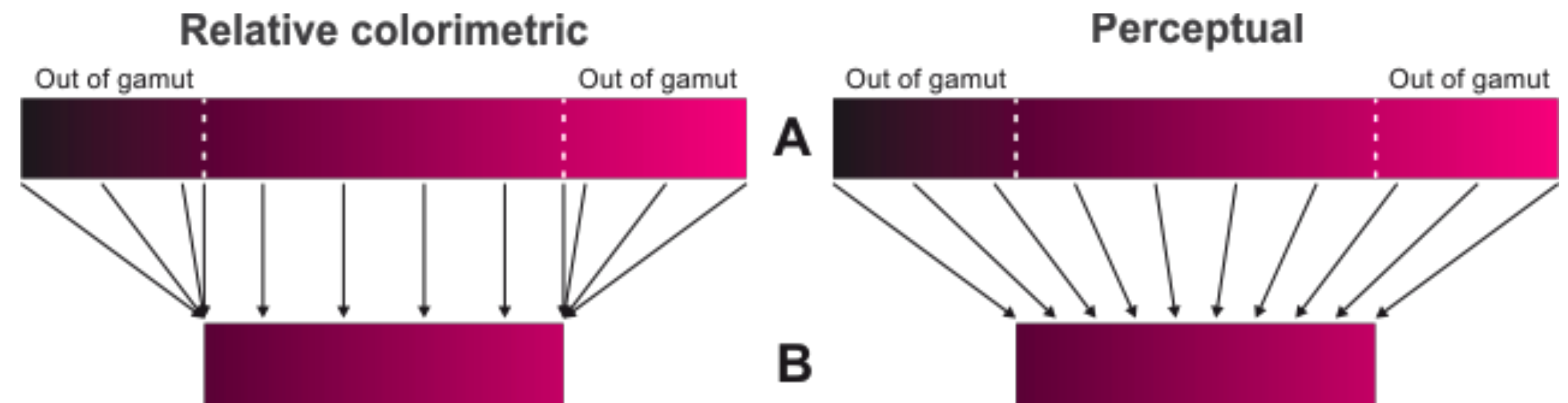


# Gamut Mapping

Modify input color so that it's reproducible on an output device — while maintaining visual quality.

Many algorithms and strategies. International Color Consortium (ICC) standards four, called **rendering intent**.

Part of "color management".





# Color Management Tool in Modern OS

Display P3.icc

#	Tag	Data	Size	Description
0	Header		128	
1	'desc'	'desc'	101	Localized description strings
2	'cprt'	'text'	35	Copyright ASCII Text String
3	'wtpt'	'XYZ '	20	Media white-point tristimulus
4	'rXYZ'	'XYZ '	20	Red colorant tristimulus
5	'gXYZ'	'XYZ '	20	Green colorant tristimulus
6	'bXYZ'	'XYZ '	20	Blue colorant tristimulus

Size: 548 bytes

Preferred CMM: Apple

Specification Version: 4.0.0

Class: Display

Space: RGB

PCS: XYZ

Created: 7/7/17, 1:22 PM

Platform: Apple

Flags: Normal Quality

Device Manufacturer: Apple

Device Model:

Device Attributes: 00000000 00000000

Rendering Intent: Perceptual

PCS Illuminant: 0.96420, 1.00000, 0.82491

Creator: Apple

MD5 Signature: ca1a9582 257f104d 389913d5 d1ea1582

Gamut mapping is dictated by the rendering intent, which is part of a ICC profile.

## Gamut mapping in ColorSync Utility

Calculator

Profile First AidProfilesDevicesFiltersCalculator

From

RGBPerceptual

sRGB IEC61966-2.1

8016858

8-bit

To

RGBPerceptual

Display P3

10316674

Extended Range

Play with an interactive gamut mapping applet [here](#)