

# Lecture 10: Sources of Color

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**Computer Imaging & Graphics**

# The Roadmap

Theoretical Preliminaries

**Human Visual Systems**

Digital Camera Imaging

Modeling and Rendering

The Remaining Cool Things



Introduction and Overview

Photoreceptors

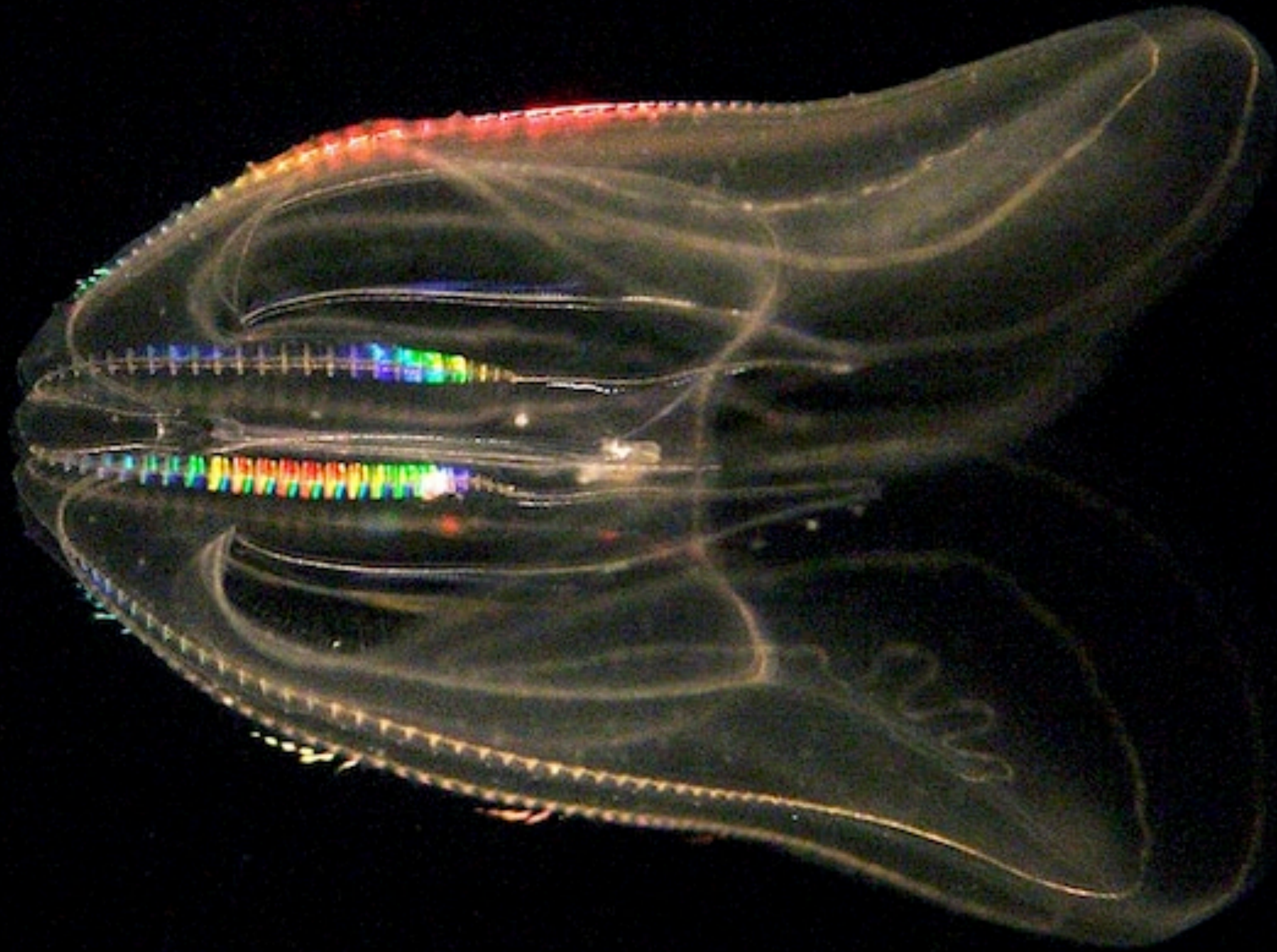
Color Vision and Colorimetry

Color Vision Deficiency

**Color Production**

Visual Adaptations

# Bioluminescence



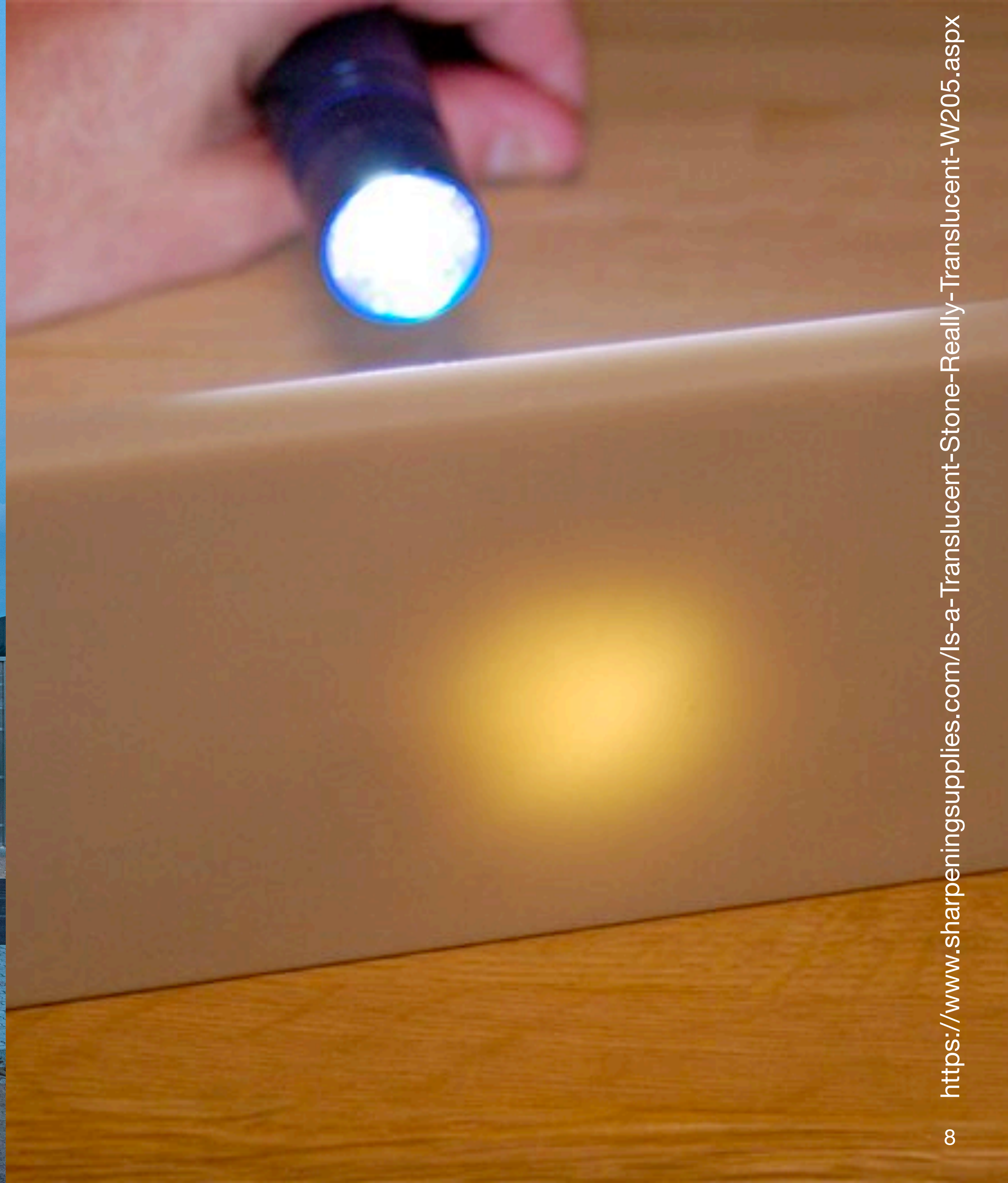
# Biofluorescence













# Sources of Colors

Color comes from lights entering our eyes.

**Emission:** objects directly generate lights.

- Lights come either directly from light-emitting objects or from materials that interact and modify light that strikes them.

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.

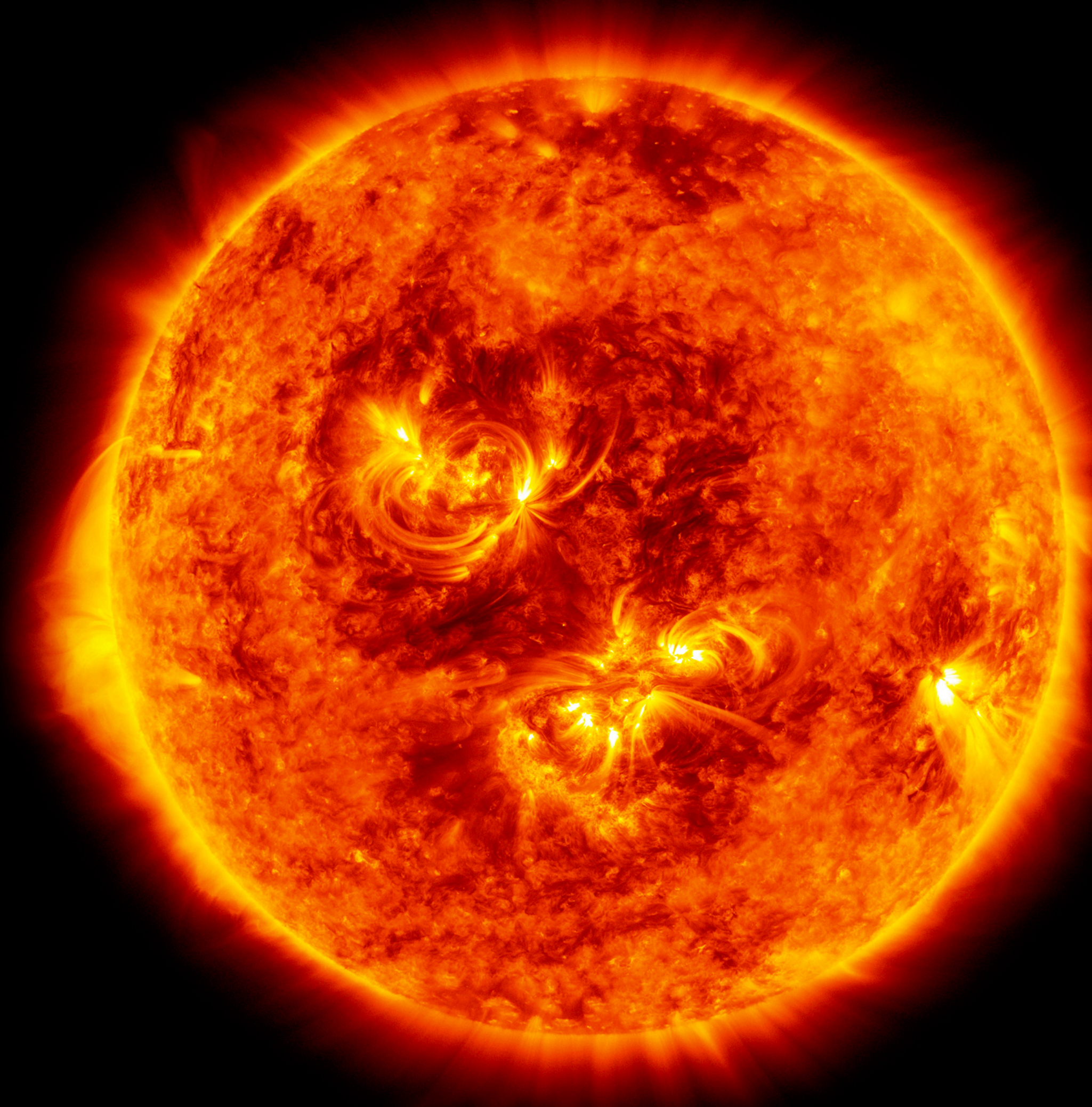
Reflection, refraction, diffusion, transmission, etc. are results of absorption and/or scattering. They are **macroscopic** abstractions, not fundamental forms of light-matter interactions.

Plan:

- This lecture: an overview of all sources
- Next lecture: color from emissions: displays and lighting systems
- Later in graphics: color from absorption + scattering: a lot of rendering is about modeling how materials absorb/scatter lights

# Color From Emission

# Color From Emission: Thermal Radiation



# 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.

# Color From Emission: Luminescence

Bioluminescence (e.g., firefly)



Electroluminescence (e.g., display)



# Luminescence

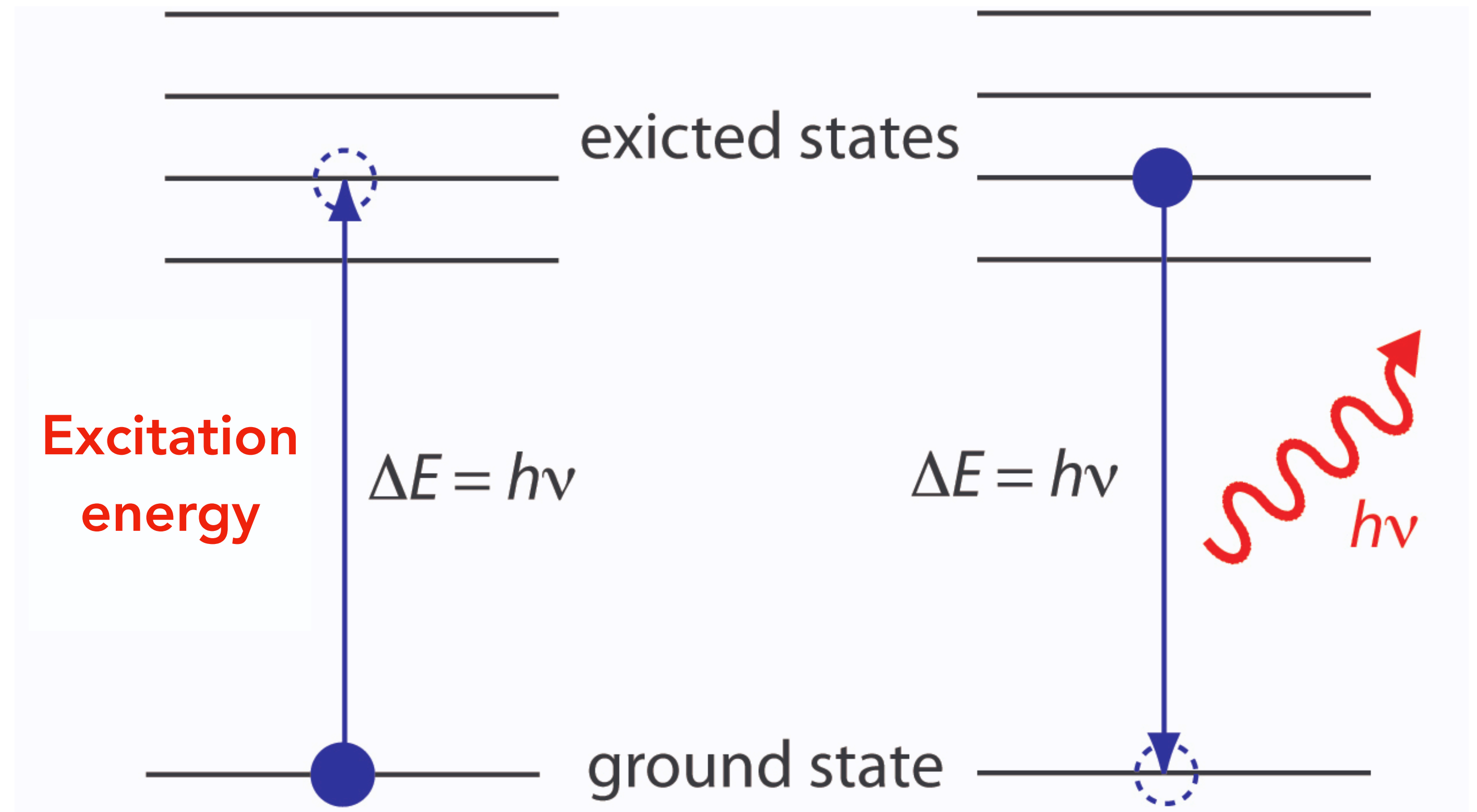
Electron absorbs energy and its energy state increases. Shortly, the energy state drops back to the ground level, emitting a photon.

Bioluminescence:

- Excitation = chemical reaction

Electroluminescence:

- Excitation = External current



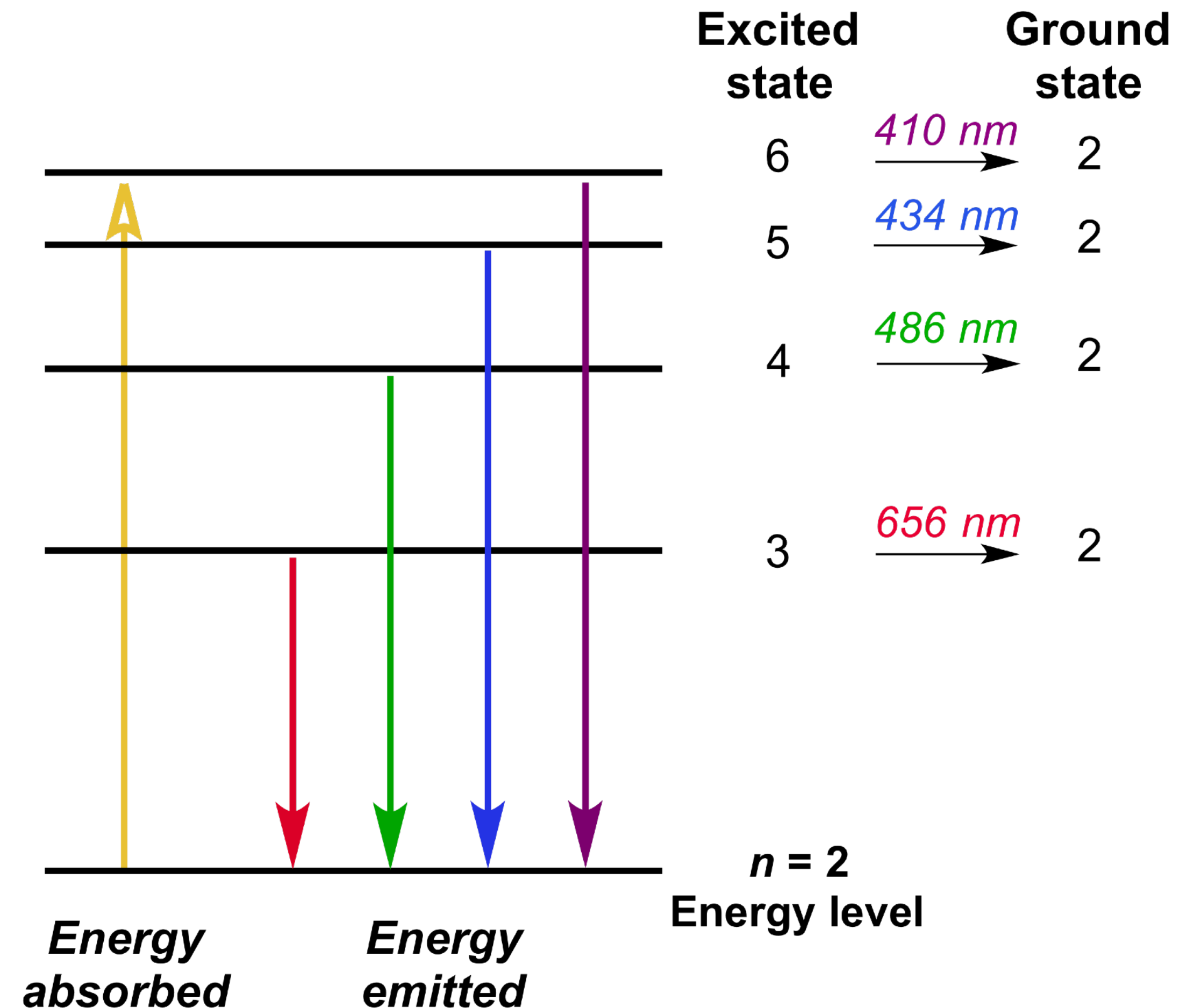
# Bioluminescence

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

- The reaction typically involves a light-emitting molecule called **luciferin** and an enzyme called **luciferase**.

Very common in ocean

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





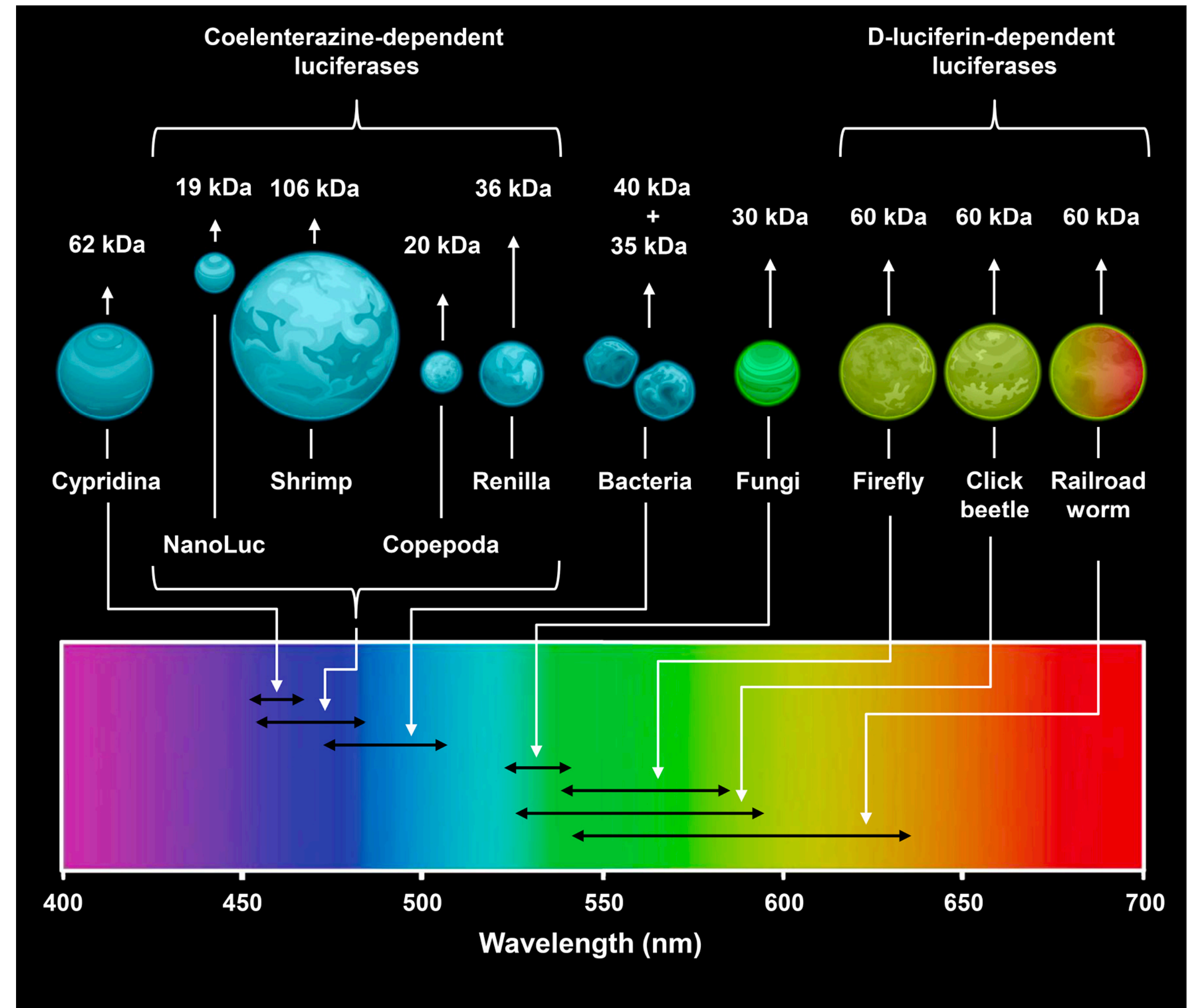
# Bioluminescence

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



# Color From Absorption and Scattering

# Color From Absorption and Scattering

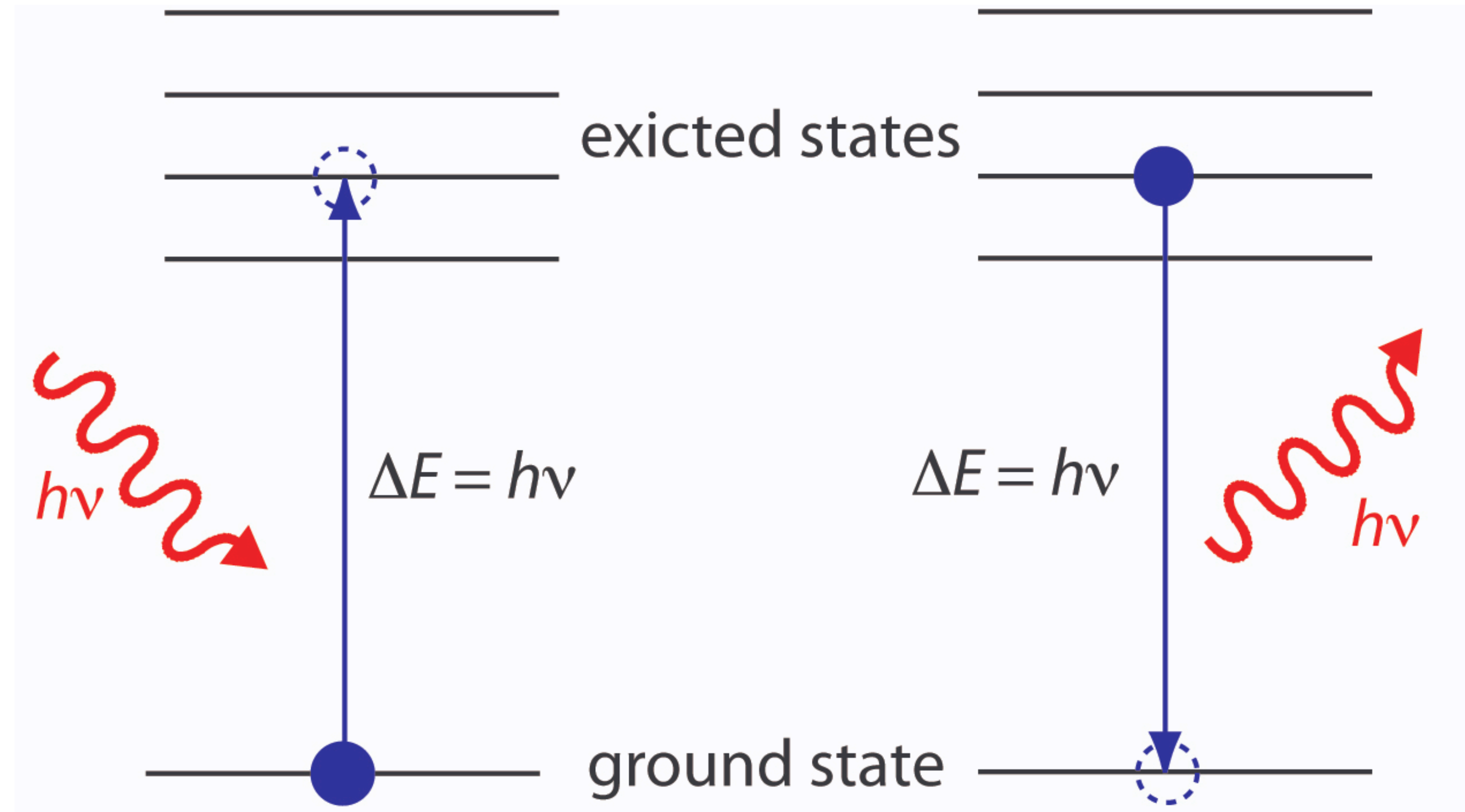
Excitation energy is from absorbing another photon.

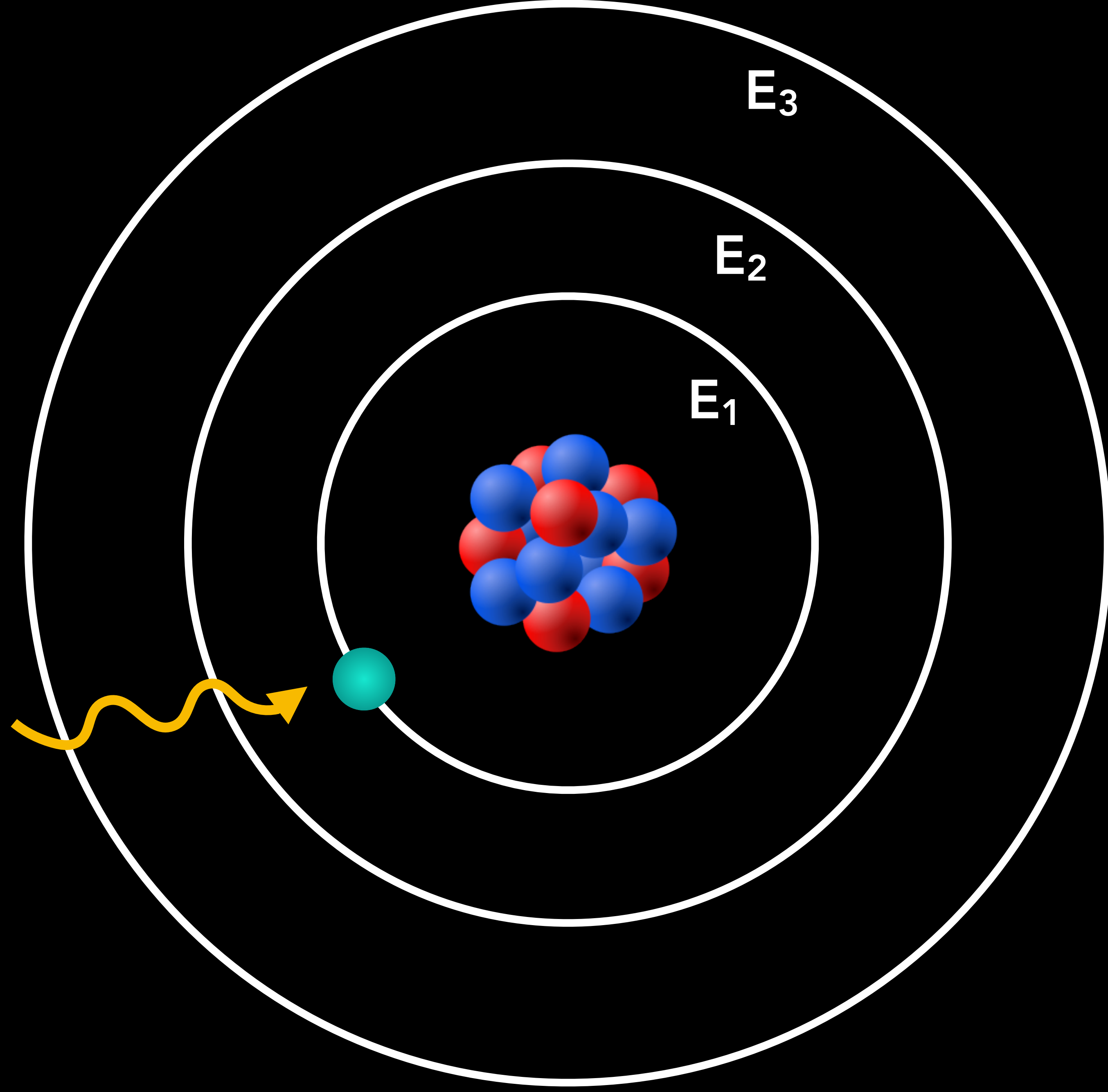
Absorption:

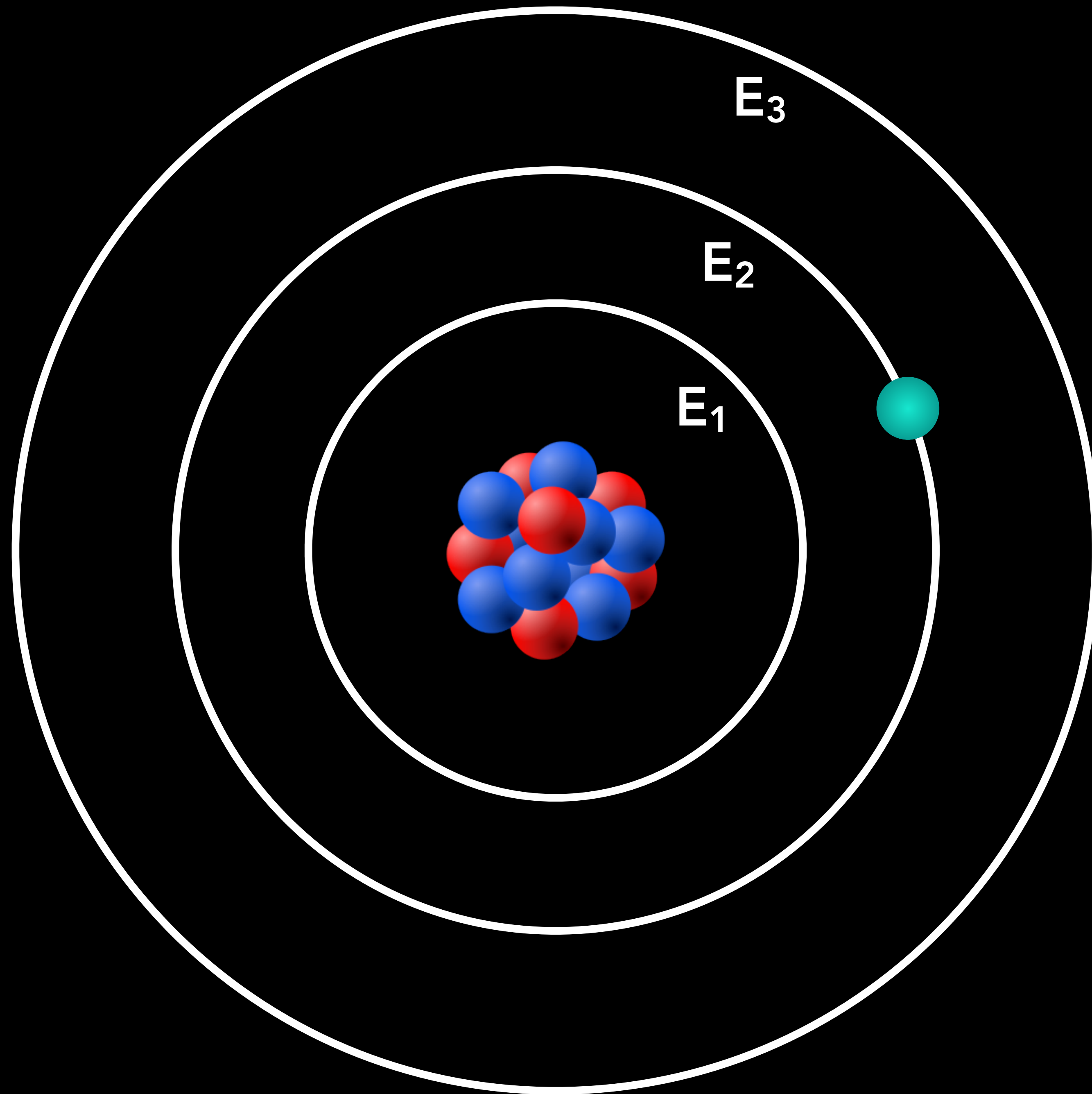
- No photon emission

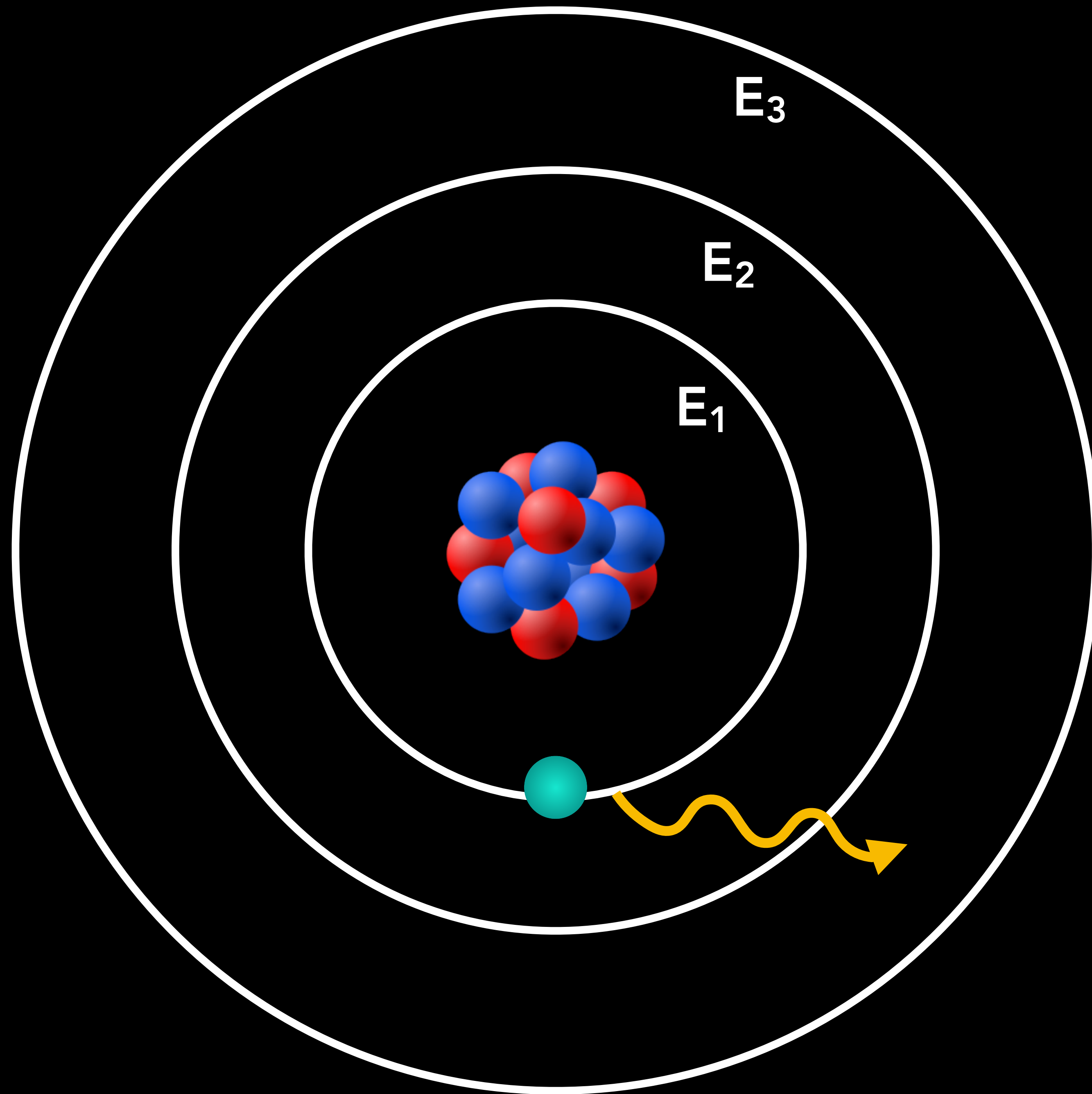
Scattering:

- Emits another photon







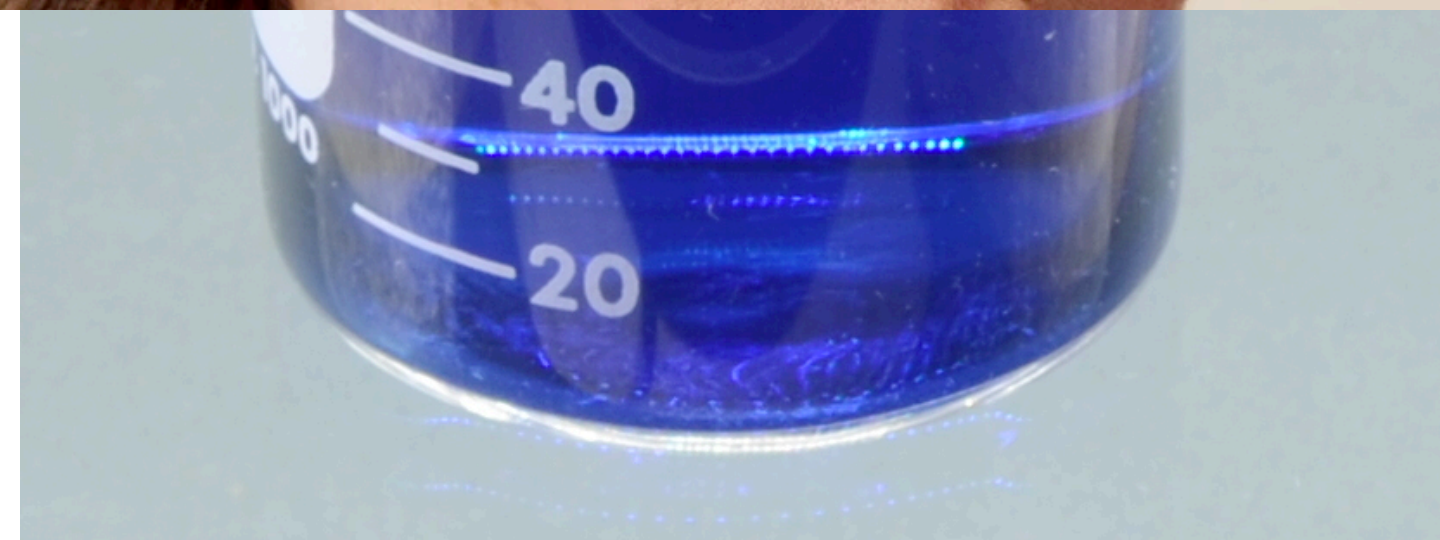
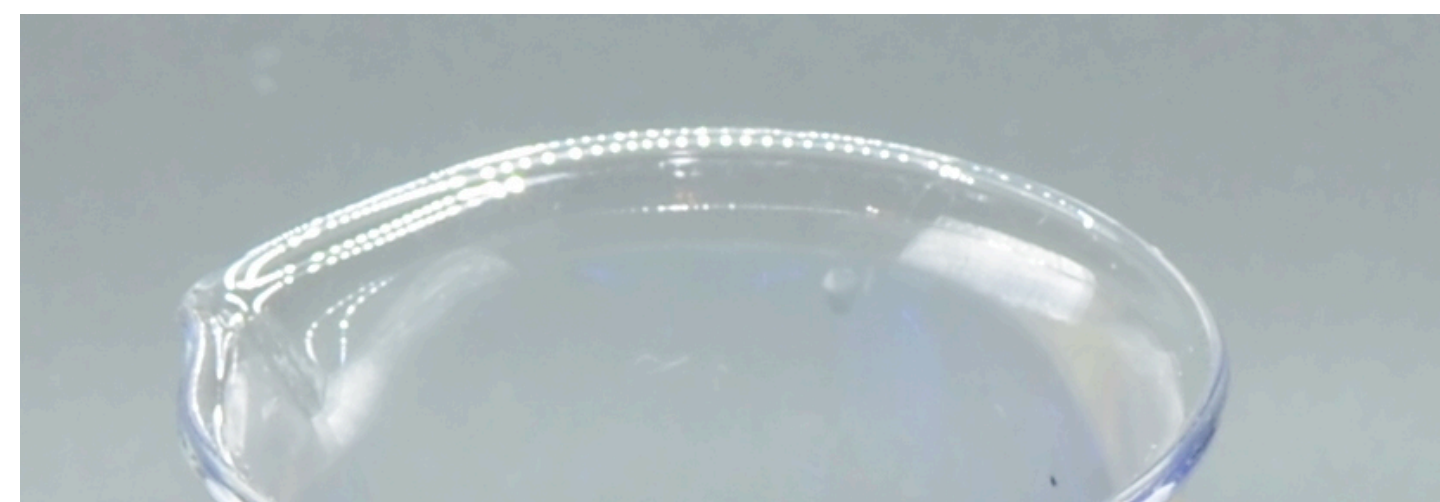
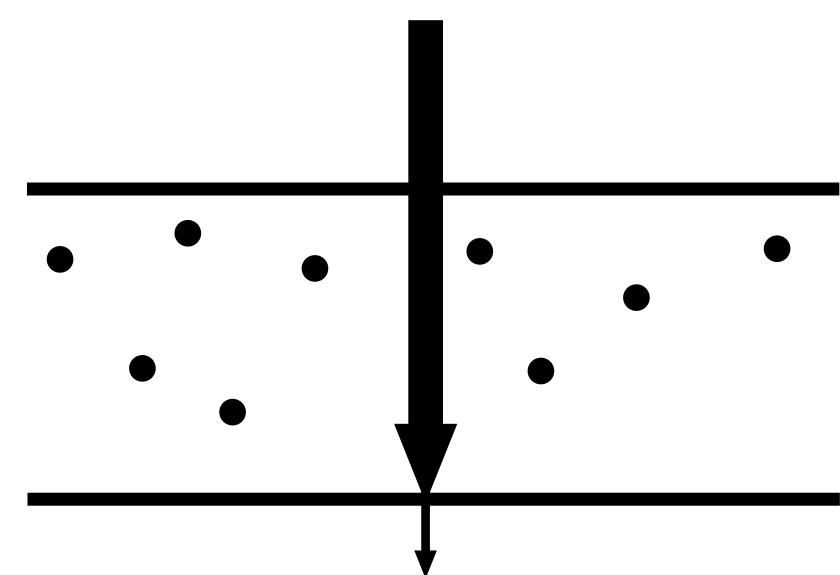


**Scattering is the result of an electron picking up a photon,  
"scratching its head", and then emitting a new photon.**

— Richard Feynman

\* The new photon might not have the same energy as the absorbed photon (Raman/inelastic scattering), and the emission can be to any direction.

# Pure Absorption: **Transparent**

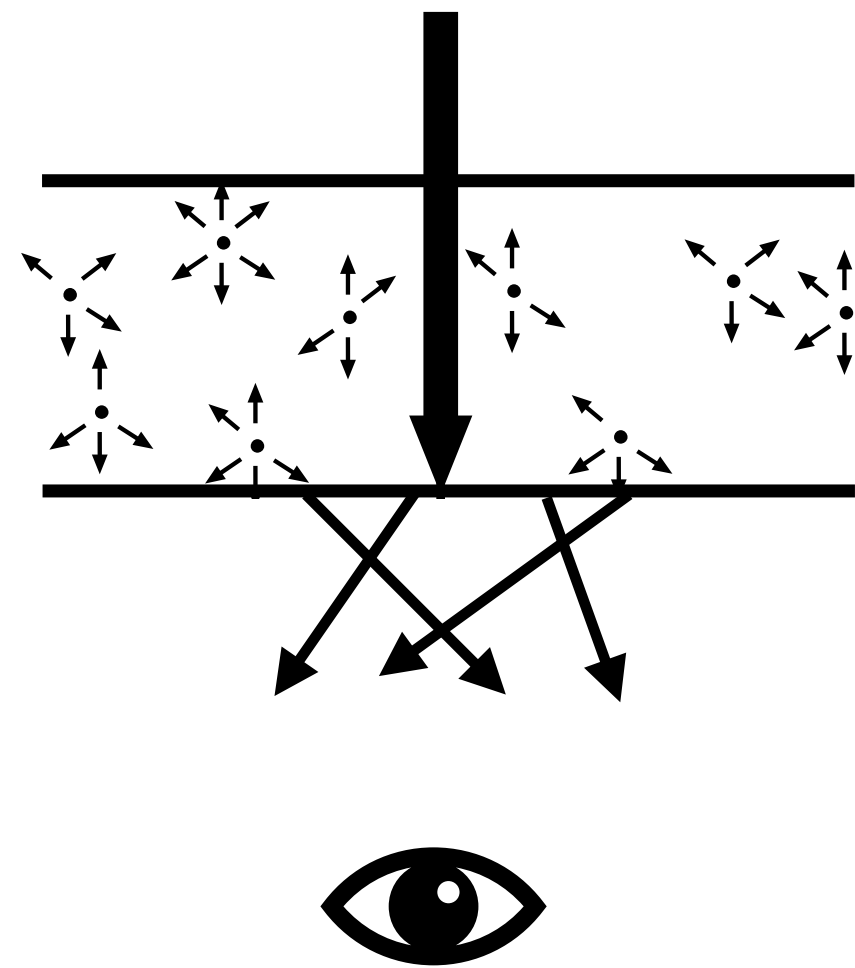


Some lights are absorbed, but the rest transmits through in one direction.

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



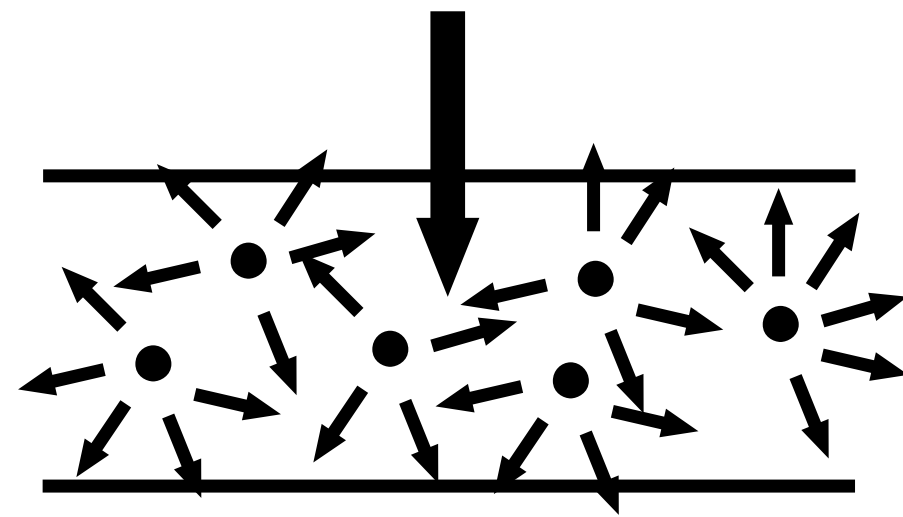
# A Little Scattering + Absorption: **Translucent**



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.

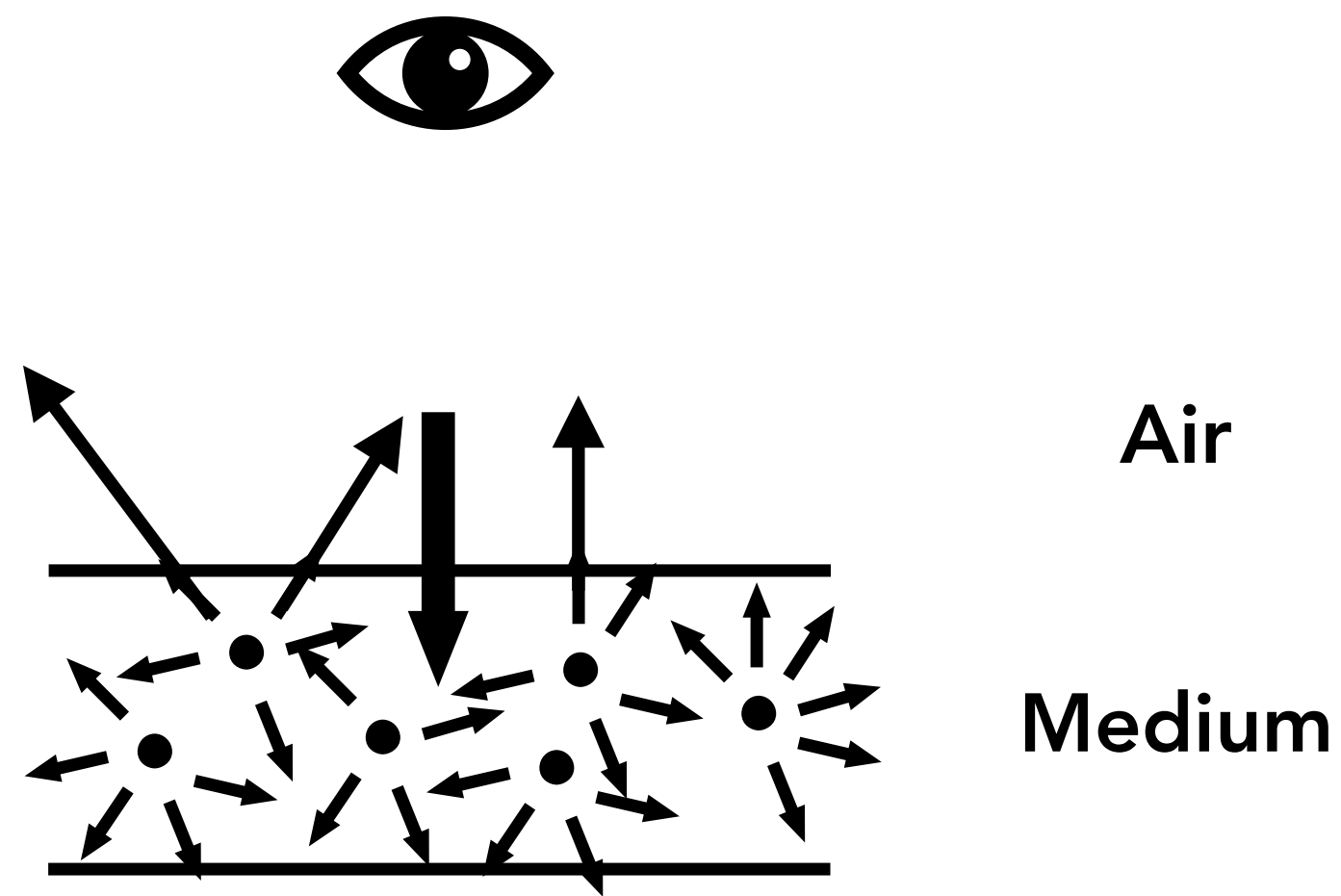
# A Lots of Scattering + Absorption: **Opaque**



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.

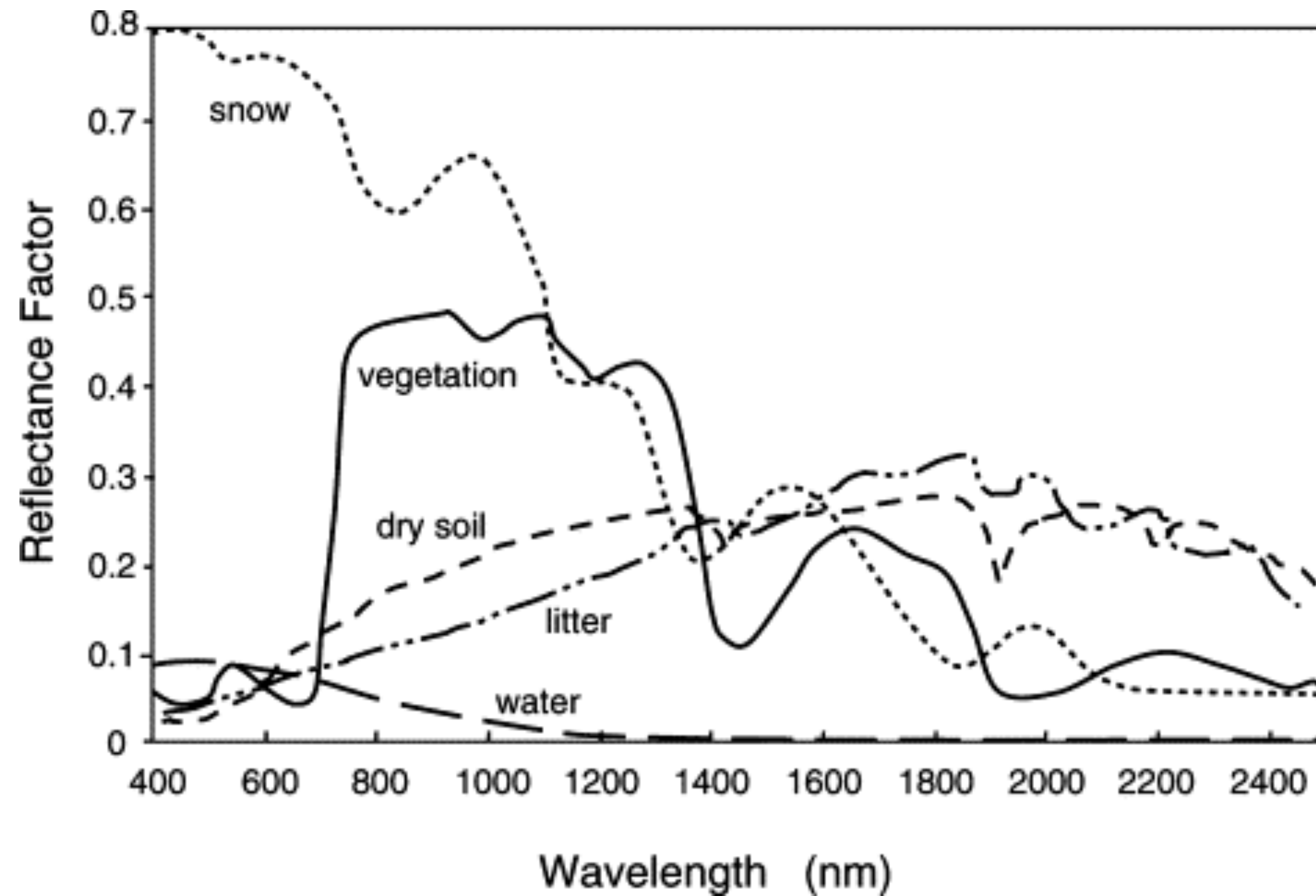
# "Color From Reflection"?



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



# Spectral Reflectance

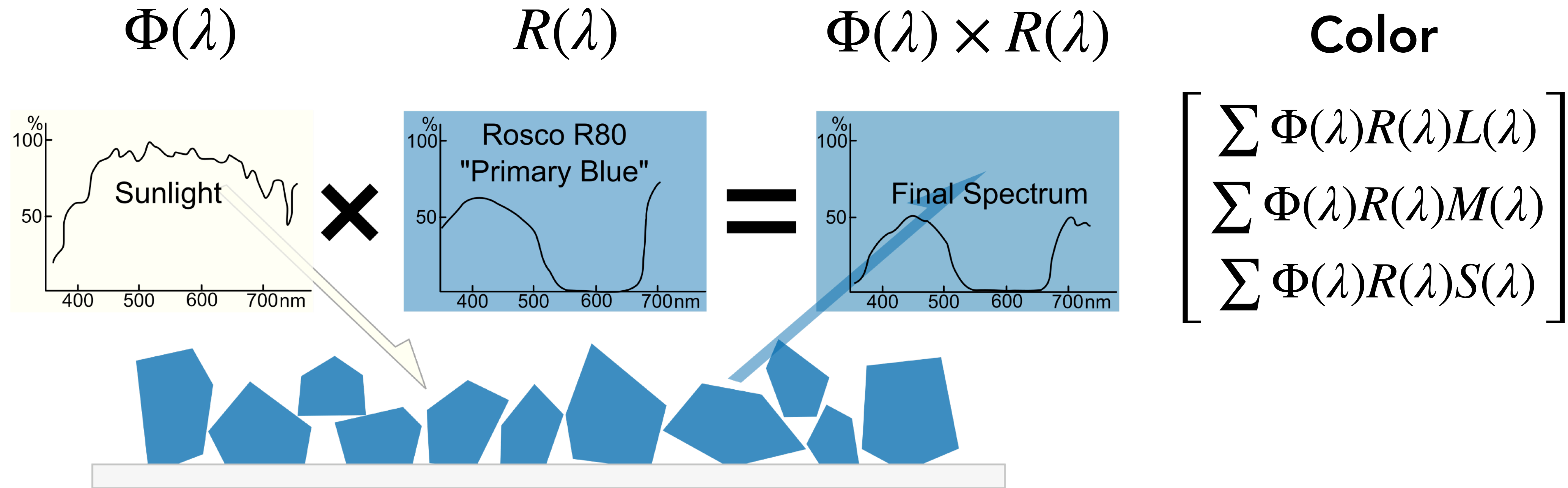


Spectral reflectance is a macroscopic, phenomenological metric: the ratio of reflected and incident light at each wavelength.

- Spectral transmittance is similarly defined.

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

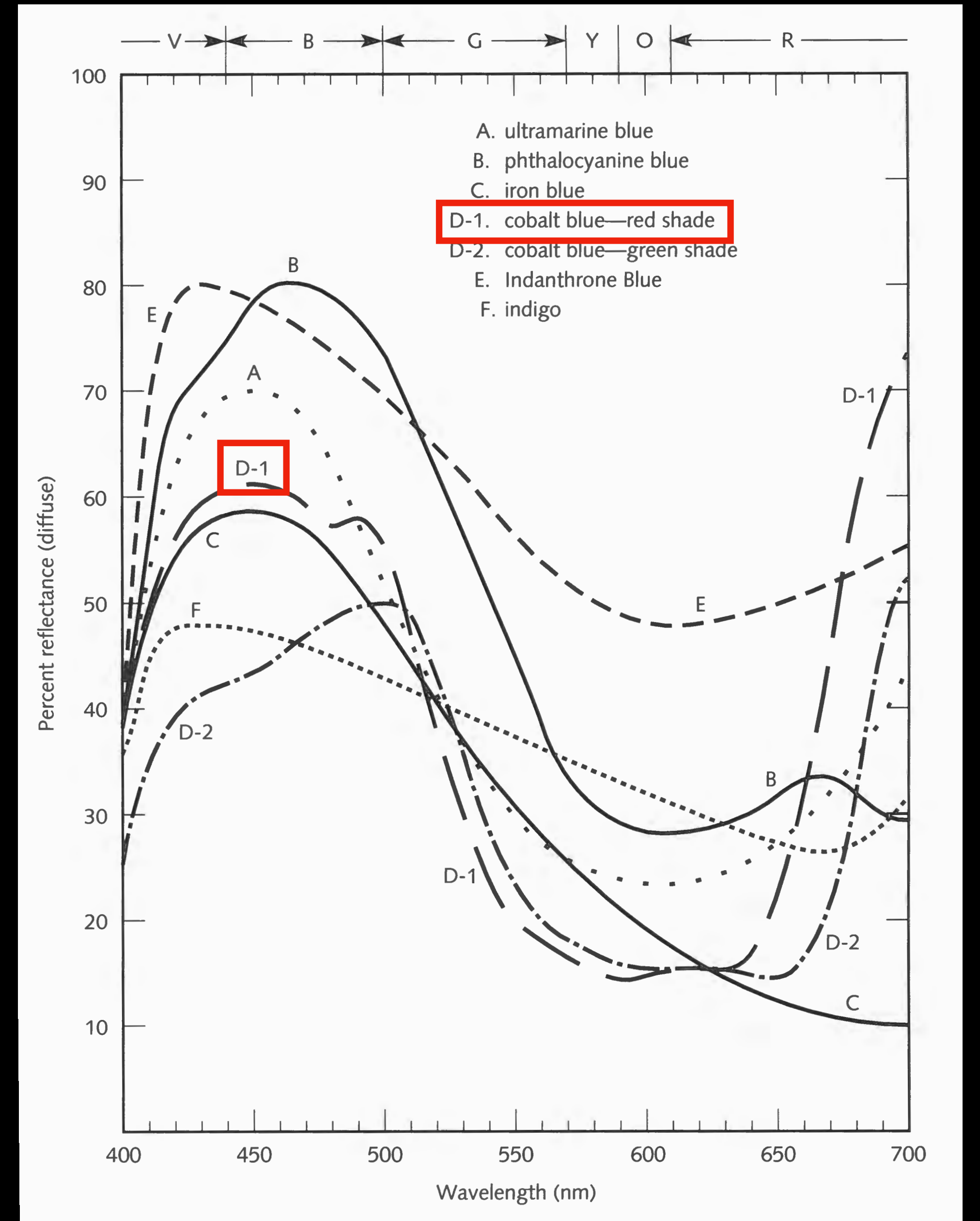
# Color of Material Depends on Illumination!!!



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



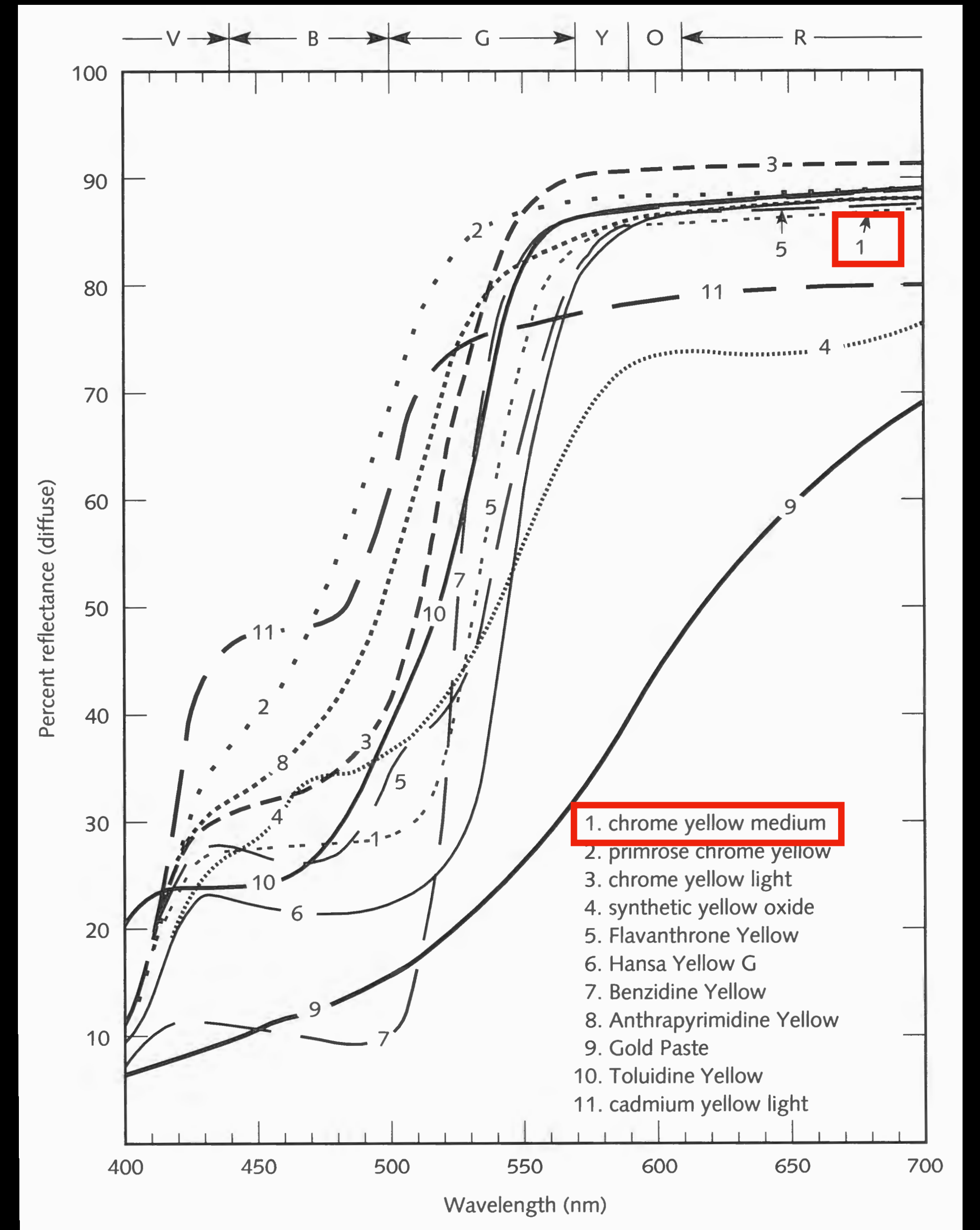
\* Spectra on the right are not the measured spectra from the painting



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



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



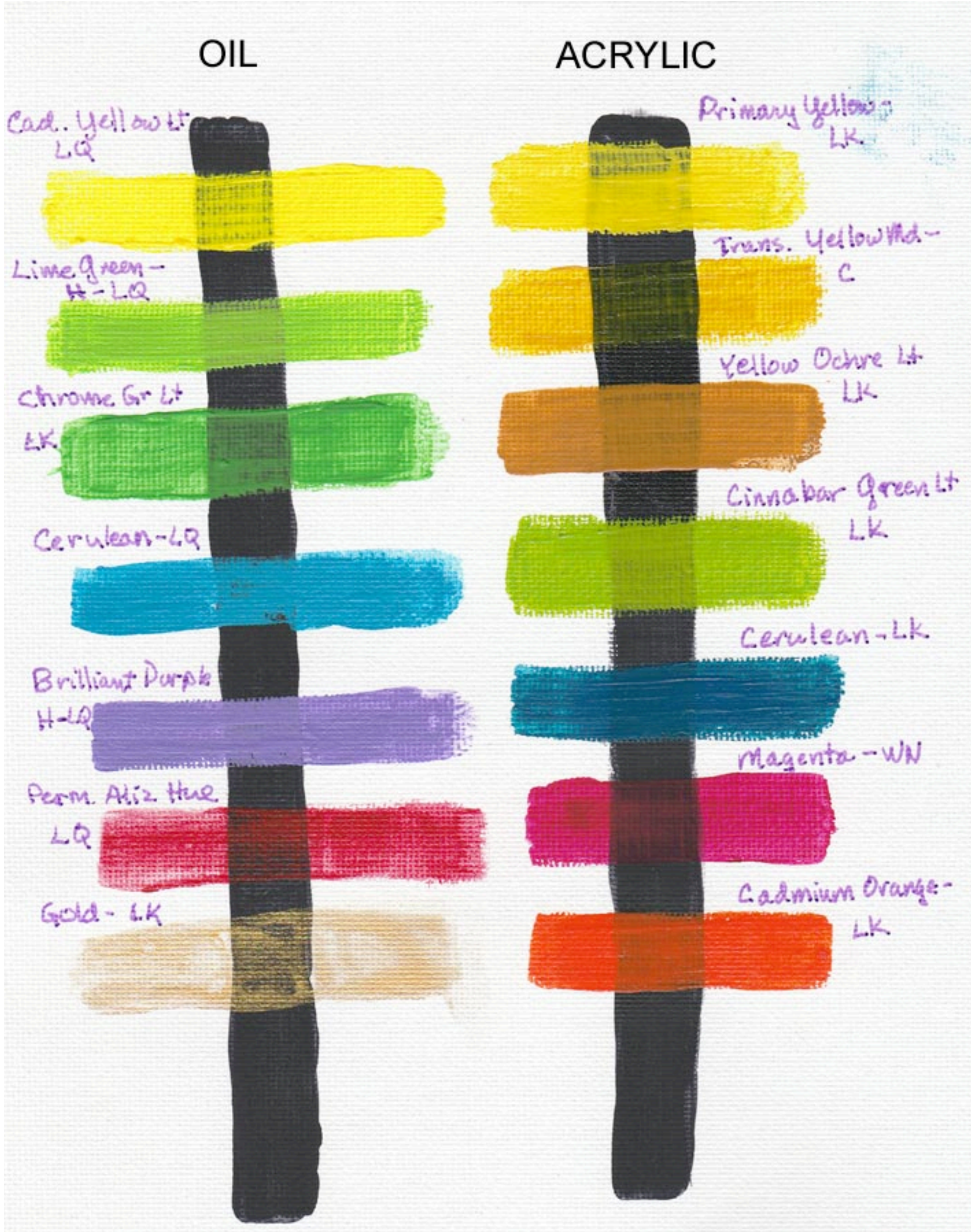
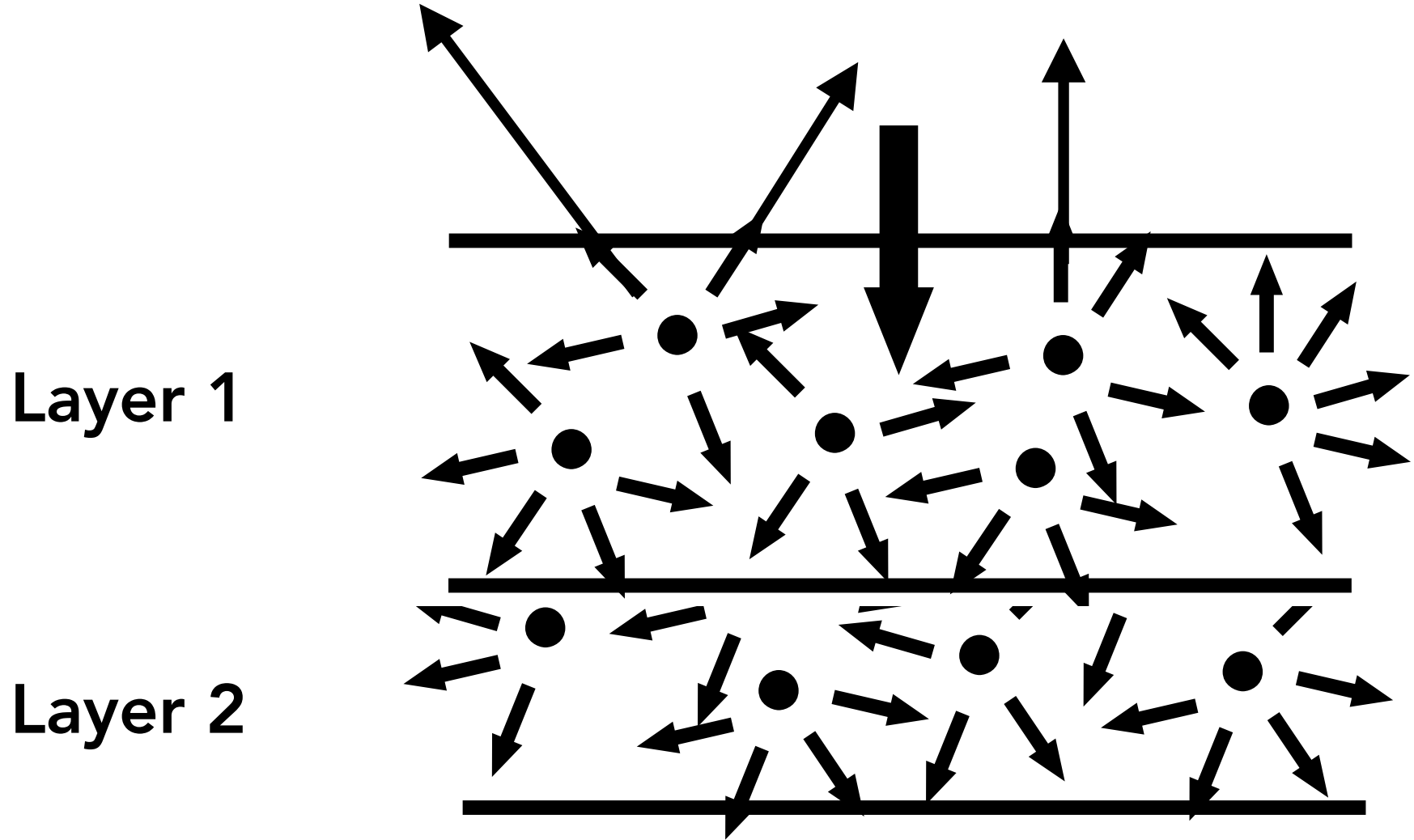
<https://colourlex.com/project/van-gogh-bedroom-in-arles/>

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

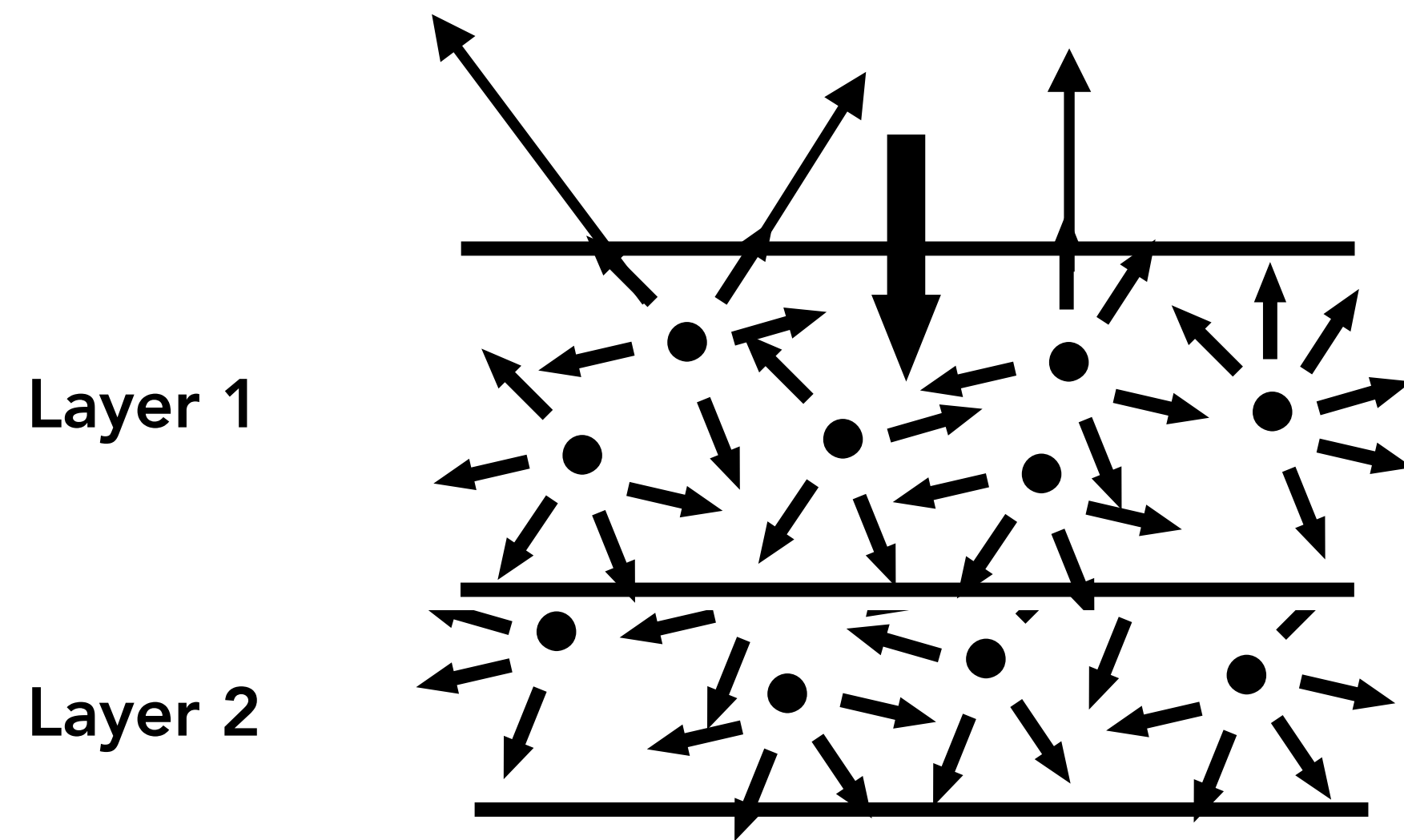




# Layering



# 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.



"Luminous Effects" from glaze

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



# Varnishing



# Varnishing = High Surface Reflection + Transparency

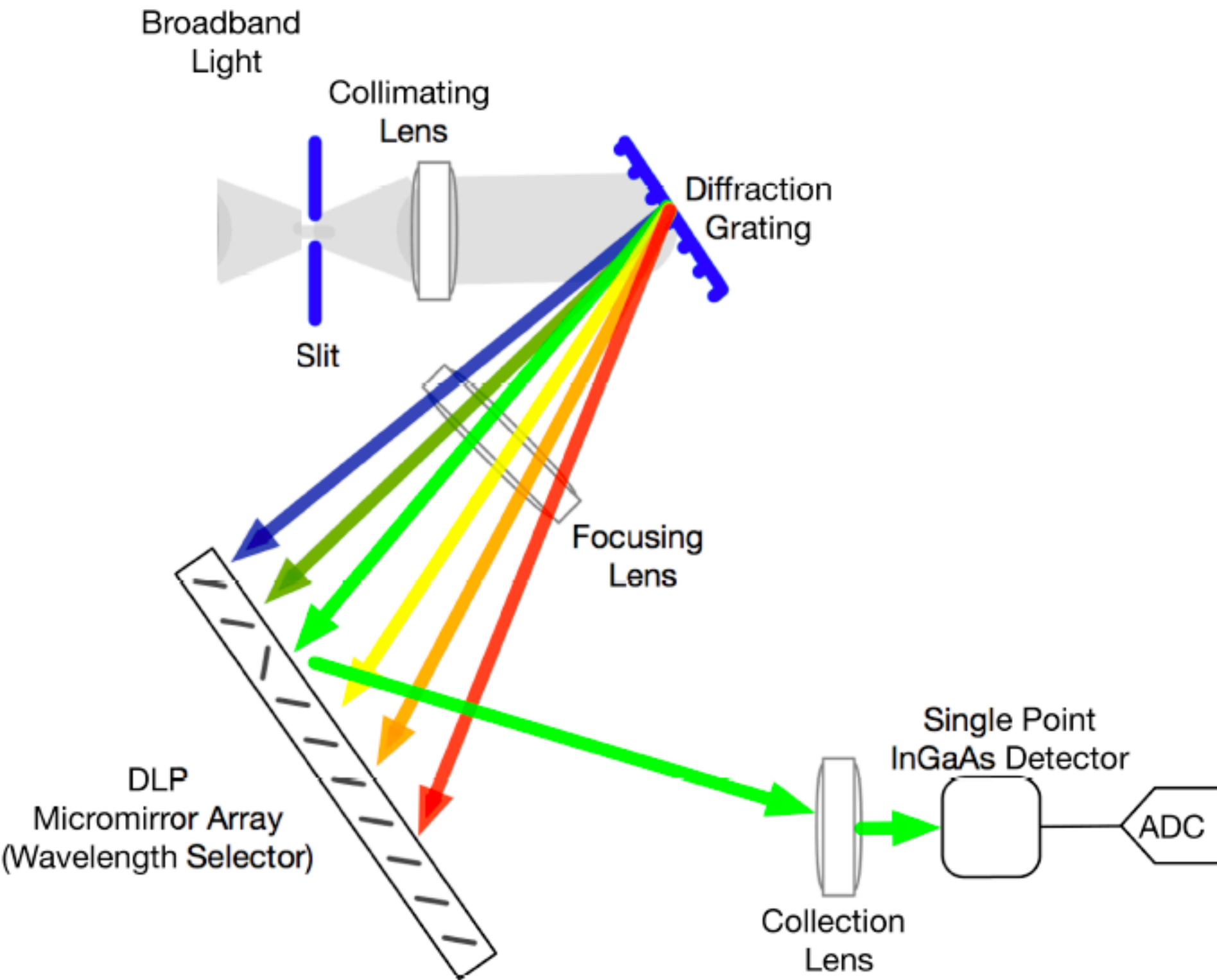


A lot of incident lights are reflected off of the surface, creating the glossy look.

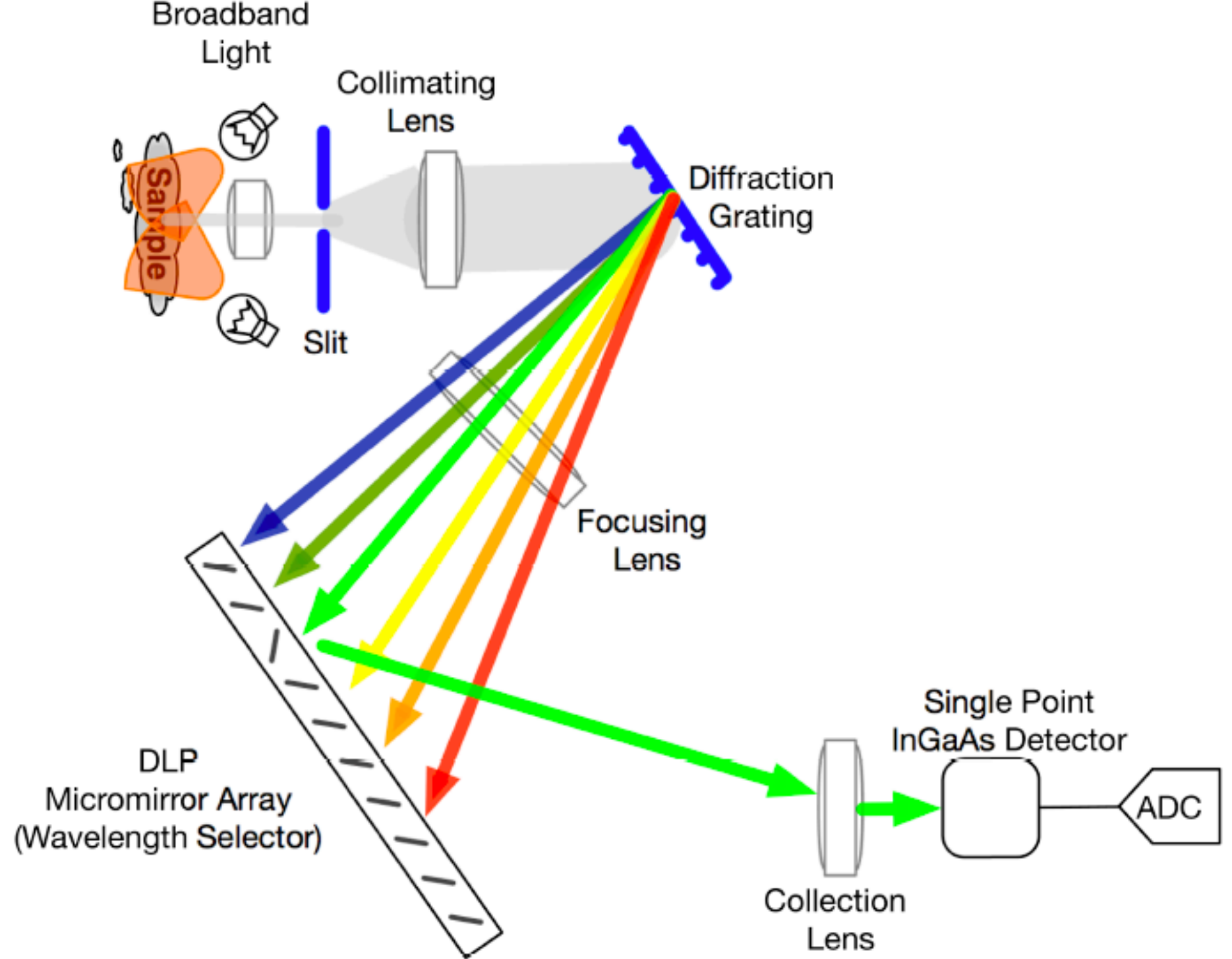
The varnish layer itself is transparent, so photons that do go through the surface layer are not scattered much. So the background is clearly seen.

# Measuring Radiation and Reflectance

## Spectroradiometer

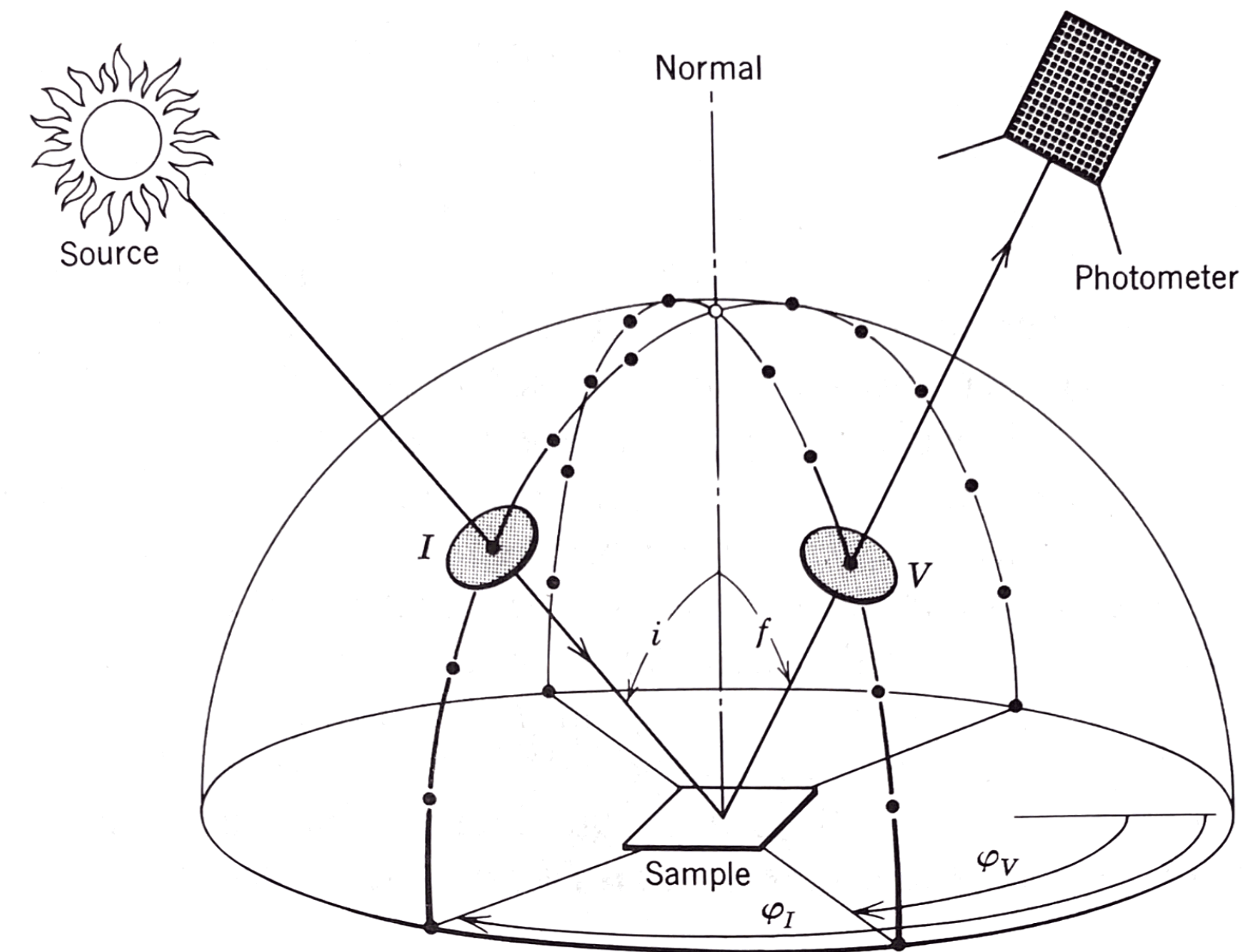
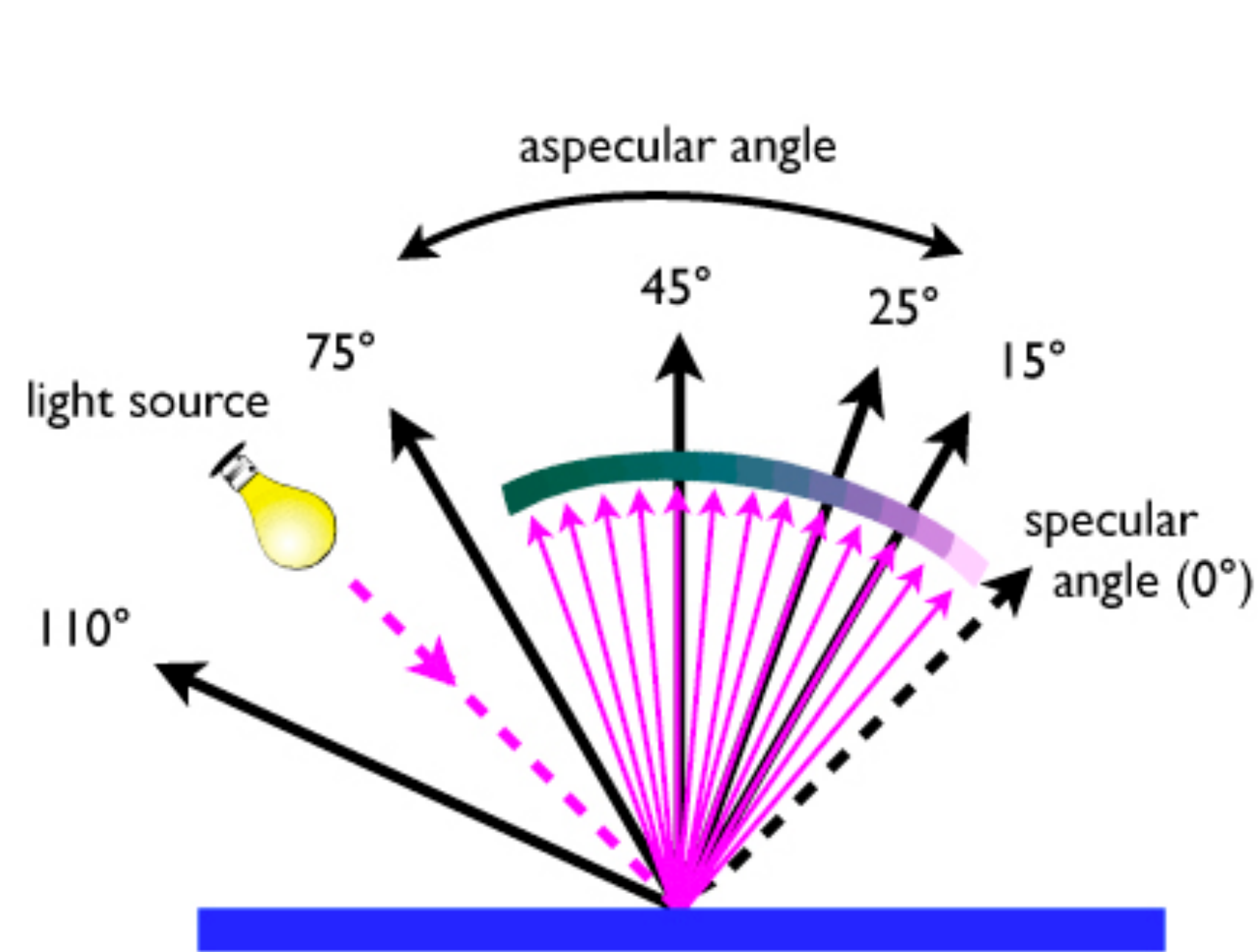


## Spectrophotometer

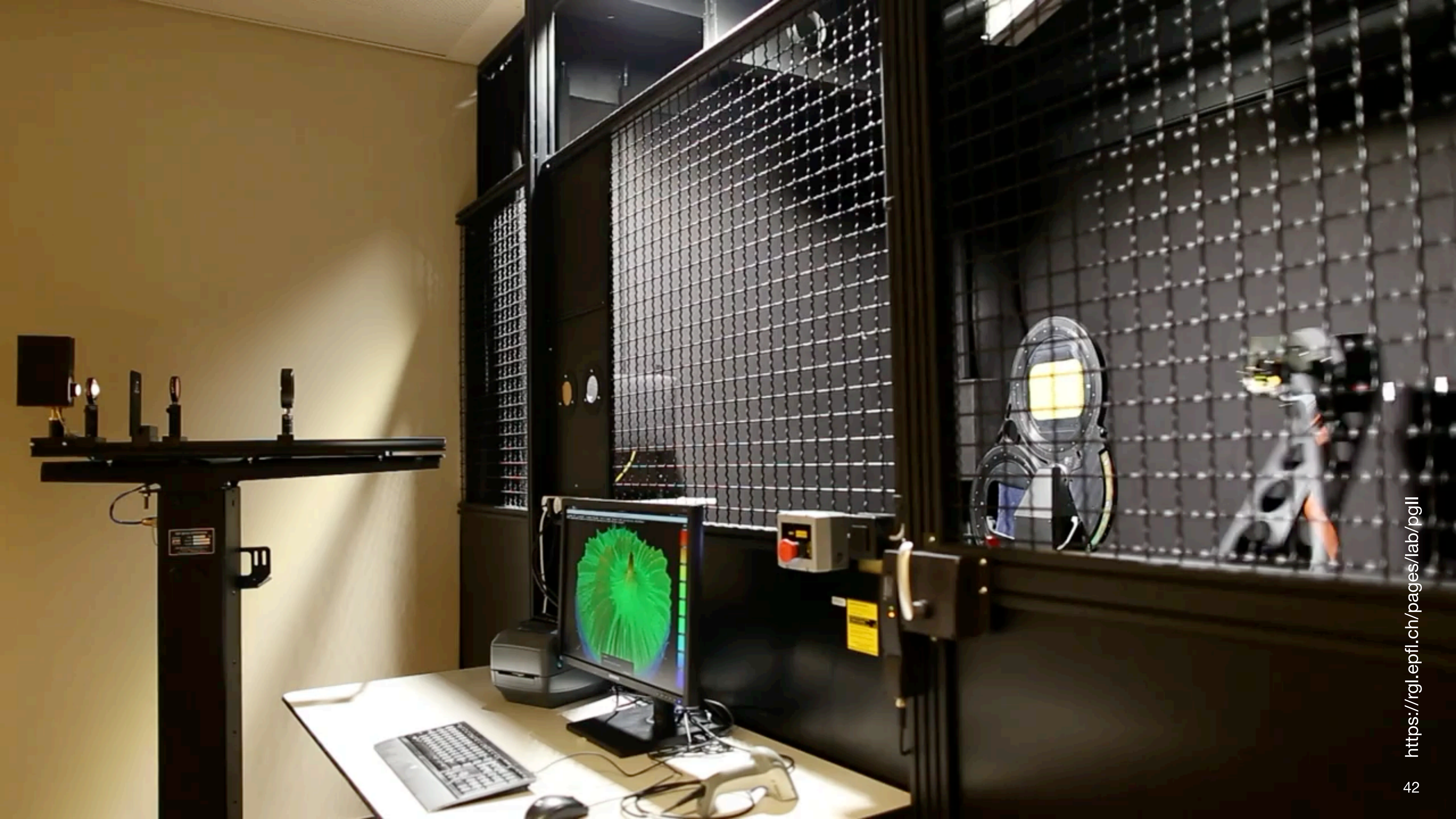




# Gonio Spectrophotometer



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



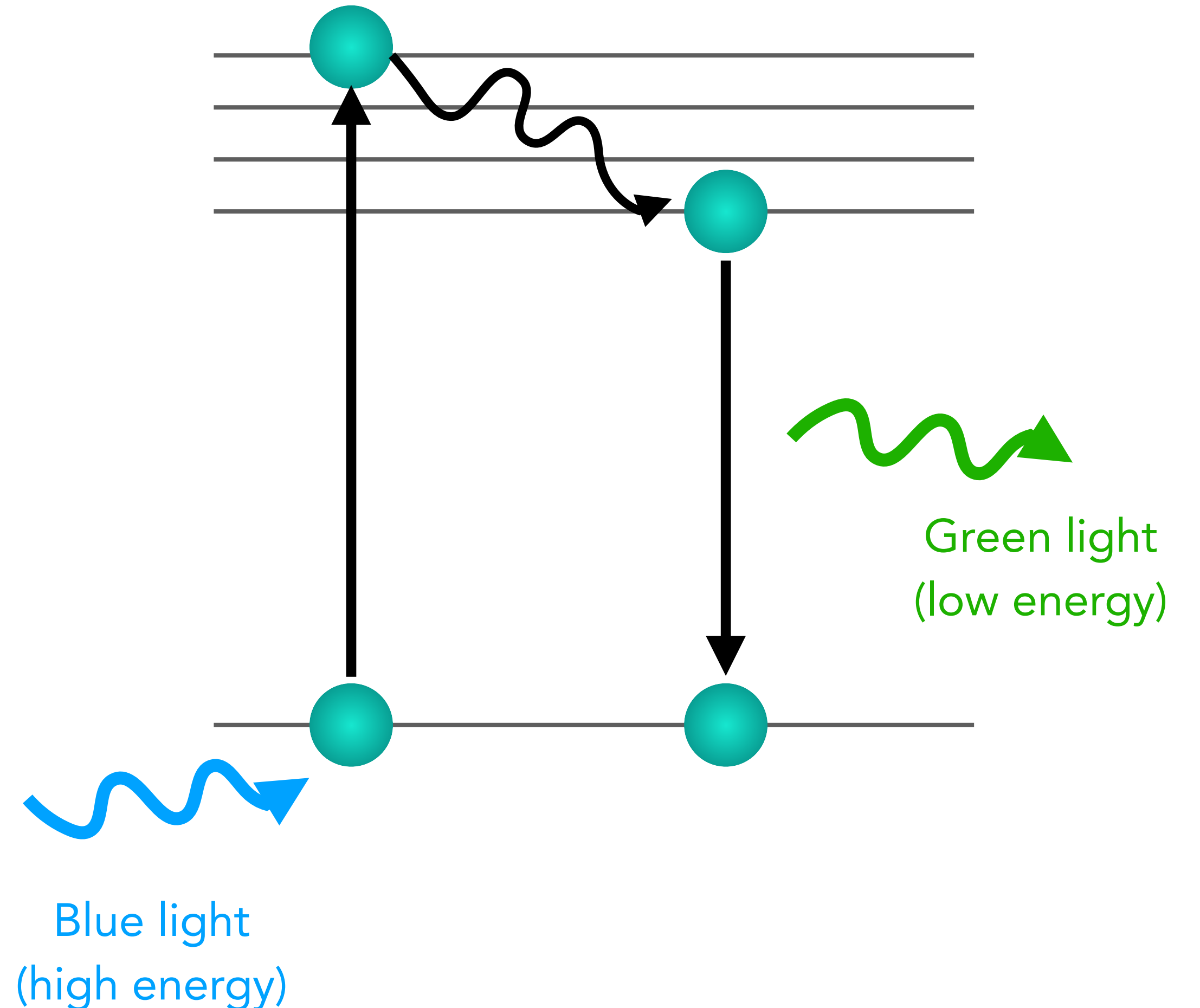
# Fluorescence: Color From Absorption and Emission

# What is Fluorescence?

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

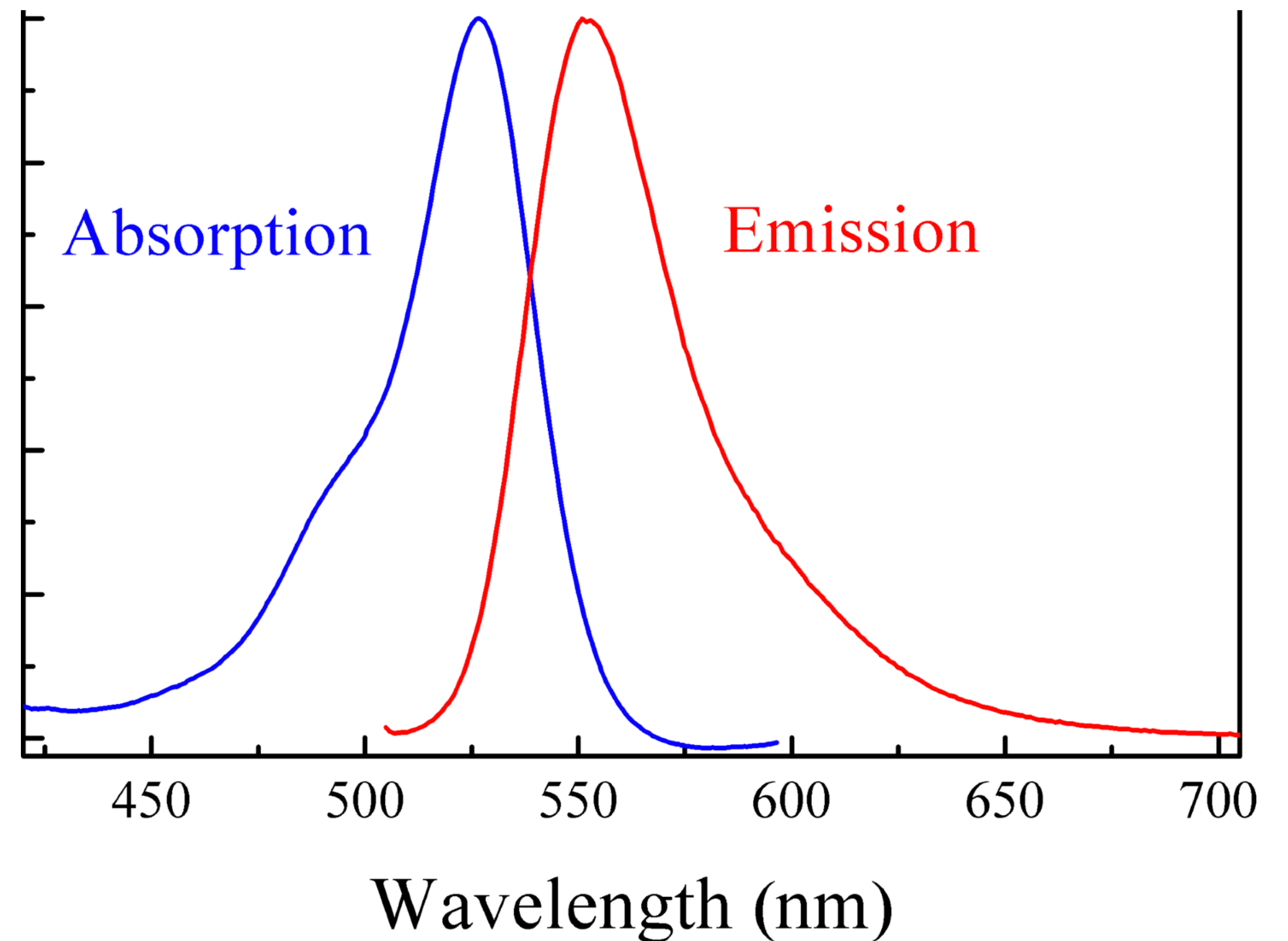
- The rest of the energy turns into other forms.

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

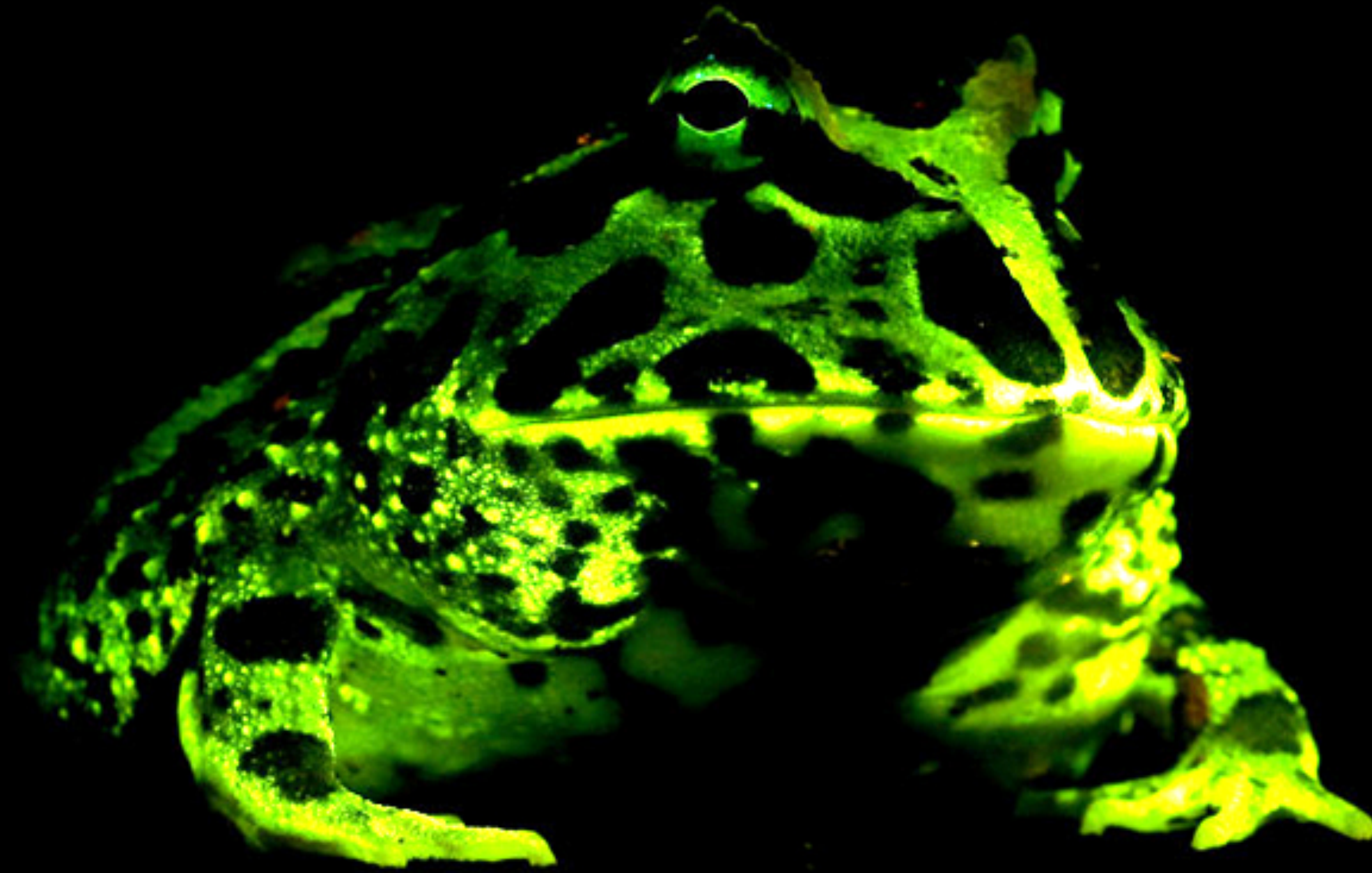


# What is Fluorescence?

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



# Biofluorescence



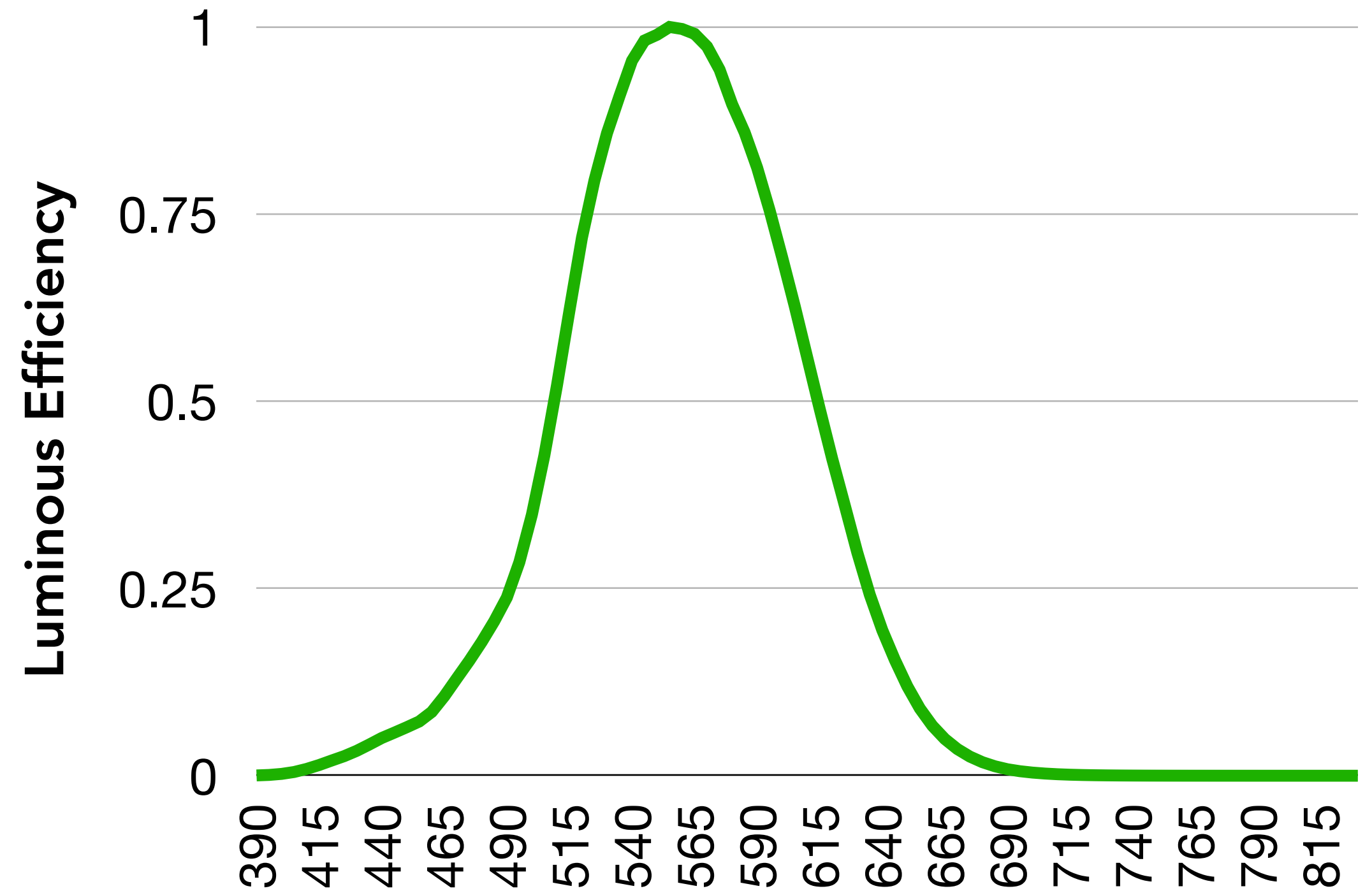
Fluorescent because of the now famous GFP

# 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 photopic luminous efficiency function peaks near 555 nm.



CIE 2008 Photopic LEF

# Fluorescent Light

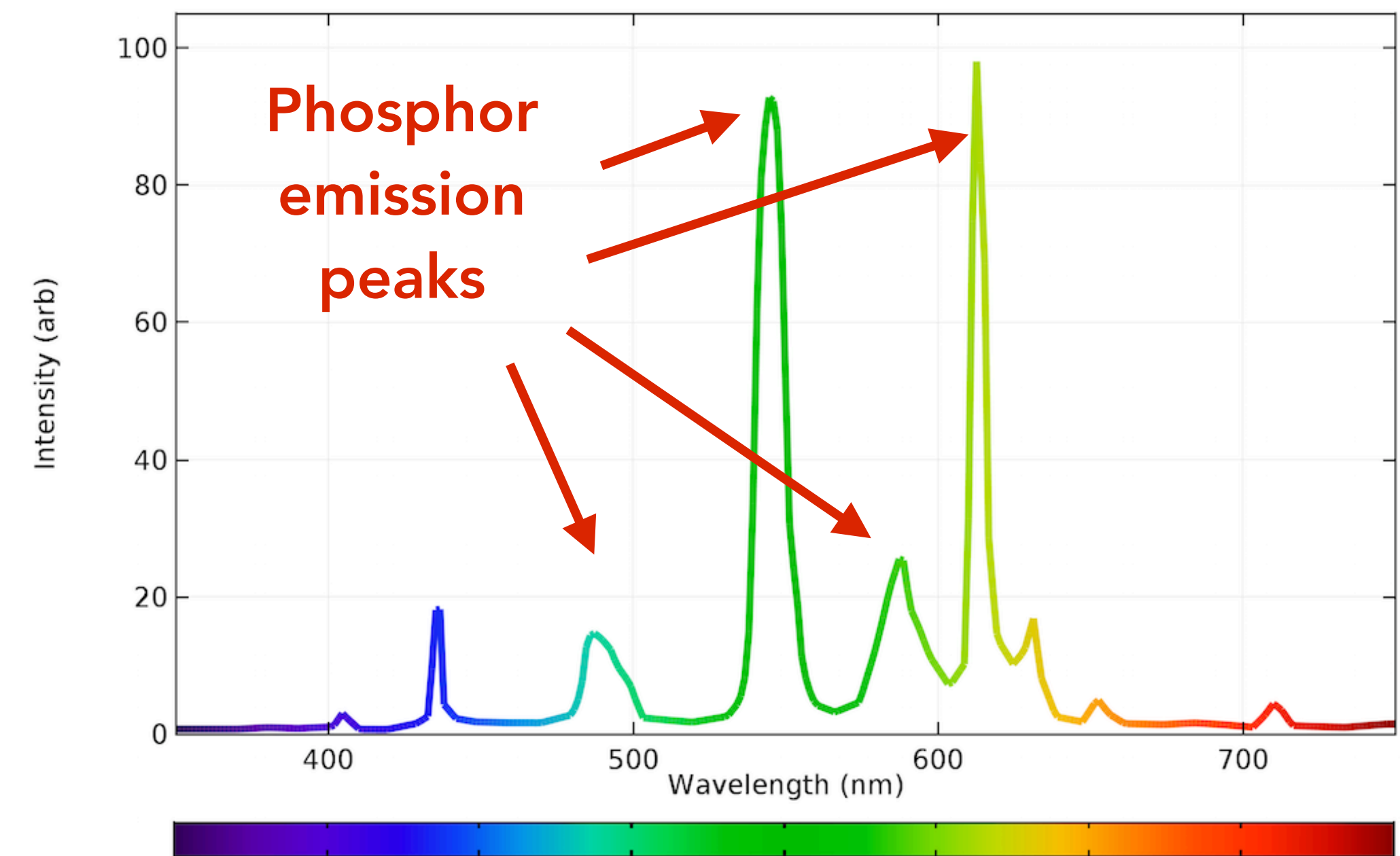
**Phosphors** used as fluorescent material.

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.



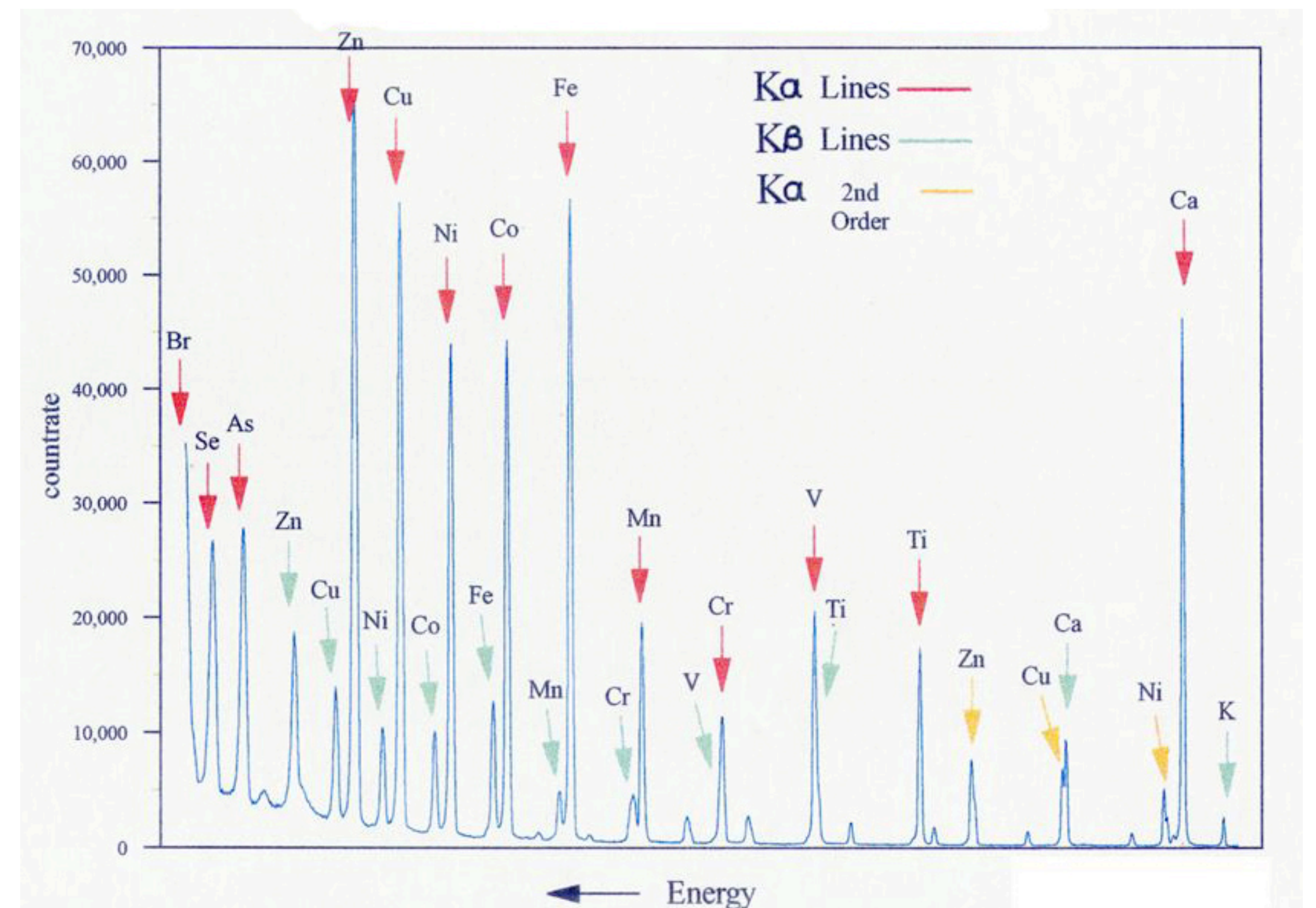


# Fluorescence in Cultural Heritage

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

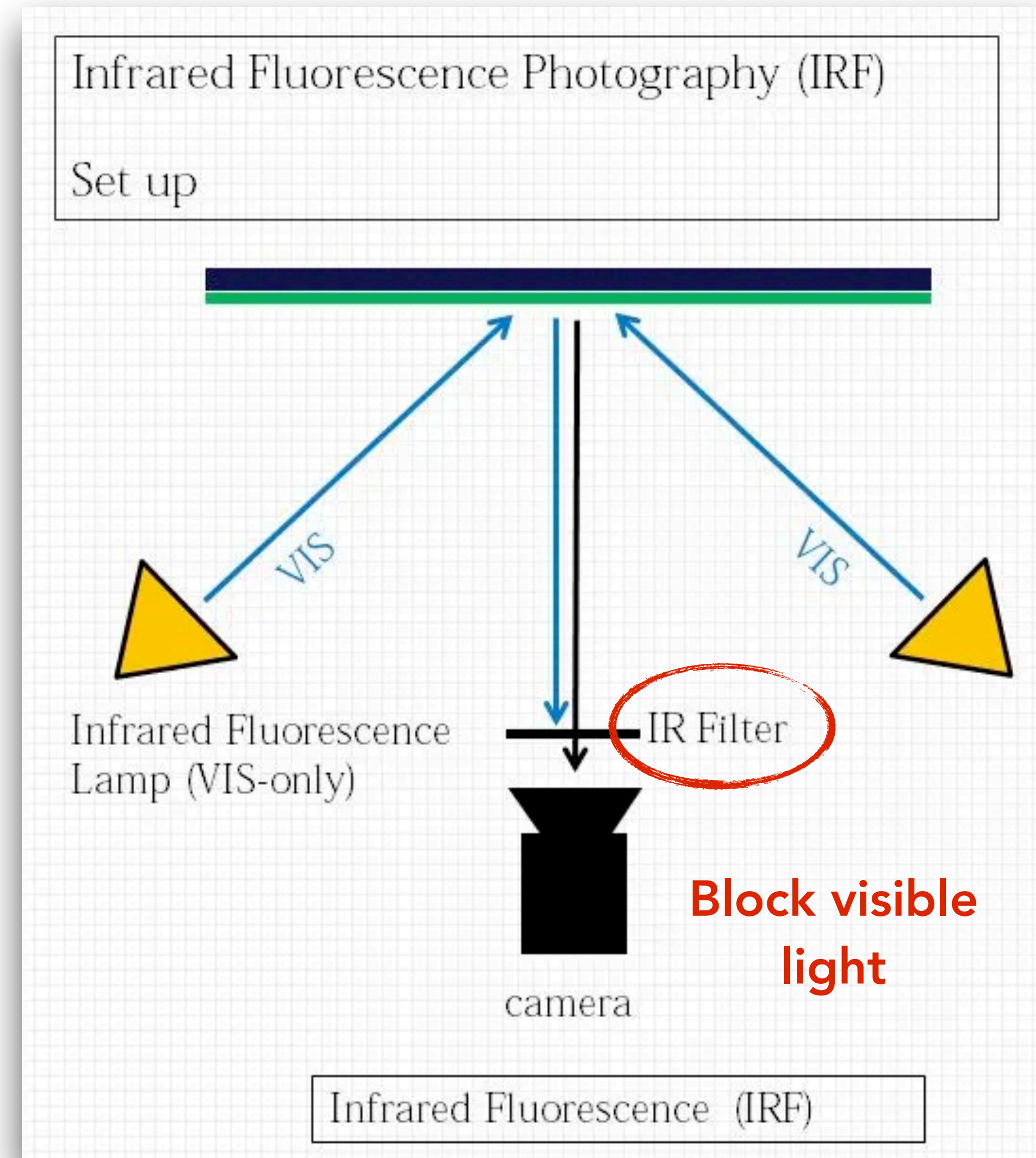
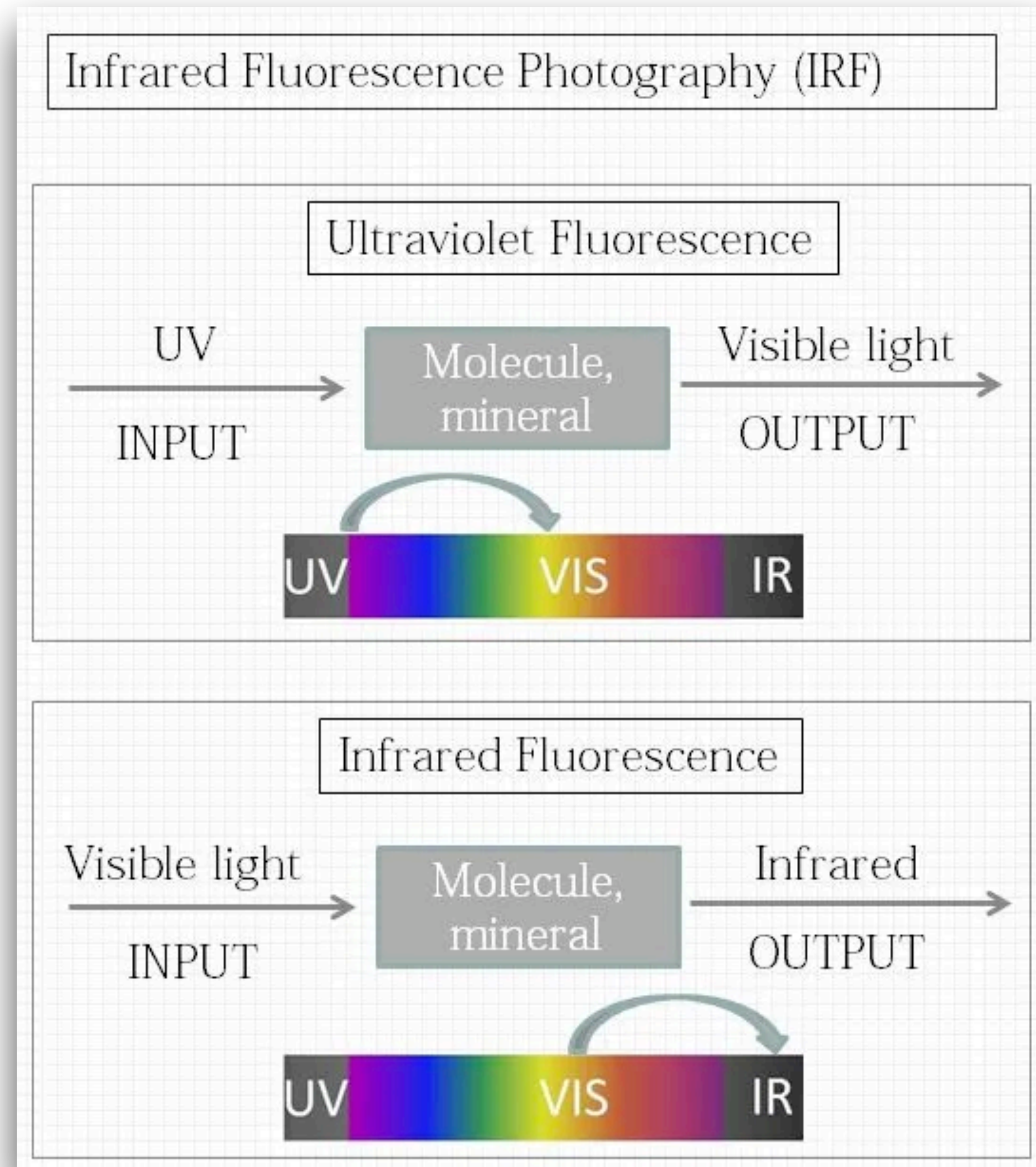
Fluorescence photography is widely used in cultural heritage for identifying pigments, pentimenti, etc.

- IR Fluorescence
- UV Fluorescence
- X-Ray Fluorescence

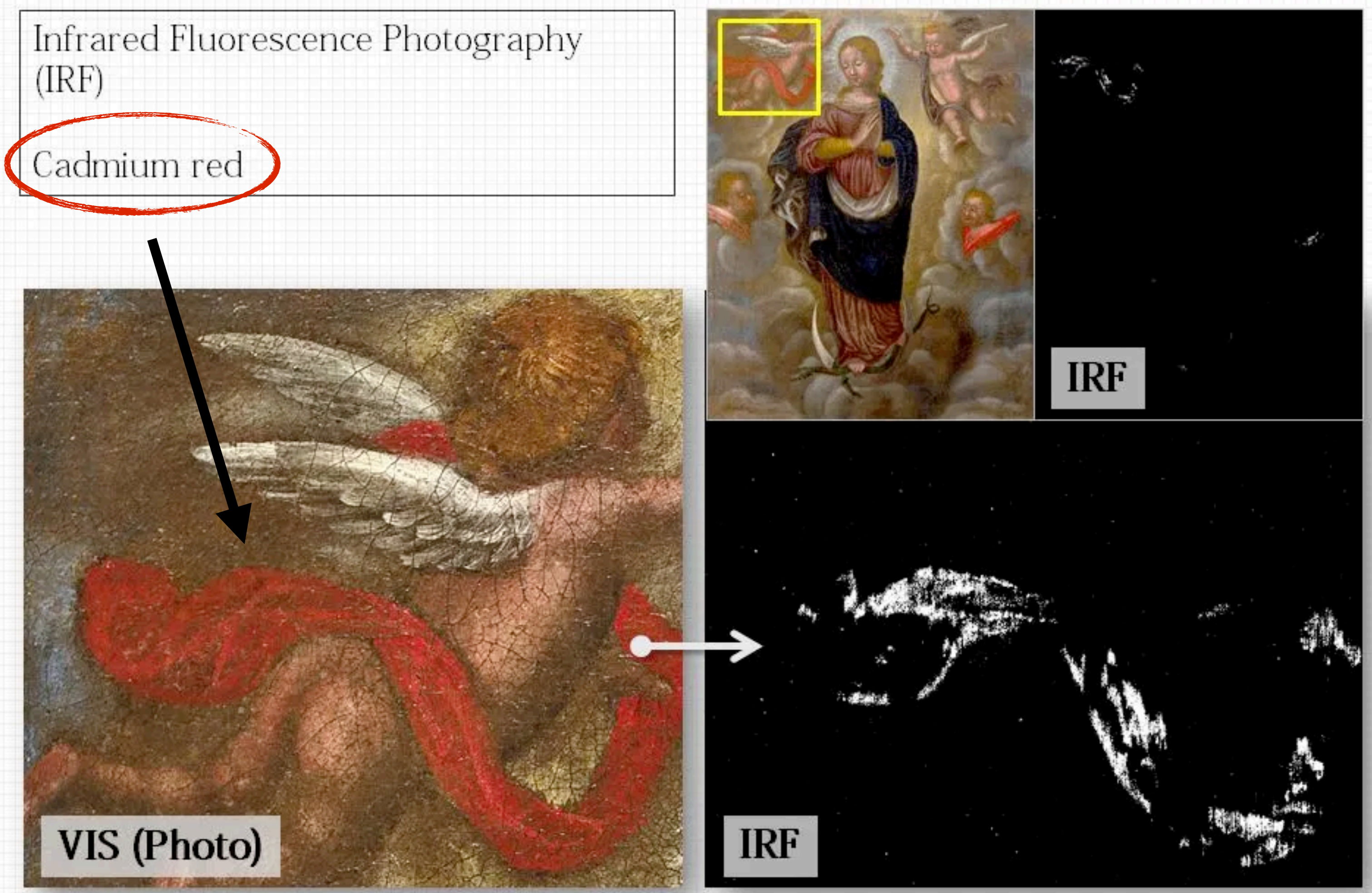


An XRF emission spectra

# 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**



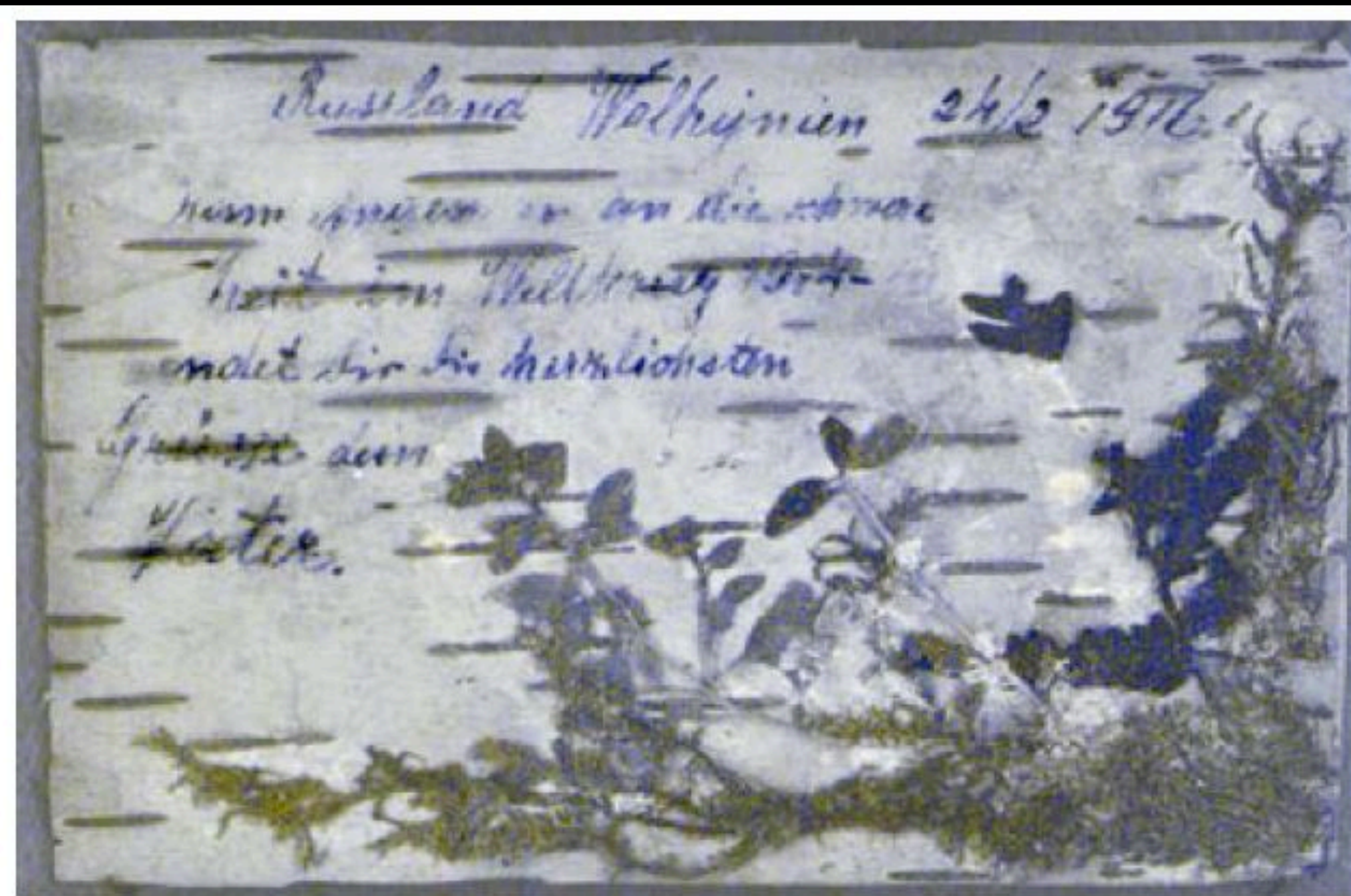
**Later retouches**

# Private postcard

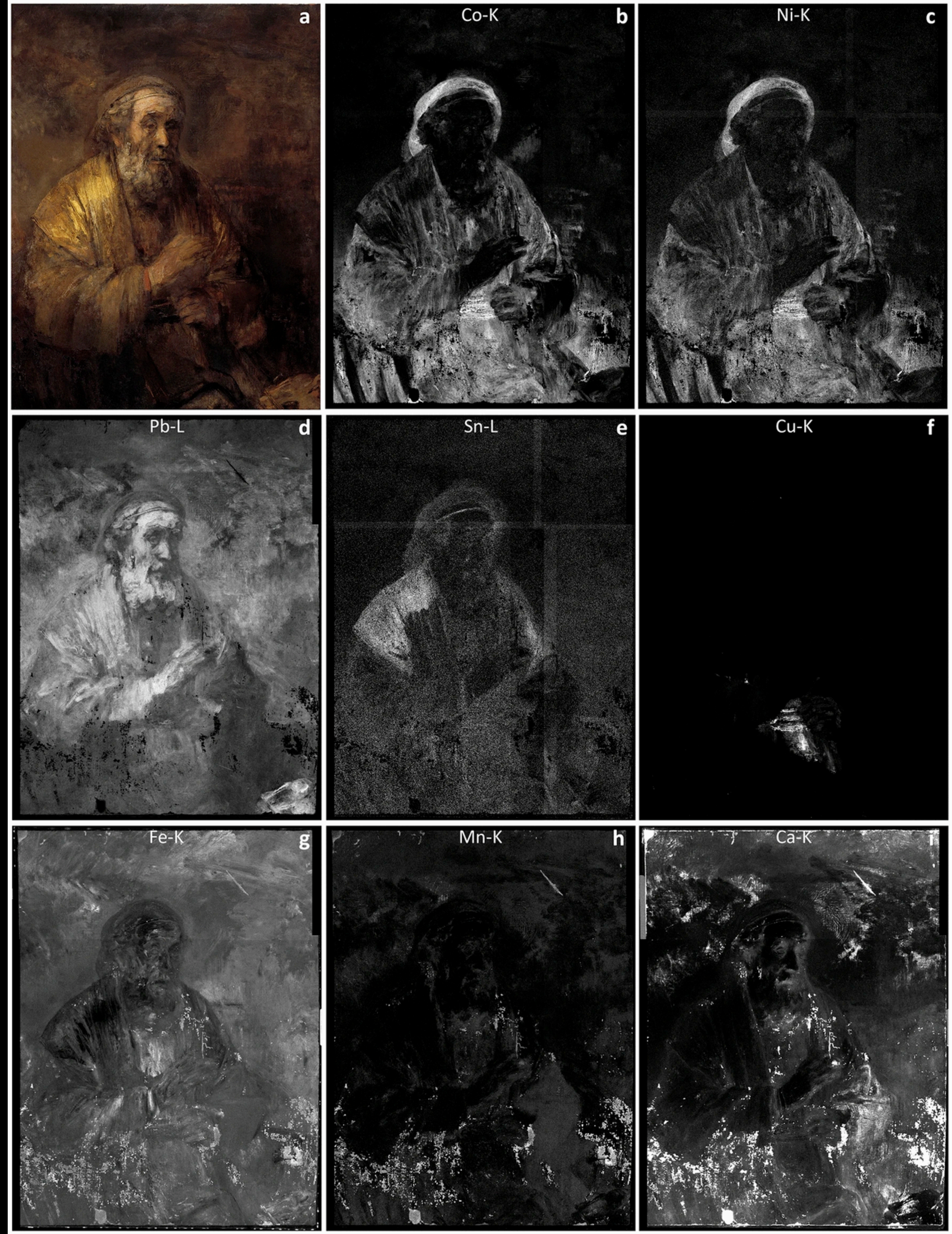
## Under visible light



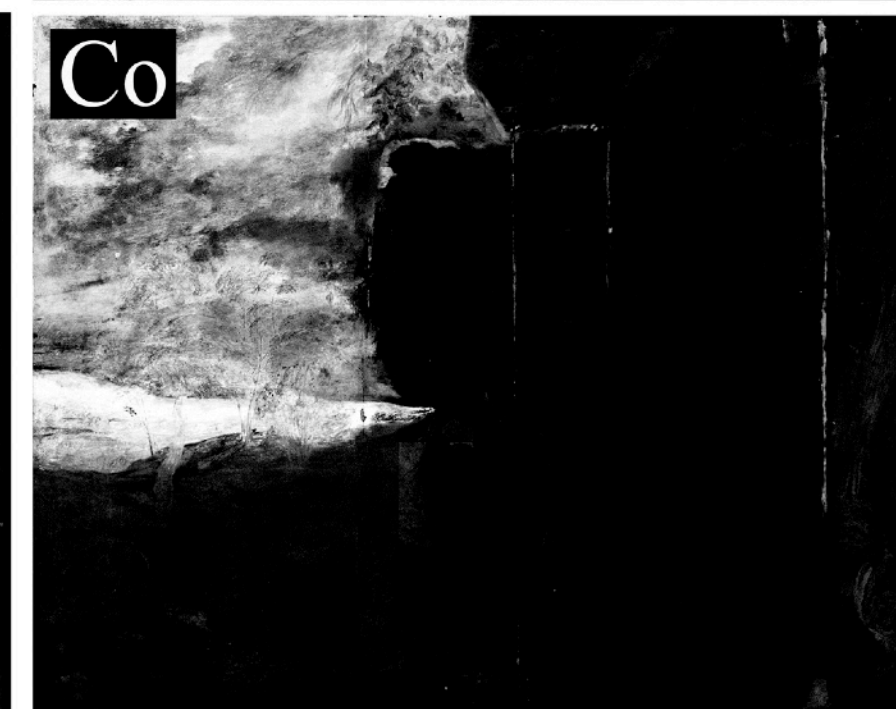
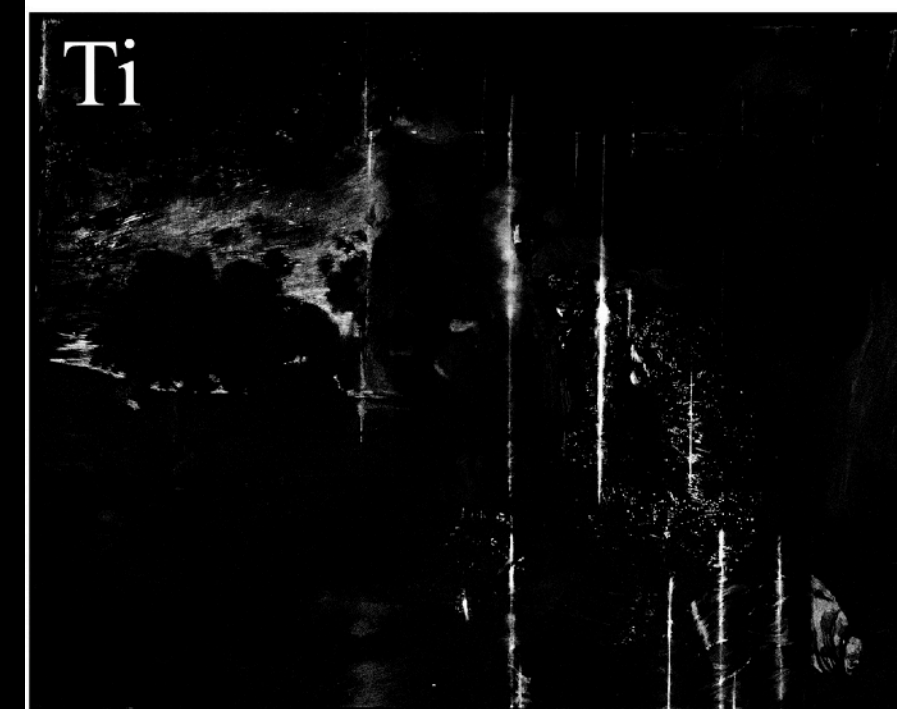
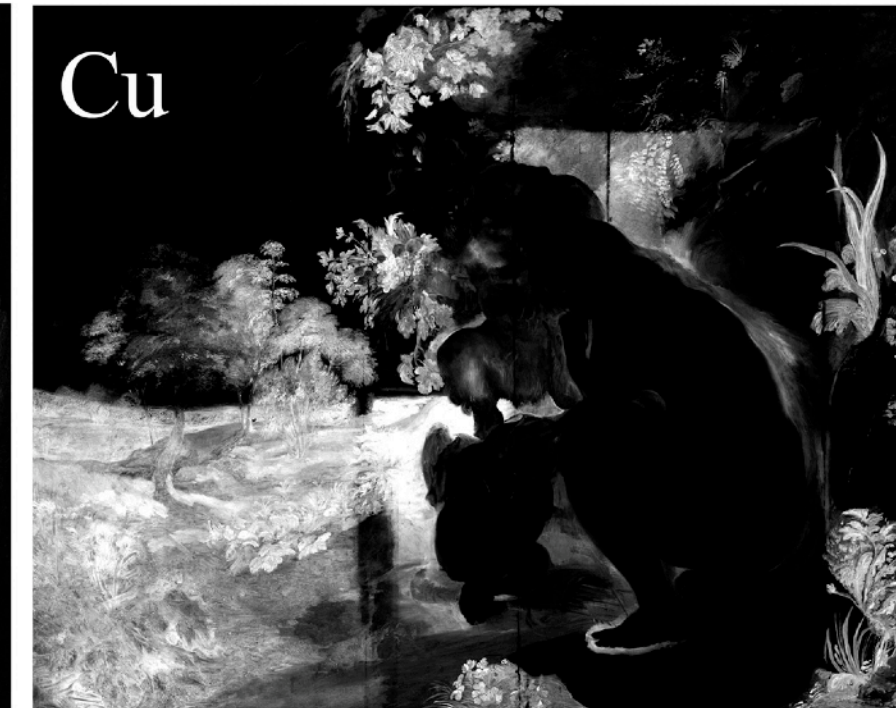
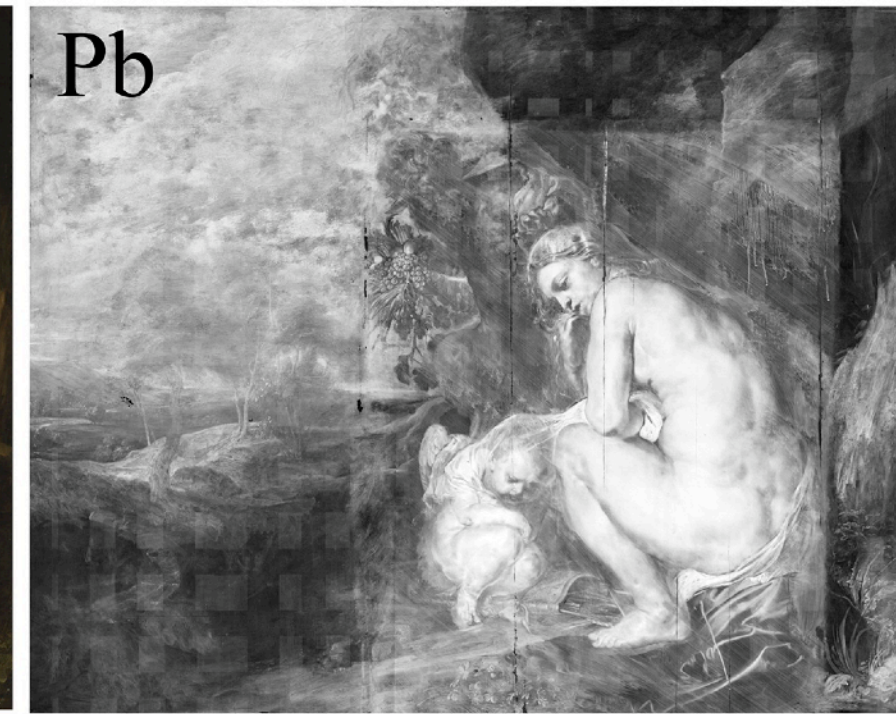
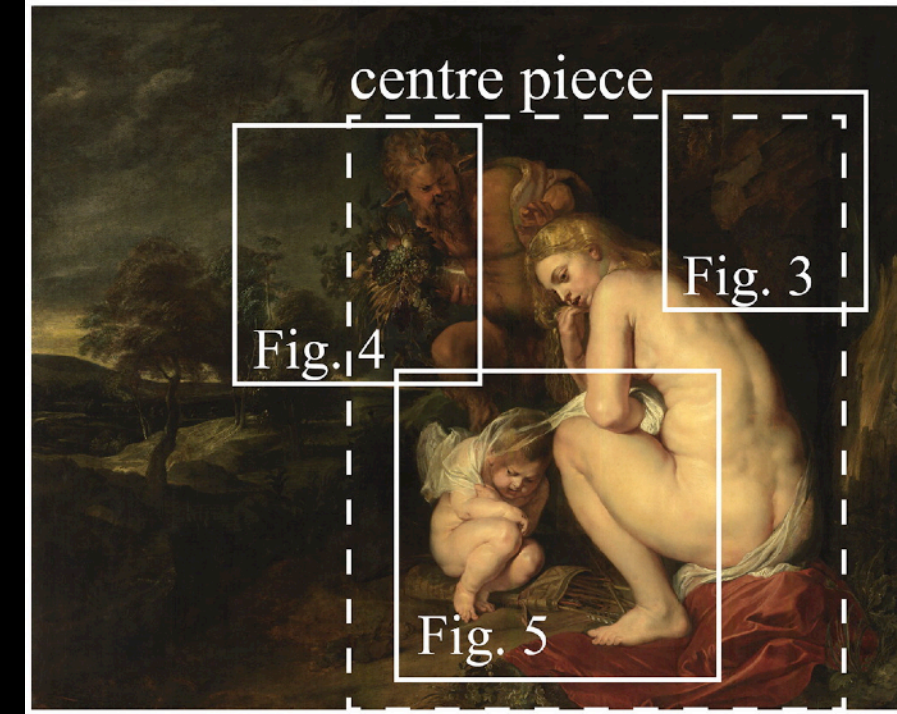
## Under UV Fluorescence



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



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



# Things to Take Away

Birth, life, and death of a photon: emission, absorption, and scattering.

Color from emission: radiation, bioluminescence, electroluminescence

Color from absorption + scattering: transparent, translucent, and opaque materials.

Color from absorption + emission: fluorescence