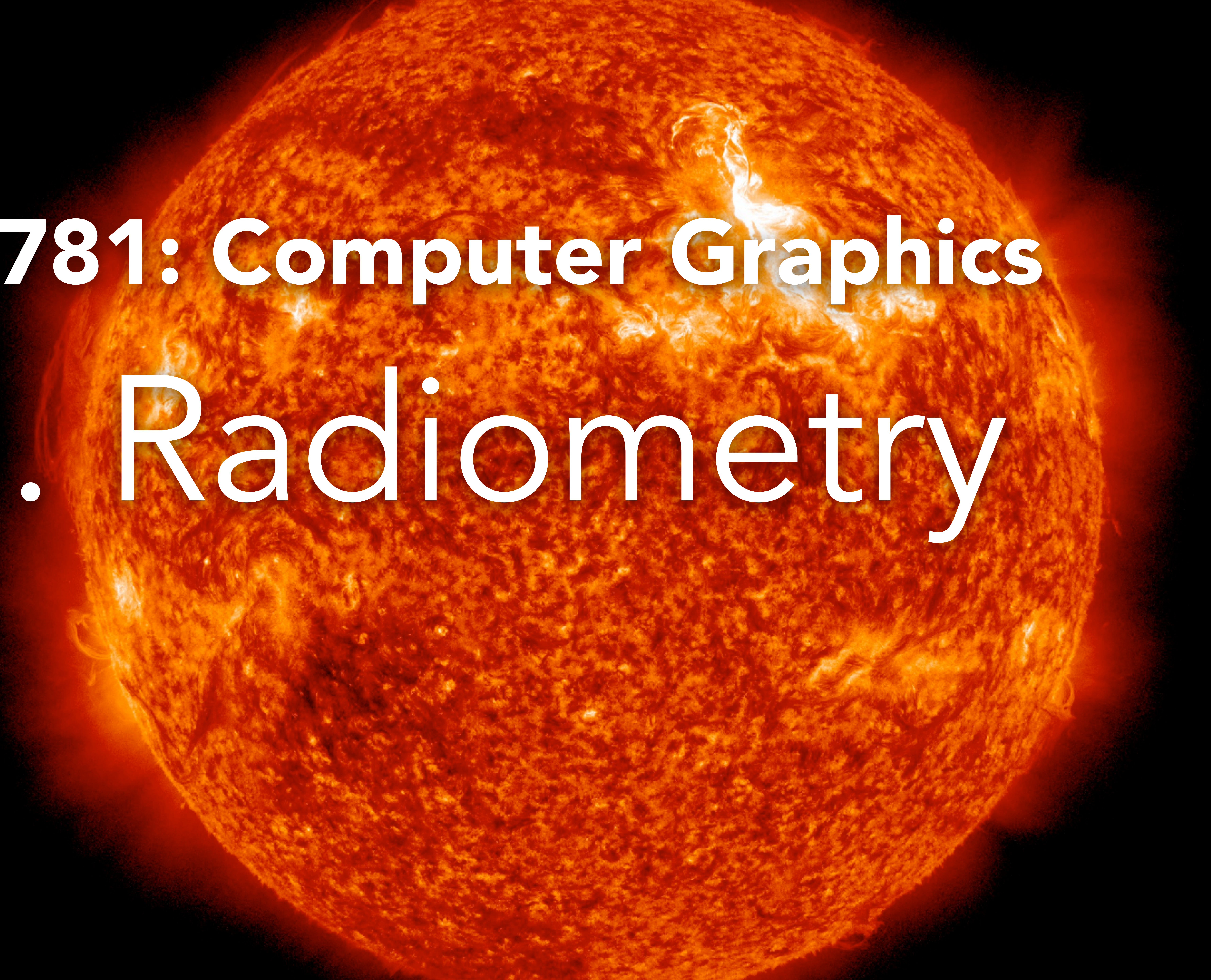
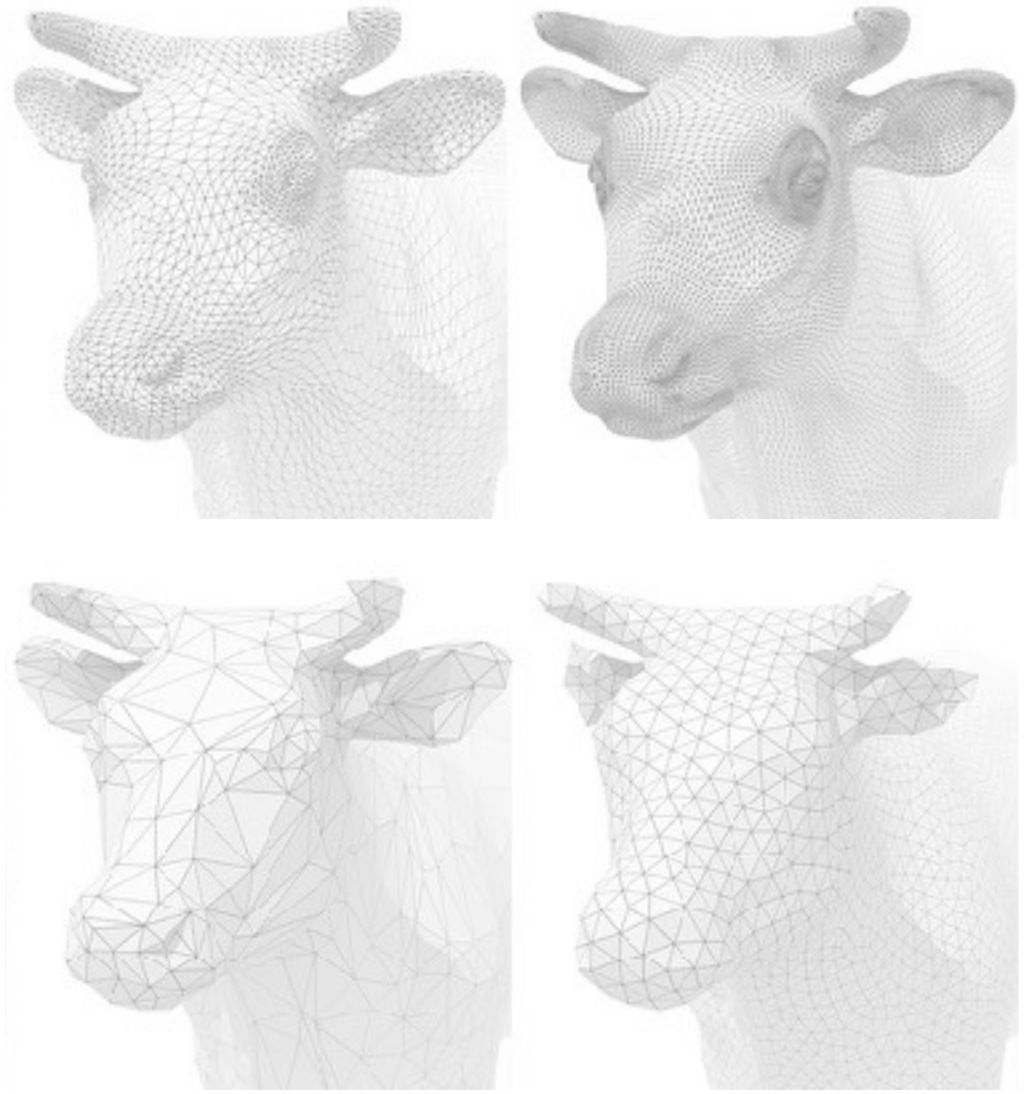
COL781: Computer Graphics

20. Radiometry



Course content

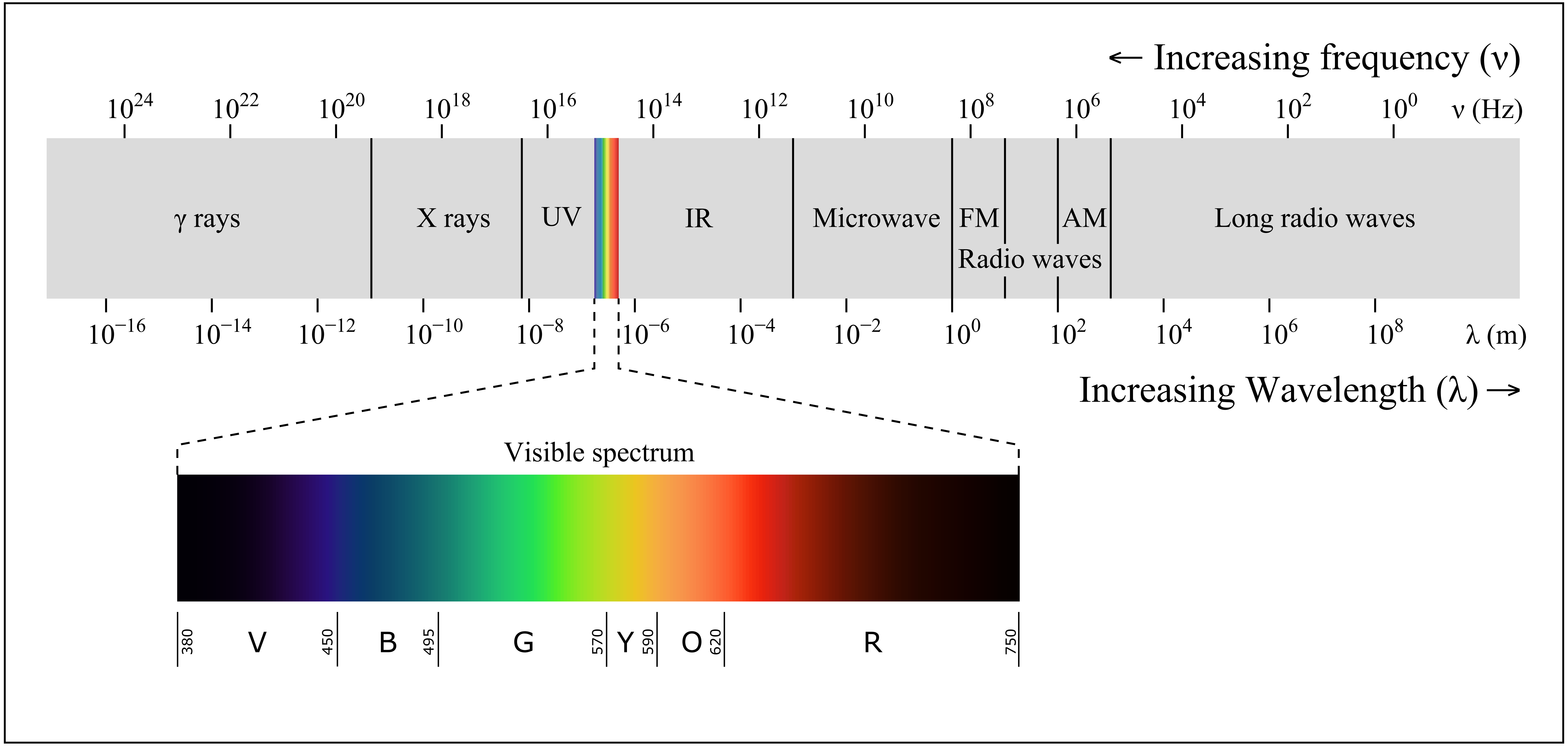


Modeling

Rendering

Animation

Light



← Increasing frequency (ν)
10^{24} 10^{22} 10^{20} 10^{18} 10^{16} 10^{14} 10^{12} 10^{10} 10^{8} 10^{6} 10^{4} 10^{2} 10^{0} ν (Hz)
γ rays
X rays
UV
IR
Microwave
FM
AM
Radio waves
Long radio waves
10^{-16} 10^{-14} 10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} 10^{6} 10^{8} λ (m)
Increasing Wavelength (λ) →
Visible spectrum
380 V 450 B 495 G 570 Y 590 O 620 R 750

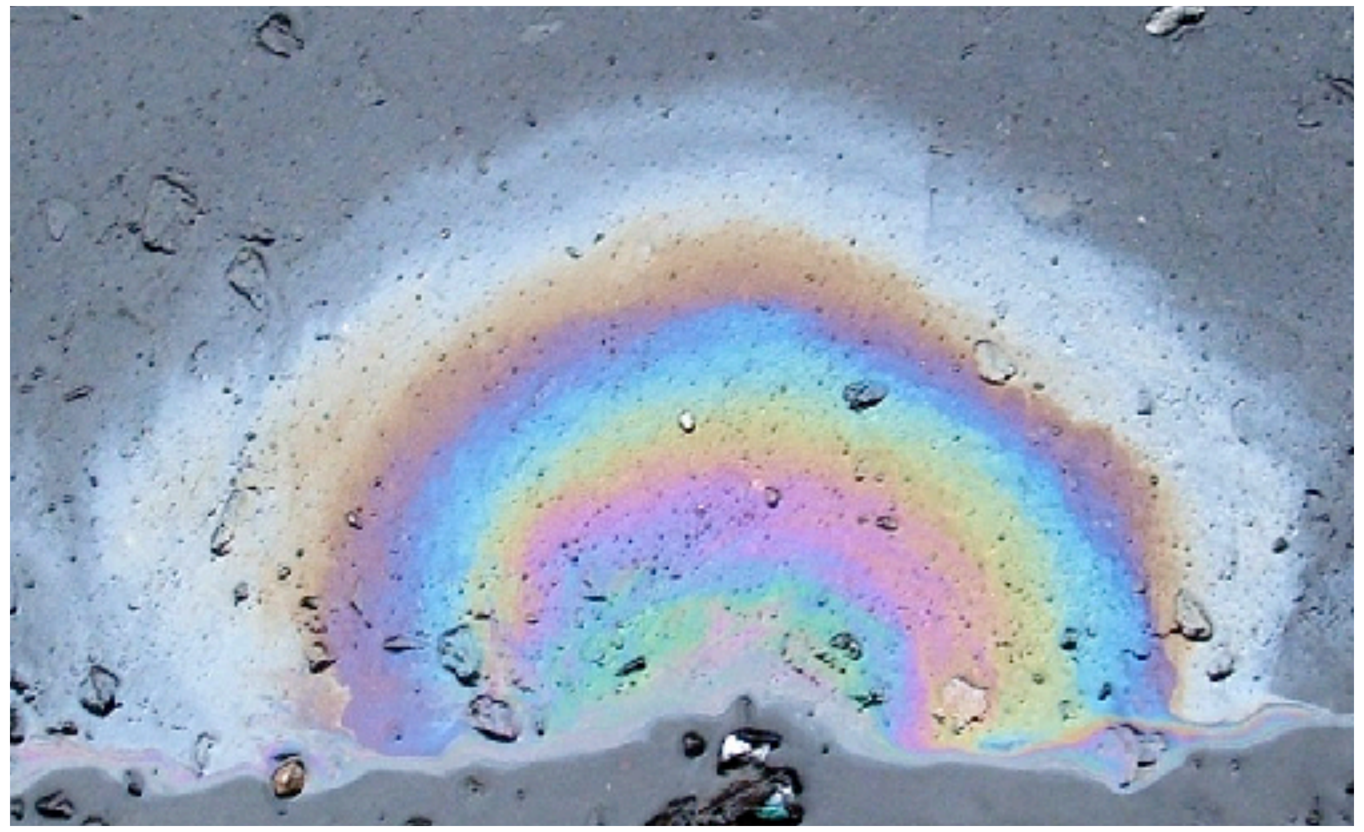
Light

Fundamentally a quantum phenomenon

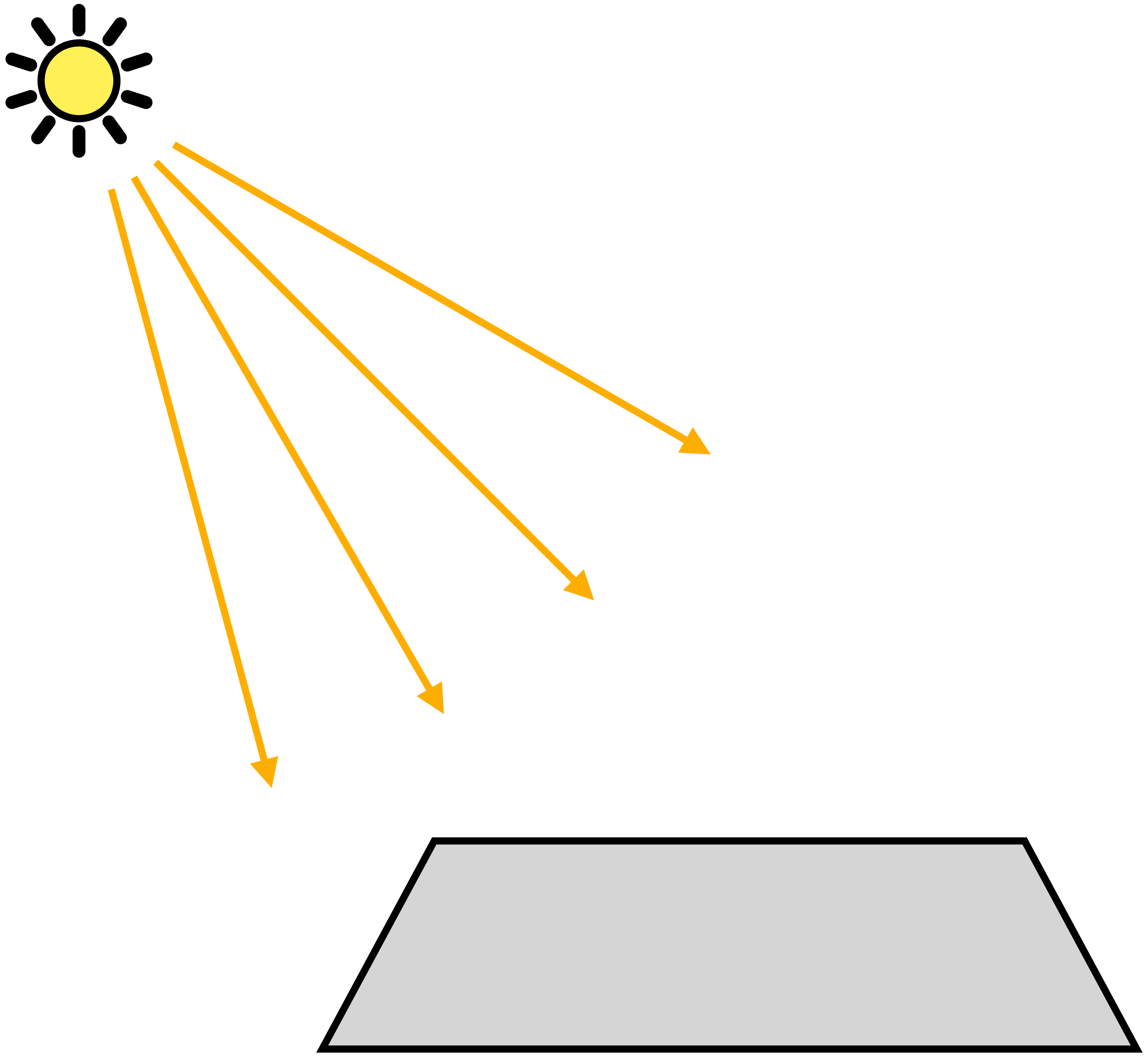
- Wave-particle duality: photoelectric effect
- Wave optics: diffraction, iridescence
- Ray optics: basically everything else

Classical ray approximation is good enough for most things!

We'll still speak informally of "photons" flying around the scene



How should we quantify how much light from the light source hits the surface?



Radiant energy and radiant flux

Light is a form of energy, so…

- Amount of light = **radiant energy** Q (in joules)

But a light source doesn't just emit a fixed amount of energy and then stop!

- Light energy per unit time = **radiant flux** Φ (J/s = watt)

(The rated wattage of a bulb doesn't actually equal the radiant flux though…)

Actually, we don't care about energy from EM radiation of *all* wavelengths…

Radiometry = measurement of any EM radiation

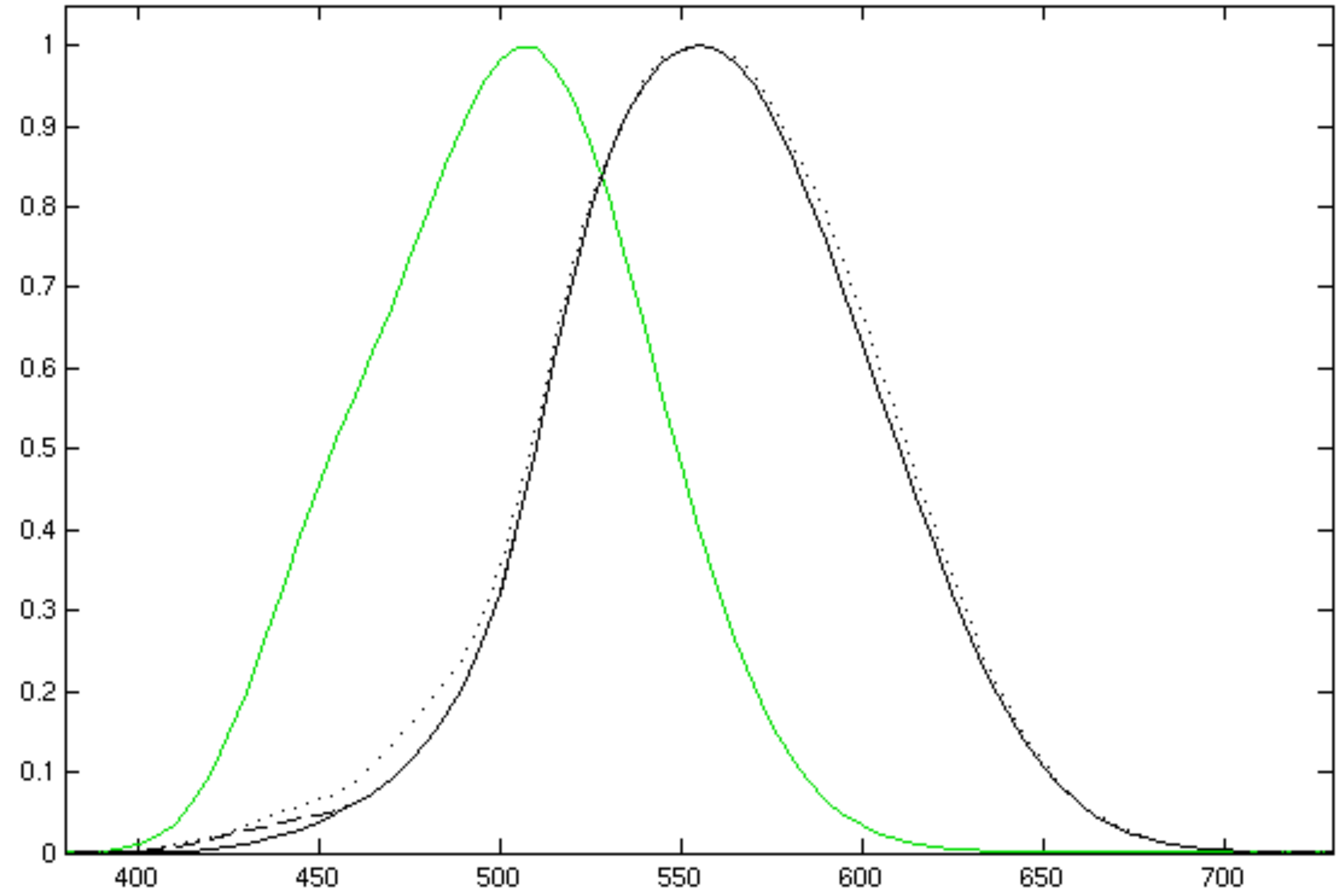
- Radiant energy (J), radiant flux (W), etc.

Photometry = measurement in terms of perceived brightness by human eye

- Luminous energy, luminous flux (lumen), etc.

To capture colour: distribution of energy from light of different wavelengths

- Spectral flux (W/nm), etc.



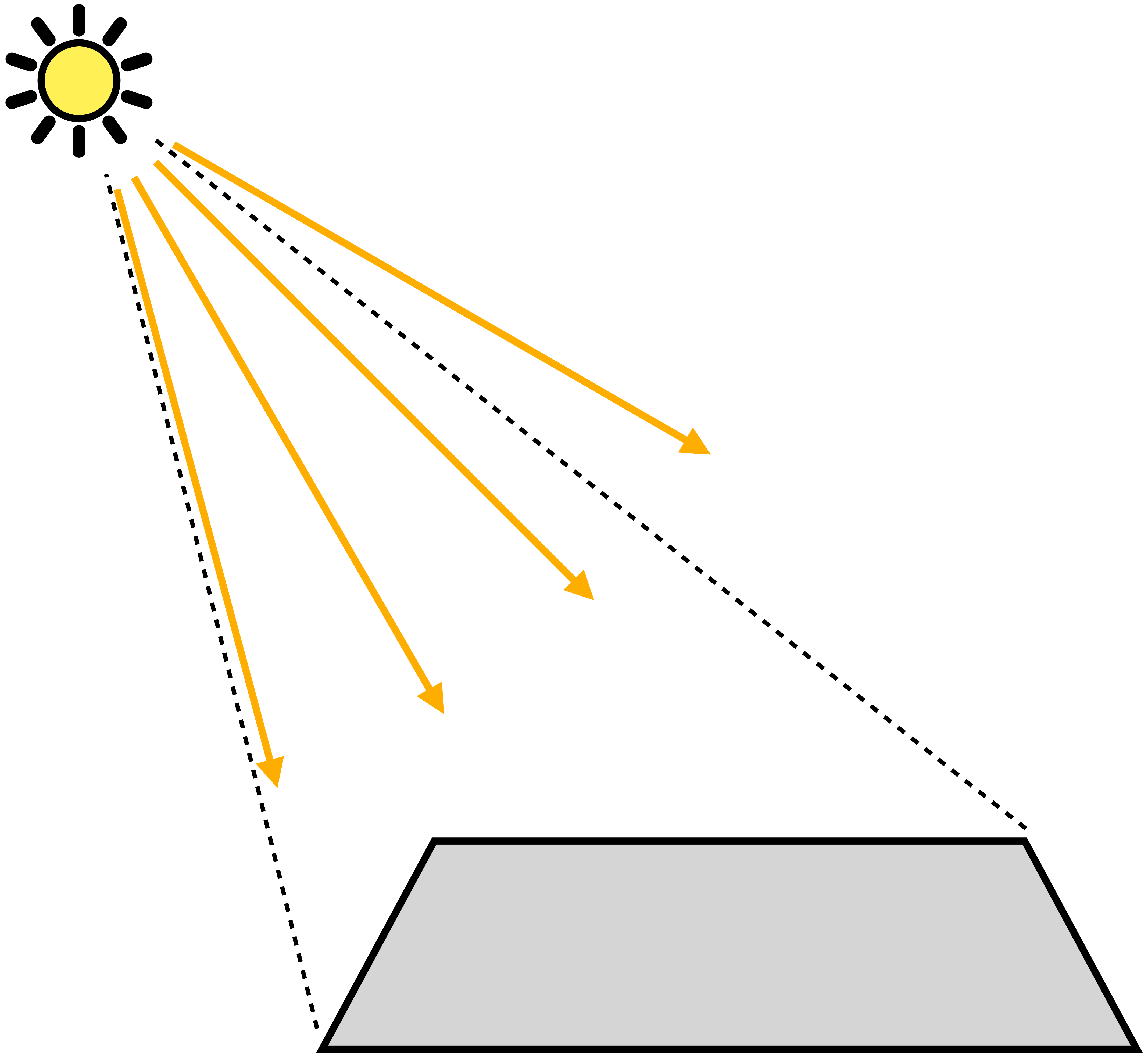
Luminosity function: sensitivity of human eye to different wavelengths in daytime (black) or darkness (green)

Radiant intensity

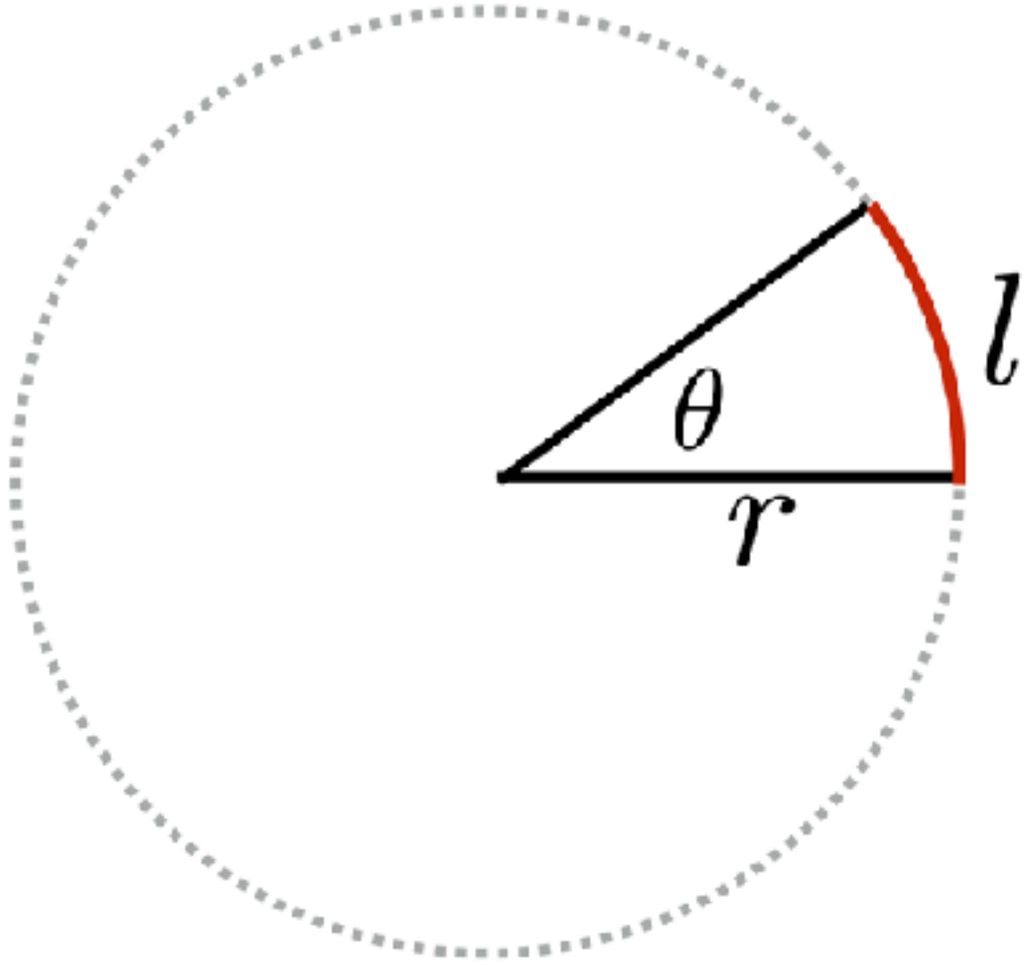
How much light from the light source reaches the surface?

Depends on the **solid angle** subtended by the surface.

Radiant intensity *I* = radiant flux per unit solid angle (W / steradian)

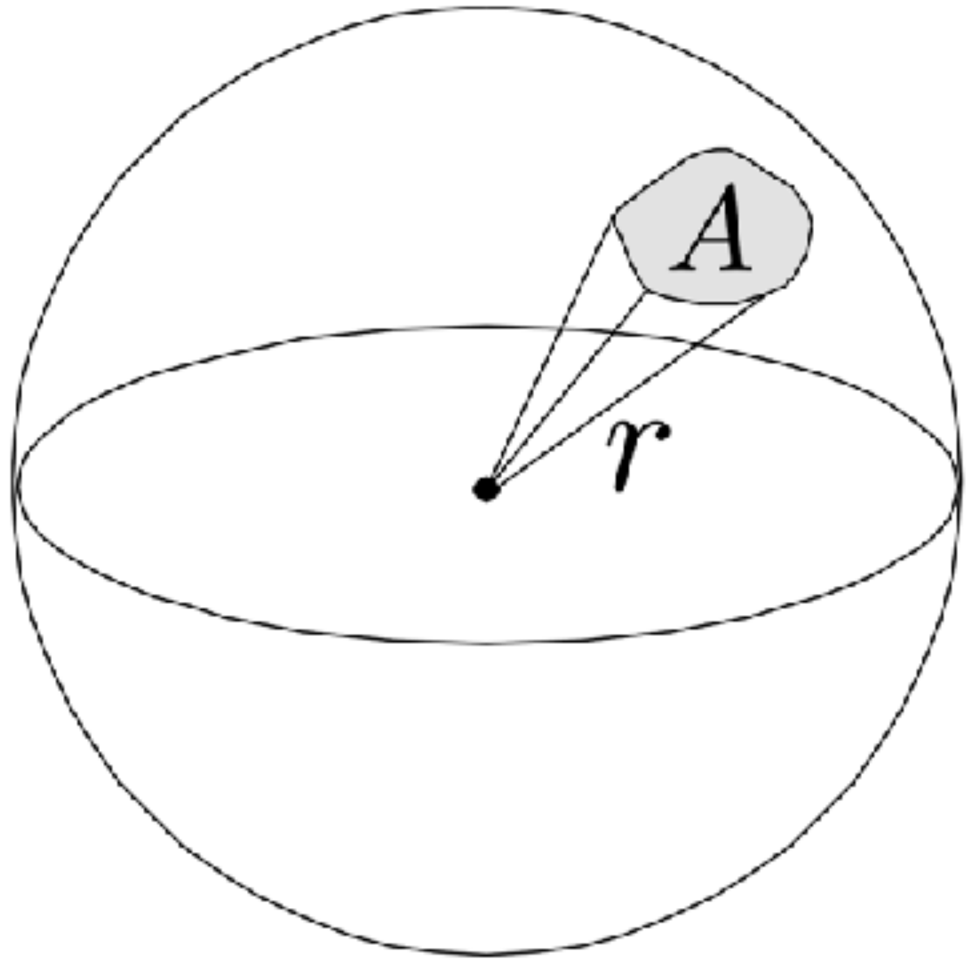


Solid angle



Angle = arc length on circle / radius

- Total angle in a circle = 2π **radians**



Solid angle = surface area on sphere / radius^2

- Total solid angle in a sphere = 4π **steradians**

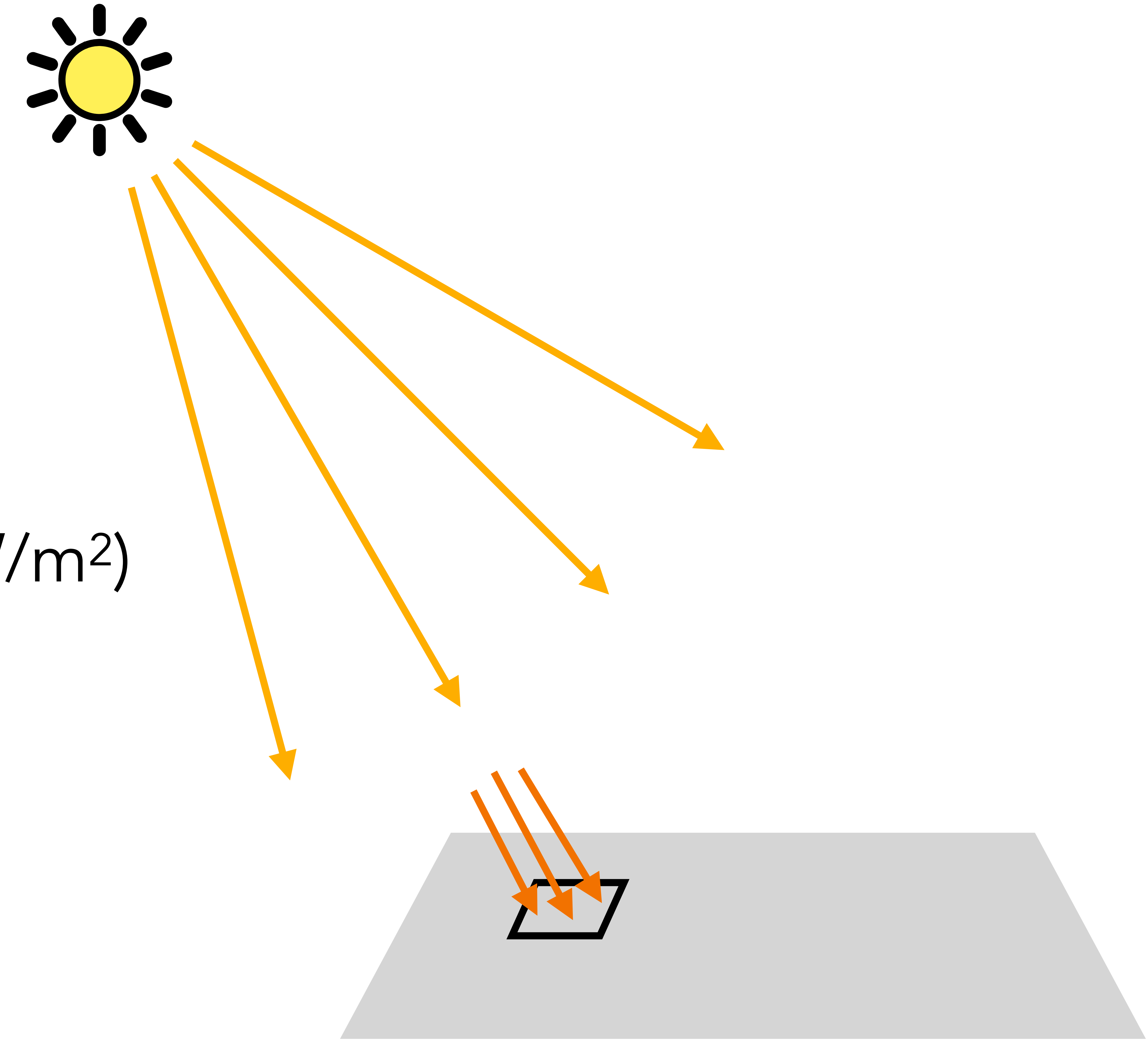
Solid angle = how much space an object occupies in your field of view.
e.g. The sun and moon both subtend ~6×10^{-5} sr when seen from Earth.

For an isotropic point light source, $I(\boldsymbol{\omega}) = \dfrac{\Phi}{4\pi}$.

Intensity can also vary with direction **ω**:

Total radiant flux $\Phi = \displaystyle\int_{S^2} I(\boldsymbol{\omega})\,\mathrm{d}\boldsymbol{\omega}$

Irradiance



From the point of view of the surface,
how much light is each location receiving?

Has to be proportional to area! (Why?)

Irradiance E = radiant flux per unit area (W/m^2)

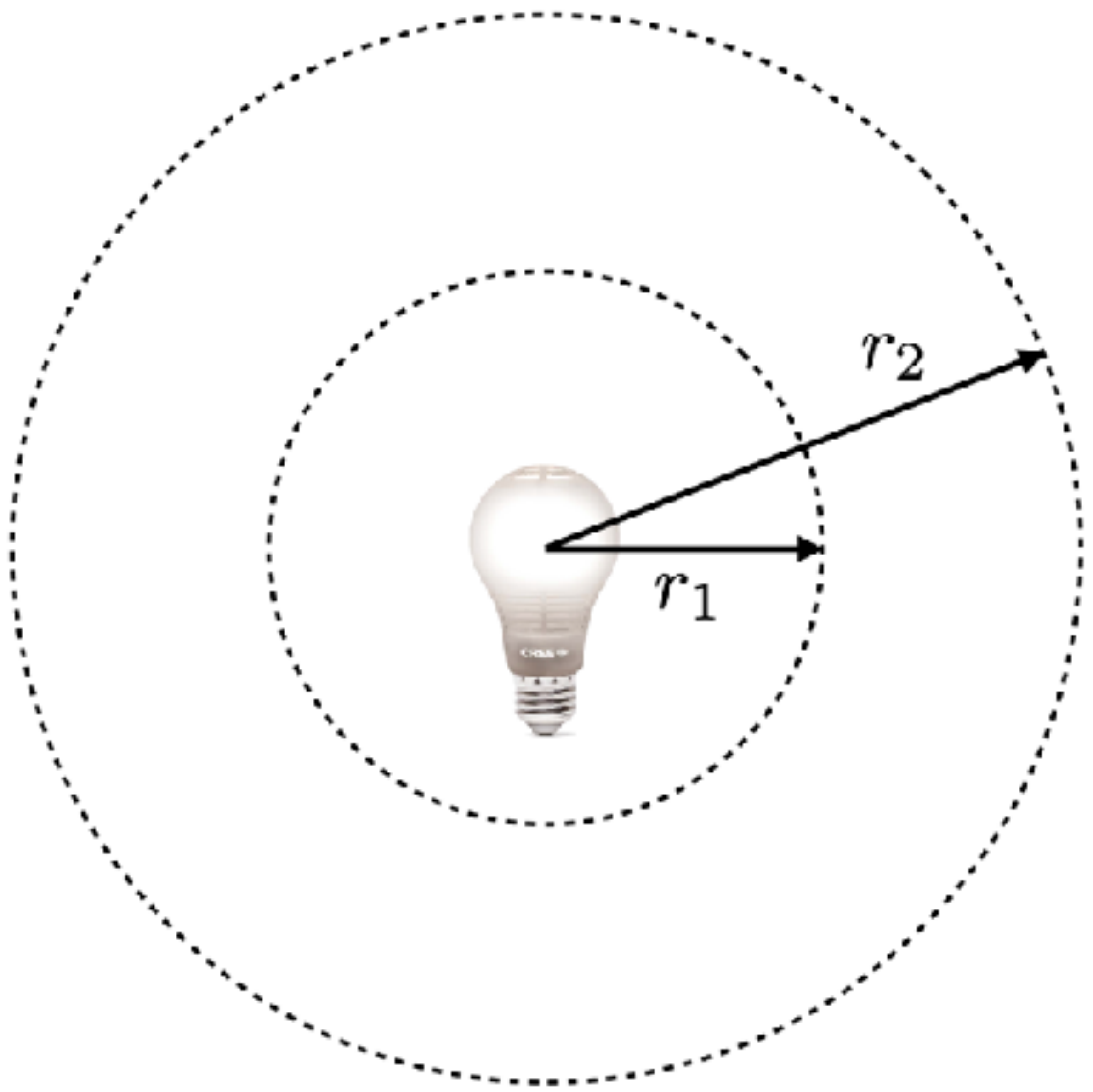
What is the irradiance due to a point source?

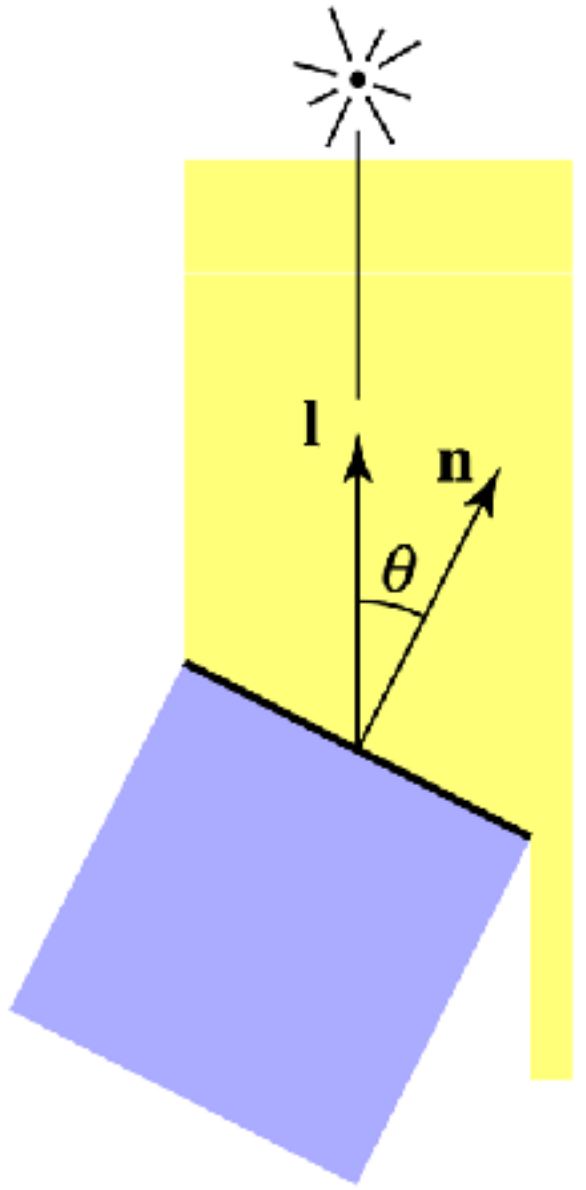
- Irradiance on sphere of radius *r* (inverse square law):

$$E_{\perp} = \frac{\Phi}{4\pi r^2}$$

- Irradiance on tilted surface (Lambert's cosine law):

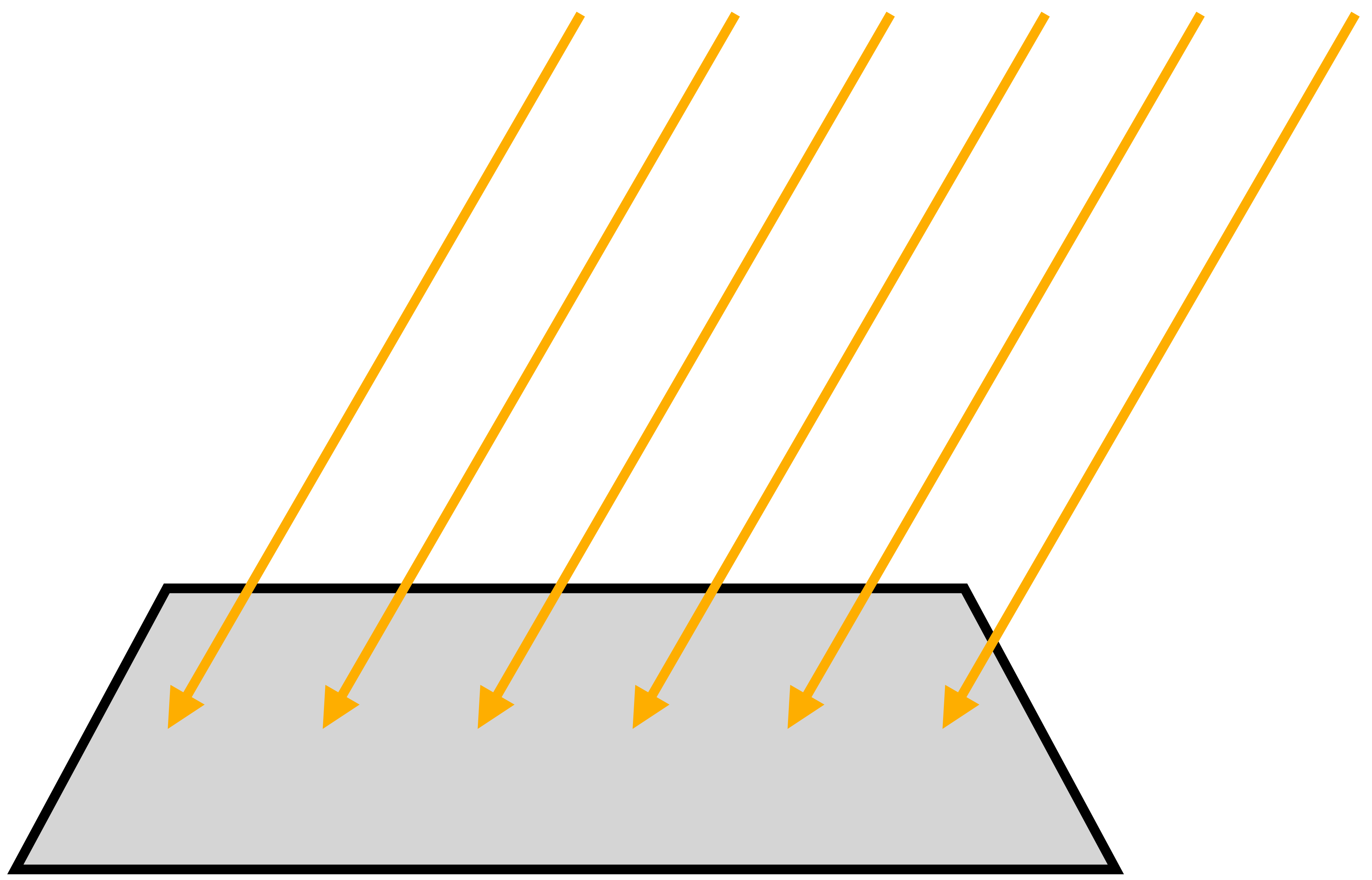
$$E = E_{\perp} \cos(\theta)$$





What about a directional light source that is infinitely far away, producing light rays that are all parallel?

Can I talk about its radiant intensity? Or only its irradiance?



Flux received by surface = $\int I(\omega)\cos(\theta)/r^2\,dA$

Light's point of view:

intensity $I(\omega)$

$\times$

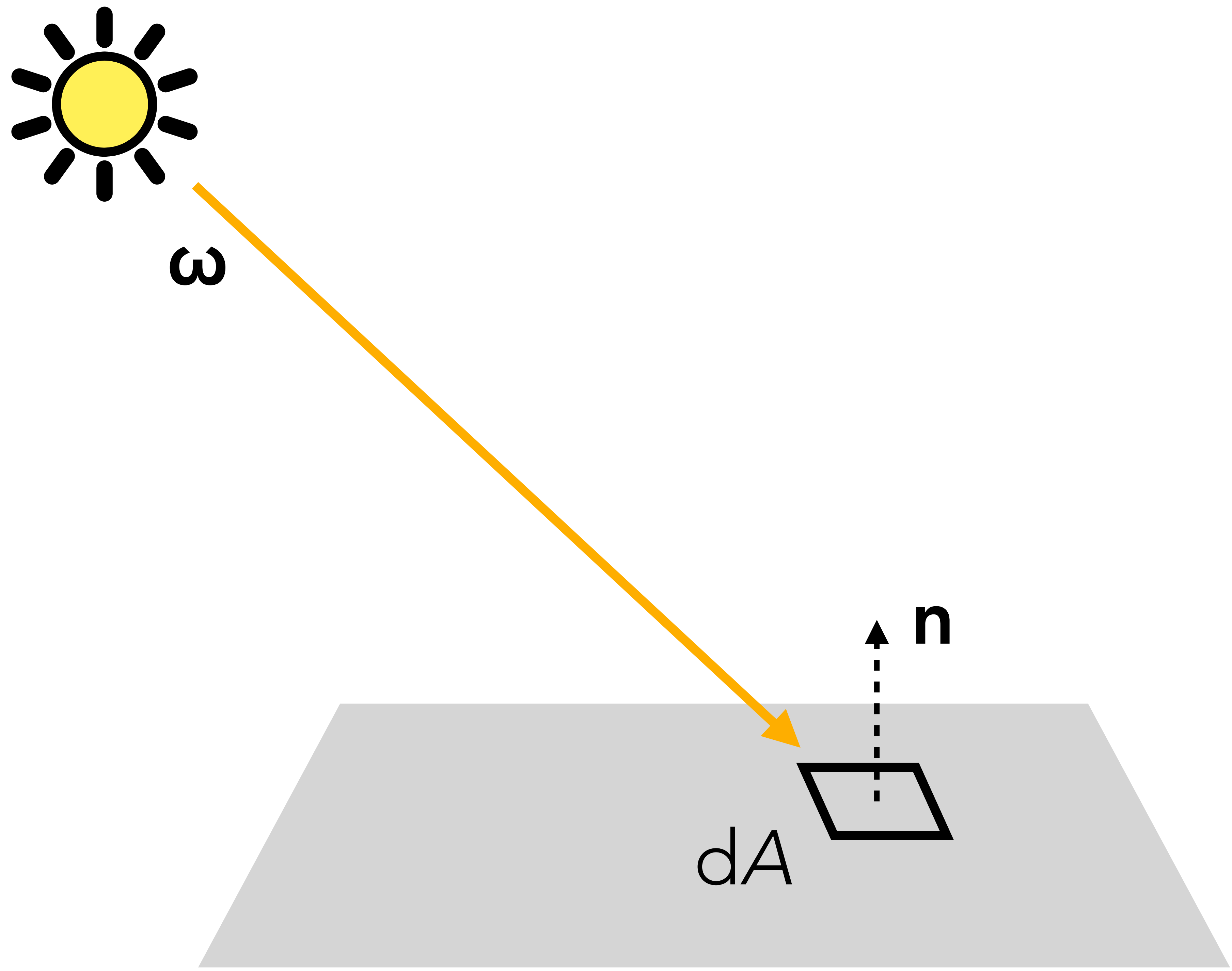
projected solid angle $dA\cos(\theta)/r^2$

Surface's point of view:

irradiance $I(\omega)\cos(\theta)/r^2$

$\times$

area dA



Irradiance values in the real world vary by many orders of magnitude!

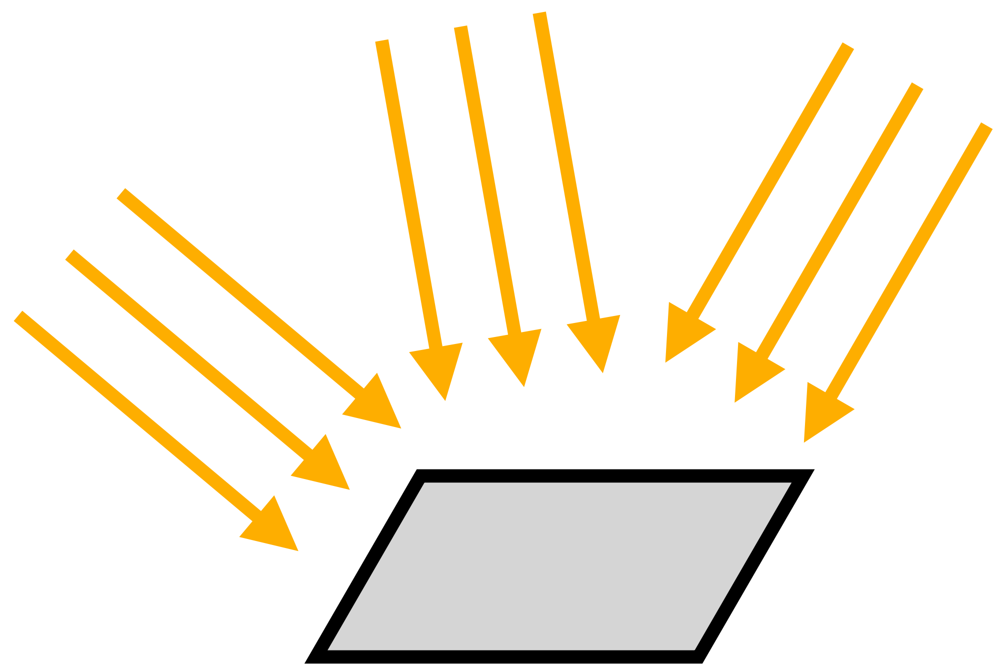
- Bright sunlight: 120,000 lux (lumen/m^2)
- Overcast day (midday): 15,000
- Interior near window (daylight): 1,000
- Residential artificial lighting: 300
- Sunrise / sunset: 40
- Illuminated city street: 10
- Moonlight (full): 0.02
- Starlight: 0.0003

Actually these are **illuminance** values: photometric version of irradiance

Light meter

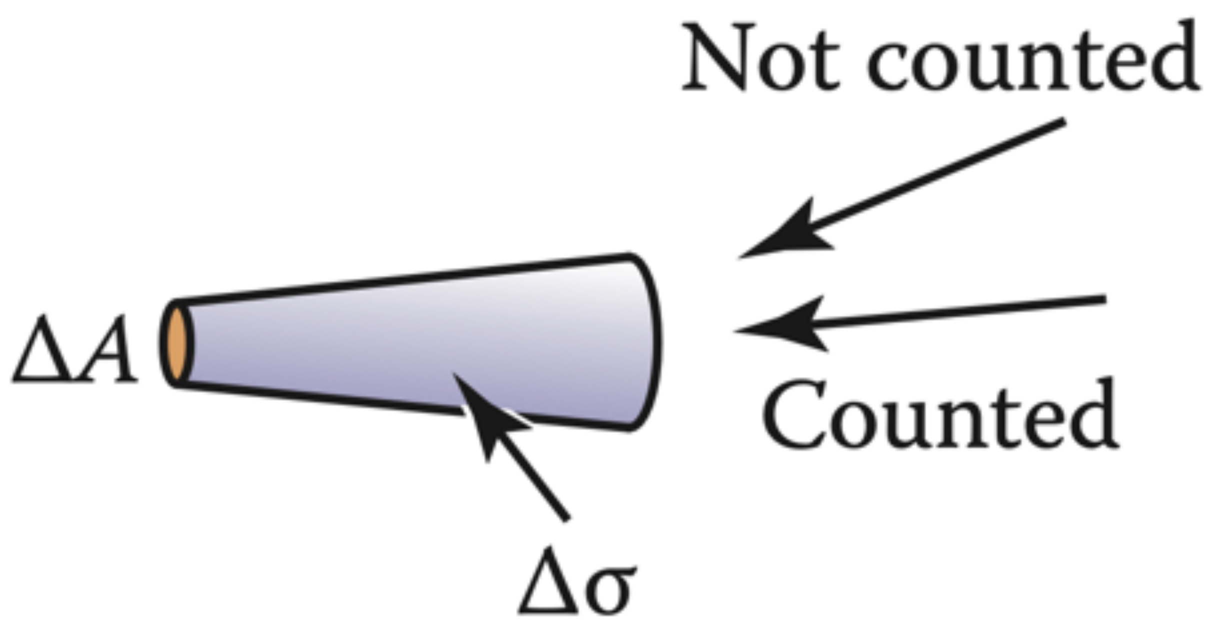
Radiance

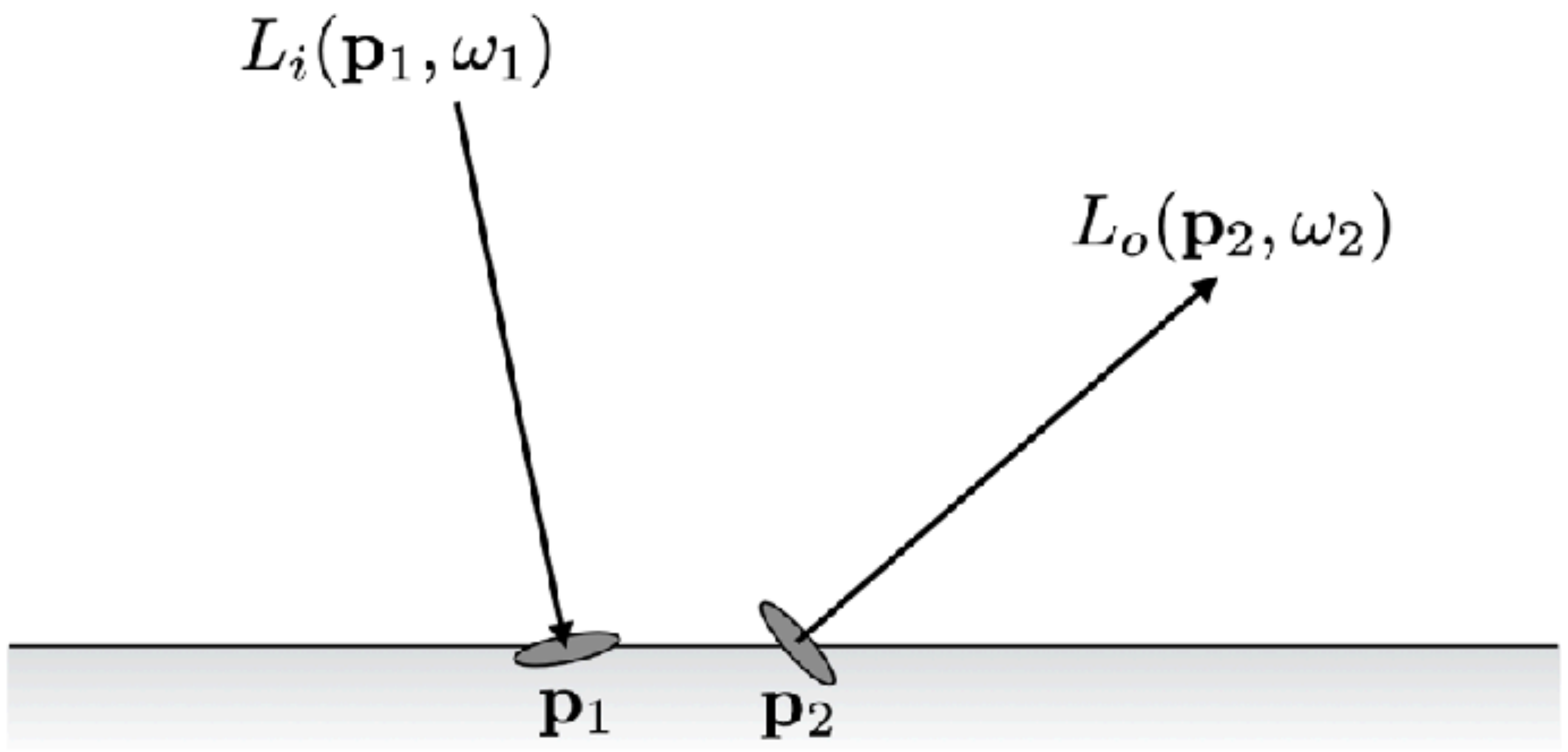
In general, a surface will receive varying amounts of light from many different directions.



Radiance $L(\mathbf{p}, \boldsymbol{\omega})$ = irradiance per unit solid angle
= flux per unit area per unit solid angle

Imagine sitting at the location **p**, pointing a sensor in the direction **ω**, and measuring the incident light



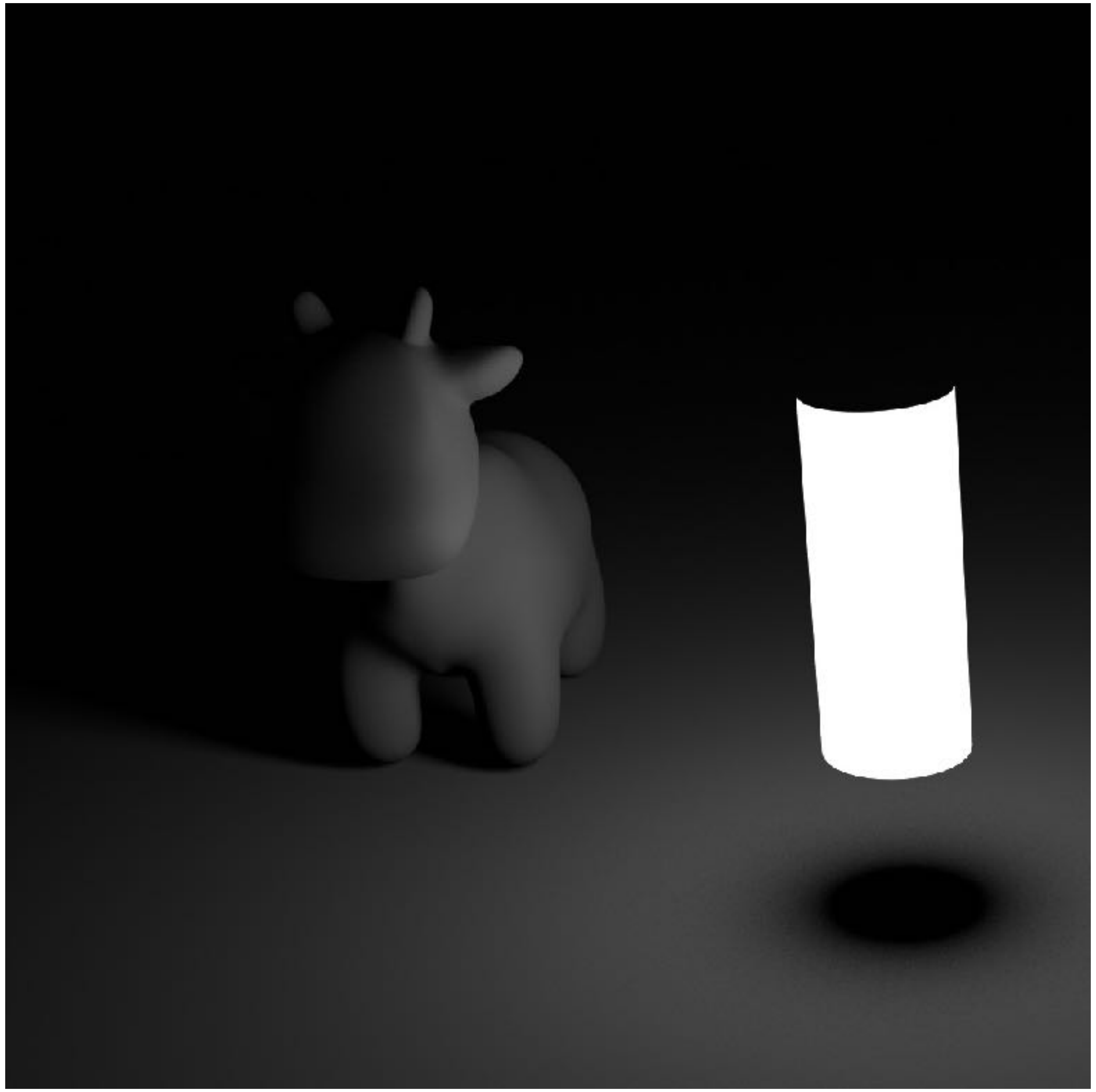


We can talk about both radiance in both directions:

- incident radiance L_i: angular distribution of incoming light
- exitant radiance L_o: angular distribution of of outgoing light (emitted/reflected/transmitted)

In general, $L_i(\mathbf{p}, \boldsymbol{\omega}) \neq L_o(\mathbf{p}, \boldsymbol{\omega})$

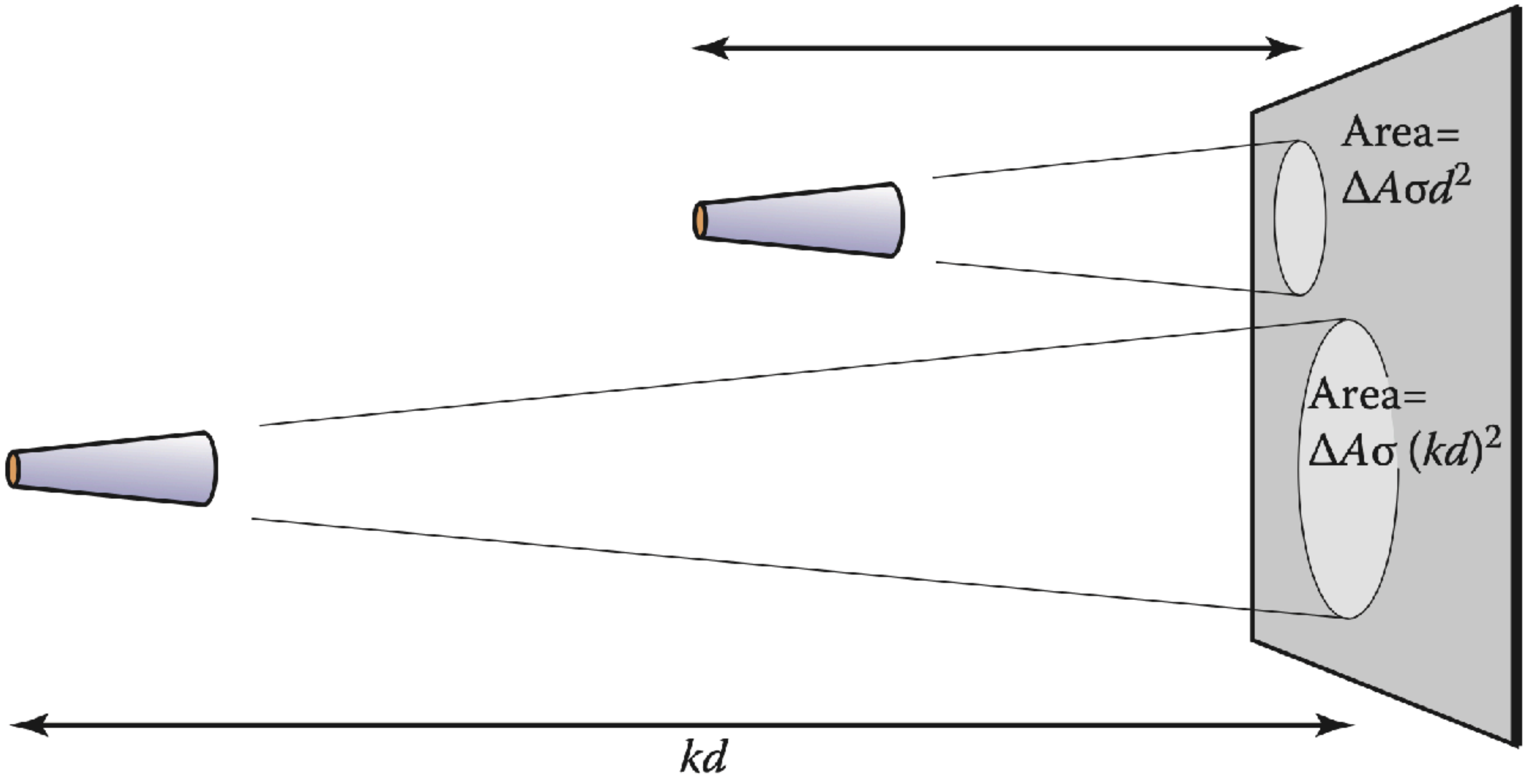
A surface with a fixed nonzero exitant radiance becomes an area light source…



Puzzle:

We know that the amount of light received from a point has an inverse square falloff with distance.

Then why don't objects look darker when they are farther away?

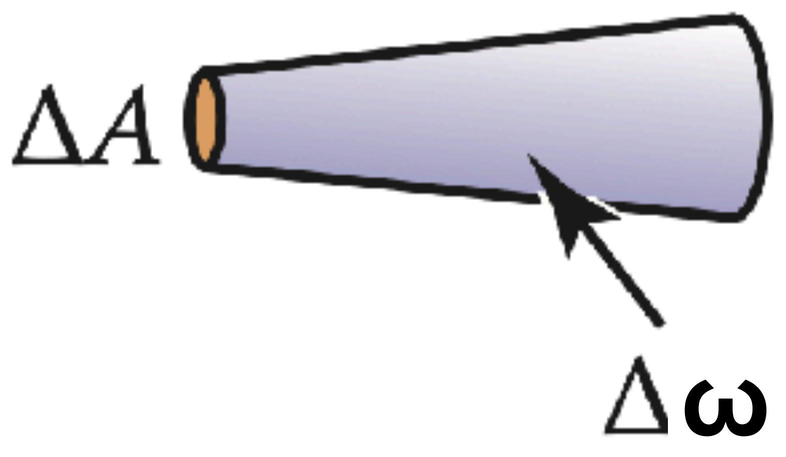


Area=
$\Delta A \sigma d^2$
Area=
$\Delta A \sigma (kd)^2$
kd

Radiance is the fundamental radiometric quantity that characterizes the distribution of light in a scene!

- Can define anywhere in scene, not just at surfaces:

$$L(\mathbf{p}, \boldsymbol{\omega}) = \frac{\mathrm{d}^2\Phi}{\mathrm{d}\omega \, \mathrm{d}A}$$

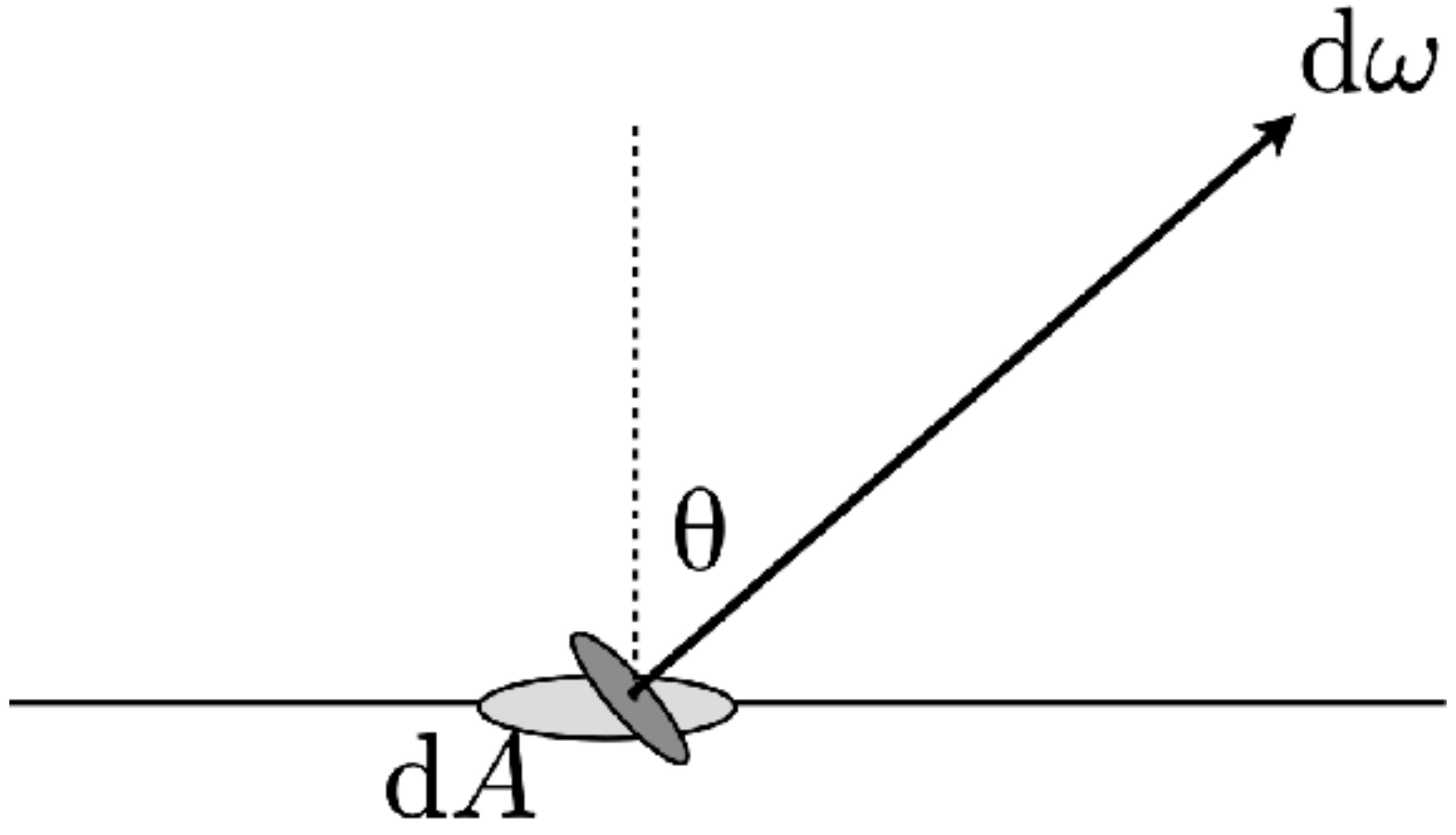


- Radiance is constant along any ray (in a vacuum)

- Radiance is what eyes and cameras observe, and what we want to compute when rendering!

At surface, incident/exitant radiance has a cos(θ) factor:

$$L(\mathbf{p}, \boldsymbol{\omega}) = \frac{\mathrm{d}E}{\mathrm{d}\boldsymbol{\omega} \cos\theta} = \frac{\mathrm{d}\Phi}{\mathrm{d}\boldsymbol{\omega}\, \mathrm{d}A \cos\theta}$$



Why? Irradiance E is per unit surface area,
radiance L is per unit area normal to the ray

- Why? Because radiance is a property of the ray, not of the surface!

Radiance also spans many orders of magnitude:

- Surface of the sun: 2,000,000,000 nits (lumen/sr/m^2)
- Sunlight clouds: 30,000
- Clear sky: 3,000
- Cellphone display: 500
- Overcast sky: 300
- Scene at sunrise: 30
- Scene lit by moon: 0.001
- Threshold of vision: 0.000001

Actually this is **luminance**…

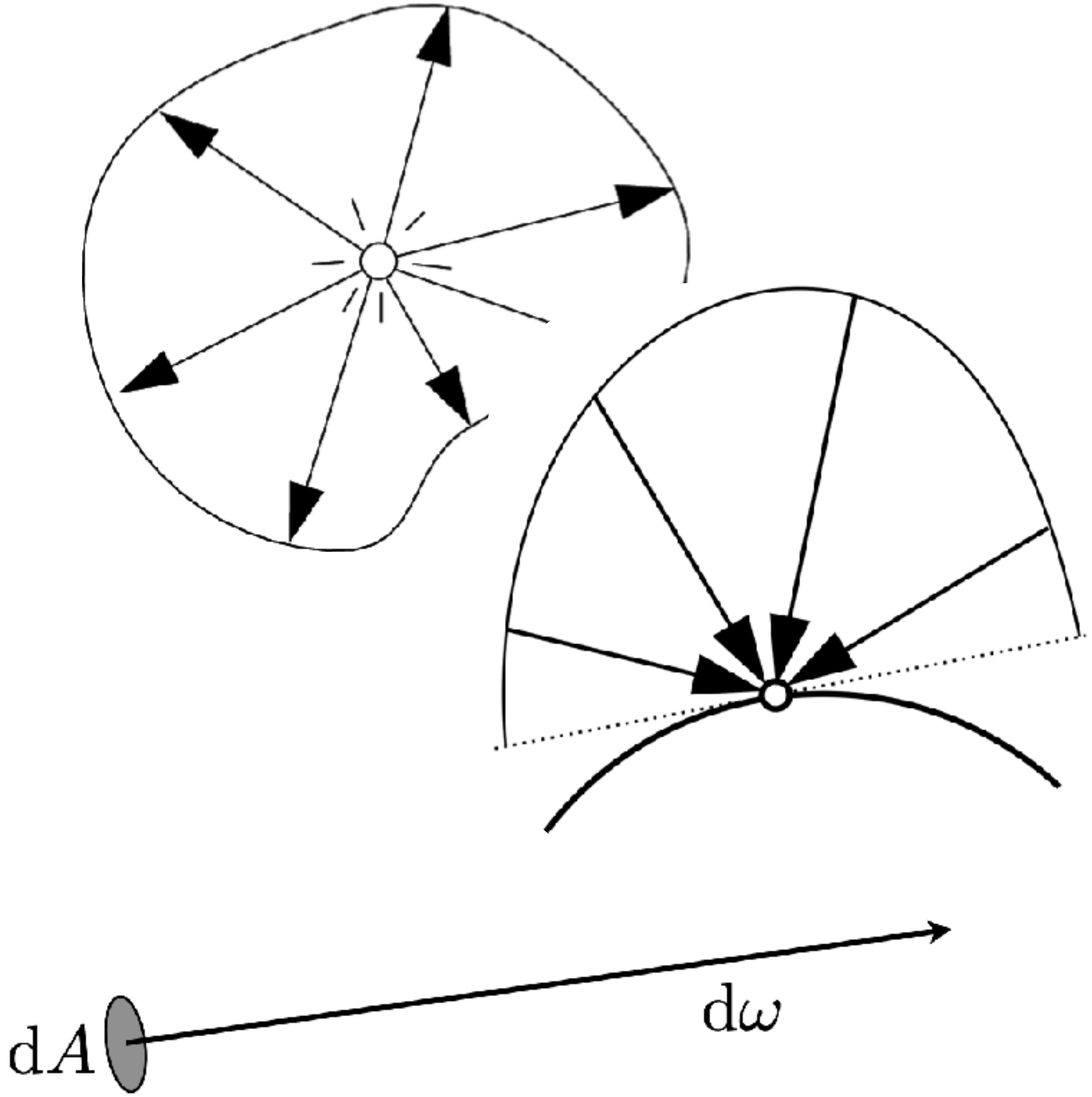
Summary

Radiant flux: total light energy per unit time

Radiant intensity: light emitted by a source in a particular direction (flux / solid angle)

Irradiance: light received by a surface (flux / area)

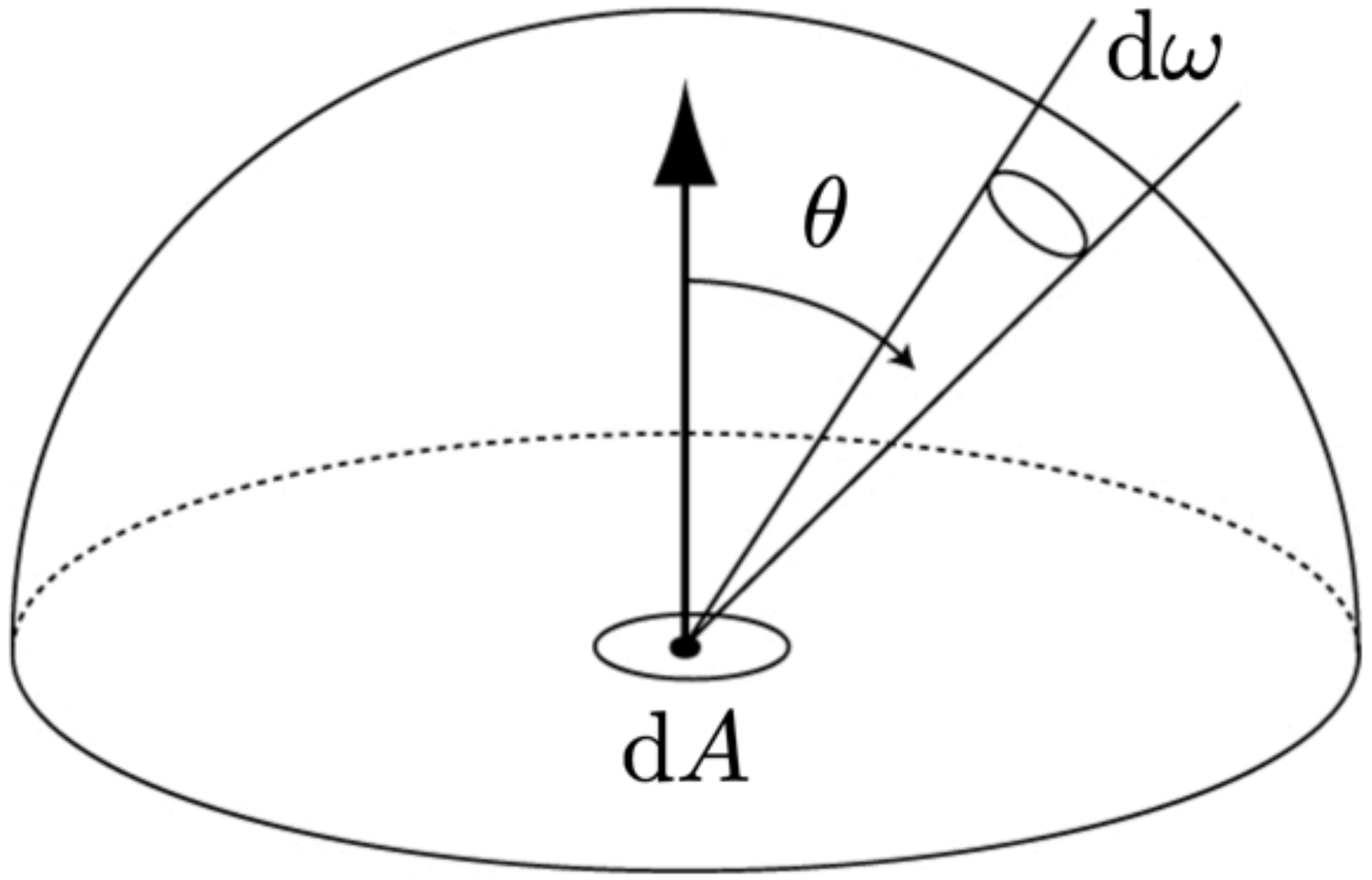
Radiance: light travelling along a ray (flux / area / solid angle)



Radiance is the fundamental radiometric quantity because we can get everything else by integrating it.

Irradiance on a surface:

$$E(\mathbf{p}) = \int_{H^2} L_i(\mathbf{p}, \boldsymbol{\omega}) \cos(\theta)\, d\boldsymbol{\omega}$$

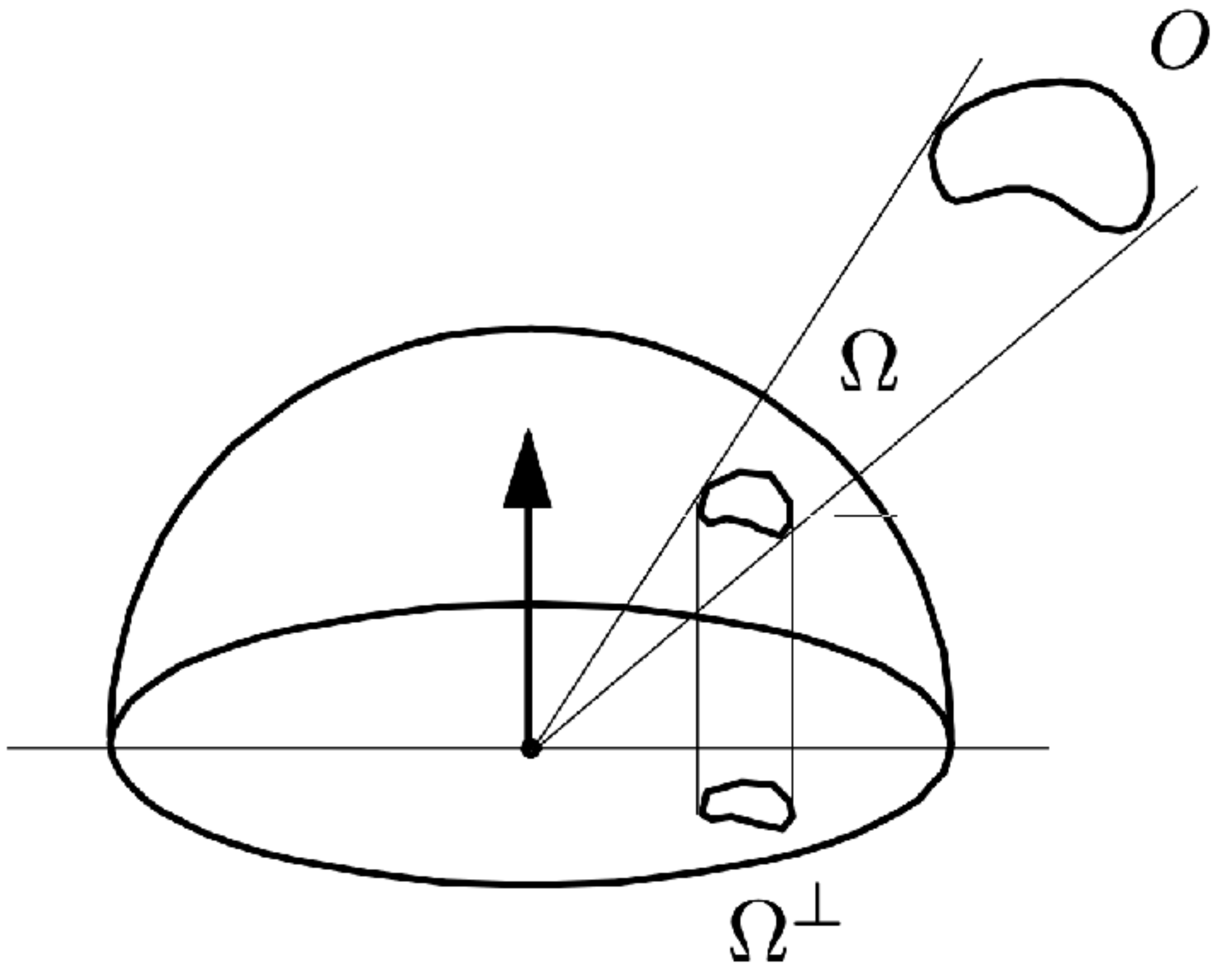


Irradiance due to a uniform area light source emitting radiance L:

$$E(\mathbf{p}) = \int_{H^2} L_i(\mathbf{p}, \boldsymbol{\omega}) \cos(\theta) \, d\boldsymbol{\omega}$$

$$= L \int_{\Omega} \cos(\theta) \, d\boldsymbol{\omega}$$

$$= L\Omega^{\perp}$$



For example, irradiance from an overcast sky with radiance L is just $L\pi$.
(Can you see why?)