Key Elements

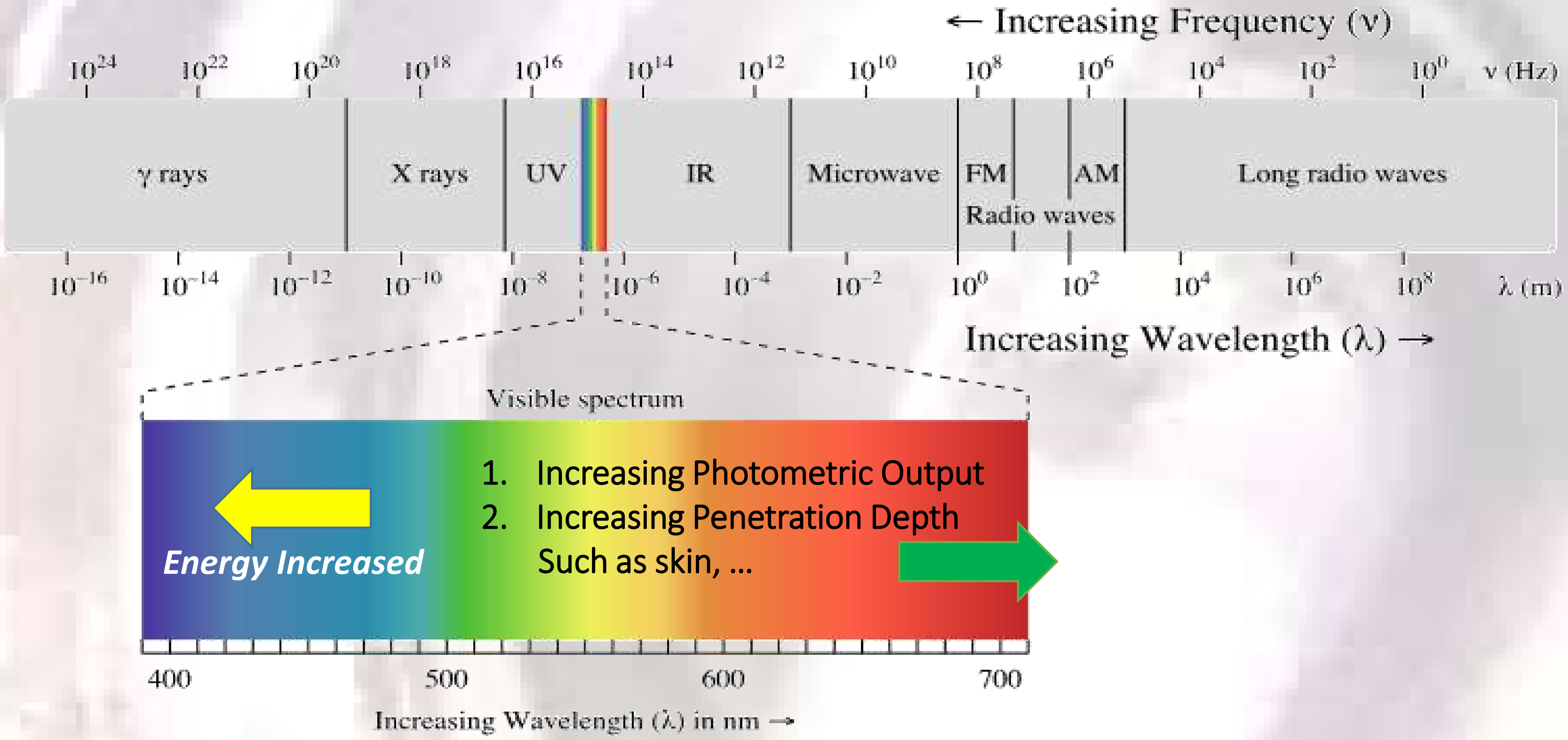
Light Source

Light sources for?

* Manufacturing is not included for this discussion

Light Source works for	Related Optical Methods	Requirement Description
Providing Illumination/ Lighting	Automatic optical Inspection	Quick On/Off (Short Response Time) High Illuminance, Low Thermal Impact, No Speckle would be plus, Size of illuminated Region
Providing Point Light Source/ Collimated Light Source	Optical Switch/ objects detection / Distance Measurement/ Spectrometer	Long life time, Always on, low power consumption, Small deviation angle/ Frequency stabilization/on-off mode
Providing Light Sheet	Object detection, Laser Triangulation	High contrast with background, uniform light intensity, no speckle would be plus
Projecting Repeat Pattern	Structure Light	High contrast with background, uniform light intensity, no speckle would be plus
measuring the dimension change/ surface defect, deformation…/vibration…	Optical interferometers	Robust to environmental disturbance, for both rough and finished surfaces,
Others?		

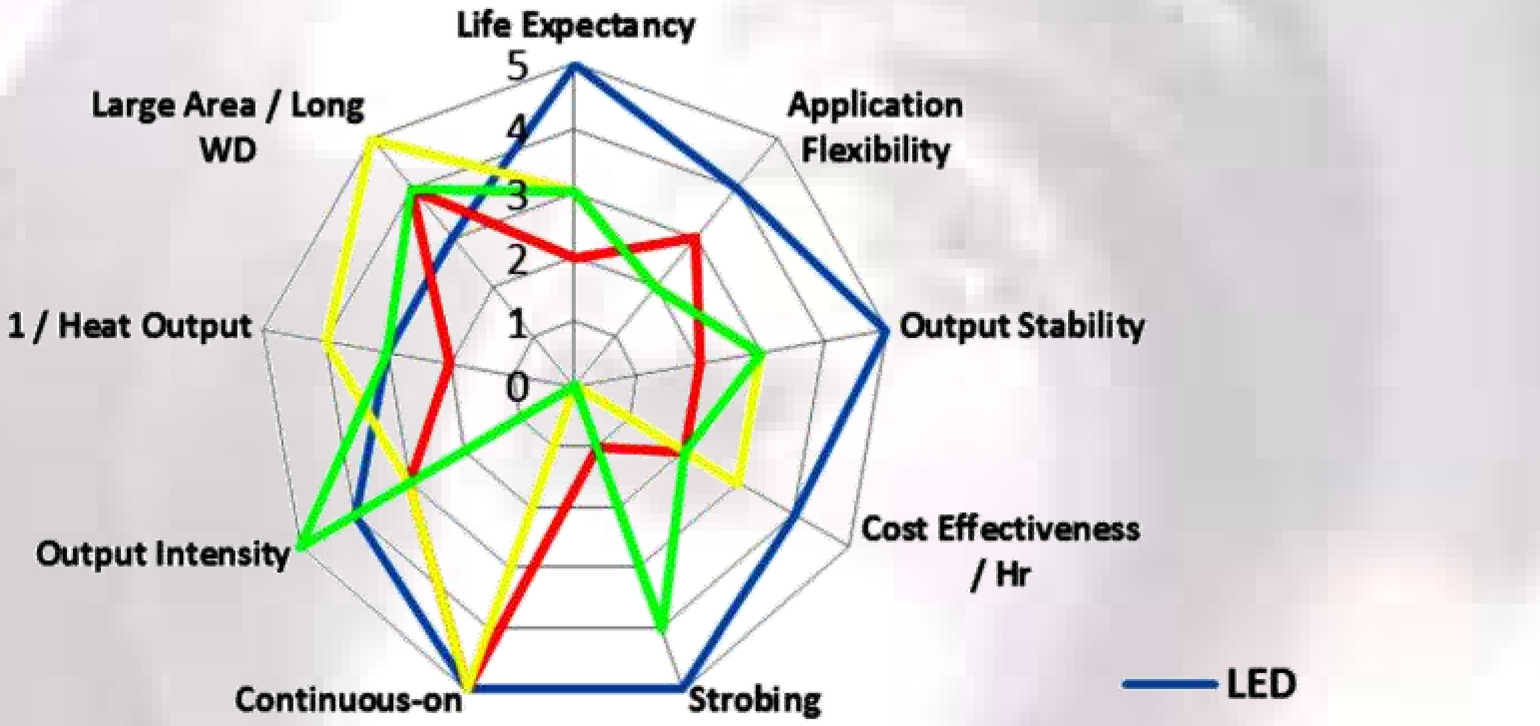
Spectrum



← 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
Energy Increased
1. Increasing Photometric Output
2. Increasing Penetration Depth
Such as skin, …
400 500 600 700
Increasing Wavelength (λ) in nm →

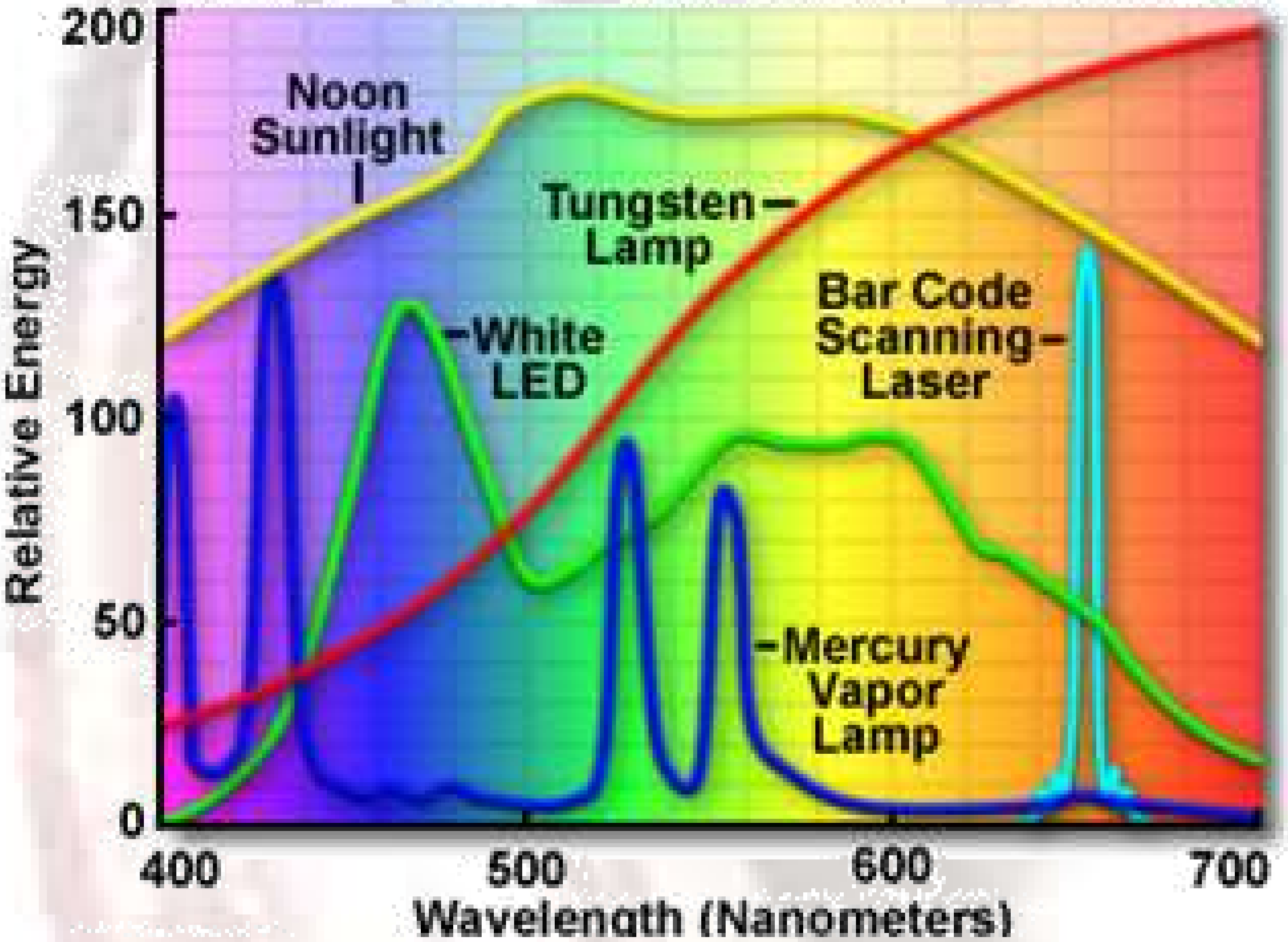
General Light Sources used for Optical Methods

- LED - Light Emitting Diode
- Quartz Halogen – W/ Fiber Optics
- Fluorescent
- Xenon (Strobing)
- Laser



http://www.ni.com/white-paper/6901/en/#toc2

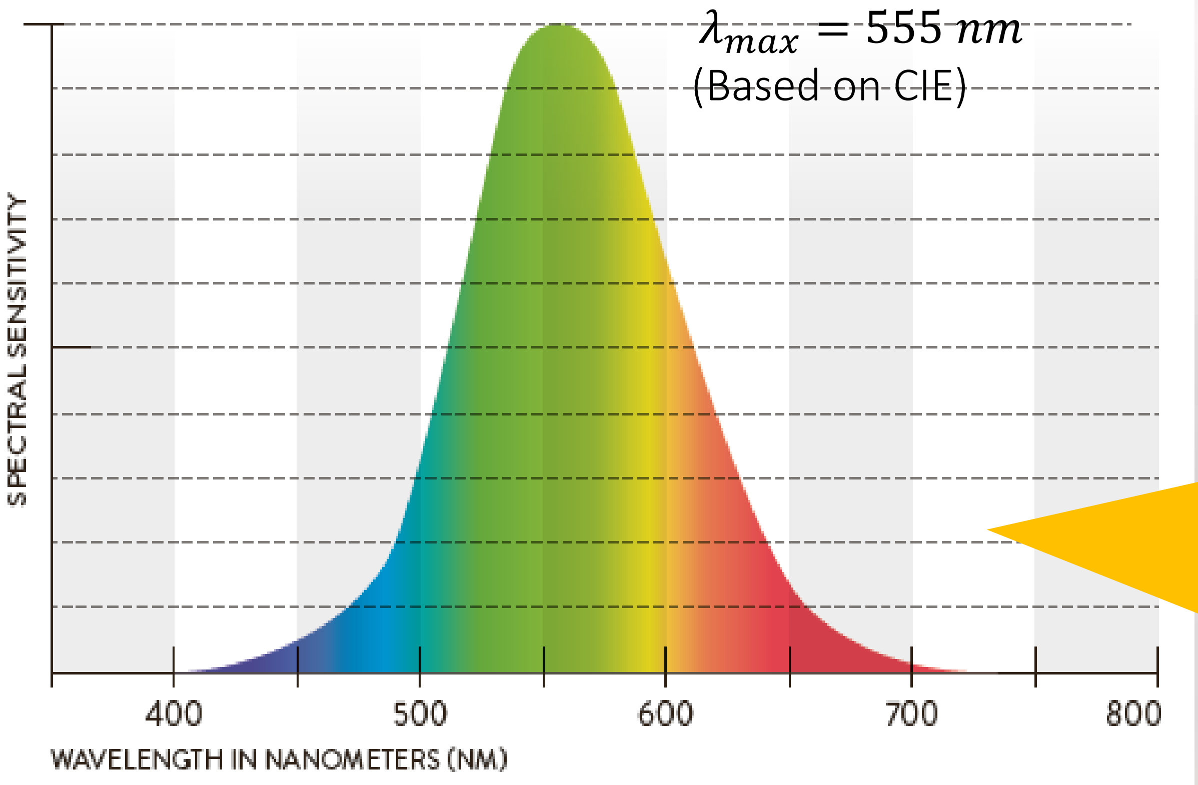
Spectrum of Light Sources

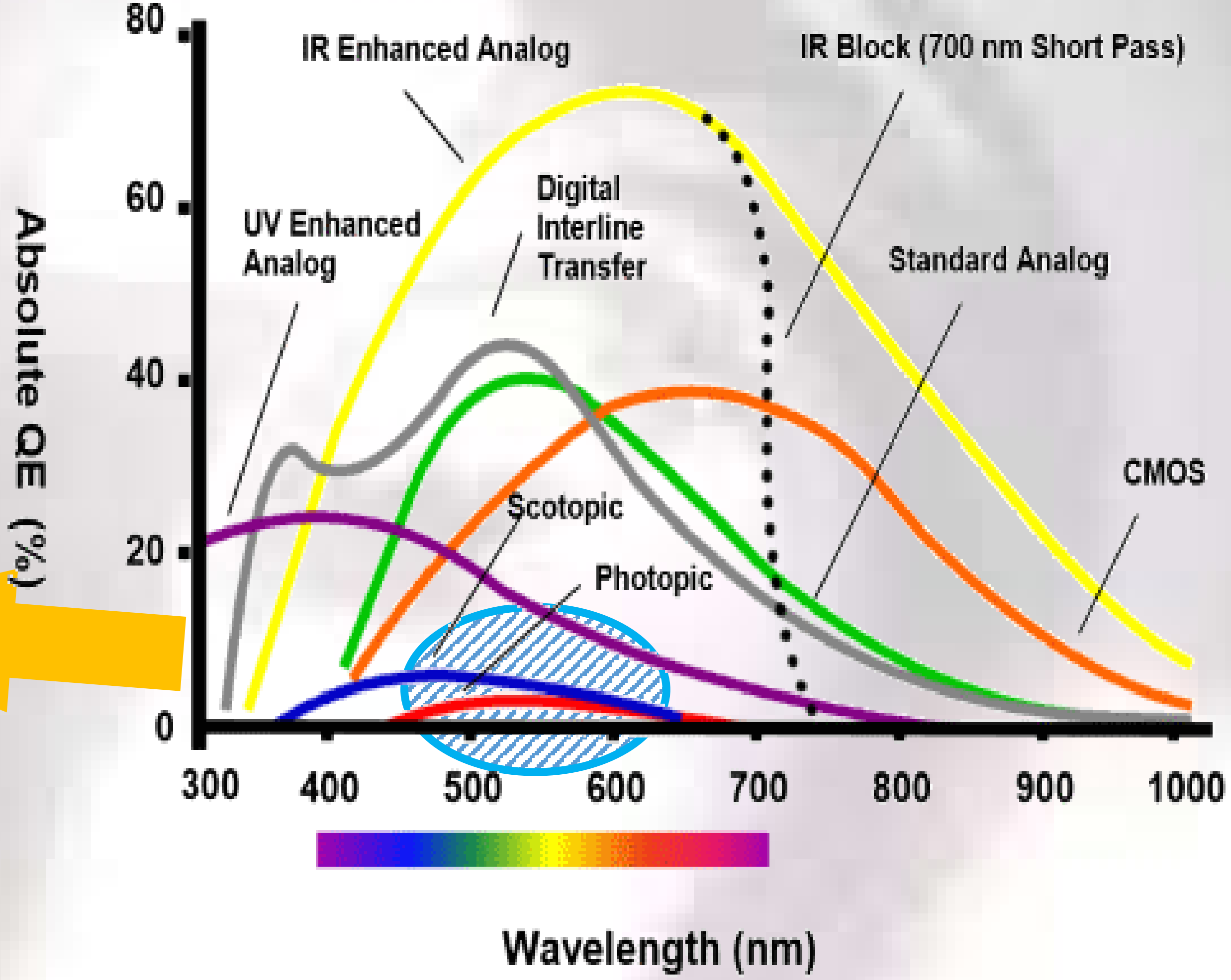


- Event the light source emits continuous light, however, it does not mean the light source can generate equal energy all over the spectrum
- Considering the light intensity all over the wavelength, ensure the light source can emit the necessary light you want

https://micro.magnet.fsu.edu/primer/lightandcolor/lightsourcesintro.html

Spectrum Responsivity





1. Photonik: Technische Anwendungen des Lichts – Infografiken
2. http://www.ni.com/white-paper/6901/en/#toc2

Photopic and Scotopic Vision

$V(\lambda)$ and $V'(\lambda)$ for photopic (明視覺) and scotopic vision (暗視覺) can be fit with a Gaussian function by using a nonlinear regression technique, and the determined equations are [21]:

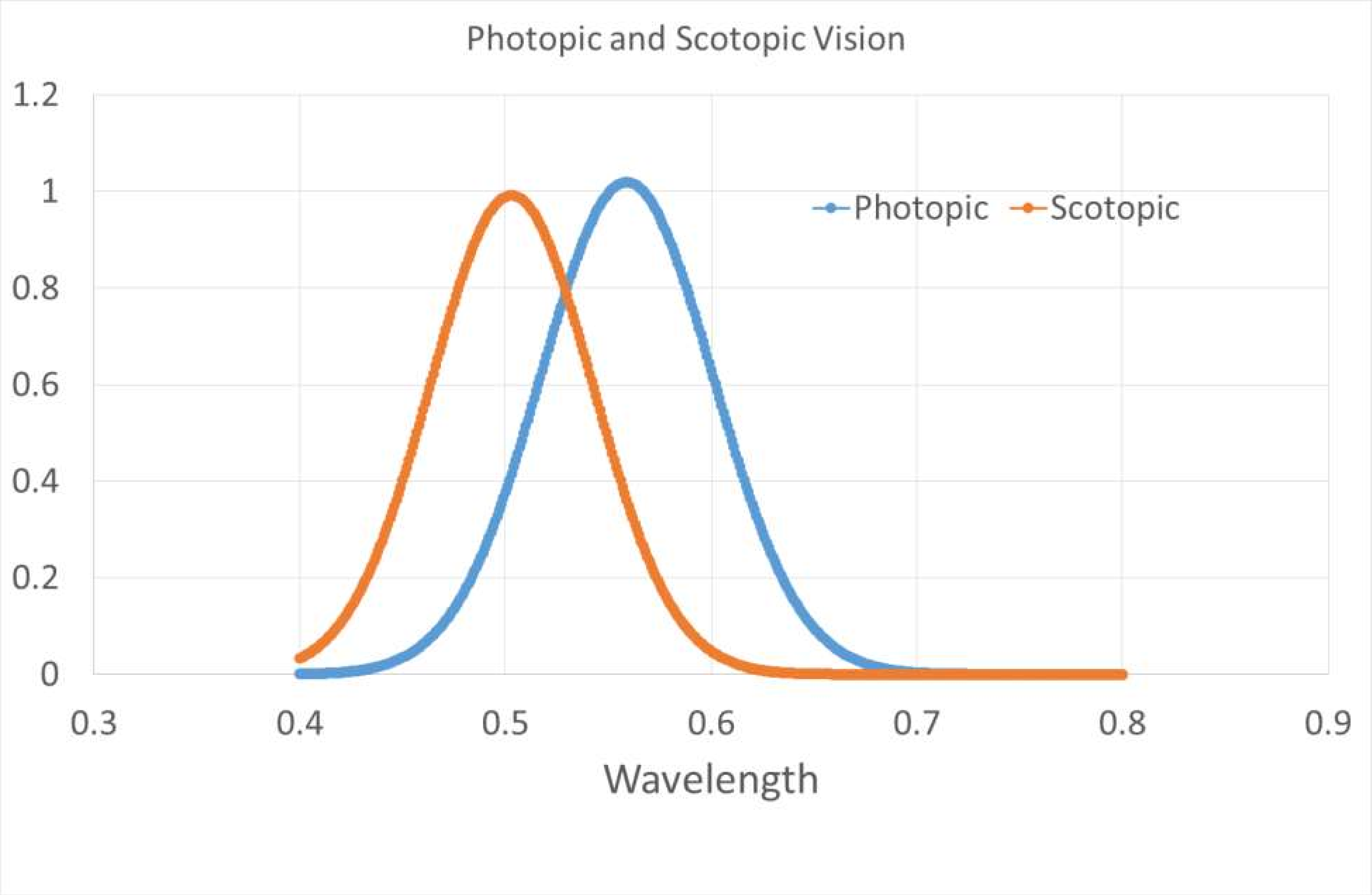
$$V(l) \cong\ 1.019e^{-285.4(\lambda-0.559)^2} \text{ for photopic vision}$$

$$V'(l) \cong\ 0.992e^{-321.9(\lambda-0.503)^2} \text{for scotopic vision}$$

However, the scotopic curve is not fit to real vision as good as the photopic curve.

The fit functions is an approximation that is acceptable for smooth curves but is not appropriate for narrow wavelength sources, like LEDs.

Palmer, J.M., Radiometry and photometry: Units and conversions, Handbook of Optics, 2nd edn., Part III, Ed. M. Bass, McGraw-Hill, New York, 2001.
Yoshizawa, Toru. Handbook of optical metrology: principles and applications. CRC Press, 2015.



Photopic and Scotopic Vision
1.2
1
0.8
0.6
0.4
0.2
0
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Wavelength
Photopic
Scotopic

The things Machine Sees are Different from human beings

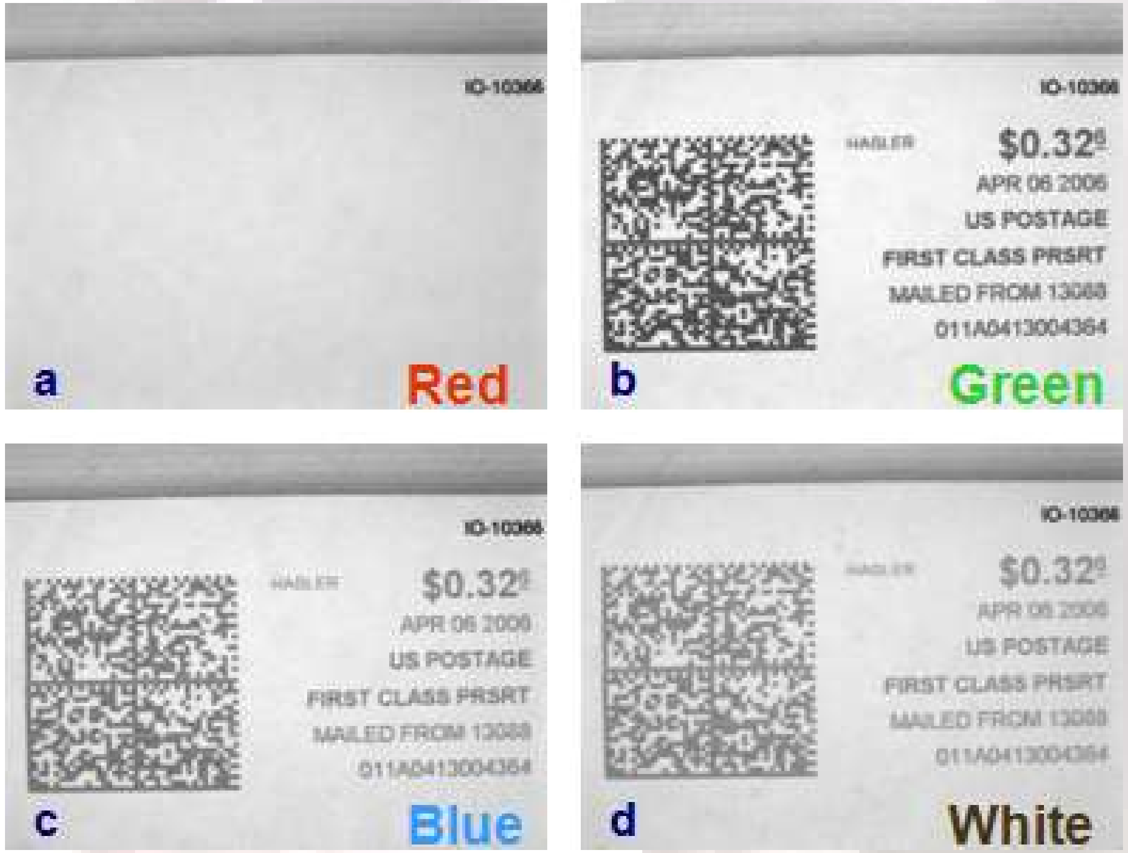
Picture taken by CCD sensor with IR-cut in front of sensor removed

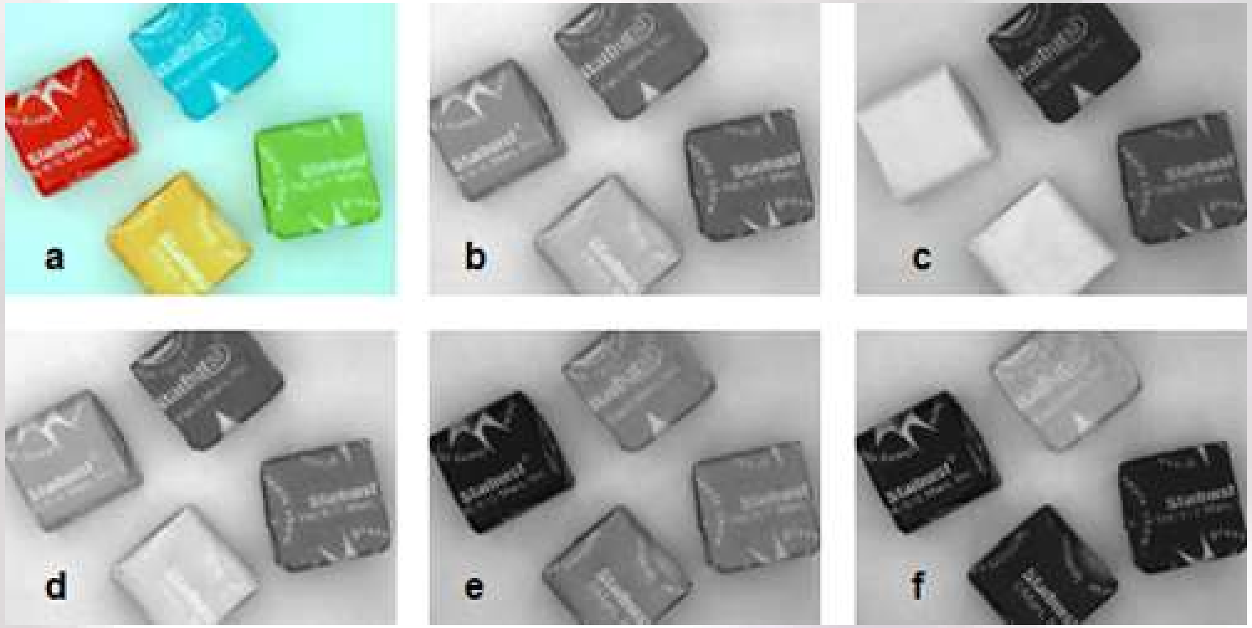
Snow?

Picture source: Instrument Technology Research Center, NARLabs

Picture source: Dr. Te-I Cheng

The things Machine Sees are Different from human beings





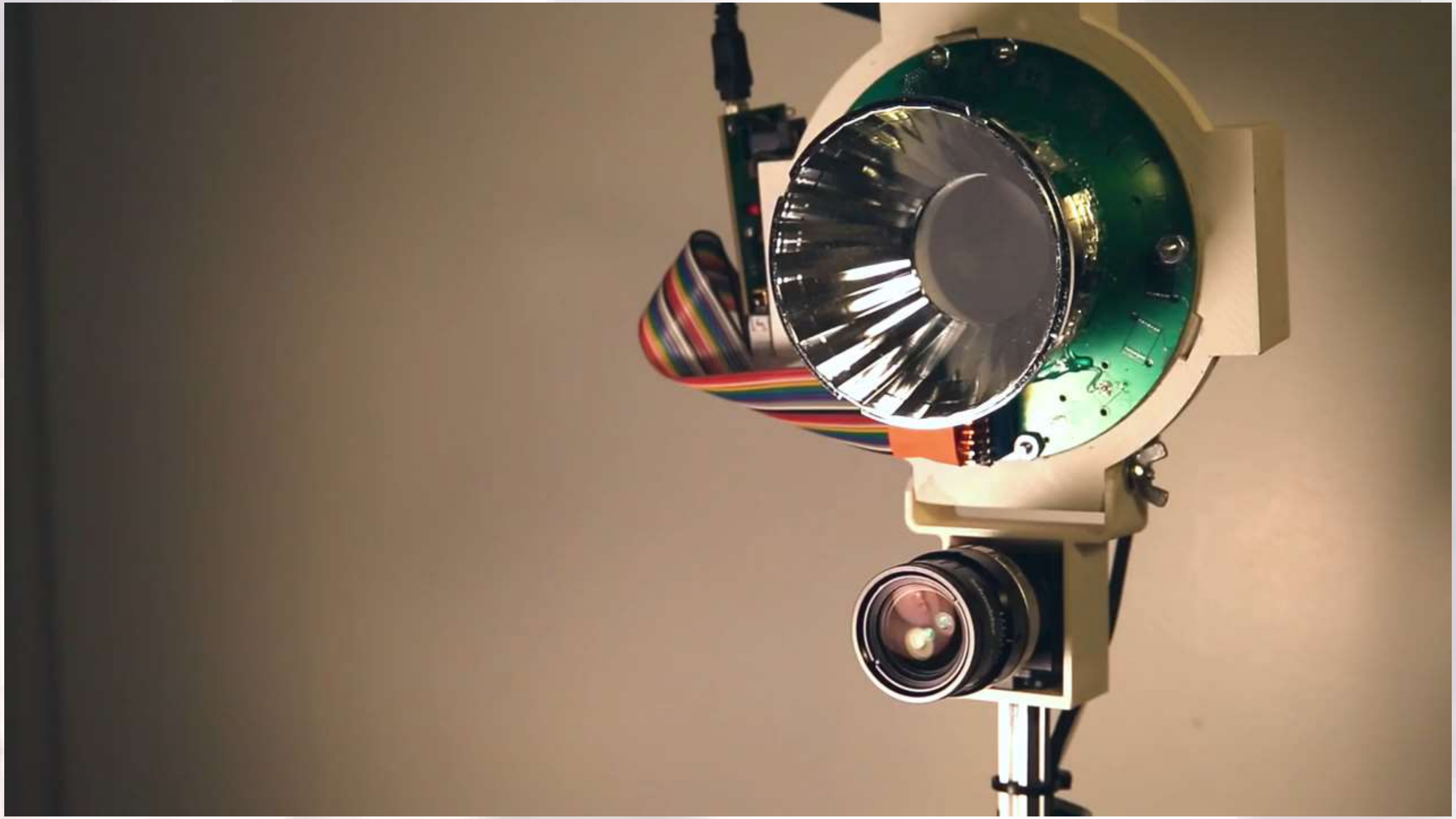
The optical sensors would only dump digitized intensity signal for you. All color images are results of post-processing.

The images might be different due to

1. Light sources—begin of lifetime/ end of lifetime will be different
2. The position of light sources might be moved without awareness, or because of machine vibration
3. The surface conditions are different
4. Ambient light is different
5. Aging of the imagers

..... (here is for your answers)

What you can see is determined by the light sources



https://www.smithsonianmag.com/innovation/camera-sees-what-your-eyes-cant-180957036/

Radiometry vs. Photometry

Parameters	Radiometry	Photometry
Range	3×10^{11} and 3×10^{16} Hz 0.01-1000 μm UV-IR	Visible Range Defined by CIE(International Commission on Illumination) 3.61×10^{14} to ~8.33×10^{14} Hz (360-830 nm)
Definition	Energy of electromagnetic radiation	response of the human eye to light and color
Quantity	Power(J)	Luminous
Wavelength	Independent	Dependent

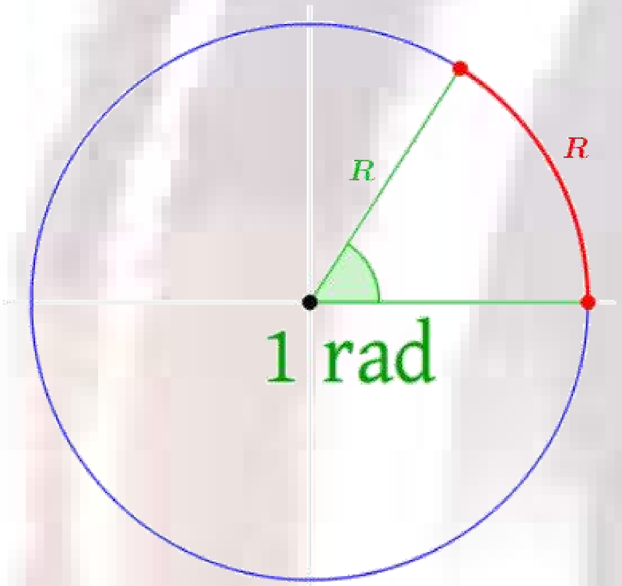
Radiometry vs. Photometry

Parameters	Radiometry		Photometry	
Energy	Radiant energy Q	J (joule)	Luminous energy Q_λ	$lm \cdot s$ or $talbot$
Energy Density	Radiant energy density, $w = dQ/dV$	J/m^3	Luminous Density, $w_\lambda = dQ_\lambda/dV$	$lm \cdot s/m^3$
Power	Radiant flux or radiant power, $\Phi = dQ/dt$	W or J/s	Luminous flux, $\Phi_\lambda = \lambda dQ/dt$	$lm = cd \cdot sr$
Power per area	Radiant exitance $M = d\Phi/dA$ (emitter) or irradiance $E = d\Phi/dA$ (receiver)	W/m^2	Luminous exitance $M_\lambda = dQ_\lambda/dA$ (emitter) or Illuminance $E_\lambda = dQ_\lambda/dA$ (receiver)	Lux or lm/m^2
Power per area per *solid angle*	Radiance $\mathrm{L} = \frac{d\Phi}{d\Omega \cdot dA \cdot cos\alpha} = \frac{dI}{da \cdot cos\alpha}$	$W/sr \cdot m^2$	Luminance $L_\lambda = \frac{dI_\lambda}{da \cdot cos\alpha}$	cd/m^2 $lm/sr \cdot m^2$; nit
Intensity	Radiant intensity $I = dQ/d\Omega$	W/sr	Luminous intensity $I_\lambda = dQ_\lambda/d\Omega$	$Candela(cd)$ or lm/sr

1 lumen= "a monochromatic light source emitting an optical power of 1/683 W at 555nm, for lighting industry"

$L(x, \omega) = \int p(x, \omega, \lambda) \times (h \times c/\lambda)\, d\lambda$

Solid Angle

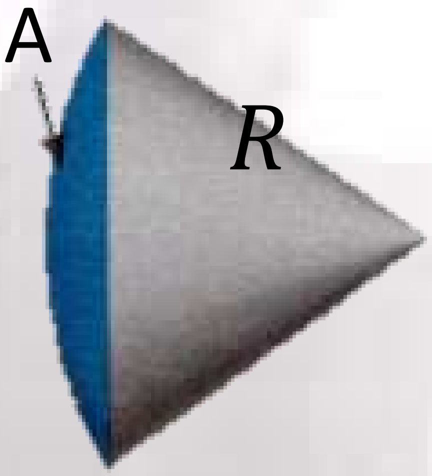


Radius for 2D

$$radius = S/R$$

$$1\ rad \equiv S = R$$

$$1\ sr \equiv A = R^2$$



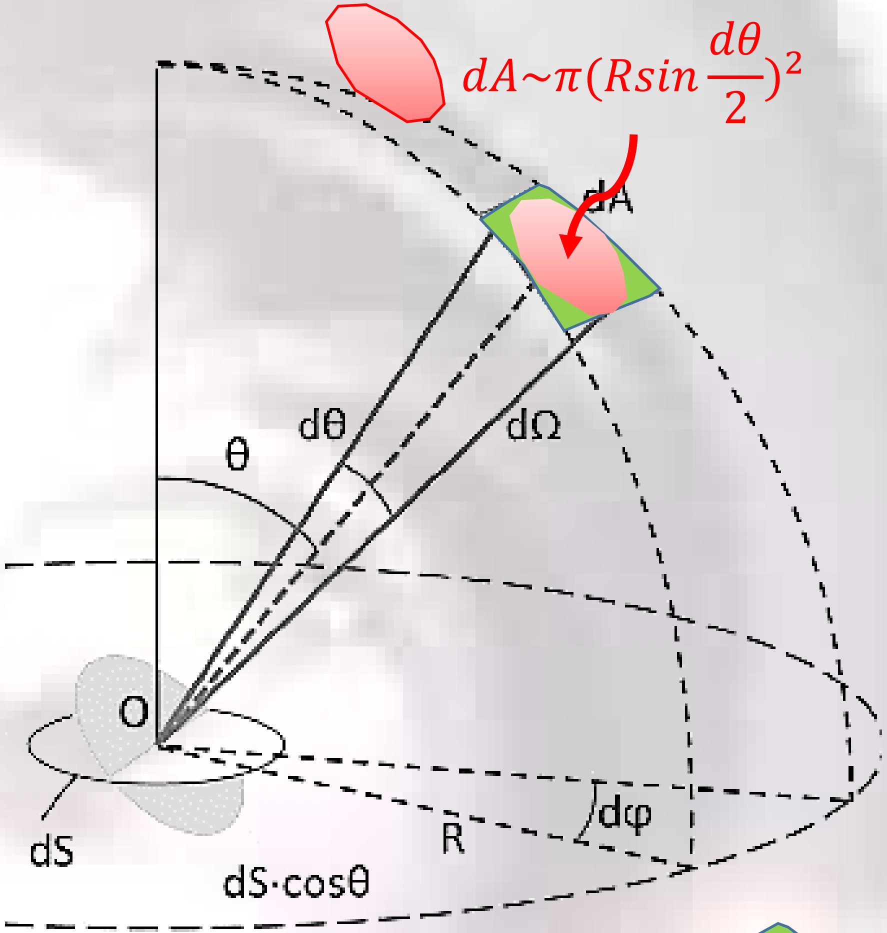
Solid Angle Ω for 3D

$sr = \frac{A}{R^2} \rightarrow$ 1 sr

steradian (***sr**, radiant squared)*

is the SI unit for measuring

solid angles

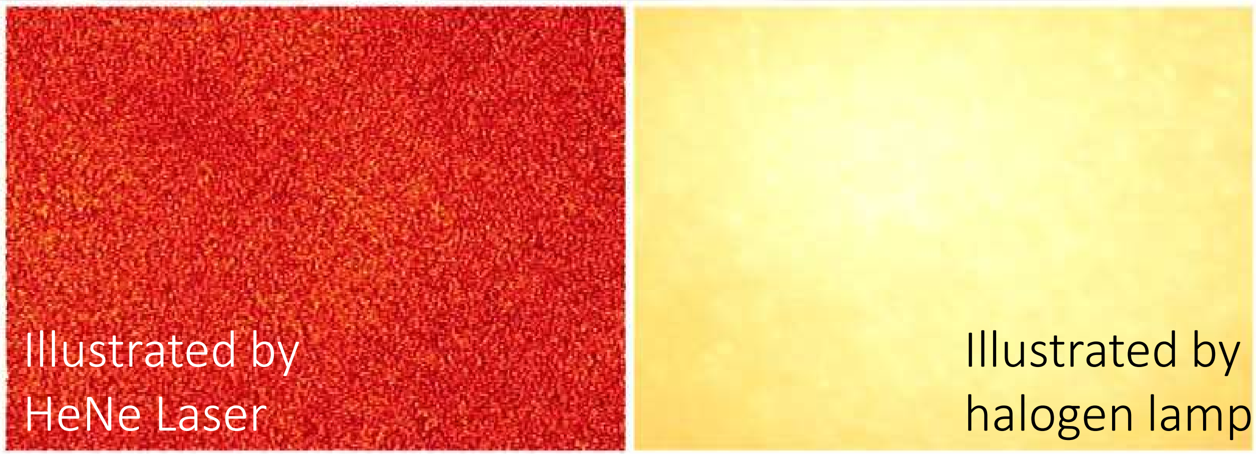


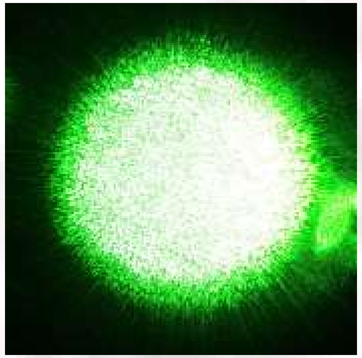
$$d\Omega = \frac{dA}{R^2} = \frac{Rsin\theta d\theta R d\varphi}{R^2}$$

$$\rightarrow d\Omega = sin\theta d\theta d\varphi$$

Speckle Noises

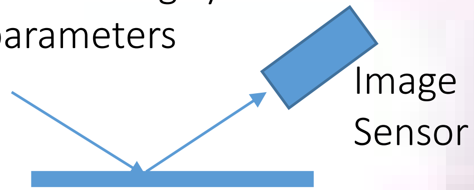
Considering as Side effect of coherent light sources, such as Laser





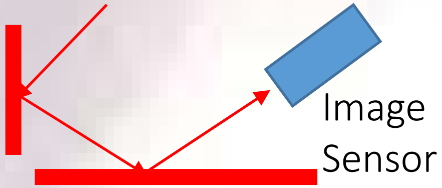
Subjective speckles

the detailed structure of the speckle pattern depends on the viewing system parameters



Objective speckles

The pattern is the same regardless of how it is imaged, just as if it were a painted pattern.



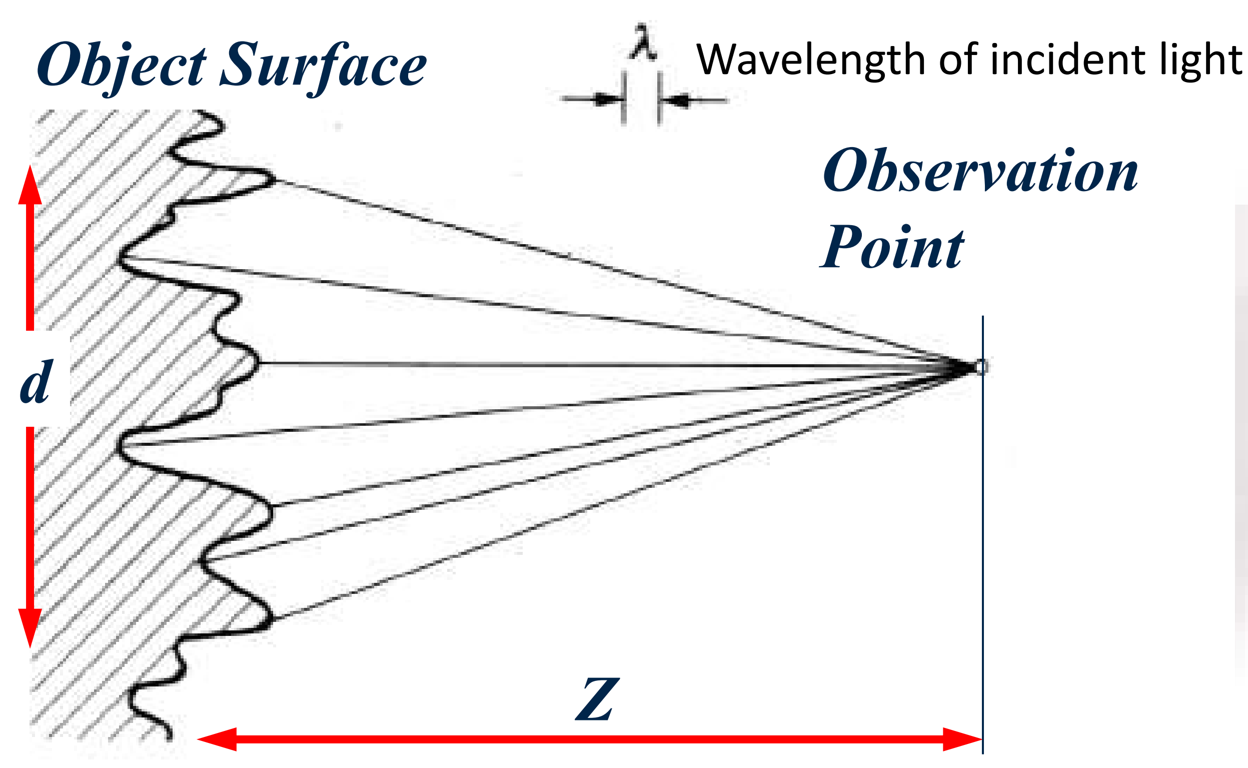
Subjective speckles : rough surface which is illuminated by a coherent light

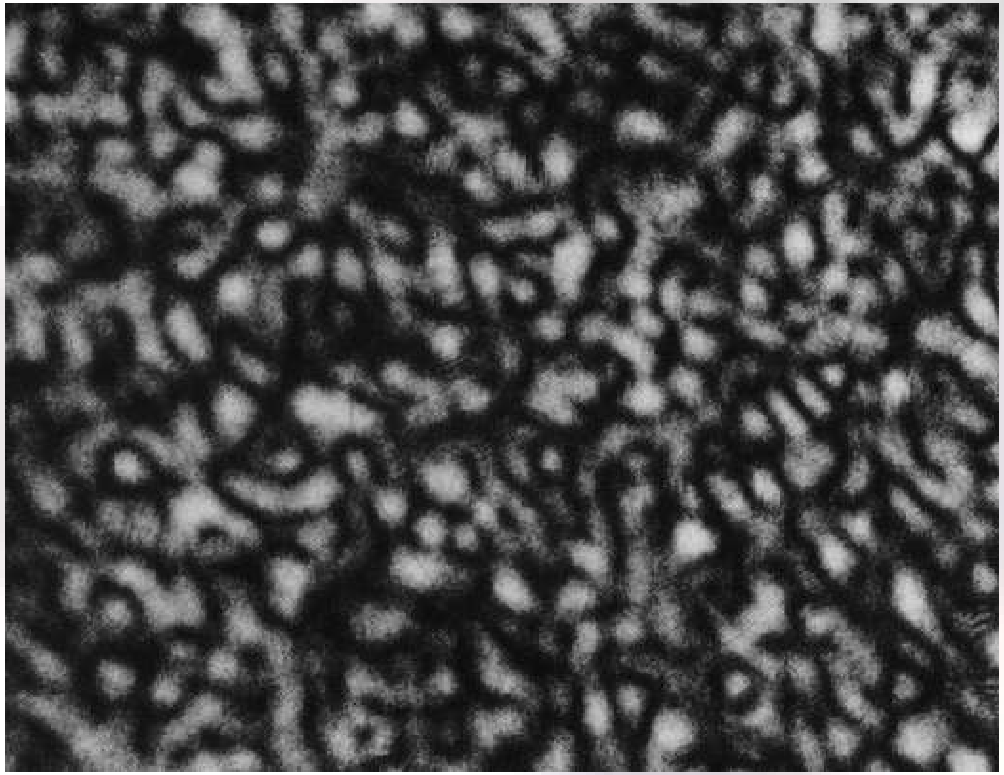
Objective speckles: laser light which has been scattered off a rough surface falls on another surface

http://www.seos-project.eu/modules/laser-rs/laser-rs-c02-p01.html

https://en.wikipedia.org/wiki/Speckle_pattern

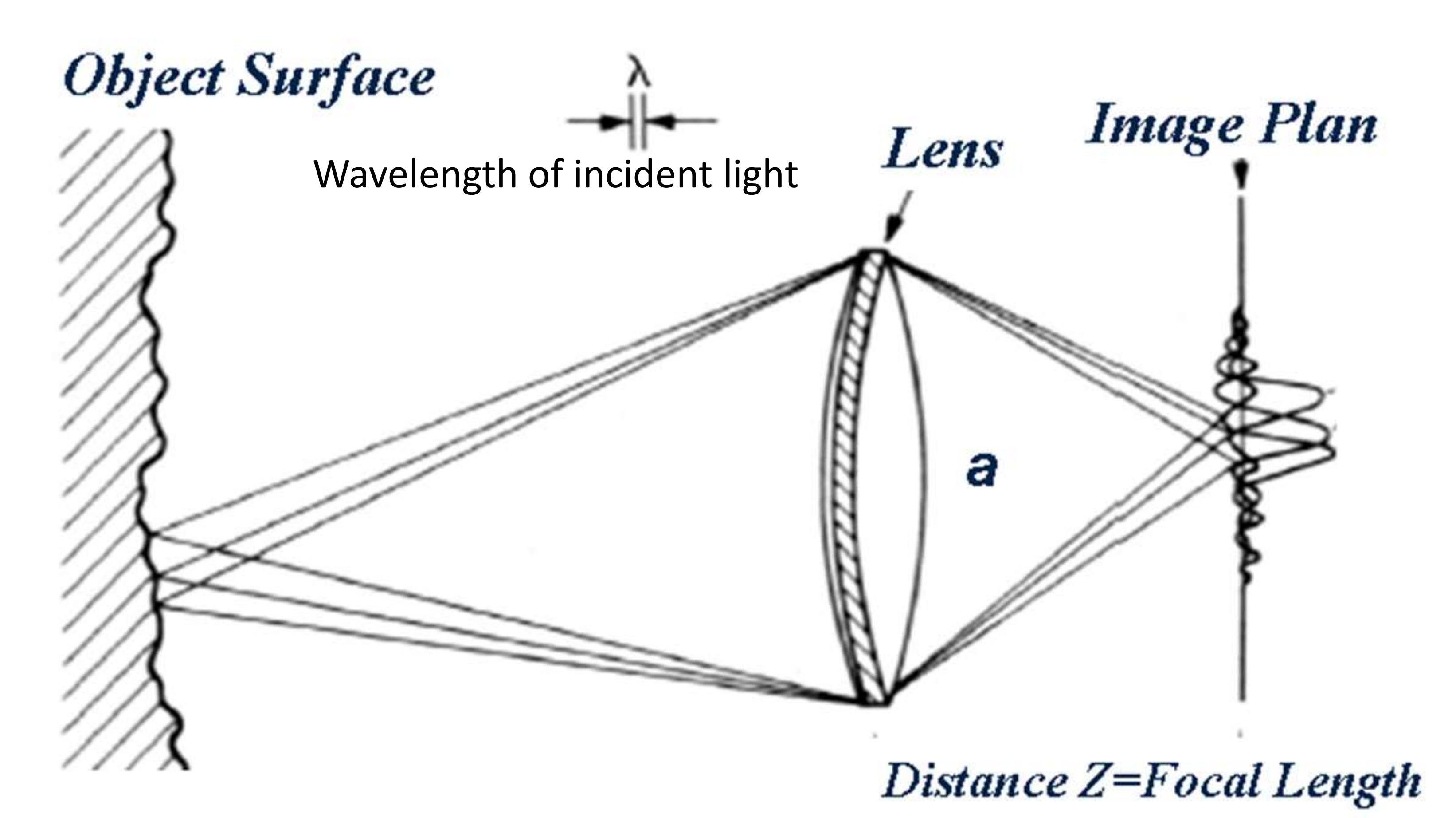
Speckle Diameter—Objective Speckle





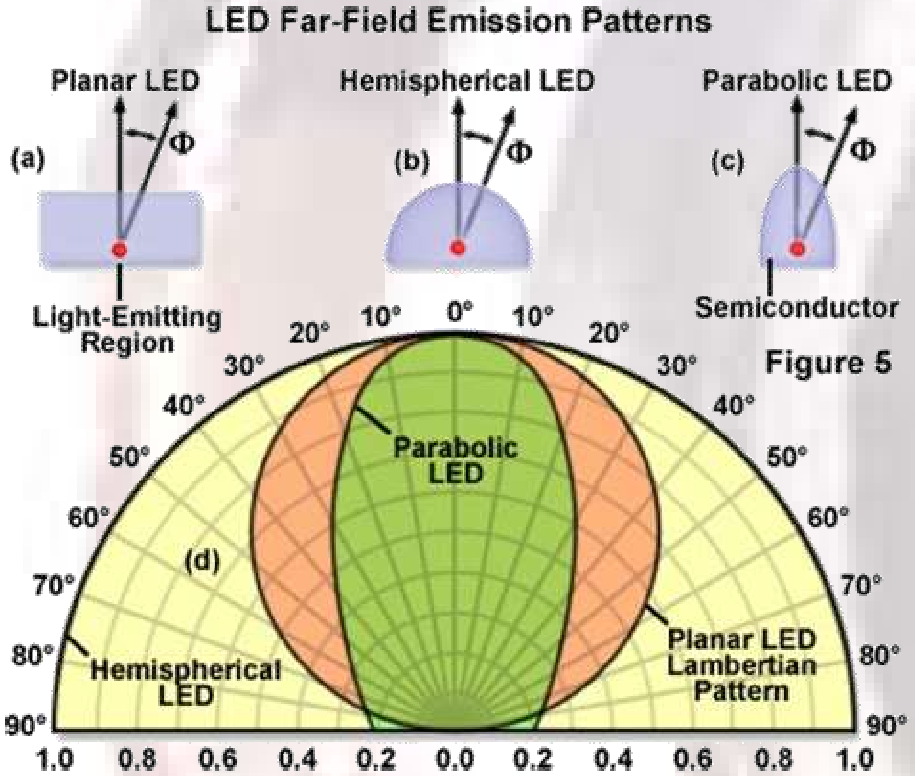
$$Mean\ Speckle\ Diameter, \emptyset \sim \frac{1.22\lambda Z}{d}$$

Speckle Diameter—Subjective Speckle

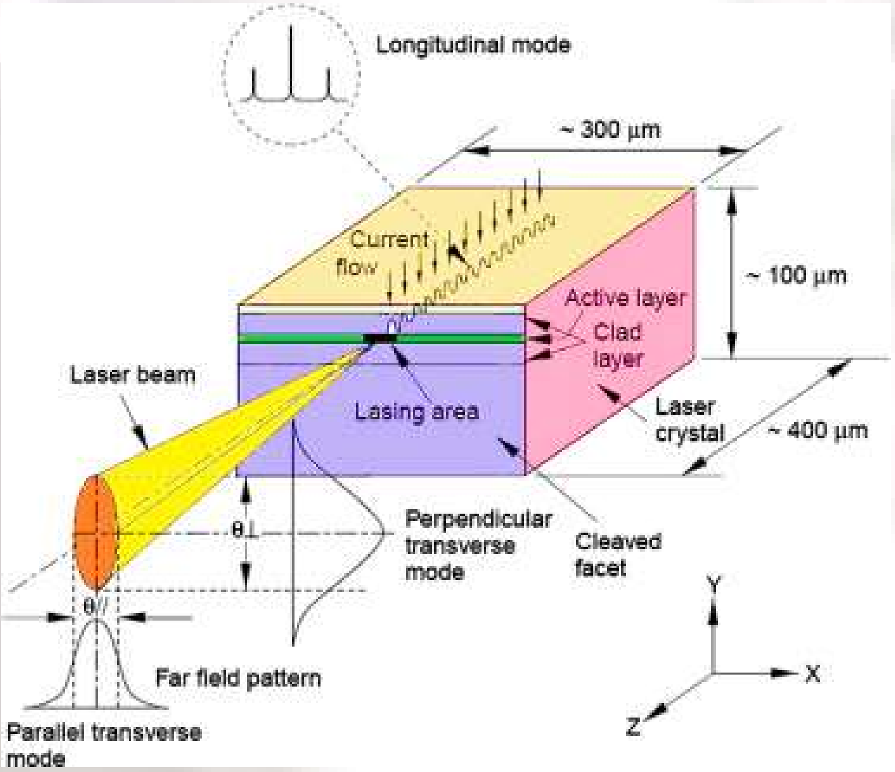


$$Mean\ Speckle\ Diameter, \phi_{subjective} \sim 1.22 \times \lambda \times f_{\#} \times (1 + M)$$

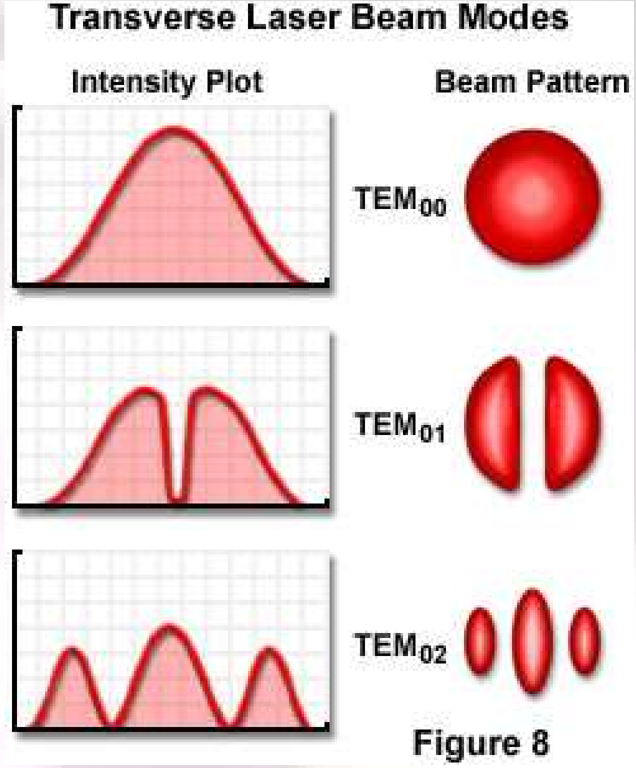
Light Pattern-energy spatial distribution/ propagation direction



LED

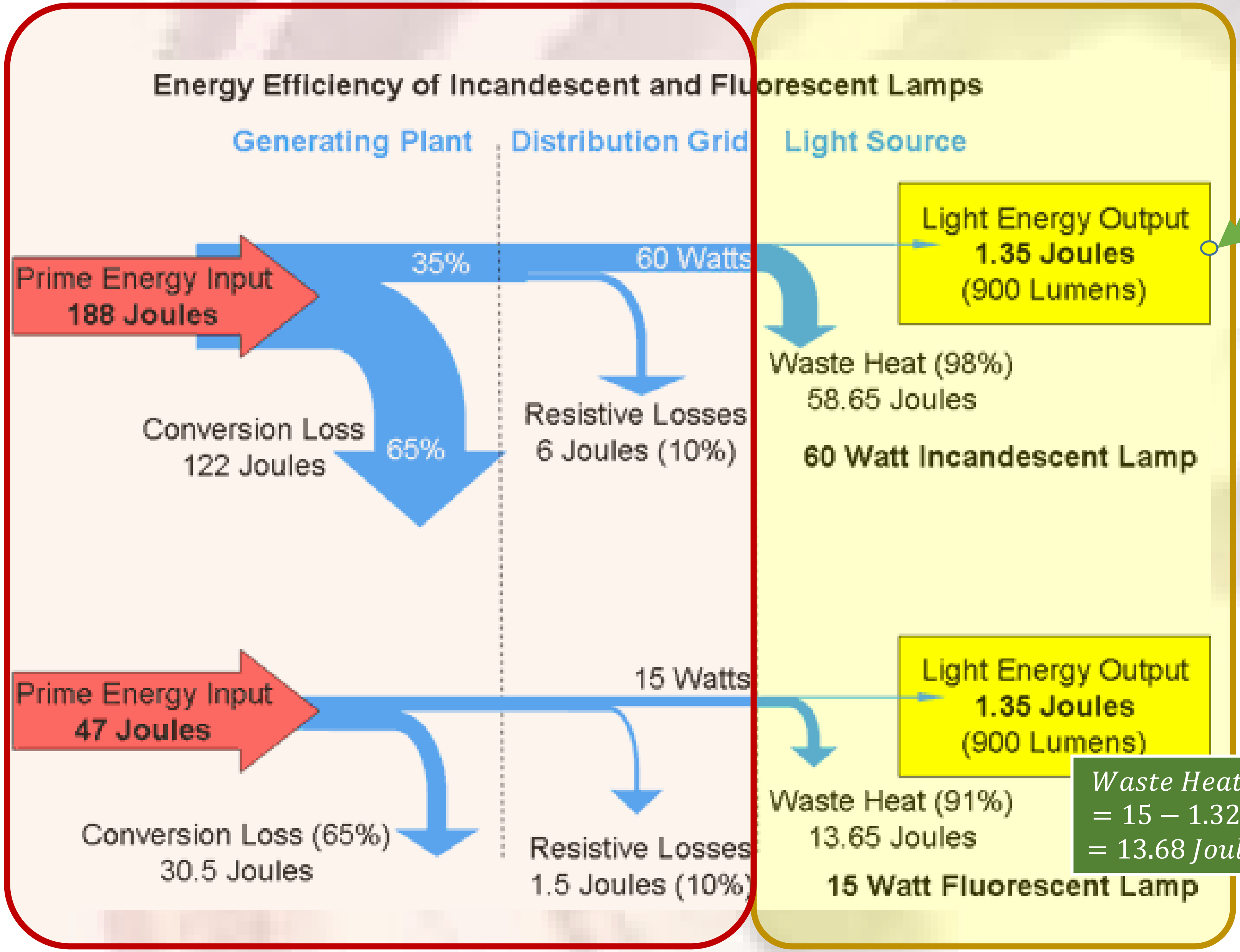


Solid State Laser



Gas Laser

Heat of Light Sources



$$\begin{aligned} Waste\ Heat &= 15 - 1.32 \\ &= 13.68\ Joules \end{aligned}$$

$$1\ lm = \frac{1}{683} W \ @\ 555nm$$

$$900\ lm = 1.32\ Joules$$

$$\begin{aligned} Waste\ Heat &= 60 - 1.32 \\ &= 58.68\ Joules \end{aligned}$$

To reduce generated waste heat
→ To reduce the input power

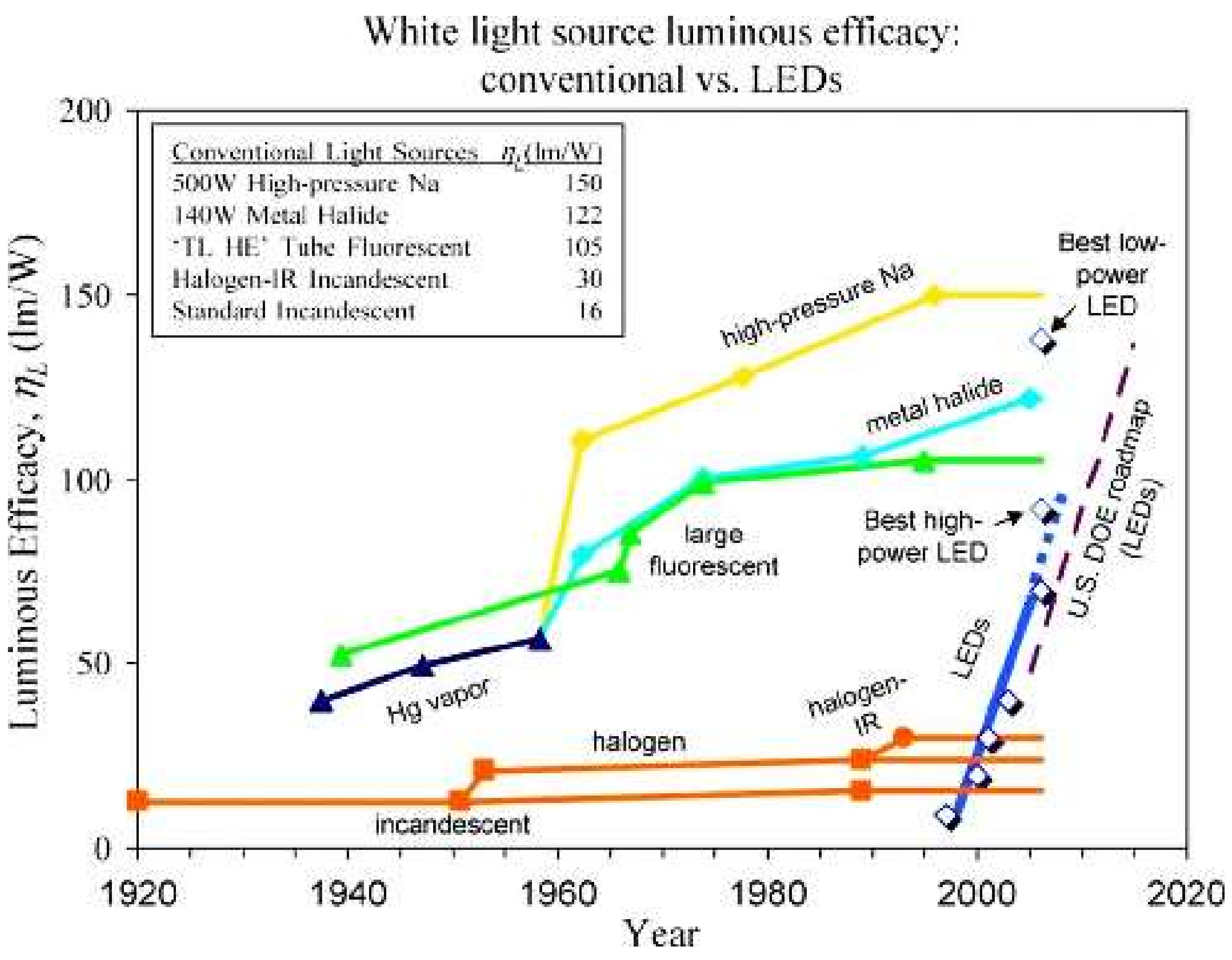
To Increase *lm/input power* ratio
→ To increase the $luminous\ efficacy$

$$\equiv \frac{\int \Phi_\lambda K_m \mathrm{V}(\lambda) d\lambda}{\Phi}$$

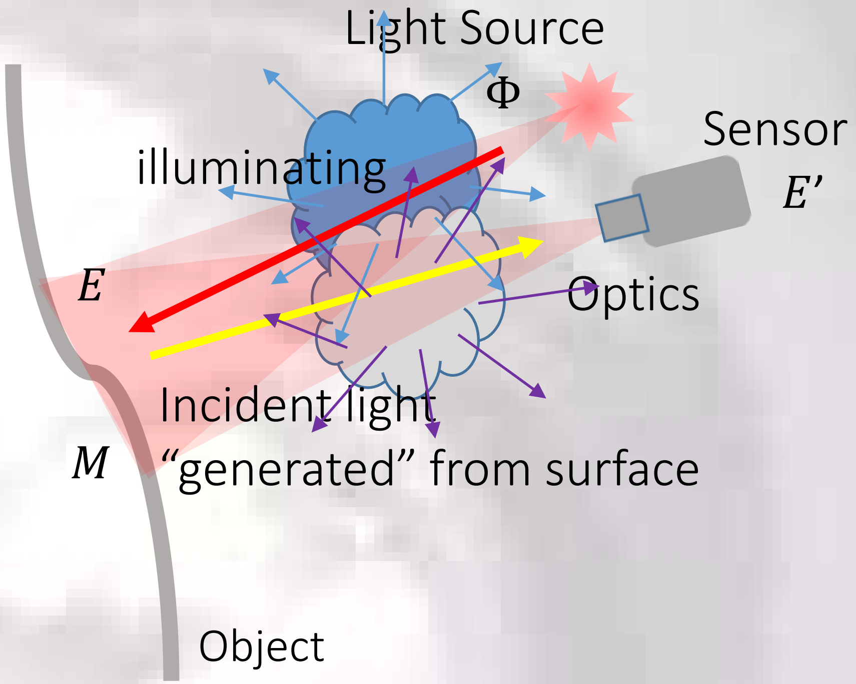
Note: this definition is for lighting defined by CIE

$V(\lambda) \cong 1.019 e^{-285.4(\lambda - 0.559)^2}$ for photopic vision

General Model for Estimating the Power Requirement of the Light Sources



Krames, Michael R., et al. "Status and future of high-power light-emitting diodes for solid-state lighting." Journal of display technology 3.2 (2007): 160-175.



General Model for Considering how much Radiant exitance Needed to perform an optical measurement

$$E = \Phi \otimes f_{medium}(\Phi, \lambda, \dots)$$
$$M = E \otimes f_{interface}(E, \lambda, \dots)$$
$$E' = M \otimes f^*_{medium}(M, \lambda, \dots) \otimes QE(\lambda)$$
$$V = E' \otimes C(E', Current, \dots)$$