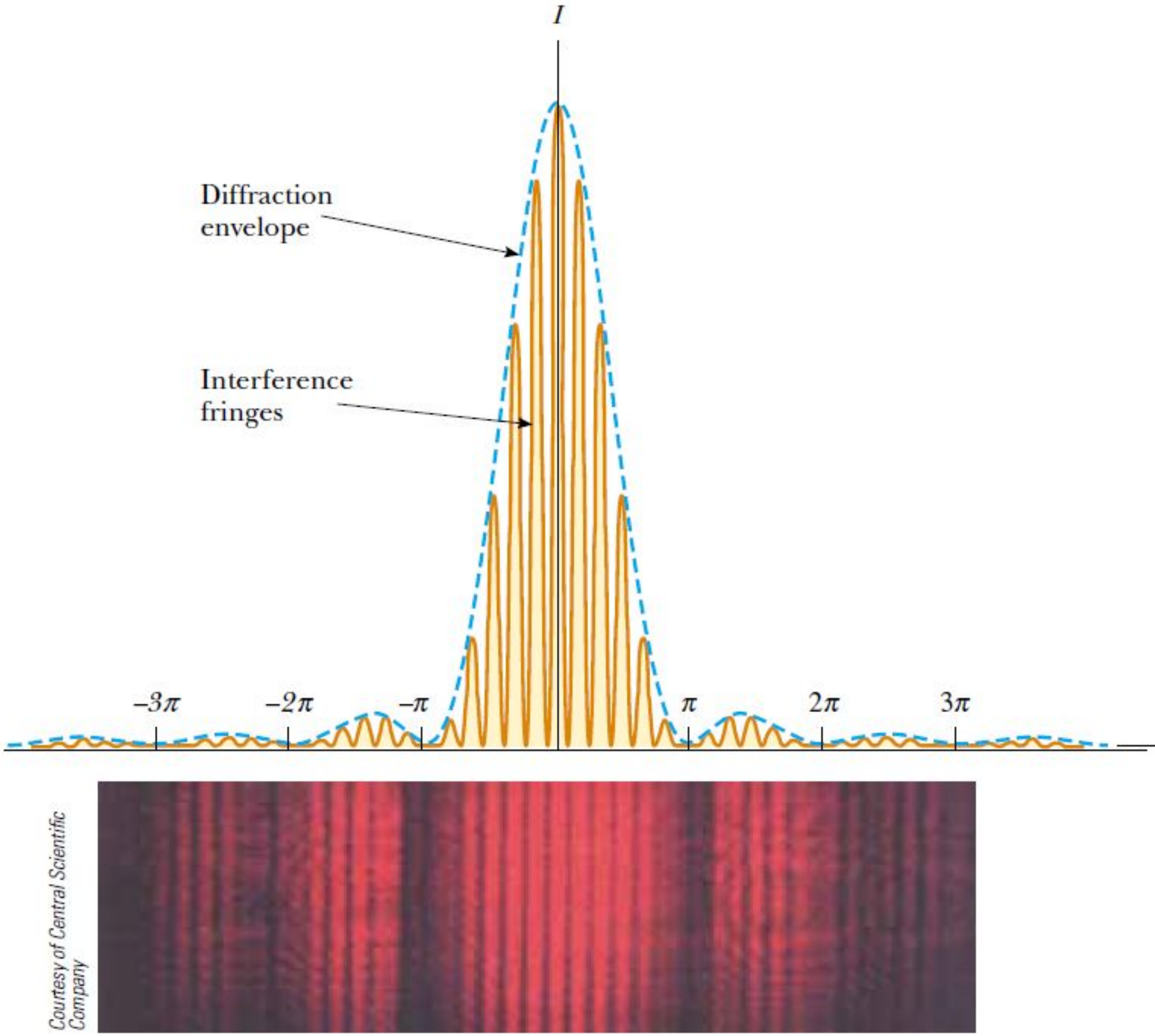
## Quick Quiz 1

If a classroom door is open slightly, you can hear sounds coming from the hallway. Yet you cannot see what is happening in the hallway. Why is there this difference? (a) Light waves do not diffract through the single slit of the open doorway. (b) Sound waves can pass through the walls, but light waves cannot. (c) The open door is a small slit for sound waves, but a large slit for light waves. (d) The open door is a large slit for sound waves, but a small slit for light waves.

# Quick Quiz 2

Using Figure as a starting point, make a sketch of the combined diffraction and interference pattern for 650-nm light waves striking two 3.0 µm slits located 9.0 µm apart.



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Cat's eyes have pupils that can be modeled as vertical slits. At night, would cats be more successful in resolving

(a) headlights on a distant car, or

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## Quick Quiz 4

If laser light is reflected from a phonograph record or a compact disc, a diffraction pattern appears. This is due to the fact that both devices contain parallel tracks of information that act as a reflection diffraction grating. Which device, (a) record or (b) compact disc, results in diffraction maxima that are farther apart in angle?

# Course of lectures «Contemporary Physics: Part2»

*Lecture №5*

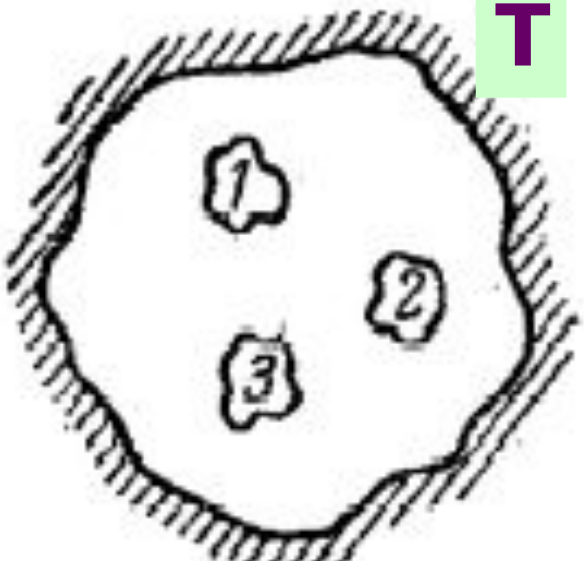
**Thermal radiation. Emissivity and absorptivity of the matter and their ratios. Blackbody radiation. Stefan–Boltzmann law. Derivation of the Planck Distribution Law. Wien's displacement law. The Rayleigh–Jeans law.**

# Kirchhoff's law

T

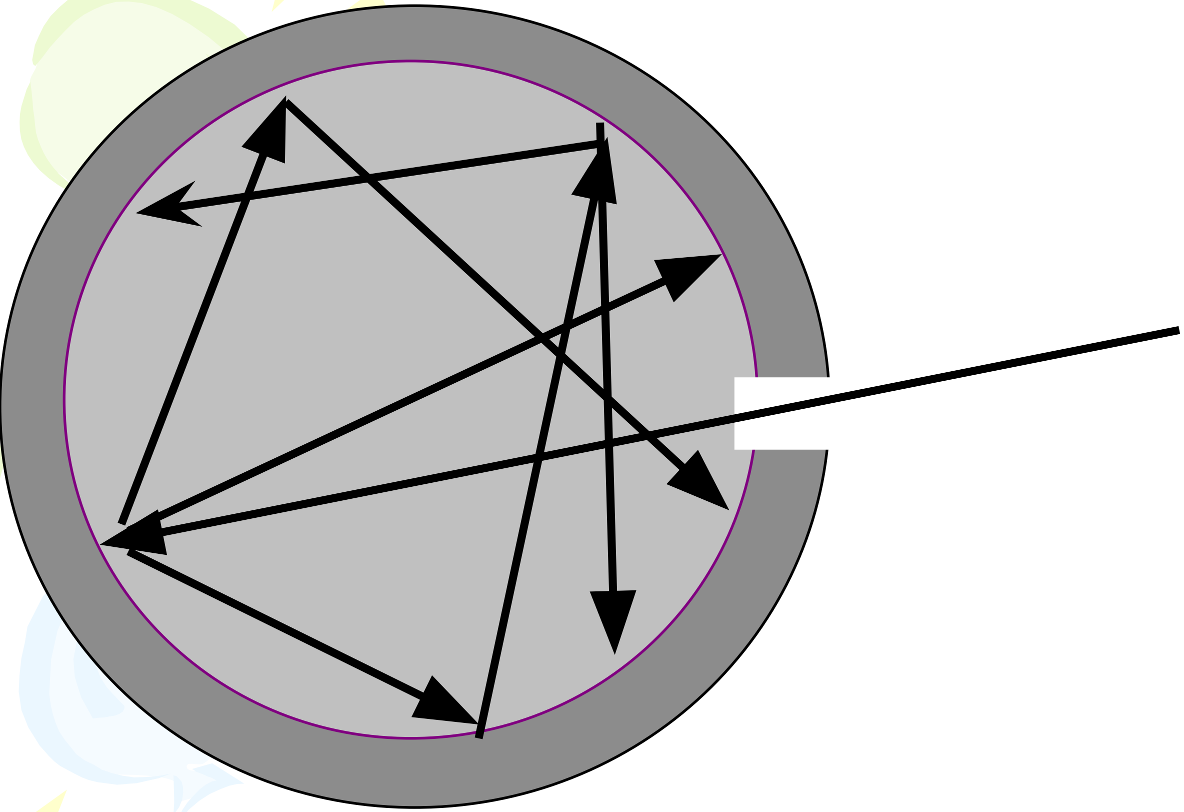
## Thermal radiation

$$\frac{E_{1(\nu,T)}}{A_{1(\nu,T)}} = \frac{E_{2(\nu,T)}}{A_{2(\nu,T)}} = \frac{E_{3(\nu,T)}}{A_{3(\nu,T)}} = \ldots \quad (1)$$




$$\frac{E(\nu,T)}{A(\nu,T)} = \frac{\varepsilon(\nu,T)}{1} = \varepsilon(\nu,T) \quad (2)$$

**Ratio of the emissivity of the body to its absorptivity is the same for all bodies and universal function of frequency and temperature of the body, equals to the emissivity of the black body $\varepsilon(\nu,T)$.**



Good model of this body is the small gap in closed cavity. Light, falling through the gap in the cavity after numerical reflections, will be practically almost absorbed by the walls and the gap outside will seem absolutely black.

If the cavity is heated up to some temperature T and inside the thermal equilibrium is established, then the own radiation of the cavity will be the radiation of the black body.

In 1879 Stephen on the base of the analysis of the experimental data found that the integral radiance of the black body is proportional to the 4th degree of absolute temperature T:

$$\varepsilon_{(T)} = \int_0^\infty \varepsilon_{(\nu,T)} d\nu = \sigma T^4$$

$\varepsilon_{(\nu,T)}$ ; $\varepsilon_{(\lambda,T)}$

Spectral density of radiation of the black body

In 1884 Boltzmann theoretically show this dependence from thermodynamical consideration. This law is the law of the Stephen- Boltzmann. Numerical method of the constant σ is

$$\sigma = 5{,}671 \cdot 10^{-8}\ \text{Вт} / (\text{м}^2 \cdot \text{K}^4).$$

**Location of the maximum of spectral density of radiation of the black body on the axis of the wavelength is reversely proportional to the body temperature.**

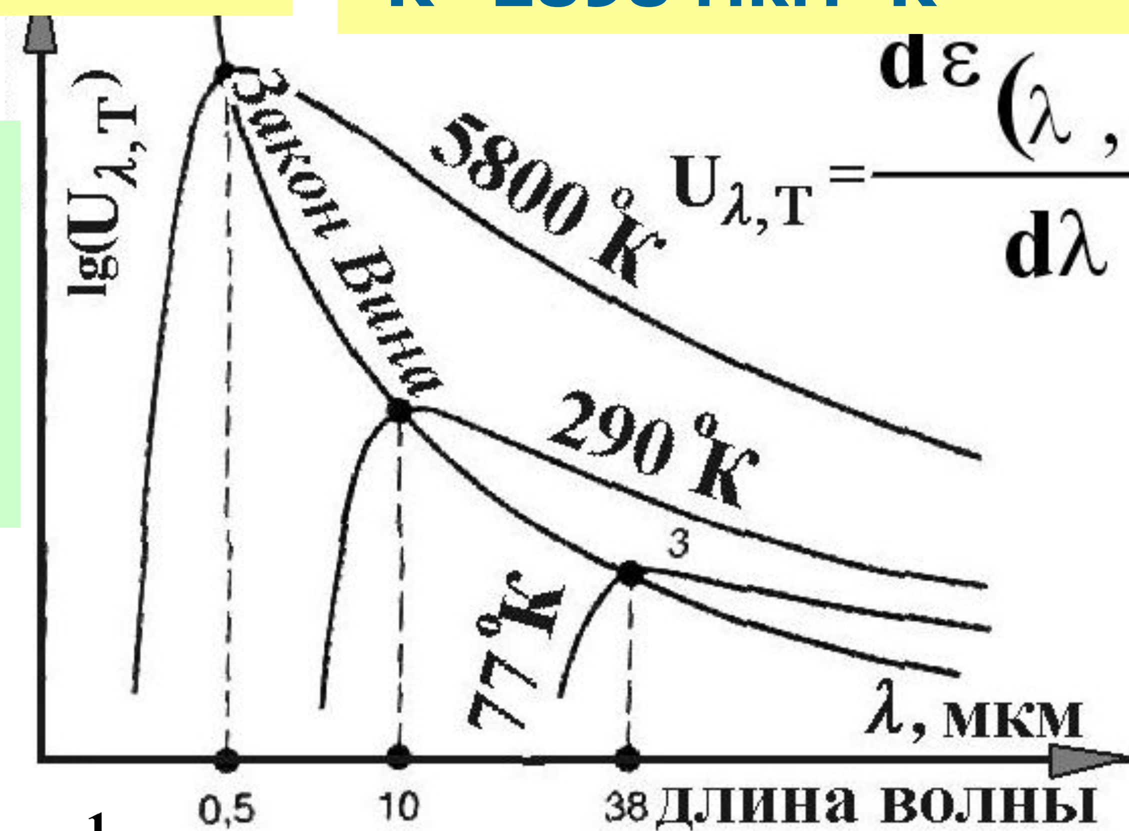
## Displacement law

$$\lambda_{max} \cdot T = const = b$$

**b =0.2898·10$^{-2}$м·°К=2898 мкм·°К**

## Wien's law

**Magnitude of the spectral density of black body radiation proportional the temperature in 5$^{th}$ degree.**




$$U_{\lambda,T} = \frac{d\varepsilon(\lambda, T)}{d\lambda}$$

$$\frac{U'_{\lambda, T'(max)}}{U_{\lambda, T(max)}} = \frac{(T')^5}{(T)^5}$$

$$U_{(\lambda, T)} = AT^5 \frac{1}{x^5} \cdot e^{-\frac{1}{x}}$$

Where $x = a \cdot \lambda$

***A , a*** **-proportional coefficients**

## the Rayleigh–Jeans law

$$U_{\omega,T} = \frac{\omega^2}{\pi^2 c^3} \cdot kT \quad (1)$$

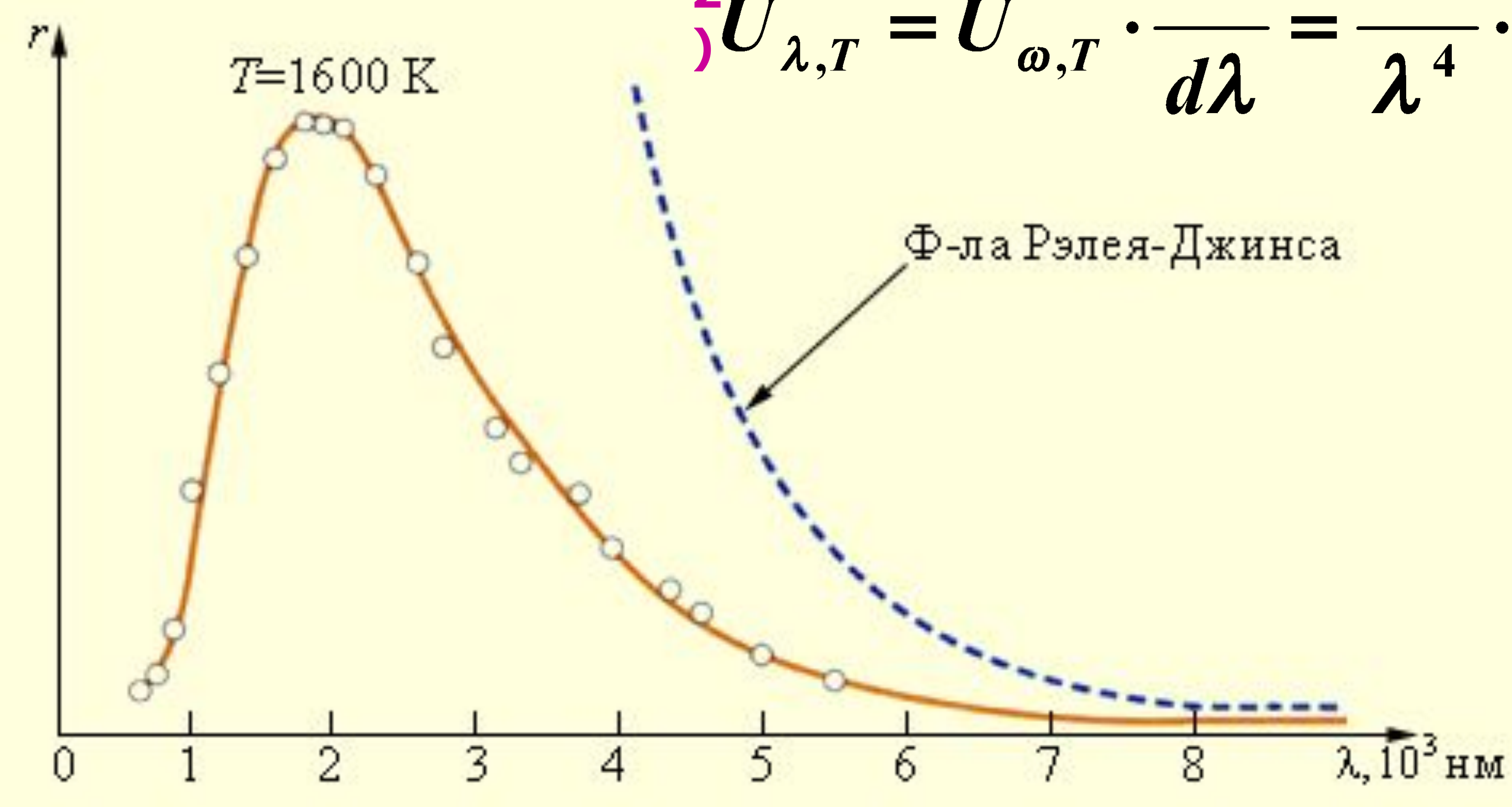
$$\omega \cdot \lambda = 2\pi\nu \cdot \lambda = 2\pi \cdot c \quad (3)$$

$$d\omega \cdot \lambda + d\lambda \cdot \omega = 0 \quad (4)$$

**Power on unit spectral interval**

$$U_{\omega,T} \cdot d\omega = -U_{\lambda,T} \cdot d\lambda \quad (2)$$

$$U_{\lambda,T} = U_{\omega,T} \cdot \frac{d\omega}{d\lambda} = \frac{8\pi}{\lambda^4} \cdot kT \quad (5)$$



Planck concluded, that the radiation and absorption processes by heated bodies of the electromagnetic energy happen not continuously, as it was considered by classic physics, but finite portions – **quants**.

$$E = \hbar\omega = h\nu$$

The spectral density of blackbody radiation

$$U_{(\omega,T)} = \frac{\hbar\omega^3}{\pi^2 c^3}\cdot\frac{1}{e^{\frac{\hbar\omega}{kT}}-1}$$

$$h = \hbar\cdot 2\pi$$

$$d\omega\cdot\lambda + d\lambda\cdot\omega = 0$$

$$U_{(\nu,T)} = \frac{8\pi\cdot h\nu^3}{c^3}\cdot\frac{1}{e^{\frac{h\nu}{kT}}-1}$$

$$U_{(\lambda,T)} = \frac{8\pi\cdot hc}{\lambda^5}\cdot\frac{1}{e^{\frac{hc}{\lambda kT}}-1}$$

$$\frac{kT\lambda}{hc} = a\cdot T\lambda = x$$

$$U_{(\lambda,T)} = \frac{8\pi\cdot k^5T^5}{c^4h^4}\cdot\frac{\frac{1}{x^5}}{e^{\frac{1}{x}}-1}$$

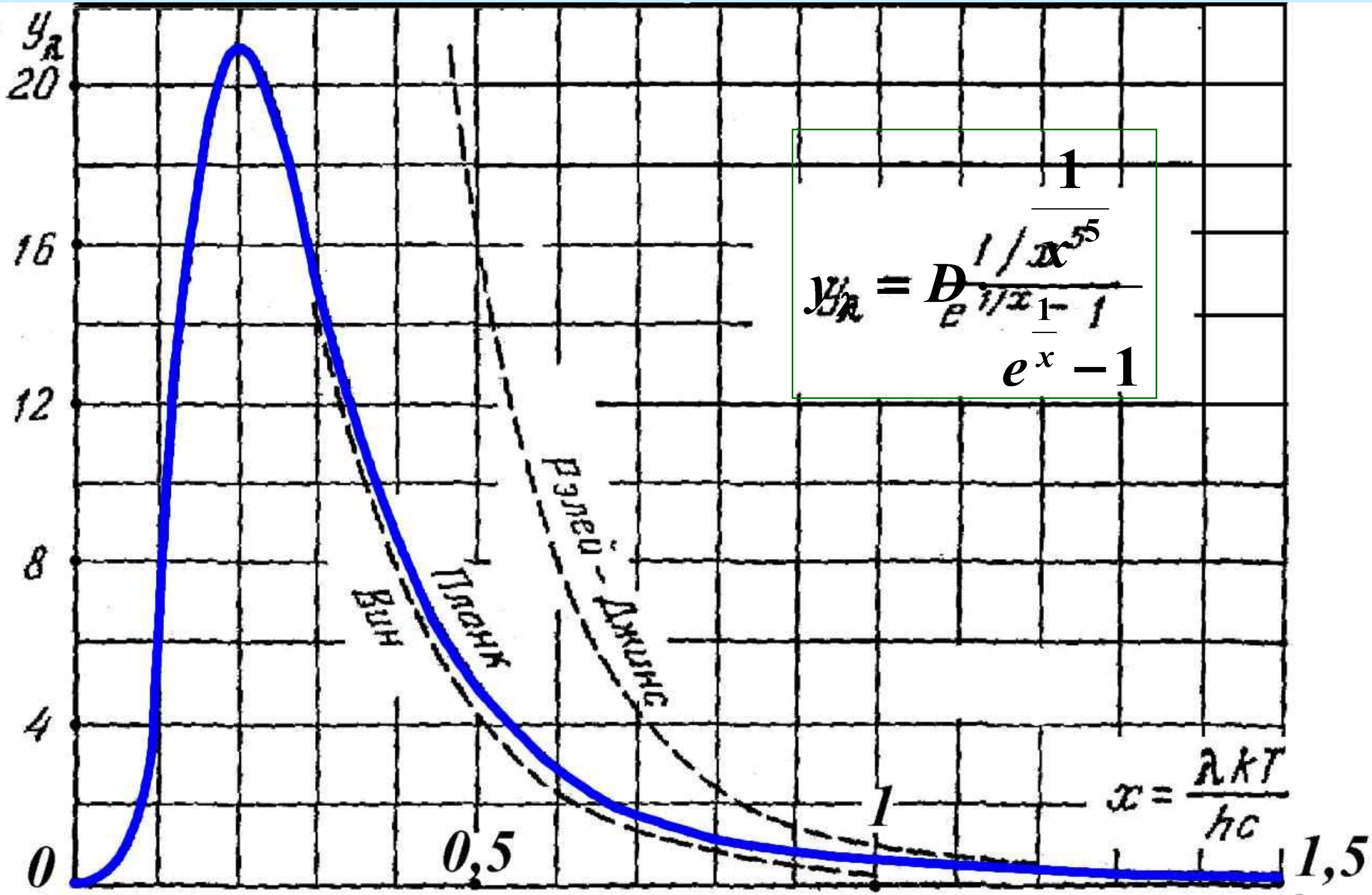
$$\hbar\omega > kT \qquad \frac{hc}{\lambda} > kT$$

$$U_{(\omega,T)} = \frac{\hbar\omega^3}{\pi^2 c^3}\cdot e^{-\frac{\hbar\omega}{kT}}$$

**Wien's law**

$$U_{(\lambda,T)} = AT^5\frac{1}{x^5}\cdot e^{-\frac{1}{x}}$$

Planck equation at small x (high frequencies or big wavelength) almost coincides with semiempirical Wien’s law. At low frequencies (hν << kT) Planck equation transfers to the Rayleigh–Jeans law.



Real bodies have different radiation and absorption. There is the coefficient of "grayness" of spectral $\varepsilon_\lambda$ and integral $\varepsilon$ radiation coefficient (don't confuse withc $\varepsilon_{(T)}$ – emissivity and $\varepsilon$- dielectric constant).

**For calculation of radiation (luminosity) of real body on Stephen-Boltzmann law it used the ratio:**

$$\varepsilon_\lambda = \frac{U_{\lambda,\,T_{const}}}{U_{(\text{АЧТ}),\,\lambda,\,T_{const}}}$$

$$\varepsilon = \int_0^\infty \varepsilon_\lambda d\lambda = \int_0^\infty \varepsilon_\nu d\nu$$

$$E_{(T)} = \int_0^\infty \varepsilon_\lambda \cdot \varepsilon_{(\lambda,T)} d\lambda = \int_0^\infty \varepsilon_\nu \cdot \varepsilon_{(\nu,T)} d\nu$$

**If the body is "gray"** $\varepsilon_\lambda = const$ → $E_{(T)} \approx \varepsilon \cdot \sigma \cdot T^4$

**If** $\varepsilon_\lambda \neq const$

**The body is colors and there is additional optical phenomenon: interference, diffraction, luminescence.**

**Sometimes to estimate the reflection of radiance from the body it is convenient to use not the "gray" coefficient $\varepsilon$, but coefficient of whiteness «albedo»: $\alpha = 1 - \varepsilon$**

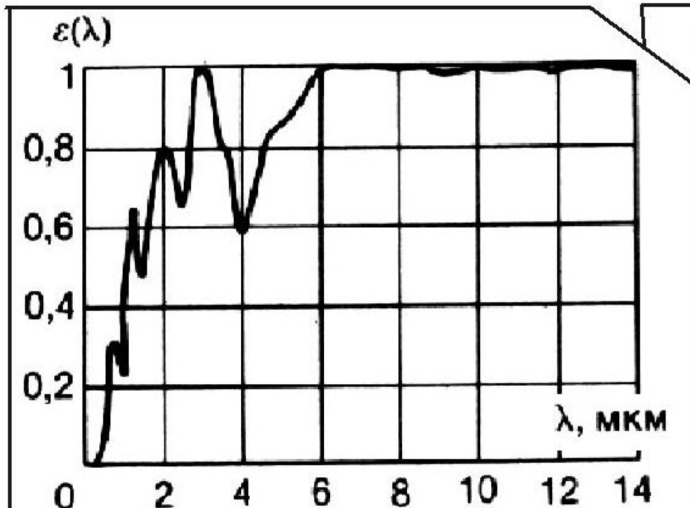
## Dielectic radiation coefficients

$$\varepsilon_\lambda = 1 - R_\lambda = \frac{4n_\lambda}{(n_\lambda + 1)^2 + \eta_\lambda^2}$$

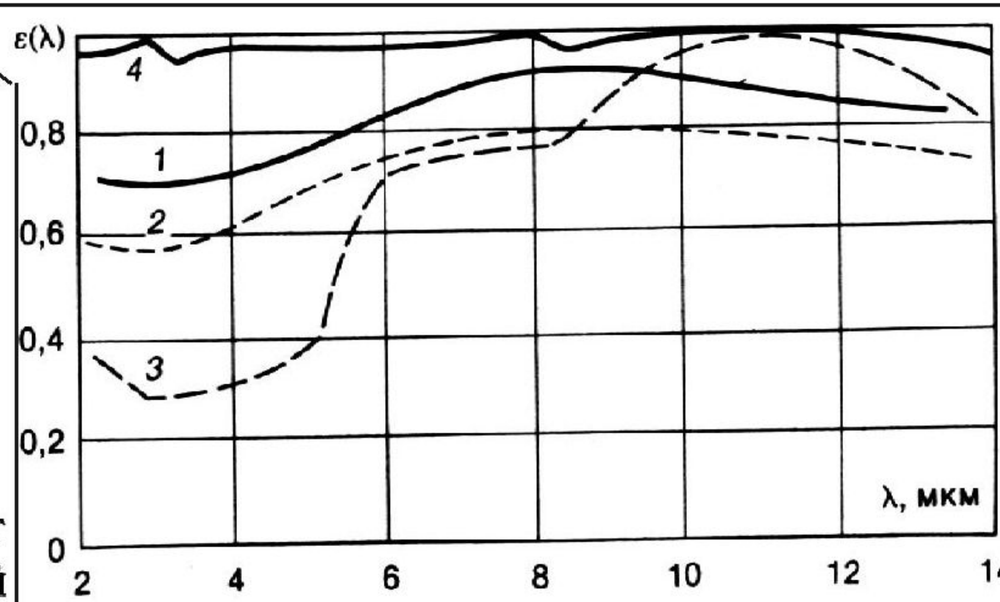
At the condition. That all radiation, which doesn't reflect from the edge of thick non transparent or semitransparent dielectric, absorbed in its thickness or on other edge.

**for** $(\omega/c)\ \eta_\lambda{*}L>>1$

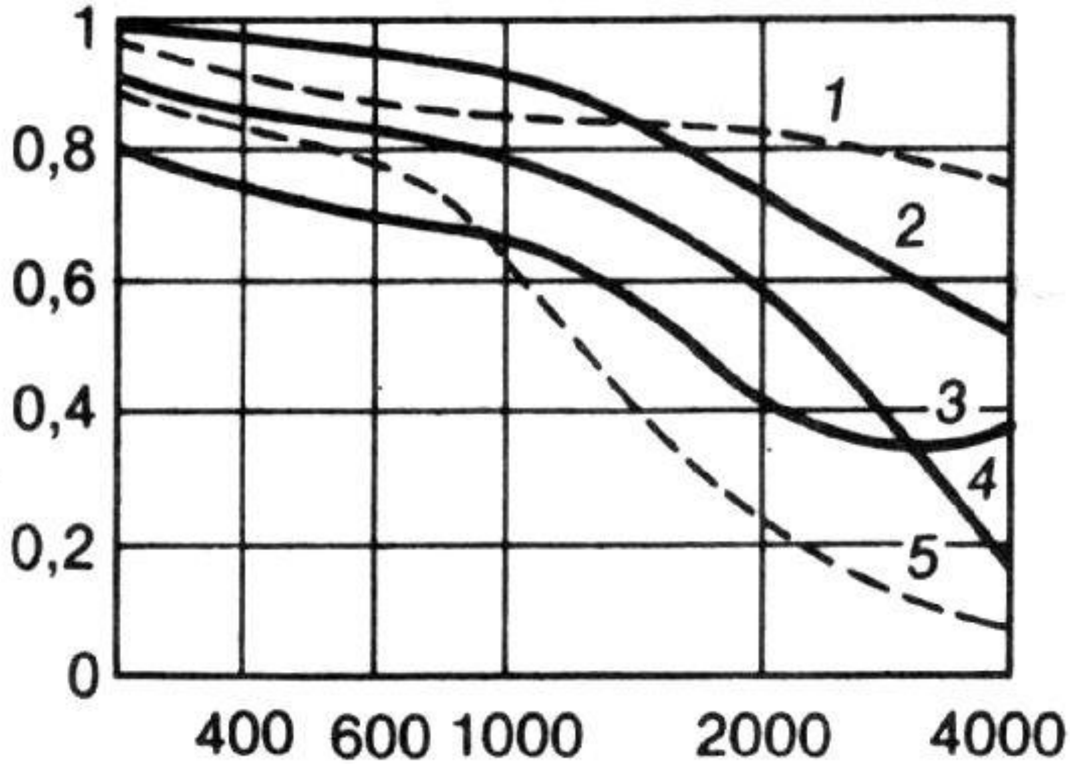
**$R_\lambda$ is the reflection coefficient of the surface dielectric-vacuum (depends on the wavelenght). $N_\lambda$ is the refraction coefficient, $\eta_\lambda$ is the index of refraction of the material, L is the thickness of dielectric la**




Спектральный коэффициент излучения ε(λ) человеческой кожи.




Спектральный коэффициент излучения ε(λ) некоторых диэлектриков. *1* — земля *2* — пластмасса; *3* — окись магния; *4* — вода (в направлении нормали к поверхности).




T, ºK

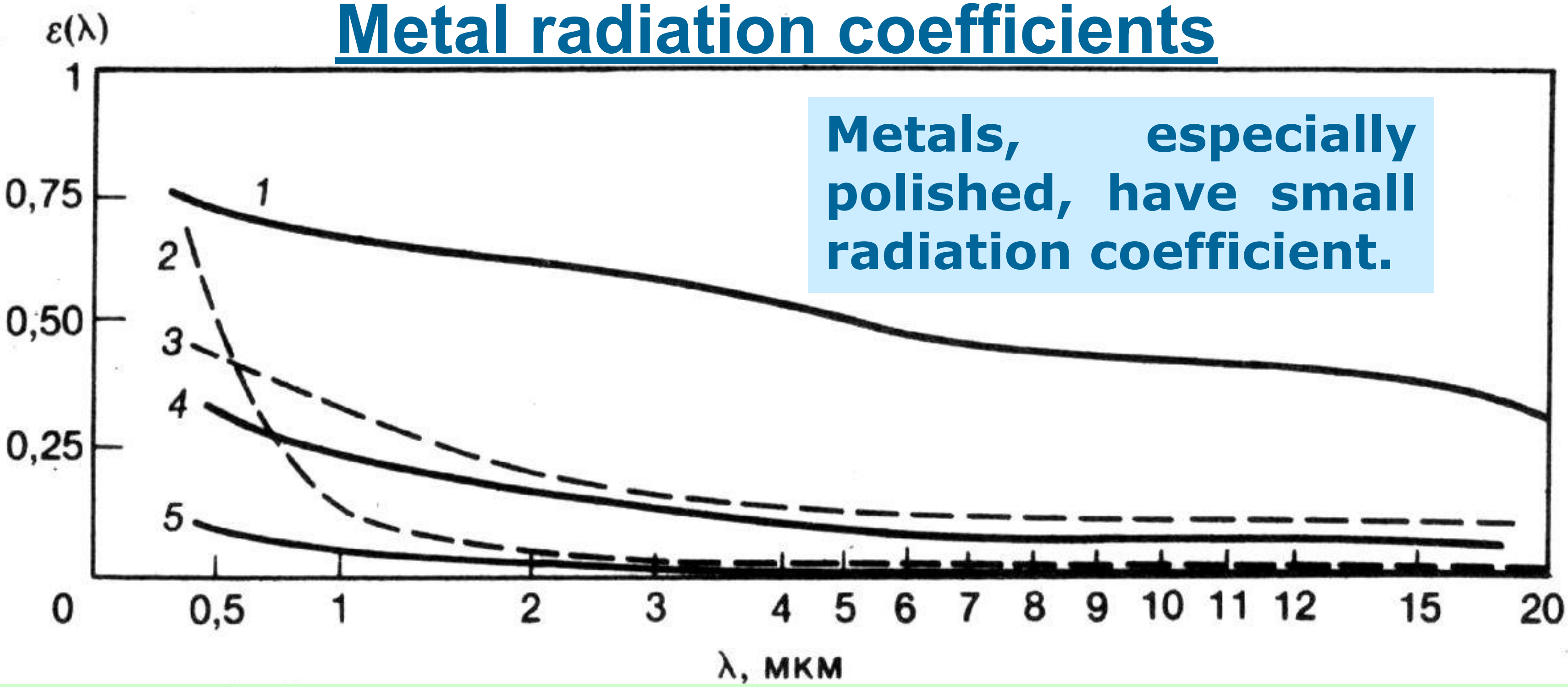
Integral radiation coefficient of several dielectrics as the function of temperature : 1-rubber, 2- porcelain, 3-cork, 4-paper, 5 fire-clay.

**Any material, covered by thin transparent dielectric layer, change its "gray" coefficient because of reflection of frontal waves, radiated body on the surface dielectric-vacuum and total internal reflection of oblique beams on this surface.**

$$\varepsilon = \varepsilon_{om}(1-R_{\lambda})\sin^2\sigma = \varepsilon_{om}\frac{4n}{(1+n)^2}\cdot\frac{1}{n^2} = \varepsilon_{om}\frac{4}{(1+n)^2 n}$$

**where $\varepsilon_{om}$ is the integral radiation coefficient of the material, $n$ is the index of refraction of films dielectric, $\sigma$ angle of total internal reflection**

# Metal radiation coefficients



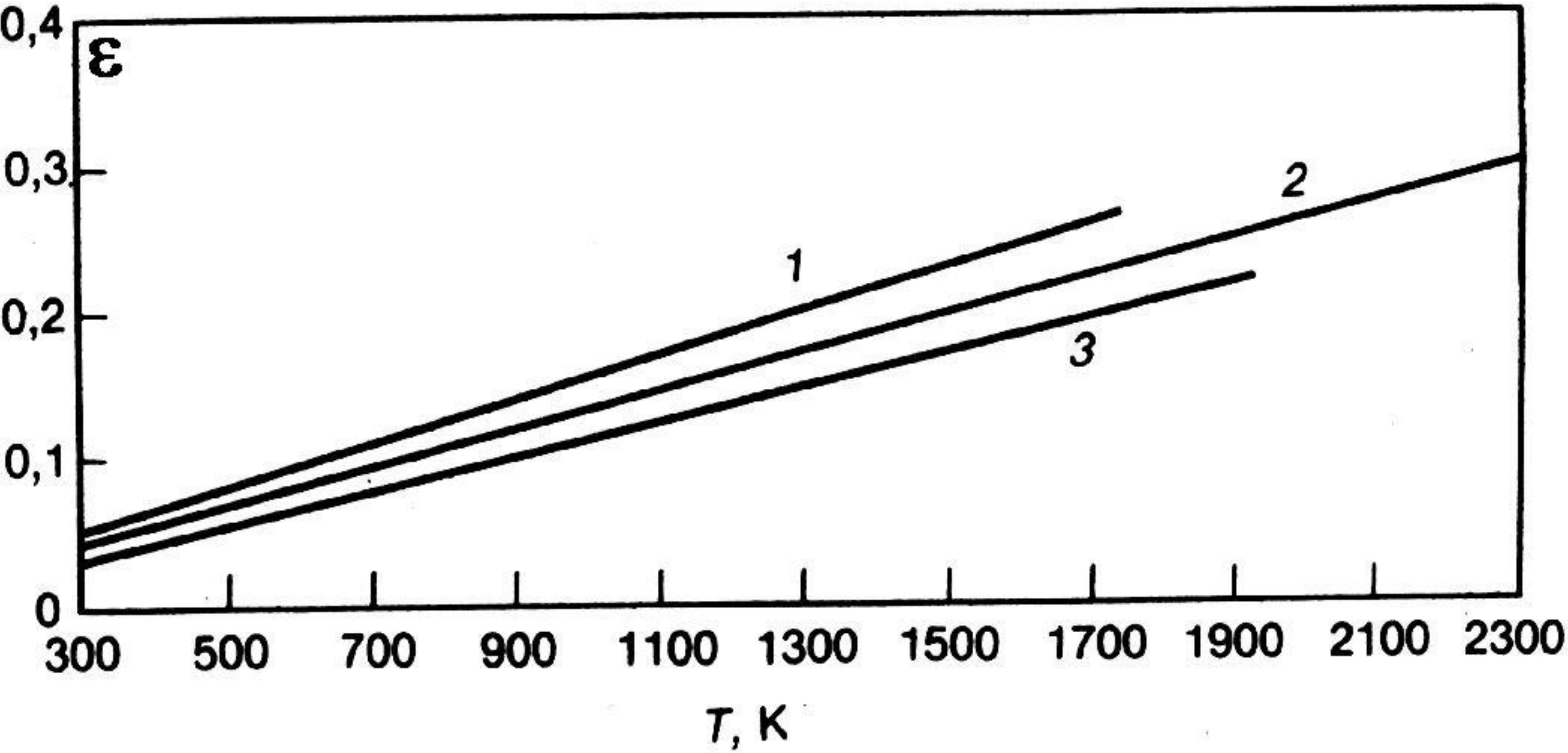

**Metals, especially polished, have small radiation coefficient.**

**Spectral radiation coefficient $\varepsilon_\lambda$ of some metals: 1-graphite, 2-copper, 3-iron, 4-aluminum, 5-silver.**

Radiation coefficient of metals Коэффициент излучения металлов uniquely connected with its index of reflection. The last one depends not only on concentration of unbound electrons and electron oscillation frequency, but on the scattering of oscillating electrons (their interaction with the impurities and defects) and magnetic permittivity of metal $\mu$. Scattering is defined by conductivity of metals σ.

$$\varepsilon_\lambda = 1 - R_\lambda = \sqrt{\frac{2\omega}{\sigma \mu c^2}}$$

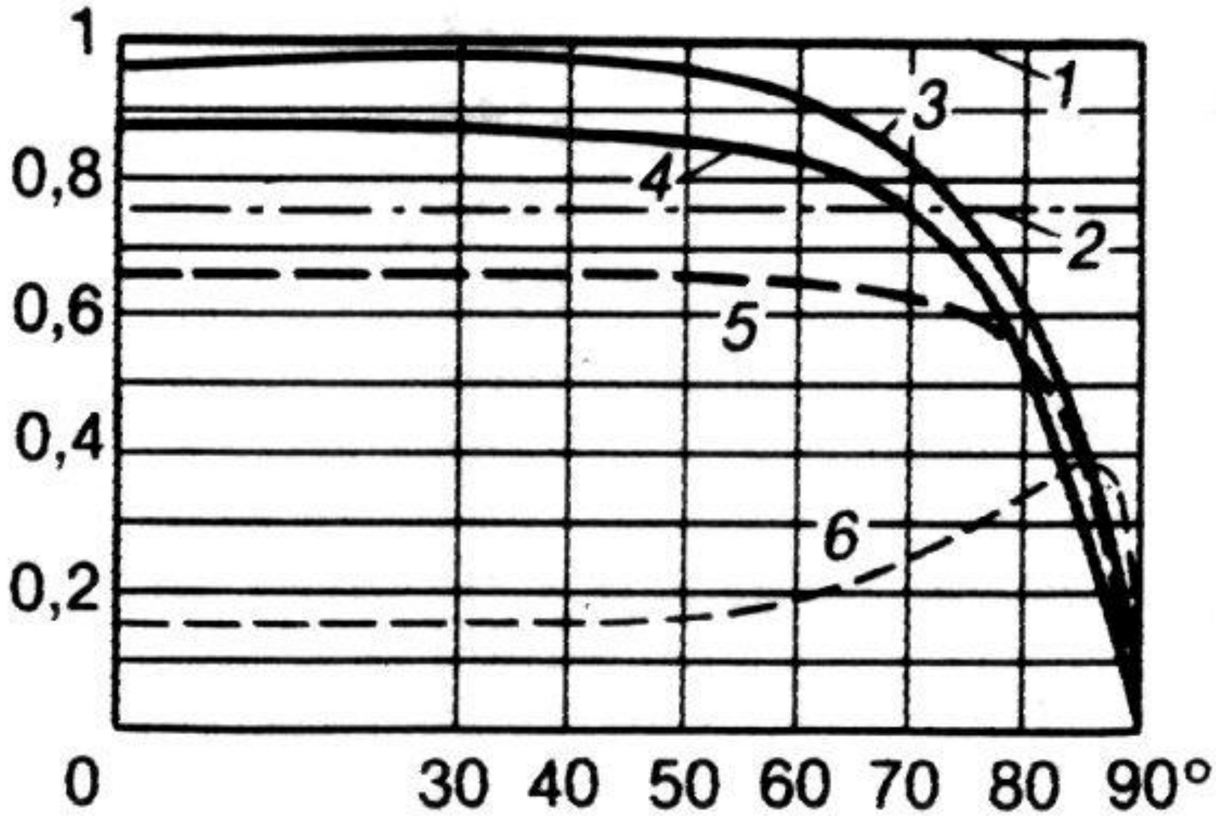
$\sigma$ is electroconductivity of metals, $c$ is the speed of light, $\omega$ is cyclic frequency of radiation.




***Integral radiation coefficient of some metals.***

***1*-nickel, *2*-tungsten, *3*-platinum.**

# Dependence of radiation coefficient from the angle of observation



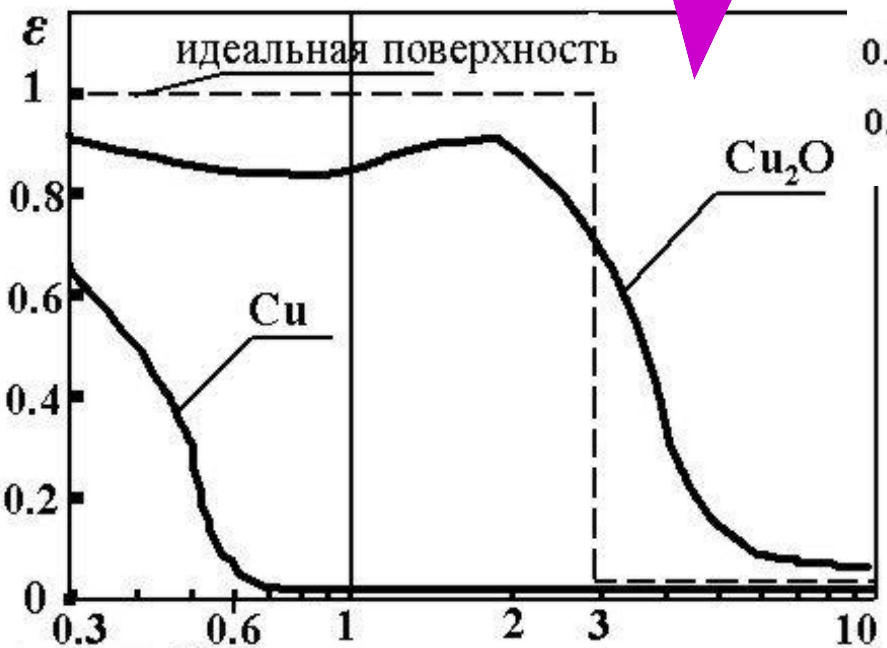

the angle of observation

**Integral radiation coefficient ε as a function of the angle of observation**

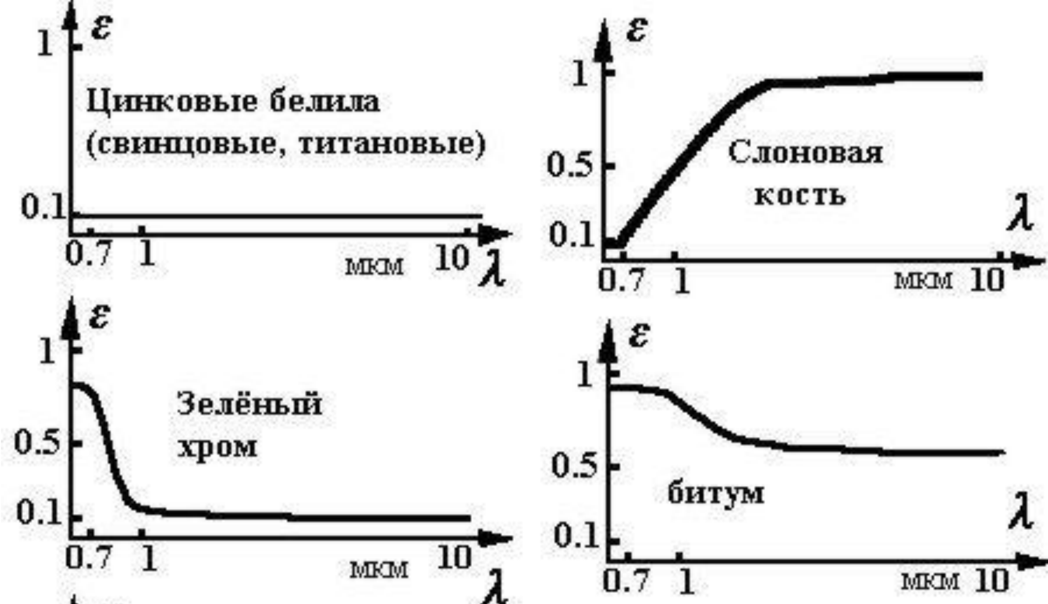
**1 – black body; 2 – gray body; 3-5 – dielectrics with the indexes of refraction n=1.5; 2 and 4 respectively; 6 – metal.**

**Selective coating are special coatings for heat control.**

**Coating of cupper collector of solar radiance by film from copper oxide led to increase the radiation coefficient of solar radiance from λ =0.3-3мкм, the same time it possible to decrease the heat losses form λ =5-15мкм.**




Спектральная характеристика селективной поверхности на основе $Cu - Cu_2O$

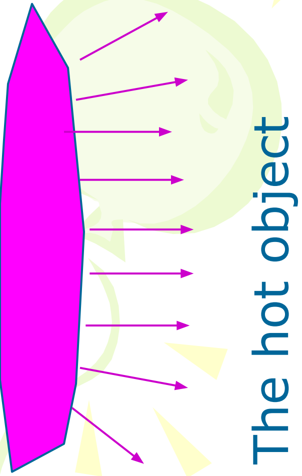


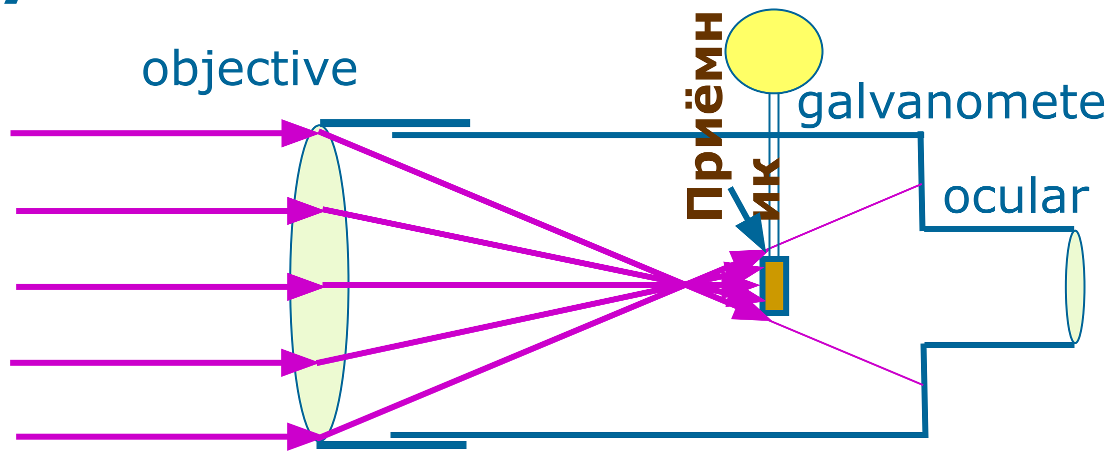


Спектральные зависимости излучательной способности распространён-ных лакокрасочных по-крытий.

**Color «ivory» (also snow and glass powder increase the heat because of high повышают теплоотдачу излучением за счёт высокой emissivity in the range λ =3-15 mkm, but looks like white in the visible range of the wavelength from λ =0.3-1mkm (all radiation in this range is reflected)**

# Radiation pyrometers



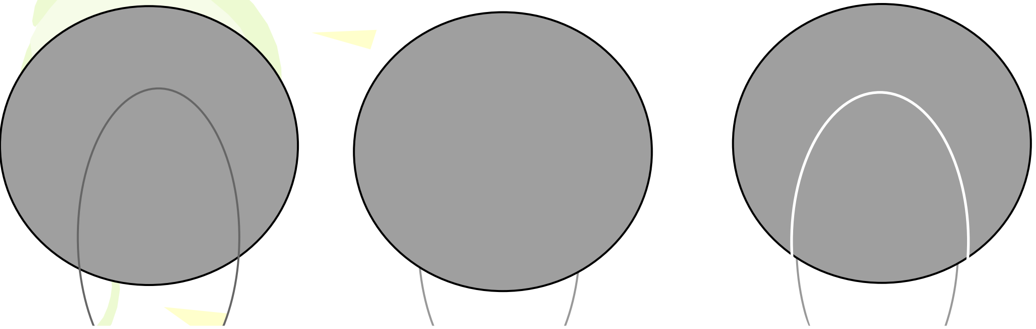



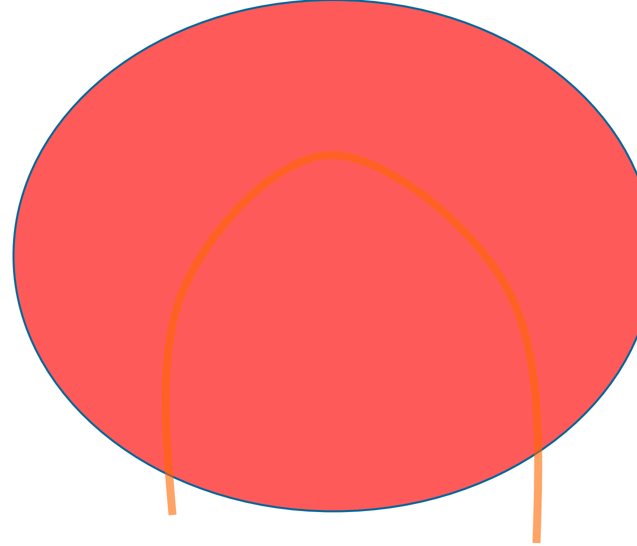

**Пирометры основаны на фокусировке излучения раскаленной поверхности на теплоприемнике. Яркость сфокусированного изображения не зависит от расстояния до объекта, если оно велико по сравнению с фокусным расстоянием объектива. Важно, чтобы создаваемое объективом изображение полностью перекрывало теплоприемник. Предварительно производится**

**<u>Поскольку энергетическая светимость реальной раскаленной поверхности при той же температуре меньше светимости абсолютно черного тела (в соответствии с законом Кирхгофа), измеренная радиационная температура оказывается меньше</u>**

**В справочниках имеются соответствующие поправочные коэффициенты, учитывающие отличие светимости поверхностей реальных материалов от светимости абсолютно черного тела. Значения этих коэффициентов в свою очередь зависят от**

## ***Яркостные пирометры***.





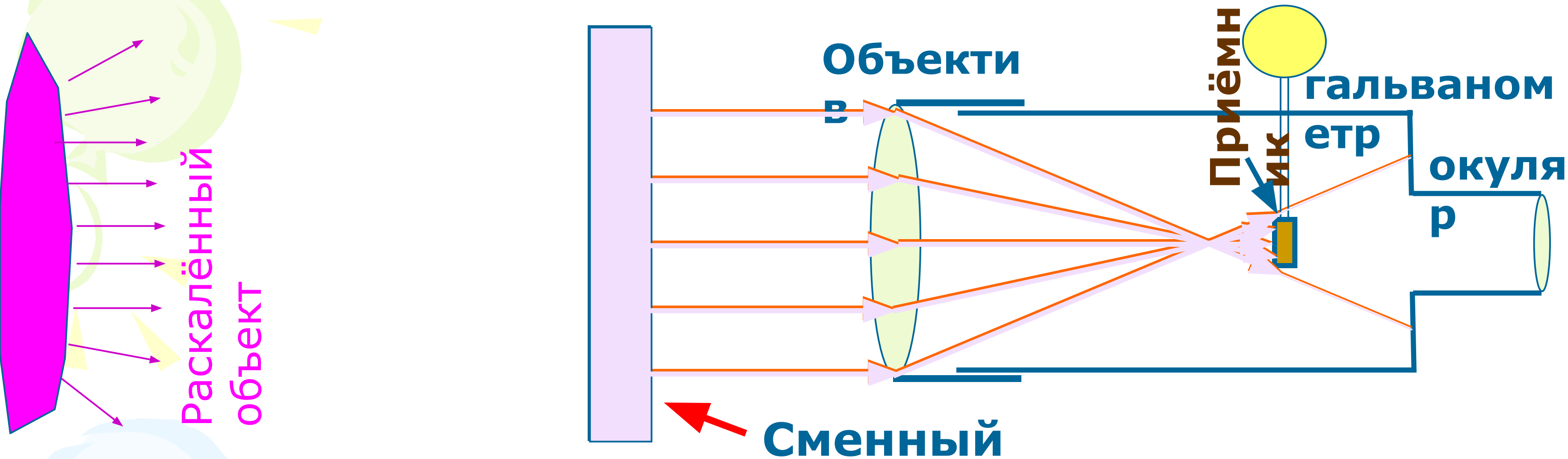
***меньше равна больше***

***яркость нити по отношению к фону***

**Действие пирометра основано на сравнении яркости свечения тела, температура которого измеряется, и нити лампы накаливания. Через красный светофильтр производится наблюдение (*λ=660 нм*). Применение пирометров обычно связано с металлургией. Производится наблюдение, например, окошка в стенки доменной или мартеновской печи. На фоне изображения светящегося окошка наблюдается нить лампочки накаливания. Регулируя ток через лампочку, добиваются уравнивания их яркостей в красном цвете. При этом нить лампочки становится невидимой - потому такой пирометр называют пирометром с “исчезающей” нитью. Пирометр градуиру-ется по абсолютно**

**<u>Поскольку светимость реального тела при той же температуре меньше, для достижения равенства яркостей черного и нечерного тел это последнее должно быть нагрето сильнее, измеренная яркостная температура тоже оказывается меньше действительной. (Также как и у радиационного пирометра).</u>**

# <u>Цветовые пирометры</u>.




Серое тело имеет тот же спектральный состав, что и абсолютно черное тело. Поэтому температуру серого тела можно определить в соответствии с законом смещения Вина, определив длину волны $\lambda_m$, на которую приходится максимум излучения. Однако, вместо исследования всего спектра излучения, производятся измерения светимостей на двух различных частотах (при двух значениях длин волн) и по их отношению определяется температура тела - для черного тела при любой температуре это отношение известно. Этот пирометр отличается от радиационного тем, что наблюдения

**Как правило, измеренная температура выше истинной, а показания ближе к истинным, чем у радиационного и яркостного методов измерения температуры.**

Учебный фильм

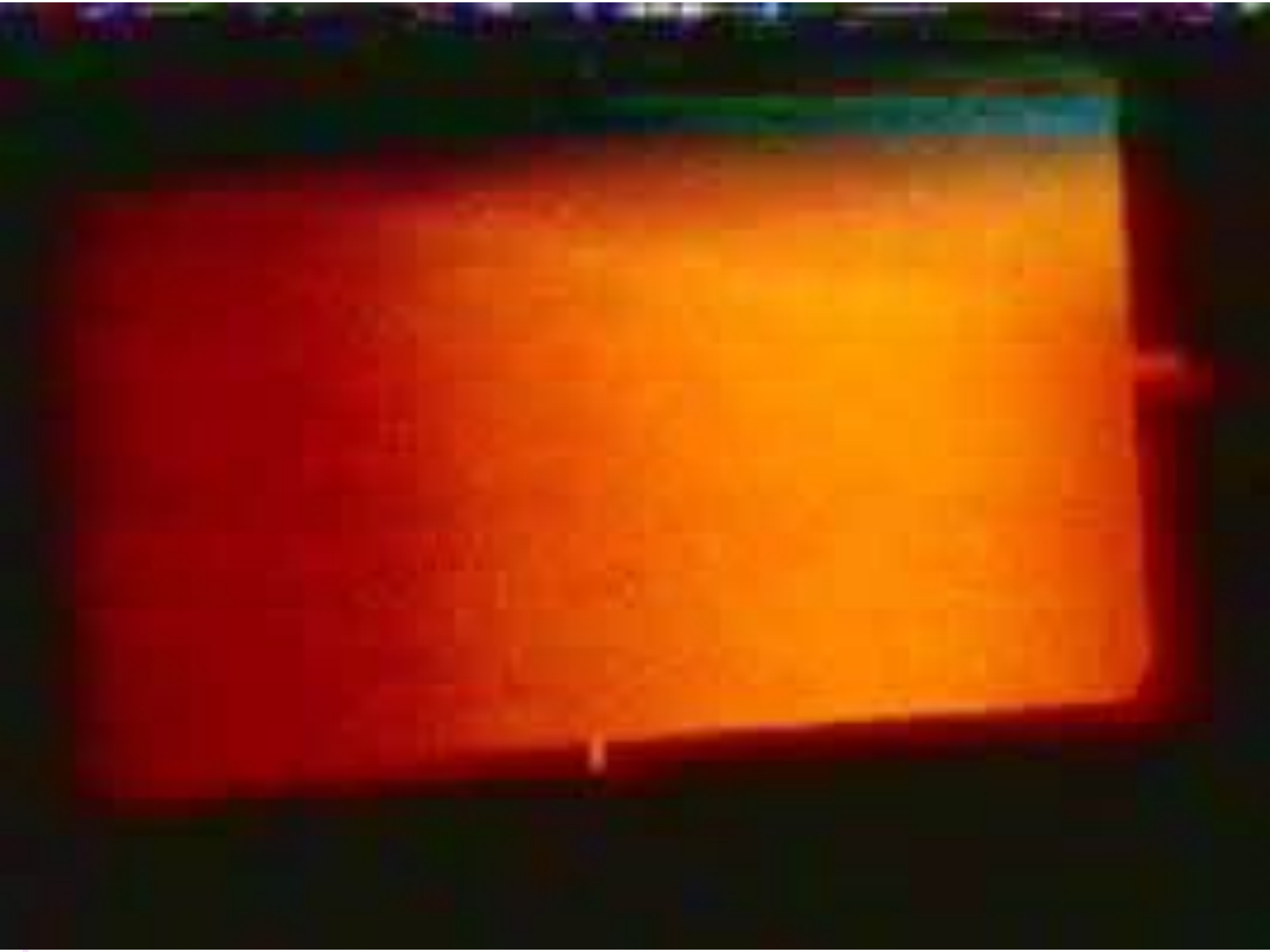
«Лучистый теплообмен»

**Нобелевская премия по физике в 2006 году присуждена за «абсолютно черное тело».**

Радиометр
Крукса

# РАДИОМЕТРИЧЕСКИЙ ЭФФЕКТ

11




PLAY
SP

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If a classroom door is open slightly, you can hear sounds coming from the hallway. Yet you cannot see what is happening in the hallway. Why is there this difference? (a) Light waves do not diffract through the single slit of the open doorway. (b) Sound waves can pass through the walls, but light waves cannot. (c) The open door is a small slit for sound waves, but a large slit for light waves. (d) The open door is a large slit for sound waves, but a small slit for light waves.

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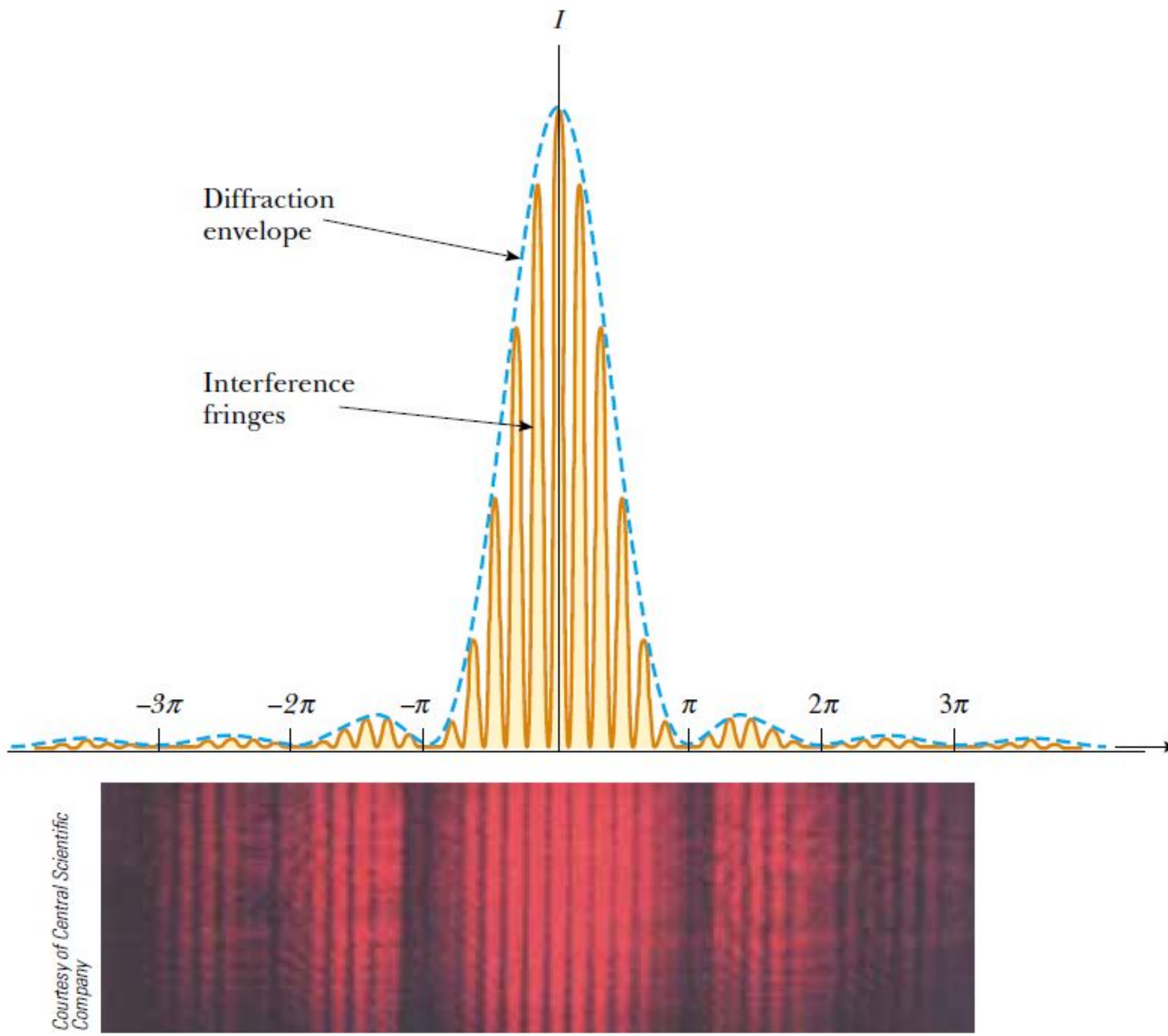

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Cat's eyes have pupils that can be modeled as vertical slits. At night, would cats be more successful in resolving

(a) headlights on a distant car, or

(b) vertically-separated lights on the mast of a distant boat?

## Quick Quiz 4

If laser light is reflected from a phonograph record or a compact disc, a diffraction pattern appears. This is due to the fact that both devices contain parallel tracks of information that act as a reflection diffraction grating. Which device, (a) record or (b) compact disc, results in diffraction maxima that are farther apart in angle?