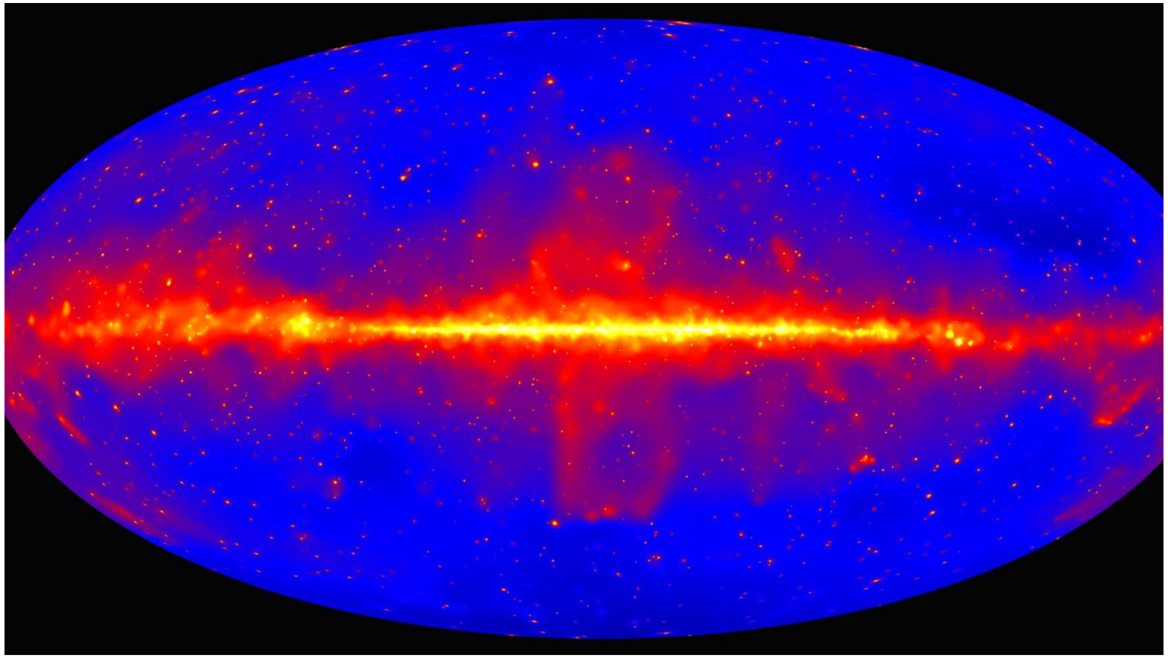
# A SHORT HISTORY OF THE PHOTON

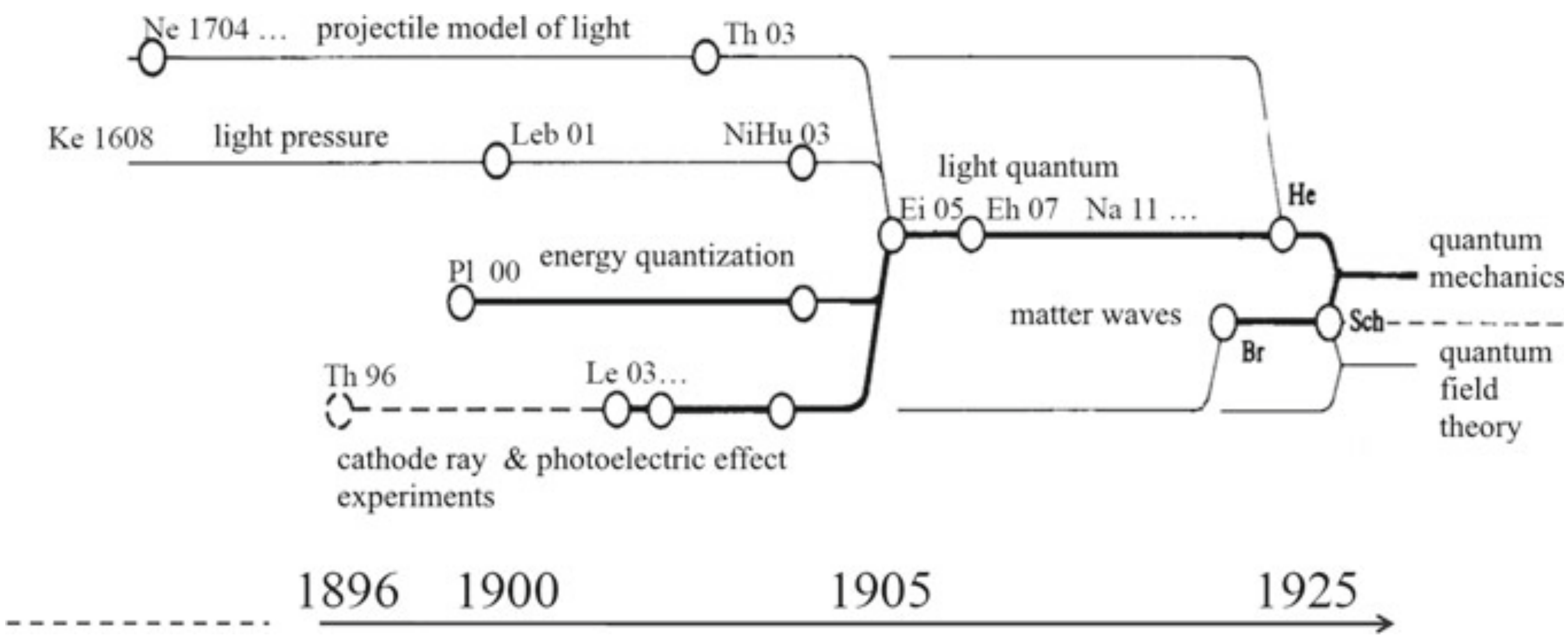

## Fulvio Parmigiani

Newton wrote in 1704: “***Do not Bodies and Light act mutually upon one another; that is to say, Bodies upon Light in emitting, reflecting, refracting and inflecting it, and Light upon Bodies for heating them, putting their parts into a vibrating motion wherein heat consists?”*** [Opticks]

# AN INTERESTING PATH

# THE ROAD MAP




Abbreviation key: Ke: Kepler, Ne: Newton, Leb: Lebedew, NiHu: Nichols and Hull, Le: Lenard, Th: J.J. Thomson, Pl: Planck, Ei: Einstein, Eh: Ehrenfest, Na: Natanson, Br: Louis de Broglie, He: Heisenberg and Sch: Schrödinger.

Credit: **Klaus Hentschel** Photons. *The History and Mental Models of Light Quanta* Springer 2018

# THE NEWTON'S PARTICLES OF LIGHT

As we have seen in the first lecture, the idea that the light is made of particles (or atoms of light) as developed by Isaac Newton (1642–1727) represents the first "physical" model about this issue.
However, Newton, in his early papers published in the ***Philosophical Transactions of the Royal Society*** from 1672 on, was careful not to reveal his basic corpuscular notion of light.
In his "**Mathematical principles of natural philosophy**", for example, he concludes that light refraction is caused by the stronger attraction of particles of light to a denser medium.

**His query in *Opticks* (added to the second edition in 1706) also reads:**

***Are not the Rays of Light very small Bodies emitted from shining Substances? For such Bodies will pass through uniform Mediums in right Lines without bending into the Shadow, which is the Nature of the Rays of Light. They will also be capable of several Properties, and be able to conserve their Properties unchanged in passing through several Mediums, which is another condition of the Rays of Light.***

# LIGHT AND COLORS

**The speed of light with different colors.**

Newton himself had shown in his ***New Theory of Light and Colors*** from 1672 that components of light of different colors manifest different angles of refraction. This seemed to suggest the assumption that the variously colored components of light would propagate at different velocities through the same medium.

Red component of the spectrum was the least refractive, according to his theory, it actually ought to be the most rapidly moving one.

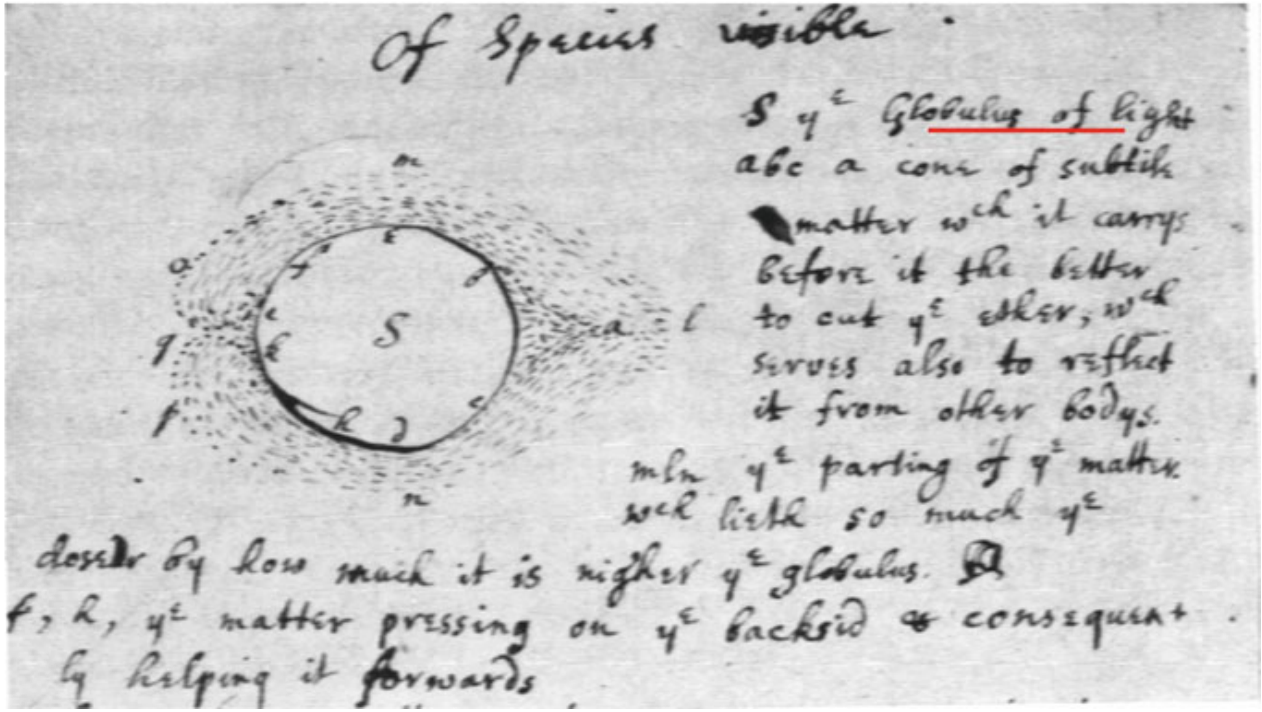
***That is why Newton asked the Astronomer Royal, John Flamsteed (1646–1719), in 1691 about his observations of Jupiter's moons***. Did the terrestrial observer first perceive the red component of the light right after their transits behind the planet and the blue component only afterwards? **Flamsteed's negative reply dissuaded Newton of the hypothesis that red light must be faster than blue light**. He then suspected that the **different color-dependent degrees of refrangibility either came from differing sizes for his light globuli or differing masses.**

# COLORS, SPEED OF LIGHT
# and
# SPACE

# WHAT IS THE SPACE?
# GEOMETRY OR PHYSICS?

## QUAESTIONES QUAEDAM PHILOSOPHICAE*

Albeit, at this stage **Newton's "projectile model" of light is formulated as a "query," not as a thesis**. **By assuming the existence of "minimally small bodies" he was just exploiting a mathematical analogy between the propagation of such tiniest particles of light and small material bodies, without having to make any positive statement about "whether they are bodies or not.**



Of Species visible.

S ye Globulus of light
abc a cone of subtile
matter wch it carrys
before it the better
to cut ye ether, wch
serves also to reflect
it from other bodys.
mln ye parting of ye matter
wch little so much ye
denser by how much it is nigher ye globulus.
f, k, ye matter pressing on ye backside & consequent-
ly helping it forwards

Newton's "**globulus of light**" 1664–65 in, ***Quaestiones quaedam philosophicae*** fol. 104v, MS Add. 3996, Cambridge University Library, Cambridge, UK.

***Quaestiones quaedam philosophicae*** (*Certain philosophical questions*) is the name given to a set of notes that Isaac Newton kept for himself during his earlier years in Cambridge. Apart from the light it throws on the formation of his own agenda for research, the major interest in these notes is the documentation of the unaided development of the scientific method in the mind of Newton, whereby every question is put to experimental test.

# THE SPEED OF LIGHT

**It was later confirmed that the propagation velocity «c» in a free space was constant and independent of the frequency, not only for all spectral components of light but also of other transversal waves (such as, thermal radiation, ultraviolet light, x-rays, γ-rays, and radio waves), all of which were interpreted according to Maxwell's theory as forms of electromagnetic radiation differing only in wavelength or frequency.**

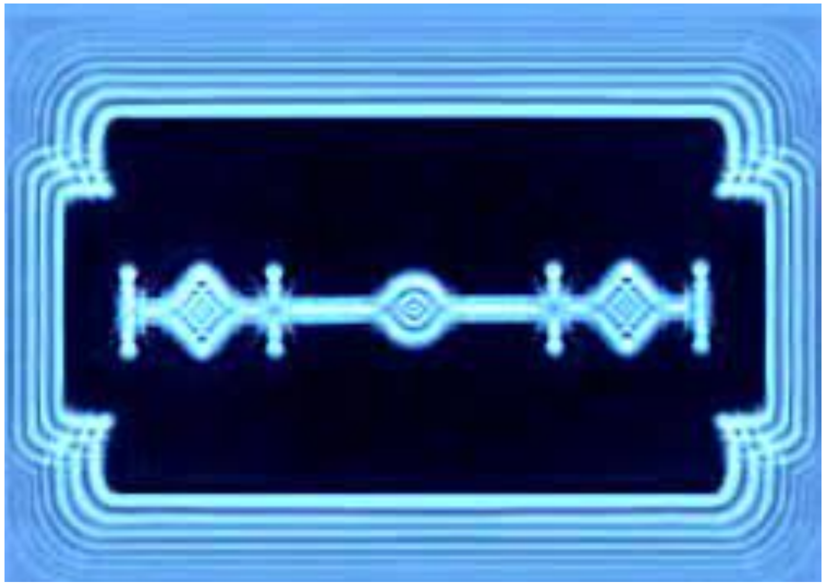
The speed of light in the Galilean relativity

Thomas Blair (1748–1828), to the *Royal Society of London* in 1786:

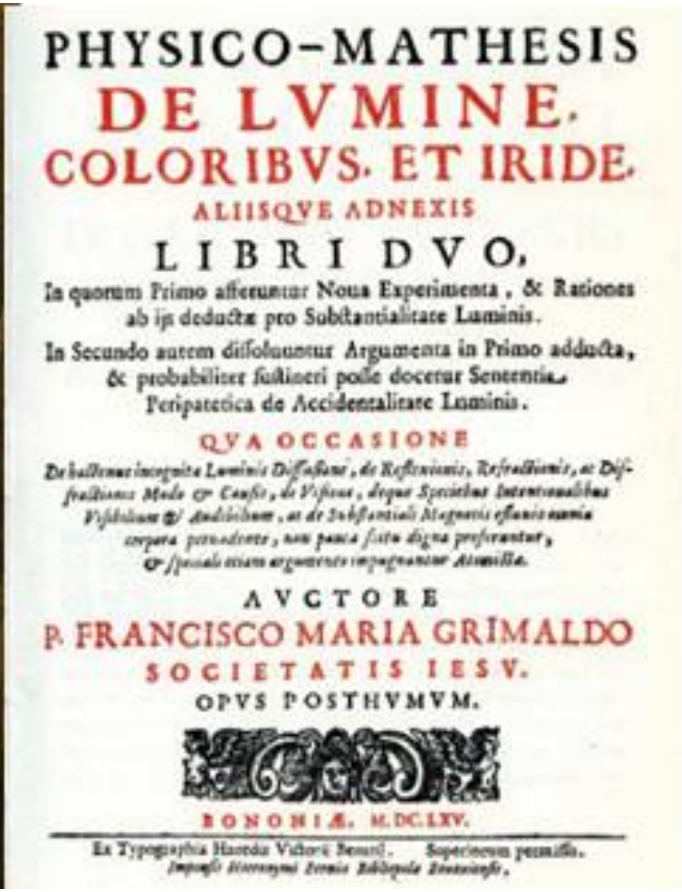
«***It appears more probable, that when light is emitted by a body in motion, the velocity of the particles projected in the direction of the motion will exceed the velocity of those, which are projected in an opposite direction, the difference being equal to twice the velocity of the moving body. And the same thing ought to take place when bodies reflect light.»***

# A SMALL DETAIL. A BIG MEANNING: THE PENUMBRA

**PENUMBRA**



# DE LUMINE COLORIBUS ET IRIDE



PHYSICO-MATHESIS
DE LVMINE.
COLORIBVS. ET IRIDE.
ALIISQVE ADNEXIS
LIBRI DVO.
In quorum Primo afferuntur Noua Experimenta, & Rationes ab ijs deductæ pro Substantialitate Luminis.
In Secundo autem dissoluuntur Argumenta in Primo adducta, & probabiliter sustineri posse docetur Sententia Peripatetica de Accidentalitate Luminis.
QVA OCCASIONE
*De hactenus incognita Luminis Diffusione, de Reflexionis, Refractionis, ac Diffractionis Modo & Causis, de Visione, deque Speciebus Intentionalibus Visibilium & Audibilium, ac de Substantiali Magnetis effluuio omnia corpora penetrante, non pauca scitu digna proferuntur, & speciali etiam argumento impugnatur Atomistica.*
AVCTORE
P. FRANCISCO MARIA GRIMALDO
SOCIETATIS IESV.
OPVS POSTHVMVM.
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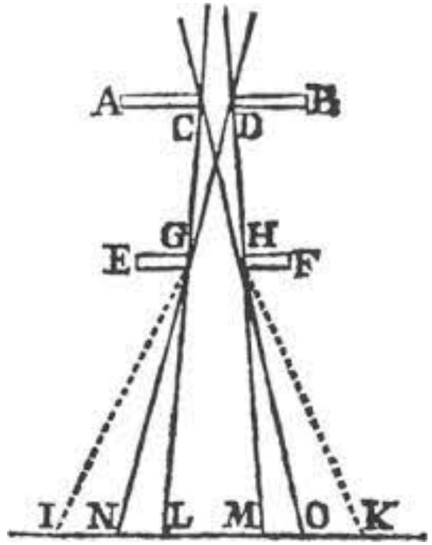
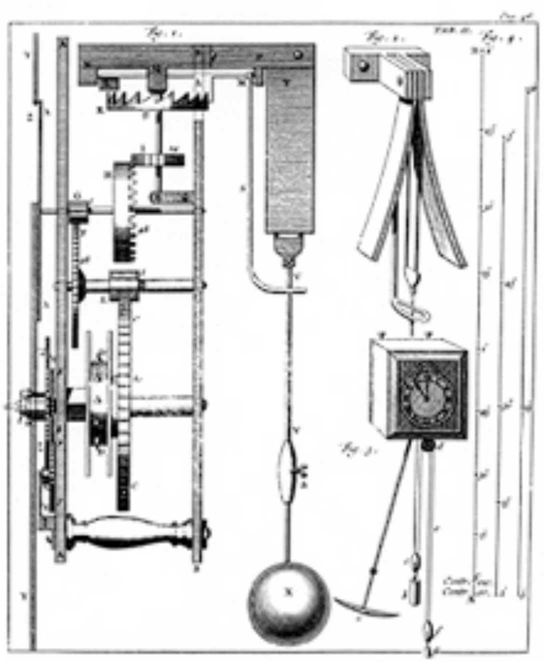


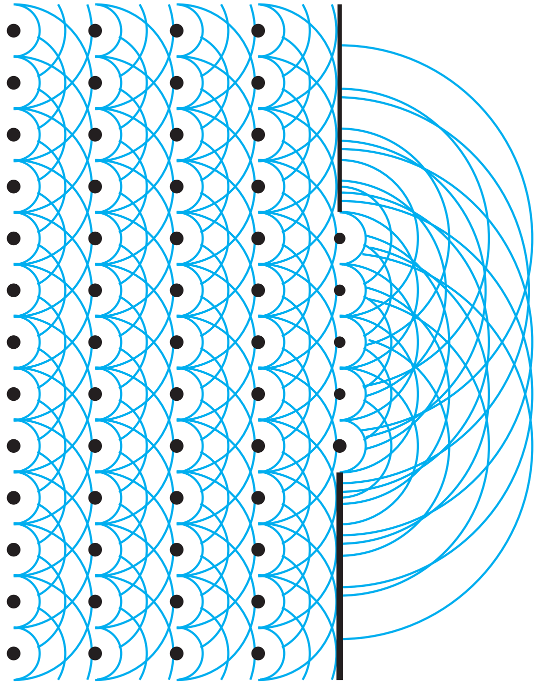

**Francesco Maria Grimaldi** (2 April 1618 – 28 December 1663) was an Italian Jesuit priest, mathematician and physicist who taught at the Jesuit college in Bologna.

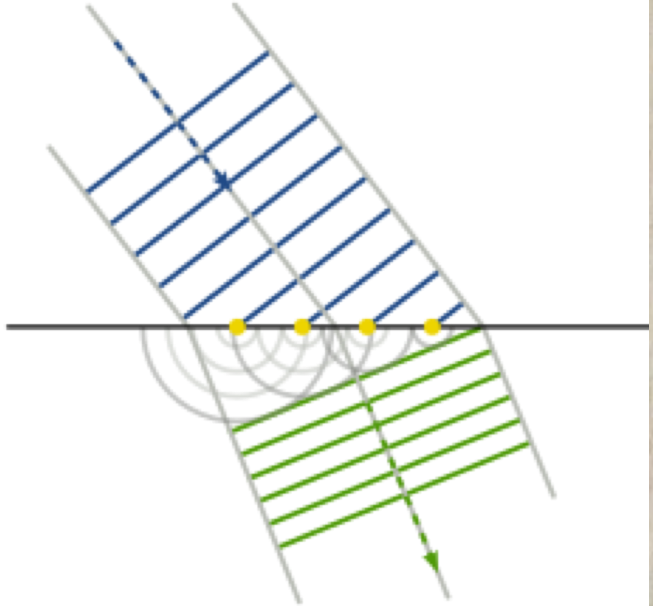
# THE RISE OF THE LIGHT WAVE

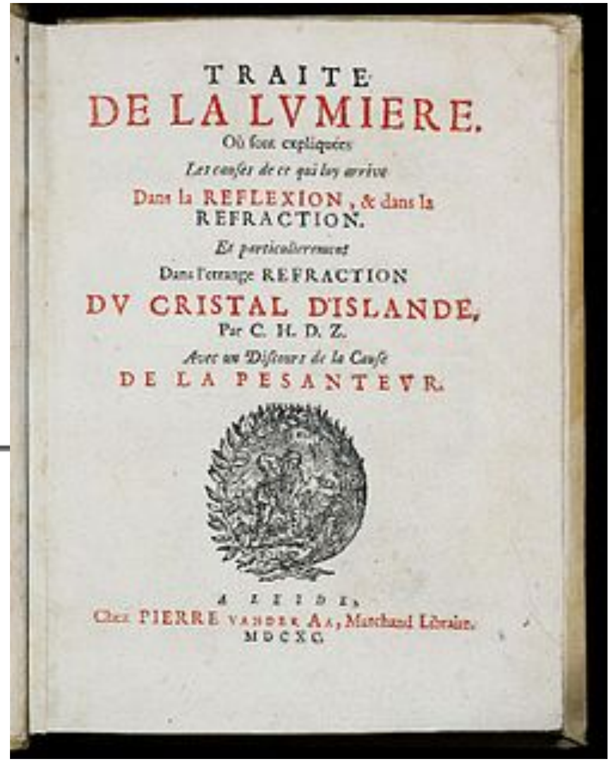
**Christiaan Huygens** 14 April 1629 – 8 July 1695), was a Dutch mathematician, physicist, astronomer and inventor, who is widely regarded as one of the greatest scientists of all time and a major figure in the scientific revolution. In physics, Huygens made groundbreaking contributions in optics and mechanics, while as an astronomer he is chiefly known for his studies of the rings of Saturn and the discovery of its moon Titan. As an inventor, he improved the design of telescopes and invented the pendulum clock, a breakthrough in timekeeping and the most accurate timekeeper for almost 300 years. Huygens was an outstanding mathematician and accomplished physicist, being the first to idealize a physical problem by a set of parameters then analyze it mathematically (*Horologium Oscillatorium*), and the first to fully mathematize a mechanistic explanation of unobservable physical phenomena (*Traite de la Lumiere*). For these reasons, he has been called the first theoretical physicist and one of the founders of modern mathematical physics.



# A MENTAL MODEL








**R. Feynman** defines the generalized principle in the following way:

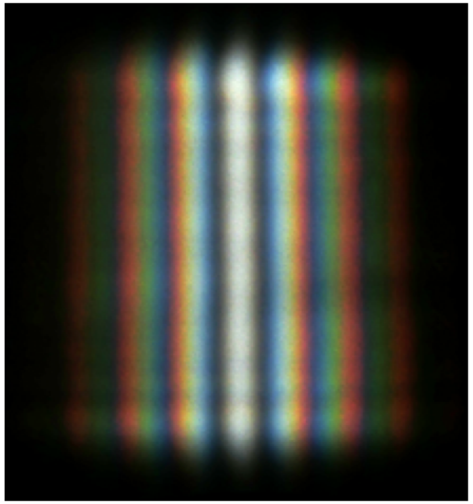
***"Actually Huygens' principle is not correct in optics. It is replaced by Kirchoff's modification which requires that both the amplitude and its derivative must be known on the adjacent surface. This is a consequence of the fact that the wave equation in optics is second order in the time. The wave equation of quantum mechanics is first order in the time; therefore, Huygens' principle is correct for matter waves, action replacing time."***

# AN INCREDIBLE EXPERIMENT

In May of 1801, while pondering some of Newton's experiments, Young came up with the basic idea for the now-famous double-slit experiment to demonstrate the interference of light waves. **The demonstration would provide solid evidence that light was a wave, not a particle.**

**In the first version of the experiment, Young actually didn't use two slits, but rather a single thin card. He covered a window with a piece of paper with a tiny hole in it. A thin beam of light passed through the hole. He held the card in the light beam, splitting the beam in two. Light passing on one side of the card interfered with light from the other side of the card to create fringes, which Young observed on the opposite wall.**

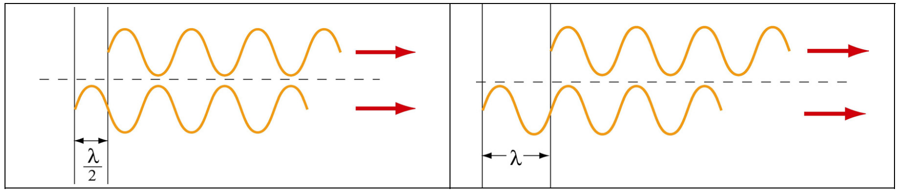
**Thomas Young**
1773-1829)

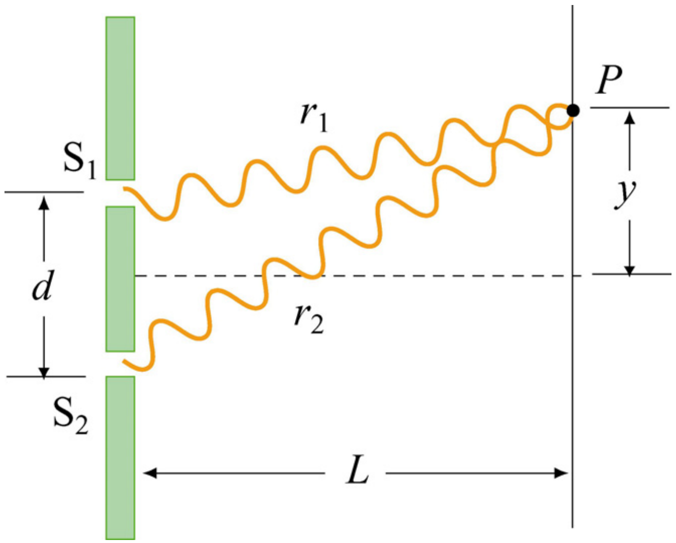


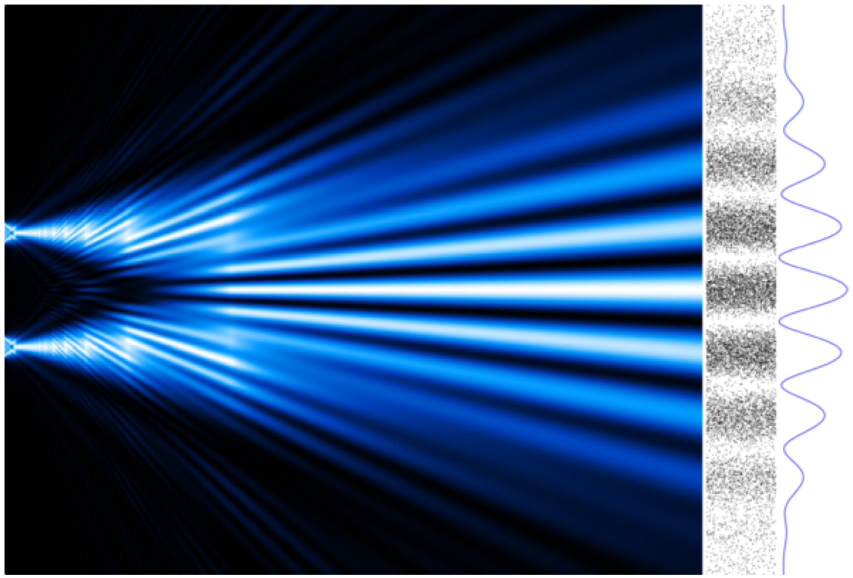
# CONFORMING THAT LIGH IS A WAVE

**Young also used his data to calculate the wavelengths of different colors of light, coming very close to modern values. In November 1801 Young presented his paper, titled “On the theory of light and color” to the Royal Society. In that lecture, he described interference of light waves and the slit experiment. He also presented an analogy with sound waves and with water waves, and even developed a demonstration of of the interference of waves travelling in a tank to show interference patterns in water.**

$$I = \langle S \rangle \propto \langle E_1^2 \rangle + \langle E_2^2 \rangle + 2\langle \vec{\mathbf{E}}_1 \cdot \vec{\mathbf{E}}_2 \rangle$$



# A SCIENTIFIC TRIAL

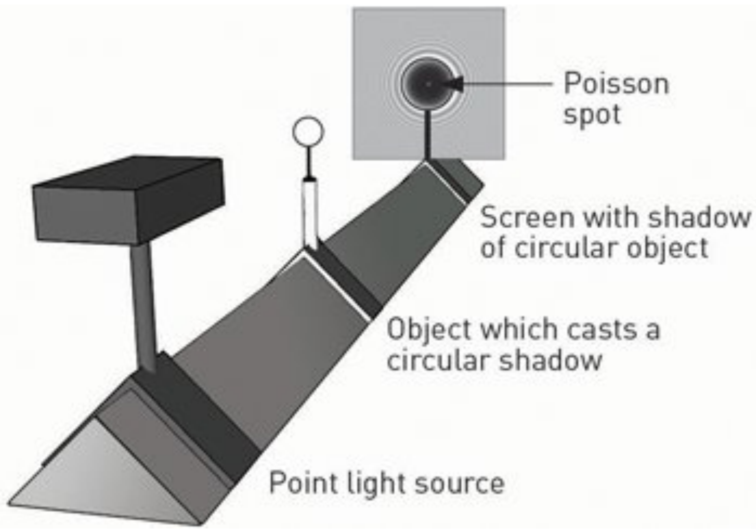
# A SCIENTIFIC TRIAL

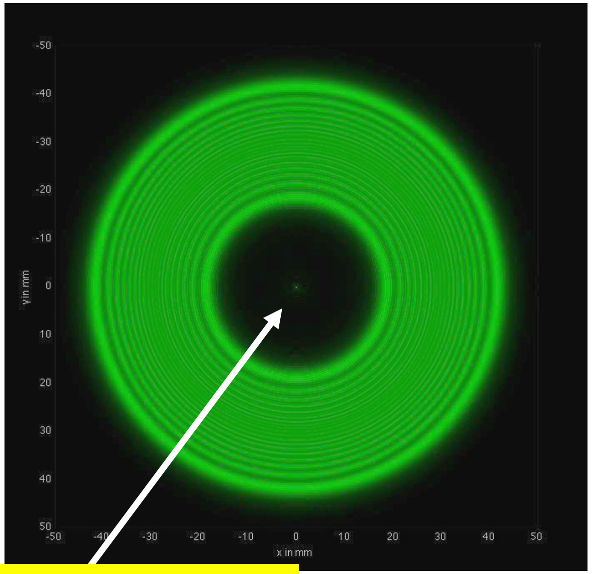
In 1817, the corpuscular theorists at the French Academy of Sciences which included Siméon Denis Poisson were so confident that they set the subject for the next year's prize as diffraction, being certain that a particle theorist would win it.

Augustin-Jean Fresnel submitted a thesis based on wave theory and whose substance consisted of a synthesis of the Huygens' principle and Young's principle of interference. Poisson studied Fresnel's theory in detail and of course looked for a way to prove it wrong being a supporter of the particle theory of light.

Poisson thought that he had found a flaw when he argued that a consequence of Fresnel's theory was that there would exist an on-axis bright spot in the shadow of a circular obstacle blocking a point source of light, where there should be complete darkness according to the particle-theory of light. Fresnel's theory could not be true, Poisson declared: surely this result was absurd. (The Fresnel spot is not easily observed in everyday situations, because most everyday sources of light are not good point sources. In fact it is readily visible in the defocused telescopic image of a moderately bright star, where it appears as a bright central spot within a concentric array of diffraction rings.)

# THE FERSNEL'S TRIUMPH



**TINY LIGHT SPOT**

**Augustin-Jean *Fresnel* (1788–1827)**

However, the head of the committee, Dominique-François-Jean Arago thought it was necessary to perform the experiment in more detail. He molded a 2-mm metallic disk to a glass plate with wax. To everyone's surprise he succeeded in observing the predicted spot, which convinced most scientists of the wave-nature of light. In the end, Fresnel won the competition.

**After that, the corpuscular theory of light was vanquished, not to be heard of again till the 20th century. Arago later noted that the phenomenon (which is sometimes called the Arago spot) had already been observed by Joseph-Nicolas Delisle and Giacomo F. Maraldi a century earlier.**

# CHARGES MOVING IN THE SPACE-TIME: THE SPECIAL RELATIVITY

# THE FIRST CONSISTEN SYNTHESIS

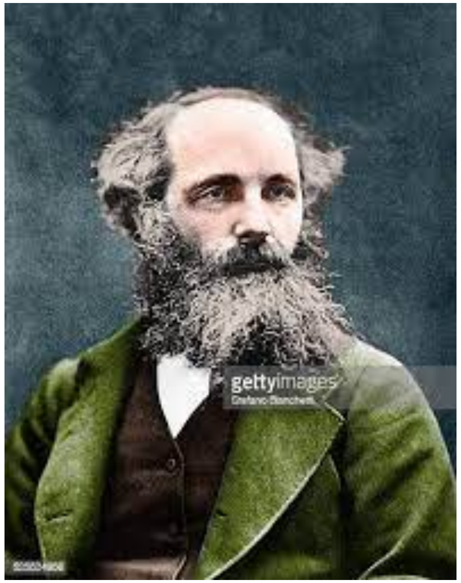
These ideas were unified in 1862, when Maxwell (1831-1879) published “On Physical Lines of Force,” in which **he established that electromagnetic radiation propagates in a vacuum at the speed of light, and concluded light is a form of electromagnetic radiation**. He remarked, **“we can scarsely avoid the conclusion that light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena.”**

$$\operatorname{div} \boldsymbol{B} = \nabla \cdot \boldsymbol{B} = 0 \qquad \text{(Gauss's flux theorem)}$$

$$\operatorname{div} \boldsymbol{E} = \nabla \cdot \boldsymbol{E} = 0 \qquad \text{(Gauss's law for magnetism)}$$

$$\operatorname{curl} \boldsymbol{E} = \nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t} \qquad \text{(Faraday's law)}$$

$$\operatorname{curl} \boldsymbol{B} = \nabla \times \boldsymbol{B} = \frac{1}{c^2}\frac{\partial \boldsymbol{E}}{\partial t}, \qquad \text{(Ampère's law)}$$



**James Clerk Maxwell (1831-1879)**

$$\operatorname{curl}\operatorname{curl} \boldsymbol{E} = -\frac{\partial}{\partial t}\operatorname{curl} \boldsymbol{B} = -\frac{1}{c^2}\frac{\partial^2 \boldsymbol{E}}{\partial t^2}.$$

Then, using the identity

$$\operatorname{curl}\operatorname{curl} \boldsymbol{E} = \nabla \operatorname{div} \boldsymbol{E} - \Delta \boldsymbol{E},$$

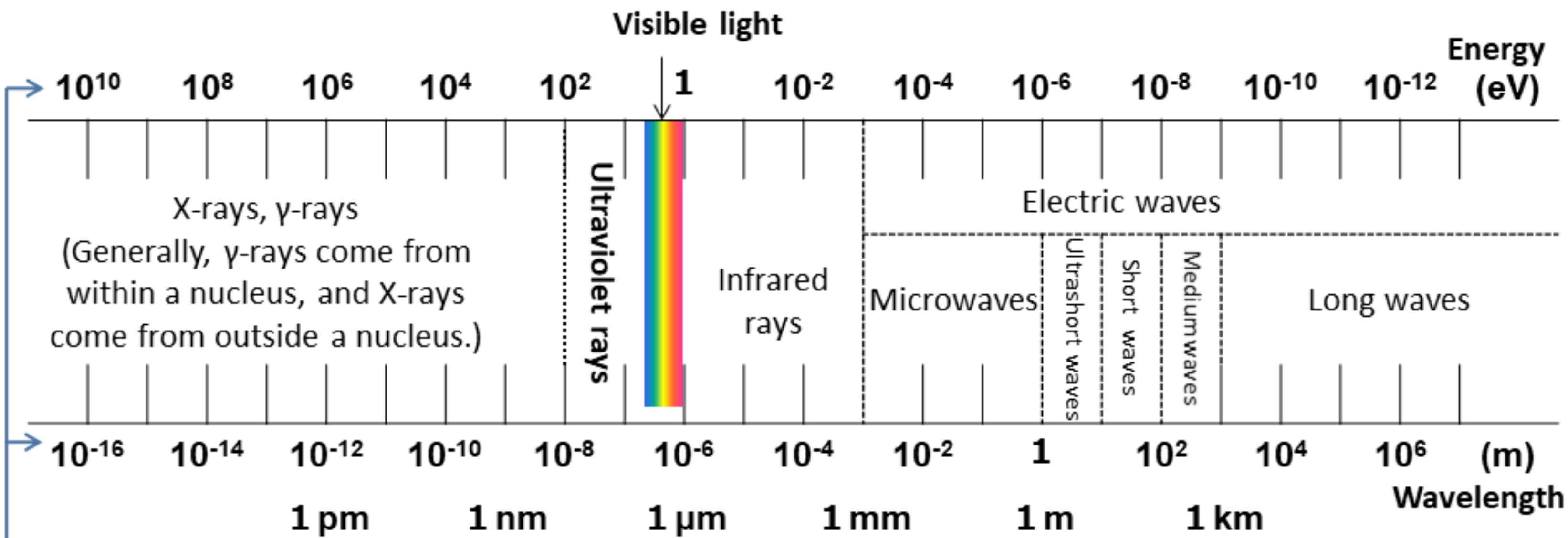
we conclude

$$\Delta \boldsymbol{E} = \frac{1}{c^2}\frac{\partial^2 \boldsymbol{E}}{\partial t^2} = 0.$$

Since this equation decouples the evolution of the three components of the field, we can solve for each component independently. We will denote the chosen component by $E$, and we look to solve the **scalar wave equation**:

$$\Delta E - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = 0.$$

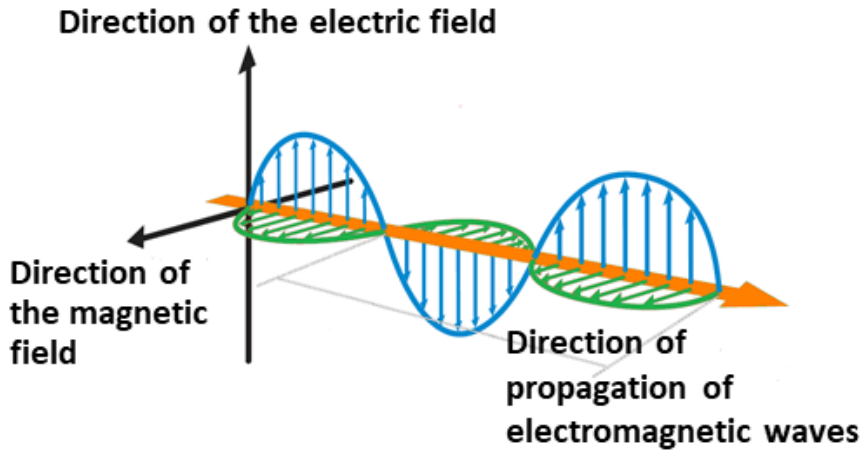
# Radiation Types of Electromagnetic Waves




- Light has particle properties in addition to wave properties.
- Electromagnetic waves are called "photons" when they are considered as particles.

The values indicated above show photons' energy (eV) and those indicated below show their wavelengths (m) as wave motions.

pm: picometers
nm: nanometers
μm: micrometers
eV: electron volts




Ministry of the Environment
Government of Japan
環境省

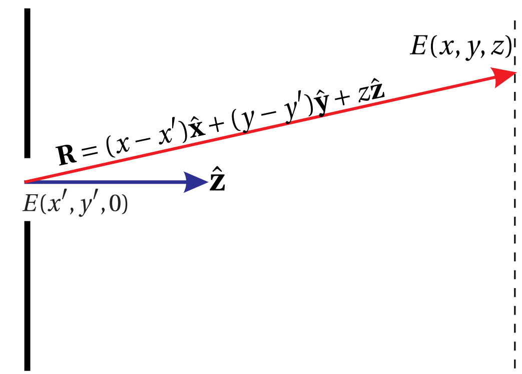
# DIFFRACTION EXPLAINED

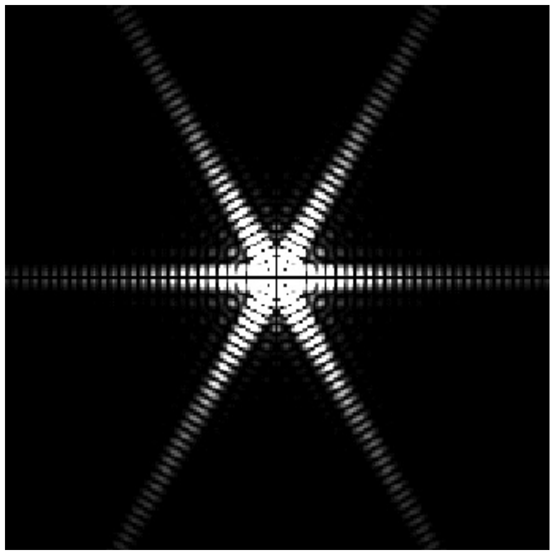
Building on Maxwell's work, and on advances in the theory of partial differential equations made by **George Green (1793- 1841)** and **Hermann von Helmholtz (1821-1894), Gustav Kirchhoff (1824-1887)** **showed that Young's and Fresnel's work could be deduced as a suitable approximation of the Fresnel-Kirchhoff integral formula**. **His deduction came to be known as Kirchhoff's theory of diffraction or the Fresnel- Kirchhoff theory of diffraction.**

Finally, in 1896 **Arnold Sommerfeld (1868-1951)** published **"Mathematical Theory of Diffraction."** He developed in the book a systematic study of diffraction of waves by formally reducing it to the study of a boundary value problem in mathematical physics.

The next year **John W. Strutt (Lord Rayleigh) (1842-1919)** published **"On the passage of waves through apertures in plane screens,"** in which he examined the consequences of imposing different boundary conditions on the solutions to the Helmholtz equation.

$$E(x,y,z) = -\frac{i}{\lambda} \iint\limits_{\text{aperture}} E(x',y',0)\, \frac{e^{ikR}}{R} \left[ \frac{1+\cos(\mathbf{R},\hat{\mathbf{z}})}{2} \right] dx'\,dy'$$

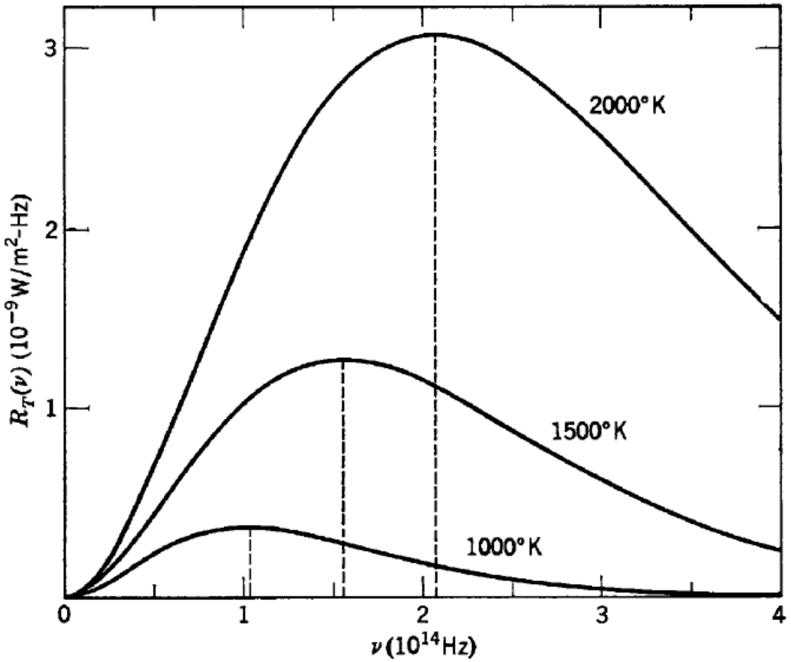


**(d)** triangular aperture

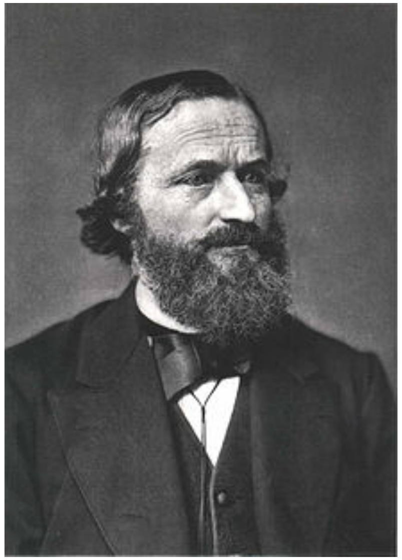
BLACKBODY

# THE RISE OF A NEW PHYSICS

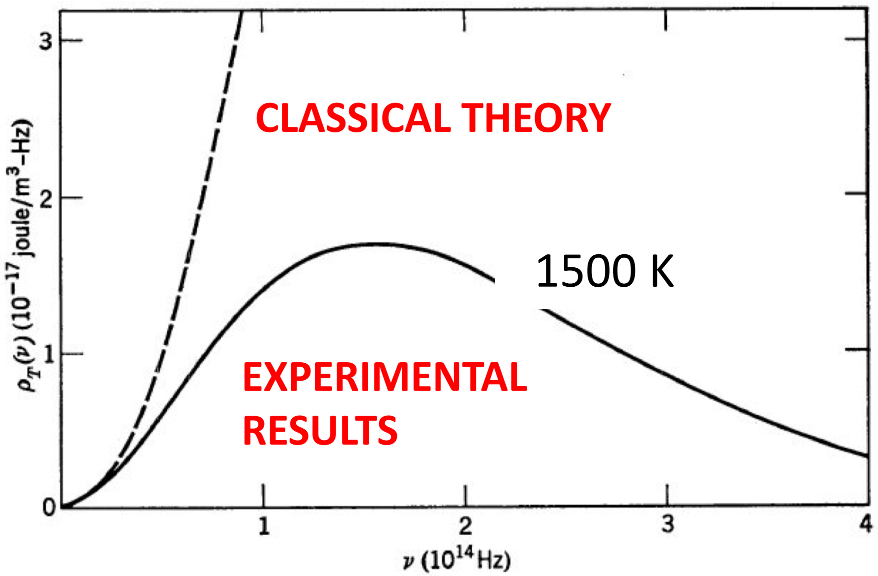


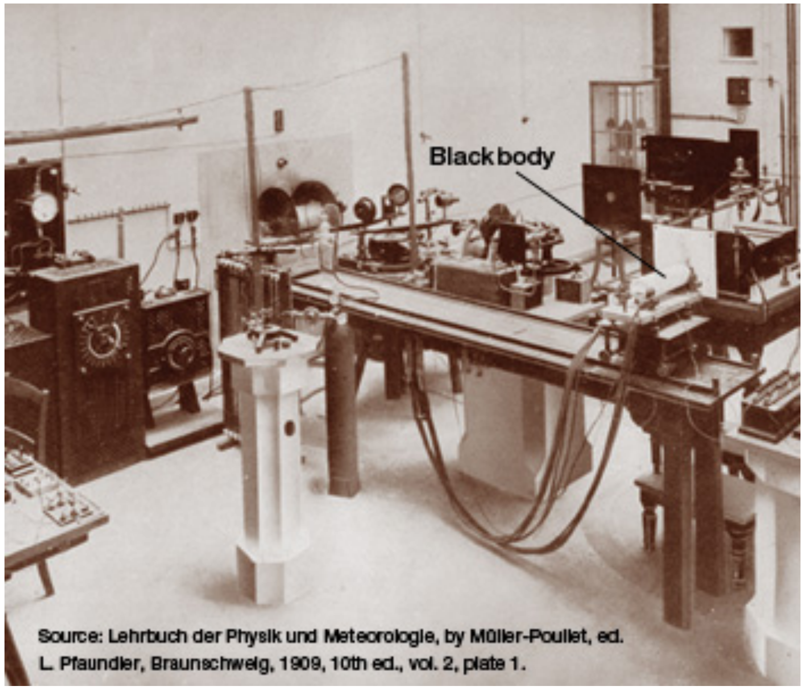

Spectral distribution of the intensity of blackbody radiation as a function of frequency for several temperatures. First accurate measurements of $R_T(\nu)$ by Lummer and Pringsheim in 1899

There are two important features of these curves:



**Gustav Robert Kirchhoff** 1824-1887)



# A DIFFICULT PUZZLE

Kirchhoff excluded any dependence on material or form by adding another idealization: so typical of his style, he limited his observations to ideal ‘black bodies,’ which he described as follows:

***When a cavity is entirely surrounded by bodies at the same temperature that are impenetrable to rays, then every beam of radiation in the interior of that space must, with regard to its quality and intensity, be constituted as if it had emanated from a perfectly black body at the same temperature and must therefore be independent of the form and nature of those bodies, having been determined by the temperature alone. One sees the validity of this assumption when one considers that a beam that has the same form and the opposite direction to the selected one is entirely absorbed after undergoing the enumerable successive reflections inside the imagined bodies. Accordingly, the same luminosity always occurs in the interior of an opaque glowing body at a particular temperature, irrespective of how it is otherwise composed***

*[Kirchhoff, Gustav Robert. 1860. Ueber das Verhältnis zwischen dem Emissionsvermögen und dem Absorptionsvermögen der Körper für Wärme und Licht, (a) Annalen der Physik, Leipzig (2) 109: 275–301 & pls. II-III; (b) Engl. transl.: On the relation between the radiating and absorbing powers of different bodies for light and heat, Philosophical Magazine, London (4) 20: 1–21; (c) reprinted in Ostwalds Klassiker series, no. 100, ed. by Max Planck. ]*

# ELECTROMAGNETISM-STATISTICAL MECHANICS-THERMODYNAMICS

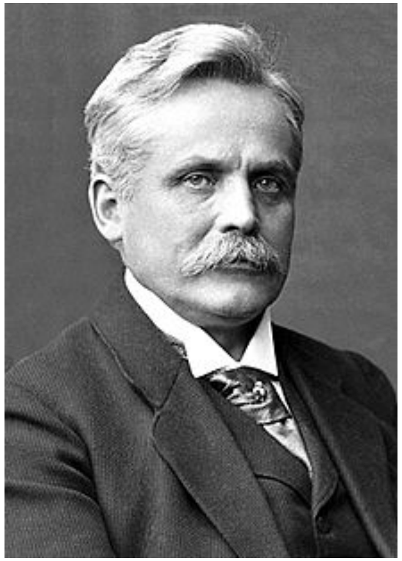
Attached to this idealization was the guarantee that the density of the radiation energy $\rho(\nu, T)$ would be independent of the material. But it also offered the possibility to transfer the concept of temperature away from the cavity walls onto the radiation in its vicinity, taking into account the thermal equilibrium between matter and radiation. It then made sense to speak of the temperature or entropy of radiation.

The problem defined by Kirchhoff one generation before was thus reduced to the question of what form this dimensionless function $\rho(\nu, T)$ should take for the idealized 'blackbody' at radiation equilibrium. Einstein described this situation in historical retrospect, with his characteristic irony:

***"It would be edifying if the brain matter sacrificed by theoretical physicists on the altar of this universal function $\rho(\nu,T)$ could be put on the scales; and there is no end in sight to this cruel sacrifice! What's more: classical mechanics also fell victim to it, and one still cannot tell whether Maxwell's electrodynamic equations will survive the crisis that this function f has brought about ."***

**Wilhelm Wien**, who was co-editor of *Annalen der Physik* at the time, had been one of the first to make a concrete suggestion regarding the form this function *f* (ν, *T* ) could take

$$\rho(\nu, T) = \alpha \nu^3 e^{b\nu/T}.$$



**Wilhelm Wien**
1864-1928)

**For a number of years Planck believed that this formula was correct. He attempted repeatedly to derive it out of fundamental electrodynamic and thermodynamic theorems, but it refused to work.**

**In 1900 Planck learned from Berlin experimenters that this formula agreed with their laboratory results to good or very good approximation only for large ν. It evidently completely failed for small ν. Another formula fit extremely well for the low-energy end of the spectrum, that is, toward the red, and even more so in the infrared spectral range. Lord Rayleigh and William Jeans in England had derived it from Maxwell's electrodynamics and from statistical mechanics**

$$\rho(\nu, T) = \frac{8\pi\nu^2}{c^3} k_{\mathrm{B}} T$$

# A SHORT HISTORY OF THE PHOTON

## END OF THE SECOND LECTURE

# A PUZZLING QUESTION

What has to do the ESHER’s figure below
with Poincaré, Minkowski and the photons?