Title: Einstein and Quantum Mechanics: Itâ€™s Not What You Think

Speakers: A. Douglas Stone

Series: Colloquium

Date: May 15, 2019 - 2:00 PM

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Abstract: Einstein is well known for his rejection of quantum mechanics in the form it emerged from the work of Heisenberg, Born and Schrodinger in 1926. Much less appreciated are the many seminal contributions he made to quantum theory prior to his final scientific verdict: that the theory was at best incomplete. In this talk I present an overview of Einsteinâ€™s many conceptual breakthroughs and place them in historical context. I argue that Einstein, much more than Planck, introduced the concept of quantization of energy in atomic mechanics. Einstein proposed the photon, the first force-carrying particle discovered for a fundamental interaction, and put forward the notion of wave-particle duality, based on sound statistical arguments 14 years before De Broglieâ€™s work. He was the first to recognize the intrinsic randomness in atomic processes, and introduced the notion of transition probabilities, embodied in the A and B coefficients for atomic emission and absorption. He also preceded Born in suggesting the interpretation of wave fields as probability densities for particles, photons, in the case of the electromagnetic field. Finally, stimulated by Bose, he introduced the notion of indistinguishable particles in the quantum sense and derived the condensed phase of bosons, which is one of the fundamental states of matter at low temperatures. His work on quantum statistics in turn directly stimulated Schrodinger towards his discovery of the wave equation of quantum mechanics. It was only due to his rejection of the final theory that he is not generally recognized as the most central figure in this historic achievement of human civilization.

Einstein and quantum mechanics: It's not what you think

A. Douglas Stone – Yale University, Applied Physics and Yale Quantum Institute

Perimeter Institute – 5/15/19

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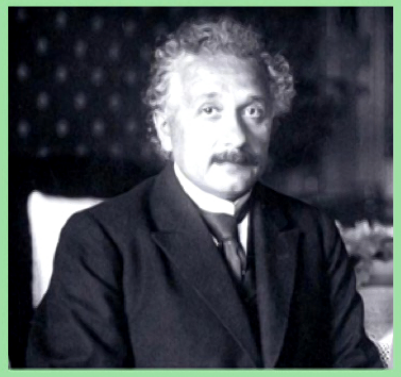
Einstein to Born, December 1926



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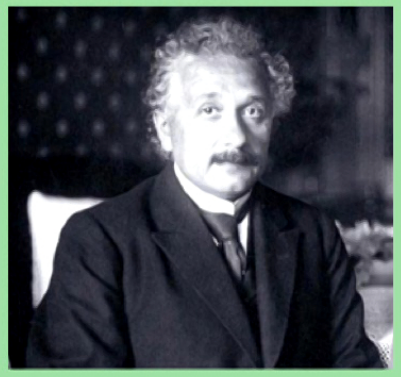

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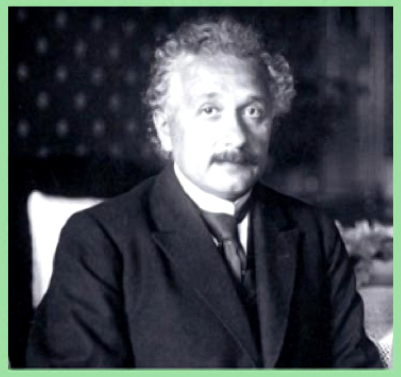

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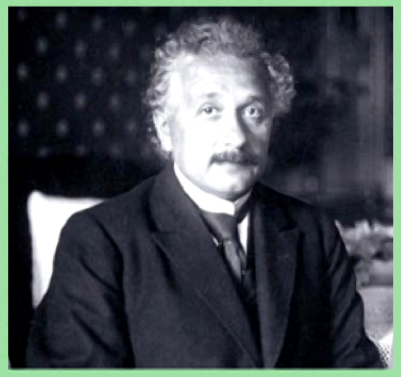

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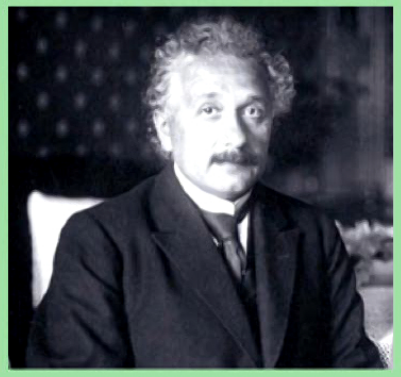
"The other great problem that I have concerned myself with since 1900 is that of radiation and the quantum theory… I have helped create the complex of ideas known by the name of quantum theory…I shall probably devote the rest of my life to the clarification of this problem, however slight the prospects for attaining the goal may be. "
Einstein, 1924



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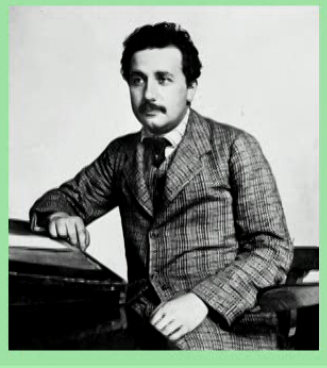
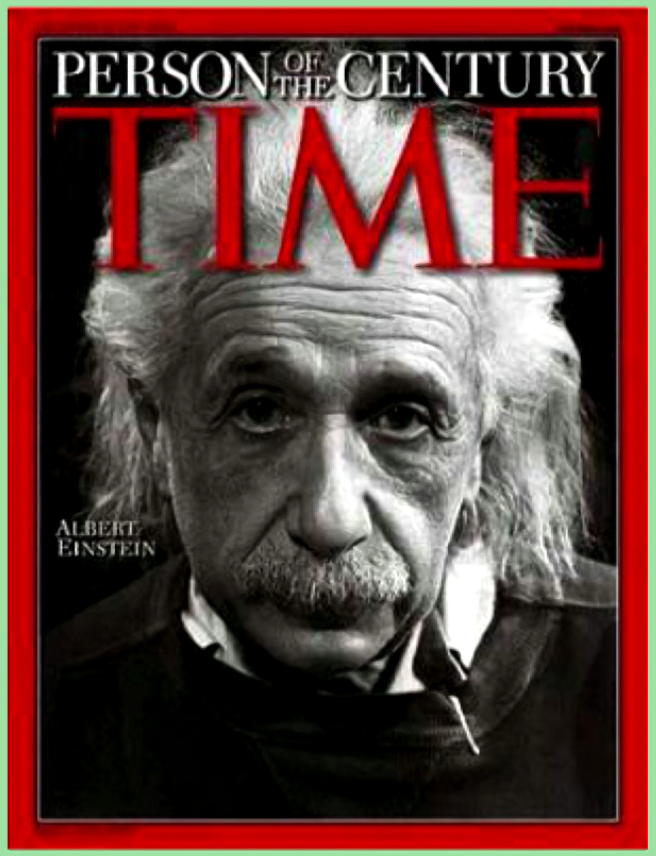
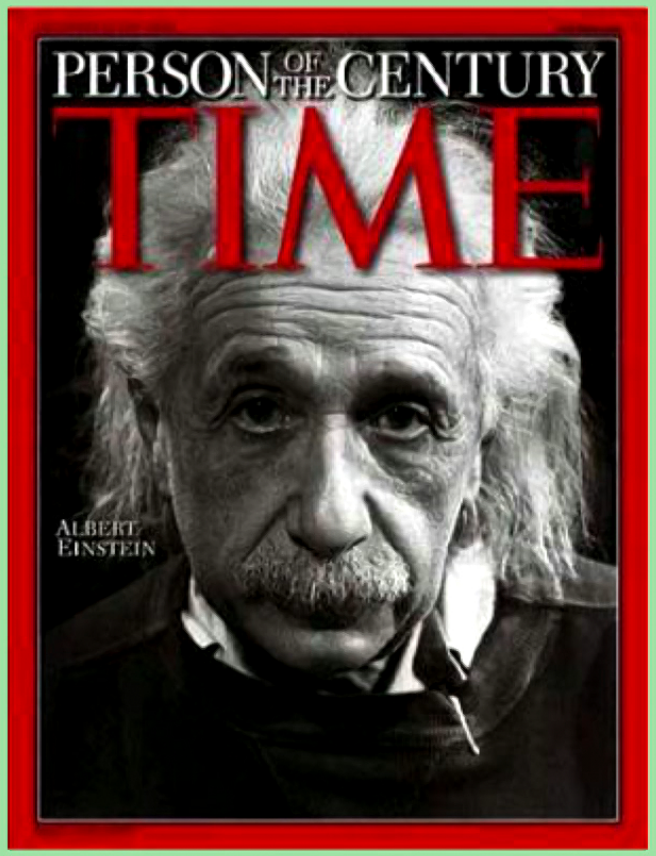
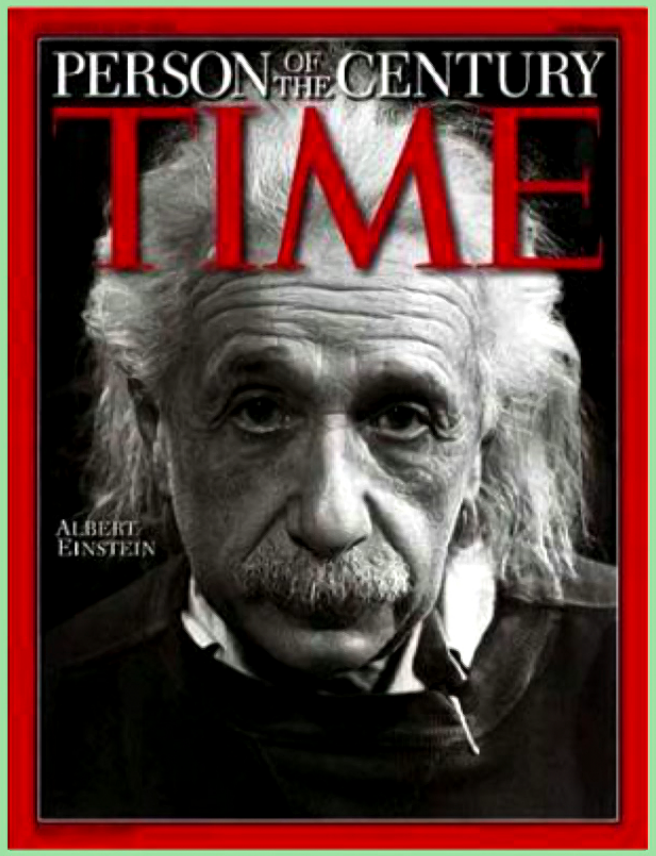


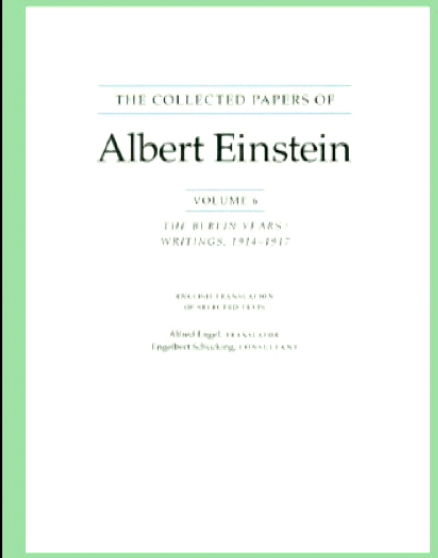

PERSON OF THE CENTURY
TIME
ALBERT EINSTEIN

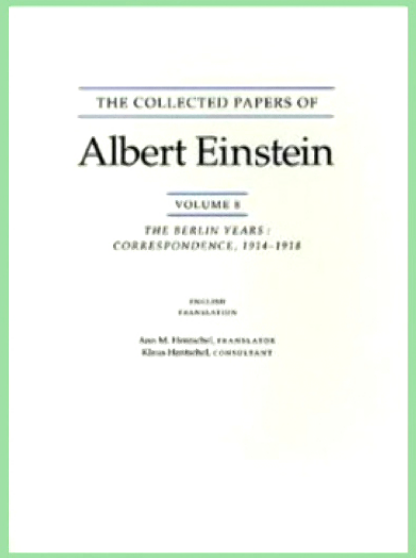
This guy doesn't get enough credit?

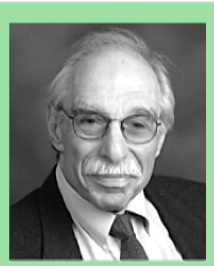




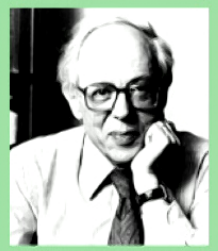
Yes!



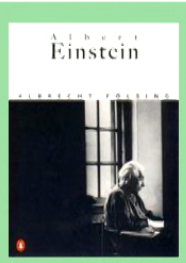




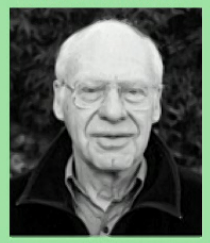
Martin Klein



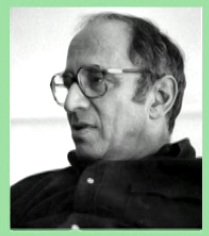
Abraham Pais



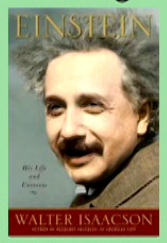
Folsing



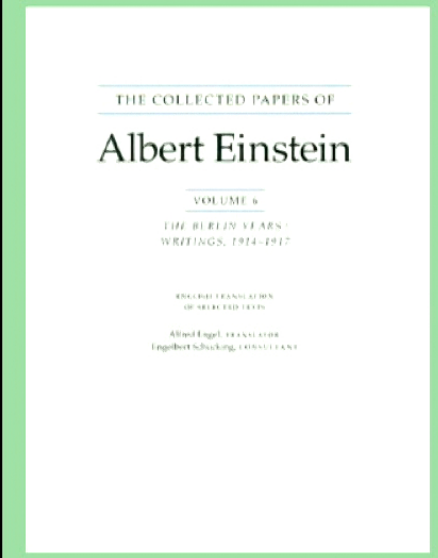
John Stachel

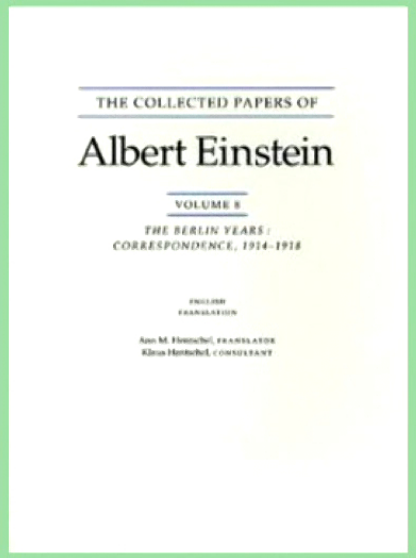


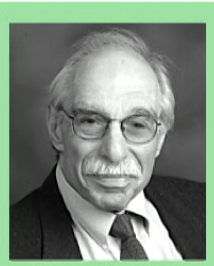
T.S. Kuhn



Isaacson



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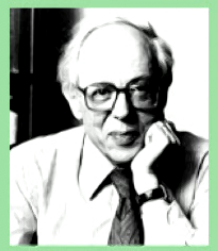
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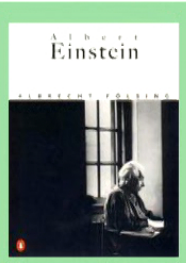

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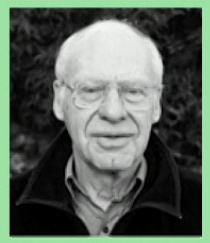
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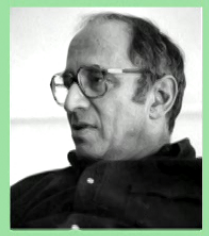
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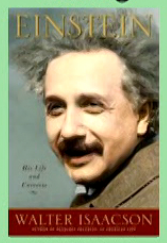

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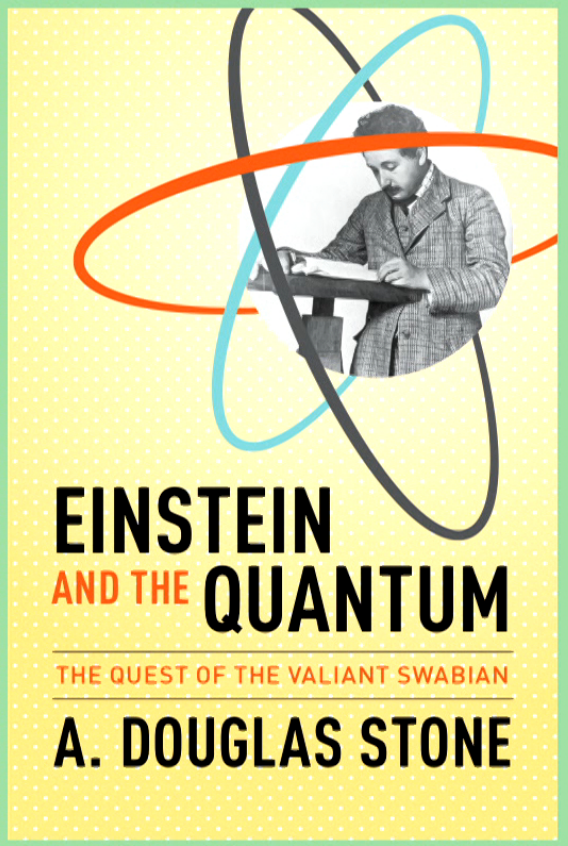
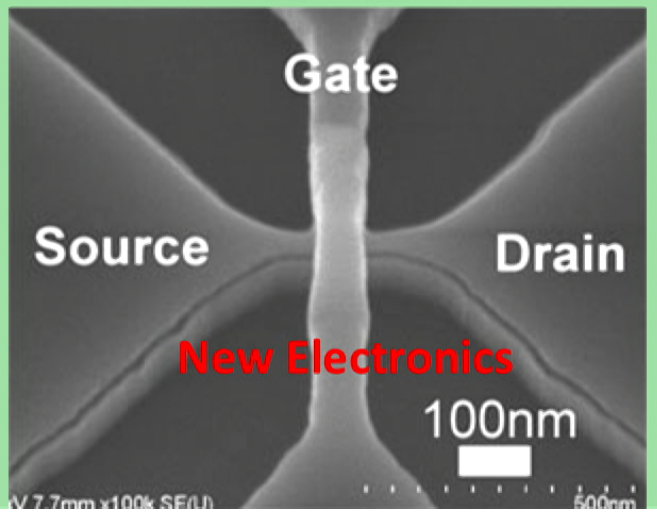


Synthetic history/biography
+ science pedagogy

20th Century: The Atomic Age

Quantum Theory/Mechanics:
A turning point in human civilization



Einstein Scientific Timeline

1902-1905
Bern patent office
The Miracle Year
(1905)

Foundations of Stat mech
Quanta of Light
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Foundations of Stat mech **Quanta of Light** Special Relativity $E=mc^2$ Brownian Motion	**Quantization of Energy** **Quantum Theory of Solids** Equivalence Principle (seed of GR)	**Wave-particle Duality** Unsuccessful Quantum Theory of Radiation

Einstein Scientific Timeline

1916-18
Univ Berlin

Quantum Theory of Radiation
Atomic Probabilities (BORN)
Gravitational Waves
Cosmology

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8 seminal ideas in quantum theory

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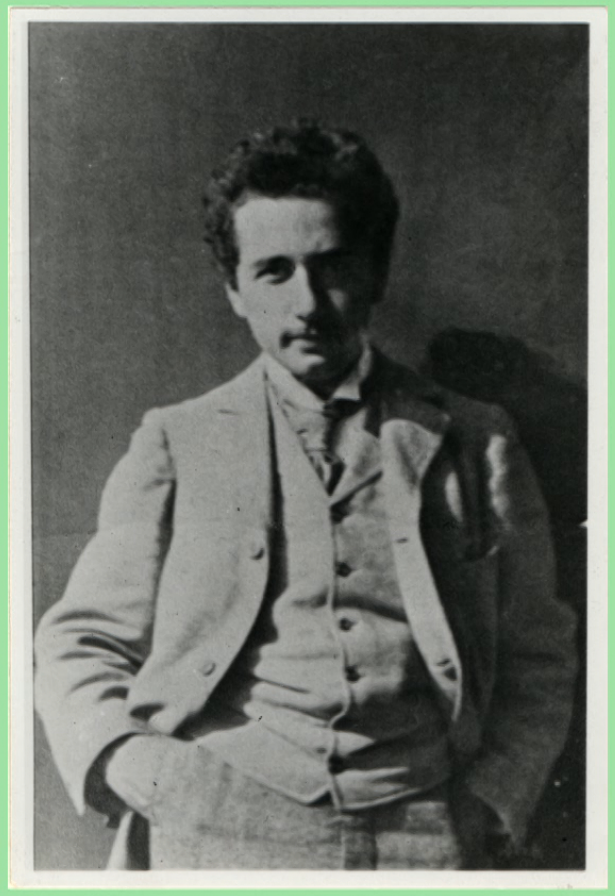
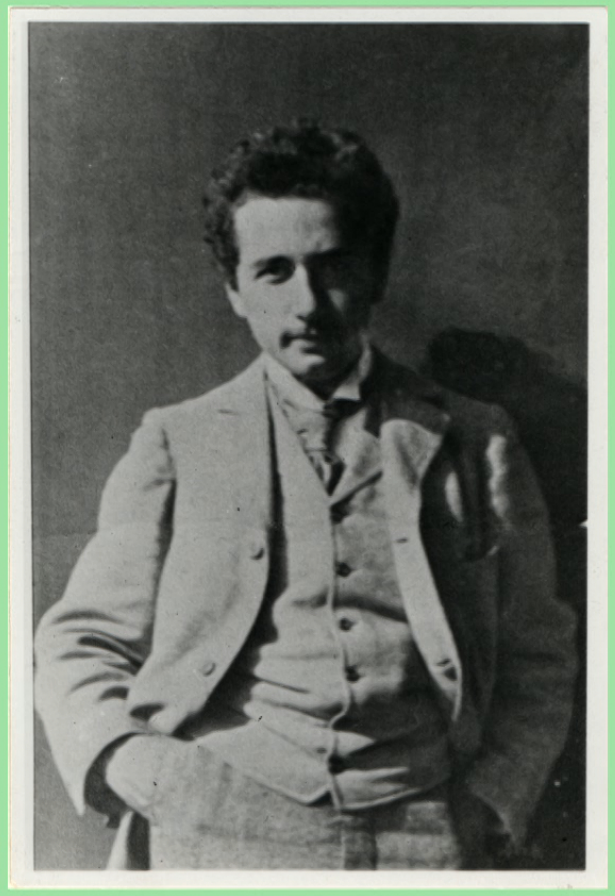
"The Valiant Swabian is not afraid"



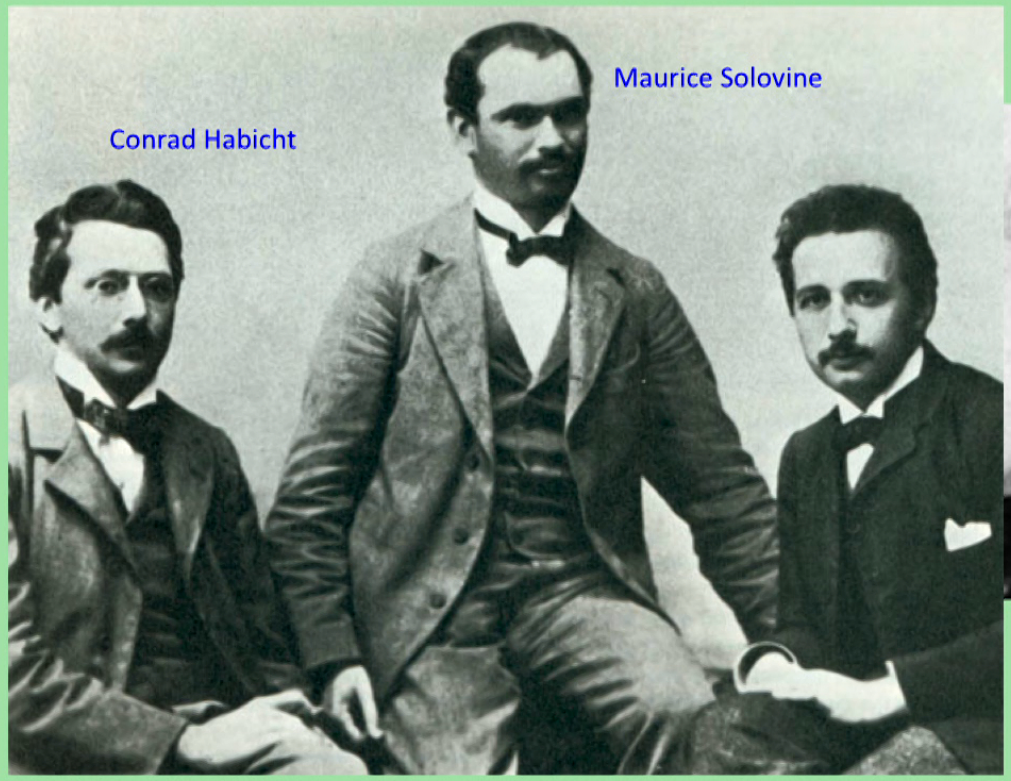
Student at ETH (1898)

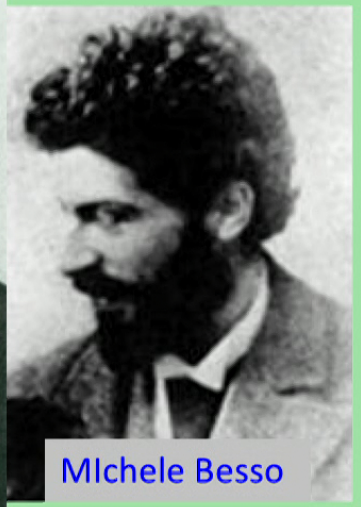


Student at ETH (1898)

Young father, Bern (1904)

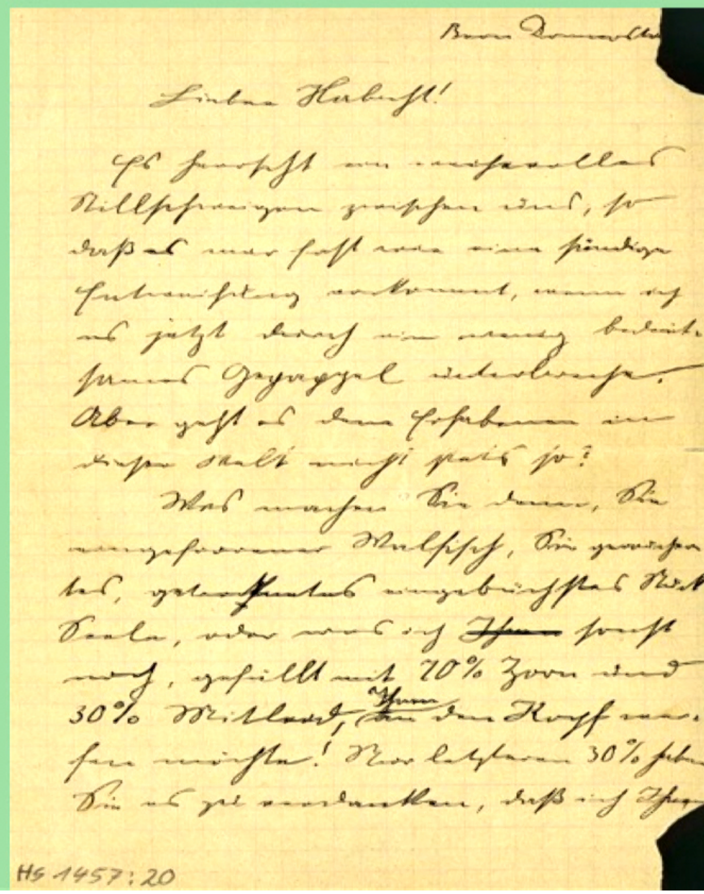
The Olympia Academy





1905 – The Miracle Year

March 1905: Einstein announces his achievements to Habicht:



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I promise you four papers in return, the first deals with radiation and the energy properties of light and is very revolutionary…
The fourth study is still a mere concept: the electrodynamics of moving bodies by the use of a modification of the theory of space and time."

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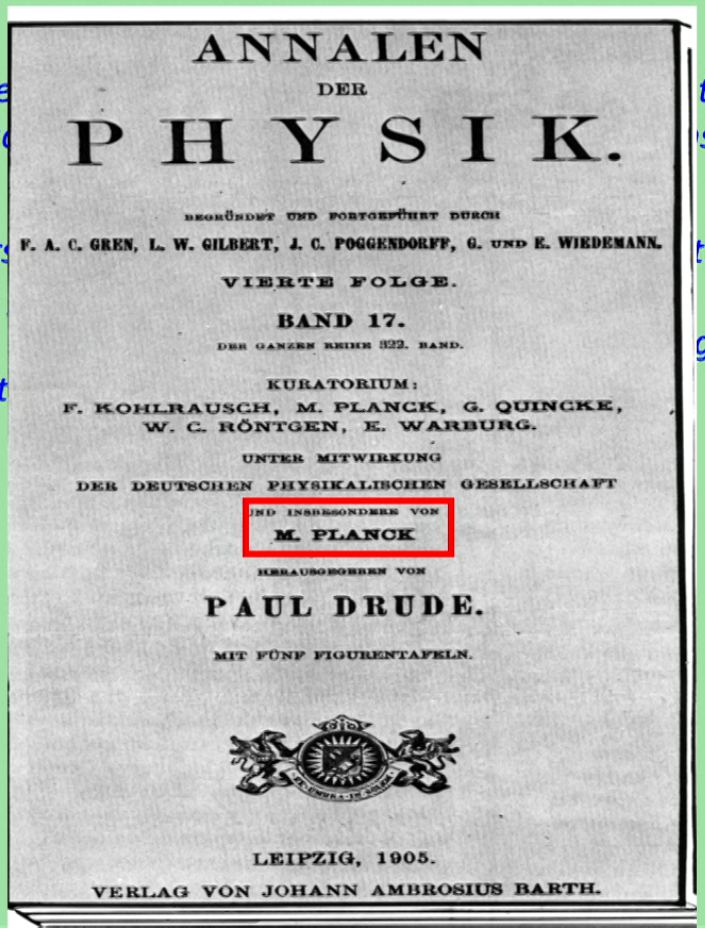

ANNALEN
DER
PHYSIK.
BEGRÜNDET UND FORTGEFÜHRT DURCH
F. A. C. GREN, L. W. GILBERT, J. C. POGGENDORFF, G. UND E. WIEDEMANN.
VIERTE FOLGE.
BAND 17.
DER GANZEN REIHE 322. BAND.
KURATORIUM:
F. KOHLRAUSCH, M. PLANCK, G. QUINCKE,
W. C. RÖNTGEN, E. WARBURG.
UNTER MITWIRKUNG
DER DEUTSCHEN PHYSIKALISCHEN GESELLSCHAFT
UND INSBESONDERE VON
M. PLANCK
HERAUSGEGEBEN VON
PAUL DRUDE.
MIT FÜNF FIGURENTAFELN.
LEIPZIG, 1905.
VERLAG VON JOHANN AMBROSIUS BARTH.

1905 – The Miracle Year

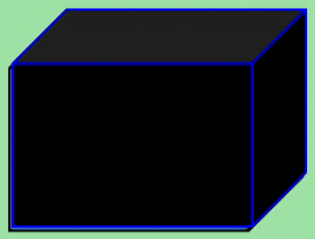
March 1905: Einstein announces his achievements to Habicht:

Dear Habicht, such a solemn air of silence has descended between us that I almost feel as if I am committing a sacrilege when I break it now with some inconsequential babble…

I promise you four papers in return, the first deals with radiation and the energy properties of light and is very revolutionary…
The fourth study is still a mere con[illegible]t: the electrodynamics of moving bodies by the use of a modification of the theory of space and time.'

Very Revolutionary

Blackbody Radiation and Planck's Law



infrared

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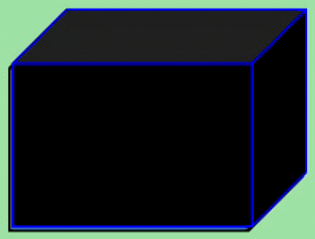

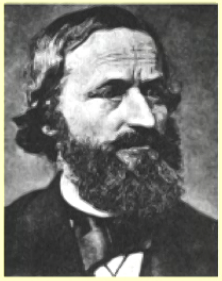

Gustav Robert Kirchhoff
(1824-1887)

Kirchoff (1860): The energy emitted by a BB at frequency ν is described by a universal mathematical function $\rho(\nu, T)$ = the law of thermal radiation

Modern point of view on BB Law

=> Just a photon gas in thermal equilibrium

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$$\rho(\nu, T) = h\nu \times \bar{n}(\nu, T) \times \frac{4\pi k^2 dk}{(2\pi)^3} \times 2$$

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Wien's Law

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Optical frequencies

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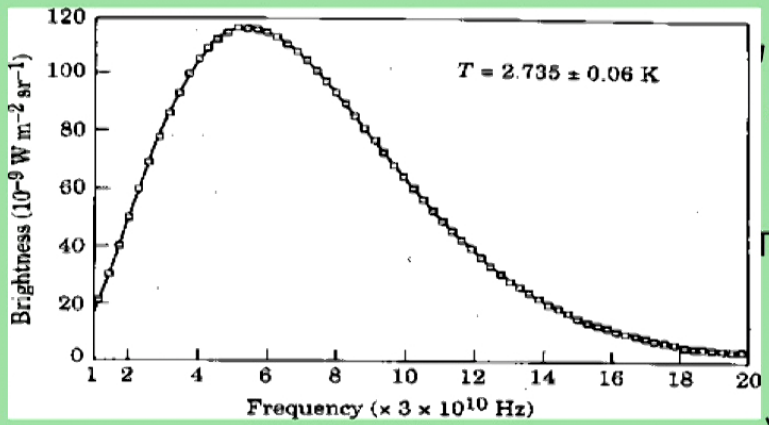

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Quantum Begins

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Planck

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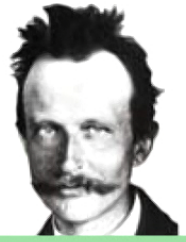

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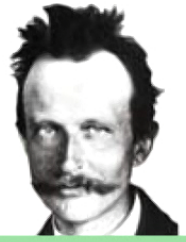

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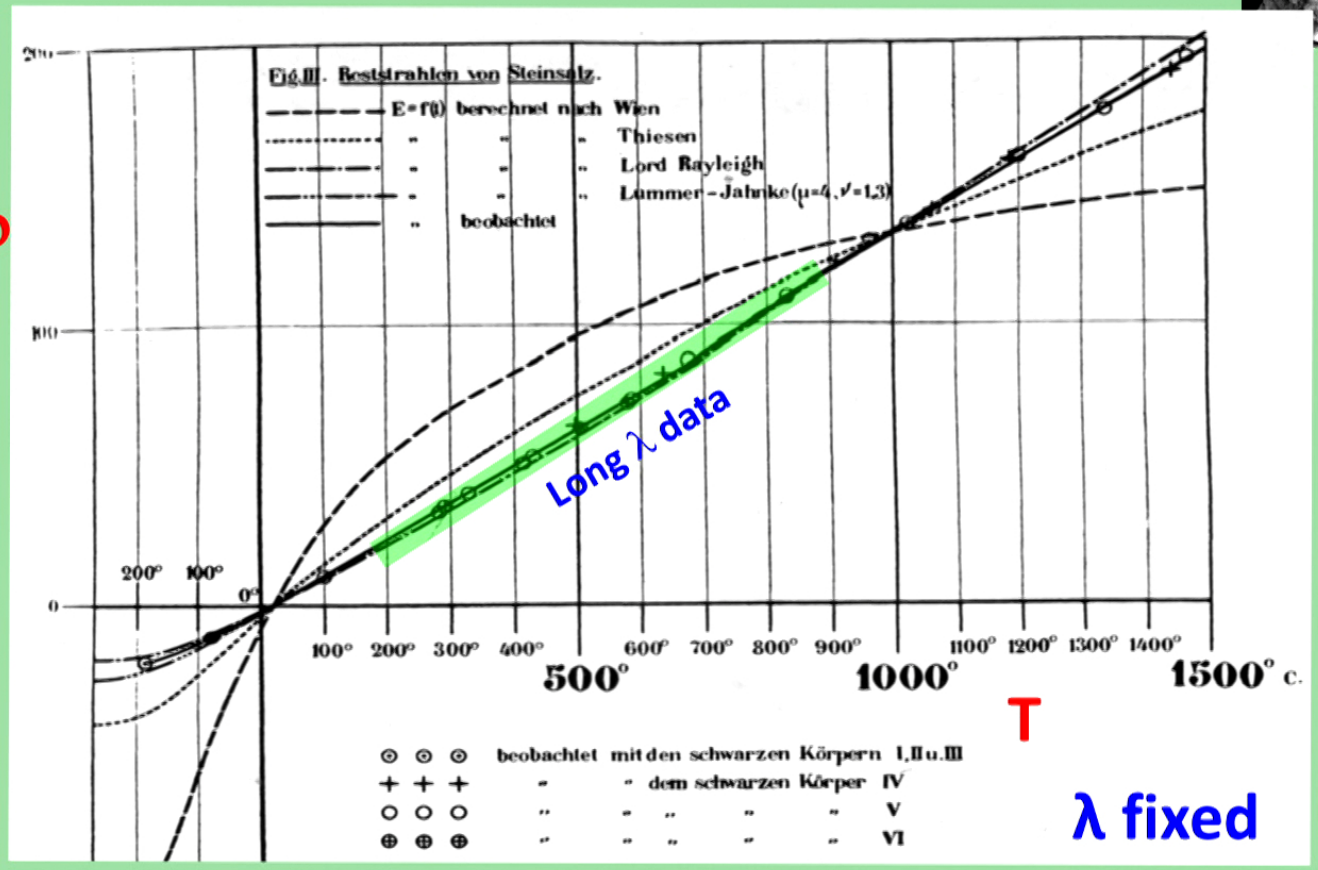
- ***PLANCK WAS COMMITTED!***

October 19th, 1900: Ferdinand Kurbaum presents latest expt data, Planck is in the audience



ρ

T

λ fixed

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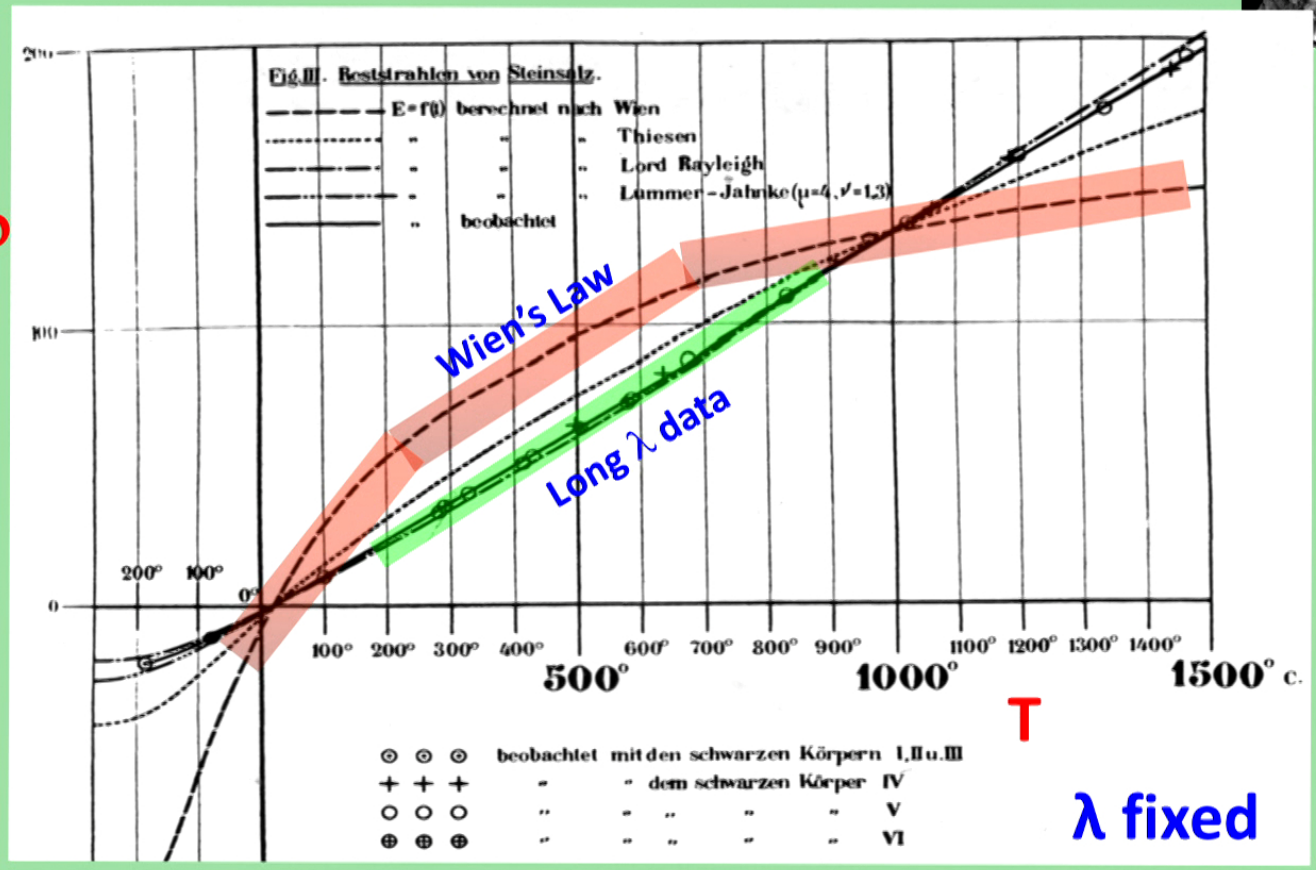

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Planck "guesses" the correct answer! It agrees beautifully with expt

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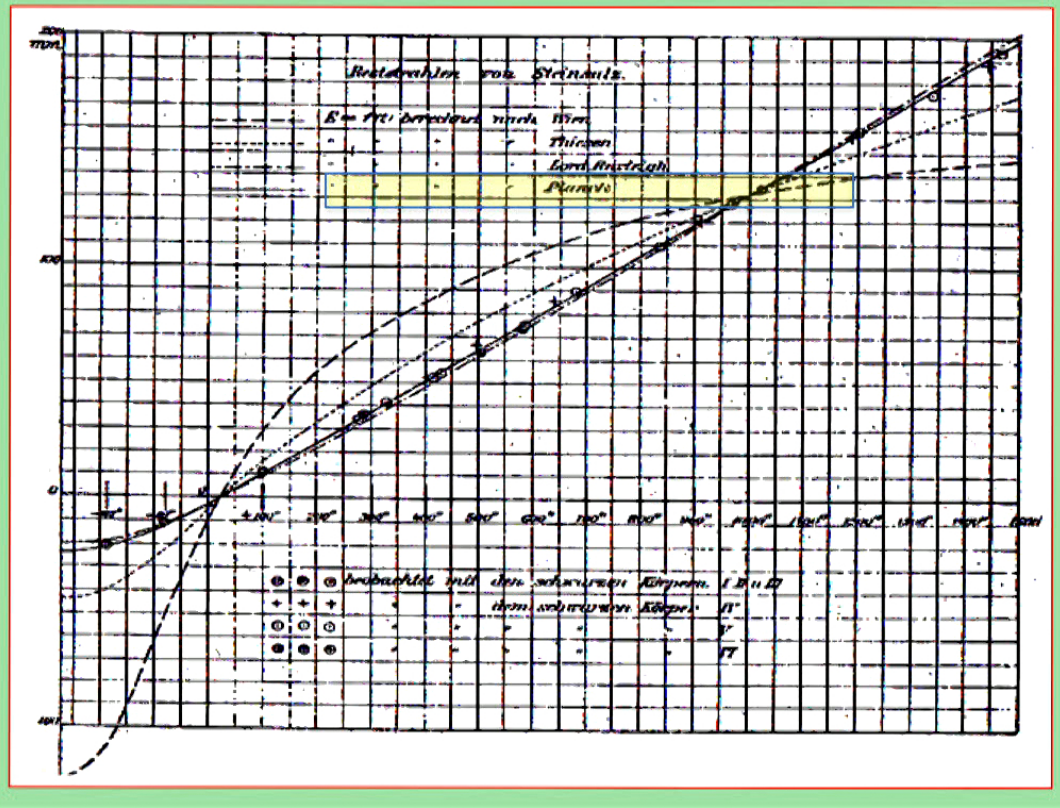

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    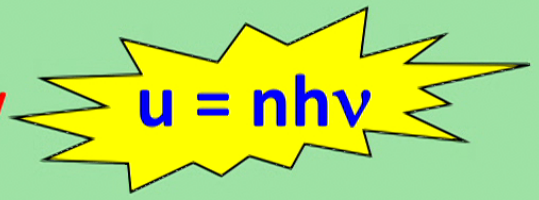

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    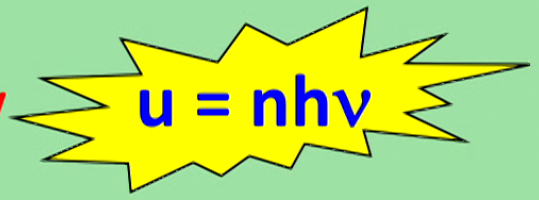

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    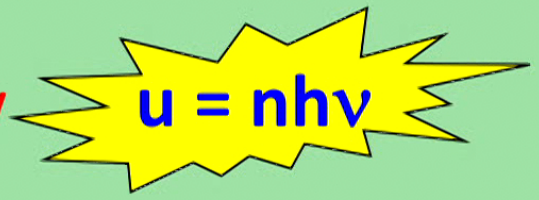

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    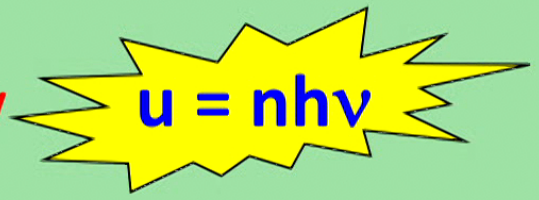

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$$W = \frac{(N+P-1)!}{(N-1)!P!}$$

The response:

Nothing, nada, bupkus, zilch, for 4 years

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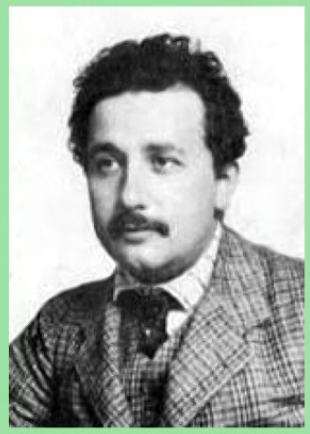
"On a Heuristic Point of View Concerning the Production and Transformation of Light", A. Einstein, March, 1905

The "revolutionary" paper – not a direct response to Planck



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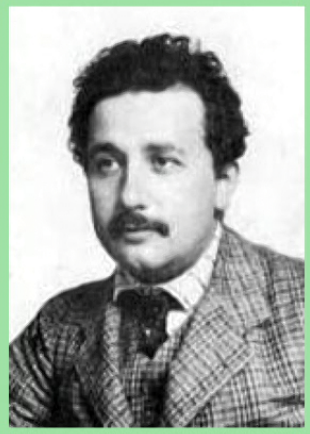

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• …{light] consists of a finite number of energy quanta, localised in space, which move without being divided and can be absorbed or emitted only as whole."

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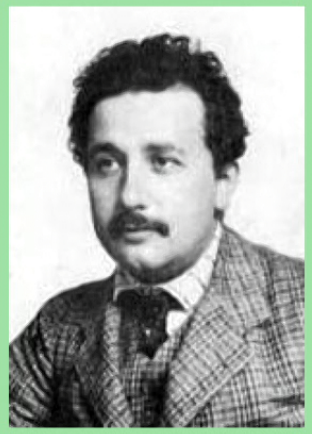

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"The most revolutionary sentence written by a physicist of the 20th century", Albrecht Folsing

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- There was little experimental evidence for photons.
- No one knows how he thought of it!

§1. *On a difficulty encountered in the theory of "black-body radiation"*

If we resolve the motion of the resonator electron into three mutually perpendicular oscillatory motions, we find for the mean value $\bar{E}$ of the energy of such a linear oscillatory motion

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$$\bar{E}_\nu = \frac{L^3}{8\pi\nu^2}\rho_\nu \ .$$

Planck

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Rayleigh-Jeans Law

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This relation, obtained as the condition of dynamic equilibrium, not only fails to agree with experience but it also states that in our model a definite distribution of energy between ether and matter is out of the question, since the wider the chosen range of the resonators' frequencies, the larger the radiation energy of the space, and we obtain in the limit

$$\int_0^\infty \rho_\nu d\nu = \frac{R}{N}\frac{8\pi}{L^3}T\int_0^\infty \nu^2 d\nu = \infty \ .$$

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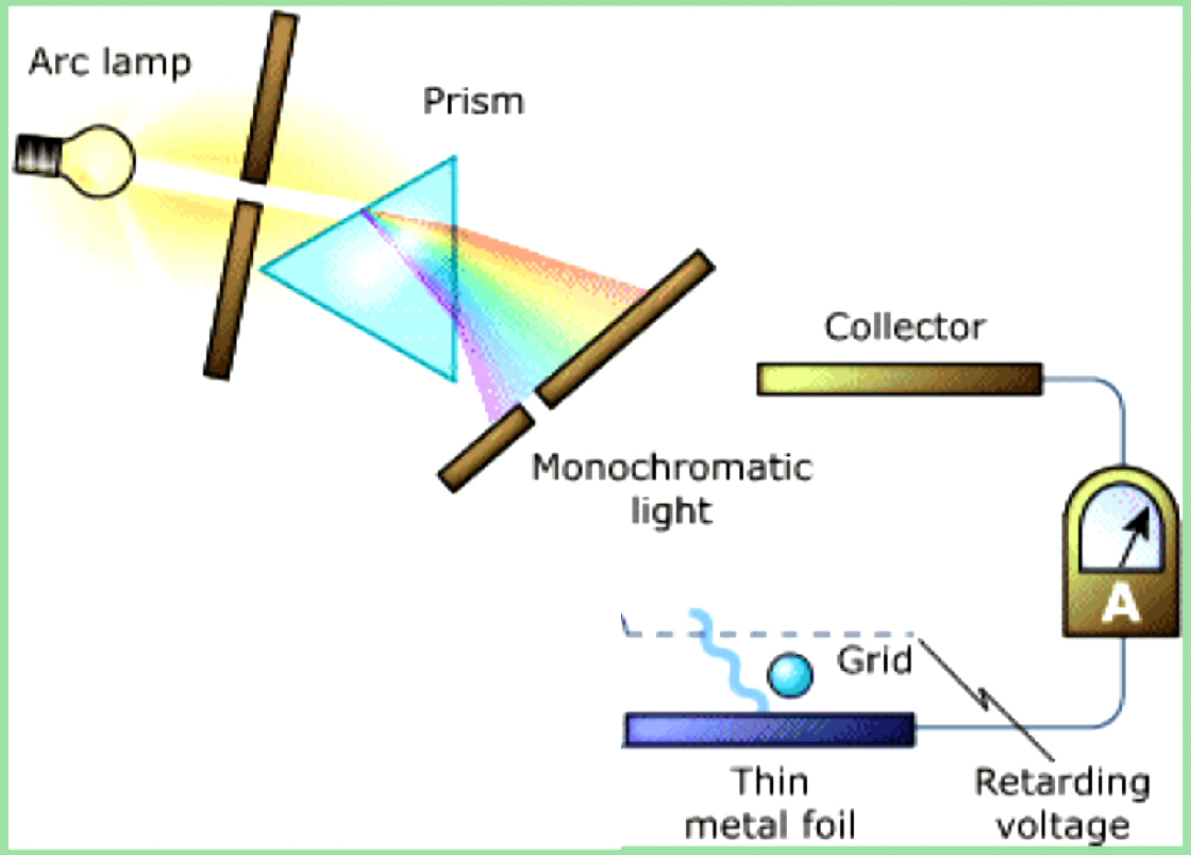
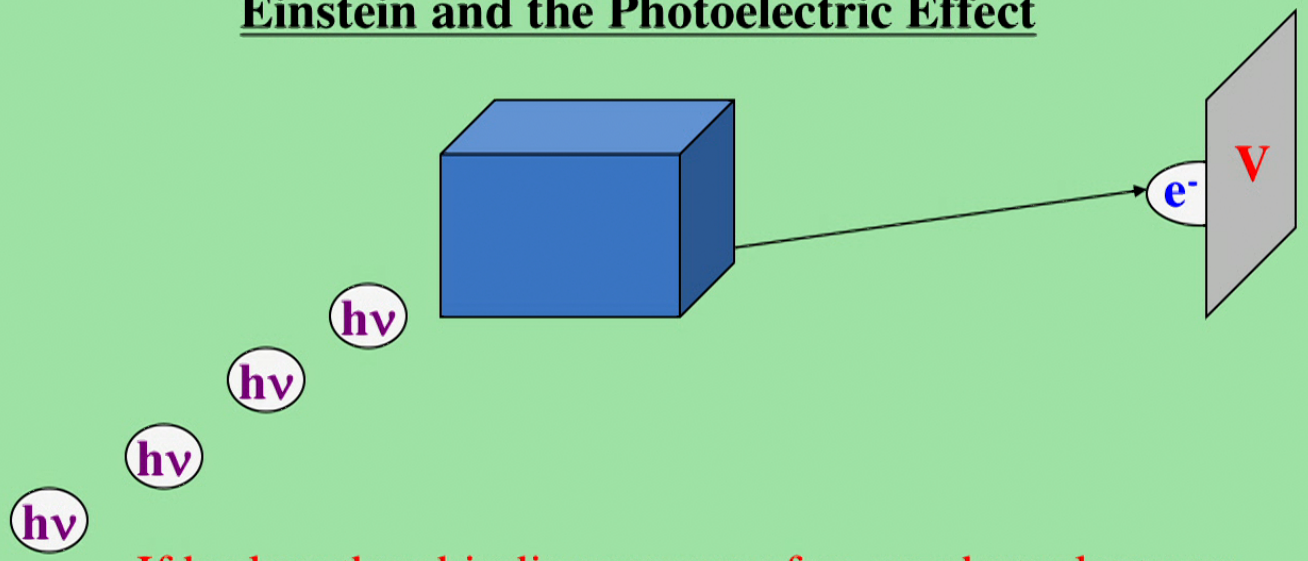
- Stokes phenomenon – fluorescent light always of lower frequency.

The photoelectric effect



Einstein and the Photoelectric Effect



If hν less than binding energy of e^-, no photoelectrons

If hν greater than energy of e^- then a photoelectron is ejected

Einstein's next step

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$$\sum_{n=0}^{\infty} e^{-nh\nu/kT} \Rightarrow <\epsilon> = \frac{h\nu}{e^{h\nu/kT} - 1}$$

Einstein's next step

- 1906: follow up to light quanta paper, "Planck's theory differs from Maxwell's…precisely because Planck's theory make implicit use of the …hypothesis of light quanta.
- What does Planck think? "I am not seeking the meaning of the quantum of action in the vacuum but rather in the place where absorption and emission occur…what happens in vacuum is rigorously described by Maxwell's equations", Planck, 1907. (And we should focus on more important topics, i.e. Relativity).
- *What does Einstein do in this paper?*

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T. S. Kuhn: in 1906 "Einstein announces the birth of quantum theory"

1907:Einstein Model for specific heat

- Begins: need to modify kinetic theory of heat due to blackbody law: ***For although one has thought before that the motion of molecules obeys the same laws that hold for the motion of bodies in our world of sense perception. […] we must now assume. […] that the diversity of states that they can assume is less than for bodies within our experience. For we make the additional assumption that […] the energy of elementary structures can only assume the values 0,hν,2hν, etc…"***

=> QUANTIZATION OF ENERGY IN MECHANICS

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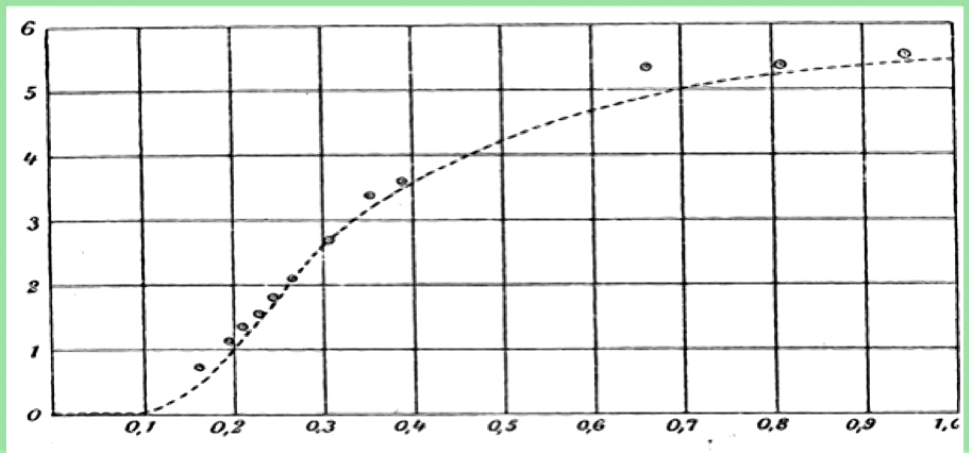

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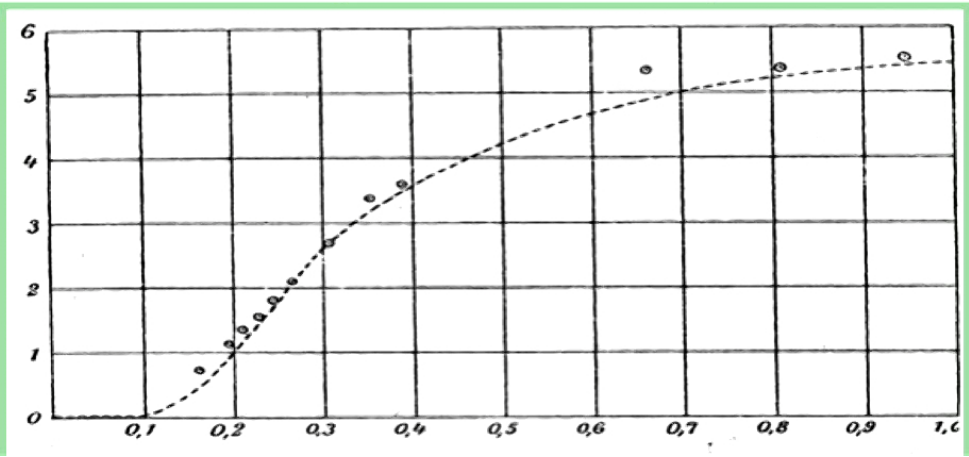
***" Einstein's quantum hypothesis is probably the strangest thing ever thought up. If correct, it opens entirely new roads… for molecular theories"*, Walther Nernst, 1910**



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A Quantum Theory of Radiation?

1908: Should he work on quantum theory of atoms or light?

He chooses light

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January 1909, article: On the present status of the radiation problem,
"The fundamental equation of optics will have to be replaced by an equation in which the charge, e, also appears...it cannot be linear and homogeneous... I have not yet succeeded in finding a system of equations .... suitable for constructing the elementary electrical quantum and the light quanta... The variety of possibilities does not seem so great for one to shrink from the task"

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Lorentz to Einstein, May, 1909: *"As soon as one makes even the slightest change in Maxwell's Equations one if faced, I believe, with the greatest difficulties..."*

- 1909: Salzburg meeting of German scientists and physicians – Einstein's coming out party: lectured on "The development of our views on the nature and composition of radiation."

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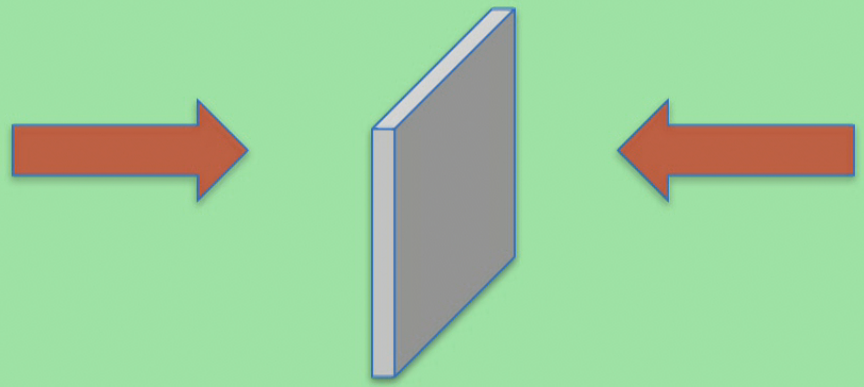

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particle term

$$var(n) = \bar{n} + \bar{n}^2$$

wave term (classical)

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The stat mech analysis is rigorous (not heuristic), but there is not yet an underlying dynamical equation to go further: *"who would have sufficient imagination to construct a theory [on this basis]…"*

Lamenting the ruins

- 1909-10 Einstein continues searches for quantum theory of radiation as a non-linear generalization the wave equation and fails.
  "the riddle of radiation will not yield…", Einstein, Dec. 1910.
- The problem: Maxwell's eqs ARE the quantum equations for the average of the fields; Planck's constant only appears in its fluctuations!

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- May 1911, to Besso: *"I no longer ask if these quanta really exist. Nor do I try to construct them any longer, for I know my brain can not get through in this way…",*
- He turns his attention to General Relativity: *"…[Einstein] is so deeply involved with the problem of gravitation that he turns a deaf ear to all else",* Sommerfeld to Hilbert.
- He leaves the pursuit of the quantum just as the rest of the community wakes up to the problem, at the first Solvay conference in 1911

Lamenting the ruins

1913: Nernst and Planck lure Einstein from Zurich to Berlin

Nernst

Picture from 1929

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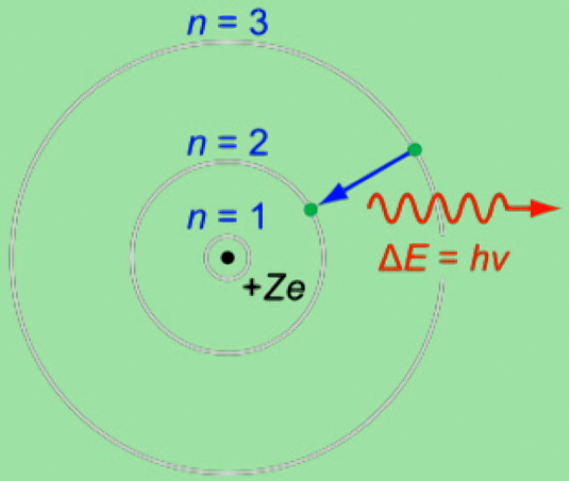
The Bohr Atom, 1913



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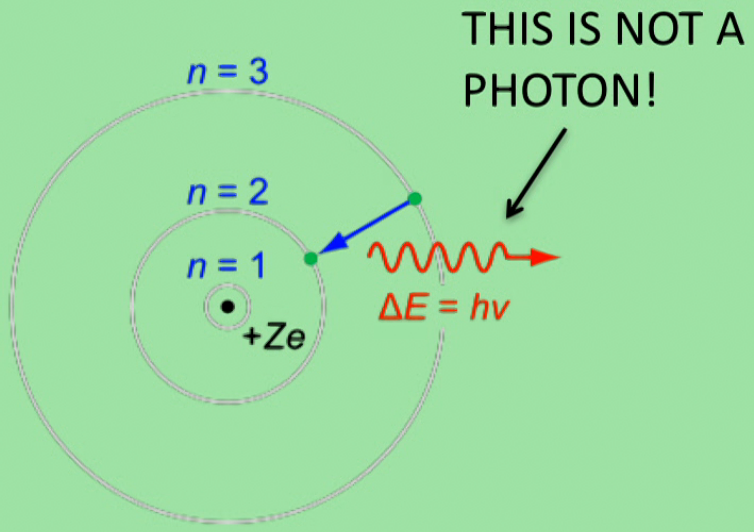

Einstein's reaction: "*Then the frequency of the light does not depend at all on the frequency of the electron*...this is an enormous achievement. The theory of Bohr must then be right. (1913)

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(

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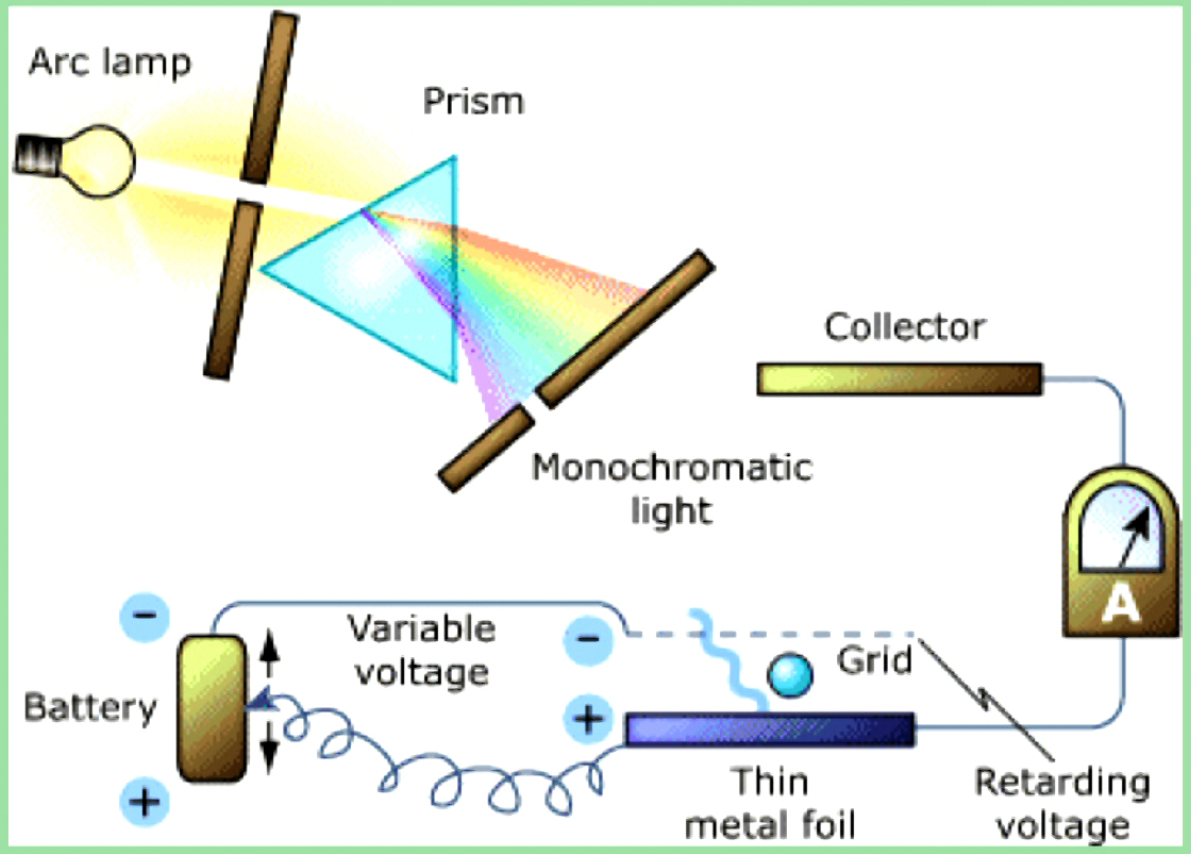
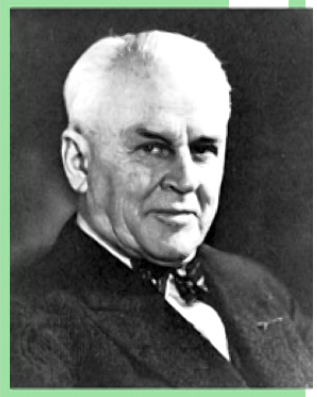
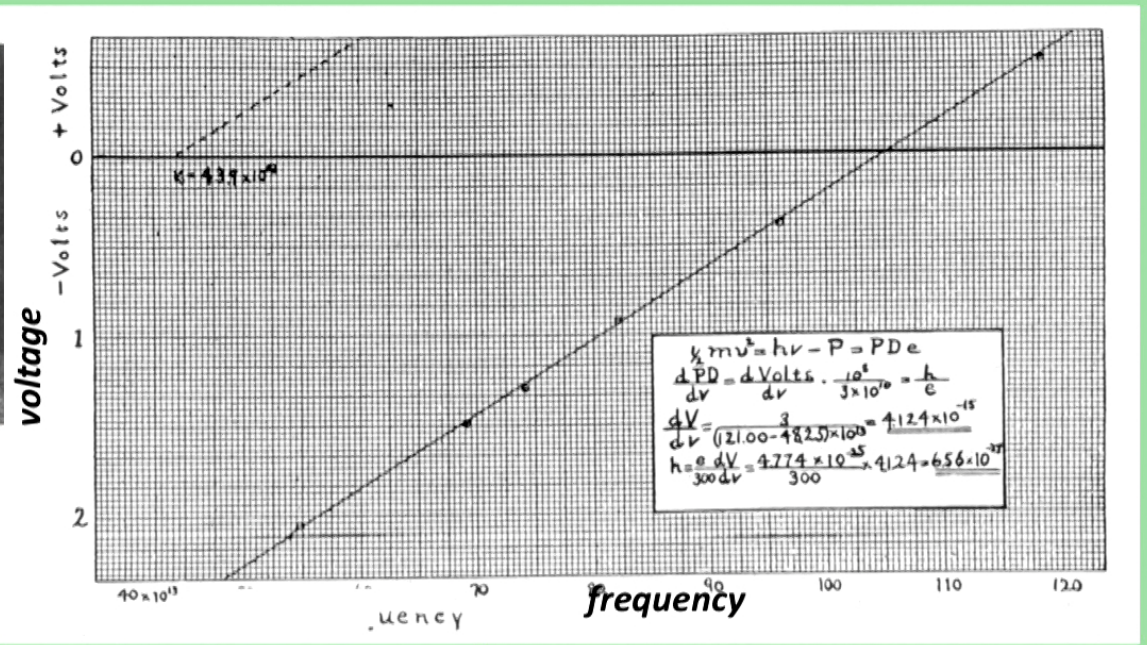
Who?

Measuring the Photoelectric Effect





Robert Millikan



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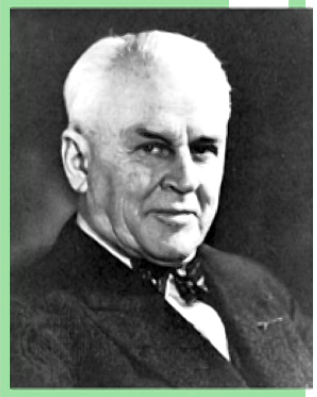
Phys. Rev. 7, 355 (1916)



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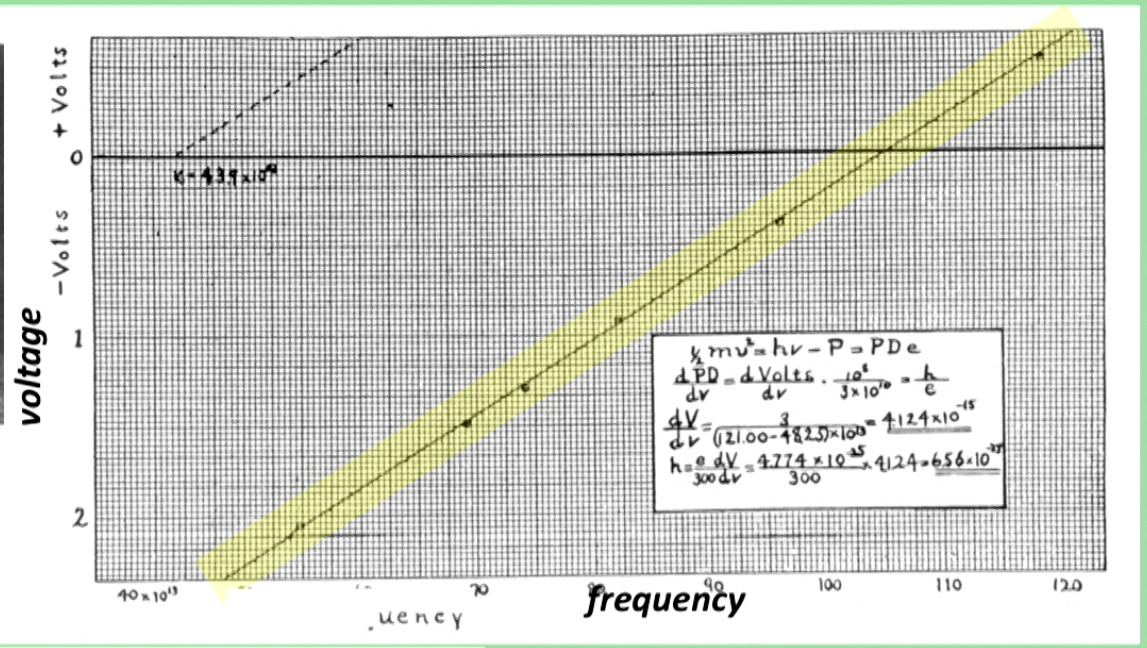

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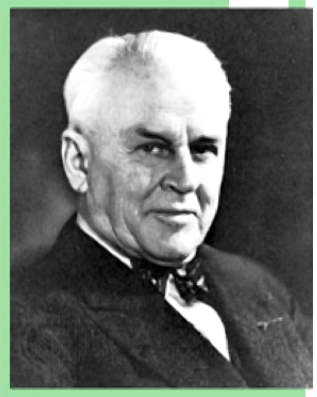

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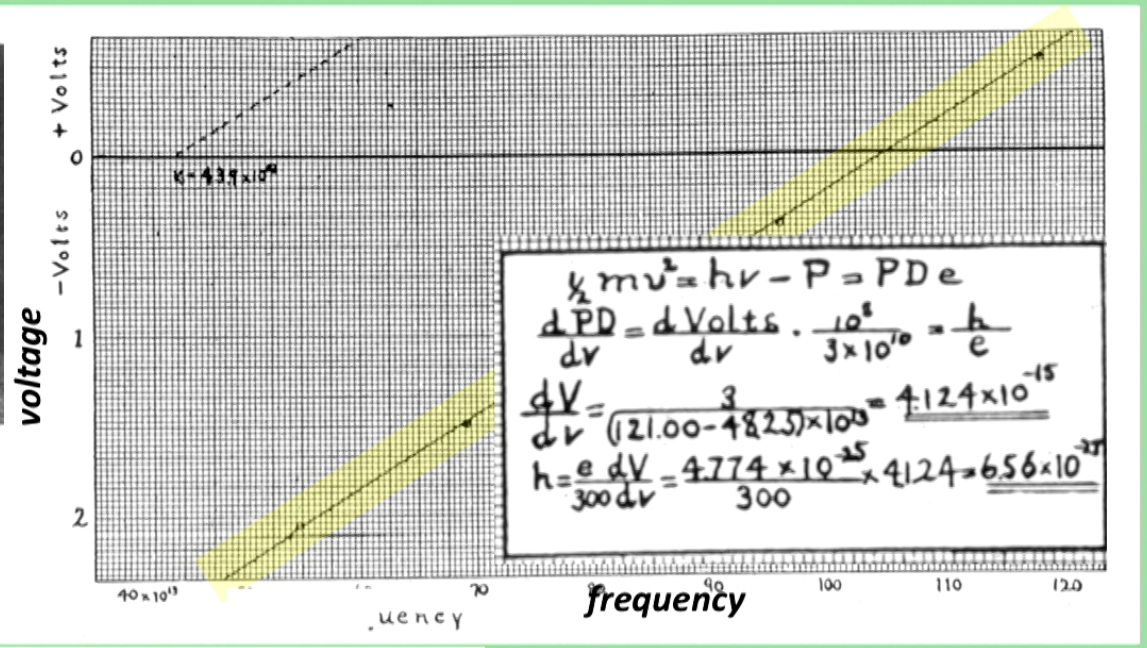

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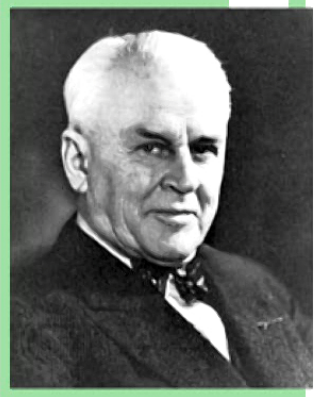

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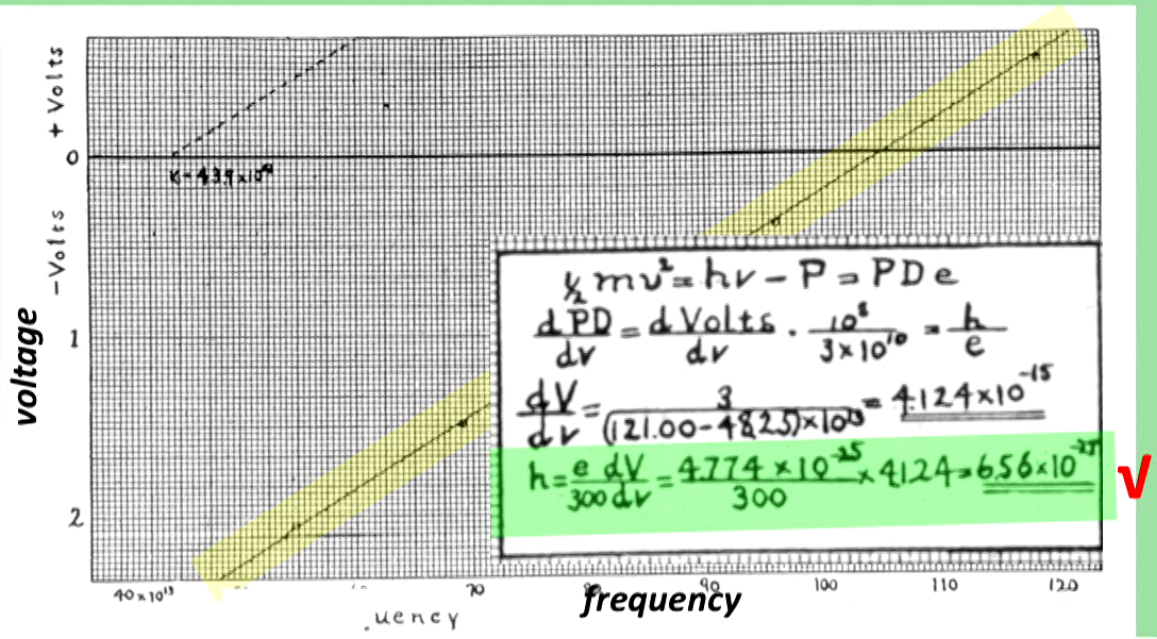

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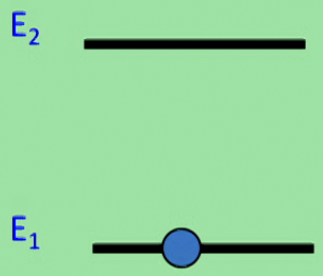
with. We are confronted, however, by the astonishing situation that these facts were correctly and exactly predicted nine years ago by a form of quantum theory which has now been pretty generally abandoned.

It was in 1905 that Einstein[2] made the first coupling of photo effects and with any form of quantum theory by bringing forward the bold, not to say the reckless, hypothesis of an electro-magnetic light corpuscle of energy $h\nu$, which energy was transferred upon absorption to an electron. This hypothesis may well be called reckless first because an electromagnetic disturbance which remains localized in space seems a violation of the very conception of an electromagnetic disturbance, and second because it flies in the face of the thoroughly established facts of interference.

Post Bohr: Einstein's "Splendid Idea"

Bohr: Atomic energy levels



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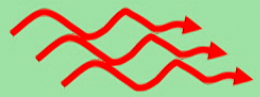

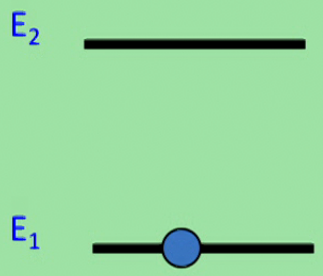

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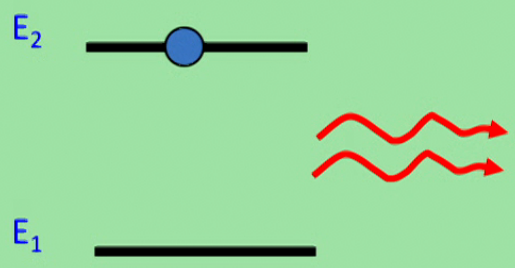

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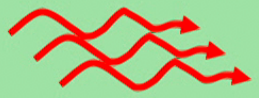

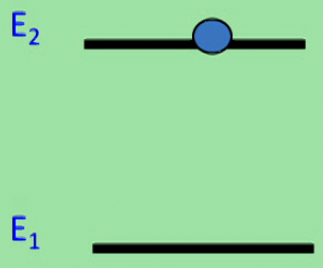

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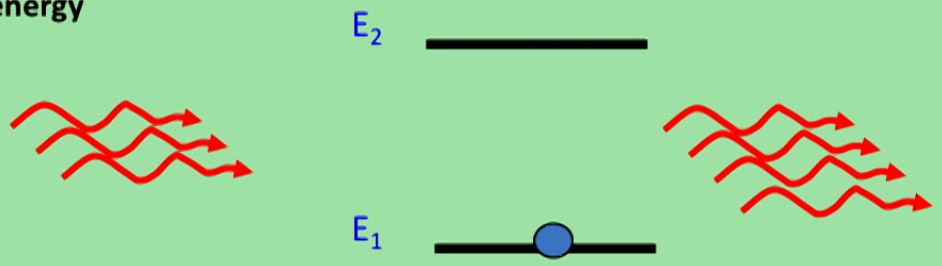

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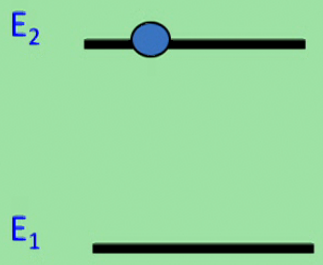

Stimulated Emission

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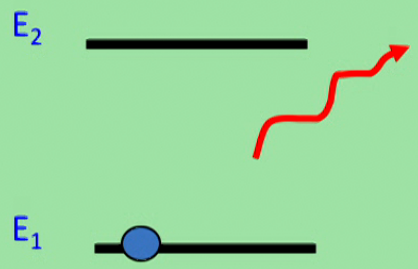

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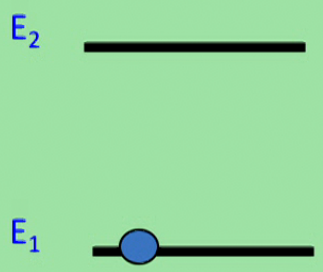

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Spontaneous Emission!

- Balance emission and absorption => Planck Radiation Law

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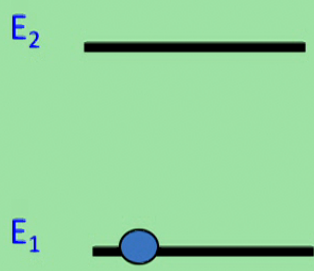

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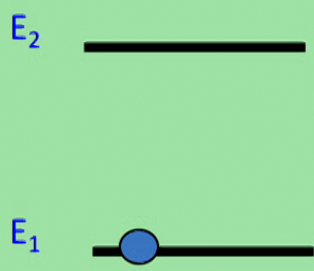

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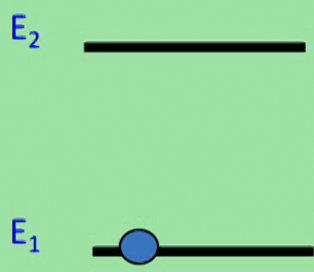

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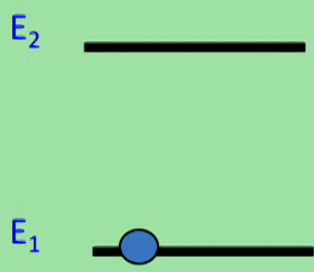

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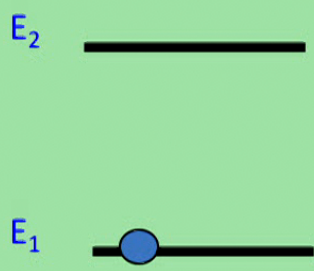

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Einstein introduces intrinsic randomness into quantum theory

"The business about causality gives me a lot of trouble…I would be very unhappy to renounce complete causality", Einstein to Born, 1920

Einstein and ghost (probability) waves

Einstein and ghost (probability) waves

Basic idea: …Upon the emission of light there are two sorts of radiation. They are:

1. An interference radiation, which occurs according to the normal laws of optics but does not transmit any energy…
The energetic radiation. It is composed of indivisible quanta of [energy] *h*ν. Their path is given by the (vanishingly small) flow of energy from the interference radiation, and therefore they can never reach a spot where this flow is zero…full interference radiation is formed [even if]…only a single quantum is emitted, which thus also can reach the receiving screen at only one spot…
[this is repeated many time]… the various quanta now distribute themselves statistically…[so] that their average number at each point on the screen is proportional to the intensity of the incident interference radiation there.
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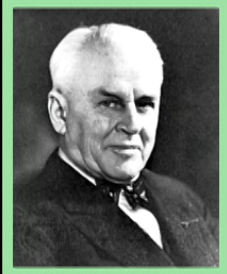
"I am entirely satisfied because my idea to look upon the Schrodinger wave field as a "ghost field" in your sense proves better all the time,
Max Born to Einstein, November 1926

But did Born or anyone else believe in quanta in 1918?

R. A. Millikan
Phys. Rev. 7, 355 – Published 1 March 1916



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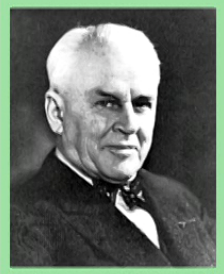

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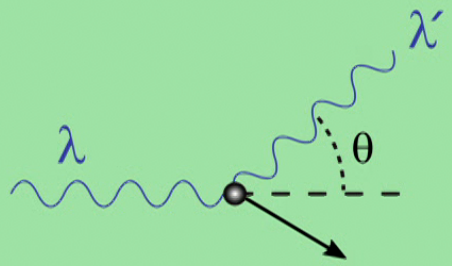
Quanta as real particles were finally widely accepted after the discovery of the Compton Effect (1923), and its verification by Bothe-Geiger (1925)



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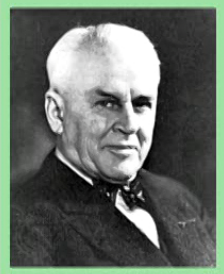

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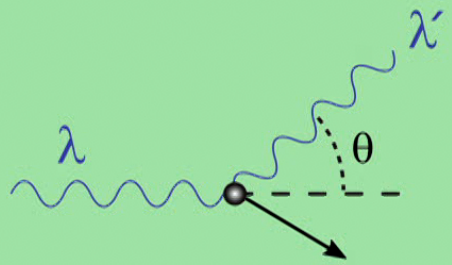

"... I was in Berlin the other day. Everyone was talking about the results of the Bothe-Geiger experiment, which decided in favor of light quanta. Einstein was exultant", Born to Bohr, January, 1925

Bose and Einstein (1924-5)

"Respected Sir:

I have ventured to send you the accompanying article for your perusal and opinion. I am anxious to know what you think of it …I do not know sufficient German to translate the paper. If you think the paper worth publication, I shall be grateful if you arrange for its publication in Zeitschrift fur Physik…
Though a complete stranger to you, I do not feel any hesitation in making such a request. Because we are all your pupils…Yours faithfully,
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What was the problem?
Can't treat BB radiation as a photon gas using classical statistics. You get Wien's Law, not Planck's

Satyendra Nath Bose, 1924

Planck's law and the light quantum hypothesis

[Satyendranath] Bose
Dacca University, India
(Received by Zeitschrift für Physik on 2 July 1924

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It is now very simple to calculate the thermodynamic probability of a macroscopically defined state. Let N^s be

number of cells containing two quanta, etc.; then the number of different distributions is

$$\frac{A^s!}{p_0{}^s! p_1{}^s! \cdots},$$

where

$$A^s = (8\pi\nu^2/c^3)\, d\nu^s.$$

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The key step, he neglects interchanges of quanta; A few steps later he gets the Planck Law

Bose doesn't say a word about the assumptions underlying this formula!

- Einstein: “In my opinion Bose’s derivation of the Planck formula signifies an important advance. The method used also yields the quantum theory of the ideal gas, as I will work out in detail elsewhere”.

- Submits paper ten days later with correct equations of massive Bose gas, only partially solved. Doesn’t realize the radical nature of the new statistics”

- Two days later, to Ehrenfest, “the essence is still obscure” (July).

- December 1924, “the thing with the quantum gas turns out to be very interesting… much of what is true and deep is lurking behind it.”

- January 1925, full theory of the Bose gas, including BEC: “…an increasing number of molecules go in to the quantum …ground state…part of the gas `condenses’…

- “[Bose statistics] expresses an implicit hypothesis about the mutual influence of the molecules of a totally new and mysterious kind”. WHAT IS THIS?

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- Revered in India, but makes no further contribution to physics.

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- All of the force-carrying particles in modern physics are called bosons in recognition of his role in the new statistics

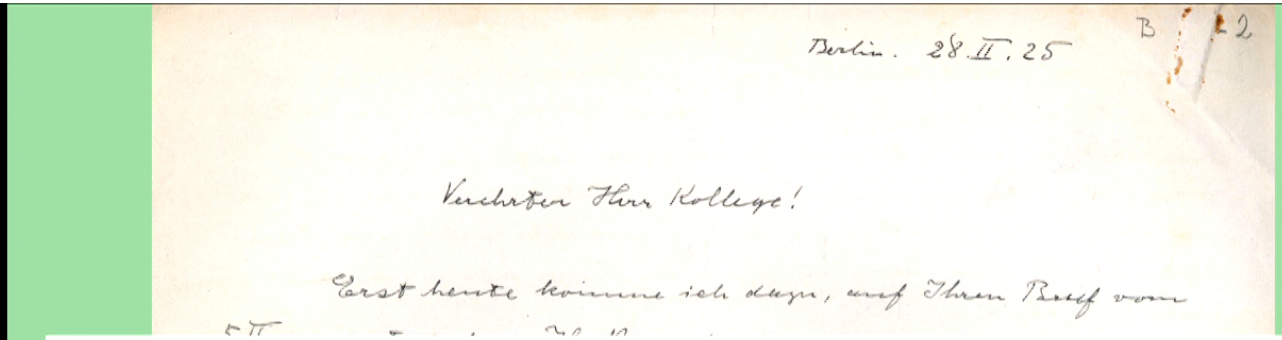
February 1925, Schrodinger writes to Einstein suggesting that he has made an error in his BEC paper

Berlin. 28.II.25

B 12

Verehrter Herr Kollege!

Erst heute komme ich dazu, auf Ihren Brief vom 5.II zu antworten. Ihr Vorwurf ist nicht ungerechtfertigt, wenn auch ein Fehler in meiner Abhandlung nicht vorliegt. In der von mir verwendeten Bose'schen Statistik werden die Quanten bezw. Molekule nicht als voneinander unabhängig behandelt. Darauf beruht es, dass die Formel



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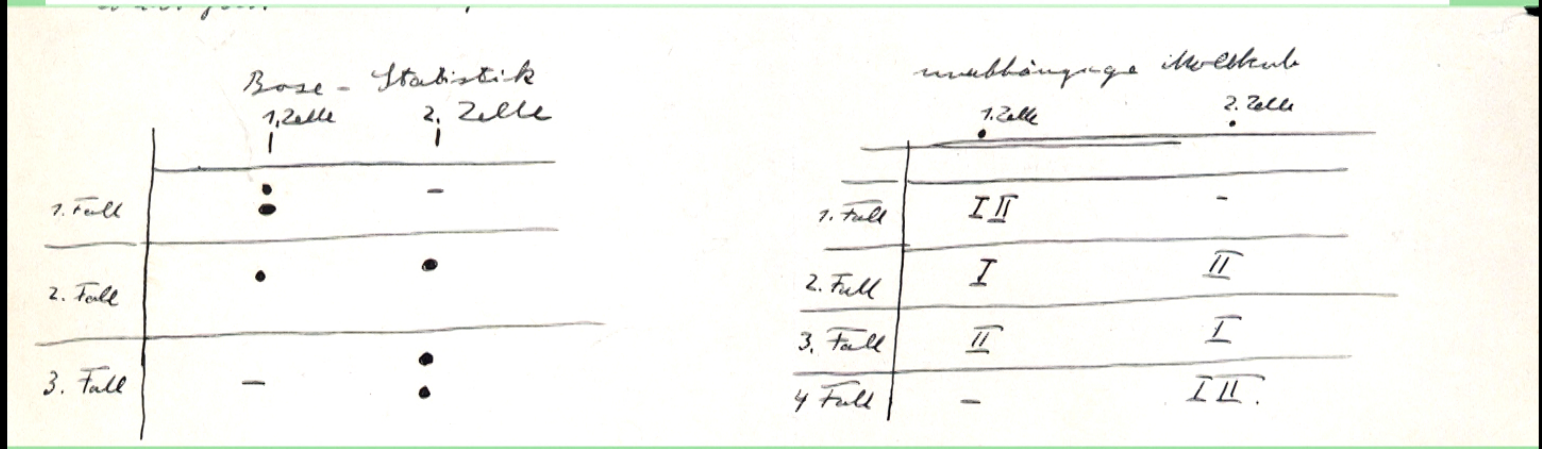

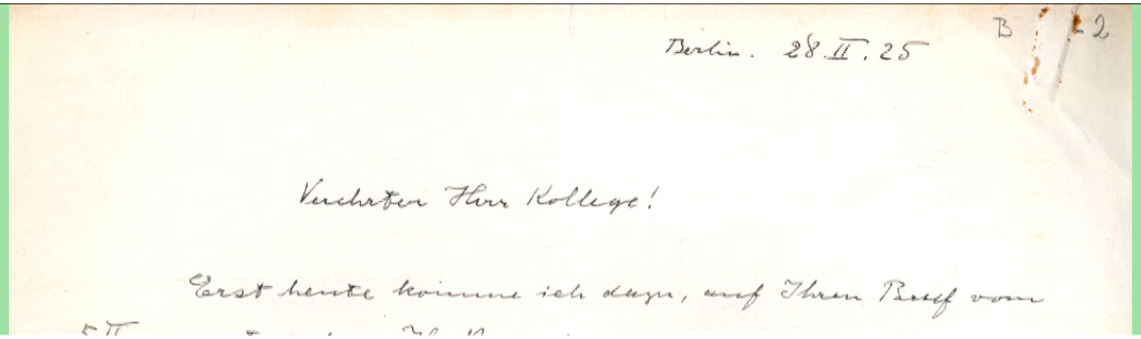
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Bose - Statistik

"I had not grasped it before at all despite the fact that Bose's paper had already come out….[Bose's work] did not seem particularly interesting to me. Only your theory of gas degeneracy is really something fundamentally new…" Schrodinger, Sept 1925

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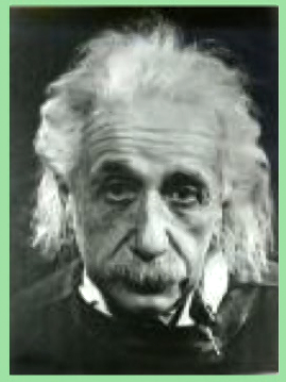
Einstein to Born, December 1926, responding to his letter about the probabilistic interpretation of wavefunction



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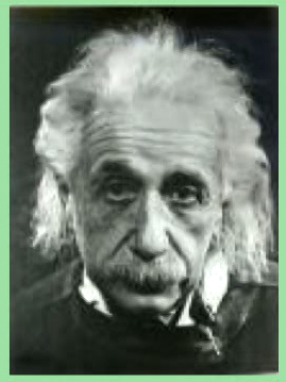

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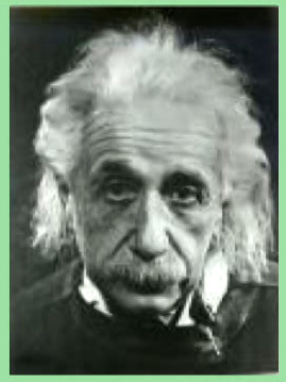

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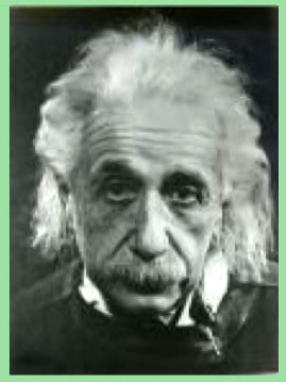

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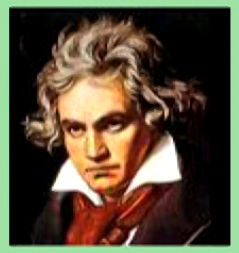

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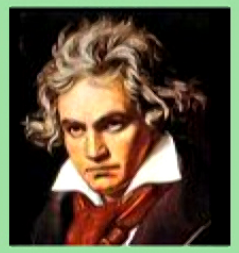

Nichte Diese Töne!


Einstein
L. de Broglie
"I see in Nature
a magnificent structure...
that must fill a thinking person with
a feeling of humility..."
Albert Einstein