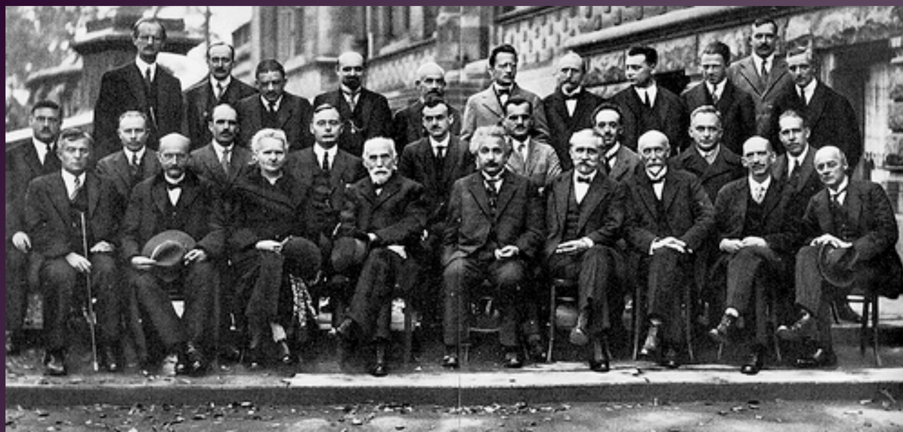
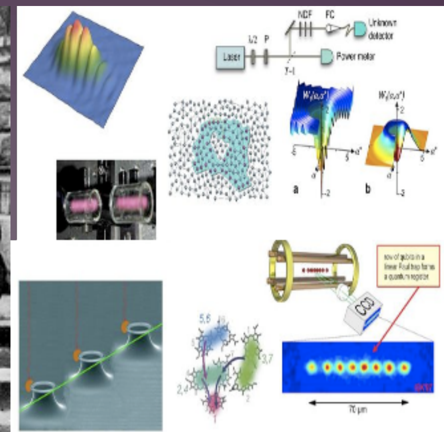
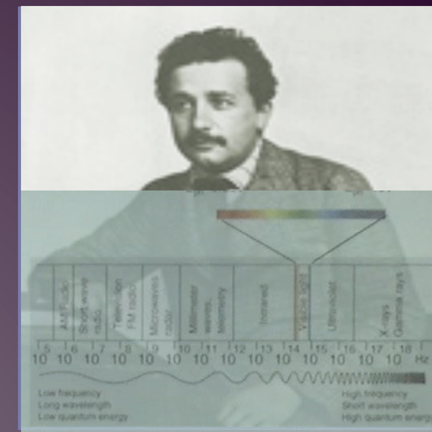
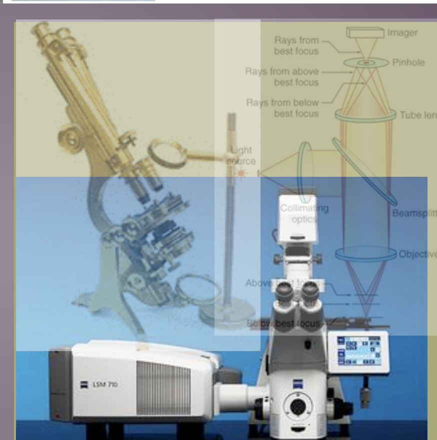






Light Meets Matter: Atoms and Lasers



A presentation based on the 2009 Teachers' Conference at the Kavli Institute for Theoretical Physics at U.C.S.B.

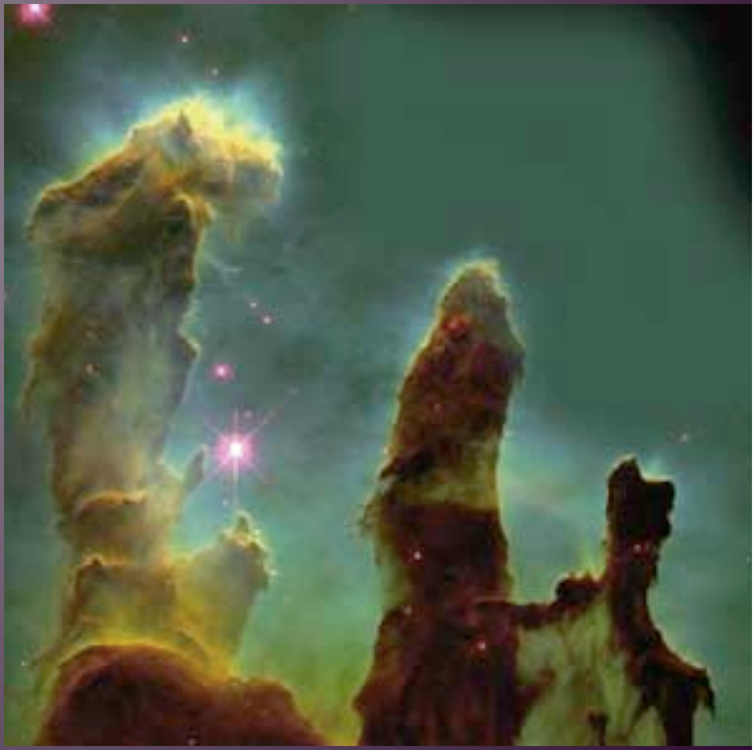
The Rise of Quantum Physics

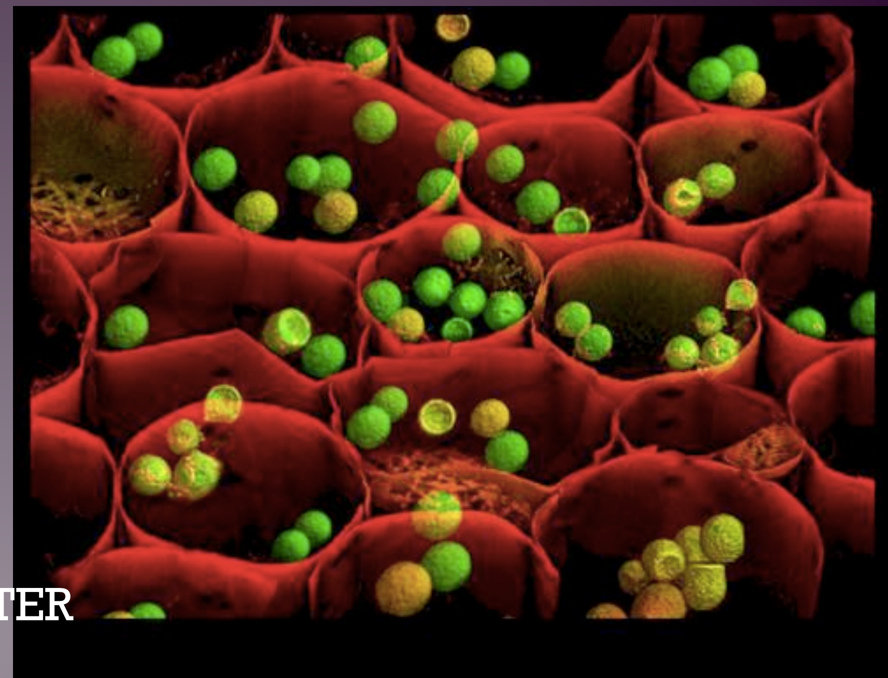
by
Nick Nicastro

THIS IS A STORY

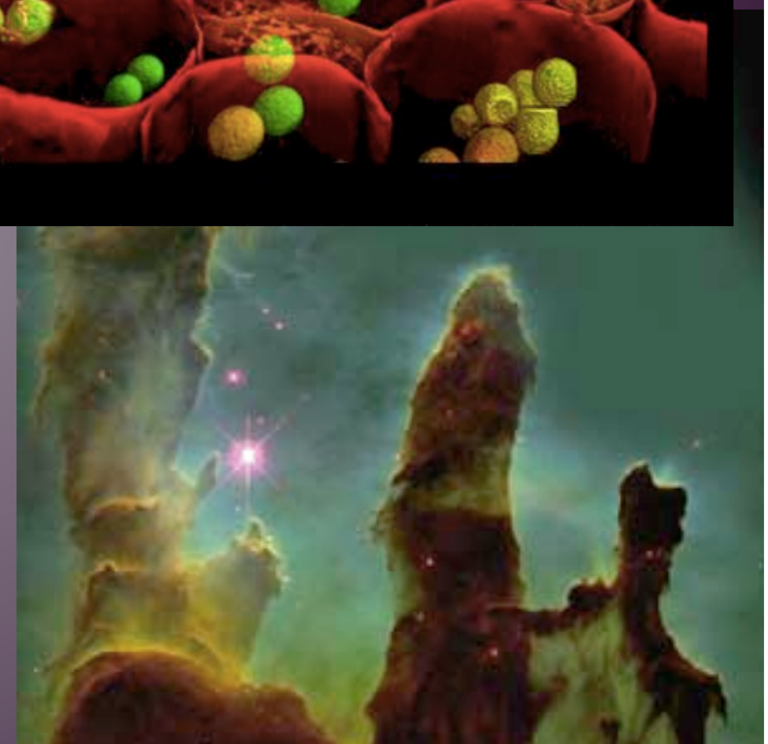
ABOUT TIME

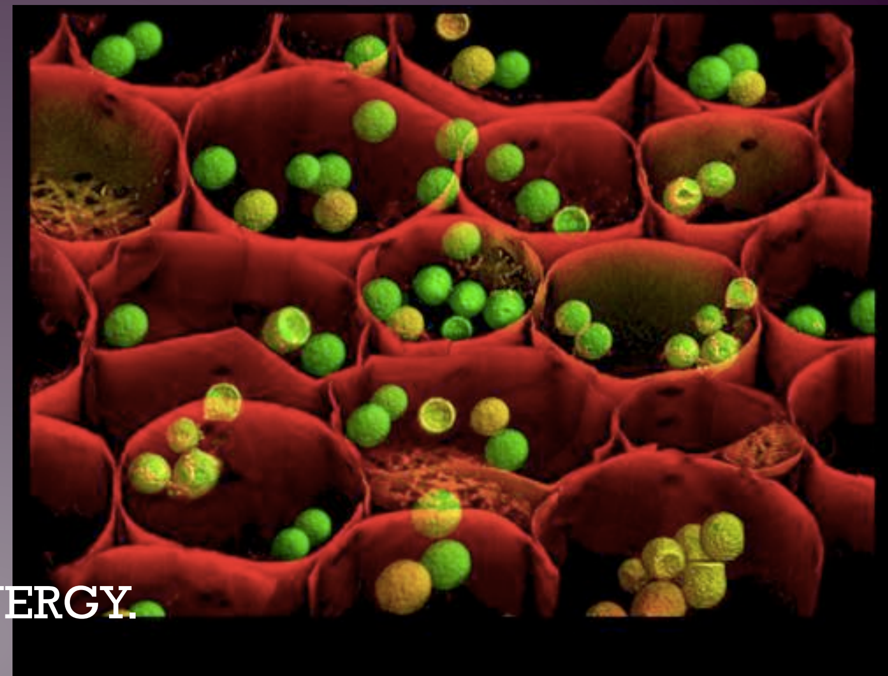
AND SPACE.





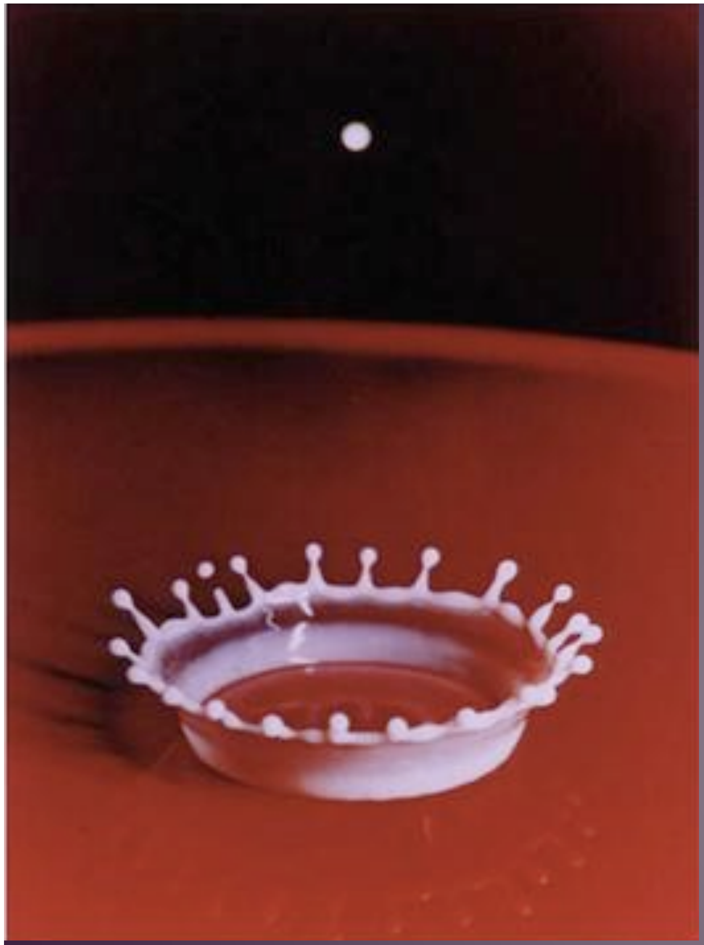
MATTER



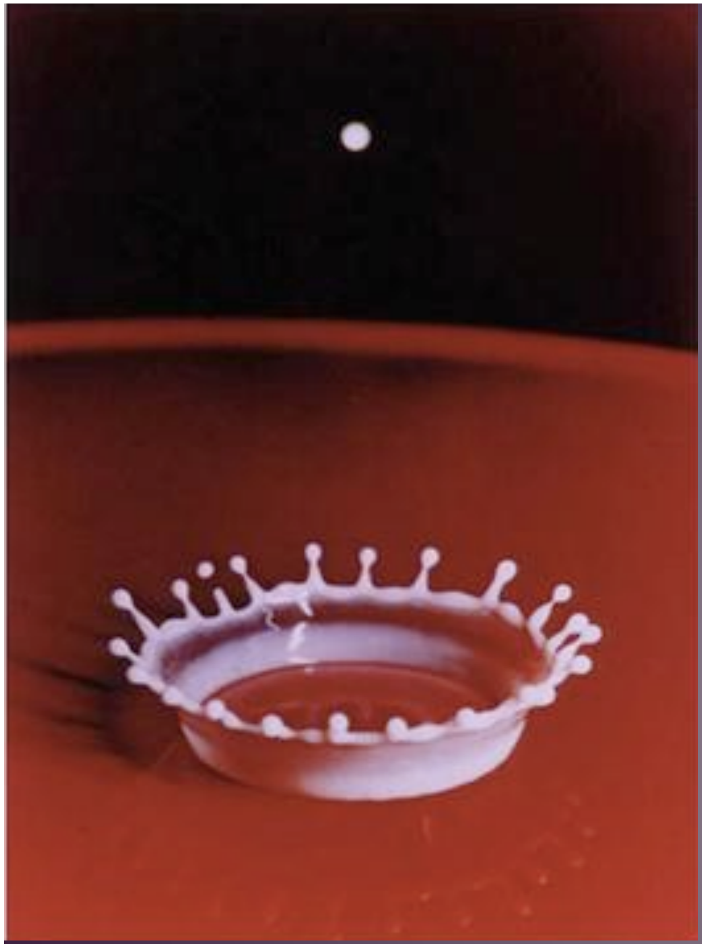


AND ENERGY.

NOT JUST *ANY* INTERVALS OF TIME



EXTREMELY SHORT
INTERVALS OF TIME



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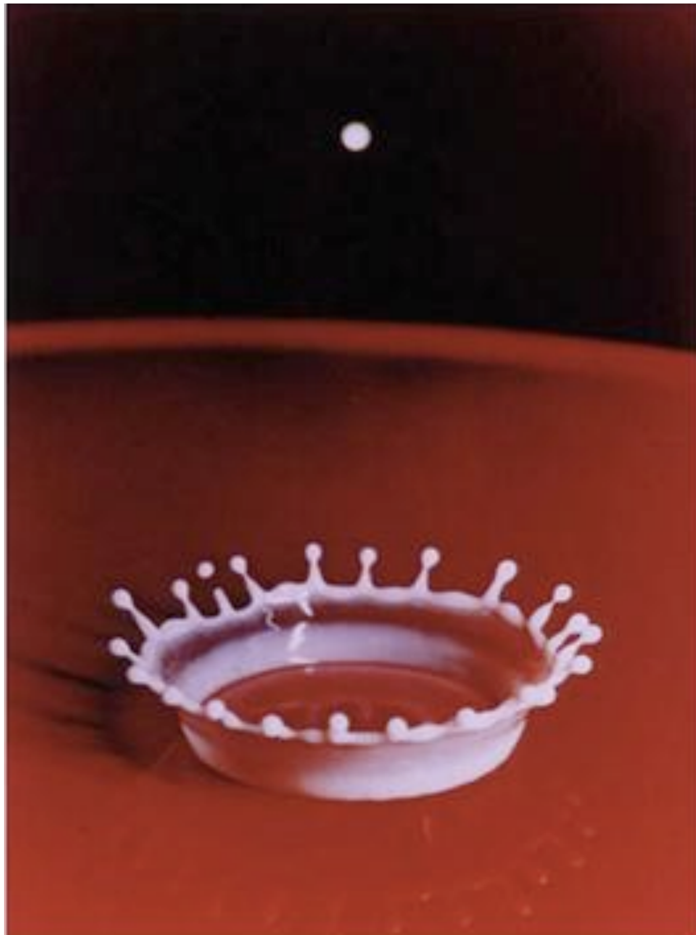

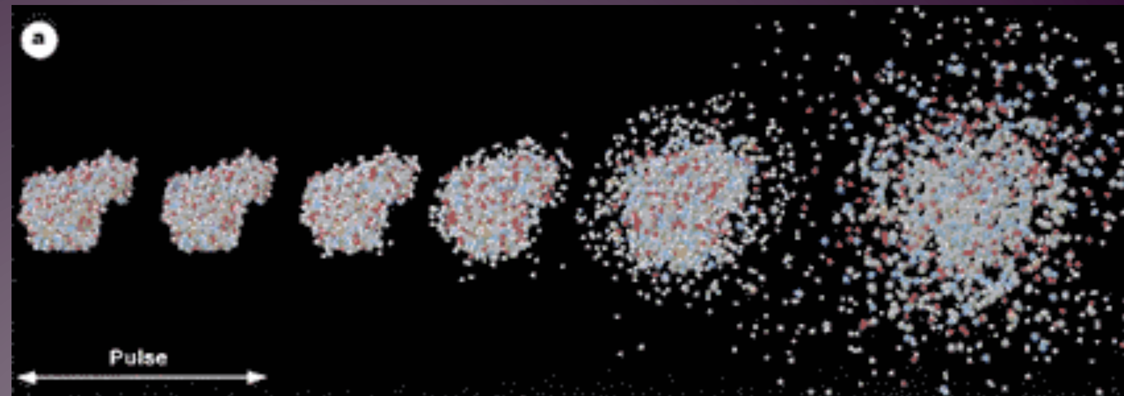

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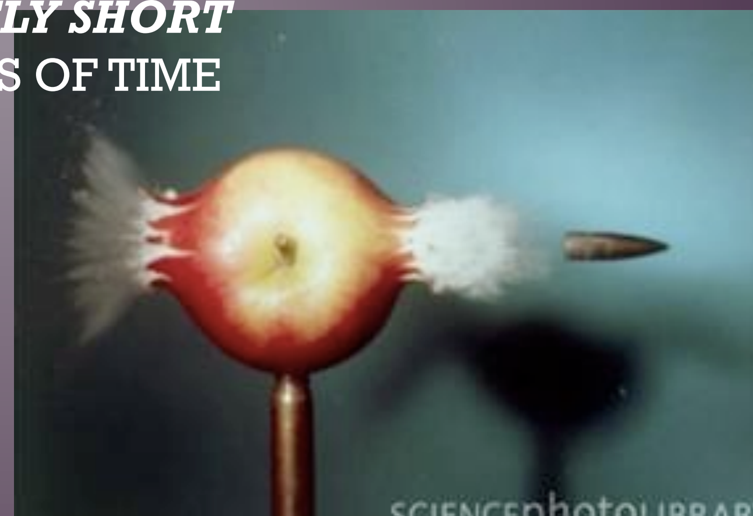
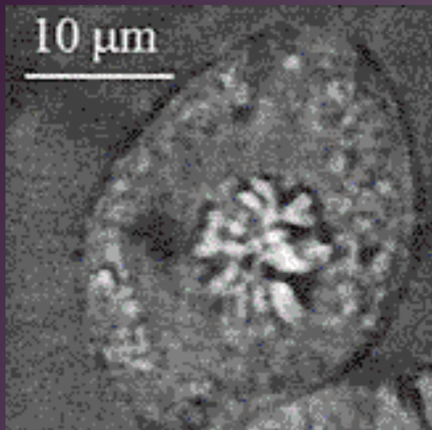


AND ***EXTREMELY SMALL***
INCREMENTS OF SPACE



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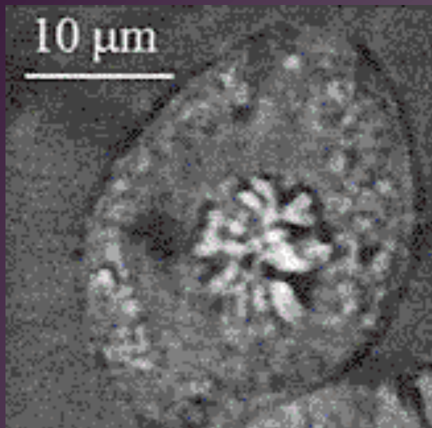

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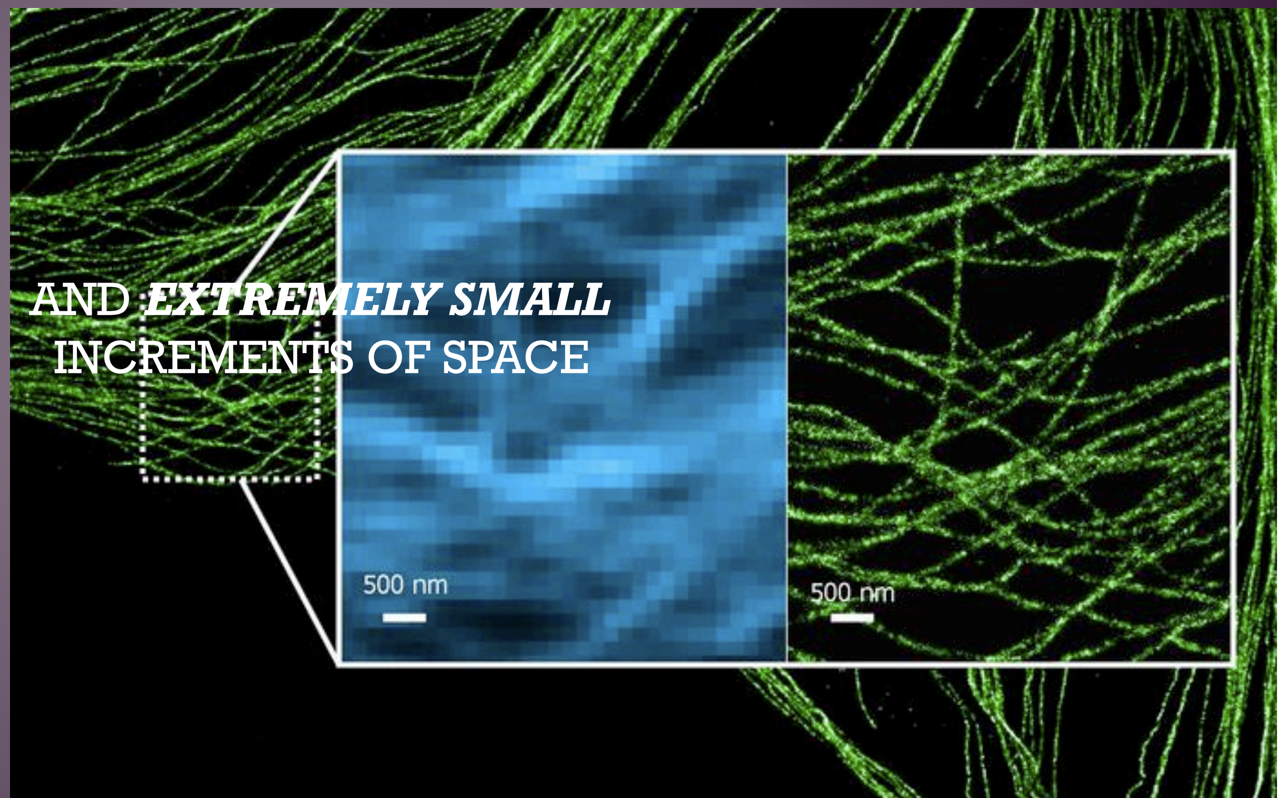

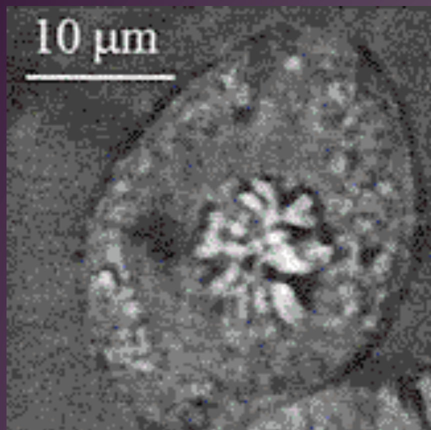

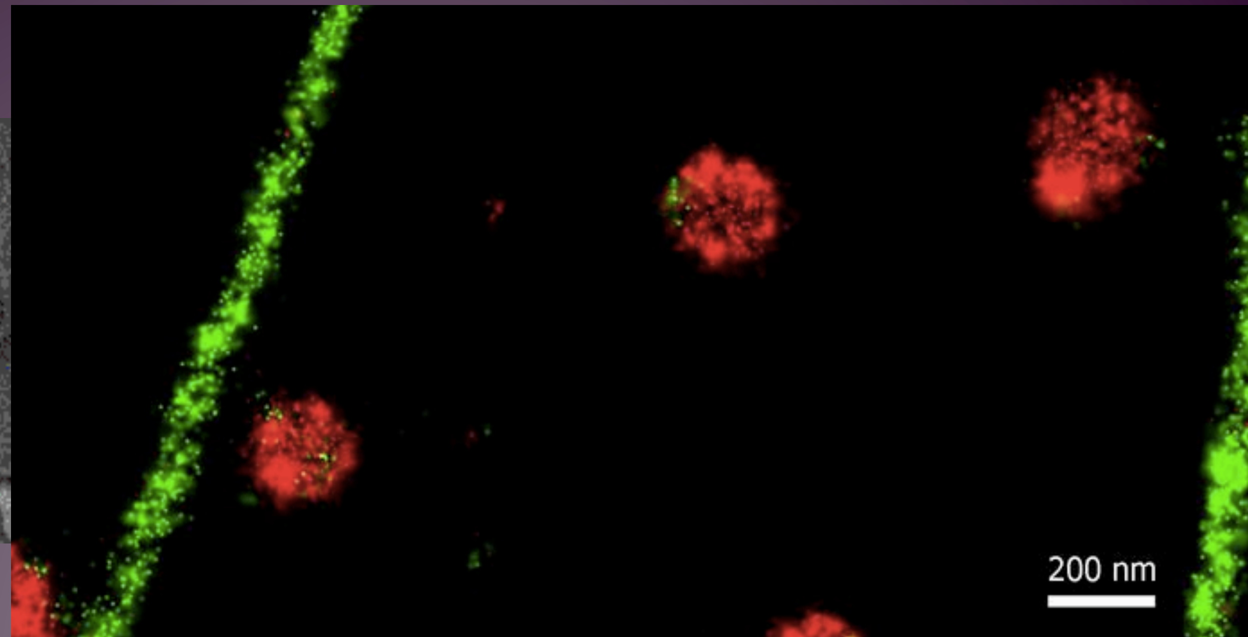

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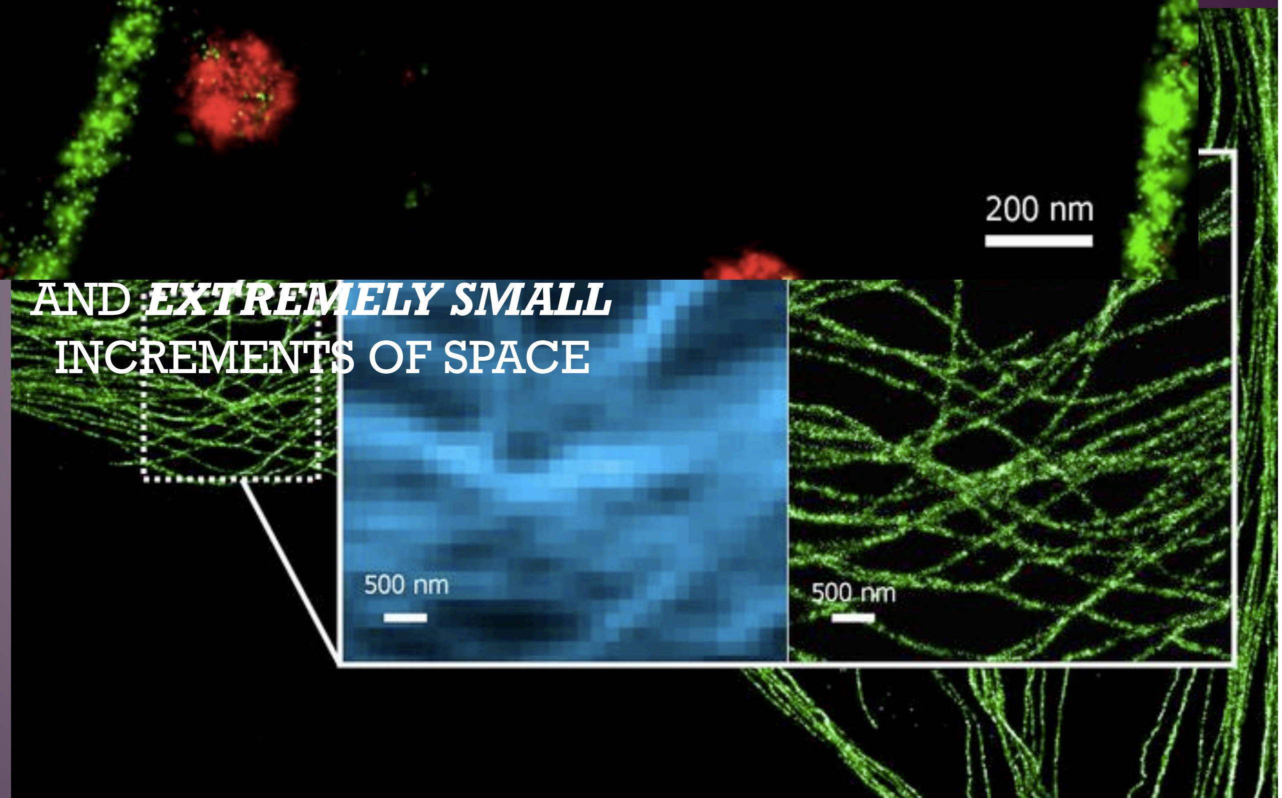

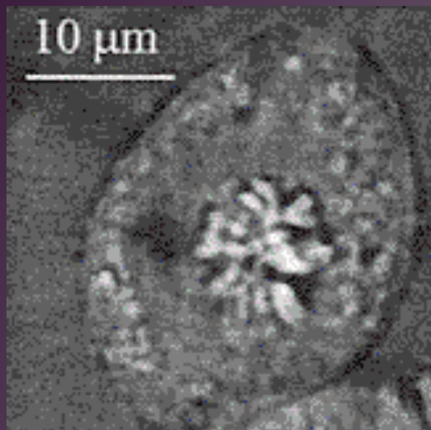

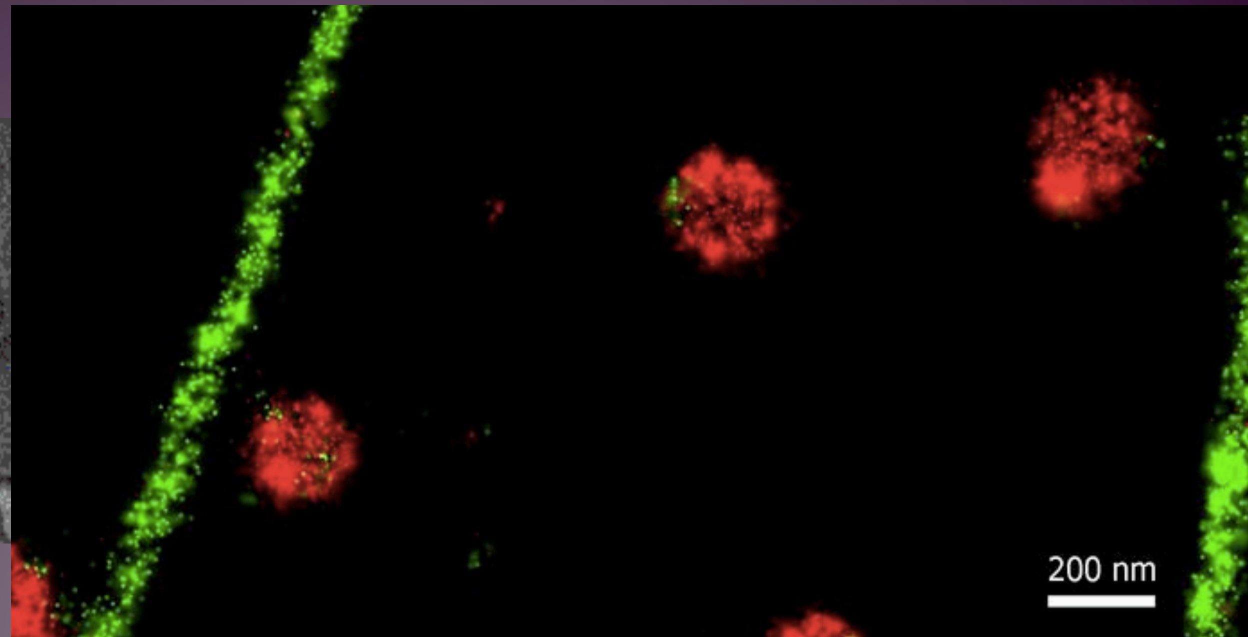

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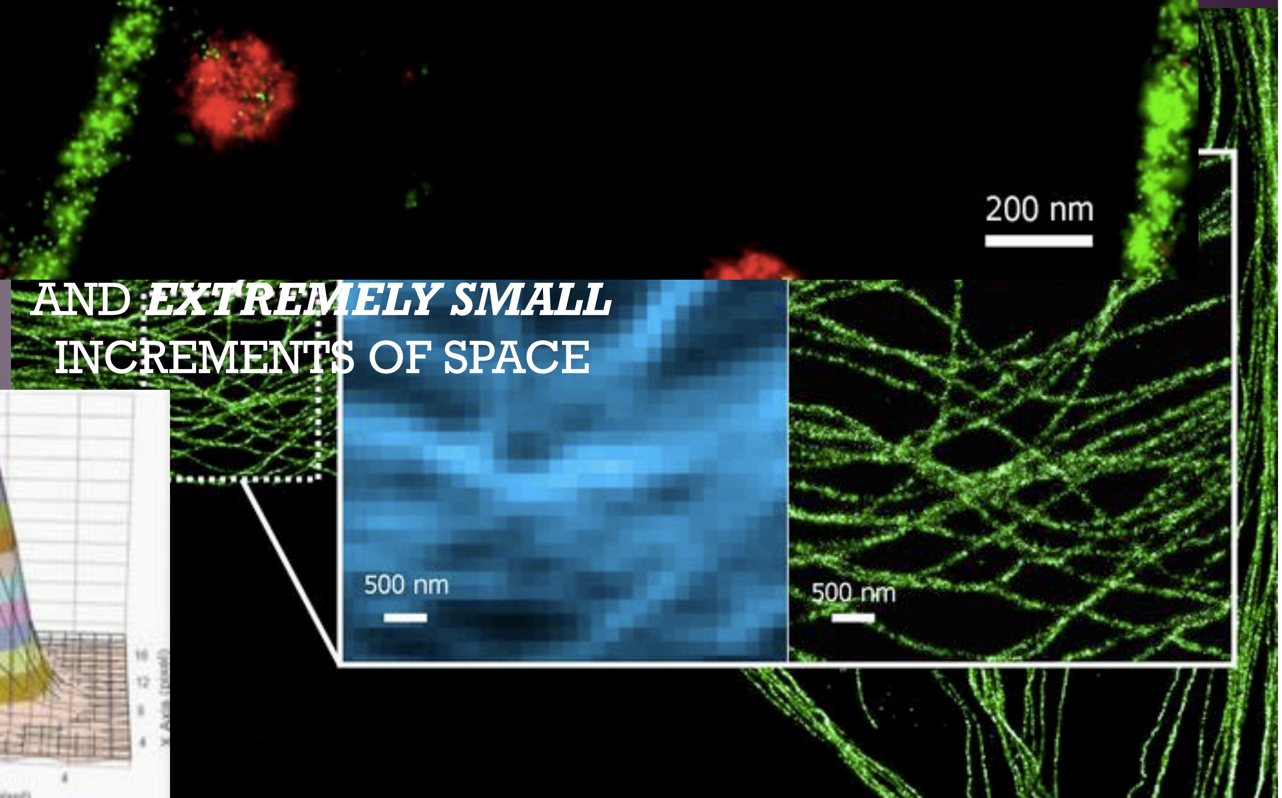
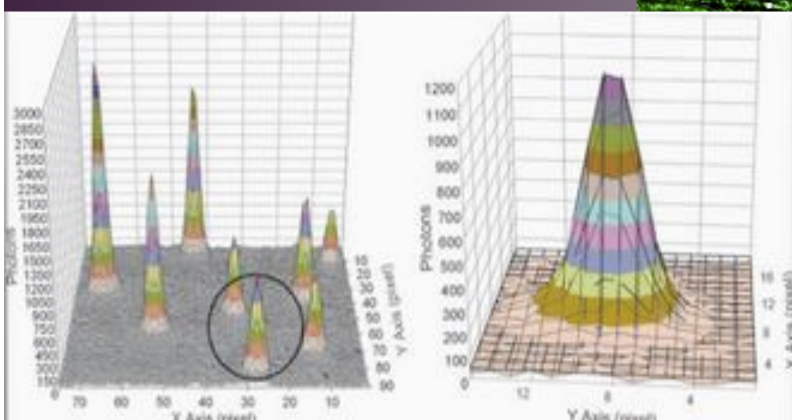
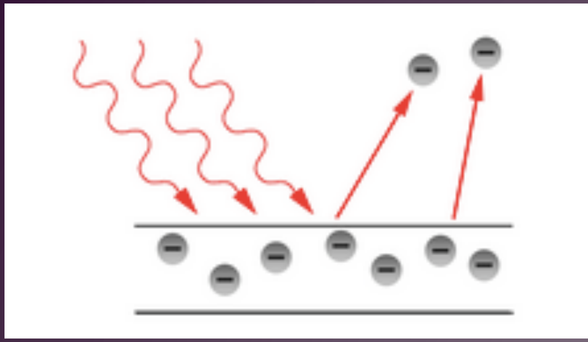




IT'S ABOUT THE EVOLUTION
OF A THEORY



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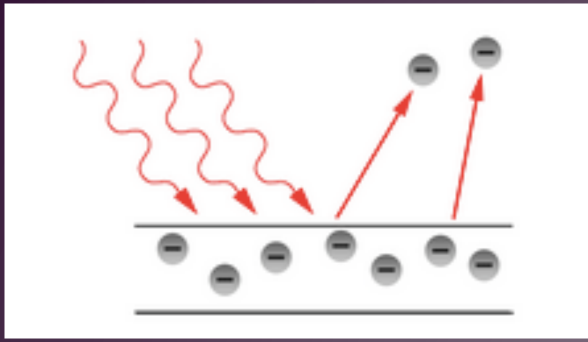

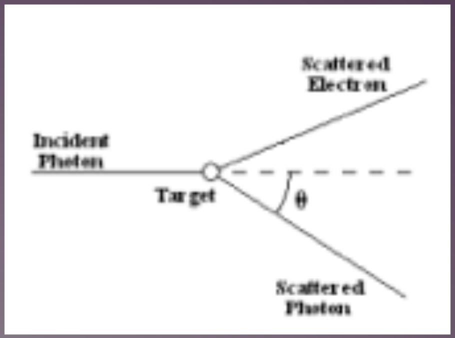

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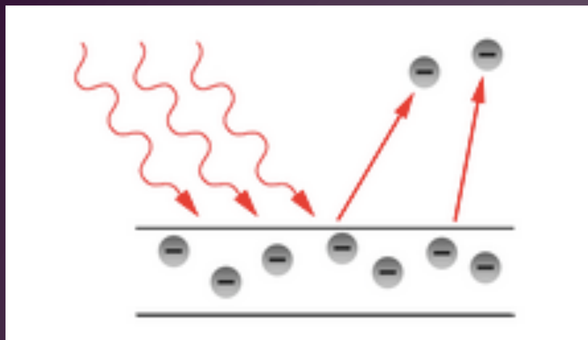

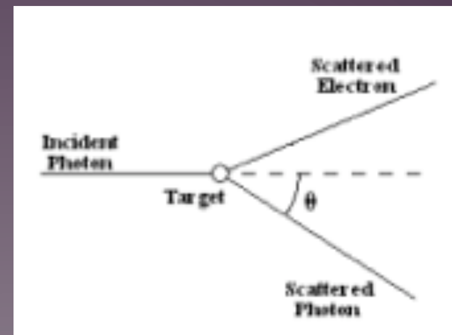

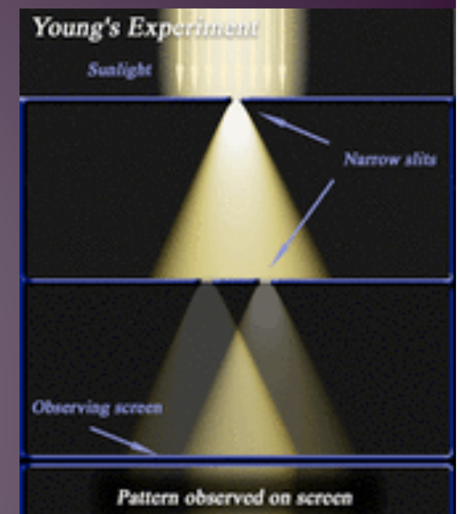

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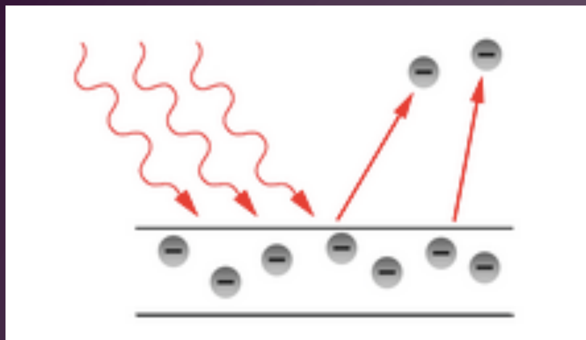

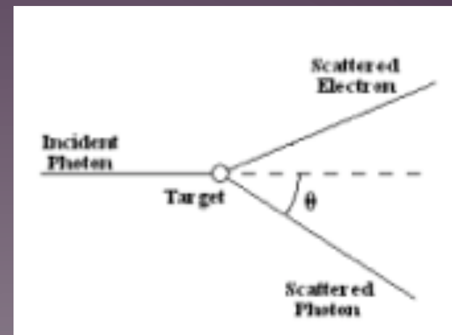

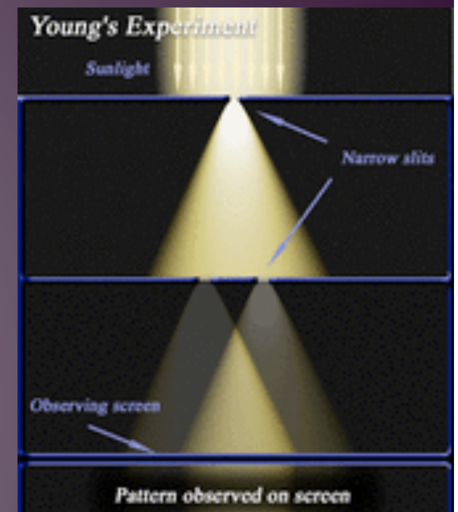

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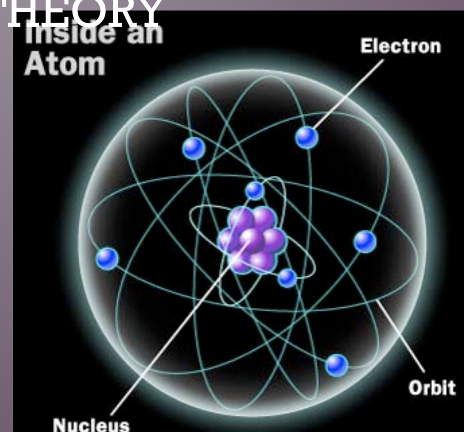

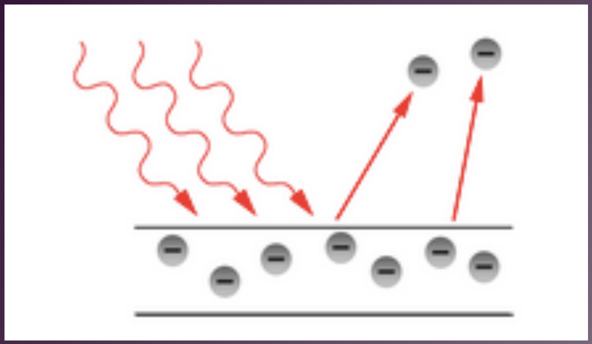

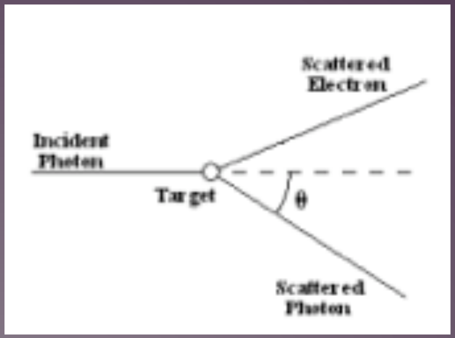

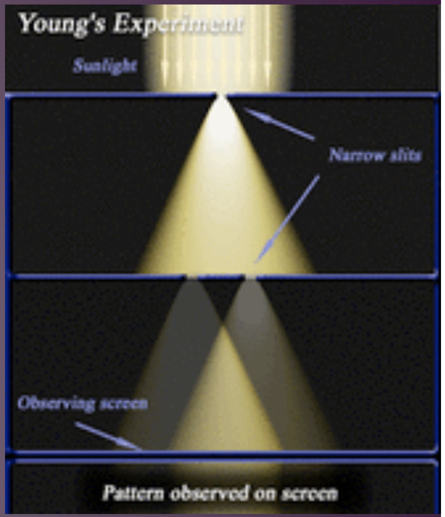

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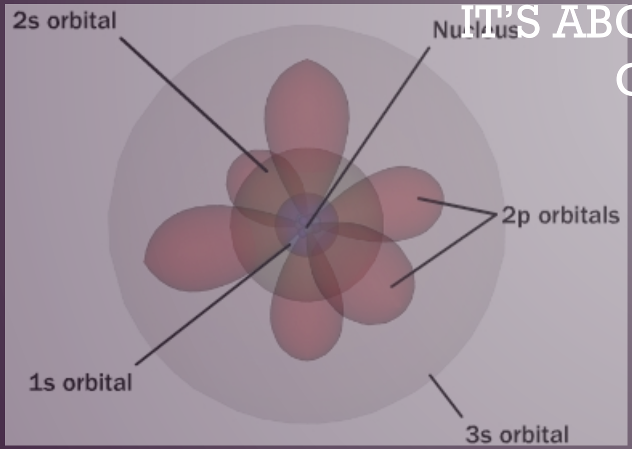
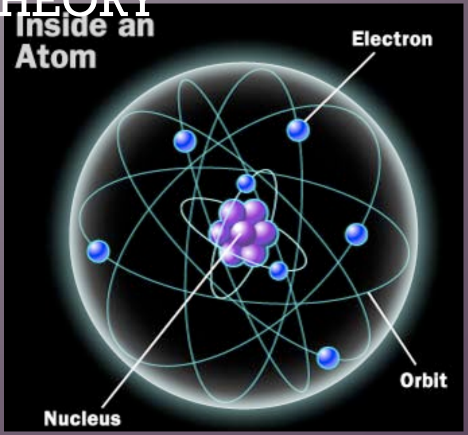
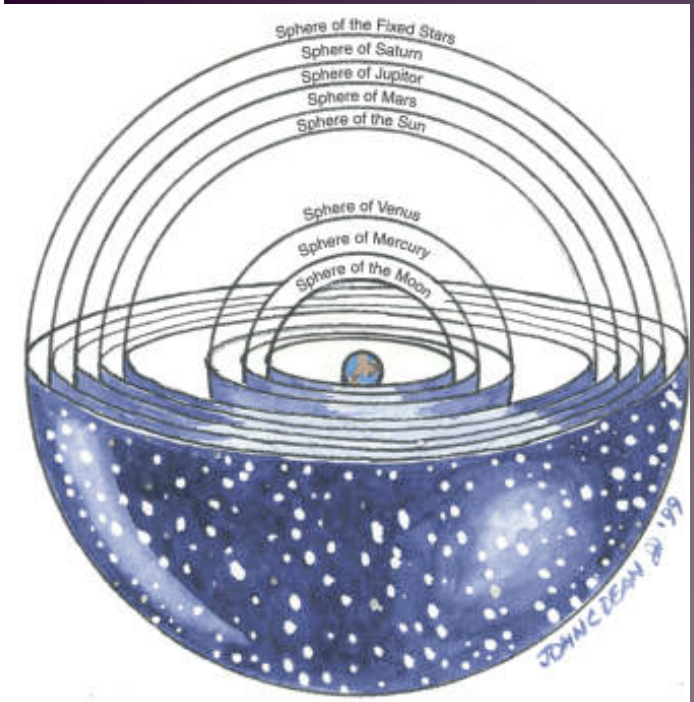




AND THE EVOLUTION
OF A SCIENCE



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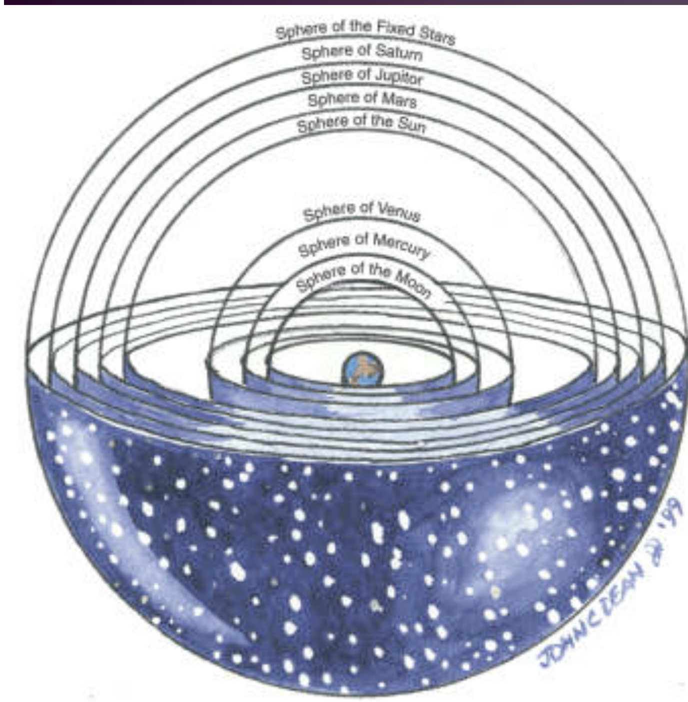

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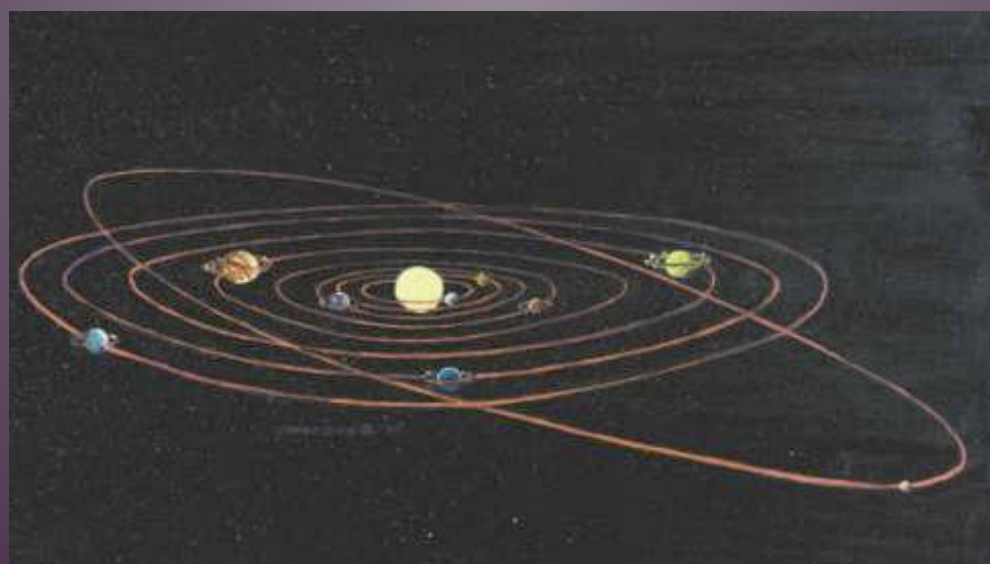

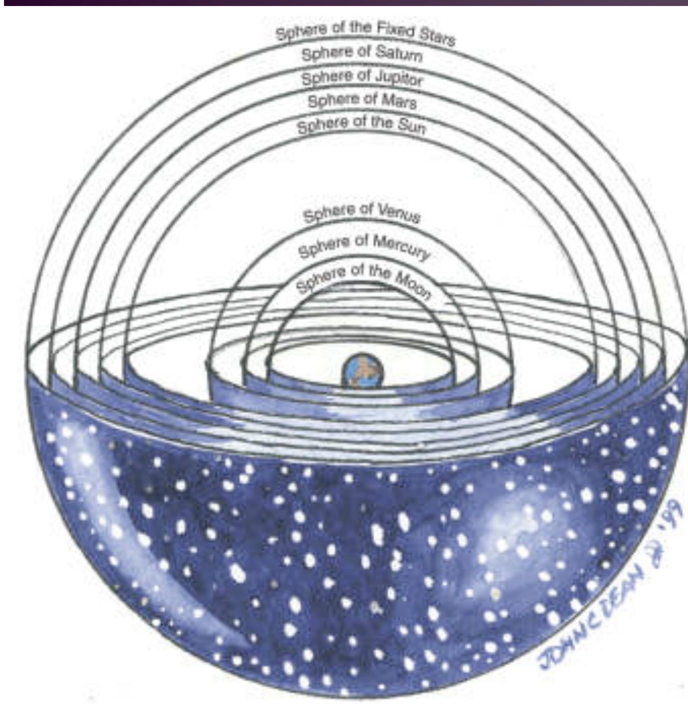

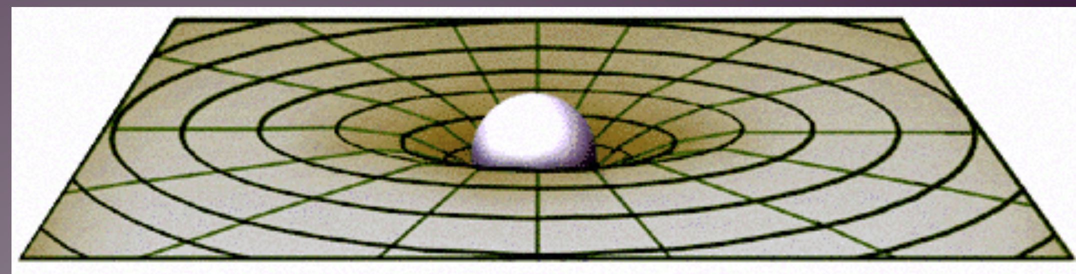

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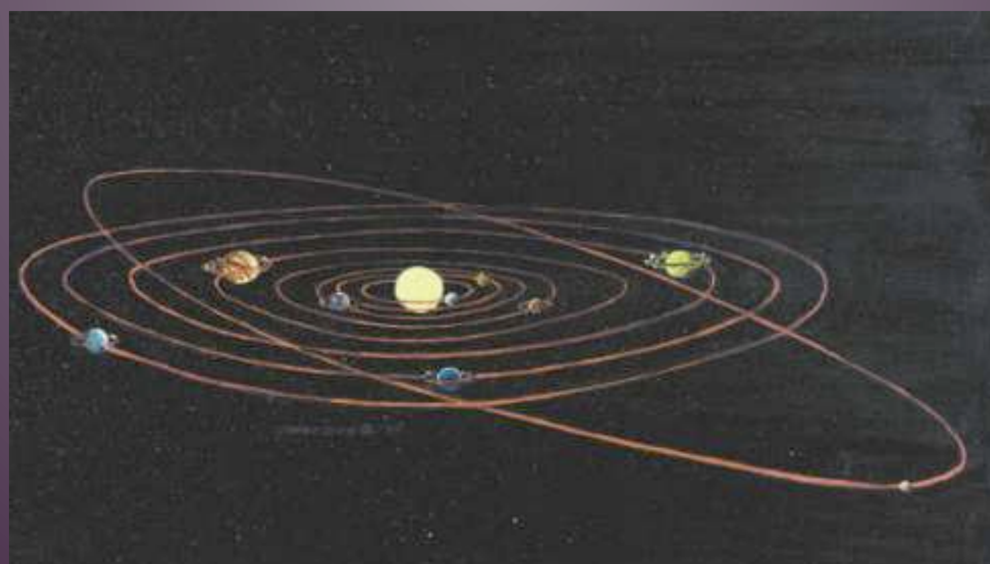
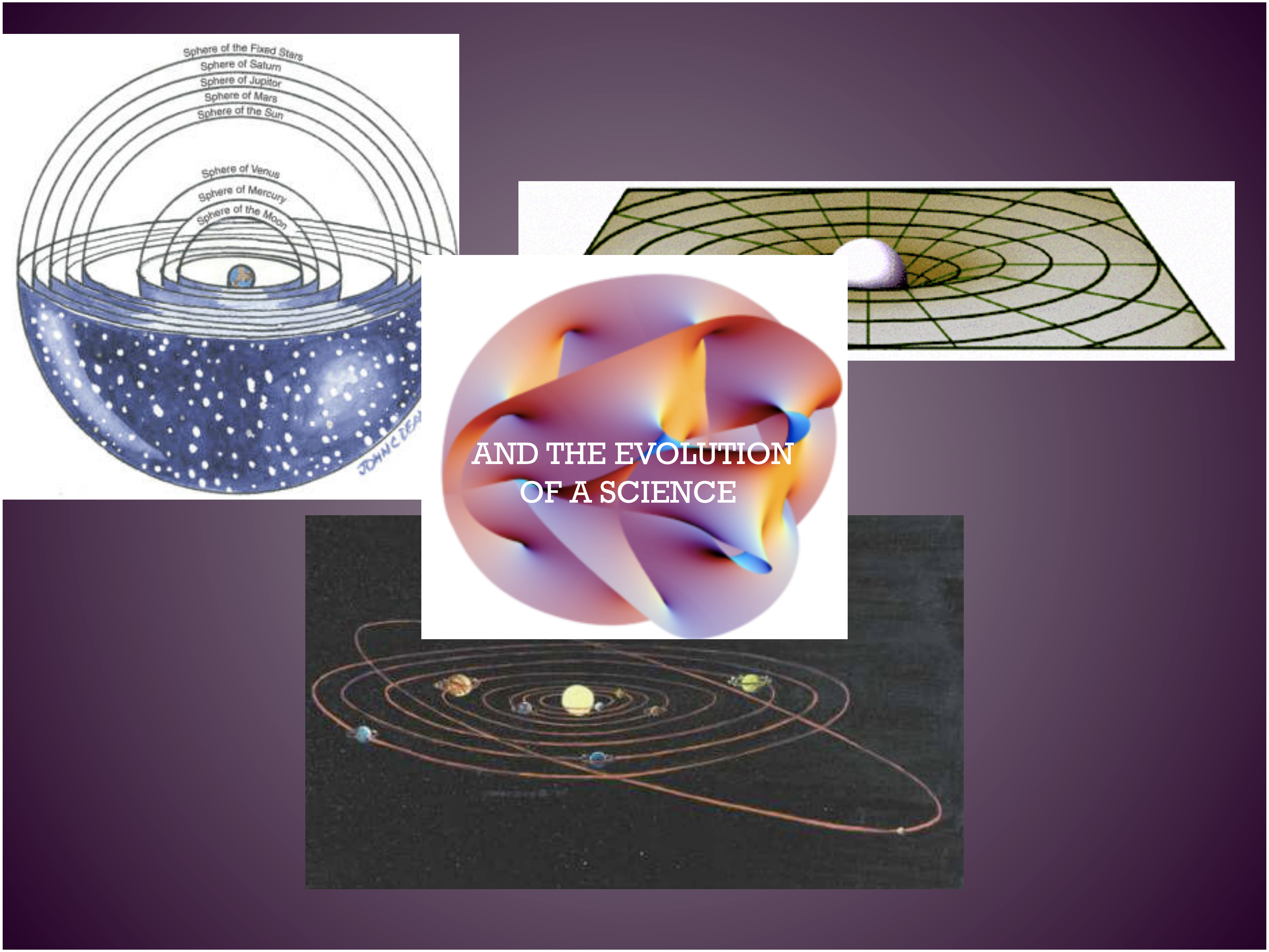
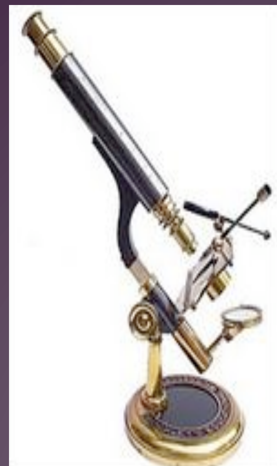


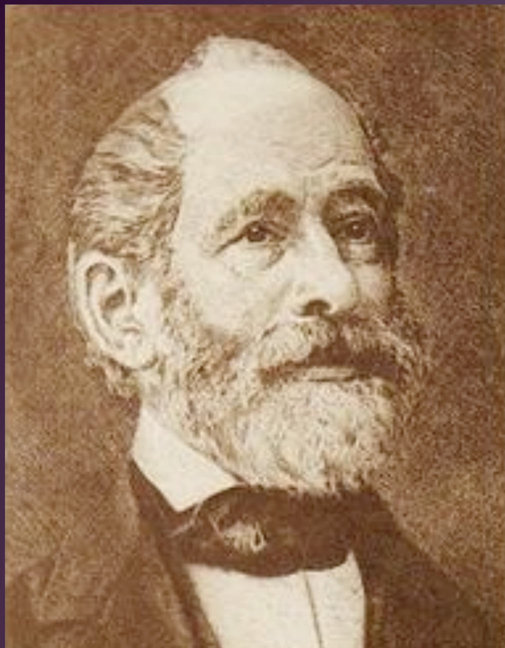

Sphere of the Fixed Stars
Sphere of Saturn
Sphere of Jupiter
Sphere of Mars
Sphere of the Sun
Sphere of Venus
Sphere of Mercury
Sphere of the Moon
AND THE EVOLUTION
OF A SCIENCE

AND ABOUT THE EVOLUTION
OF A TECHNOLOGY



AND ABOUT THE EVOLUTION
OF A TECHNOLOGY

AND ABOUT THE SCIENTISTS, ENGINEERS AND INVENTORS WHO DEVELOPED IT.



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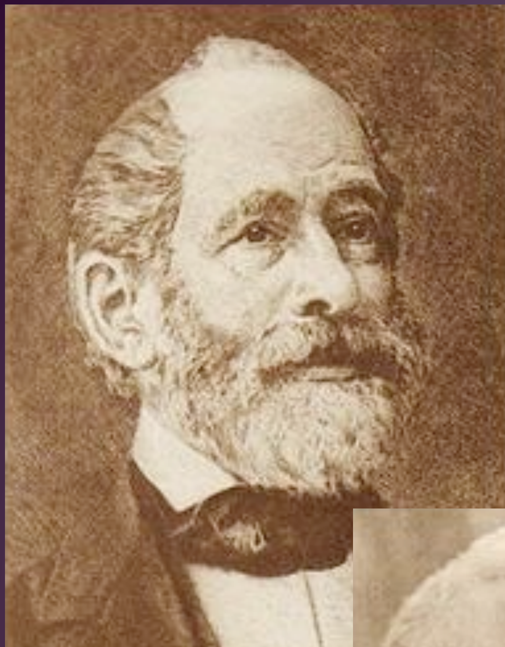
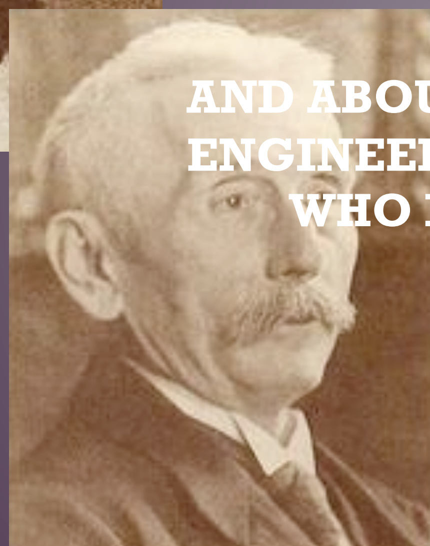
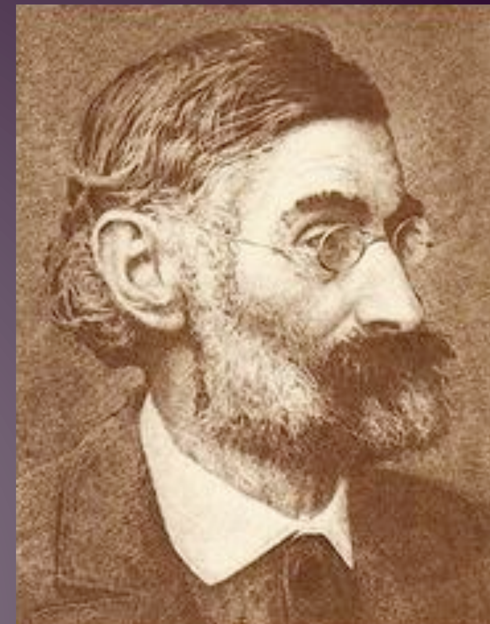

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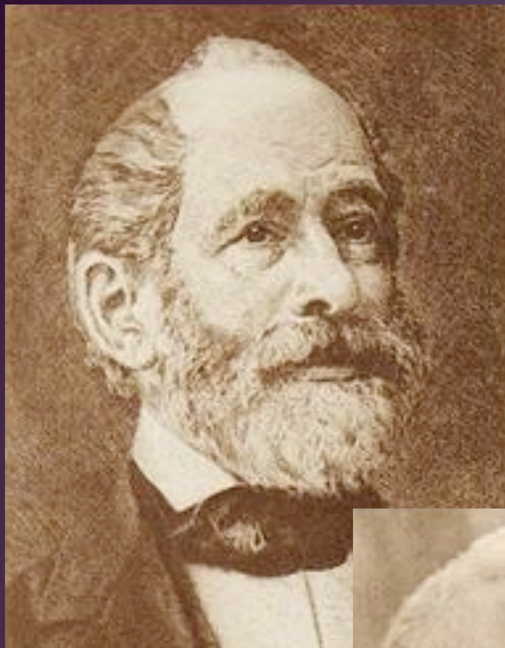


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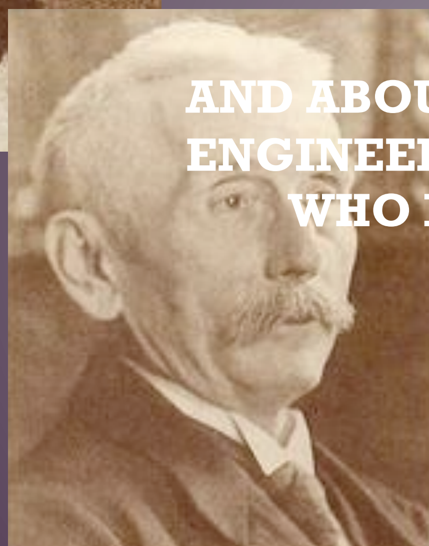
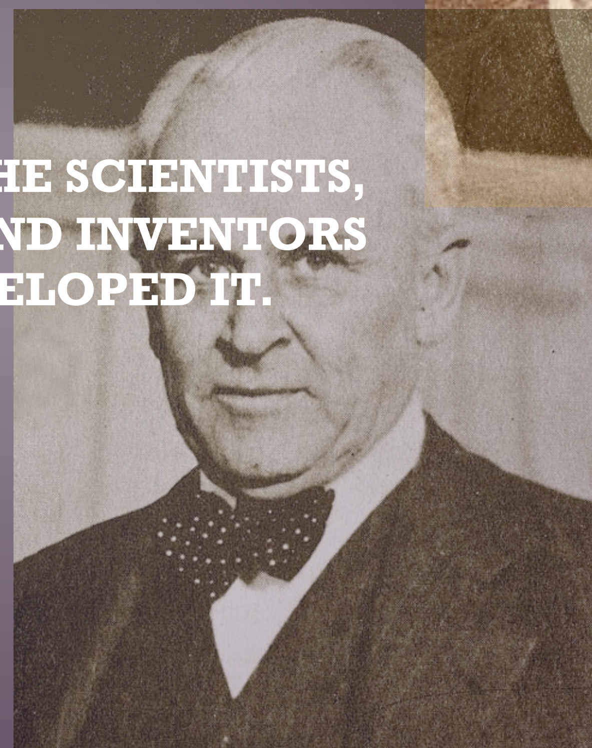

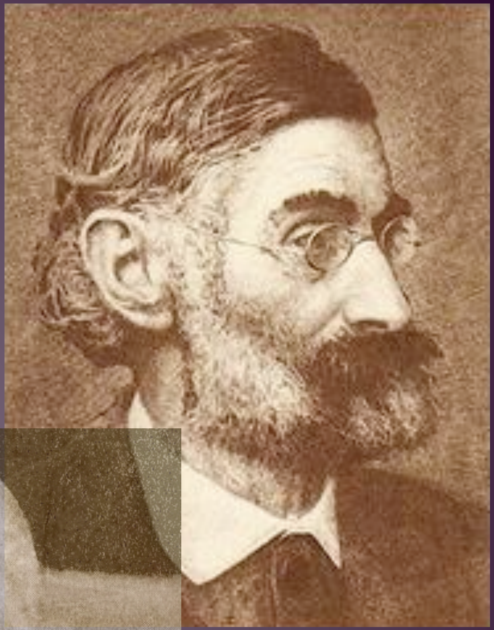

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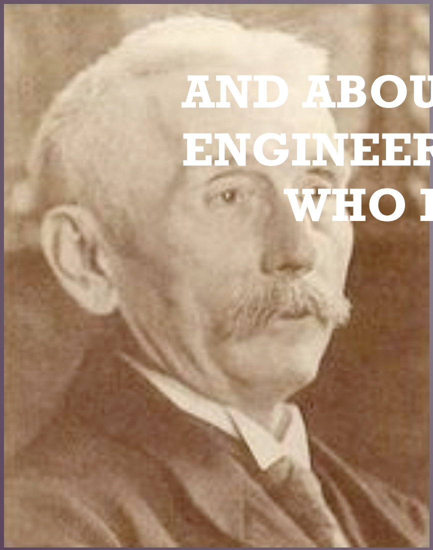

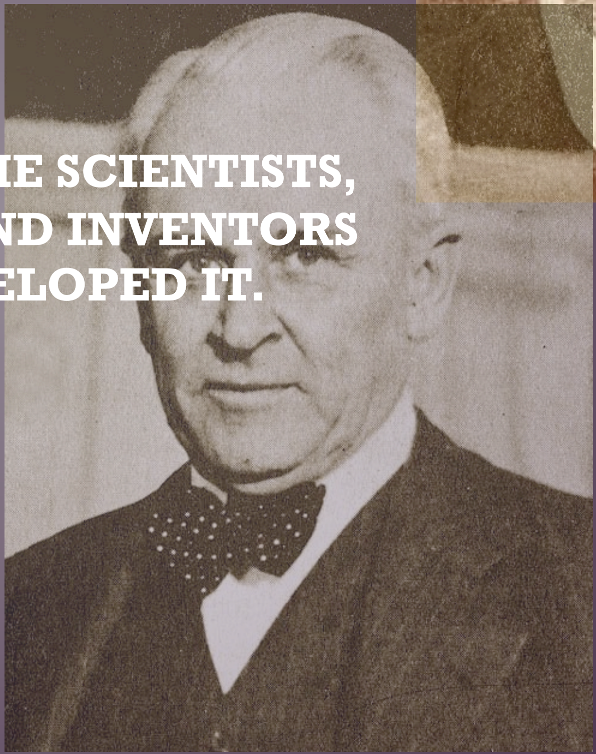


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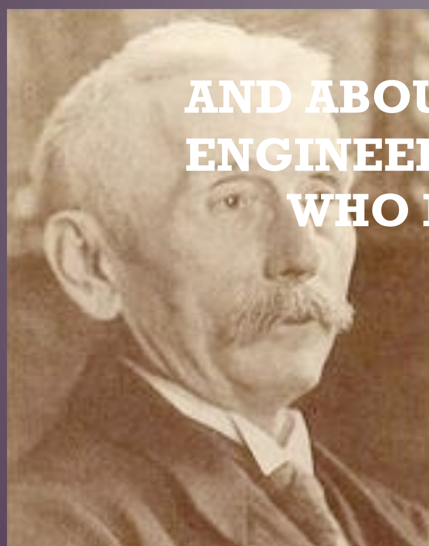
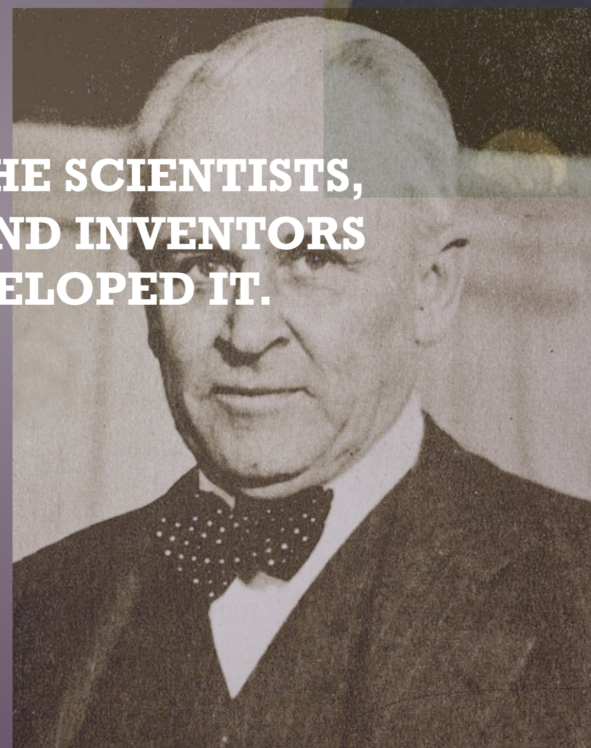

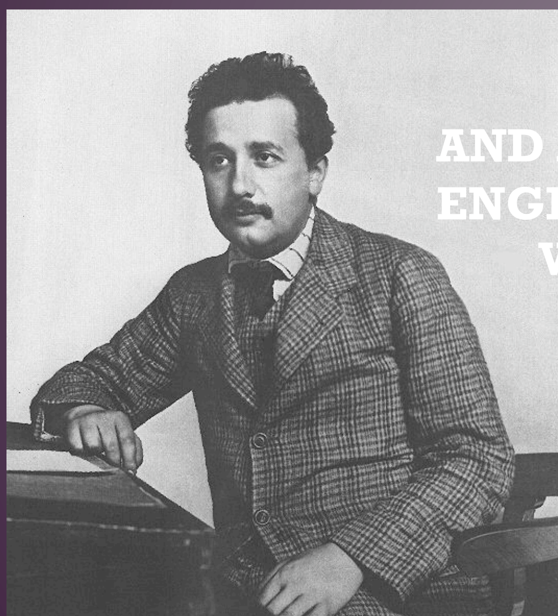

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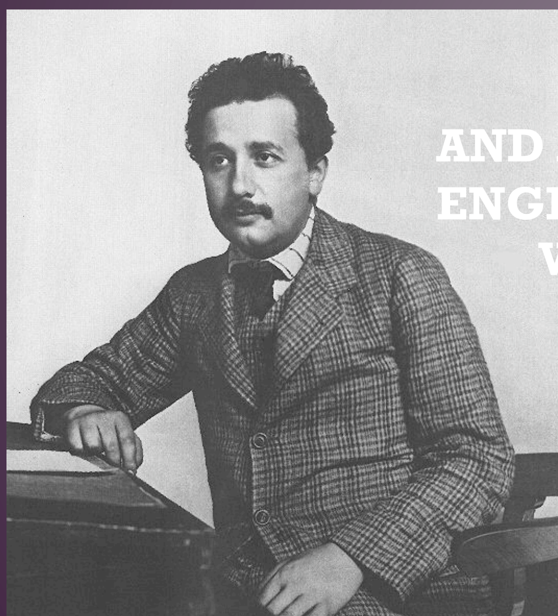

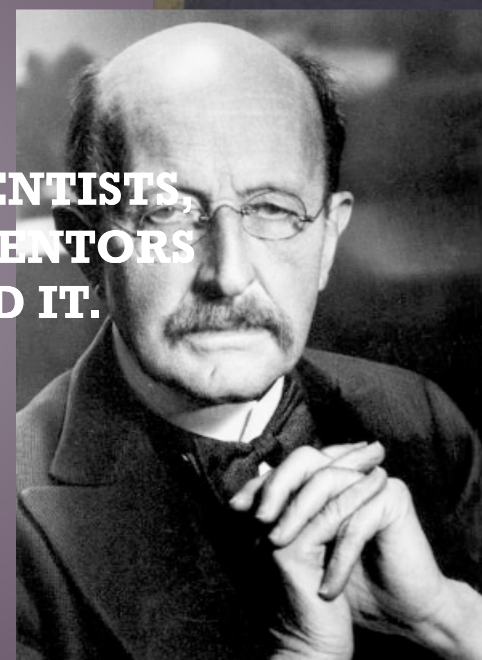

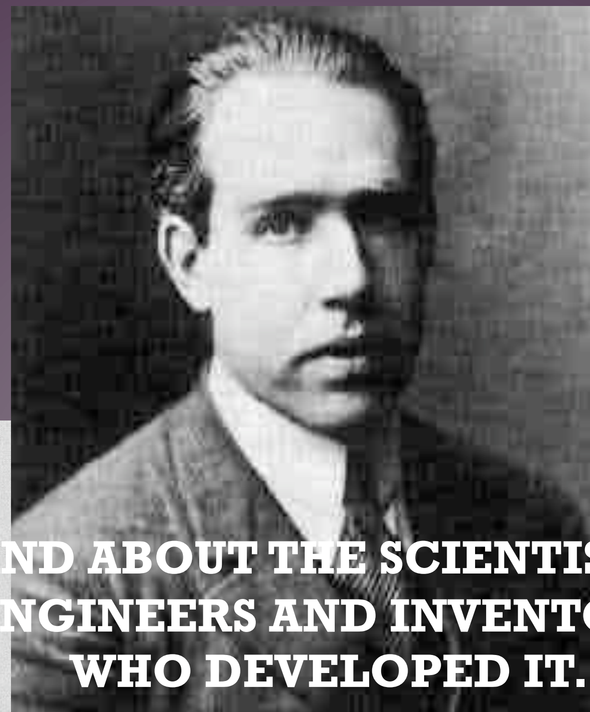

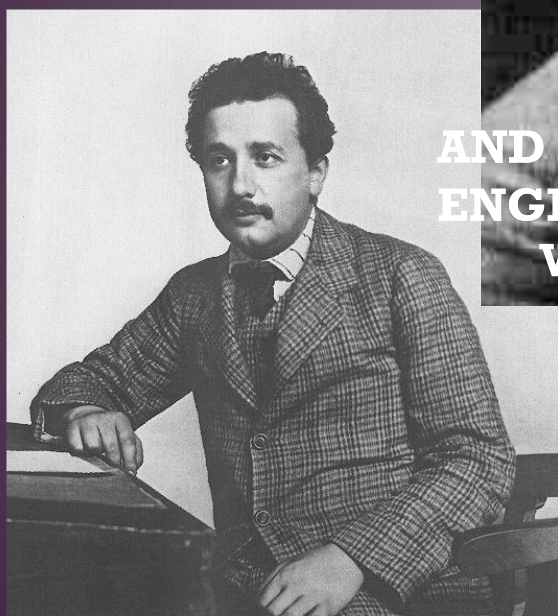

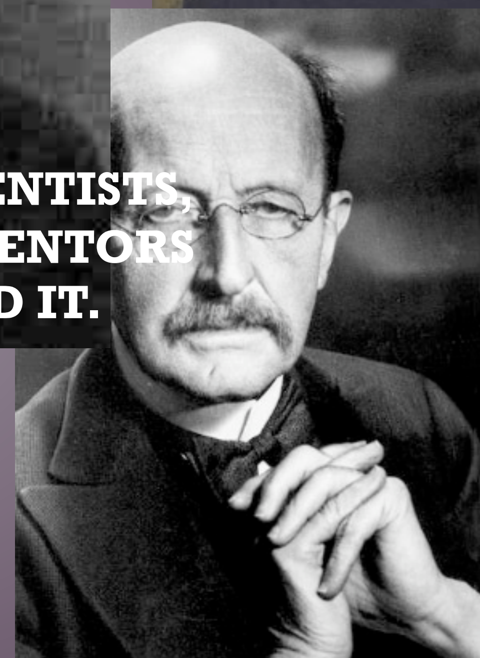

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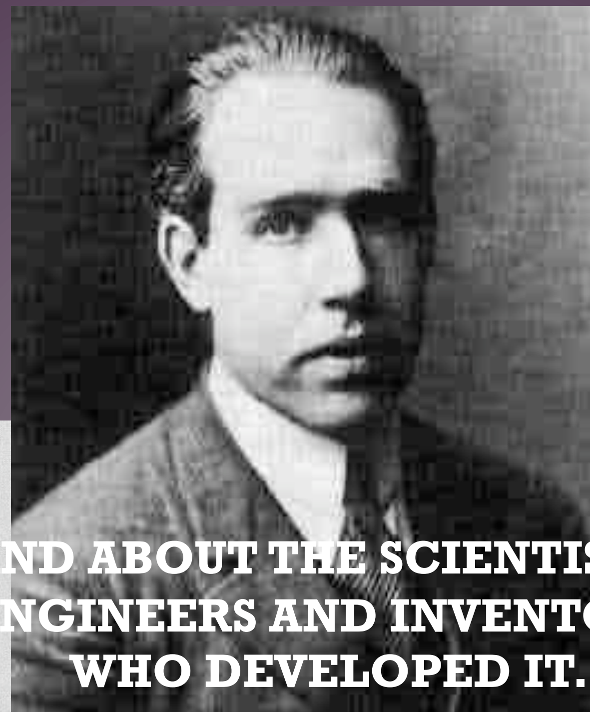


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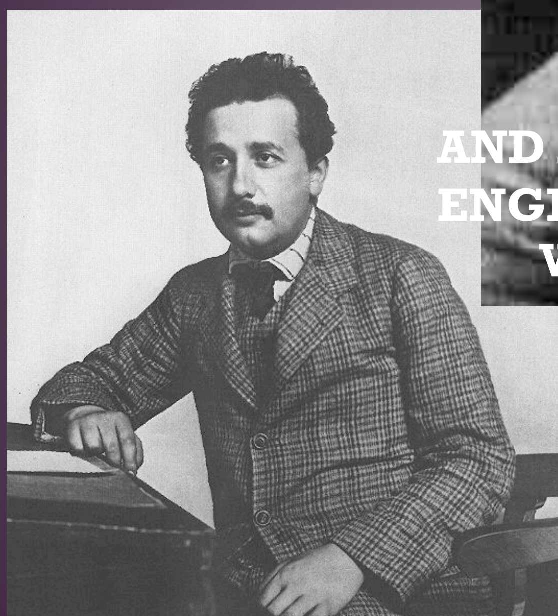
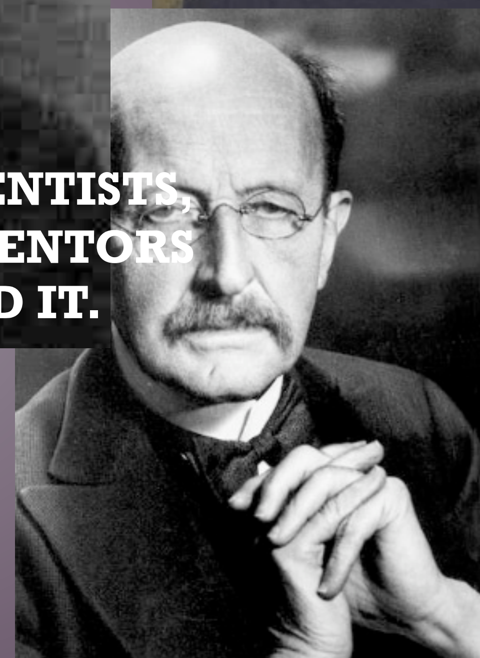

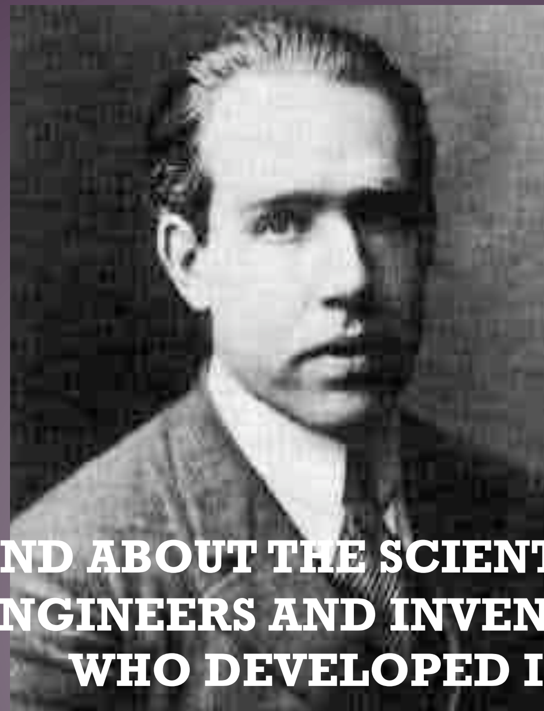

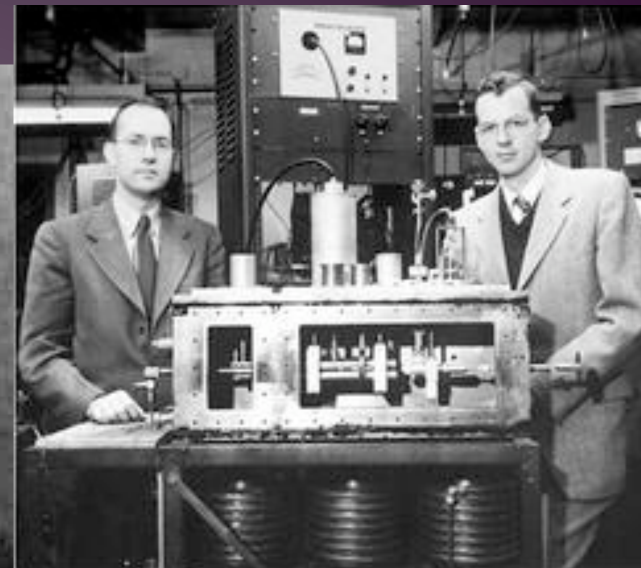

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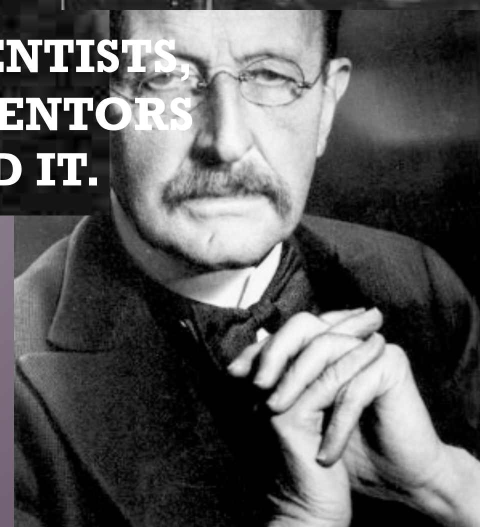
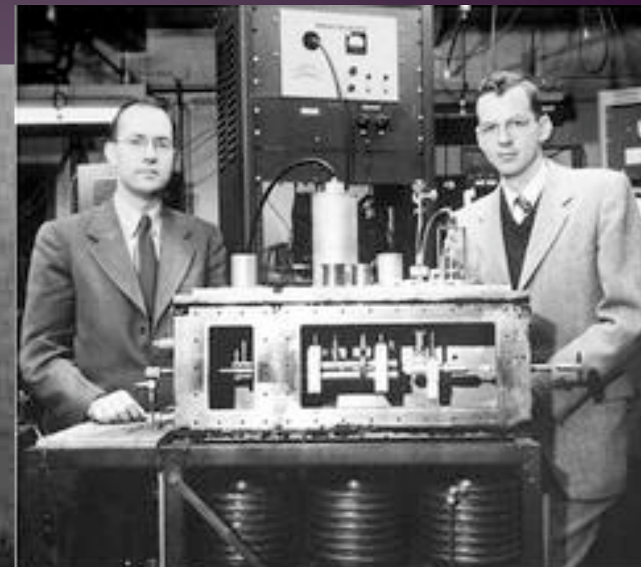
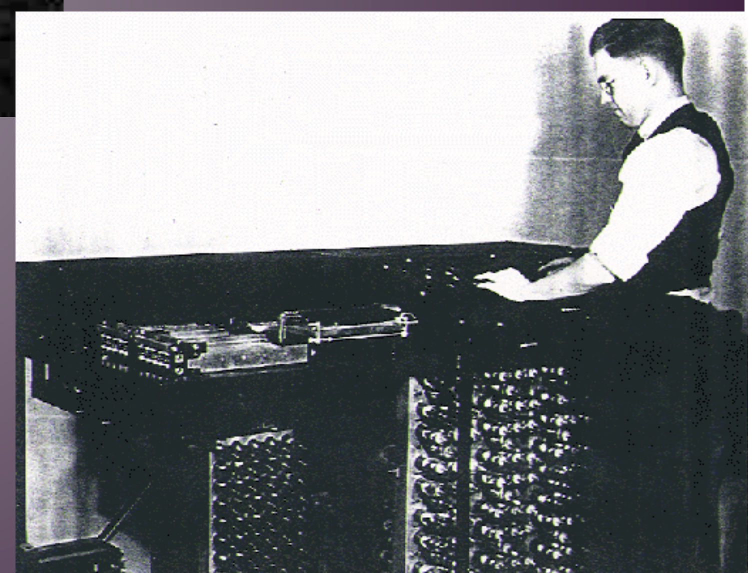
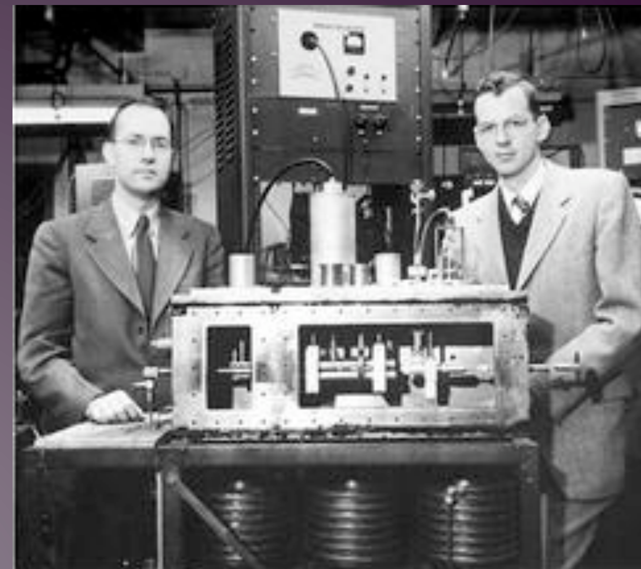






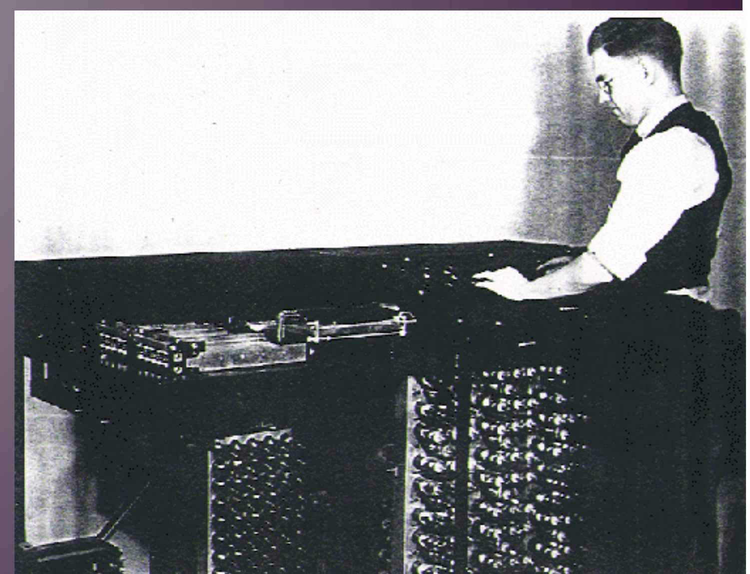
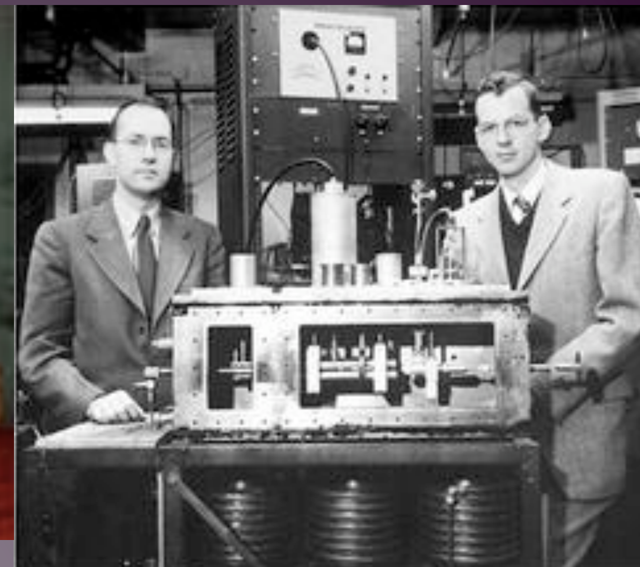
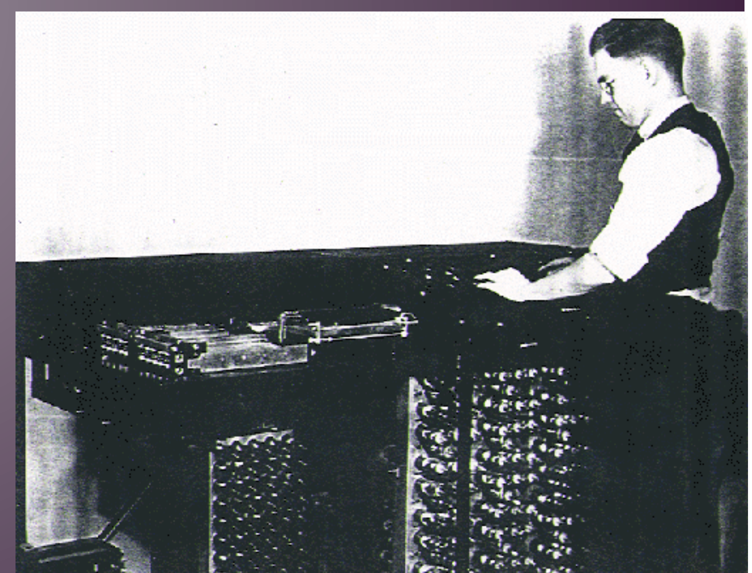




Photo: IBM



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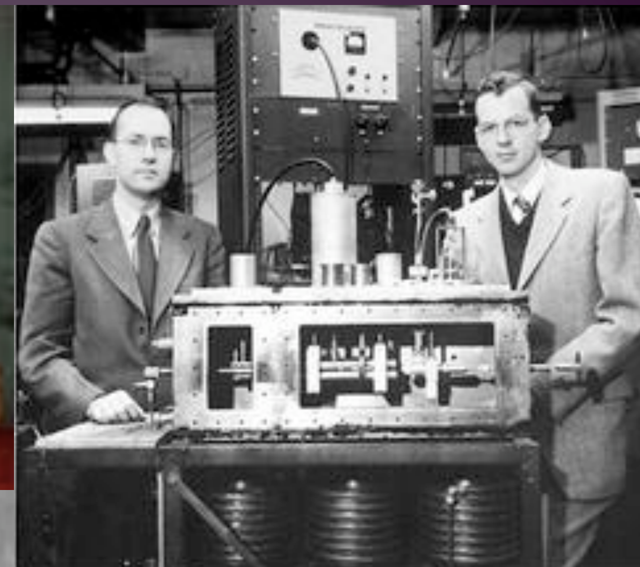

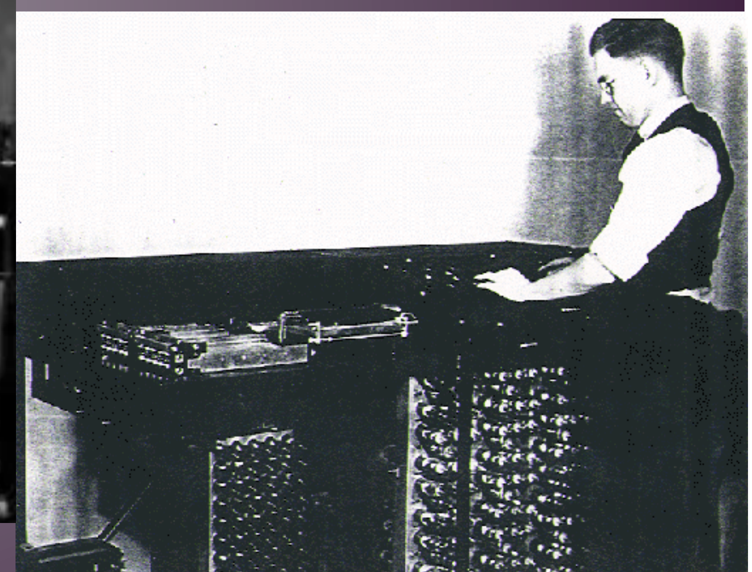

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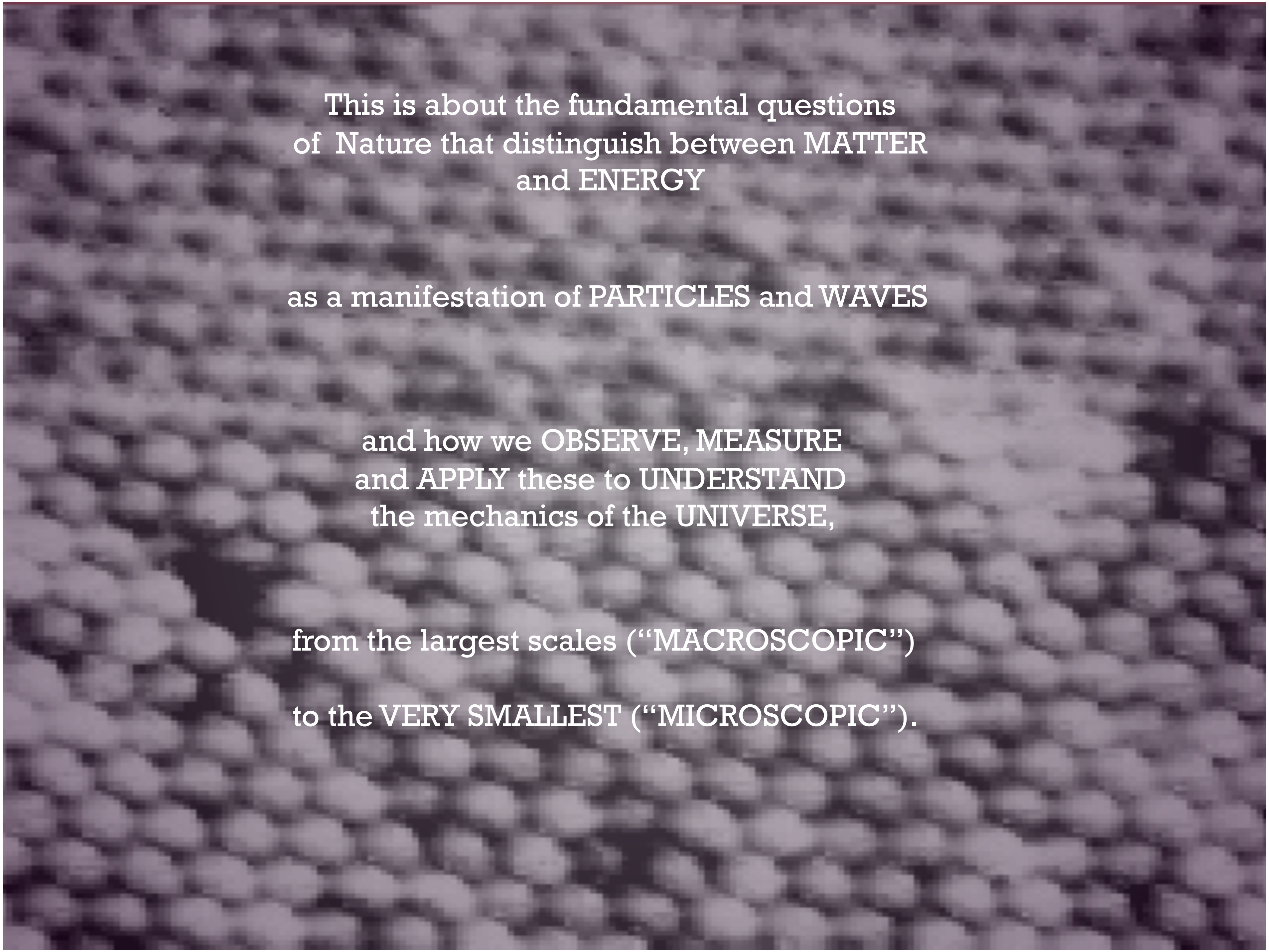
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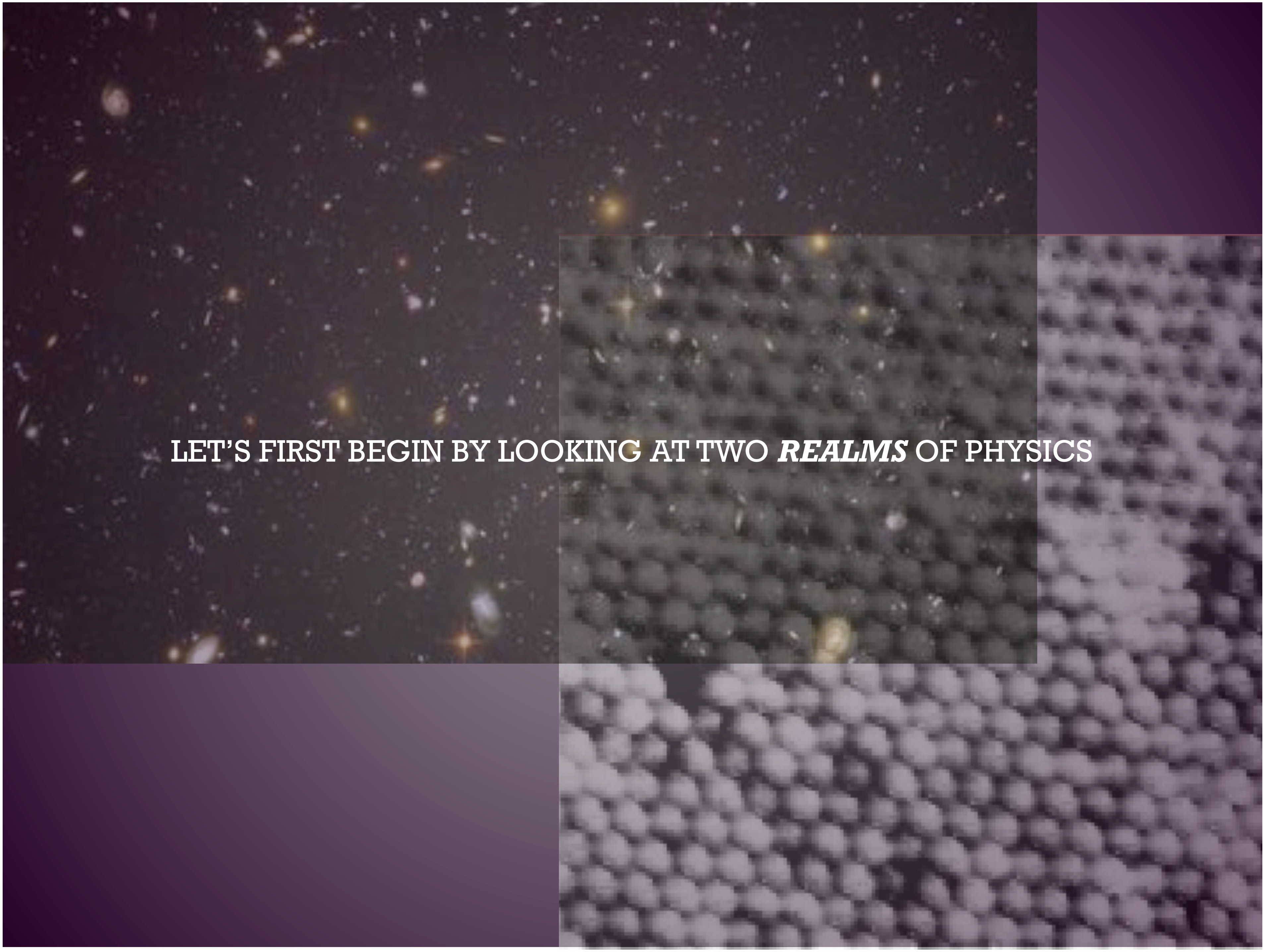
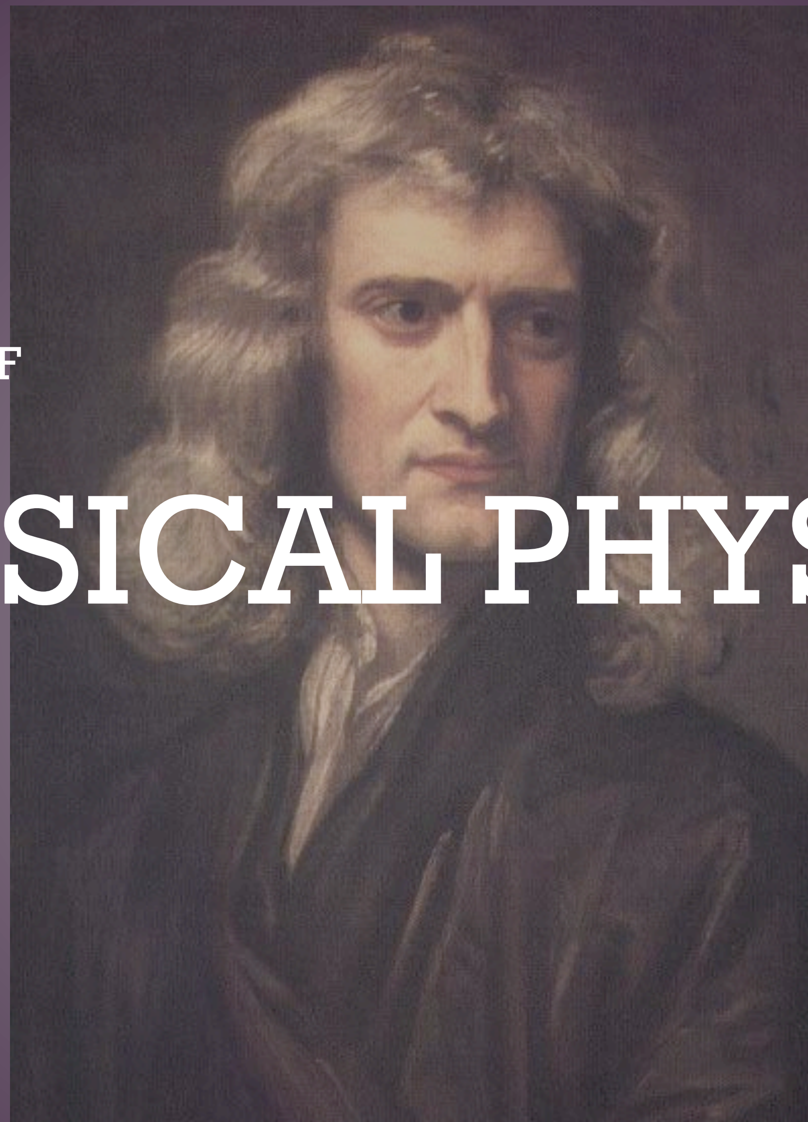

LET'S FIRST BEGIN BY LOOKING AT TWO ***REALMS*** OF PHYSICS

I. THE REALM OF

CLASSICAL PHYSICS



CLASSICAL PHYSICS

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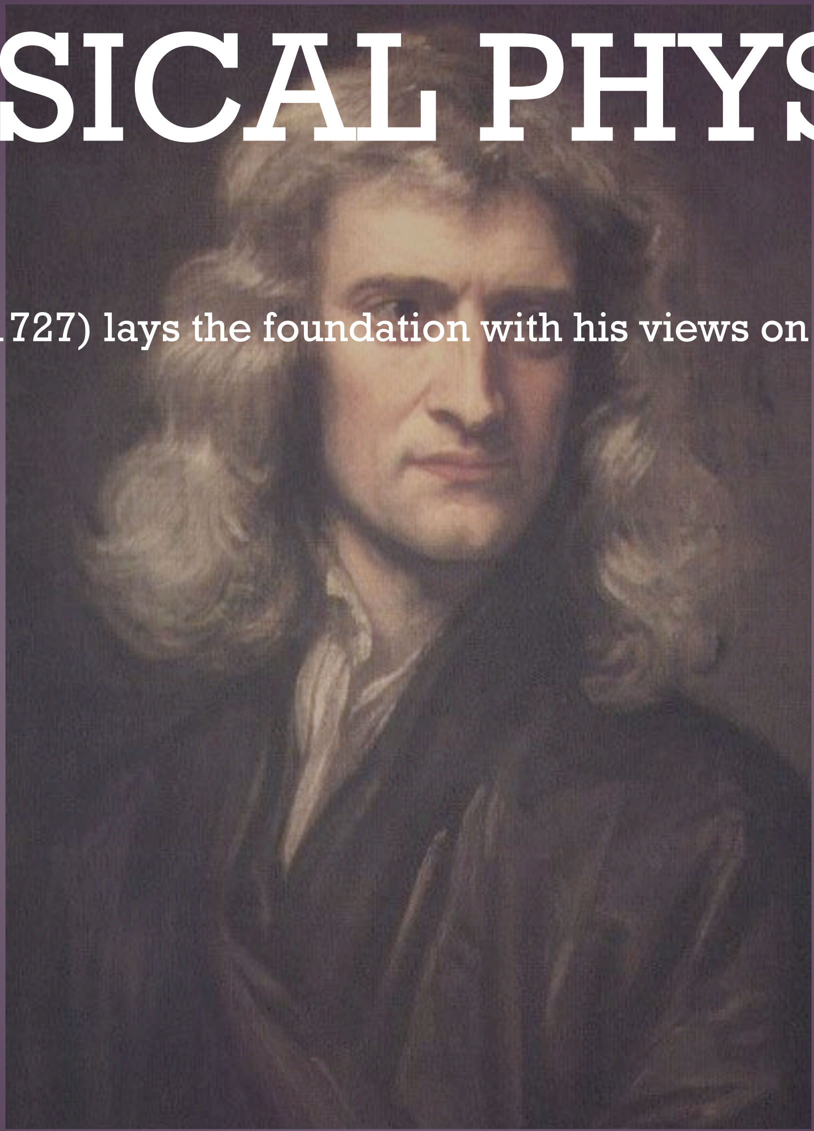

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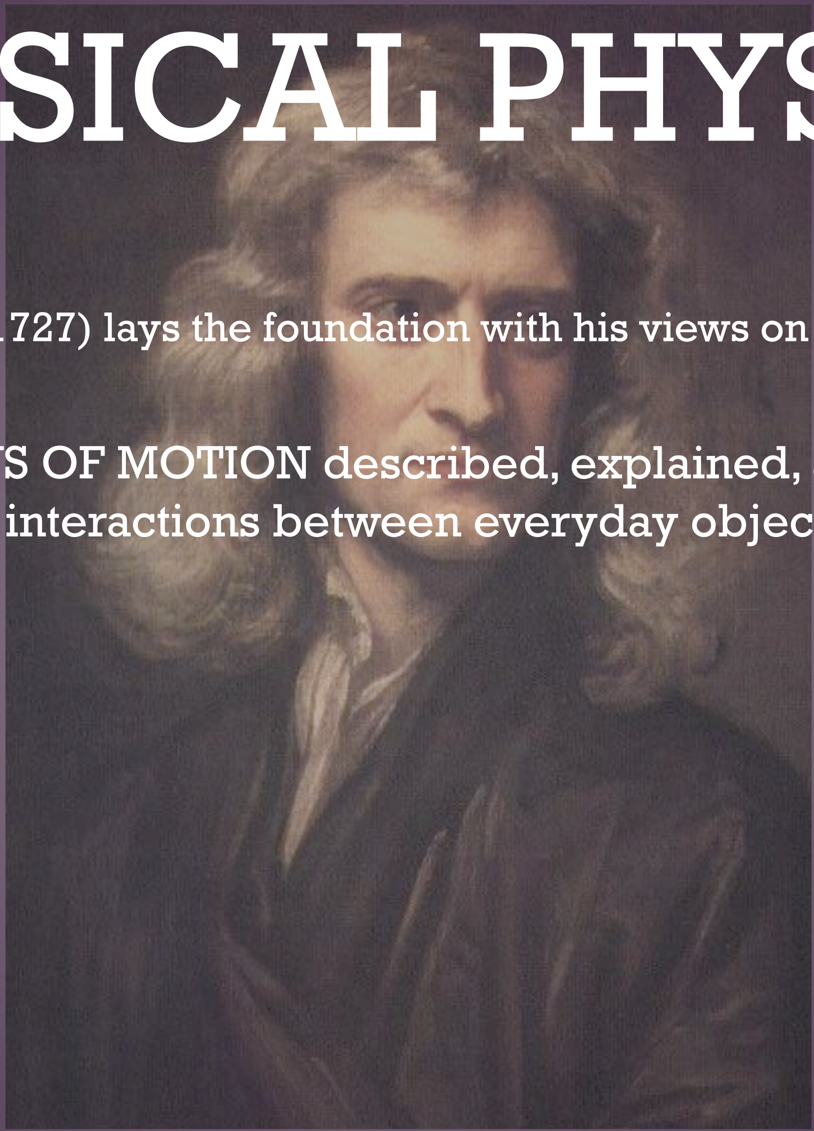

2. His LAWS OF MOTION described, explained, and quantified interactions between everyday objects.

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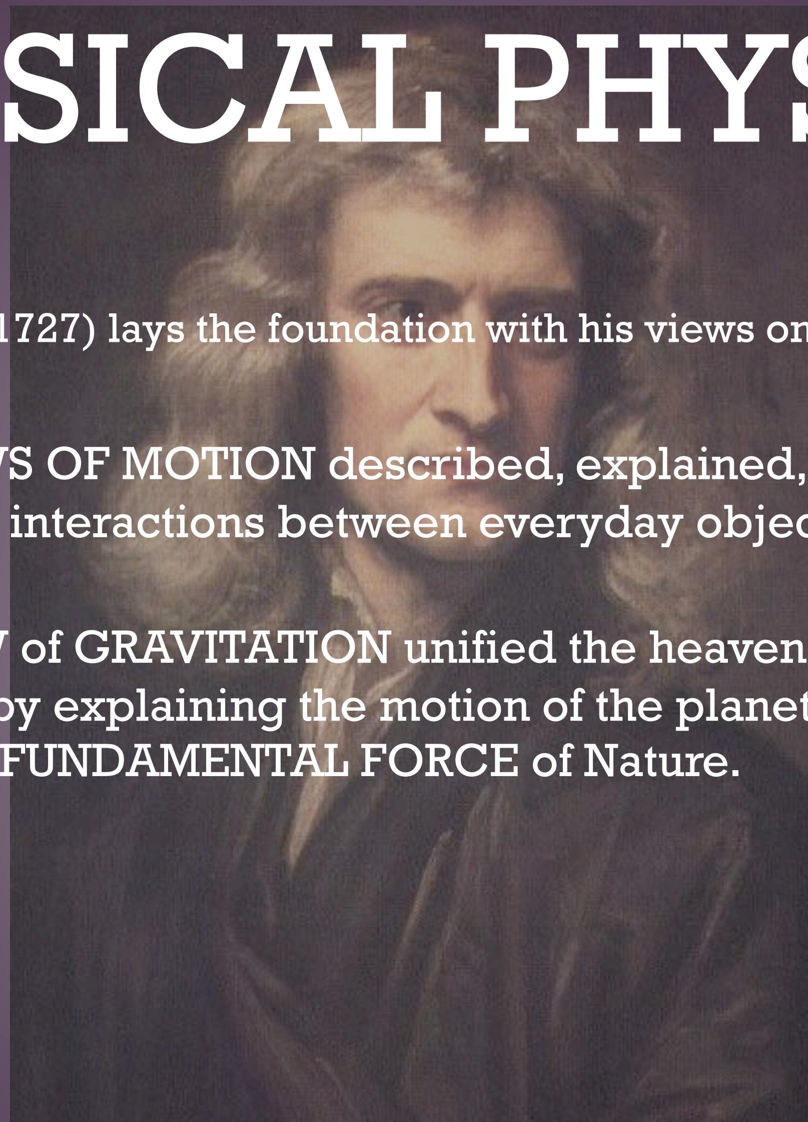

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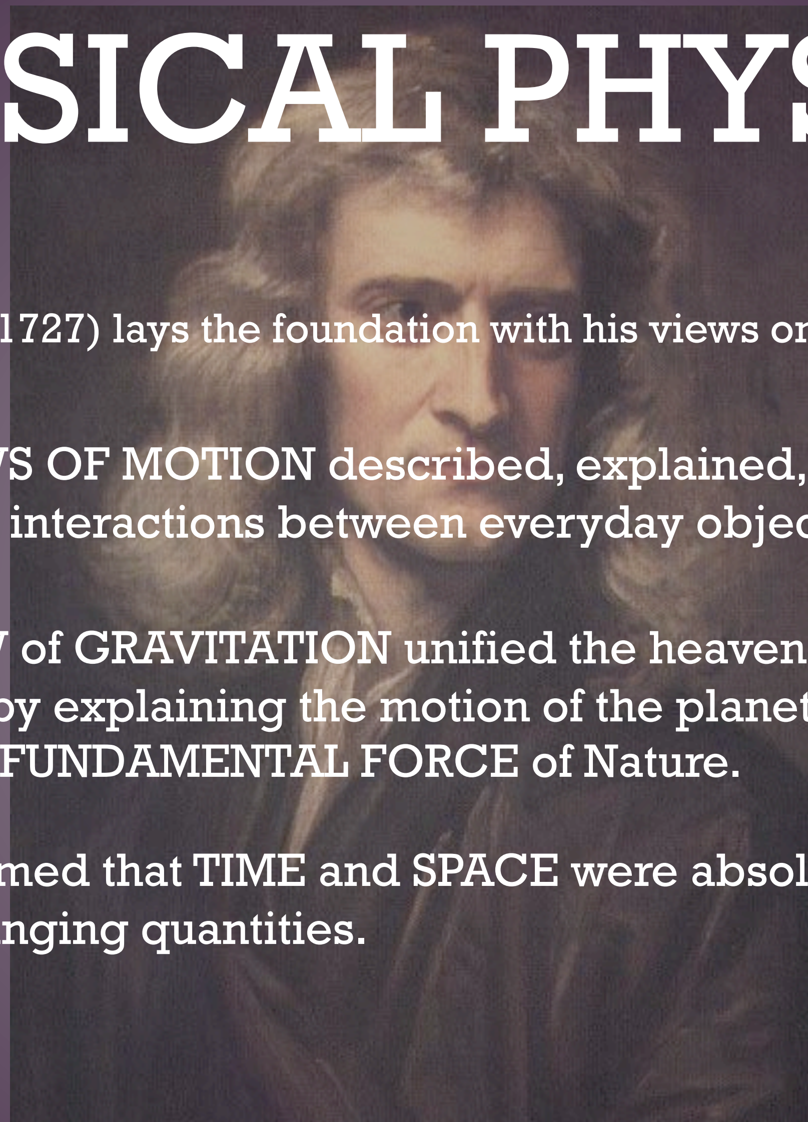

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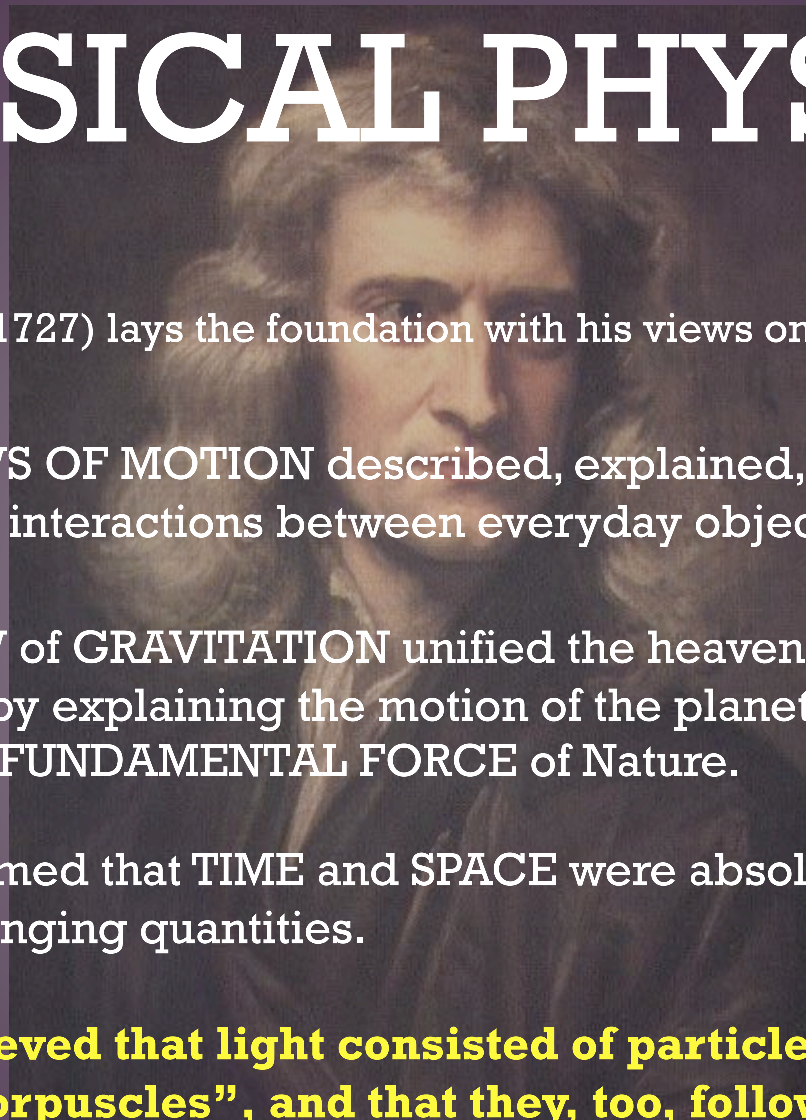

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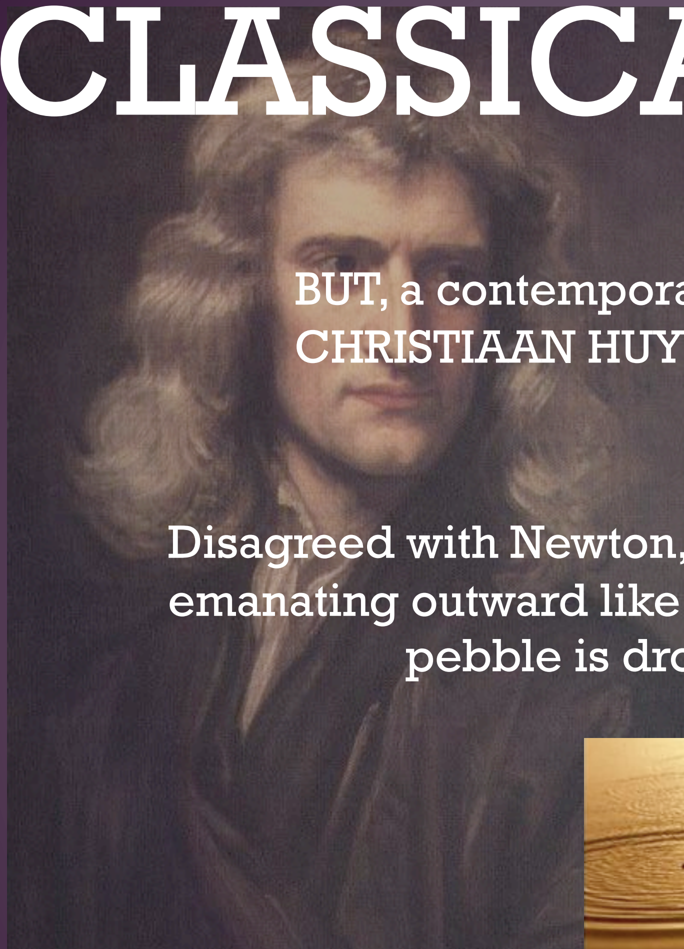
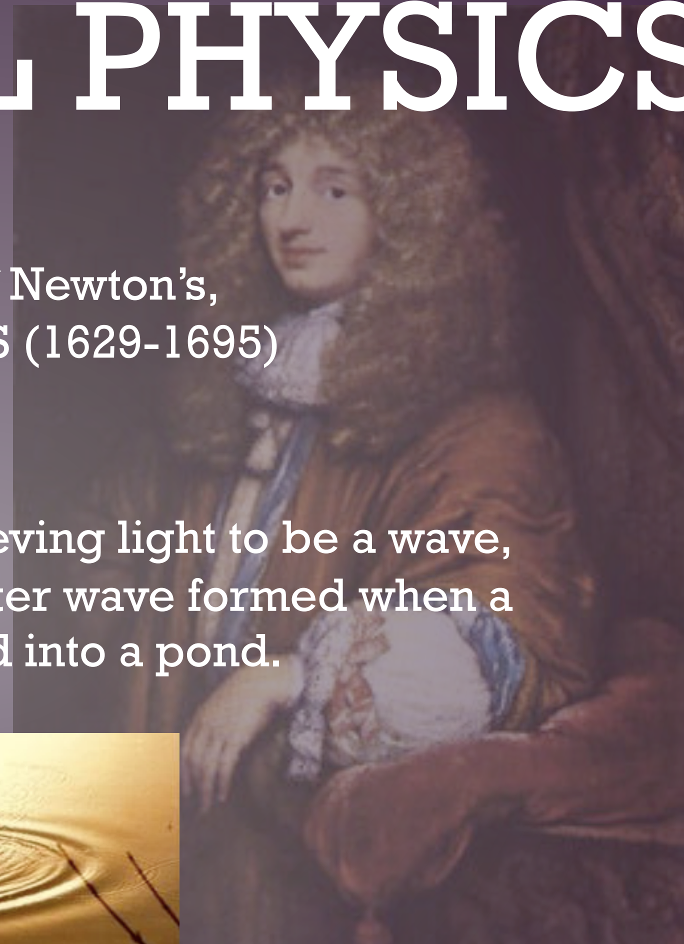
5. **He believed that light consisted of particles called "corpuscles", and that they, too, followed his rules of interaction like all objects.**

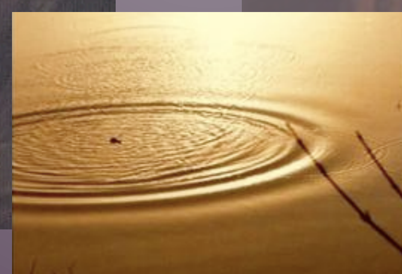
CLASSICAL PHYSICS





BUT, a contemporary of Newton's,
CHRISTIAAN HUYGENS (1629-1695)

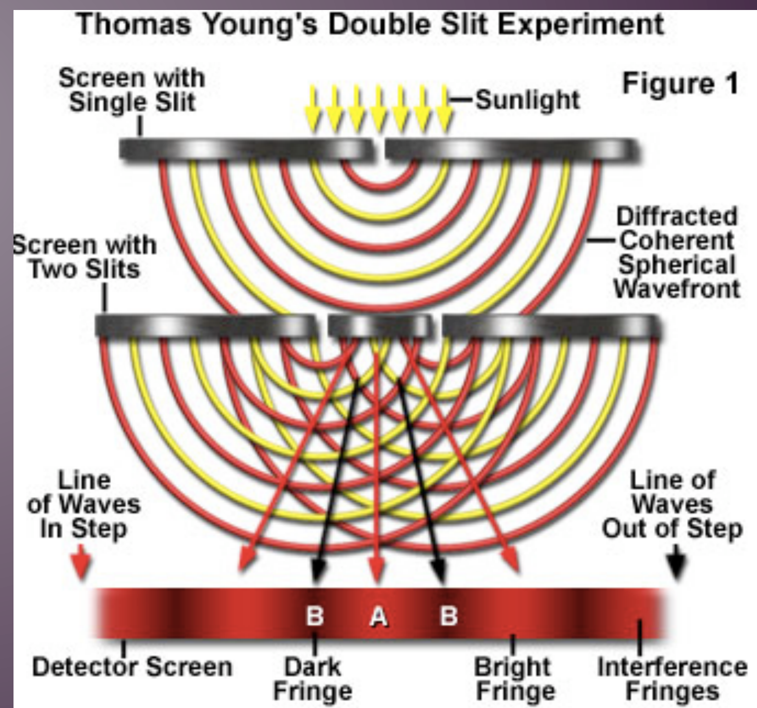
Disagreed with Newton, believing light to be a wave, emanating outward like a water wave formed when a pebble is dropped into a pond.

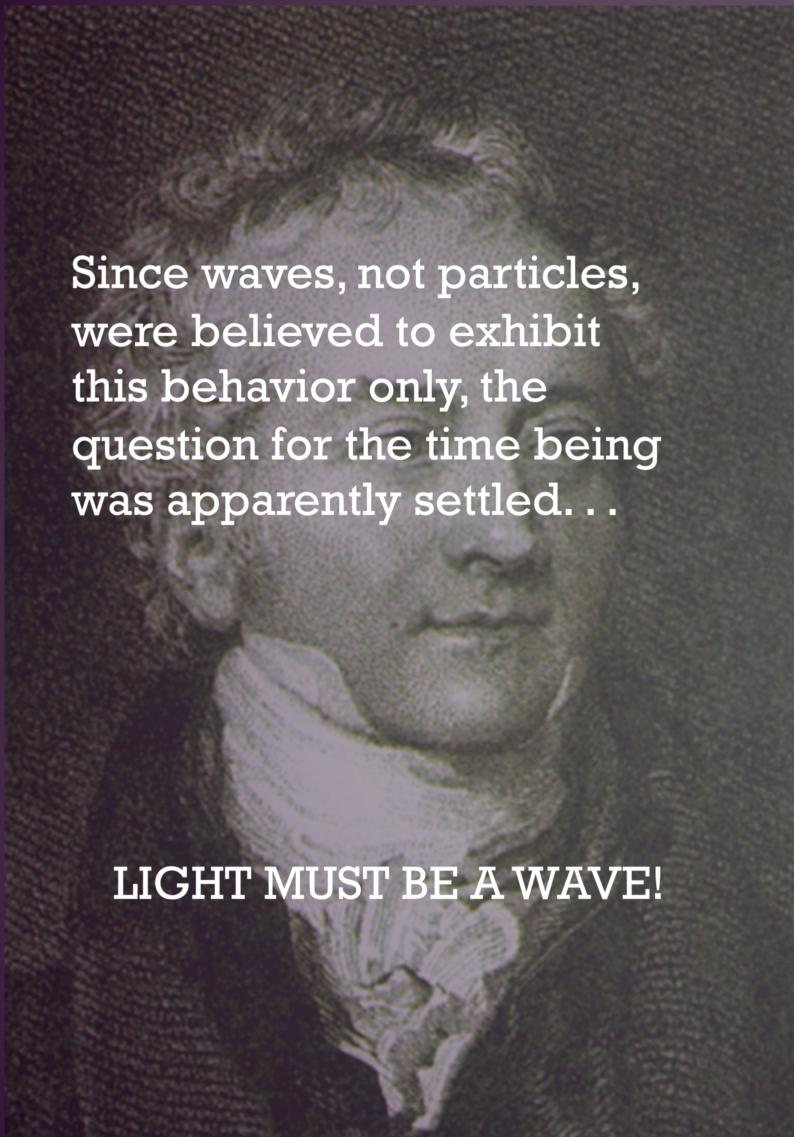


But, later, at the beginning of the 19th century,

THOMAS YOUNG (1773-1829)

In one of the most important experiments in history, showed that light DOES behave like a WAVE, by demonstrating how light waves INTERFERE with each other.





Since waves, not particles, were believed to exhibit this behavior only, the question for the time being was apparently settled. . .

LIGHT MUST BE A WAVE!

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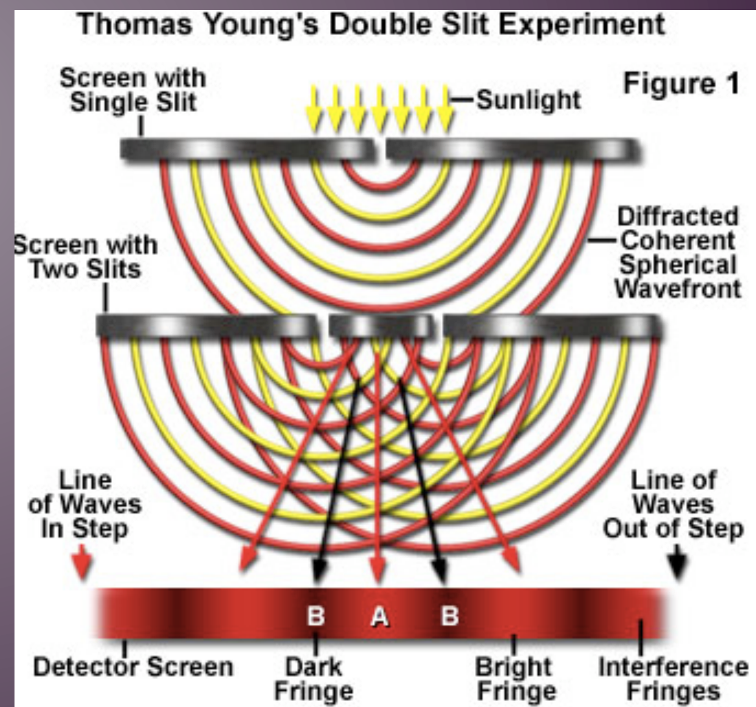
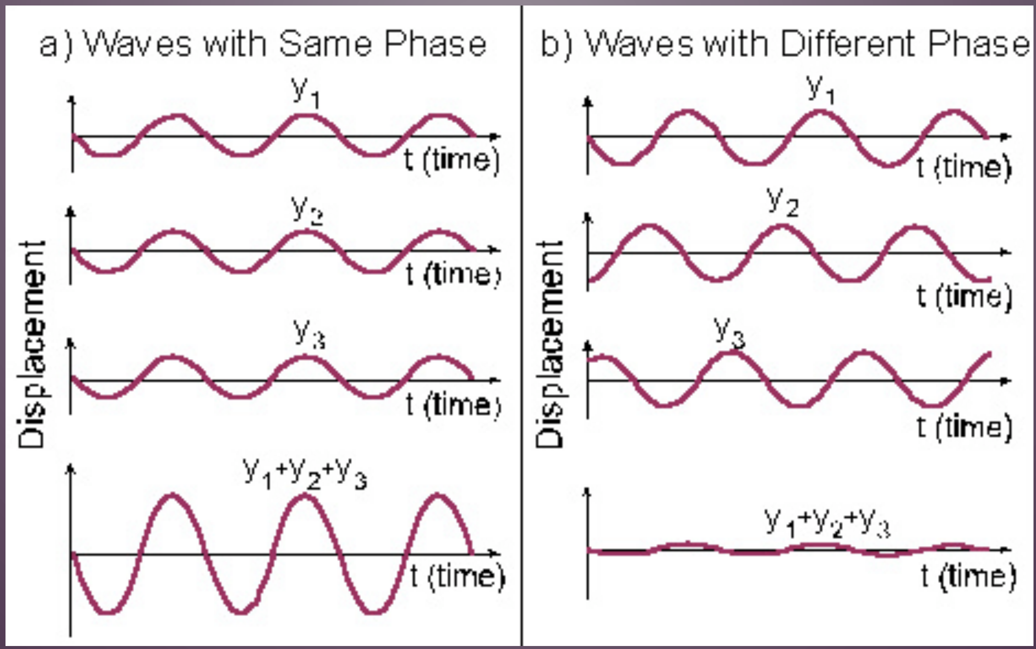


Young, along with AUGUSTIN FRESNEL (1788-1827), proposed a

THEORY OF SUPERPOSITION OF WAVES

in which waves can "interpenetrate" each other like waves on the surface of a pond, with their resulting displacements adding up algebraically.



BY the mid 19th century, a Scottish physicist,
JAMES CLERK MAXWELL

Unified the forces of
ELECTRICITY and MAGNETISM
into a

THEORY OF
ELECTROMAGNETISM

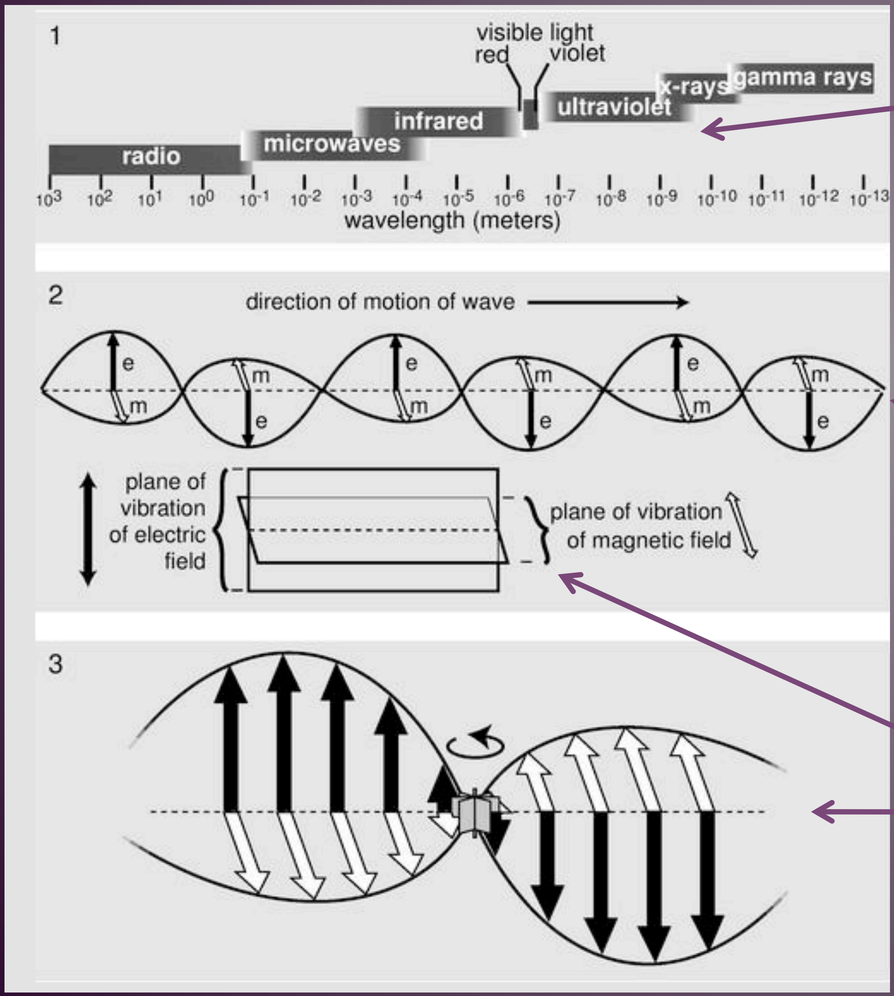
Maxwell's theory showed that light waves consist of oscillating ELECTRIC and MAGNETIC FIELDS that he was able to describe in

FOUR eloquent equations:

$$
\begin{aligned}
\nabla \cdot \mathbf{E} &= 4\pi\rho \\
\nabla \times \mathbf{E} &= -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} \\
\nabla \cdot \mathbf{B} &= 0 \\
\nabla \times \mathbf{B} &= \frac{4\pi}{c}\mathbf{J} + \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t},
\end{aligned}
$$

ELECTROMAGNETISM

ELECTROMAGNETISM



The ELECTROMAGNETIC SPECTRUM

PROPAGATION OF THE E/M WAVE

RELATIONSHIP OF ELECTRIC FIELD TO MAGNETIC FIELD

The theory has been so perfect in describing the dynamics of electricity and magnetism over laboratory scale distances, that it has remained precisely intact.

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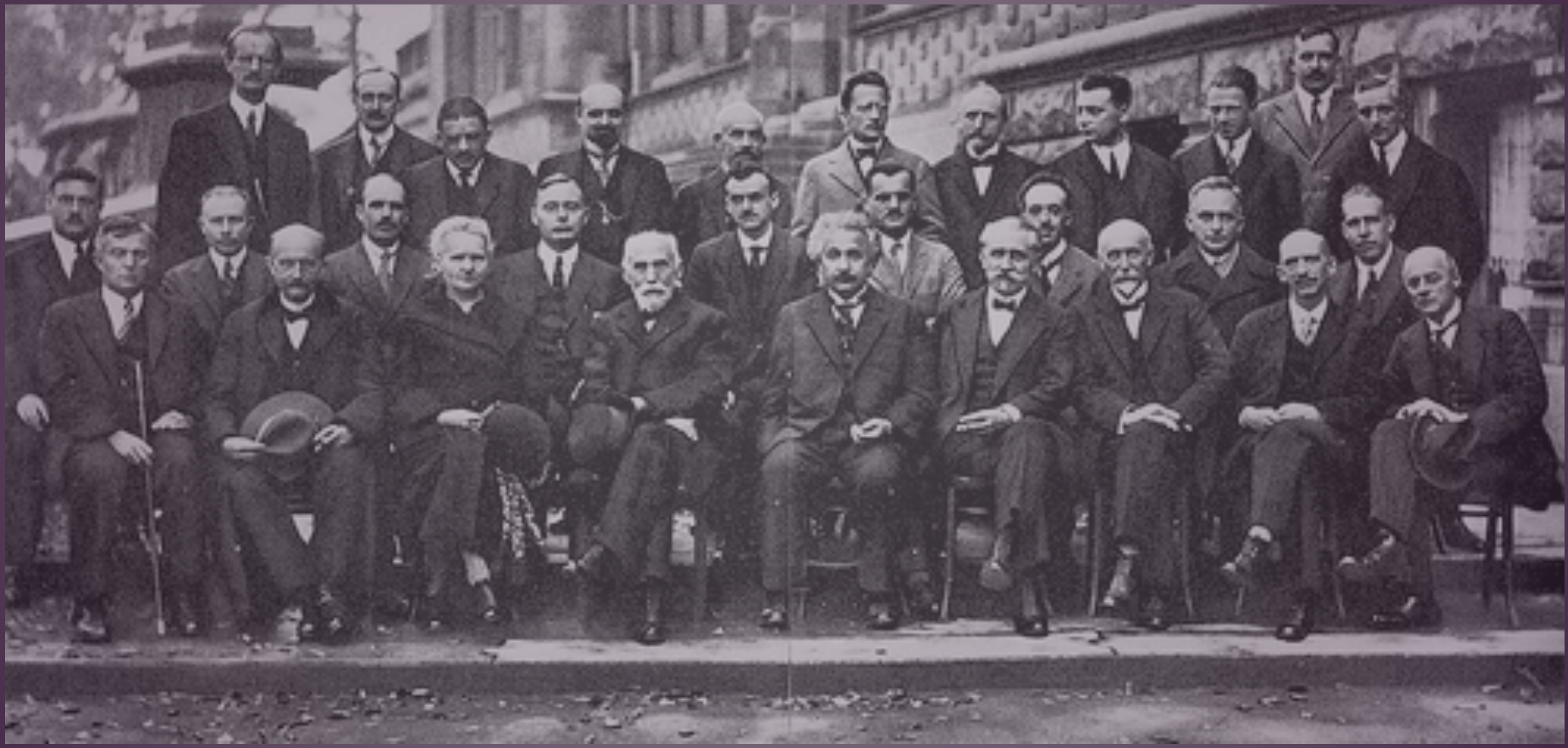
But, on October 19, 1900,
in a presentation made to the German Physical Society,
a NEW REALM OF PHYSICS was to begin.

THE 5th SOLVAY CONFERENCE, 1927

It is here, in Belgium, that many of the architects of physics in the 20th Century would meet to discuss (and argue) new developments that would challenge, and eventually change our views of physics, and the universe.

THE 5th SOLVAY CONFERENCE, 1927



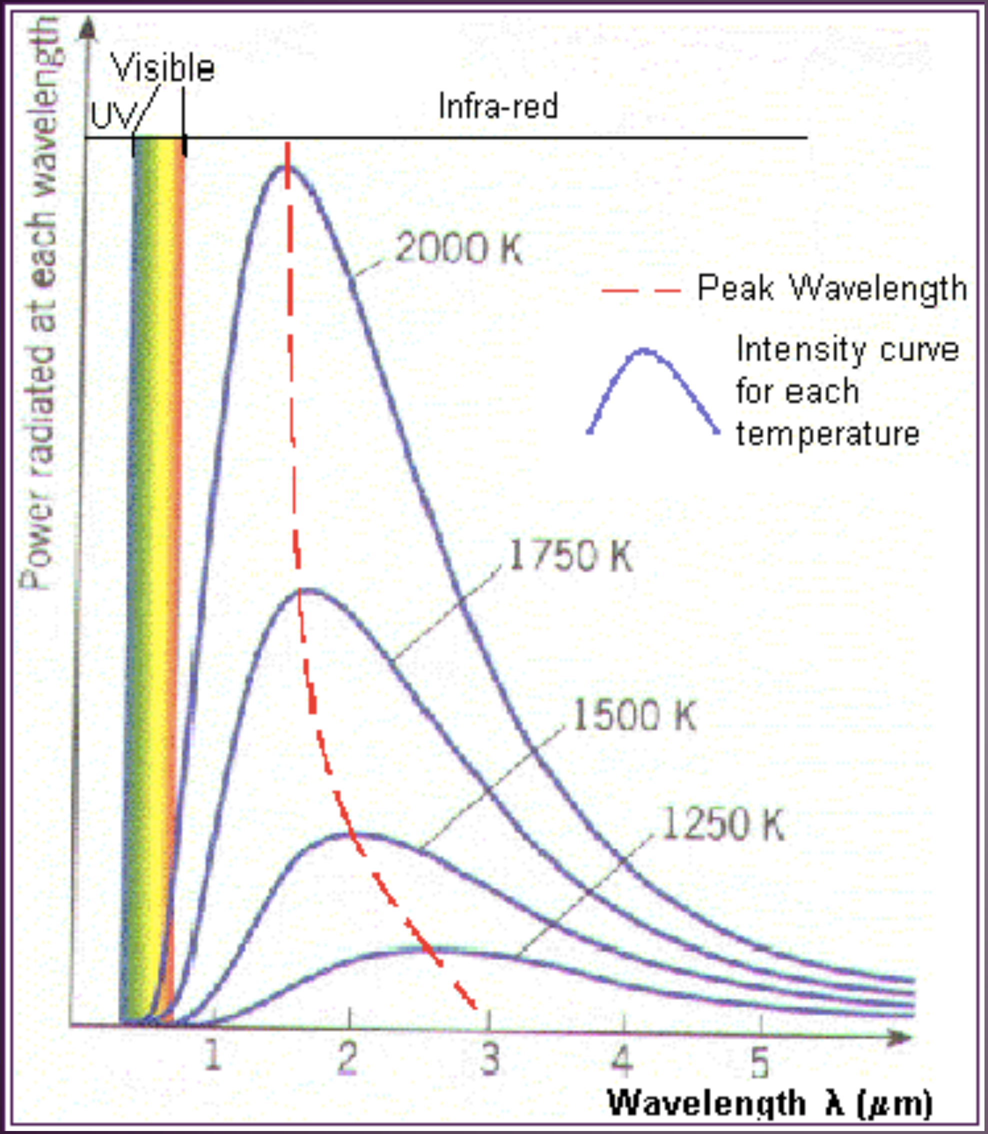
Seventeen of the twenty-nine attendees are Nobel Prize winners.
Most of the others would make significant contributions to the development of Modern Physics.

German physicist

MAX PLANCK (1858-1947)

Confronted the many measurements of the spectral distribution of the thermal radiation that is given off by a hot object.

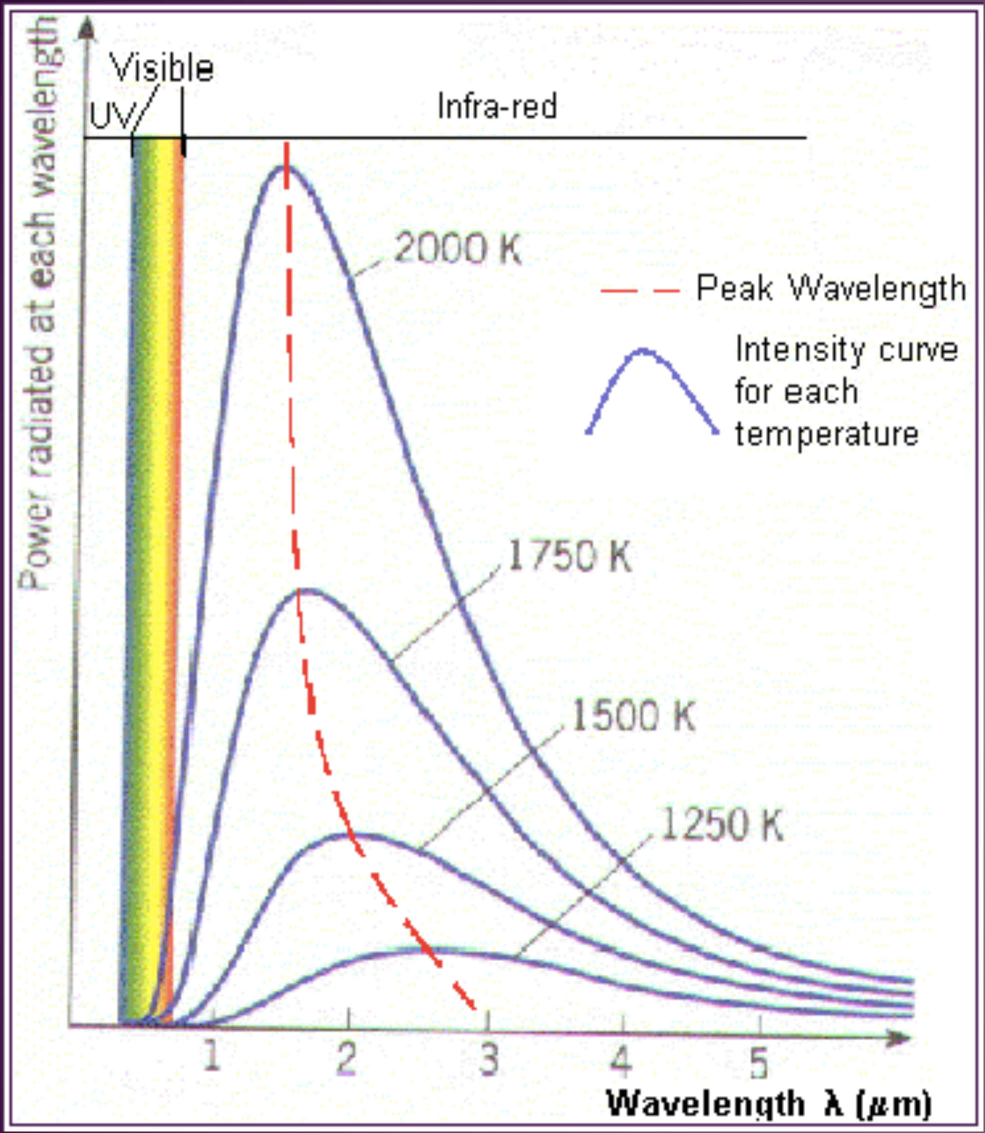
It was known that under ideally defined conditions, that is for complete (or black) absorbers and correspondingly perfect emitters this is a unique radiation distribution.



Black body radiation curves showing peak wavelengths at various temperatures.

This graph shows how the black body radiation curves change at various temperatures. These all have their peak wavelengths in the infra-red part of the spectrum.

The graph shows:



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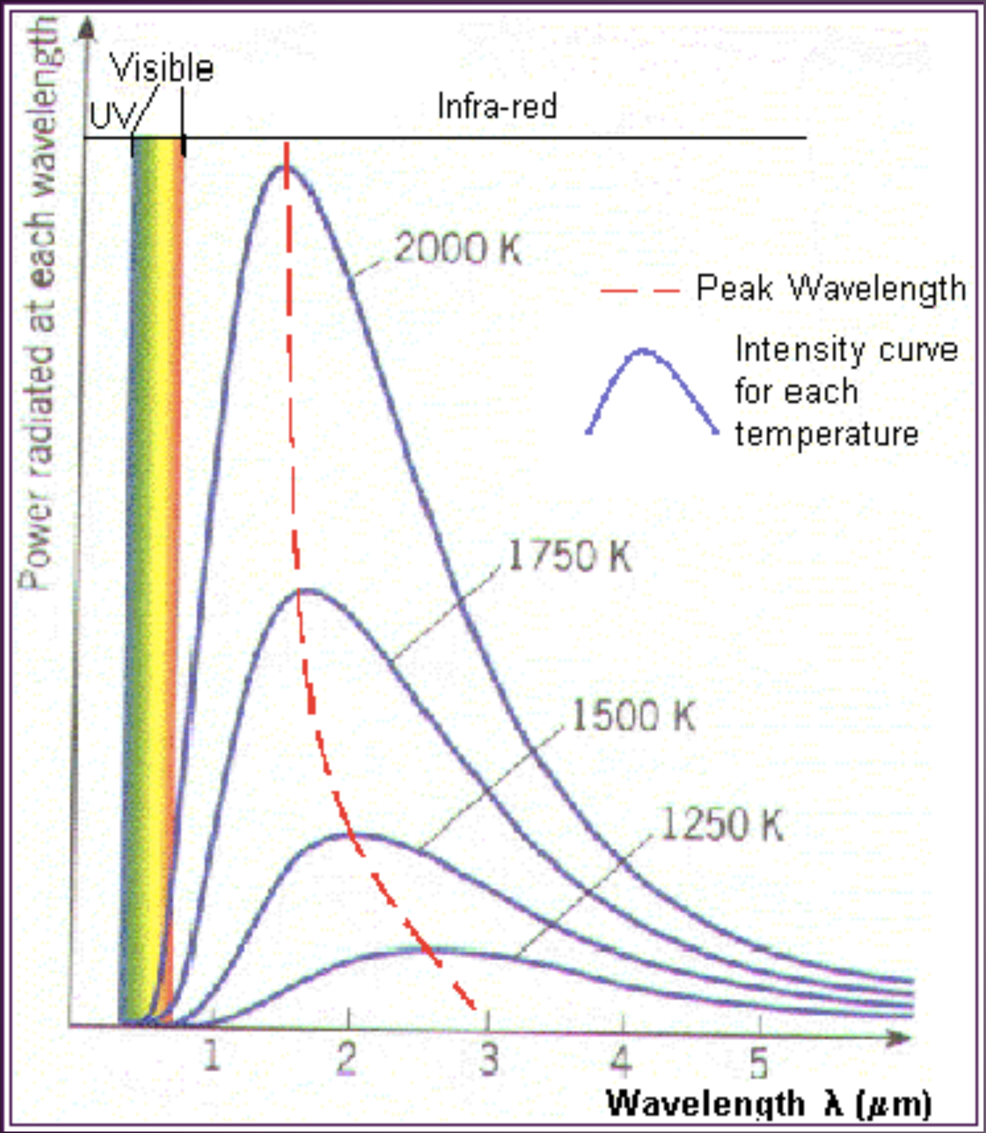

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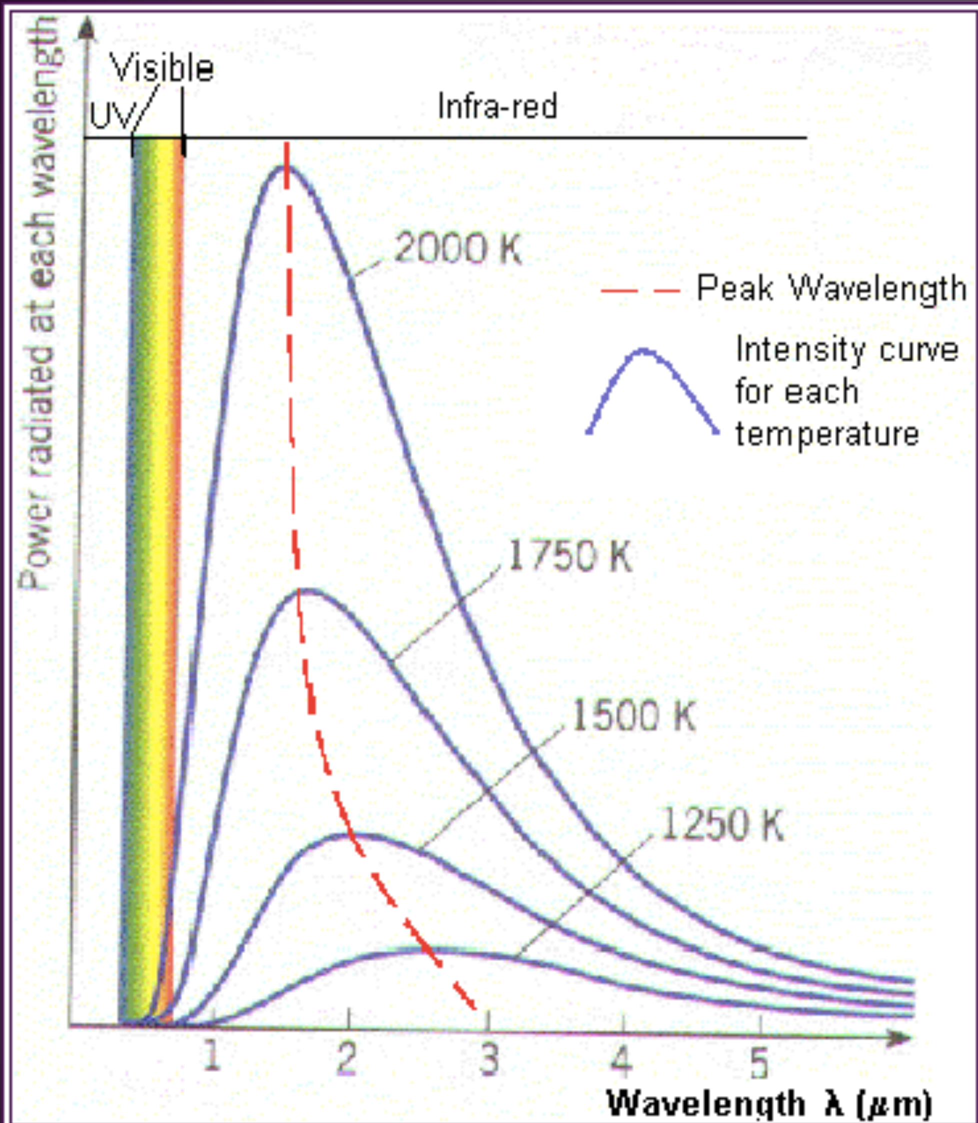

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3. The relationship is not linear as the area does not increase in even steps.

According to CLASSICAL THEORY, radiation within a BLACKBODY cavity should be made up of a series of STANDING WAVES.

Electromagnetic radiation was emitted by oscillating atoms in the walls of the black body and this radiation set up a standing wave between the walls, according to the following formula (Raleigh and Jeans)

$$I = \frac{2\pi ckT}{\lambda^4}$$

I = Intensity

For large wavelengths it fitted the experimental data but it had major problems at shorter wavelengths. The problem was the wavelength term in the denominator. It meant that as the wavelength tended to zero, the curve would tend to infinity.

The failure of these formulae to account for the decrease in energy emitted at short wavelengths (the ultraviolet wavelengths) became known as the

ultraviolet catastrophe

Before Planck it was assumed that the energy of radiation emitted by oscillating electrons at the blackbody surface could take any value. Planck found that if he assumed instead that only ***discrete*** values of energy were allowed, proportional to the light frequency, that he obtained the experimental result! *He did this originally for calculational convenience – he had intended to take his "constant" (h) to zero at the end, but found that the finite value (not zero) gave the right answer!*

As energy is proportional to frequency, this means that ***energy is also quantized***.

$$P_\lambda = \frac{2\pi hc^2}{\lambda^5(e^{(hc/\lambda kt)}-1)}$$

P_l=Power per m^2 area per m wavelength
h = Planck's constant (6.626×10^{-34} Js)
c = Speed of Light (3×10^8 m/s)
l = Wavelength (m)
k = Boltzmann Constant (1.38×10^{-23} J/K)
T = Temperature (K)

This is Planck's formula for the correct expression for the SPECTRAL DISTRIBUTION OF THERMAL RADIATION.

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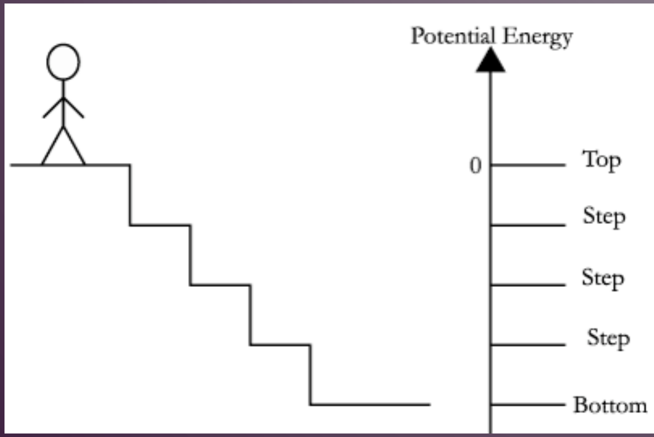
IT WOULD LEAD TO A STARTLING PHILOSOPHICAL CONCLUSION – (which he found all but unacceptable)

His "electron oscillators" would have to be restricted to energy values that were integer multiples, i.e. n-fold multiples (with n = 0, 1, 2, 3...) of something he called the QUANTUM of energy, "hf".

That number h was, in effect, the single number that he had to introduce in order to fit his magic formula to the observed data at a single temperature.

So he was saying, in effect, that these hypothetical harmonic oscillators representing a simplified image of matter could have only a sequence amounting to a "ladder" of energy states.



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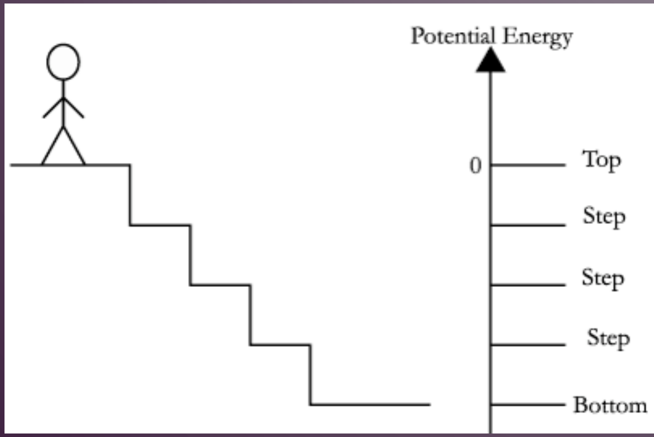

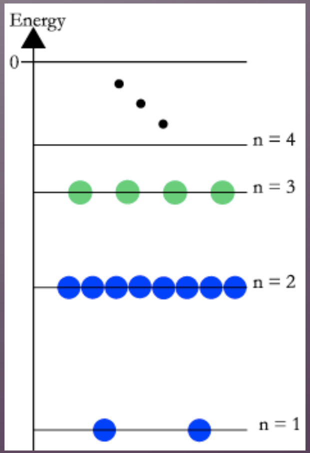

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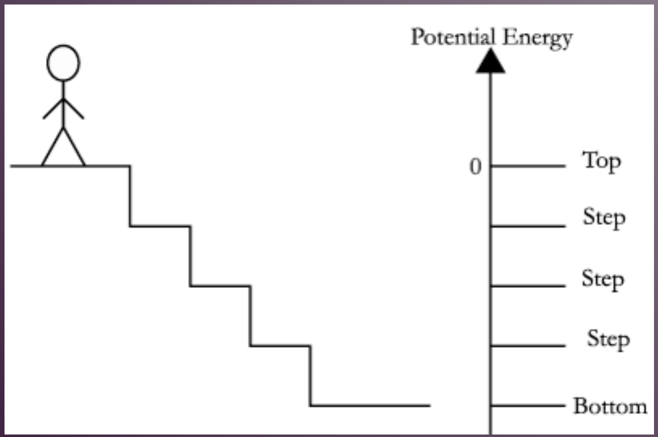

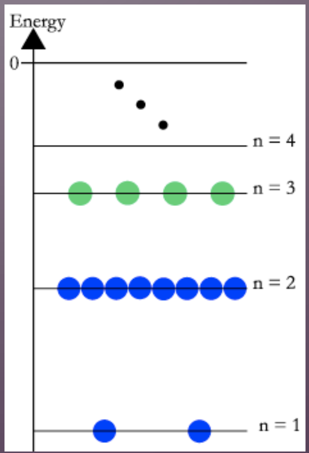

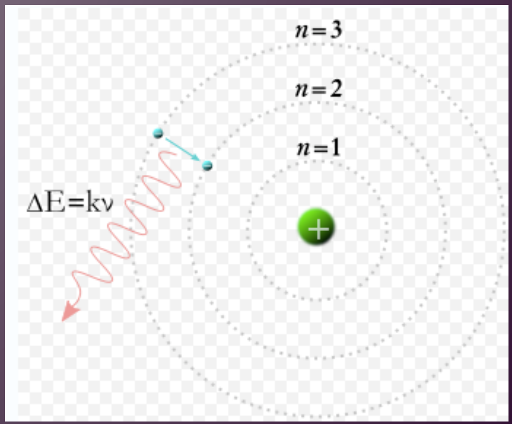

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So he was saying, in effect, that these hypothetical harmonic oscillators representing a simplified image of matter could have only a sequence amounting to a "ladder" of energy states.

Planck presented this revolutionary suggestion to the Physical Society on December 14, 1900, although he could scarcely believe it himself.

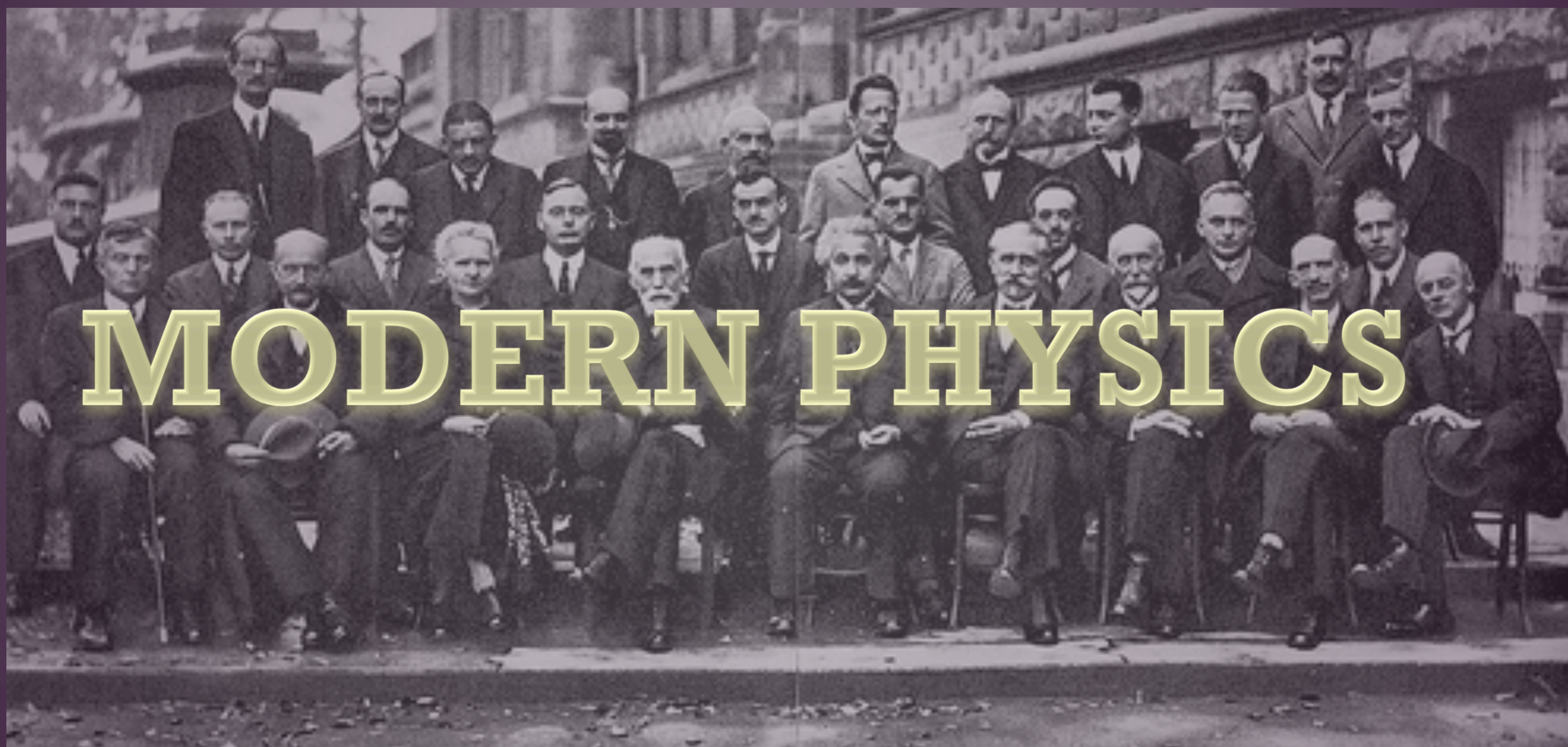
IT WOULD EVENTUALLY BECOME KNOWN AS THE "**QUANTUM THEORY".**

"By nature I am peacefully inclined and reject all doubtful adventures. But a theoretical interpretation had to be found at all costs, no matter how high . . . I was ready to sacrifice every one of my previous convictions about physical laws."

Max Planck

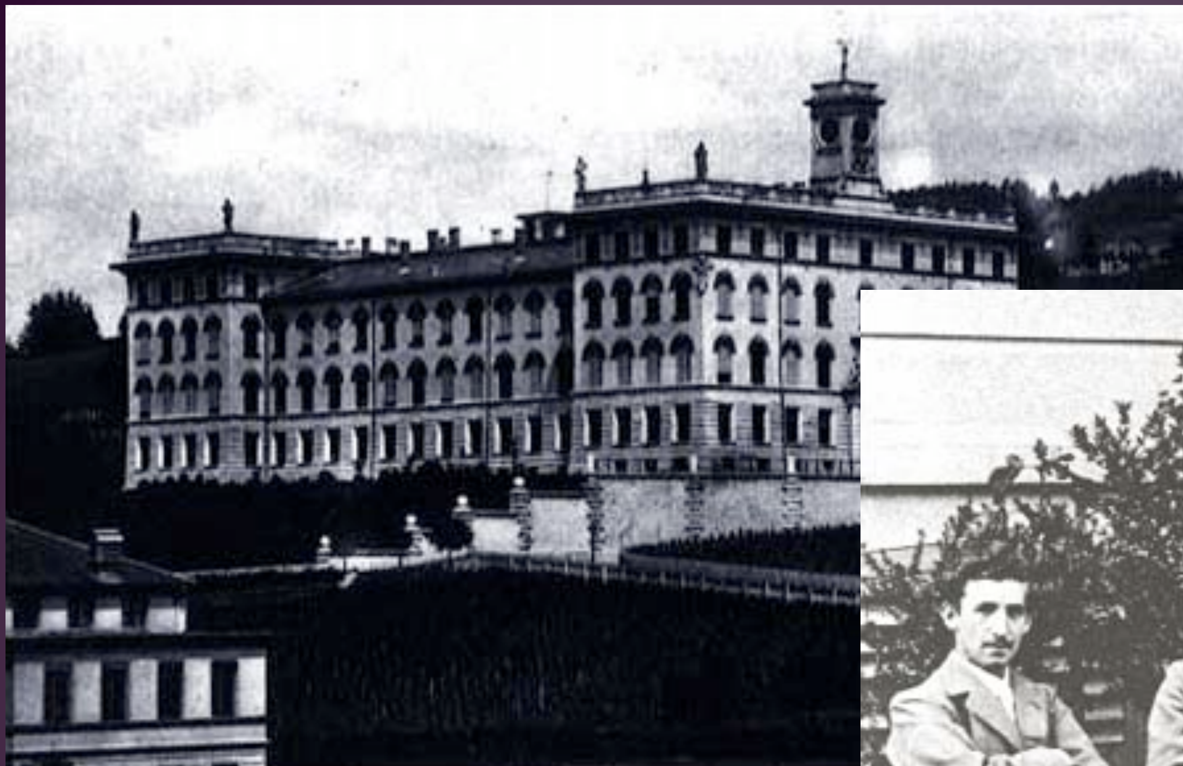
AND SO BEGINS THE . . .

II. REALM OF



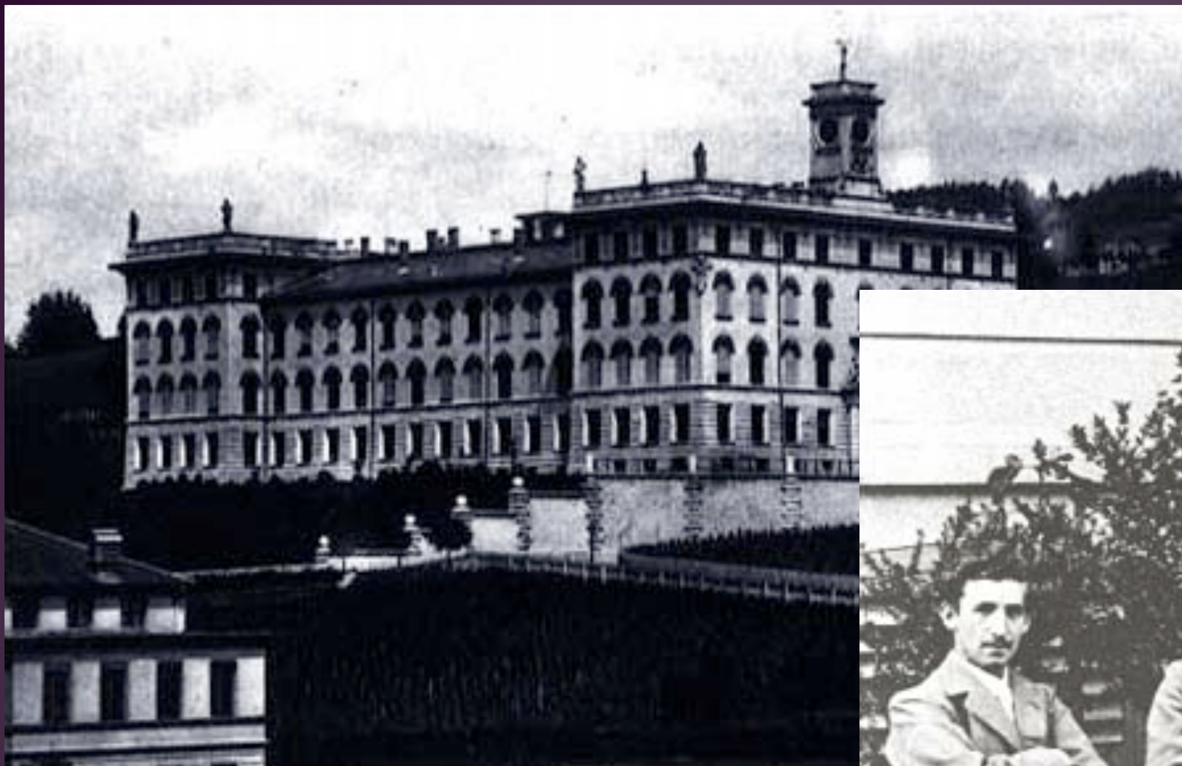
Enter, a twenty six-year-old upstart clerk
working in a patent office in BERN, SWITZERLAND.

The year is 1905.



Albert Einstein graduated from the Swiss Federal Institute of Technology (ETH) with an undistinguished record. He was a brilliant thinker whose unorthodox demeanor in the classroom often irritated his professors. He made a number of efforts to get a University job, and failed.

He was finally able to get a job at the Swiss Patent Office in Bern.



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This gave him the time to pursue his ideas on physics.

1905: BERN, SWITZERLAND

Einstein first observed that Planck's formula
for the entropy of the radiation distribution,
when he examined its high frequency contributions,
looked like the entropy of a perfect gas of free
particles of energy ***hf***.
That was a suggestion that light itself might be
discrete in nature, but hardly a conclusive one.

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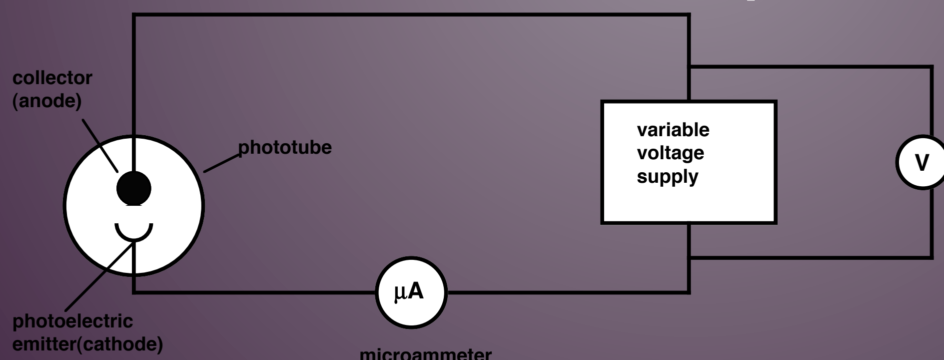
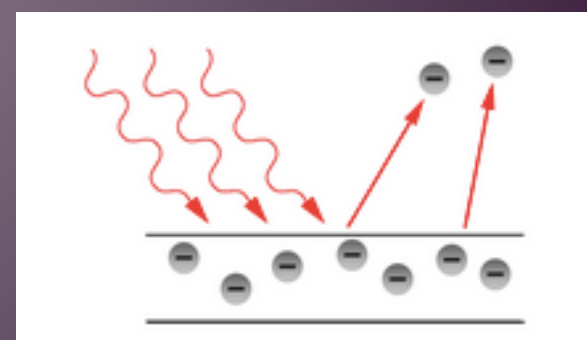
To reach a stronger conclusion he turned
to an examination of the ***photoelectric effect***,
which had first been observed in 1887 by Heinrich Hertz.





THE EXPERIMENTS:

IN 1902, Philipp Lenard showed how the energy of the emitted photoelectrons varied with the intensity of the light. He used a carbon arc light, and could increase the intensity a thousand-fold. The ejected electrons hit another metal plate, the collector, which was connected to the cathode by a wire with a sensitive ammeter, to measure the current produced by the illumination.

To measure the energy of the ejected electrons, Lenard charged the collector plate negatively, to repel the electrons coming towards it. Thus, only electrons ejected with enough kinetic energy to get up this potential hill would contribute to the current. Lenard discovered that there was a well defined minimum voltage that stopped any electrons getting through, we'll call it V_{stop}.

To his surprise, he found that V_{stop} did not depend at all on the intensity of the light! Doubling the light intensity doubled the number of electrons emitted, but did not affect the energies of the emitted electrons. The more powerful oscillating field ejected more electrons, but the maximum individual energy of the ejected electrons was the same as for the weaker field.

EINSTEIN'S PREDICTIONS:

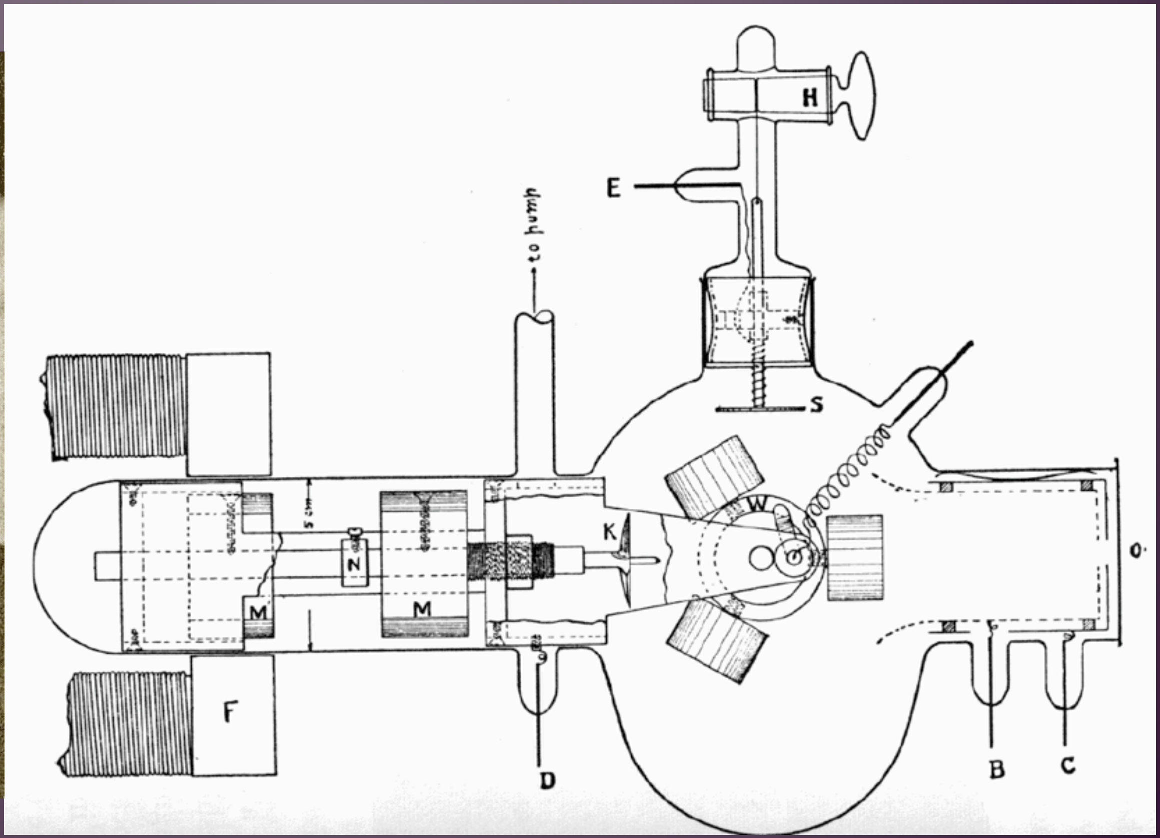
Light itself consists of localized energy packets and each possesses one quantum of energy.

When light strikes the metal, each packet is absorbed by a single electron.

That electron then flies off with a unique energy, an energy which is just the packet energy "hf" minus whatever energy the electron needs to expend in order to escape the metal.

THE EXPERIMENTS:

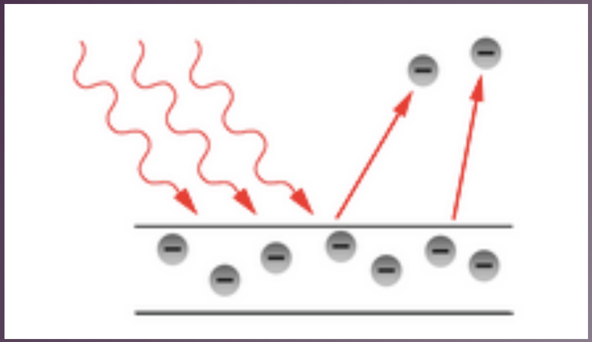
IN 1916, DR. ROBERT A. MILLIKEN USED THIS APPARATUS:



Light "quanta" shines on clean sodium metal in a vacuum.

THE EXPERIMENTS:

Electrons (called "photoelectrons") are ejected from the metal.



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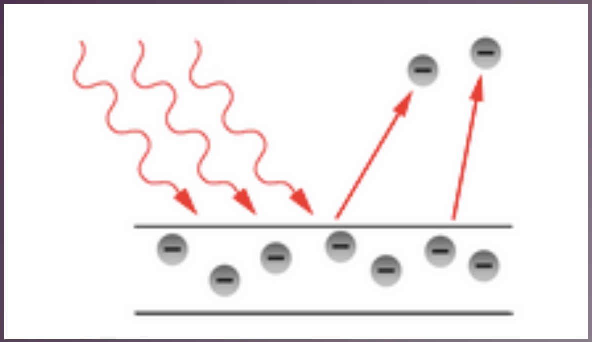

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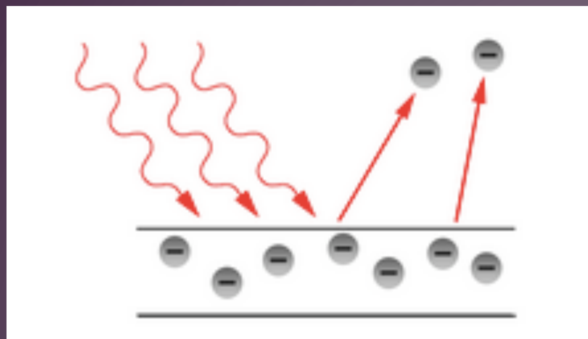

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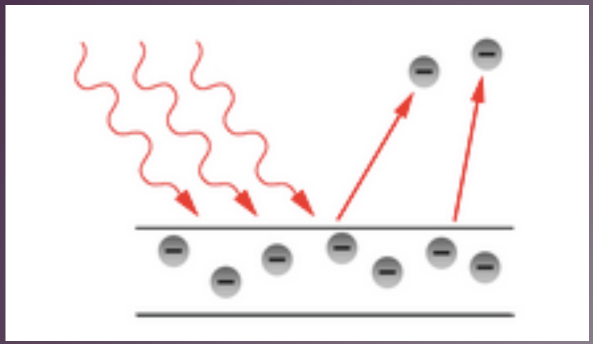

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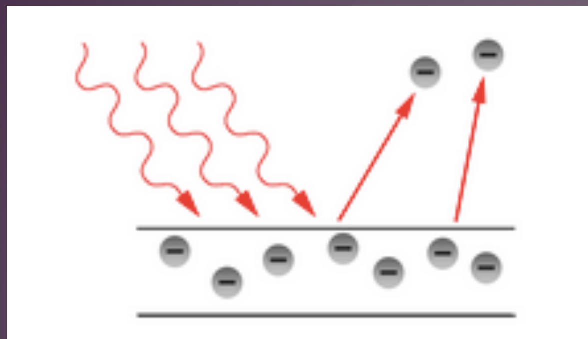

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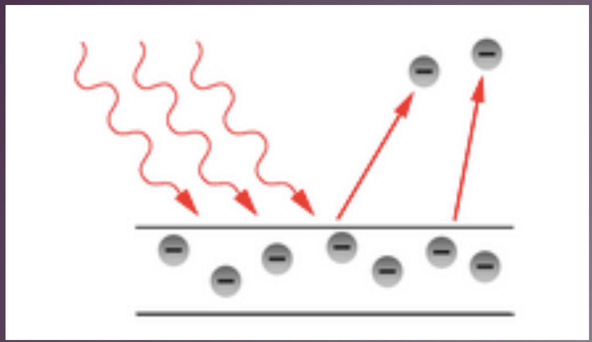

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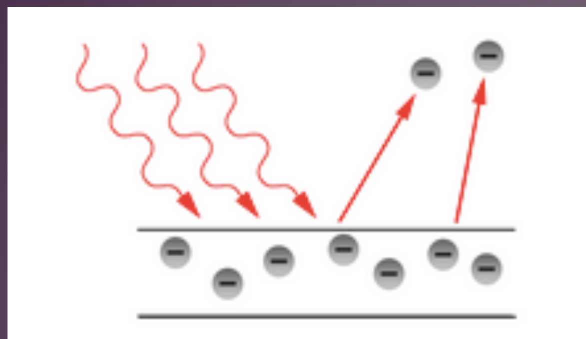

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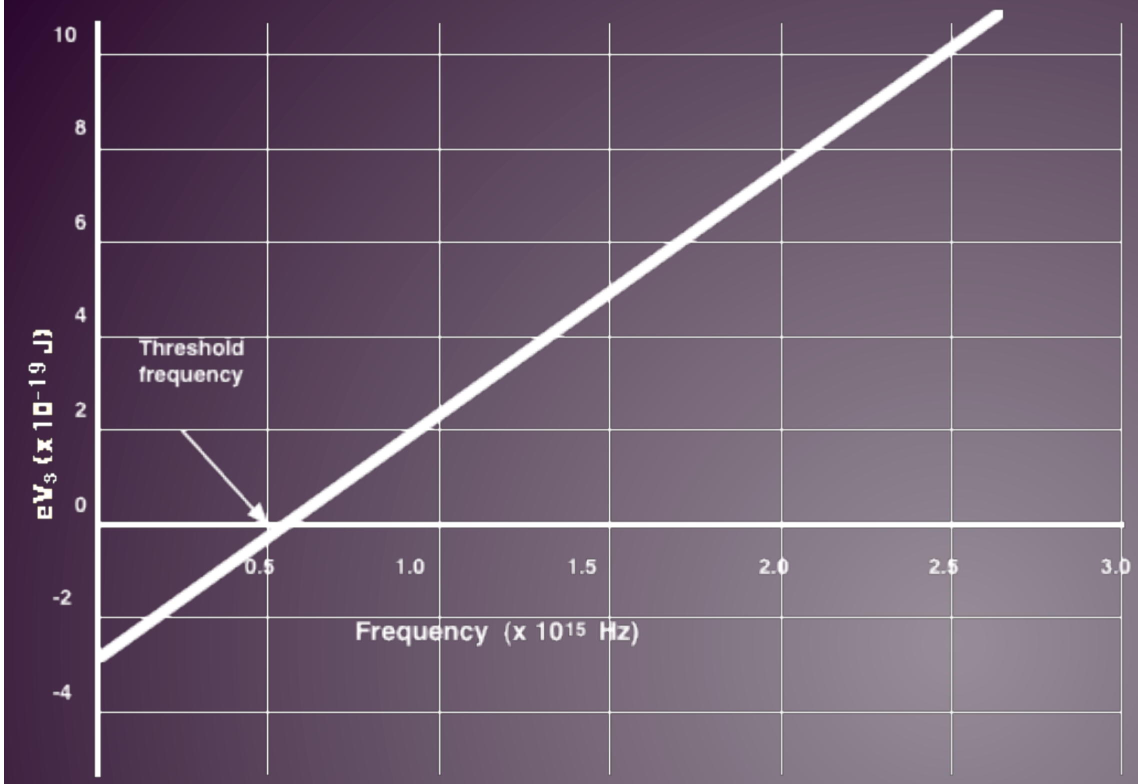
HIGHER FREQUENCY -> MORE ENERGY -> FASTER EJECTED PHOTOELECTRON
LOWER FREQUENCY -> NOT ENOUGH ENERGY TO EJECT PHOTOELECTRONS



10
8
6
4
2
0
-2
-4
eVs (x 10-19 J)
Threshold frequency
0.5
1.0
1.5
2.0
2.5
3.0
Frequency (x 1015 Hz)

THE RESULTS:

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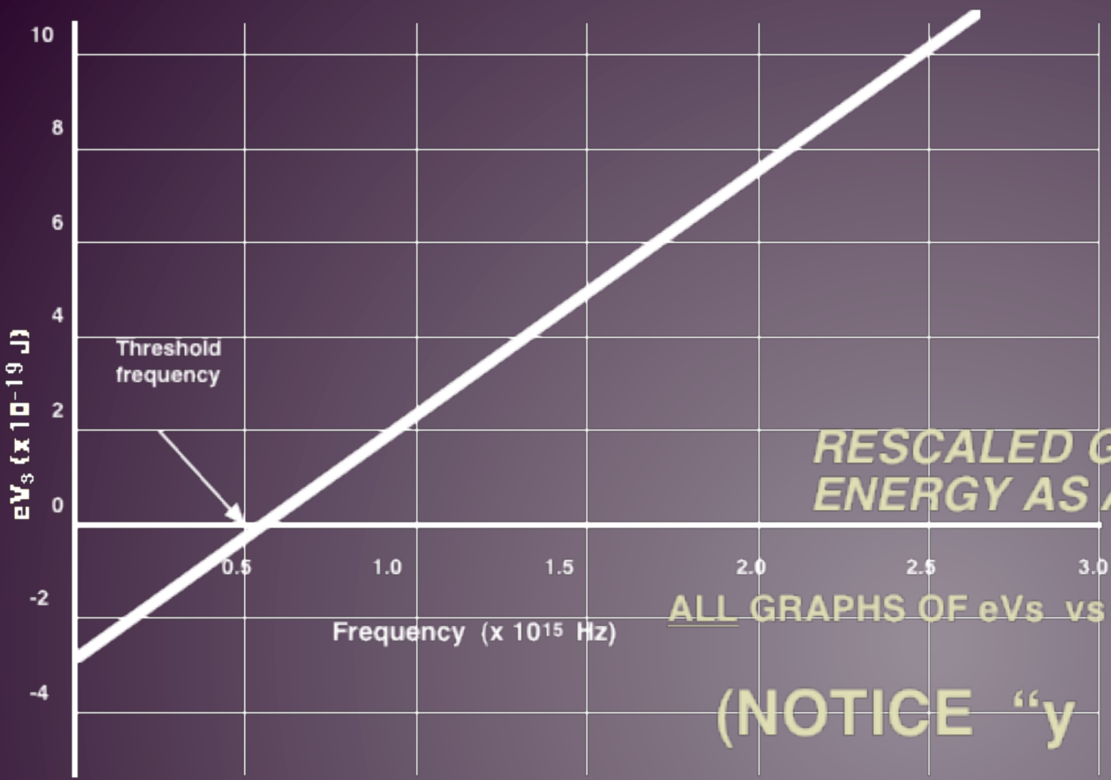


RESCALED GRAPH:
ENERGY AS A FUNCTION OF FREQUENCY

ALL GRAPHS OF eVs vs f HAVE THE SAME SLOPE AS ABOVE!!!!

(NOTICE "y = mx + b" FORM)

REWRITE AS:

$$KE_{max} = hf - W$$

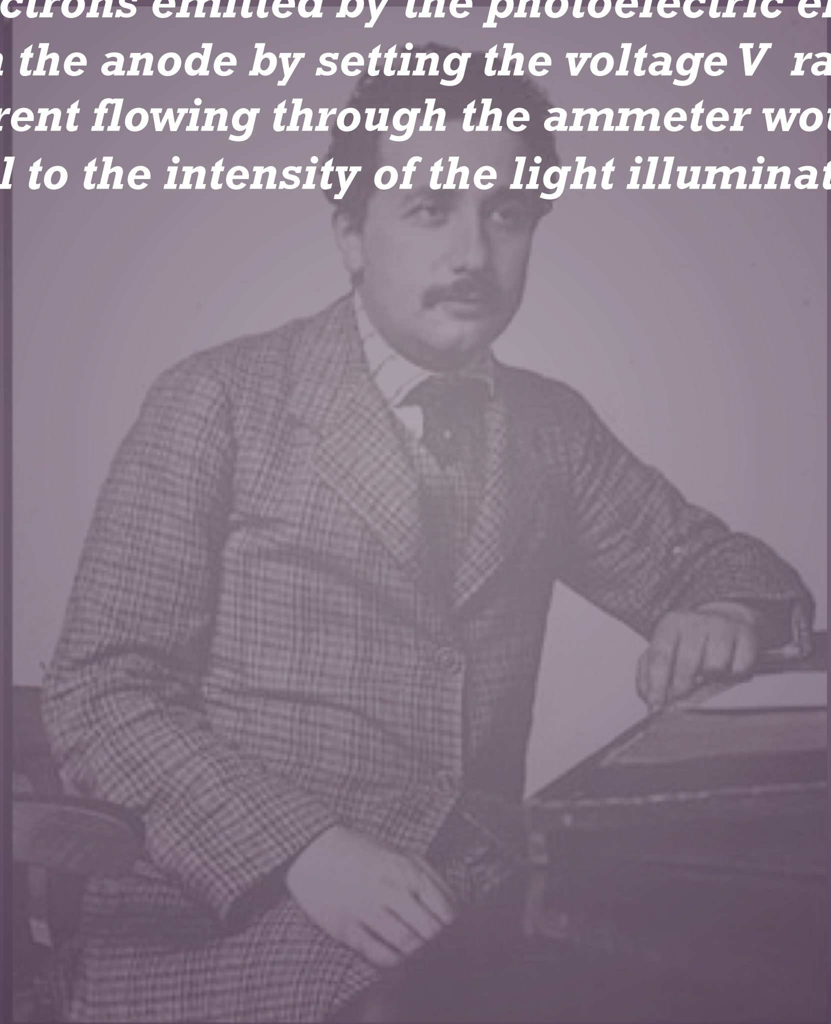
KINETIC ENERGY OF THE EJECTED PHOTOELECTRON → KE_{max}

hf: total energy absorbed by the photoelectron

W: "work function" of the metal (energy required to free the electron)

EINSTEIN'S PREDICTIONS VERIFIED:

(1) If all the electrons emitted by the photoelectric effect are collected on the anode by setting the voltage V rather high, the electric current flowing through the ammeter would be proportional to the intensity of the light illuminated on the cathode.



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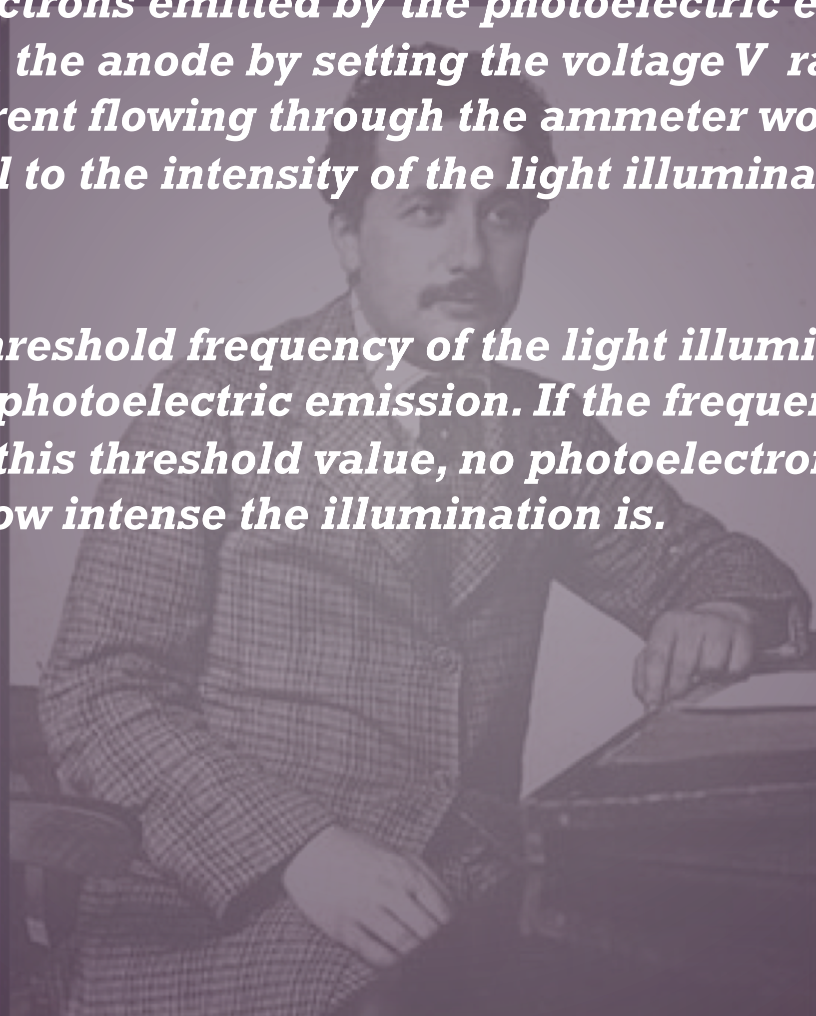

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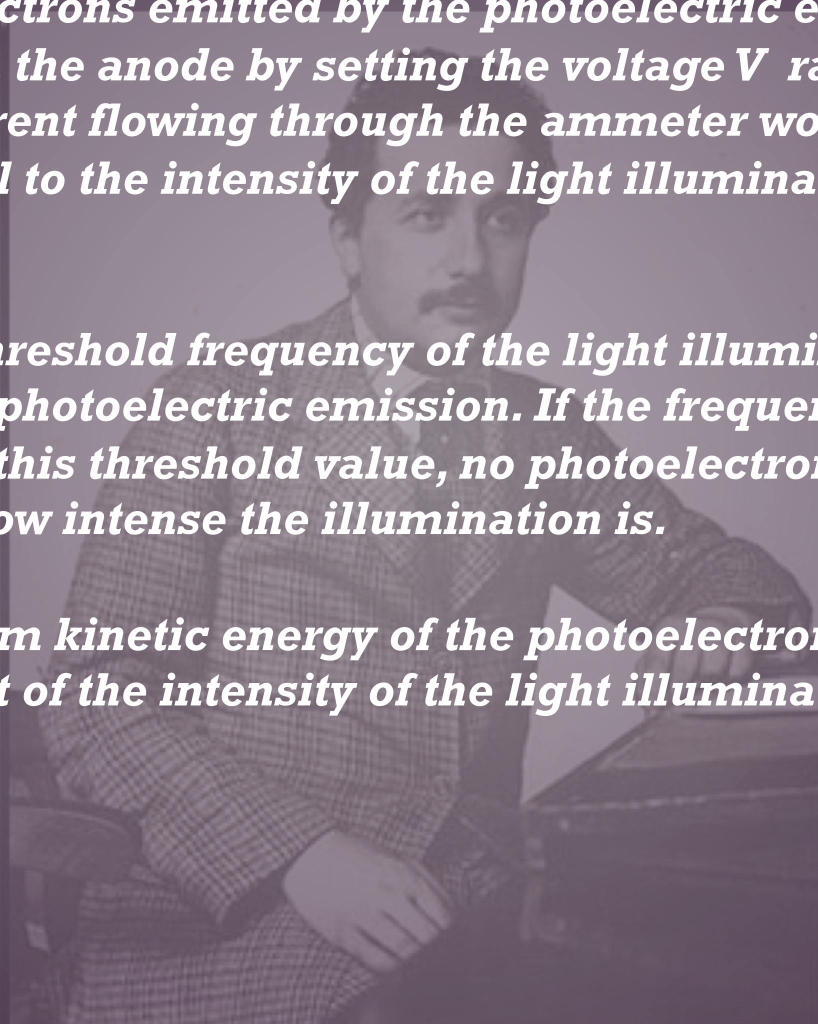

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3) The maximum kinetic energy of the photoelectron is independent of the intensity of the light illuminated.

(4) The maximum kinetic energy of the emitted electrons is a linear function of the frequency, which is exactly the same as Einstein's hypothesis, i.e., Millikan obtained the constant h from this experiment as which is well fit to the value obtained by Planck's analysis about the cavity radiation.

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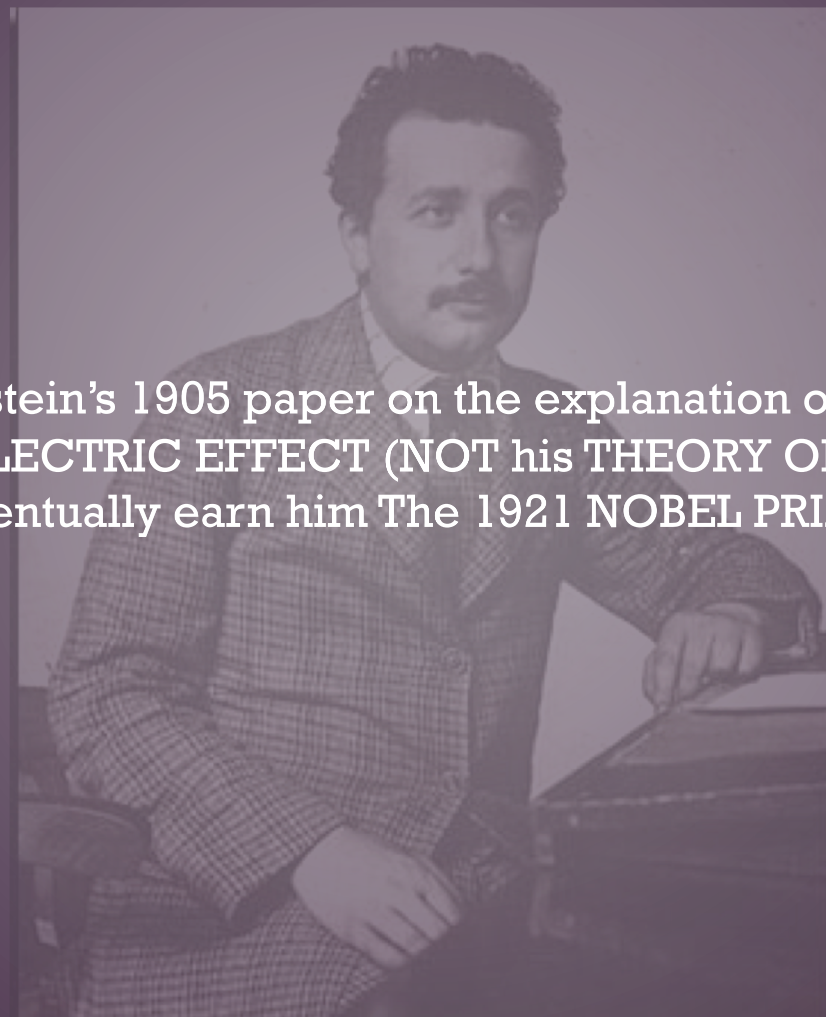

Einstein's 1905 paper on the explanation of the PHOTOELECTRIC EFFECT (NOT his THEORY OF RELATIVITY) would eventually earn him The 1921 NOBEL PRIZE in PHYSICS.

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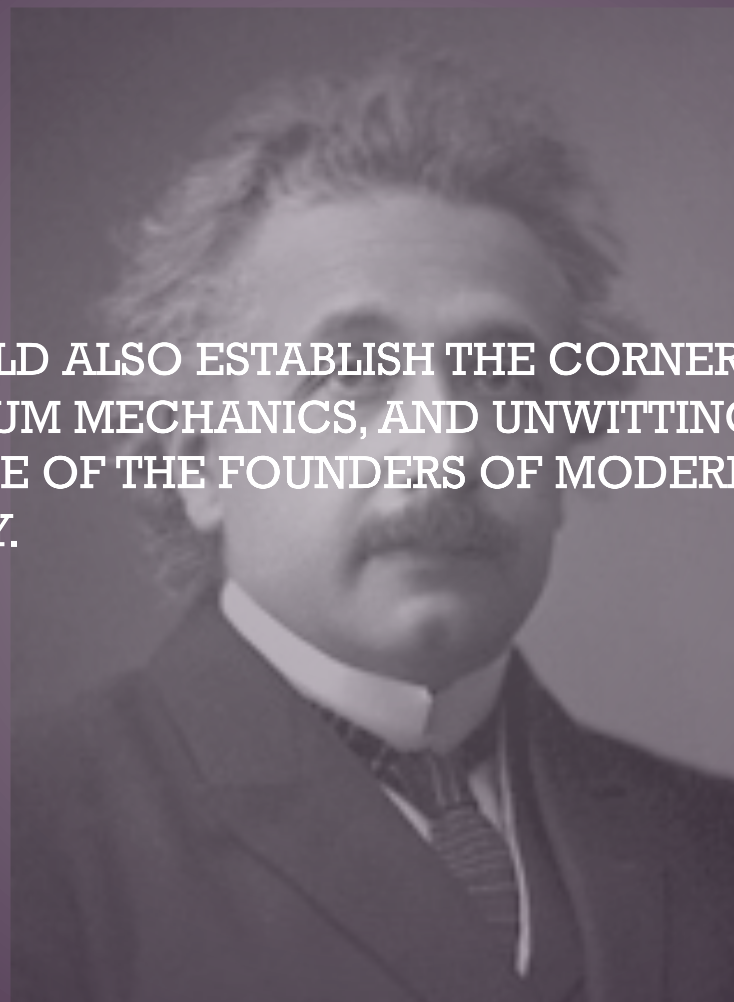

IT WOULD ALSO ESTABLISH THE CORNERSTONE OF QUANTUM MECHANICS, AND UNWITTINGLY, MAKE HIM ONE OF THE FOUNDERS OF MODERN QUANTUM THEORY.

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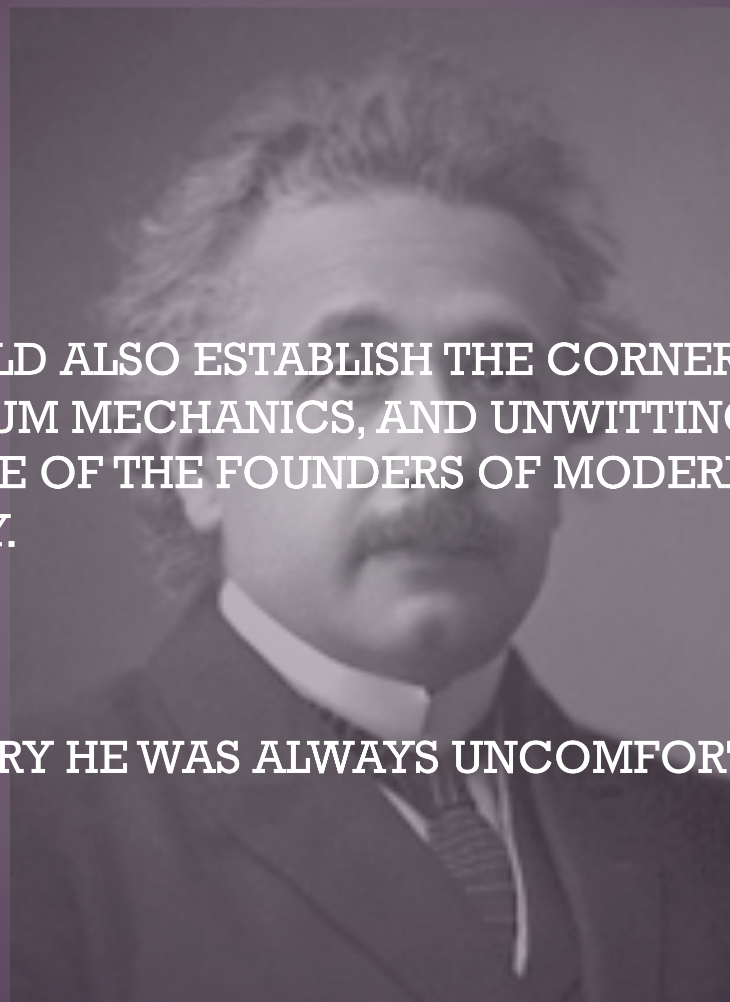

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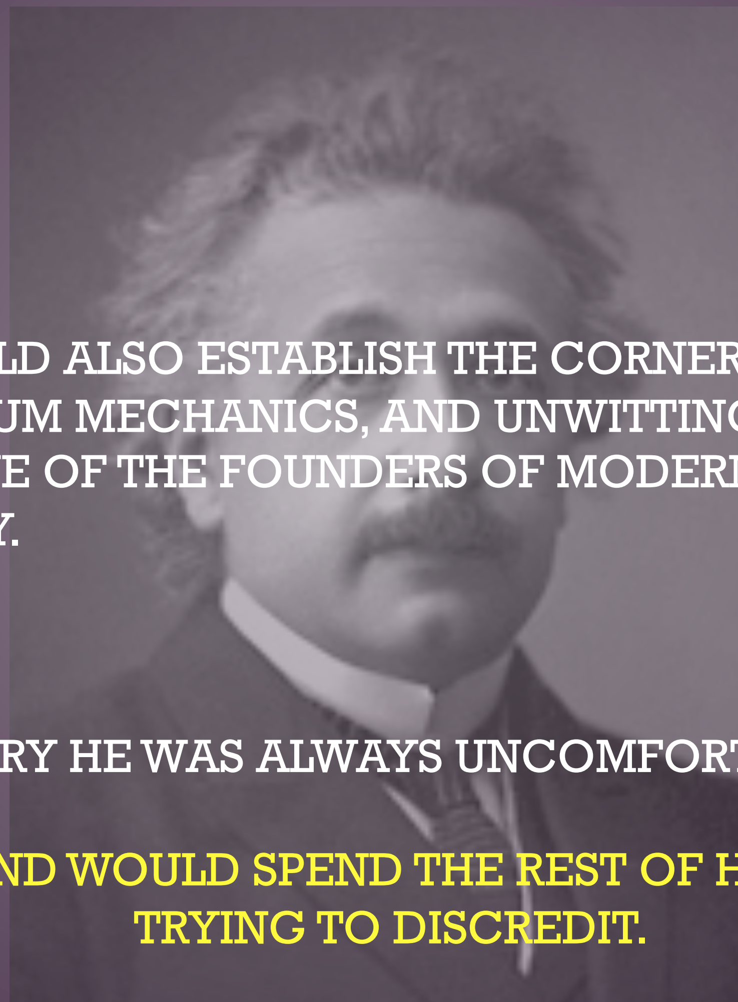

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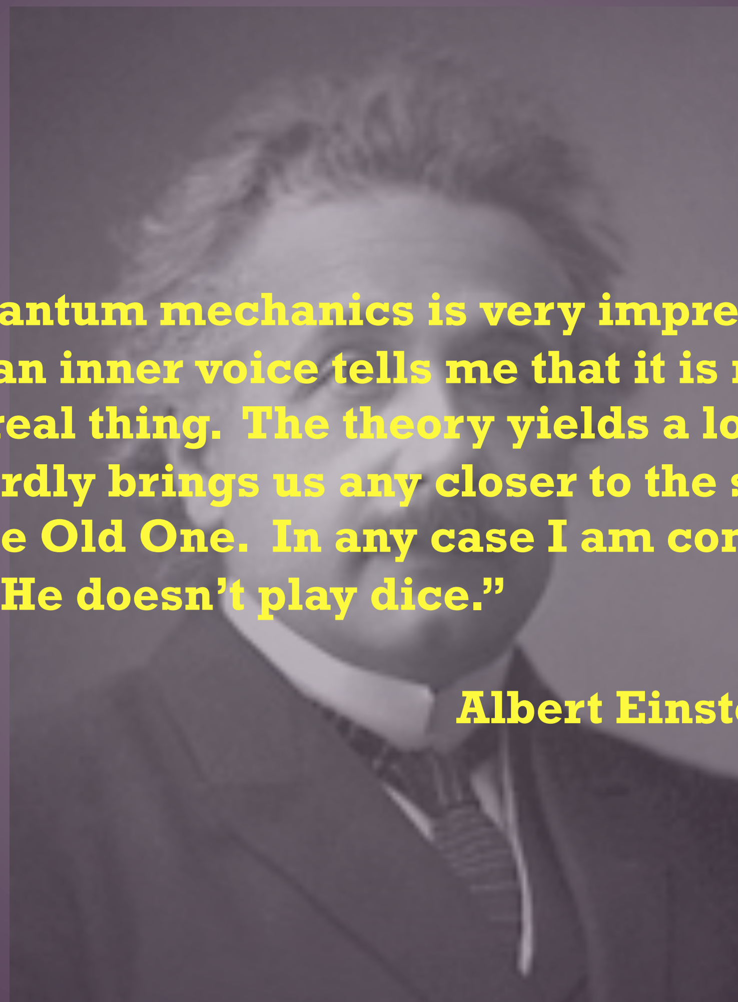
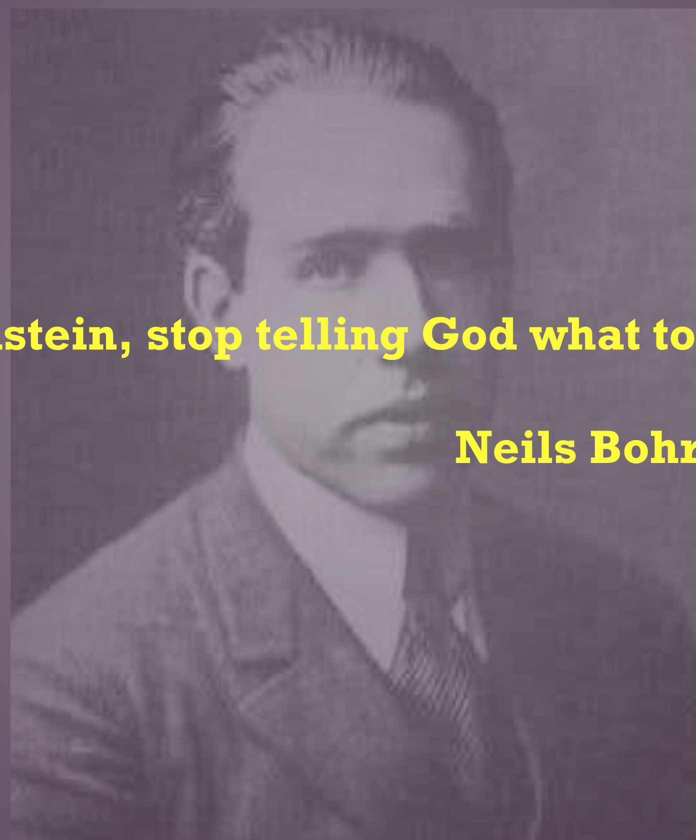
. . . .AND WOULD SPEND THE REST OF HIS LIFE TRYING TO DISCREDIT.



“Quantum mechanics is very impressive. But an inner voice tells me that it is not yet the real thing. The theory yields a lot, but it hardly brings us any closer to the secret of the Old One. In any case I am convinced that He doesn’t play dice.”

Albert Einstein



“Einstein, stop telling God what to do.”

Neils Bohr

SO, WHAT DOES THIS MEAN?

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THE QUANTIZATION OF ENERGY IS THE

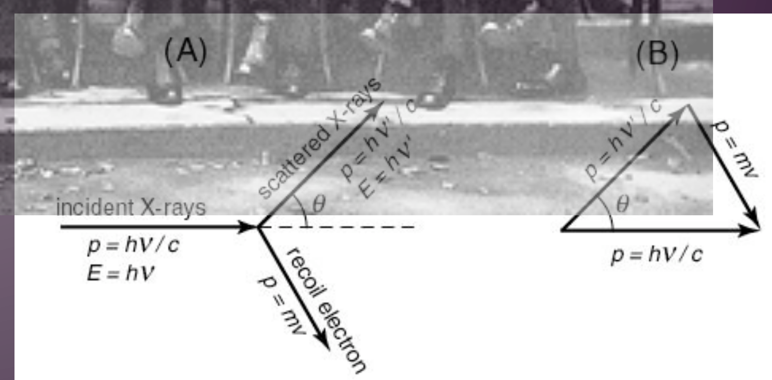
BREAKTHROUGH

THAT UNDENIABLY SHOWS THAT. . .

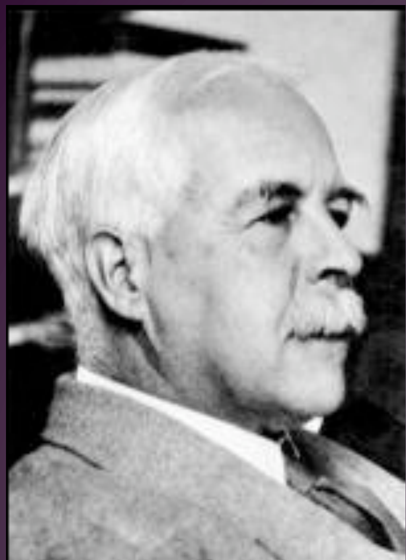

THERE IS *CLEARLY* AN INTERACTION BETWEEN
MATTER AND LIGHT!!!

In 1922, A.H. Compton discovered that x-ray quanta are scattered by electrons according to the same rules as govern the collisions of billiard balls.

They both obey the conservation rules for energy and momentum in much the same way.



THE "COMPTON EFFECT"



In 1926 G. N. Lewis suggested that
LIGHT QUANTA be called

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since they seemed every bit as
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even if their existence was more transitory, and they were at times freely
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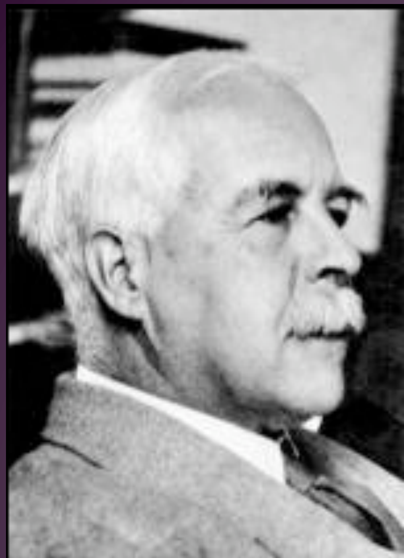

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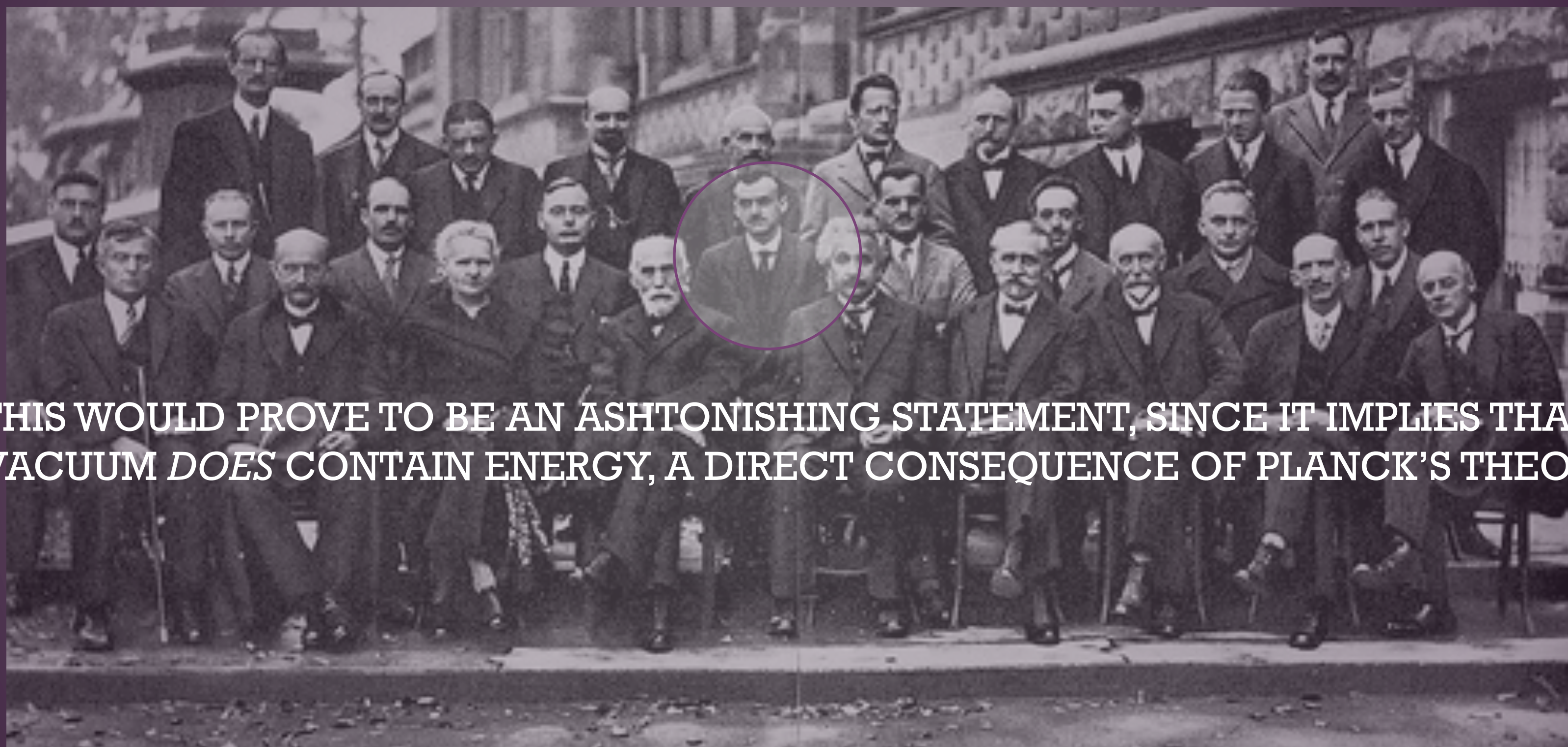
NOTE: The term "PHOTON" is not only still in use today to refer to A LIGHT QUANTUM, it has been labeled by particle physicists as the CARRIER PARTICLE of the ELECTROMAGNETIC FORCE.

The true "semiclassical era," lasted only a few years.

The "beginning of the end" may have started with the discovery by Paul Dirac that one must treat the vacuum, that is to say empty space, as a ***dynamical system***.



THIS WOULD PROVE TO BE AN ASHTONISHING STATEMENT, SINCE IT IMPLIES THAT A VACUUM *DOES* CONTAIN ENERGY, A DIRECT CONSEQUENCE OF PLANCK'S THEORY!

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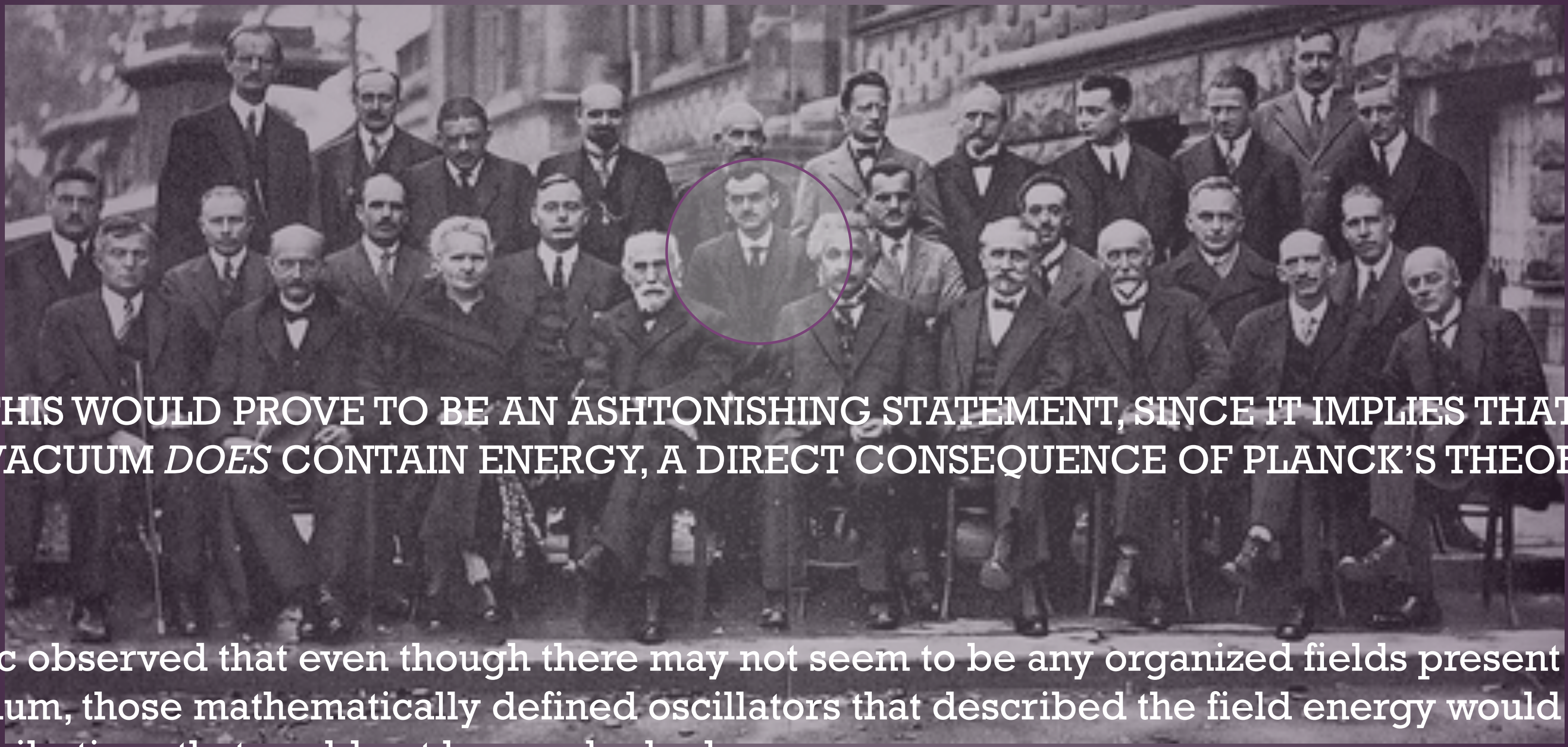

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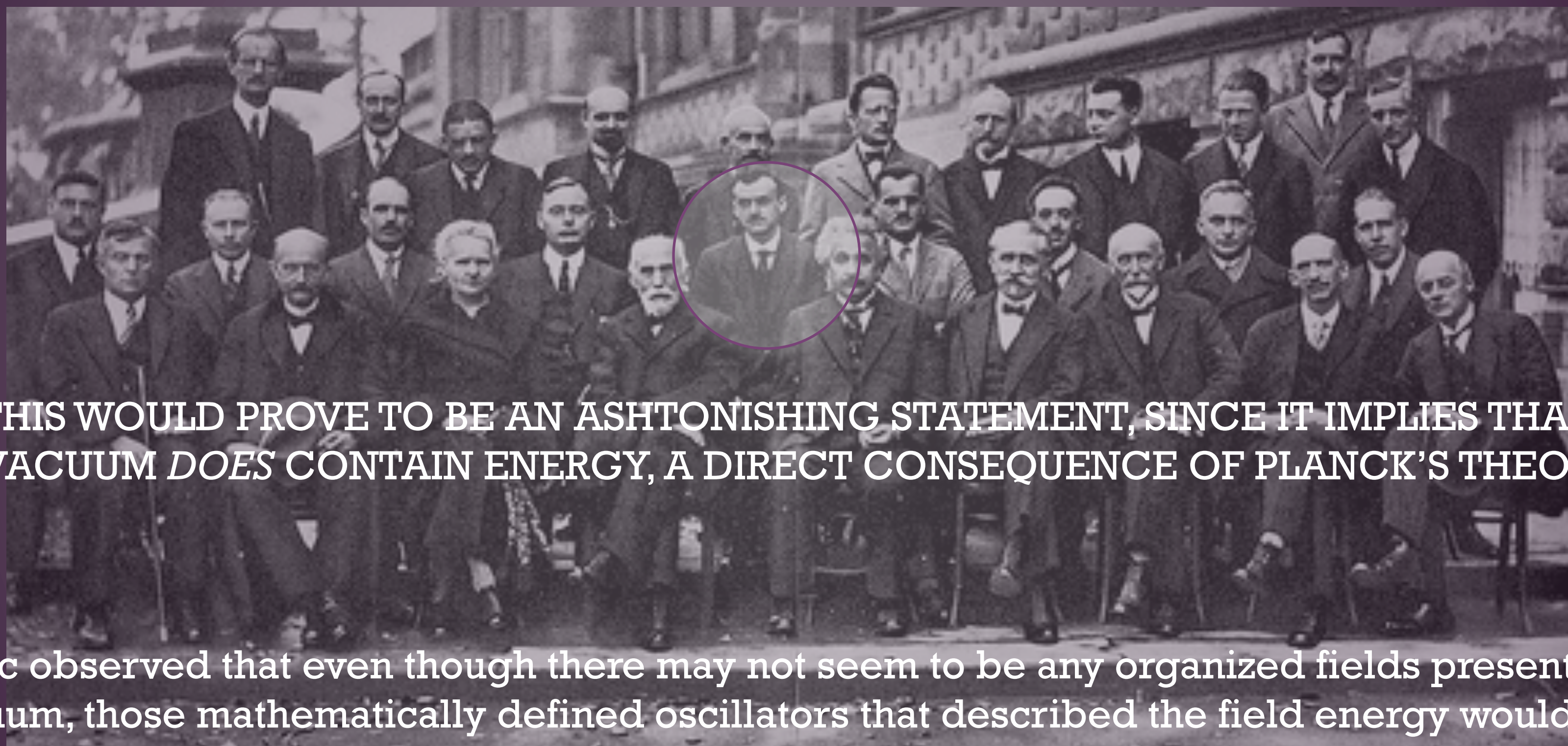

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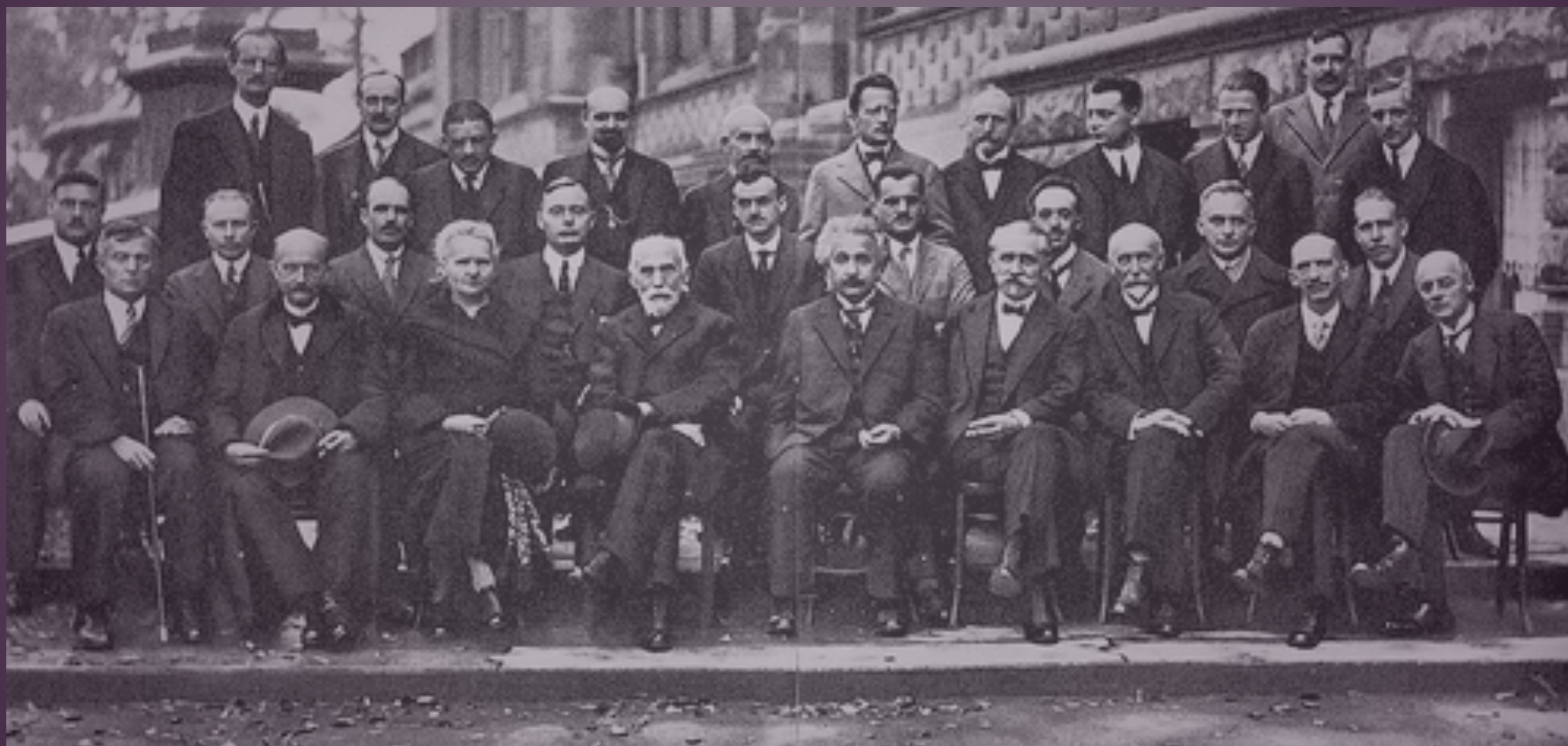
Planck had said the energies of harmonic oscillators are restricted to values n times the quantum energy, hf.

The fully developed quantum mechanics had shown in fact that those energies are not nhf but $(n + \frac{1}{2})hf$!



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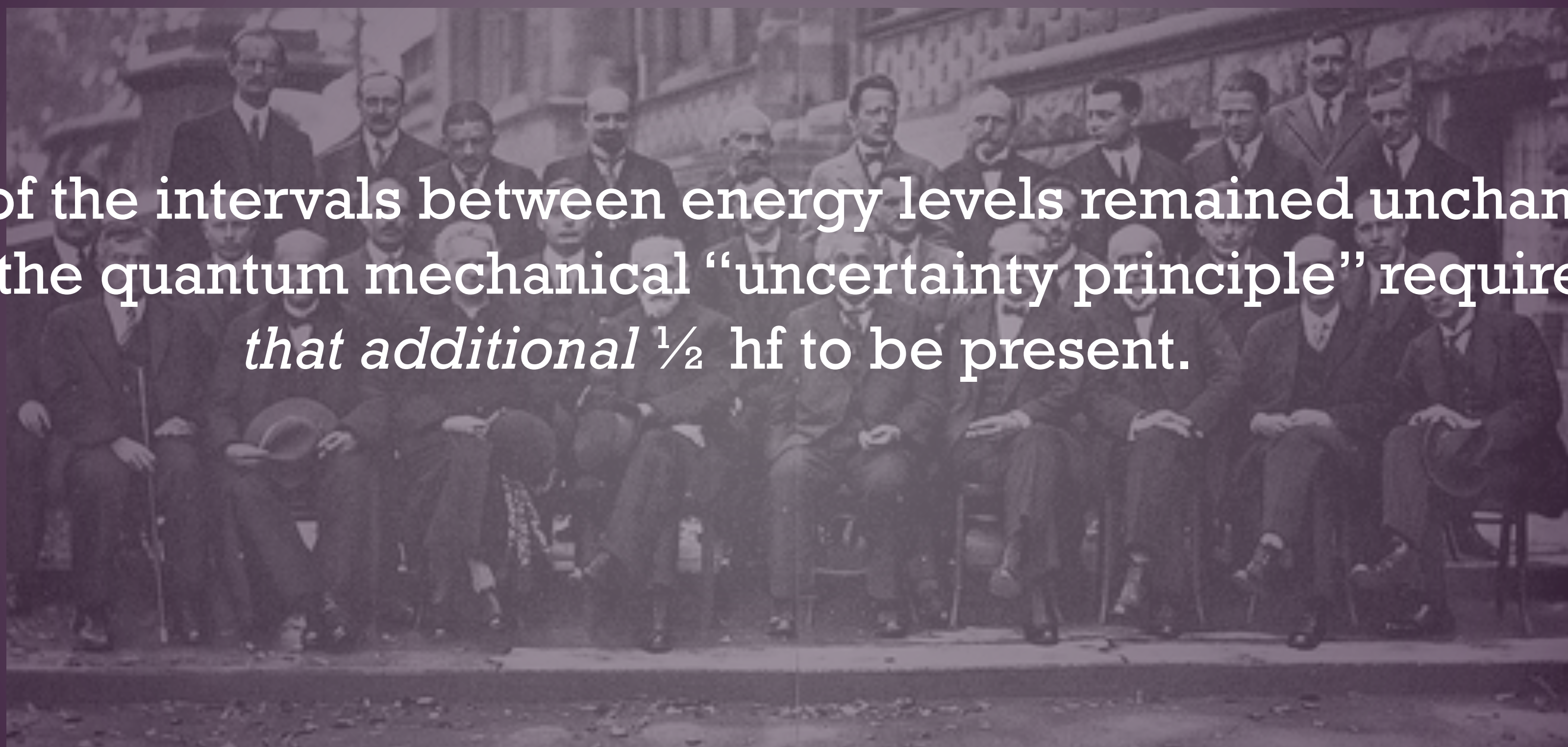

All of the intervals between energy levels remained unchanged, but the quantum mechanical “uncertainty principle” required *that additional* $\frac{1}{2}$ hf to be present.

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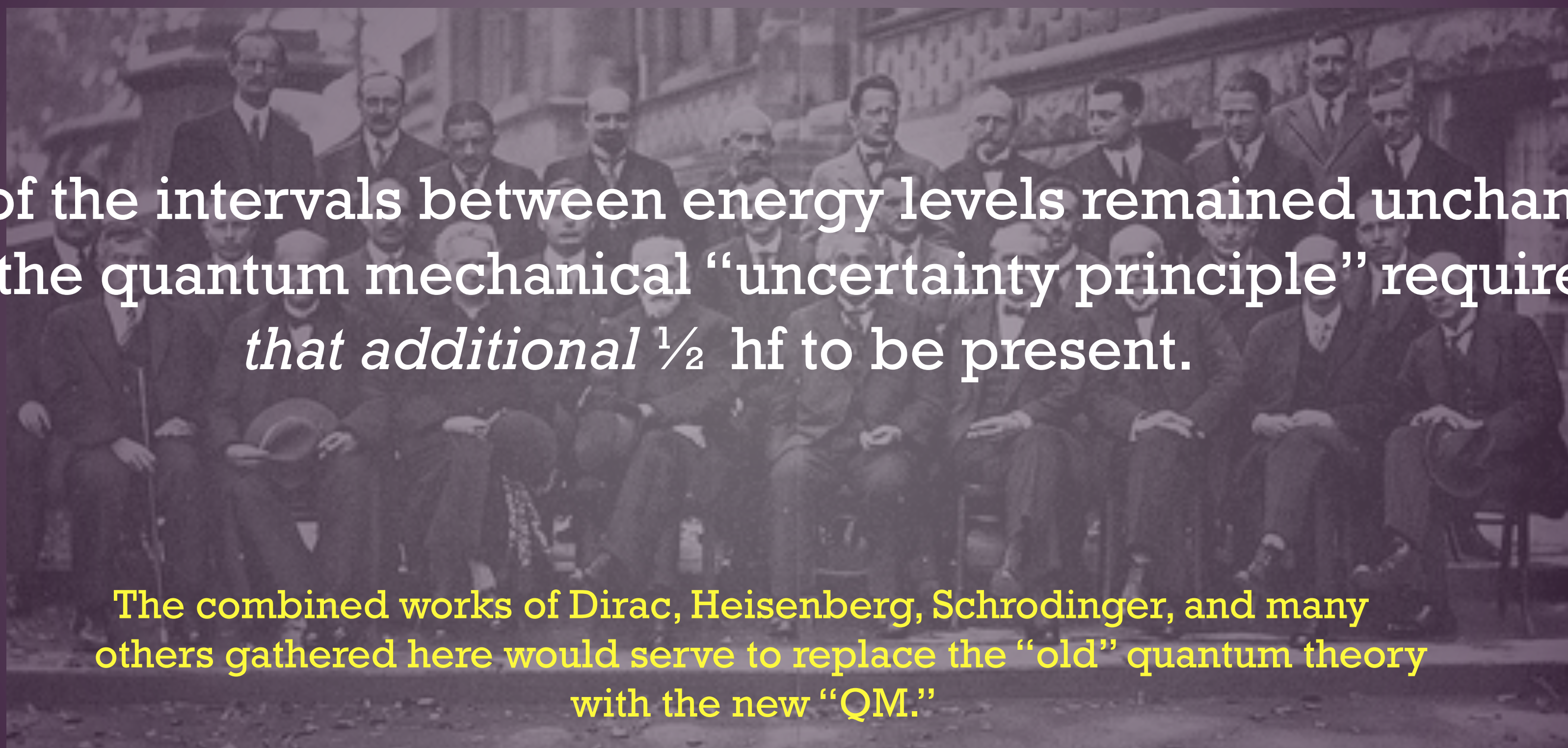

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The combined works of Dirac, Heisenberg, Schrodinger, and many others gathered here would serve to replace the "old" quantum theory with the new "QM."

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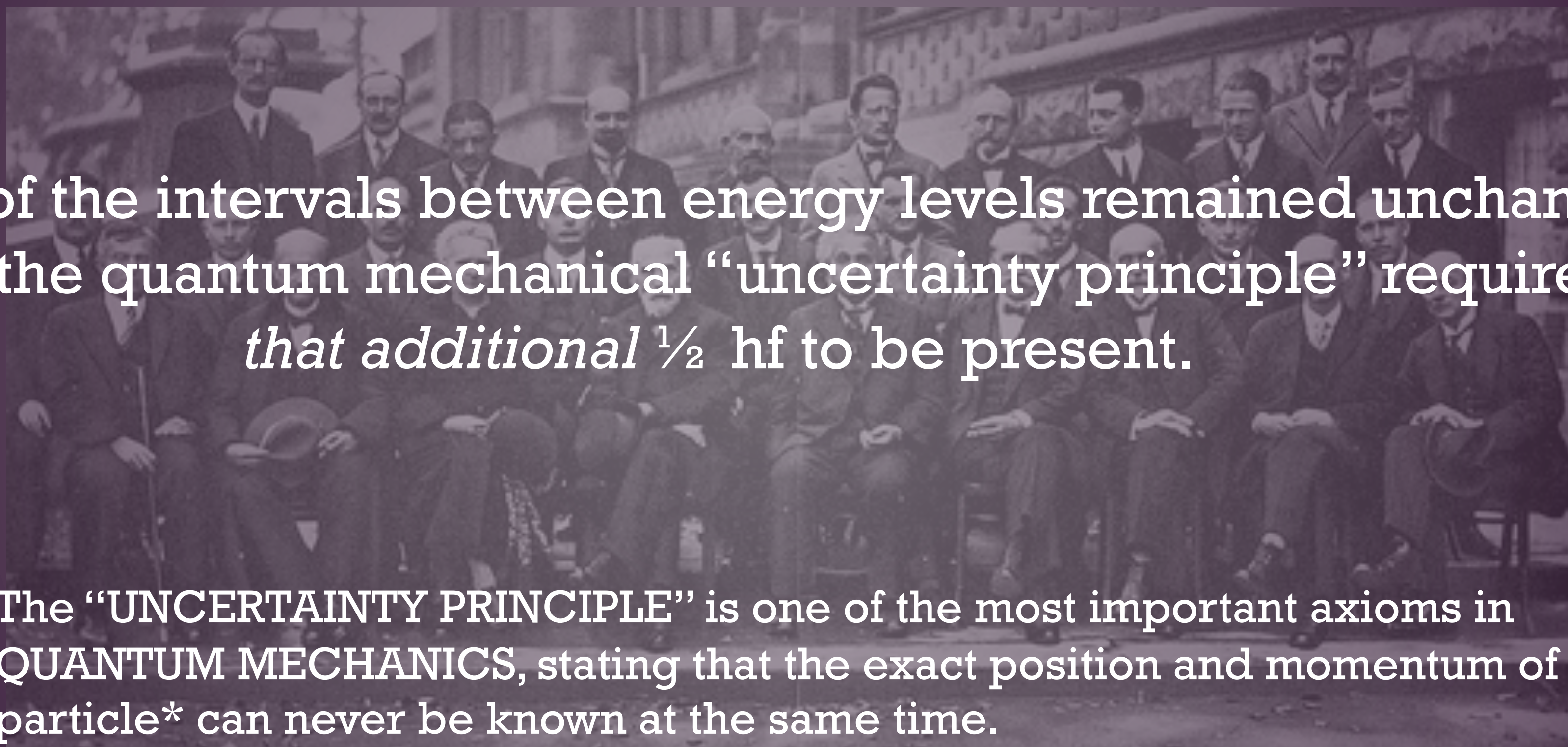

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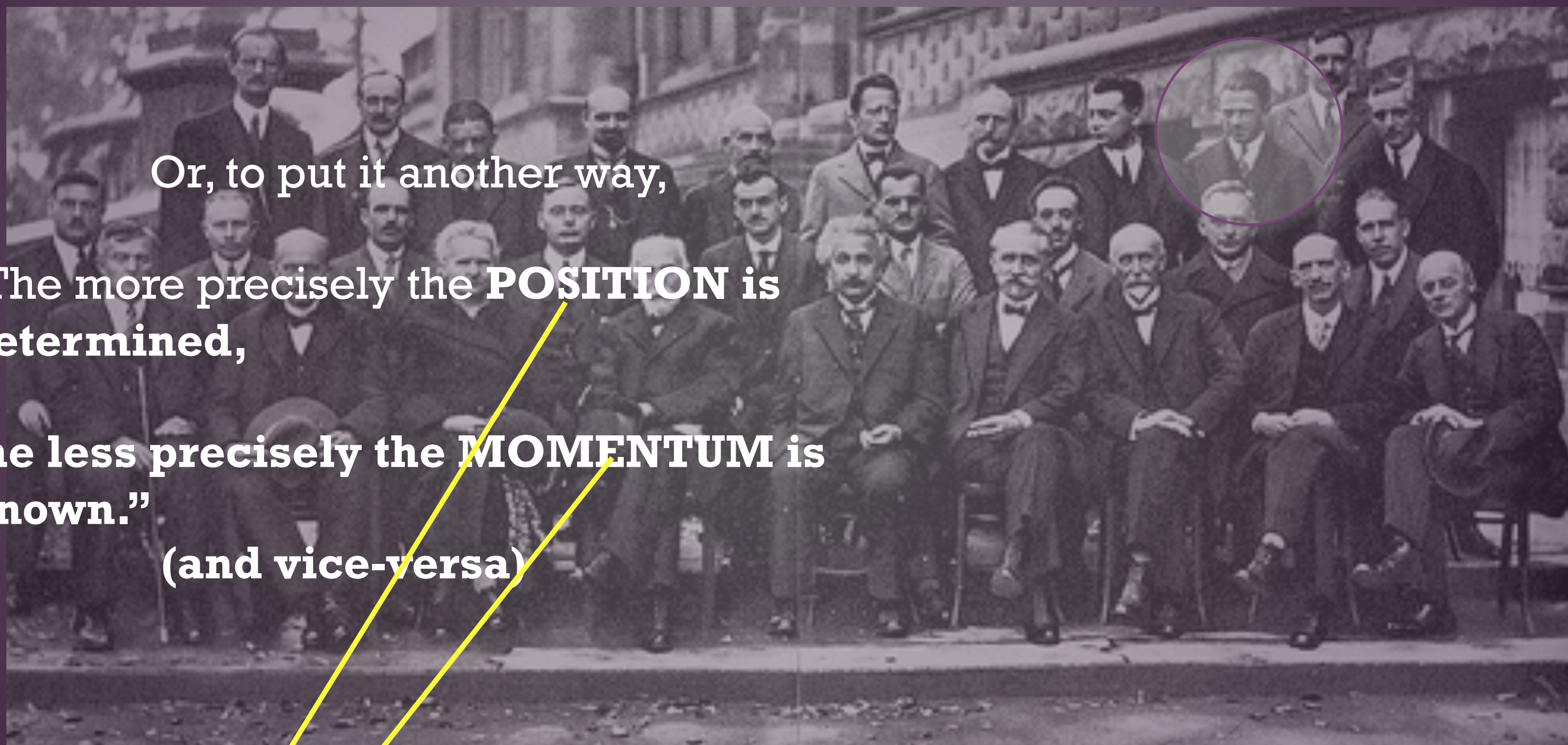
The "UNCERTAINTY PRINCIPLE" is one of the most important axioms in QUANTUM MECHANICS, stating that the exact position and momentum of a particle* can never be known at the same time.

NOTE: Although in theory it applies to all "particles", it is most commonly applicable to VERY TINY (microscopic) particles, at the atomic and subatomic levels.

IT WAS DEVELOPED IN 1927 BY GERMAN PHYSICIST

WERNER HEISENBERG (1901-1976)



Or, to put it another way,

"The more precisely the **POSITION is determined,**

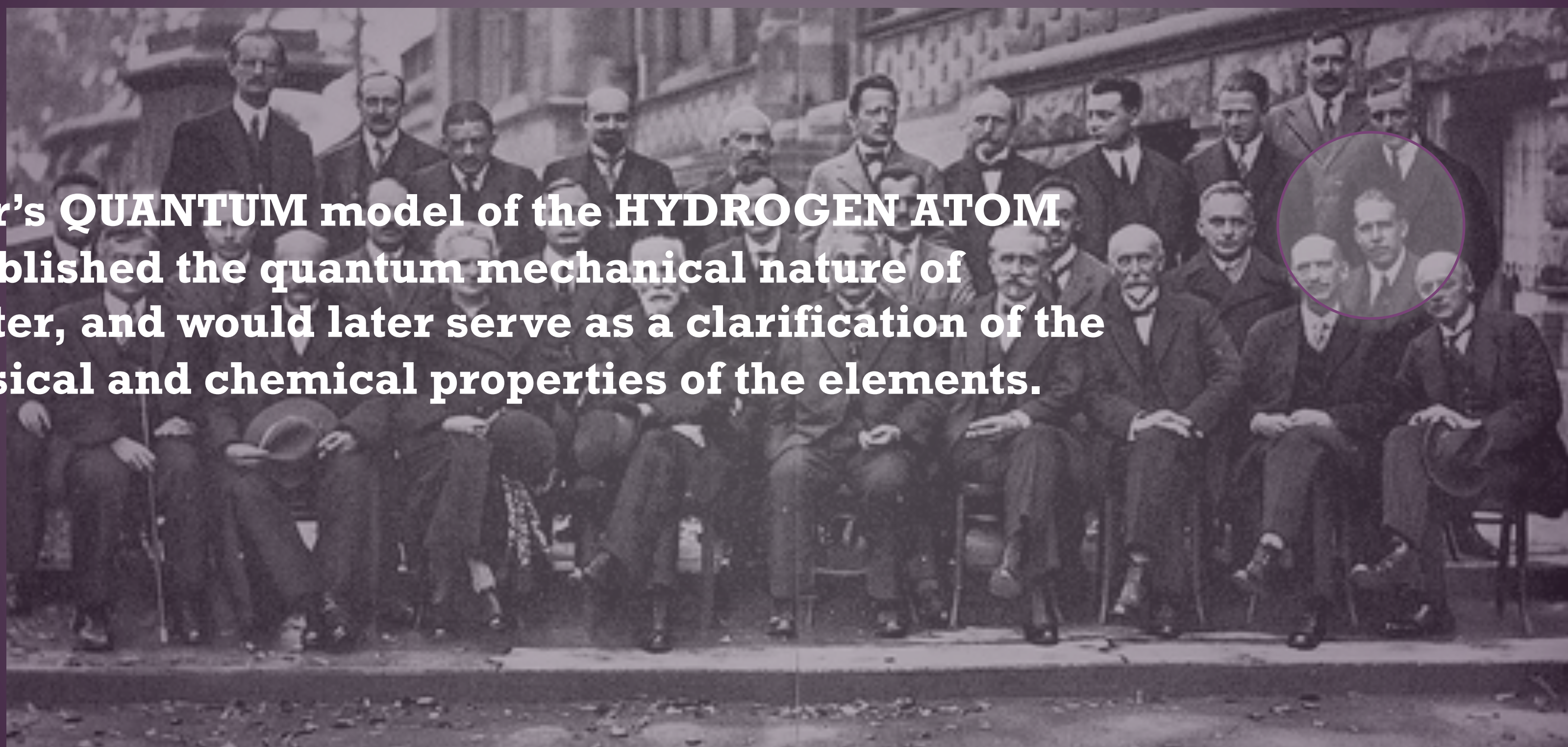
the less precisely the MOMENTUM is known.”

(and vice-versa)

$$\Delta x \, \Delta p \geq \frac{\hbar}{2}$$

Planck’s Constant divided by 2π.

HEISENBERG'S MENTOR WAS THE RENOWNED DANISH PHYSICSIST NEILS BOHR (1885-1962).



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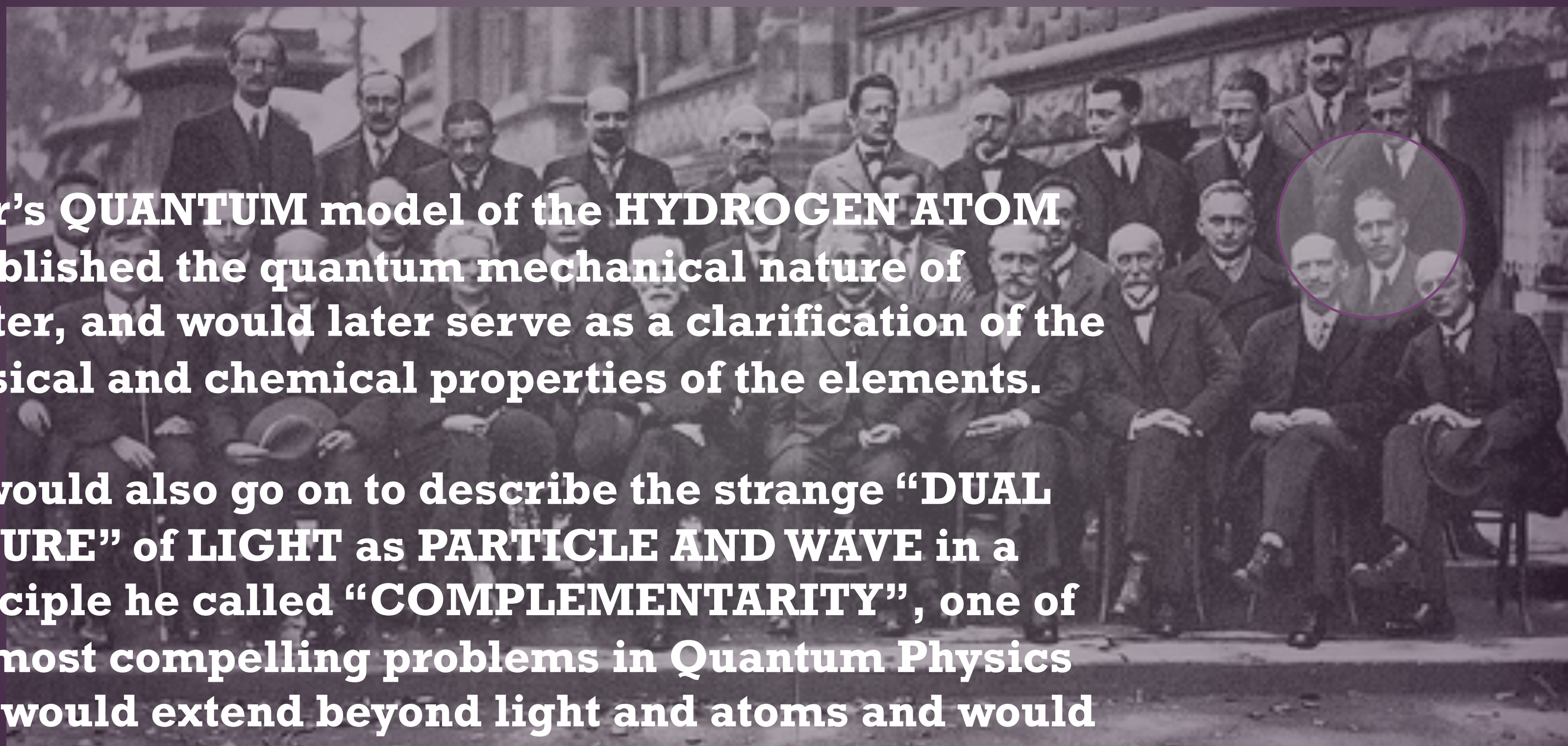

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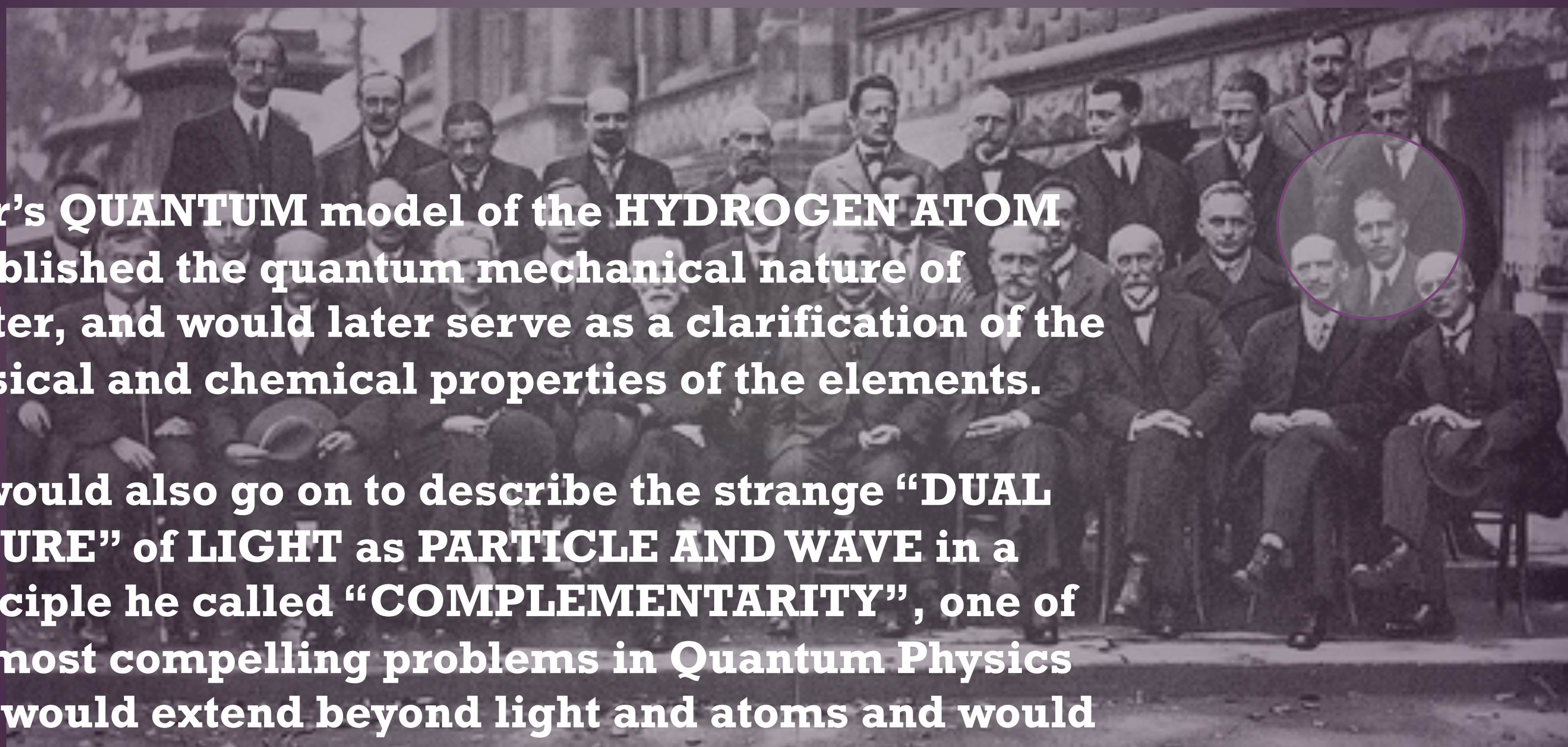

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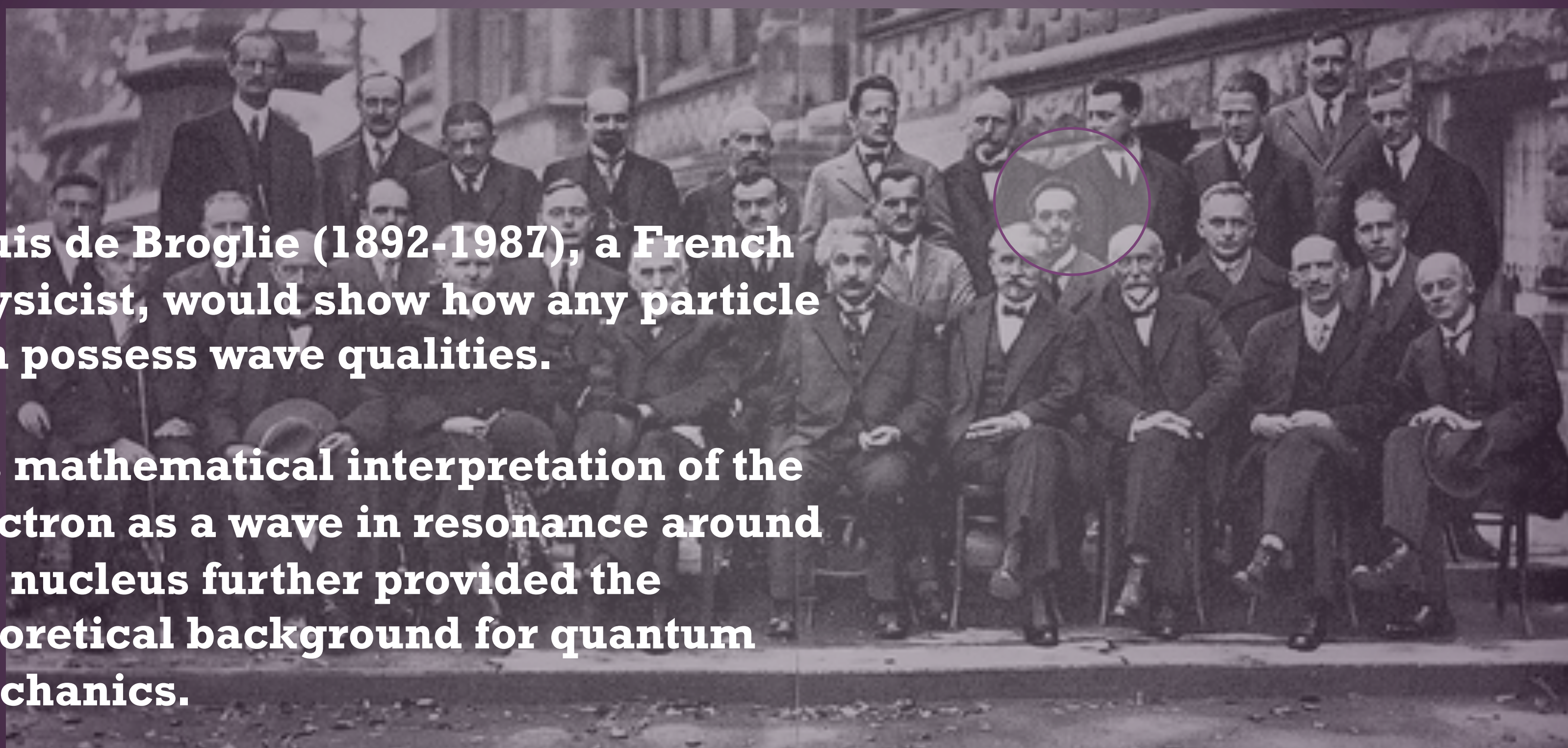
"If quantum mechanics hasn't profoundly shocked you, you haven't understood it yet."

Neils Bohr

SOME OTHER NOTABLE CONTRIBUTORS TO THE DEVELOPMENT OF QUANTUM MECHANICS:



Louis de Broglie (1892-1987), a French Physicist, would show how any particle can possess wave qualities.

His mathematical interpretation of the electron as a wave in resonance around the nucleus further provided the theoretical background for quantum mechanics.

$$\lambda = h / p$$

λ = wavelength
h = Planck's Constant
p = momentun (mv)

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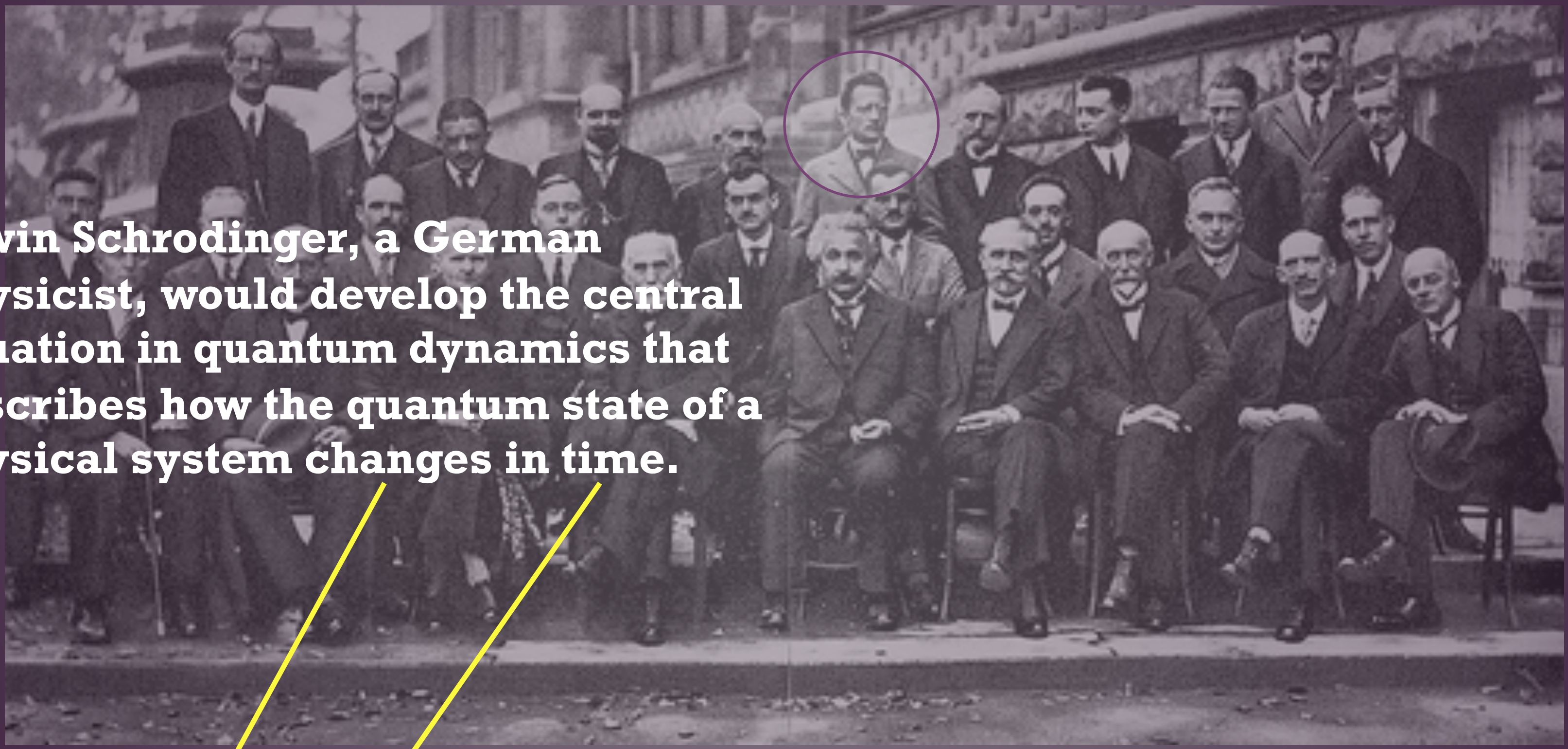

Erwin Schrodinger, a German Physicist, would develop the central equation in quantum dynamics that describes how the quantum state of a physical system changes in time.

$$i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},\,t) = \hat{H}\Psi(\mathbf{r},\,t)$$

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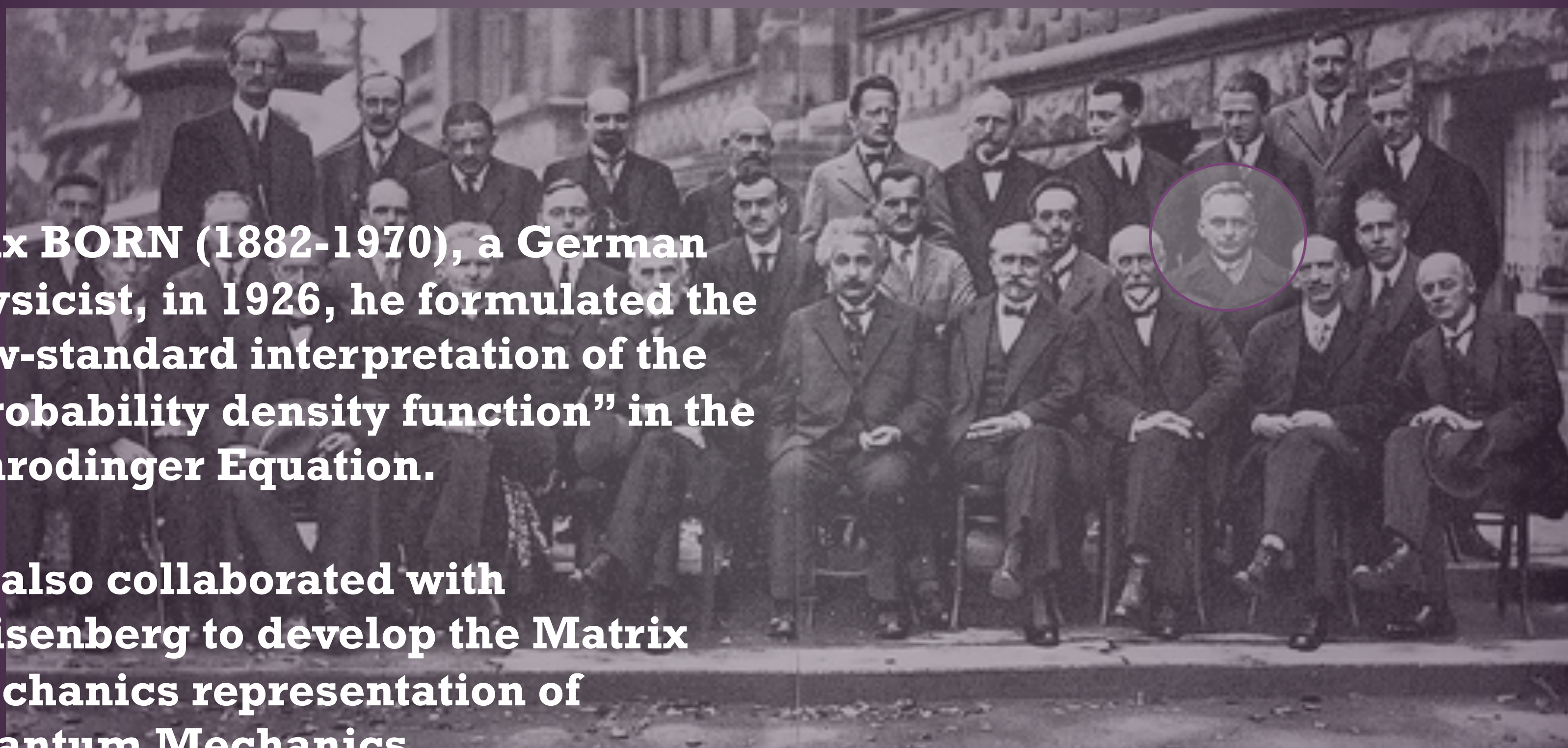

Max BORN (1882-1970), a German physicist, in 1926, he formulated the now-standard interpretation of the "probability density function" in the Schrodinger Equation.

He also collaborated with Heisenberg to develop the Matrix Mechanics representation of Quantum Mechanics.

So, what does all this mean?

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TRANSLATION. . .

So, what does all this mean?

We can never have a harmonic oscillator completely empty of energy because that would require its position coordinate and its momentum simultaneously to have precise zero values.

Because of the ever-present half-quantum of energy ½ hf, the electromagnetic field in space can never be permanently at rest,

They must always have their fundamental excitations, the so-called "zero-point fluctuations" going on.

So, what does all this mean?

The vacuum, then, ***is*** an active dynamical system.

It is not empty.

It is forever buzzing with weak electromagnetic fields.

They are part of the ground state of emptiness.

We can withdraw no energy at all from those fluctuating electromagnetic fields.

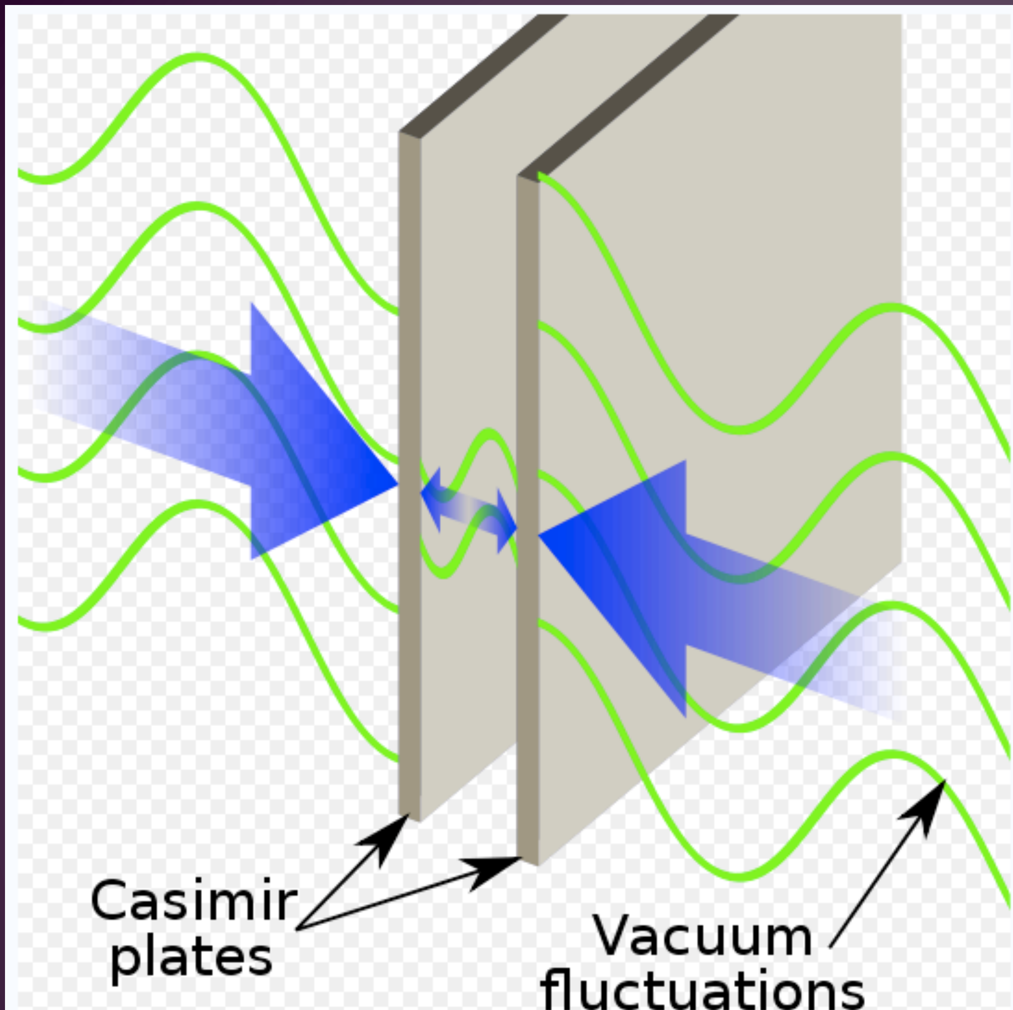
We have to regard them nonetheless as real and present even though we are denied any way of perceiving them directly.

“. . . Nothing really *matters*”

Freddie Mercury
(Bohemian Rhapsody, 1975)

HERE'S A CONSEQUENCE OF

"ZERO-POINT ENERGY"



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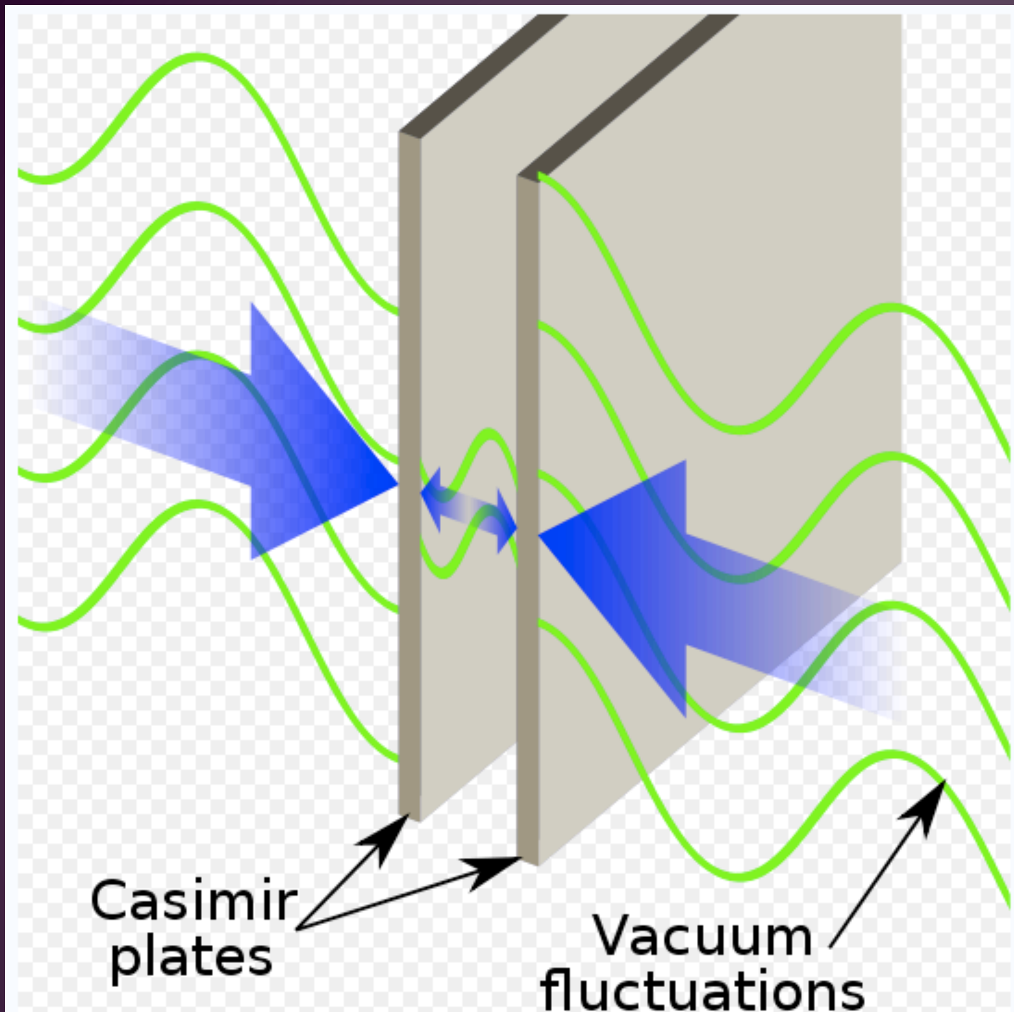

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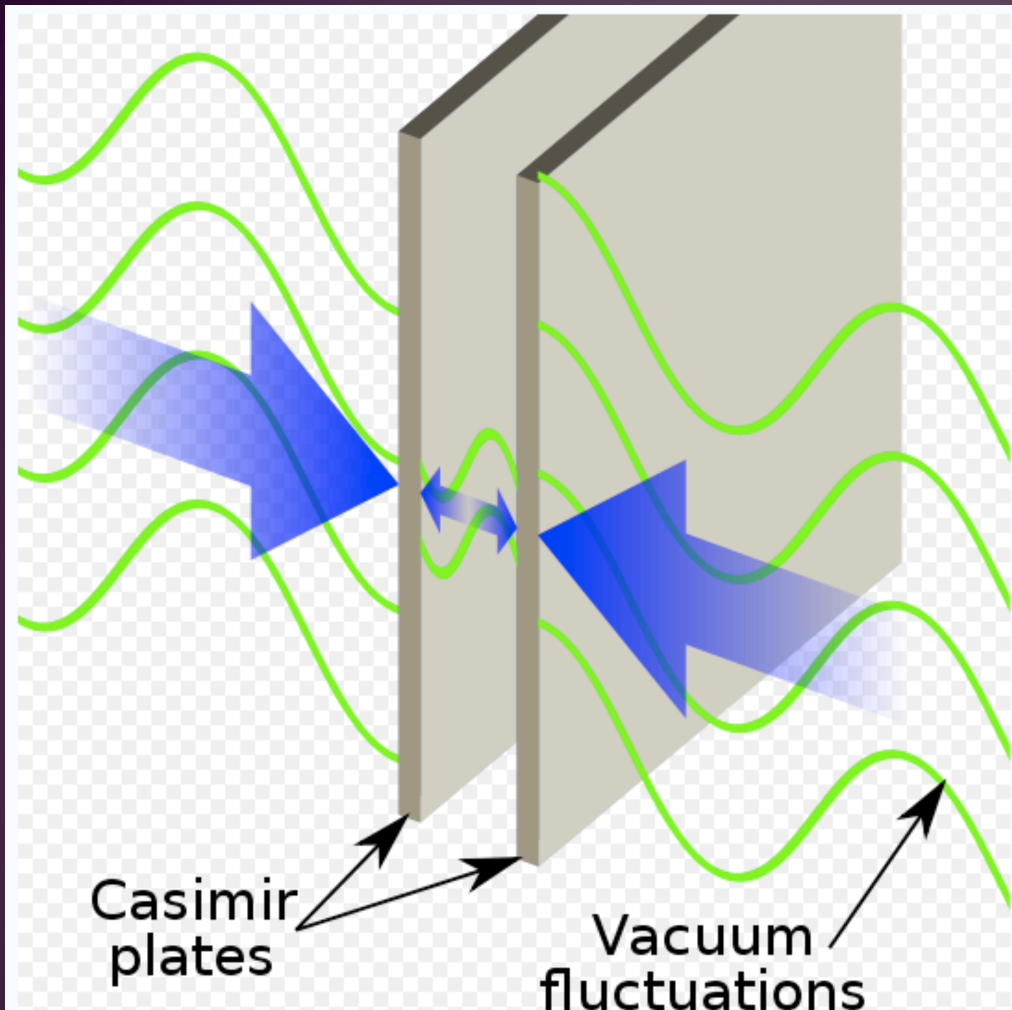

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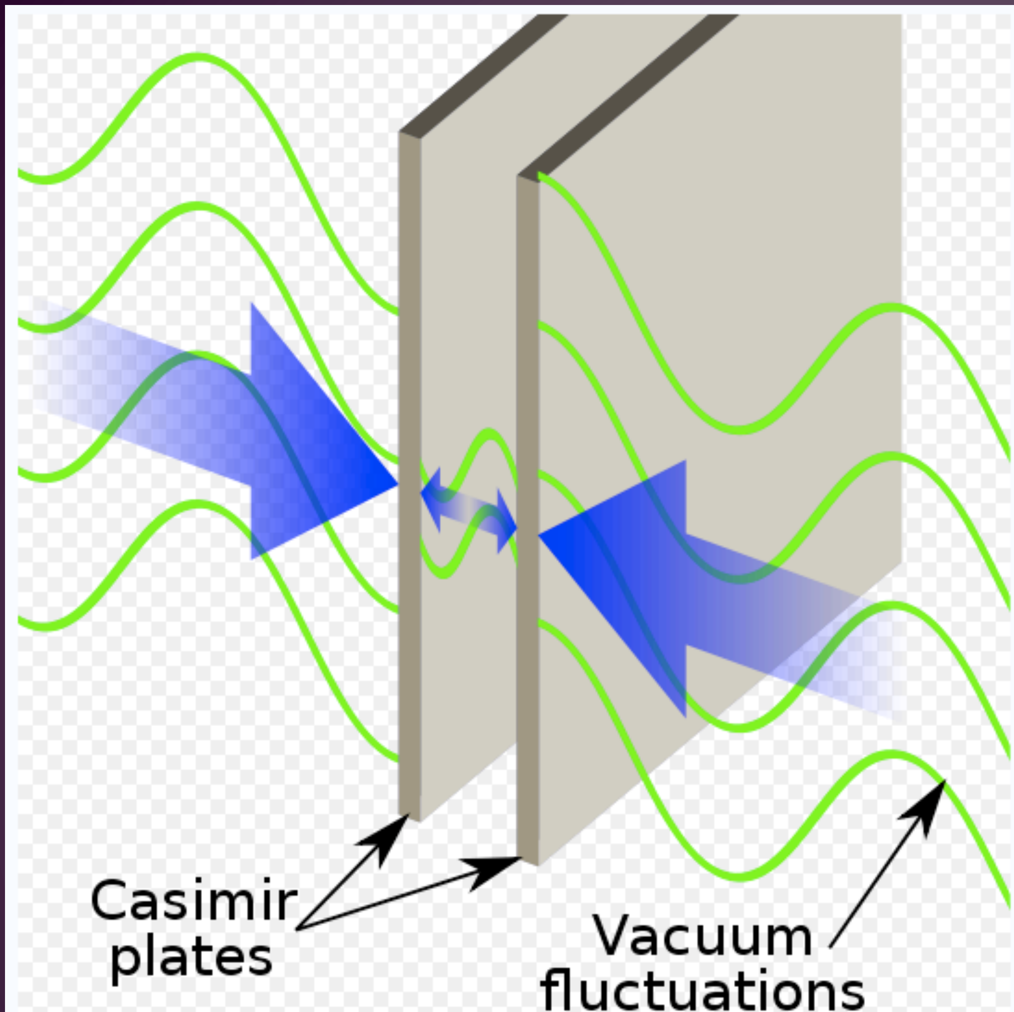

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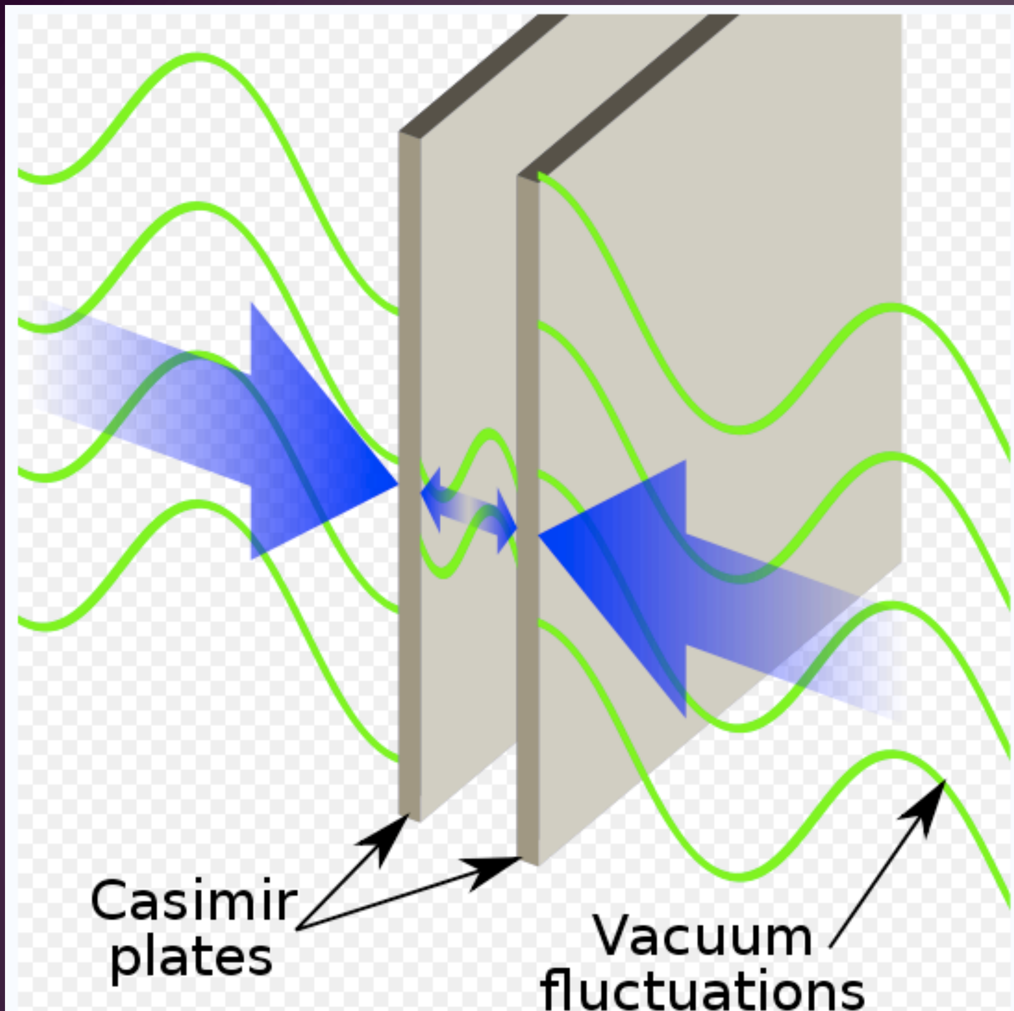
It has been observed and measured that if the distance between the plates is about 100 times the diameter of an atom (or less), a force equivalent to 1 atmosphere of pressure (101.3 kPa) exists between the plates!



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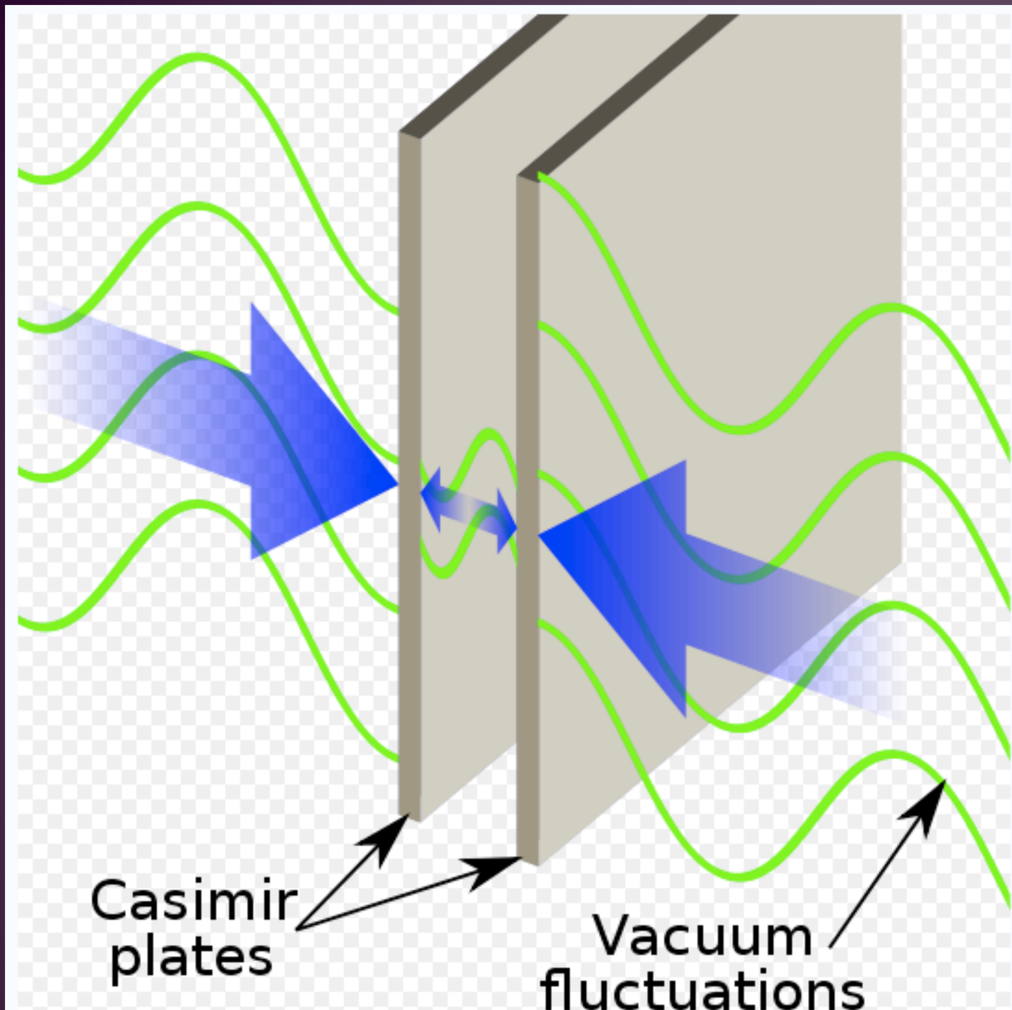
THIS IS KNOWN AS THE "CASIMIR* EFFECT" AND IS ATTRIBUTED TO THE "ZERO-POINT" ENERGY OF THE VACUUM PUSHING THE PLATES TOGETHER.

*Named in honor of Dutch physicist Hendrik B. G. Casimir in 1948.



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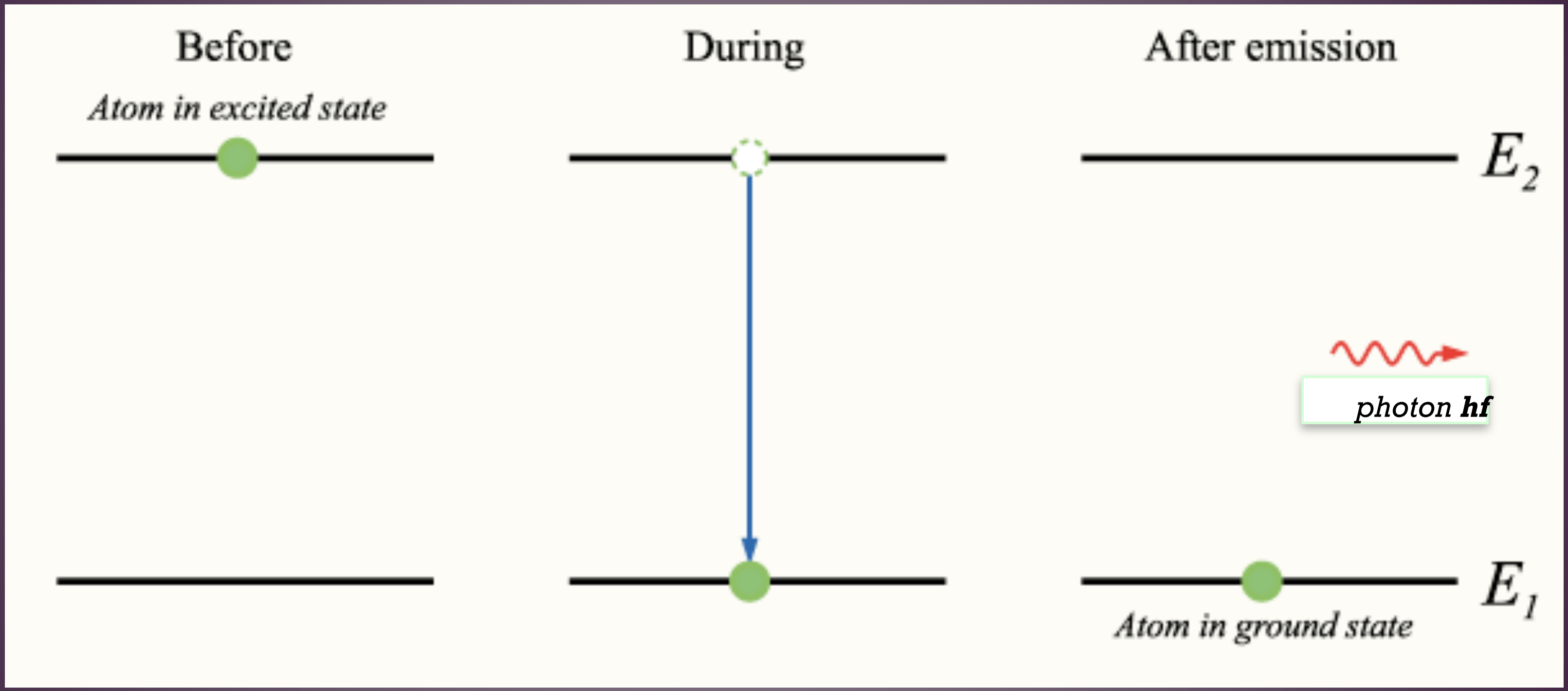
Zero-point Energy is also known as **"VACUUM ENERGY"**

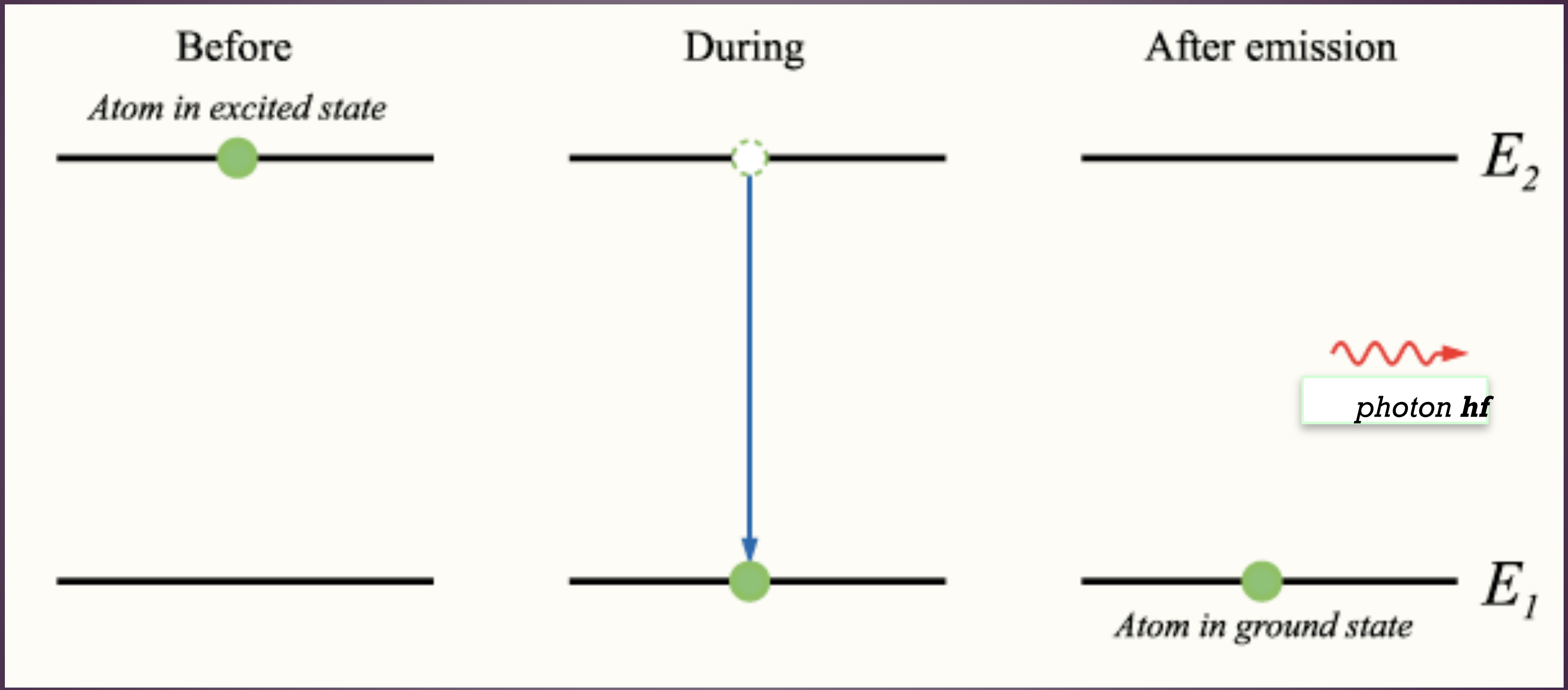
SPONTANEOUS AND INDUCED EMISSION.

SPONTANEOUS EMISSION



An electron in an excited state in an atom, molecule, nanocrystal, or nucleus "spontaneously" drops down to the ground state, and, in the process releases a photon whose energy (hf) equals $E_2 - E_1$.

SPONTANEOUS EMISSION



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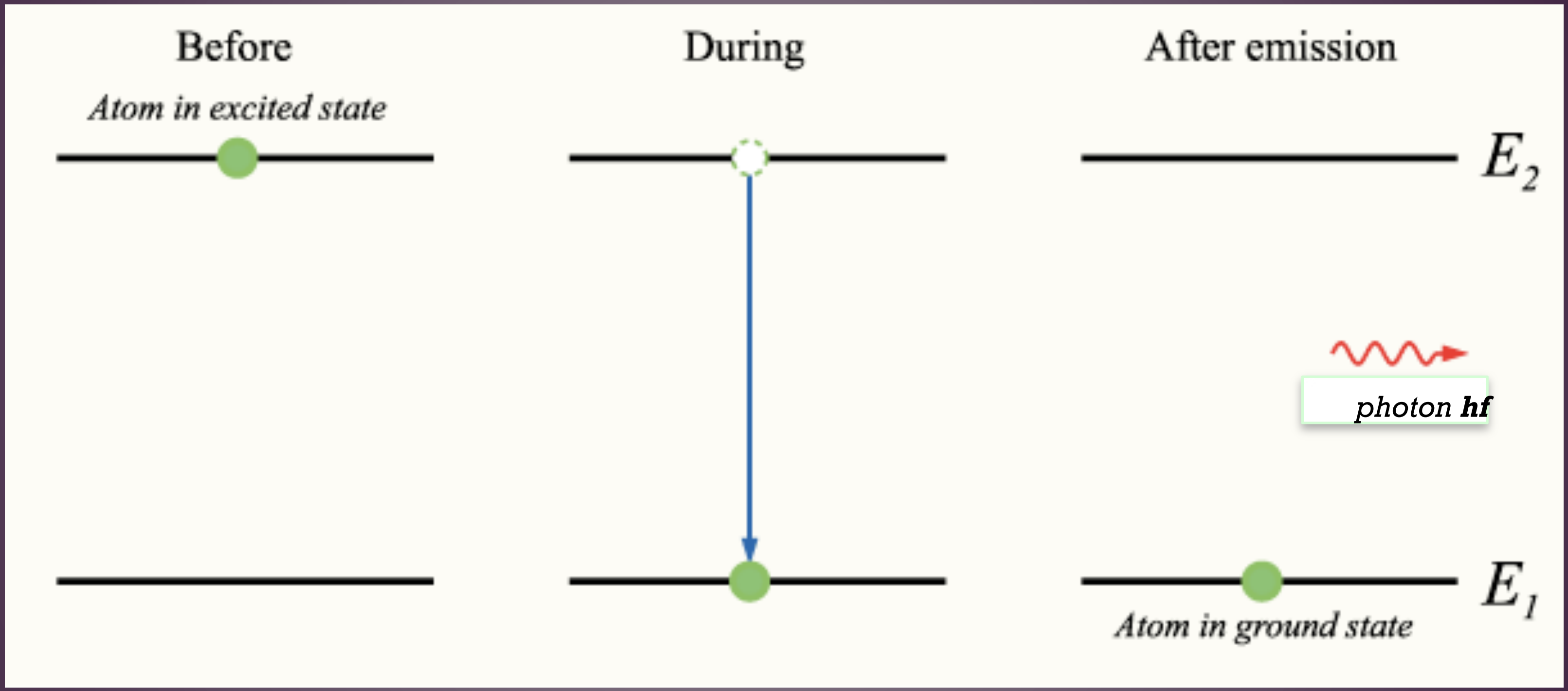
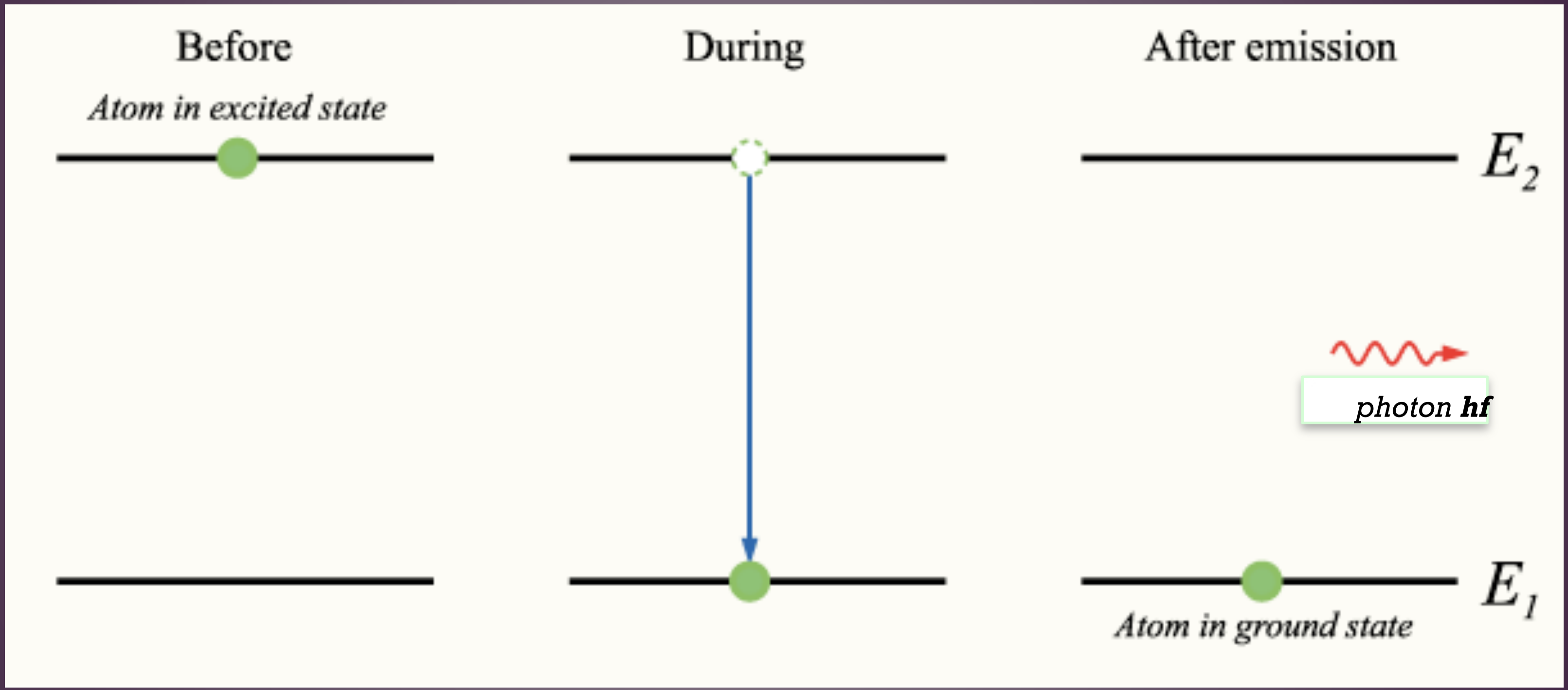
This is a QUANTUM EFFECT, since, in theory, it is caused in free space by fluctuations in the vacuum at that point in the quantum field. REMEMBER, the UNCERTAINTY PRINCIPLE prohibits exactly zero vacuum energy for any measurable time at any determinable point in space simultaneously.

SPONTANEOUS EMISSION



Applications of this effect include:

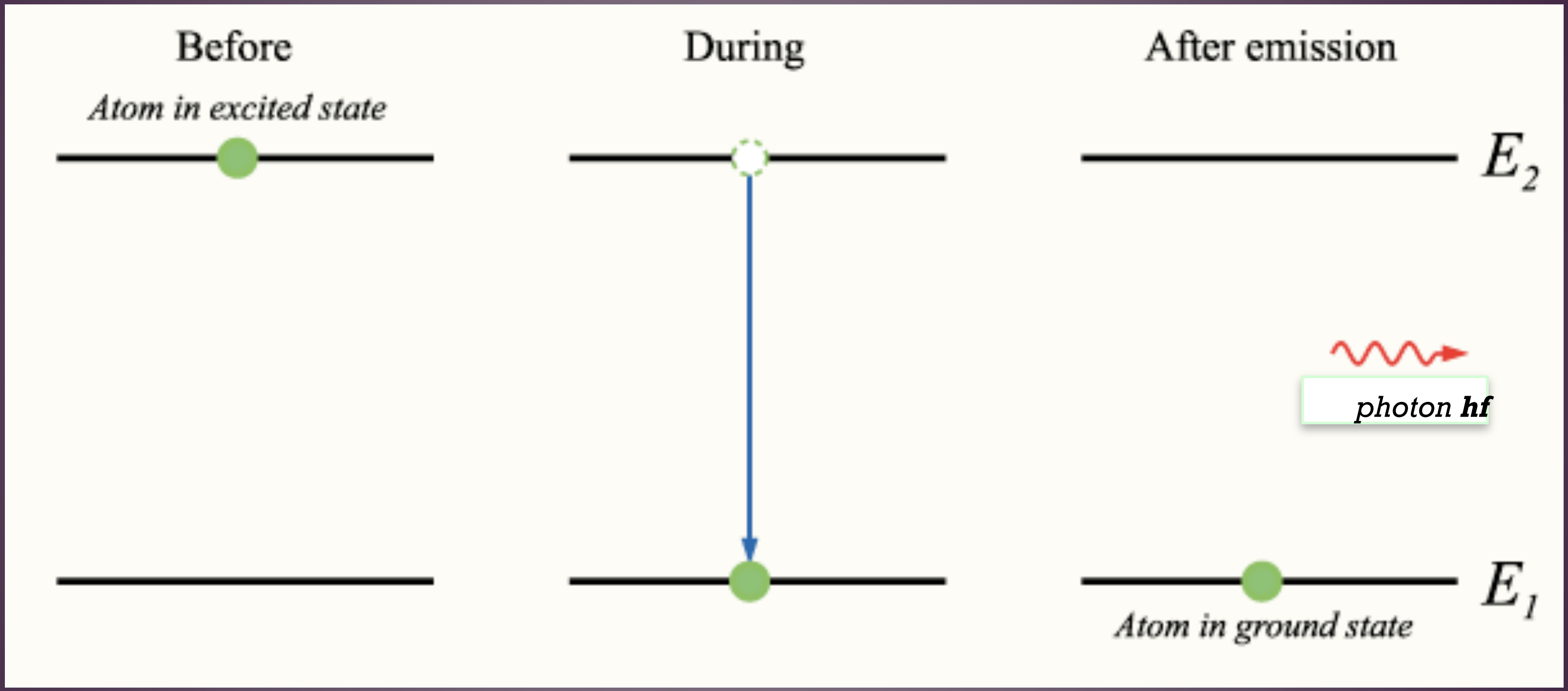
SPONTANEOUS EMISSION



Applications of this effect include:

FLUORESCENT TUBES

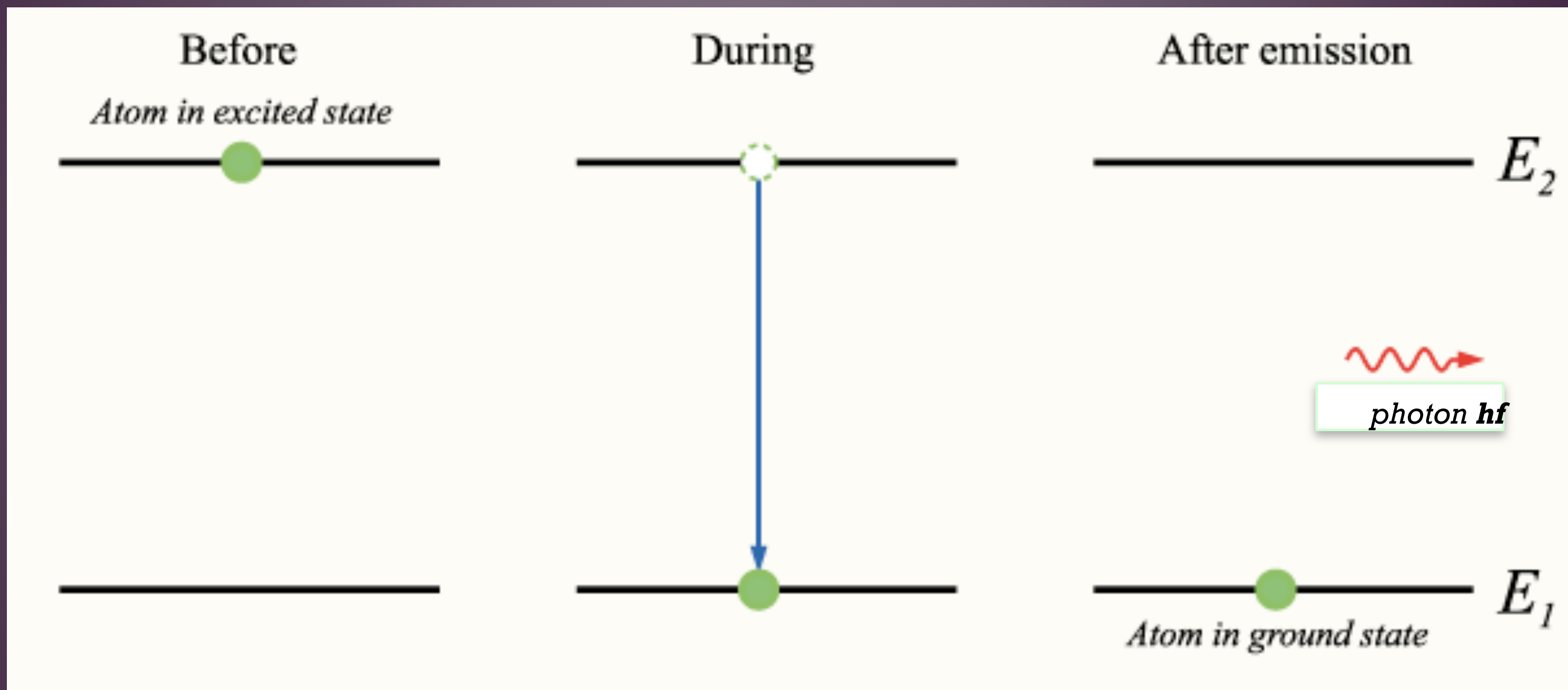
SPONTANEOUS EMISSION



Applications of this effect include:

CATHODE RAY TUBES
(older tv tube)

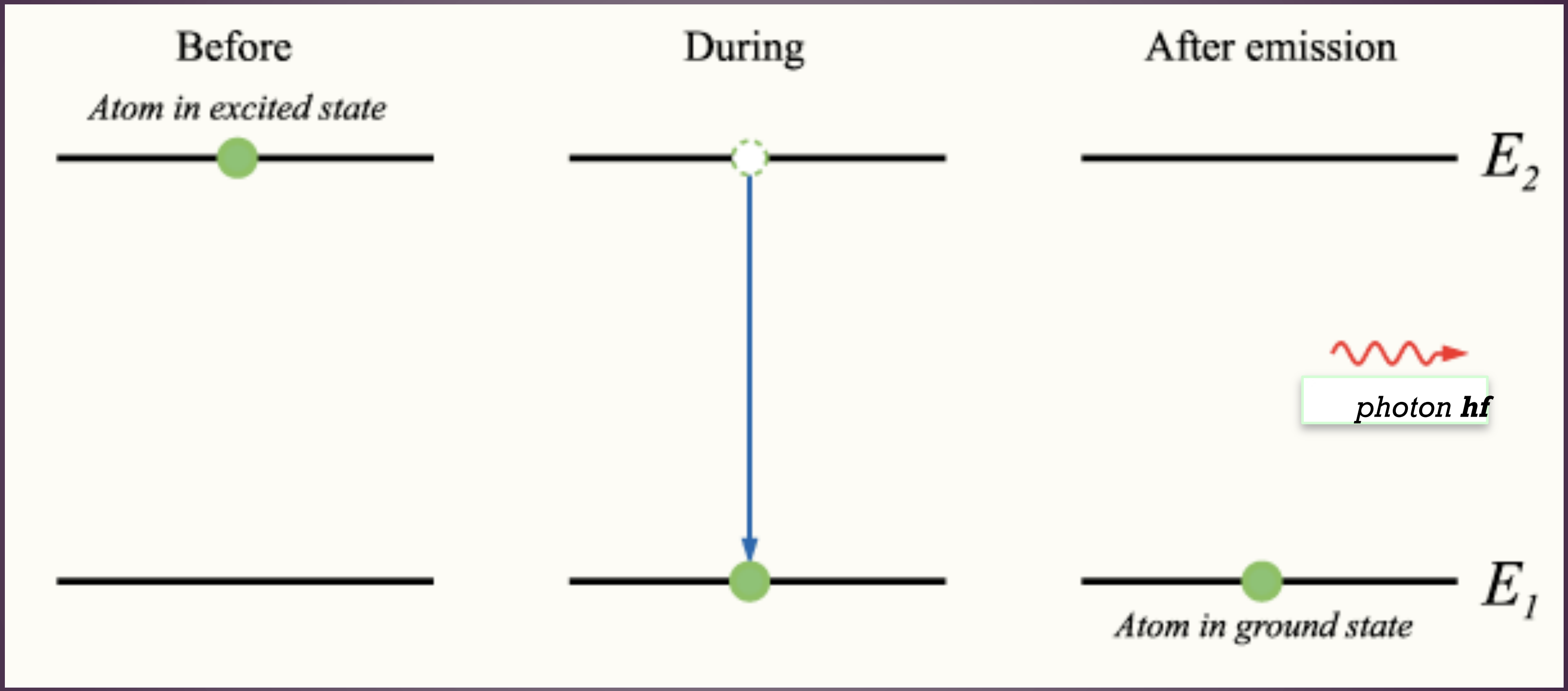
SPONTANEOUS EMISSION



Applications of this effect include:

and PLASMA DISPLAY PANELS

SPONTANEOUS EMISSION



The study of the quantum field theory of electrons and electromagnetic fields is called QUANTUM ELECTRODYNAMICS (QED).

BUT SPONTANEOUS EMISSION OF PHOTONS IS NOT THE ONLY QUANTUM-MECHANICAL PROCESS THAT INVOLVES ABSORBSION AND RELEASE OF FREQUENCY-SPECIFIC ENERGY.

IF AN ATOM IS *ALREADY* IN THE EXCITED STATE, AND IT ABSORBS A PHOTON WHOSE ENERGY IS *PRECISELY IN PHASE* WITH THE ATOM'S TRANSITION ENERGY, THEN IT WILL *STIMULATE* THE EMISSION OF A SECOND PHOTON IN THE SAME STATE. (OTHERWISE, SPONTANEOUS EMISSION WOULD OCCUR.)

THIS IS KNOWN AS

STIMULATED EMISSION

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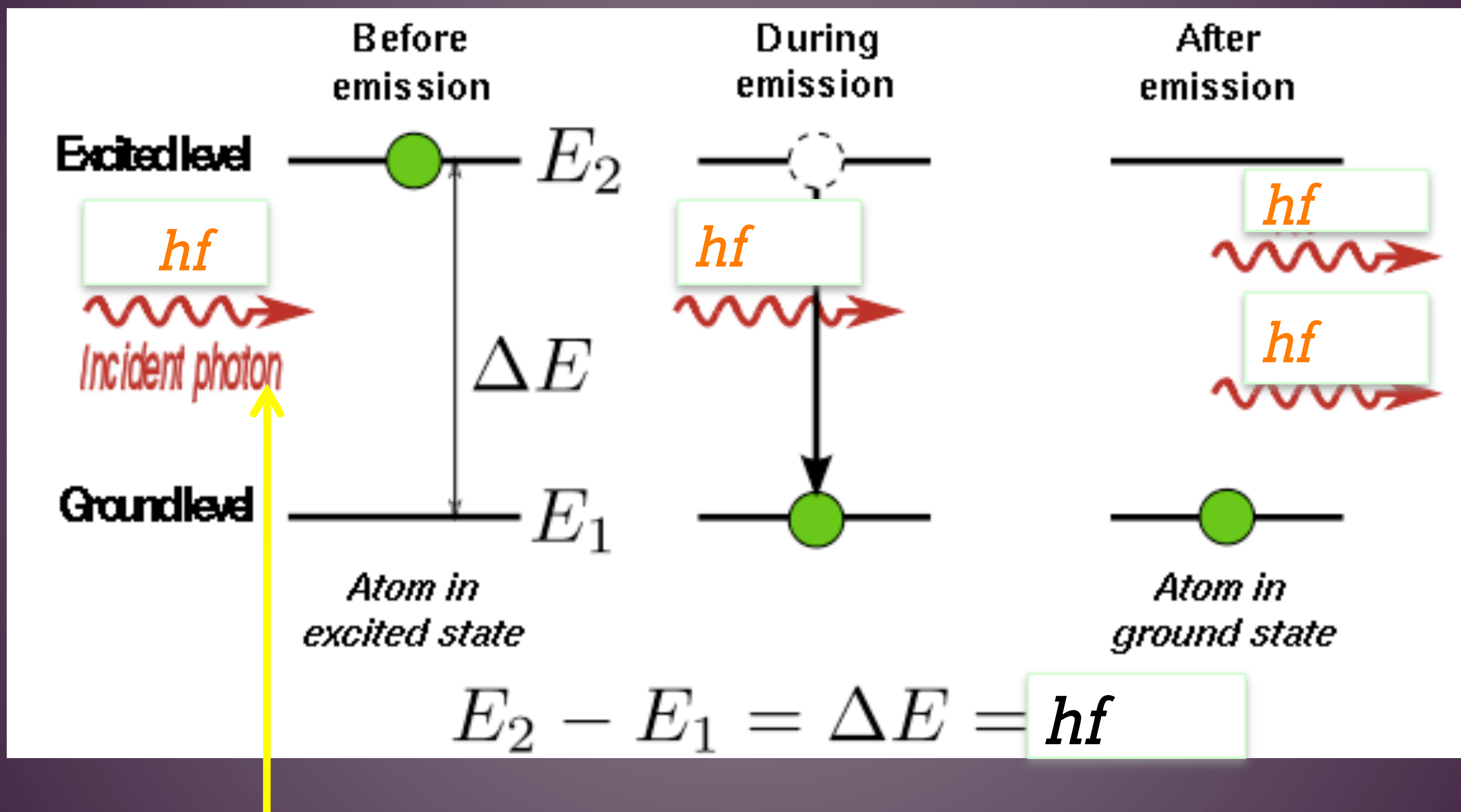
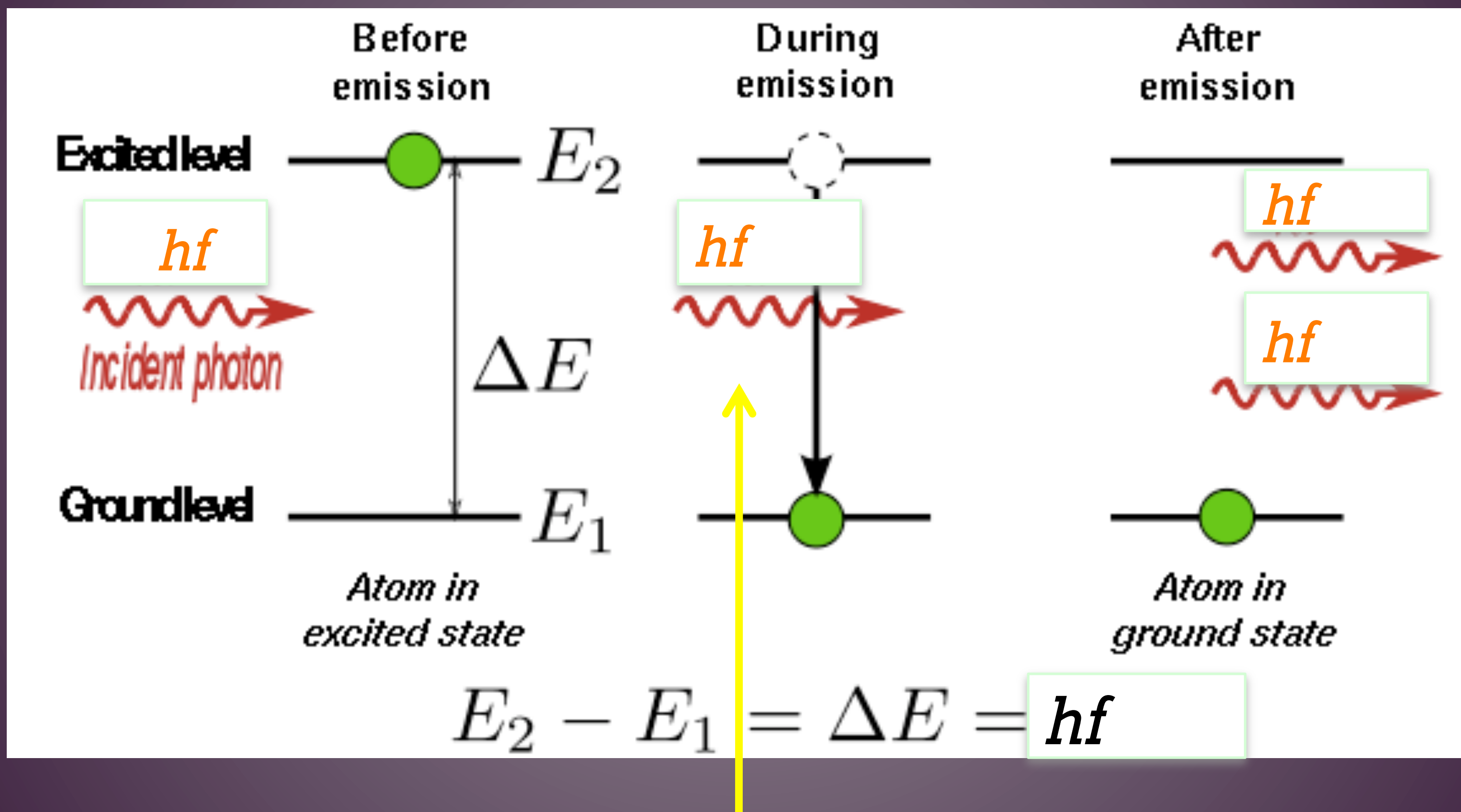


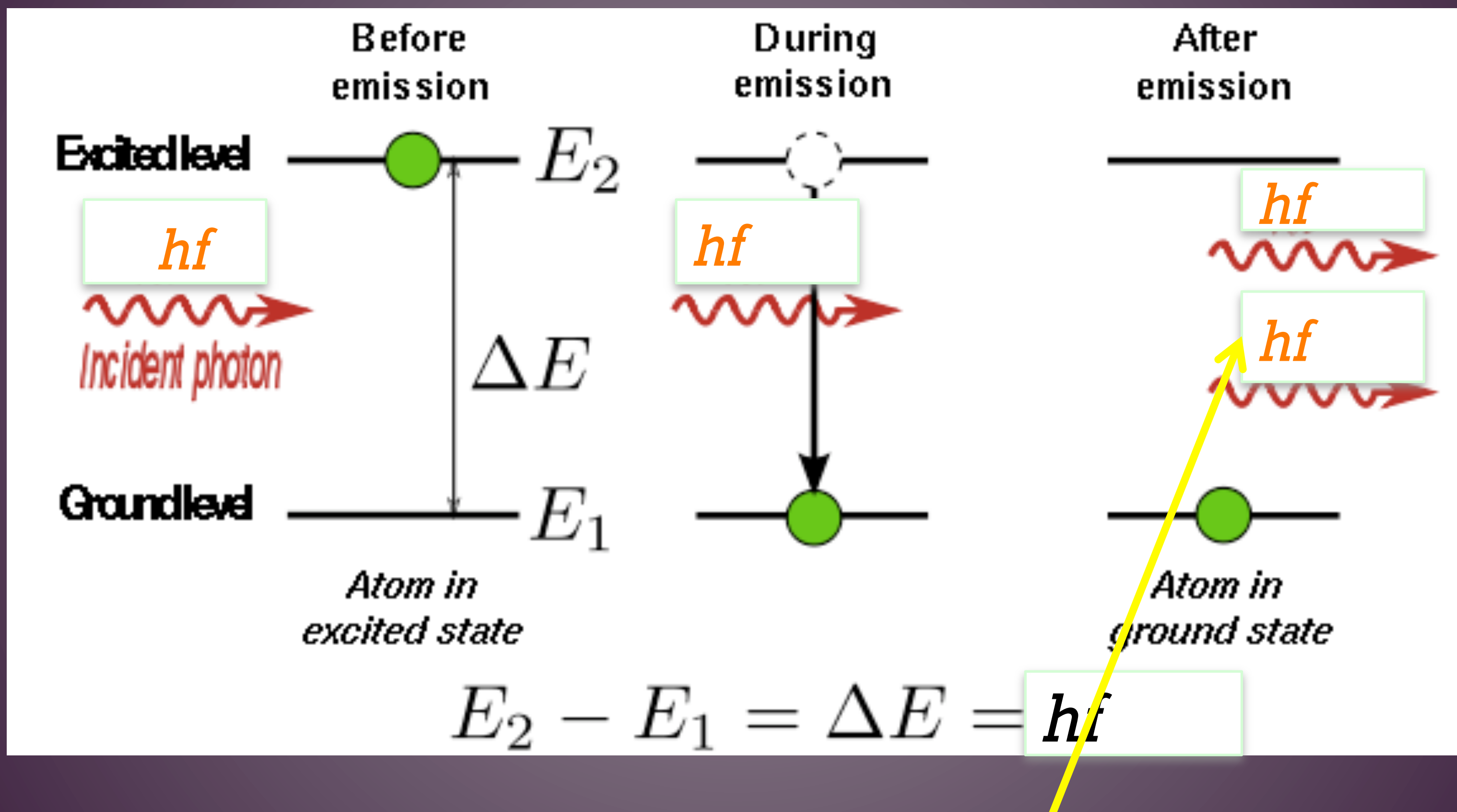
Here, an incident photon interacts with an atom in the excited state.

STIMULATED EMISSION



The electron jumps down into the ground state as a result.

STIMULATED EMISSION



Two photons emerge after emission, constituting an "AMPLIFICATION" of sorts.
(One photon in, TWO photons OUT.)

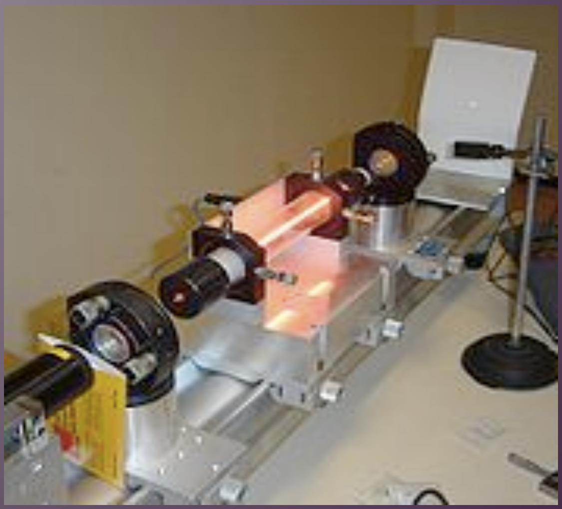
THIS IS THE UNDERLYING PRINCIPLE OF THE

L A S E R

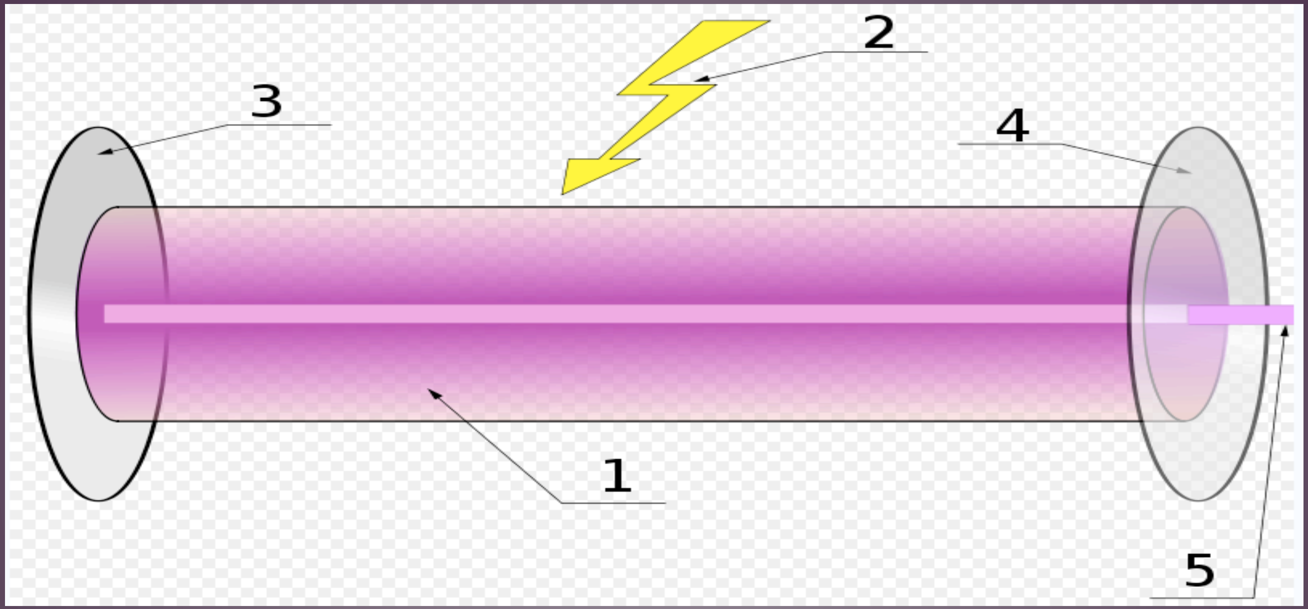
An acronym for "Light Amplification by Stimulated Emission of Radiation"

The first working LASER was made by Theodore H. Maiman in 1960 at Hughes Research Laboratories in California.

It was not the first device to apply the principle of stimulated emission. In 1953, Charles H. Townes produced the first microwave amplifier, which produced microwaves instead of light. It was known as the MASER, and has been used not only to amplify microwave signals, but also as an ATOMIC CLOCK.



COMPONENTS OF THE LASER



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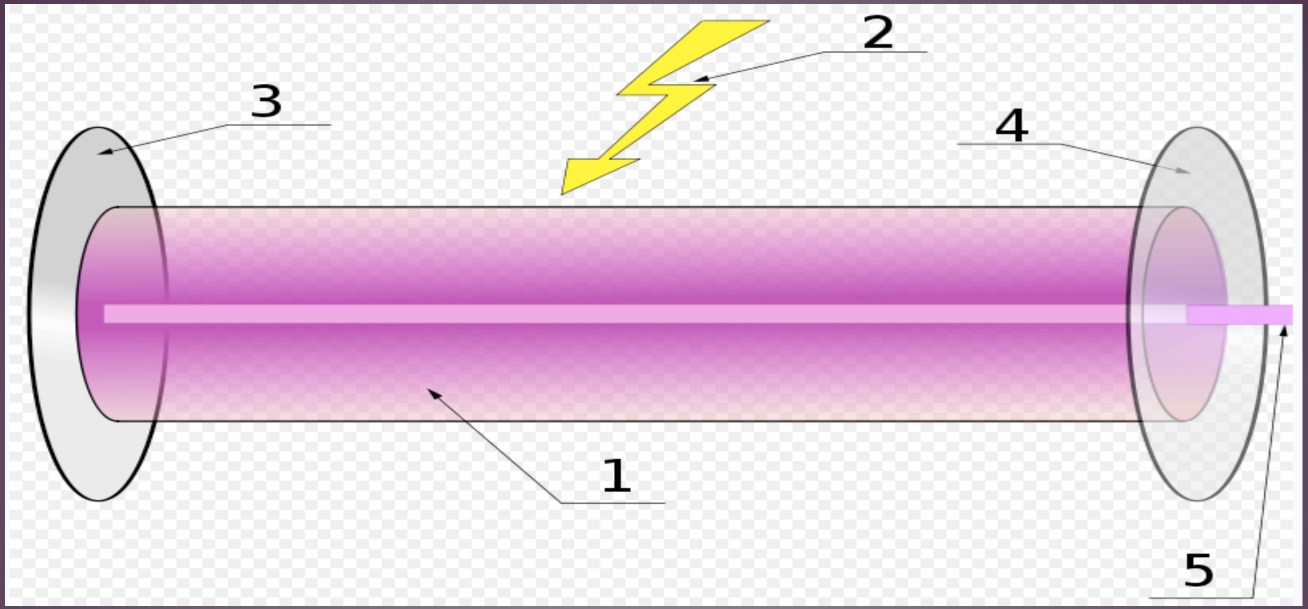
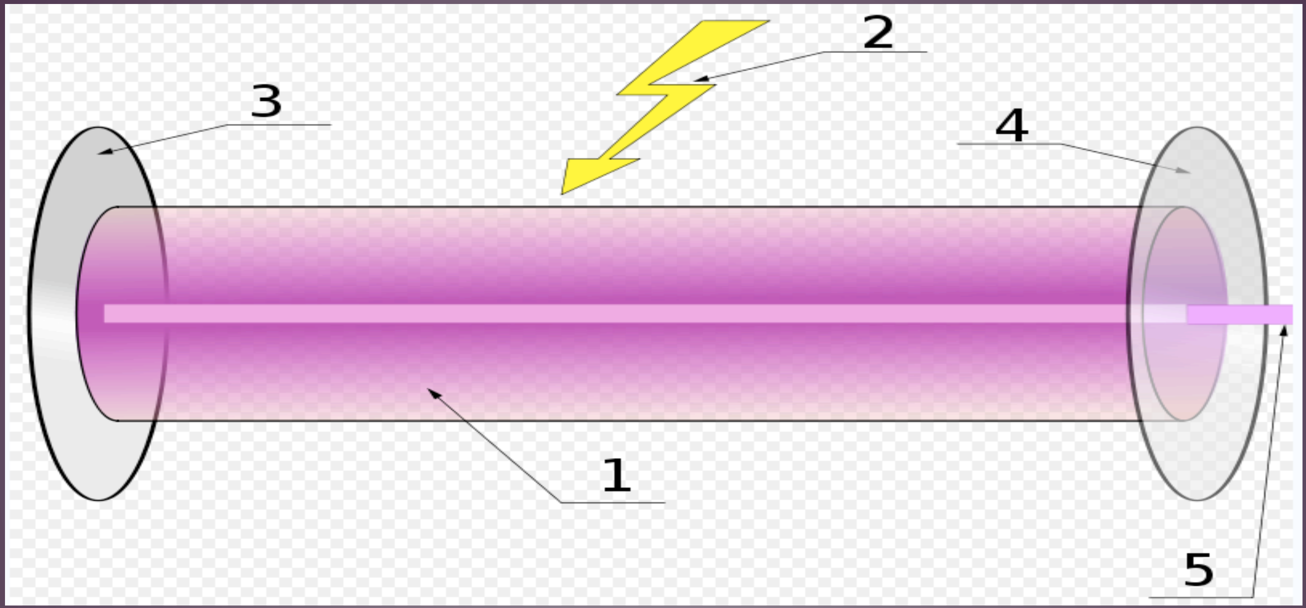


1. GAIN MEDIUM: A material with properties that allow it to amplify light by stimulated emission.

COMPONENTS OF THE LASER



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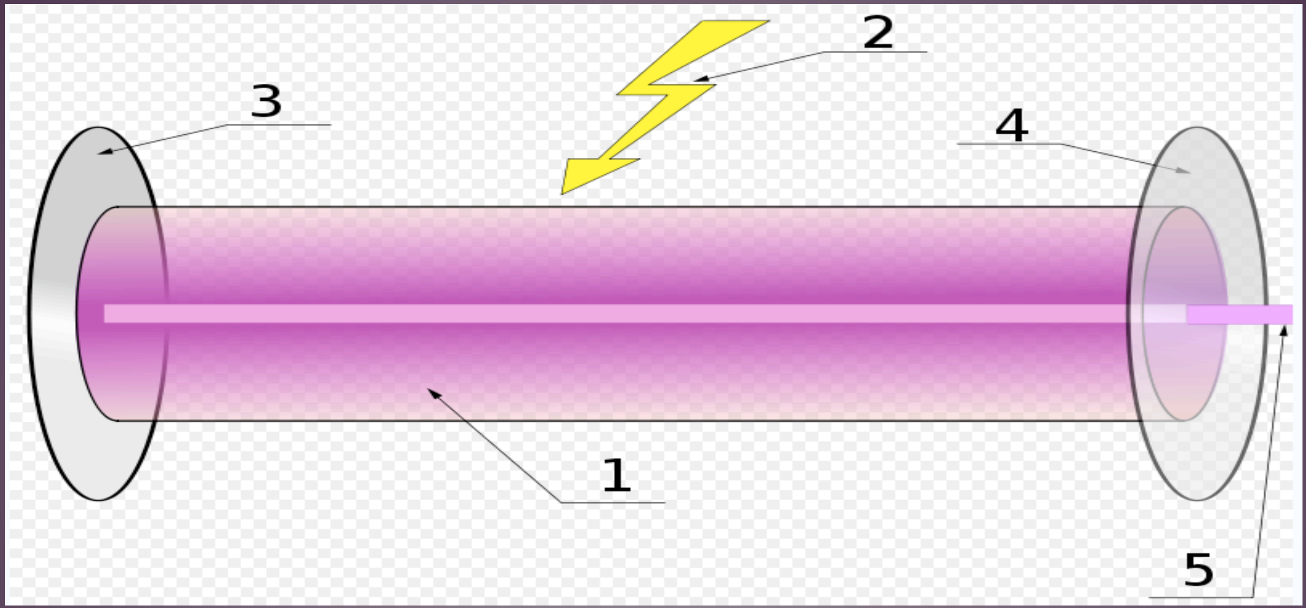

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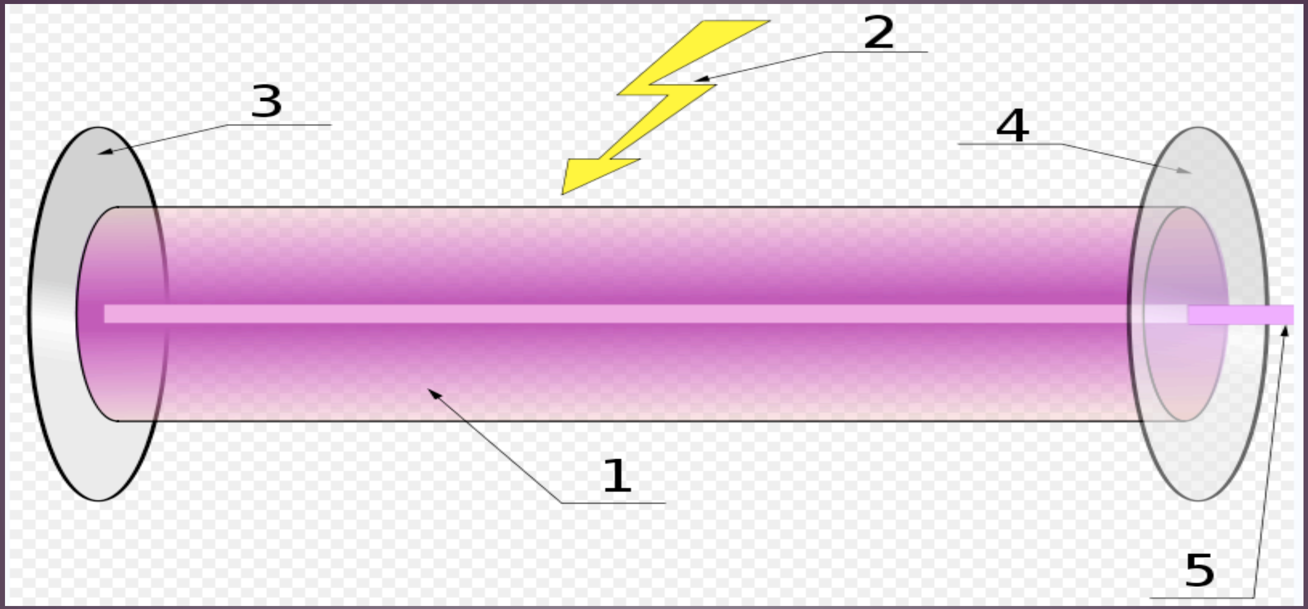

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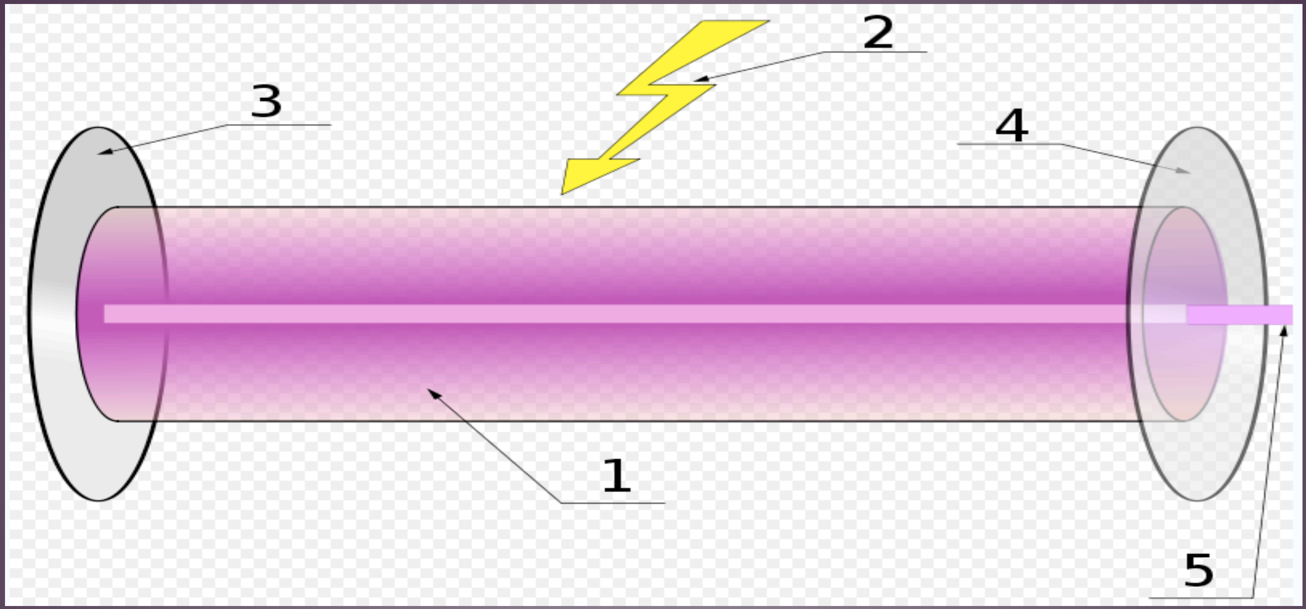

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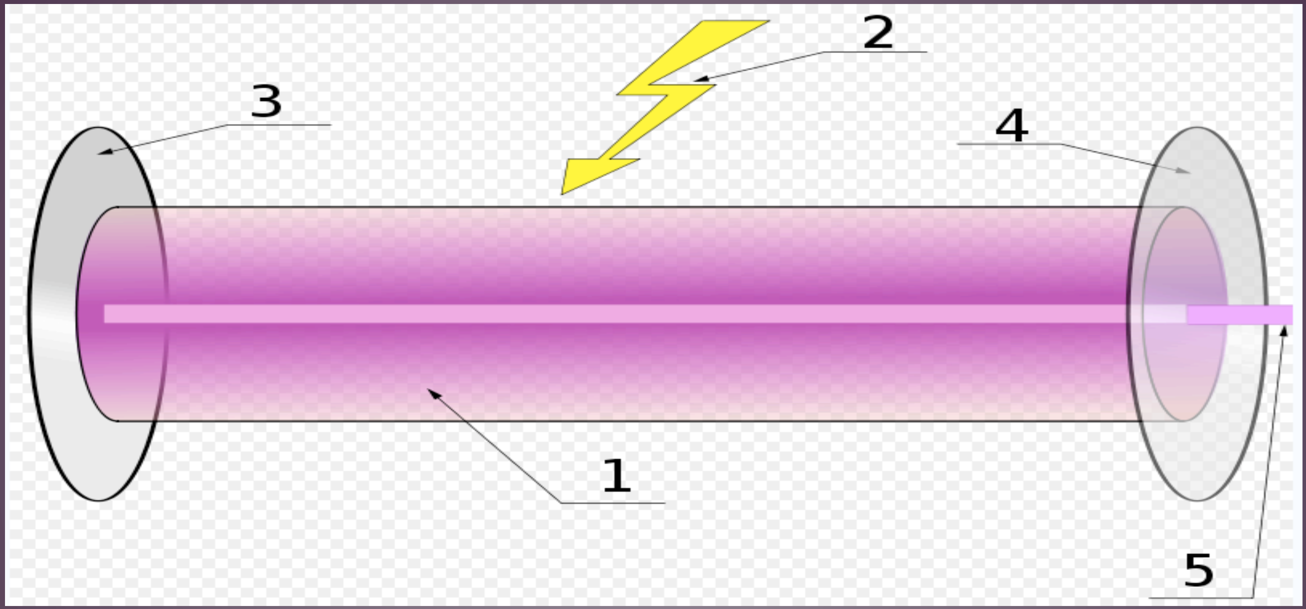

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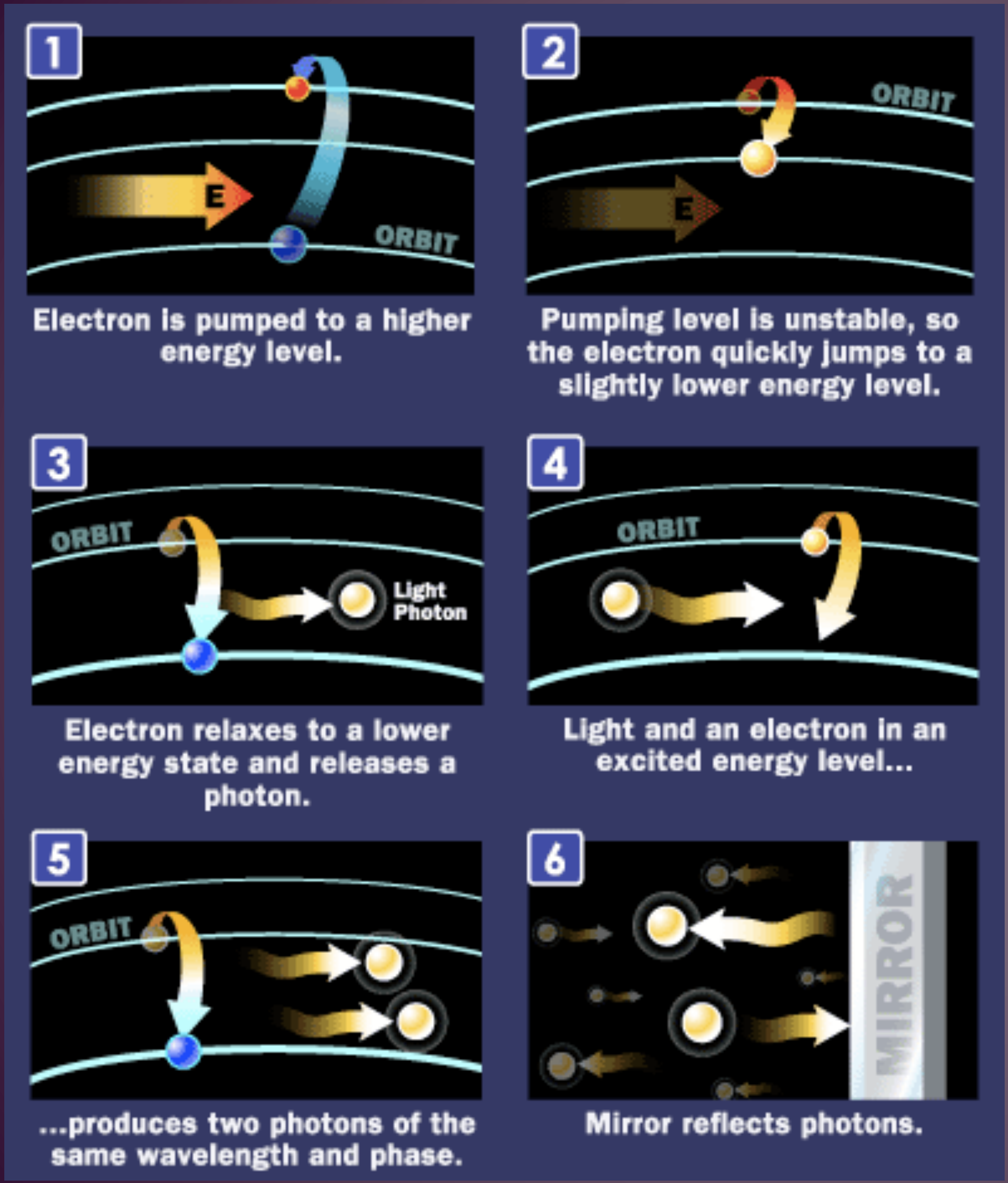
Although LASERS may differ in type, based on gain medium and energy pumping source (e.g.: gas, chemical, solid state, etc.), they all use STIMULATED EMISSION to produce a beam based on principles of QM.

GETTING "PUMPED UP"



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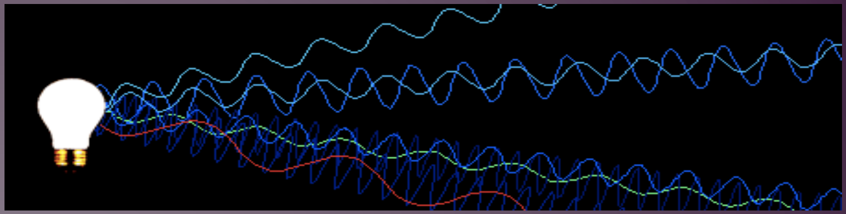

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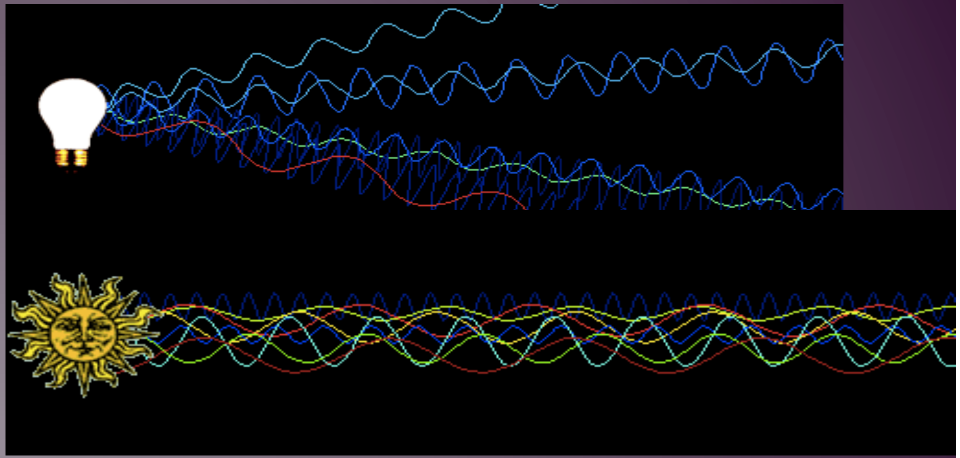

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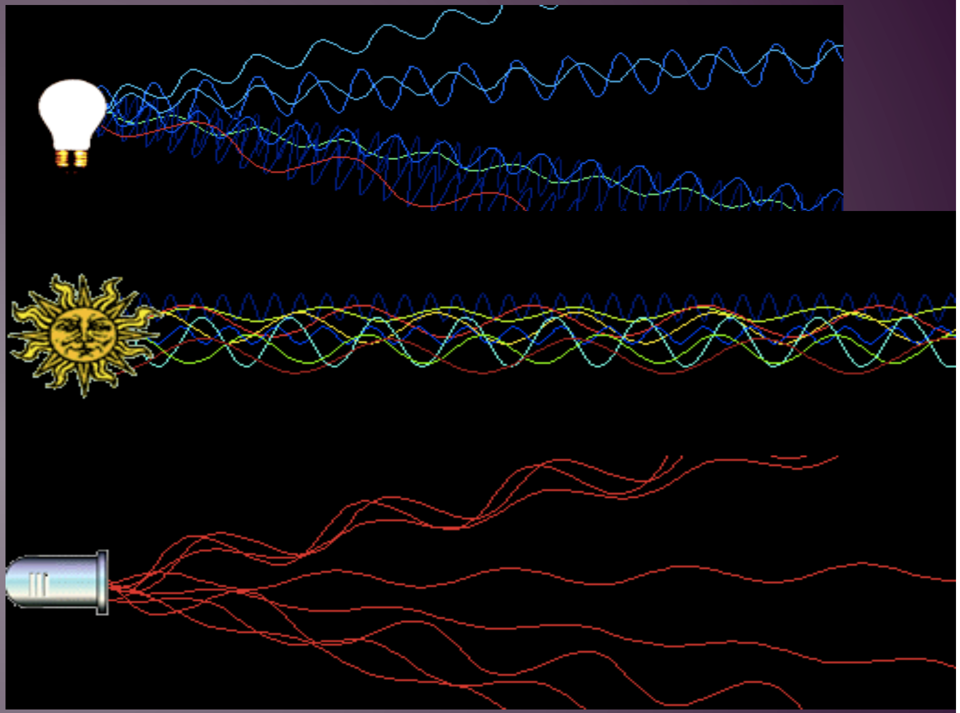

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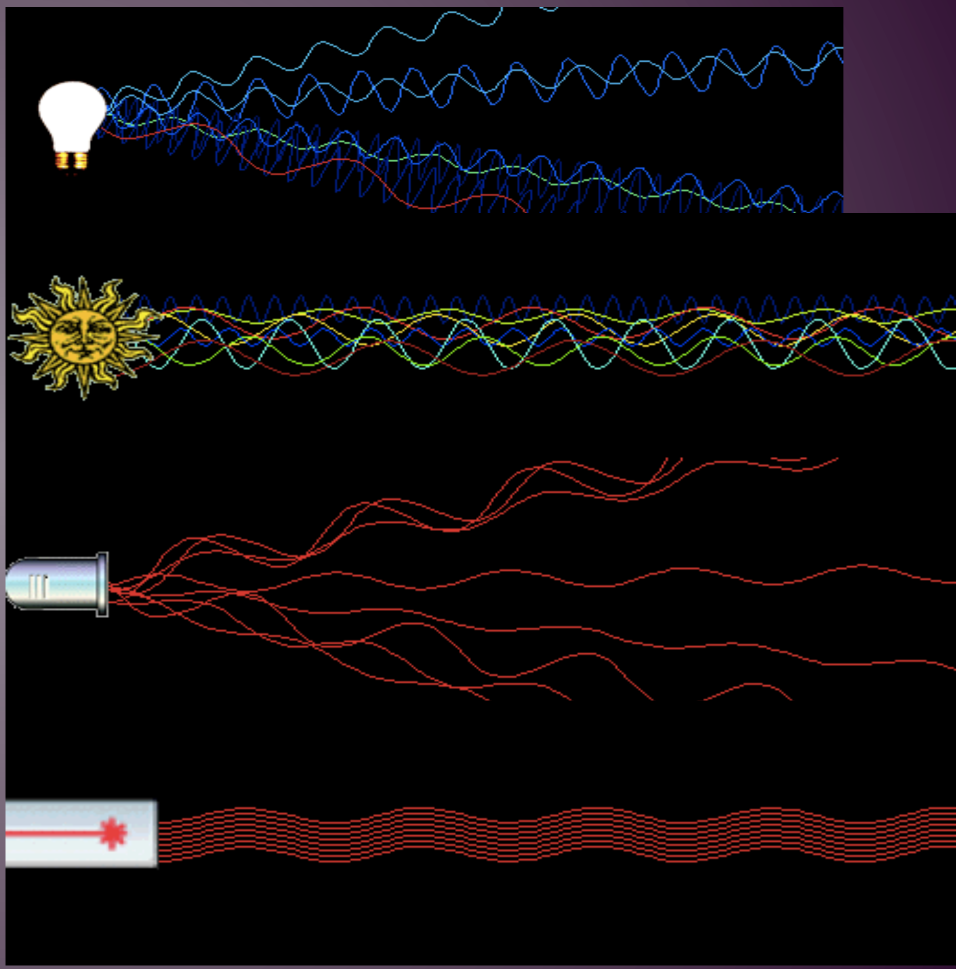

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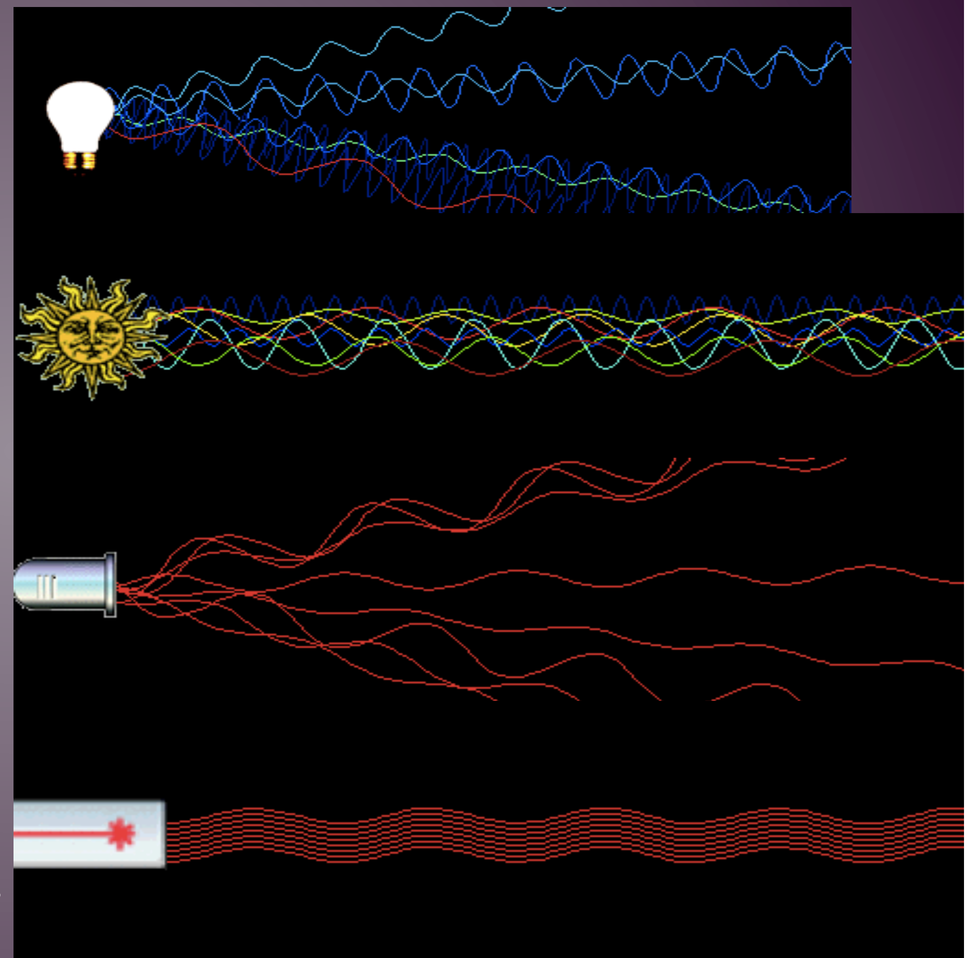

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Not all LASER types produce the same wavelength, or at the same power, and some LASERS emit light in a broad spectrum, and some even emit multiple distinct wavelengths.

LASER pointers; Solid-state/very low power (<1 mW)

LASERS are used today in MANY applications.

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CD and DVD players, Solid-state (5-10 mW)

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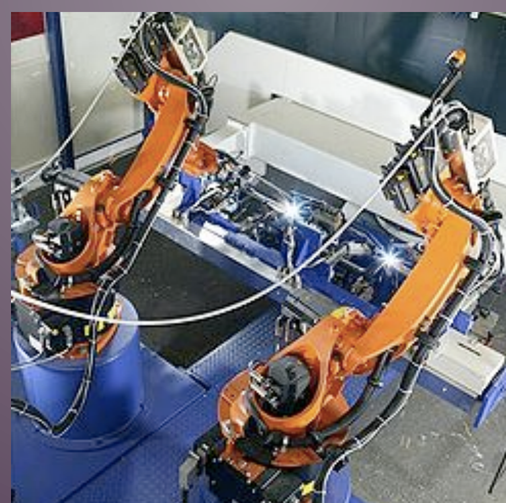

Cutting and welding (100-3000W)

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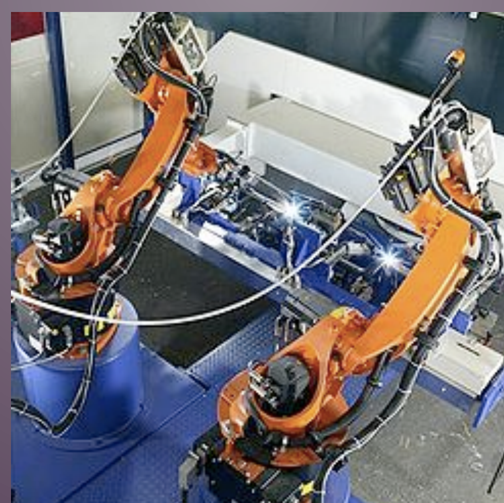

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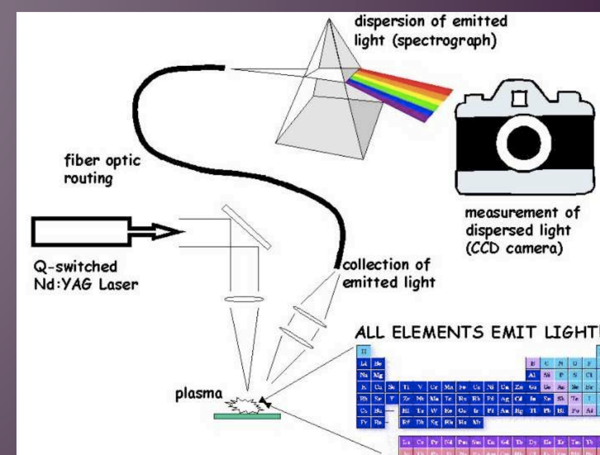

LASER-induced breakdown spectroscopy

LET'S LOOK AT ONE EXAMPLE OF HOW LASERS HAVE COMPLEMENTED AND ENHANCED "CLASSICAL" TECHNOLOGY:

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OF HOW LASERS HAVE
COMPLEMENTED AND ENHANCED
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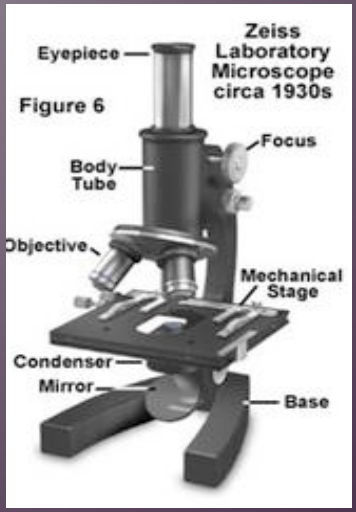
LASERS AND MICROSCOPY

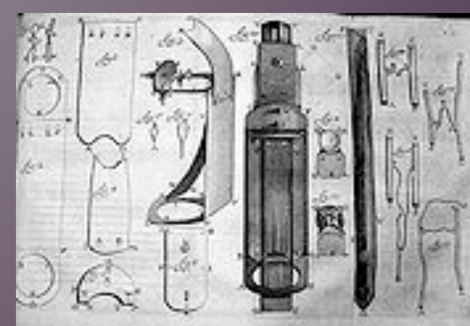


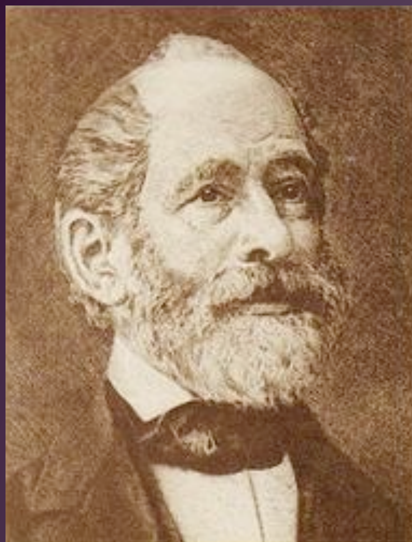
I. HISTORY

ANTONIE van LEEUWENHOEK
(1632-1723)

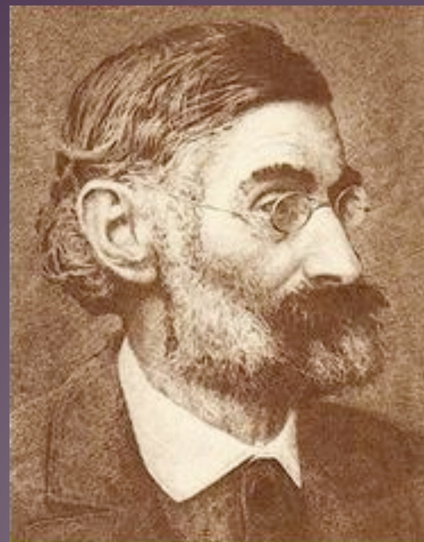
Credited with first developing the microscope as a tool of science.

He used it to describe cellular organisms in water, and red blood cells.





Carl Zeiss (1816–1888)



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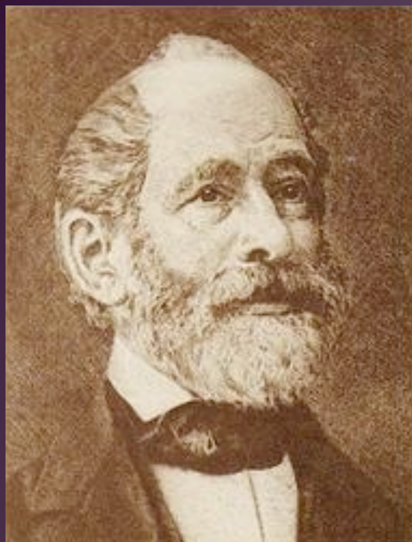

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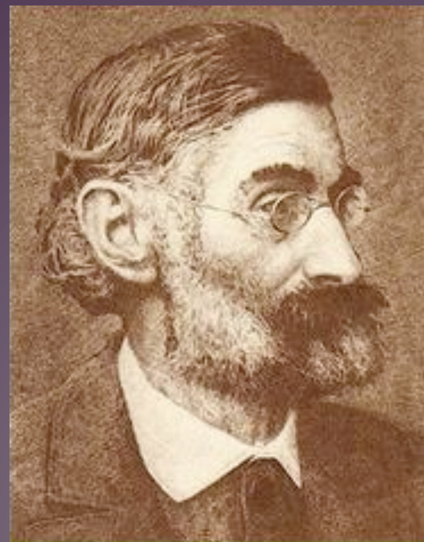

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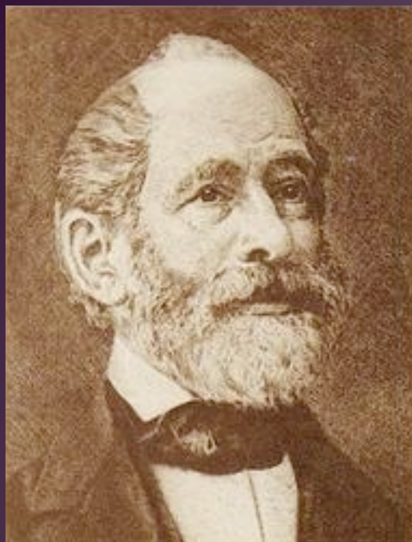
In 1872, they discovered how to make improved lenses and lens systems, based on an optical principle (the "Abbe Sine Condition).

Up until this time, microscope systems were made on a kind of "trial-and-error" basis.



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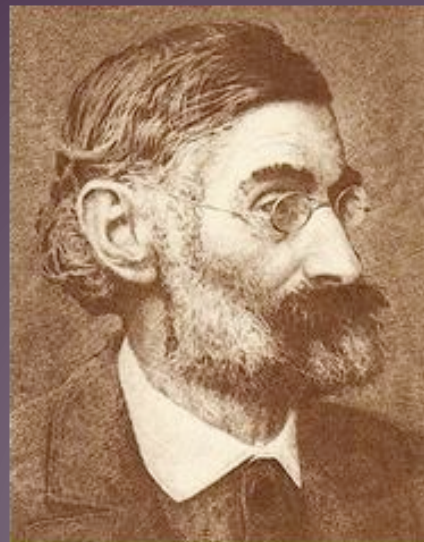

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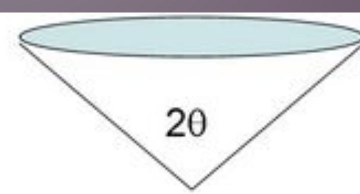
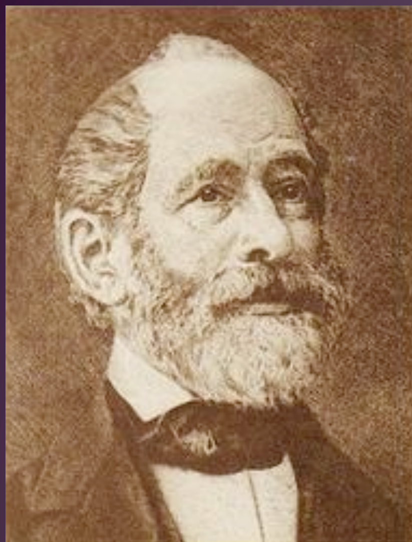
This discovery led to increased image resolution.



$$d = \frac{\lambda}{2n\sin(\theta)}$$



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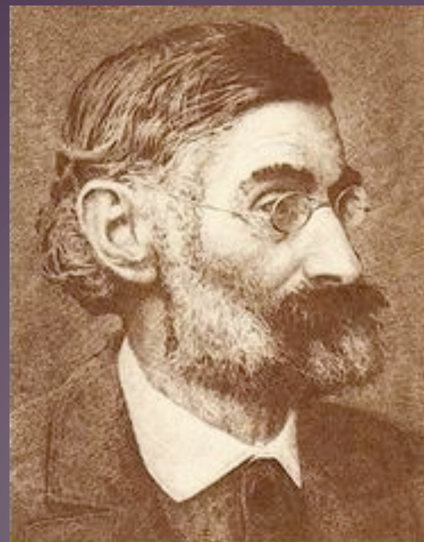

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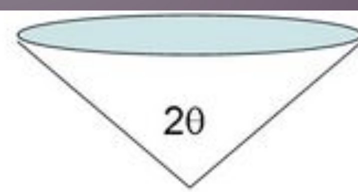
Otto Schott (1851-1935)

In the 19th century, German lens maker Carl Zeiss and German physicist Ernst Abbe worked together to form what may have been the first "high-tech" company to improve and manufacture sophisticated brass microscopes.

In 1872, they discovered how to make improved lenses and lens systems, based on an optical principle (the "Abbe Sine Condition").

This discovery led to increased image resolution.



$$d = \frac{\lambda}{2n\sin(\theta)}$$

In 1884, German glass chemist Otto Schott joined Zeiss and Abbe.


Otto Schott (1851-1935)

Schott developed a variety of glasses with different optical and thermal properties, including a lithium-based glass that he used to make lenses.

When used in combination with other lenses with different refractive indexes, the resolution of the images greatly increased.

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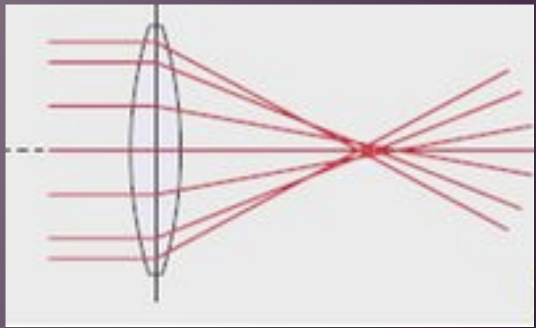

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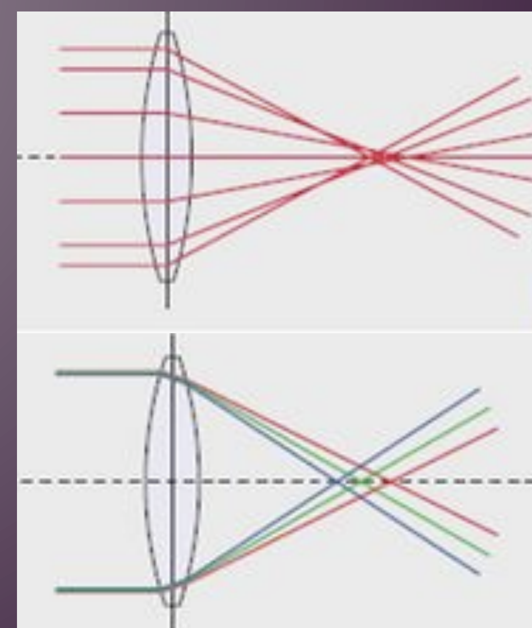
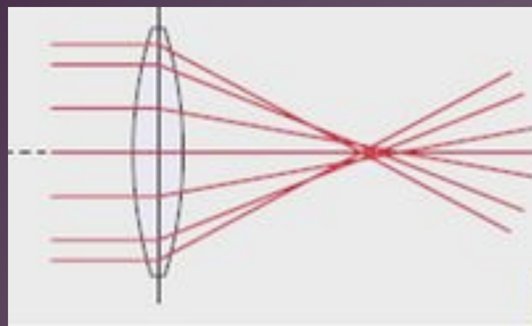
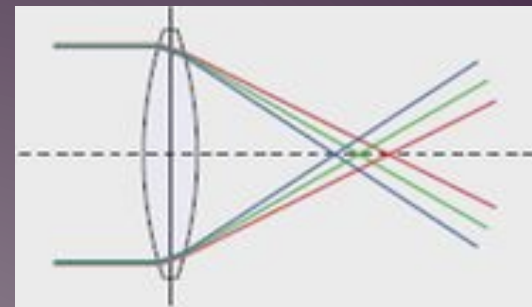
and

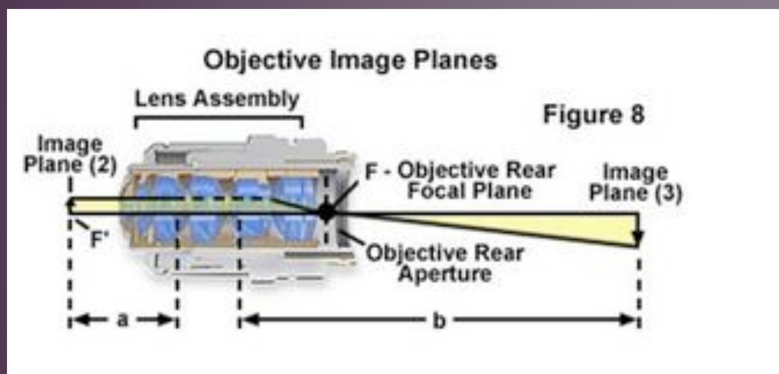
CHROMATIC ABERRATION:

Since different wavelengths of light are refracted at different angles, false colors appear in the image.









Correcting these defects vastly improved the ability of the MICROSCOPE (and other optical instruments) to collect more light, magnify to greater powers, and resolve images with much greater clarity than ever before.

THE SCIENCE OF MICROSCOPY PUSHED LIGHT TO NEW LIMITS, OPENING THE DOOR FOR MANY DISCOVERIES AND ADVANCEMENTS IN SCIENCE, PARTICULARLY THE LIFE SCIENCES.

II. FURTHER ADVANCEMENTS IN MICROSCOPY,

PUSHING LIGHT TO EVEN GREATER LIMITS.

FRITZ ZERNIKE (1888-1966), A DUTCH PHYSICIST

Developed a technique for enhancing image quality of a biological specimen WITHOUT STAINING.

He did this by illuminating transparent specimens with light of varying phase shifts.

THIS TECHNIQUE BECAME KNOWN AS

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PHASE CONTRAST MICROSCOPY

Using the interference between a reference beam of fixed phase and a beam transmitted through the sample, whose phase is shifted by an amount depending on the local refractive index of the sample.

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This is a phase contrast image of an epithelial cheek cell.

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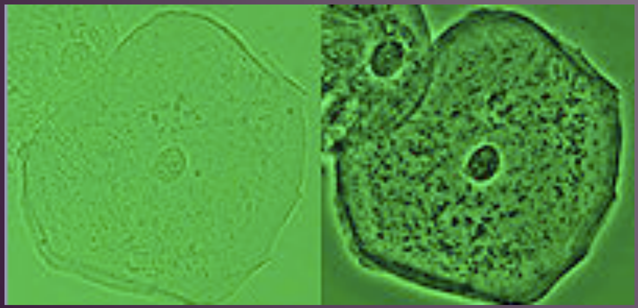

Epithelial cell in brightfield (BF) using a Plan Fluor 40x lens (NA 0.75) (left) and with phase contrast using a DL Plan Achromat 40x (NA 0.65) (right). A green interference filter is used for both images.

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PHASE CONTRAST MICROSCOPY

Since staining a biological specimen was necessary in ordinary optical microscopy, biologists were limited to studying cellular specimens that may be significantly altered, or even destroyed.

Phase Contrast Microscopy made it possible to study live, unaltered specimens in real time. Cellular mitosis and other cellular transitions could be observed, leading to breakthroughs in the life sciences.

This technique became so valuable that Zernike was awarded the Nobel Prize in 1953.

FLUORESCENCE MICROSCOPY

If a point of interest in a specimen is labeled with a fluorescent molecule (fluorophore), then illuminated with light of a specific wavelength, this light is absorbed by the fluorophore. It then emits a slightly longer wavelength, and this light can be separated out by filtering the illumination light.
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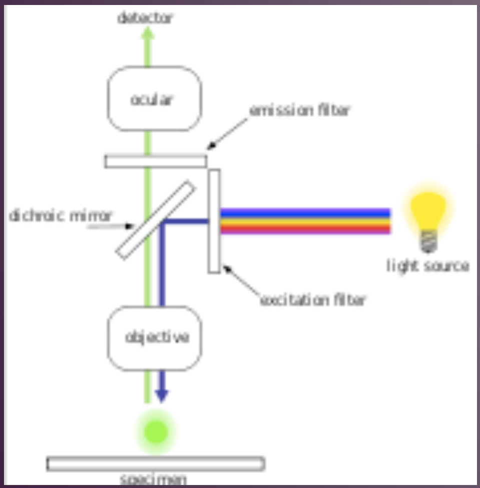

This is a simplified diagram of a FLUORESCENCE MICROSCOPE.

It can result in greatly-enhanced imaging of biological specimens even down to molecular scale.

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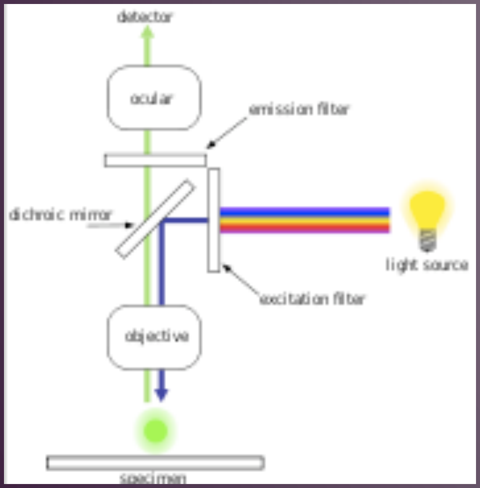

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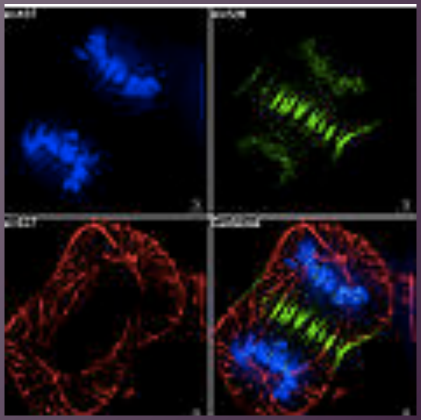

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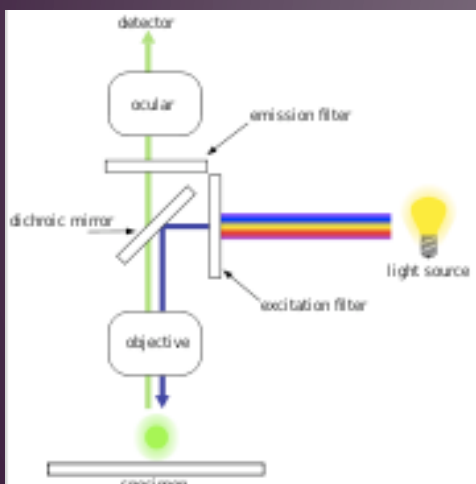

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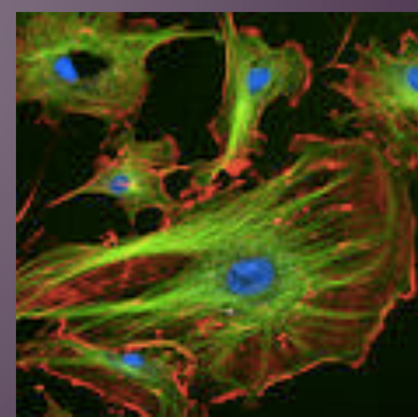

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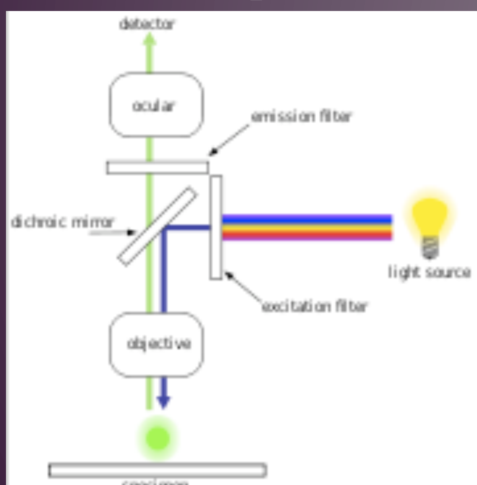

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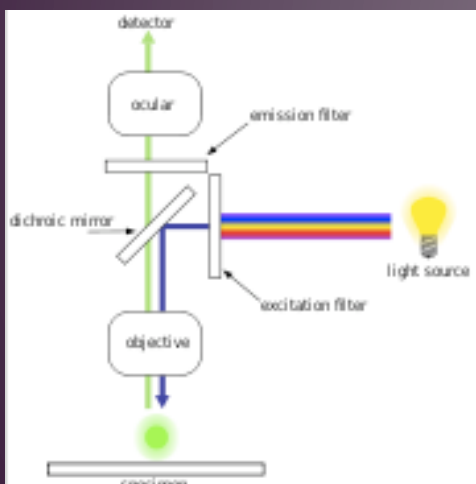

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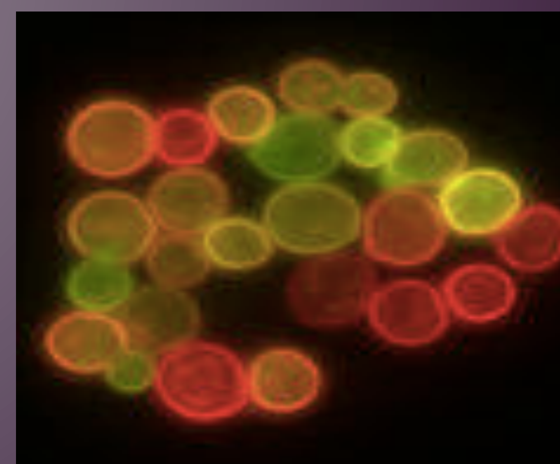

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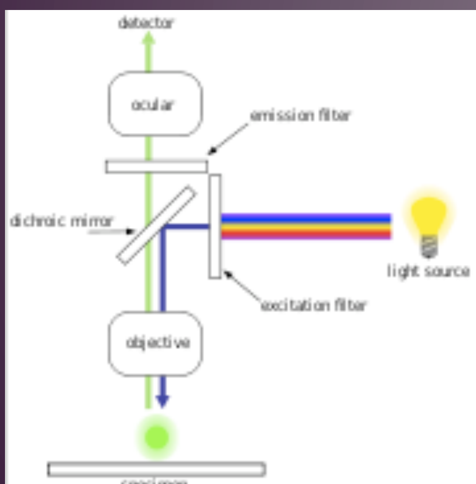

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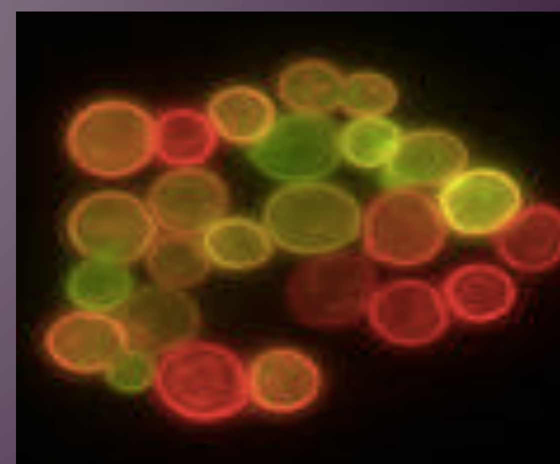

THIS TECHNIQUE WOULD LEAD TO THE DEVELOPMENT OF THE NEXT GENERATION OF IMAGING, AND BRING MICROSCOPY TO A NEW LEVEL.

III. LASERS MEET MICROSCOPY,

ENTER APPLIED QUANTUM MECHANICS

WITH THE DEVELOPMENT OF THE LASER IN THE 1960's,
MICROSCOPY WOULD TAKE A GIANT LEAP (. . .a quantum leap?)

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LASERS , using coherent, collimated, frequency-tunable pinpoint light sources, could now be used to SCAN very specific areas of a specimen, and even use interference (remember wave superposition) to produce 3-D imaging and look INTO a specimen!

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THE APPLICATION OF LASER SCANNING APPLIED TO MICROSCOPY IS CALLED

CONFOCAL MICROSCOPY

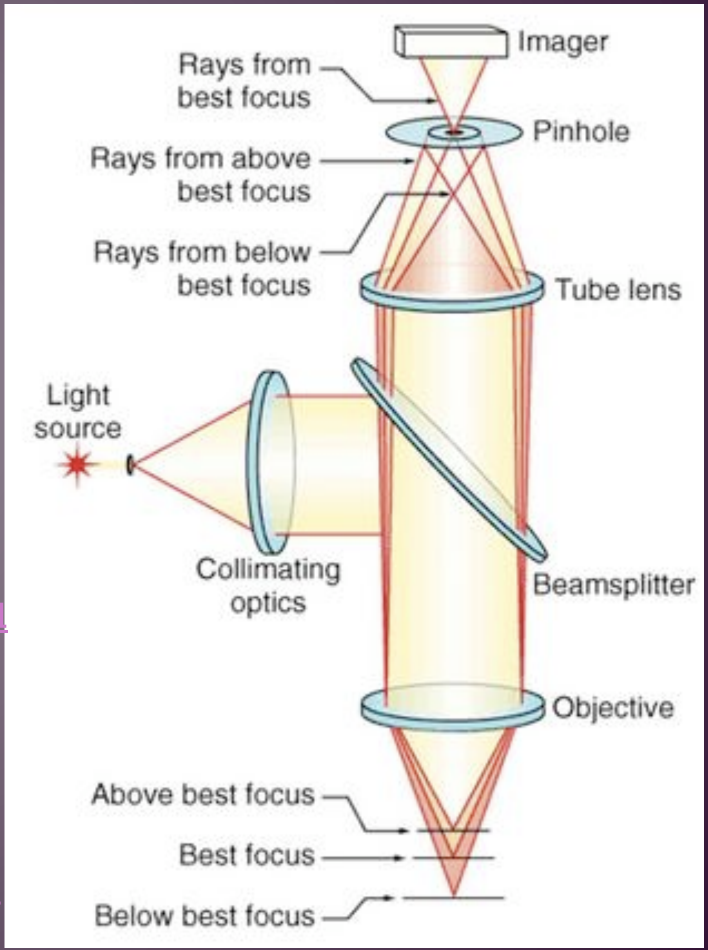
CONFOCAL MICROSCOPY

By using a pinpoint aperture and a scanning beam of coherent light, extreme depth-of-field imagery of a precise area can be achieved, a great advancement over widefield scattering.

CONFOCAL MICROSCOPY

The principle of CONFOCAL IMAGING was
First developed in 1957 by Marvin Minsky.

In a confocal laser scanning microscope, a laser beam passes through a light source aperture and then is focused by an objective lens into a small (ideally diffraction limited) focal volume within or on the surface of a specimen. In biological applications especially, the specimen may be fluorescent. Scattered and reflected laser light as well as fluorescent light from the illuminated spot is then re-collected by the objective lens. A beam splitter separates off some portion of the light into the detection apparatus, which in fluorescence confocal microscopy will also have a filter that selectively passes the fluorescent wavelengths. After passing a *pinhole, the light intensity is detected by a photodetection device (usually a photomultiplier tube (PMT) or avalanche photodiode), transforming the light signal into an electrical one that is recorded by a computer*



CONFOCAL MICROSCOPY

THE RESULT IS HIGH-DEFINITION IMAGERY ON A MOLECULAR LEVEL, WITH MANY APPLICATIONS RANGING FROM CELL BIOLOGY AND GENETICS TO MICROBIOLOGY, DEVELOPMENTAL BIOLOGY AND THE EVALUATION OF PATHOLOGICAL CONDITIONS, INCLUDING CORNEAL DISEASE.

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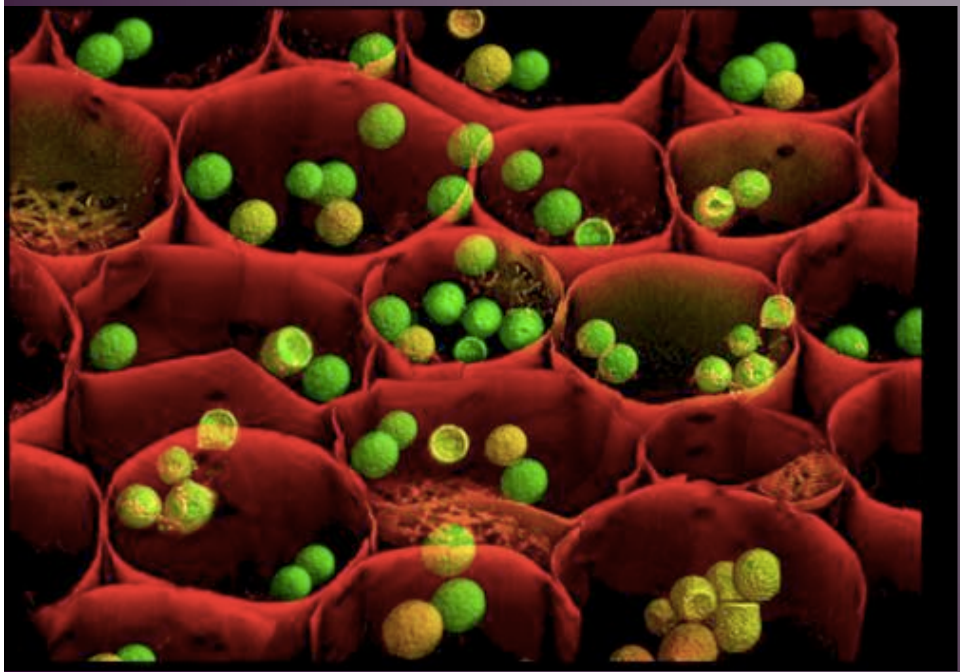

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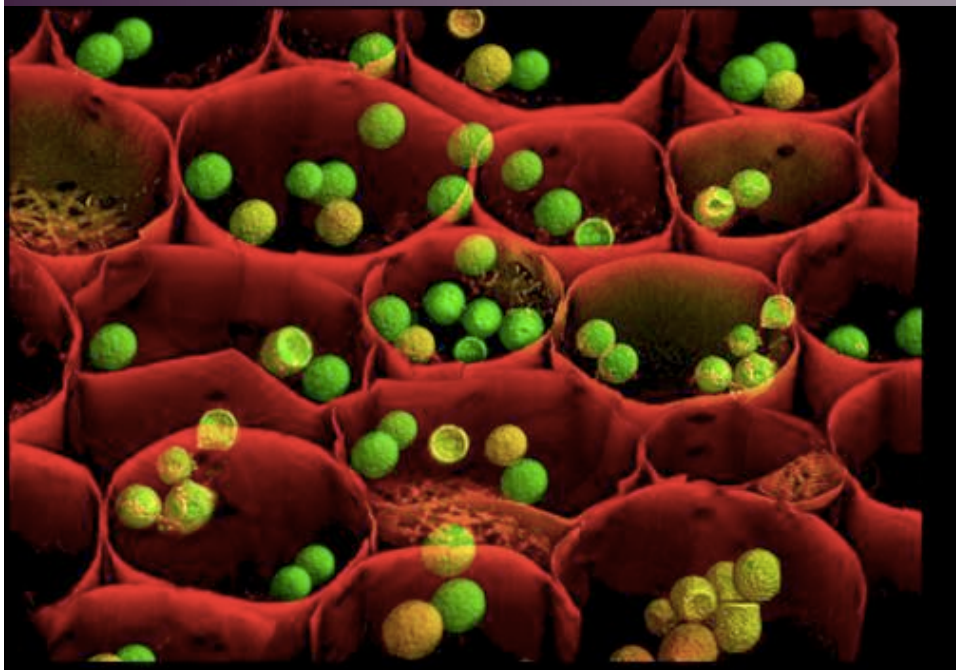

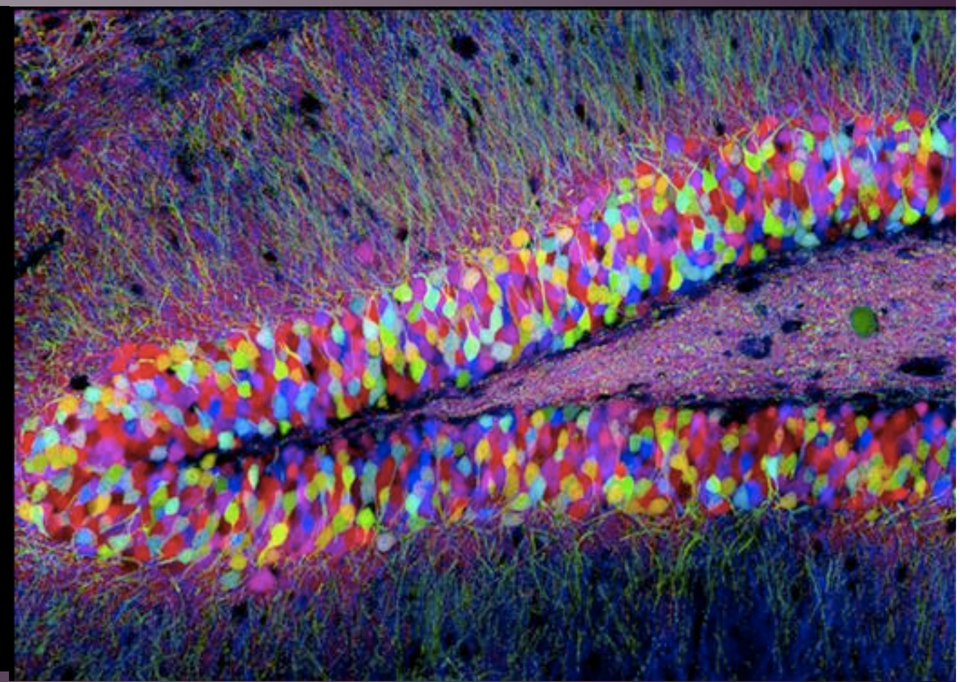

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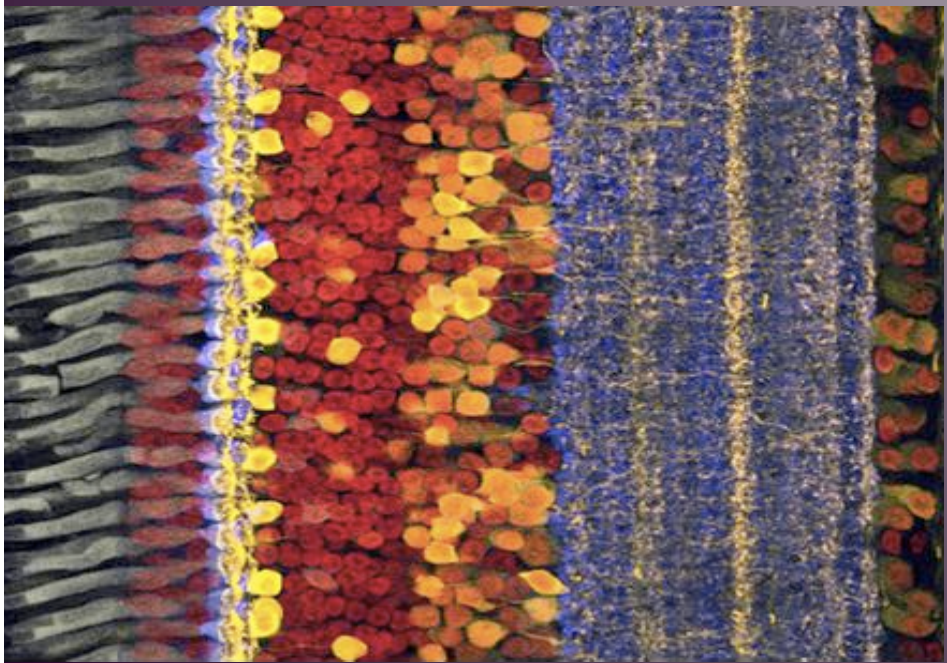

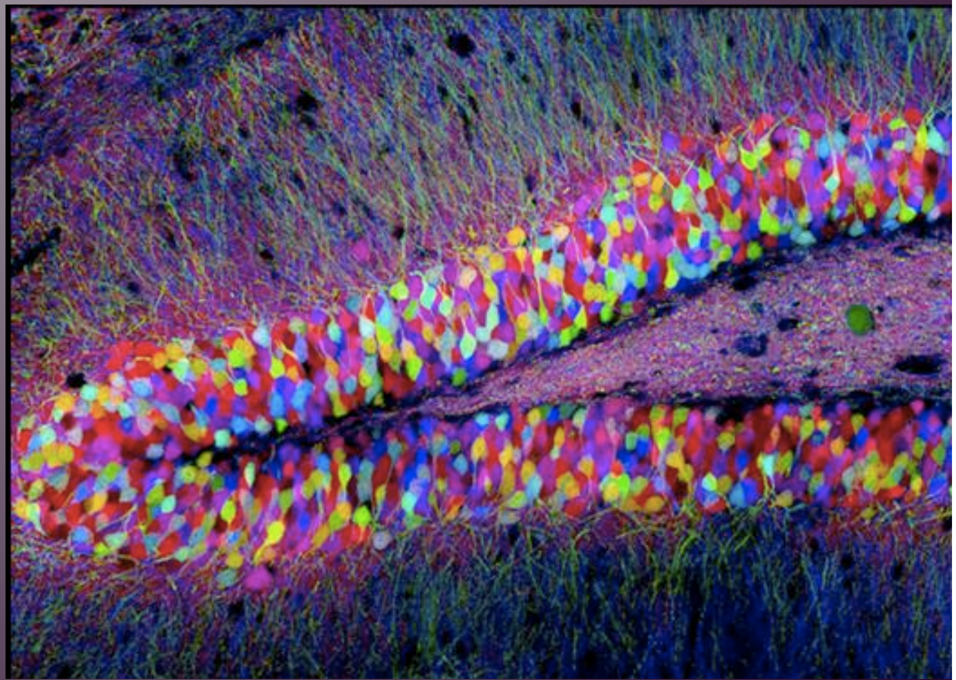

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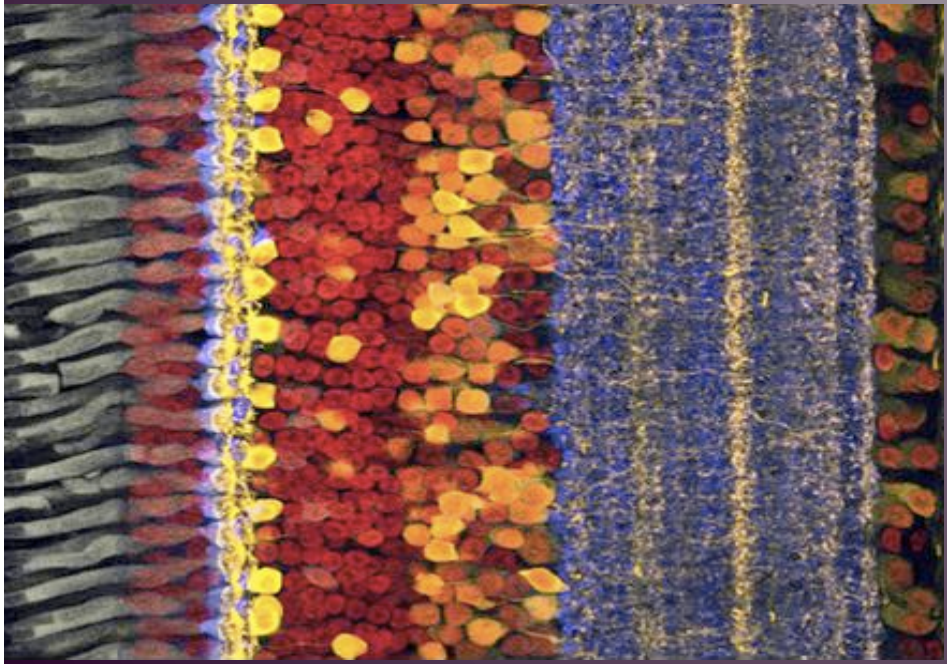

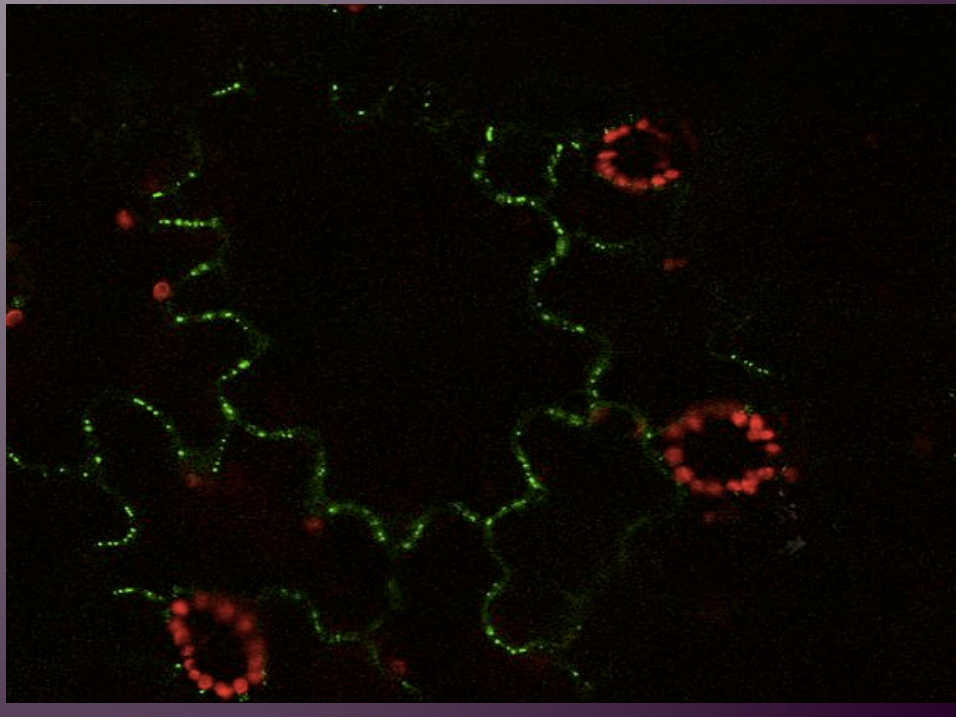

IV. NONLINEAR MICROSCOPY

USING INDIVIDUAL PHOTONS TO PROBE DEEPER INTO MATTER

As much as CONFOCAL MICROSCOPY has advanced optical imaging and biological science, it does have drawbacks and limitations.

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SCATTERING IN THICK SAMPLES: Deep layers are hard to view.

NEED FOR STAINING: Some specimens may be altered, damaged or destroyed.

THIS LEADS TO THE DEVELOPMENT OF A NEW BRANCH OF MICROSCOPY:

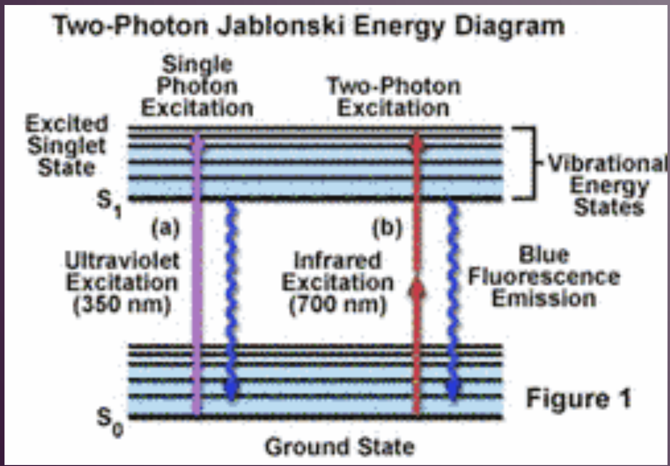
NONLINEAR MICROSCOPY

INCOHERENT

PRODUCES A SIGNAL WHOSE OPTICAL PHASE IS RANDOM AND WHOSE POWER IS PROPORTIONAL TO THE CONCENTRATION OF THE RADIATING MOLECULES.

EXAMPLE:

"TWO PHOTON EXCITED FLUORESCENCE" (TPEF)

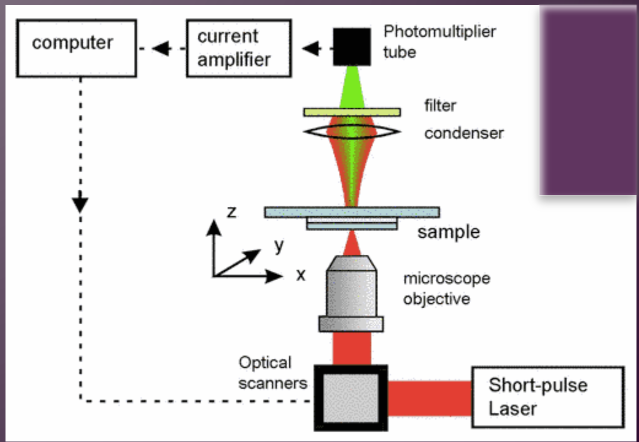


COHERENT

Coherent microscopes produce optical signals whose phase is rigorously prescribed by a variety of factors including the excitation light phase and the geometric distribution of the radiating molecules. Coherent signal power is proportional to the concentration of radiating molecules squared. Nonlinear versions of coherent microscopy are based on the *simultaneous* scattering of two or more photons.

EXAMPLES:

SECOND HARMONIC GENERATION (SHG)
COHERENT ANTI-STOKES RAMAN SCATTERING (CARS)



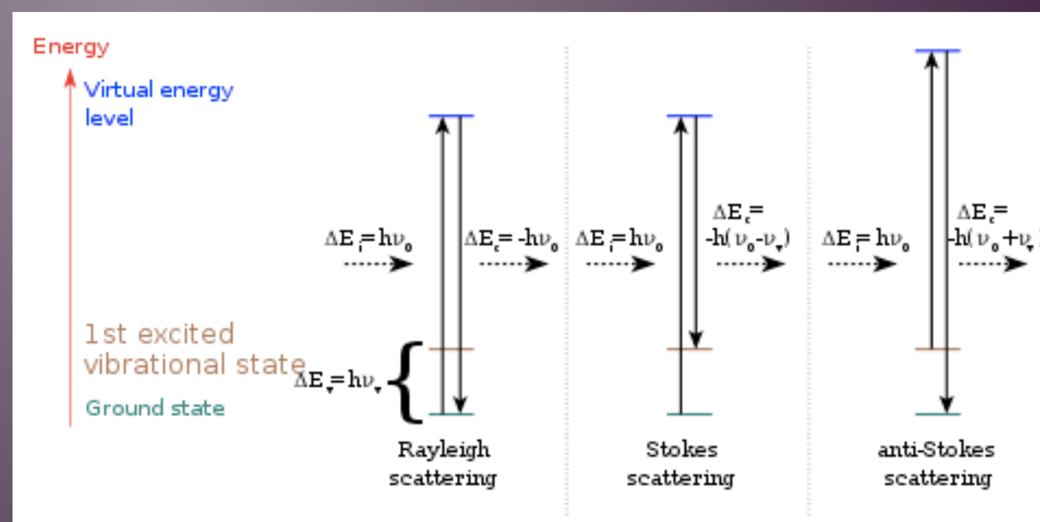
NONLINEAR MICROSCOPY

COHERENT ANTI-STOKES RAMAN SCATTERING (CARS)

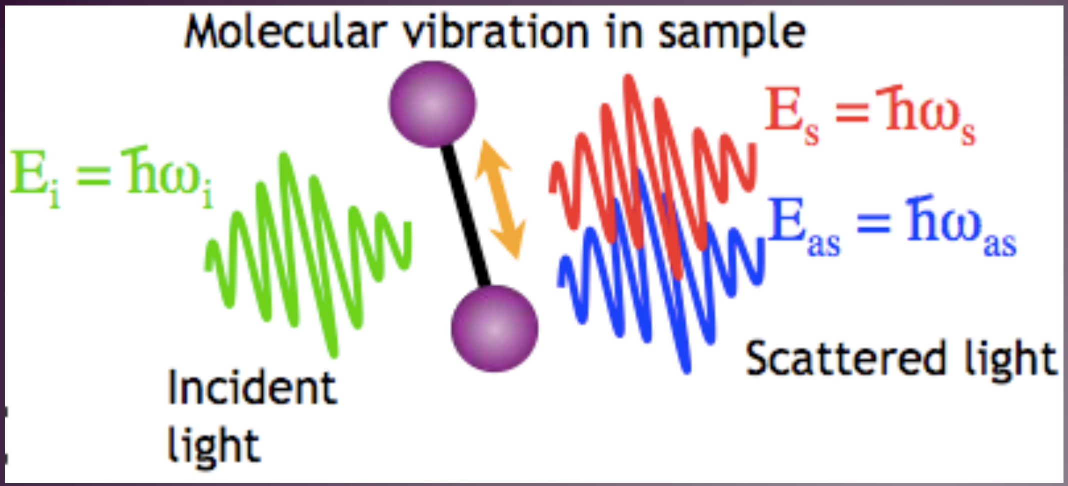
In 1928, Indian Physicist C.V. Raman discovered that when light is scattered from an atom or molecule, most photons are elastically scattered (Rayleigh scattering), such that the scattered photons have the same energy (frequency) and wavelength as the incident photons. However, a small fraction of the scattered light (approximately 1 in 10 million photons) is scattered by an excitation, with the scattered photons having a frequency different from, and usually lower than, the frequency of the incident photons.

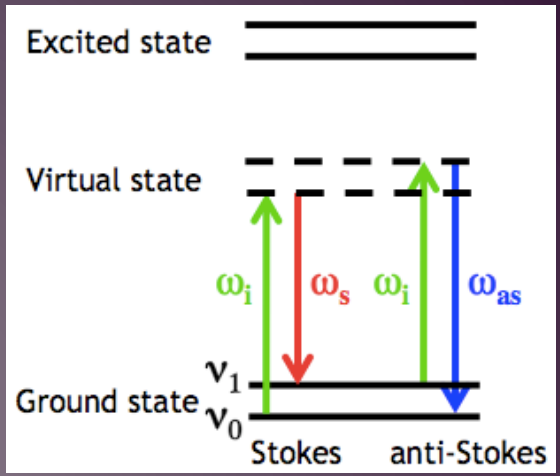
C.V. Raman
(1888-1970)

The different possibilities of visual light scattering, Rayleigh (no Raman Effect), Stokes scattering (molecule absorbs energy), and anti-Stoles scattering (molecule loses energy).



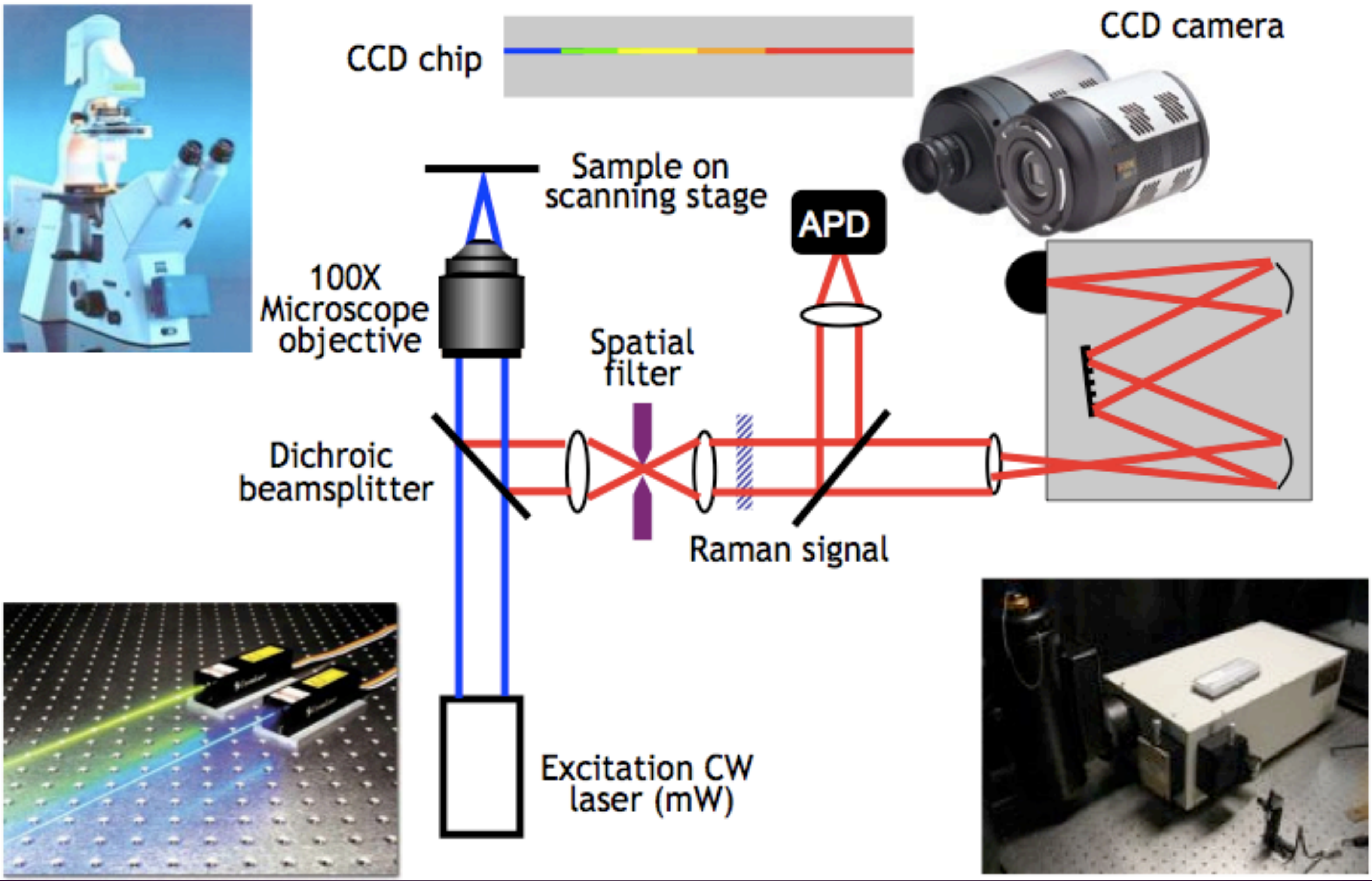
Raman scattering is the interaction of photons and intrinsic molecular bonds.





The Raman effect occurs when light impinges upon a molecule and interacts with the electron cloud and the bonds of that molecule. The incident photon excites the molecule into a virtual state. For the spontaneous Raman effect, the molecule will be excited from the ground state to a virtual energy state, and relax into a vibrational excited state. Two series of lines exist around this central vibrational transition. They correspond to the complimentary rotational transition. Anti-Stokes lines correspond to rotational relaxation whereas Stokes lines correspond to rotational excitation.

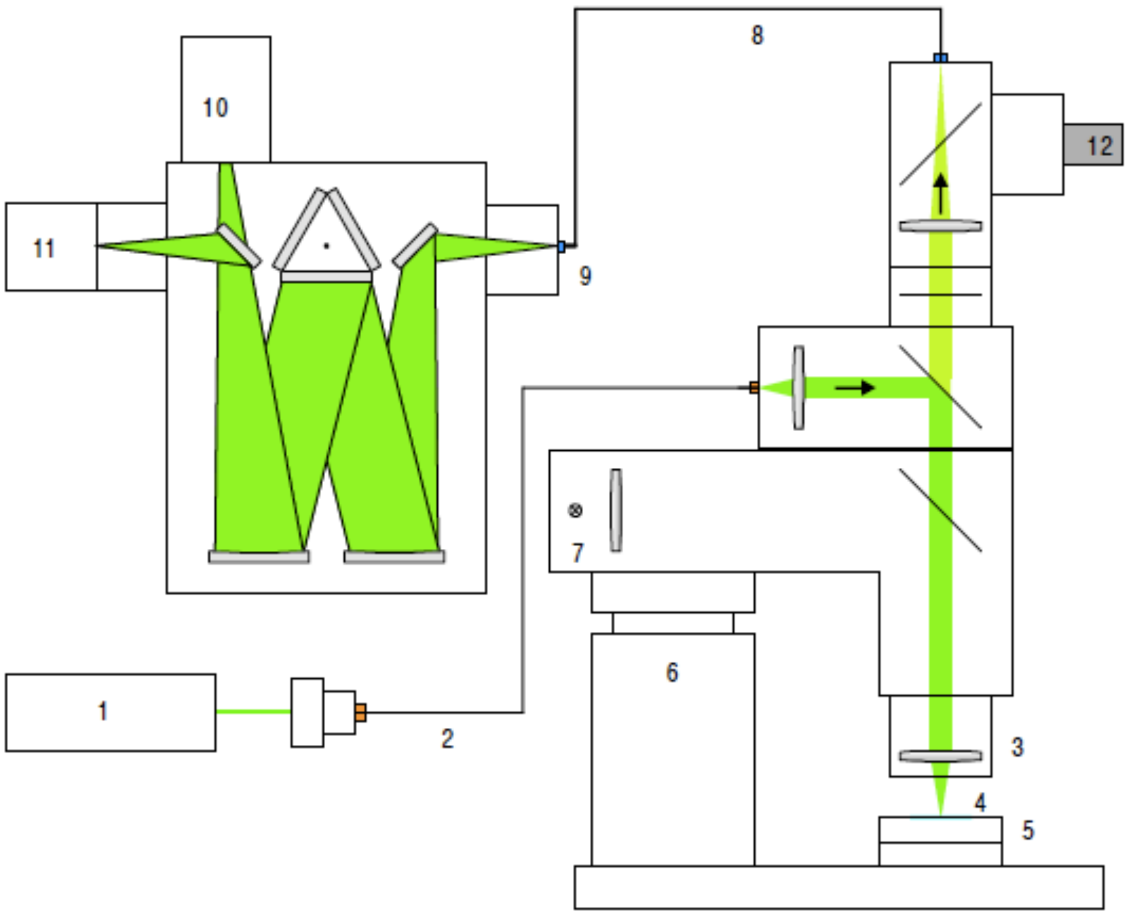
Confocal Raman microscope for microspectroscopy and imaging



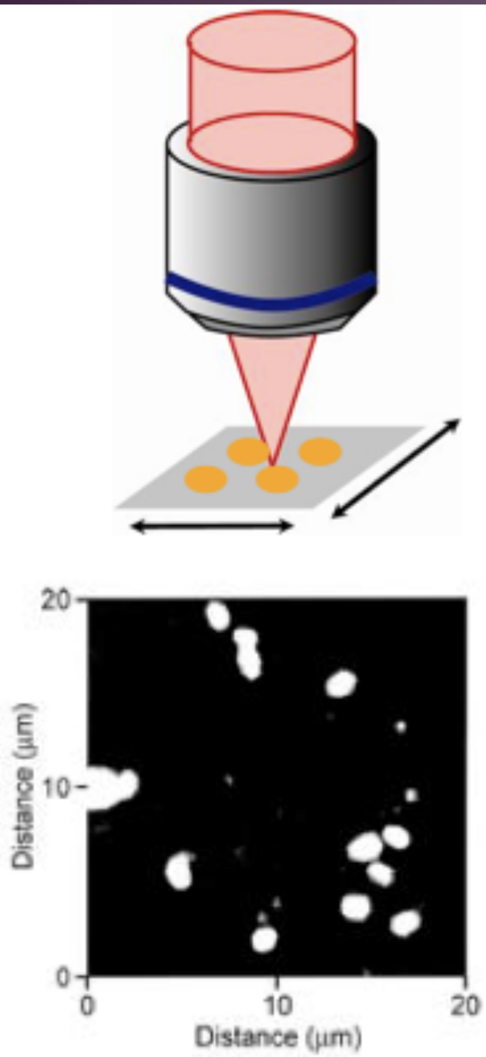
Confocal Raman microscope for microspectroscopy and imaging

How it works.

1. laser
2. single mode fiber
3. objective
4. sample
5. scan unit
6. z-stage for focusing
7. white light source
   for Köhler illumination
8. multi mode fiber
9. fiber entrance of spectrograph
10. CCD camera
11. APD detector
12. colour video camera

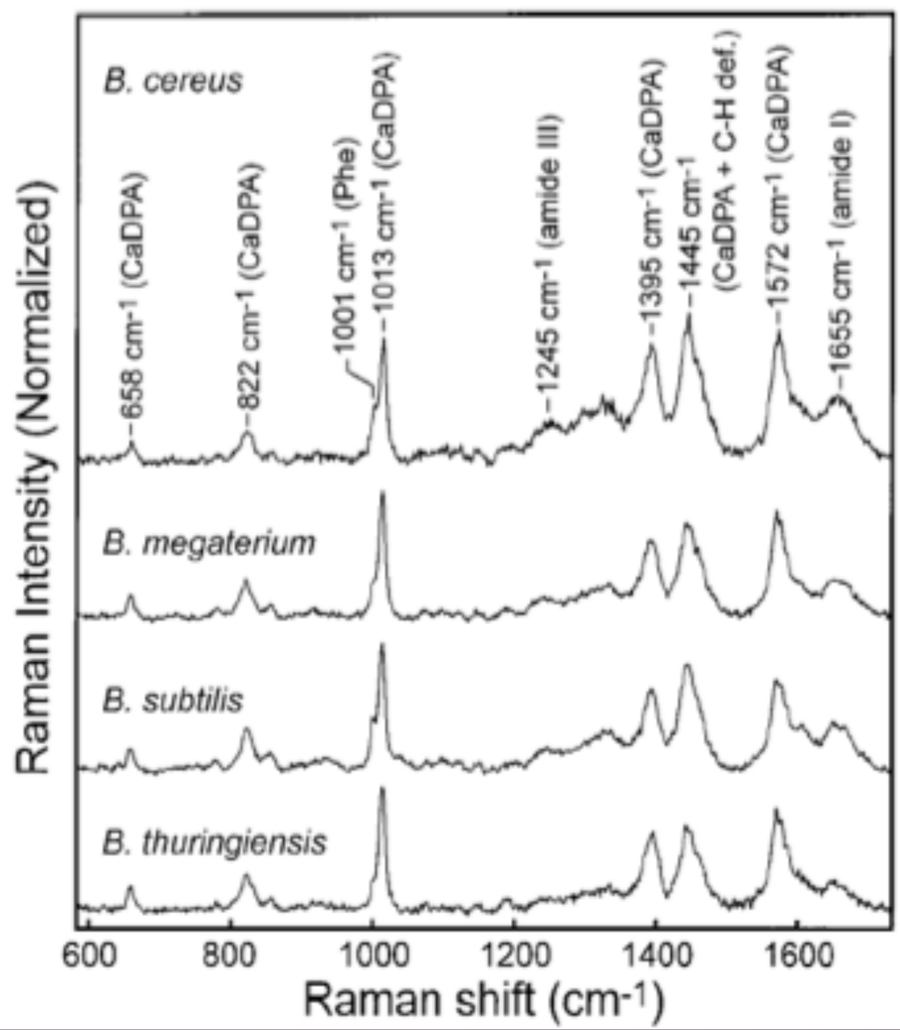


Conventional single cell Raman spectroscopy is usually performed on surfaces

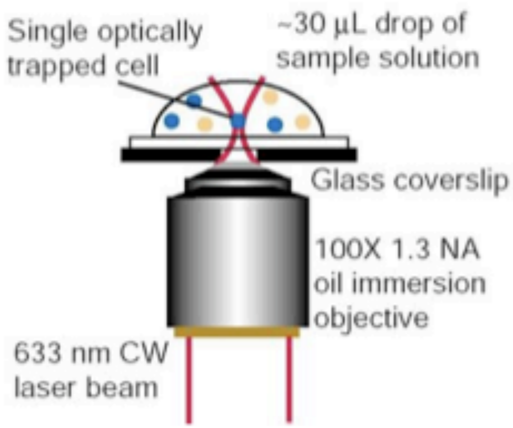


Spores dried on a surface

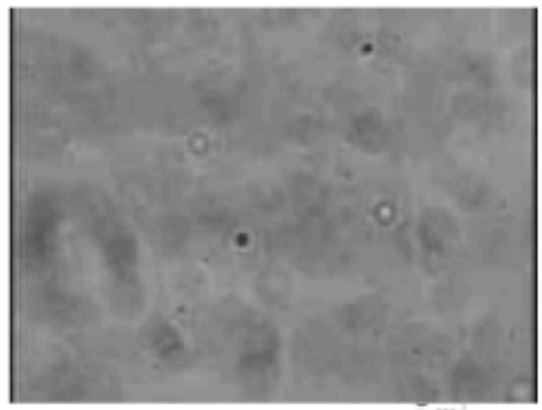
Esposito et. al., Appl. Spec. 57 (7) 868 (2003)

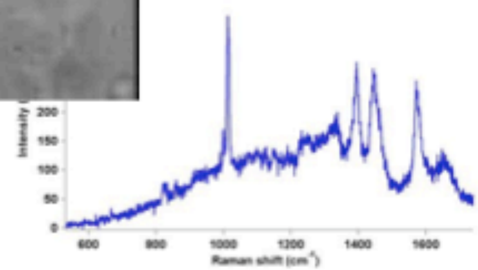


Optical trapping combined with Raman spectroscopy simplifies the analysis of single cells



Optically trapped spore

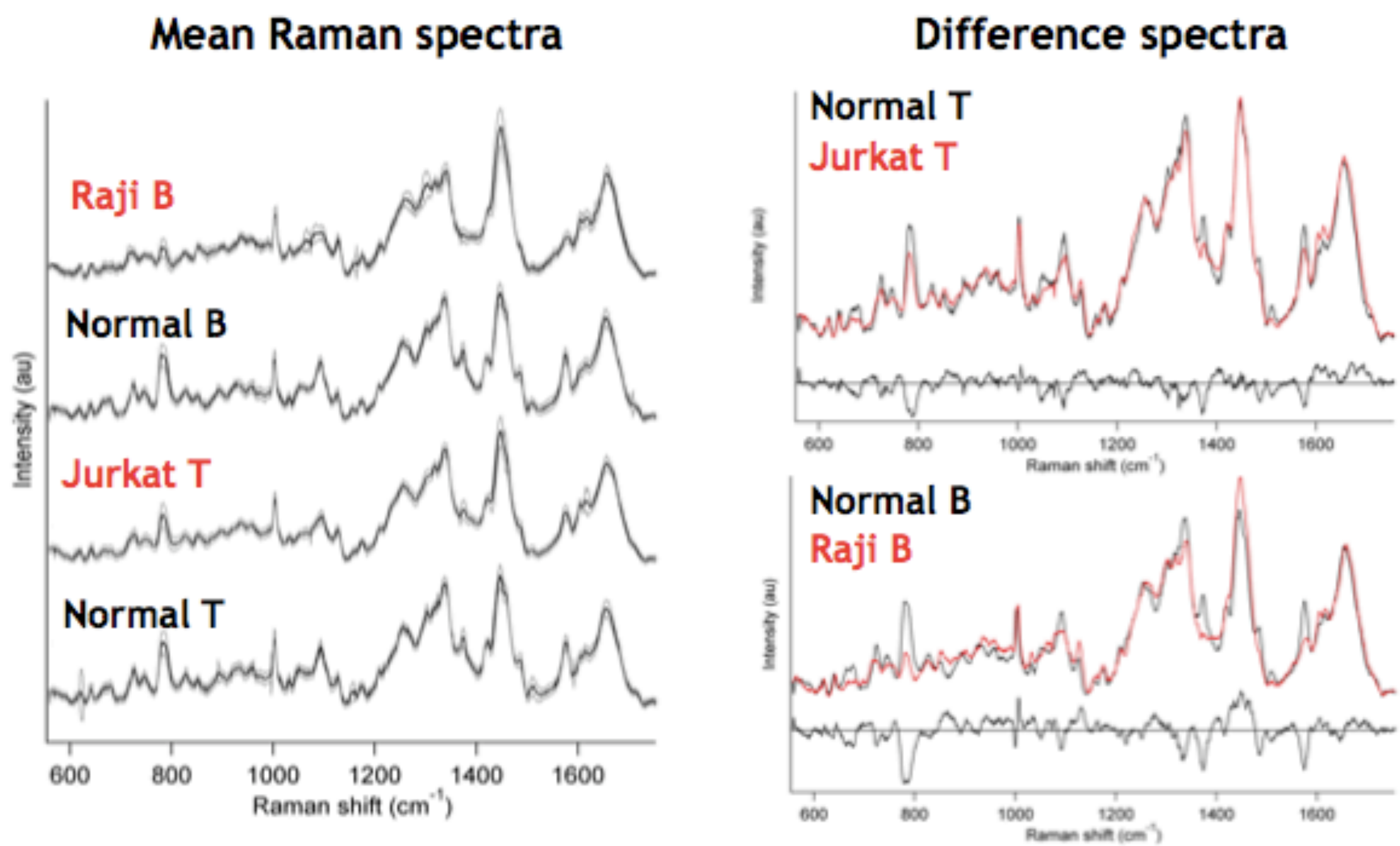




- Advantages:
  - Rapid sampling of many particles in solution
  - Reduces background signals from surfaces
  - Maximizes Raman signals
  - Enables manipulation and sorting of particles

Chan et. al., Analytical Chemistry, 76 599 (2004)

Pediatric leukemia: Normal and malignant cells can be discriminated by their Raman fingerprint



Reproducible within group spectra

Cancer spectral markers

Chan et. al., Biophysical Journal 90 648-656 (2006)

Advantages and limitations of spontaneous Raman spectroscopy/imaging:

Advantages

- Minimally invasive technique
- Non-photobleaching signal for live cell studies
- Works under different conditions (temperatures and pressures)
- Chemical imaging without exogenous tags
- Works with different wavelengths

Limitations

- Fluorescence interference
- Limited spatial resolution
- Weak signal – long integration times

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1 in 10^8 incident photons are Raman scattered

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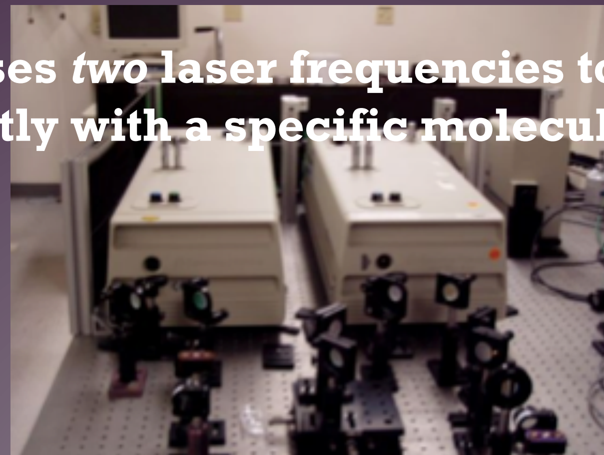
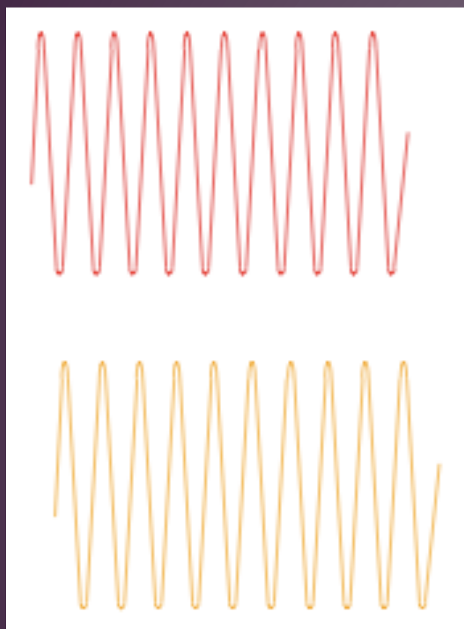
SO, WHY DEVELOP "CARS"?

(Coherent Anti-Stokes Raman Scattering Microscopy)

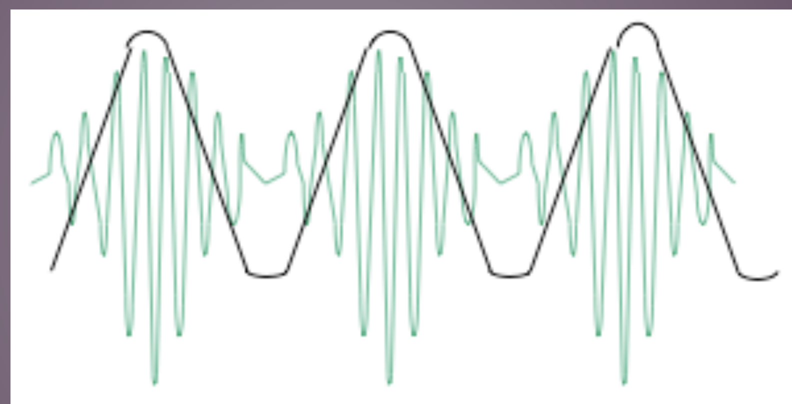
CARS uses *two* laser frequencies to interact resonantly with a specific molecular vibration



f_{pump}

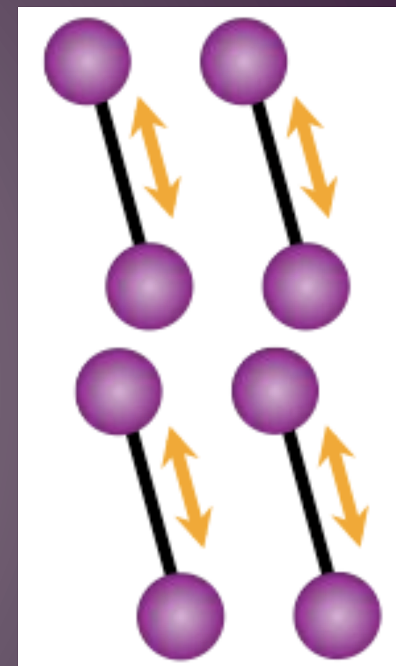


f_{Stokes}



Beating at $f_{pump} - f_{Stokes}$

$f_{vib} = f_{pump} - f_{Stokes}$



Coherent vibration of specific molecules resonant at f_{vib}

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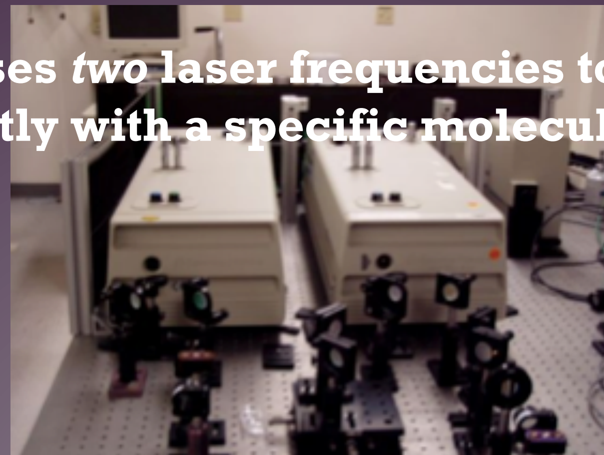

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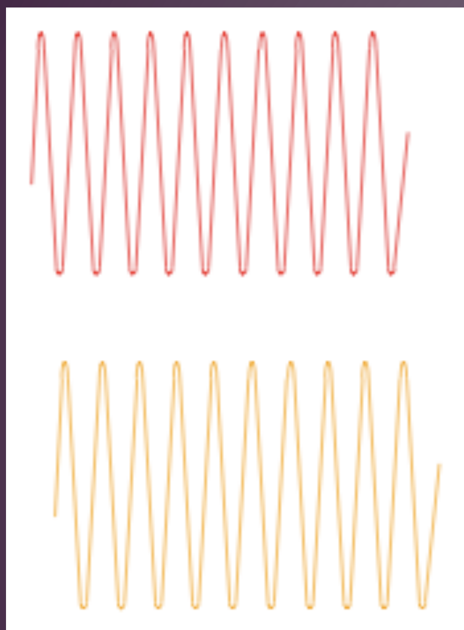

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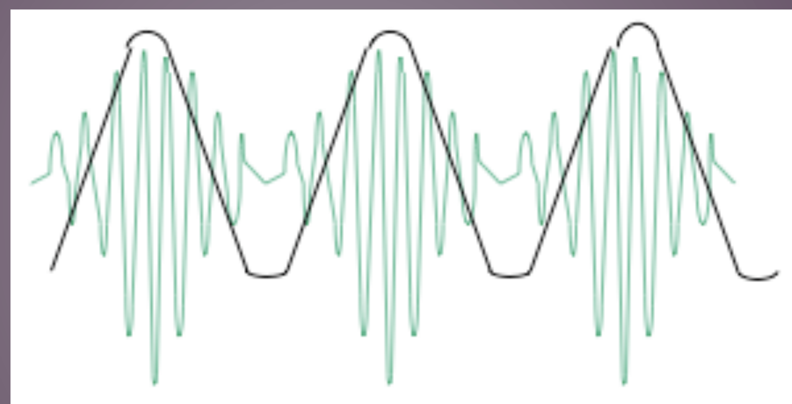

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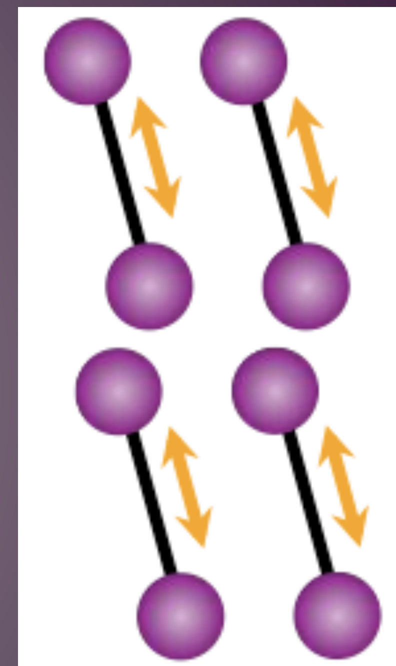

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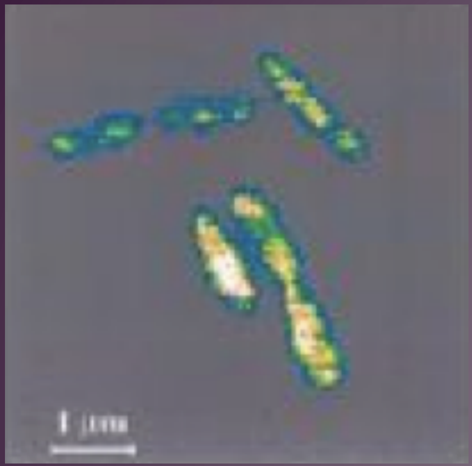
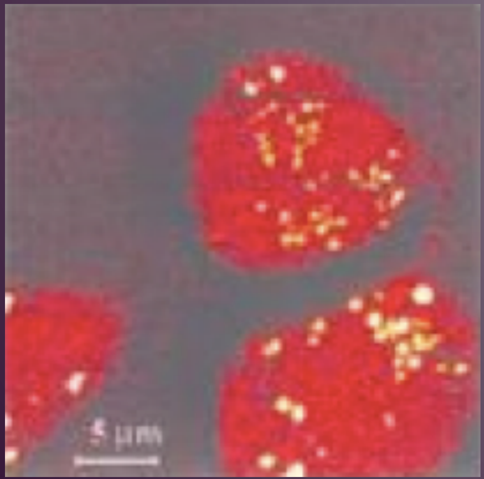
THE RESULTS:

Examples of live cell imaging



Unstained live bacterial cells. Signal due to cell membranes.



Unstained live HeLa cells. Bright spots due to mitochondria.

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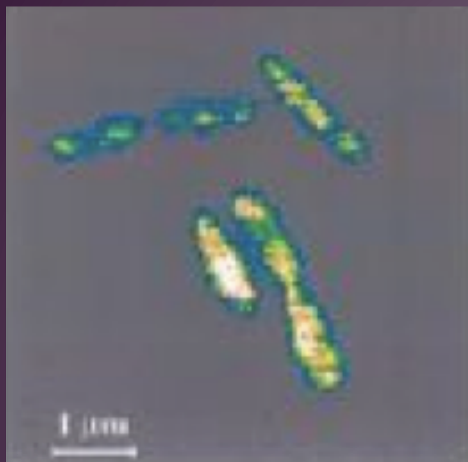

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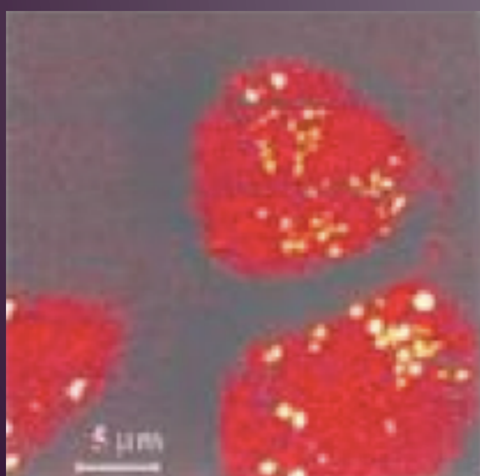

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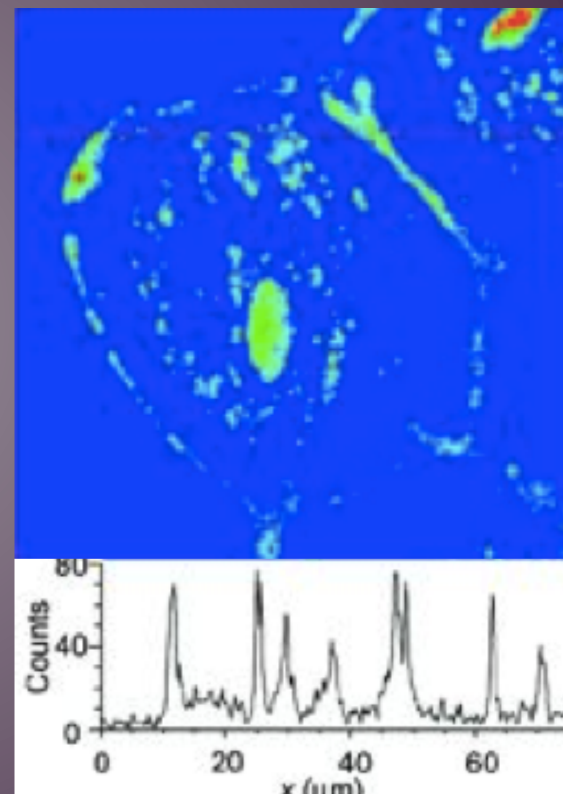
CARS image of protein, nucleic acid in a single cell

Unstained live human epithelial cell

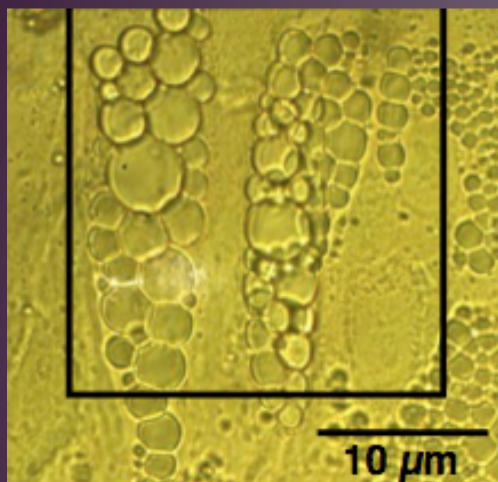


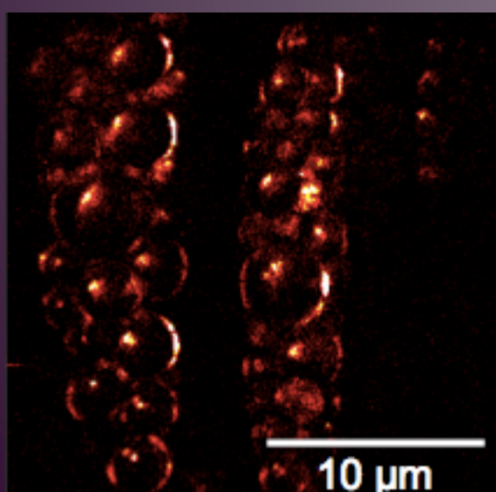
Laser powers - 2 and 1 mW, tuned to 1570 cm^{-1} (protein, nucleic acid) image acquired in 8 min, smallest feature <300 nm

Cheng et. al., J. Phys. Chem. B. V105,1277 (2001)

Examples of live cell imaging

CARS image of MSC-derived adipocytes rich in lipid structures





Courtesy: Iwan Schie, Tyler Weeks, Gregory McNerney

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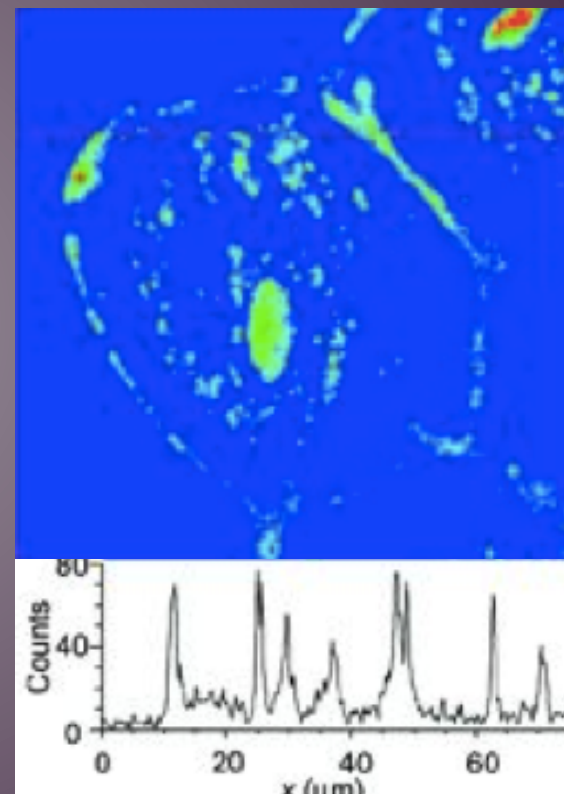

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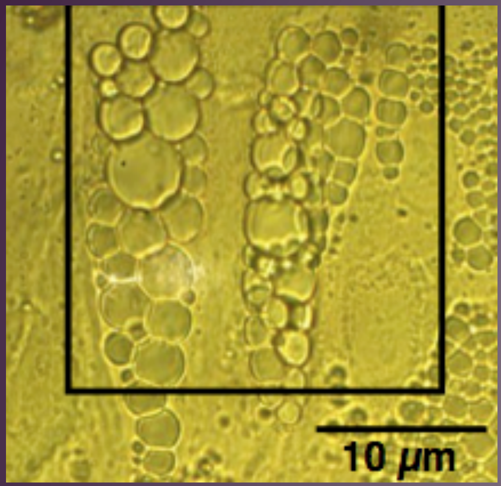

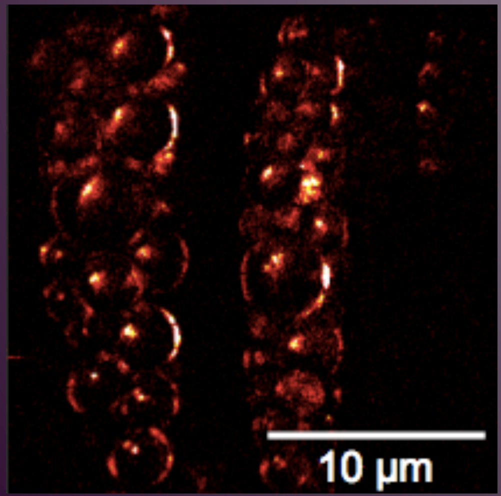

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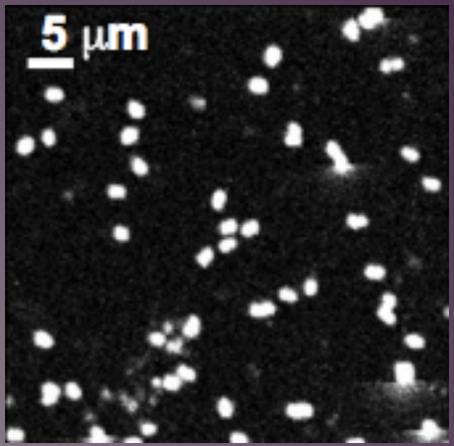
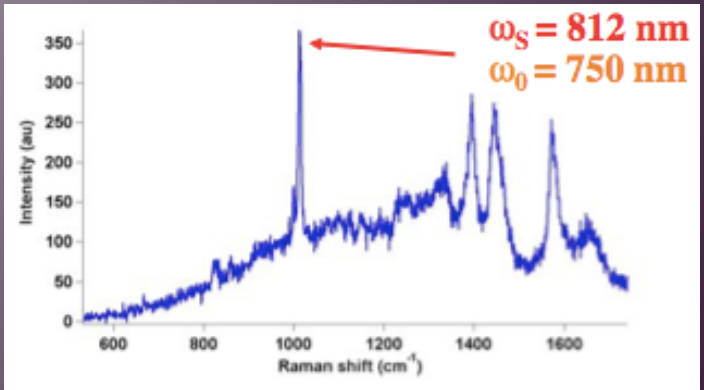
CARS imaging of bacterial spores



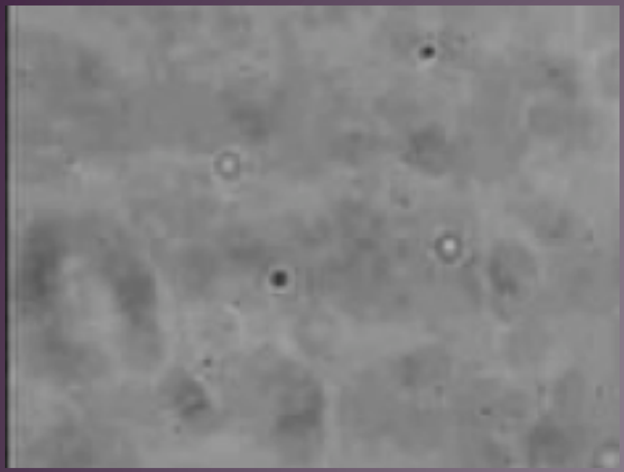
CARS image of spores on glass substrate



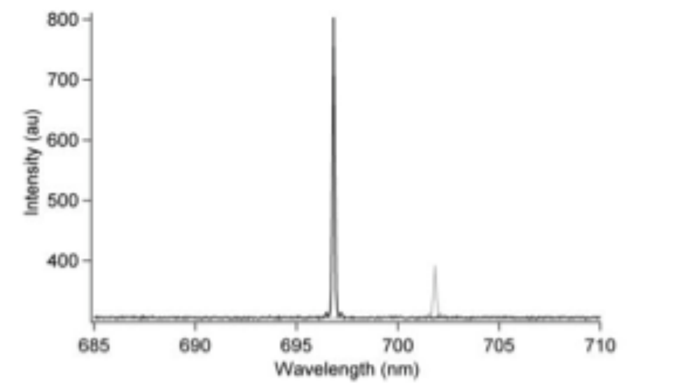
Raman spectrum of bacterial spore

CARS cytometry for rapid, label-less cancer cell detection and sorting

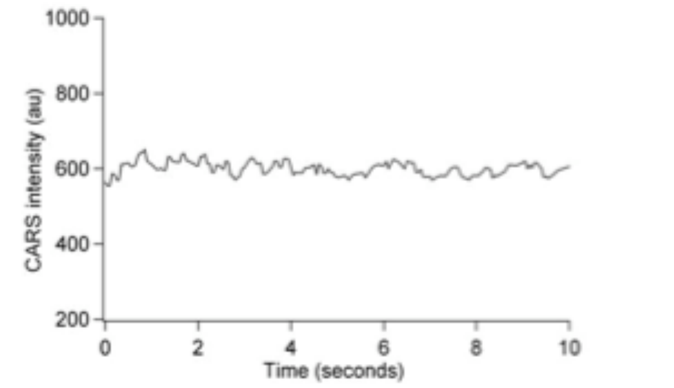
This is an example of how optical trapping can be applied with CARS for FASTER SPECTRAL ANALYSIS.



Trapped polystyrene bead using two CARS beams



CARS signal from a C=C bond



Microsecond temporal resolution

AS A POTENTIAL SOLUTION FOR FASTER CHEMICAL ANALYSIS OF CELLS, CARS TECHNIQUES CAN PROVIDE QUICKER AND MORE PRECISE DIAGNOSIS OF CANCER CELLS.

Chan et. al., IEEE J. Sel. Topics. Quant. Elec. V11 858 (2005)

ADVANTAGES OF USING CARS TECHNIQUES:

More sensitive (stronger signals) than spontaneous Raman microscopy – faster, more efficient imaging for real-time analysis

Contrast signal based on vibrational characteristics, no need for fluorescent tagging.

CARS signal is at high frequency (lower wavelength) – minimal fluorescence interference

Higher resolution

AND, NEW VARIATIONS ARE BEING DEVELOPED THAT WILL CONTINUE TO PUSH THE RESOLUTION LIMIT!!

HOWEVER, HIGHER RESOLUTION IMAGING OF VERY SMALL OBJECTS WILL HAVE TO DEAL WITH THE UNPREDICTABILITY OF MOTION AT A QUANTUM LEVEL. THIS MEANS EXTREMELY FAST PULSE LASERS AT EXTREMELY SHORT INTERVALS OF TIME, AS WAS JUST SEEN IN CARS IMAGING.

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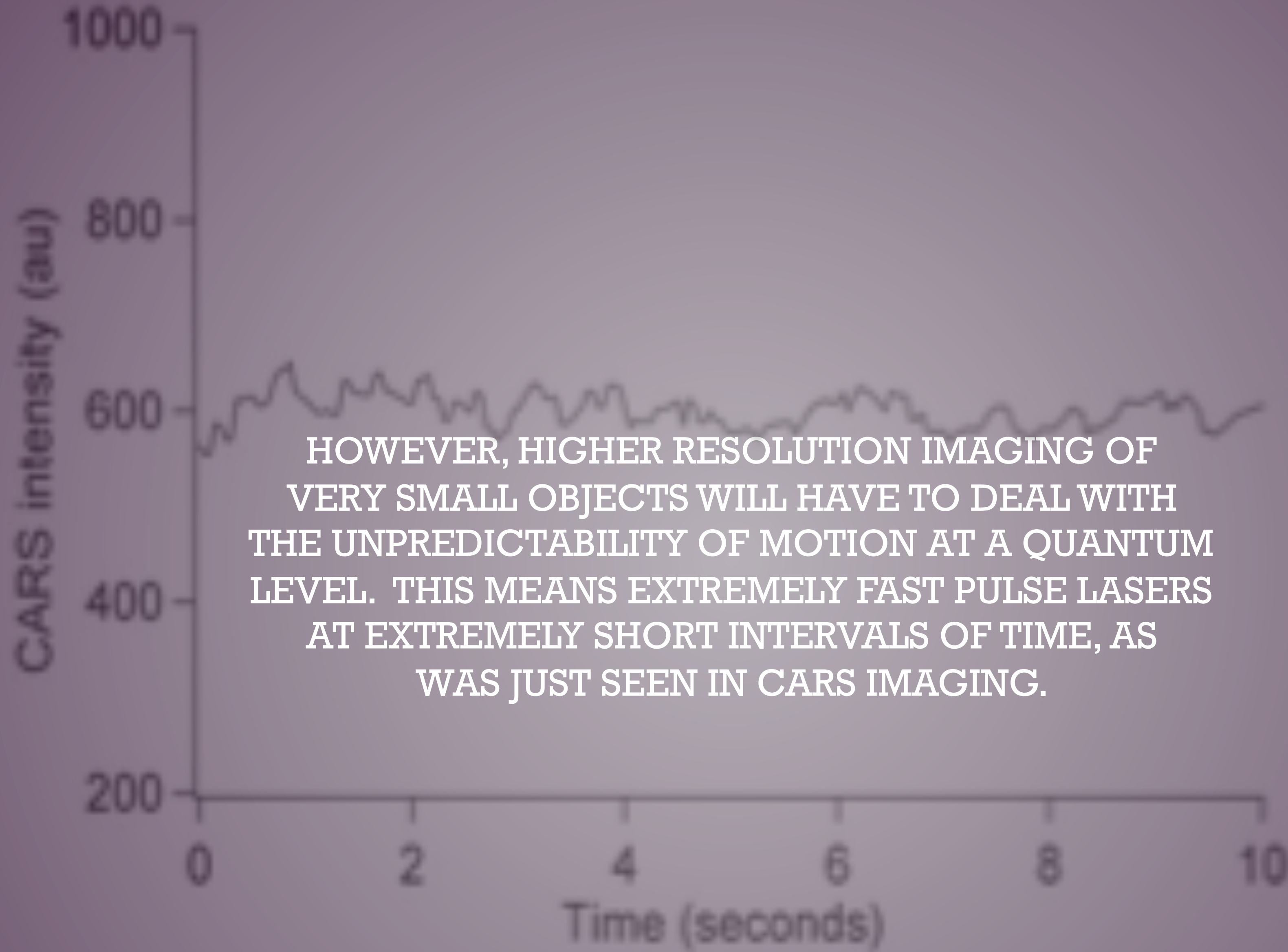


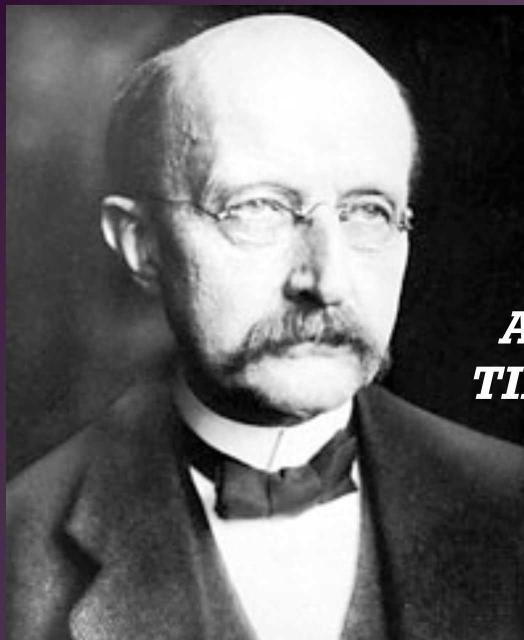
Microsecond temporal resolution

THIS BRINGS US TO THE QUESTION OF TIME,

IN PARTICULAR, EXTREMELY SHORT INTERVALS OF TIME.

THE WORLD AT THE QUANTUM LEVEL DOES ***NOT*** OPERATE ACCORDING TO THE SAME PHYSICAL PRINCIPLES WE ARE ACCUSTOMED TO AT THE MACROSCOPIC LEVEL.

SO, EXACTLY ***HOW SMALL*** AN INTERVAL OF TIME SEPARATES AND DEFINES THE BOUNDARY BETWEEN CLASSICAL AND QUANTUM PHYSICS?



***“PLANCK TIME”*, REPRESENTS A TIME *SHORTER* THAN THE SHORTEST AMOUNT OF TIME PHYSICS CAN REASON ABOUT IN A MEANINGFUL WAY.**

IT IS THE SHORTEST FUNDAMENTAL TIME.

$$t_P = \sqrt{\frac{\hbar G}{c^5}} \approx 5.39124(27) \times 10^{-44}\ \mathrm{s}$$

IN QUANTUM PHYSICS, THE SCALE OF EXPERIMENTAL TIMES IS SET BY THE FREQUENCIES OF OBJECTS IN THE QUANTUM REGIME - -

MOLECULAR VIBRATIONS, ELECTRONIC MOTION, ETC.

$$t_P = \sqrt{\frac{\hbar G}{c^5}} \approx 5.39124(27) \times 10^{-44}\ \mathrm{s}$$

But, how short a period of time can one observe with the human eye?

THIS WOULD BE A GOOD TIME TO REVIEW THE METRIC PREFIXES:

METRIC PREFIXES

Multiplication Factor	Prefix	Symbol	American Term
10^{18}	exa	E	One quintillion
10^{15}	peta	P	One quadrillion
10^{12}	tera	T	One trillion
10^{9}	giga	G	One billion
10^{6}	mega	M	One million
10^{3}	kilo	K	One thousand
10^{2}	hecto	h	One hundred
10^{1}	deka	da	Ten
10^{-1}	deci	d	One tenth
10^{-2}	centi	c	One hundredth
10^{-3}	milli	m	One thousandth
10^{-6}	micro	μ	One millionth
10^{-9}	nano	n	One billionth
10^{-12}	pico	p	One trillionth
10^{-15}	femto	f	One quadrillionth
10^{-18}	atto	a	One quintillionth

Let's start off with a "decisecond" (10^{-1} sec), and work down:

At the “decisecond” (one-tenth of a second) scale,

10^{-1} sec

At the “decisecond” (one-tenth of a second) scale,

10^{-1} sec

. . . the blink of an eye

At the “centisecond” (one-hundreth of a second) scale,

10^{-2} sec

At the “centisecond” (one-hundredth of a second) scale,

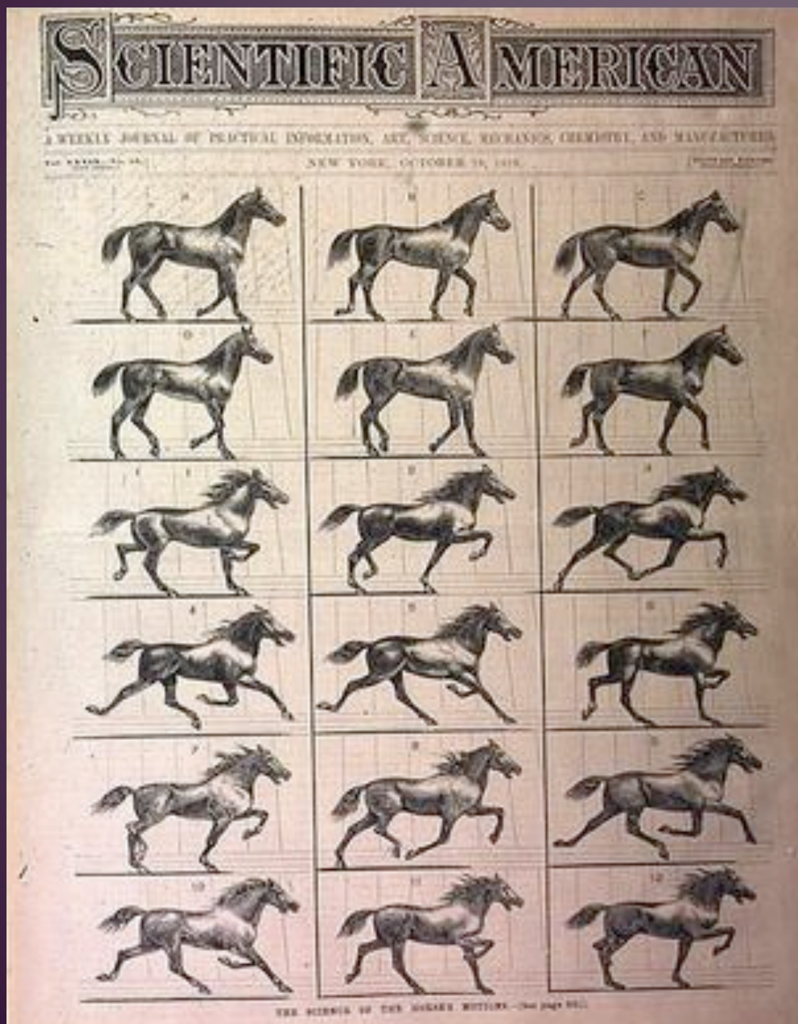
10^{-2} sec

The time it takes for a stroke of lightning to strike the ground.

On a millisecond scale,

10^{-3} sec

The human eye cannot detect motion at these time scales.



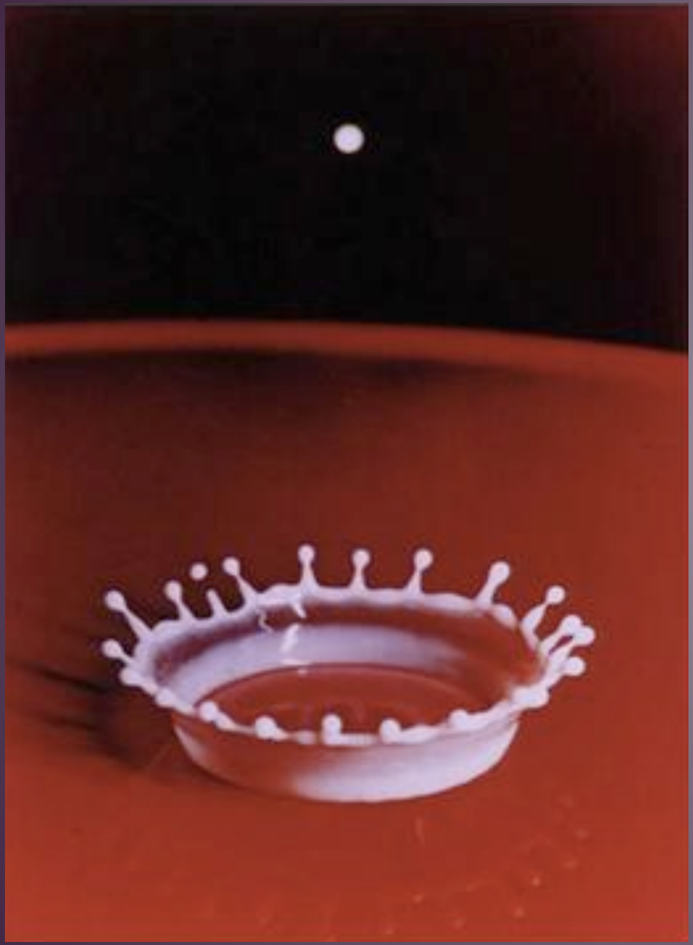
Photographer Eadweard Muybridge was able to show the motion of a galloping horse, in a series of rapid succession photographs taken in 1878 (as seen in this first cover of Scientific American magazine).

His work (at the millisecond scale of time) would go on to serve as the prototype of modern motion pictures.

On a microsecond scale,

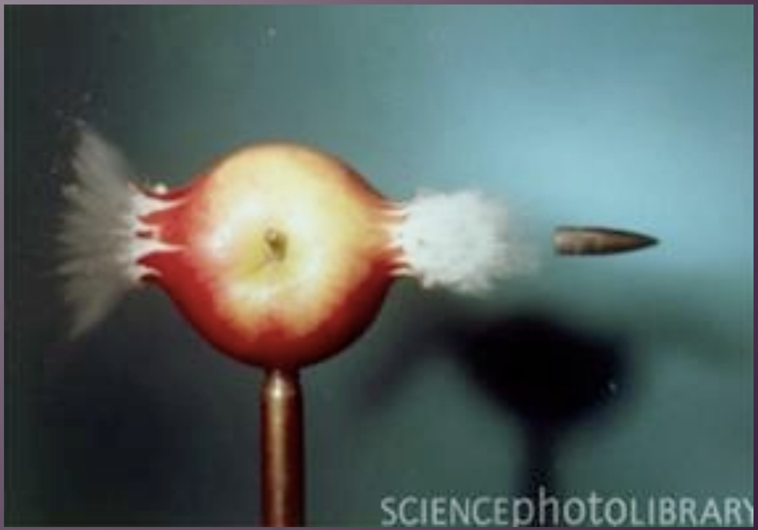
The human eye cannot detect motion at these time scales.

10^{-6} sec



M.I.T. Physicist Harold E. Edgerton “froze” the motion of a milk drop as it strikes a surface, and a fired bullet at the instant it emerges from an apple in 1938.

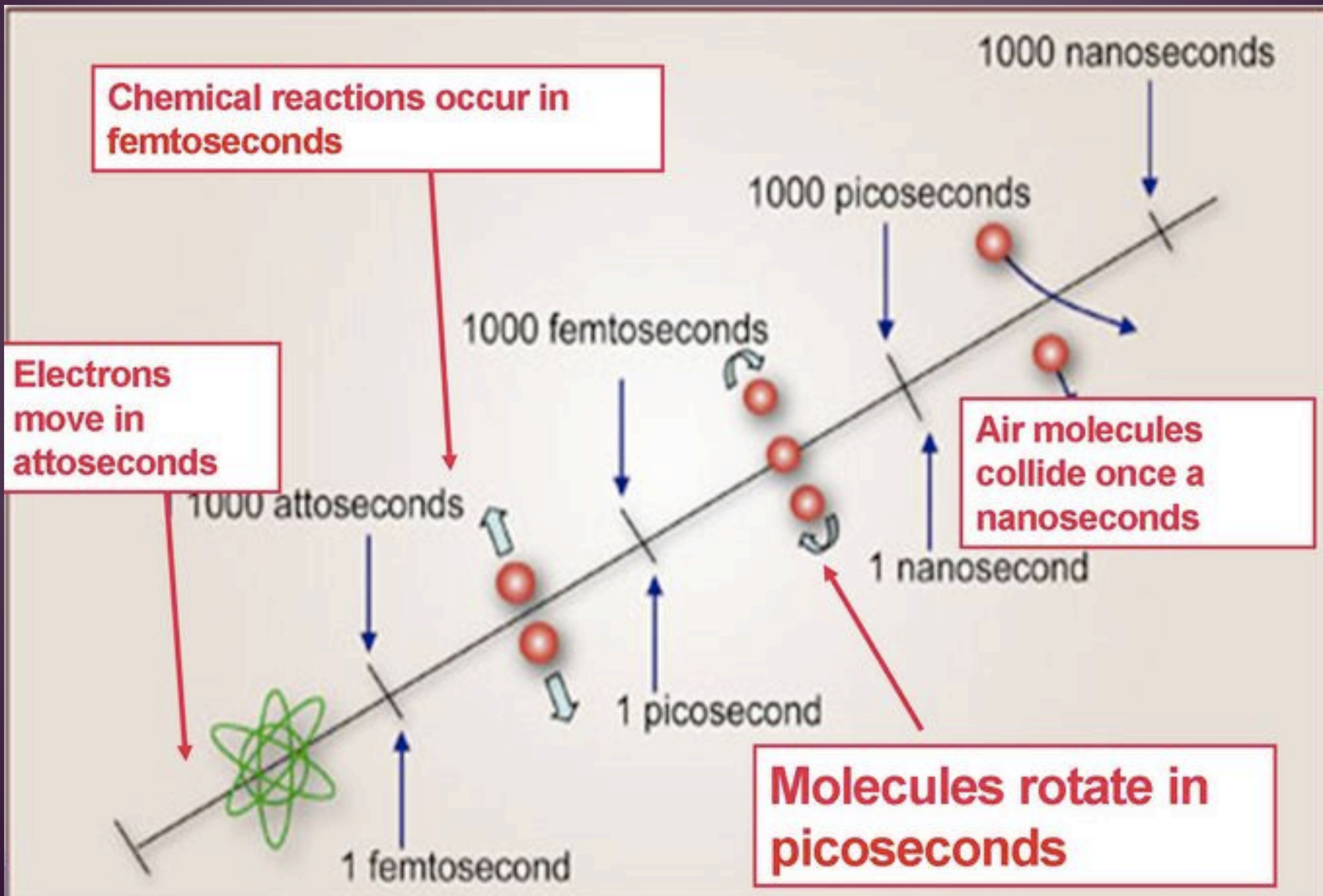
ART MEETS SCIENCE????



On LESS THAN a microsecond scale,

The human eye cannot detect motion at these time scales.

$<10^{-6}$ sec



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If you divide one second into 1,000,000,000 pieces

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you would have 1 NANOSECOND   (10^{-9} sec)

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OR TO PUT IT ANOTHER WAY,

1 ATTOSECOND IS TO 1/2 SECOND, AS

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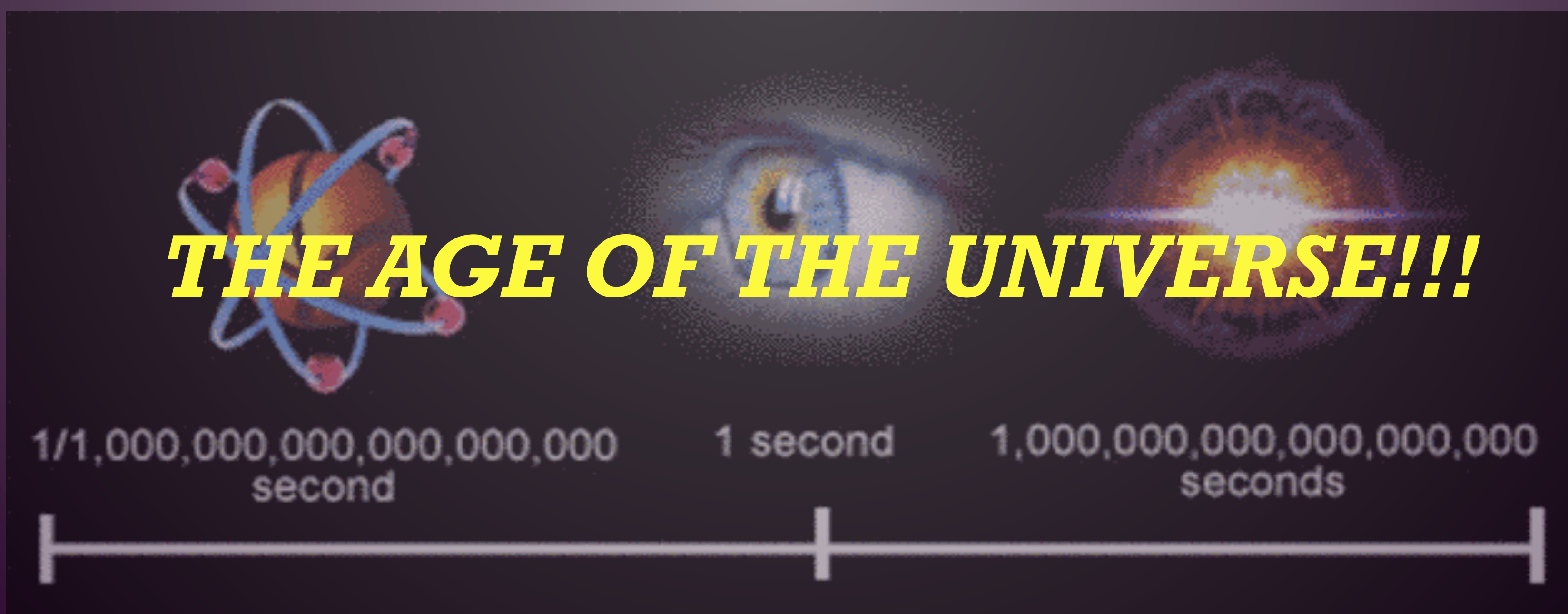

THE AGE OF THE UNIVERSE!!!

So, in order to “see” very small objects moving with very great speeds, let’s learn a lesson from photography:

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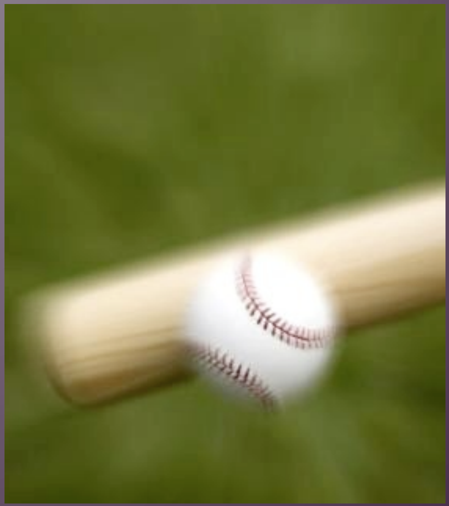

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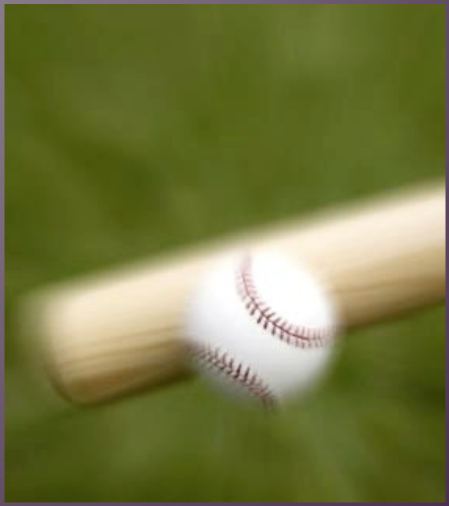
If you want to take a picture of something moving very fast,

The shutter speed must be very fast, that is, the time that the light gathers on the film, must also be very short.



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But, when you are imaging objects that approach
PLANCK LENGTHS, in near ATOMIC TIME intervals,
We need to turn to LASER PULSES and QUANTUM MECHANICS!

WE INTERRUPT OUR PROGRAM WITH AN AMAZING NEWS


FLASH !

By carefully controlling the waveform of an ultrafast laser pulse and sending it through a jet of neon gas, briefly ionizing it, researchers at the Max-Planck-Institut für Quantenoptik (MPQ; Garching, Germany), the Ludwig-Maxmilians-Universität (also in Garching), and the Lawrence Berkeley National Laboratory (Berkeley, CA) have created the ***shortest light pulse yet***—only 80 attoseconds (as) in duration!

80 attoseconds = 8 x 10^{-17} seconds!

or,

0.00000000000000008 second

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HOW CAN THIS BE DONE, AND WHAT ARE THE IMPLICATIONS FOR SCIENCE?

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BY USING A 720 nm NEAR-INFRARED (NIR) LASER, THE 3.3 fs PULSE IS SHORT ENOUGH IN DURATION THAT THE ONE OPTICAL CYCLE CLOSEST TO THE PEAK OF THE ENVELOPE IS MUCH GREATER IN INTENSITY THAN ANY OTHER PART OF THE PULSE.

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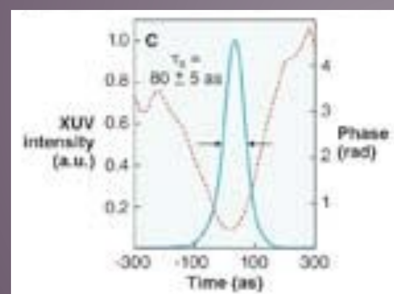

A sub-1.5-cycle ultrafast laser pulse strikes a jet of neon atoms, ionizing some of them. The recombination of the electrons with the atoms creates a pulse of extreme-UV light with an 80 as duration.

(Courtesy of Max-Planck-Institut für Quantenoptik

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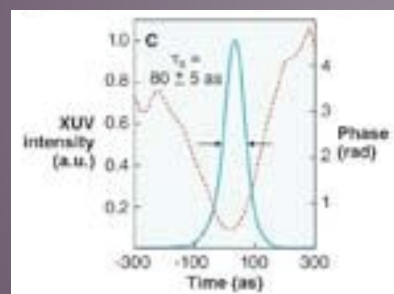

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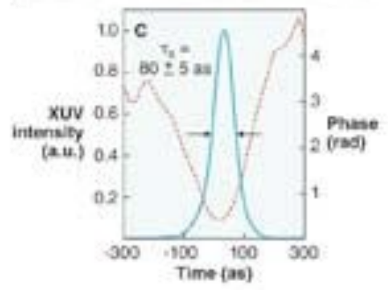
Because of this, the neon gas receives a single electric-field pulse powerful enough to ionize it, even if the peak of the envelope is not perfectly aligned with the peak of the optical cycle. The subsequent recollisions of the ionized electrons with the neon atoms produce the 80 as pulse, which is broadband with a peak in the extreme-ultraviolet (XUV) range.

AT 80 ATTOSECOND INTERVALS, WE ARE NOW "SEEING" ELECTRONS INTERACTING WITH ATOMS AND MOLECULES!

BY USING A 720 nm NEAR-INFRARED (NIR) LASER, THE 3.3 fs PULSE IS SHORT ENOUGH IN DURATION THAT THE ONE OPTICAL CYCLE CLOSEST TO THE PEAK OF THE ENVELOPE IS MUCH GREATER IN INTENSITY THAN ANY OTHER PART OF THE PULSE.



A sub-1.5-cycle ultrafast laser pulse strikes a jet of neon atoms, ionizing some of them. The recombination of the electrons with the atoms creates a pulse of extreme-UV light with an 80 as duration.

(Courtesy of Max-Planck-Institut für Quantenoptik

To measure the pulse length, both the XUV pulse and the NIR laser pulse were shone into a second neon-gas jet so that the XUV pulse ionized the neon in the presence of the NIR light.

Depending on when the electrons were ionized in relation to the arrival of the XUV pulse, the NIR pulse caused them to either gain or lose momentum, allowing the duration and other characteristics of the XUV pulse to be calculated from the energy distribution of the ionized electrons.

TO REVIEW: remember, in 1925 Louis de Broglie proposed a "Particle-Wave" theory:

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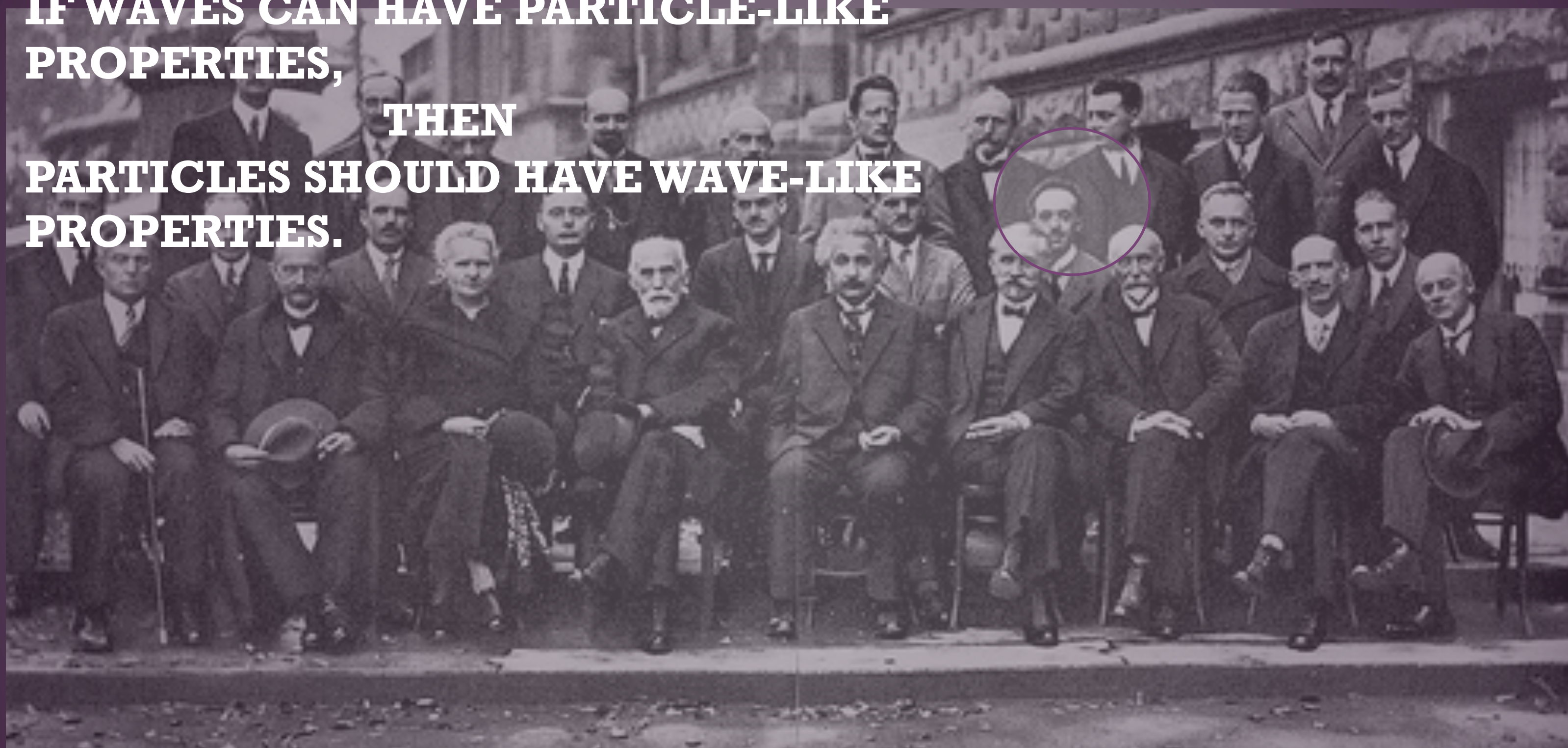
IF WAVES CAN HAVE PARTICLE-LIKE PROPERTIES,

THEN

PARTICLES SHOULD HAVE WAVE-LIKE PROPERTIES.



THIS IMPLIES THAT ELECTRONS COULD BE USED LIKE LIGHT TO TAKE PICTURES!!

CLASSICALLY, AN OBJECT HITTING A SUFFICIENTLY LARGE BARRIER WILL NOT PASS THROUGH. BUT OBJECTS WITH VERY SMALL MASS, SUCH AS THE ELECTRON, SINCE IT HAS WAVELIKE CHARACTERISTICS, WILL PERMIT SUCH AN EVENT!

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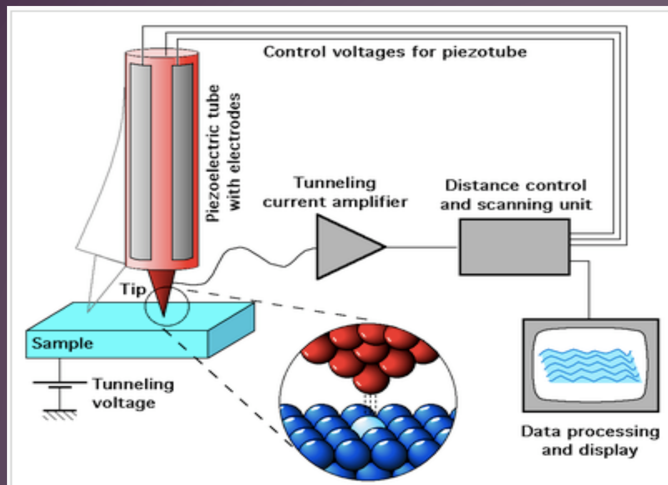
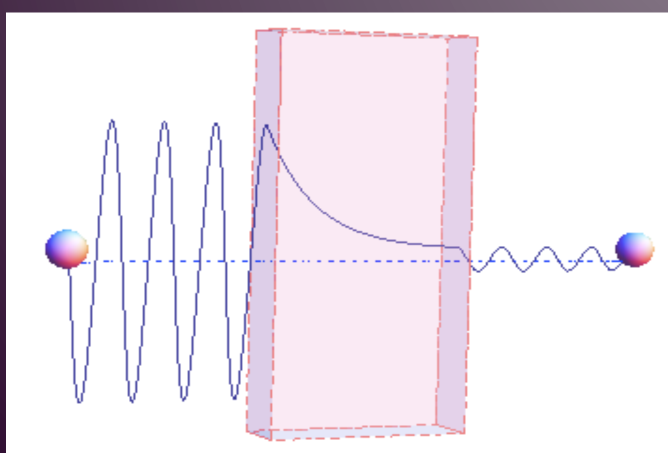
IT IS A QUANTUM PROCESS,
APPRECIABLE ONLY FOR PARTICLES OF *VERY SMALL MASS*

The SCANNING TUNNELING MICROSCOPE (STM)

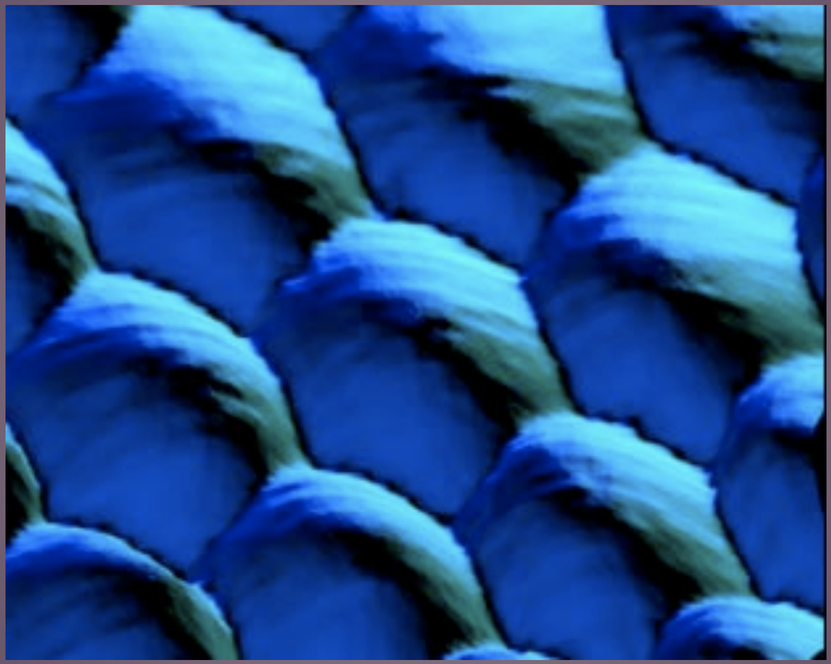


Schematic representation of quantum tunneling through a barrier. The energy of the tunneled particle is the same, only the quantum amplitude (and hence the probability of the process) is decreased.



TUNNELING HAS TRANSFORMED SURFACE SCIENCE, ALLOWING US TO SEE THE STRUCTURE OF MOLECULES AND EVEN ATOMS

SOME EXAMPLES OF STM PHOTOMICROGRAPHIC IMAGES



Blue Platinum

The surface of Platinum.

Courtesy: IBM Research, Almaden Research Center.

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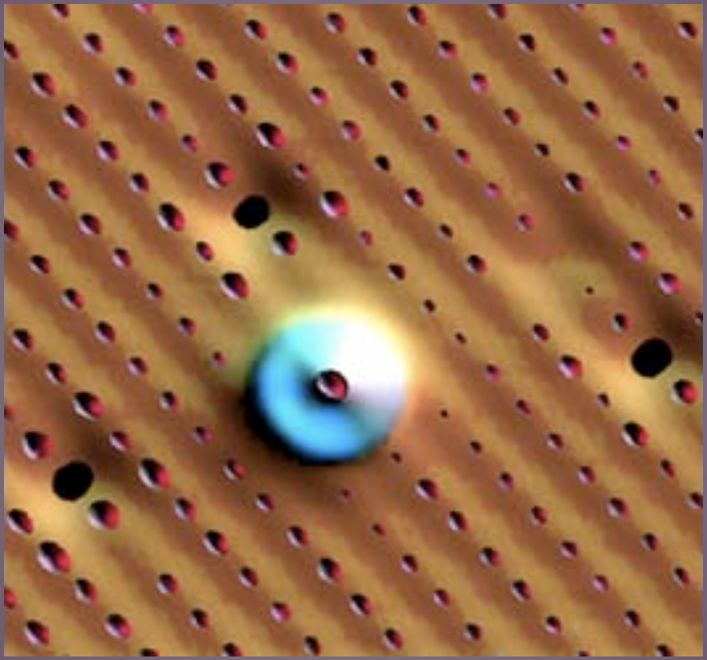

Xenon on Nickel

This image shows xenon on a nickel surface. The image is actually a combination of two images. Defects in the nickel surface were used to position the two images correctly above each other.

Courtesy: IBM Research, Almaden Research Center.

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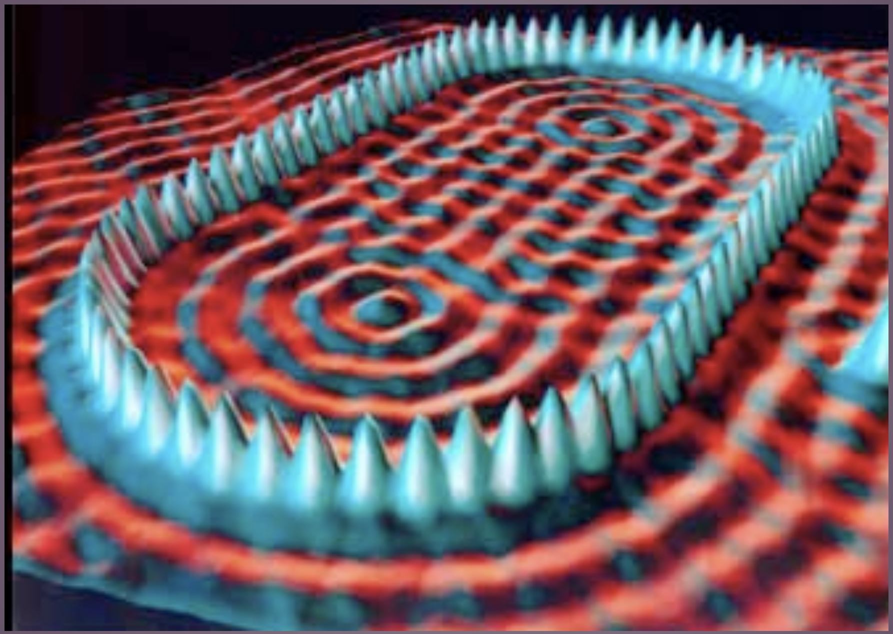
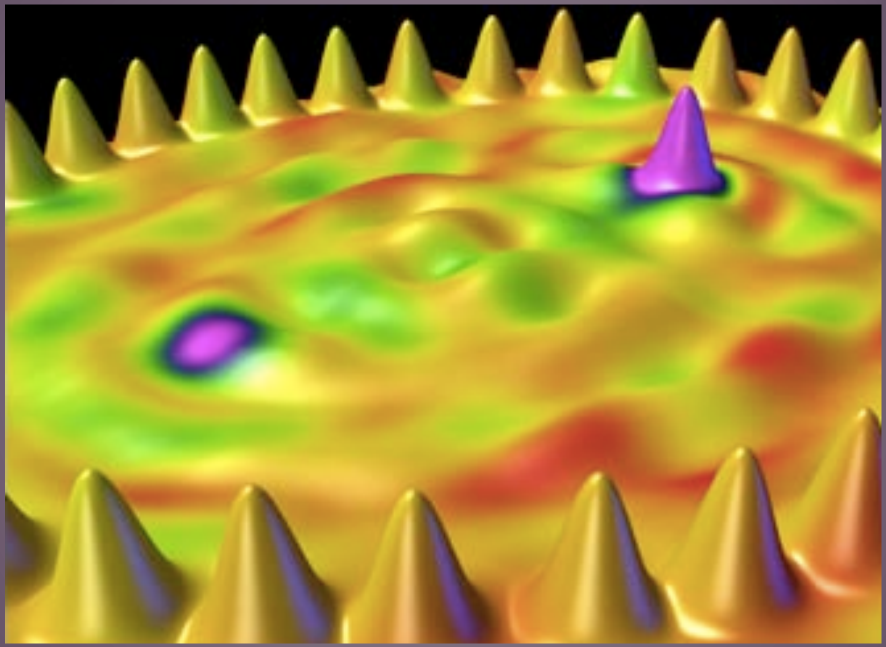


Stadium Corral

A stadium shaped corral made by iron atoms on a copper surface.

Courtesy: IBM Research, Almaden Research Center.

SOME EXAMPLES OF STM PHOTOMICROGRAPHIC IMAGES

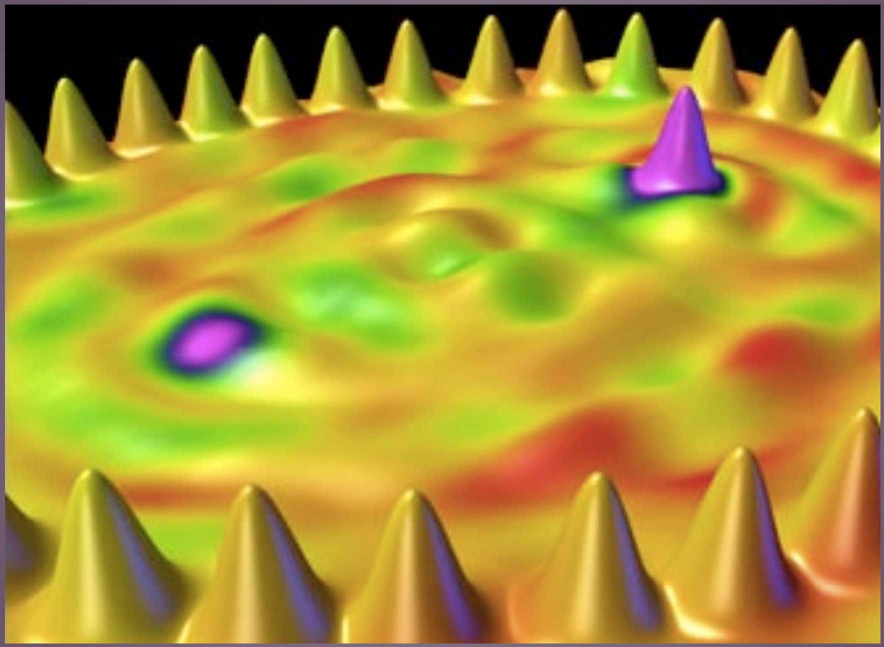


Quantum Mirage – Closeup

The Quantum Mirage effect is a way to transport information on the atomic scale.It uses the wave nature of electrons instead of conventional wiring.

Courtesy: IBM Research, Almaden Research Center.

SOME EXAMPLES OF STM PHOTOMICROGRAPHIC IMAGES



QUANTUM MECHANICS AND INFORMATION TRANSFER??

Courtesy: IBM Research, Almaden Research Center.

HOW CAN QUANTUM INTERACTIONS AT THE ATOMIC LEVEL BE USED TO ADVANCE INFORMATION TECHNOLOGY AND COMMUNICATION?

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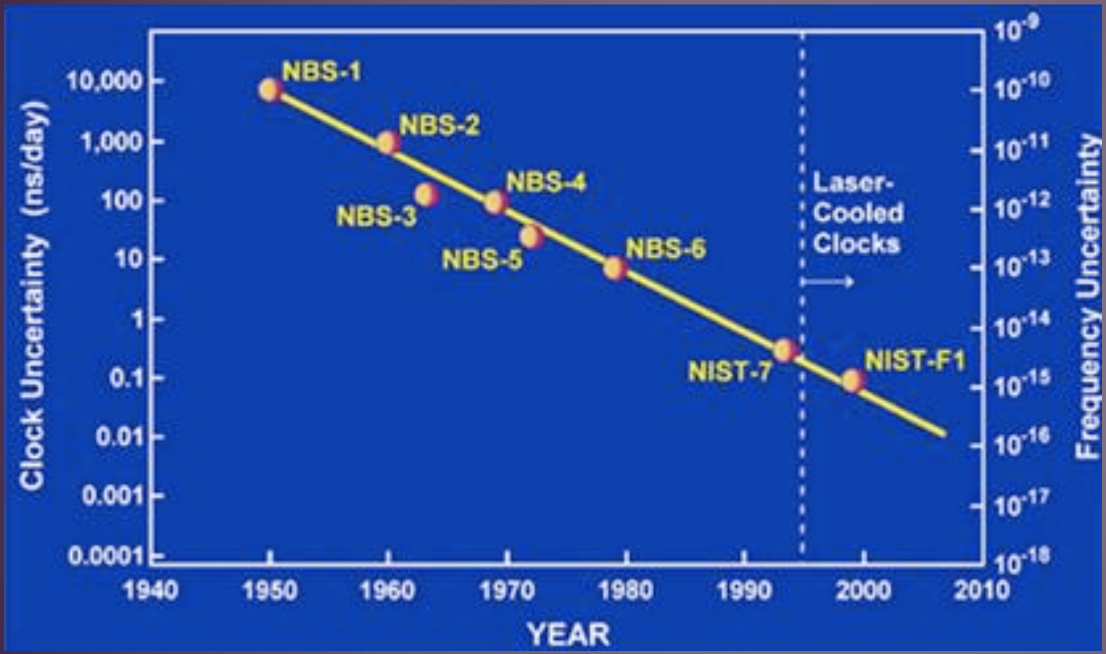

THIS GRAPH SHOWS THE PROGRESS MADE IN THE MEASUREMENT OF TIME SINCE THE FIRST "ATOMIC CLOCK" IN 1949 (NBS-1).

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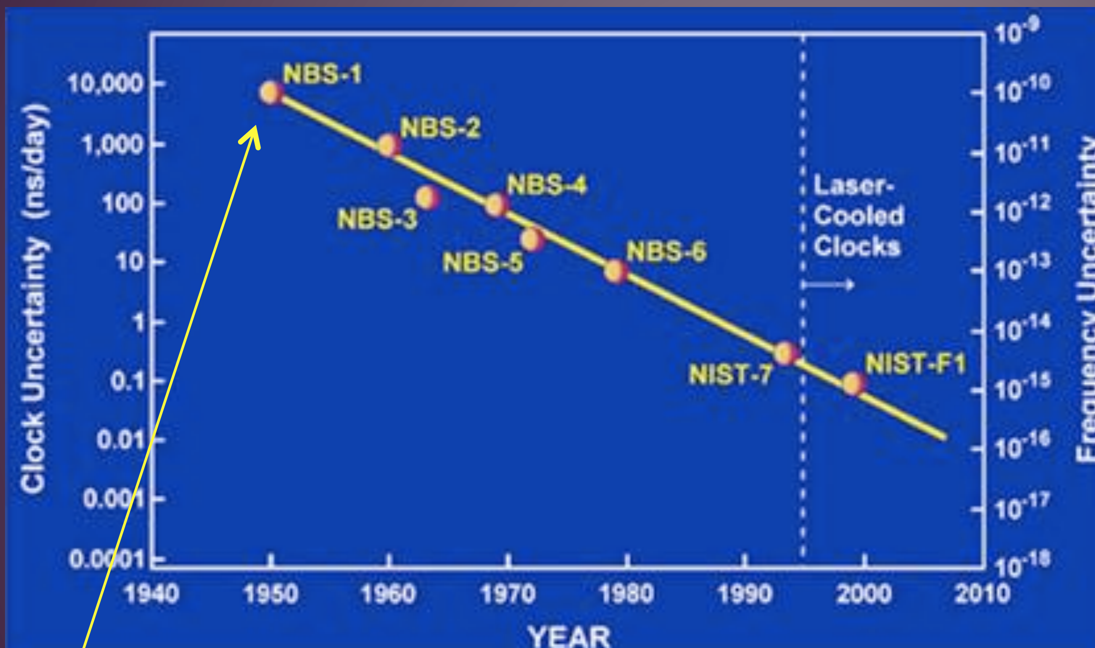

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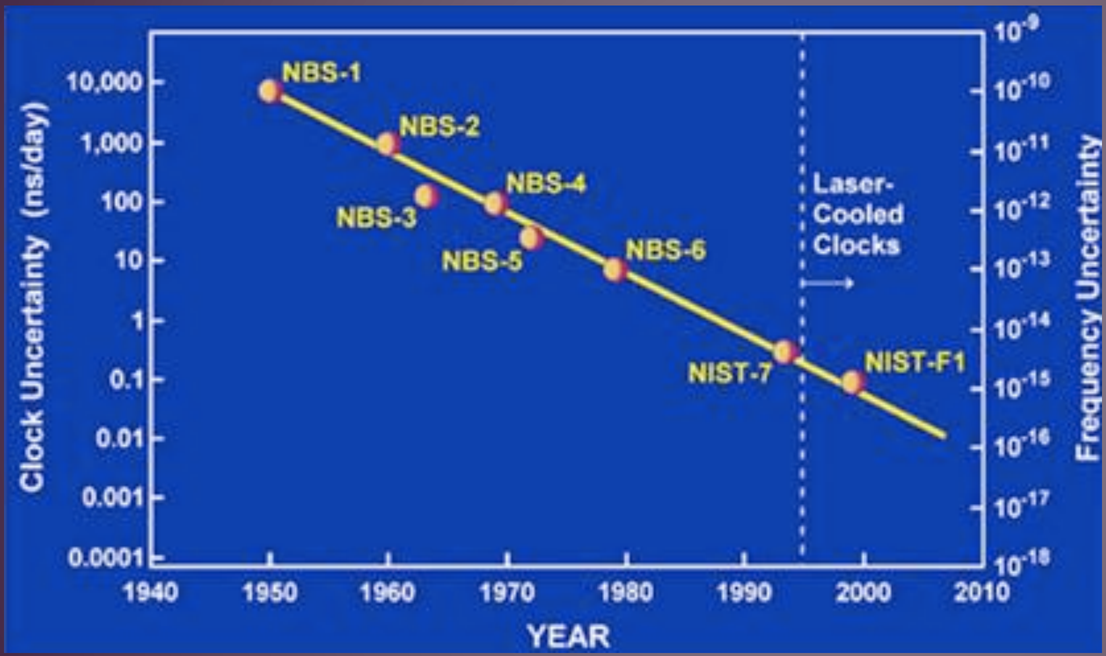

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The Bureau atomic clock program sought to provide a spectroscopic standard capable of being used as a new atomic standard of time and frequency to replace the mean solar day and so change the arbitrary units of time to atomic ones. With such a clock, new precise values might be found for the velocity of light; new measurements of the rotation of the earth would provide a new tool for geophysicists; and new measurments of the mean sidereal year might test whether Newtonian and atomic time are the same, yielding important results for relativity theory and cosmology.

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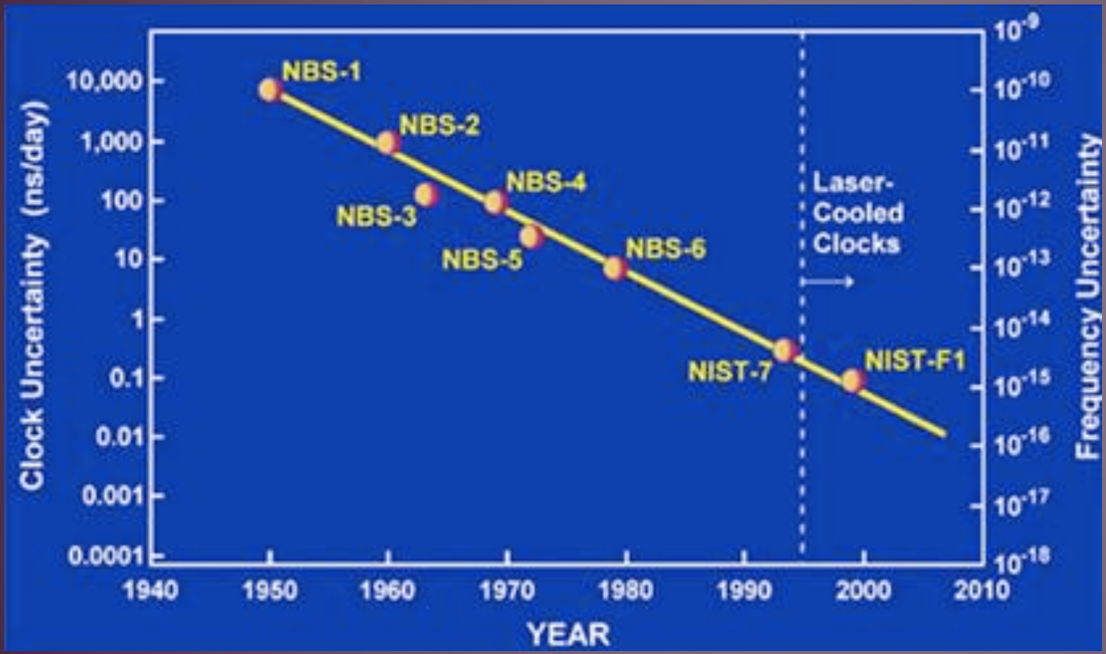

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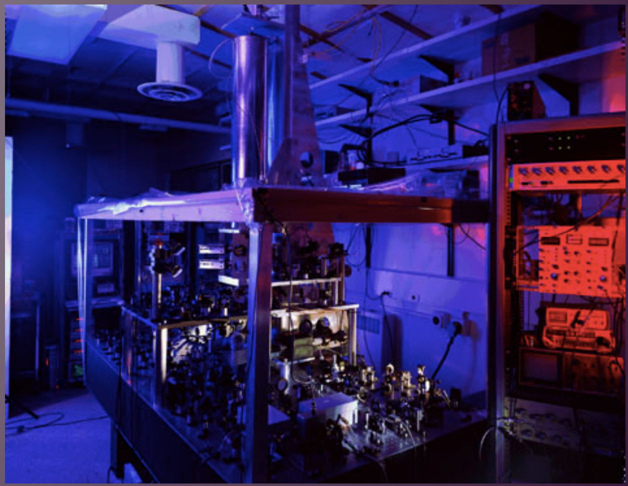

Today, the NIST-F1 (soon to be replaced by NIST-2), is the most precise timekeeping (and frequency-measuring) device in the world.

As of 2005, it is so accurate that it will neither gain nor lose one second in EIGHTY MILLION YEARS.

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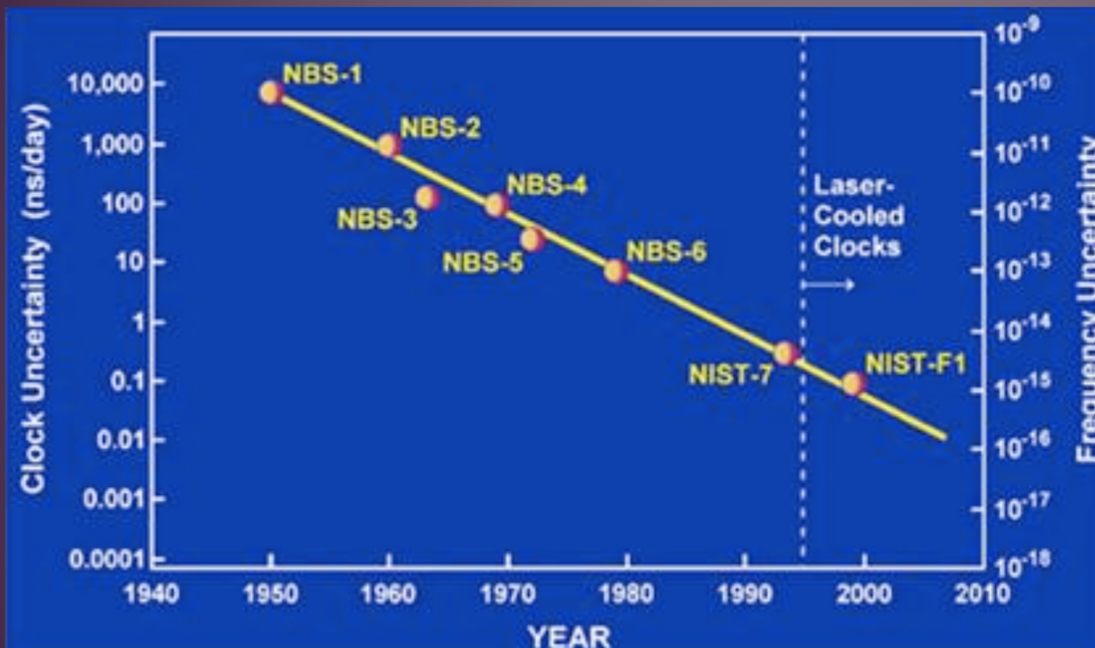

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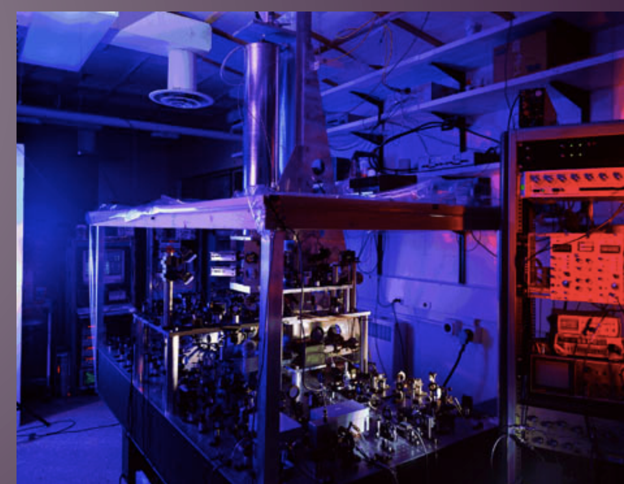

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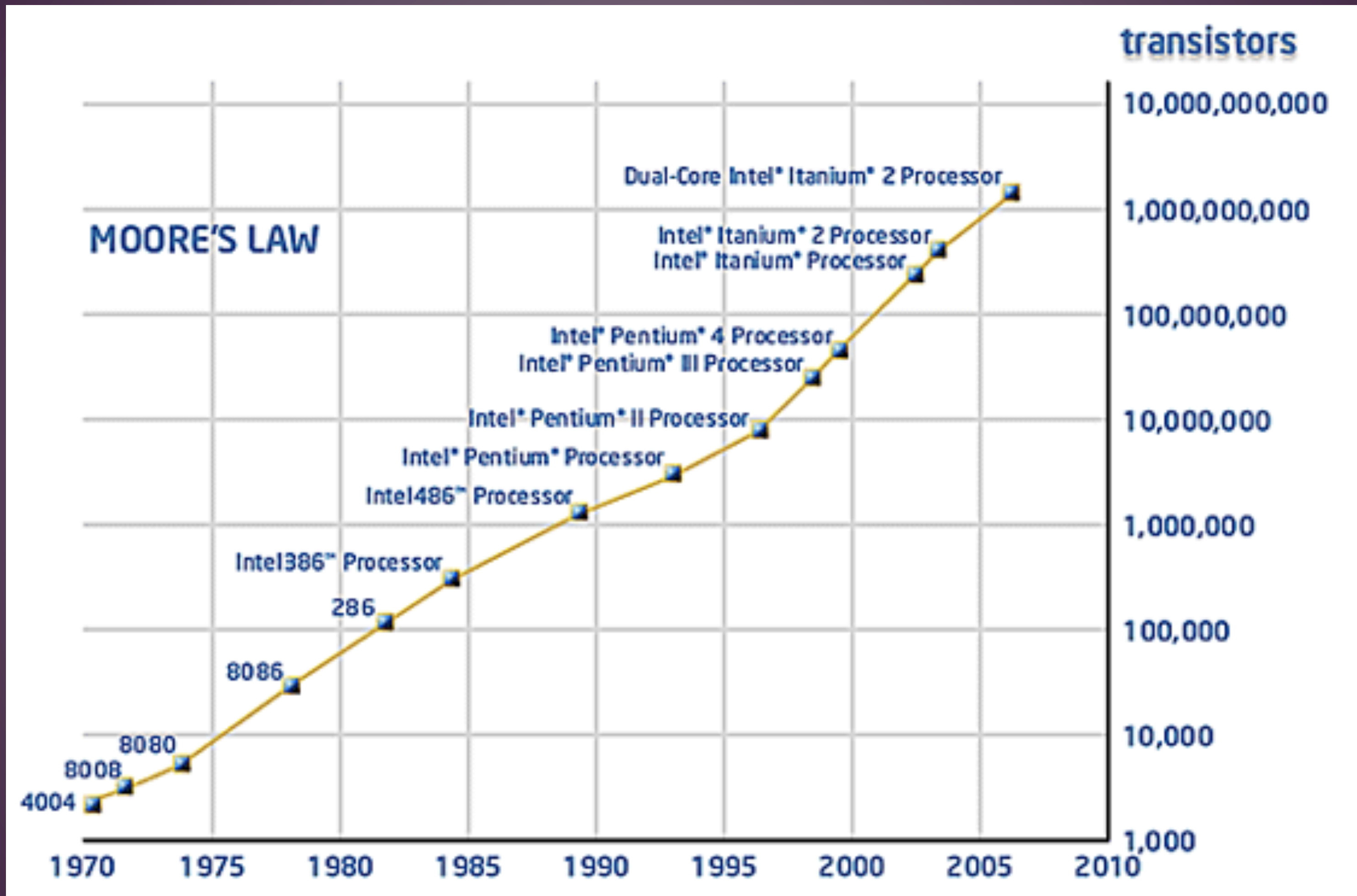
AS OUR TIME AND FREQUENCY-KEEPING DEVICES CONTINUE TO IMPROVE, SO WILL OUR QUANTUM-MECHANICAL-BASED TECHNOLOGIES.

ADVANCEMENTS IN INTEGRATED CIRCUIT TECHNOLOGY



In 1965, Gordon Moore, founder of the Intel Company, predicted that the number of transistors per square inch on integrated circuits would double every year. Although the pace has slowed down a bit, DATA DENSITY *HAS* DOUBLED approximately every 18 months, and this is the currently-used definition of MOORE'S LAW.

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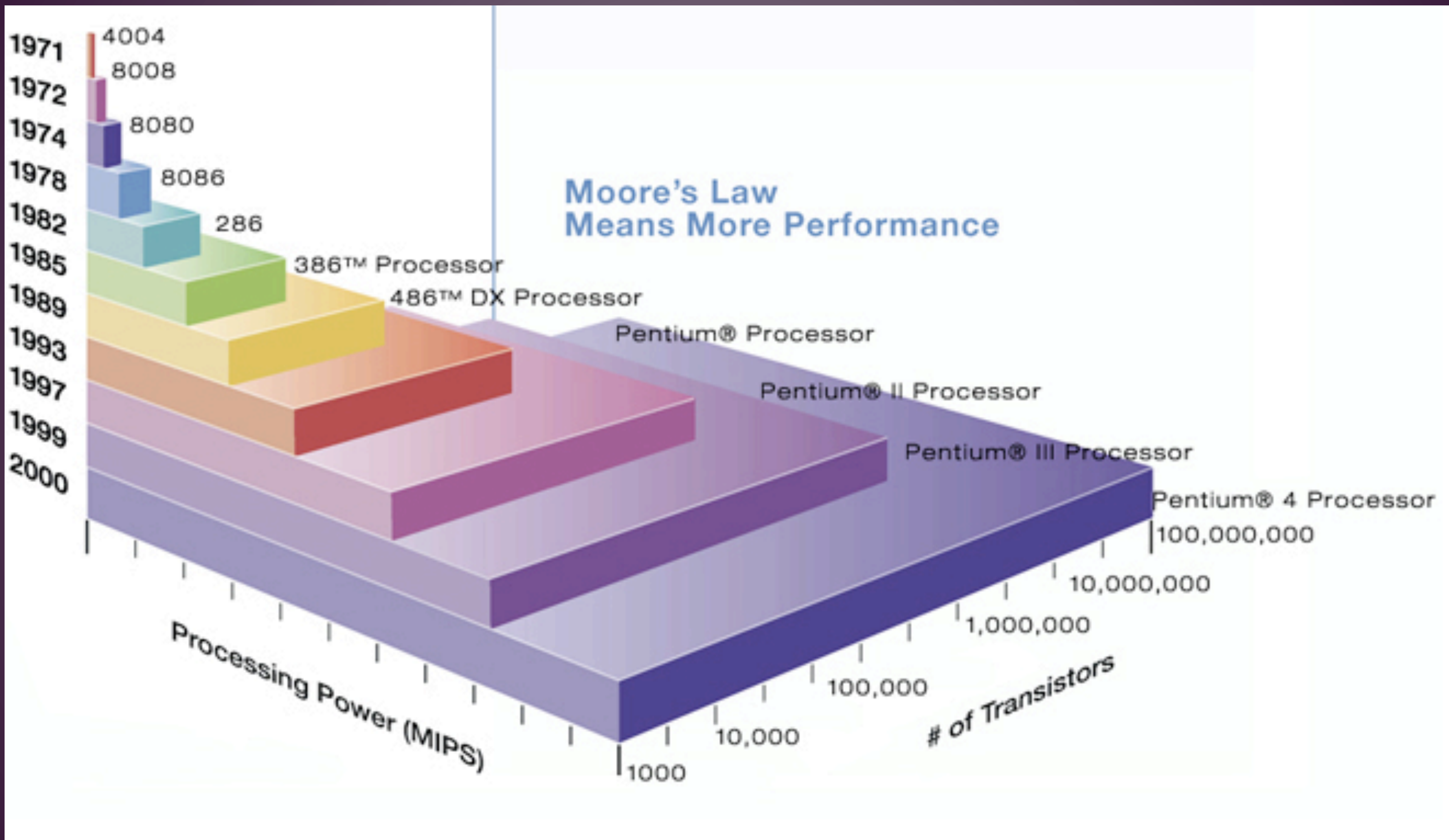

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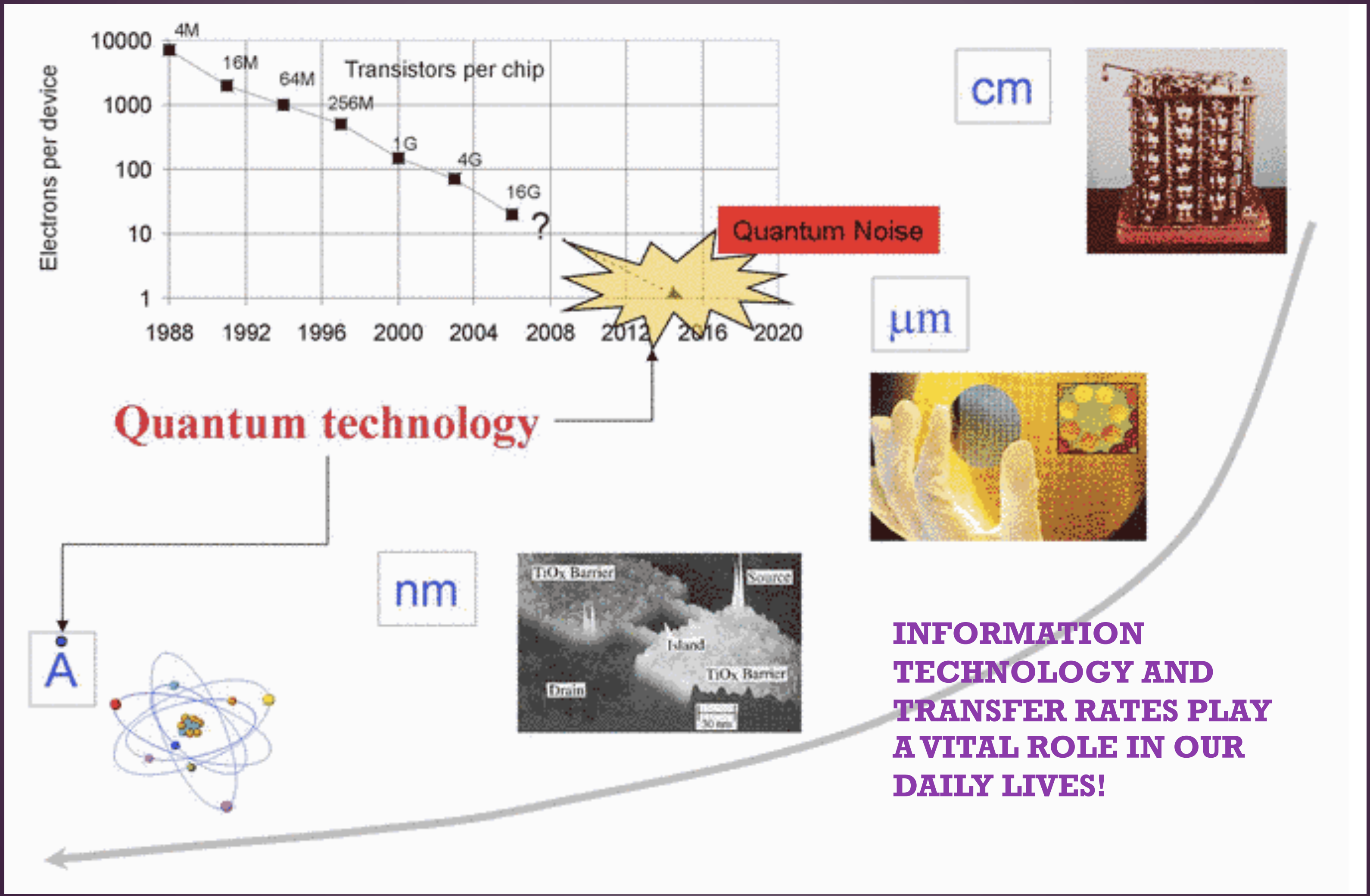

TECHNOLOGICAL PROGRESS HAS DRIVEN ENGINEERING INTO THE QUANTUM REALM.

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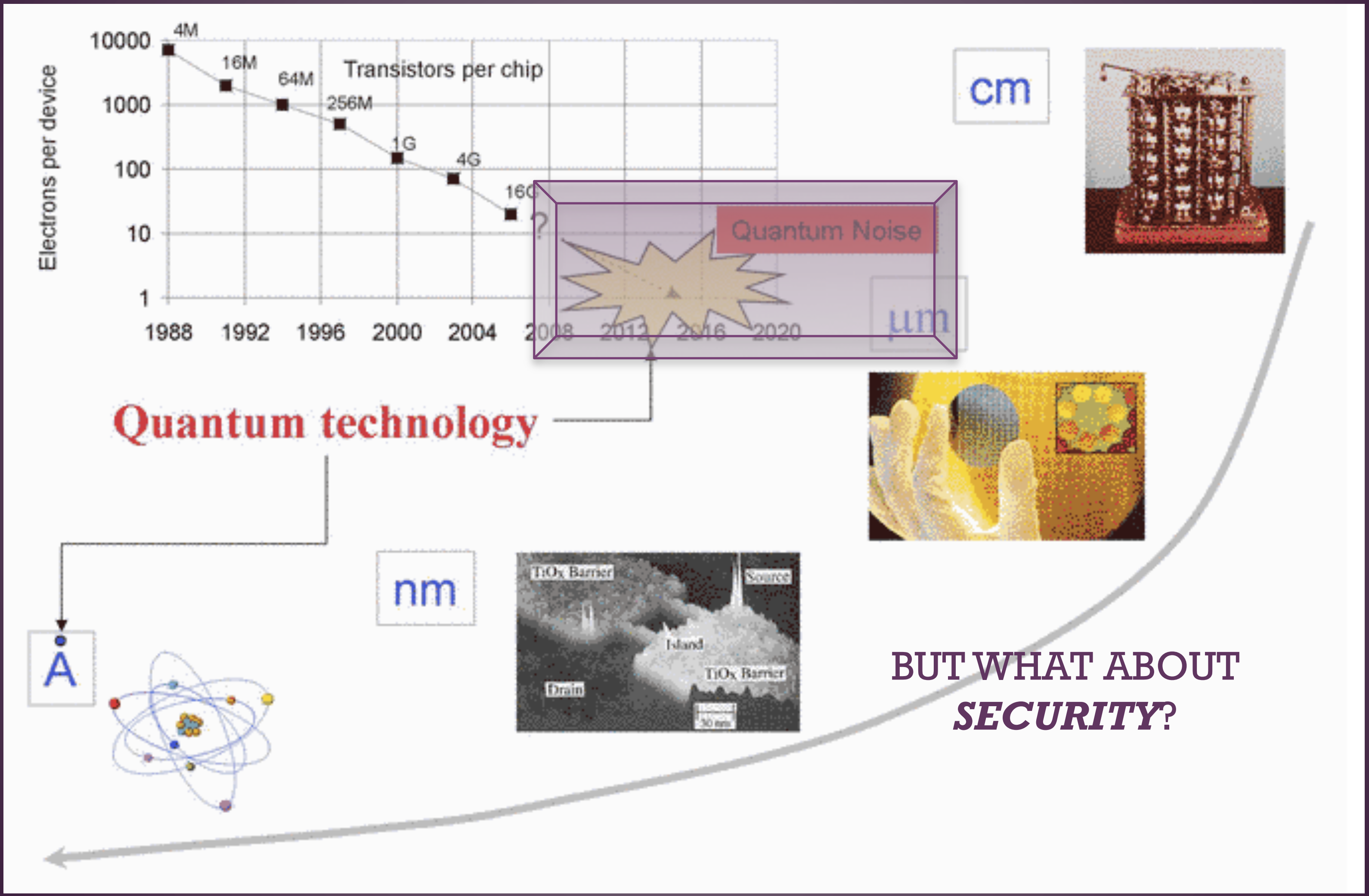
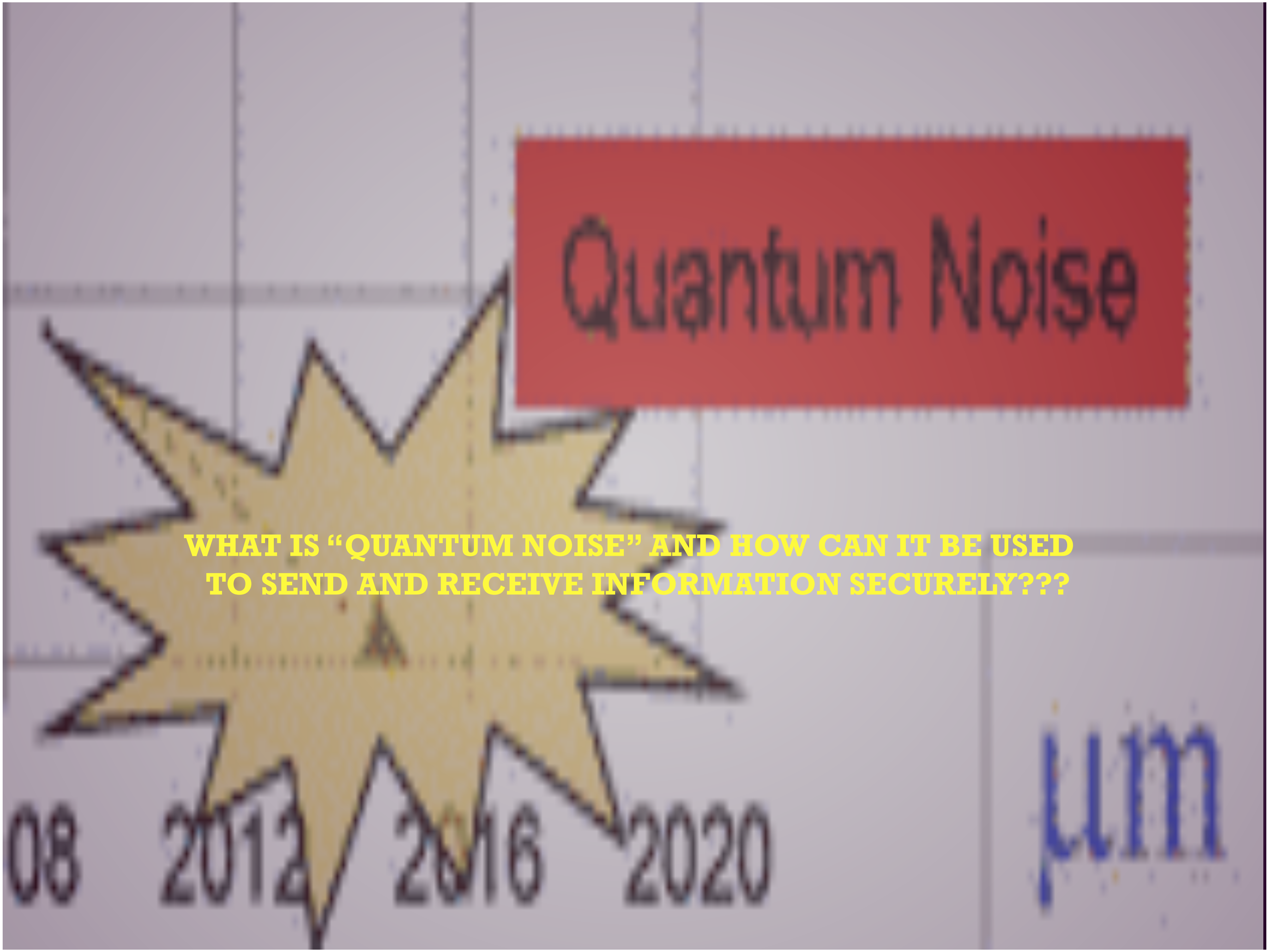


Here's where QUANTUM NOISE comes in!



WHAT IS "QUANTUM NOISE" AND HOW CAN IT BE USED TO SEND AND RECEIVE INFORMATION SECURELY???

Information technology relies on two major information carriers:

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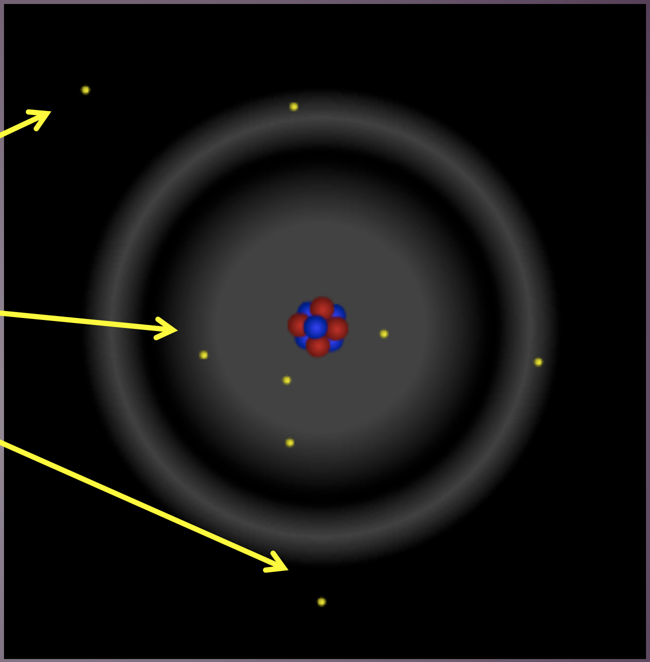
I. ELECTRONS



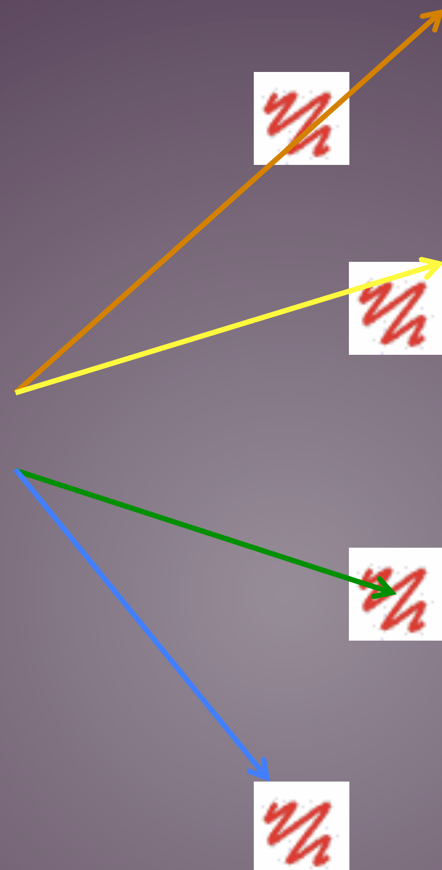
USED IN

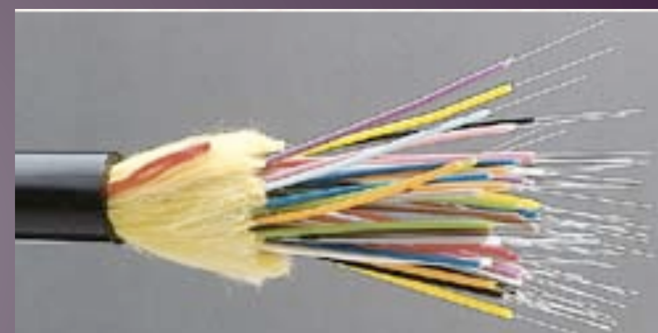
wires and silicon microprocessors
with device sizes in the sub-100nm range

ELECTRICAL IN NATURE

AND

II. PHOTONS





very high bandwidth data in optical fibers

HANDLED AS PROPAGATING WAVES

WHICH IS BETTER FOR UNCONDITIONALLY SECURE COMMUNICATION?

I. ELECTRICAL

OR

II. OPTICAL

?

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OPTICAL!

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WHY?

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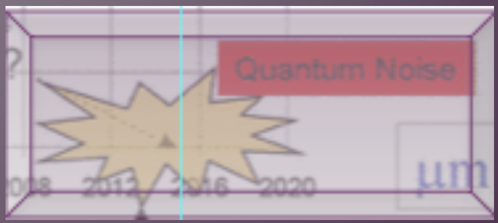
IT HAS TO DO WITH



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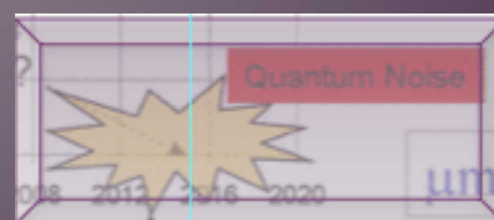

SO WHAT EXACTLY ***IS*** QUANTUM NOISE?

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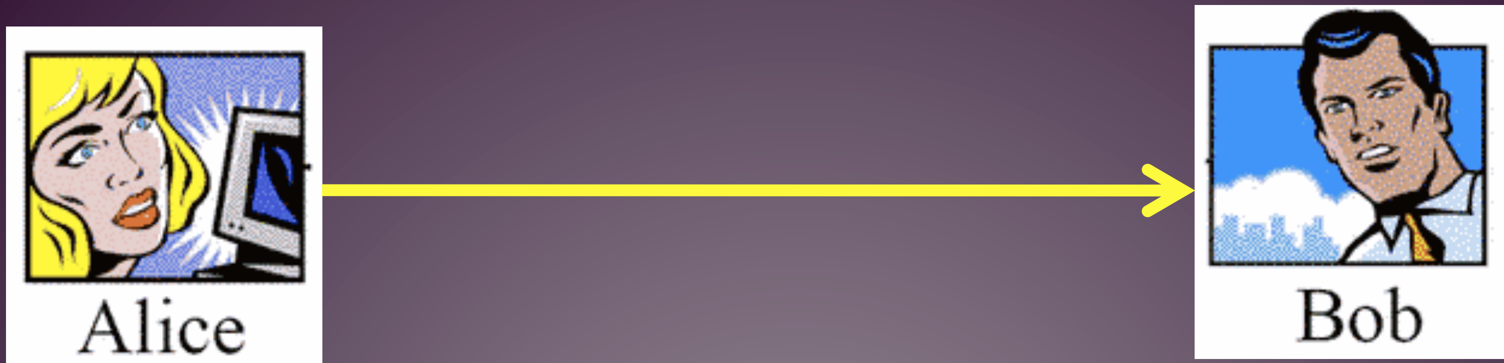
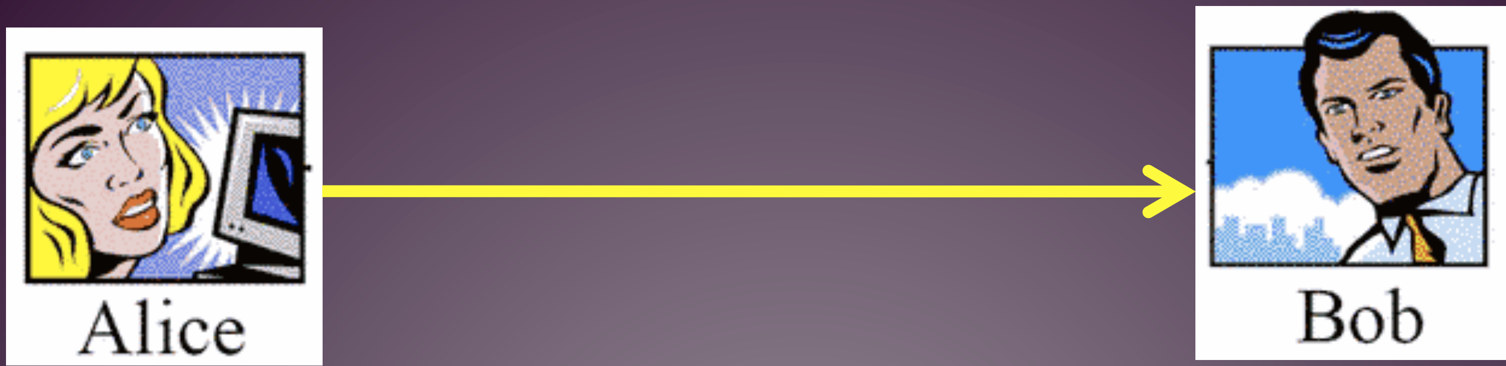
HOW DO THEY KNOW IT IS SECURE?



Alice sends out a sequence of single photons.
For each photon, it randomly chooses one of two possible base states, with one of them having the possible polarization directions up/down and left/right, and the other one polarization directions which are tilted by 45°. In each case, the actual polarization direction is also randomly chosen.



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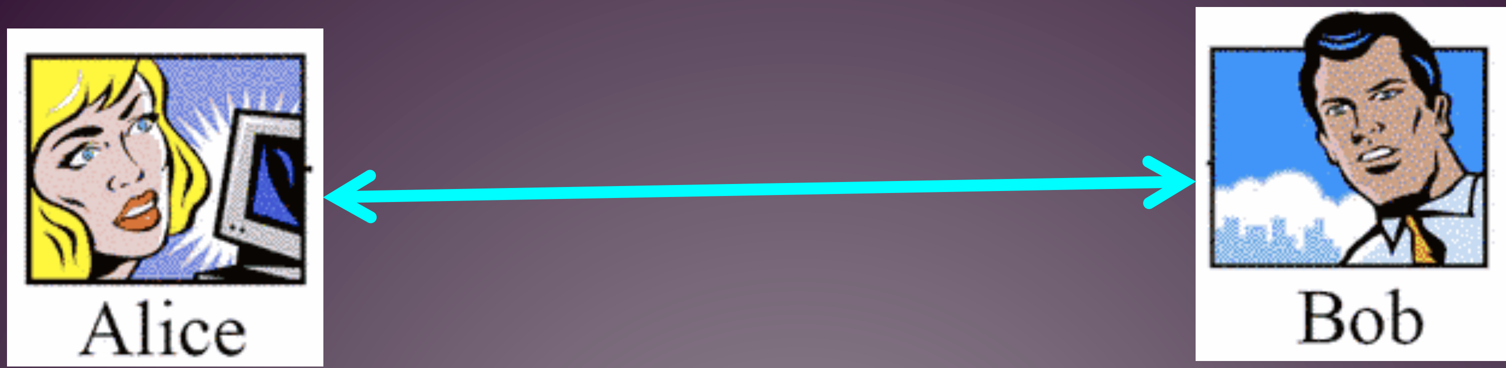
Bob detects the polarizations of the incoming photons, also randomly choosing the base states. This means that on average half of the photons will be measured with the "wrong" base states, i.e. with states not corresponding to those of Alice's.



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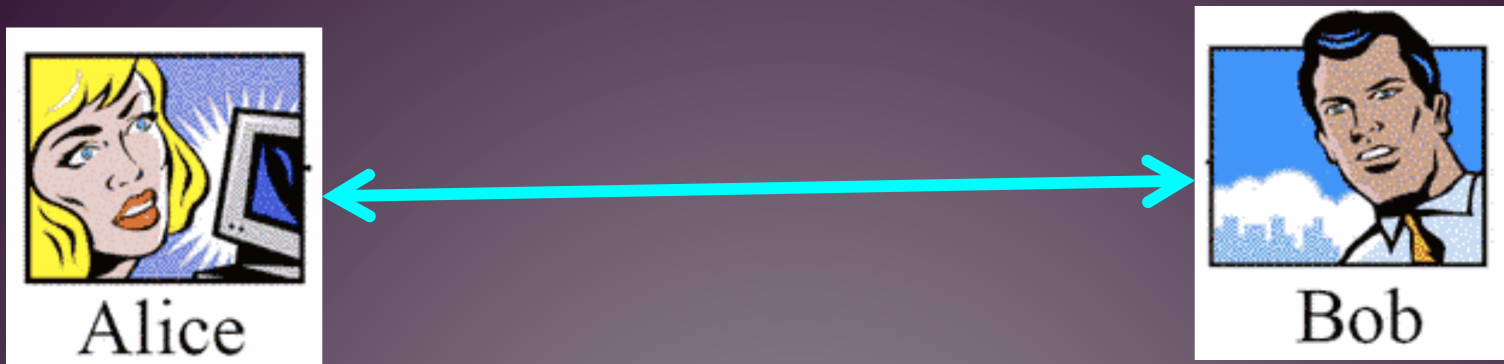
Later, Alice and Bob use a public (possibly interceptable) communication channel to talk about the states used for each photon (but not on the chosen polarization directions). In this way, they can find out which of the photons were by chance treated with the same base states on both sides.



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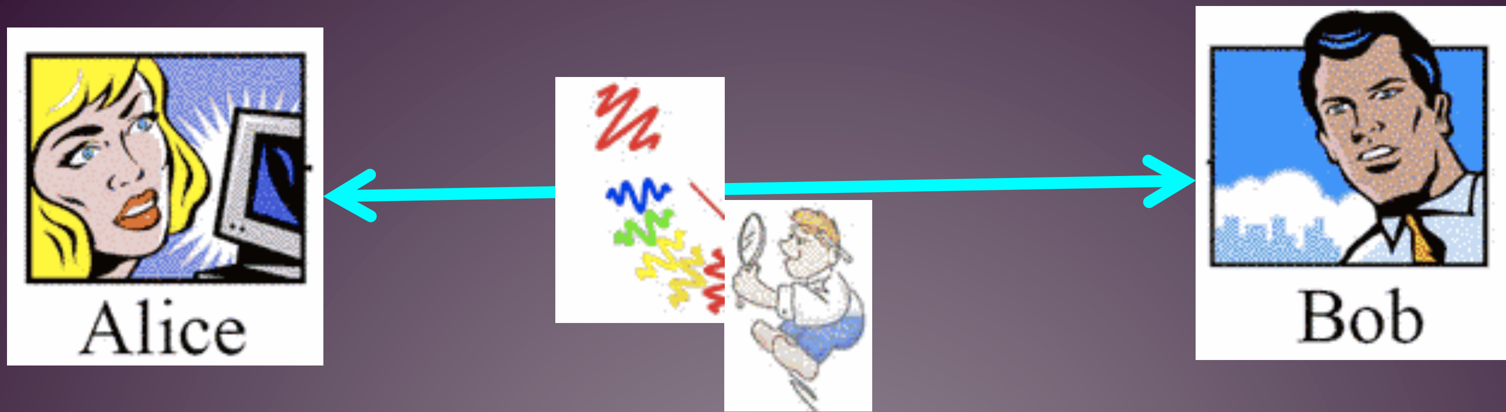
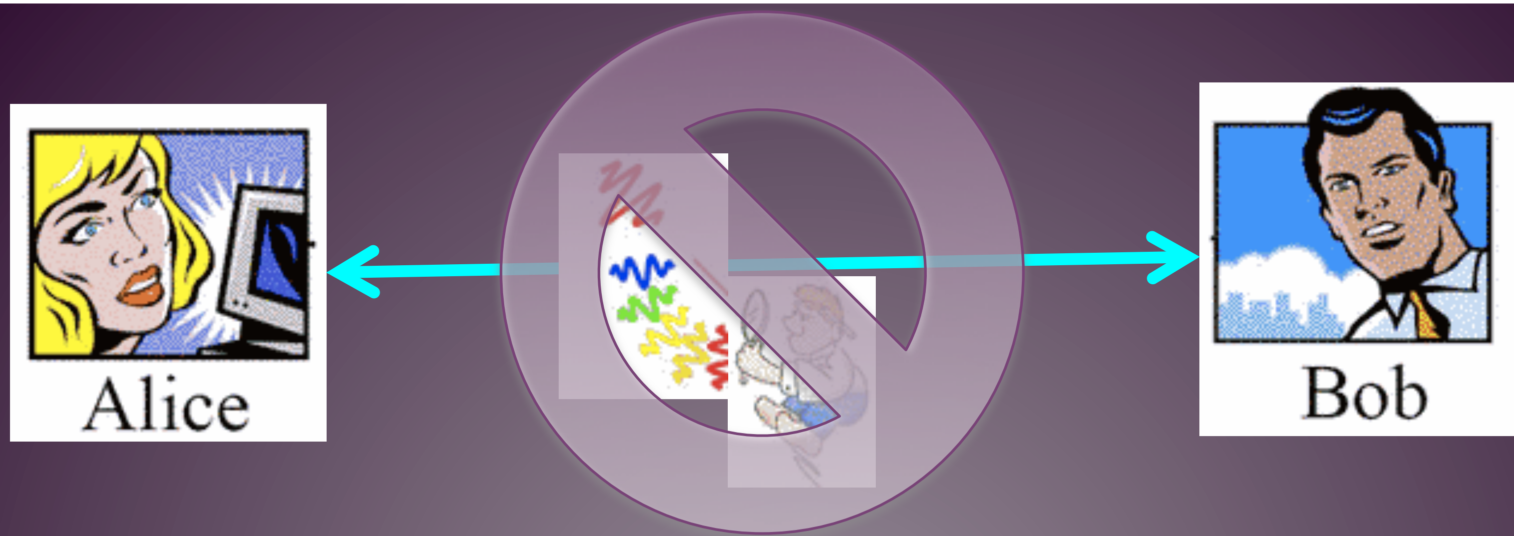
They then discard all photons with a "wrong" basis, and the others represent a sequence of bits which should be identical for Alice and Bob and should be known only to them, provided that the transmission has not been manipulated by anybody. Whether or not this happened they can test by comparing some number of the obtained bits via the public information channel. If these bits agree, they know that the other ones are also correct and can finally be used for the actual data transmission.



EVE

If an "Eavesdropper" (named Eve) tries to intercept the message, she would have to detect the photons' polarization directions without knowing the corresponding base states. Quantum mechanics would not allow Eve to do a polarzation measurement without projecting the photon state onto the chosen base states, that is, without ALTERING the base states. Therefore, employing basic principles of quantum mechanics, including suitable use of QUANTUM NOISE, allows the near-perfect undetectable transmission.



THIS ALTERED SIGNAL WOULD ALERT BOB AND ALICE THAT A THIRD PARTY (EVE) IS TRYING TO GAIN ACCESS!!

TODAY, SCIENTISTS AND ENGINEERS ARE WORKING TO USE QUANTUM MECHANICS TO DEVELOP COMPUTERS THAT WOULD HAVE THE POTENTIAL TO OPERATE MANY MAGNITUDES OF ORDER FASTER THAN OUR CURRENT FASTEST INTEGRATED CIRCUIT-BASED MICROPROCESSORS.

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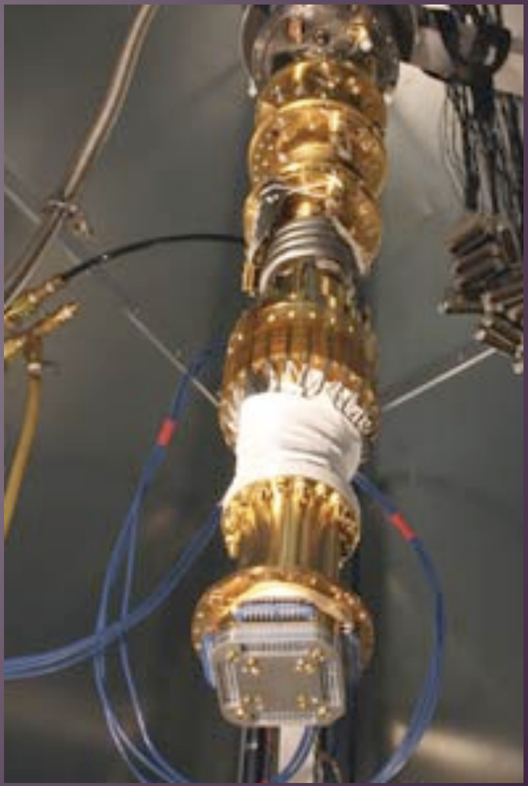
Today's computers work by manipulating bits that exist in one of two states: a 0 or a 1.
Quantum computers aren't limited to two states; they encode information as quantum bits, or qubits, which can exist in superposition.
Qubits represent atoms, ions, photons or electrons and their respective control devices that are working together to act as computer memory and a processor. Because a quantum computer can contain these multiple states simultaneously, it has the potential to be millions of times more powerful than today's most powerful supercomputers.



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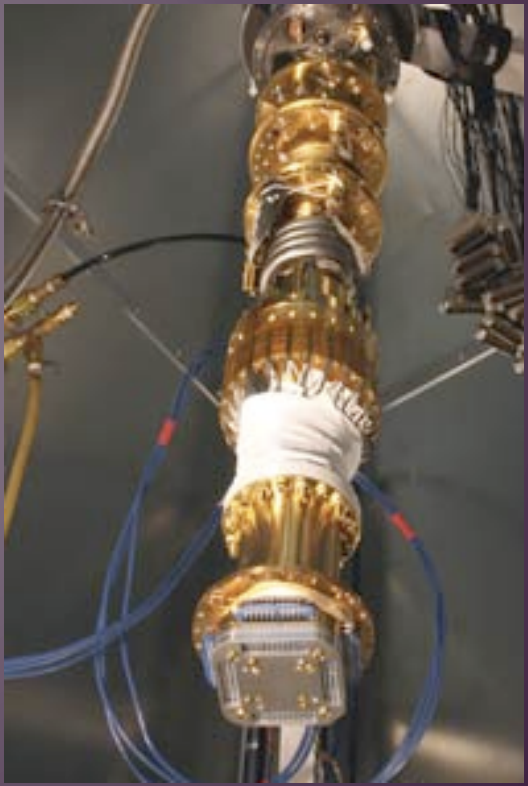
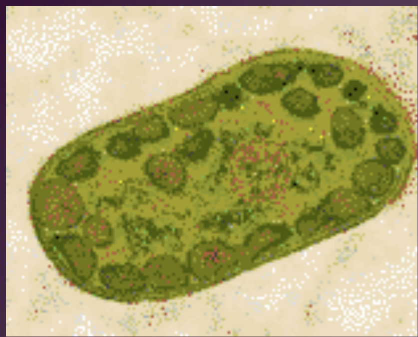


WE STILL HAVE MUCH TO LEARN ABOUT QUANTUM MECHANICS AND QUANTUM SYSTEMS.

FOR EXAMPLE:

Biophysicist Gregory Engel and his colleagues cooled a green sulfur bacterium—*Chlorobium tepidum, one of the oldest photosynthesizers on the planet—to 77 kelvins [–321 degrees Fahrenheit] and then pulsed it with extremely short bursts of laser light.*



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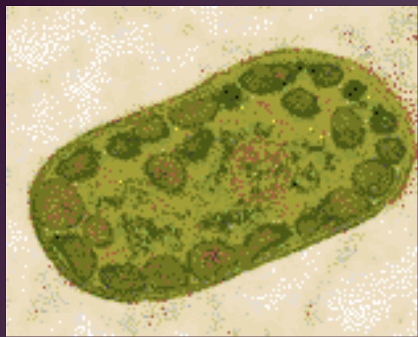
By manipulating these pulses, the researchers could track the flow of energy through the bacterium's photosynthetic system.

It seems that plants are employing the basic principles of quantum mechanics to transfer energy from chromophore (photosynthetic molecule) to chromophore until it reaches the so-called reaction center where photosynthesis, as it is classically defined, takes place.
The particles of energy are behaving like waves.



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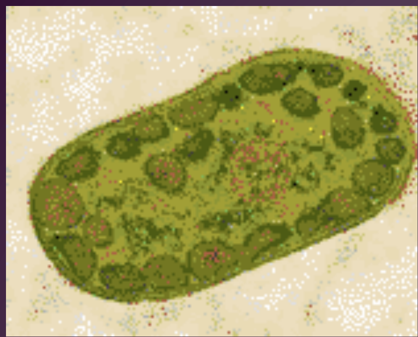

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QUANTUM BIOLOGY?

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"The mathematical predictions of quantum mechanics yield results that are in agreement with experimental findings. That is the reason we use quantum theory. That quantum theory fits experiment is what validates the theory, *but why experiment should give such peculiar results is a mystery. This is the shock to which Bohr referred.*"

Marvin Chester with slight modifications.

"All mass is interaction."

Richard Feynman

"Stuck on this carousel
my little eye can catch
one-million-year-old
light.

A vast pattern — of which
I am a part…

What is the pattern or the
meaning or the *why?*

*It does not do harm to the
mystery to know a little
more about it."*

Richard Feynman

CREDITS

The Kavli Institute for Theoretical Physics (KITP)
at the University of California, Santa Barbara,
David Gross, Director

The plenary presenters at the 2009 Teachers' Conference:

Paul Corkum (National Research Council of Canada)

Peter Knight (Imperial College, London)

Martin Plenio (Imperial College, London)

Yaron Silberberg (Weizmann Institute, Israel)

and

Roy J. Glauber (Harvard University)