The Physics of Vacuum 1

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OVERVIEW

Vacuum Idea Development

Beginning from Buddha until Present times

The Concept of Vacuum in Ancient times

Levels of the Reality

Void,
Fire,
Air,
Water,
and Earth.

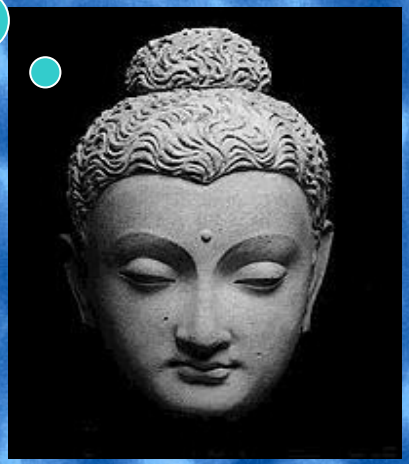
5 — ***The Physical Vacuum***

4 — ***Plasma***

3 — ***Gas***

2 — ***Liquid***

1 — ***Solid***

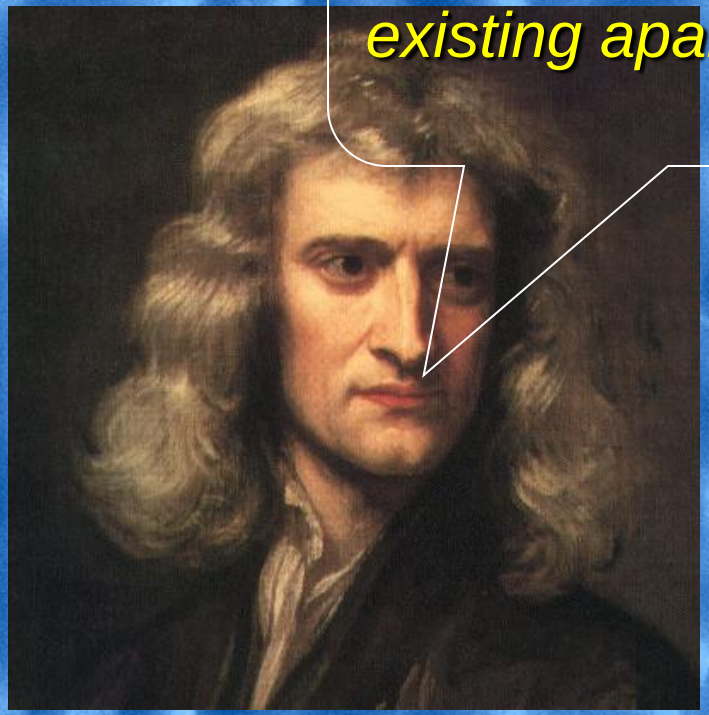


Buddha (6th c. BC)

Modern physics

The debate on the nature of space engaged the Greatest minds of Science :

Space is the sensorium of God. It is absolute, existing apart from matter.



Isaac Newton
(1642-1727)

Space is relative and must be thought of as a set of relationships between material objects.

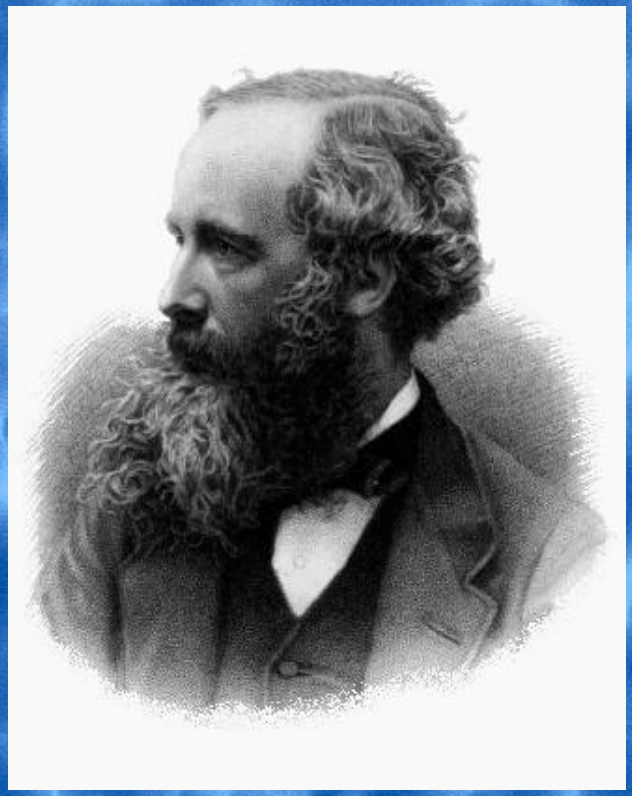
Gottfried Wilhelm
Leibniz (1646-1716)

Summary of the Vacuum in Classical Mechanics:

- Vacuum is 3D "absolute" space
- The passive "stage" not effecting the "play" of force and motion.
- Space is static and unchangeable.
- Geometry is Euclidean.
- Time marches according to an absolute, universal clock.

Electromagnetic Waves and Ether

- We are familiar with many types of waves: water waves, sound waves…
- In each case as above the wave needs some medium (water, air, …) to propagate.
- In 1863, James Clerk Maxwell demonstrated that light was an electromagnetic wave.
- "Obviously," light should propagate in a physical medium too. This medium replaced Ether.



James Clerk Maxwell (1831-1879)

The Special Theory of Relativity (1905)

- Einstein elevated the Michelson-Morley null result up to fundamental principles of Nature: There is no Ether and

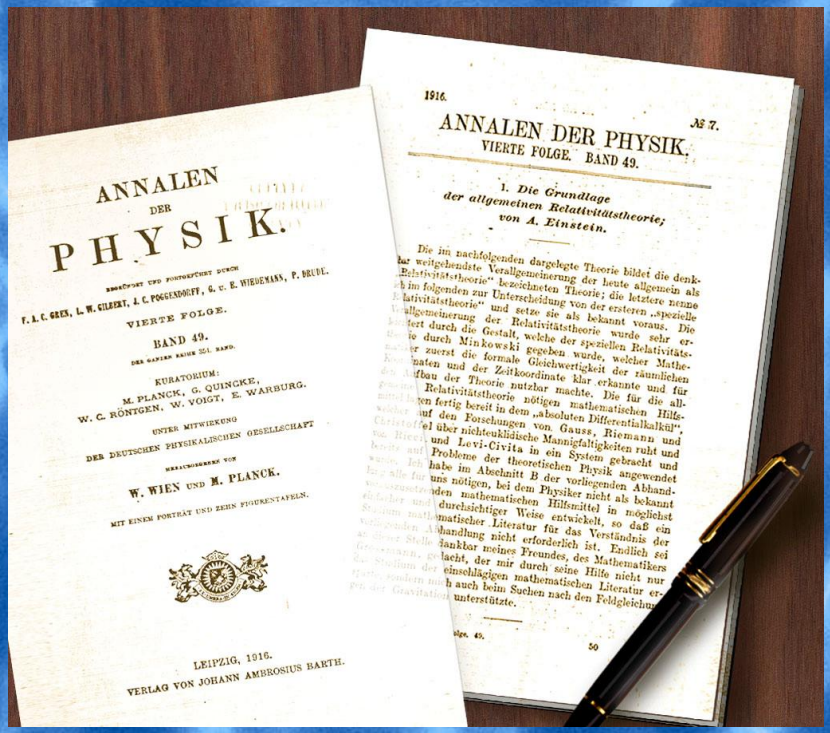
> ***The speed of light is constant, independent from the motion of the source or the observer.***

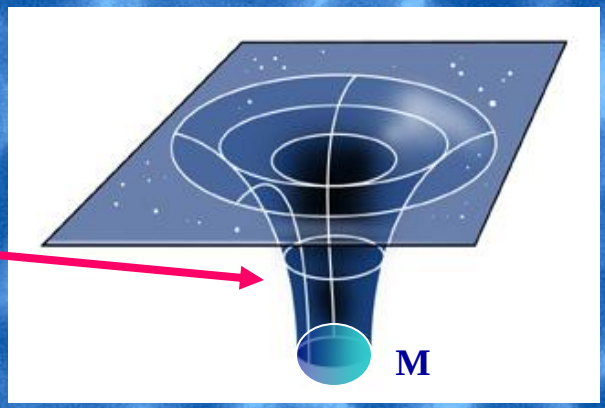
This fact made him to interpret "space" and "time" as a single entity:

Albert Einstein (1879-1955)

The General Theory of Relativity (1915)

- Matter warps spacetime; falling object follows straight lines in the curved 4D spacetime.
- "Space tells matter how to move; matter tells space how to curve"
- Ether is Physical Vacuum, possessing properties of elasticity

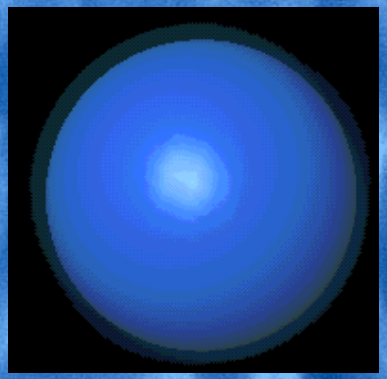




Summary:
Vacuum in General Relativity

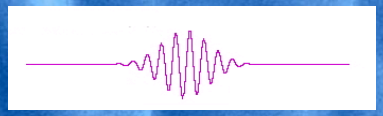
- Active player in the dynamics of physics.
- Space can change. In fact, it is difficult to attain a static Universe . The dynamics of spacetime determines the fate of the Universe.
- Geometry can be non-Euclidean.
- Vacuum is to be described by the equations, which were confirmed experimentally

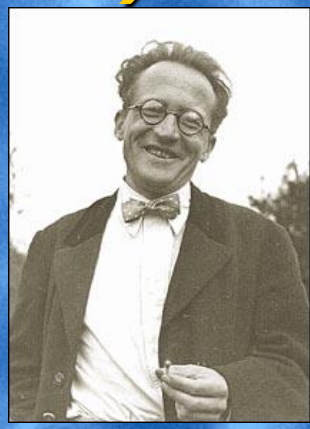
Schrödinger's Wave Mechanics (1926)



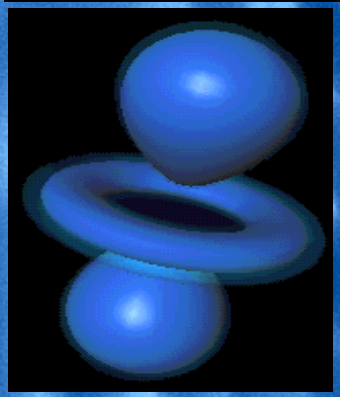
$$i\hbar\frac{\partial}{\partial t}\Psi = -\frac{\hbar^2}{2m}\nabla^2\Psi + V\Psi$$

Wave – Particle

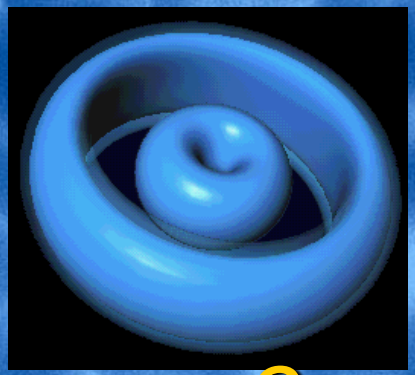


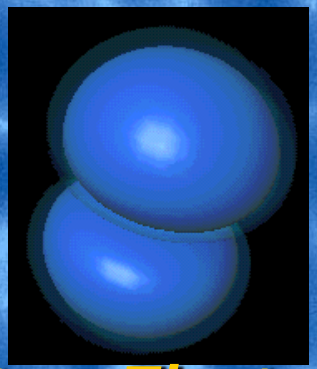


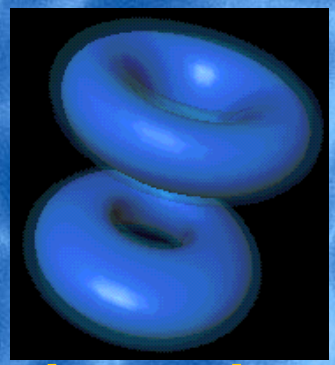
Erwin Schrödinger (1887-1961)

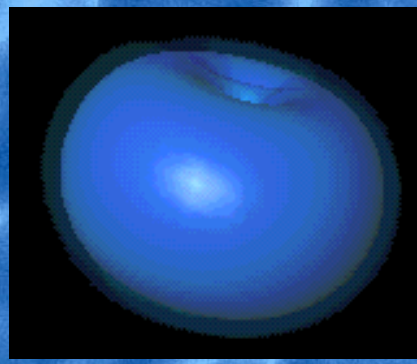


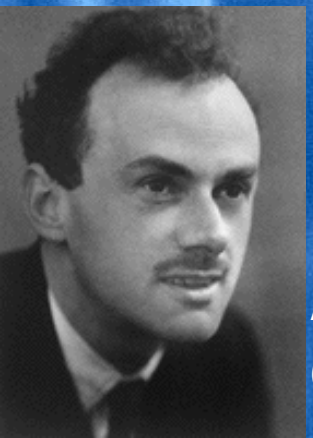
The Schrödinger's equation predicts the structure of all atoms









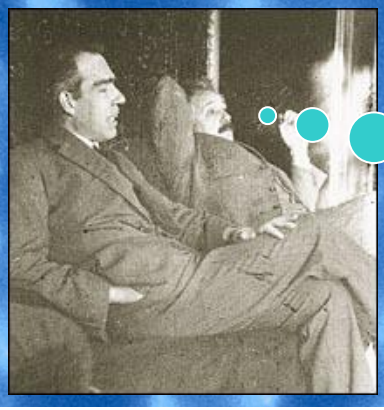


Paul Dirac (1902-1984)

Quantum Electrodynamics is the most accurate theory known to mankind. A predicted precision is better than a part in a billion

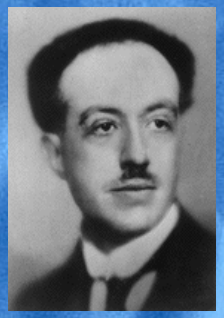
The Quantum Crisis

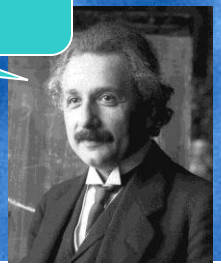
Bohr and Einstein in discussion 1933



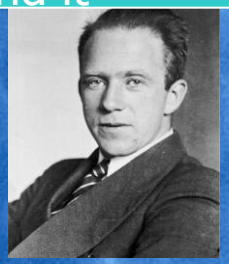
God does not play dice !

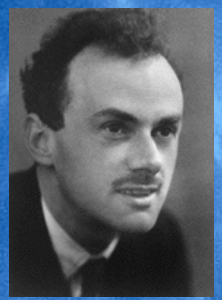
We don't understand Quantum Physics





It is not necessary to understand it





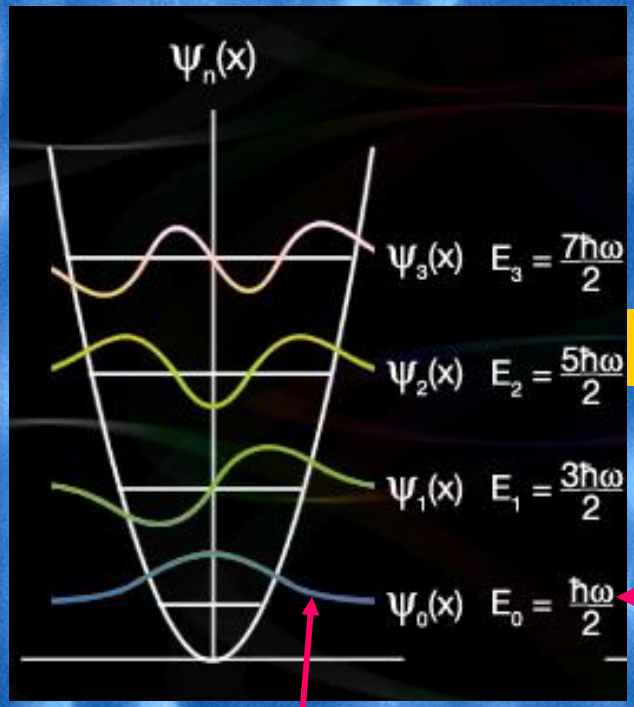
$$
\begin{aligned}
&Einstein && \mathbf{p} = \hbar\mathbf{k} \\
&Plank && E = \hbar\omega \\
&de\ Broglie && \psi = \psi_0\ \exp(-i\frac{E}{\hbar}t - i\frac{\mathbf{p}}{\hbar}\mathbf{r}) \\
&Schrödinger && i\hbar\frac{\partial\psi}{\partial t} = \hat{H}\psi
\end{aligned}
$$

$$
\begin{aligned}
&Bohr && \hbar\omega_{mn} = E_m - E_n \\
&Heisenberg && q_{mn} = a_{mn}\exp(i\omega t) \\
&Born && W = \psi^*\psi \\
&Dirac && (\gamma^n\frac{\partial}{\partial x^n} + \frac{mc}{\hbar})\psi = 0
\end{aligned}
$$

Later have accepted Einstein's point of view

Vacuum Energy

Quantum Oscillator

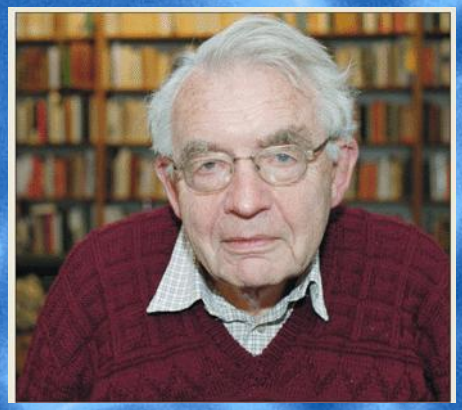


$$i\hbar\frac{\partial}{\partial t}\Psi = -\frac{\hbar^2}{2m}\nabla^2\Psi + V\Psi$$

$E_n = (n+ ½)\hbar\omega \quad (n=0,1,2\ldots)$

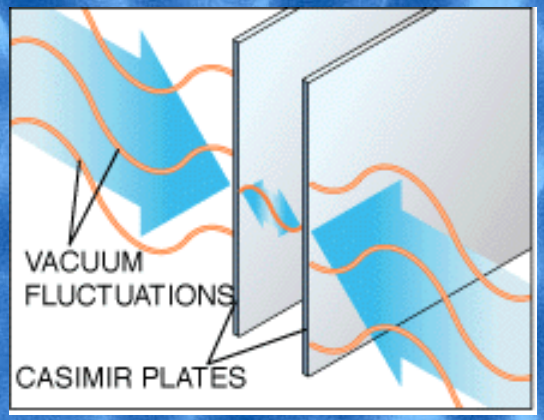
Zero-point 'vacuum fluctuation' energy

The minimum possible energy for the quantum oscillator is $E_0 = ½ \hbar\omega$.

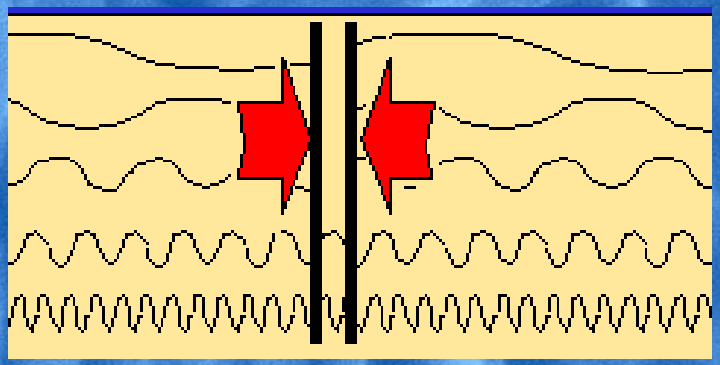


Hendrik Cazimir (1909-2000)

Casimir Effect



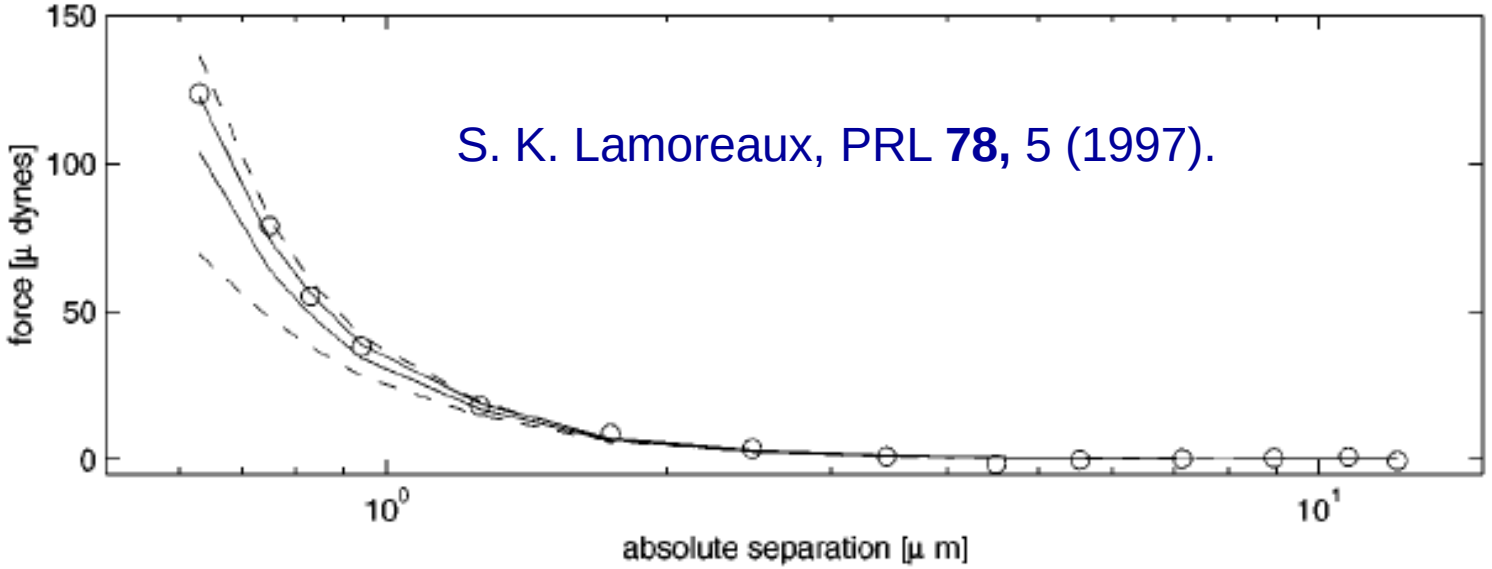
Vacuum is a seething fluctuation of electromagnetic field



Prediction (1948): A weak attractive force between the two mirrors:

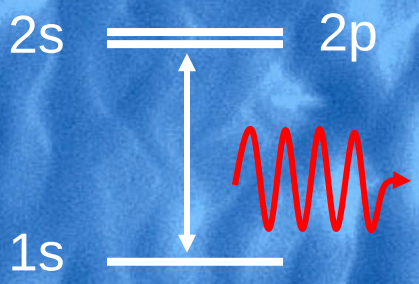
$$F = \frac{\pi hc}{480 d^4}(\text{Area})$$

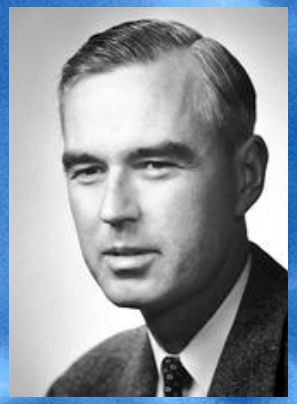
That force was measured in 1996:



S. K. Lamoreaux, PRL **78,** 5 (1997).

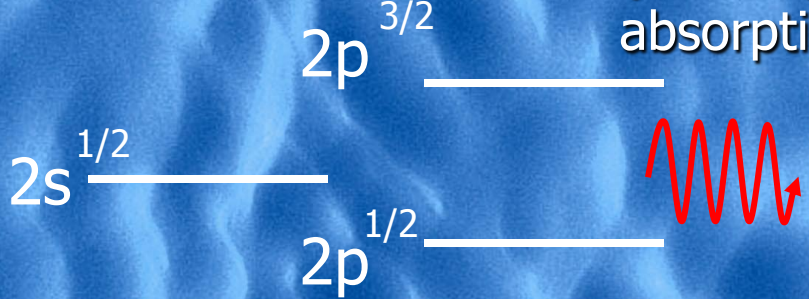
Lamb Shift
in the hydrogen atom produced by





Willis Lamb (1913-2008)

Vacuum Fluctuations (virtual photon emission and absorption)



$\gamma \approx 1075$ MHz

The Energy of Vacuum:

- With the quantum nature of the vacuum this is no longer required that the energy density of the vacuum is zero.
- We can calculate the vacuum energy density, E_{vac}, by adding up the zero-point energies of all the quantum oscillators that make up the fields.

Theory:

$E_{vac} \longrightarrow$ infinity (simplest calculation)

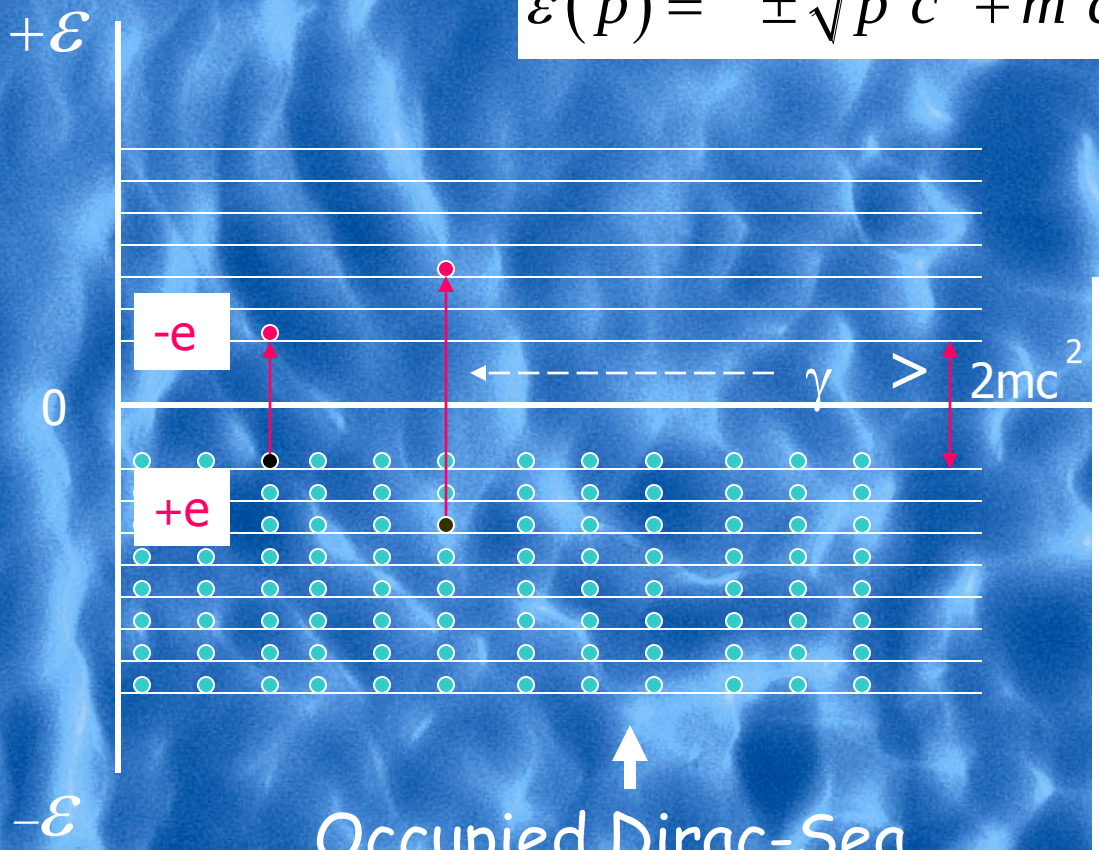
$E_{vac} = 10^{55}$ (calculation - supersymmetry)

Reality:

$\langle E \rangle_{vac} \approx 0$

Electron- Positron Vacuum of Dirac

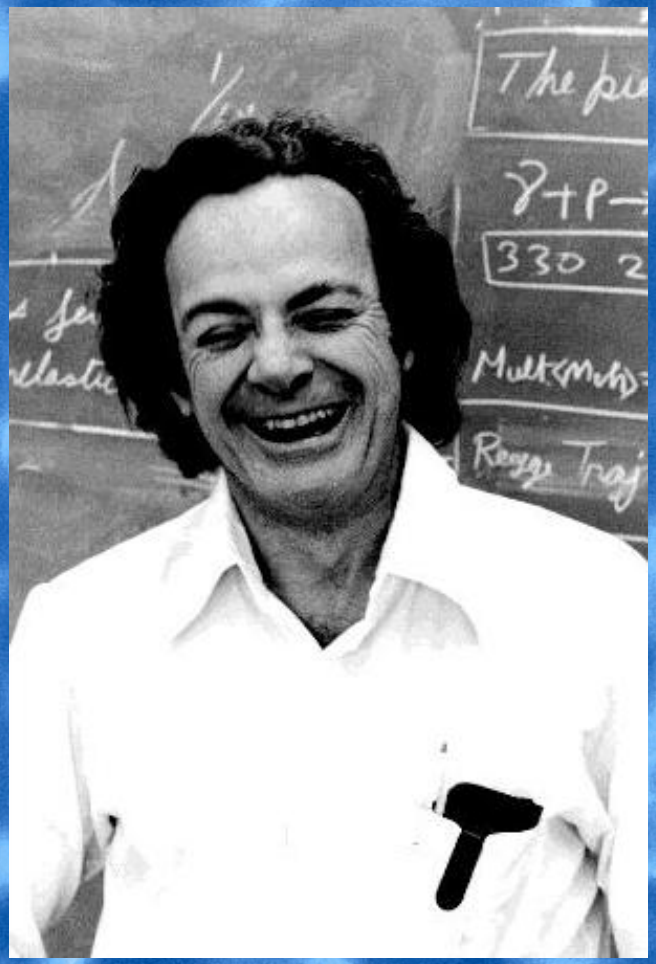
$$\varepsilon(p) = \pm\sqrt{p^2c^2 + m^2c^4}$$



- *Photon of energy > 2 mc² can excite electron from negative energy state to empty positive energy state*
- *e⁺e⁻ pair creation!*
- *Hole in electron sea of vacuum = positron*
- *(analogy: solid state physics: metals)*
- *1st model for vacuum structure ever: Dirac sea*
- *Prediction of antiparticles*

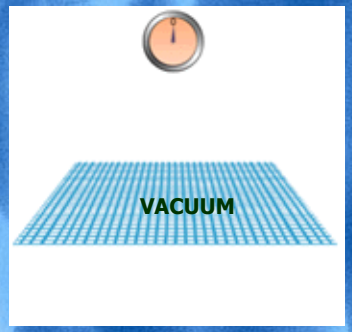
Quantum Fields

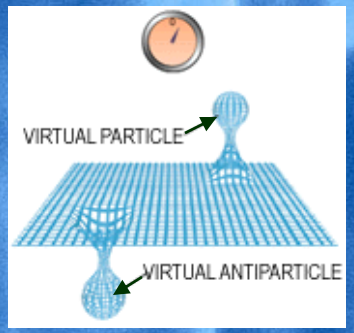
- Relativity meets quantum mechanics: everything is an oscillator!
- Each type of particle (photon, electron,…) is described by a field that fills all the space.
- At each point in space, the field has the ability to oscillate at any frequency.
- Vacuum is the sea of the quantum oscillators

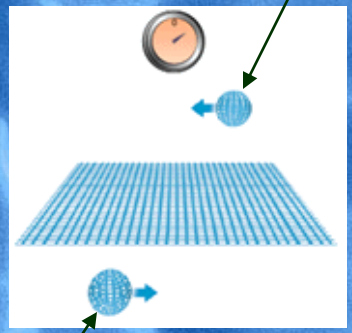


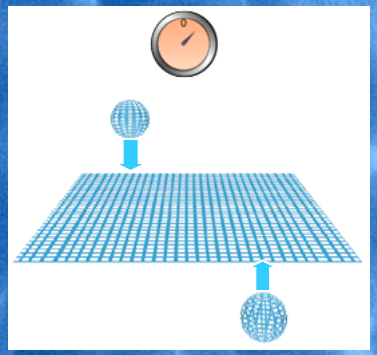
Richard Feynman (1918-1988)

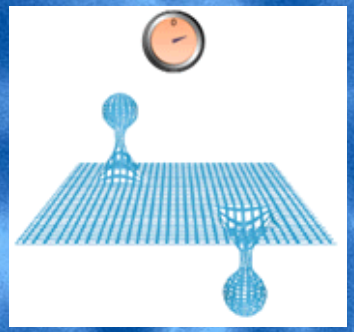
Virtual and Real Particles

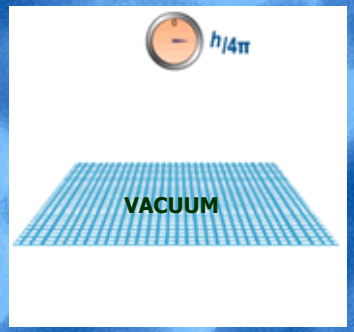










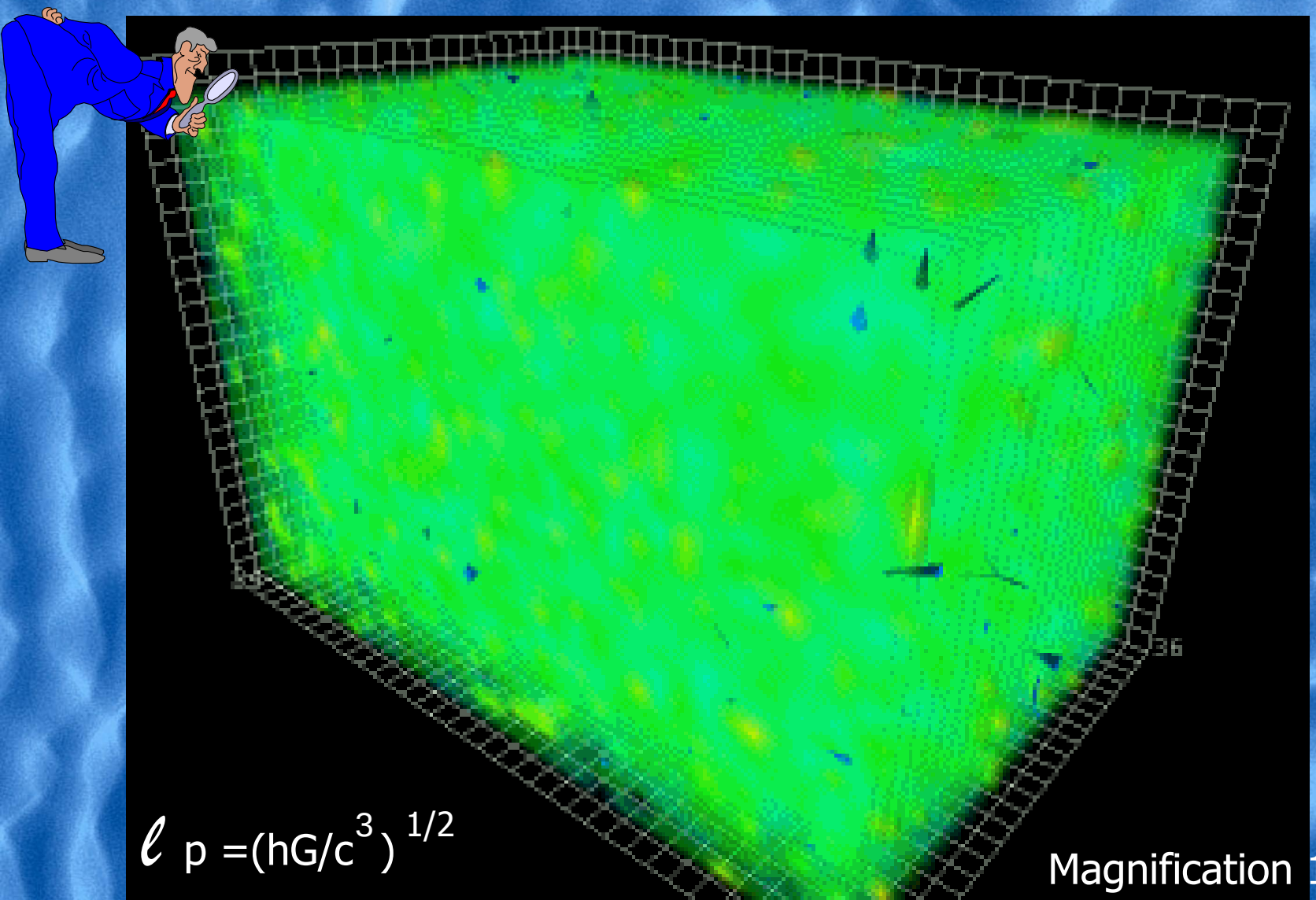


Main Law of Conservation of the Physical Vacuum

$0 \equiv 0$

A simulation of the Physical Vacuum

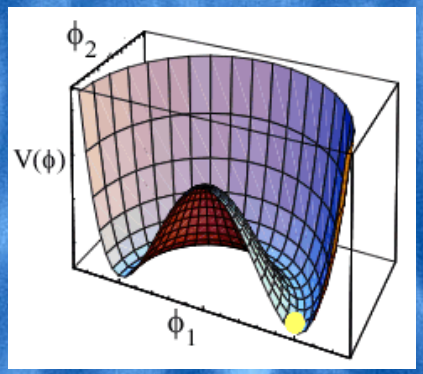
$\ell_p = 16.163 \times 10^{-36}$ m

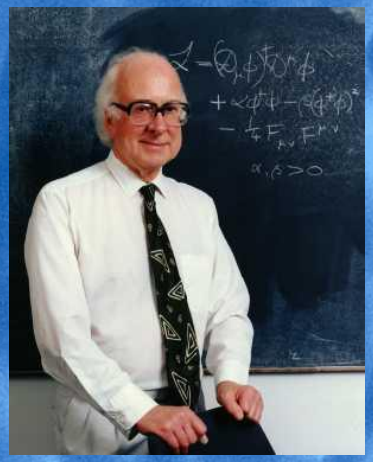


$\ell_p = (hG/c^3)^{1/2}$

Magnification 10^{34}

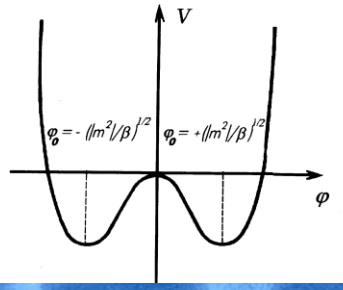
Spontaneous vacuum symmetry breaking

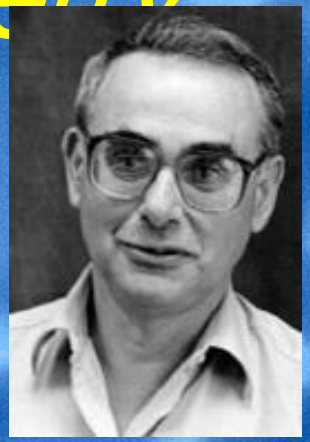




Peter Higgs

$$\Box\varphi - \mu^2\varphi + \beta\varphi^3 = 0\ ,$$





Jeffrey Goldstone

Goldstone Theorem

Every symmetry of nature, that is not a symmetry of the ground State implies the existence of an elementary particle.

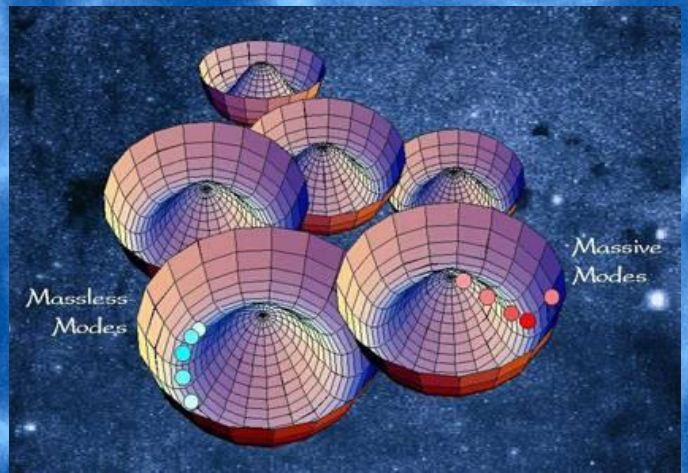
$$V(\phi) = -|\mu^2||\phi|^2 + \lambda\left(|\phi|^2\right)^2$$

$\mu^2 < 0$

The Higgs boson mass

$m_H = (-2\mu^2)^{1/2}$

God particle



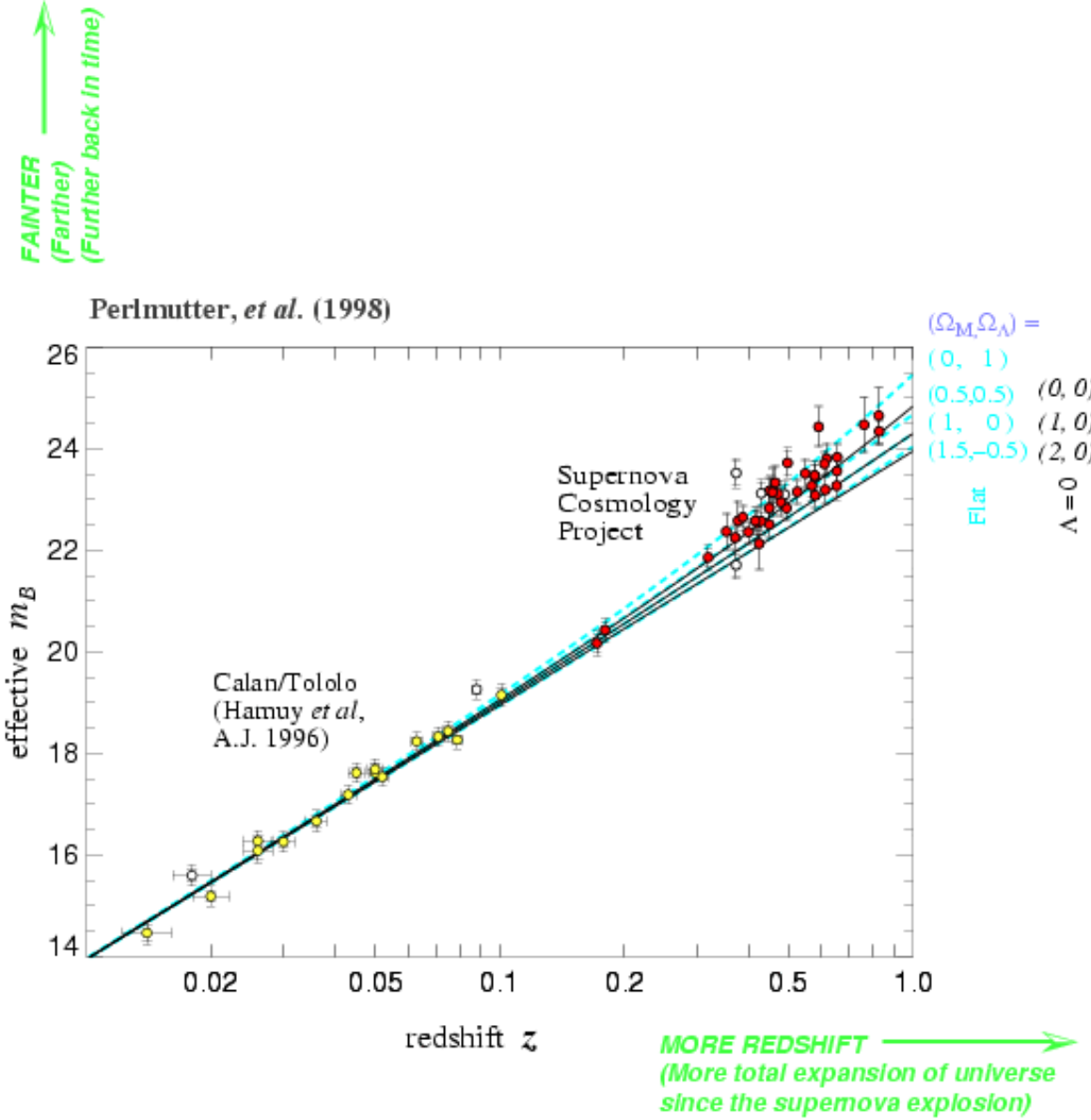
Summary of the Quantum Vacuum

- Filled with the fields corresponding to each type of a particle.
- Think of the field as describing the potential for particles to exist.
- Quantum fluctuations of the fields, even when no particles are present, meaning that the vacuum contains a sea of "virtual particles".

Dark Energy - is the Energy of Physical Vacuum in the Space

Perlmutter et al., 1998
Riess et al., 1998

The Universe was expanding slower in the distant past!



In flat universe: $\Omega_M = 0.28$ [± 0.085 statistical] [± 0.05 systematic]

Prob. of fit to $\Lambda = 0$ universe: 1%

Dark Energy

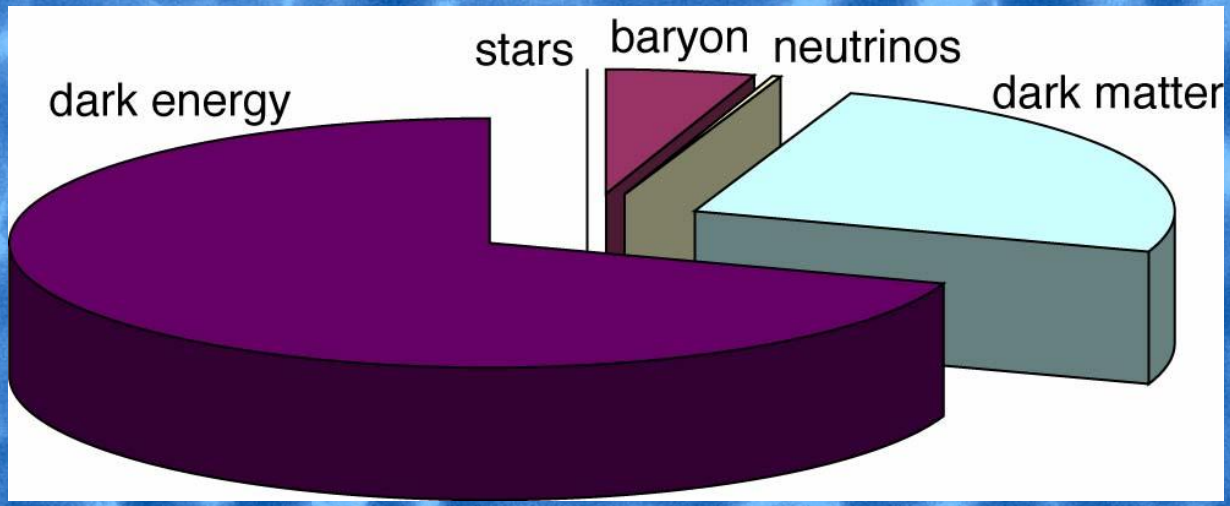
- The vacuum appears to have a nonzero energy density that is propelling the accelerating expansion of the Universe.
- Data (Feb. 2003):

$$E_{vac} = 0.73 \pm 0.04$$

- This result implies that nearly ¾ of the energy density of the Universe resides not in matter or radiation but in the Vacuum itself!
- **The cosmological constant: Einstein's greatest legacy?!**

Energy budget of Universe

- Stars and galaxies are only ~0.5%
- Neutrinos are ~0.3–10%
- Rest of ordinary matter (electrons and protons) are ~5%
- Dark Matter ~30%
- Dark Energy (vacuum energy of the space) ~65%
- Anti-Matter 0%



Conclusion

The vacuum is a dynamic place:

- Space and time are intertwined.
- Curved by matter; this curvature affects motion.
- A roiling sea of virtual particles created by quantum fluctuations.
- Contains a nonzero energy density that makes up ~70% of the energy of the Universe. The nature of this "dark energy" is almost completely unknown.
- The dark energy propels the accelerating expansion of the Universe.

Perhaps <u>the</u> hottest topic in physics right now.

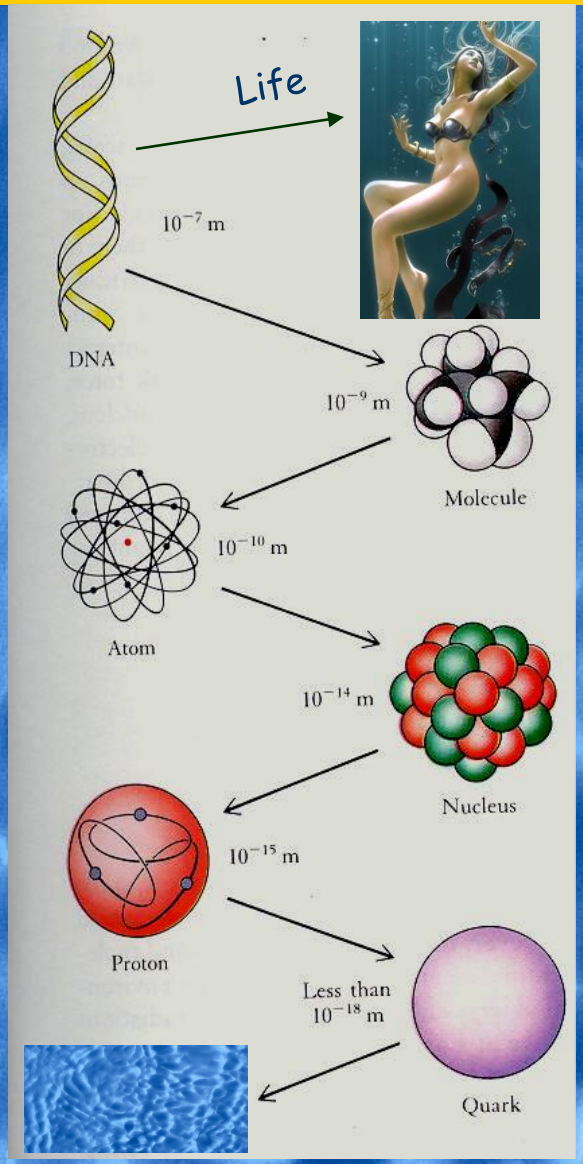
Of what we consist?

DNA

Atom

Proton

Vacuum



Life

Molecule

Nucleus

Quark

We are highly organized vacuum!

Kob Khun Krab!

Thank You for Your Attention

To be continued by
Vacuum 2