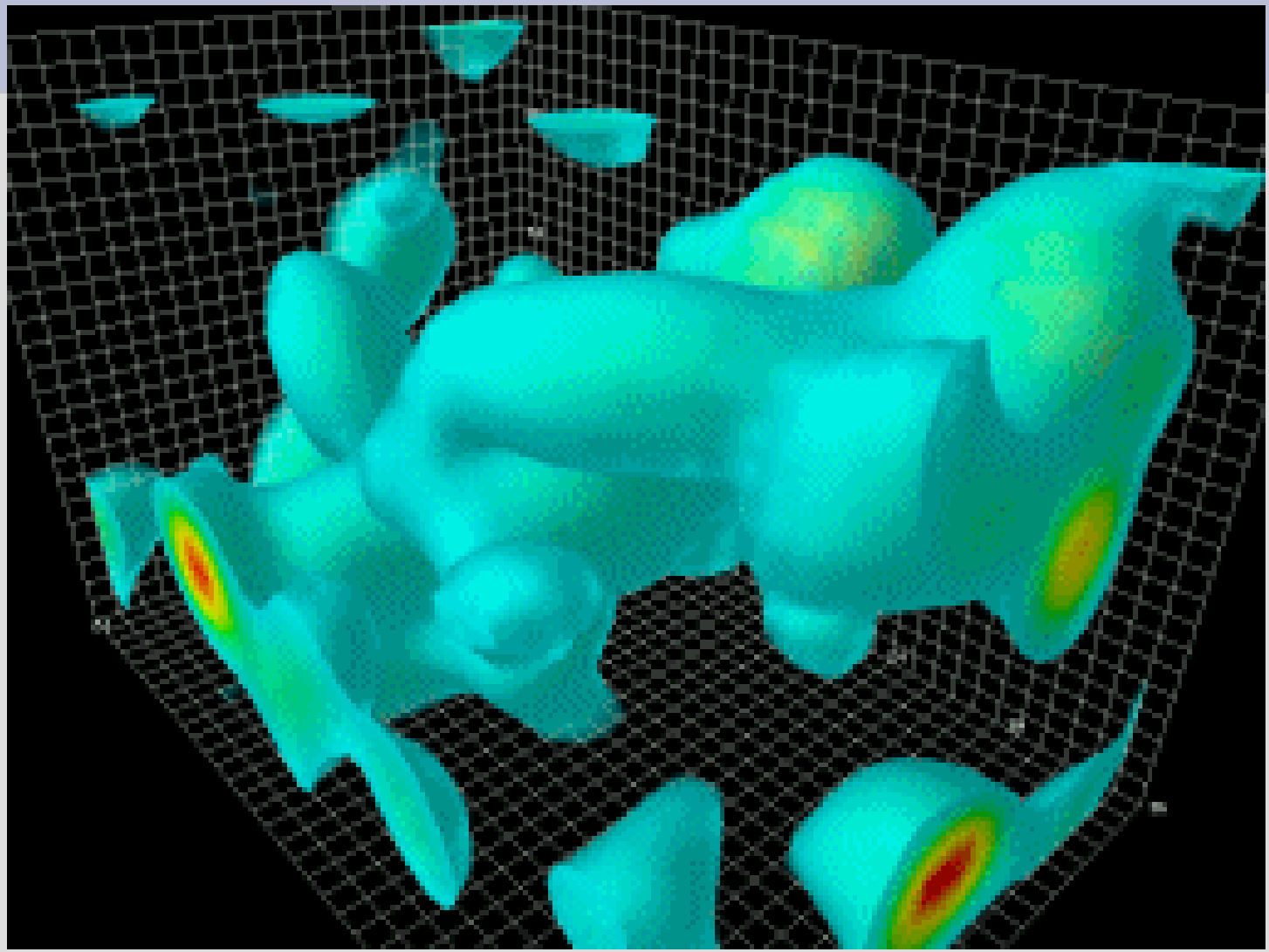
The **vacuum** is not empty

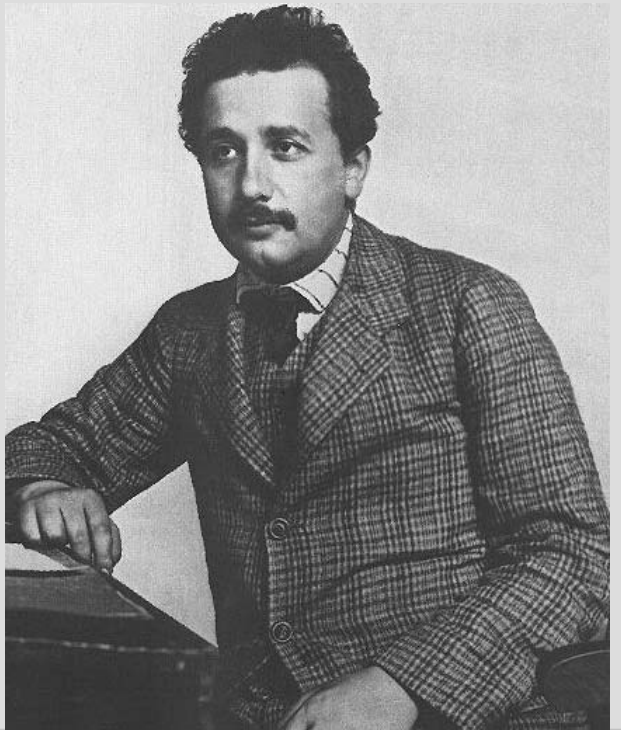


Vacuum, the primordial imponderable “matter”

Johann Rafelski, Department of Physics, U of Arizona
presented at Ecole Polytechnique, March 20, 2009

Primordial aether: with Aristotle, Maxwell, Einstein, Dirac we ponder the question – what is the empty space, is there an aether?

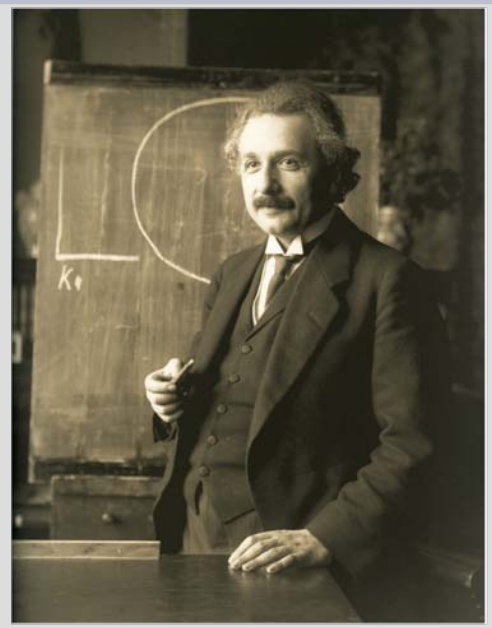
Einstein 1920: “But this aether may not be thought of as endowed with the quality characteristic of ponderable media, as consisting of parts which may be tracked through time. The idea of motion may not be applied to it.”



How can the laws of physics be known in all Universe?

"Recapitulating, we may say that according to the general theory of relativity space is endowed with physical qualities; in this sense, therefore, there exists an aether"

"According to the general theory of relativity space without aether is unthinkable; for in such space there not only would be no propagation of light, but also no possibility of existence for standards of space and time (measuring-rods and clocks), nor therefore any space-time intervals in the physical sense."



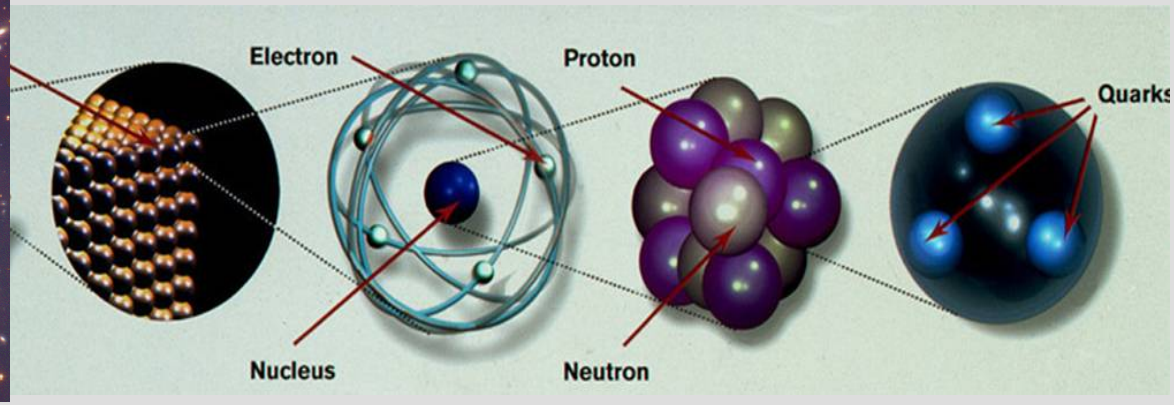
Albert Einstein, "Ather und die Relativitaetstheorie" (Berlin, 1920):

The laws of physics are **encoded** in vacuum structure

Why are stars the same everywhere in the Universe

We “see” everywhere we can look in the Universe that the laws of physics are the same as far back in time we can look.

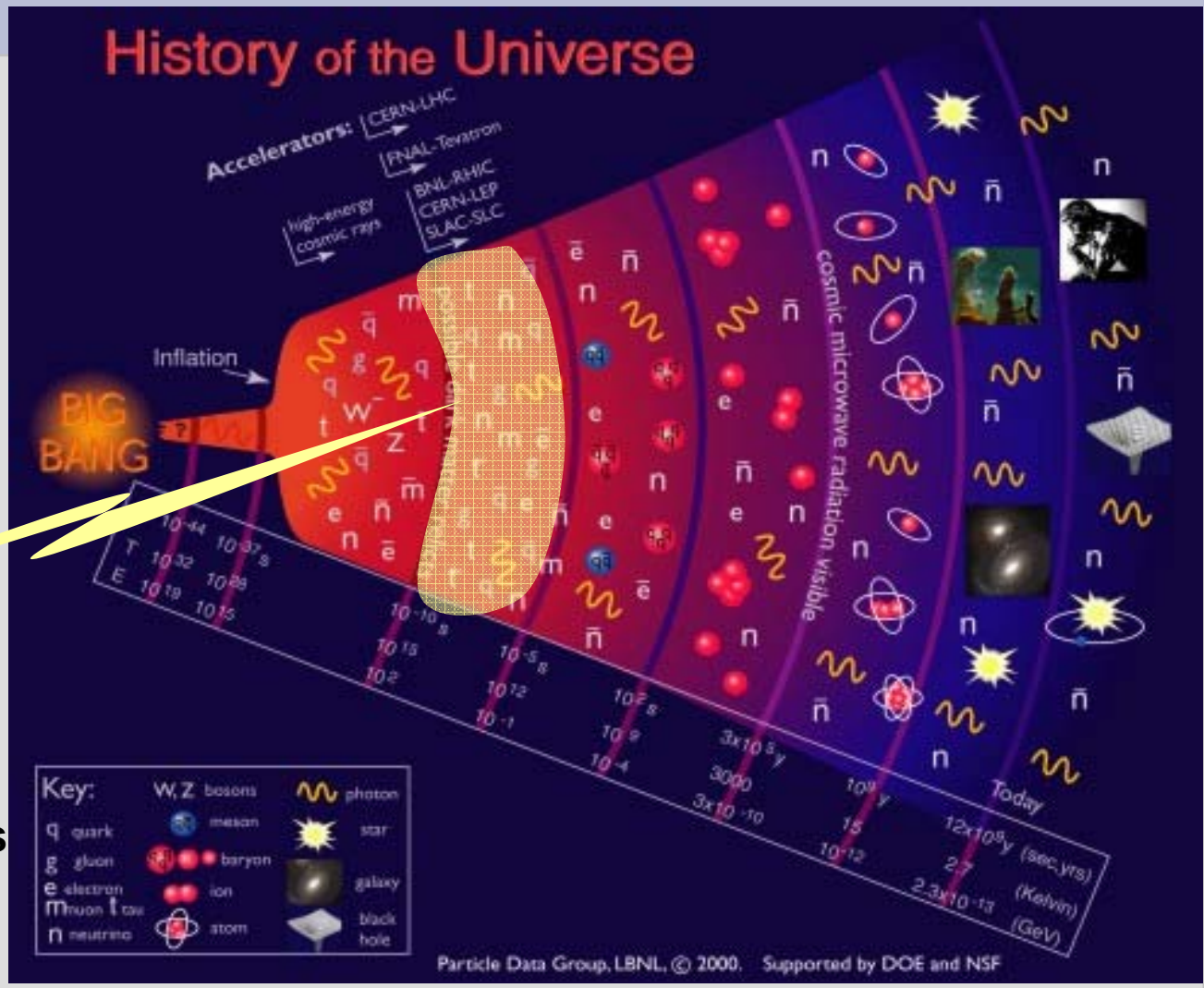
We conclude: THE VACUUM (aether) IS THE SAME



How was matter created?

Matter emerges from quark-gluon plasma

After Big-Bang the "vacuum" was different till about at 30 μs – expansion cooled the temperature T to a value at which vacuum changed and our matter "froze out". At that time the density of matter was about ~10^{16} gm / cm^3 (energy density ~ 10 GeV / fm^3, well above that of the center of neutron stars, that is ~60 times nuclear energy density), and temperature was T ~ 160 MeV, that is ~ $2x10^{12}$K.



Four elements and the aether

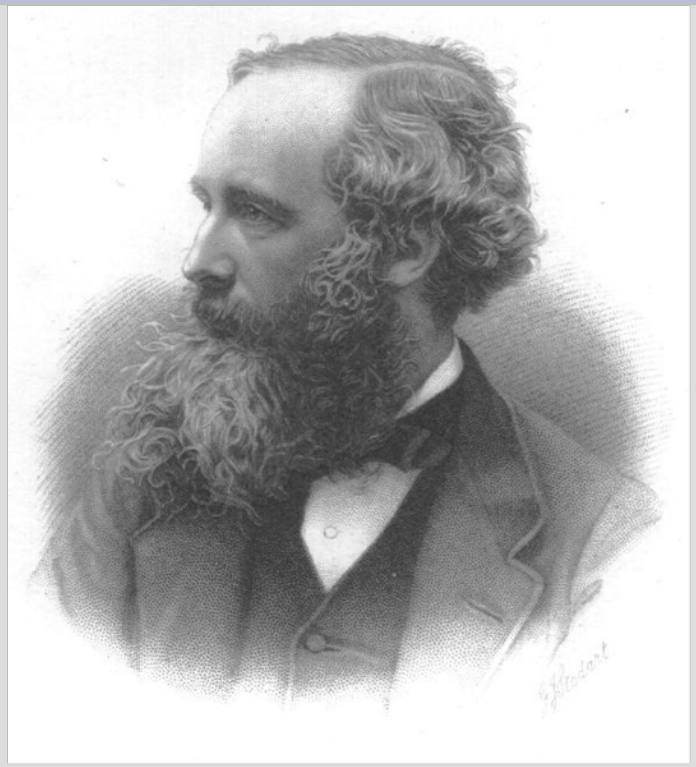
- The word aether in Homeric Greek means ``pure, fresh air'' or ``clear sky'', pure essence where the gods lived and which they breathed. The aether was believed in ancient and medieval science to be the substance that filled the region of the universe above the terrestrial sphere.

Fire:=energy; Air:=gas phase; Water:=liquid phase; Earth:=solid phase; Aether=vacuum

Aether fills the Vacuum

The ancient Greek philosophers needed “vacuum” to harbor indivisible atoms. Aristotle imposed aether as a fifth element filling all space. Aether was hence also called quintessence (from quinta essentia, "fifth element"). The "luminiferous aether" (light carrying aether) is the “substance” believed by Maxwell to permeate all the Universe..

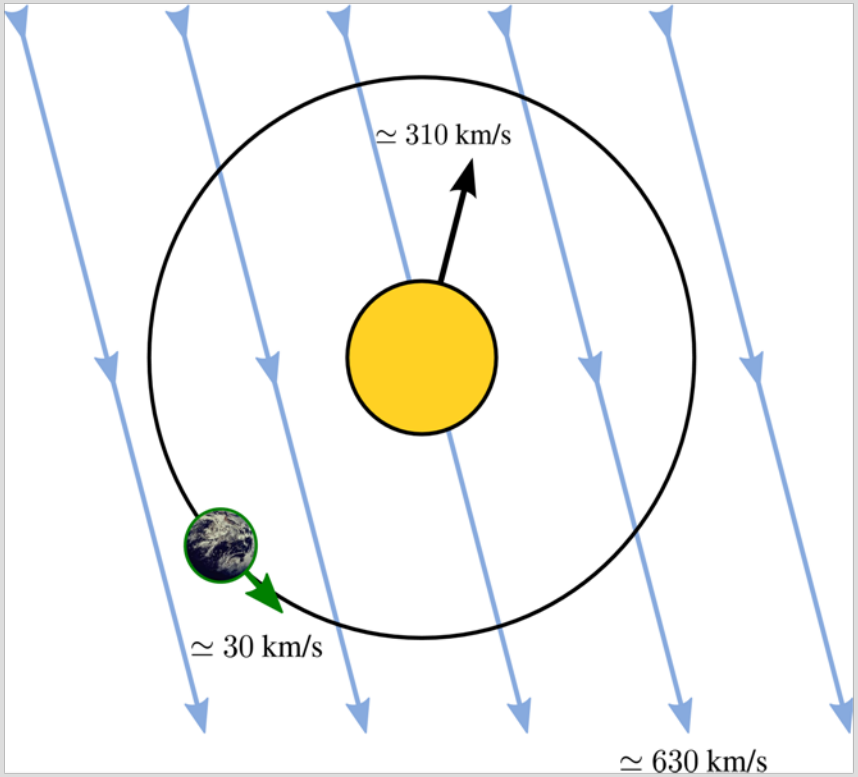
Maxwells “great guns” discovery: electromgnetic waves propagate at same speed as light; Maxwell is sure that the aether assures propagation of a new family of waves just like air does for sound,



James Clerk Maxwell, 1831-1879

Maxwell's aether is as hard as a rock, to assure that light waves would be transverse to direction of motion. In fact all force mediating gauge fields we discovered in past 150 years are transverse!

No aether wind, no drag

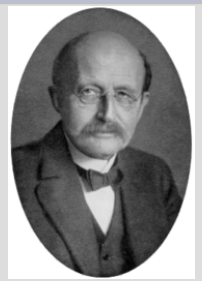


The Earth moves in space (today we even know the speed with reference to the big-bang frame of reference). Michelson-Morley experiment: no aether dragged along, birth of Lorentz-Fitzgerald contraction and relativity. Einstein 1905: who needs aether? Newton's vacuum is back, but all inertial observers are equivalent (principle of relativity).

Einstein's view changes drastically by 1920

Quantum Mechanics $\hat{H}|\psi\rangle = i\hbar\frac{\mathrm{d}}{\mathrm{d}t}|\psi\rangle$

The quantum uncertainty challenges the idea of "empty" space free of matter


M Planck


N Bohr


L de Broglie


E Schroedinger


W Heisenberg


M Born

The uncertainty principle of quantum physics

$$\Delta E \cdot \Delta t \geq \hbar$$

Forbids a truly empty world

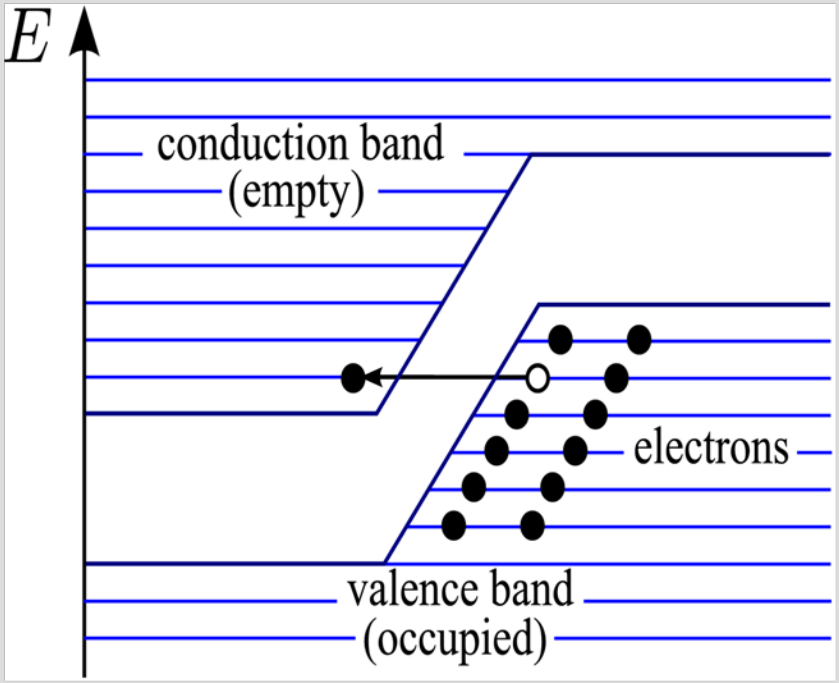
radiation fluctuations in vacuum needed to induce radiative atomic transitions.

Vacuum = "ground state" of lowest energy of a physical system

...enter relativistic quantum
Paul Dirac, St Maurice, VS

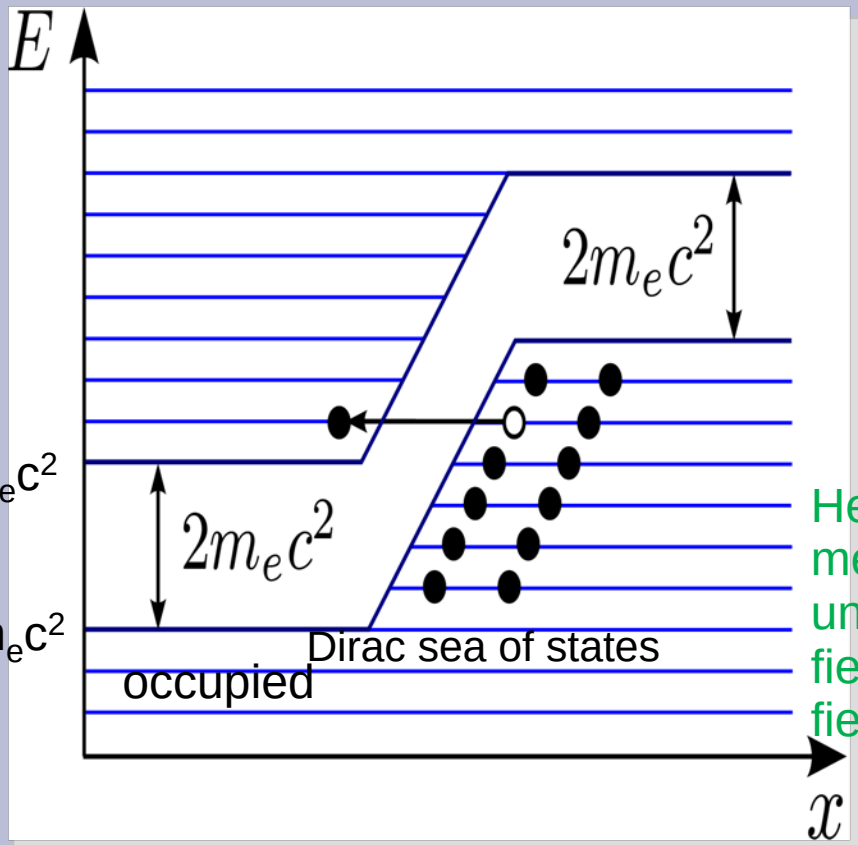
Relativistic quantum physics

The equation relating energy, mass and momentum in special relativity is: $E^2 = p^2c^2 + m^2c^4$, in quantum physics there are two possible energy bands $E = \pm mc^2$.



The relativistic gap in energy reminiscent of insulators, where conductive band is above the valance (occupied) electron band

Dirac sea and “anti” matter

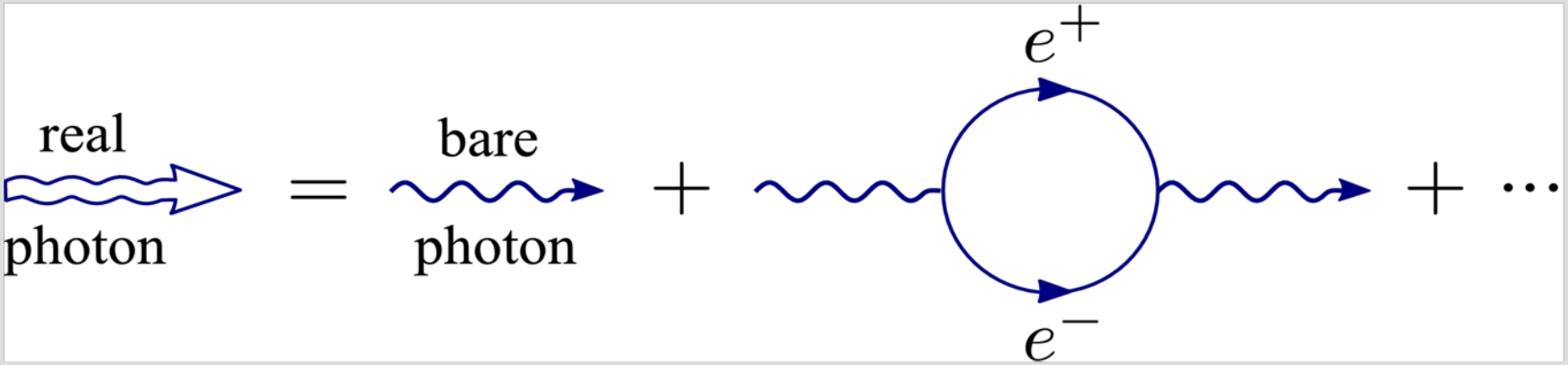


Dirac equation has negative energy states: to stop collapse of matter **Dirac invokes Pauli principle and postulates antimatter:** Positrons are holes in the occupied sea of electrons.

Heisenberg recognizes tunnelling as a new quantum mechanism of pair production. Any electric field is unstable (with a very long lifespan except when fields “bridge” the gap. Nonperturbative quantum field physics ahead of Feynman diagrams

... with the new theory of electrodynamics we are rather forced to have an aether.
– P.A.M. Dirac, ‘Is There an Aether?,’ *Nature*, v.168, 1951, p.906.

The vacuum is a dielectric



The vacuum is a dielectric medium: a charge is screened by particle-hole (pair) excitations. In Feynman language the real photon is decomposed into a bare photon and a photon turning into a “virtual” pair. The result: renormalized electron charge smaller than bare, Coulomb interaction stronger (0.4% effect)

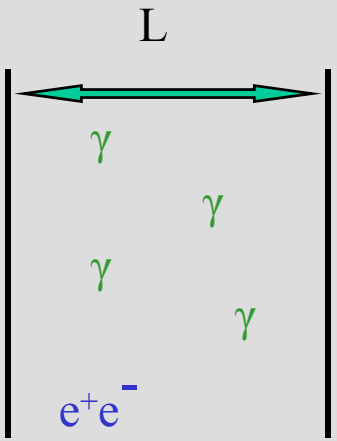
This effect has been studied in depth in atomic physics, is of particular relevance for exotic atoms where a heavy charged particle replaces an electron.

The quantum vacuum fluctuates

Vacuum fluctuations of photons can be measured:

Attractive force between two adjacent metal plates

(Casimir force, 1948) $F = \frac{\pi^2}{240}\frac{\hbar c}{L^4}A$

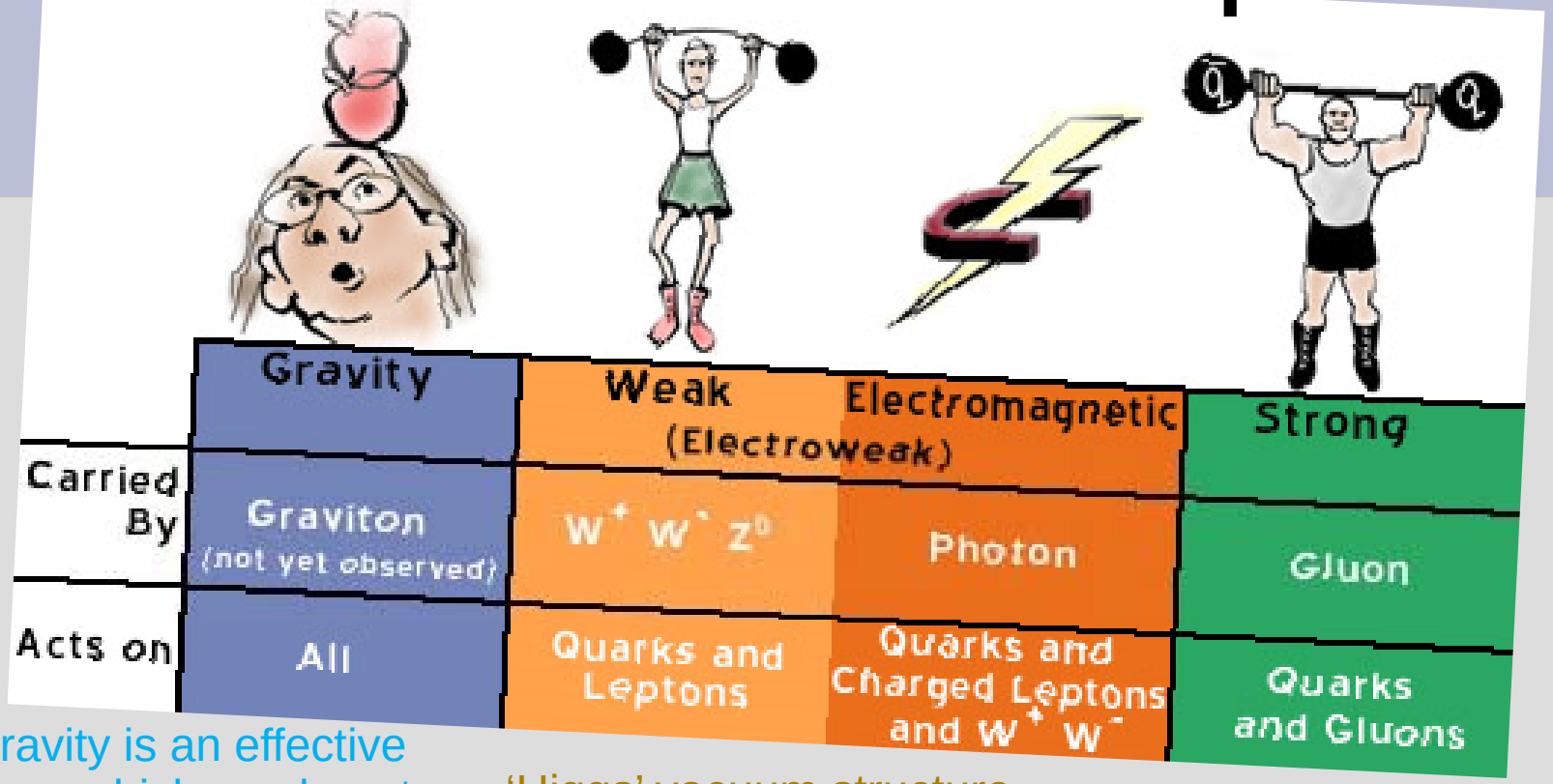


Hendrik B.G. Casimir

More fluctuations outside the plates compared to the space between: outside pressure, plates attract

NOTE: Each ‘elementary’ particle, each interaction add a new element to vacuum structure.

Interactions between matter particles



Gravity is an effective force which we do not understand, **conflict with quantum physics**

'Higgs' vacuum structure breaks the electro-weak symmetry: W,Z turn very massive, weak interactions.

Quantum Chromo-Dynamics (QCD): theory of strong interactions with a confinfinng dynamical vacuum structure

Imagine a world in which photons would have a 'magnetic moment': vacuum would consist from a ferromagnetic alignment of glue fluctuations

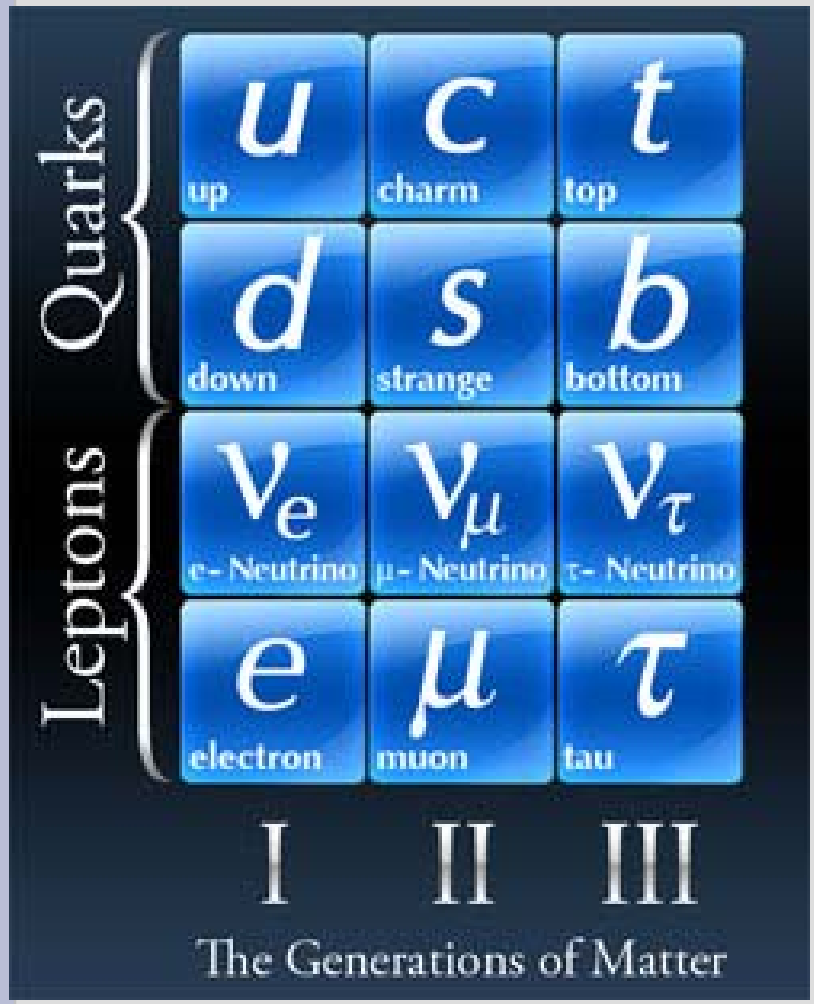
Summary: The particle vacuum

- "Elementary" masses are generated by the vacuum. Two dominant mechanisms:
- Higgs vacuum: <H> = 246 GeV; scale of mass for W, Z; contributes to matter particle mass, all of heavy quark mass
- QCD vacuum latent heat at the level of $<EV_p>=0.3$ GeV =: nuclear mass scale, quarks get mass and are confined.

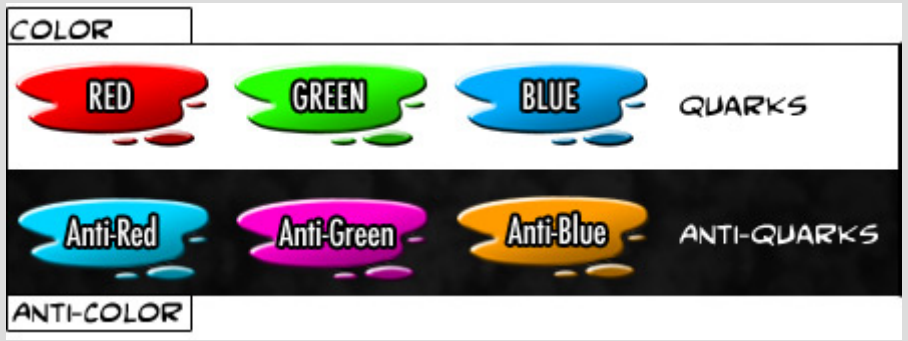
$m_e c^2$ =0.511MeV $m_N c^2$ =0.940GeV

Units are G=giga, M=mega e=electron charge, V=Volt,

‘Fundamental’ matter particles and the origin of the word ‘chromo-dynamics’



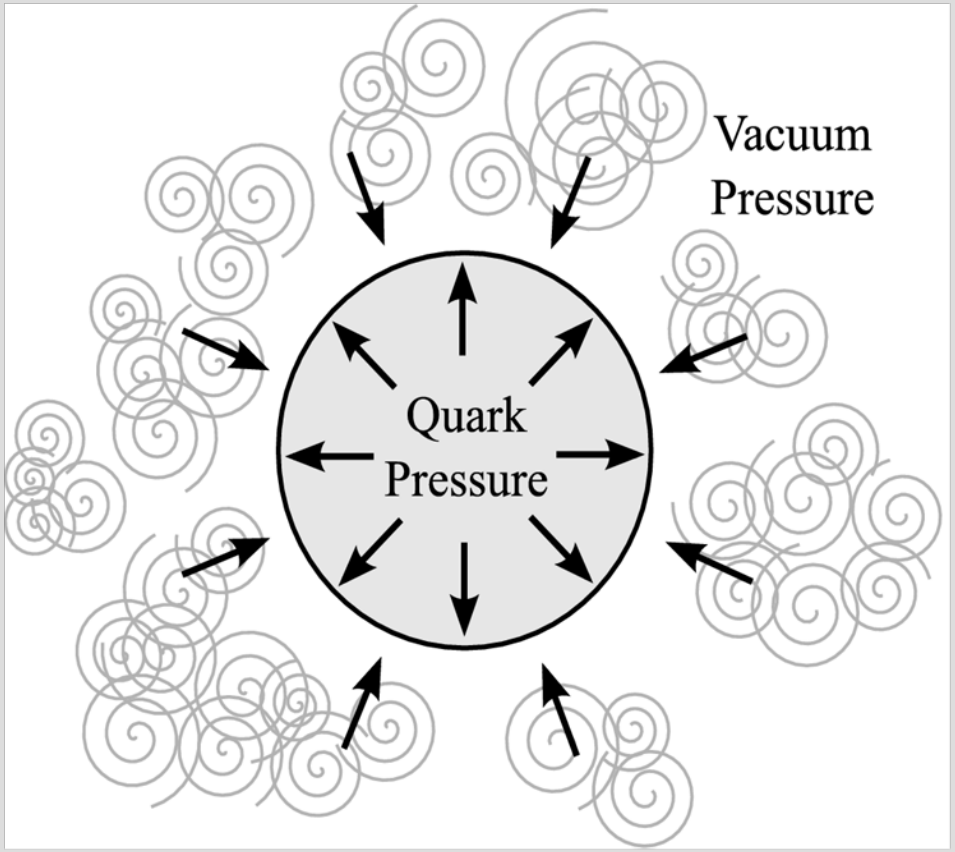
Quarks differ from electrons in an additional charge: the ‘color’



"Color charge" has nothing to do with the visible colors, it is just convenient for book keeping given three fold nature of all quarks and the associated color-anticolor charge of gluons

First generation makes all matter around us. Who ordered generation two and three (paraphrasing Pauli), needed to induce the vacuum structrue

A simple vacuum structure model of quarks bound in hadrons

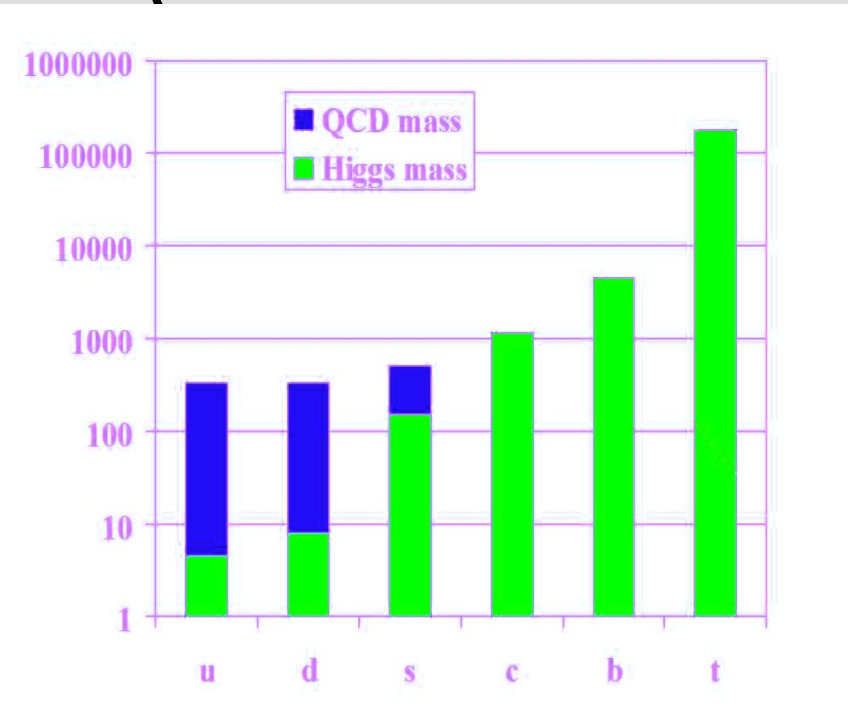


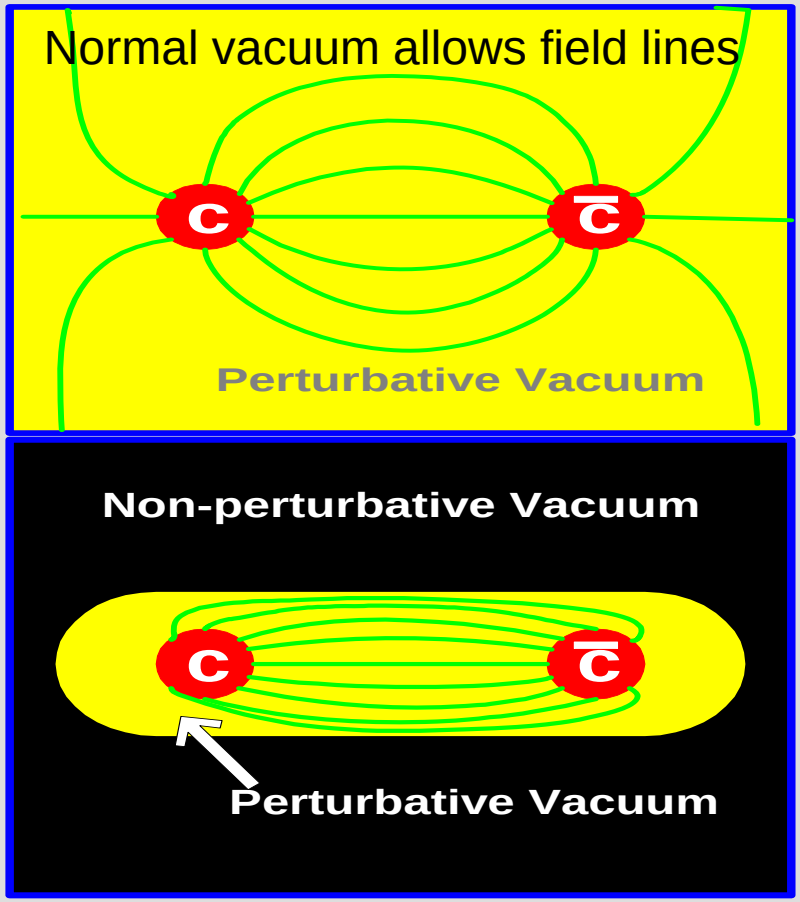
Quarks live inside a domain where the (perturbative) vacuum is without gluon fluctuations. This outside structure wants to enter is kept away by quarks trying to escape.

The model assumes that the energy density E/V=0 of the true vacuum is lower thant that of inside of a hadron.

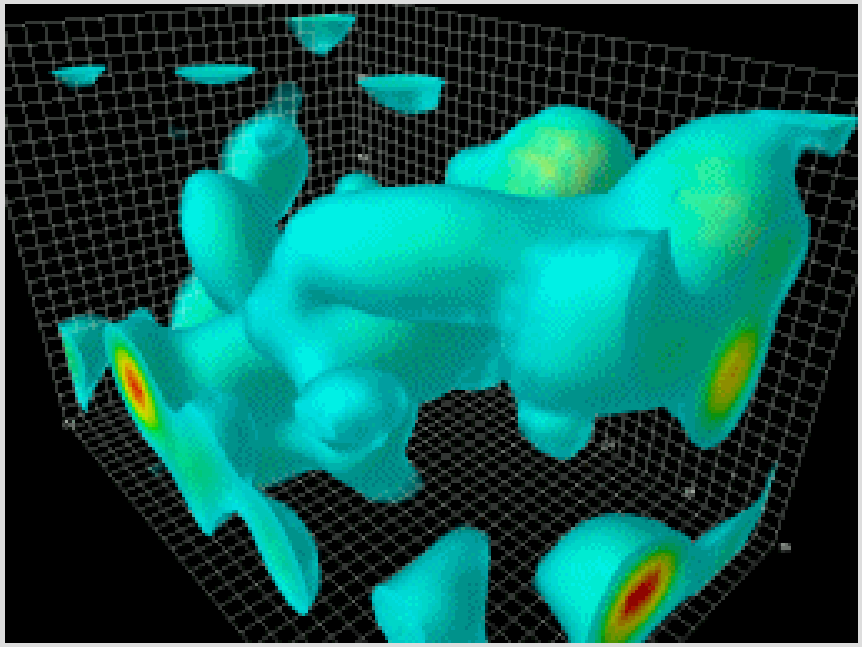
Quantum Chromo-Dynamics(QCD): Quark colour field lines confined

Most of the mass of visible matter is due to QCD - confinement





Confinement due to gluon fluctuations in vacuum



Numerical Method used:
lattice in space time

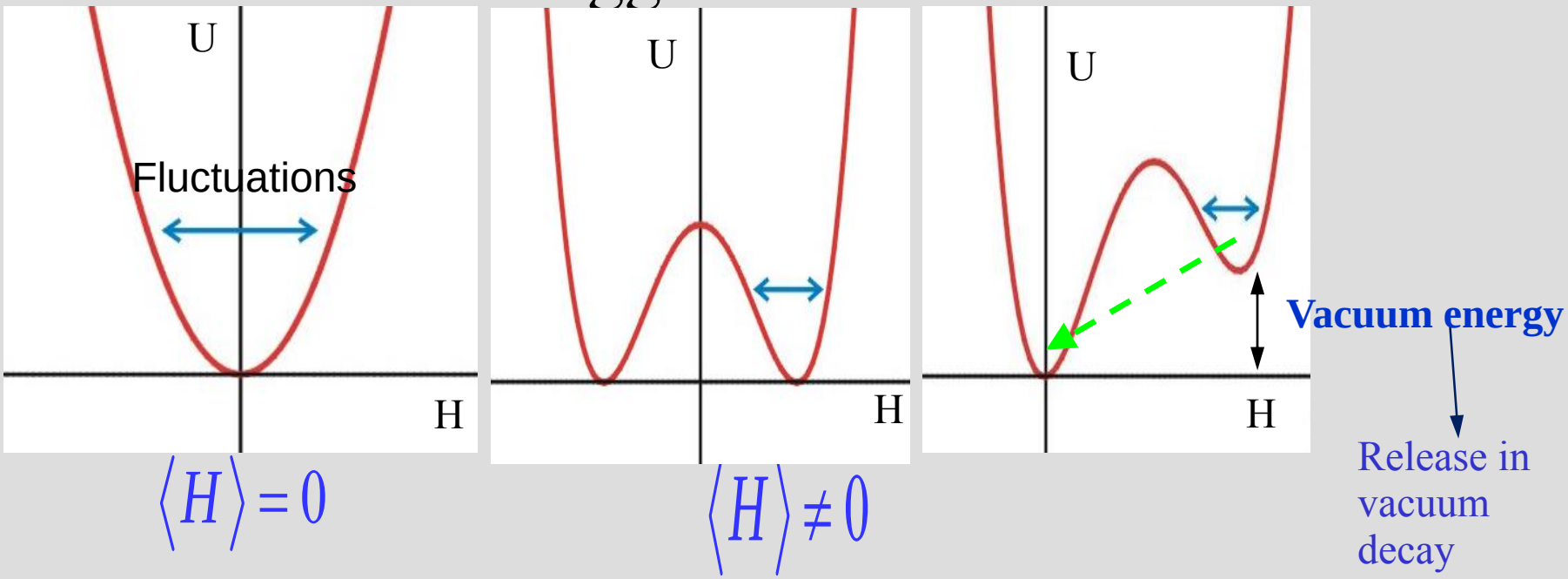
- QCD induces chromo-electric and chromo-magnetic fields throughout space-time – the vacuum is in its lowest energy state, yet it is strongly structured. Fields must vanish exactly everywhere $\langle H \rangle = 0$
- This is an actual computation of the four-d (time +3-dimensions) structure of the gluon-field configuration. The volume of the box is 2.4 by 2.4 by 3.6 fm, big enough to hold a couple of protons.
- Created by Derek B. Leinweber's (U Adelaide)

Square of fields does not average out: "condensates

$$\langle \bar{q}q \rangle = (235\ \mathrm{MeV})^3, \left\langle \frac{\alpha_s}{\pi} G_{\mu\nu} G^{\mu\nu} \right\rangle = (335\ \mathrm{MeV})^4$$

The Higgs vacuum and the quantum harmonic oscillator

Normal, "Higgs" and False Vacuum



$\langle H \rangle = 0$ $\langle H \rangle \neq 0$

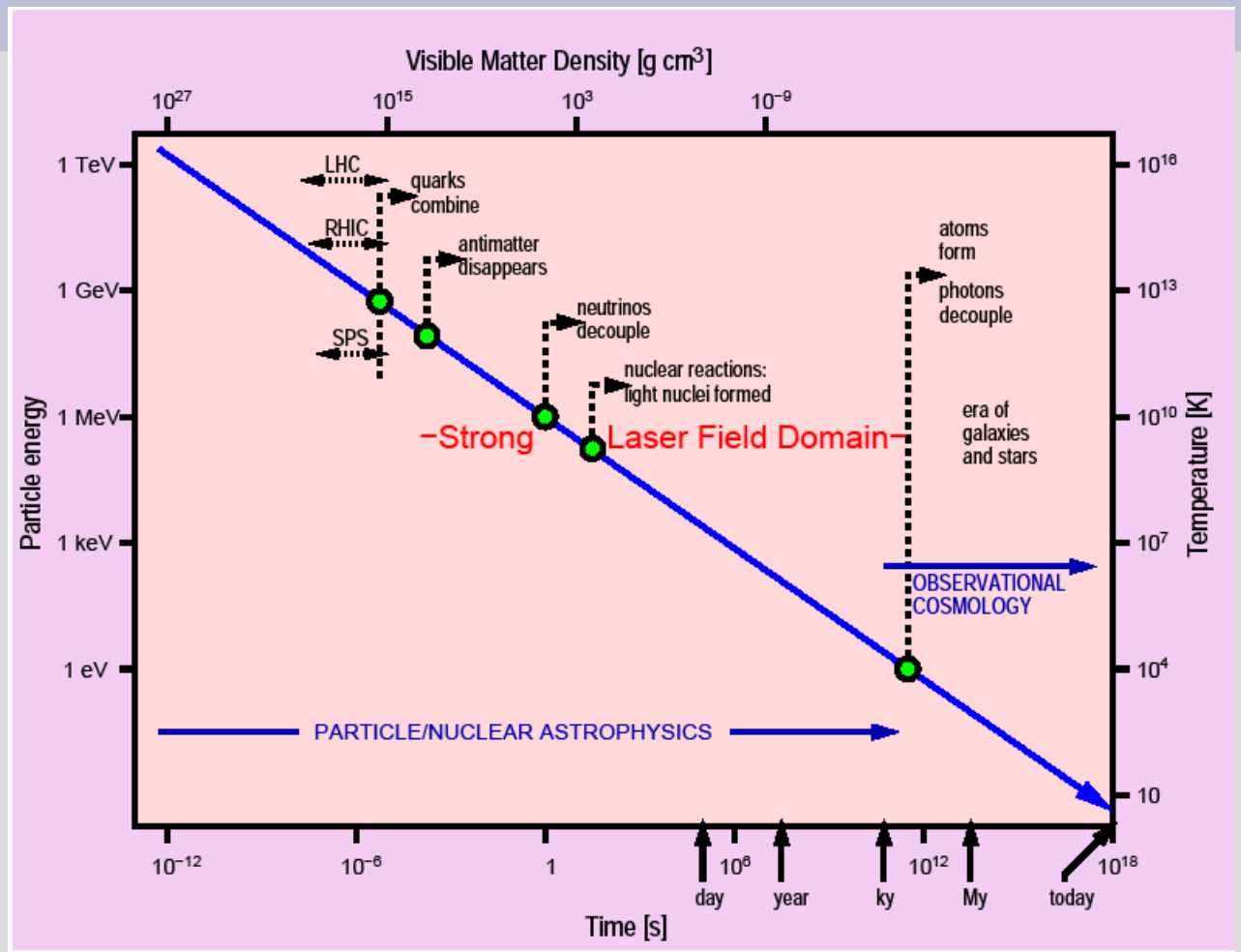
Higgs field in the vacuum makes weak interactions weak and 2nd and 3rd generation heavy

Do we live in False vacuum?

"We conclude that there are no credible mechanisms for catastrophic scenarios (with heavy ion collisions at RHIC)" (Jaffe, R.L., Busza, W., Sandweiss, J., and Wilczek, F, 2000, *Rev. Mod. Phys.* 72, 1125-1140)

We can proceed to plan experiments and to travel back in time to the beginning of the Universe.

Travel back in time in the Universe history



Melt the vacuum

- $T < \sim 10^3$ K ➡ molecules intact
  $T > \sim 10^3$ K (0.1 eV) ➡ molecular dissociation

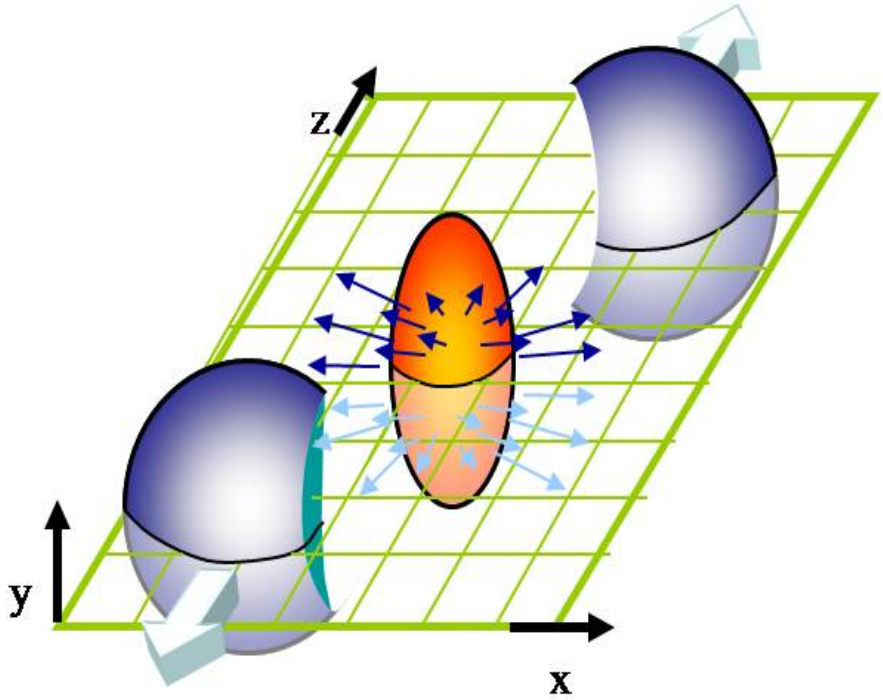
- $T < \sim 10^4$ K ➡ atoms intact
  $T > \sim 10^4$ K (1 eV) ➡ atomic ionization, plasma formation

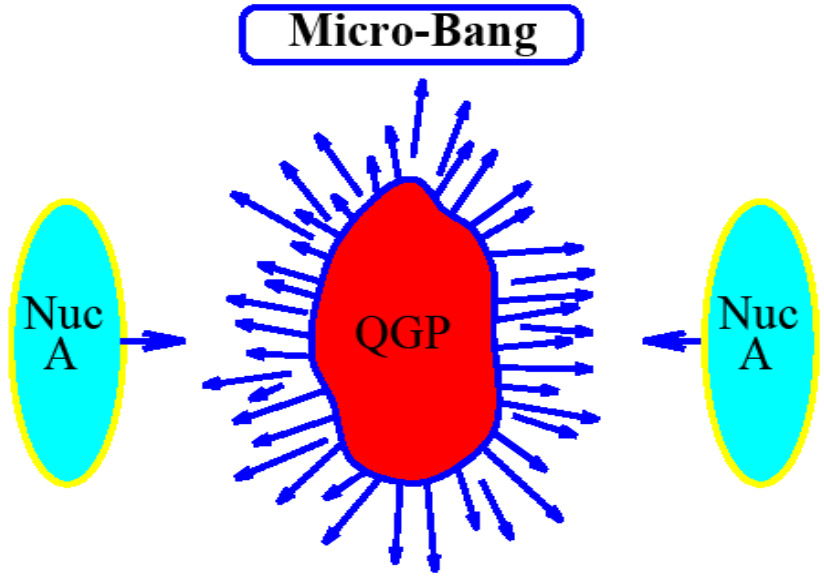
- $T < \sim 10^9$ K ➡ nuclei intact
  $T > \sim 10^9$ K (0.1 MeV) ➡ nuclear reactions

- $T < \sim 10^{12}$ K ➡ protons intact
  $T > \sim 10^{12}$ K (160 MeV) ➡ vacuum melts, quarks free

- $T < \sim 10^{15}$ K ➡ electromagnetic and weak interactions separate
  $T > \sim 10^{15}$ K (160 GeV) ➡ Higgs vacuum melts, all quarks massless

Melting the QCD vacuum



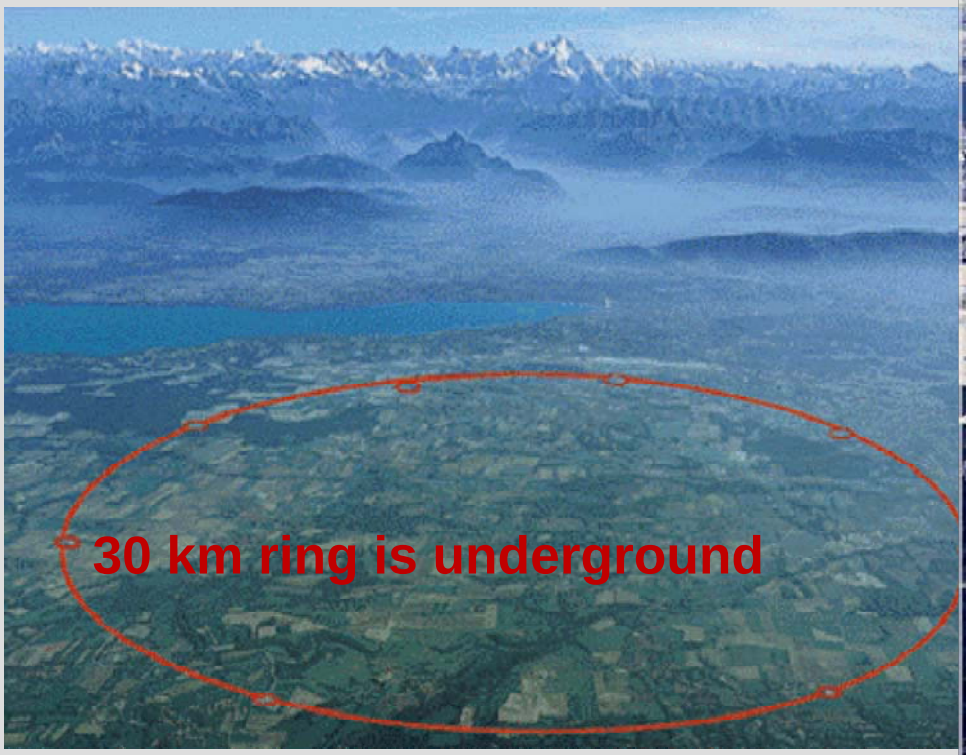


Nuclear Collisions at energy $E>>Mc^2$

Big-Bang	Micro-Bang
$\tau \simeq 10\mu s$	$\tau \simeq 4\ 10^{-23} s$
$N_b / N \simeq 10^{-10}$	$N_b / N \simeq 0.1$

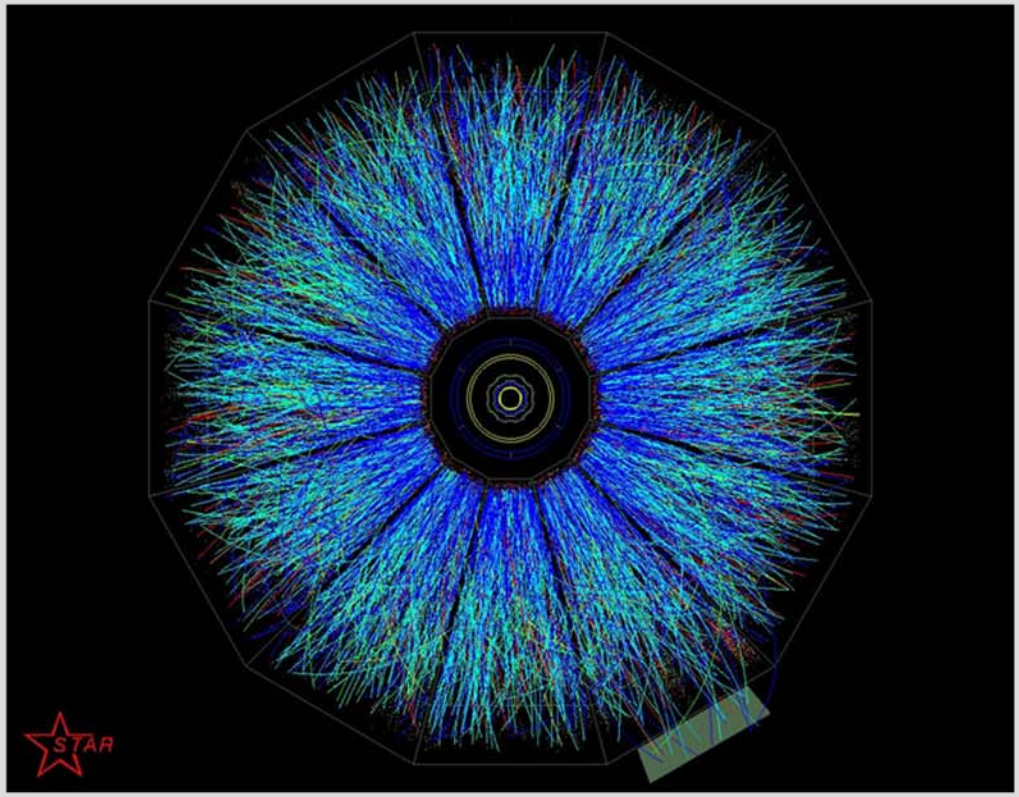
Old tools: Visible from space

CERN LHC



Nuclei deposit 10 erg of energy in the hot small vacuum zone which becomes a large multitude of particles: in a process we call “hadronization”=vacuum freezing

Collisions of gold nuclei heat nuclear matter to temperatures exceeding two trillion degrees, the “melting point” of the vacuum. Quarks move freely within the new vacuum, and the u, d, s quarks lose most of their mass.



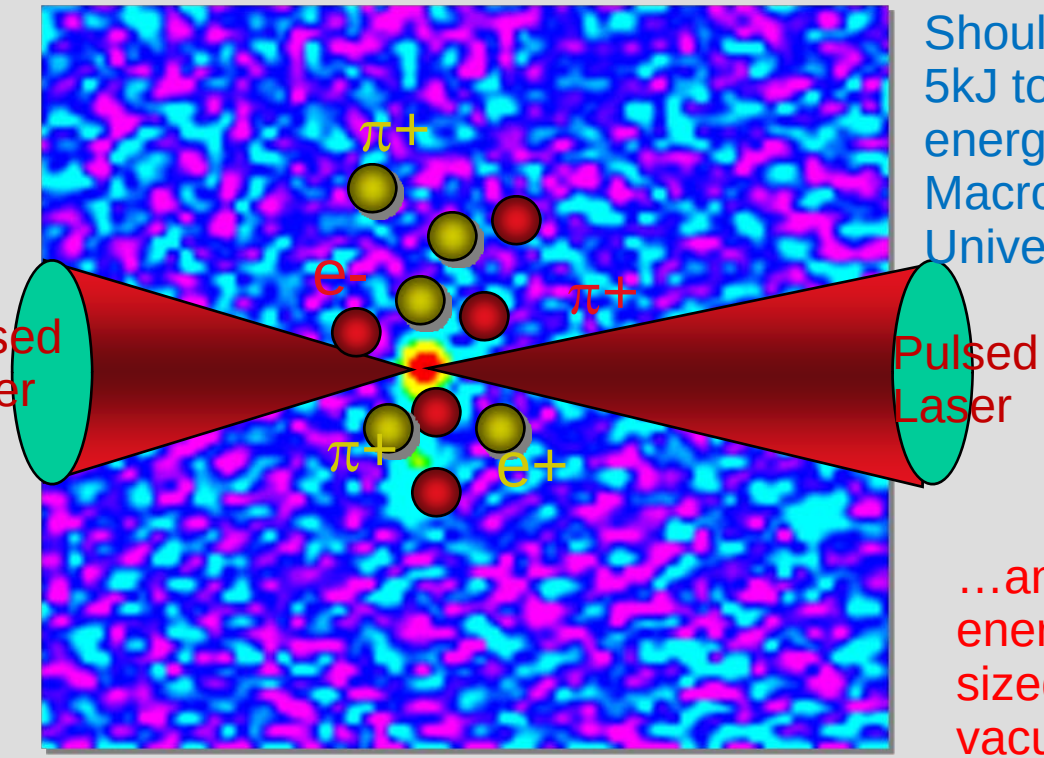
New path to probing the quantum vacuum

The new idea is to collide kJ pulses with laser spot intense enough to hadronize the vacuum

On the way we can study nonlinear QED

Pair e+e- production

EM fields polarize quarks in QCD vacuum



Should we be able to focus of 5kJ to 10% atom size we reach energy density of QGP. Macroscopic domain of early Universe

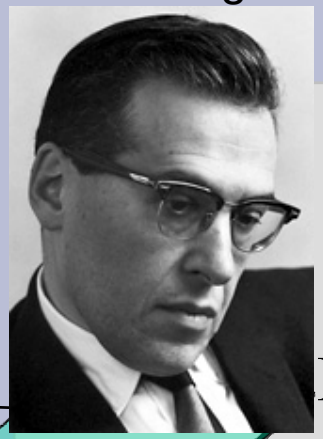
…and if we get that energy into proton sized volume the Higgs vacuum will melt

The pulsed laser allows the study of the aether and solves the energy content issue. Many challenges await us in effort to focus the energy to small volume. This and size of experiments will keep us busy for 50 years to come.

Particle pair production

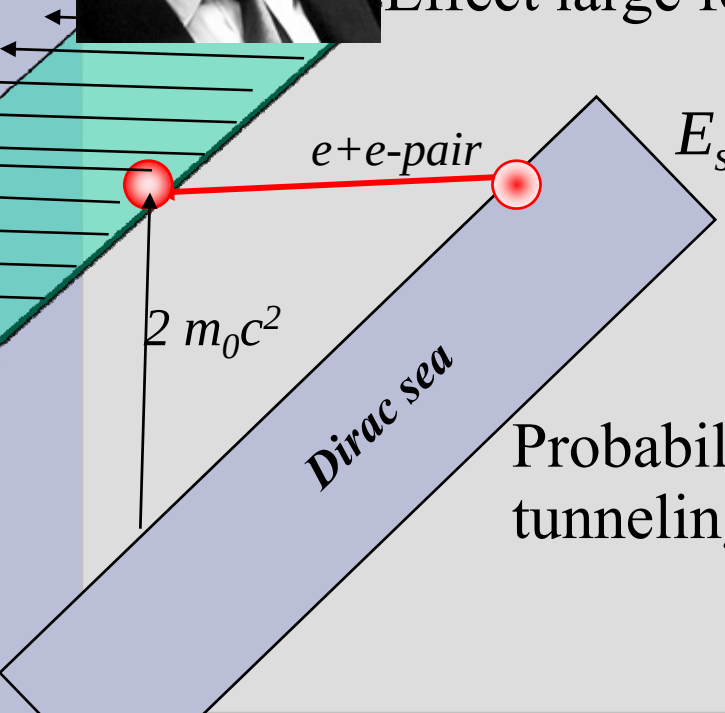
Euler and Heisenberg, Schwinger, Brezin and Itzykson

J Schwinger



Next: study of the vacuum properties in QED alike to a dielectric matter. Short term: pair production

Effect large for Schwinger Field $E_s = \frac{2 m_0 c^2}{e \lambda\!\!\!^{-}_c}$ with $\lambda\!\!\!^{-}_c = \frac{\hbar}{m_0 c^2}$

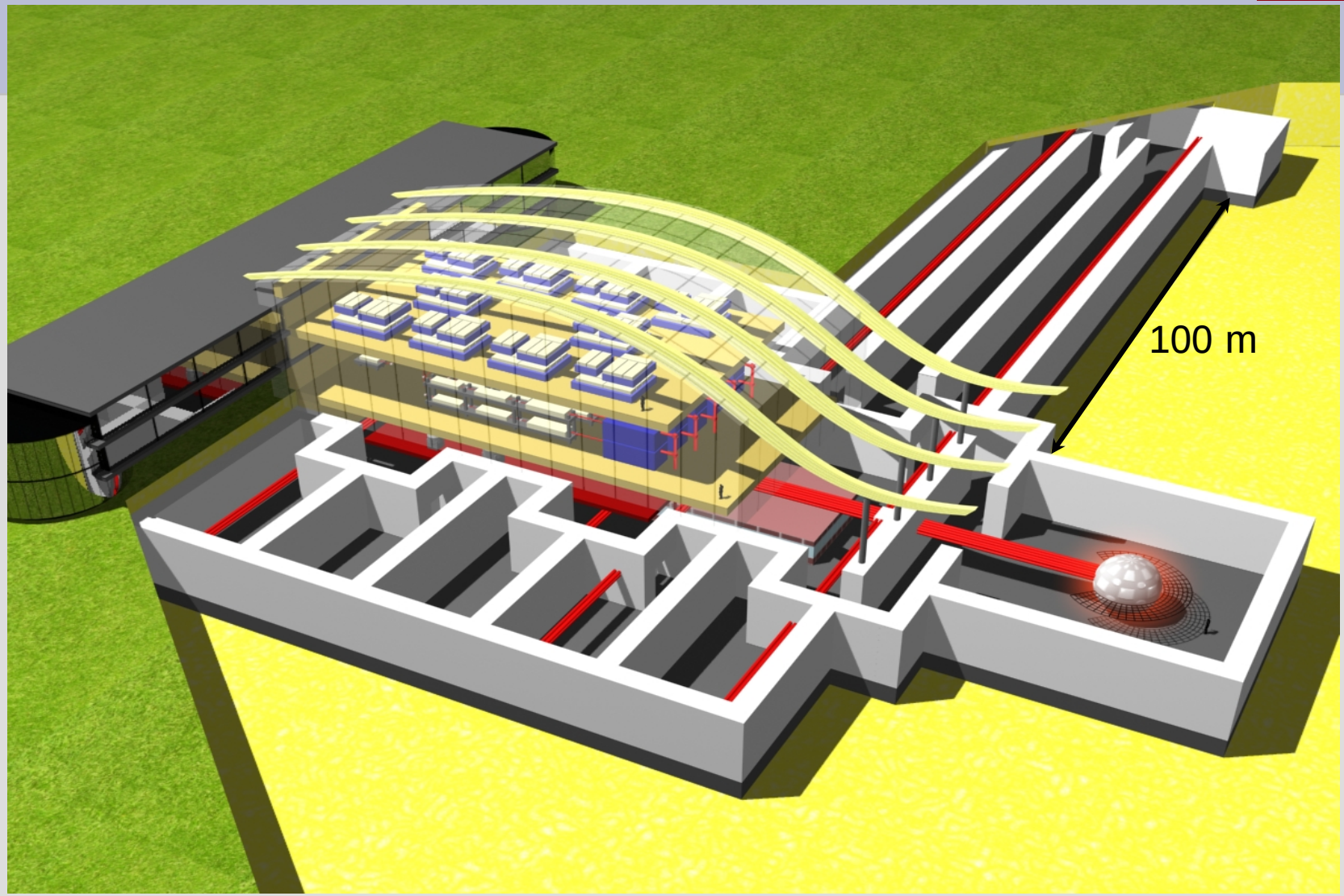


$E_s = 1.3\ 10^{16}$ V/cm

In laser focus this corresponds to $I_s = 10^{30} W/cm^2$

Probability of vacuum pair production in tunneling $W \propto \exp\left(-\frac{\pi E_s}{E}\right)$

The «Extreme Light Infrastructure»



The End

Thanks to:

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Friends and colleagues with whom the work on vacuum structure was carried out over many years and in particular Prof. Berndt Mueller of Duke University, and my thesis advisor Prof. Walter Greiner of Frankfurt University (see below).

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