Relativistic Optics and Nuclear Photonics

Faculty of Physics, University of Warsaw
Pasteura 5, 02-093 Warszawa
Room 1.40

November 7, 2016

Programme and time schedule

10.00  Welcome

10.15  Johann Rafelski (University of Arizona, Tucson, USA)
     “Fundamental Physics Acceleration Frontier”
New science, unique research opportunities

ELI will comprise 4 branches:

- **Attosecond Laser Science**, which will capitalize on new regimes of time resolution (*ELI-ALPS, Szeged, HU*)

- **High-Energy Beam Facility**, responsible for development and application of ultra-short pulses of high-energy particles and radiation stemming from relativistic and later ultrarelativistic interaction (*ELI-Beamlines, Prague, CZ*)

- **Nuclear Physics Facility** with ultra-intense lasers and brilliant gamma beams (up to 19 MeV) enabling also brilliant neutron beam generation with a largely controlled variety of energies (*ELI-NP, Magurele, RO*)

- **Ultra-High-Field Science** centred on direct physics of the unprecedented laser field strength (*ELI 4, to be decided*)
High-Energy Beam Facility, responsible for development and application of ultra-short pulses of high-energy particles and radiation stemming from relativistic and later ultrarelativistic interaction.
Foundational Physics
Acceleration Frontier
with connection between topics

• Vacuum structure
• Supercritical fields, positron production
• Critical Fields = Critical Acceleration
• Experiments in regime of critical acceleration
• Radiation Reaction
• Inertia and Mach’s principle
• Einstein aether = quantum vacuum
Vacuum structure
The **vacuum** is not empty
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.
Matter Influences Vacuum

Photons fluctuations altered by matter, Casimir effect can be measured:

Attractive force between two adjacent metal plates (Casimir force, 1948)

\[ F = \frac{\pi^2}{240} \frac{\hbar c}{L^4} A \]

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

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

Hendrik B.G. Casimir
A “naive” vacuum structure model of quark confinement in hadrons

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

- The model assumes that the energy density $E/V=0$ of the true vacuum is lower than the inside of a hadron.
Supercritical Fields, Positron Production
Pair production in constant fields

The sparking of the QED dielectric

Effect large for Field

\[ E_s = 1.3 \times 10^{16} \text{ V/cm} \]

\[ E_s = \frac{2m_0 c^2}{eD_c} \quad \text{with} \quad D_c = \frac{h}{m_0 c^2} \]

In laser focus this corresponds to \( I_s = 2.3 \times 10^{29} \text{W/cm}^2 \)

Probability of vacuum pair production can be evaluated in WKB description of barrier tunneling: All E-fields are unstable and can decay to particles – footnoted by Heisenberg around 1935, added into Schwinger's article as a visible after finish-point.
The Dirac equation uses energy, mass and momentum of special relativity $E^2 = p^2c^2 + m^2c^4$, taking root we find in quantum physics two energy (particle) bands.

Relativistic Dirac quantum physics predicts antimatter and allows formation of pairs of particles and antiparticles.

The relativistic gap in energy reminiscent of insulators, where conductive band is above the valance (occupied) electron band.
Strong Fields-seeking tests: positrons from (quasi-)superheavy elements 1971-91

(quasi)Atoms beyond \( Z \simeq 100 \)

Single Particle Dirac Equation

\[
(\bar{\alpha} \cdot i \nabla + \beta m + V(r)) \Psi_n(\vec{r}) = E_n \Psi_n(\vec{r})
\]

\[
V(r) = \begin{cases} 
- \frac{Z \alpha}{r} & r > R_N \\
- \frac{3}{2} \frac{Z \alpha}{R_N} + \frac{r^2}{2} \frac{Z \alpha}{R_N^3} & r < R_N 
\end{cases}
\]

Supercritical fields

The bound states drawn from one continuum move as function of \( Z \) across into the other continuum. Mix-up of particle/antiparticle states


Decay of the Vacuum

Undercritical

\(+mc^2\)

Overcritical

\(-mc^2\)

If diving state ‘empty’ vacuum decays

\(|Q = 0\rangle \rightarrow |Q = e\rangle + e^+\) by positron

state occupied by an electron, ‘smooth’ transition of charge distribution

UW 7 XI 2016 JR
Experimental Realization: Heavy Ion collision
A new structured stable local vacuum state

New Stable Ground State: The Charged Vacuum

There is localized charge density in the vacuum, not a particle of sharp energy. Formation of the charged vacuum ground state observable by positron emission: which fills any vacancies among ‘dived’ states in the localized domain.

Speed of decay of false vacuum controlled by (Heisenberg-Schwinger) field strength.

UW 7 XI 2016 JR
Critical Fields = Critical Acceleration
Critical Fields=

Critical Acceleration

An electron in presence of the critical 'Schwinger' (Vacuum Instability) field strength of magnitude:

\[ E_s = \frac{m_e^2 c^3}{e\hbar} = 1.323 \times 10^{18} \text{ V/m} \]

is subject to critical natural unit = 1 acceleration:

\[ a_c = \frac{m_e c^3}{\hbar} \rightarrow 2.331 \times 10^{29} \text{ m/s}^2 \]

Truly dimensionless unit acceleration arises when we introduce specific acceleration

\[ \Xi = \frac{a_c}{mc^2} = \frac{c}{\hbar} \]

Specific unit acceleration arises in Newton gravity at Planck length distance:

\[ \Xi_G \equiv \frac{G}{L_p^2} = \frac{c}{\hbar} \text{ at } L_p = \sqrt{\hbar G/c}. \]

In the presence of sufficiently strong electric field \( E_s \) by virtue of the equivalence principle, electrons are subject to Planck 'critical' force.
Planck units

\[ \frac{\hbar}{k_B} = \sigma = 0.4818 \cdot 10^{-10} \text{[sec} \times \text{Celsiusgrad]} \]
\[ \hbar = b = 6.885 \cdot 10^{-27} \text{[cm}^2 \text{gr/sec]} \]
\[ c = \varepsilon = 3.00 \cdot 10^{10} \text{[cm/sec]} \]
\[ G = \mu = 6.685 \cdot 10^{-3} \text{[cm}^3 \text{gr/sec}^2] \]

Wählt man nun die "natürlichen Einheiten" so, dass in dem neuen Massensystem jede der vorstehenden vier Konstanten den Wert 1 annimmt, so erhält man als Einheit der Länge die Größe:
\[ \sqrt{\frac{2 \pi L_{pl}}{c^3}} = 4.15 \cdot 10^{-33} \text{cm} \]
als Einheit der Masse:
\[ \sqrt{\frac{2 \pi M_{pl}}{c^5}} = 5.56 \cdot 10^{-8} \text{gr} \]
als Einheit der Zeit:
\[ \sqrt{\frac{2 \pi t_{pl}}{c^3}} = 1.38 \cdot 10^{-23} \text{sec} \]
als Einheit der Temperatur:
\[ \sqrt{2 \pi T_{pl}} = \sigma \sqrt{\frac{c^5}{\mu}} = 3.50 \cdot 10^{32} \text{Cels} \]

Diese Größen behalten ihre natürliche Bedeutung so lange bei, als die Gesetze der Gravitation, der Lichtfortpflanzung im Vacuum und die beiden Hauptsätze der Wärmetheorie in Gültigkeit bleiben, sie müssen also, von den verschiedensten Intelligenzen nach den verschiedensten Methoden gemessen, sich immer wieder als die nämlichen ergeben.

"These scales retain their natural meaning as long as the law of gravitation, the velocity of light in vacuum and the central equations of thermodynamics remain valid, and therefore they must always arise, among different intelligences employing different means of measuring."

M. Planck, "Über irreversible Strahlungsvorgänge." Sitzungsberichte der Königlich Preußischen Akademie der Wissenschaften zu Berlin 5, 440-480 (1899), (last page)
Experiments in regime of critical acceleration
Probing super-critical (Planck) acceleration
\[ a_c = 1 \rightarrow m_e c^3 / \hbar = 2.331 \times 10^{29} \text{m/s}^2 \]

Plan A: Directly laser accelerate electrons from rest, requires Schwinger scale field and may not be realizable – backreaction and far beyond today’s laser pulse intensity technology.
Plan B: Ultra-relativistic Lorentz-boost: we collide counter-propagating electron and laser pulse.
Puls Lorentz Transform (LT)

Relativistic electron-laser pulse collision

\[ u^\beta = \gamma(1, \vec{v}) \rightarrow \text{In electron's rest frame: } u'_\beta = (1, \vec{0}) \]

\[ A^\mu \]

Doppler shift: \( \omega' = \gamma(1 + \vec{n} \cdot \vec{v}) \omega \)

Unit acceleration condition: \( a_0 \frac{\omega'}{m_e} \approx 2\gamma a_0 \frac{\omega}{m_e} \rightarrow 1 \)
Critical acceleration probably achieved at RHIC

Two nuclei smashed into each other from two sides: components ‘partons’ can be stopped in CM frame within $\Delta \tau \simeq 1$ fm/c. Tracks show multitude of particles produced, as observed at RHIC (BNL).

- The acceleration $a$ achieved to stop some/any of the components of the colliding nuclei in CM: $a \simeq \frac{\Delta y}{M_i \Delta \tau}$. Full stopping: $\Delta y_{\text{SPS}} = 2.9$, and $\Delta y_{\text{RHIC}} = 5.4$. Considering constituent quark masses $M_i \simeq M_N/3 \simeq 310$ MeV we need $\Delta \tau_{\text{SPS}} < 1.8$ fm/c and $\Delta \tau_{\text{RHIC}} < 3.4$ fm/c to exceed $a_c$.

Melt the vacuum

- $T < \sim 10^3 \, \text{K}$ → molecules intact
  $T > \sim 10^3 \, \text{K}$ (0.1 eV) → molecular dissociation

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

- $T < \sim 10^9 \, \text{K}$ → nuclei intact
  $T > \sim 10^9 \, \text{K}$ (0.1 MeV) → nuclear reactions

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

- $T < \sim 10^{15} \, \text{K}$ → electromagnetic and weak interactions separate
  $T > \sim 10^{15} \, \text{K}$ (160 GeV) → Higgs vacuum melts, all quarks massless
Radiation Reaction
Strong Field Unsolved Problem Radiation-Acceleration-Reaction

Conventional Lorentz-Electromagnetic force is incomplete: accelerated charged particles can radiate: “radiation friction” instability – some acceleration produces friction slowdown, produces more slowdown etc. Need acceleration that is not negligible to explore the physics of radiation friction. Problem known for 115 years.

Microscopic justification in current theory (LAD)

1) Inertial Force = Lorentz-force with friction - > get world line of particles=source of fields
2) Source of Fields = Maxwell fields - > get fields, and omit radiated fields
3) Fields fix Lorentz force with friction - > go to 1.

So long as the radiated fields are small, we can modify the Lorentz Force to account for radiated field back reaction. The “Lorentz-Abraham-Dirac (LAD)” patch is fundamentally inconsistent, and does not follow from an action principle. Many other patches exist, some modifying inertia, others field part of Lorentz force - it introduces a nonlinear and partially nonlocal Lorentz-type force. No action principle is known

UW 7 XI 2016 JR
### Sample of proposed LAD extensions

<table>
<thead>
<tr>
<th>LAD</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landau-Lifshitz</td>
<td>[ \mu^\alpha = qF^{\alpha \beta} u_\beta + \tau_0 \left{ F^{\alpha \beta} F_{\beta \gamma} u^\gamma + \frac{q}{m} \left[ F^{\alpha \beta} F_{\beta \gamma} u^\gamma - (u_{\gamma} F^{\gamma \beta})(F_{\beta \delta} u^\delta) u^\alpha \right] \right} ]</td>
</tr>
<tr>
<td>Caldirola</td>
<td>[ 0 = qF^{\alpha \beta} (\tau) u_\beta (\tau) + \frac{m}{2\tau_0} \left[ u^\alpha (\tau - 2\tau_0) - u^\alpha (\tau) u_\beta (\tau) u^\beta (\tau - 2\tau_0) \right] ]</td>
</tr>
<tr>
<td>Mo-Papas</td>
<td>[ \mu^\alpha = qF^{\alpha \beta} u_\beta + q\tau_0 \left[ F^{\alpha \beta} F_{\beta \gamma} u^\gamma + F^{\alpha \beta} u_\beta - F^{\alpha \beta} u_\gamma u^\alpha \right] ]</td>
</tr>
<tr>
<td>Eliezer</td>
<td>[ \mu^\alpha = qF^{\alpha \beta} (\tau) u_\beta (\tau) + \frac{m}{\tau_0} \left[ u^\alpha (\tau - \tau_0) - u^\alpha (\tau) u_\beta (\tau) u^\beta (\tau - \tau_0) \right] ]</td>
</tr>
<tr>
<td>Caldirola-Yaghjian</td>
<td>[ \mu^\alpha = qF^{\alpha \beta} (\tau) u_\beta (\tau) + \frac{m}{\tau_0} \left[ u^\alpha (\tau - \tau_0) - u^\alpha (\tau) u_\beta (\tau) u^\beta (\tau - \tau_0) \right] ]</td>
</tr>
</tbody>
</table>

T. C. Mo and C. H. Papas, "A New Equation Of Motion For Classical Charged Particles,"
A. D. Yaghjian, "Relativistic Dynamics of a Charged Sphere,"

Other recent references
Example: Electron de-acceleration by a pulse

Lorentz invariant acceleration $\sqrt{-\dot{u}^{\alpha}\dot{u}_{\alpha}}$ [$m_e$] function of time

Red: solution of Lorentz equation as

Collision between a circularly polarized square plane wave with $a_0 = 100$ and initial $E_e = 0.5$ GeV, $\gamma = 1,000$ electron,

Radiation reaction regime

Deviations from Lorentz force impact significantly Lorentz dynamics in dark shaded area of the $\gamma, a_0$ plane

<table>
<thead>
<tr>
<th></th>
<th>Electron</th>
<th>Laser</th>
<th>X/Gamma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>.1 – 5 GeV</td>
<td>J and kJoule</td>
<td>MeV</td>
</tr>
<tr>
<td>Duration</td>
<td>1-10 fs</td>
<td>20 – 150 fs</td>
<td>10 – 1000 fs</td>
</tr>
<tr>
<td>Rep.rate</td>
<td>10Hz</td>
<td>10Hz</td>
<td>10Hz</td>
</tr>
</tbody>
</table>
Moving foil-electron cloud: Coherent backscattering

\[ \omega_r = \frac{C + V}{C - V} \omega_0 = > 4\gamma^2 \omega_0 \]
Inertia and Mach’s principle
Inertia & Mach’s Principle

Measurement of (strong) acceleration requires a Reference frame: what was once the set of fixed stars in the sky is today CMB photon freeze-out reference frame. To be consistent with special relativity: all inertial observers with respect to CMB form an equivalence class, we measure acceleration with reference to the CMB inertial frame.

In Einstein’s gravity reference frame provided by metric. However, there is no “acceleration”, a dust of gravitating particles is in free fall. Only in presence of a rigid body created by quantum physics combined with EM force, Mach’s principle a concern, and we are lead to remember the “aether”.

... 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.
Einstein aether = quantum vacuum
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.
Aether returns 1919/20

General Relativity and Cosmology: gravity as space-time geometry, time has a beginning
Gravity metric is the new 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.”

TODAY: The laws of physics are encoded in quantum vacuum structure.

Albert Einstein, Ather und die Relativitaetstheorie (Berlin, 1920):
To resolve inconsistencies: we need to formulate a NEW “large acceleration” theory of electro-magnetism, comprising Mach’s principle, and challenging understanding of inertia.

THEORY Question: How to achieve that charged particles when accelerated radiate in self-consistent field – and we need EM theory with Mach principle accounted for (gravity, quantum physics=zero acceleration theories)!

EXPERIMENT: strong acceleration required. What is strong: unit acceleration=Heisenberg-Schwinger Field

Is there a limit to how fast we can accelerate electrons to ultra high energy? Example of early Model: Born-Infeld electromagnetism/

Can the empty space remain transparent to a plane wave of arbitrary intensity? And why? **Perfect translational symmetry required.**
Summary: A new path to probing space time

The new idea is to collide kJ pulses with themselves or with particles, with light intense enough to crack 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.
EXTRA SLIDES
SLAC ’95 experiment below critical acceleration

\[ p_e^0 = 46.6 \text{ GeV}; \text{ in } 1996/7 \ a_0 = 0.4, \ \left| \frac{du^\alpha}{d\tau} \right| = 0.073[m_e] \ (\text{Peak}) \]

Multi-photon processes observed:
- Nonlinear Compton scattering
- Breit-Wheeler electron-positron pairs


Relativity changes the quantum world:

Paul Dirac - St Maurice, VS
Old tools: Visible from space
Melting the QCD vacuum

Nuclear Collisions at Relativistic energy $E \gg M c^2$

Micro-Bang

<table>
<thead>
<tr>
<th>Big-Bang</th>
<th>Micro-Bang</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \approx 10 \mu s$</td>
<td>$\tau \approx 4 \times 10^{-23} s$</td>
</tr>
<tr>
<td>$N_b / N \approx 10^{-10}$</td>
<td>$N_b / N \approx 0.1$</td>
</tr>
</tbody>
</table>
Strangeness Signature of QGP
Origin of forces and nature of mass stability of matter
Origin of Forces and Nature of Mass, Stability of Matter

- “Elementary” masses are generated by the vacuum. Two dominant mechanisms:

- Higgs vacuum: $\langle H \rangle = 246 \text{ GeV}$; scale of mass for W, Z; contributes to matter particle mass, all of heavy quark mass

- QCD vacuum latent heat at the level of $\langle EV_p \rangle = 0.3 \text{ GeV}$ = nuclear mass scale, quarks get mass and are confined.

$m_e c^2 = 0.511 \text{ MeV} \quad m_N c^2 = 0.940 \text{ GeV}$

Units are G=giga, M=mega e=electron charge, V=Volt,
Quantum Chromo-Dynamics (QCD): Quark colour field lines confined

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

![Diagram showing normal and non-perturbative vacuums with field lines]

- Normal vacuum allows field lines
- Non-perturbative vacuum
- Perturbative vacuum

Bar chart showing QCD mass and Higgs mass for quark flavors (u, d, s, c, b, t).
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 confining dynamical vacuum structure.

QCD: a world in which “photons” have a “color magnetic moment”: vacuum consists of a ferromagnetic alignment of glue fluctuations.
The Higgs vacuum and symmetry breaking

Higgs field in the vacuum makes weak interactions weak and 2\textsuperscript{nd} and 3\textsuperscript{rd} particle generation heavy
Color confinement due to gluon fluctuations

- 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.

- Derek B. Leinweber's group (U Adelaide)

Numerical Method used: lattice in space time

Square of fields does not average out: “condensates”

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

UW 7 XI 2016 JR
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)
Do we live in False vacuum?

Dark Energy: (unlike dark matter) a property of the vacuum indicating we are not in ground state in the Universe (could be the case near to matter).

Can we really proceed to plan experiments and to travel back in time to the beginning of the Universe.
We do.

Dynamical Emergence of the Universe into the False Vacuum


Johann Rafelski and Jeremiah Birrell
Department of Physics, University of Arizona, Tucson, Arizona, 85721, USA

Abstract. We study how the hot Universe evolves and acquires the prevailing vacuum state, demonstrating that in specific conditions which are believed to apply, the Universe becomes frozen into the state with the smallest value of Higgs vacuum field $v = \langle h \rangle$, even if this is not the state of lowest energy. This supports the false vacuum dark energy A-model. Under several likely hypotheses we determine the temperature in the evolution of the Universe at which two vacua $v_1, v_2$ can swap between being true and false. We evaluate the dynamical surface pressure on domain walls between low and high mass vacua due to the presence of matter and show that the low mass state remains the preferred vacuum of the Universe.

1 Introduction

This work presents relatively simple arguments for why the cosmological evolution selects the vacuum with smallest Higgs VEV $v = \langle h \rangle$ which, in general, could be and likely is the ‘false’ vacuum. Our argument relies on the Standard Model (SM) minimal coupling $m \to gh$, or similar generalizations in ‘beyond’ SM (BSM), so that the vacuum with the smallest Higgs VEV also has the smallest particle masses. In anticipation of the model with multiple vacua, we call the vacuum state with lowest free energy at temperature $T$ ‘the true vacuum’ and all others ‘the false vacua’. Note that this is a temperature dependent statement: we live today in the false vacuum which as we will show was once the true vacuum.

In the presence of pairs of particles and antiparticles at high temperatures the vacuum state with smallest $v$ is energetically preferred, even if it has a huge vacuum energy. This is so because smaller $v$ implies smaller particle masses and hence less energy, and free energy, in the particle distributions. By the time the Universe cools sufficiently for the larger vacuum energy to dominate the smaller particle free energies, the probability of swap to the large mass true vacuum is vanishingly small in general.

Therefore, the Higgs minimum with the lowest value of the Higgs field $v$, and thus not necessarily the lowest value of the effective potential $W(v) \sim (V(h))$, emerges as the prevalent vacuum in our Universe. The difference, $\rho_v = \Delta W$, between the prevalent vacuum state today and the true minimum is a natural candidate to explain the observed dark energy density,

$$\rho_v = 25.6 \, \text{meV}^4.$$  

(1.1)
How was matter created?

Matter emerges from quark-gluon plasma

After the 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 $\sim 10^{16}$ gm/cm$^3$ (energy density $\sim 10$ GeV/fm$^3$, well above that of the center of neutron stars, that is $\sim 60$ times nuclear energy density), and temperature was $T \sim 160$ MeV, that is $\sim 2 \times 10^{12}$K.