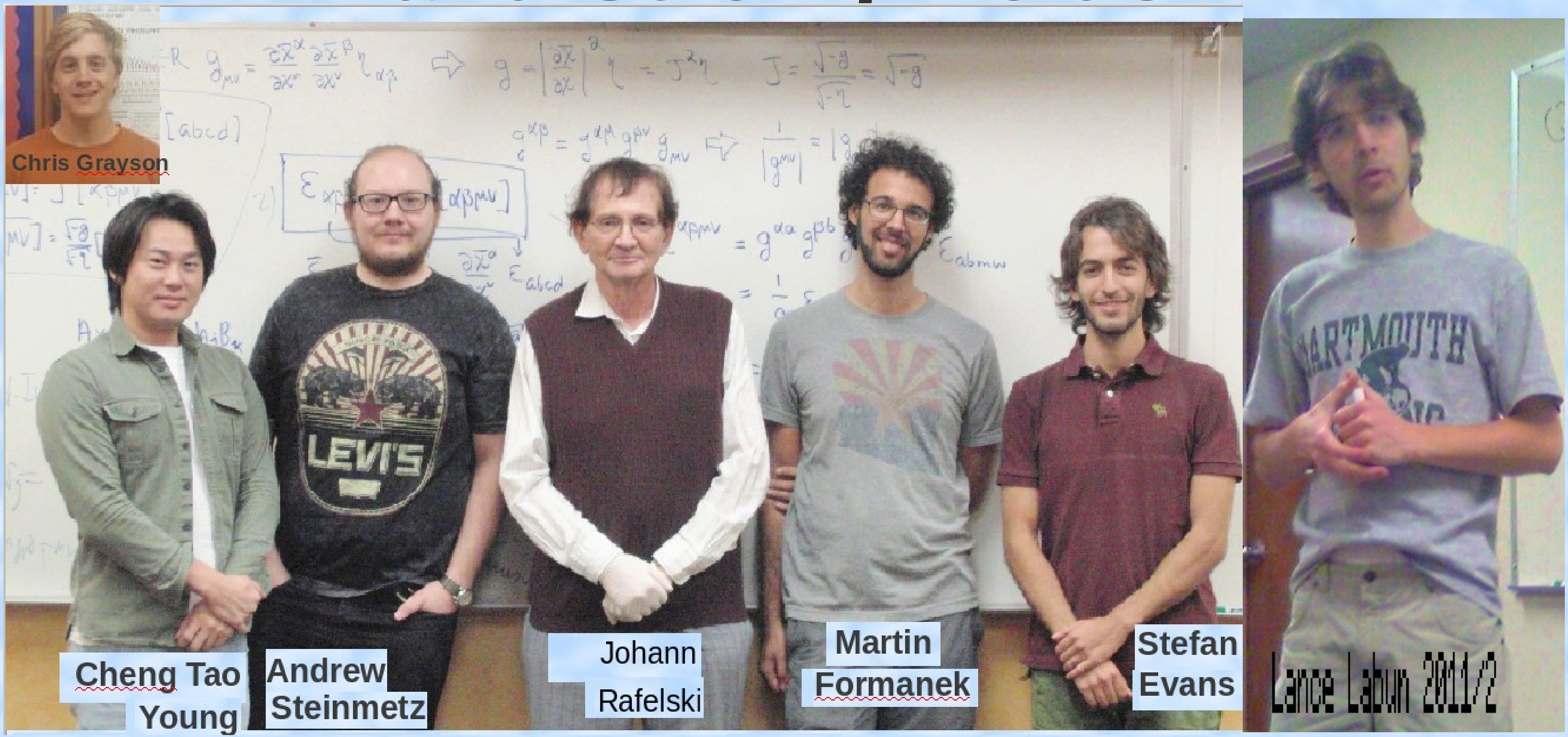
Quantum Vacuum and Strong Fields



After celebrating my 60th BD in Krakow at SQM Conference I celebrate 25,000th (25,074) day in my life

May 19, 1950 - January 11, 2019

Talking Points

Aether according to Langevin and Einstein

Aether of XXI Century = Structured Quantum Vacuum

Dirac and (anti)Matter

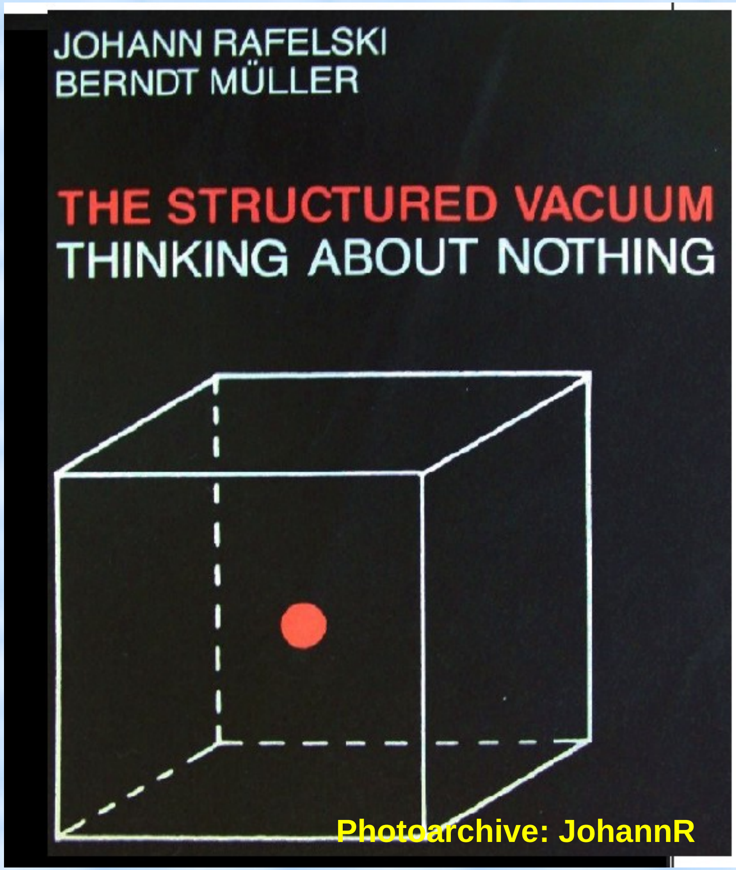
Strong Fields: Local Structured Vacuum 1968-86

Quark Confinement a vacuum effect

Vacuum Determines Laws of Physics and The Universe

Critical Fields=Critical Acceleration /Radiation-Reaction

Further reading a 1984 antique



JOHANN RAFELSKI
BERNDT MÜLLER

IL VACUUM STRUTTURATO
PENSANDO AL NULLA

Contenuti

Tradotto in Italiano da Riccardo Viola

English, German, Italian,..

A technical preparation:

Book 2017 link.springer.com/book/10.1007%2F978-3-319-51231-0

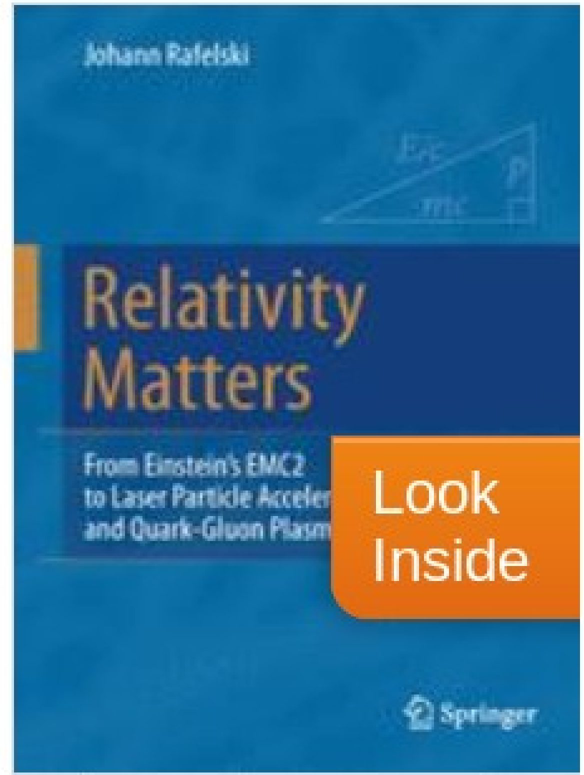
Relativity Matters

From Einstein's EMC2 to Laser Particle Acceleration and Quark-Gluon Plasma

Authors: Johann Rafelski

ISBN: 978-3-319-51230-3 (Print) 978-3-319-51231-0 (Online)

Springer Link



Text pdf available for free if your library subscribes to Springer Physics

First Ideas about space-time

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

Ernst Mach
1838-1916

The Scientific Revolution begins:
Inertia & Mach's Principle
How can we know about "acceleration"

Measurement of accleration requires a universal inertial reference frame: what was once the set of fixed stars in the sky is today CMB photon freeze-out reference frame.
All inertial observers with respect to CMB form an "equivalence class", **we measure acceleration with reference to the CMB inertial frame.**
It is rather clear that the information about who is accelerating must be provided locally and instantanously
In Einstein's gravity reference frame provided by metric tensor. However, in GR there is no "acceleration", a dust of gravitating particles is in free fall. TODAY: The laws of physics are **encoded** in **quantum vacuum structure**

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

Paul Langevin 1911; Einstein 1919/20 -->

Paul Langevin in 1911 provides a more general hypothesis concerning the æther, recognizing that bodies interact with the æther when the motion is non-inertial. Upon completion of the theory of gravity Einstein returned to the æther challenge seeing the need for further understanding needed to characterize forces governing electromagnetism. In 1919/20 Einstein introduced the non-ponderable (we would say today, non-material) æther.

ÉVOLUTION DE L'ESPACE ET DU TEMPS p47

: une translation uniforme dans l'éther n'a pas de sens expérimental.

Mais il ne faut pas conclure pour cela, comme on l'a fait parfois prématurément, que la notion d'éther doit être abandonnée, que l'éther est inexistant, inaccessible à l'expérience. Seule une vitesse uniforme par rapport à lui ne peut être décelée, mais tout changement de vitesse, toute accélération a un sens absolu. En particulier c'est un point fondamental dans la théorie électromagnétique que tout changement de vitesse, toute accélération d'un centre électrisé s'accompagne de l'émission d'une onde qui se propage dans le milieu avec la vitesse de la lumière, et l'existence de cette onde a un sens absolu; inversement toute onde électromagnétique, lumineuse par exemple, a son origine dans le changement de vitesse d'un centre électrisé. Nous avons donc prise sur l'éther par l'intermédiaire des accélérations, l'accélération a un sens absolu comme déterminant la production d'ondes partant de la matière qui a subi le changement de vitesse, et l'éther

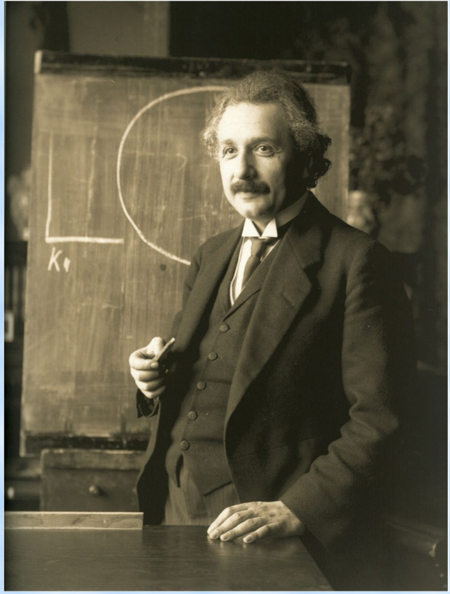
. . . a uniform translation motion in the æther is not experimentally detectable. . . . From this it should not be concluded prematurely, as has sometimes happened, that the æther cannot be experimentally probed, thus having no physical reality, and must be abandoned. Only the uniform velocity relative to the æther cannot be detected, any change of velocity, that is, any acceleration, has an absolute meaning.

Kra

Paul Langevin, *L'Évolution de L'Espace et du Temps*, *Scientia* **X** 31-54 (1911)

Einstein:

Letter to Lorentz 1919: *“It would have been more correct if I had limited myself, in my earlier publications,to emphasizing only the non-existence of an aether velocity, instead of arguing the total non-existence of the aether, for I can see that with the word aether we say nothing else than that space has to be viewed as a carrier of physical qualities."*



Ather und die Relativitaetstheorie (Berlin, 1920):

“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.”

“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.”

Aether of XXI Century=
The Structured Quantum Vacuum

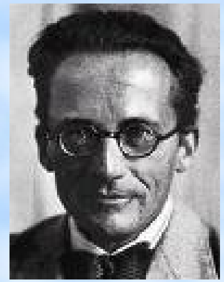
What is new in Quantum Mechanics?

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

M Planck

N Bohr

L de Broglie



E Schroedinger

W Heisenberg

M Born

The uncertainty principle of quantum physics

$\Delta E \cdot \Delta t \geq h$ **Forbids a truly empty world**

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

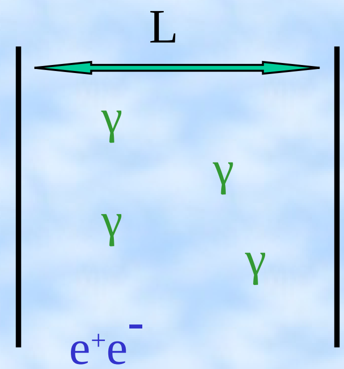
Vacuum = "ground state" of lowest energy of a physical system

Matter Influences Quantum Vacuum

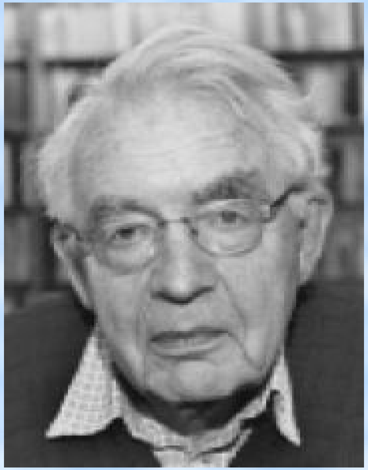
Photons fluctuations altered by matter, Casimir effect can be measured:

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

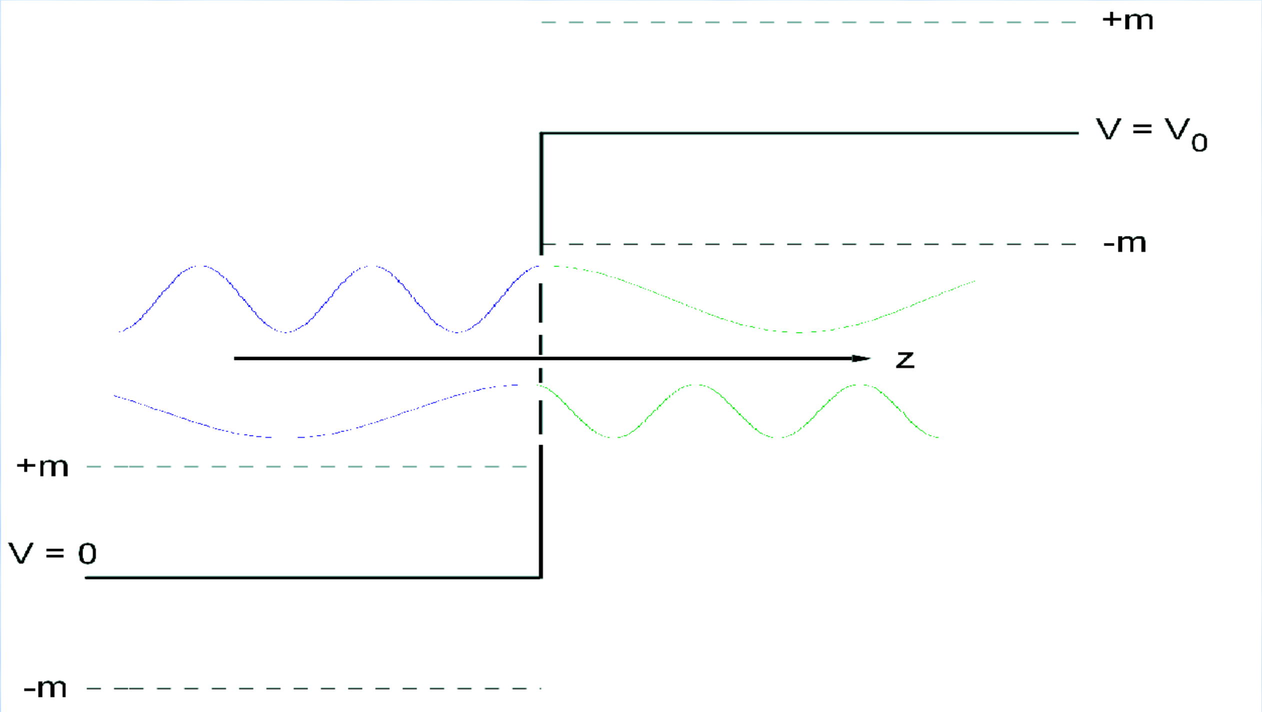


Hendrik B.G. Casimir

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

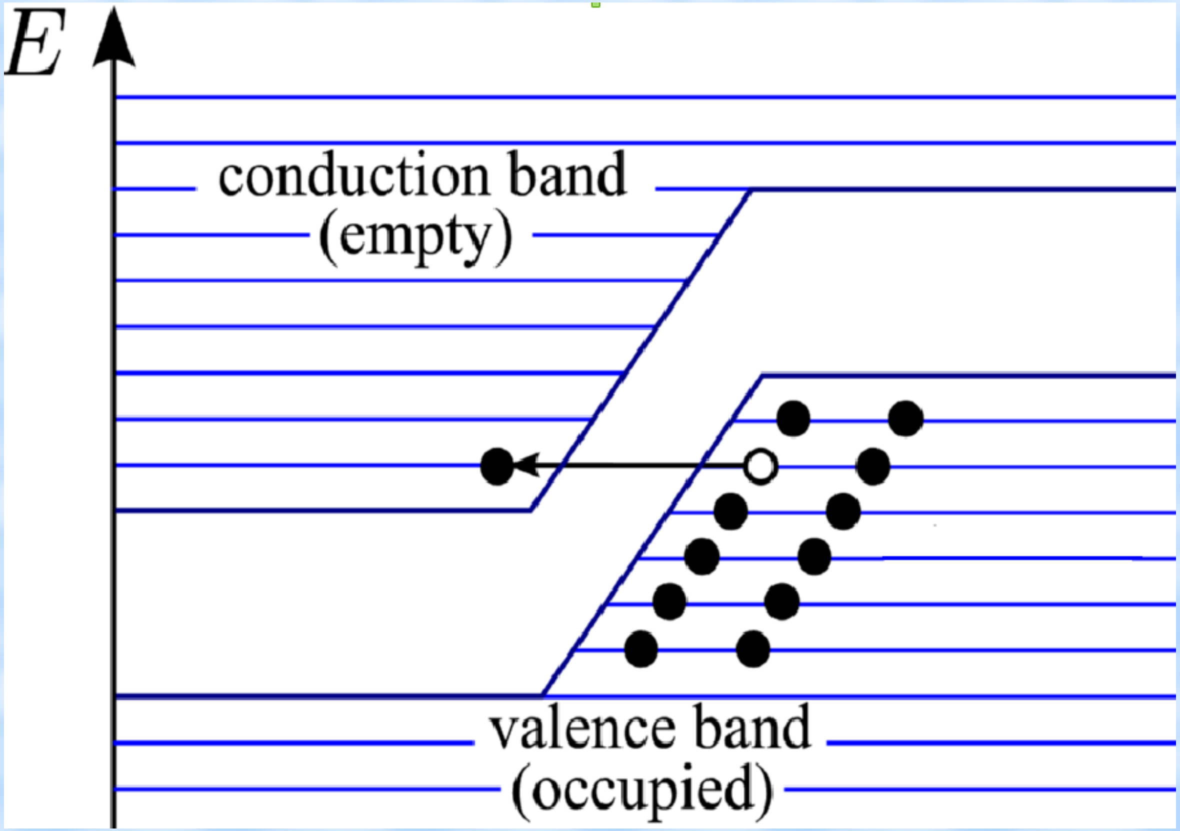
Relativity extends the quantum world: Paul Dirac – memorial in St Maurice, VS

Antimatter not yet recognized: Klein's “Paradox”



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. A potential mixes these states!

Tunneling instability and pair production: Extension of Klein's paradox



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

W Heisenberg

Rate of surface pair production in “constant” fields

J Schwinger

The sparking of the QED dielectric

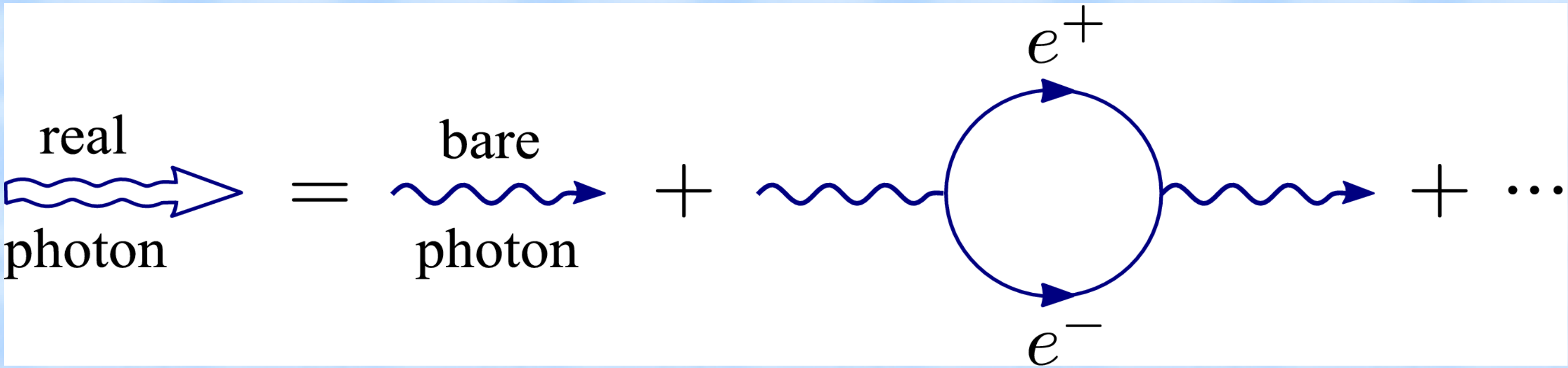
Effect large for Field

E_s=1.323 10^{18} V/m

$$P \sim exp\left(-\pi\frac{m^2c^3}{eE\hbar}\right)$$

Probability of pair production can be evaluated in WKB description of barrier tunneling: All E-fields are unstable and can decay to particles if energy is available and rate is large enough – Stated with all detail by Heisenberg around 1935, rederived in 1950 Schwinger's article as an visibly after finish-point (*my idea how this happened: invited by referee=Heisenberg*?).

Virtual Pairs:
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, Observable Coulomb interaction stronger (0.4%) at distance 1/m

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

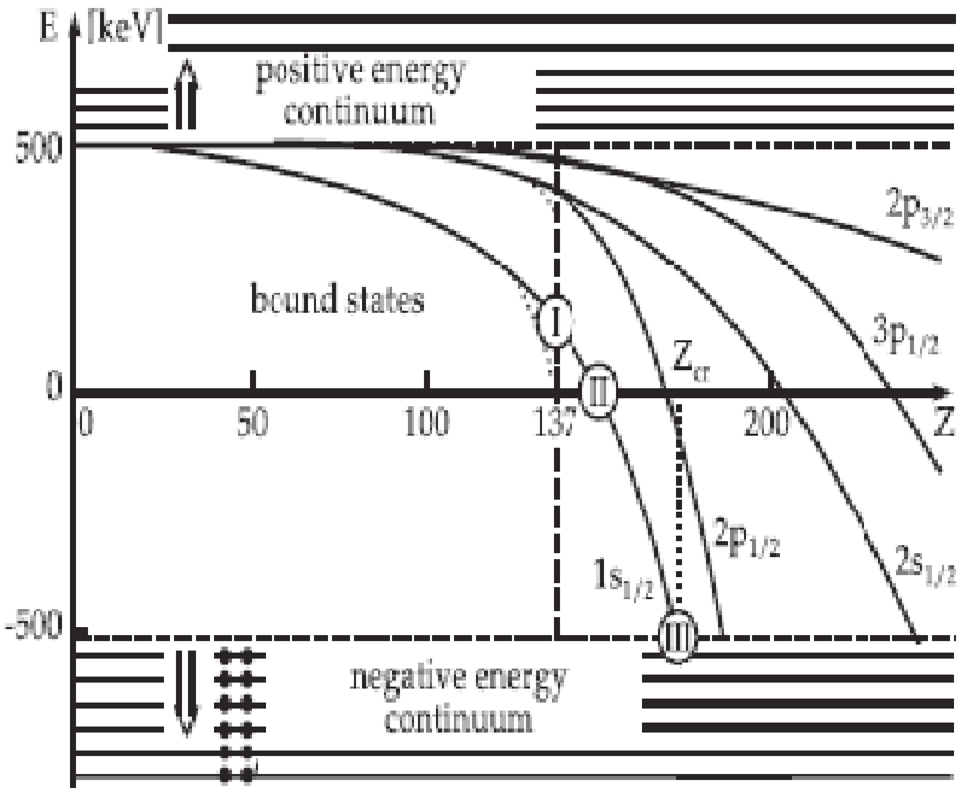
Strong Fields in Atomic Physics

Local Structured Vacuum

1st step: Dirac relativistic atom Singularity

Pomeranchuk-Smorodinsky J. Phys. USSR 9, 97 (1945)
Werner-Wheeler Phys Rev 109, 126-144 (1958)
Pieper-Greiner Z. Physik 218, 327-340 (1969 sub: 14.8.1968)
Popov Zh. Eksp. Teor. Fiz. 59, 965 (1970)

Strong Fields in High Z Atoms



Single Particle Dirac Equation

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

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

Key feature: bound states pulled from one continuum move as function of $Z\alpha$ across into the other continuum.

2nd step: Walter's great invention

Embedding a super bound electron in positron continuum

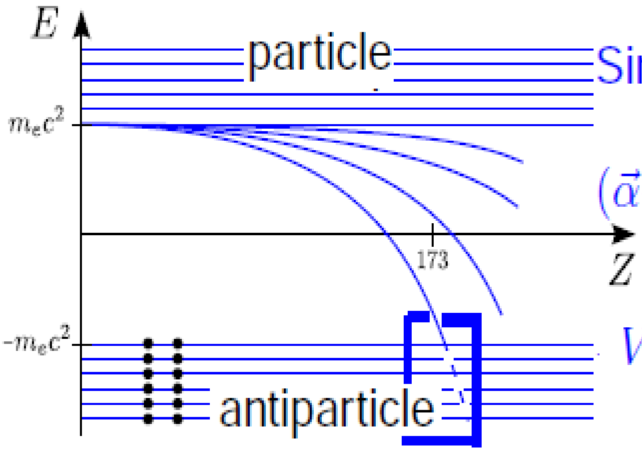
VOLUME 28, NUMBER 19 PHYSICAL REVIEW LETTERS 8 MAY 1972

Solution of the Dirac Equation for Strong External Fields*

Berndt Müller, Heinrich Peitz, Johann Rafelski, and Walter Greiner
Institut für Theoretische Physik der Universität Frankfurt, Frankfurt am Main, Germany
(Received 14 February 1972)

The 1*s* bound state of superheavy atoms and molecules reaches a binding energy of $-2mc^2$ at $Z \approx 169$. It is shown that the *K* shell is still localized in *r* space even beyond this critical proton number and that it has a width Γ (several keV large) which is a positron escape width for ionized *K* shells. The suggestion is made that this effect can be observed in the collision of very heavy ions (superheavy molecules) during the collision.

What is (mostly) this about?



Single Particle Dirac Equation

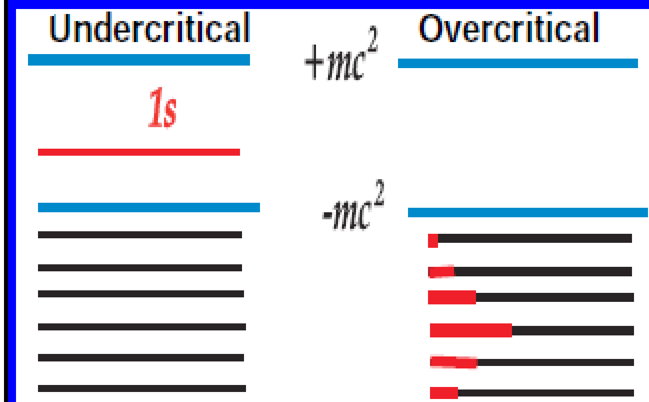
$$(\vec{\alpha}\cdot i\vec{\nabla}+\beta m+V(r))\Psi_n(\vec{r}) = E_n\Psi_n(\vec{r})$$

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

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

Reference: W. Greiner, B. Müller and JR ISBN 3-540-13404-2. "Quantum Electrodynamics of Strong Fields," (Springer Texts and Monographs in Physics, 1985),



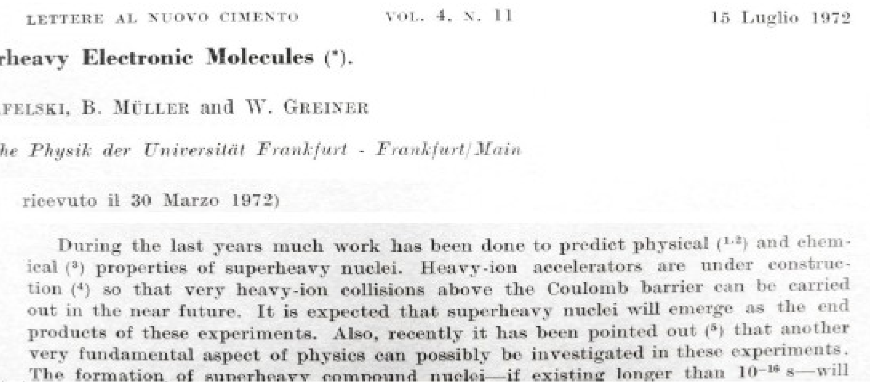
If diving state 'empty' vacuum decays

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

state occupied by an electron, 'smooth' transition of charge distribution

3rd step: 1972 HI Collisions replace the need for super-super-heavy nuclei

HI collisions: electrons in quasimolecuar fields


LETTERE AL NUOVO CIMENTO VOL. 4, N. 11 15 Luglio 1972

Superheavy Electronic Molecules (*).

J. RAFELSKI, B. MÜLLER and W. GREINER

Institut für Theoretische Physik der Universität Frankfurt - Frankfurt/Main

ricevuto il 30 Marzo 1972)

During the last years much work has been done to predict physical (1,2) and chemical (3) properties of superheavy nuclei. Heavy-ion accelerators are under construction (4) so that very heavy-ion collisions above the Coulomb barrier can be carried out in the near future. It is expected that superheavy nuclei will emerge as the end products of these experiments. Also, recently it has been pointed out (5) that another very fundamental aspect of physics can possibly be investigated in these experiments. The formation of superheavy compound nuclei—if existing longer than 10^{-16} s—will

SUPERHEAVY ELECTRONIC MOLECULES

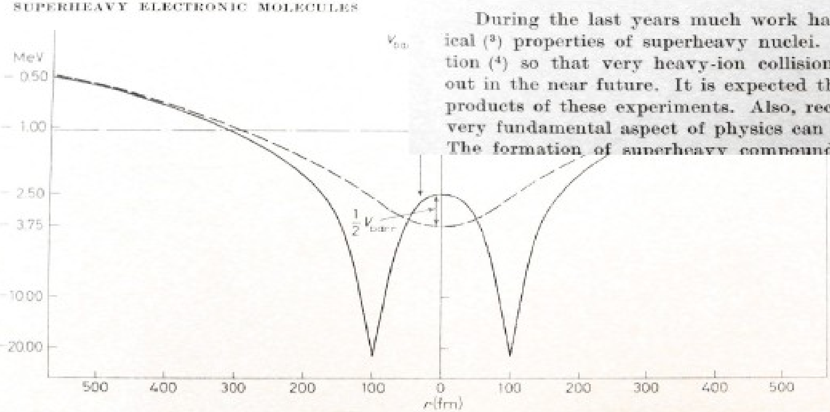
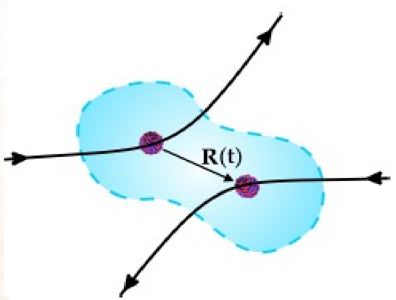
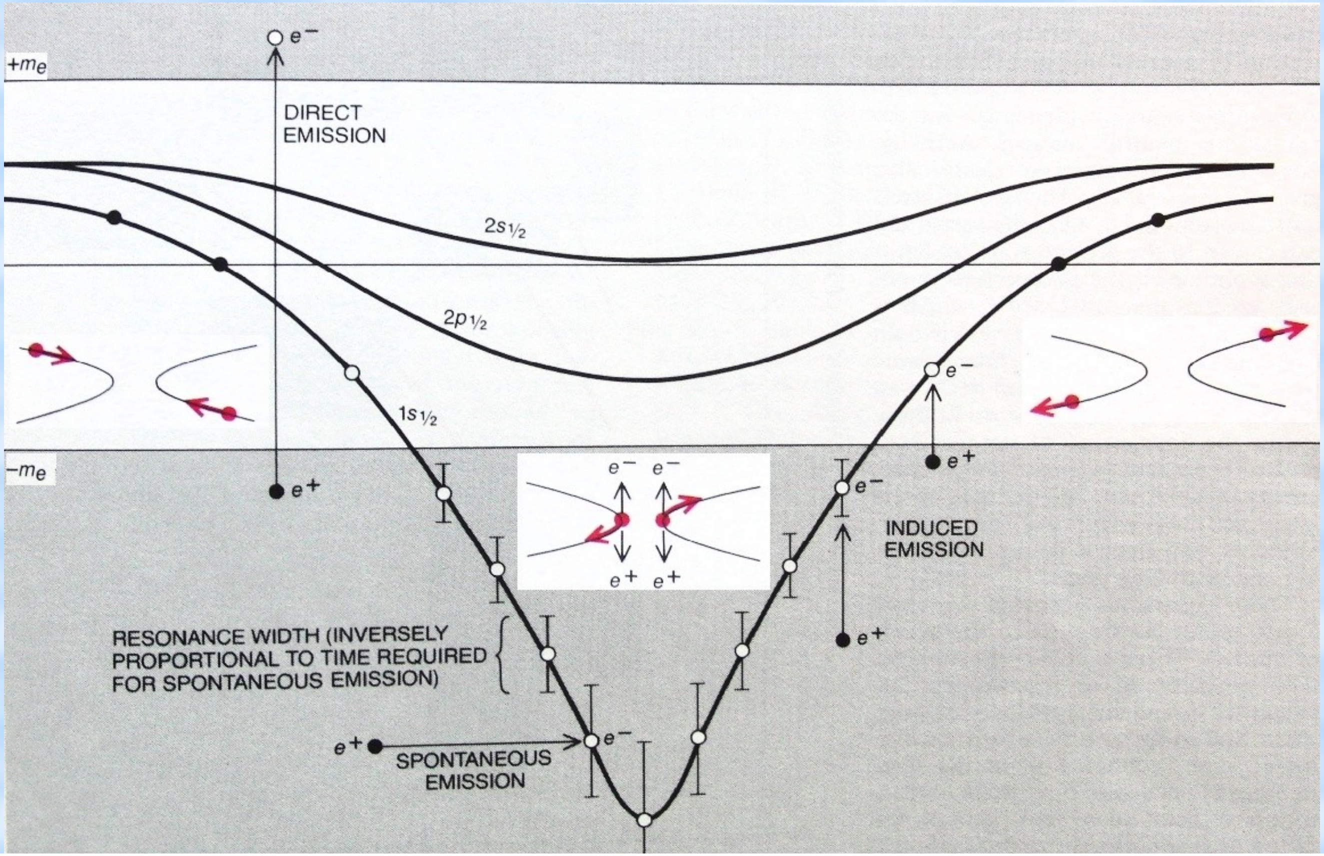


Fig. 2. – The two-centre Coulomb potential is shown for two lead nuclei separated by 200 fm. The dashed curve corresponds to the monopol approximation used in the present numerical calculation of the «molecular» energy eigenvalues. $2 \times Z = 82$, —— two-centre potential, – – – potential of monopol approximation.



A decade of process computation in heavy ion collisions



Probing QED Vacuum with Heavy Ions

**Johann Rafelski, Johannes Kirsch, Berndt Müller,
Joachim Reinhardt and Walter Greiner**

Abstract We recall how nearly half a century ago the proposal was made to explore the structure of the quantum vacuum using slow heavy-ion collisions. Pursuing this topic we review the foundational concept of spontaneous vacuum decay accompanied by observable positron emission in heavy-ion collisions and describe the related theoretical developments in strong fields QED.

By early 1970 the Strong Fields Frankfurt group was invited by Walter Greiner to a Saturday morning palaver in his office. In the following few years this was the venue where the new ideas that addressed the strong fields physics were born. At first the predominant topic was the search for a mechanism to stabilize the solutions of the Dirac equation, avoiding the "diving" of bound states into the Dirac sea predicted by earlier calculations [3]. However, a forced stability contradicted precision atomic spectroscopy data [6–8]. In consequence the group discussions turned to exploring the opposite, the critical field instability, and the idea of spontaneous positron emission emerged.

S. Schramm and M. Schäfer (eds.), *New Horizons in Fundamental Physics*,
FIAS Interdisciplinary Science Series, DOI 10.1007/978-3-319-44165-8_17

4th step 1973: no stable vacuum, hence vacuum decay in Strong Fields

Nuclear Physics B68 (1974) 585–604. North-Holland Publishing Company

THE CHARGED VACUUM IN OVER-CRITICAL FIELDS*

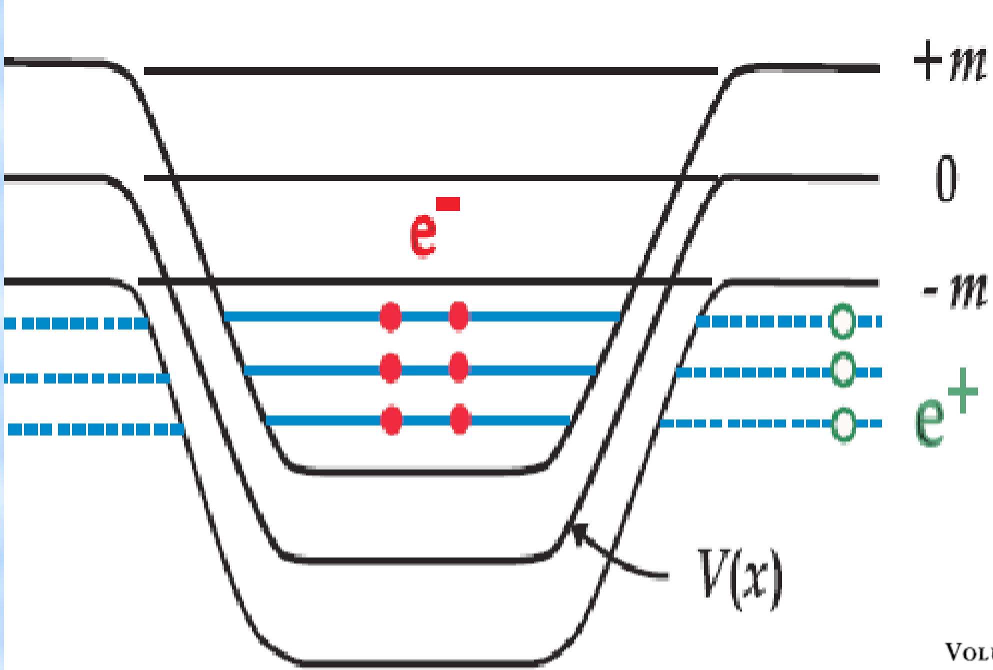
J. RAFELSKI, B. MÜLLER and W. GREINER
Institut für Theoretische Physik der Universität Frankfurt, Frankfurt am Main, Germany

Received 4 June 1973
(Revised 17 September 1973)

Abstract: The concept of over-critical fields, i.e. fields in which spontaneous, energy-less electron-position pair creation may occur, is discussed. It is shown that only a charged vacuum can be a stable ground state of the overcritical field. The time-dependent treatment confirms previous results for the cross sections for the auto-ionizing positrons. The questions in connection with the classical Dirac wave functions in over-critical fields are extensively discussed in the frame of the self-consistent formulation of QED including the effects of vacuum polarization and self-energy.

5th step: Stabilization of local vacuum

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



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.

SCIENTIFIC AMERICAN
DECEMBER 1979
VOL. 241, NO. 6 PP. 150—159

The Decay of the Vacuum

by Lewis P. Fulcher, Johann Rafelski and Abraham Klein

Near a superheavy atomic nucleus empty space may become unstable, with the result that matter and antimatter can be created without any input of energy. The process might soon be observed experimentally

VOLUME 34, NUMBER 6 PHYSICAL REVIEW LETTERS 10 FEBRUARY 1975

Stabilization of the Charged Vacuum Created by Very Strong Electrical Fields in Nuclear Matter*

Berndt Müller and Johann Rafelski

(Received 2 December 1974)

The expectation value of electrical charge in charged vacuum is calculated utilizing the Thomas-Fermi model. We find almost complete screening of the nuclear charge. For any given nuclear density there is an upper bound for the electrical potential. For normal nuclear densities this value is – 250 MeV. This suggests that the vacuum is stable against spontaneous formation of heavy, charged particles.

6^{th} Step "Accelerated" Vacuum – compare BH accelerated observer and BH

Recognize external fields as a TEMPERATURE

Volume 63A, number 3 PHYSICS LETTERS 14 November 1977

INTERPRETATION OF EXTERNAL FIELDS AS TEMPERATURE*

Berndt MÜLLER and Walter GREINER
Institut für Theoretische Physik, Johann Wolfgang Goethe Universität, 6000 Frankfurt am Main, W.-Germany
and
Johann RAFELSKI
Gesellschaft für Schwerionenforschung, 6100 Darmstadt, W.-Germany

Received 5 September 1977

We show that average excitation of the vacuum state in the presence of an external electric field can be described by an effective temperature $kT = eE/(2\pi m)$. We present a qualitative generalization of our result to other interactions. Some phenomenological implications concerning matter at low temperatures in strong electric fields (10^5 V/cm) are

Strong Fields in RHI Collisions

In past 25 years main advance in HI Collisions was the development of relativistic capabilities. Relativity greatly amplifies the EM fields. Near future research opportunity and an active research topic addressed in my group, not ready for a report.

QED of Strong Fields Book: 1986

W. Greiner B. Müller J. Rafelski

Quantum Electrodynamics of Strong Fields

With an Introduction into
Modern Relativistic Quantum Mechanics

With 258 Figures

Springer-Verlag
Berlin Heidelberg New York Tokyo

1. Introduction

The structure of the vacuum is one of the most important topics in modern theoretical physics. In the best understood field theory, Quantum Electrodynamics (QED), a transition from the neutral to a charged vacuum in the presence of strong external electromagnetic fields is predicted. This transition is signalled by the occurrence of spontaneous e^+e^- pair creation. The theoretical implications of this process as well as recent successful attempts to verify it experimentally using heavy ion collisions are discussed. A short account of the history of the vacuum concept is given. The role of the vacuum in various areas of physics, like gravitation theory and strong interaction physics is reviewed.

1.1 The Charged Vacuum

Our ability to calculate and predict the behaviour of charged particles in weak electromagnetic fields is primarily due to the relative smallness of the fine-structure constant $\alpha \approx 1/137$. However, physical situations exist in which the coupling constant becomes large, e.g. an atomic nucleus with Z protons can exercise a much stronger electromagnetic force on the surrounding electrons than could be described in parturbation theory, and hence it is foreseeable that the new expansion parameter $(Z\alpha)$ can quite easily be of the order of unity. In such cases non-perturbative methods have to be used to describe the resultant new phenomena, of which the most outstanding is the massive change of the ground-state structure, i.e. of the vacuum of quantum electrodynamics.

Strong Fields = Strong Acceleration

Critical Fields=Critical Acceleration with Radiation Reaction

Critical Fields=

Critical Acceleration

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

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

is subject to critical natural unit =1 acceleration:

$$a_c = \frac{m_e c^3}{\hbar} \to 2.331 \times 10^{29} \mathrm{m/s}^2$$

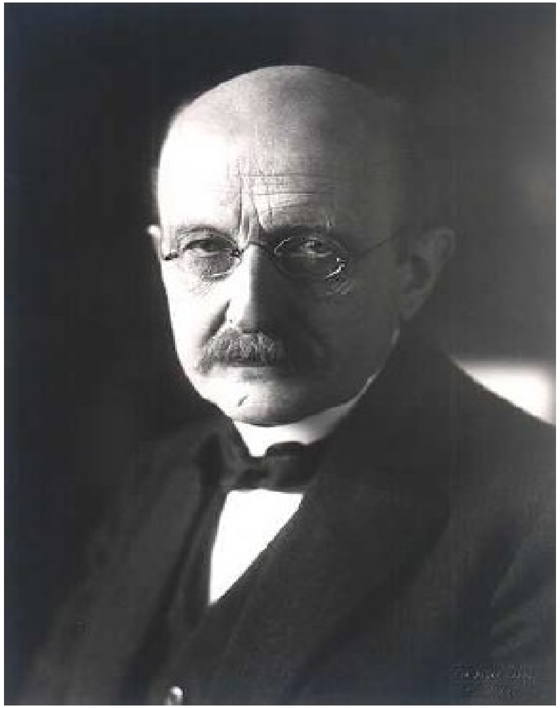
Truly dimensionless unit acceleration arises when we introduce specific acceleration

$$\aleph = \frac{a_c}{mc^2} = \frac{c}{\hbar}$$

Specific unit acceleration arises in Newton gravity at Planck length distance: $\aleph_G \equiv G/L_p^2 = c/\hbar$ 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



$$h/k_B = a = 0.4818 \cdot 10^{-10} [\text{sec} \times \text{Celsiusgrad}]$$
$$h = b = 6.885 \cdot 10^{-27} \left[\frac{\text{cm}^2\text{gr}}{\text{sec}}\right]$$
$$c = c = 3.00 \cdot 10^{10} \left[\frac{\text{cm}}{\text{sec}}\right]$$
$$G = f = 6.685 \cdot 10^{-8} \left[\frac{\text{cm}^3}{\text{gr. sec}^2}\right]^1.$$

Wählt man nun die »natürlichen Einheiten« so, dass in dem neuen Maasssystem jede der vorstehenden vier Constanten den Werth 1 annimmt, so erhält man als Einheit der Länge die Grösse:

$$\sqrt{2\pi}\,L_{Pl} = \sqrt{\frac{bf}{c^3}} = 4.13 \cdot 10^{-33}\,\text{cm}, \mapsto \sqrt{2\pi}\,1.62 \times 10^{-33}\,\text{cm}$$

als Einheit der Masse:

$$\sqrt{2\pi}\,M_{Pl} = \sqrt{\frac{bc}{f}} = 5.56 \cdot 10^{-5}\,\text{gr}, \mapsto \sqrt{2\pi}\,2.18 \times 10^{-5}\,\text{g}$$

als Einheit der Zeit:

$$\sqrt{2\pi}\,t_{Pl} = \sqrt{\frac{bf}{c^5}} = 1.38 \cdot 10^{-43}\,\text{sec}, \mapsto \sqrt{2\pi}\,5.40 \times 10^{-44}\,\text{s}$$

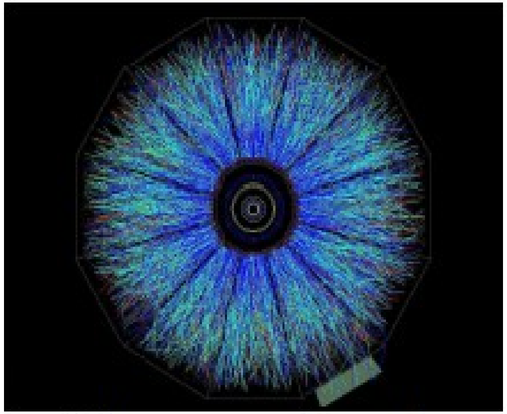
als Einheit der Temperatur:

$$\sqrt{2\pi}\,T_{Pl} = a\sqrt{\frac{c^5}{bf}} = 3.50 \cdot 10^{32}\,{}^\circ\,\text{Cels} \mapsto \sqrt{2\pi}\,1.42 \times 10^{32}\,\text{K}$$

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)*

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: $\Delta y_{\rm SPS} = 2.9$, and $\Delta y_{\rm RHIC} = 5.4$. Considering constituent quark masses $M_i \simeq M_N/3 \simeq 310$ MeV we need $\Delta\tau_{\rm SPS} < 1.8$ fm/c and $\Delta\tau_{\rm RHIC} < 3.4$ fm/c to exceed a_c.
- Observed unexplained soft electromagnetic radiation in hadron reactions *A. Belognni et al. [WA91 Collaboration], "Confirmation of a soft photon signal in excess of QED expectations in π–p interactions at 280-GeV/c," Phys. Lett. B* **408**, *487 (1997)*

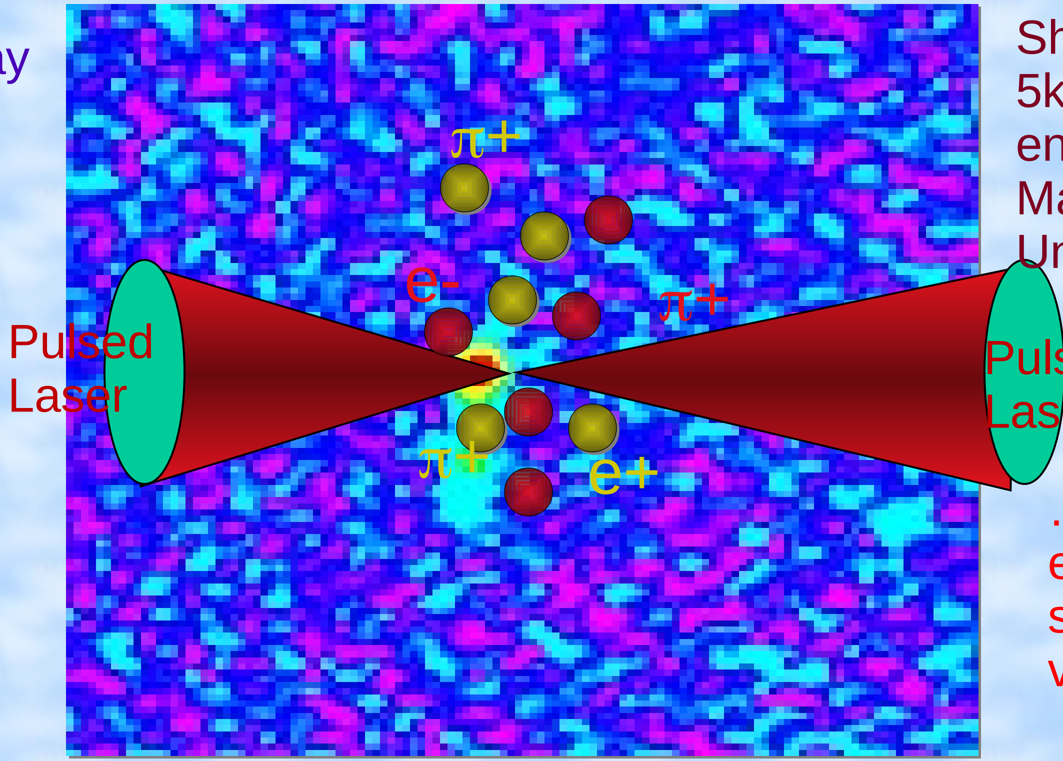
A new path to probing space time

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

Half of 2018 Nobel Prize: for Invention of the Method leading to creation of Laser Strong fields

Gerard Mourou +Marcelle
Donna Strickland
In company of friends
Lake Geneva in 2013

LASERS

The light-pulse horizon

Rapid advances in high-intensity laser technology are closing in on the technological breakthrough of a compact particle accelerator, and with it a new means to study the structure of the vacuum. **Gérard Mourou**, **Johann Rafelski** and **Toshiki Tajima** explain.

CERN Courier *March 2009* 21

Strong Field Unsolved Problem Radiation-Acceleration-Reaction

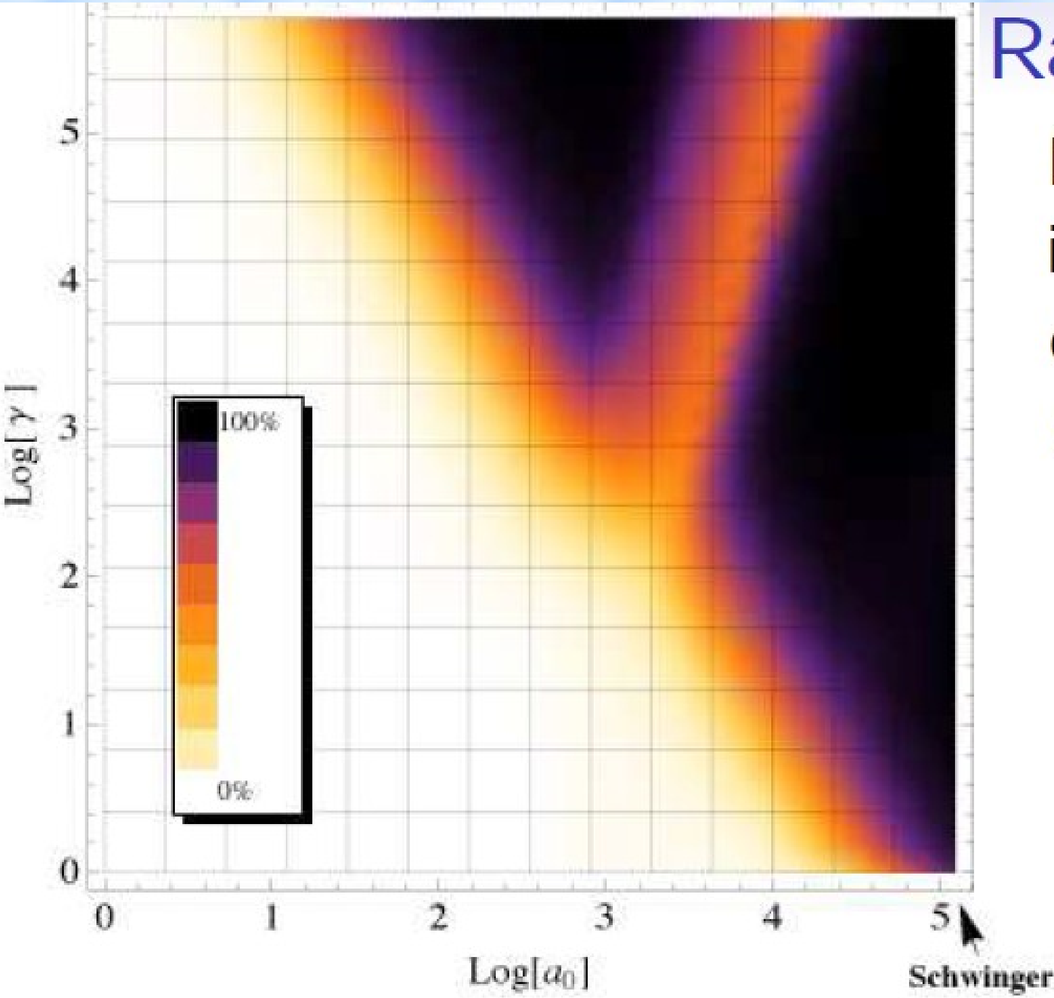
Conventional Lorentz-Electromagnetic force is incomplete: accelerated charged particles can radiate: “radiation friction” instability – some acceleration produces friction slowdown, produces more slowdown etc. Need acceleration that is not negligible to explore the physics of radiation friction. Problem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

Radiation reaction regime



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

Laser-Electron COLLIDER

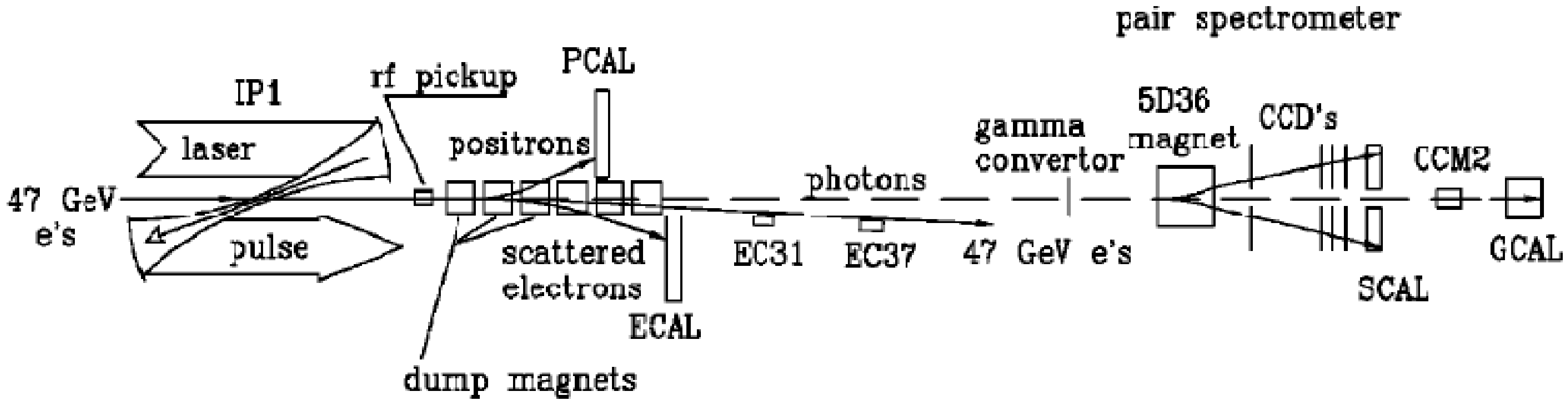
	Electron	Laser	X/Gamma
Energy	.1 – 5 GeV	**J and kJoule**	MeV
Duration	1-10 fs	20 – 150 fs	10 – 1000 fs
Rep.rate	10Hz	10Hz	10Hz

SLAC'95 experiment below critical acceleration

$p_e^0 = 46.6$ GeV; in 1996/7 $a_0 = 0.4$, $\left|\frac{du^\alpha}{d\tau}\right| = .073[m_e]$ (Peak)

Multi-photon processes observed:

- Nonlinear Compton scattering
- Breit-Wheeler electron-positron pairs



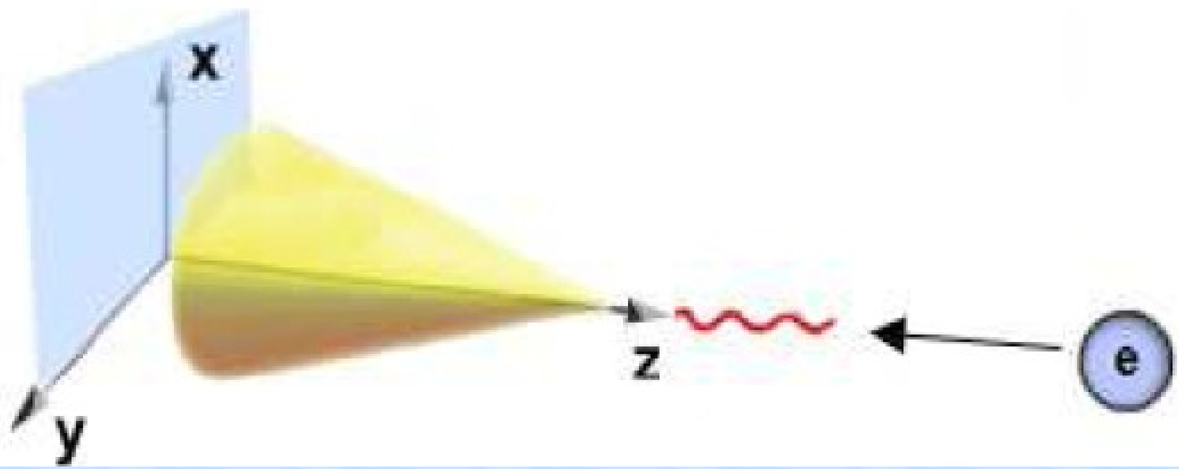
- **D. L. Burke** *et al.*, "Positron production in multiphoton light-by-light scattering," Phys. Rev. Lett. **79**, 1626 (1997)
- **C. Bamber** *et al.*, "Studies of nonlinear QED in collisions of 46.6 GeV electrons with intense laser pulses" Phys. Rev. D **60**, 092004 (1999).

Probing super-critical (Planck) acceleration

$$a_c = 1(\to m_e c^3/\hbar = 2.331 \times 10^{29} \mathrm{m/s}^2)$$

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.

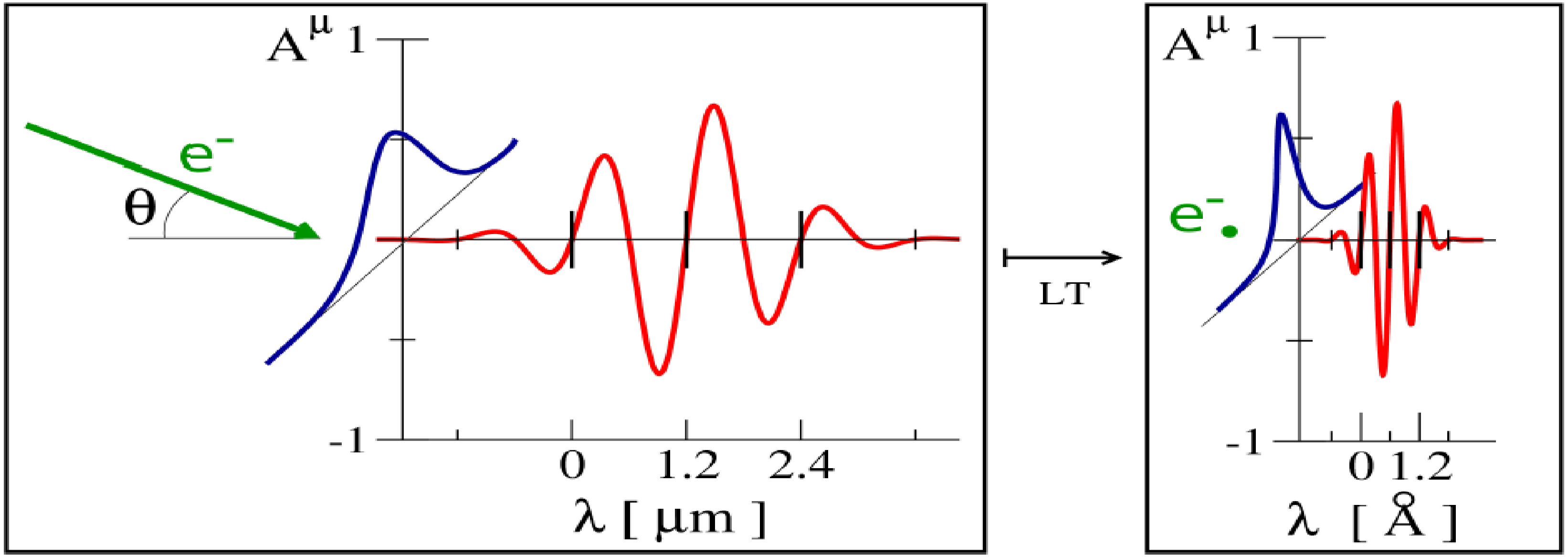
Plan B: Ultra-relativistic Lorentz-boost: we collide counter-propagating electron and laser pulse.



Pulse Lorentz Transform (LT)

Relativistic electron-laser pulse collision

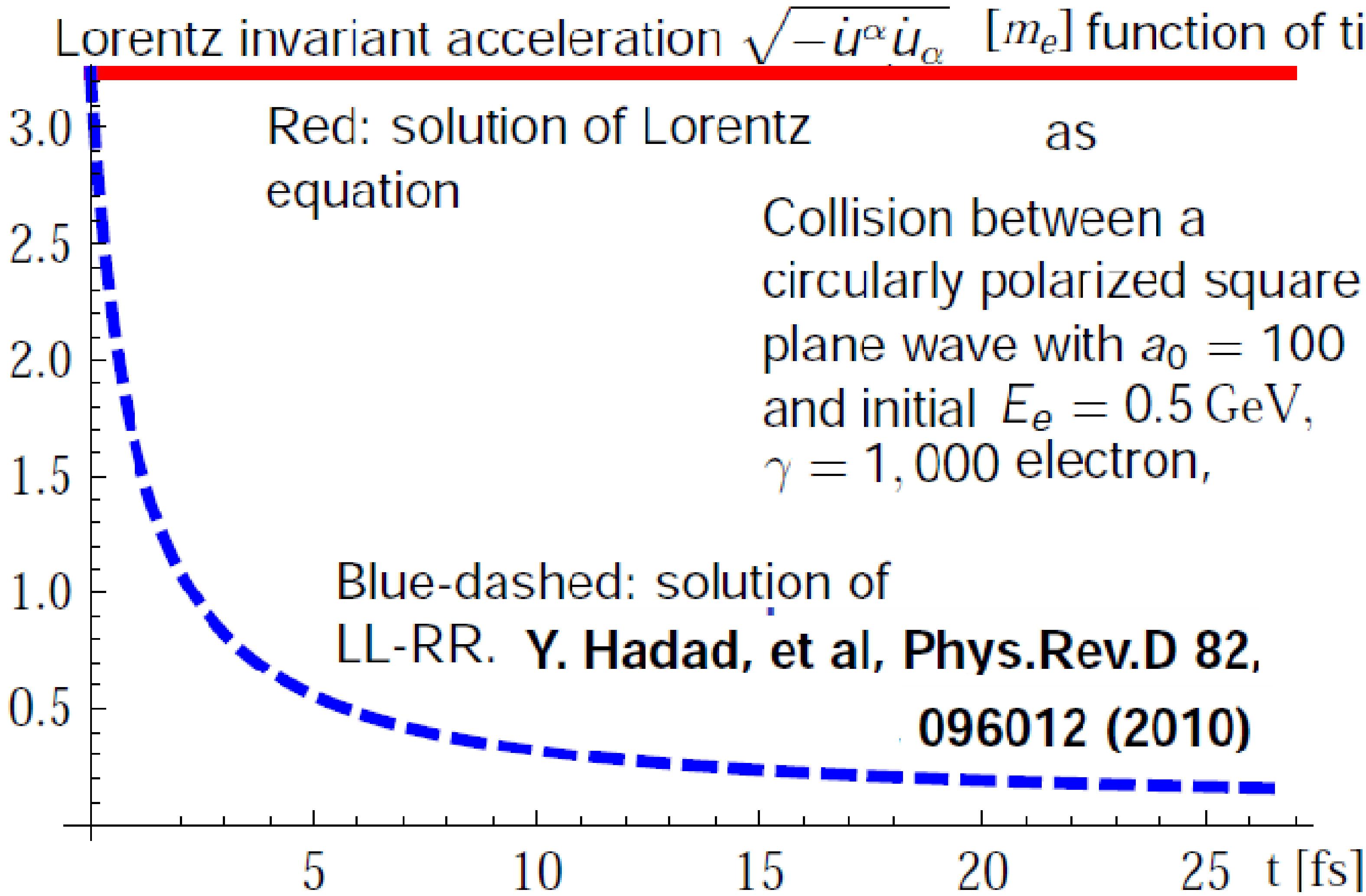
$u^\beta = \gamma(1, \vec{v}) \rightarrow$ In electron's rest frame: $u'_\beta = (1, \vec{0})$



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

Unit acceleration condition: $a_0 \dfrac{\omega'}{m_e} \simeq 2\gamma a_0 \dfrac{\omega}{m_e} \rightarrow 1$

Example: Electron de-acceleration by a pulse



Red: solution of Lorentz equation

as

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

Blue-dashed: solution of LL-RR. **Y. Hadad, et al, Phys.Rev.D 82, 096012 (2010)**

Sample of proposed LAD extensions

LAD	$\mathbf{m}\dot{\mathbf{u}}^{\alpha} = \mathbf{q}\mathbf{F}^{\alpha\beta}\mathbf{u}_{\beta} + m\tau_0\left[\ddot{u}^{\alpha} + u^{\beta}\ddot{u}_{\beta}u^{\alpha}\right]$
Landau-Lifshitz	$\mathbf{m}\dot{\mathbf{u}}^{\alpha} = \mathbf{q}\mathbf{F}^{\alpha\beta}\mathbf{u}_{\beta} + q\tau_0\left\{F^{\alpha\beta}_{,\gamma}u_{\beta}u^{\gamma} + \frac{q}{m}\left[F^{\alpha\beta}F_{\beta\gamma}u^{\gamma} - (u_{\gamma}F^{\gamma\beta})(F_{\beta\delta}u^{\delta})u^{\alpha}\right]\right\}$
Caldirola	$\mathbf{0} = \mathbf{q}\mathbf{F}^{\alpha\beta}(\tau)\,\mathbf{u}_{\beta}(\tau) + \frac{m}{2\tau_0}\left[u^{\alpha}(\tau - 2\tau_0) - u^{\alpha}(\tau)\,u_{\beta}(\tau)\,u^{\beta}(\tau - 2\tau_0)\right]$
Mo-Papas	$\mathbf{m}\dot{\mathbf{u}}^{\alpha} = \mathbf{q}\mathbf{F}^{\alpha\beta}\mathbf{u}_{\beta} + q\tau_0\left[F^{\alpha\beta}\dot{u}_{\beta} + F^{\beta\gamma}\dot{u}_{\beta}u_{\gamma}u^{\alpha}\right]$
Eliezer	$\mathbf{m}\dot{\mathbf{u}}^{\alpha} = \mathbf{q}\mathbf{F}^{\alpha\beta}\mathbf{u}_{\beta} + q\tau_0\left[F^{\alpha\beta}_{,\gamma}u_{\beta}u^{\gamma} + F^{\alpha\beta}\dot{u}_{\beta} - F^{\beta\gamma}u_{\beta}\dot{u}_{\gamma}u^{\alpha}\right]$
Caldirola-Yaghjian	$\mathbf{m}\dot{\mathbf{u}}^{\alpha} = \mathbf{q}\mathbf{F}^{\alpha\beta}(\tau)\,\mathbf{u}_{\beta}(\tau) + \frac{m}{\tau_0}\left[u^{\alpha}(\tau - \tau_0) - u^{\alpha}(\tau)\,u_{\beta}(\tau)\,u^{\beta}(\tau - \tau_0)\right]$

P. A. M. Dirac, "Classical theory of radiating electrons," Proc. Roy. Soc. Lond. **A 167**, 148 (1938)

L. D. Landau and E. M. Lifshitz, "The Classical theory of Fields," *Oxford: Pergamon (1962)* 354p.

P. Caldirola, "A Relativistic Theory of the Classical Electron," Riv. Nuovo Cim. **2N13**, 1 (1979).

T. C. Mo and C. H. Papas, "A New Equation Of Motion For Classical Charged Particles," Izv. Akad. Nauk Arm. SSR Fiz. **5**, 402 (1970)

C. Eliezer, "On the classical theory of particles" Proc. Roy. Soc. Lond. **A 194**, 543 (1948).

A. D. Yaghjian, "Relativistic Dynamics of a Charged Sphere," *Lecture Notes in Physics, Springer-Verlag, Berlin (1992) 152p.*

Other recent references

H. Spohn, *Dynamics of charged particles and their radiation field,* (CUP, Cambridge, UK 2004, ISBN 0521836972)

F. Rohrlich, "Dynamics of a charged particle" Phys. Rev. E **77**, 046609 (2008)

Insight:

To resolve inconsistencies: we need to formulate a NEW "large accelaration" theory of electro-magnetism, comprising Mach's principle, and challenging understanding of inertia.

EXPERIMENT strong acceleration required. What is strong: unit acceleration=Heisenberg-Schwinger Field: immediate realization in (relativistic) heavy ion collisions, future potential with intense lasers

THEORY Question: How to achieve that charged particles when accelerated radiate in self-consistent field – the outcome of Maxwell equations need to be made consistent with Lorentz force.

Near Future: Abundant particle production in RHI collisions (fields amplified with Lorentz factor)