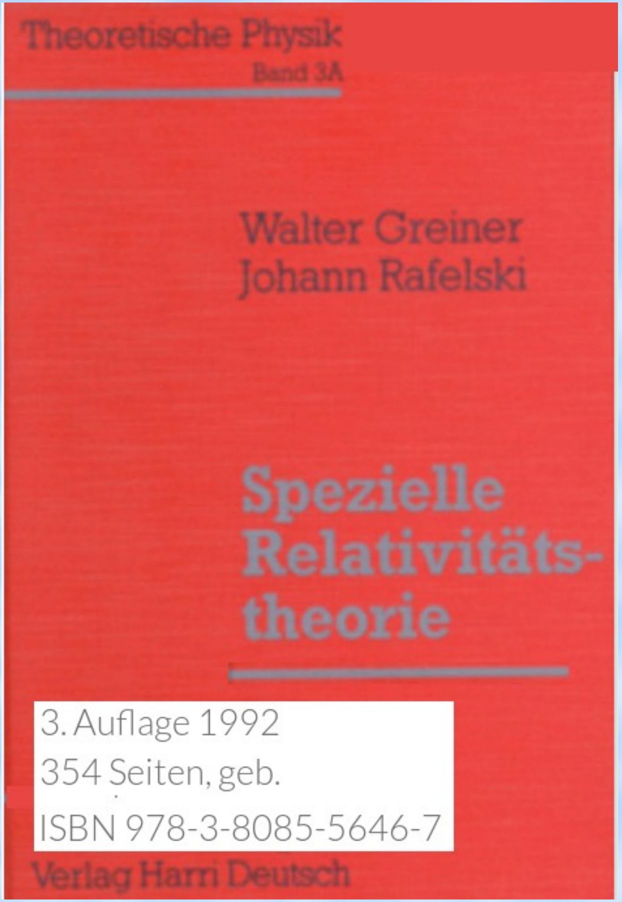
Reviving Teaching of Special Relativity

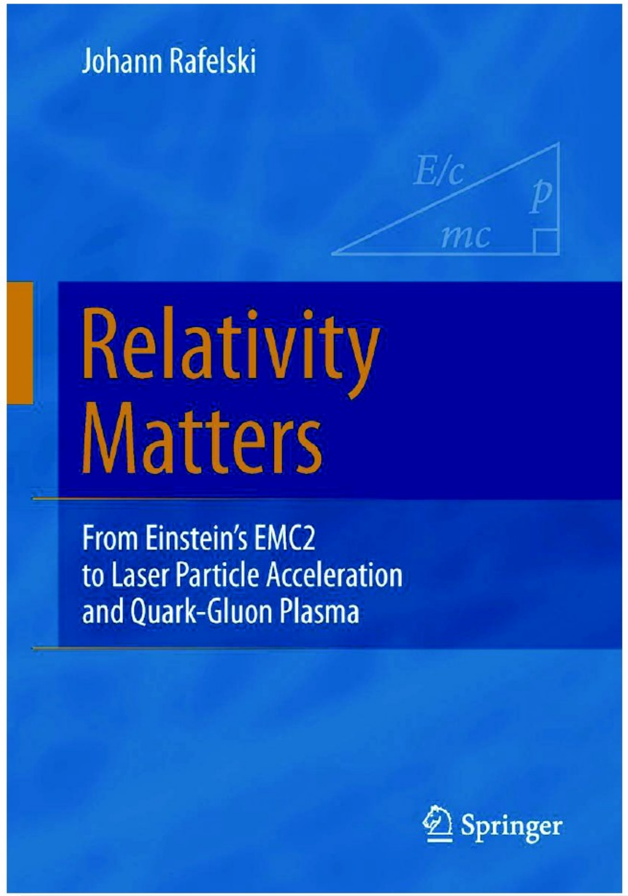
Johann Rafelski
Department of Physics, UA

Many undergraduate students experience Special Relativity (SR) in a few lectures given often by non-expert lecturer employing a non-expert “modern physics” text. I will begin introducing classic misunderstandings resulting from this mix, before turning to the related research topics. I argue that **SR is today a separate physics discipline needing more thorough attention.**

QUALIFICATIONS: Long Interest in R&T in SR:
I tracked developments discussed with colleages,

worked in the field for nearly 50 years





Einstein 1905: extended relativity principle to be valid for EM (only inertial motion) and light

Time recognized as a 4th coordinate

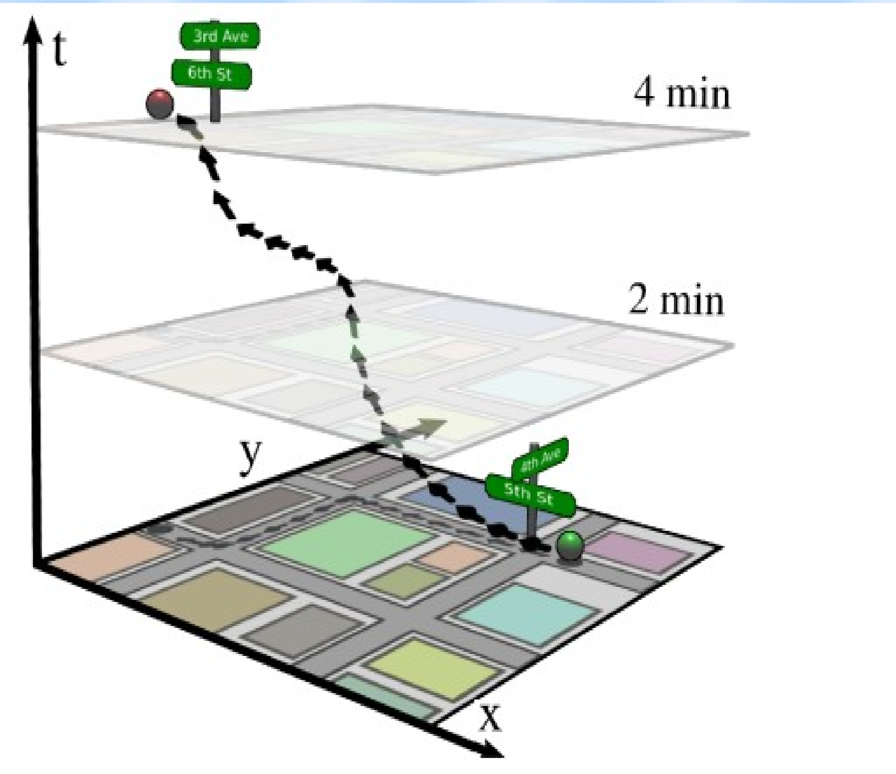


Fig. 1.2 A world line, shown here, of a four-minute walk from the corner of 4th Ave and 5th St to the corner of 3rd Ave and 6th St. Motion in the x, y, and time t dimensions is shown, with the z dimension suppressed (except for the street signs)

$$x' = \frac{x - vt}{\sqrt{1-(v/c)^2}}, \quad t' = \frac{t-(v/c^2)x}{\sqrt{1-(v/c)^2}} \, .$$

Lorentz Coord. Transformation

Set t=0: $$x = \sqrt{1-(v/c)^2}\, x'$$ x<x'

Observer measuring at their equal time report event separation consistent with 'contraction'

$$x' = x\sqrt{1-(v/c)^2} - t'v, \quad t' = t\sqrt{1-(v/c)^2} - \frac{x'v}{c^2} \, .$$

Larmor's form of the Lorentz transformation

Set x'=0: $$t' = t\sqrt{1-(v/c)^2}$$ t'<t

Clock sticking to a body measures shorter time: time dilation

Each body has its proper time

Teaching SR I ask students about body contraction: I offer a choice

What is "Lorentz contraction":

Some say space is contracted. Can this be true?

Other say this is distance contraction. What is this?

A few claim this is "apparent" body contraction. Apparent?

Einstein wrote a "response" in 1911 explaining that his and Lorentz views in this matter **agree**: body contraction is real (just like kinetic energy and momentum of a car is real even if it is zero for the driver).

Before GR in 1911 nobody would confound properties of material body with space-time. Only Gravity Relativity (GR) changes space time and confounds thinking about the real relativity theory!

Issues in Learning Special Relativity

- When in a lecture we need to claim a "paradox", or "not real", it means we are not sure what we are teaching
- Students: choose SR sources carefully, lots of bad stuff around (many false prophets)
- Remember: "S" R is a bigger unfinished theory compared to GR and yet GR in minds of many supersedes SR (bad name choice)

SR in 1905 format is "incomplete" allows inertial motion only

Beware of qualitative arguments: SR is very subtle.

SR is evolving: we use it daily in situations where strong forces are relevant and are trying-out fix-ups.

LIST OF challenges->

Misunderstanding (MU) 1:
Space is contracted??

When posing the question, **Is the "Lorentz contraction" that of space or of a body?** a frequent reply is: *space is contracted??* However, the Lorentz-Fitzgerald (LFG) body contraction cannot be a contraction of space, for the simple reason that SR does not address the properties of the space-time in which we live. Gravity Relativity (GR) looks at this question generalizing Newton's law of gravity to strong field and relativistic context.

That is why I speak of "**body contraction**," rather than simply "contraction." We keep in mind and always remember: space and time are not impacted in any way in SR; in particular, they are not impacted by the inertial motion of particles or extended material bodies. The fact that one inertial observer (IO) measures event coordinates that are different from those measured by another IO does not mean that there is a change of the space-time manifold.

390 SCIENCE. [Vol. XIII. No. 328

LETTERS TO THE EDITOR.

*** Correspondents are requested to be as brief as possible. The writer's name is in all cases required as proof of good faith.*

The editor will be glad to publish any queries consonant with the character of the journal.

Twenty copies of the number containing his communication will be furnished free to any correspondent on request.

The Ether and the Earth's Atmosphere.

I HAVE read with much interest Messrs. Michelson and Morley's wonderfully delicate experiment attempting to decide the important question as to how far the ether is carried along by the earth. Their result seems opposed to other experiments showing that the ether in the air can be carried along only to an inappreciable extent. I would suggest that almost the only hypothesis that can reconcile this opposition is that the length of material bodies changes, according as they are moving through the ether or across it, by an amount depending on the square of the ratio of their velocity to that of light. We know that electric forces are affected by the motion of the electrified bodies relative to the ether, and it seems a not improbable supposition that the molecular forces are affected by the motion, and that the size of a body alters consequently. It would be very important if secular experiments on electrical attractions between permanently electrified bodies, such as in a very delicate quadrant electrometer, were instituted in some of the equatorial parts of the earth to observe whether there is any diurnal and annual variation of attraction, — diurnal due to the rotation of the earth being added and subtracted from its orbital velocity; and annual similarly for its orbital velocity and the motion of the solar system. GEO. FRAS. FITZ GERALD.

Dublin, May 2.

Lorentz or FitzGerald??

Since practically all books attribute body contraction to Lorentz I keep Lorentz name but factually FitzGerald was way ahead in 1889 and Lorentz once aware renamed the body contraction as FitzGerald body contraction. The problem was and is: names stick. Lorentz also gets the credit for coordinate transformation he never derived (it was correctly and independently obtained by Larmor, Einstein, Poincare…..)

Is a passenger on a relativistic rocket aware s/he is "body contracted"?

A. Einststein 1911: No - there is no absolute reference frame in the Universe, s/he cannot know against what she contracts.

J. S. Bell 1976 of "Bell inequality fame": adapts Lorentz-Janossy point of view: using acceleration he transports IO from one to another reference frame. This is called Lorentz-Bell or "physical reality" SR pedagogy.

CERN 1985 March 12

Dear Johann, the only thing I can thoroughly recommend on relativity is my own paper. I enclose a copy. I refer there to the book of Janossy. But it is very long, and insufficiently explicit that the Einstein approach is perfectly sound, and very elegant and powerful, (but pedagogically dangerous, in my opinion).

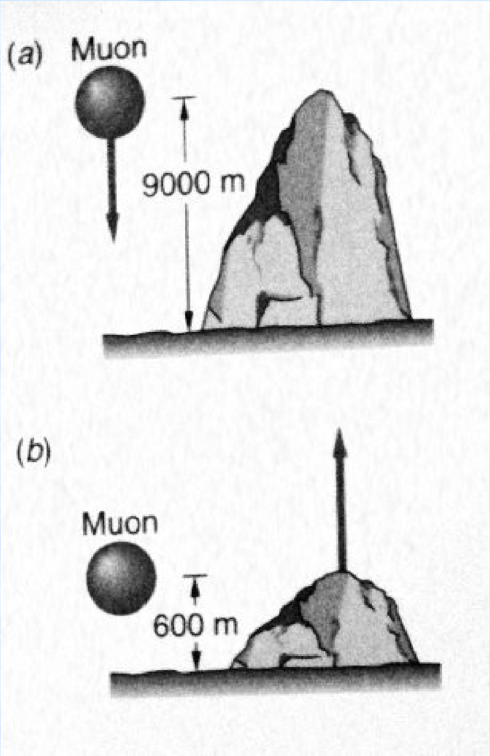
best wishes

John

MU 2: The LFG body contraction and time dilation confirm each other??

In SR both the Lorentz-FitzGerald (LFG) body contraction and time dilation are unrelated body property phenomena (unlike energy and momentum which are related). That they are unrelated is easily recognized by remembering that an elementary point particle (*e.g.* a muon) can experience time dilation but cannot experience a LFG body contraction.

A finite size body is often introduced in a discussion of time dilation to facilitate concurrent observation of some evidently unrelated LFG body contraction: Since an unstable particle (muon)experiences time dilation irrespective of another finite size material body being present, this motivates a frequently made claim that the two effects, body contraction and time dilation, confirm each other. This is not a logically correct line of argument: this claim depends on a material body that is not required in the study of *e.g.* the unstable particle flight distance. NO»NO»NO»



Example: unstable particle travel range

Imagine you perform muon range measurement in intergalactic empty space so there is no LFG body contraction of anything. Using time dilation:

$$c^2\tau^2 = (1 - v^2/c^2)\; c^2 t^2$$

AND LORENTZ-INVARIANCE OF PROPER TIME:

$$c^2\tau^2 = c^2 t^2 - x^2$$

$$x^2 = c^2 t^2 - c^2\tau^2$$

$$x^2 = v^2\tau^2 / (1 - v^2/c^2)$$

Which is to be read: for an inertial observer seeing the muon travel at velocity v the the muon travels the distance x.

MU 3:The LFG body contraction is not real??

The fact that the LFG body contraction and time dilation are largely independent phenomena contributes in “better” books to claims that body contraction is not real, *i.e.* observable, while time dilation is real and measurable by the common clock.

The LFG body contraction has not been measured directly. Sometimes it is argued that the Michelson-Morley interferometer does not allow to measure absolute motion due to LFG body contraction. However, MM experiment proves the principle of relativity for EM phenomena of which LFG body contraction is a consequence, and not an explanation.

While LFG body contraction “clock” does not exist today, it can be build in principle (Bell “rockets”). This assures that, like time dilation, the body contraction is real and can be measured. In fact we can measure LFG body contraction “tomorrow”:

Eur. Phys. J. A (2018) 54: 29
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Letter

THE EUROPEAN
PHYSICAL JOURNAL A

Measurement of the Lorentz-FitzGerald body contraction

Johann Rafelski[a]

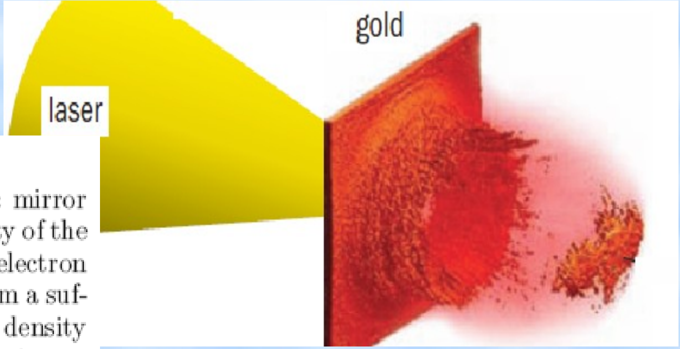
Dedicated to Walter Greiner; October 1935 – October 2016.

Published online: 20 February 2018

Department of Physics, The University of Arizona, Tucson, AZ, 85721, USA

Abstract. A complete foundational discussion of acceleration in the context of Special Relativity (SR) is presented. Acceleration allows the measurement of a Lorentz-FitzGerald body contraction created. It is argued that in the back scattering of a probing laser beam from a relativistic flying electron cloud mirror generated by an ultra-intense laser pulse, a first measurement of a Lorentz-FitzGerald body contraction is feasible.

The moving electron cloud mirror is body compressed.



Johann Rafelski: Measurement of the Lorentz-FitzGerald Body Contraction

Body contraction experiment. — To accomplish our goal to build a laboratory-sized experiment we consider an ultra-intense ultra-short laser pulse shot at a thin (micron) foil. Such a pulse in its focal point can act as a micron-sized hammer pushing out of the foil an electron cloud accelerated to ultrarelativistic motion with a high value of Lorentz-factor γ_e. The emerging electron cloud compared to the original foil thickness will be Lorentz-FitzGerald compressed by γ_e.

A moving electron cloud acts as a relativistic mirror for a low intensity laser light bounce. The capability of the ultrarelativistic mirror to function depends on the electron cloud density; laser light can scatter coherently from a sufficiently high density cloud – what is low and high density is determined by comparing mean electron separation to the light wavelength.

two Lorentz transforms, first into the rest-frame of the mirror and upon reversal of the propagation direction of the light motion, transform back to the laboratory frame.

MU 3b: LFG body contraction is not reversible!

To avoid the need for a decision on the matter of reality of the LFG body contraction most modern physics books speak of "distance contraction," generally without clarifying what this expression means, (and never mention body contraction). The correct way to argue is to note that a measurement at equal observer time reports two event separation consistent with the LFG body contraction.

Speaking "loosely" of distance contraction books create "contraction reversal paradox" (bad). The way this works is: we look at a long train starting at a station entering a shorter tunnel. Train will fit, the mountain will never be shorter. But not so in "distance contraction" books: a paradox like the "twin paradox" which also is created by bad physics.

MU5: Time dilation is observer-reversible?? = "twin paradox"

A returning space traveler will always be younger compared to his twin on Earth. The twin paradox is created by claims that the relativity principle allows "exchange" of the argument, thus it should be the laboratory twin that is younger. However, such exchange is not possible since only the laboratory twin was inertial, not the traveler.

The time measurement process must include a definition of how both space and time are measured. We are specifically not allowed to exchange the two twin time measurements without adjusting for associated difference in measurement of space coordinates. Remembering space removes the time dilation reversibility.

Only so called Lorentz invariant quantities, such as the proper time of a body, are measured to be the same by all IO. Therefore, for each body only its proper time is a meaningful measure of proper time flow; that is the time measured by a clock at relative rest with that body: $c^2\tau^2 = c^2t^2 - x^2 = c^2t'^2 - x'^2$

MU6: Relativistic Doppler (RD) effect: like sound + time dilation??

Time dilation of the source cannot be part of the RD effect since the relative speed with respect to the yet undetermined observer is not known at the time of light emission. Moreover, different time dilation effects would be needed, depending on the motion state of several different observers of the same light emission process.

Since the “luminiferous aether” is non-material, there is no wavelength shift due to relative motion between source and the light medium contrary to the case of sound in air.

Einstein paper works in the following way: the light wave carries to the observer the information about the source allowing the determination of the RD shift in frequency and wavelength   at the actual observation of the light signal. All results are stated without derivation and the argument is very terse, leading to numerous misreads in particular if you do not read the original German manuscript.

Einstein postulates invariance of light phase

~~Beobachter untersucht werden~~. — Durch Anwendung der in § 6 gefundenen Transformationsgleichungen für die elektrischen und magnetischen Kräfte und der in § 3 gefundenen Transformationsgleichungen für die Koordinaten und die Zeit erhalten wir unmittelbar:

$$X' = X_0 \sin \Phi', \qquad L' = L_0 \sin \Phi',$$

$$Y' = \beta\left(Y_0 - \frac{v}{V} N_0\right) \sin \Phi', \qquad M' = \beta\left(M_0 + \frac{v}{V} Z_0\right) \sin \Phi',$$

$$Z' = \beta\left(Z_0 + \frac{v}{V} M_0\right) \sin \Phi', \qquad N' = \beta\left(N_0 - \frac{v}{V} Y_0\right) \sin \Phi',$$

$$\Phi' = \omega'\left(\tau - \frac{a'\xi + b'\eta + c'\zeta}{V}\right),$$

wobei

$$\omega' = \omega \beta\left(1 - a\frac{v}{V}\right), \qquad a' = \frac{a - \frac{v}{V}}{1 - a\frac{v}{V}},$$

$$b' = \frac{b}{\beta\left(1 - a\frac{v}{V}\right)}, \qquad c' = \frac{c}{\beta\left(1 - a\frac{v}{V}\right)}$$

gesetzt ist.

Aus der Gleichung für ω' folgt: Ist ein Beobachter relativ zu einer unendlich fernen Lichtquelle von der Frequenz ν mit der Geschwindigkeit v derart bewegt, daß die Verbindungslinie „Lichtquelle–Beobachter“ mit der auf ein relativ zur Lichtquelle ruhendes Koordinatensystem bezogenen Geschwindigkeit des Beobachters den Winkel φ bildet, so ist die von dem Beobachter wahrgenommene Frequenz ν' des Lichtes durch die Gleichung gegeben:

$$\nu' = \nu \frac{1 - \cos\varphi \frac{v}{V}}{\sqrt{1 - \left(\frac{v}{V}\right)^2}}.$$

Dies ist das Doppelersche Prinzip für beliebige Geschwindig-

Doppler Shift

Not to be confounded with cosmological redshift (which has nothing to do with motion of stars) or gravitational (red) shift which describes the work done escaping the gravity potential.

Einstein postulated (in our language) the Lorentz invariance of light wave phase. This suffices to obtain the SR Doppler formulas for both shift and direction abberation (he states results only).

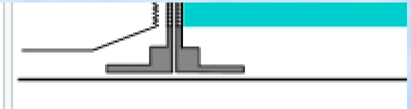
$$\Phi = \omega t - \mathbf{x}\cdot\mathbf{k} = \omega t - \mathbf{x}\cdot\mathbf{n}|\mathbf{k}| = \omega/c(ct - \mathbf{x}\cdot\mathbf{n}) = \Phi' = \omega'/c\,(ct' - \mathbf{x}'\cdot\mathbf{n}')\ .$$

After that it is slowly downhill. Ives and Stilwell 1938 experiment measuring (transverse)Doppler shift states they measure time dilation. Resnick around 1960 leans on text of von Laue SR without knowing German so relies on language of Ives-Stilwell. This is copied in all English language books and all over the Internet. Dark ages of relativity???

Ives–Stilwell experiment

From Wikipedia, the free encyclopedia

https://en.wikipedia.org/wiki/Ives–Stilwell_experiment



Ives–Stilwell experiment (1938). "Ca
mostly H_2^+ and H_3^+ ions) were acce

The **Ives–Stilwell experiment** tested the contribution of relativistic time dilation to the Doppler shift of light.[1][2] The result was in agreement with the formula for the transverse Doppler effect and was the first direct, quantitative confirmation of the time dilation factor.

JOURNAL OF SYNCHROTRON RADIATION

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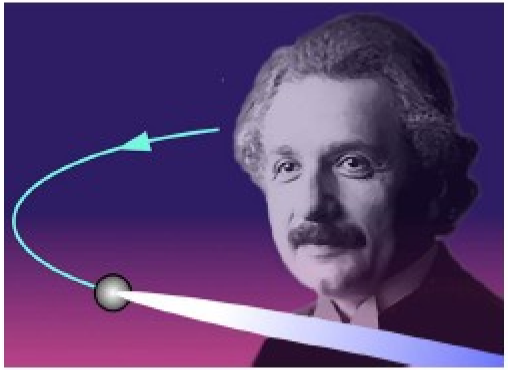
Keywords: special relativity; Doppler; time dilation; Lorentz transformation.



The relativistic foundations of synchrotron radiation

Giorgio Margaritondo[a]* and Johann Rafelski[b]

[a]Faculté des Sciences de Base, Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne 1015, Switzerland, and [b]Department of Physics, The University of Arizona, Tucson, AZ, USA. *Correspondence e-mail: giorgio.margaritondo@epfl.ch

Special relativity (SR) determines the properties of synchrotron radiation, but the corresponding mechanisms are frequently misunderstood. Time dilation is often invoked among the causes, whereas its role would violate the principles of SR. Here it is shown that the correct explanation of the synchrotron radiation properties is provided by a combination of the Doppler shift, not dependent on time dilation effects, contrary to a common belief, and of the Lorentz transformation into the particle reference frame of the electromagnetic field of the emission-inducing device, also with no contribution from time dilation. Concluding, the reader is reminded that much, if not all, of our argument has been available since the inception of SR, a research discipline of its own standing.

MU 7: Extended bodies have no place in SR

Not true! In SR we strive to comprehend what happens to extended material bodies. It is in this context that the LFG body contraction emerges as a pivotal concept. A cohesive extended body is naturally different from a cloud of non-interacting particles. Since space does not contract, a free particle cloud does not either (assuming a density well below some interaction range). All cohesive material bodies are contracted.

Between a non-interacting cloud and a rigid stick are many other complicated structures. This does not mean that SR is somehow not applicable to such objects or that it could not with success be used in their study.

Spatial distance vs body length: Bell rockets

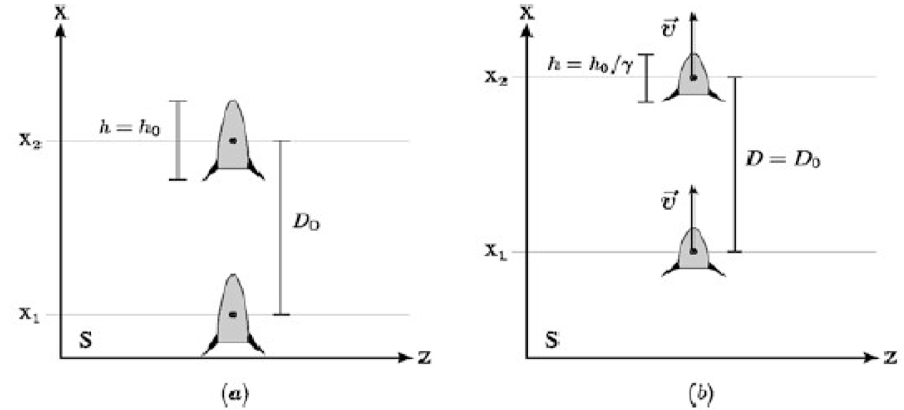


Fig. 10.2 Two rockets of length h separated by distance $D = x_2 - x_1 = D_0$. (**a**) at rest, and in case (b) moving at velocity $\vec{v}$ acquired at a later time

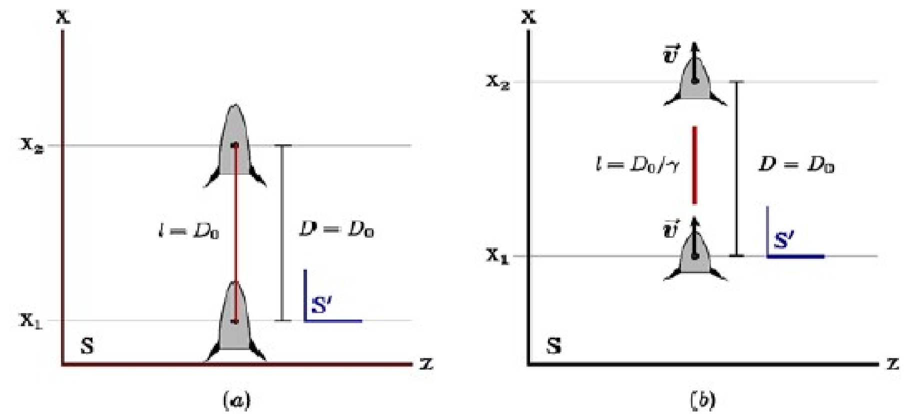


Fig. 10.3 Two rockets separated by distance $D = x_2 - x_1 = D_0$ and connected by a thin thread of (a) at rest, and in case (b) moving at velocity $\vec{v}$ acquired at a later time

Building a clock for LFG body contraction

J. S. Bell 1976 of “Bell inequality fame”: moves using acceleration the finite size rod connecting rockets from one to another inertial frame of reference. Spatial distance between rockets is preserved, so if rod is replaced by thread, the spool releases and winds up the thread.

As we move rockets between different inertial frames of reference we can wind and unwind rocket connecting thread creating a “clock” for LFG body contraction.

Part II:
Acceleration Frontier

In S-Relativity we need to figure out what to do with acceleration in general and other forces in particular (EM overdue!). Therefore S-Relativity is still incomplete.

Immediate question: how does a body "know" that it is accelerated (and subject to radiation reaction friction force.) Here we meet the **strong acceleration – strong fields physics frontier** of classical and quantum physics where the quantum vacuum, *a.k.a* Einstein's non-material ether, can be probed.

(Special) Relativity evolves

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

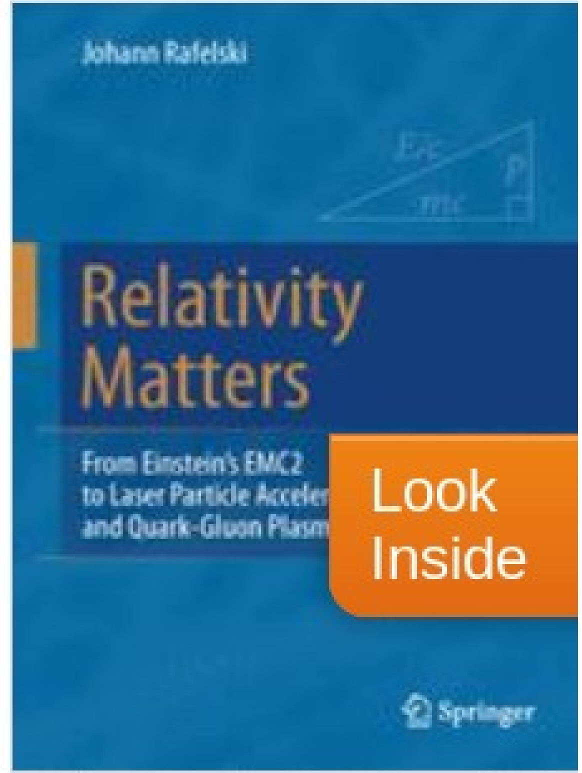
Relativity Matters

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



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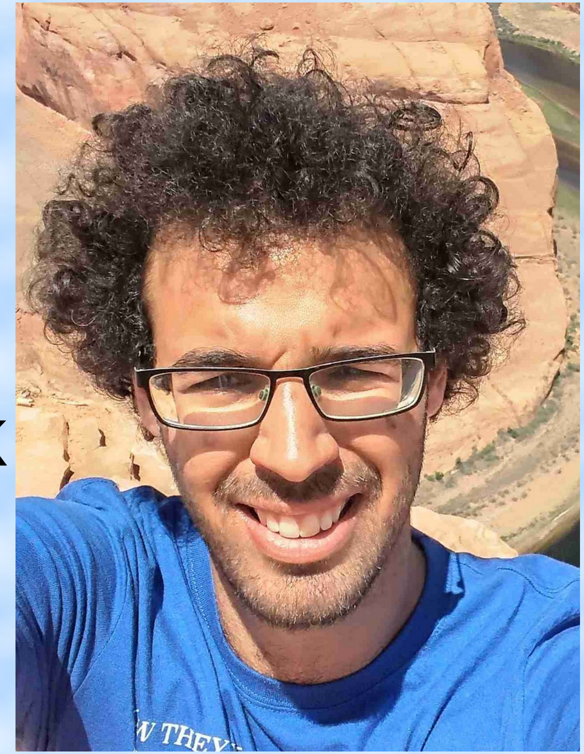
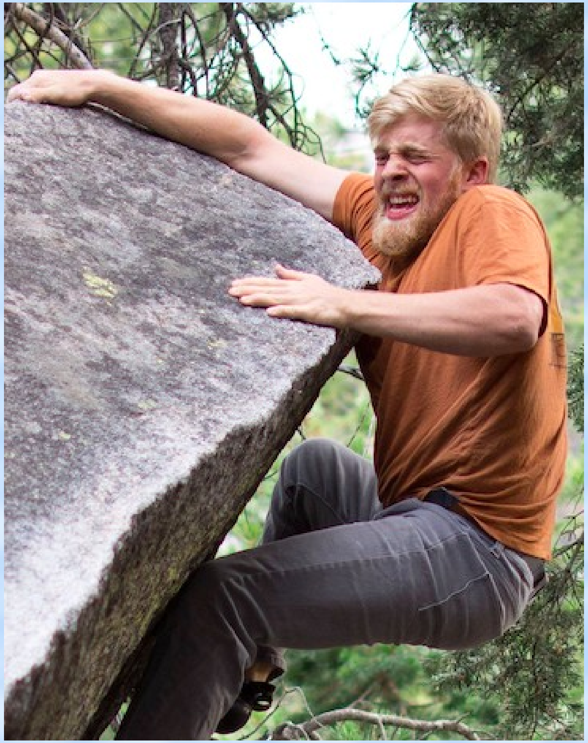


How EM strong fields modify vacuum structure and stability: fields turning into particles. Continues work of Lance Labun (PhD Dec. 2011)

How forces influence dynamical relation between proper time and laboratory time

Chris Grayson



Gustavs Kehris

Relativistic Electro-magnetic Field Dynamics of Particle Collisions: ripping up the vacuum with relativistic strong fields.

Relativistic Hamiltonian Dynamics for EM interactions. Emeritus Undergraduate student is finishing his research paper, in Sept.begins graduate study at Cambridge, UK.

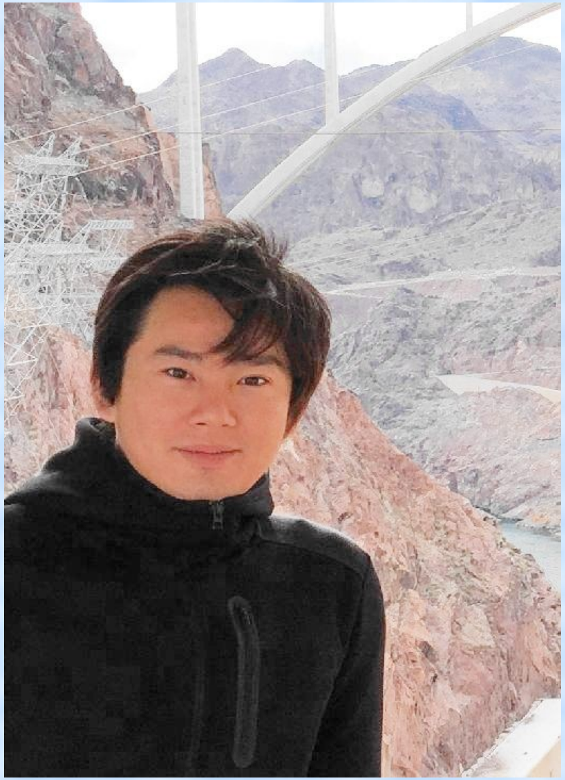
Will Price

Andrew Steinmetz

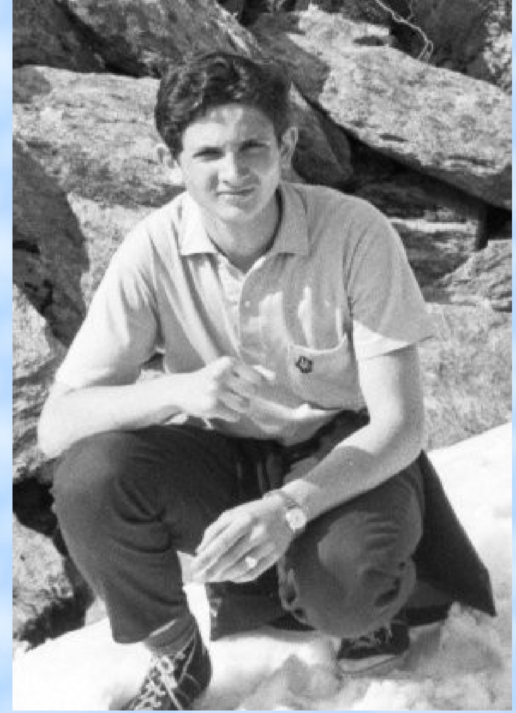
Classical dynamics of relativistic charged particle collisions, including radiation reaction in strong fields. Started in the group as an undergrad

Relativistic dynamics of particles with anomalous magnetic moment and connection with quantum dynamics

Cheng Tao Yang

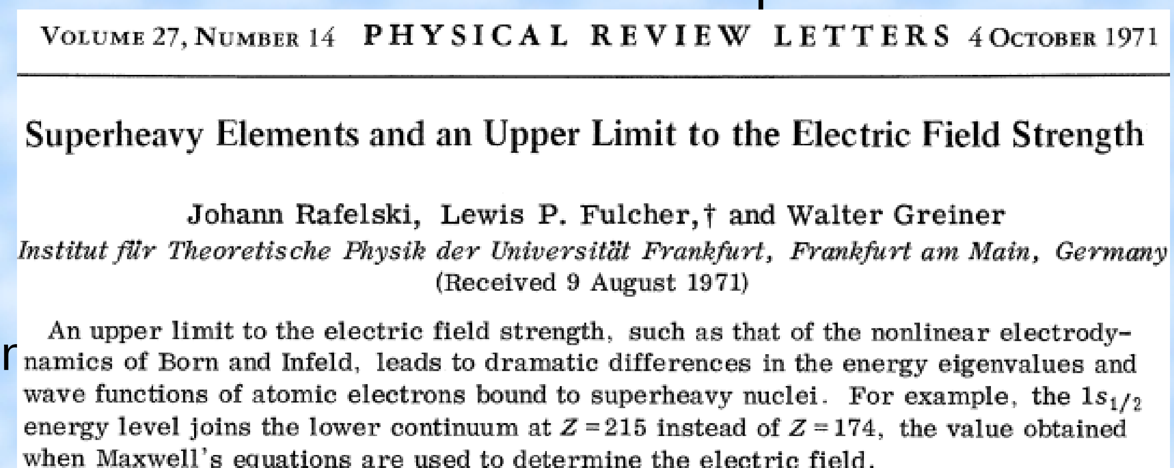


Johann Rafelski



48 years of work in relativistic everything. Current passion: critical acceleration phenomena.

Relativistic Thermodynamics in expanding primordial Universe: from quarks to BBN. Continues work of Jeremey Birrell, PhD May,2014



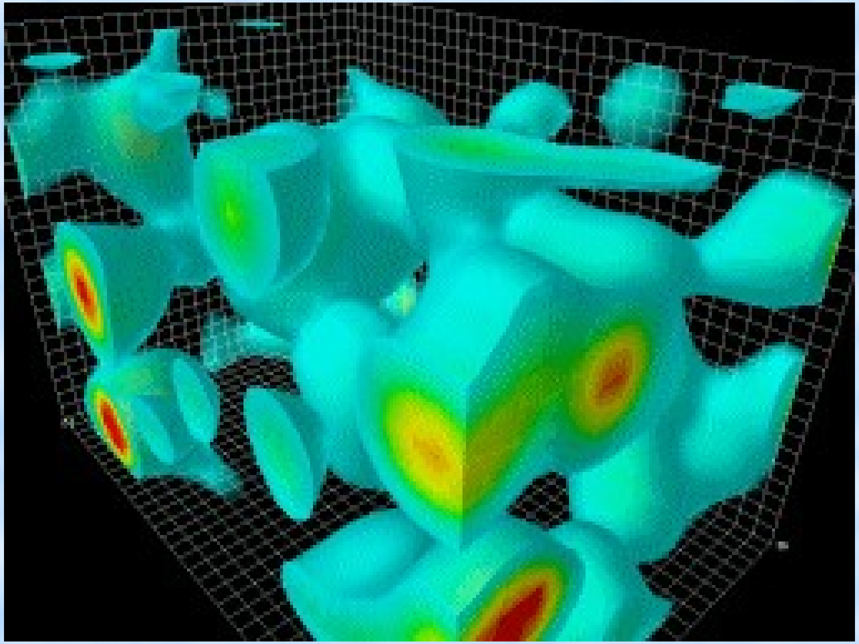
VOLUME 27, NUMBER 14 PHYSICAL REVIEW LETTERS 4 OCTOBER 1971

Superheavy Elements and an Upper Limit to the Electric Field Strength

Johann Rafelski, Lewis P. Fulcher,† and Walter Greiner
Institut für Theoretische Physik der Universität Frankfurt, Frankfurt am Main, Germany
(Received 9 August 1971)

An upper limit to the electric field strength, such as that of the nonlinear electrodynamics of Born and Infeld, leads to dramatic differences in the energy eigenvalues and wave functions of atomic electrons bound to superheavy nuclei. For example, the $1s_{1/2}$ energy level joins the lower continuum at $Z=215$ instead of $Z=174$, the value obtained when Maxwell's equations are used to determine the electric field.

Seeking Acceleration Reference Frame: The Aether and the Quantum Vacuum



Color confinement due to gluon fluctuations QCD This is an actual computation of the four-d (time +3-dimensionsuon-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.

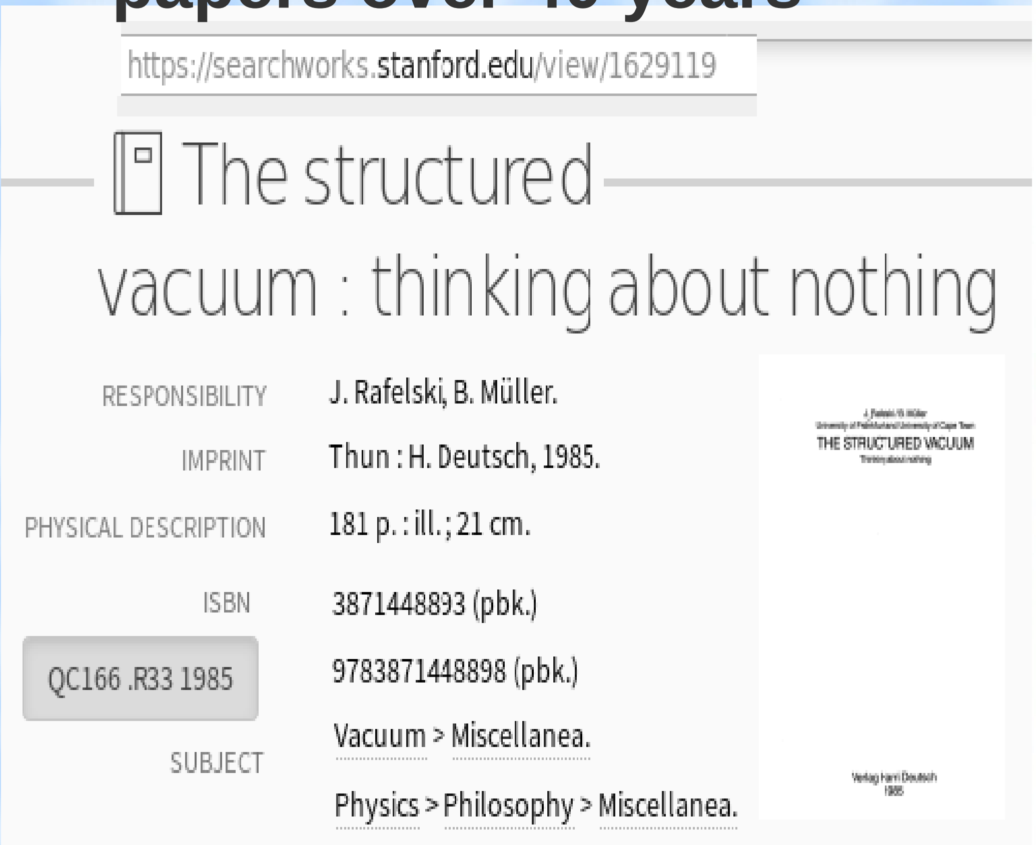
- Derek B. Leinweber's group (U Adelaide)

Numerical Method used: lattice in space time

Square of fields does not average out: “condensates

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

Long-standing interest in quantum vacuum structure: 1985 book and a chain of 20 papers over 40 years

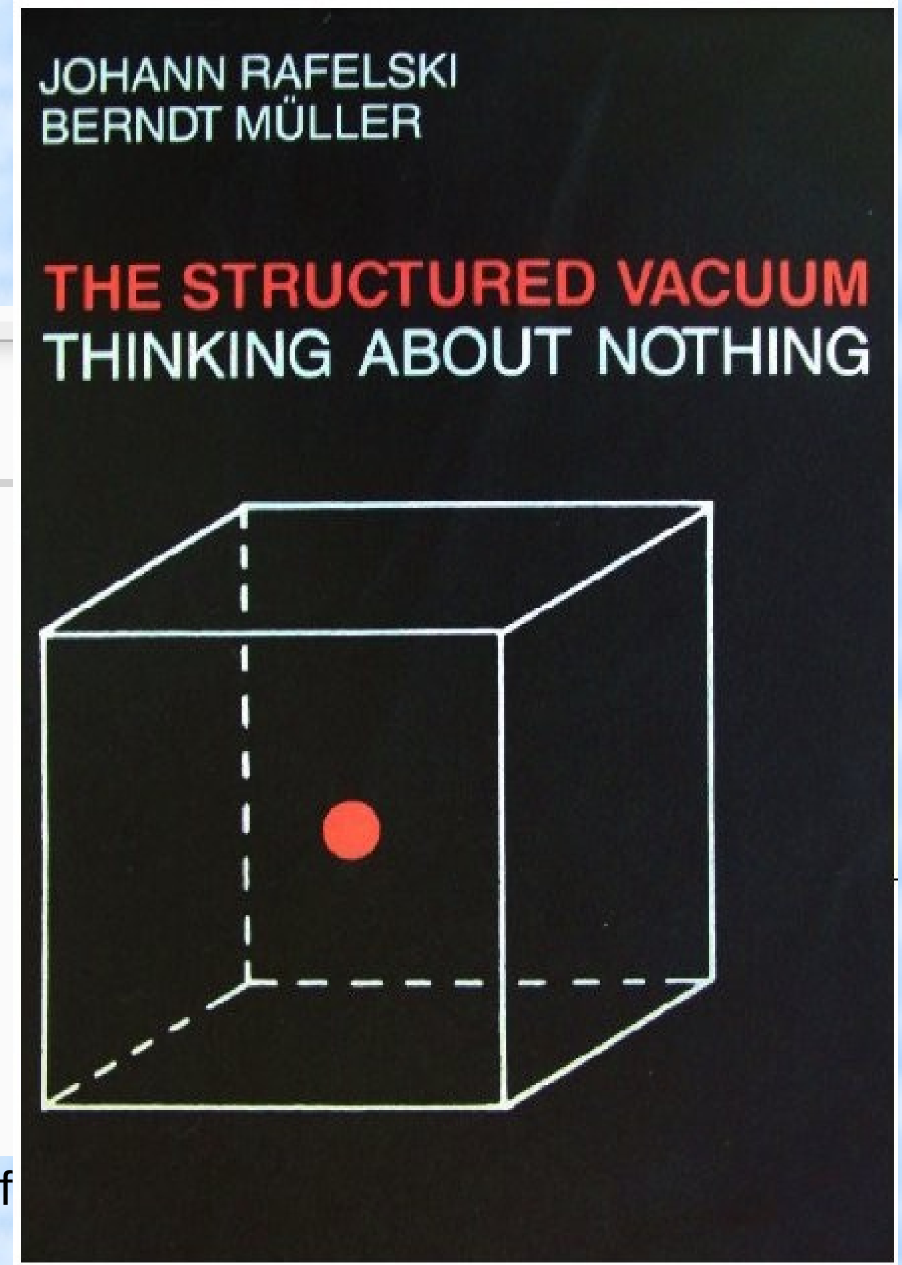

https://searchworks.stanford.edu/view/1629119

The structured vacuum : thinking about nothing

RESPONSIBILITY	J. Rafelski, B. Müller.
IMPRINT	Thun : H. Deutsch, 1985.
PHYSICAL DESCRIPTION	181 p. : ill. ; 21 cm.
ISBN	3871448893 (pbk.)
	9783871448898 (pbk.)
SUBJECT	Vacuum > Miscellanea.
	Physics > Philosophy > Miscellanea.

QC166 .R33 1985

THE STRUCTURED VACUUM



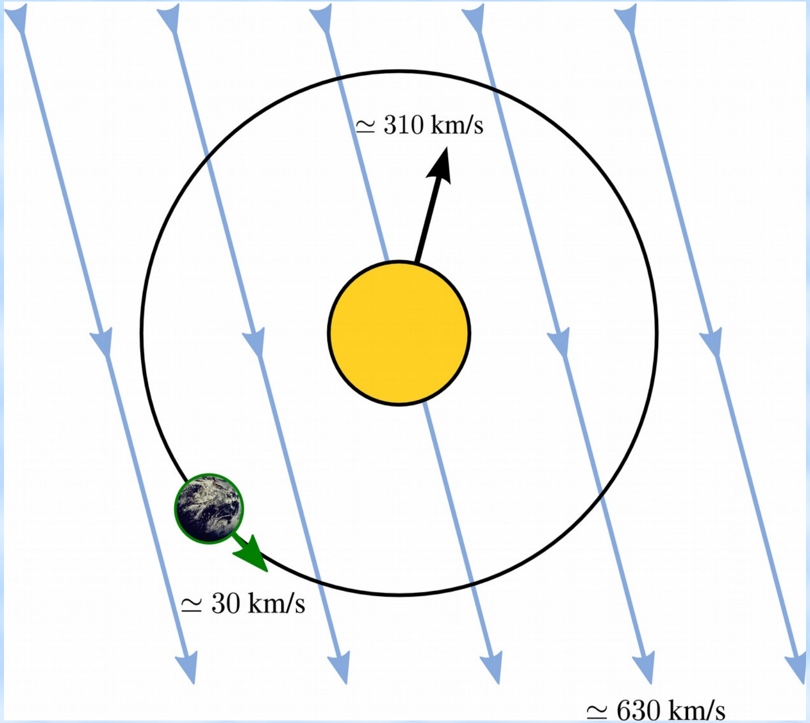
Mach's Principle

Ernst Mach
1838-1916

Measurement of 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,** some say the structured QuantumVacuum.

Michelson-Morley: No aether wind, no drag



- The Earth moves in space (today we know the speed with reference to the big-bang frame of reference). Michelson-Morley experiment: no aether dragged along, birth of Lorentz-Fitzgerald body contraction and relativity.
- **Einstein 1905:** who needs aether? All inertial observers are equivalent (principle of relativity).

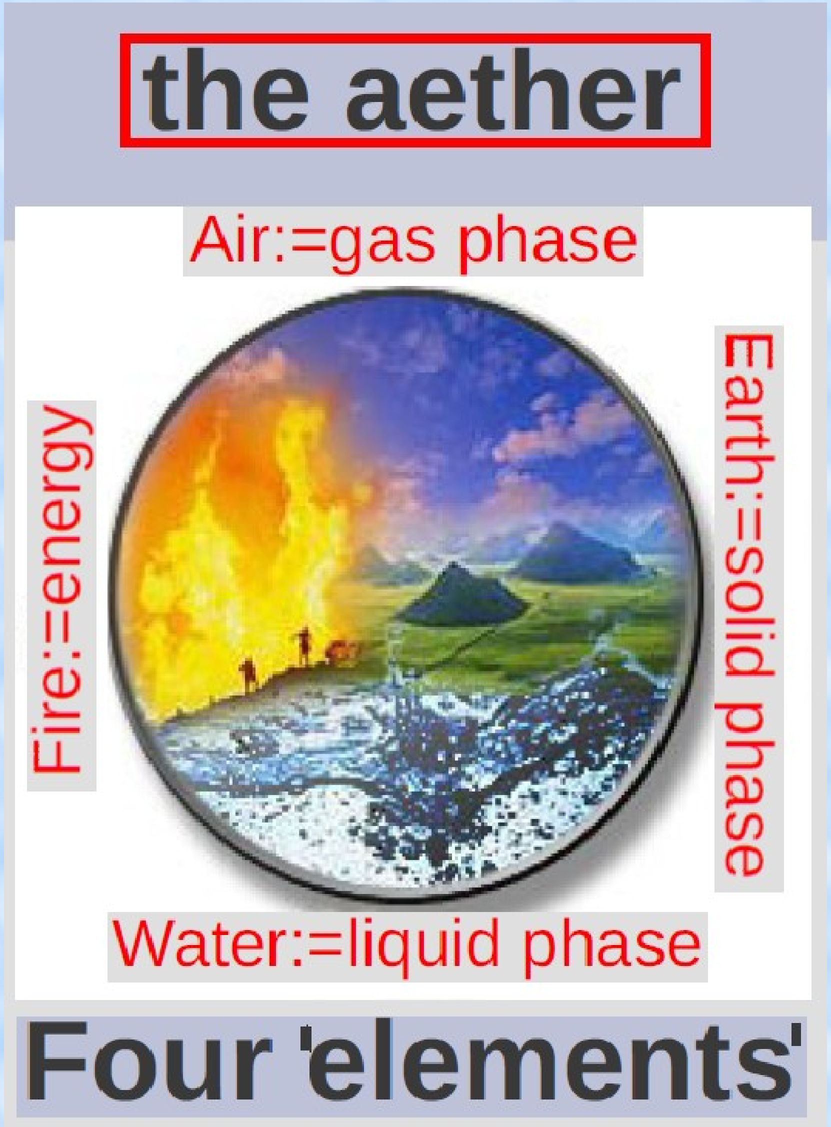
Einstein's view about aether changes drastically by 1920

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."



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. Aristotle imposed aether as a fifth element filling all space. Aether was later called **quintessence** (from quinta essentia, "fifth element"). The **"luminiferous aether"** (light carrying aether) is the “substance” believed by Maxwell, Larmor, Lorentz to permeate all the Universe. Einstein flips on the topic, introduces **relativistic aether 1920.**

A few decades later:

Quantum vacuum structure replaces Aether defining locally the class of inertial observers

Quantum vacuum defines structure of physical laws, clarifies meaning of inertia and allows us to locally recognize acceleration (no need to study the stars light years away).

Nonmaterial aether differs from material aether: for example objects falling in material atmosphere are subject to friction resulting in a constant fall speed. Difference to (nonmaterial) Einstein aether: acceleration related friction leads to constant maximum critical acceleration

Critical Fields= Critical Acceleration

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

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

is subject to critical natural unit =1 acceleration:

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

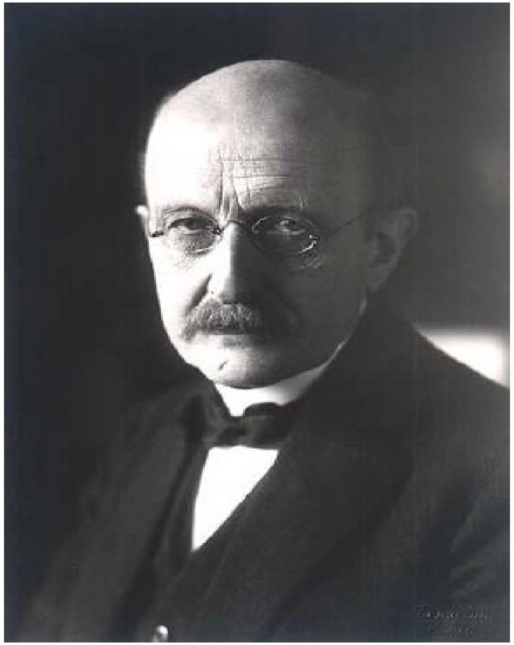
Truly dimensionless unit acceleration arises when we introduce specific acceleration

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

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



$h/k_B = a = 0.4818 \cdot 10^{-10}$ [sec × 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)*

Small a cceleration approximation

How big is usually "a" in laboratory?

Ultra-relativistic electron in a magnet of 4.41Tesla

$a_{MAX}=(e/M_e)$ **vxB**

$=1.6\ 10^{-19}\ 3\ 10^{8}\ 4.41\ /(9.11\ 10^{-31})=\mathbf{2.33x10^{20}m/s^{2}=nano\ a_{cr}}$

Compare: Natural "unit-1" acceleration

$\mathbf{a_{cr}}=M_e c^2\ c/(h/2\pi)=9.11\ 10^{-31}\ 27\ 10^{24}/1.05\ 10^{-34}=\mathbf{2.33\ 10^{29}m/s^2}$

This is also the acceleration generated by "critical" or Schwinger EM fields": $E_{cr}=(M_e c^2)^2/(ehc/2\pi)=1.323\ 10^{18}$ V/m

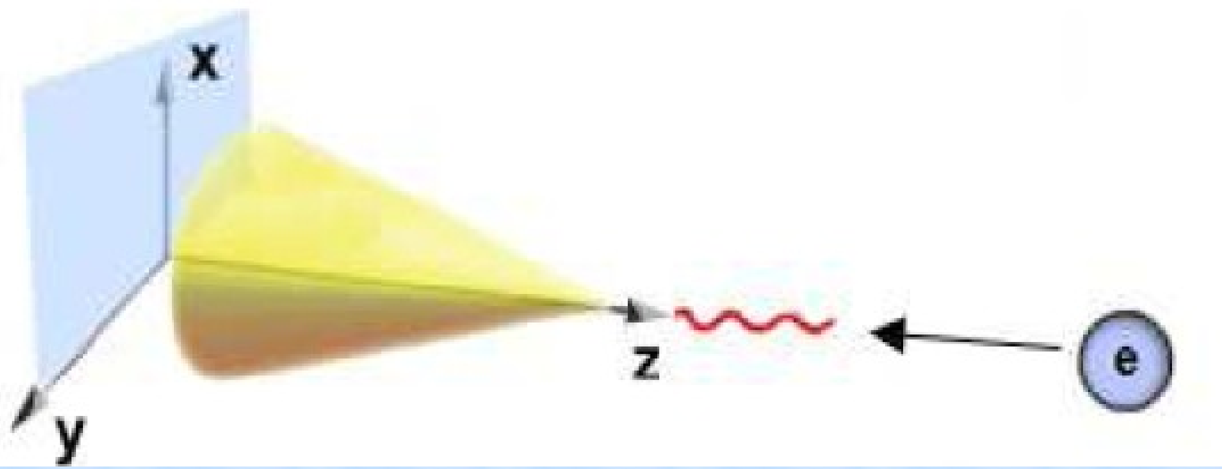
$B_{cr}=(M_e c^2)^2/(ehc^2/2\pi)=4.414\ 10^{9}$ T

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.

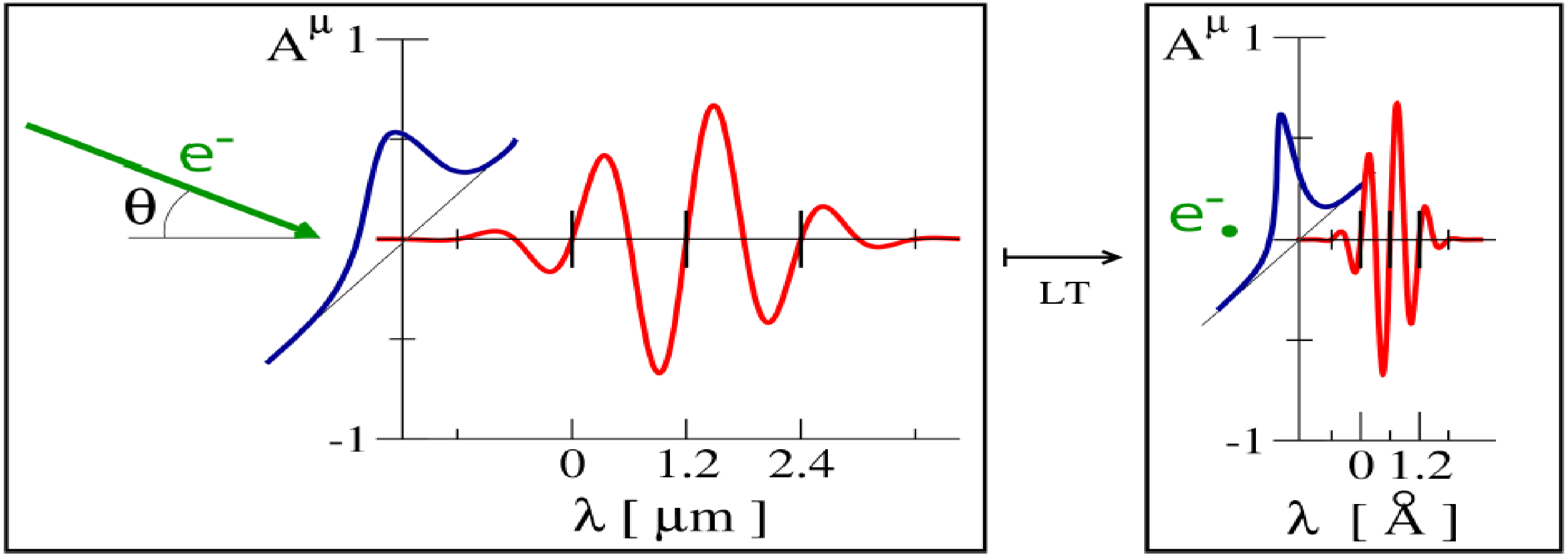
Plan B: Ultra-relativistic Lorentz-boost: we collide counter-propagating electron and laser pulse.



Puls Lorentz Transform (LT)

Relativistic electron-laser pulse collision

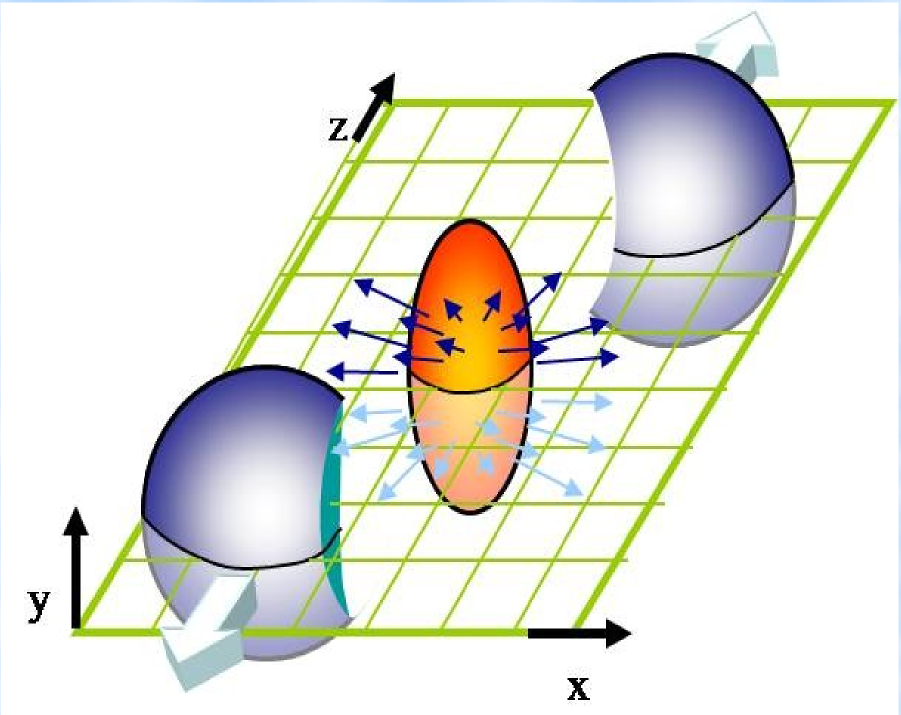
$u^\beta = \gamma(1, \vec{v}) \rightarrow$ In electron's rest frame: $u'_\beta = (1, \vec{0})$

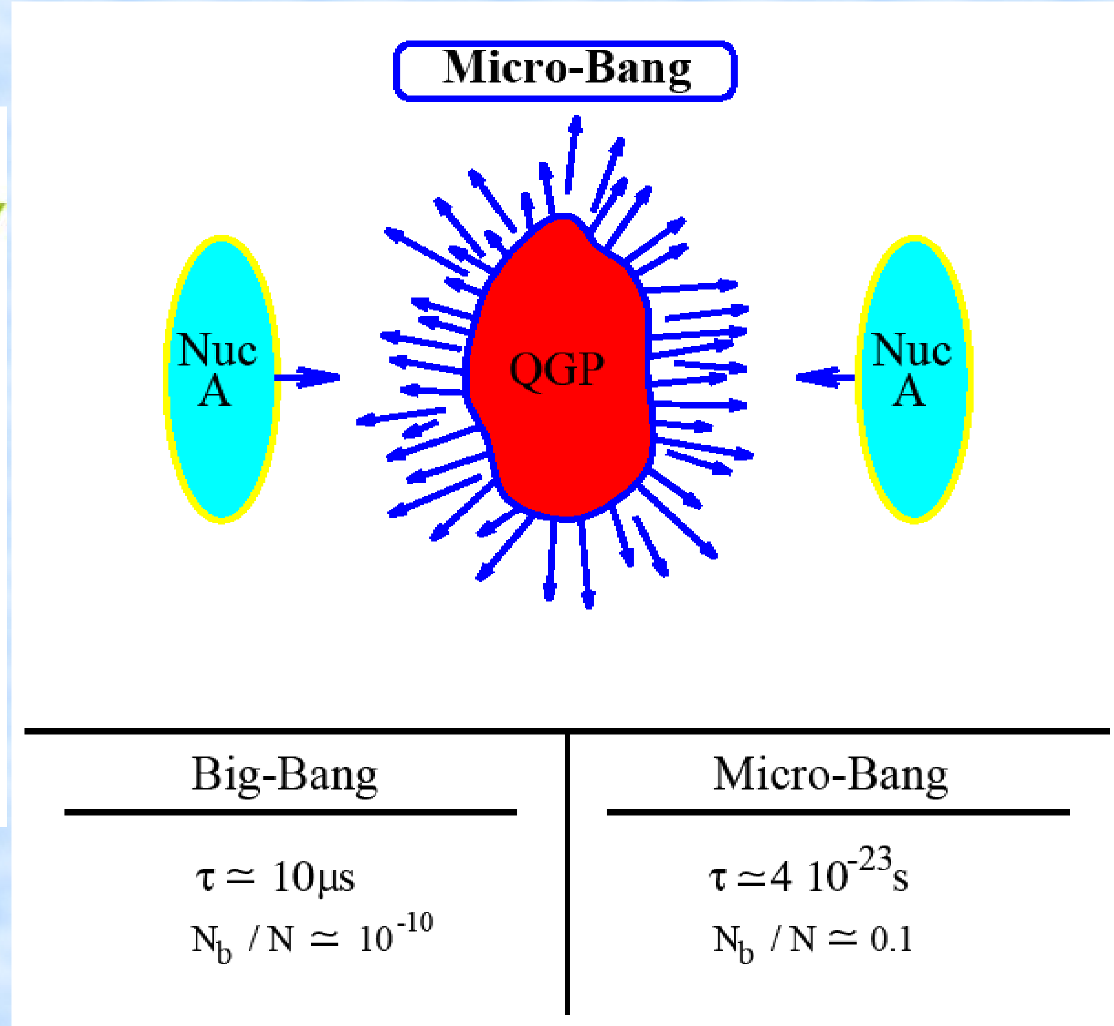


Doppler shift: $\omega' = \gamma(1 + \vec{n} \cdot \vec{v})\omega$

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

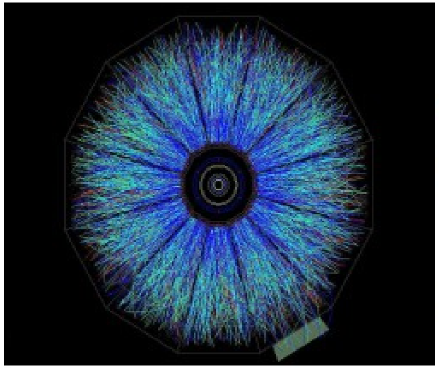
Another context for critical acceleration experiments: Relativistic Nuclear Collisions





Nuclear Collisions at energy E>>Mc²

Unit Acceleration in Strong Interactions



Two nuclei smashed into each other at highest achievable energy: components can be stopped in CM frame within $\Delta\tau \simeq 1$ fm/c. Tracks show multitude of particles produced, as seen at RHIC (BNL) and at CERN.

- The acceleration *a* required to stop some/any of the components of the colliding nuclei in CM: $a \simeq \frac{\Delta y}{M_i \Delta\tau}$. Full stopping: $\Delta y_{\rm SPS} = 2.9$, $\Delta y_{\rm RHIC} = 5.4$, larger at CERN. Considering constituent quark masses $M_i \simeq M_N/3 \simeq 310$ MeV we need $\Delta\tau_{\rm SPS} < 1.8$ fm/c and longer times at colliders to exceed critical *a*.

- The 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) [arXiv:hep-ex/9710006].*) and heavy ion reactions exceeds the perturbative QED predictions significantly

Radiation-Acceleration Trouble

Conventional SR+Electromagnetic theory is incomplete: radiation emitted needs to be incorporated as a back-reaction “patch”:

1) **Inertial Force = Lorentz-force**-->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 --> go to 1**.

So long as radiated fields are small, we can modify the Lorentz Force to account for radiated field back reaction approximately

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Table 29.1 Models of radiation reaction extensions of the Lorentz force

Maxwell-Lorentz	$m\dot{u}^\mu = eF^{\mu\nu}u_\nu$
LAD[33]	$m\dot{u}^\mu = eF^{\mu\nu}u_\nu + m\tau_0\left[g^{\mu\nu} - \frac{u^\mu u^\nu}{c^2}\right]\ddot{u}_\nu\,,\ \tau_0 = \frac{2}{3}\frac{e^2}{4\pi\epsilon_0 mc^3}$
Landau-Lifshitz[35]	$m\dot{u}^\mu = eF^{\mu\nu}u_\nu + e\tau_0\left\{u^\gamma\partial_\gamma F^{\mu\delta}u_\delta + \frac{e}{m}\left(g^{\mu\gamma} - \frac{u^\mu u^\gamma}{c^2}\right)F_{\gamma\beta}F^\beta_\delta u^\delta\right\}$
Caldirola[36]	$0 = eF^{\mu\nu}(\tau)u_\nu(\tau) - m\left[g^{\mu\nu} - \frac{u^\mu(\tau)u^\nu(\tau)}{c^2}\right]\frac{u_\nu(\tau) - u_\nu(\tau - 2\tau_0)}{2\tau_0}$

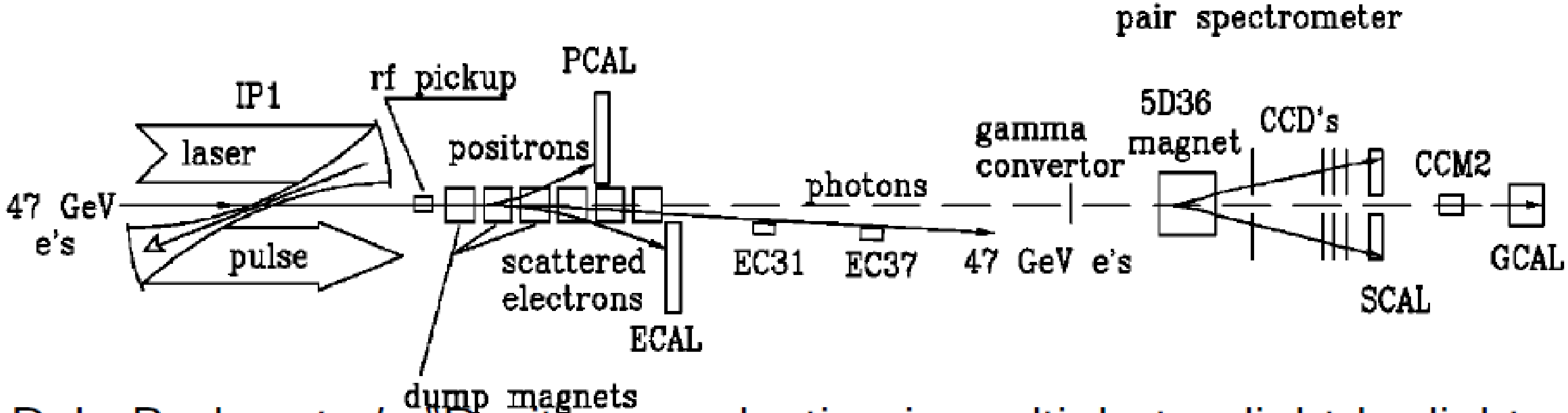
Probing EM-unit acceleration possible today

SLAC'95 experiment — *Proof of Principle*

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

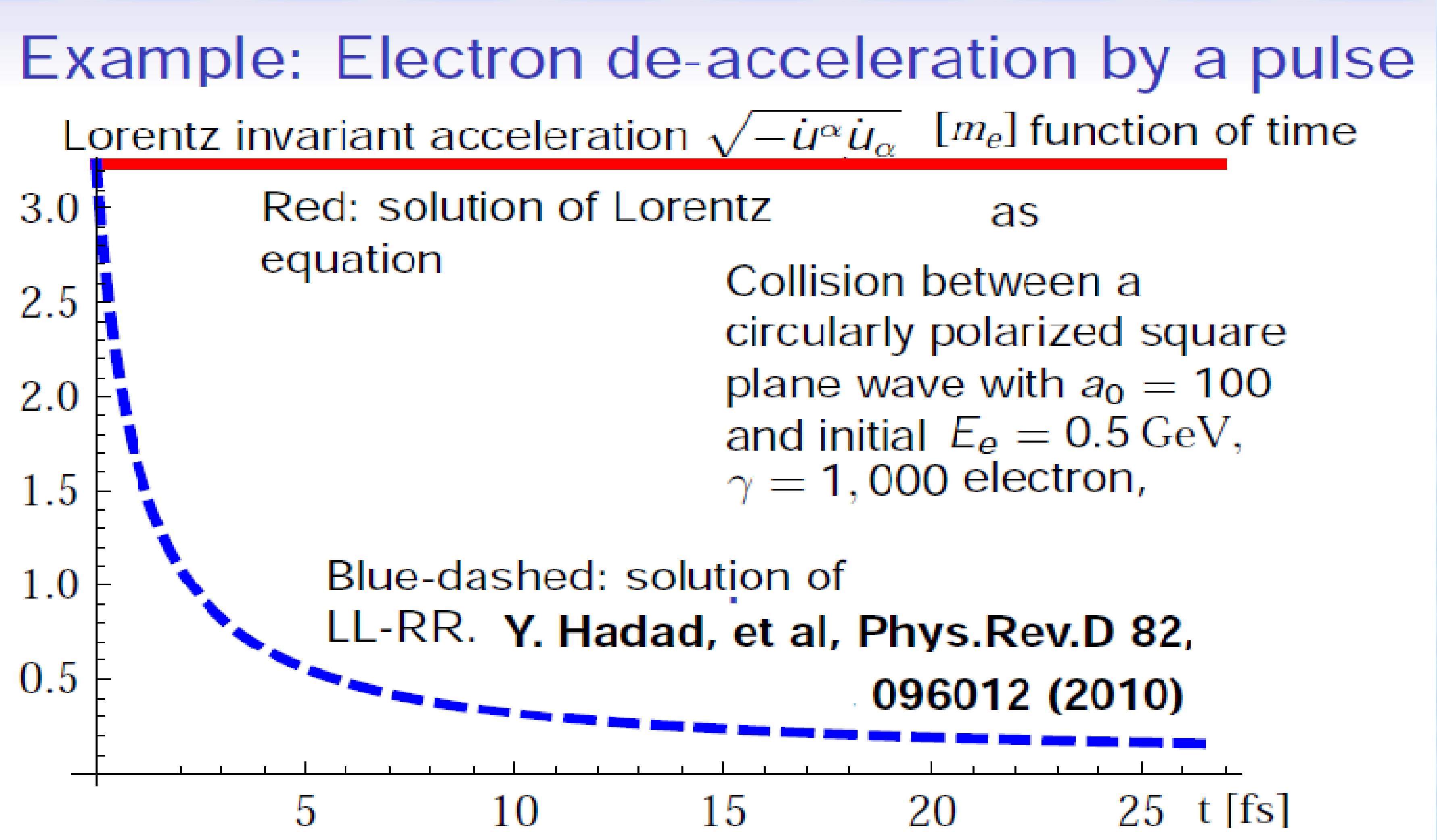
Multi-photon processes observed:

- 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).

Solving LL Equation for a-crit



Conclusions

After many years of neglect we find ourselves already immersed into **an encore of SR** with opportunties in probing acceleration frontier in high intensity laser-particle interaction and RHI experiments at CERN and RHIC probing critical acceleration. Challenge: Teaching relativity to future researchers in this field .