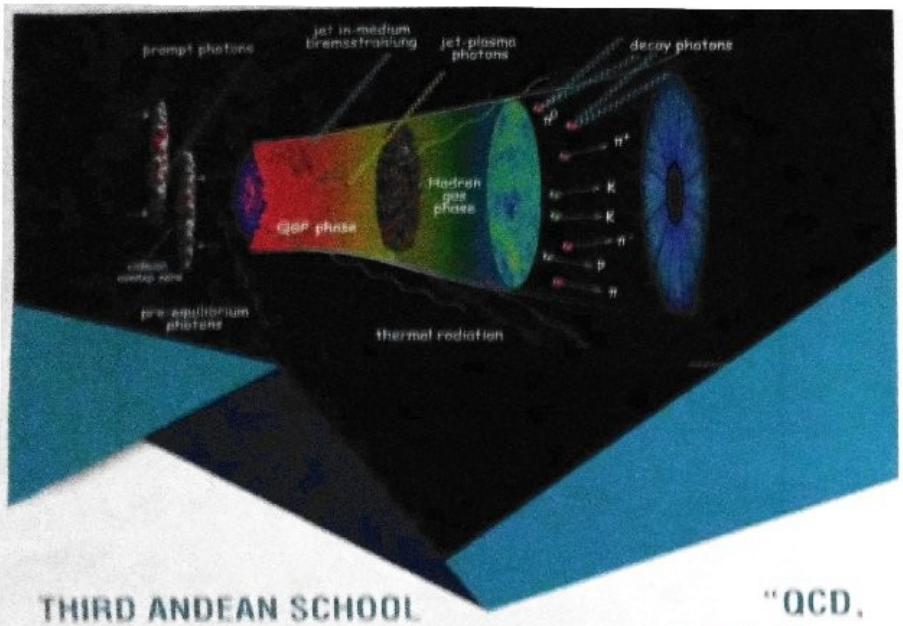


THIRD ANDEAN SCHOOL
ON NUCLEAR PHYSICS

"QCD, Quark Gluon Plasma and Heavy Ion Collisions"

Lecturers

Johann Rafelski, Arizona, U.S.A.
Michael Strickland, Kent State, U.S.A.
Roelof Bijker, UNAM, Mexico
Julia Velkovska, Vanderbilt, U.S.A.

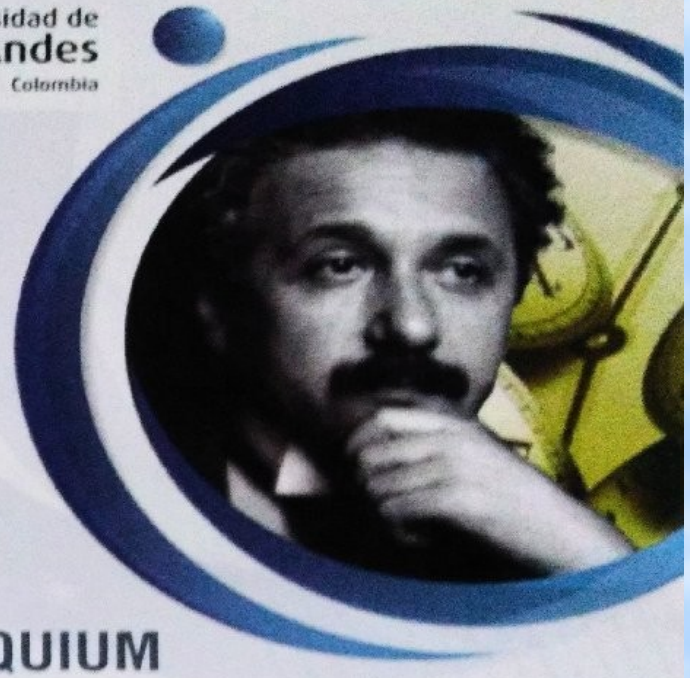
July 24 - 28, 2017
Universidad de los Andes
Bogotá, Colombia

More information:
escuelafisicanuclear3.uniandes.edu.co

email contact
escuela.fisica.nuclear2@uniandes.edu.co

Universidad de los Andes Colombia
Universidad Nacional de Colombia
ICTP International Centre for Theoretical Physics

Universidad de los Andes Colombia



COLLOQUIUM

"Relativity Matters: The Acceleration Frontier"

I remind how properties of moving bodies while "undone" by coordinate transformations can have real physical consequences. This leads to improved understanding of the behavior of material finite size bodies moving with speed approaching that of light, i.e. clarification of the meaning of Lorentz-FitzGerald body contraction. Next, we study acceleration, and recognize the uniqueness of "inertial" observers in Einstein's Special Relativity. In general, accelerated and inertial frames of reference are not equivalent. The exceptional context of gravity force described by "general relativity" is recognized. I characterize what means weak and strong acceleration and show in the context of both, relativistic nuclear collisions and laser-relativistic particle collision experiments that we reach required "strong" conditions. Looking closer at the Lorentz force we see the acts of consistency in electromagnetic forces when critical strength acceleration is reached.

Prof. Johann Rafelski
Department of Physics
The University of Arizona

Lunes, 24 de julio de 2017
Edificio Mario Laserna ML 617
4:00 p.m.
Entrada libre

Prof. J. Rafelski has recently authored a book "Relativity Matters" published by Springer which presents Special Relativity on a level accessible to students.

Special Relativity Matters: Acceleration Frontier

- Special Relativity Introduction
- Lorentz-FitzGerald Body Contraction
- The Aether aka: Quantum Structured Vacuum
- Does Acceleration Exist and if so, how big is it
- Probing limits of validity of SR+EM: Acceleration Frontier

Relativity

Einstein 1905: Inertial Motion

(a consistent framework)

Problems with

Bodies and Forces:

Matter+Electromagnetism

F=e(**E**+**v** x **B**) Lotentz F

- SR: Incomplete

"Special" Relativity

Works since acceleration negligible "nano-forces"

- 1916 Einstein Included Force of Gravity by allowing curved space-time

NOT topic of today

- GR : consistent

"General" Relativity

(Special) Relativity evolves

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

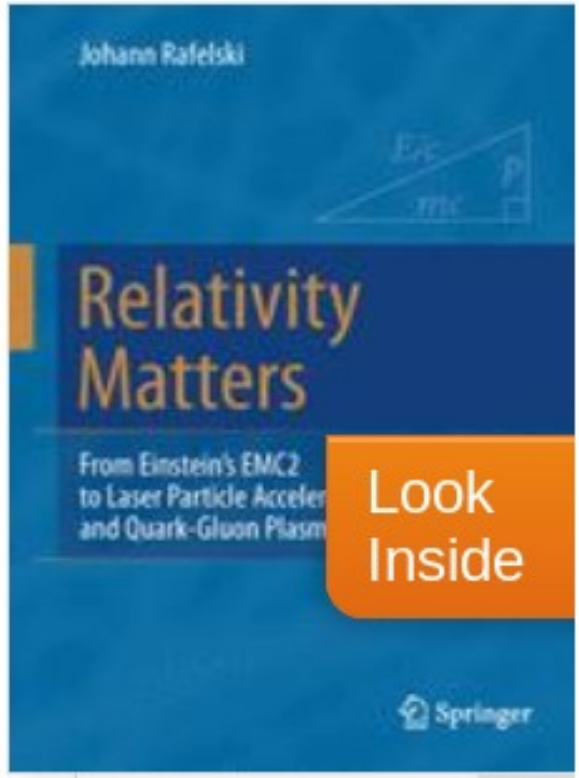
Relativity Matters

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



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

898 https://doi.org/10.1107/S160057751700769X J. Synchrotron Rad. (2017). 24, 898–901

teaching and education

JSR JOURNAL OF SYNCHROTRON RADIATION

ISSN 1600-5775

Received 4 April 2017
Accepted 24 May 2017

Edited by M. Eriksson, Lund University, Sweden

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

OPEN ACCESS

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.

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.

Issues Teaching Special Relativity

Professors: If you need to use words “paradox”, “not real”, you do not know what you are teaching

Students: choose sources carefully, lots of bad stuff around (many false prophets)

MixUp: SR bigger but unfinished theory compared to GR and yet GR in minds of many distorts contents of SR

Wrong Message: SR “complete” while it is unfinished (acceleration)

Wrong explanations: body contraction, time dilation

Wrong context: evolving concepts presented 1905 way

I like asking students

What is Lorentz contraction: $\gamma = (1 - v^2/c^2)^{-1/2}$

Some will space is contracted. Can this be true?

Other say this is distance contraction. What is this?

A few admit this is “apparent” body contraction. Apparent?

After in the decade after 1905 claiming that since Lorentz transformation can undo body contraction, thus it is “apparent”, Einstein wrote a response explaining that body contraction is real (just like kinetic energy and momentum of a car is real even if it is zero for the driver, jr).

What is Lorentz-Fitzgerald body contraction?

Since time is not absolute but ticks in each material body in a different way (proper time) we must define how a body is observed: we measure body size with an apparatus in laboratory that sizes up the body at equal time in lab frame of reference. This means that two different points of a moving body are observed at different proper times of the body if it is **not at rest** with respect to the lab frame. Therefore a laboratory observer always sees direction of motion contraction of a moving body. Once it is specified in which reference frame the measurement is at equal time the outcome is unique and impossible to alter or make “apparent”.

Is a passenger on a relativistic rocket aware she is “contracted”

A. Einststein 1911: never, since there is no absolute reference frame in the Universe and thus an inertial observer does not know her velocity.

J. S. Bell 1976: advocates “physical reality” view of relativity (begins around 1959): use accelerated motion to move from one inertial frame to another. The history of the shift between frames of reference allows to construct a clock for Lorentz contraction.

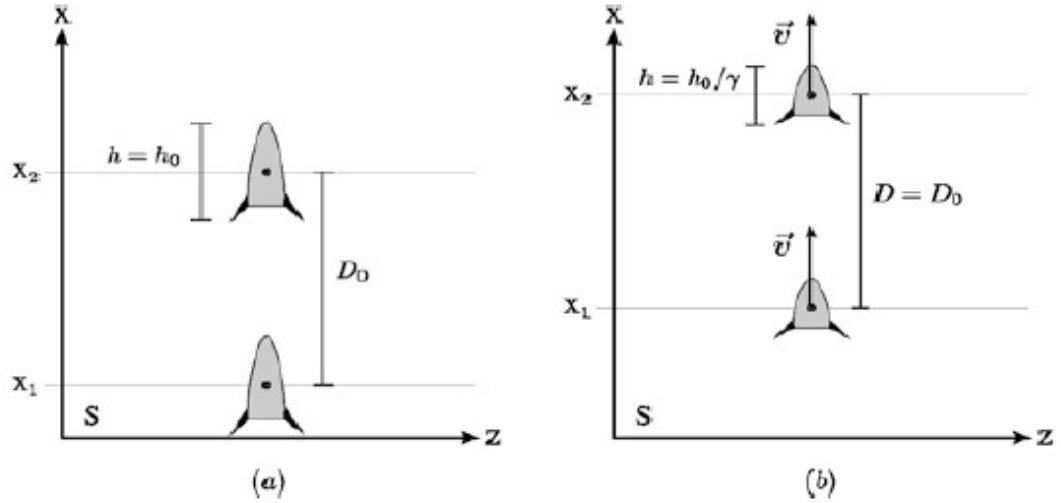


Fig. 10.2 Two rockets of length h separated by distance $D = x_2 - x_1 = D_0$. (a) at rest, and in case (b) moving at velocity $\vec{v}$ acquired at a later time

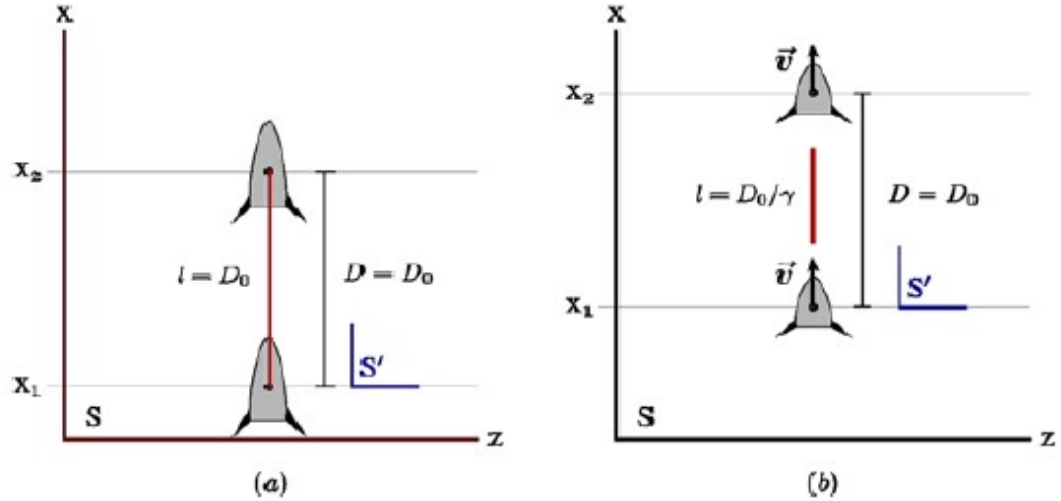


Fig. 10.3 Two rockets separated by distance $D = x_2 - x_1 = D_0$ and connected by a thin thread of (a) at rest, and in case (b) moving at velocity $\vec{v}$ acquired at a later time

Two views on SR and the Aether

Einstein 1905:

Only inertial motion

Lorentz transformations between different observers

Unsolved: EM forces.

Bell 1976:

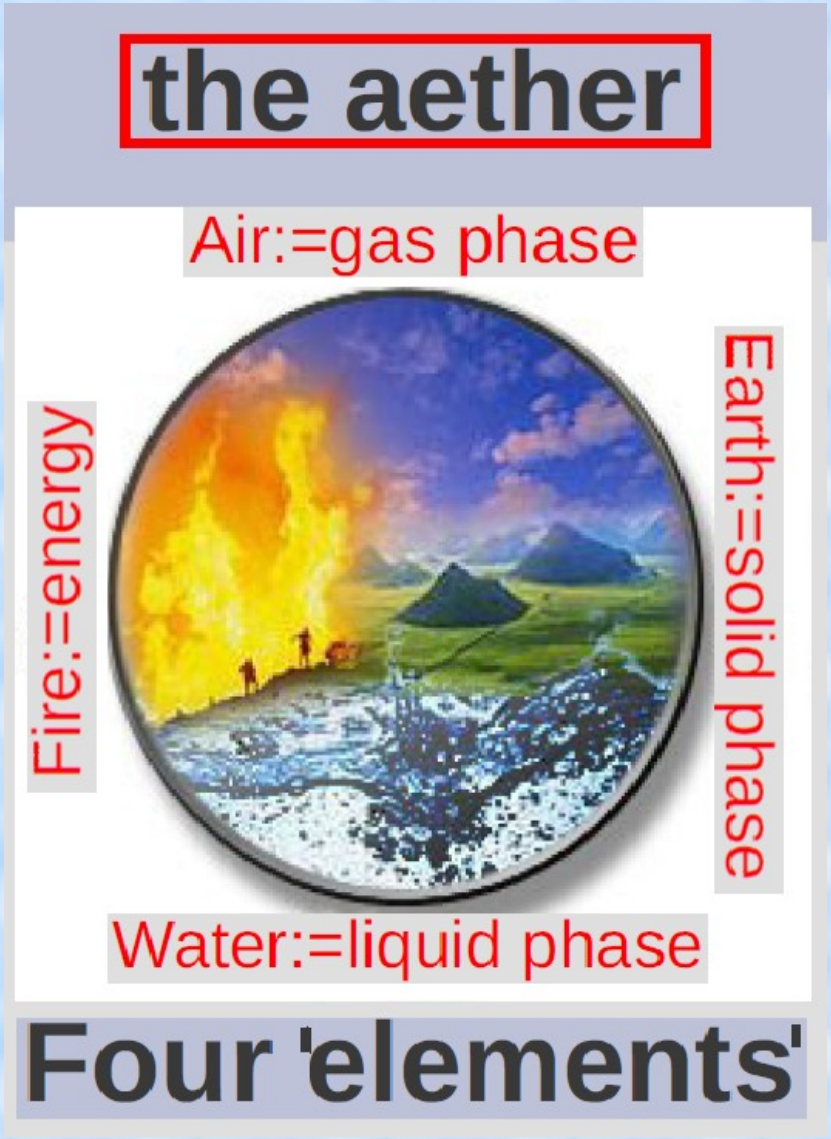
Use acceleration to move between different inertial observers. Each object "knows" if it is accelerated!

Aether and later the structured quantum vacuum:

Einstein 1920: aether carrier of physical laws

Larmor, Lorentz: allows local recognition of acceleration

Higgs, Weinberg etc: mass of matter, nature of interactions



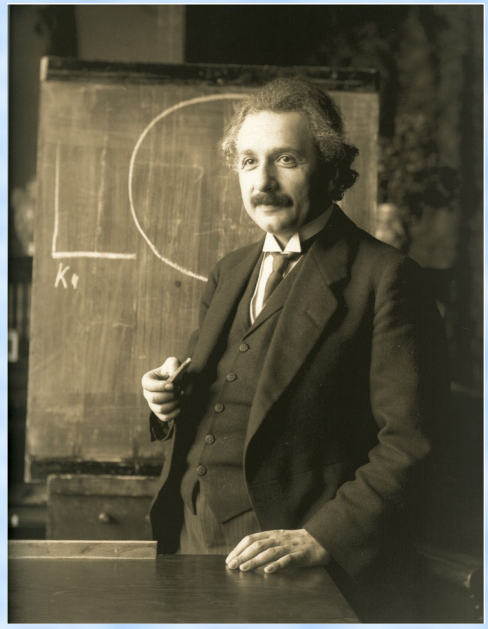
The word aether in Homeric Greek means ``pure, fresh air'' or ``clear sky'', pure essence where the gods lived and which they breathed. The aether was believed in ancient and medieval science to be the substance that filled the region of the universe above the terrestrial sphere. Aristotle imposed aether as a fifth element filling all space. Aether was hence also 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 introduces **relativistic aether.**

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. **B**ut 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.

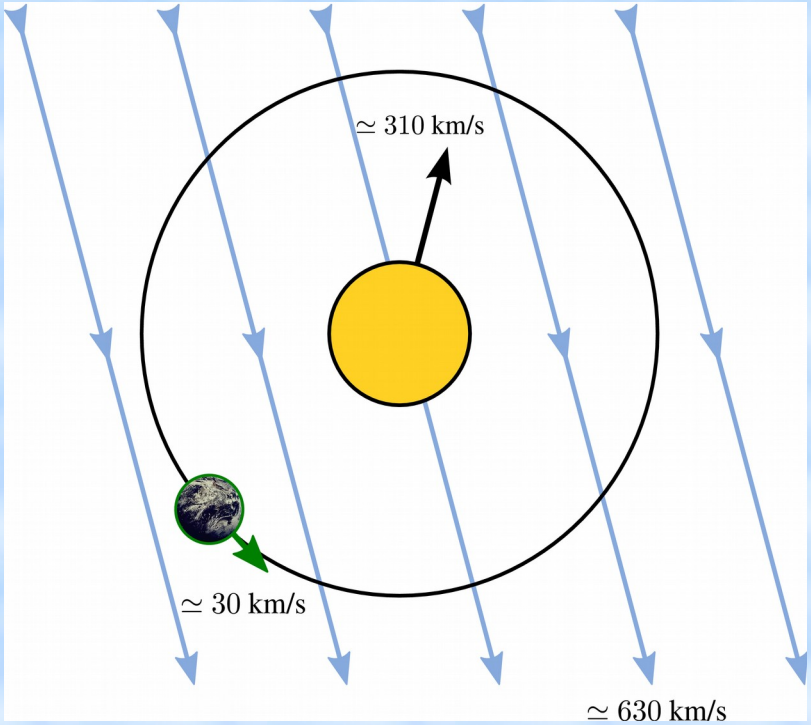
"According to the general theory of relativity space without aether is unthinkable; for in such space there not only would be no propagation of light, but also no possibility of existence for standards of space and time (measuring-rods and clocks), nor therefore any space-time intervals in the physical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

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



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

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 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

Does Acceleration Exist?

- Acceleration not inherent to quantum mechanics: all quantum operators made of x,p

Gravity as deformation of space time geometry: motion on geodetics (generalized straight lines)

However: A classical "charged" accelerated particle radiates demonstrating it "knows" when in state of accelerated motion. How is "know" possible?

Mach's Principle: Acceleration REQUIRES as reference a (set of equivalent) inertial frame(s).

Ernst Mach
1838-1916

Mach's Principle

Measurement of accleration 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 other words the Universe, some say the structured Quantum Vacuum.

In Einstein's gravity alone there is no "acceleration", all observers are in a free fall. Mach's principle visible in **presence of other forces**

Acceleration exists, can be measured, so how big is it?

Ultra-Relativistic electron bend by a magnet of 4.4Tesla

$a_{MAX}=(e/M_e)(\mathbf{v}/c)\mathbf{xB}=(1.6\ 10^{-19}\ /9.11\ 10^{-31})4.4 = 0.77 \times 10^{22} m/s^2$

Note: energy of electron in LEP accelerator was limited by Larmor radiation loss

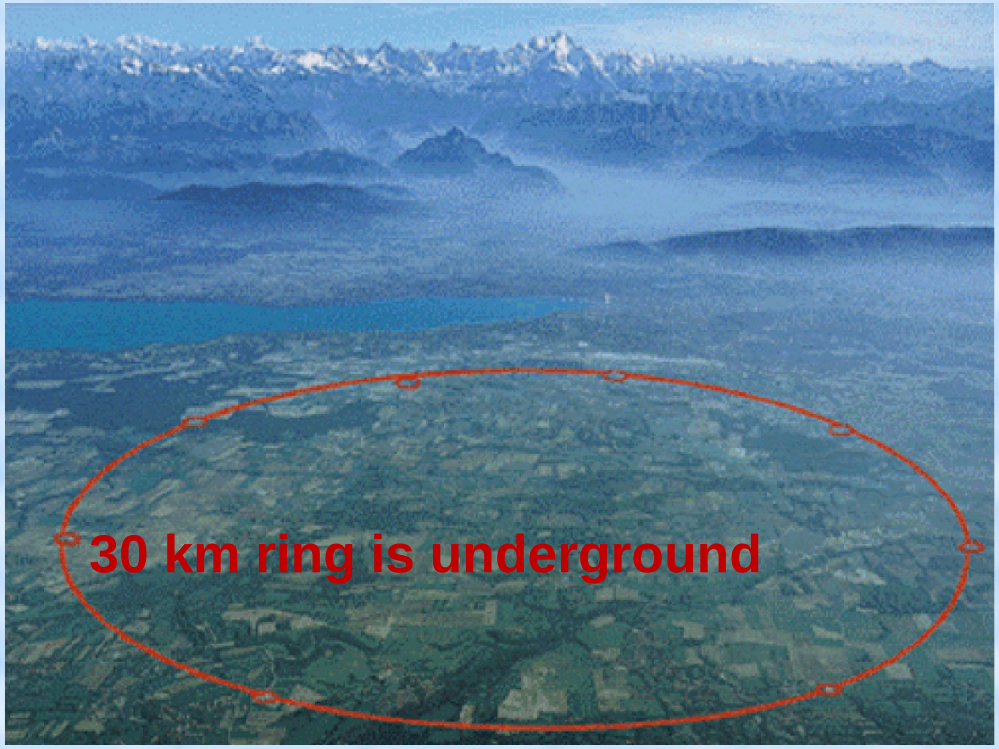
Natural "unit-1" acceleration

$\mathbf{a_{cr}}=M_e c^3/(h/2\pi)=9.11\ 10^{-31}\ 27\ 10^{24}/1.05\ 10^{-34}=\mathbf{2.33\ 10^{29} m/s^2}$

This is 30 000 000 larger compared to above a_{MAX}

Therer are elementary processes that allow to reach $\mathbf{a_{cr}}$

CERN LEP - LHC



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:

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

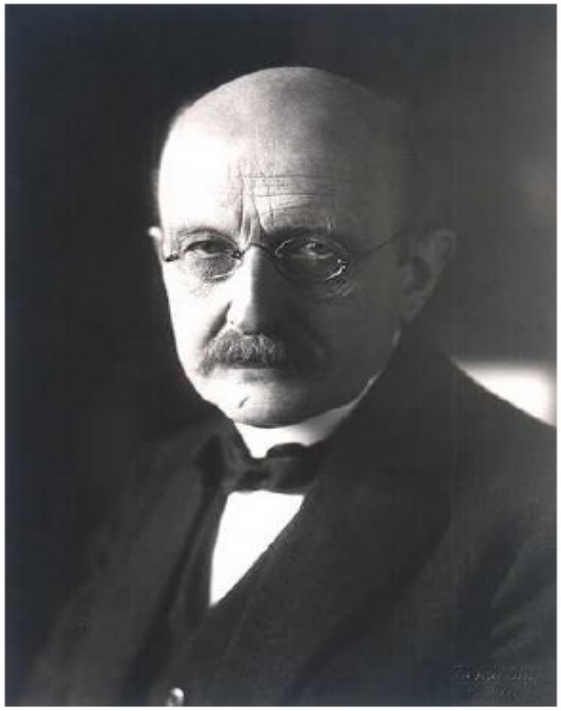
Truly dimensionless unit acceleration arises when we introduce specific acceleration

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

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]

$h = b = 6.885 \cdot 10^{-27} \left[\frac{cm^2 gr}{sec}\right]$

$c = c = 3.00 \cdot 10^{10} \left[\frac{cm}{sec}\right]$

$G = f = 6.685 \cdot 10^{-8} \left[\frac{cm^3}{gr.\,sec^2}\right]^{1}$.

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:

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

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)*

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

458 29 Afterword: Acceleration

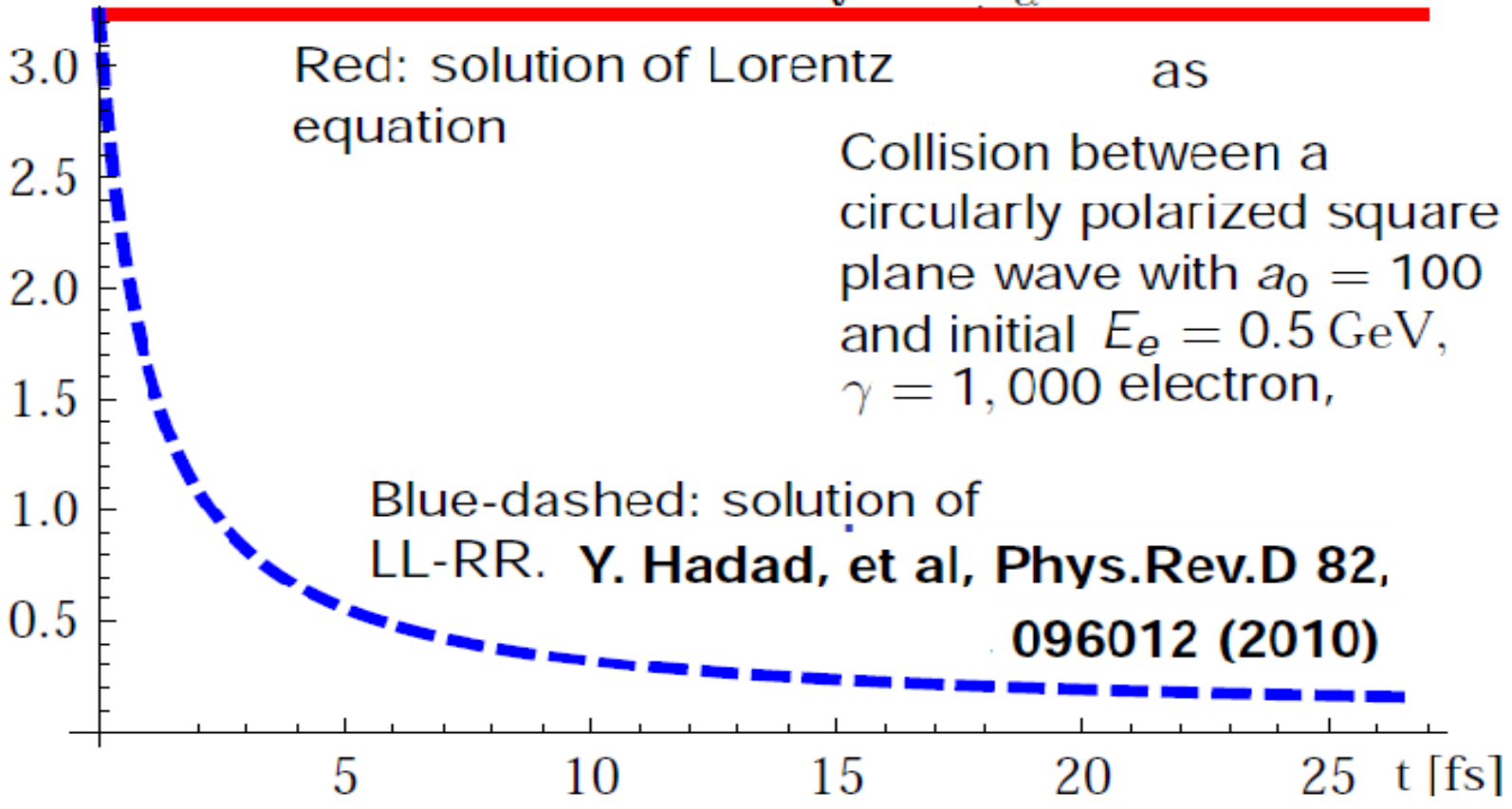
Table 29.1 Models of radiation reaction extensions of the Lorentz force

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]	$0 = eF^{\mu\nu}(\tau)u_{\nu}(\tau) - m\left[g^{\mu\nu} - \frac{u^{\mu}(\tau)u^{\nu}(\tau)}{c^2}\right]\frac{u_{\nu}(\tau) - u_{\nu}(\tau - 2\tau_0)}{2\tau_0}$

Solving LL Equation for a-crit

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 $E_e = 0.5\,\mathrm{GeV}$, $\gamma = 1,000$ electron,

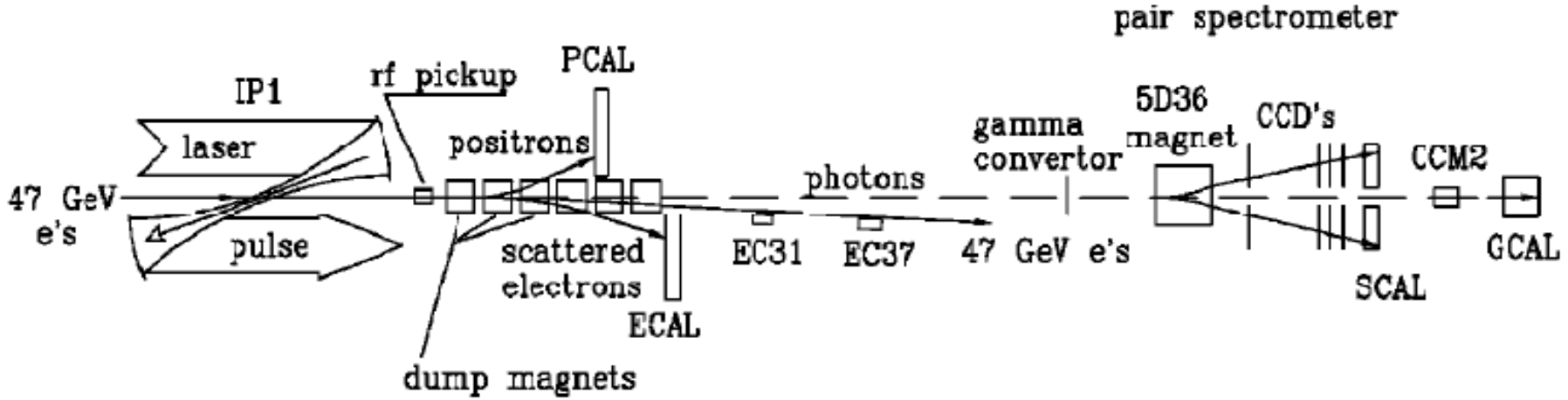
Blue-dashed: solution of LL-RR. **Y. Hadad, et al, Phys.Rev.D 82, 096012 (2010)**

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)

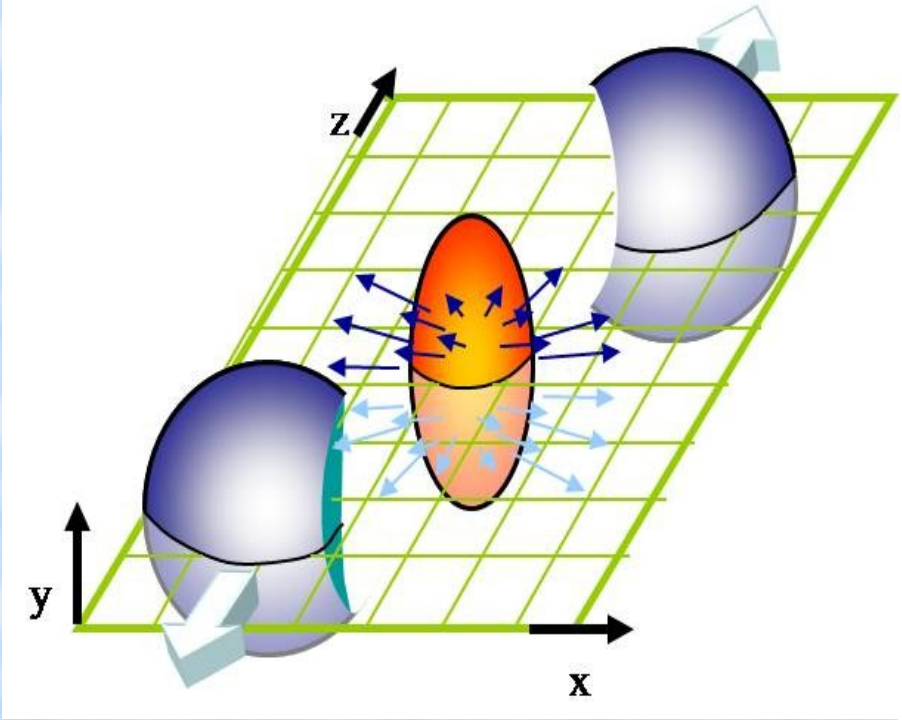
Multi-photon processes observed:

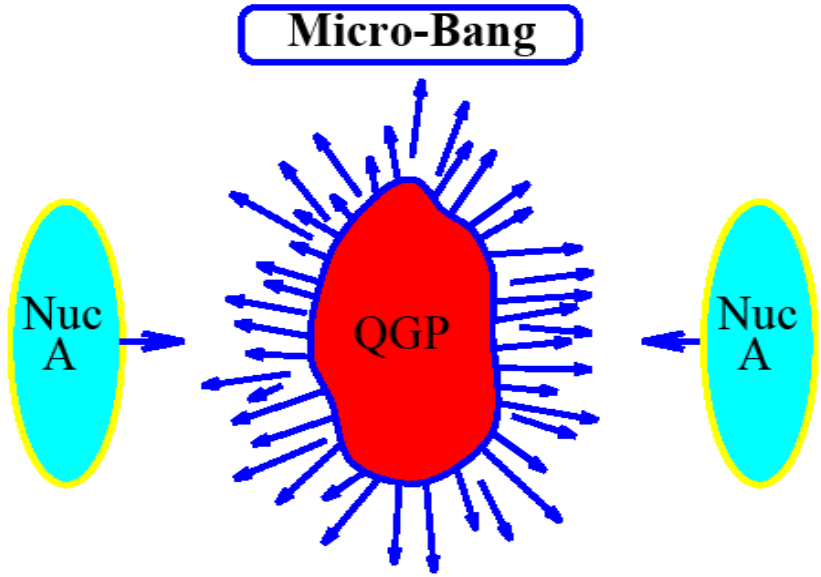
- Nonlinear Compton scattering
- Breit-Wheeler electron-positron pairs



- **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).

Relativistic Nuclear Collisions

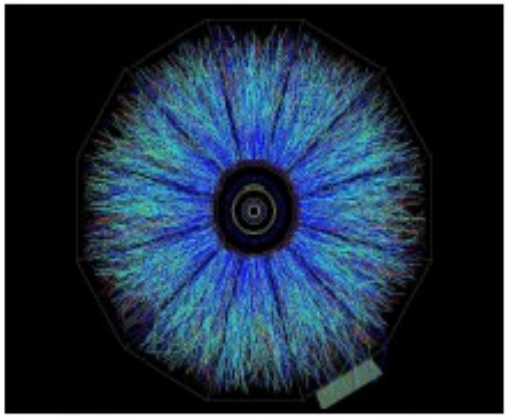




Nuclear Collisions at energy $E >> Mc^2$

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

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)*

Ultrarelativistic heavy ion collisions: the 4-acceleration magnitude is

$$a \equiv c\frac{dy_p}{d\tau}, \quad \text{or} \quad a \equiv c\frac{dy_p}{dt}\cosh y_p .$$

When big nuclei collide head-on in a relativistic heavy ion collider experiment, the duration time of the collision in the laboratory frame is $dt \to \Delta t = R/c$, where R is the nuclear radius. This is the maximum time; the actual time dt could be a fraction of Δt, but we want to be conservative in estimating the value of a

$$a \simeq c\frac{\Delta y_p}{\Delta t}\cosh \Delta y_p = a_{\text{RHIC}}\,\Delta y_p \cosh \Delta y_p ,$$

where the scale on which we measure acceleration in these collisions is

$$a_{\text{RHIC}} \equiv \frac{c}{\Delta t} = \frac{c^2}{R} \simeq 2 \times 10^{31}\frac{\text{m}}{s^2}.$$

This result is by a factor 100 greater

when nucleons from the incoming nucleus are stopped so that rapidity shifts significantly from a value prior to collision, critical acceleration must have been achieved, ripping nucleons apart. In such process there is creation of a large particle multiplicity. This finding coincides with the formation of quark-gluon plasma (QGP) at CERN

Fig. 29.3 CERN announces the discovery of quark-gluon plasma in a press-release on 10 February 2000 press.web.cern.ch/press-releases/2000/02/new-state-matter-created-cern

To resolve SR inconsistencies: we need a NEW “large acceleration” theory framework (other than Gravity=GR)

THEORY Question: How can charged accelerated particles know to radiate, that there is inertial reference frame telling -- is the Universe or is the body accelerating

EXPERIMENT:
High acceleration radiation properties?

Is there a limit to how fast we can accelerate electrons to ultra high energy?

ETC

Conclusions

After many years of neglect we find ourselves already immersed into **an encore of SR** with RHI experiments inadvertently probing critical acceleration and future light pulse – relativistic electron collisions exploring systematically physics at the acceleration frontier. Manpower preparation for this COULD BE BETTER