Space-time, Acceleration & Matter

Presented by Johann Rafelski

Prepared by Johann Rafelski & Andrew Steinmetz

Presented at

ELI-BL Dolni Brezany, Czechia

December 13th , 2022

The University of Arizona

School of Athens **by Raphael with Leonardo da Vinci representing Plato (cover of new SR book)**

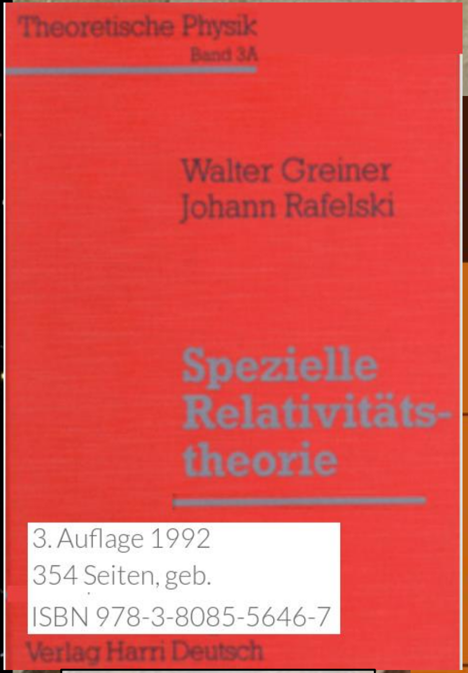
BG Image credit: NASA, ESA, and S. Beckwith (STScI) and the HUDF Team

Strong Fields and Acceleration Group at Tucson, Arizona

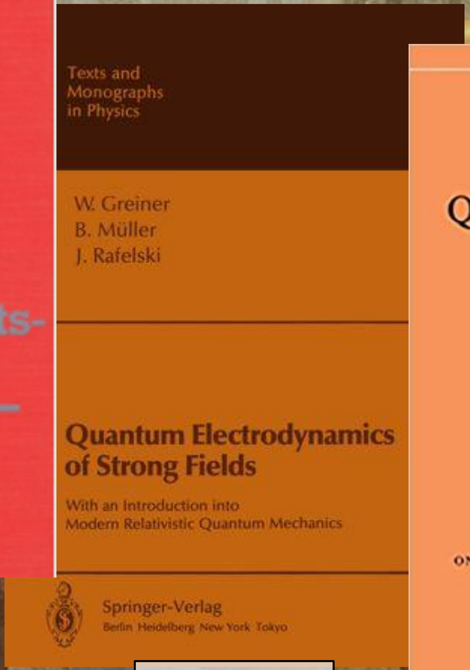
1. **Dr. Johann Rafelski**
2. **Dr. Martin Formanek**
3. **Chris Grayson**
4. **Will Price**
5. **Cheng Tao Yang**
6. **Andrew Steinmetz**
7. **Dr. Stefan Evans**

Research group with decades-long interest in Special Relativity, Strong Fields and matter creation

Source of key elements for these presentations



(1983-1992)



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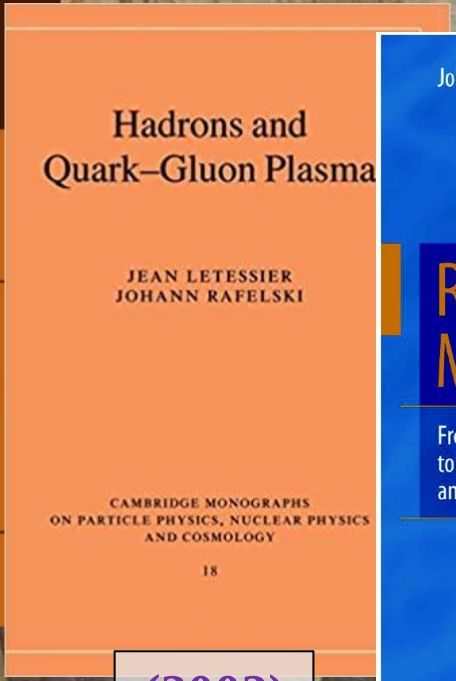
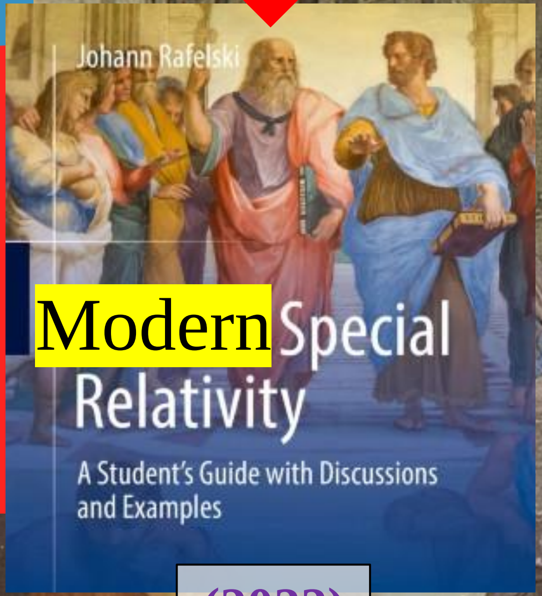


(2002)

(2006-2016)

(2018)



(2022)

What is “Modern” about Special Relativity?

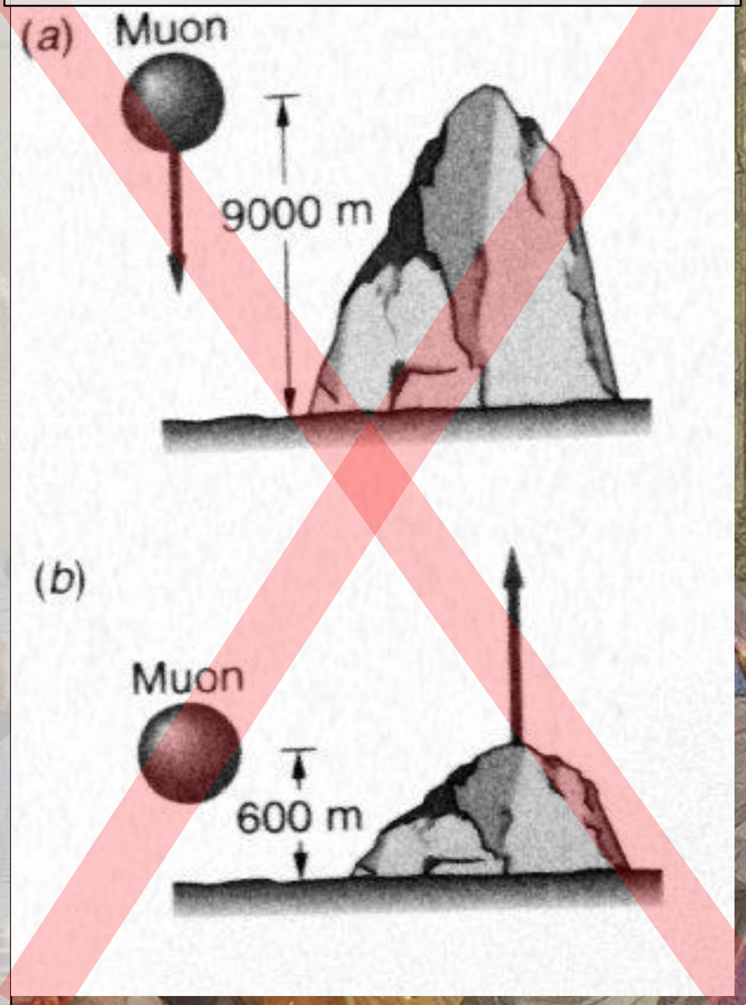
- Clarification of concepts in SR and recognition of the role of acceleration
- Arbitrarily small acceleration accumulates to generate body contraction and time dilation
- Modern developments in understanding origin of matter
- Modern applications of using light to accelerate particles
- Horizons of relativistic interstellar space travel
- Aether is back as structured quantum vacuum: Exploration with intense laser pulses

Scope of change in a 150 years since need (Maxwell’s Equations) for SR was born

Challenges teaching SR to students

- Some books claim that Lorentz body contraction and time dilation are the same and that one confirms the other; or that space is contracted **(???)**. The first is wrong, the second is nonsense.
- Incorrect use of SR generates claims of “paradoxes” or “not real” effects.
- Frame-dependant phenomena are well established in all areas of physics.
- Students fact-check you live against SR hobbyist know-how and their **entertaining videos with invented truths.**
- We think SR is a living and evolving theory while SR is taught as a footnote of Gravity Relativity (GR).
- **Teaching of SR as an independent topic is necessary to ensure correct use in diverse scientific research fields.**

From a serious book that millions of students have used.



Challenges teaching classical electromagnetism

We have two separate theories:

- Given sources of charges and currents, solve **[improved]** Maxwell's eq. for EM fields.
- Given EM fields, solve **[improved]** Lorentz force for charged particle motion.

"… a complete satisfactory treatment of the reactive effects of radiation [caused by acceleration, JR] does not exist."

– J. D. Jackson, *Classical Electrodynamics*, p. 781, (1999).

There is a disconnect as accelerated charges radiate and lose energy and momentum which should be reflected in their motion! A self-consistent reaction/friction force and/or a modification to the fundamental properties of EM fields is needed.

There are many models of radiation friction and modifications to EM like Born-Infeld.

There is no action principle for radiation reaction models.

To solve the problem, we need to connect acceleration and SR.

==Challenges== understanding strong forces and strong acceleration

Einstein in 1905 developed SR invoking only inertial observers.

Einstein discusses electromagnetic fields: The word acceleration does not appear.

In daily life, all accelerations are far below the natural "unit-1" value of acceleration.

$$a_{cr} = m_e c^2 \frac{c}{\hbar} = 2.33 \times 10^{29} \frac{\mathrm{m}}{\mathrm{s}^2}$$

This is also the acceleration generated by Schwinger "critical" EM fields:

$$E_{cr} = \frac{(m_e c^2)^2}{e\hbar c} = 1.323 \times 10^{18} \frac{\mathrm{V}}{\mathrm{m}}$$

$$B_{cr} = \frac{(m_e c^2)^2}{e\hbar c^2} = 4.414 \times 10^{9}\ \mathrm{T}$$

SR absorbs nano-acceleration setting Δv = aΔt however: Accelerated twins age slower compared to inertial twins.

Ultra-relativistic electron in a magnetic field of 4.41 T at CERN experiences:

$$a_{CERN} = \left(\frac{e}{m_e}\right) \boldsymbol{v} \times \boldsymbol{B} = 2.33 \times 10^{20} \frac{\mathrm{m}}{\mathrm{s}^2} \sim \textbf{nano } \boldsymbol{a_{cr}}$$

Near to critical acceleration/fields: Electromagnetism must be improved!

Part I
Special Relativity:
The Foundation of all Modern Physics

- GR: Gravity Relativity aka General Relativity
- Weak Interaction
- **Electromagnetic Interaction**
- Strong Interaction

"On the Electrodynamics of Moving Bodies" A. Einstein, 1905

"Does the Inertia of a Body Depend upon its Energy Content?" A. Einstein, 1905

3. *Zur Elektrodynamik bewegter Körper;*
von A. Einstein.

Daß die Elektrodynamik Maxwells — wie dieselbe gegenwärtig aufgefaßt zu werden pflegt — in ihrer Anwendung auf bewegte Körper zu Asymmetrien führt, welche den Phänomenen nicht anzuhaften scheinen, ist bekannt. Man denke z. B. an die elektrodynamische Wechselwirkung zwischen einem Mag-

13. *Ist die Trägheit eines Körpers von seinem Energieinhalt abhängig?*
von A. Einstein.

Die Resultate einer jüngst in diesen Annalen von mir publizierten elektrodynamischen Untersuchung[1]) führen zu einer sehr interessanten Folgerung, die hier abgeleitet werden soll.

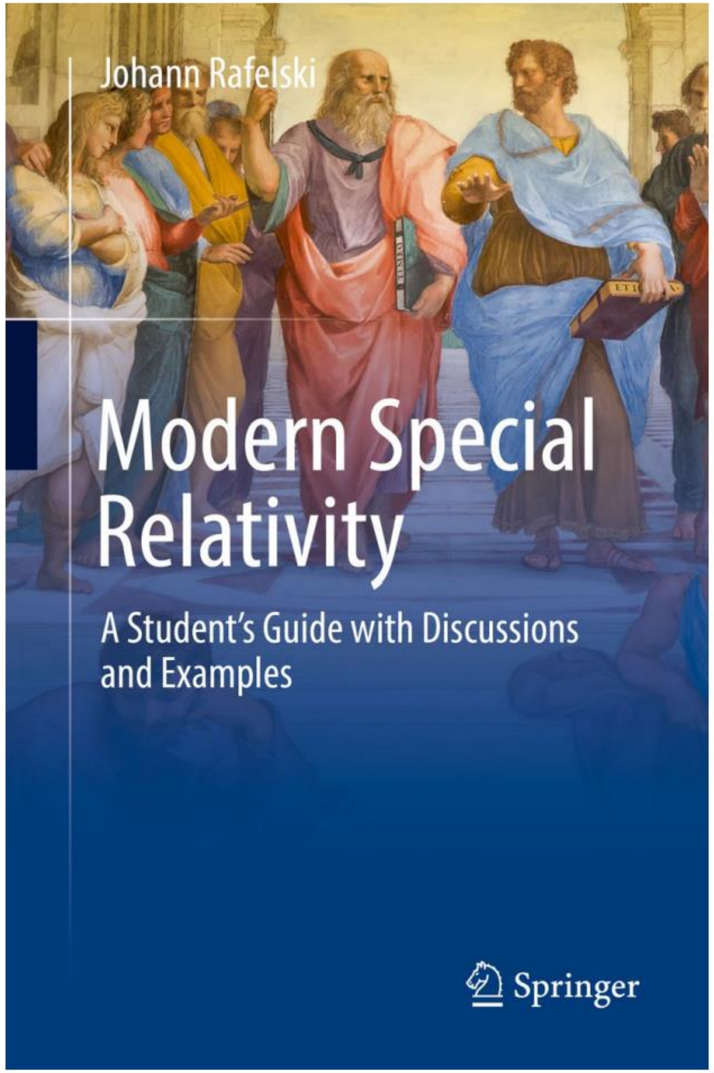
As Einstein titles/content imply SR is about:

- Electromagnetism.
- Body contraction.
- Time dilation.
- $E = mc^2$
- Constancy of the speed of light.

Einstein in 1905 SR introduced the principle of relativity into EM and explored consistency consequences.

SR is **not** about gravity and/or space-time.

Conceptual Clarifications



J. Rafelski

Modern Special Relativity

A Student's Guide with Discussions and Examples

- **Designed for students, it provides many solved problems that help master the subject**
- **The concepts of special relativity are introduced in a clear and simple way, without making use of four-vector formalism**
- **Presents the existing connections between special relativity and particle, nuclear, and high intensity pulsed laser physics**

Section 3.5: Resolving Misunderstandings of SR, pg. 59-63

1: Space Is NOT Contracted
The fact that one IO measures event coordinates that are different from those measured by another IO does not mean that there is a change to the space-time manifold.

2: Extended Bodies HAVE a Place in SR A cohesive extended body is naturally different from a cloud of non-interacting particles. Since space does not contract, a particle cloud does not either. All cohesive material bodies are contracted.

3: Lorentz-FitzGerald Body Contraction and Time Dilation ARE Independent of Each Other
Any elementary particle can experience large time dilation but cannot experience a Lorentz-FitzGerald body contraction irrespective of another material body being present.

4: The Lorentz-FitzGerald Body Contraction IS Real
Since a Lorentz-FitzGerald body contraction ‘clocking’ instrument could be constructed, body contraction is a real and independent phenomenon.

Section 3.5: Resolving Misunderstandings of SR, pg. 59

5: Small Acceleration IS ALWAYS RELEVANT

Accelerated observers are never equivalent to IOs for the simple reason that no matter how small the acceleration is, we can tell it is present. Bell Rocket example: no matter how small the acceleration is which propels the two independent rockets, only a material body connecting them will be contracted, and not the spatial separation between these rockets.

6: Time Dilation Is NOT Observer-Reversible = ~~'Twin Paradox'~~

A returning space traveler will always be younger since the laboratory twin was inertial. This is so because for each body only its proper time is a meaningful measure of time flow. There is no paradox.

7: Relativistic Doppler Effect is NOT Related to Time Dilation at Source

Einstein: The light wave carries to the observer the information about the source, allowing later decoding of the relative motion and thus the determination of the relative shift in frequency and wavelength. The SR Doppler shift is created in the process of observation.

Minkowski in 1908 clarifies space-time and proper time

Space-time distance is unique, and simultaneity is not protected in SR

There is only one observer independent distance in SR.

- If $\Delta t^2 - \frac{\Delta x^2}{c^2} > 0$ then this is a “time-like” distance.
- If $\Delta x^2 - \Delta t^2 c^2 > 0$ then this is a “space-like” distance.
- This notion never changes under Lorentz coordinate transformations.

Lorentz transformations (in Lorentz form):

$$\Delta t = \frac{\Delta t' + \frac{v_x}{c^2}\Delta x'}{\sqrt{1 - \frac{v_x^2}{c^2}}} \qquad \Delta x = \frac{\Delta x' + v_x \Delta t'}{\sqrt{1 - \frac{v_x^2}{c^2}}}$$

Imagine if two events occur at the same time in two different places for one observer O' so that

$$\Delta t' = t_1' - t_2' = 0$$

Then another observer O with relative velocity v will see

$$\Delta t = t_1 - t_2 \neq 0$$

And will believe the events happen at different times.

Coordinate transformations must be consistent with physical phenomena in SR: Two examples

Galilean transformations:

$$t' = t \qquad y' = y$$

$$x' = x - v_x t' \qquad z' = z$$

Galilean transformations assure simultaneity for all observers.

Time transforms so simultaneity is not assured. For Lorentz transforms, one only observer is simultaneous.

Lorentz transformations (in Larmor form) accommodate:

$$t' = t\sqrt{1 - \frac{v_x^2}{c^2}} - \frac{v_x}{c^2}x' \qquad y' = y$$

I. When $x' = 0$, then t' corresponds to the clock time of the body and we have time dilation.

$$x' = x\sqrt{1 - \frac{v_x^2}{c^2}} - v_x t' \qquad z' = z$$

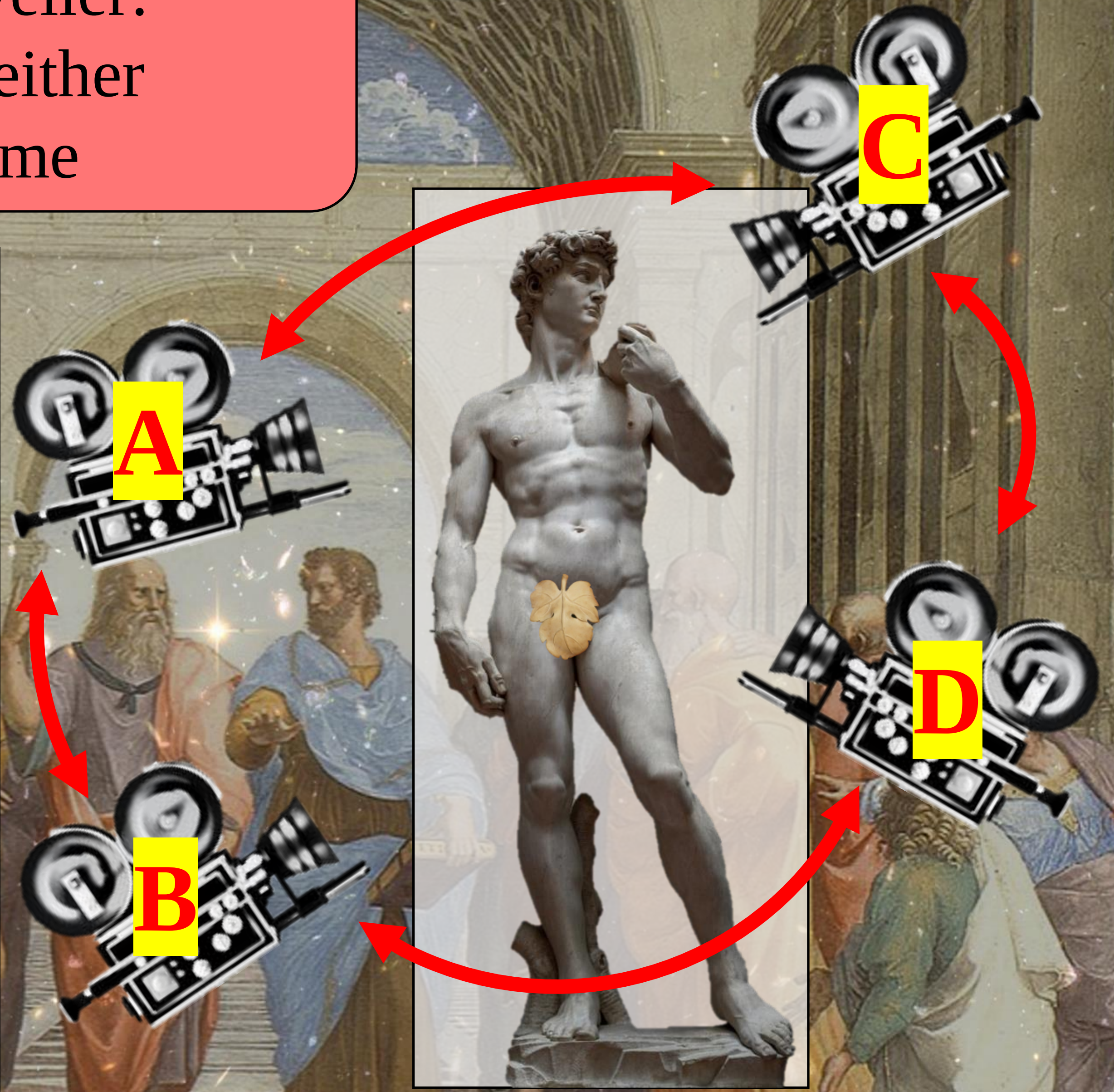
II. When $t' = 0$, then x' corresponds to the contracted observed body length of a moving object.

Differences in observing the traveller: Coordinate transforms change neither the observed body nor spacetime

Lorentz coordinate transformations let you describe the coordinate systems of different observers.

The “set” of all possible transformations (rotations, translations, and more) in an empty spacetime is called the Poincare group.

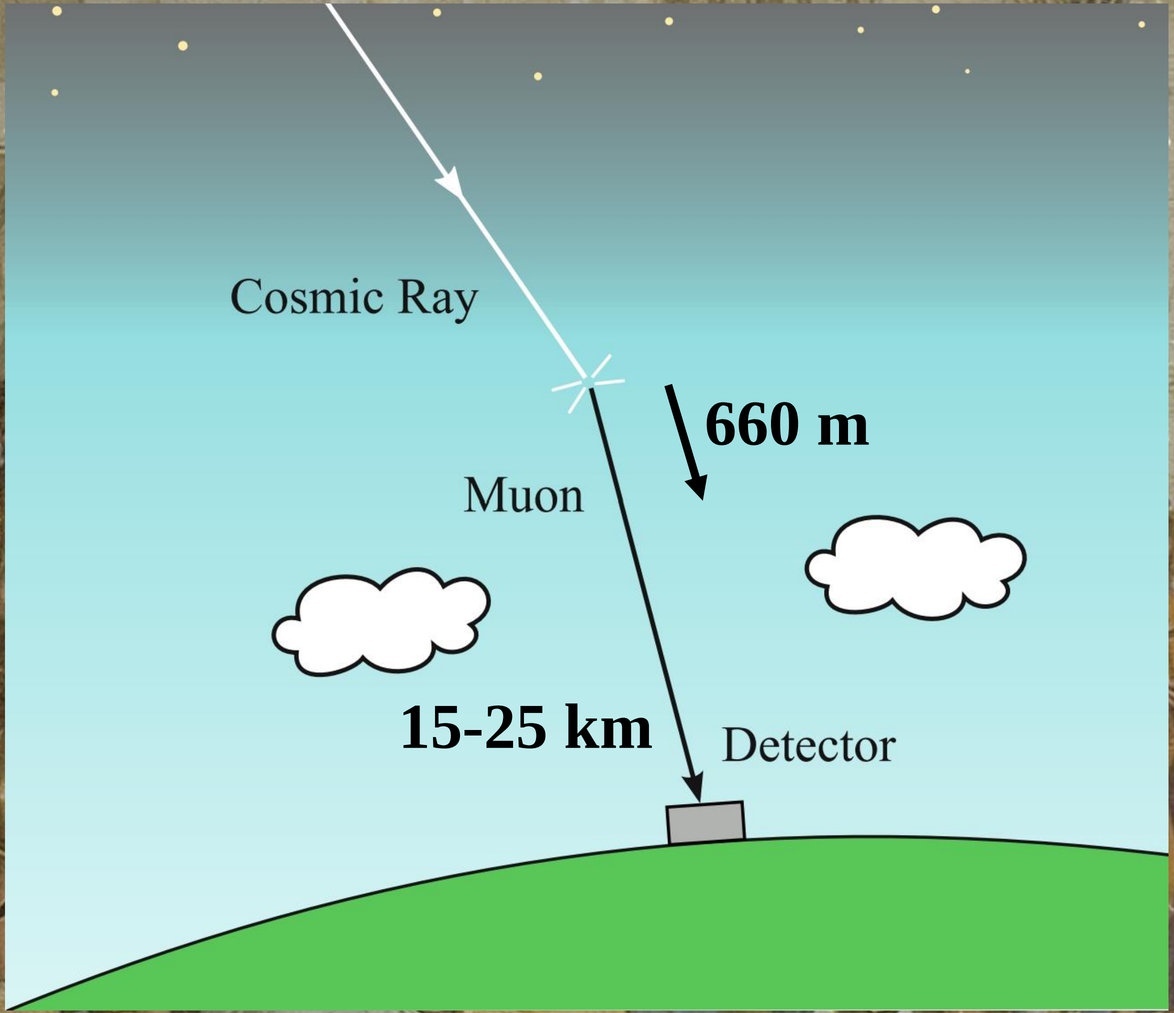
But no matter what perspective you take, the object itself is unchanged. Coordinate transformations do **<u>NOTHING</u>** to the object or spacetime.



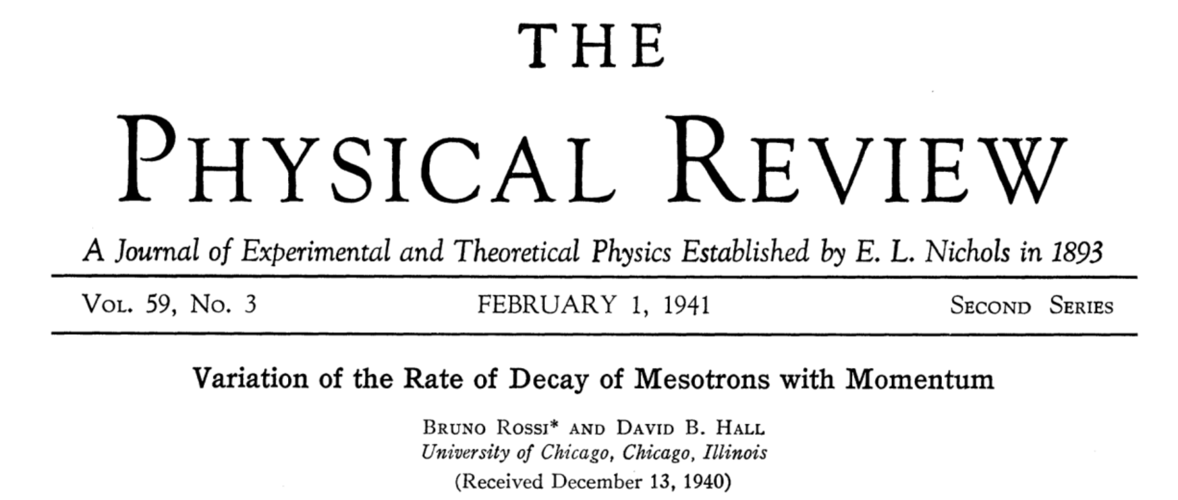
Part II
Special Relativity: Consequences

- Time dilation
- Doppler effect
- Body contraction
- Space-time travel
- Energy and Matter

Muon decay



In a Galilean world, when muons are produced in the upper atmosphere, they should only live 2.197 μs and travel at most 660 m.
Instead, they make it all the way to the ground. How can this be?


THE

PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics Established by E. L. Nichols in 1893

VOL. 59, No. 3 FEBRUARY 1, 1941 SECOND SERIES

Variation of the Rate of Decay of Mesotrons with Momentum

BRUNO ROSSI* AND DAVID B. HALL
University of Chicago, Chicago, Illinois
(Received December 13, 1940)

Unstable particle range during its proper lifespan

Imagine observing a muon in intergalactic empty space (no nearby mountains) so there is no LFG body contraction of anything. Using the invariant proper lifespan of the particle and its relative velocity to the observer, we obtain the distance traveled in empty space as reported by the observer.

$$c^2\tau^2 = \left(1 - \frac{v^2}{c^2}\right) c^2 t^2$$

Time dilation

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

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

Space-time interval

$$\frac{E}{mc^2} \approx 39$$

$$v = \frac{x}{t}$$

$$x = \frac{\tau v}{\sqrt{1 - \frac{v^2}{c^2}}} = \frac{(2.197\ \mu\text{s})(0.99968c)}{\sqrt{1 - 0.99968^2}} = \mathbf{26\ km}$$

The muon travels the range $\boldsymbol{x}$ during its lifespan $\boldsymbol{\tau}$ in vacuum with reference to an observer who measures its velocity $\boldsymbol{v}$. The travel distance of the muon has:

a) Nothing to do with body contraction and

b) Nothing to do with nonsensical idea of "space contraction."

Very similar to the time dilation of a star explorer, but without acceleration.

Time dilation: Direct clock measurement

The only observer independent time quantity is the Lorentz invariant **proper time $\boldsymbol{\tau}$** of a body:

$$c^2\tau^2 - 0 = c^2t^2 - x^2 = c^2t'^2 - x'^2$$

Proper time of a body ($\boldsymbol{x = 0}$) is meaningful. A returning traveller must have aged $\boldsymbol{\tau < t}$. For two airplanes going around the rotating Earth: When they meet after a full circle, Earth has rotated underneath and one has travelled further than the other, hence clock on airplanes would have travelled different distances and recorded different passages of time. Note that one airplane moves with the speed added to rotation, while the other moves with speed subtracted from rotation.

Around-the-World Atomic Clocks: Predicted Relativistic Time Gains

Abstract. *During October 1971, four cesium beam atomic clocks were flown on regularly scheduled commercial jet flights around the world twice, once eastward and once westward, to test Einstein's theory of relativity with macroscopic clocks. From the actual flight paths of each trip, the theory predicts that the flying clocks, compared with reference clocks at the U.S. Naval Observatory, should have lost 40 ± 23 nanoseconds during the eastward trip, and should have gained 275 ± 21 nanoseconds during the westward trip. The observed time differences are presented in the report that follows this one.*

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RICHARD E. KEATING
Time Service Division, U.S. Naval Observatory, Washington, D.C. 20390

Relativistic Doppler effect (RDE):
No relation to time dilation

Time dilation of the source cannot be part of RDE since the relative speed with respect to the yet undetermined observer cannot be known at the time of light emission.

Einstein's 1905 paper works in the following way: The light wave carries to the observer information about the source allowing the determination of the RDE shift in frequency and wavelength and position aberration at the time of actual observation of the light signal.

$$\Phi = \Phi'$$

$$\omega t - \boldsymbol{k} \cdot \boldsymbol{x} = \omega' t' - \boldsymbol{k}' \cdot \boldsymbol{x}'$$

Use the Lorentz transformation for $\boldsymbol{x}'$ and t' to obtain Doppler effect including aberration.

As Einstein's argument is very terse and he presents without detailed calculation, it can be easily misunderstood. von Laue's SR book discussing RDE can also be misread.

Zur Elektrodynamik bewegter Körper. 911

~~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-

Einstein's correct derivation

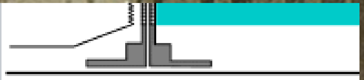
How did the mix up between time dilation and Doppler effect happen?

Ives and Stilwell in 1938 measure (transverse) Doppler shift claiming they measure time dilation.

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.

Resnick around 1960 learns using what appears to be non-expert translation of von Laue's SR book and relies on the language of Ives-Stilwell. **This is copied in most English language books and is today found all over the internet.**

Further reading on Relativistic Doppler Effect

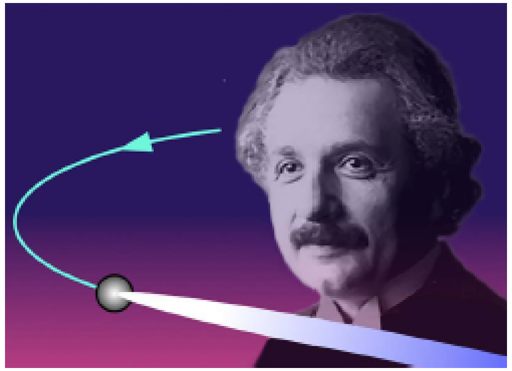
JOURNAL OF SYNCHROTRON RADIATION

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

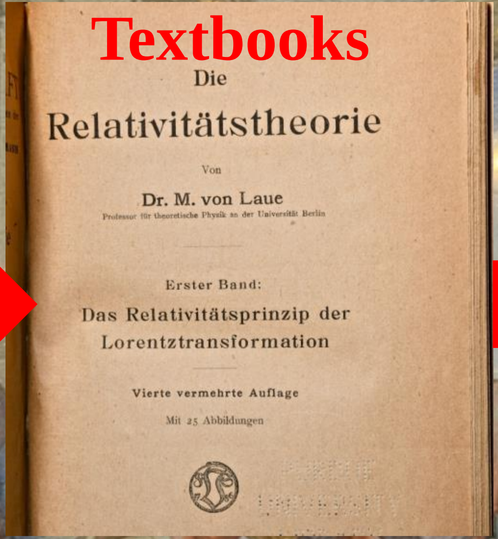
Giorgio Margaritondo[a]* and Johann Rafelski[b]

[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. *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.

To understand principles of special relativity, it is best to look at original work. Why?

Telephone game with Lorentz-FitzGerald body contraction:



"Body is contracted."
Correct.

"Length is contracted."
Correct,
but requires context.

"Distance is contracted."
↓ **Misleading.**
"Space is contracted."
Junk!

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.

Origin of Lorentz-FitzGerald Body Contraction, 1889

Body contraction in the direction of motion was first described by FitzGerald in 1889.
Lorentz once made aware, called it "FitzGerald body contraction." FitzGerald who passed away before SR was fully developed could not defend his priority.

Restatement of FitzGerald text:

"We know that electric forces are affected by the motion of the electrified bodies relative to the ether, and it seems not an improbable supposition that the molecular forces are affected by the motion, and that the size of a body alters consequently."

Is Lorentz-FitzGerald body contraction “real”?

The kinetic energy of a car depends on your frame of reference like a pedestrian versus the driver point of view.

In special relativity body properties and the passage of time depends on your frame of reference.

The point of view matters.

Lorentz-FitzGerald body contraction:
Is a passenger on a relativistic train aware they are “body contracted?”

A. **Einstein, 1911:** “For a comoving observer it is not present and as such it is not observable; however, it is real and in principle observable by physical means by any non-comoving observer.”
“Sie besteht nämlich nicht “wirklich”, insofern sie für einen mitbewegten Beobachter nicht existiert; sie besteht aber “wirklich”, d. h. in solcher Weise, daß sie prinzipiell durch physikalische Mittel nachgewiesen werden könnte, für einen nicht mitbewegten Beobachter.“
– *Physikalische Zeitschrift* **12**, pp. 509–510 (1911)

J. S. Bell, 1976 (of “Bell inequality fame”) invokes Lorentz-Janossy reality point of view: Using **acceleration** the passenger transports from one inertial frame to another. This allows them to know and measure relative contraction.

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

PART IV: Measurement 135

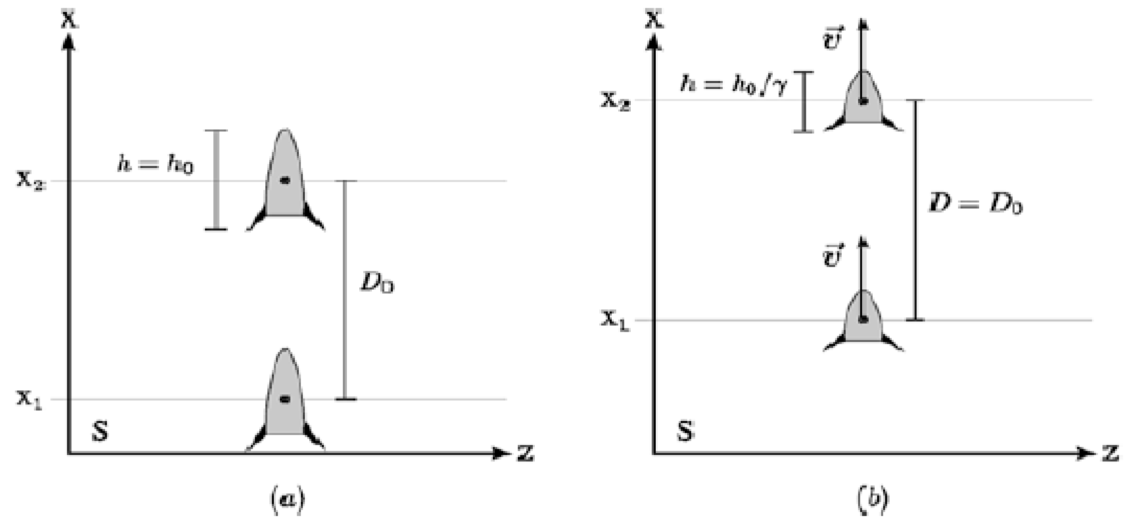


Fig. 10.2 Two rockets of length h separated by distance $D = x_2 - x_1 = D_0$. (a) at rest, and in case (b) moving at velocity $\vec{v}$ acquired at a later time

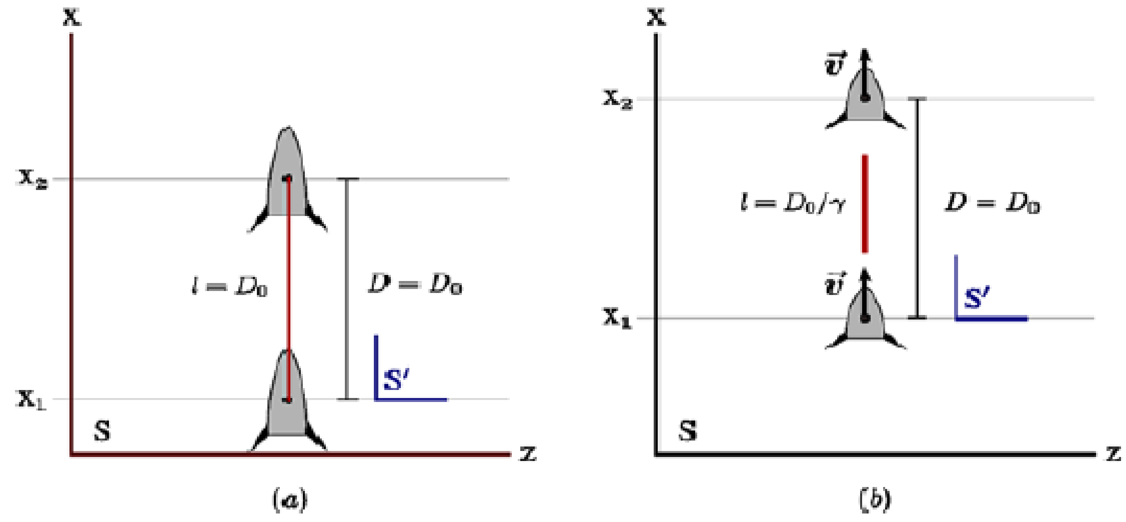


Fig. 10.3 Two rockets separated by distance $D = x_2 - x_1 = D_0$ and connected by a thin thread of (a) at rest, and in case (b) moving at velocity $\vec{v}$ acquired at a later time

Bell rockets: Spatial distance versus body length

If you connect two rockets with a thin string and let them identically accelerate, each rocket and the string will body contract.

A thin string can’t handle the stress and will break.

The spatial distance between the rockets however is unchanged.

Lorentz-FitzGerald body contraction:
What is possible today?

Eur. Phys. J. A (2018) 54: 29
DOI 10.1140/epja/i2018-12370-4

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

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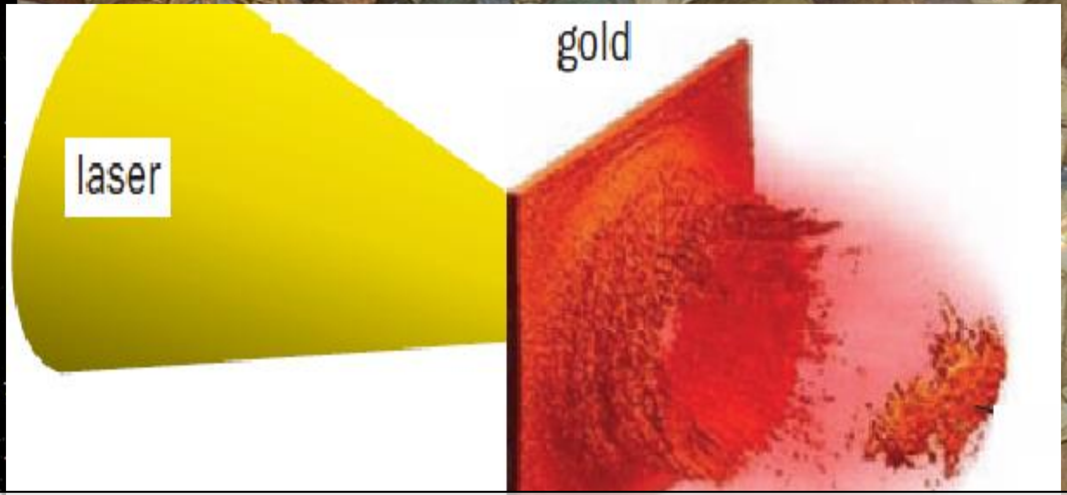
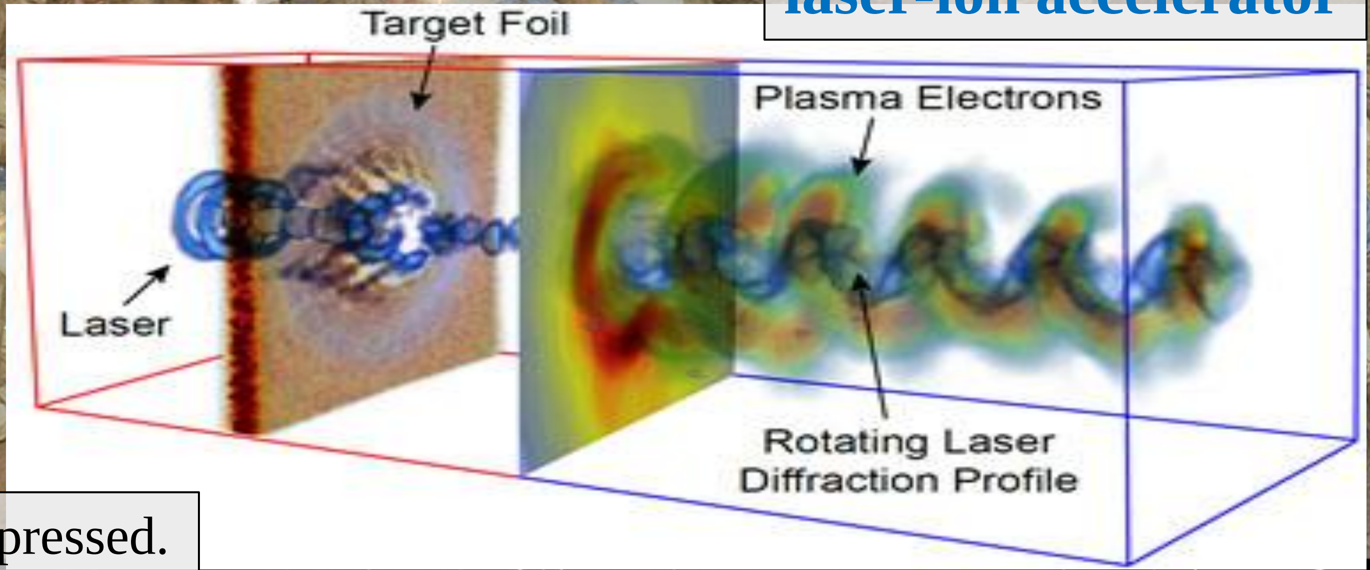
Abstract. A complete foundational discussion of acceleration in the context of Special Relativity (SR) is presented. Acceleration allows the measurement of a Lorentz-FitzGerald body contraction created. It is argued that in the back scattering of a probing laser beam from a relativistic flying electron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

Concept drawing of laser-ion accelerator





The "moving electron cloud mirror" is body compressed.

Space-time Travel

The only observer independent time quantity is the Lorentz invariant **proper time** of a body:

$$c^2\tau^2 = c^2t^2 - x^2 = c^2t'^2 - x'^2$$

Proper time of a body is meaningful and depends on $\boldsymbol{x}(\boldsymbol{t})$. A returning space traveller (who has accelerated) must have aged $\boldsymbol{\tau} < \boldsymbol{t}$.

If you reverse this, you introduce accelerated observers which are not yet incorporated in SR. Given proper time (which could be the lifespan of a particle) any two sets of values $\boldsymbol{t}$ and $\boldsymbol{x}$ are permissible associated with a specific Lorentz transform.

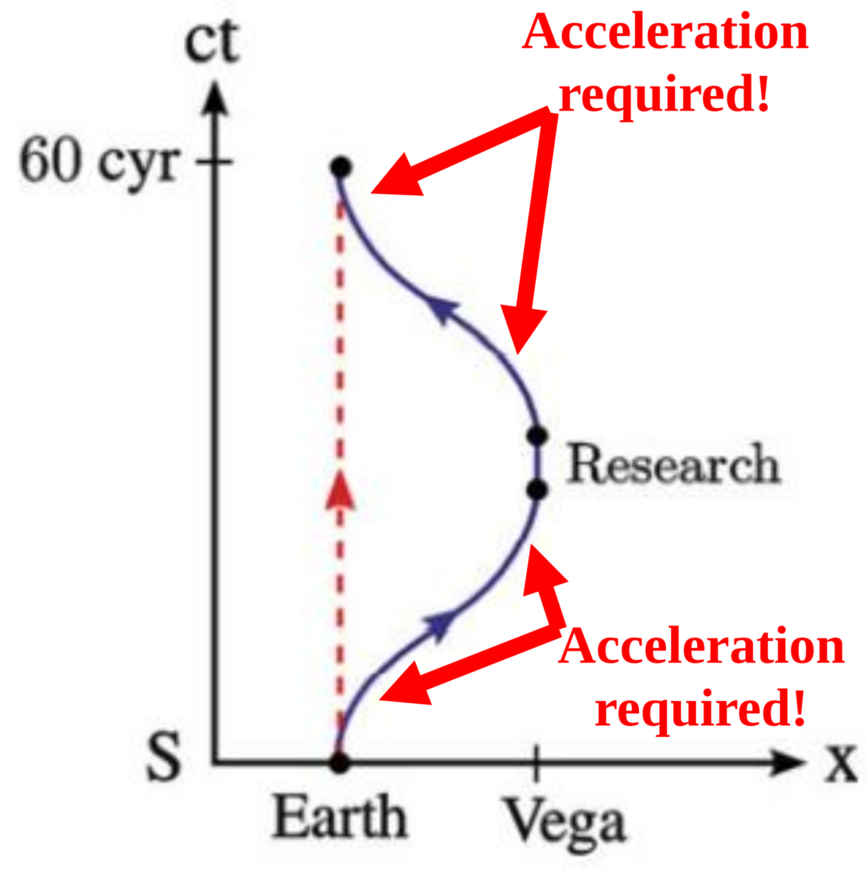
Time dilation is not reversible:

There is no twin "paradox" (See discussion of Langevin, 1911 below)

A trip to the stars:
Traveling to Vega and back

Two teams plan a trip to the star Vega. One team stays at base, while the other flies a rocket to Vega.

The rocket team has to accelerated at least four time to visit Vega and come back. The rocket team will be younger than the base team because of this.



See pg. 435-436 in "Modern Special Relativity"

Time on Earth:

$$t = 54.1 \text{ years}$$

Proper time of traveller:

$$\tau = 13.4 \text{ years}$$

In this example, acceleration of traveller:

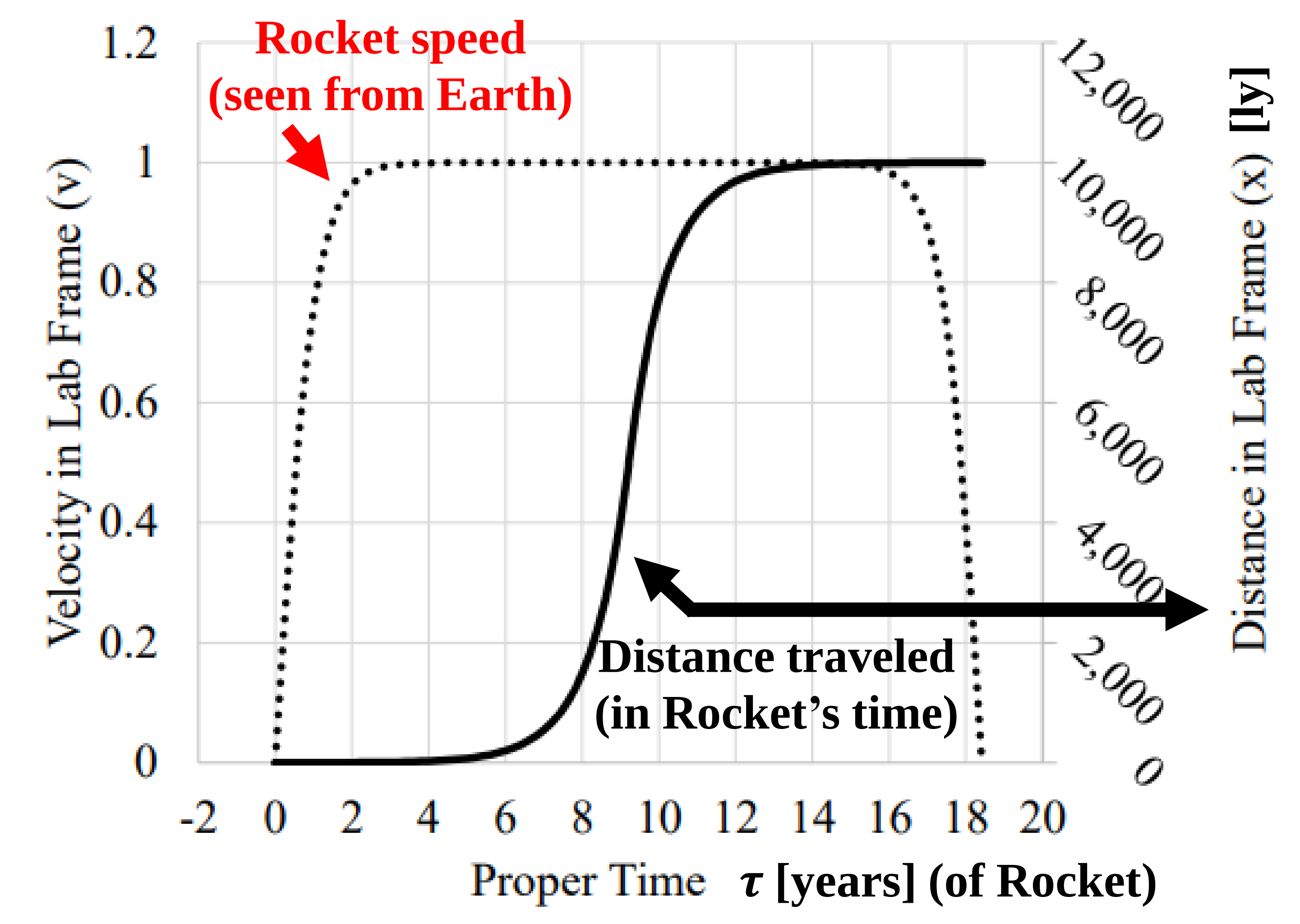
$$a_T = 1\,\text{g} = 9.8\,\frac{\text{m}}{\text{s}^2}$$

Whether the traveller's acceleration is large or small, they will be younger because they accelerated and travelled far. $c^2 d\tau^2 = c^2 dt^2 - dx^2 = c^2 dt'^2 - dx'^2$

A trip to the edge of the galaxy is possible:
One way trip going 10,000 light-years

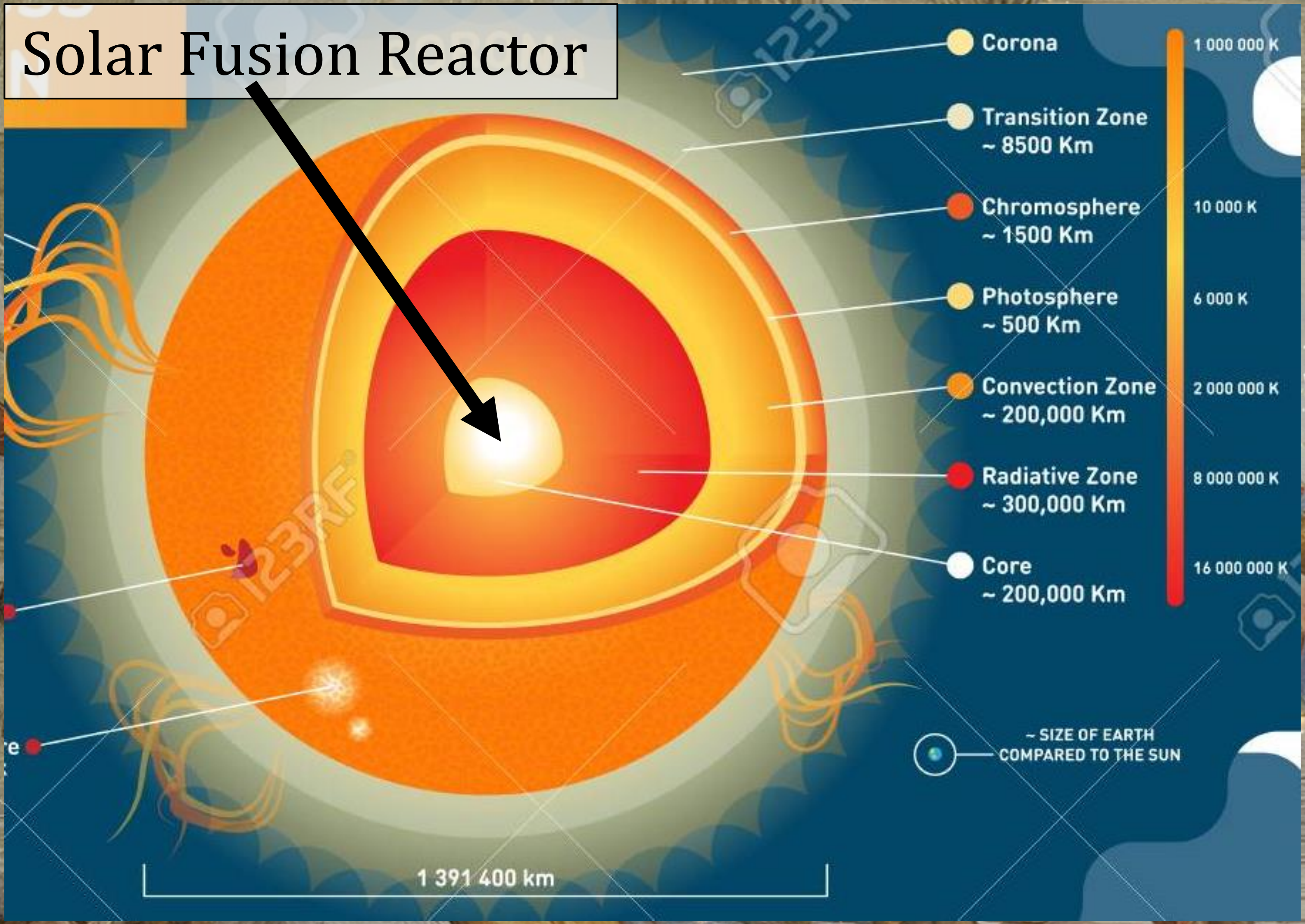
Large acceleration isn't needed to visit the stars. Instead, we only need a small acceleration over a long period of time.

A rocket going with acceleration $\mathbf{1}\boldsymbol{g} = \mathbf{9.8}\,\frac{\mathbf{m}}{\mathbf{s^2}}$ can travel thousands of light-years within a human lifespan.



Matter to Energy: $E = mc^2$

Solar Fusion Reactor

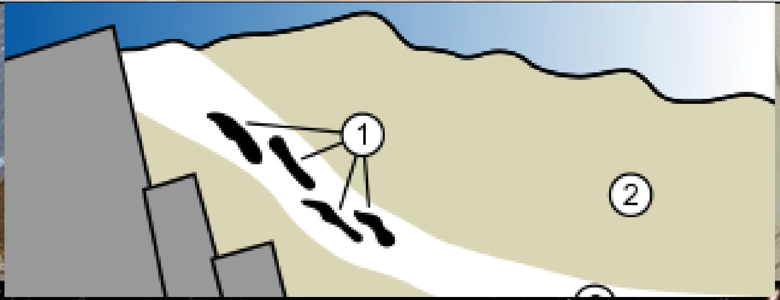


Man-made fission reactor

Pale Verde Generating Station west of Phoenix, AZ

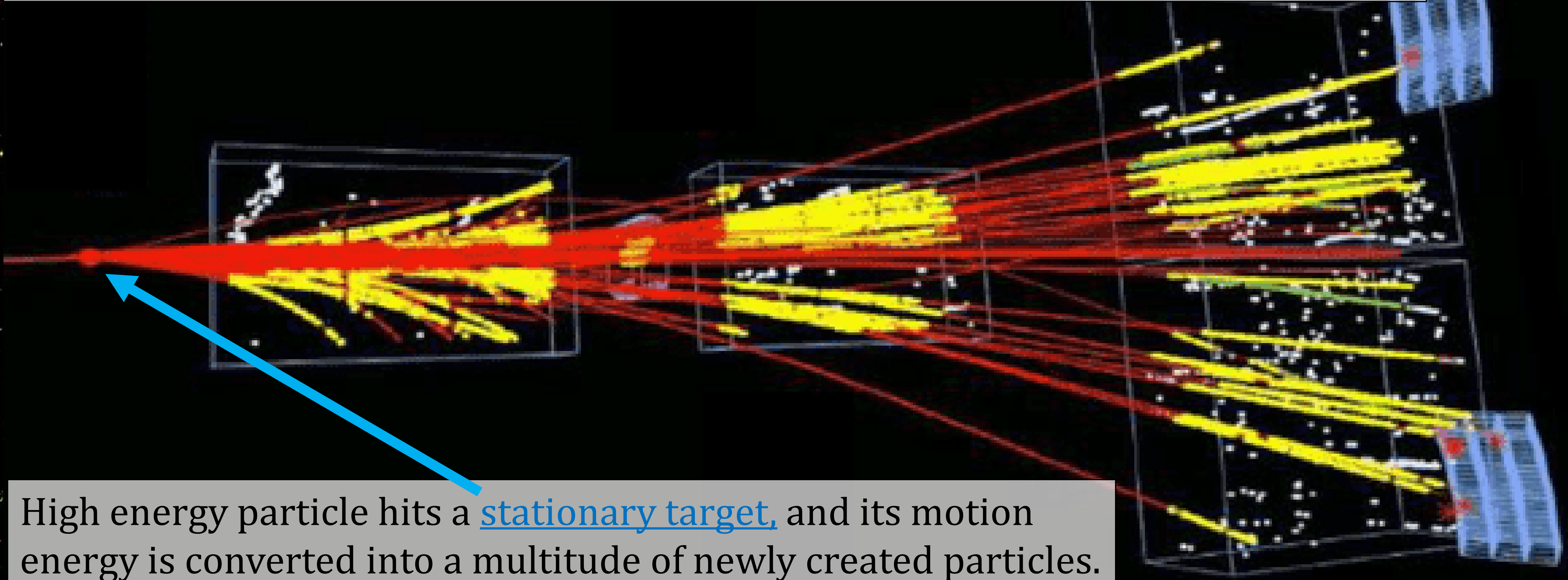
Natural fission reactor

Only known example was 2 billion years ago at Oklo, Gabon in Africa



Energy to Matter: $E = mc^2$

NA61/SHINE Collab. (adapted from CERN/Seweryn Kowalski lecture)



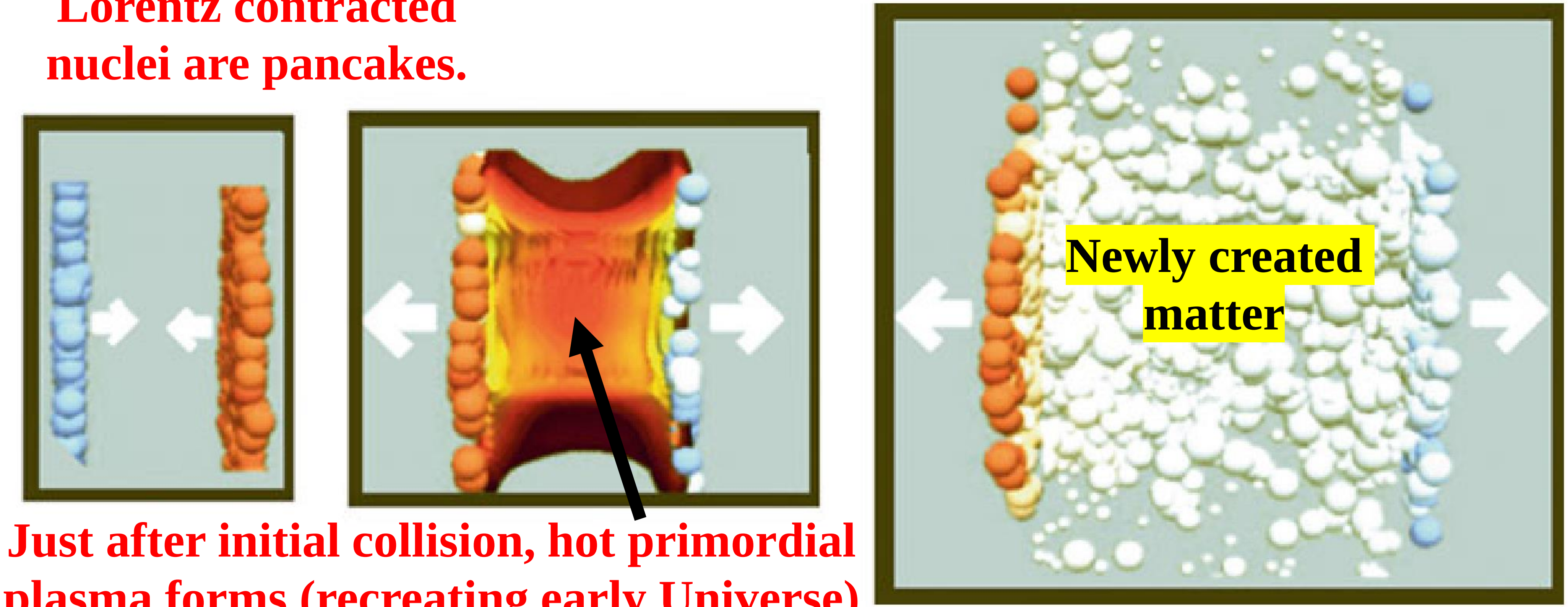
High energy particle hits a stationary target, and its motion energy is converted into a multitude of newly created particles.

Energy to Matter: $E = mc^2$

Lorentz-FitzGerald body contraction and mechanism of matter creation

When atoms nuclei (or any object) travels at a relativistic speed relative to you, it becomes body contracted and flattened like a pancake.

Lorentz contracted nuclei are pancakes.



Just after initial collision, hot primordial plasma forms (recreating early Universe)

Part III
Current Research Directions

- Pair production in strong fields
- Quantum vacuum
- Acceleration, forces, and fields
- **Fragments of Arizona research program**

The sparking of the QED vacuum in quasi-constant fields

All E-fields are unstable and can decay into particles if energy is available and rate is large enough.

– Explained by Heisenberg in 1935 and by Schwinger's article in 1950 appearing almost an after thought. (*my idea how this happened: invited by referee=Heisenberg*?)

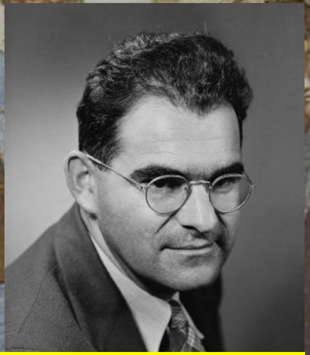
Effect large for E-field:

$$E_{cr} = \frac{\left(m_e c^2\right)^2}{e\hbar c} = 1.323 \times 10^{18}\,\frac{\mathrm{V}}{\mathrm{m}}$$

Persistence probability of the empty vacuum:

$$P \sim \exp\left(-\pi \frac{E_{cr}}{|\boldsymbol{E}|}\right)$$

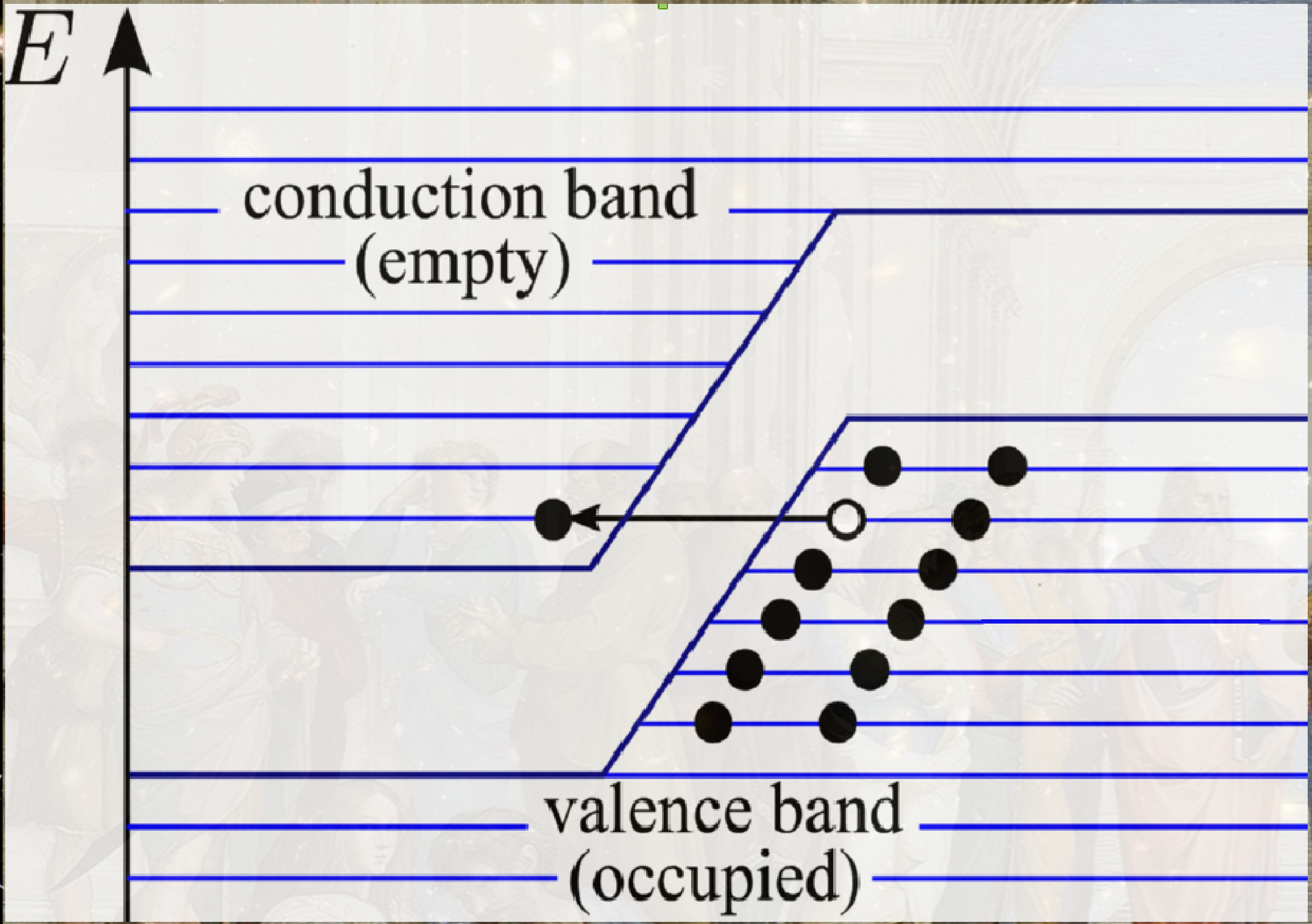
W. Heisenberg



V. Weisskopf

J. Schwinger

Vacuum decay: Pair production instability



- Relativistic Dirac quantum physics **predicts antimatter** and allows for the formation of pairs of particles and antiparticles.
- The relativistic gap in energy is reminiscent of insulators where the conductive band is above the valance (occupied) electron band.

F. Sauter, “Zum ‘Kleinschen Paradoxon’,” Z. Phys. 73 (1932), 547-552 doi:10.1007/BF01349862
S. Evans, and J. Rafelski. "Particle production at a finite potential step: transition from Euler–Heisenberg to Klein paradox." The European Physical Journal A 57.12 (2021): 1-10.

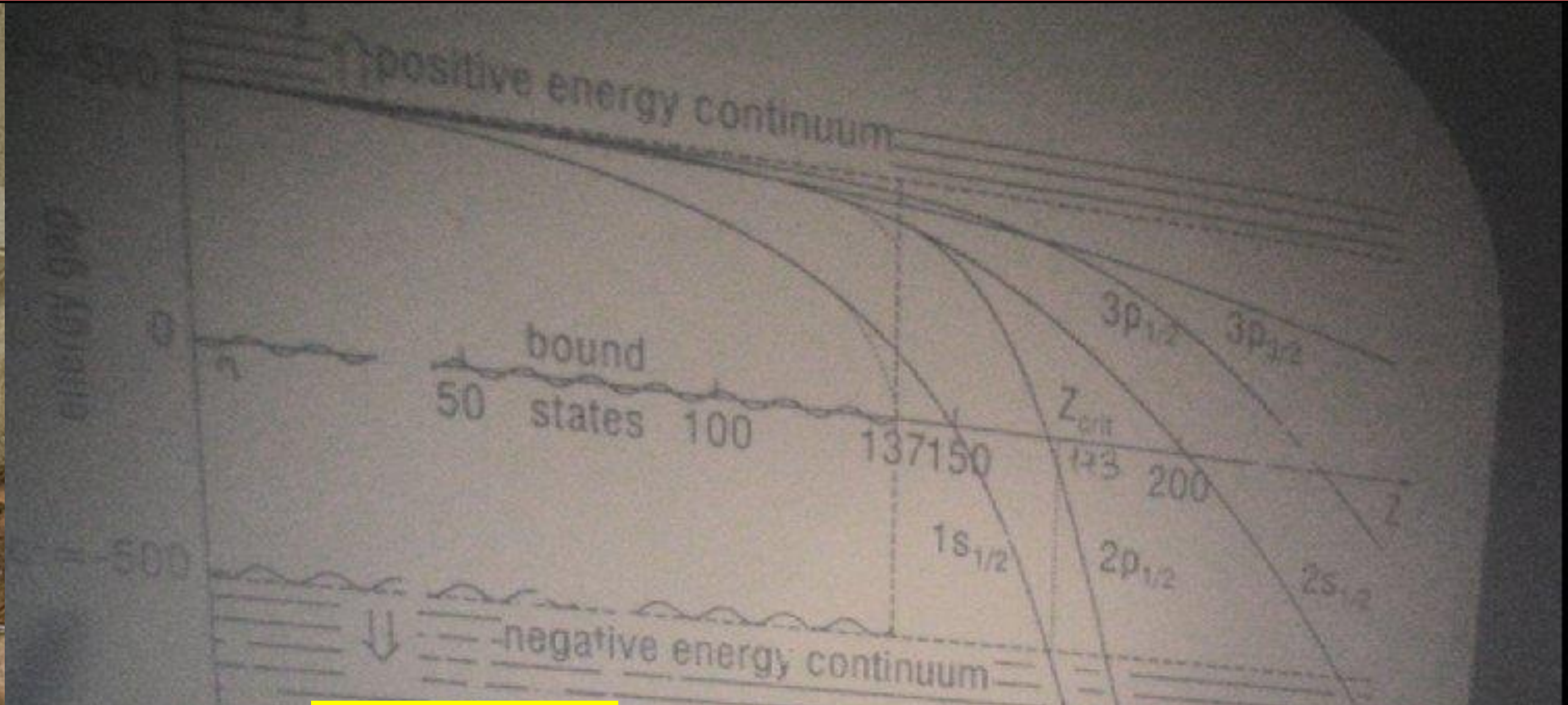
Virtual pairs: The vacuum is a dielectric

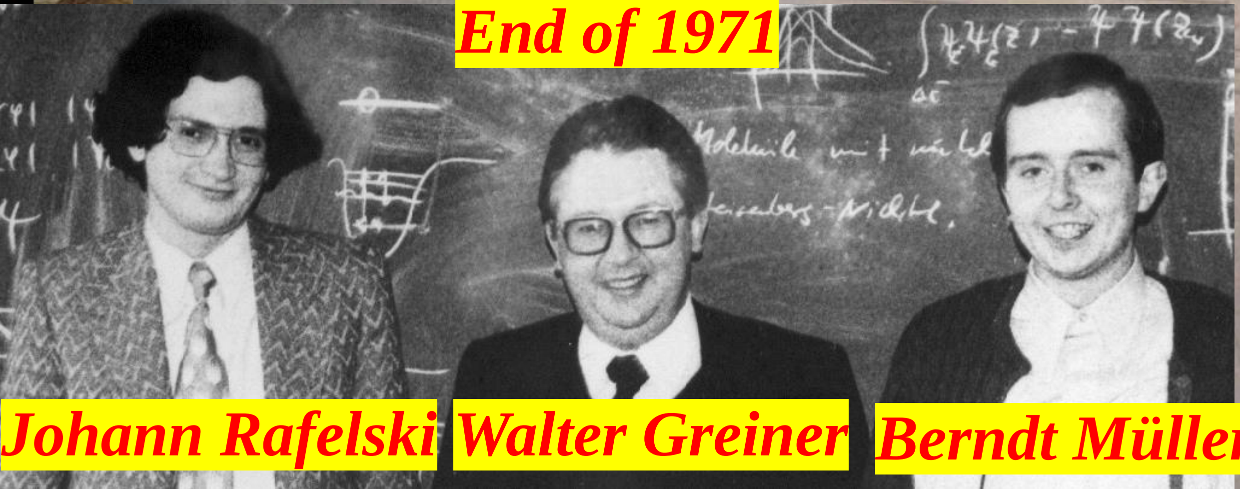
The vacuum is a dielectric medium as charges are screened by particle-hole (pair) excitations. In Feynman's language the real photon is decomposed into a bare photon and a photon turning into a "virtual" pair. The result: renormalized electron charge smaller than bare. The observable Coulomb interaction stronger (0.4%) at distance $\hbar c/m_e$

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

E. A. Uehling, "Polarization effects in the positron theory." Physical Review 48.1 (1935): 55.

Continuing the Frankfurt School legacy of strong fields physics



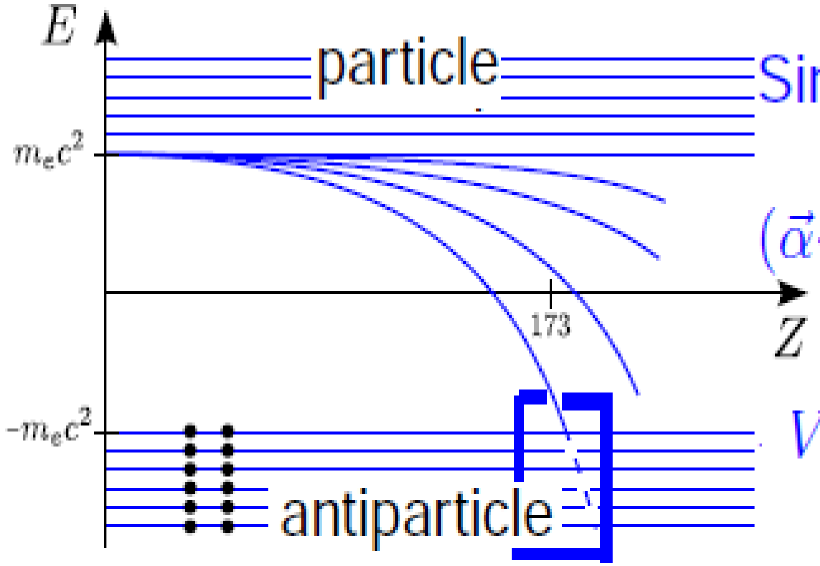


End of 1971

Johann Rafelski *Walter Greiner* *Berndt Müller*

UCLA, 2006

Vacuum instability in highly charged atomic systems: What is this (mostly) about?



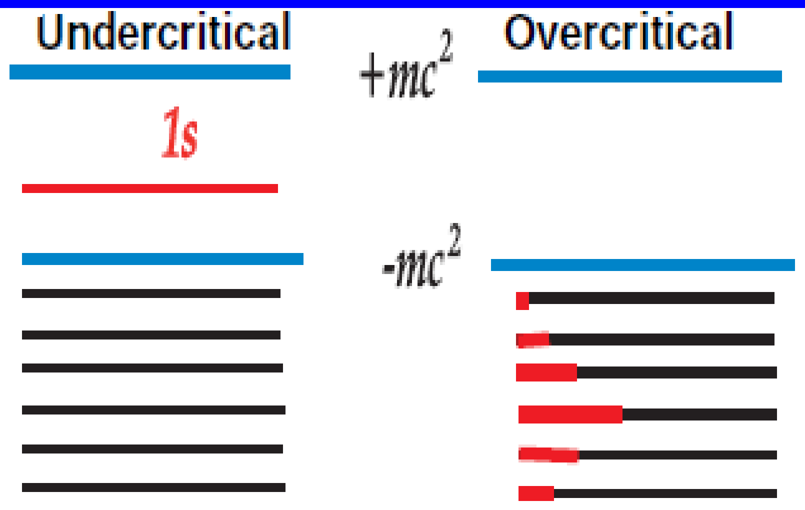
Single Particle Dirac Equation

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

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

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

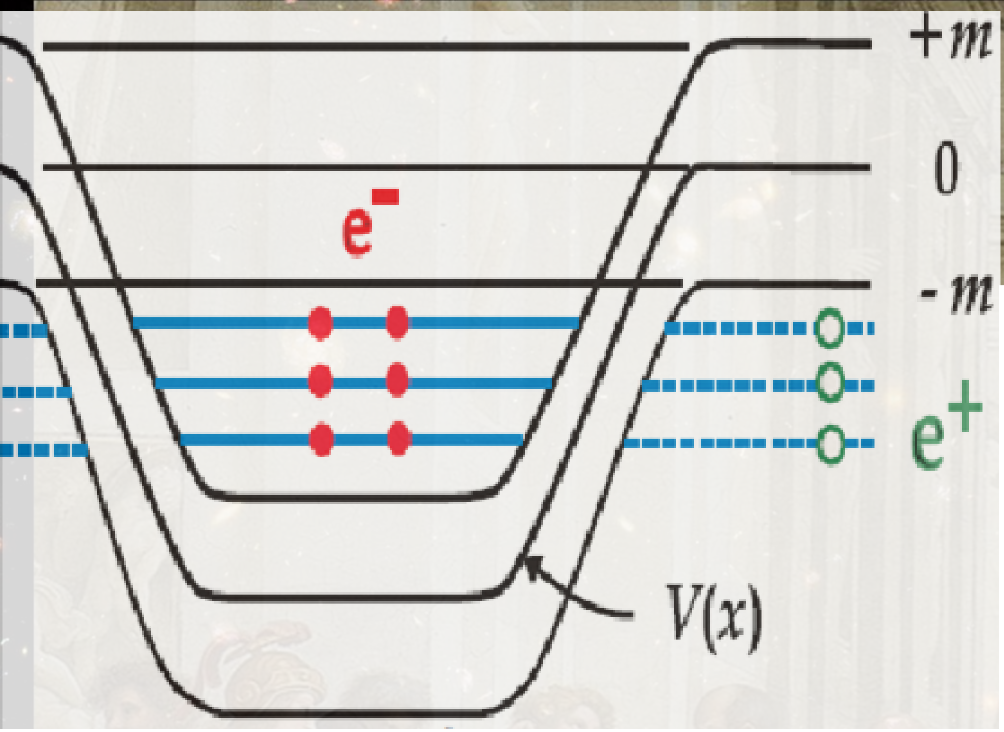


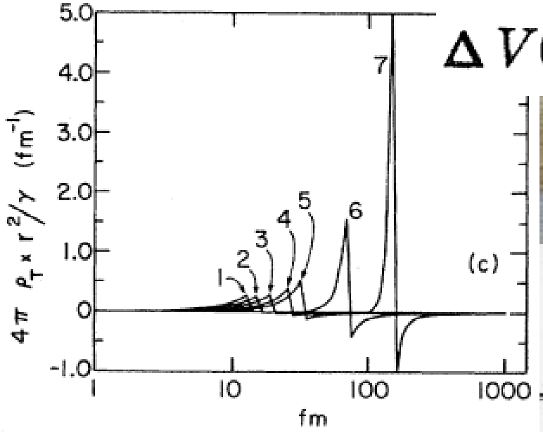
If diving state 'empty' vacuum decays
$|Q=0\rangle \to |Q=e\rangle + e^+$ by positron
state occupied by an electron, 'smooth' transition of charge distribution

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

Stabilization of the local vacuum state

Back reaction of accumulated vacuum charge can be accounted for self-consistently.





$$\Delta V(r) = e\rho_N(r) - (e^2/3\pi^2)(2mV + V^2)^{3/2}$$

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.

ИНСТИТУТ ТЕОРЕТИЧЕСКОЙ ФИЗИКИ
им. Л. Д. ЛАНДАУ

Воробьевское шоссе, 2. Тел. 137-32-44

4 августа 1977 г.

PROFS.B.MULLER & J.RAFELSKI
INSTITUTE FUR THEORETISCHE PHYSIK
DER JOHANN WOLFGANG GOOTHE UNIVERSITAT
FRANKFURT-AM-MAIN
B R D

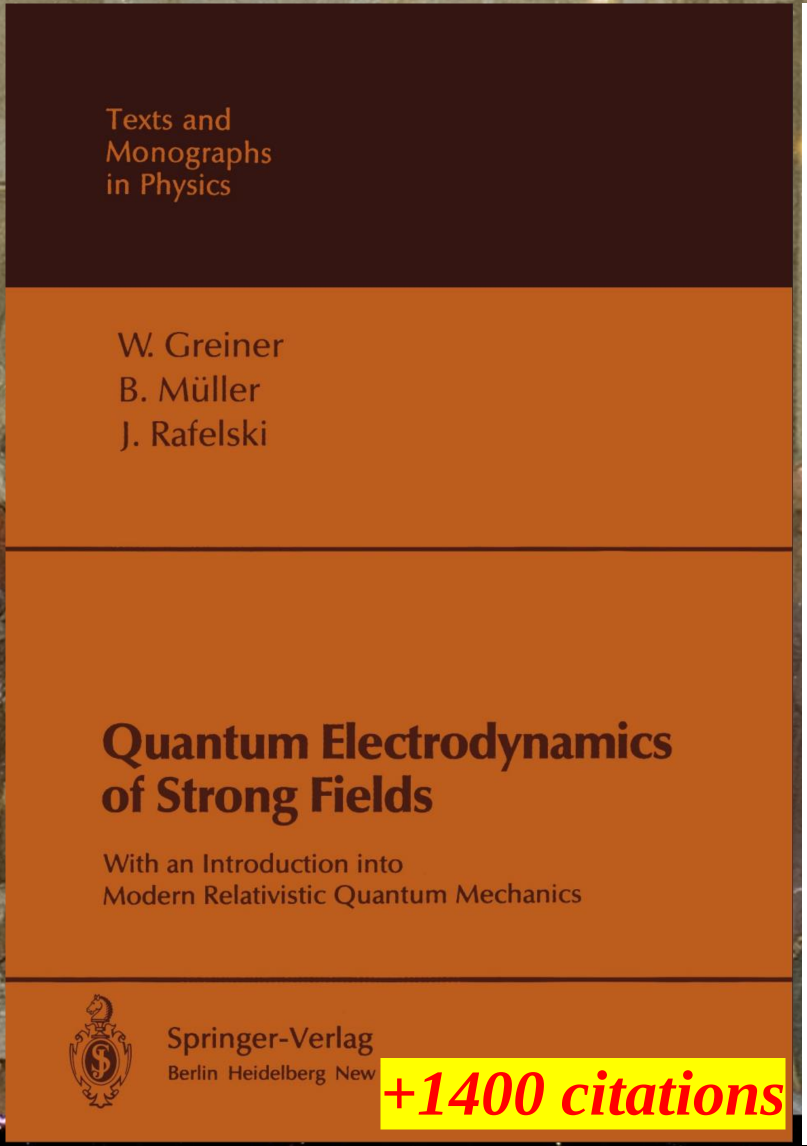
Dear Professors Müller & Rafelski,

Thank you very much for your reprint of the article (Phys.Rev. Lett.,34,349,1975) where you have applied the relativistic Thomas-Fermi equation to the problem of screening supercharged nuclei by vacuum electrons. To our regret, we do not understand how it could have happened that your article has escaped our attention while we were working on this problem. This is the only reasons we have not referred to you in our works (Pisma v ZhETF,24,186,1976; ZhETF, 72,834,1977), devoted to the same problem. That is why we would like to bring our sincere apologies. It goes without saying that our

B. Müller, and J. Rafelski. "Stabilization of the charged vacuum created by very strong electrical fields in nuclear matter." Physical Review Letters 34.6 (1975): 349.

Continuing the Frankfurt School legacy of QED strong field physics

Report of strong fields physics: 1986



+1400 citations

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 perturbation 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.

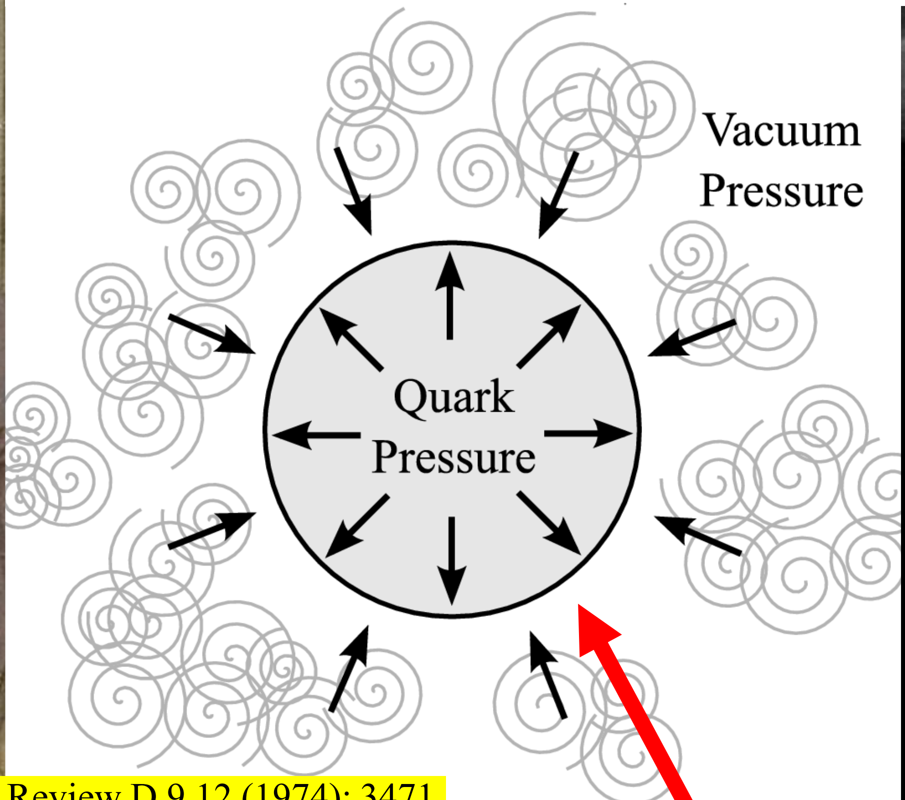
Application of local vacuum structure model to quark confinement inside hadrons: 1974

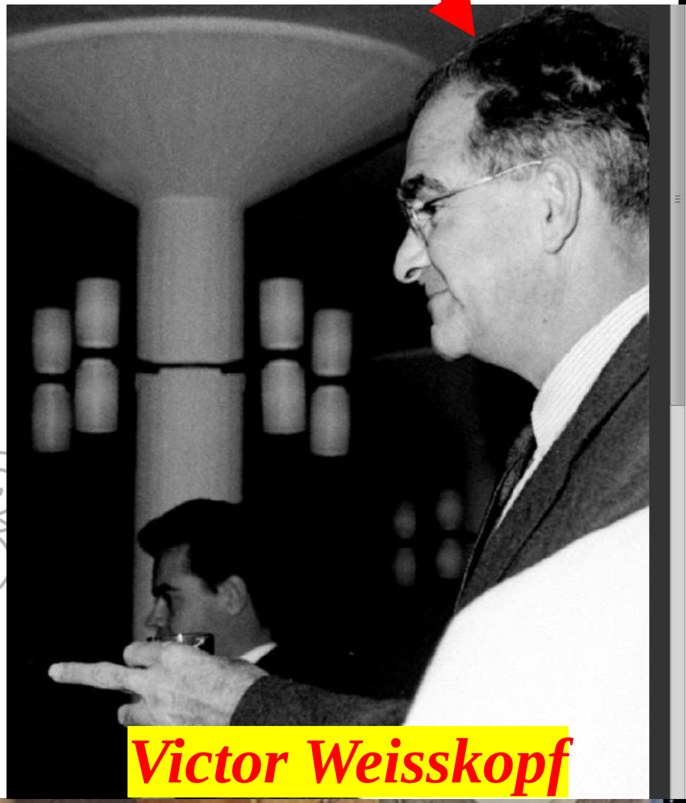
- Quarks live inside a domain where the (perturbative) vacuum is without gluon fluctuations. This outside structure wants to enter but is kept away by the quarks trying to escape: $P_{quark} = B$.
- The inside of the hadron is an excited state where the energy density is $E/V = B$.

PHYSICAL REVIEW D VOLUME 9, NUMBER 12 15 JUNE 1974

New extended model of hadrons*

A. Chodos, R. L. Jaffe, K. Johnson, C. B. Thorn, and V. F. Weisskopf
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 25 March 1974)



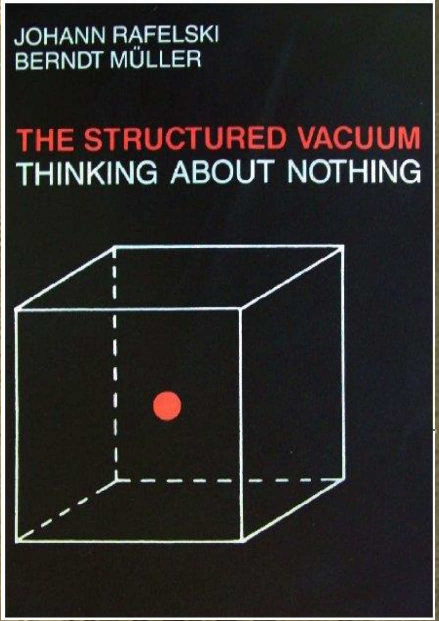


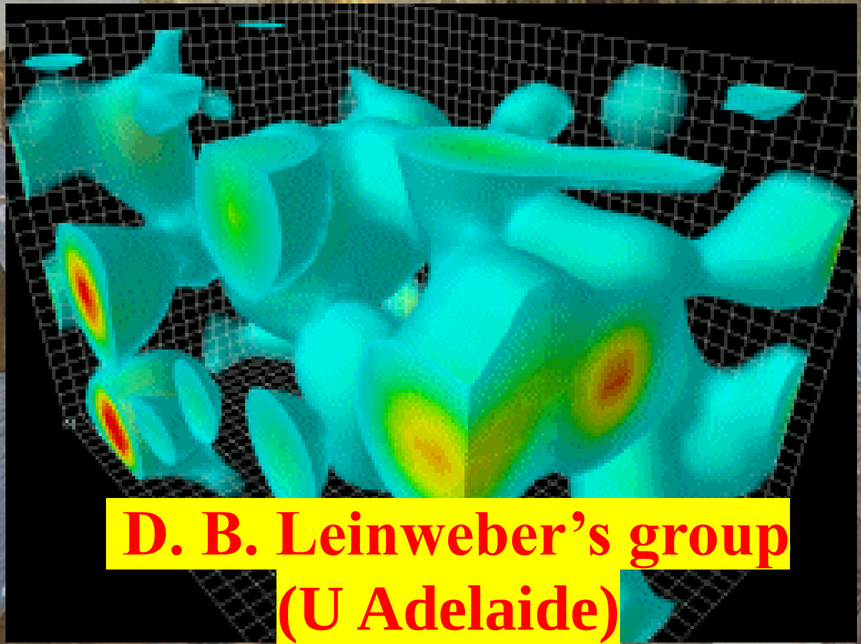
A. Chodos, et al. "New extended model of hadrons." Physical Review D 9.12 (1974): 3471.
V. Weisskopf, "The electrodynamics of the vacuum based on the quantum theory of the electron," Kong. Dan. Vid. Sel. Mat. Fys. Med. 14, N6, 1 (1936).

After fourteen years (1919/1920) Einstein brings back the Aether

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

Second widening of SR scope





D. B. Leinweber’s group (U Adelaide)

Outlook:
Today, the modern understanding of the aether is the **“structured quantum vacuum.”**

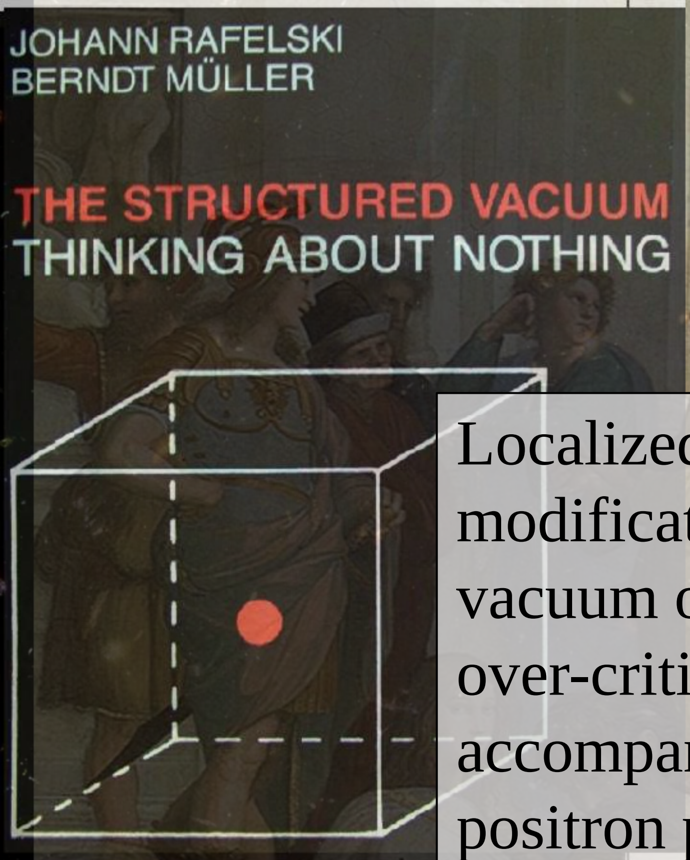
First local vacuum structure model: Strong fields and charged vacuum: 1973

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



Localized modification to the vacuum occurs in over-critical fields accompanied by positron production

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 ...critical fields are extensively discussed in the frame of the self-consistent formulation of QED including the effects of vacuum polarization and self-energy

L. P. Fulcher, J. Rafelski, and A. Klein. "The Decay of the Vacuum." Scientific American 241.6 (1979): 150-159.
J. Rafelski, B. Müller, and W. Greiner. "The charged vacuum in over-critical fields." Nuclear Physics B68.2 (1974): 585-604.

An archeological footprint: Langevin, 1911: Conceptually describes role of acceleration in SR

L' ÉVOLUTION DE L' ESPACE ET DU TEMPS 47

tions de la physique doivent conserver leur forme quand on passe de l'un à l'autre. Pour de tels systèmes tout se passe comme s'ils étaient immobiles par rapport à l'éther: 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

L' ÉVOLUTION DE L' ESPACE ET DU TEMPS 49

aura moins vieilli entre son départ et son retour que si elle n'avait pas subi d'accélérations, que si elle était restée immobile par rapport à un système de référence en translation uniforme.

On peut dire encore qu'il suffit de s'agiter, de subir des accélérations pour vieillir moins vite; nous allons voir dans un instant combien l'on peut espérer gagner de cette manière.

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

"Concluding, we can say it is sufficient to be set in motion, to experience acceleration in order to age less quickly."

- Langevin, Scientia X (1911)

Velocity is "relative," and acceleration is "absolute."

It is impossible to reverse non-inertial with inertial points of view

A few remarks about Planck acceleration

As per Wikipedia, the definition of “true” Planckian acceleration is

$$a_{Pl} = \frac{c^2}{\ell_{Pl}} = 5.55 \times 10^{51}\,\frac{\mathrm{m}}{\mathrm{s}^2} \qquad \ell_{Pl} = \sqrt{\frac{G\hbar}{c^3}} \qquad M_{Pl} = \sqrt{\frac{G\hbar}{c}}$$

However, we define critical acceleration via the Compton wavelength λ_C as

$$a_{cr} = \frac{c^2}{\lambda_C} = m_e c^2 \frac{c}{\hbar}$$

The appearance of mass clarifies that the critical acceleration is related to particle mass. Replacing m_e by the Planck mass M_{Pl} reproduces a_{Pl}. Critical “Planck” acceleration is the same acceleration felt by two particles due to Newtonian gravity at a distance of ℓ_{Pl}.

$$ma = \frac{Gm^2}{\ell_{Pl}^2} \rightarrow a_{cr} = \frac{Gm_e}{\ell_{Pl}^2} = \frac{c^2}{\lambda_C} = 2.33 \times 10^{29}\,\frac{\mathrm{m}}{\mathrm{s}^2}$$

We call study of the critical acceleration a_{cr} domain the **Acceleration Frontier** of which the lowest accessible case is that of the electron.

"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)*

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.

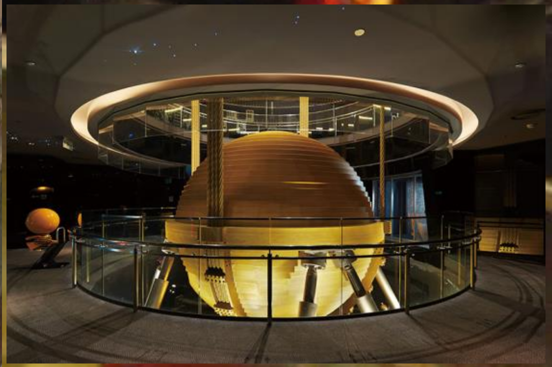
Maybe acceleration is not what we think: Connecting temperature and acceleration
Is there an acceleration?

Strong Fields → ***Temperature*** ← ***Acceleration***

Interpretation of external fields as temperature

Temperature representation of Euler-Heisenberg action in electric-dominated fields.

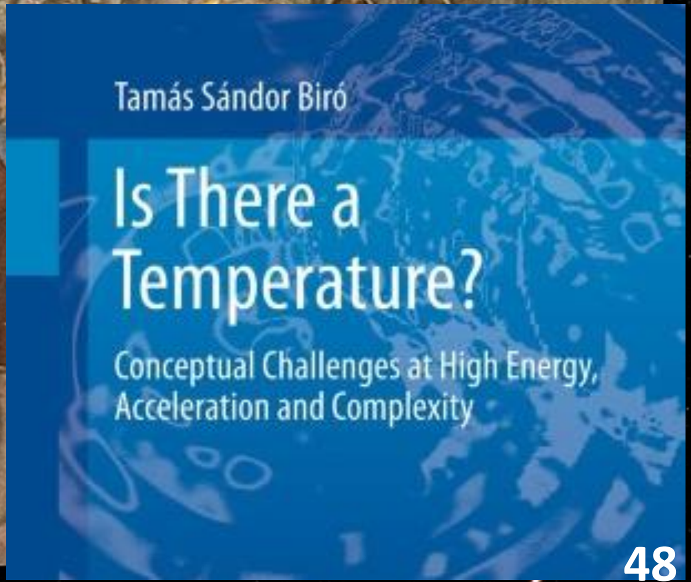
Gravity Swing, Taipei 101, (2012)



W. H. Unruh

Notes on black-hole evaporation

Thermal background (Unruh temperature) experienced by an observer undergoing constant acceleration in a field-free vacuum.



B. Müller, W. Greiner, and J. Rafelski. "Interpretation of external fields as temperature.' Physics Letters A 63.3 (1977)
W. G. Unruh, "Notes on black-hole evaporation." Physical Review D 14.4 (1976)
L. Labun and J. Rafelski, "Acceleration and vacuum temperature." Phys. Rev. D 86, 041701(R) (2012)

Completing EM interactions: Covariant classical radiation reaction

Will Price **_Martin Formanek_**

$$\tau_0 = \frac{2}{3}\frac{e^2}{4\pi\epsilon_0 mc^3}$$

$$P^{\mu\nu} = g^{\mu\nu} - \frac{u^\mu u^\nu}{u^2}$$

Principle models:

$$ma^\mu = \frac{e}{c}F^{\mu\nu}u_\nu + m\tau_0\left(\frac{da^\mu}{d\tau} + \frac{a_\nu a^\nu}{c^2}u^\mu\right)$$

Lorentz-Abraham-Dirac (LAD)

As far as Jackson text goes

$$ma^\mu = \frac{e}{c}F^{\mu\nu}u_\nu + e\tau_0\left(u\cdot\partial F^{\mu\nu}u_\nu + \frac{e}{m}P^{\mu\nu}F_{\nu\alpha}F^{\alpha\beta}u_\beta\right)$$

Landau-Lifshitz (LL)

As far as LL text goes

$$ma^\mu = \frac{e}{c}F^{\mu\nu}u_\nu + \tau_0 P^\mu_\nu \frac{d}{d\tau}\left(\frac{e}{c}F^{\nu\alpha}u_\alpha\right)$$

Eliezer-Ford-O'Connell (EFO)

The Cinderella of RR?

W. Price, M. Formanek, and J. Rafelski. "Radiation reaction and limiting acceleration". PRD 105 (2022)

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

L. D. Landau and E. M. Lifshitz, The Classical Theory of Fields, 2ed, London, England: Pergamon (1962)

S. E. Gralla, A. I. Harte, R. M. Wald. "A Rigorous Derivation of Electromagnetic Self-force." Rev. D80, 024031(2009)

Radiation reaction and limiting acceleration

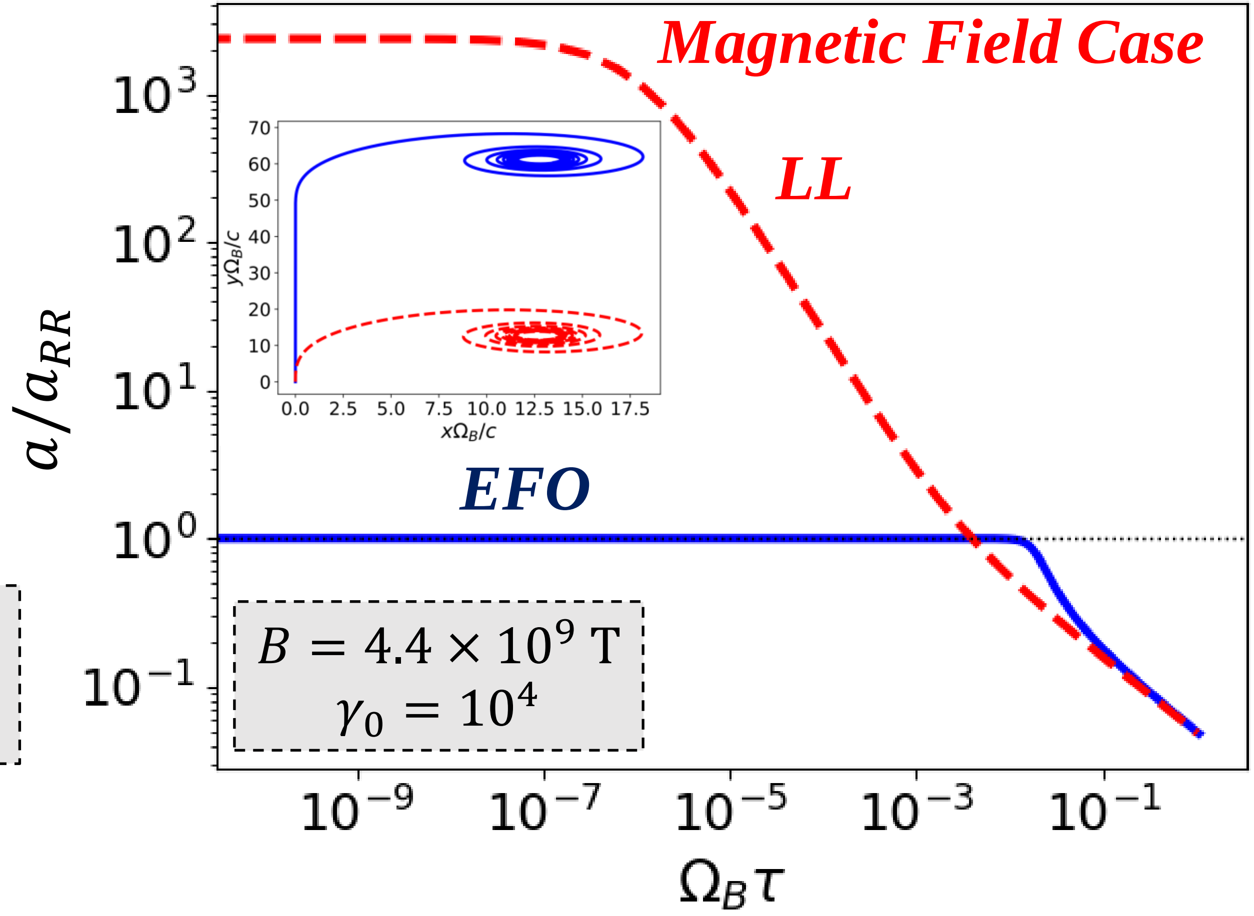
$$\tau_0 = \frac{2}{3}\frac{e^2}{4\pi\epsilon_0 m_e c^3} = 6.27\times 10^{-24}\ \mathrm{s}$$

Eliezer-Ford-O'Connell (EFO) in homogenous fields

$$a^2 = -a_{LF}^2 \frac{1+\tau_0^2 \frac{e^4}{m^4}\frac{c^2\mathcal{P}^2}{|a_{LF}^2|}}{1+\tau_0^2\left(\frac{e^2}{m^2}2\mathcal{S}+\frac{|a_{LF}^2|}{c^2}\right)}$$

$$\lim_{\gamma\to\infty} a^2 \to -\frac{c^2}{\tau_0^2}$$

$$|a_{RR}| = \frac{c}{\tau_0} = \frac{3}{2\alpha}a_{cr}$$



Limiting acceleration: A common feature with **Born-Infeld EM theory**

$$a_{LF}^\mu = \frac{e}{m}F^{\mu\nu}u_\nu \qquad \Omega_B = \frac{eB}{m}$$

W. Price, M. Formanek, and J. Rafelski. "Radiation reaction and limiting acceleration". PRD 105 (2022)
M. Born and L. Infeld. "Foundations of the new field theory." Proc. Roy. Soc. Lond. A 144, no.852, 425 (1934)
I. Birula. "Nonlinear Electrodynamics: Variations On A Theme By Born And Infeld." In: B. Jancewicz, J. Lukierski: Quantum Theory Of Particles and Fields, World Scientific (1983)

Born-Infeld EM theory

Born-Infeld theory is a theory of EM which tries to stabilize electromagnetism by requiring a finite maximum electric field and acceleration. The electric only Lagrangian equation which governs the theory is:

$$\mathcal{L}_{BI} = -\epsilon_0 E_{BI}^2 \left(\sqrt{1 - \frac{\boldsymbol{E}^2}{E_{BI}^2}} - 1 \right) \qquad E_{BI} = 1.187 \times 10^{20}\, \frac{\mathrm{V}}{\mathrm{m}}$$

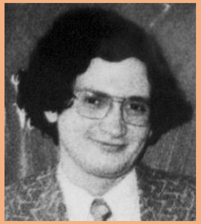
The resulting displacement $\boldsymbol{D}$ and electric fields $\boldsymbol{E}$ are then given by:

$$\boldsymbol{D} = \frac{\partial \mathcal{L}}{\partial \boldsymbol{E}} = \frac{\boldsymbol{E}}{\sqrt{1 - \frac{\boldsymbol{E}^2}{E_{BI}^2}}} \rightarrow \boldsymbol{E} = \frac{\boldsymbol{D}}{\sqrt{1 + \frac{\boldsymbol{D}^2}{E_{BI}^2}}} < \boldsymbol{E}_{BI} \qquad |\boldsymbol{a}| < \frac{eE_{BI}}{m}$$

The displacement diverges to infinity as the electric field approaches the limit E_{BI} and the electric field has an upper bound at that value.

Born, Max. "On the quantum theory of the electromagnetic field." Proc. Royal Soc A 143, 410 (1934)

My 51^{st}_{10} year anniversary of strong fields physics and limiting acceleration publications!



VOLUME 27, NUMBER 14 PHYSICAL REVIEW LETTERS 4 OCTOBER 1971

Superheavy Elements and an Upper Limit to the Electric Field Strength*

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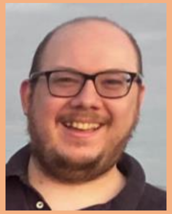
(Received 9 August 1971)

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.

One can also celebrate my 60^{th}_{12} birthday in base 12.

J. Rafelski, L. P. Fulcher, and W. Greiner. "Superheavy elements and an upper limit to the electric field strength." Physical Review Letters 27.14 (1971): 958.



Another Lorentz force incompleteness: Acceleration by torque due to magnetic force

The Thomas-Bargmann-Michel-Telegdi (TBMT) equation is

$$\frac{ds^\alpha}{d\tau} = \frac{e}{m}\left[\frac{g}{2}F^{\alpha\beta}s_\beta + \left(\frac{g}{2} - 1\right)u^\alpha\left(s_\alpha F^{\alpha\beta}u_\beta\right)\right]$$

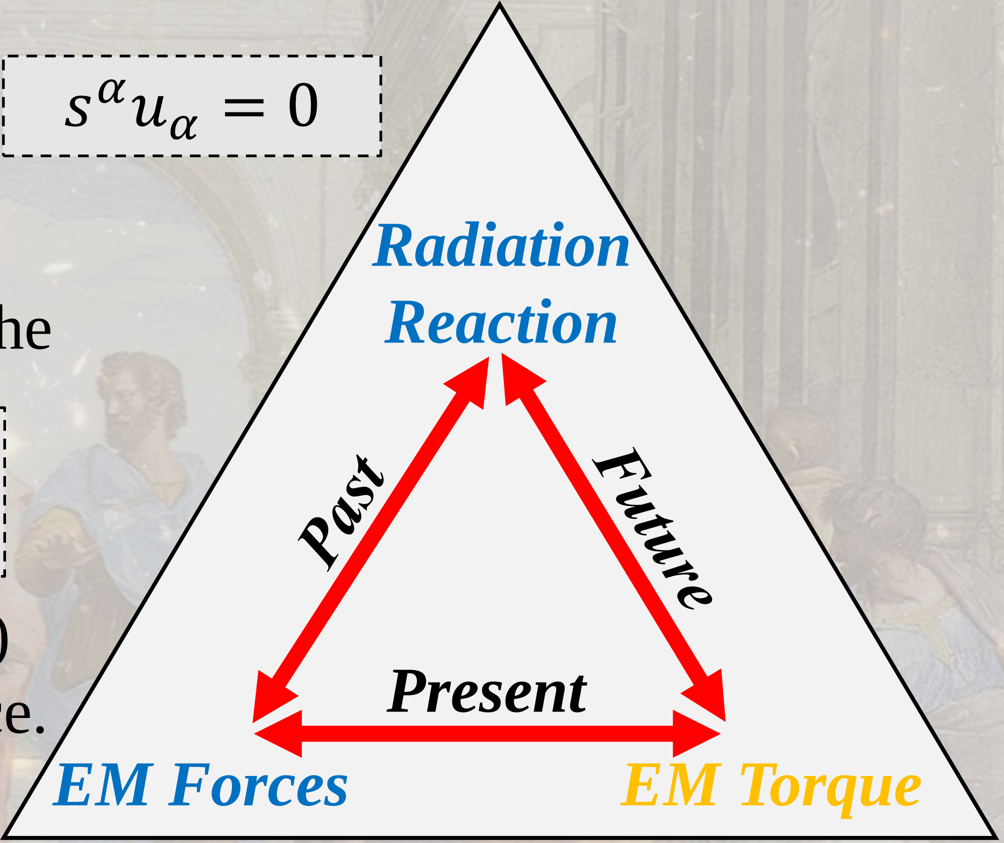
$$s^\alpha u_\alpha = 0$$

This describes the torque experienced by a particle with spin under the influence of homogenous EM fields via the Lorentz force.

$$\frac{du^\alpha}{d\tau} = \frac{e}{m}F^{\alpha\beta}u_\beta$$

This alone does not describe SGF.

a) Inhomogeneous fields where the Stern-Gerlach (SG) magnetic dipole force must be added to Lorentz force.
b) Interplay between dipole forces and torque.
c) Interplay between dipole forces and radiation reaction.



V. Bargmann, L. Michel, and V. L. Telegdi, Phys. Rev. Lett. 2, 435 (1959).
J. Rafelski, M. Formanek, and A. Steinmetz. "Relativistic dynamics of point magnetic moment." EPJC 78.1 (2018): 1-12.
J. Schwinger. "Spin precession - a dynamical discussion." American Journal of Physics 42.6 (1974): 510-513.

More need to complete EM interactions: Unified covariant classical magnetic dipole interaction

Electric energy: $E_{el} = ecA^0$

Magnetic energy: $E_{mag} = d_m c B^0$ → **Magnetic dipole charge** $\boldsymbol{\mu} = (d_m c)\boldsymbol{S}$

A covariant magnetic potential B^μ can be introduced

$$B_\mu \equiv F^*_{\mu\nu} s^\nu = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}F^{\alpha\beta}s^\nu$$

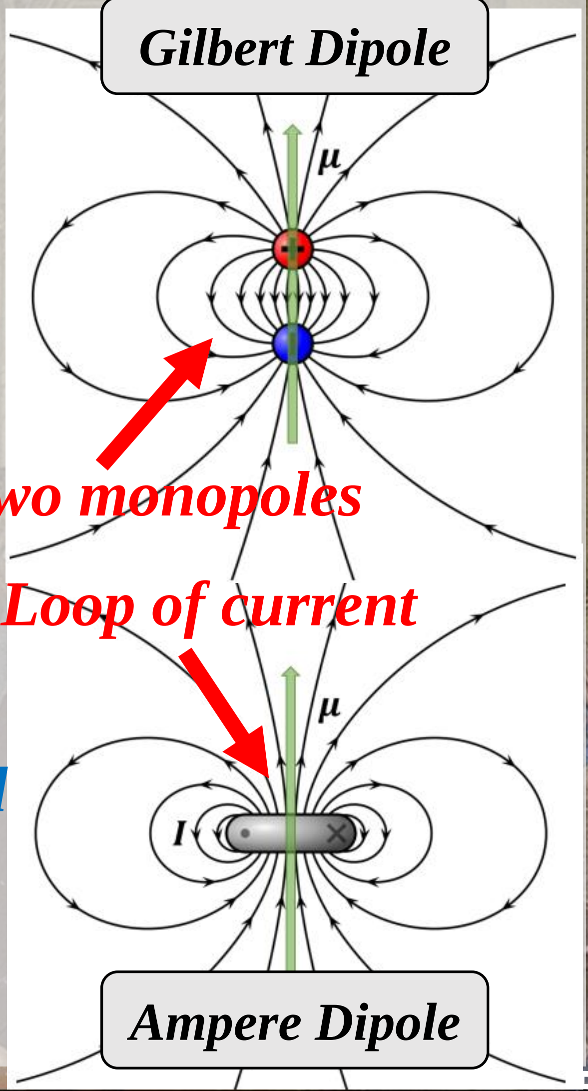
→ **Define a Force Field Tensor**

$$G^{\mu\nu} \equiv \partial^\mu B^\nu - \partial^\nu B^\mu$$

Point particle classical Lagrangian

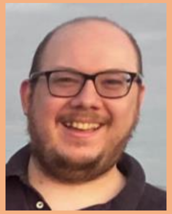
$$L = mc\sqrt{u^2} + eA\cdot u + d_m B\cdot u$$

Covariant description contains both Gilbert and Ampere dipole structure



This formulation incorporates the magnetic moment d_m as an elementary property of particles like charge and mass.

J. Rafelski, M. Formanek, and A. Steinmetz. "Relativistic dynamics of point magnetic moment." EPJC 78.1 (2018): 1-12.

Completing EM interactions: Unified covariant classical magnetic dipole interaction

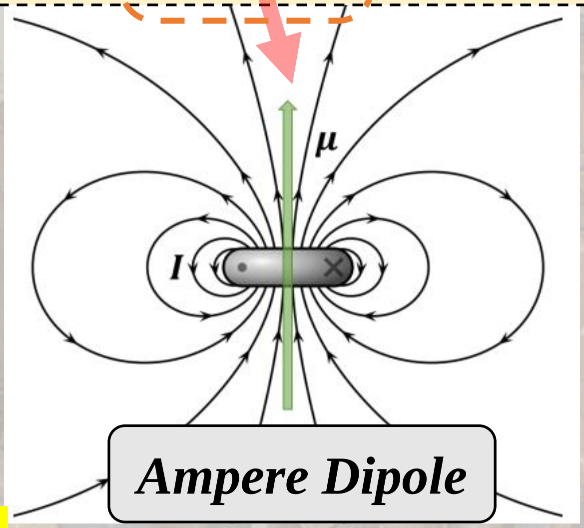
The equations of motion for the above are then

$$\dot{u}^\mu = \frac{e}{m}F^{\mu\nu}u_\nu - \frac{d_m}{m}s\cdot\partial(F^{*\mu\nu})u_\nu - \frac{d_m}{m}\mu_0\epsilon^{\gamma\alpha\beta\mu}j_\gamma u_\alpha s_\beta$$

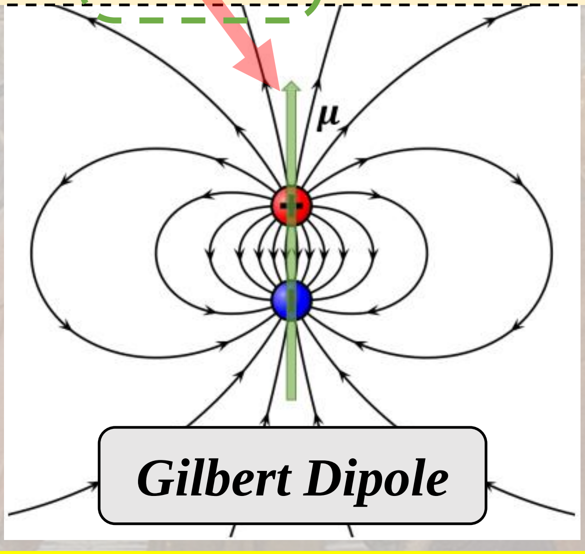
Amazingly, Martin can solve this complex equation exactly for several examples.

Comoving Frame (CF)

$$\boldsymbol{F}\Big|_{\mathrm{CF}} = e\boldsymbol{E} + \boldsymbol{\nabla}(\boldsymbol{\mu}\cdot\boldsymbol{B}) - \boldsymbol{\mu}\times\frac{\partial\boldsymbol{E}}{\partial t} = e\boldsymbol{E} + (\boldsymbol{\mu}\cdot\boldsymbol{\nabla})\boldsymbol{B} + \mu_0\boldsymbol{\mu}\times\boldsymbol{j}$$



OR

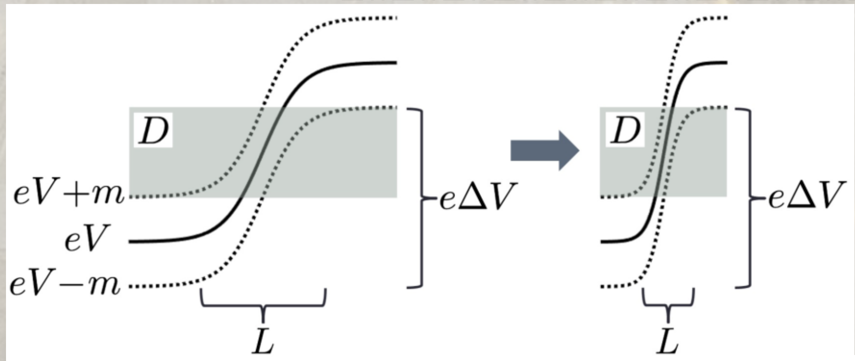


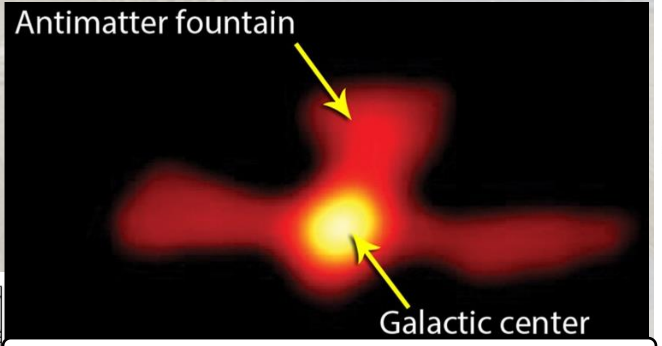
M. Formanek, A. Steinmetz, and J. Rafelski. "Motion of classical charged particles with magnetic moment in external plane-wave electromagnetic fields." Physical Review A 103.5 (2021): 052218.
J. Rafelski, M. Formanek, and A. Steinmetz. "Relativistic dynamics of point magnetic moment." EPJC 78.1 (2018): 1-12.

Sauter potential step

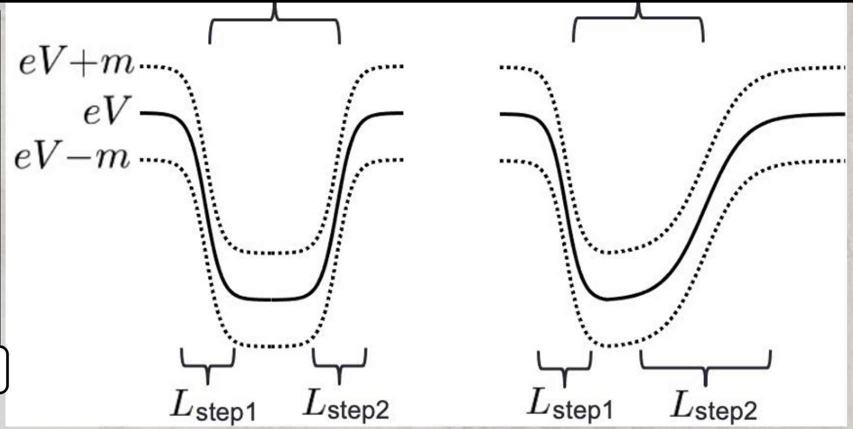
$$V_z = \frac{\mathcal{E}_0 L}{2}\tanh\left[\frac{2z}{L}\right]$$

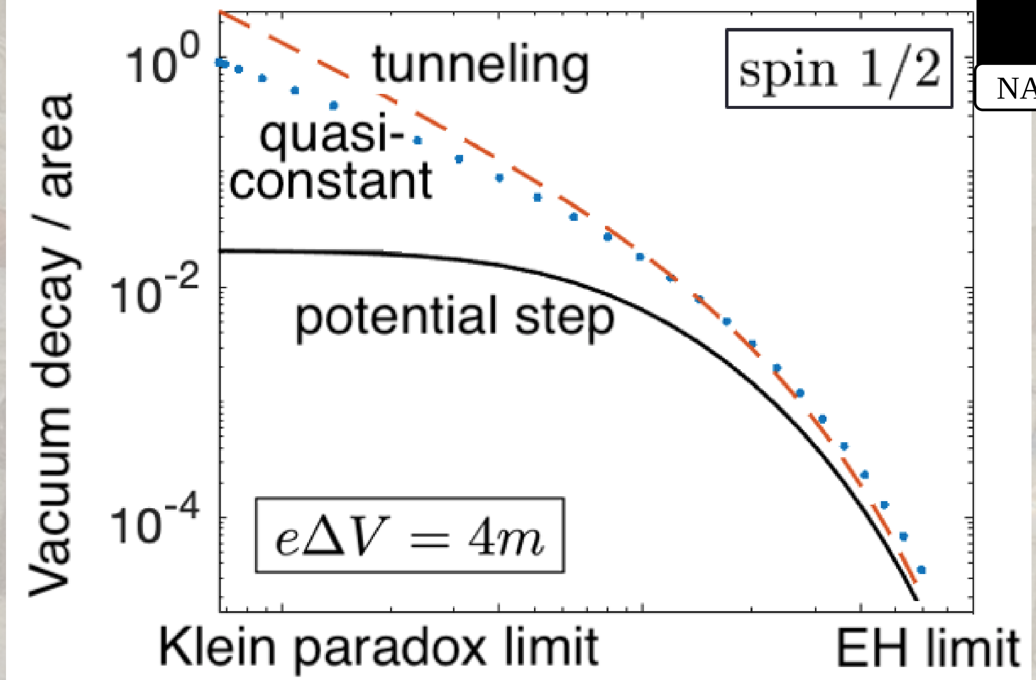
Sauter step surface pair production transition in pair production from Euler-Heisenberg to Klein paradox limit





NASA/W. Purcell, et al. APOD May 1st, 1997.





Step to well

Single potential step or two steps forming a well:

- Finite pair production per unit area versus the diverging rate per volume

Two steps forming a well required for:

- A good definition of vacuum
- Pair production highly sensitive to the shape of the well

F. Sauter, "Zum 'Kleinschen Paradoxon'," Z. Phys. 73 (1932), 547-552 doi:10.1007/BF01349862

S. Evans and J. Rafelski. "Particle production at a finite potential step: Transition from Euler-Heisenberg to Klein paradox." (2022) EPJA 57 (12), 1-10

S. Evans, J. Rafelski, "Emergence of periodic in magnetic moment effective QED action" Physics Letters B, 137190

The intergalactic magnetic field B_{relic} is not strongly constrained at the megaparsec scale:

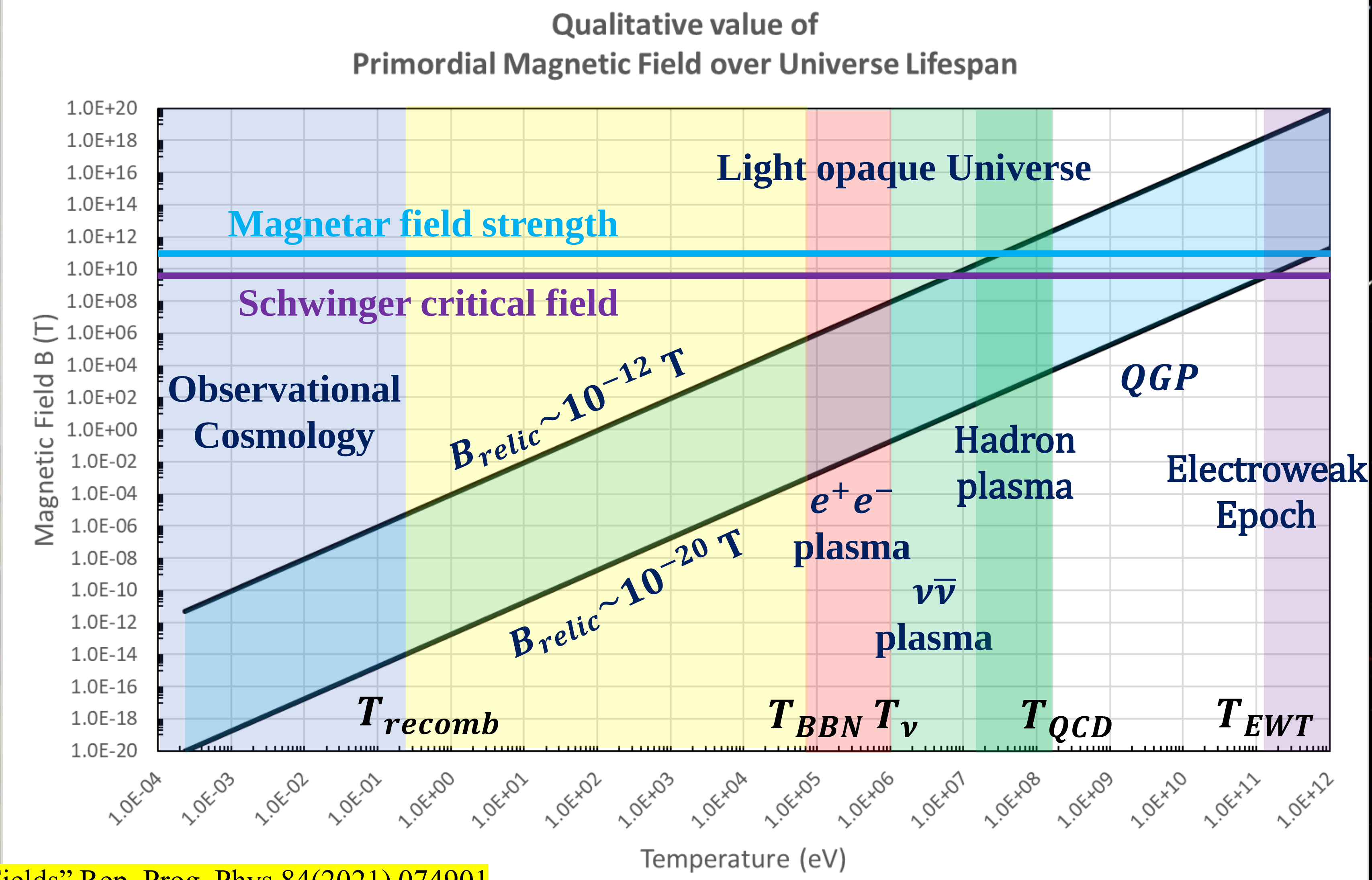
$$10^{-20}\ \mathrm{T} < B_{relic} < 5 \times 10^{-12}\ \mathrm{T}$$

The relic fields likely diluted in the universe's expansion due to the conservation of magnetic flux $\boldsymbol{M}(t) \to 0$

$$\boldsymbol{B}(t) = \boldsymbol{M}(t) + \frac{\boldsymbol{B}_{relic}}{a(t)^2}$$

We expect CP violation to depend on transition magnetic moments in the presence of magnetic fields.

Andrew Steinmetz's work in preparation



T. Vachaspati, "Progress on Cosmological Magnetic Fields" Rep. Prog. Phys.84(2021) 074901
S. Mtchedlidze, et al. "Evolution of primordial magnetic fields during large-scale structure formation." arXiv preprint arXiv:2109.13520 (2021).
K. Subramanian, "The origin, evolution and signatures of primordial magnetic fields." Reports on Progress in Physics 79.7 (2016): 076901.

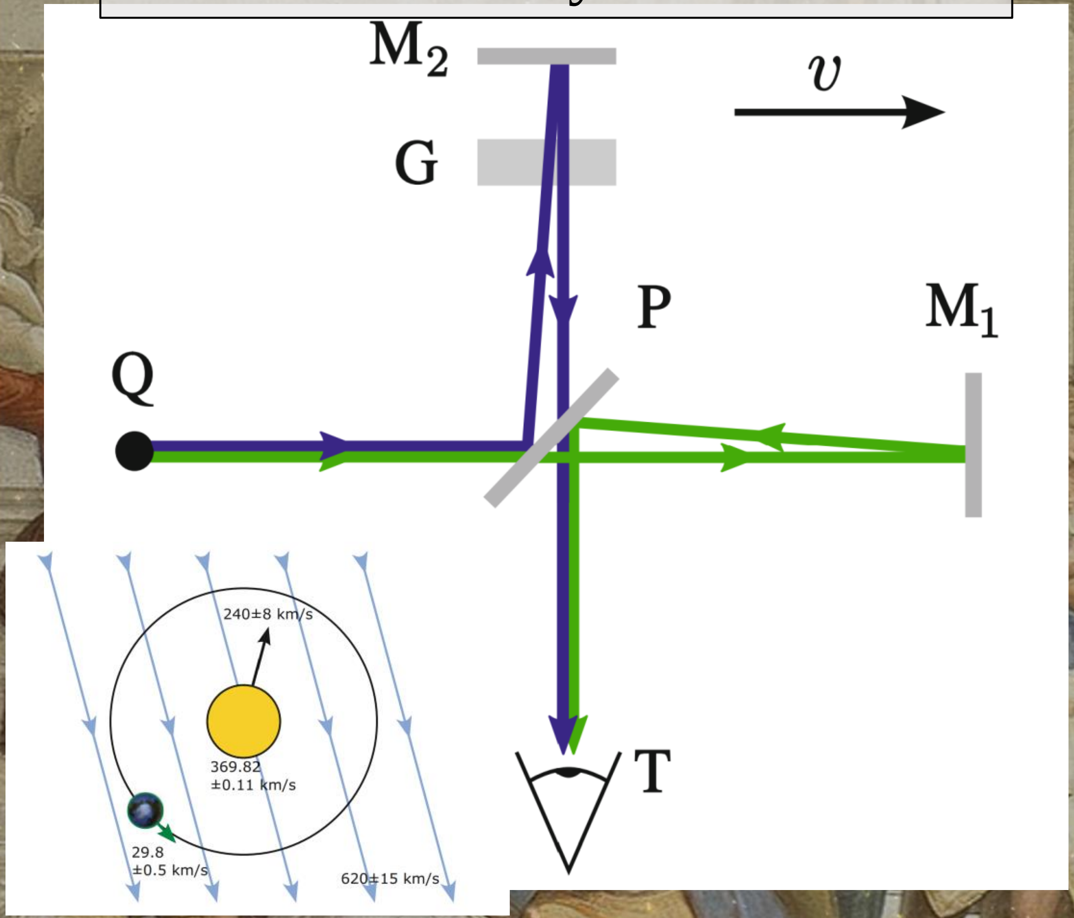
Conclusions

- Special Relativity (SR) is a rich and neglected topic in research and education.
- Even the smallest acceleration accumulates to break 1905 SR which is the basis of elementary texts.
- Strong fields and strong acceleration are theoretically incomplete. EM with acceleration and/or spin is in process of being improved.
- Strong field physics: Pair production and changes to vacuum structure.
- This lecture demonstrates the huge research opportunities in understanding how acceleration enters every aspect of physical law.

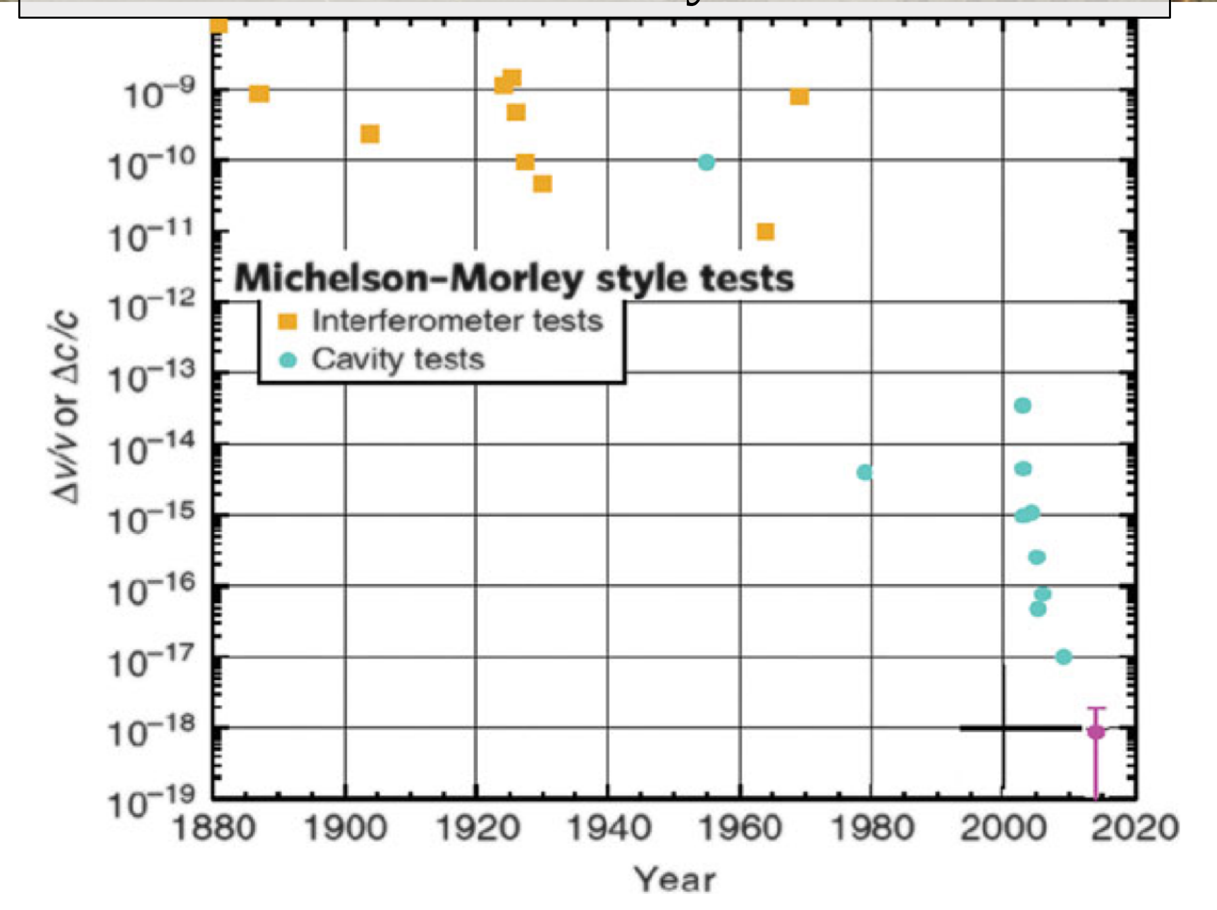
We call this the acceleration frontier.

Maxwell poses the question: Is there a (material) aether? Michelson-Morley (end of 19th century) experiment says no.

Michelson-Morley Interferometer



No evidence for a velocity-sensitive aether.



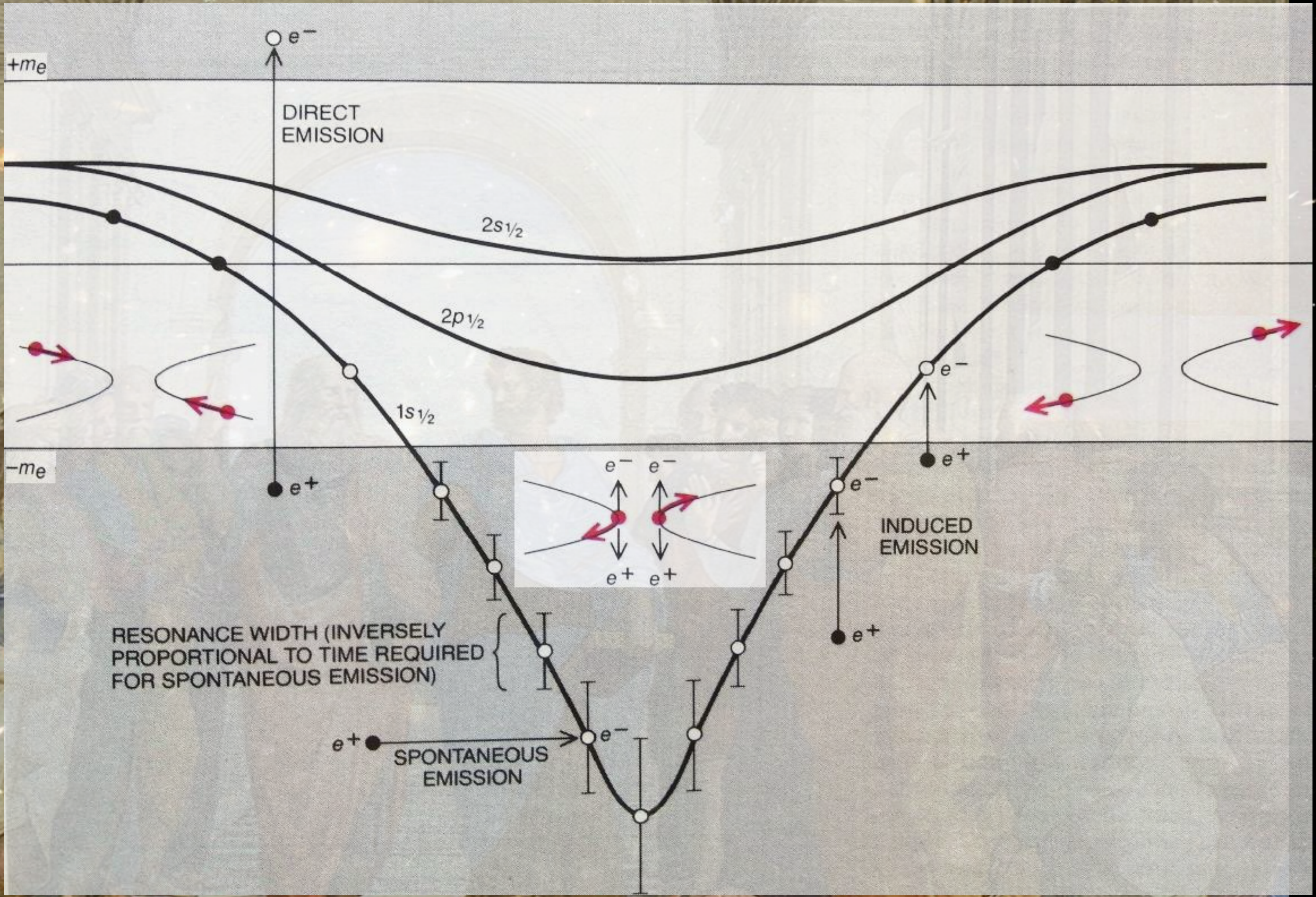
Vacuum instability and strong fields in heavy ion collisions
Multitude of possible dynamical processes

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, 7, 8]. In consequence the group discussions turned to exploring the opposite, the critical field instability and the idea of spontaneous positron emission emerged.



J. Rafelski, et al. "Probing QED vacuum with heavy ions." New horizons in fundamental physics. Springer, Cham, 2017. 211-251.