Title: On the Observability of the Unruh Effect

Date: Aug 14, 2015 11:30 AM

URL: http://pirsa.org/15080034

Abstract: This year marks the 40â€™th anniversary of the Unruh effect as described at the first Marcel Grossmann meeting in 1975. We revisit it with emphasis on the observability issue which might be a concern at first sight, since the linear acceleration needed to reach a temperature 1 K is of order 10^20 m/s^2 . We close the talk by emphasizing that the Unruh effect does not require any verification beyond that of relativistic free field theory itself. The Unruh effect lives among us.

On the observability of the Unruh effect

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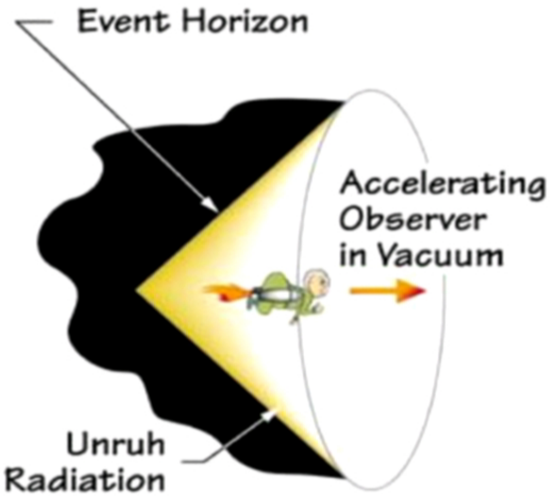
The Unruh effect in a nutshell

Uniformly accelerating observers in Minkowski vacuum experience a thermal bath of elementary particles at a temperature proportional to their proper acceleration.



Stanford Linear Accelerator Center courtesy

Chronology

- (November/1972) Steve Fulling (U.W. - Milwaukee) submits "Nonuniqueness canonical field quantization in Riemaninan space- time", Phys. Rev. D, **7**, 2850 (1973).
  - p. 2854: gives the Bogoliubov coefficient $V(i,j)$ ("β_{ij}") relating Minkowski and Rindler vacua and states that it does not vanish: *"The notion of particle is completely different in the two theories".*

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- **(August/1974) Paul Davies** (King's College - UK) submits "Scalar particle production in Schwarzschild and Rindler metrics", J. Phys. A: Math. Gen., **8**, 609 (1975).
  - p. 614: *"to such an (accelerated) observer the wall surface would appear to have a temperature of* **acceleration/2π**... *The apparent production of particles is somewhat paradoxical, because there is no obvious source of energy for such a production".*

PROCEEDINGS OF THE FIRST

MARCEL GROSSMANN MEETING ON GENERAL RELATIVITY

organized and held at the

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS, TRIESTE

and

ISTITUTO DI FISICA TEORICA, UNIVERSITY OF TRIESTE

7-12 July 1975

ok

Edited by

REMO RUFFINI

Department of Physics
University of Rome

N·H
P·C

1977

NORTH-HOLLAND PUBLISHING COMPANY
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Contents

Probably, July 11th (Friday)

Proceedings of the 1st Marcel Grossmann meeting on G.R published in 1977

Chronology

- (June/1981) Geoffrey Sewell (Q. Mary College - UK) submits "Quantum fields on manifolds: PCT and gravitationally induced thermal states", Ann. Phys. **141,** 201 (1982).
  - p. 204: *"for uniformly accelerated observers, ... the Bisognano-Wichmann theorem implies the Unruh effect". [Bisognano and Wichmann, J. Math Phys. **17**, 303 (1976).]*

Nontrivial & Nonintuitive

R. Feynman last blackboard – May/1988

Interestingly, 40 years later, there is still much confusion about what the Unruh effect is (and is not).

The observability issue

- Bell and Leinaas pioneered the attempt to explain experimental data in terms of the Unruh effect, namely, the depolarization of e^- s in storage rings, with partial success; *recall that the Unruh effect was derived for linearly accelerated observers.* J. Bell and J. Leinaas, *Electrons as accelerated thermometers*, NPB **212**, 131 (1983).

The observability issue

ALTHOUGH

"Direct" experimental confirmation is difficult because the linear acceleration needed to reach a temperature of $1\ K$ is of order $10^{20}\ m/s^2$. (Sprinters do not sweat because of the Unruh effect.)

IT HAPPENS THAT

The Unruh effect does not require any verification beyond that of free QFT itself.

Accelerated proton decay in Minkowski vacuum

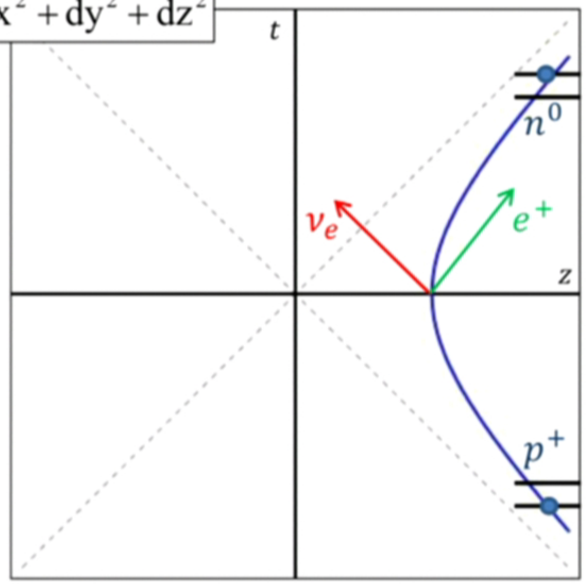
$$p^+ \xrightarrow{\ a\ } n^0$$

- R. Muller, *Decay of accelerated particles*, Phys. Rev. D **56**, 953 (1997).

- D. Vanzella and GEAM, *Decay of accelerated protons and the existence of the Fulling-Davies-Unruh effect*, Phys. Rev. Lett. **87**, 151301 (2001).

Inertial observer calculation

$$ds^2 = -dt^2 + dx^2 + dy^2 + dz^2$$



Baryon fields: $\hat{j}^\mu$

Lepton fields: $\hat{\psi}(t,x,y,z) = \sum_{\sigma=\pm} \int d^3k \left[\hat{a}_{\vec{k}\sigma} \psi^{(+\omega)}_{\vec{k}\sigma} + \hat{c}^*_{\vec{k}\sigma} \psi^{(-\omega)}_{-\vec{k}-\sigma} \right]$

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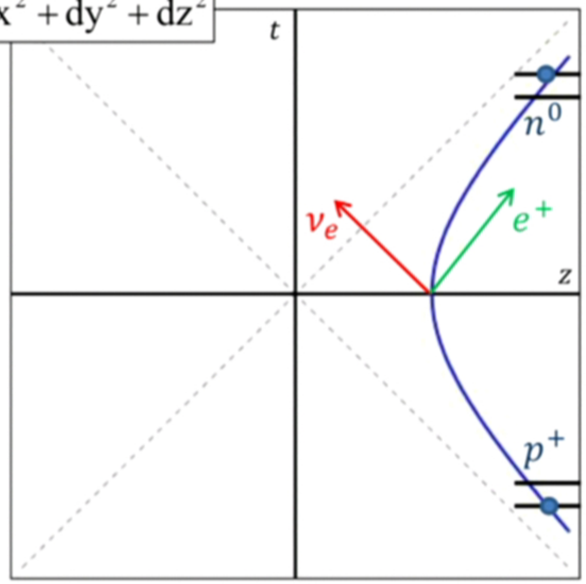

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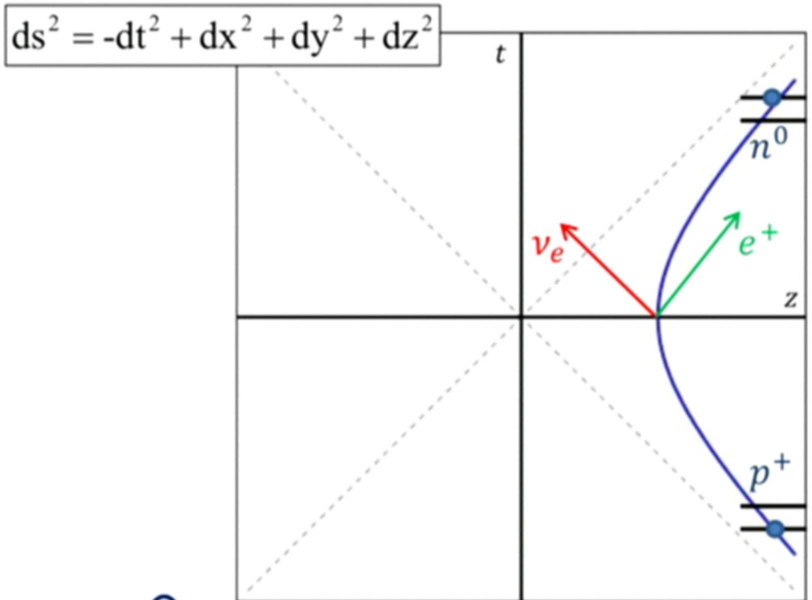

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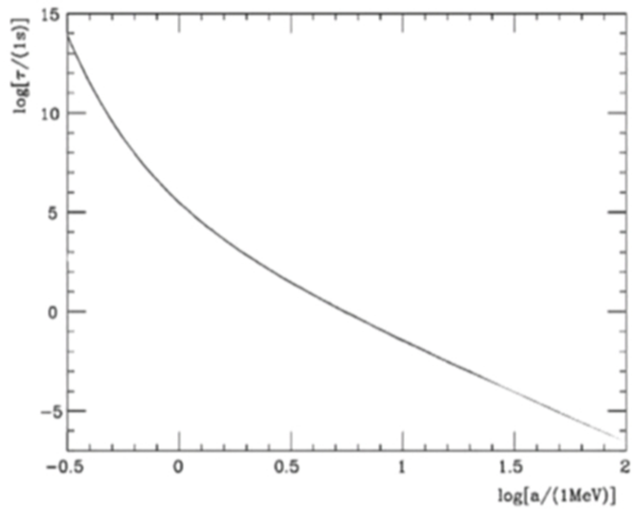
Inertial observer (tree-level) calculation



$$\tau^{p^+ \xrightarrow{a} n^0} = \left[\frac{G_F{}^2 m_e^3 a^2}{16\pi^{7/2} e^{\pi \Delta M / a}} G_{24}^{40}\left(\frac{m_e^2}{a^2} \middle| \begin{matrix} 3/2 & 2 & & \\ 1/2 & -3/2 & 3/2 + i\Delta M / a & 3/2 - i\Delta M / a \end{matrix} \right) \right]^{-1}$$

$$\mathrm{c_v} = c_a = 1, \quad G_F = 1.7\times 10^{-5}\ GeV^{-2}, \quad \Delta M \equiv m_n - m_p = 1.3\ MeV, \quad m_e = 0.5\ MeV, \quad m_\nu = 0$$

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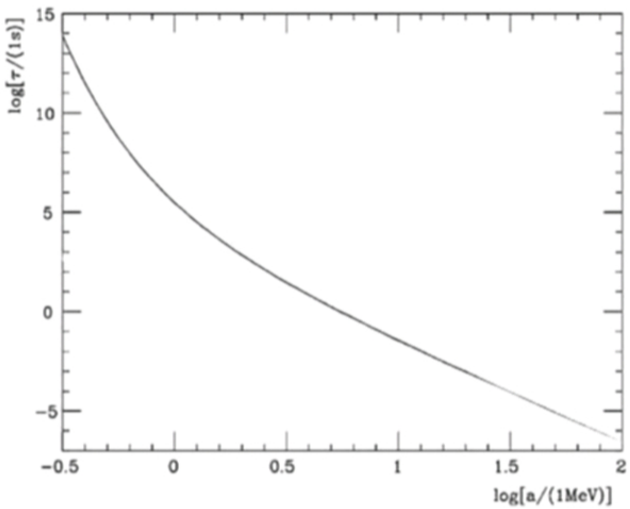

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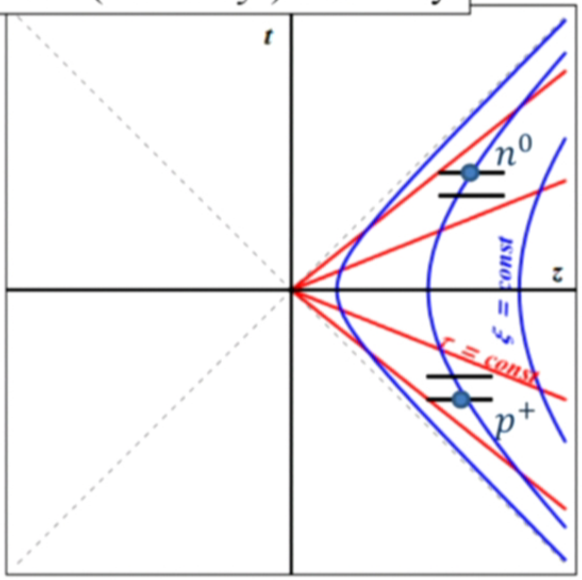
Rindler observer calculation

$$ds^2 = e^{2a\xi}(-d\tau^2 + d\xi^2) + dx^2 + dy^2$$



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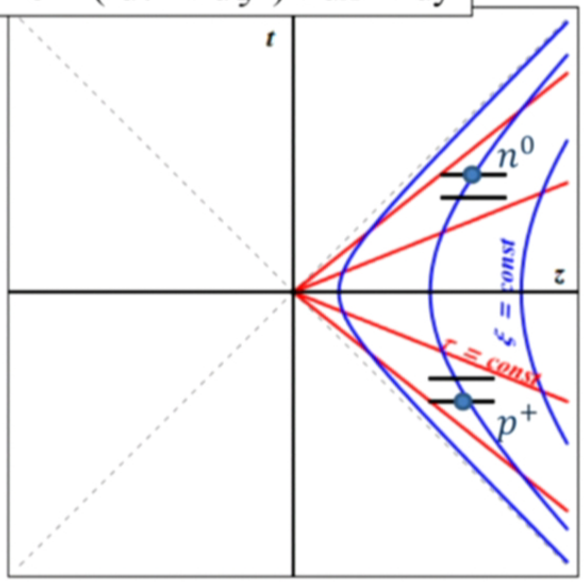

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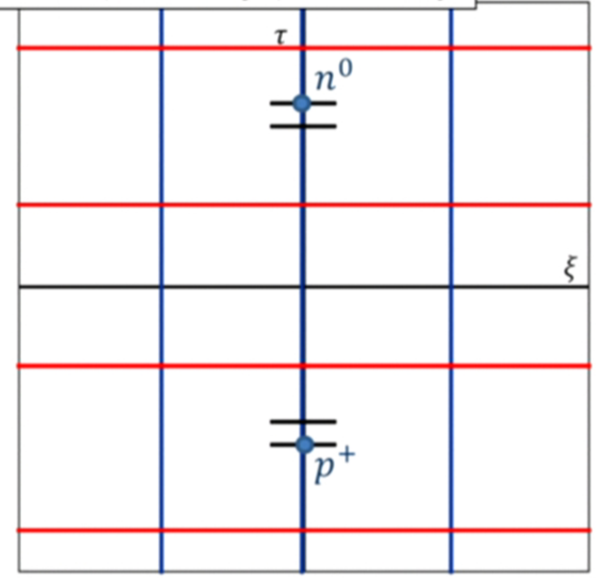

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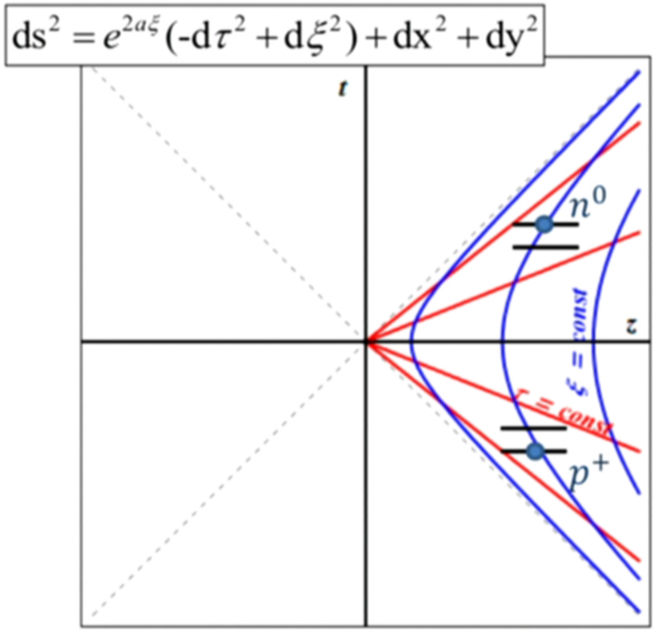

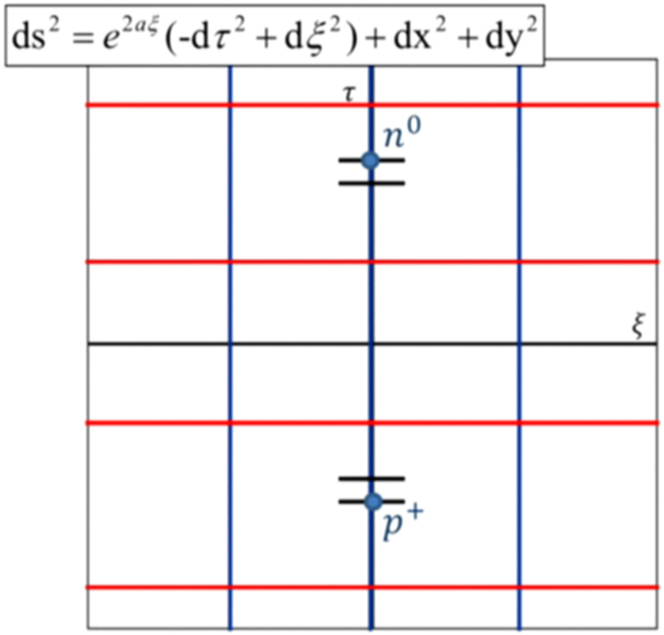

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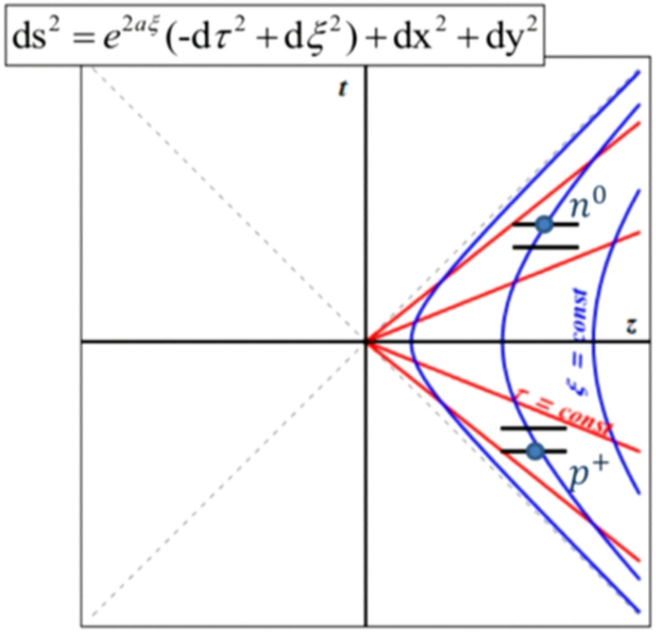

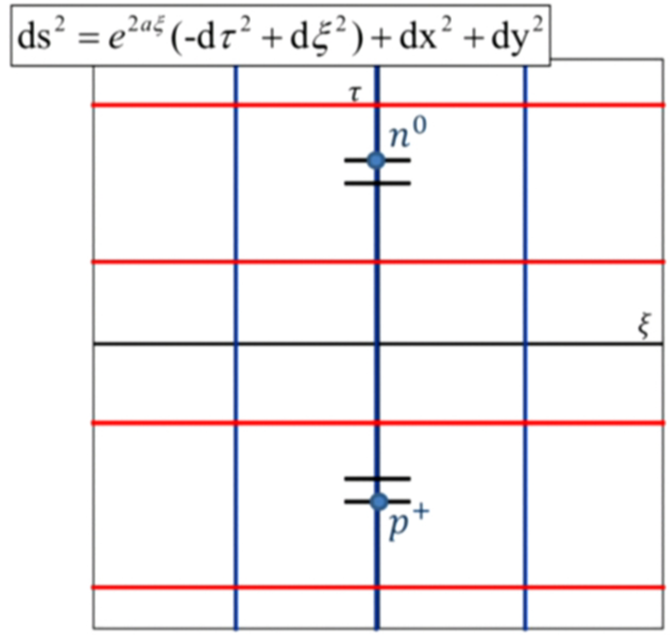

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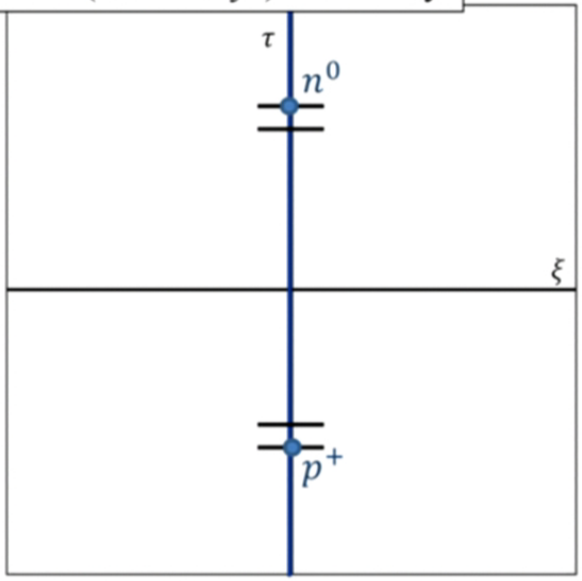
- Rindler observers follow timelike isometries.

- Because energy is conserved for Rindler observers, p^+ s cannot decay through $p^+ \rightarrow n^0 e^+ \nu_e$ according to them.

- If the inertial vacuum were equivalent to the Rindler vacuum, Rindler observers would conclude that accelerated $p^+ s$ would not decay, which would be in disagreement with our inertial observer calculation.



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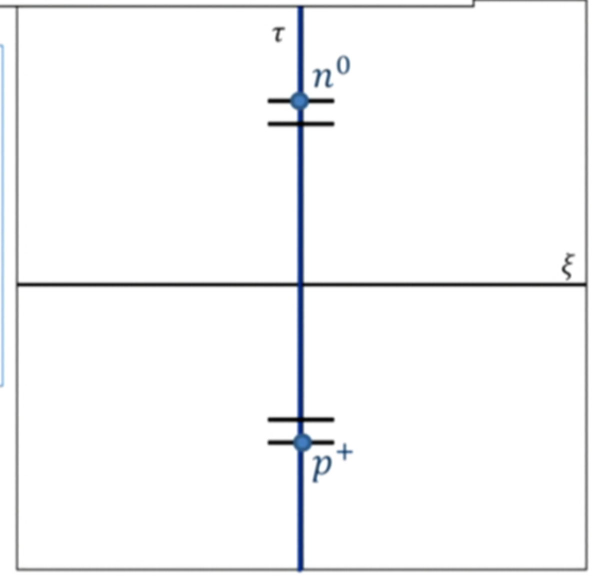

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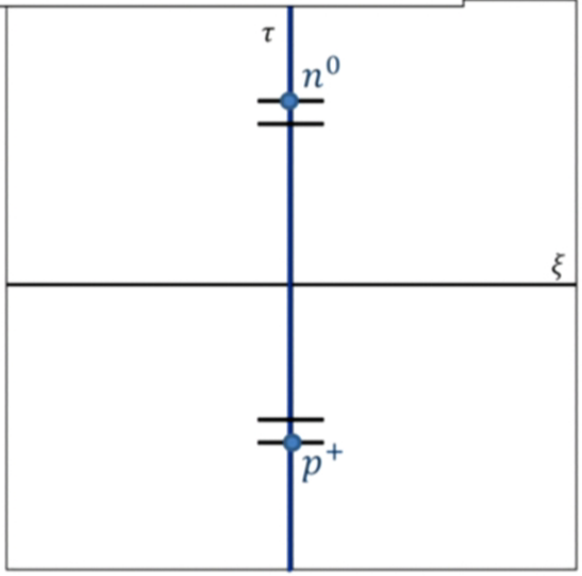

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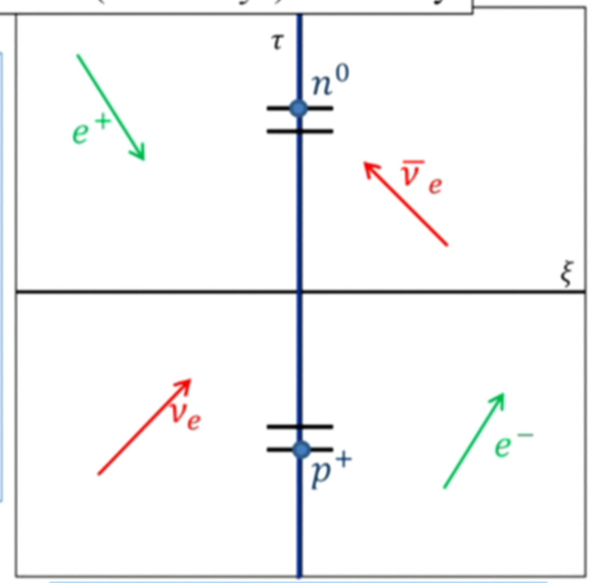
- **The Unruh effect will be necessary to make inertial and uniformly accelerated observers description consistent with each other.**



Unruh thermal bath of $e^-, e^+, \nu_e, \bar{\nu}_e$

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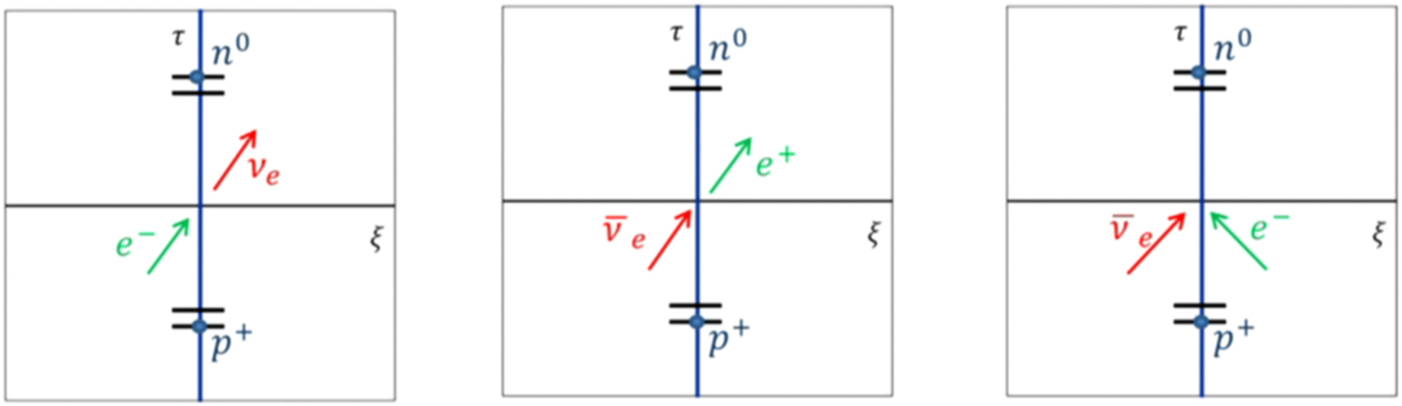

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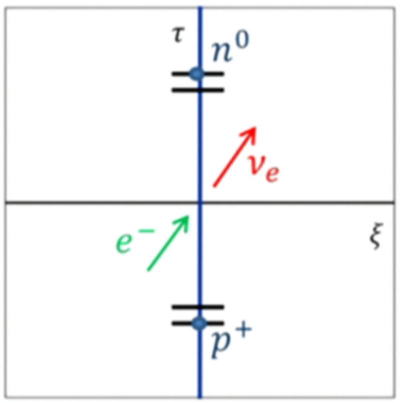

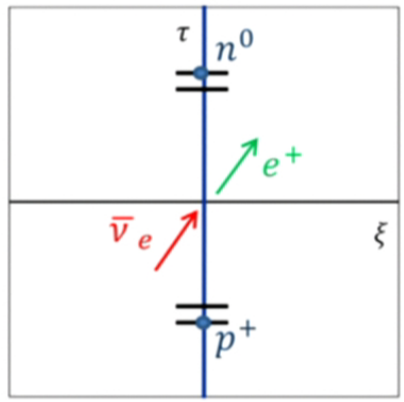

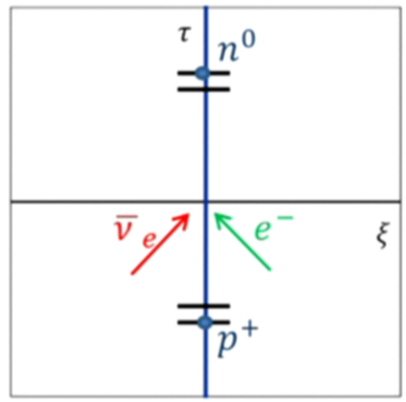

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Weak interaction effective action: $\hat{S}_I=\int dx^4\sqrt{-g}\,\hat{j}_{\mu}\left[\hat{\bar{\psi}}_e\,\gamma^{\mu}\left(c_v-c_a\gamma^5\right)\hat{\psi}_{\nu}+H.c.\right]$

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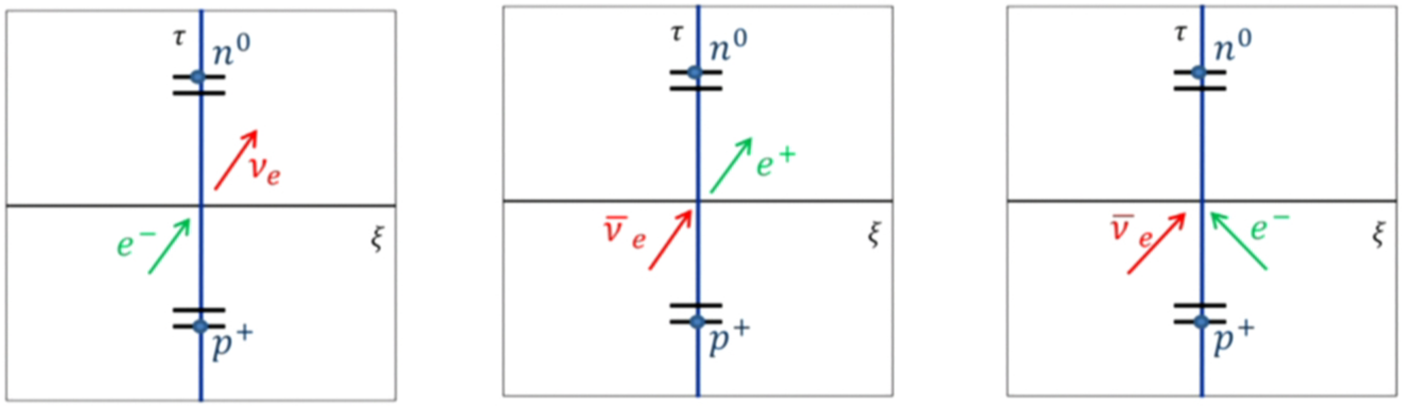

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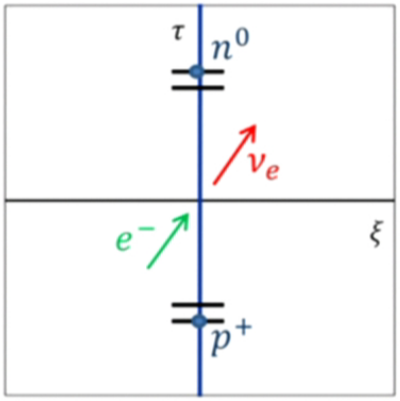
Rindler observer (tree-level) calculation



Decay amplitude

$$A_{ac}^{p^+e^- \xrightarrow{a} n^0 \nu_e} \equiv \left\langle n^0 \nu_{\varpi k_\perp \sigma_\nu} \left| \hat{S}_I \right| p^+ e^-_{\varpi k_\perp \sigma_e} \right\rangle$$

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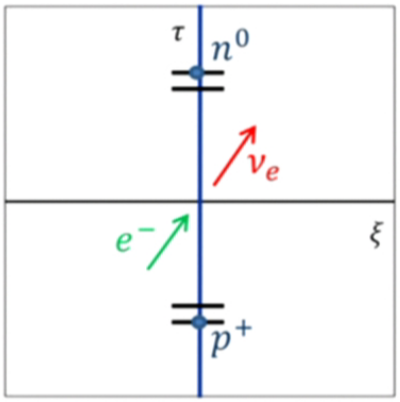

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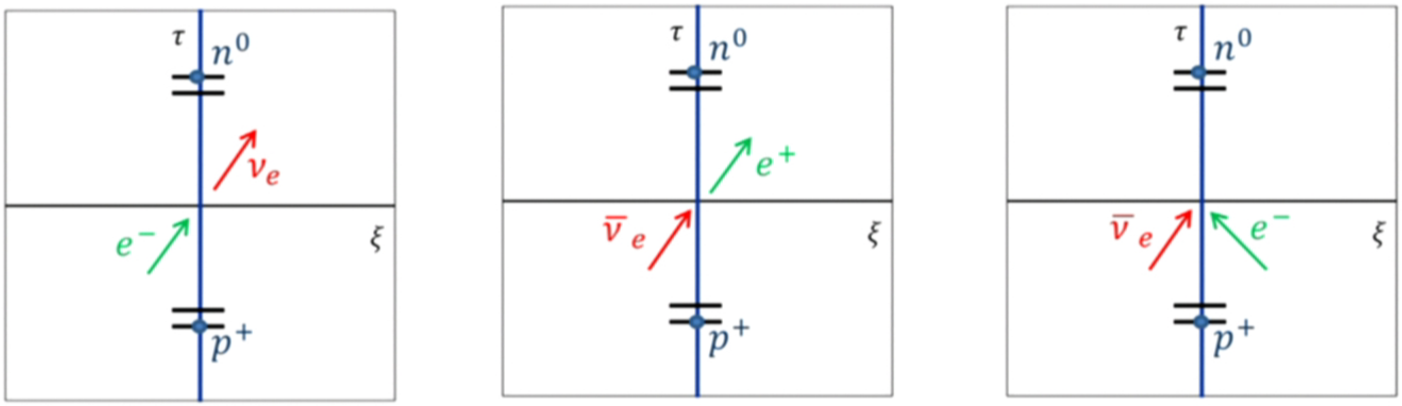
Spectral distribution

$$\frac{d\Gamma_{ac}^{p^+e^- \xrightarrow{T_U} n^0\nu_e}}{d^2k_{\perp e} d^2k_{\perp \nu}} = \frac{d}{d\tau} \sum_{\sigma_e \sigma_\nu} \int_0^{+\infty} d\varpi_e \int_0^{+\infty} d\varpi_\nu \left| A_{ac}^{p^+e^- \to n^0\nu_e} \right|^2 n_F(\varpi_e) [1 - n_F(\varpi_\nu)]$$

$$n_F(\varpi) \equiv \frac{1}{1 + e^{\varpi / T_U}}$$

Rindler observer (tree-level) calculation

Analogously…



$\Gamma_{ac}^{p^+e^- \xrightarrow{T_U} n^0\nu_e}$ $\Gamma_{ac}^{p^+\bar{\nu}_e \xrightarrow{T_U} n^0e^+}$ $\Gamma_{ac}^{p^+e^-\bar{\nu}_e \xrightarrow{T_U} n^0}$

Dominant for $T_U \gg m_n - m_p + m_e$

Dominant for $T_U \ll m_n - m_p + m_e$

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Rindler observer (tree-level) calculation

$$\text{Proton mean proper lifetime}: \quad \tau^{p^+ \xrightarrow{T_U} n^0} = \left[\Gamma_{ac}^{p^+ e^- \xrightarrow{T_U} n^0 \nu_e} + \Gamma_{ac}^{p^+ \bar{\nu}_e \xrightarrow{T_U} n^0 e^+} + \Gamma_{ac}^{p^+ e^- \bar{\nu}_e \xrightarrow{T_U} n^0} \right]^{-1}$$

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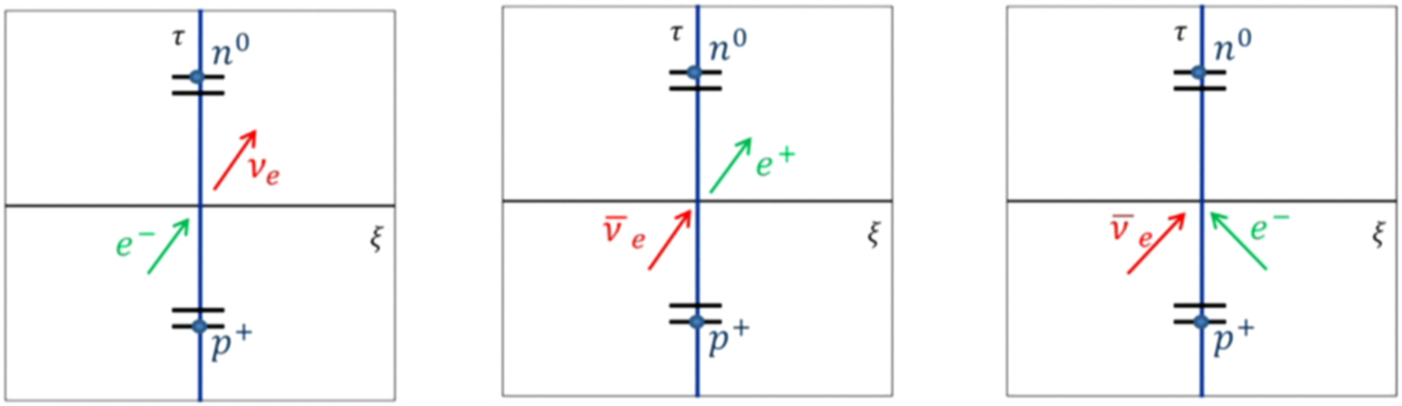
Identical to the inertial observer result

- D. Vanzella and GEAM “Decay of accelerated protons and the existence of the Fulling-Davies-Unruh effect”, Phys. Rev. Lett. **87**, 151301 (2001), H. Suzuki and K Yamada “Analytic evaluation of the decay rate for an accelerated proton”, Phys. Rev. D 6**7**, 065002 (2003).

Rindler observer calculation



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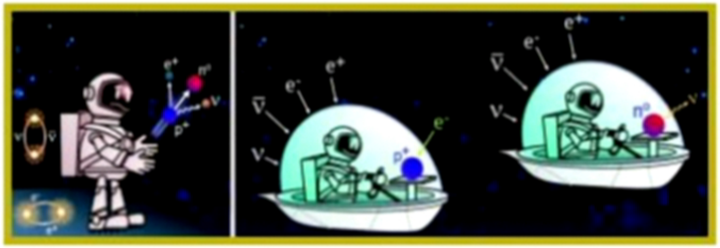
The Unruh effect as an "inertial force"

Inertial observer description

$$p^+ \xrightarrow{a} n^0 + e^+ + \nu$$

Ciência Hoje Courtesy



$$p^+ + e^- \xrightarrow{T_U} n^0 + \nu_e$$
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Uniformly accelerated observer description

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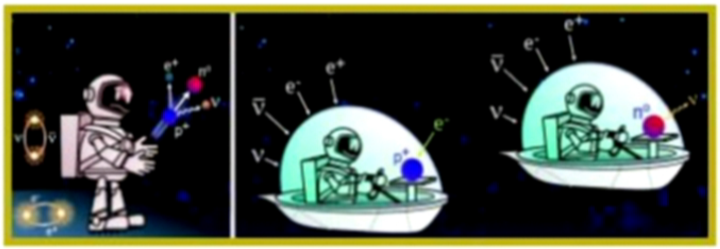

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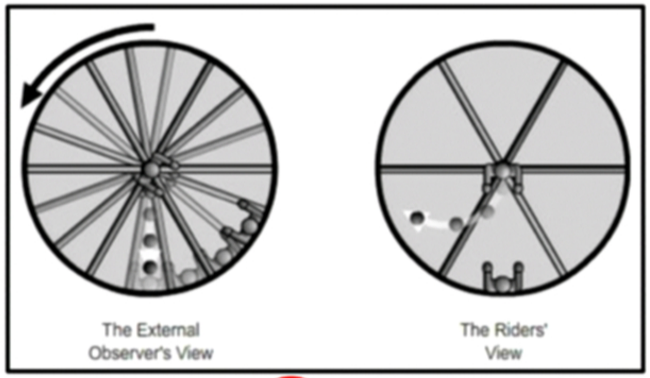
Inertial observer description

$$\vec{F}_{in} = m\vec{a}, \quad \vec{\Omega} = \text{const}$$



$$\vec{F}_{cir} = m\vec{a} + \vec{F}_{fict}$$
$$\vec{F}_{fict} = -2m\vec{\Omega} \times \vec{v}' - m\vec{\Omega} \times \left(\vec{\Omega} \times \vec{r}'\right)$$

Circularly moving observer description

$$\vec{r} = \vec{r}\left(\vec{v}_0, \vec{\Omega}\right)$$

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The Unruh effect in laboratory

The fact that the Unruh effect is a necessity to free QFT, does not make the search for lab phenomena which may be explained more "naturally" w.r.t. Rindler observers in terms of the Unruh effect less interesting . **This is not trivial:**

- p^+s at LHC have $\mathrm{a_{LHC}} \approx 10^{-9}\ MeV \ll m_n - m_p + m_e \approx 1.8\ MeV \to \tau^{p\to n} \ggg \tau_{Univ}$. D. Vanzella and GEAM, *Weak decay of uniformly accelerated protons and related processes*, PRD **63**, 014010 (2001).

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- The analogous process $e^- \to \mu^-$ may be observable in IceCube. M. Lynch, *Electron decay at icecube*, arXiv:1505.04832 (2015).

Reviews

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- I. Peña and D. Sudarsky, *On the possibility of measuring the Unruh effect*. Found. Phys. **44,** 689 (2014).
- L. Crispino, A. Higuchi, G.E.A.M, Rev. Mod. Phys. **80**, 787 (2008).

The Unruh effect in ultra-intense lasers

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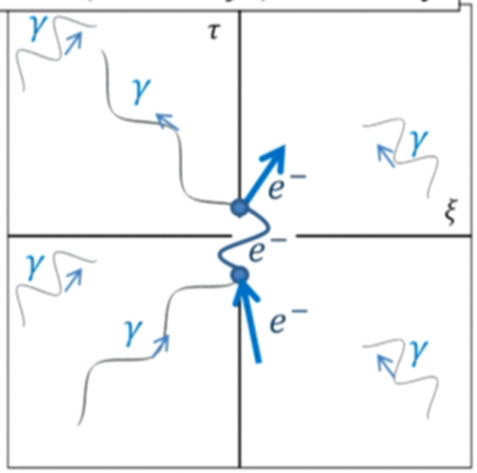
$$ds^2 = e^{2a\xi}(-d\tau^2 + d\xi^2) + dx^2 + dy^2$$



Unruh thermal bath of Rindler photons

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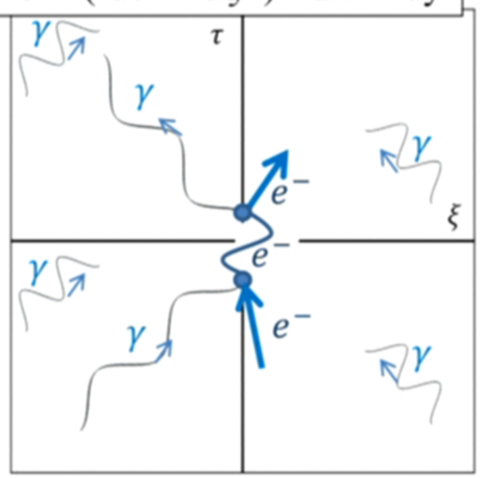
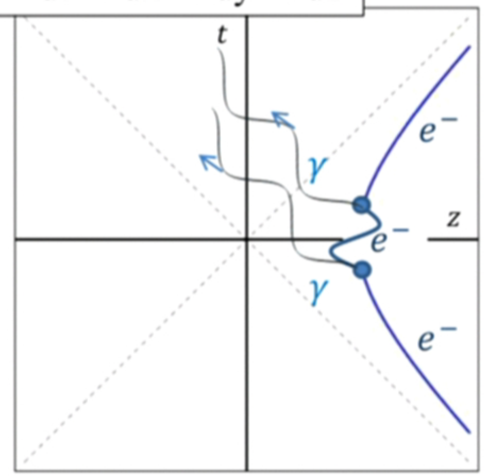


Unruh thermal bath of Rindler photons

$$ds^2 = -dt^2 + dx^2 + dy^2 + dz^2$$



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The Unruh effect in ultra-intense lasers

$$e^- \xrightarrow{a} e^- + 2\gamma$$

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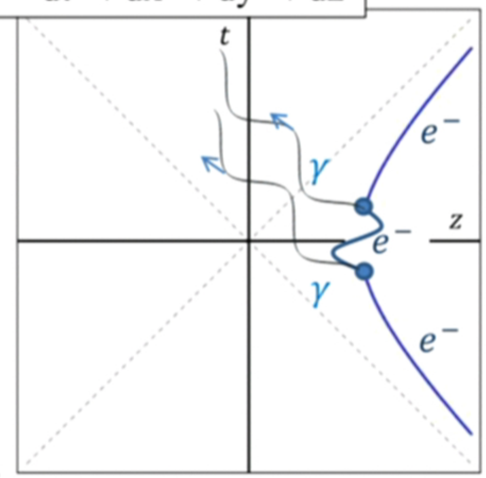

The Unruh effect in moderate electric fields

$$e^- \xrightarrow{a} e^- + \gamma$$

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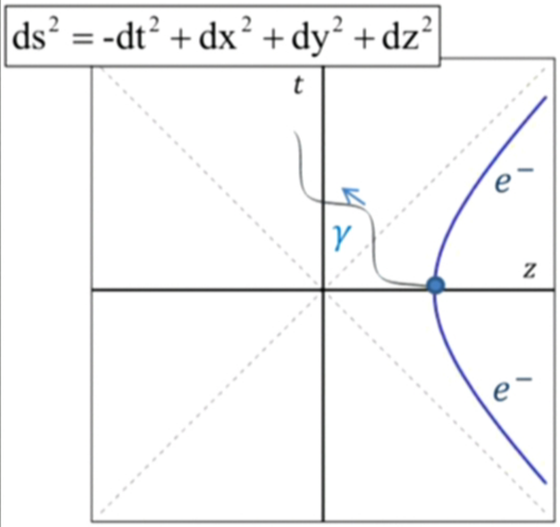

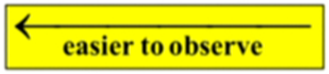

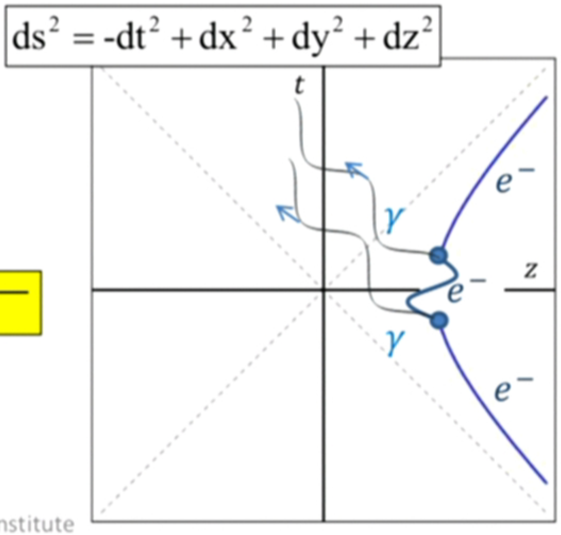

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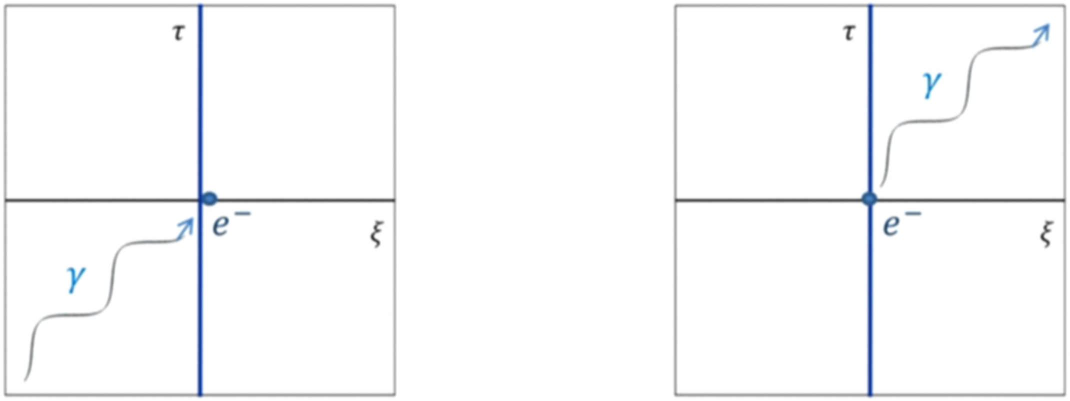
Rindler observer calculation



Charge current : j^{μ} Photon field : $\hat{A}^{\mu}(\tau,\xi,y,z)=\sum_{\lambda}\int d^2k_{\perp}\int_{0}^{+\infty} d\varpi\left[\hat{a}_{k_{\perp}\varpi\lambda}\,A^{\mu}_{k_{\perp}\varpi\sigma}+H.c.\right]$

Interaction action : $\hat{S}_I=\int dx^4\sqrt{-g}\,j_{\mu}\hat{A}^{\mu}$

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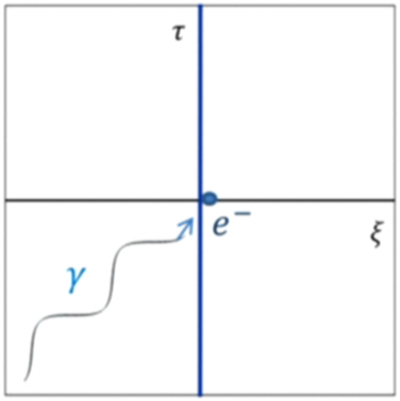

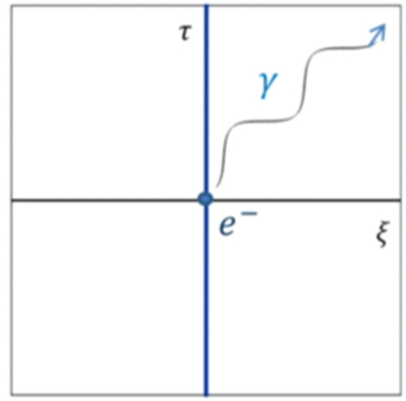

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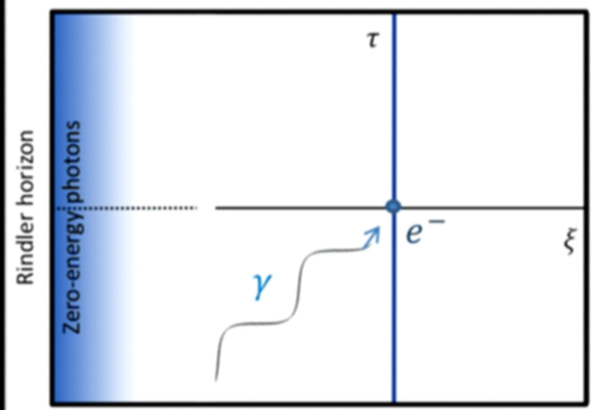
Rindler observer (tree-level) calculation



Absorption amplitude

$$A_{ac}^{e^-\gamma \xrightarrow{a} e^-} \equiv \left\langle e^- \middle| \hat{S}_I \middle| e^-\gamma \right\rangle$$

Absorption probability per $k_\perp$

$$\frac{d\Gamma_{ac}^{e^-\gamma \xrightarrow{T_U} e^-}}{d^2 k_\perp} = \frac{d}{d\tau} \sum_\lambda \int_0^{+\infty} d\varpi_\gamma \left| A_{ac}^{e^-\gamma\to e^-} \right|^2 n_B(\varpi_\gamma)$$

$$n_B(\varpi_\gamma) \equiv \frac{1}{e^{\varpi_\gamma / T_U} - 1}$$

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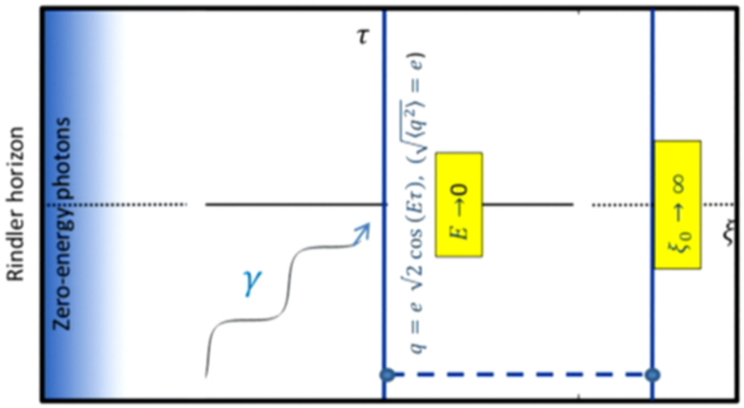

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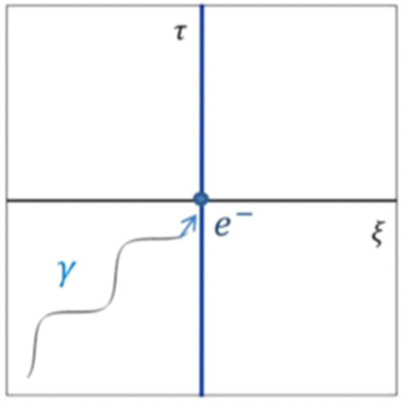
PREDICTION

Inertial observers must detect the following photon emission rate from a uniformly accelerated charge :

$$\frac{d\Gamma^{e^- \xrightarrow{a} e^- \gamma}}{d^2 k_\perp} = 2 \times \frac{e^2}{8\pi^3 a} \left| K_1 (k_\perp / a) \right|^2$$



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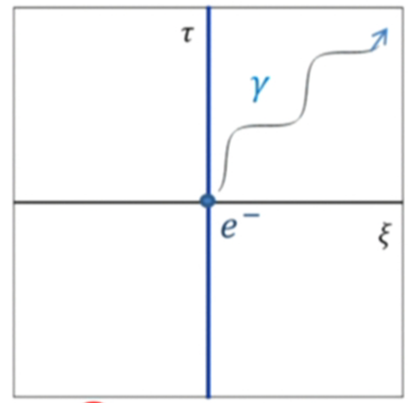

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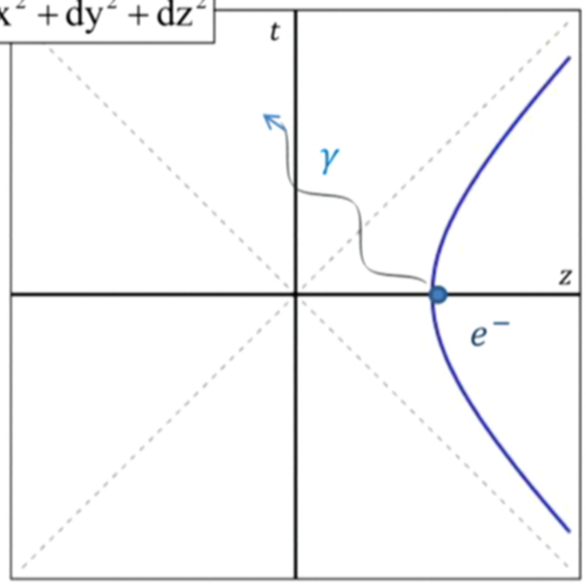

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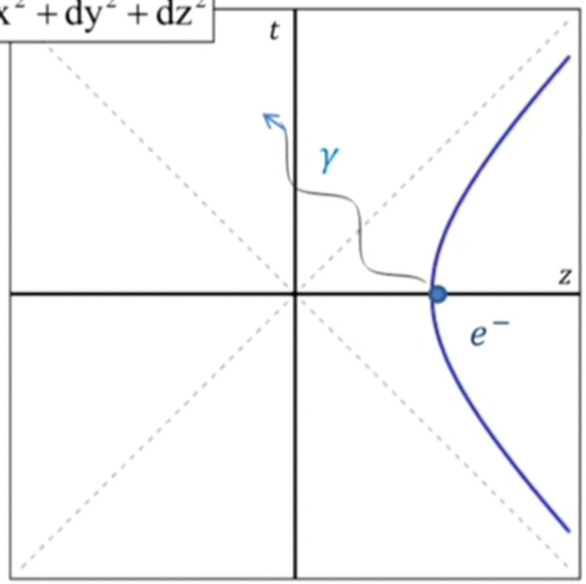

$$\frac{d\Gamma}{d^2k_\perp} = \frac{e^2}{4\pi^3 a}\left|K_1(k_\perp / a)\right|^2$$ ✓!

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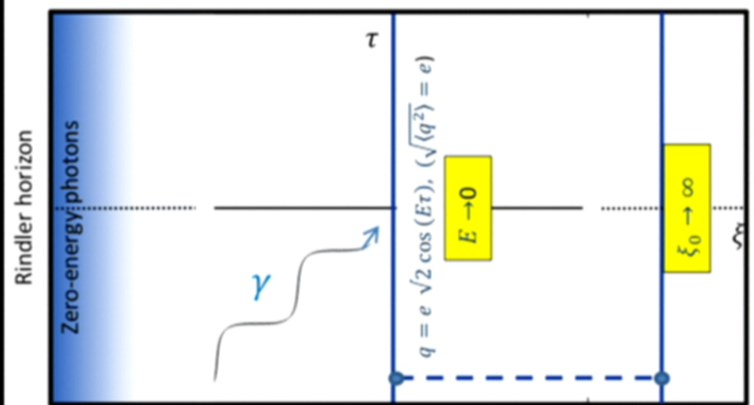

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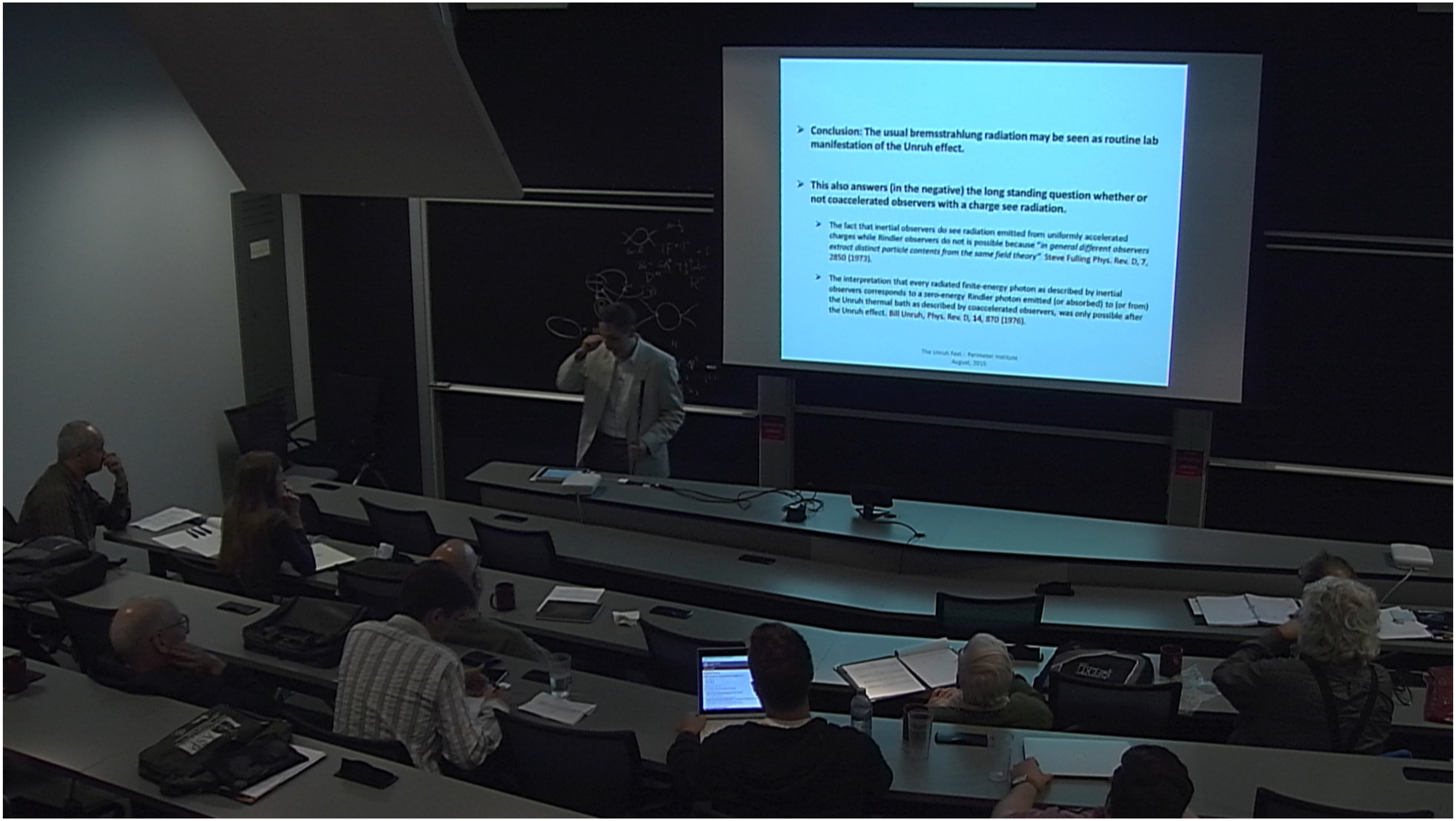
- **Conclusion: The usual bremsstrahlung radiation may be seen as routine lab manifestation of the Unruh effect.**

- **This also answers (in the negative) the long standing question whether or not coaccelerated observers with a charge see radiation.**

  - The fact that inertial observers do see radiation emitted from uniformly accelerated charges while Rindler observers do not is possible because *"in general different observers extract distinct particle contents from the same field theory".* Steve Fulling Phys. Rev. D, **7**, 2850 (1973).

  - The interpretation that every radiated finite-energy photon as described by inertial observers corresponds to a zero-energy Rindler photon emitted (or absorbed) to (or from) the Unruh thermal bath as described by coaccelerated observers, was only possible after the Unruh effect. Bill Unruh, Phys. Rev. D, **14**, 870 (1976).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Final Conclusion: the Unruh effect lives among us

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Thank you very much!

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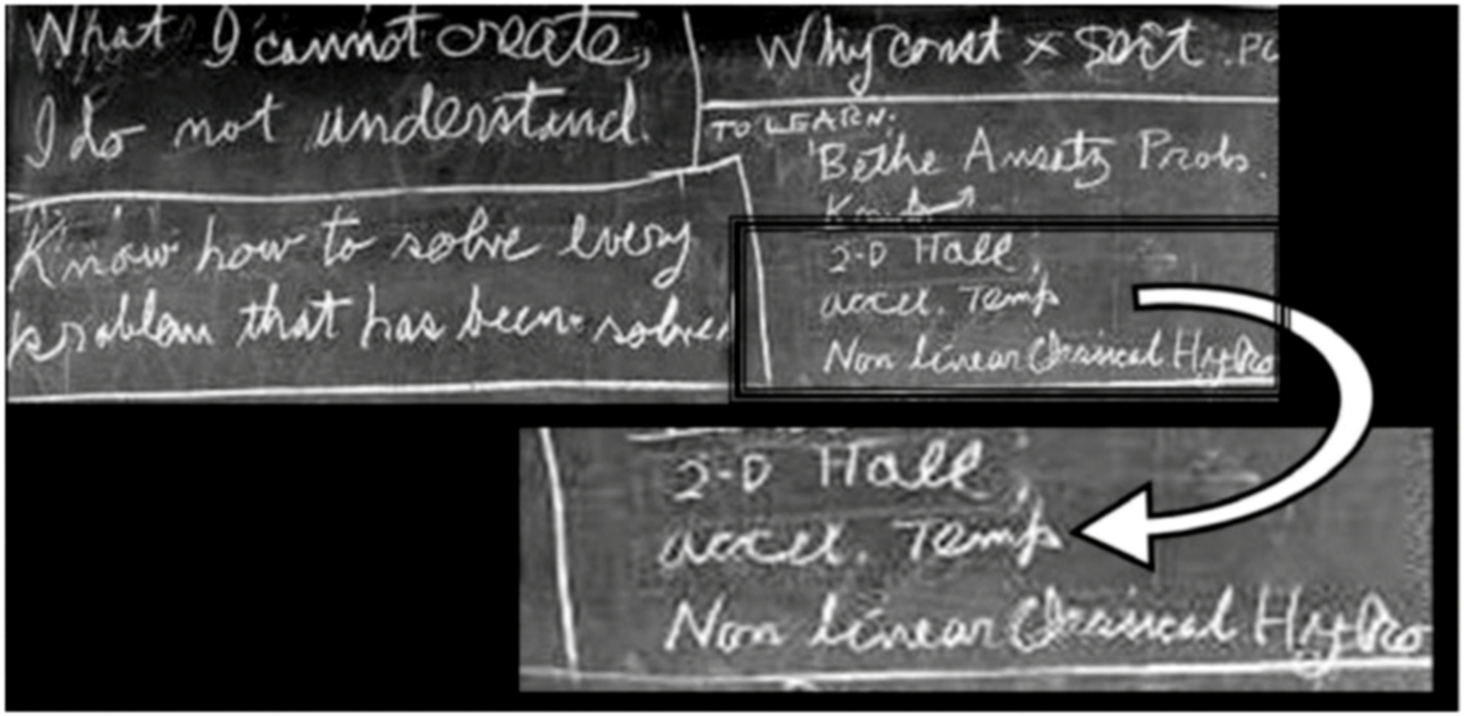

R. Feynman last blackboard – May/1988