Group Report on Strong Fields, Particles, Plasma, and the Aether

Presented by Johann Rafelski

THE UNIVERSITY OF ARIZONA

LeCosPA 4th International Symposium: Unity of Physics

Prior work on relic matter (2011 - 2014)

PHYSICAL REVIEW D **89,** 023008 (2014)

Relic neutrinos: Physically consistent treatment of effective number of neutrinos and neutrino mass

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(Received 10 December 2013; published 24 January 2014)

We perform a model independent study of the neutrino momentum distribution at freeze-out, treating the freeze-out temperature as a free parameter. Our results imply that measurement of neutrino reheating, as characterized by the measurement of the effective number of neutrinos N_ν, amounts to the determination of the neutrino kinetic freeze-out temperature within the context of the standard model of particle physics where the number of neutrino flavors is fixed and no other massless (fractional) particles arise. At temperatures on the order of the neutrino mass, we show how cosmic background neutrino properties, i.e., energy density, pressure, and particle density, are modified in a physically consistent way as a function of neutrino mass and N_ν.

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Relic neutrino freeze-out: Dependence on natural constants

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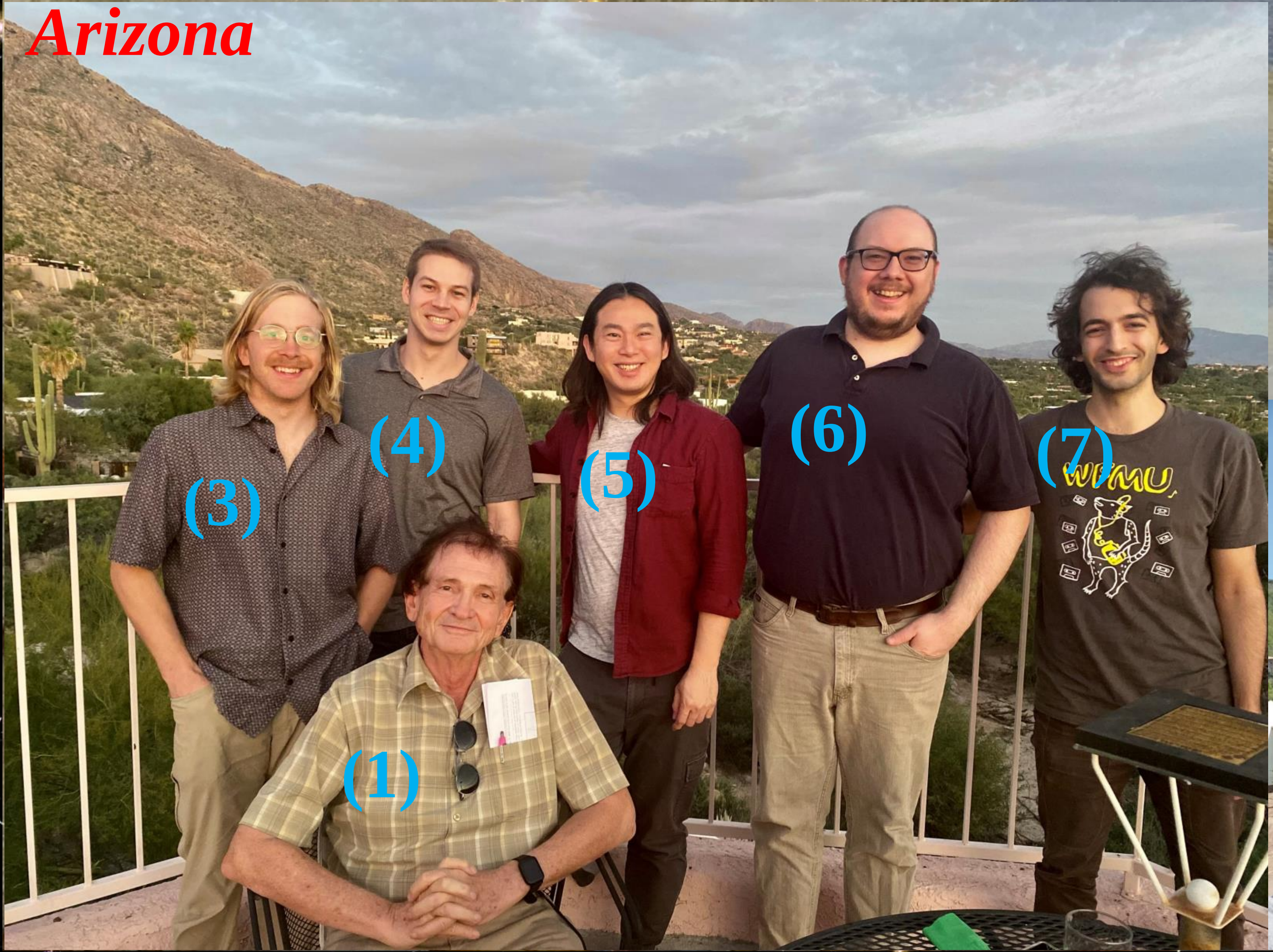
Abstract

Analysis of cosmic microwave background radiation fluctuations favors an effective number of neutrinos, $N_\nu > 3$. This motivates a reinvestigation of the neutrino freeze-out process. Here we characterize the dependence of N_ν on the Standard Model (SM) parameters that govern neutrino freeze-out. We show that N_ν depends on a combination η of several natural constants characterizing the relative strength of weak interaction processes in the early Universe and on the Weinberg angle $\sin^2\theta_W$. We determine numerically the dependence $N_\nu(\eta, \sin^2\theta_W)$ and discuss these results. The extensive numerical computations are made possible by two novel numerical procedures: a spectral method Boltzmann equation solver adapted to allow for strong reheating and emergent chemical non-equilibrium, and a method to evaluate Boltzmann equation collision integrals that generates a smooth integrand.

Research Group at Arizona & Heidelberg (2014 - present)

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



Research Group at Arizona & Heidelberg (2014 - present)

The early Universe is filled with plasmas

The Universe of plasmas

Quark-gluon plasma (QGP)
probed in heavy-ion collisions

Hadronic plasmas

e^+e^- and neutrino plasmas

Classical & quantum magnetization
Matter in laser fields
Radiation reaction
Temperature & acceleration

The Entire Universe… today.

Where is the plasma hiding? In time.

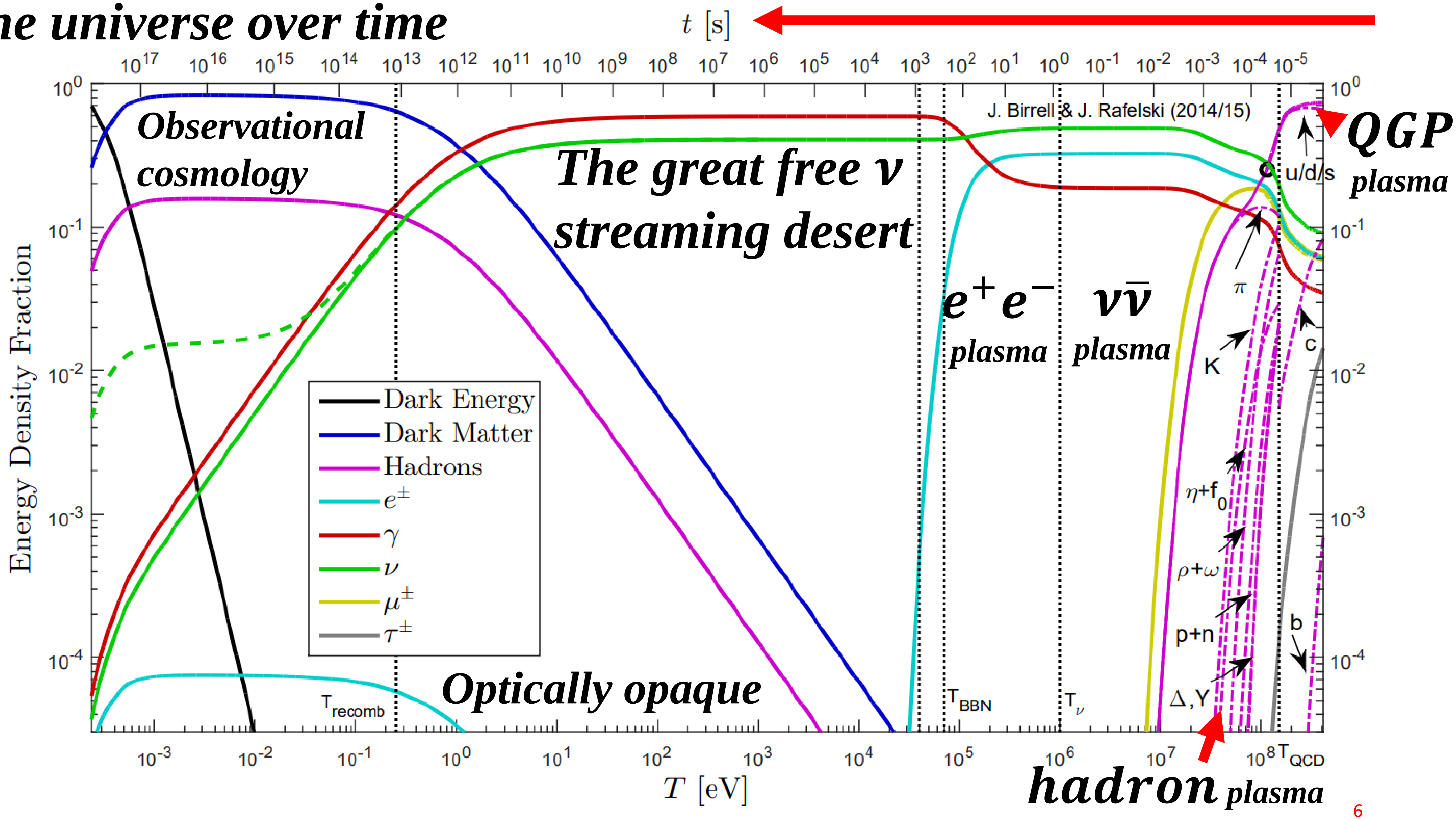
Everything according to ΛCDM

- Radiation (≪ 1%)
- Matter
  - Visible Matter (4.9%)
  - Dark Matter (26.5%)
  - Relics (≪ 1%)
- Dark Energy (68.5%)

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

M. Tanabashi et al. (Particle Data Group), "Review of Particle Physics" Phys. Rev. D 98, 030001 (2018)

The universe over time



Part 1: Plasmas in the Universe
From QGP to BBN

We use strong fields in heavy-ion collisions to probe QGP which existed from the Big Bang to when the universe was only 25 microseconds old.

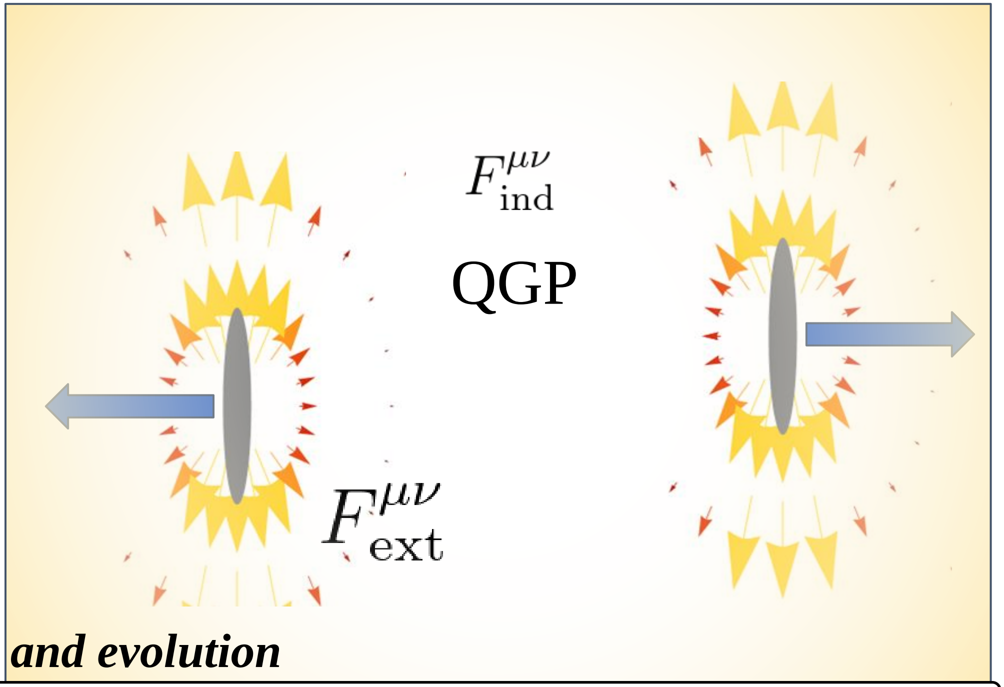
- **Primordial QGP** ($130\ \mathrm{GeV} > T > 150\ \mathrm{MeV}$)
  At this point deconfined quarks, leptons, gauge mesons freely propagating.
- **Hadronic plasma** ($150\ \mathrm{MeV} > T > 10\ \mathrm{MeV}$)
  Hadronization occurs around $T_h \approx 150\ \mathrm{MeV}$ converting free quarks into confined states.
- **Neutrino plasma** ($10\ \mathrm{MeV} > T > 1\ \mathrm{MeV}$)
  Dense plasma of electrons, positrons, and neutrinos still coupled to the charged leptons.
- $\boldsymbol{e^+e^-}$ **plasma** ($1\ \mathrm{MeV} > T > {\sim}0.02\ \mathrm{MeV}$)
  Neutrino freezeout occurs around $T_\nu \approx 1\ \mathrm{MeV}$ leaving the plasma only now electrons and positrons. **Big Bang Nucleosynthesis (BBN) occurs within this plasma.**

Quark-gluon plasma (QGP)
probed in heavy-ion collisions

Ultra-strong electromagnetic fields in heavy-ion collisions:

- Combined self consistent ion and QGP electromagnetic fields
- Probing short lived systems, EM pair production and QGP plasma

We model the QGP as an infinite plasma.



Qualitative illustrations of QGP formation and evolution

M. Formanek, C. Grayson, J. Rafelski, B. Müller, "Current-Conserving Relativistic Linear Response for Collisional Plasmas" Annals of Physics 434 (2021) doi:10.1016/j.aop.2021.168605 [arXiv:2105.07897]

K. Tuchin, "Particle production in strong electromagnetic fields in relativistic heavy-ion collisions." Advances in High Energy Physics 2013 (2013)

J. L. Anderson, and H. R. Witting. "A relativistic relaxation-time model for the Boltzmann equation." Physica 74.3 (1974)

Quark-gluon plasma (QGP)
probed in heavy-ion collisions

Scattering damping: κ
Medium 4-velocity: u
Distribution function: f_{eq}

$$\frac{m_\pi^2 c^2}{e\hbar} \approx 3.1 \times 10^{14}\ \mathrm{T}$$

The induced EM fields $F^{\mu\nu}_{ind}$ generated by the QGP can be modelled using the Vlasov-Boltzmann equation with scattering term.

$$(p \cdot \partial) f(x,p) + q F^{\mu\nu}_{ext} p_\nu \left(\frac{\partial f(x,p)}{\partial p^\mu} \right) = \kappa (p \cdot u) \left(f_{eq}(p) \frac{n(x)}{n_{eq}} - f(x,p) \right)$$

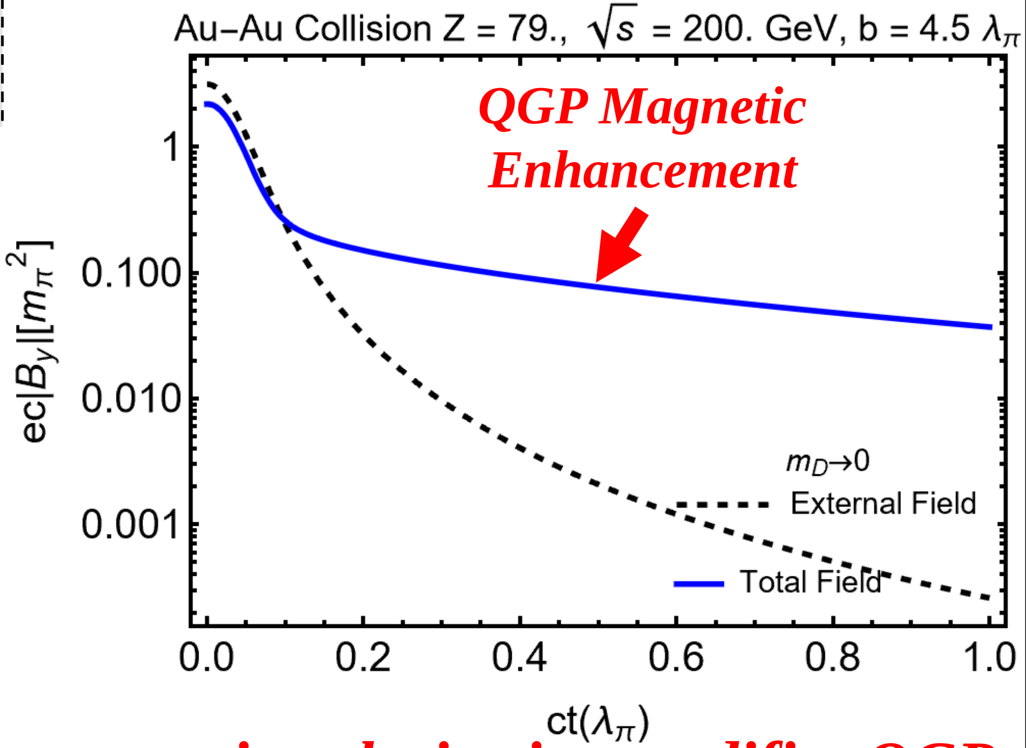
The induced 4-current $J^\mu_{ind}(k)$, in Fourier modes, is then

$$\tilde{J}^\mu_{ind}(k) = 2N_c \int \frac{d^4p}{(2\pi)^4} 4\pi \delta_+(p^2 - m^2) p^\mu \sum_{u,d,s} q_f \left(\tilde{f}_f(k,p) - \tilde{f}_{\bar{f}}(k,p) \right)$$

The polarization can then be identified

Relativistic Ohm's Law in QGP

$$\tilde{J}^\mu_{ind}(k) = \Pi^\mu_\nu \tilde{A}^\nu(k)$$



Strong electromagnetic polarization modifies QGP

M. Formanek, C. Grayson, J. Rafelski, B. Müller, "Current-Conserving Relativistic Linear Response for Collisional Plasmas" Annals of Physics 434 (2021) doi:10.1016/j.aop.2021.168605 [arXiv:2105.07897]

K. Tuchin, "Particle production in strong electromagnetic fields in relativistic heavy-ion collisions." Advances in High Energy Physics 2013 (2013)

J. L. Anderson, and H. R. Witting. "A relativistic relaxation-time model for the Boltzmann equation." Physica 74.3 (1974)

Hadronic plasma: Strangeness abundance

Strangeness persists in plasma

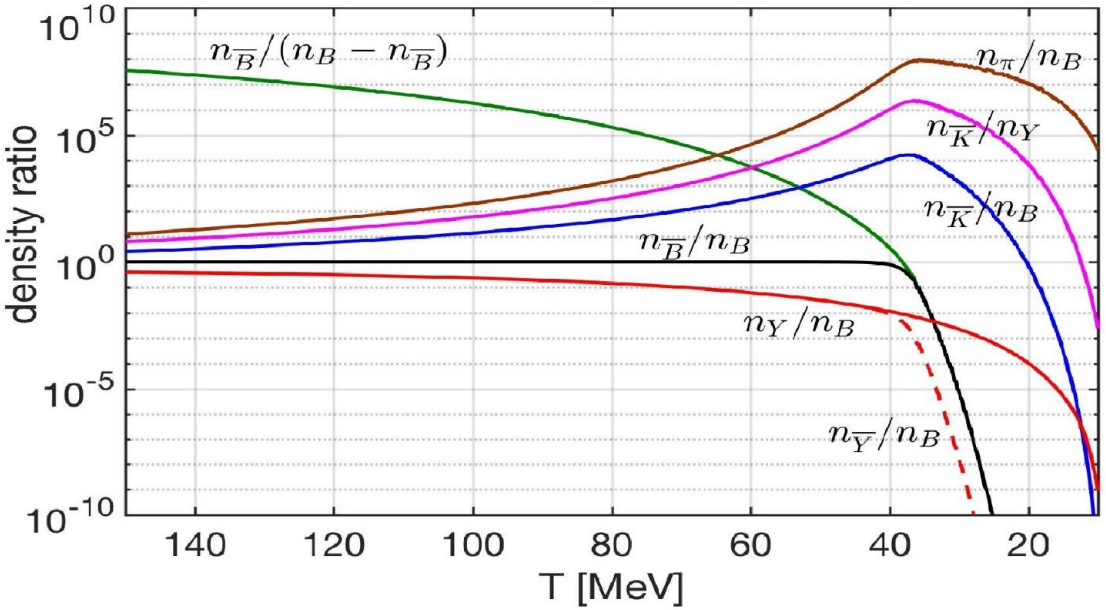


Figure 3: Ratios of hadronic particle number densities as a function of temperature 150 MeV > T > 10 MeV in the early Universe with baryon B yields: pions π (brown line), kaons $K(q\bar{s})$ (blue), antibaryon $\overline{B}$ (black), hyperon Y (red) and anti-hyperons $\overline{Y}$ (dashed red). Also shown $\overline{K}/Y$(purple).

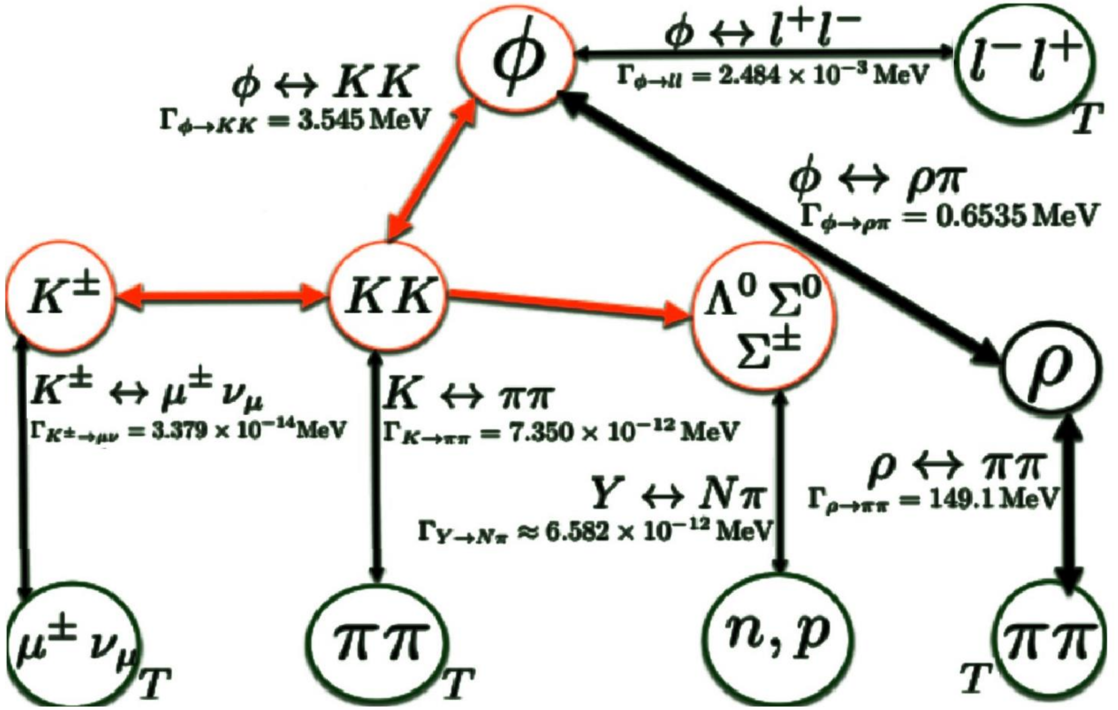


Figure 4: The strangeness abundance changing reactions in the primordial Universe. The red circles show strangeness carrying hadronic particles; red thick lines denote effectively instantaneous reactions. Black thick lines show relatively strong hadronic reactions.

C. T. Yang and J. Rafelski, "Cosmological Strangeness Abundance," (2021) [arXiv:2108.01752]

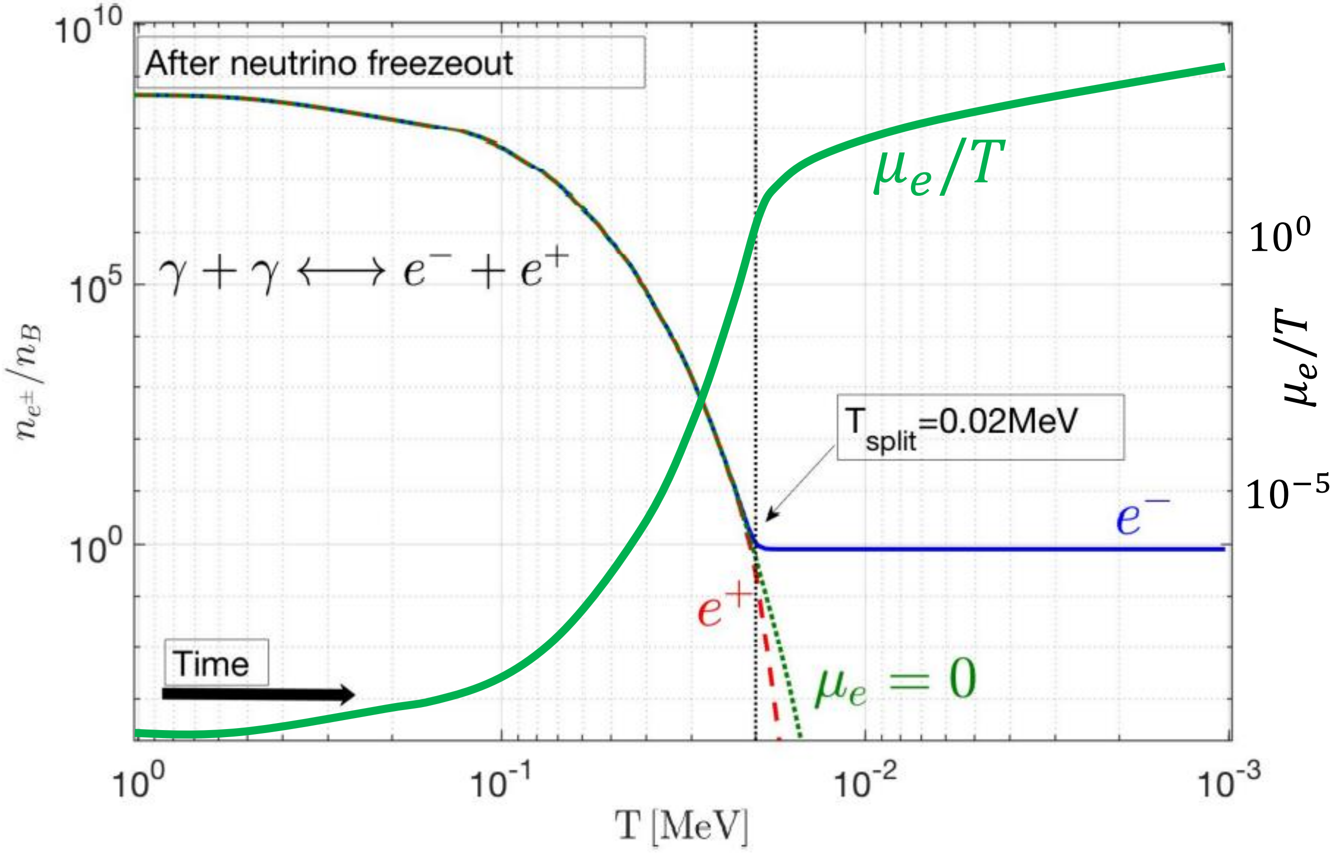
Early universe plasmas

e^+e^- and neutrino plasmas

e^+e^- plasma 1 MeV > T > ~0.02 MeV

Neutrino freezeout occurs around $T_\nu \approx 1.5$ MeV leaving the plasma only now electrons and positrons. **Big Bang Nucleosynthesis (BBN) occurs within this plasma.**

Could lead to changes in final abundance of select light elements.



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B. Wang, C. A. Bertulani and A. B. Balantekin, "Electron screening and its effects on Big-Bang nucleosynthesis" Phys. Rev. C 83, 018801 (2011) doi:10.1103/PhysRevC.83.018801 [arXiv:1010.1565]

Part 2: Unity of Physics:
From plasma physics to laws of physics

Plasma theory should in full detail contain:

"… a complete satisfactory treatment of the reactive effects of radiation [that] does not exist."
– J. D. Jackson, 1999, p. 781

- ***Magnetic moment and spin dynamics***
- ***Quantum vacuum in strong fields***
- ***Relativistic radiation friction***

J. D. Jackson. "Classical electrodynamics." (1999)

Completing 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

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

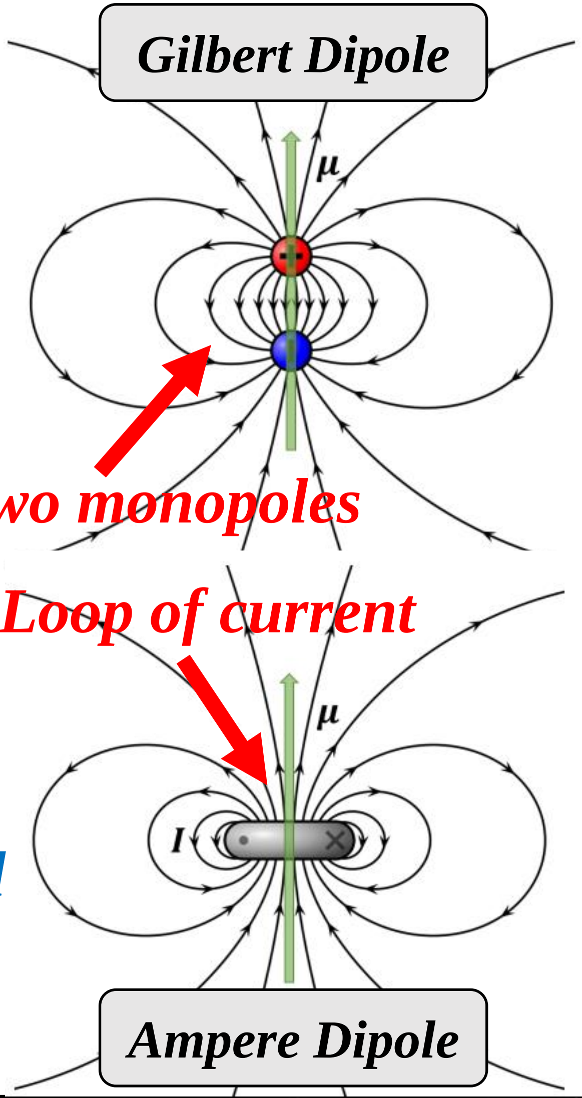
Define a Force Field Tensor

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

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



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

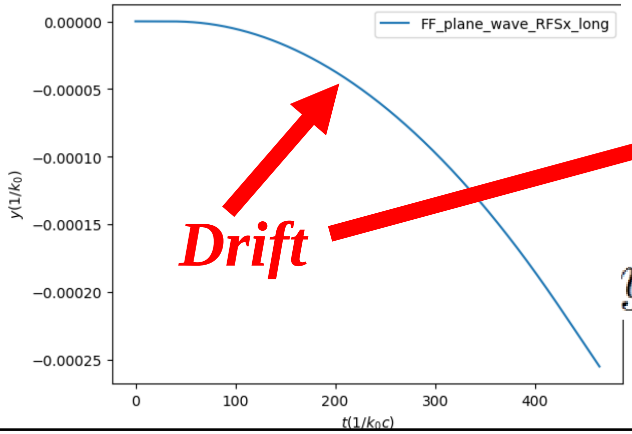
Extended Lorentz force with magnetic dipole: covariant equations are exactly soluble for important examples

Demonstration of charged solutions for EM plane waves.

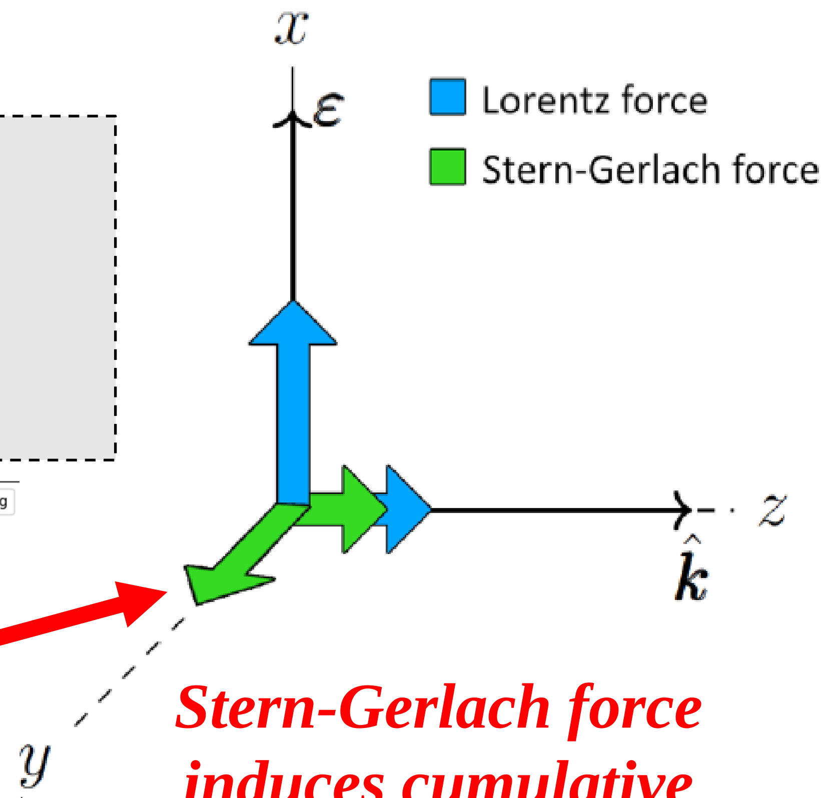
$$u^\mu(\tau) = u^\mu(0) - \frac{e}{m}\mathcal{A}_0\psi(\tau)\epsilon^\mu + \frac{1}{2}h^2(\tau)\hat{k}\cdot u(o)\hat{k}^\mu + \frac{e}{m}\frac{\mathcal{A}_0\psi(\tau)}{\hat{k}\cdot u(0)}\left[\epsilon\cdot u(0) + \frac{1}{2}\frac{e}{m}\mathcal{A}_0\psi(\tau)\right]\hat{k}^\mu + h(\tau)\epsilon^{\mu\nu\alpha\beta}u_\nu(0)\hat{k}_\alpha\epsilon_\beta$$

$$h(\tau) \equiv -\frac{d_m\mathcal{A}_0\omega^2}{mc^2}\int_{\tau_0=0}^{\tau}\hat{k}\cdot s(\tilde{\tau})f''(\xi(\tilde{\tau}))d\tilde{\tau}$$

We have also done neutral particles in plane waves.



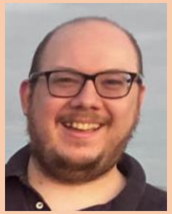
Drift



Stern-Gerlach force induces cumulative off-axis particle drift.

M. Formanek, A. Steinmetz, and J. Rafelski. "Classical neutral point particle in linearly polarized EM plane wave field." Plasma Physics and Controlled Fusion 61.8 (2019): 084006.

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.



Quantum magnetic dipoles: Diverse forms of quantum equations

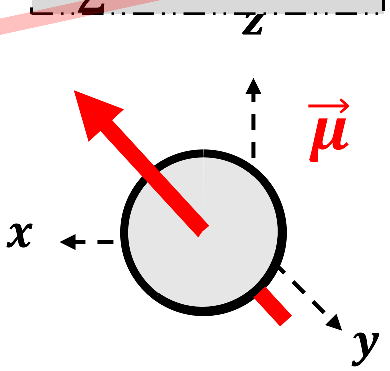
$$\boldsymbol{\mu} \leftarrow \frac{g}{2}\frac{e\hbar}{2m}$$

$$\frac{g}{2} = 1 + a$$

Non-relativistic magnetic dipole has the Hamiltonian:

$$\hat{H}_{Mag.} = -\vec{\boldsymbol{\mu}} \cdot \vec{\boldsymbol{B}}$$

Relativistic magnetic dipoles have a diversity of models:



$$\left(\gamma \cdot (i\hbar\partial - eA) - mc - \left(\boldsymbol{\mu} - \frac{e\hbar}{2m}\right)\frac{1}{2c}\sigma_{\alpha\beta}F^{\alpha\beta}\right)\psi = 0$$

Dirac-Pauli (DP)

$$\left((i\hbar\partial - eA)^2 - m^2c^2 - \boldsymbol{\mu} m \sigma_{\alpha\beta}F^{\alpha\beta}\right)\psi = 0$$

Klein-Gordon-Pauli (KGP)

$$\left((i\hbar\partial - eA)^2 - \tilde{m}^2c^2\right)\psi = 0$$

"Improved" Klein-Gordon-Pauli (IKGP)

$$\tilde{m}c = mc + \boldsymbol{\mu}\frac{1}{2c}\sigma_{\alpha\beta}F^{\alpha\beta} \rightarrow \tilde{m}^2c^2 = m^2c^2 + \boldsymbol{\mu} m \sigma_{\alpha\beta}F^{\alpha\beta} + \boldsymbol{\mu}^2\frac{1}{4c^2}\left(\sigma_{\alpha\beta}F^{\alpha\beta}\right)^2$$

A. Steinmetz, M. Formanek, and J. Rafelski. "Magnetic dipole moment in relativistic quantum mechanics." EPJA 55.3 (2019): 1-17.

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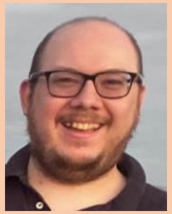
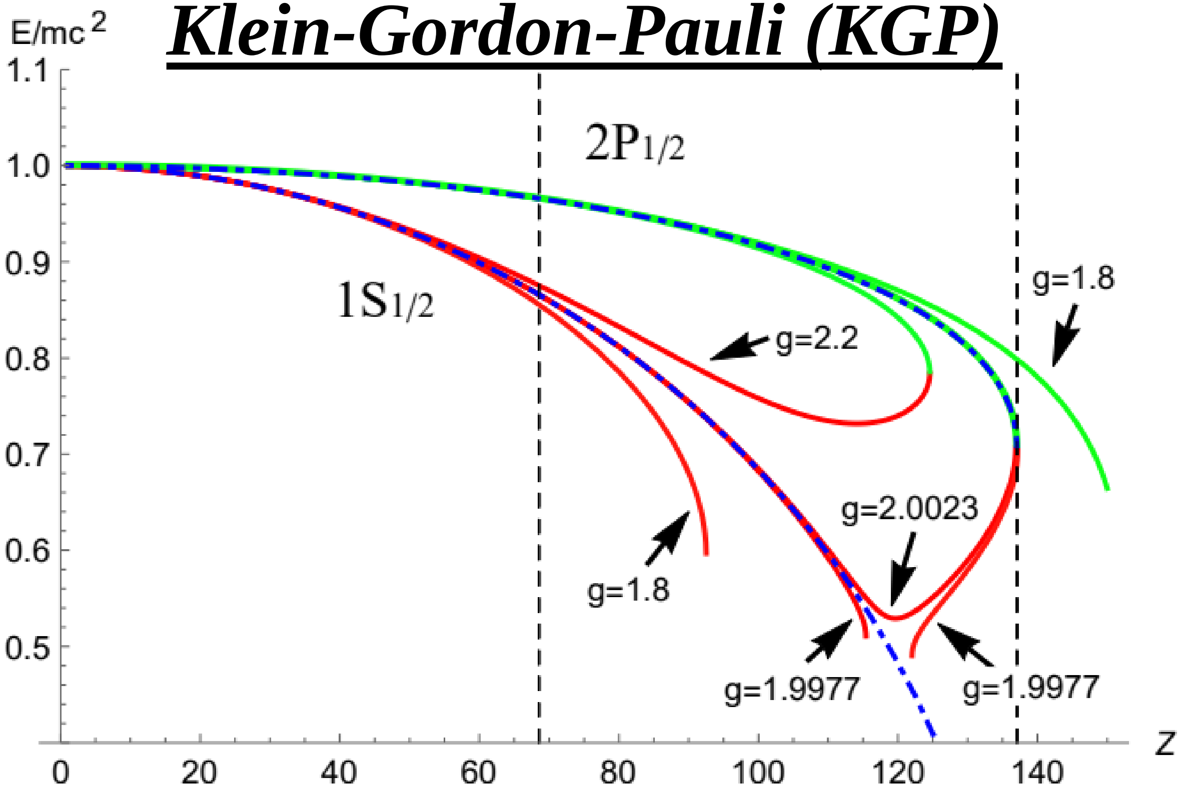
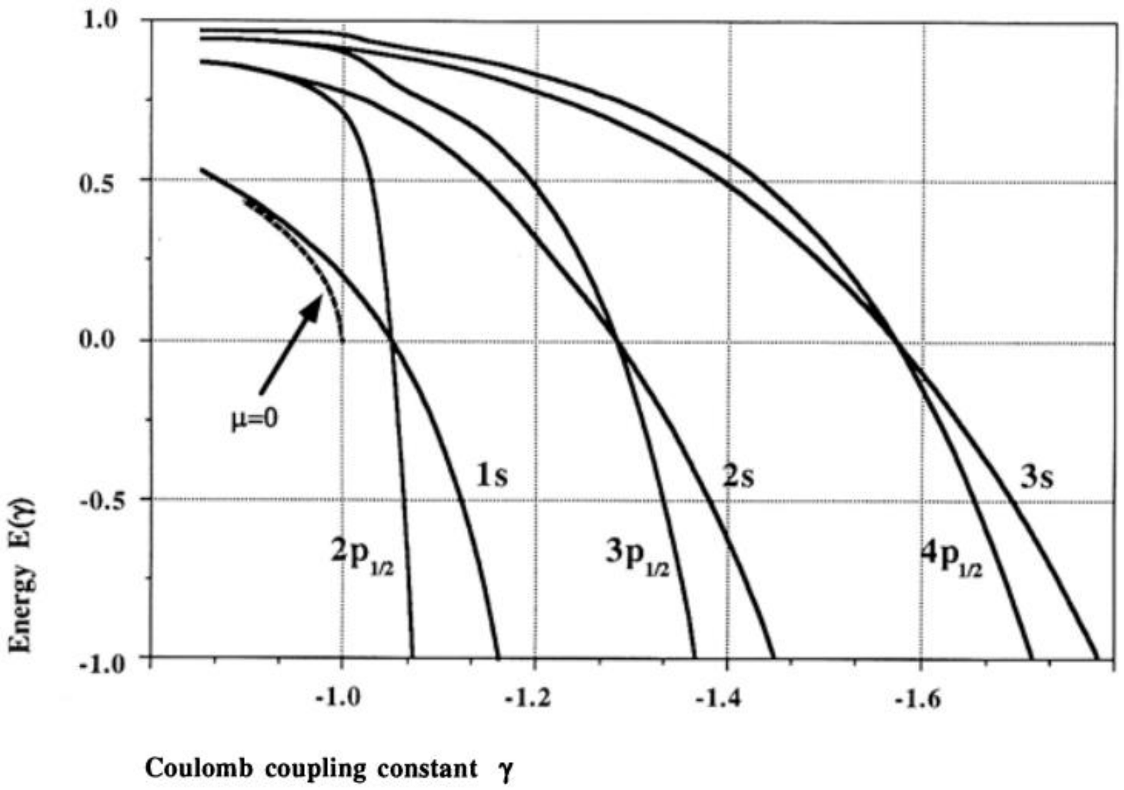


Strong Coulomb field eigen-energies

Klein-Gordon-Pauli (KGP)

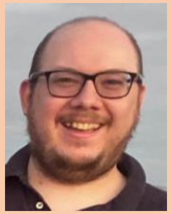


Dirac-Pauli (DP)



A. Steinmetz, M. Formanek, and J. Rafelski. "Magnetic dipole moment in relativistic quantum mechanics." EPJA 55.3 (2019): 1-17.

B. Thaller. The Dirac equation. Springer Science & Business Media, 2013.

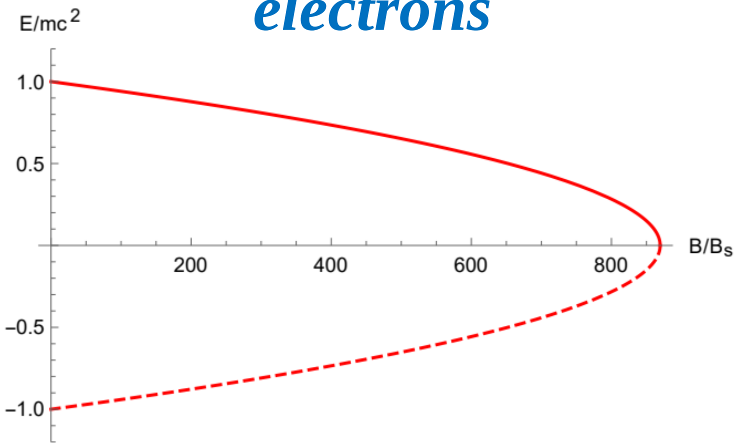


Constant magnetic field eigen-energies

$$\boldsymbol{B_S} \equiv \frac{m^2c^2}{e\hbar} = \begin{cases} 4.41 \times 10^9 \text{ T (electrons)} \\ 1.49 \times 10^{16} \text{ T (protons)} \end{cases}$$

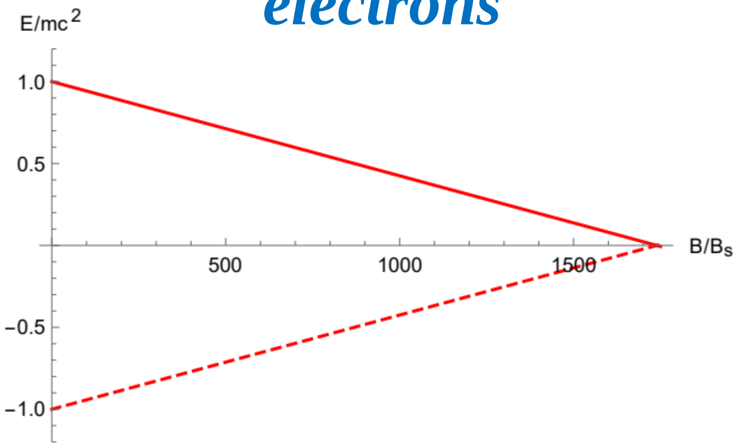
Klein-Gordon-Pauli (KGP)

electrons



Dirac-Pauli (DP)

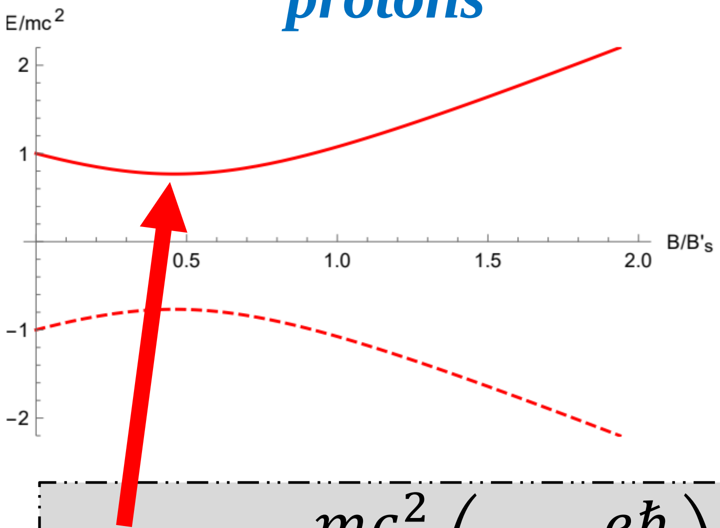
electrons



"Improved"

Klein-Gordon-Pauli (IKGP)

protons



$$\boldsymbol{B_{min}} \equiv \frac{mc^2}{\mu}\left(\mu - \frac{e\hbar}{2m}\right)$$

Expect grossly different properties in magnetars.

A. Steinmetz, M. Formanek, and J. Rafelski. "Magnetic dipole moment in relativistic quantum mechanics." EPJA 55.3 (2019): 1-17.

E. J. Ferrer, & A. Hackebill. "Thermodynamics of neutrons in a magnetic field and its implications for neutron stars" Phy. Rev. C 99.6 (2019): 065803.

QED quantum vacuum in strong fields

KGP introduces corrections into Euler-Heisenberg (**EH**) action:

- Pair production modification due to periodicity of g.

$$L_{EH} = -\frac{1}{8\pi^2}\int_{\delta}^{\infty}\frac{ds}{s^3}e^{-m_e^2 s}\left(\frac{abe^2s^2\cos\left[\frac{g}{2}eas\right]\cosh\left[\frac{g}{2}ebs\right]}{\sin[eas]\sinh[ebs]} - 1\right)$$

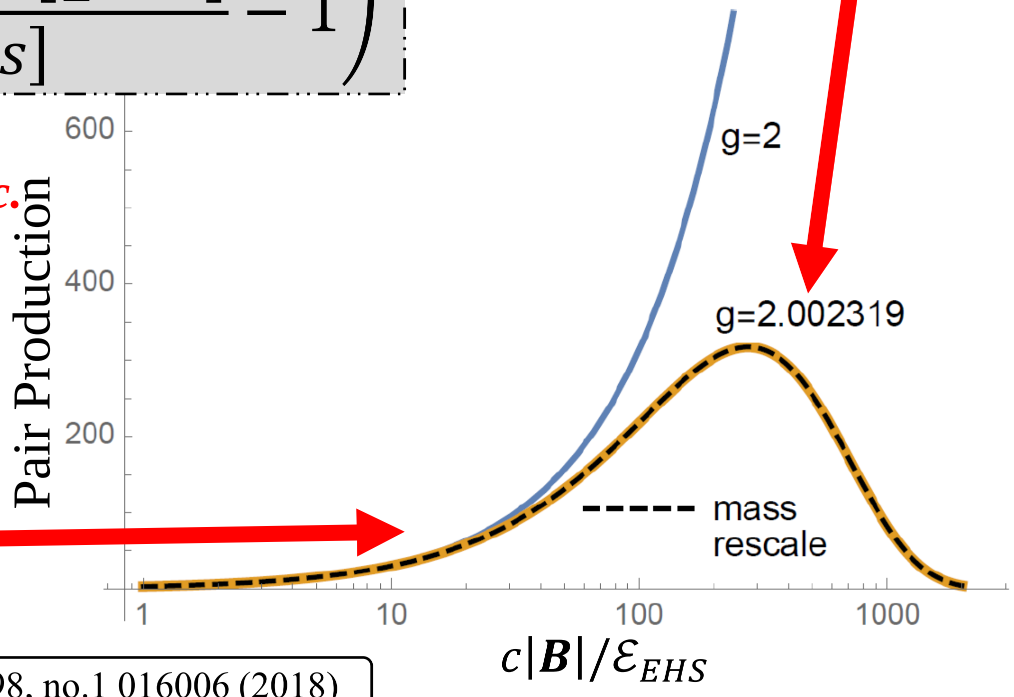
Origin of electron mass? Higgs and electromagnetic.

$$\mathcal{E}_{EHS} = \frac{m_e^2c^3}{e\hbar} = 1.323\times 10^{18}\,\frac{\mathrm{V}}{\mathrm{m}}$$

$$a^2 - b^2 = E^2 - B^2$$
$$a^2b^2 = (E\cdot B)^2$$

$$m_{rescale}^2c^2 = m_e^2c^2 + \left|\frac{g}{2} - 1\right| e\hbar B$$

Modification to pair production



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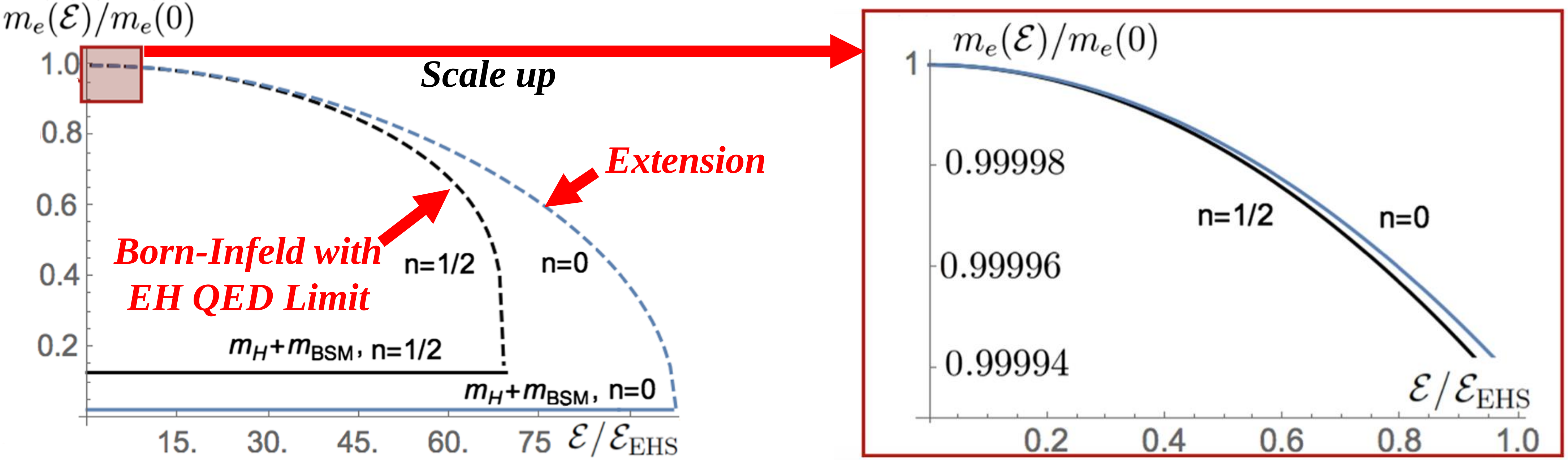
W-Y. P. Hwang, S. P. Kim, "Vacuum Persistence and Inversion of Spin Statistics in Strong QED." Phys.Rev.D 80 065004 (2009)

Strong fields probe the origin of electron mass

Origin of mass:

- EM and non-EM (Higgs+BSM) mass components
- EM mass melting in external fields
- Self-consistent feedback with nonlinear EM action

Using Born-Infeld model of the electron.



EM mass content controlled by model parameter $\boldsymbol{n}$

S. Evans and J. Rafelski. "Electron electromagnetic-mass melting in strong fields." Phys. Rev. D 102, 036014 (2020)

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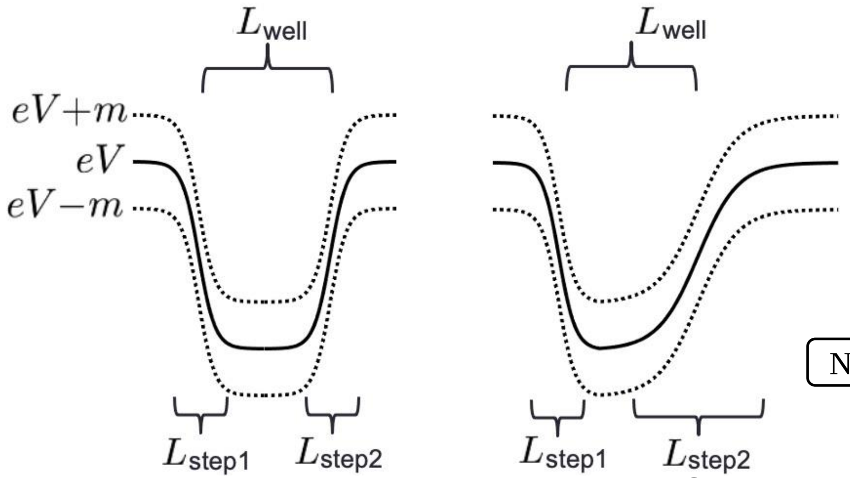
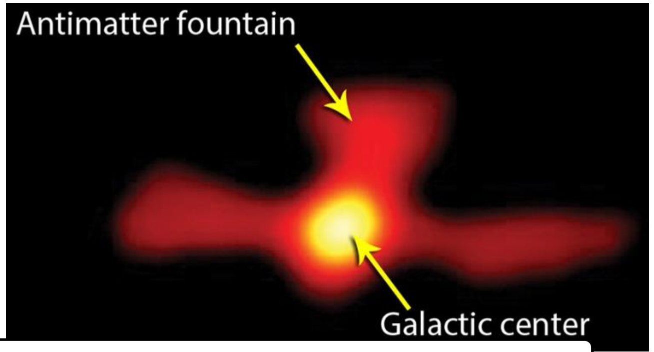
I. Birula. "Nonlinear Electrodynamics: Variations On A Theme By Born And Infeld." In: B. Jancewicz, J. Lukierski: Quantum Theory Of Particles and Fields, World Scientific (1983)

Transition in pair production from Euler-Heisenberg to Klein paradox limit





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

Single potential step or two steps forming a well:
- Finite pair production per unit area versus the diverging rate per volume

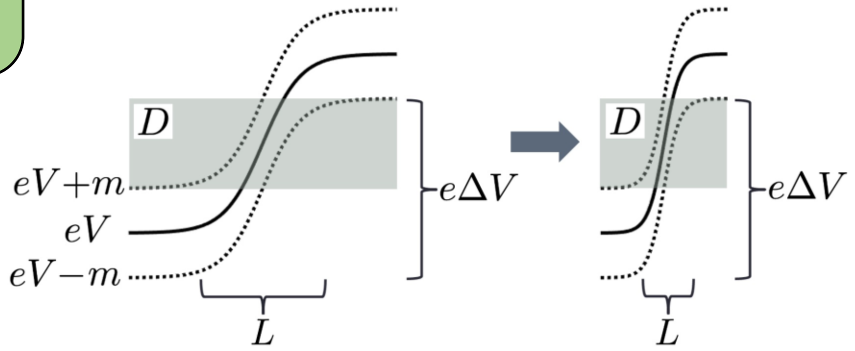
Step to well

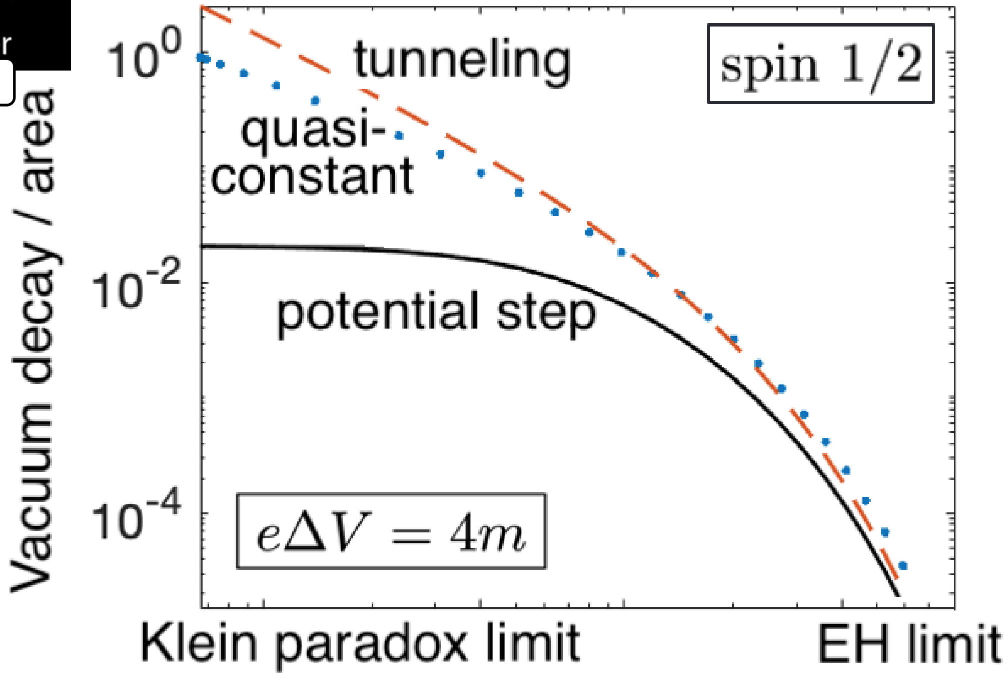
Two steps forming a well required for:
- A good definition of vacuum
- Pair production highly sensitive to the shape of the well

Next Slide

As step becomes steep, the forces become very large inducing radiation effects.

Transition from quasi-constant to sharp fields





S. Evans and J. Rafelski. "Particle production at a finite potential step: Transition from Euler-Heisenberg to Klein paradox." (2021) [arXiv:2108.12959]

S. P. Kim, H. K. Lee and Y. Yoon, "Effective action of QED in electric field backgrounds. II. Spatially localized fields." Phys. Rev. D 82, 025015 (2010)

A. Chervyakov and H. Kleinert, "On Electron–Positron Pair Production by a Spatially Inhomogeneous Electric Field." Phys. Part. Nucl. 49 no.3, 374-396 (2018)

Completing EM interactions: Covariant classical radiation reaction

$$\tau_0 = \frac{2}{3}\frac{e^2}{4\pi m c^3}$$

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

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". In preparation. (2021)

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)

Example of limiting acceleration

$$\Omega_B = \frac{eB}{m}$$

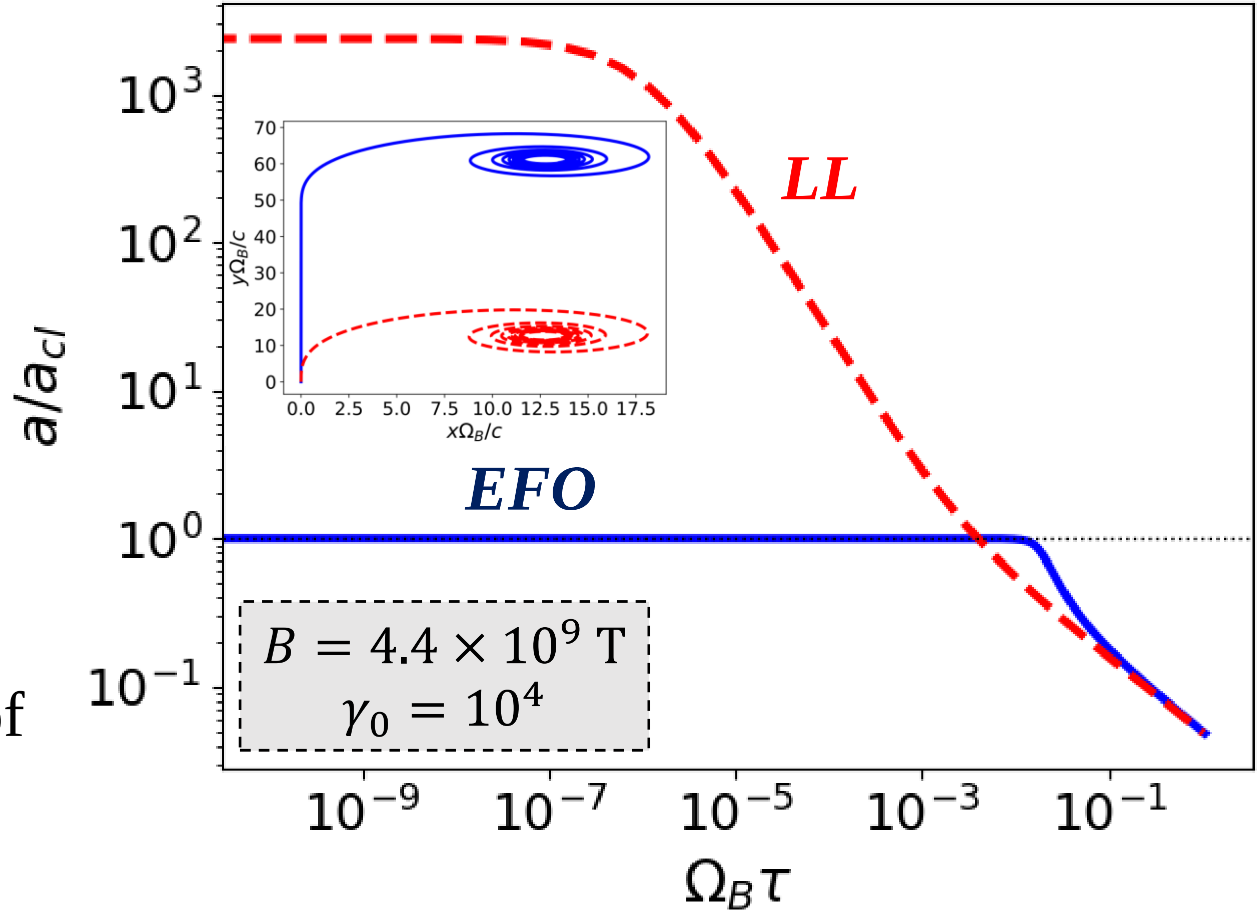
$$\tau_0 = \frac{2}{3}\frac{e^2}{4\pi m c^3}$$

Eliezer-Ford-O'Connell (EFO) in constant magnetic fields

$$a^2 = -\frac{\Omega_B^2\left(c^2(\gamma^2-1)\right)}{1+(\tau_0\Omega_B\gamma)^2}$$

$$\lim_{\gamma\to\infty} a^2 \to -\frac{c^2}{\tau_0^2} \quad \Rightarrow \quad |a_{cl}| = \frac{c}{\tau_0}$$

Limiting acceleration is a common feature of Born-Infeld EM theory



W. Price, M. Formanek, and J. Rafelski. "Radiation reaction and limiting acceleration". In preparation. (2021)

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)

Path warping:
The new idea for radiation reaction

Start with point external force + Larmor term

$$m\dot{u}^\mu = f^\mu + m\tau_0 \frac{\dot{u}^2}{c^2} u^\mu$$

Omitting problematic Schott term

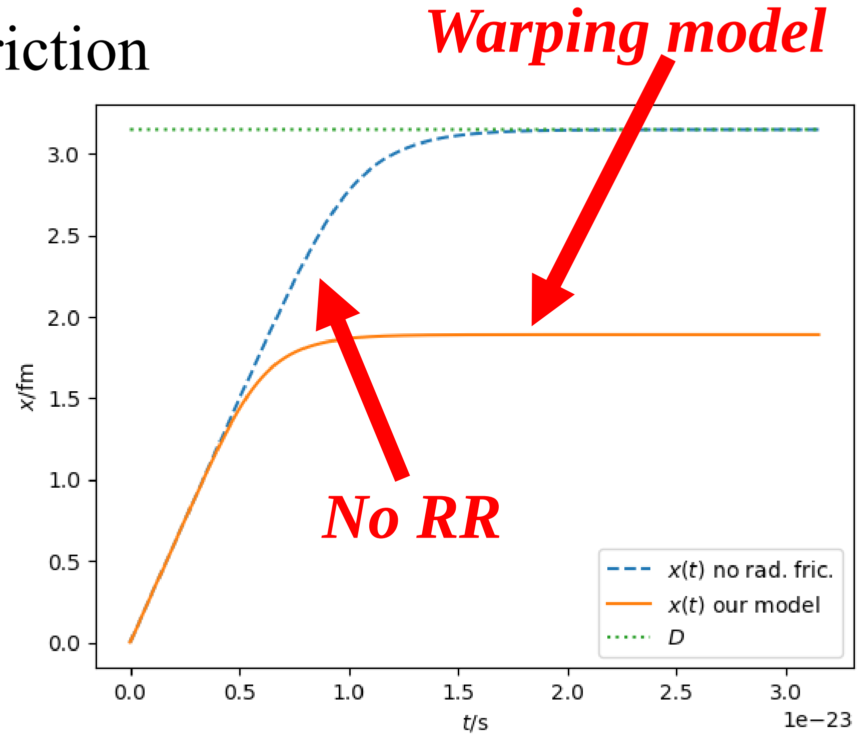
$$m\tau_0 \ddot{u}^\mu$$

Introduce "path warping" for particles with medium friction

$$u \cdot \dot{u} = \tau_0 \dot{u}^2 \neq 0 \quad \leftrightarrow \quad u^2 = w_{\mu\nu} u^\mu u^\nu = c^2$$

Path warping along world-line of particle

$$u \cdot \dot{u} = -\frac{1}{2}\frac{dw_{\mu\nu}}{d\tau} u^\mu u^\nu \neq 0$$



Unique particle stopping distance predictions versus other models.

Applications for quark jet quenching in QGP

M. Formanek, A. Steinmetz, and J. Rafelski. "Radiation reaction friction: Resistive material medium." Physical Review D 102.5 (2020): 056015.

Temperature connecting acceleration to strong electric fields

PHYSICAL REVIEW D VOLUME 14, NUMBER 4 15 AUGUST 1976

Notes on black-hole evaporation

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This paper examines various aspects of black-hole evaporation. A two-dimensional model is investigated where it is shown that using fermion-boson cancellation on the stress-energy tensor reduces the energy outflow to zero, while other noncovariant techniques give the Hawking result. A technique for replacing the collapse by boundary conditions on the past horizon is developed which retains the essential features of the collapse while eliminating some of the difficulties. This set of boundary conditions is also suggested as the most natural set for a preexistent black hole. The behavior of particle detectors under acceleration is investigated where it is shown that an accelerated detector even in flat spacetime will detect particles in the vacuum. The similarity of this case with the behavior of a detector near the black hole is brought out, and it is shown that a geodesic detector near the horizon will not see the Hawking flux of particles. Finally, the work of Berger, Chitre, Nutku, and Moncrief on scalar geons is corrected, and the spherically symmetric coupled scalar-gravitation Hamiltonian is presented in the hope that someone can apply it to the problem of black-hole evaporation.

Volume 63A, number 3 PHYSICS LETTERS 14 November 1977

INTERPRETATION OF EXTERNAL FIELDS AS TEMPERATURE★

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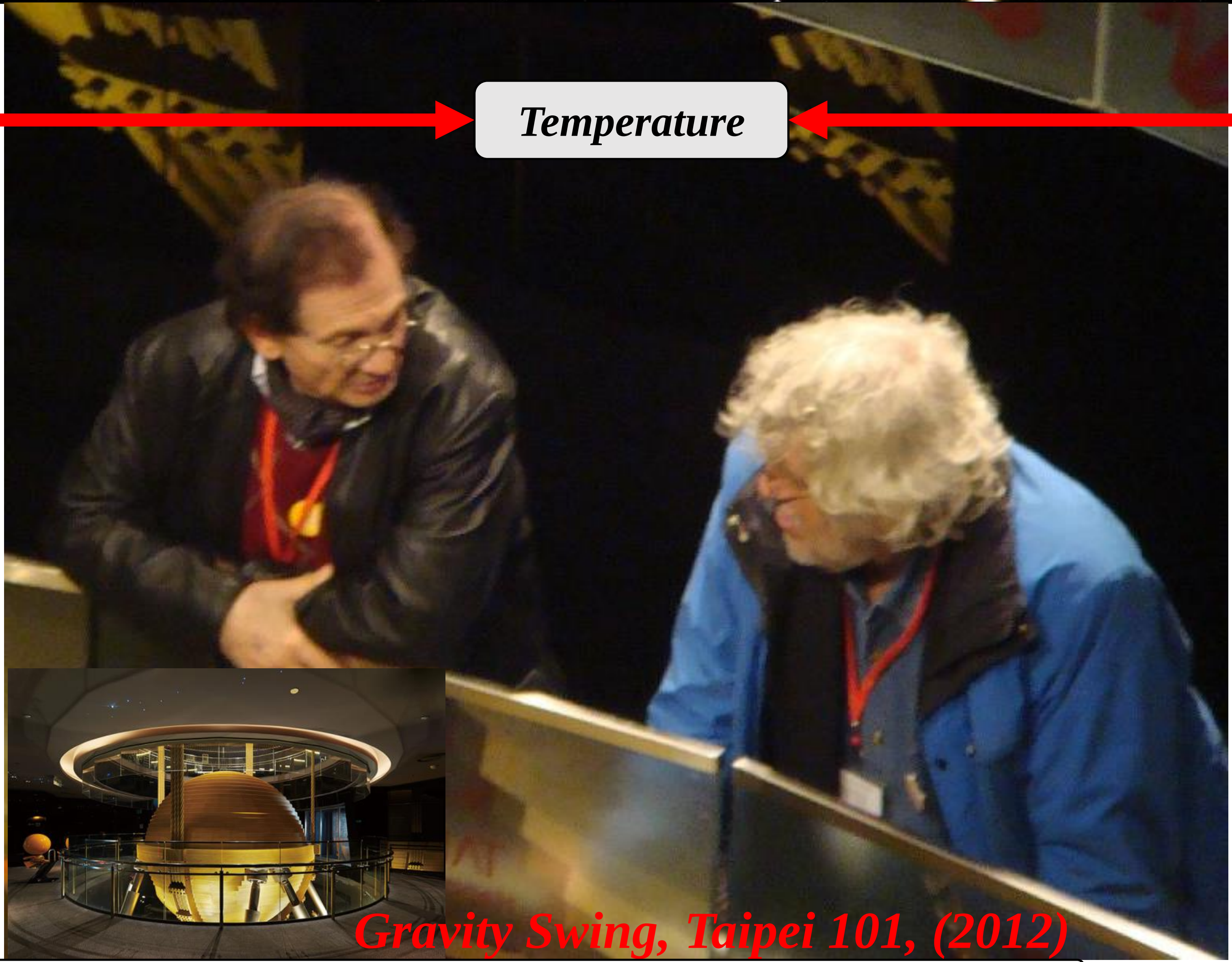
Received 5 September 1977

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

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



Gravity Swing, Taipei 101, (2012)

Interpretation of external fields as temperature

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

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)

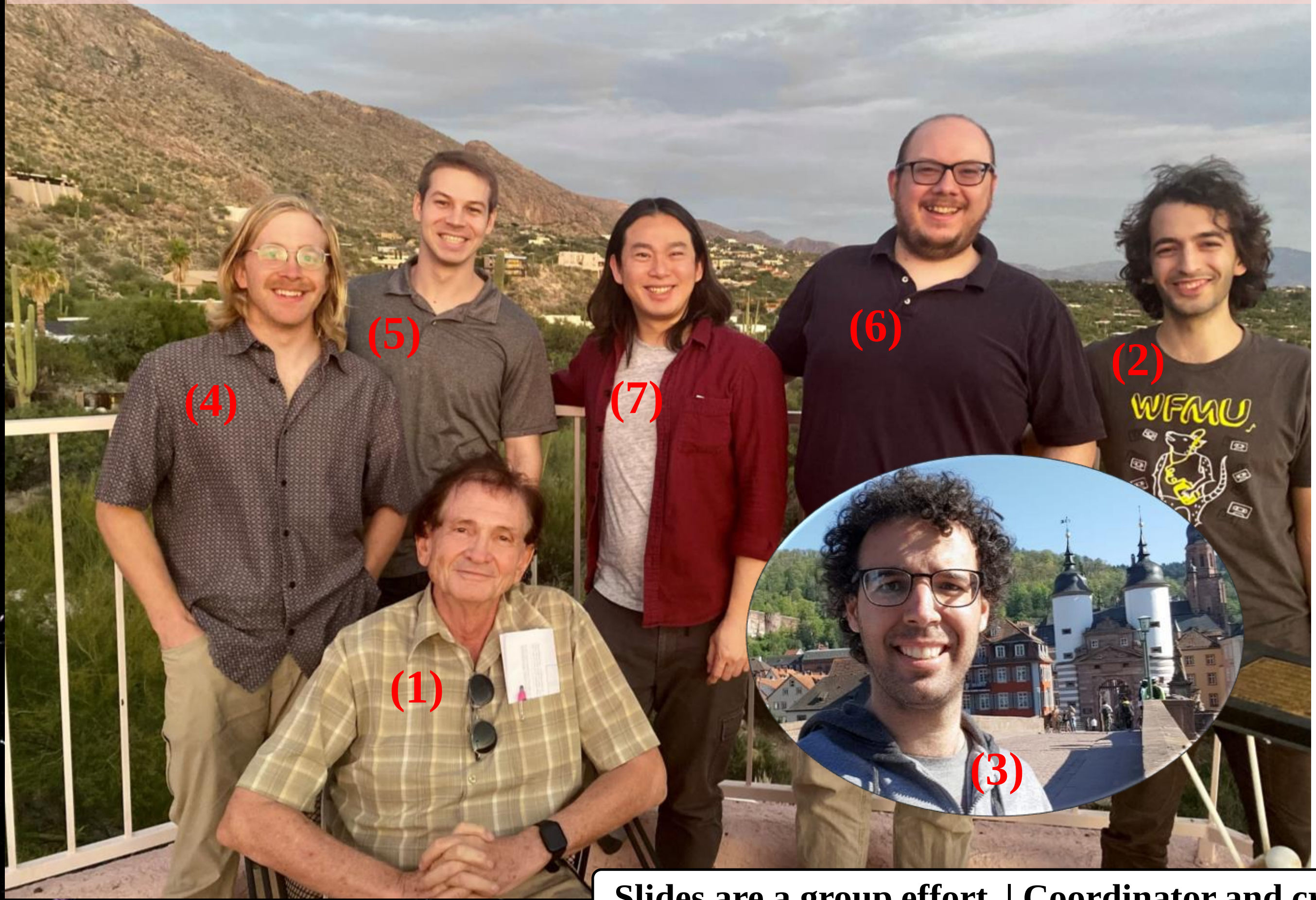
W-Y. P. Hwang, S. P. Kim, "Vacuum Persistence and Inversion of Spin Statistics in Strong QED." Phys.Rev.D 80 065004 (2009)

(2014 – 2021)

- **Identify challenges in the universe of electromagnetic interactions.**

(2022 – 2030?)

- **Accomplish understanding of fundamental laws of physics with strong acceleration.**



All co-authors available for questions and discussions

Strong Fields: Particles, Plasmas and the Æther Report

(1) Johann Rafelski[a], (2) Stefan Evans[a], (3) Martin Formanek[b], (4) Christopher Grayson[a], (5) William Price[a], (6) Andrew Steinmetz[a], (7) Cheng-Tao Yang[a]

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Abstract

We describe recent advances in our understanding of classical and quantum particle dynamics in the presence of strong electromagnetic fields. Strong fields imply strong forces and accelerations in regimes where electrodynamics becomes nonlinear and radiation effects become dominant. The present understanding of the laws of physics was arrived at by observing applied forces in nano-scale regimes as measured in natural units. Therefore, we seek extensions of these laws to fully describe the strong fields physics regime. We explore unit strength acceleration in the experimentally accessible context of ultra-short pulsed lasers, and nonrelativistic and relativistic heavy-ion collisions. We connect individual classical and quantum particle dynamics with high density plasma behavior, and illustrate applications involving atomic, nuclear, and elementary particle physics in the laboratory, in astrophysics and in cosmology. The 'acceleration frontier' is then emerging as a novel research opportunity at the forefront of modern fundamental physics. This is so since acceleration, unlike velocity has an absolute meaning. Exploring strong forces at the acceleration frontier we are probing the structure of Einstein's imponderable æther, today called quantum vacuum.

Keywords: strong fields, critical acceleration, radiation reaction, Euler-Heisenberg, spontaneous particle production, plasma in extreme conditions

Slides are a group effort. | Coordinator and creator/artist: Andrew Steinmetz

Supplemental Slide

Visualization of fields in relativistic heavy-ion collisions

$$\lambda_\mu = \frac{h}{m_\mu c}$$

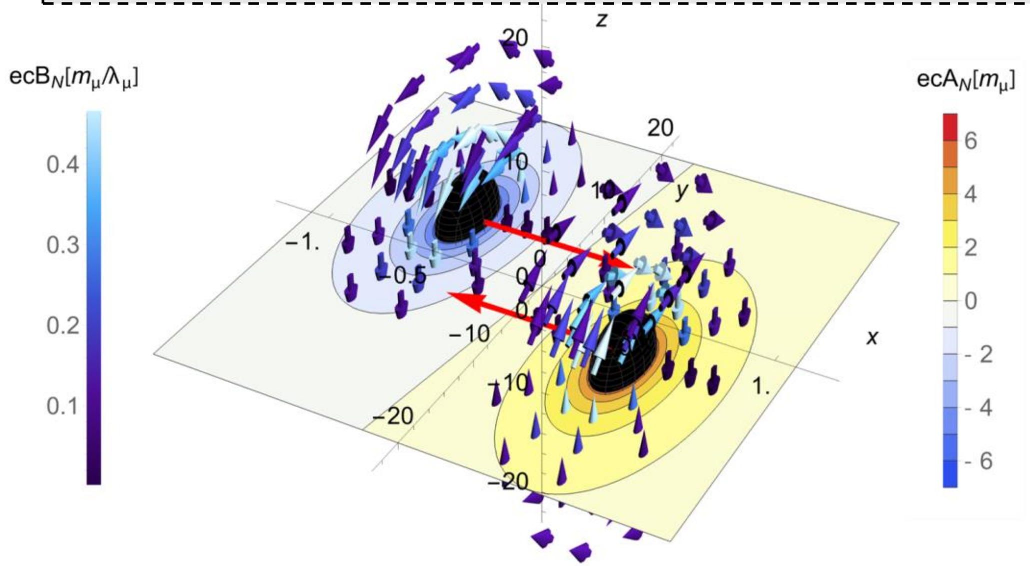
The natural EM fields $F^{\mu\nu}_{ext}$ of the ions is described used Lienard-Wiechert fields, which contains a boosted Coulomb field proportional to velocity and an acceleration or radiation field.

$$e\boldsymbol{E}(\boldsymbol{r},t) = Z\alpha\hbar c\left(\frac{\boldsymbol{n}-\boldsymbol{\beta}}{\gamma^2(1-\boldsymbol{n}\cdot\boldsymbol{\beta})^3|\boldsymbol{r}-\boldsymbol{r_s}|^2} + \frac{\boldsymbol{n}\times\left((\boldsymbol{n}-\boldsymbol{\beta})\times\dot{\boldsymbol{\beta}}\right)}{c(1-\boldsymbol{n}\cdot\boldsymbol{\beta})^3|\boldsymbol{r}-\boldsymbol{r_s}|}\right)_{t_r}$$

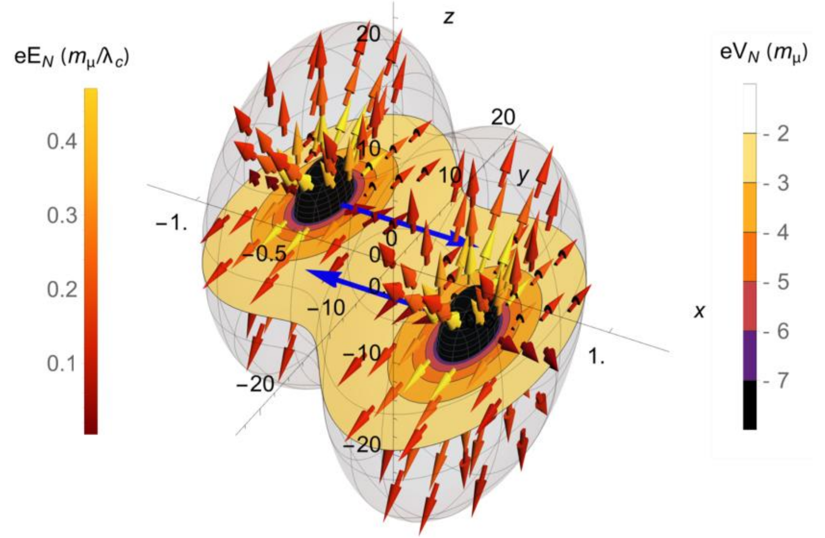
Velocity Field *Acceleration Field*

Ions in the center-of-momentum frame are truly relativistic pancakes.

Here, we are simulating Pb-Pb collisions with a Lorentz factor of $\gamma = 37$.

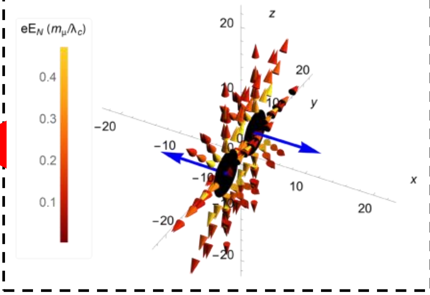


Magnetic Field



Electric Field

Original scale



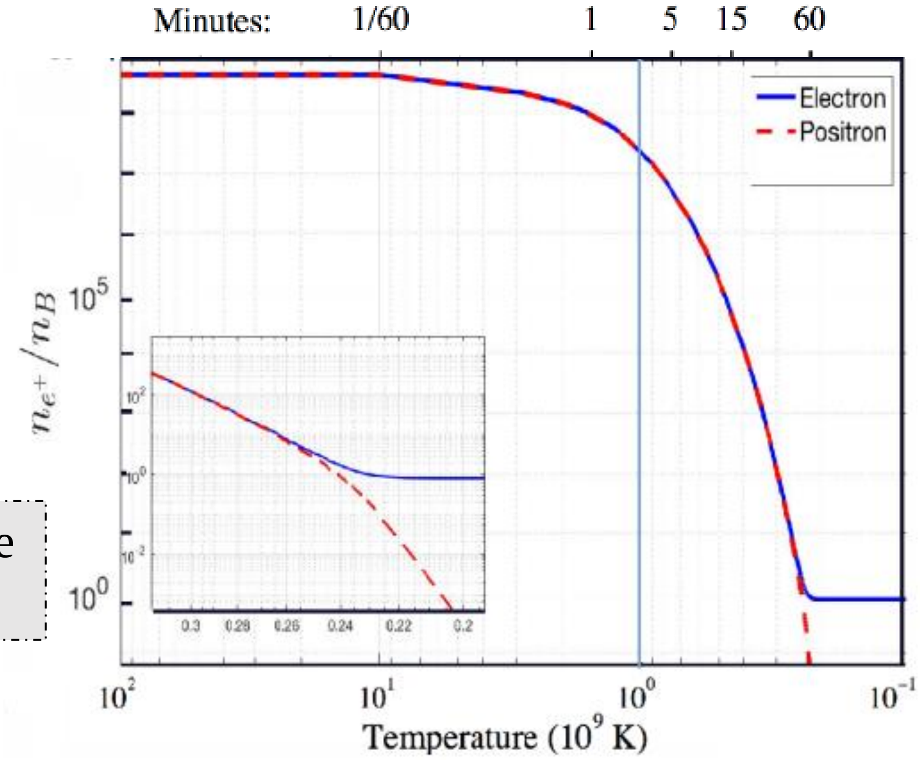
Supplemental Slide

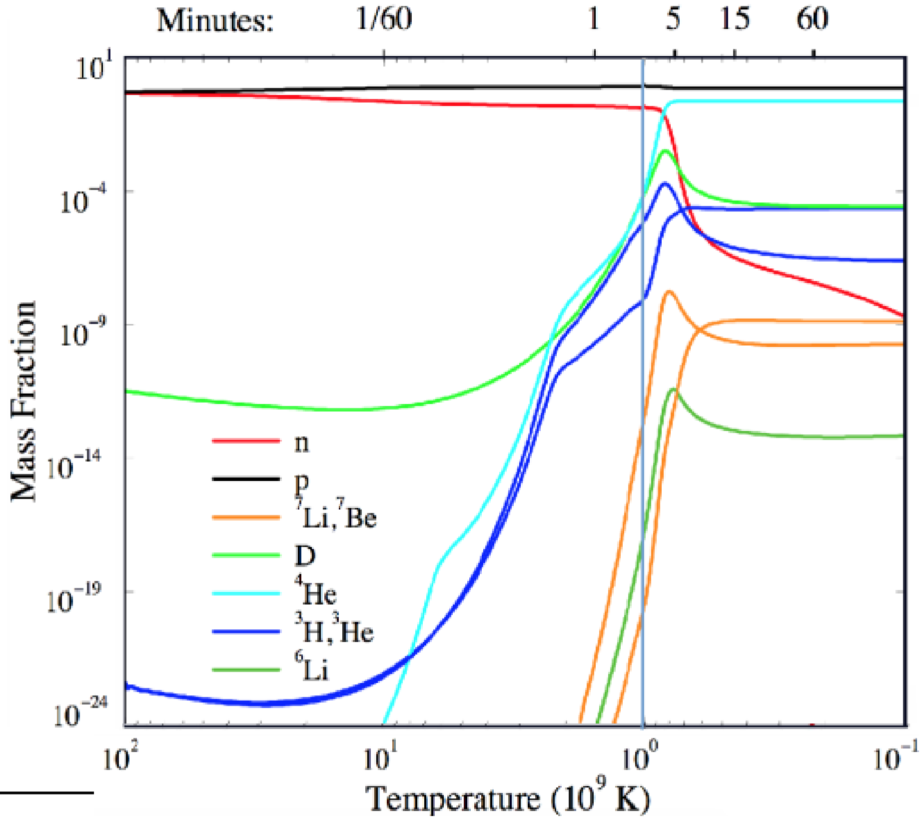
e^+e^- and BBN

Direct overlap between the electron-positron plasma regime and BBN processes.

Plasma screens charges making nuclear reactions faster!

At $T = 0.07$ MeV we have $n_{e^\pm} \approx 10^7 n_B$





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Supplemental Slide

Features of radiation reaction models

$$\tau_0 = \frac{2}{3}\frac{e^2}{4\pi m c^3}$$

Diversity of models:

LAD

- Requires self-interaction
- Unphysical runaway solutions
- Computationally impossible

Kinematic variables only
$\boldsymbol{a^\mu, \dot{a}^\mu}$

LL

- Equivalent to LAD in perturbative limit
- Useless for strong accelerations

Field variables only
$\boldsymbol{F^{\mu\nu}, \dot{F}^{\mu\nu}}$

EFO

- Maximum limiting acceleration.
- Equivalent to LL for weak acceleration.

Kinematic and Fields
$\boldsymbol{a^\mu, \dot{F}^{\mu\nu}}$

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P. A. M. Dirac, "Classical theory of radiating electrons," Proc. R. Soc. A 167, 148 (1938)
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S. E. Gralla, A. I. Harte, R. M. Wald. "A Rigorous Derivation of Electromagnetic Self-force." Rev. D80, 024031(2009)