# Cooling and emission of newborn quark stars

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# Preamble: Vacuum breakdown

There is an opinion, sometimes attributed to Niels Bohr, that electric field of the strength of the critical electric field of quantum electrodynamics $E_c = m^2c^3/e\hbar \sim 10^{18}$ V/m, capable of pair production, could never be created in principle (e.g. Fedotov. Narozhny, Mourou, Korn, 2010).

Several directions were considered to explore overcritical field:

- nuclei with high Z and heavy-ion collisions (superheavy nuclei are unstable; sticking time of quasimolecules is too short);
- colliding ultraintense laser pulses (so far below $10^{-3}E_c$);
- overcritical field in astrophysical environments:
  - induced by charge separation in neutron or strange stars,
  - induced by rotation in magnetars or black holes.

# Pair plasma

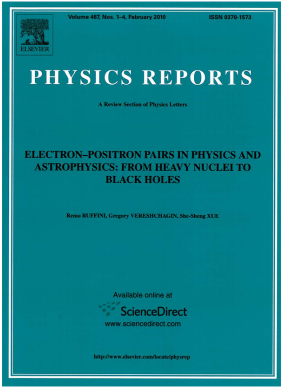
QED predicts the creation of $e^{\pm}$ pairs in strong electric field out of vacuum as a nonperturbative process when $E > E_c$. At such field strength the number of pairs produced is enormous: pair plasma is generated.

In *laboratory* the most promising pathway to create $e^{\pm}$ plasma is linked with the development of ultra-intense lasers within large projects, such as ELI, CoReLS and XCELS.

In *astrophysics* $e^{\pm}$ plasma is present in relativistic and transient high energy sources: gamma-ray bursts, soft gamma repeaters, in magnetospheres of compact objects.

Appearance of pairs in plasma greatly enhances opacity. Short time-scales of variability of astrophysical sources and non-thermal spectra of observed radiation imply that such plasmas are not in thermal equilibrium: the description requires kinetic approach.

# Literature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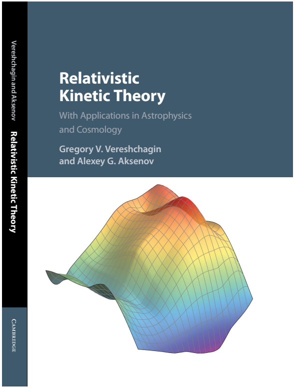
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Relativistic Kinetic Theory
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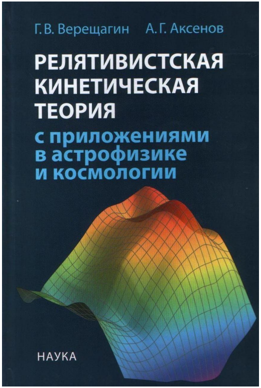
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РЕЛЯТИВИСТСКАЯ КИНЕТИЧЕСКАЯ ТЕОРИЯ
с приложениями в астрофизике и космологии
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# Outline

In what follows, I will present very recent results of the work done by Mikalai Prakapenia and myself:

- ”Pair creation in hot electrosphere of compact astrophysical objects”, ApJ 963, 149 (2024).
- ”Pair creation from radial electromagnetic perturbation of a compact astrophysical object”, Phys. Rev. D 111, 043023 (2025).
- ”Pair luminosity and cooling of newborn strange star: Unpaired quarks”, Phys. Rev. D 113, 023007 (2026).
- ”Pair luminosity and cooling of newborn strange star: CFL and 2SC quarks”, submitted to Phys. Rev. D (2026) [co-authored with Cheng-Jun Xia].
- ”Emission and cooling of a newborn quark star”, submitted to Phys. Rev. D (2026).

# Electrosphere of compact objects

1. Strong electric fields may exist on bare surfaces of quark stars (Alcock, 1986) or neutron stars (e.g. Belvedere et al., 2012). The region with overcritical $E > E_c$ electric field is called *electrosphere*.
2. It is formed because the sharpness of the quark (neutron) star surface is determined by the strong interactions, while electrons are bound by electromagnetic interactions. Thus electron spatial distribution extends to larger, yet microscopic, distances.
3. In vacuum such a field should produce electron-positron pairs, but this does not happen at small temperatures due to the *Pauli blocking*. This is possible when the compact object is just formed, with its surface temperature $k_B T_S \sim \varepsilon_F \sim 20$ MeV (Usov, 1998).
4. Electrons moving in external electric field also produce bremsstrahlung radiation.

# Determination of the rate of pair creation

We solve numerically the system of Vlasov-Boltzmann-Maxwell equations (reduced to Vlasov-Boltzmann-Ampere equations) self consistently, taking into account:

1. pair creation by the Schwinger process;
2. Pauli blocking;
3. particle collisions;
4. backreaction of pairs and electrons on the electric field.

# Vlasov-Boltzmann-Ampere equations

The symmetry of the problem leaves only one spatial coordinate $z$, orthogonal to the surface boundary, and two momentum coordinates: parallel $p_{||}$ and orthogonal $p_{\perp}$ to the electric field direction. The system of equations is

$$\frac{\partial f_{\pm}}{\partial \tilde{t}} + \frac{\tilde{p}_{||}}{\tilde{p}^0}\frac{\partial f_{\pm}}{\partial \tilde{z}} \mp \tilde{E}\frac{\partial f_{\pm}}{\partial \tilde{p}_{||}} = (1 - f_+ - f_-)S + \mathrm{St} f,$$

$$\frac{\partial E}{\partial t} = 2\alpha \int d^3\tilde{p}\,\frac{\tilde{p}}{\tilde{p}^0}(f_- - f_+) - 4\alpha \frac{1}{\tilde{E}} \int d^3\tilde{p}\,\tilde{p}\tilde{p}_0 (1 - f_+ - f_-)S,$$

$$S = -|\tilde{E}| \ln \left[1 - \exp\left(-\frac{\pi(1+\tilde{p}_{\perp}^2)}{|\tilde{E}|}\right)\right] \delta(\tilde{p}_{||}),$$

$$\mathrm{St} f = -\frac{f - f_0}{\tau}, \qquad \tau \simeq (\sigma_T n_e)^{-1}.$$

where $\tilde{t} = tm$, $\tilde{z} = zm$, $\tilde{p} = p/m$, $\tilde{E} = Ee/m^2$, $\alpha = e^2/(\hbar c)$.

# Static electrosphere

It is assumed that electrons obey Fermi-Dirac distribution

$$f_e = \left\{ \exp\left[ \left( \sqrt{\tilde{p}^2 + 1} - \tilde{\mu}_e \right) / \tilde{T} \right] + 1 \right\}^{-1}. \tag{1}$$

The chemical equilibrium condition for electrons is $\tilde{\mu}_e = \tilde{\varphi}$, implying that $\partial \tilde{f}_e / \partial \tilde{t} = 0$. The number density of electrons for $\tilde{p} \gg 1$ and $\tilde{T}_s \ll \tilde{\mu}$ is

$$\tilde{n}_e \approx \tilde{\mu}_e^3 / (3\pi^2) + \tilde{\mu}_e \tilde{T}^2 / 3. \tag{2}$$

The Poisson equation for $\tilde{\varphi} = \varphi m / e$ is

$$\frac{d^2 \tilde{\varphi}}{d\tilde{z}^2} = 4\pi\alpha \left[ \tilde{n}_q - \tilde{n}_e(\tilde{\varphi}) \right], \tag{3}$$

where $n_q$ is the density of a positively charged core. One can choose (1) or (2) to integrate (3). Both approximations fail at large $\tilde{z}$.

# Pair luminosity

The differential pair creation rate is

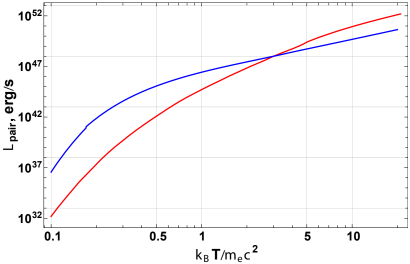
$$\frac{dn_{\pm}}{dt} = -\frac{E/E_c}{2\pi^2} \int_0^{\infty} dp_{\perp}\, p_{\perp}\, (1 - f_e) \times \ln\left[1 - \exp\left(-\frac{\pi(p_{\perp}^2 + m_e^2)}{E/E_c}\right)\right],$$

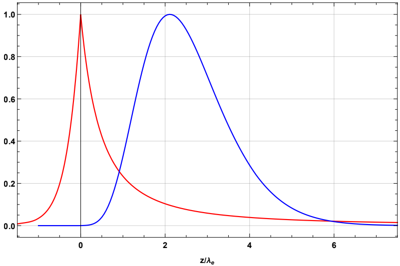
where $p_{\perp}$ is electron momentum orthogonal to the electric field, i.e. $z$ direction. The Schwinger luminosity is estimated as

$$L_{\rm Schwinger} = 4\pi R^2 \gamma m_e \int_0^{z_0} \frac{dn_{\pm}}{dt} dz,$$

where $\gamma$ is the Lorentz factor of positrons, $R$ is the radius of the star, and $z_0$ is the distance from the surface where $\mu_e = m_e$.

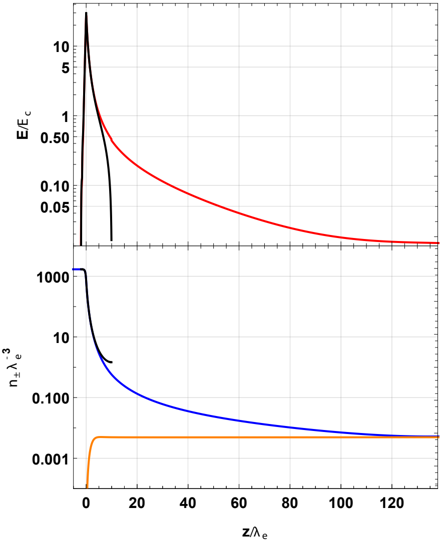
# Pair luminosity and rate



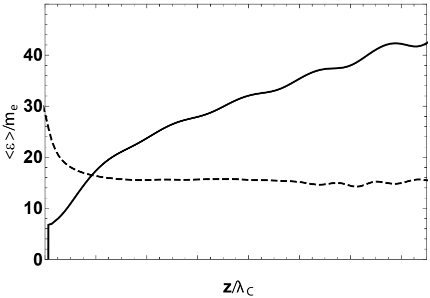



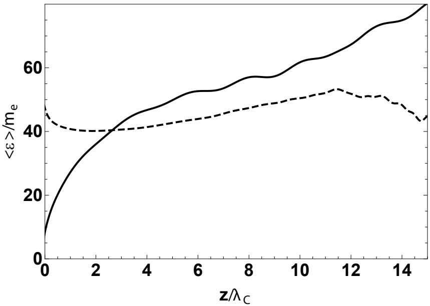

Left: Usov's rate (blue) vs our rate (red). Right: Normalized Schwinger rate (blue) and normalized electric field (red), $T = 1$ MeV.

# Electrosphere at T=1 MeV

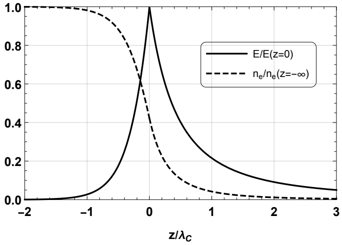


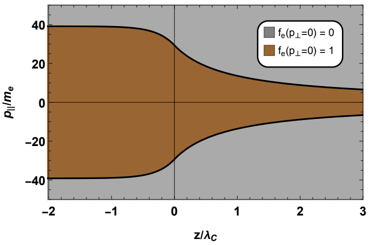
# Lorentz factors: T=1.5 MeV and 3.5 MeV

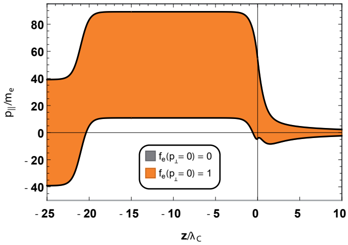


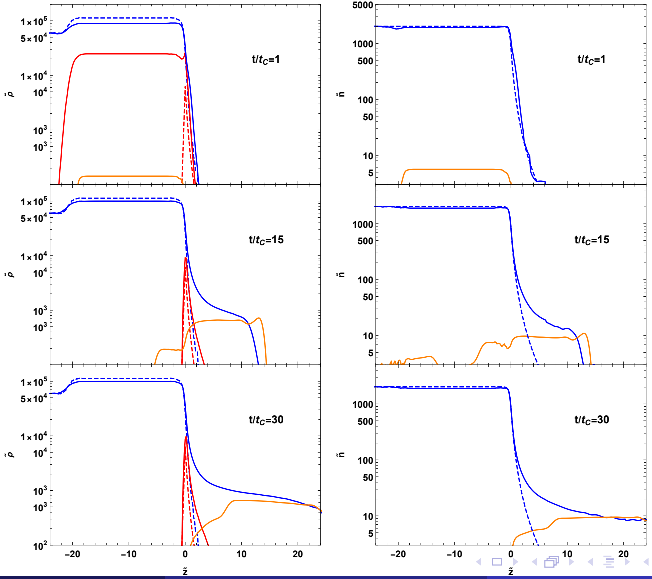
# Radial perturbation: initial condition



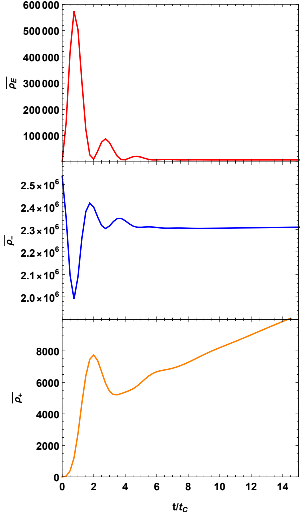



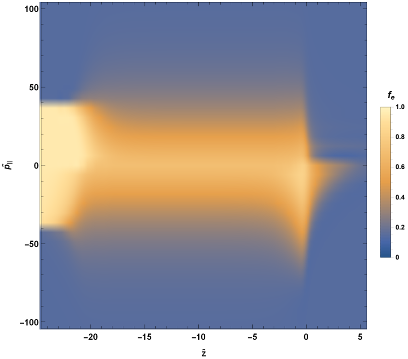



# Radial perturbation: results



# Radial perturbation: more result



# Photon emission from the surface

So far we ignored important emission channel: photons. It was long believed that quark stars are poor emitters because plasma frequency of quarks is very large: about 20 MeV. Therefore quark surface cannot emit thermal radiation (Alcock 1986).
Emission of electroshere has been studied in a number of papers, considering mainly electron-electron bremsstrahlung. It was Zakharov (2010,2011) who demonstrated that the dominant mechanism of photon emission is bremsstrahlung of electrons in electric field. It produces radiation comparable to the black body, both in intensity and in spectrum. Below we adopt his results.

# Photon luminosity

The photon rate is

$$\frac{dn_\gamma}{dtdk} = \int d^3p f_e(\epsilon)[1 - f_e(\epsilon - \omega)] \times \left( \frac{a}{p\chi} \mathrm{Ai}'(\chi) + \frac{b}{p} \int_\chi^\infty dy \mathrm{Ai}(y) \right),$$

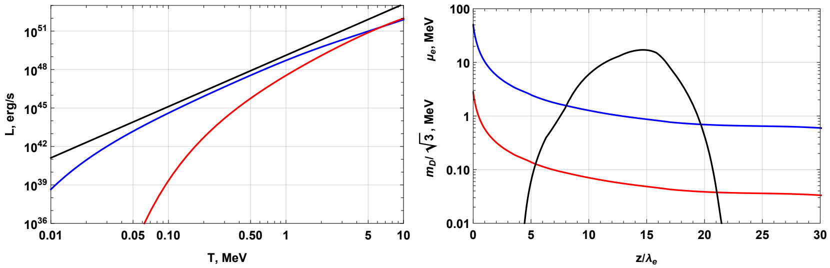
where $k$ is photon momentum, $\omega$ is photon energy, $p$ is electron momentum, $\epsilon$ is electron energy and $a = -2Ng_1/M$, $b = Mg_2 - Ng_1/M$, $\chi = Np^{2/3}/(MxeEp_\perp)^{2/3}$, $g_1 = \alpha x^{-1}(1 - x + x^2/2)$, $g_2 = \alpha 2^{-1} x^3 m_e^2 M^{-2}$, $M = px(1-x)$, $N = m_e^2 x^2 + (1-x)m_\gamma^2$, $x = k/p$.

$$m_\gamma = \omega_{pl} = m_D/\sqrt{3}, \qquad m_D^2 = \frac{4\alpha}{\pi}\left(\mu_e^2 + \frac{\pi^2 T^2}{3}\right).$$

The photon luminosity is

$$L_{\mathrm{Zakharov}} = 4\pi R^2 \int_0^{z_0} dz \int_0^\infty dk \omega(k) \frac{dn_\gamma}{dtdk}.$$

# Comparison of surface luminosities




Left: black body (black), Zakharov photons (blue), Schwinger pairs (red). Right: photon rate (black), $\mu_e(z)$ (blue) and $m_\gamma(z)$ (red).

# Cooling and emission of hot quark star

So far we focused on the structure of electrosphere, pair creation and photon emission in it on microscopic timescales.
Now we turn to the long term cooling of hot bare quark star, taking into account relevant emission processes.
In what follows we consider heat transfer in the quark star. The basic assumptions are the following:

- heat capacity is due to quarks;
- heat transfer operates through quarks;
- cooling is due to neutrinos from the volume, as well as photons and pairs from the surface;
- initial state is isothermal.

# Heat transfer equation

The heat transfer equation with the boundary conditions

$$c_v \frac{\partial T}{\partial t} = -\frac{1}{4\pi r^2}\frac{\partial (4\pi r^2 F_r)}{\partial r} - Q_\nu, \quad F_r = -\kappa \frac{\partial T}{\partial r},$$
$$F_r|_{r=R} = (L_{\text{Schwinger}} + L_{\text{Zakharov}})/4\pi R^2, T(t=0,r) = T_0,$$

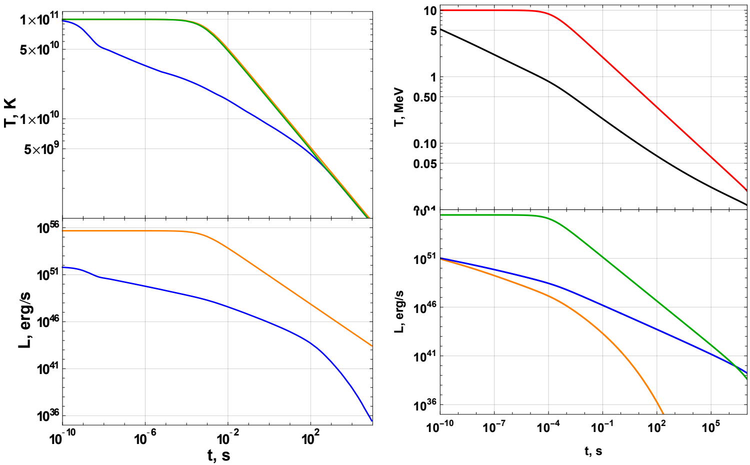
here $L_{\text{Schwinger}}$ is the luminosity in $e^{\pm}$ pairs, $L_{\text{Zakharov}}$ is the luminosity in photons. For the heat capacity of unpaired, 2SC and 2SC+s phases, we use the standard expression of relativistic degenerate fermion gas for ungapped quarks, while for CFL phase we use an expression of superfluid phonons.

Neutrino emissivity is

$$Q_{\nu,2SC} = 3\times 10^{25}\alpha_s \frac{\mu_u \mu_d}{(400\text{MeV})^2}\frac{\mu_e}{10\text{MeV}} T_9^6,$$

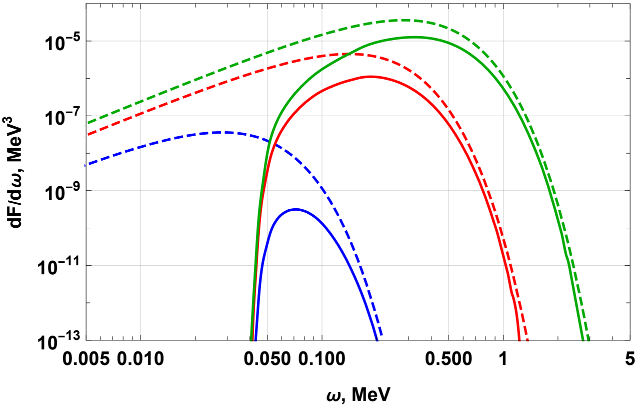
$$Q_{\nu,CFL} = 10^{20}\left(\frac{n_q}{0.22\ \text{fm}^{-3}}\right)^{1/3} T_9^8 e^{-2\Delta/k_B T}\ \frac{\text{erg}}{\text{s cm}^3}.$$

# Cooling of hot quark star




Left: unpaired quarks, right: 2SC quarks.

# Bremsstrahlung spectrum from electrosphere




Photon spectra of the electrosphere: $T = 0.01$ MeV (blue), $T = 0.05$ MeV (red), $T = 0.1$ MeV (green). Dashed: black body.

# Spectral evolution

- The electrosphere itself is collisionless and transparent.
- However, for $T_{tr} > 22$ keV, the process $\gamma\gamma \to e^{+}e^{-}$ makes the medium opaque.
- Photons and pairs thermalize (Aksenov, Ruffini, GV, 2007) and produce relativistic outflow.
- Such outflow emits from relativistic photosphere (Ruffini, Siutsou, GV, 2013), with the spectrum of black body (accelerating photon thick pair dominated case).
- When temperature decreases below $T_{tr} = 22$ keV the medium becomes transparent the spectrum of electrosphere should be observed.

# Conclusions

1. We revisited the observational appearance of hot bare compact object endowed with electrosphere.
2. The surface cools due to bremmstrahlung photons and pair creation in the electrosphere, while the interior cools down due to neutrino emission.
3. The birth of a quark star is manifested as a flash of black body radiation originating from the relativistic photosphere with temperature decreasing below 1 MeV in a ms. The spectrum remains a black body up to $t \simeq 10^6$ s. At $T < 22$ keV, the spectrum transforms into a narrow peak, centered at 40 keV.
4. This characteristic spectral feature is a unique feature of compact astrophysical object possessing an electrosphere. We expect that such observatories as Einstein Probe, Fermi, INTEGRAL, NuSTAR, and planned XEUS will be able to detect these objects.