Pair creation and photon emission by newborn quark star

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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:

- In laboratory conditions:
  - 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 $10^{-3}E_c$);
- In astrophysical environments:
  - gravitational collapse of a charged star (self-regulated, $E < 0.06E_c$);
  - induced by rotation in magnetars or black holes;
  - induced by charge separation in neutron or strange stars.

Outline and the literature

In what follows, I will present the results obtained with Mikalai Prakapenia within the joint ICRANet-BRFFR project (2024-2026):

- "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 (2026a).
- "Pair luminosity and cooling of newborn strange star: CFL and 2SC quarks", Phys. Rev. D 114, 043029 (2026b) [co-authored with Cheng-Jun Xia].
- "Emission and cooling of a newborn quark star", Phys. Rev. D 114, L081307 (2026c).

These results were possible thanks to our earlier joint work: PLA (2019, 2020) and especially PRD (2023), also supported by ICRANet and BRFFR.

Strange stars

- Soon after quarks were introduced by Gell-Mann it was proposed (Ivanenko, Kurdgelaidze 1965) that at densities larger than nuclear one, hadrons may dissolve into quarks.
- Bodmer (1971) and Witten (1984) formulated the strange quark matter hypothesis: quark matter containing equal amount of u, b, s quarks is a true ground state of matter.
- First comprehensive studies of strange stars is done in the 1980s (Alcock, Farhi, Olinto, 1986). For reviews see Weber (2005) and Zhang, Huang, Zou (2024).
- Quark matter may also be present inside neutron stars: hybrid stars.

Observational evidence?

Quark star candidates: PSRB0943+10 (pulsar, low mass 0.02 $M_\odot$), 3C 58 (pulsar), XTE J1739-285 (low mass X-ray binary), ASASSN-15lh (quark-nova), GW190425 (remnant is a QS).

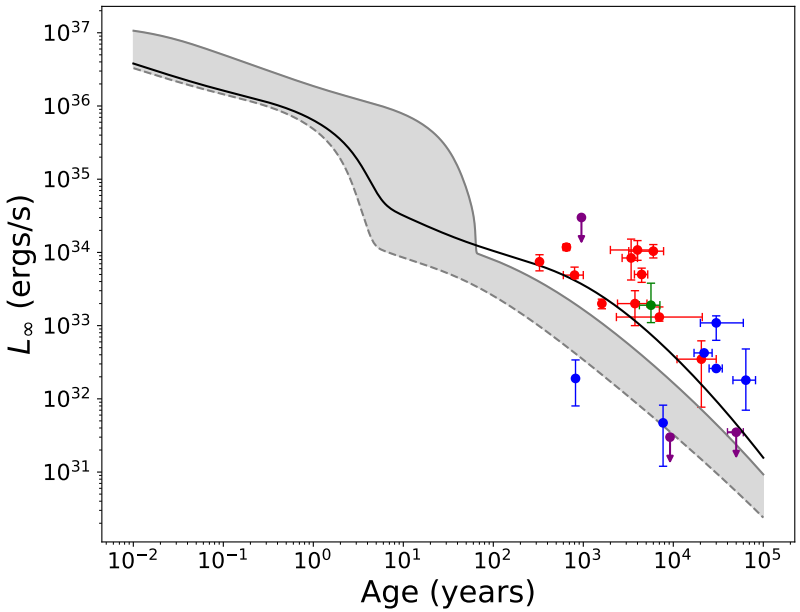


Figure: Cooling QSs with hadron crust vs data from isolated NSs [Fonseca, Fraga Phys. Rev. D 113, 083015 (2026)].

Example of SS with unpaired quarks

The conditions of chemical equilibrium and electric neutrality read

$$\mu_s = \mu_u + \mu_e, \quad \mu_d = \mu_u + \mu_e,$$
$$\frac{2}{3}n_u - \frac{1}{3}n_d - \frac{1}{3}n_s - n_e = 0,$$

Recall that $m_u \sim m_d \ll m_s$. The bag model:

$$P = \sum_{i=u,d,s,e} P_i - B,$$
$$\epsilon = \sum_{i=u,d,s,e} \epsilon_i + B,$$

where B is the bag constant, pressure P_i and energy density ϵ_i of complete degenerate matter. Temperature effects on the structure of SS can be neglected, provided $T \ll \mu_q$.

Strange star structure

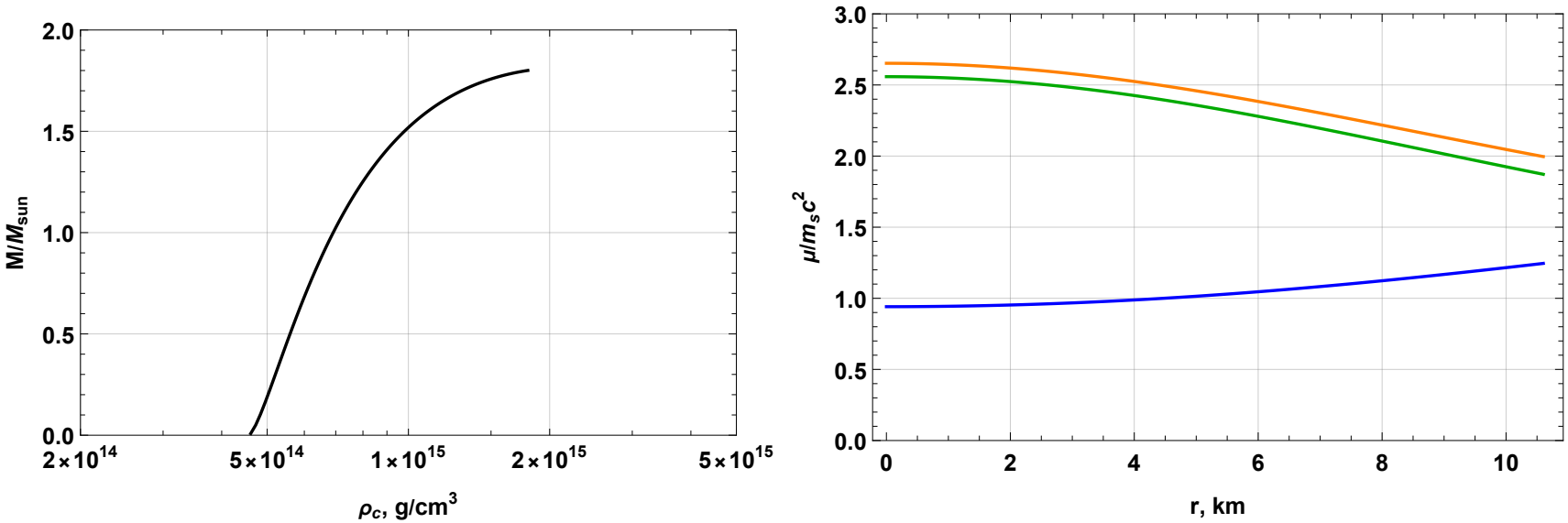


Figure: Left: total mass vs. central density for stable quark stars. Right: chemical potentials as functions of radius of the star with $M = 1.4M_\odot$: $\mu_s = \mu_d$ (orange), μ_u (green), $10\mu_e$ (blue).

Electrosphere of a strange star

1. Strong electric fields may exist on bare surfaces of strange 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 star surface is set by the strong interactions, while electrons spatial distribution is extends to larger, yet microscopic, distances.
3. Hot, newly formed strange stars must be bare, as neutrino winds blow off the matter from their surface.
4. In vacuum $E > E_c$ produces electron-positron pairs, but at low temperatures the process is blocked by the *Pauli principle*. So pair wind must be a signature of hot ($T_S \sim \varepsilon_F \sim 20$ MeV) strange star (Usov, 1998).
5. Electrons moving in external electric field also produce bremsstrahlung radiation.

Structure of electrosphere

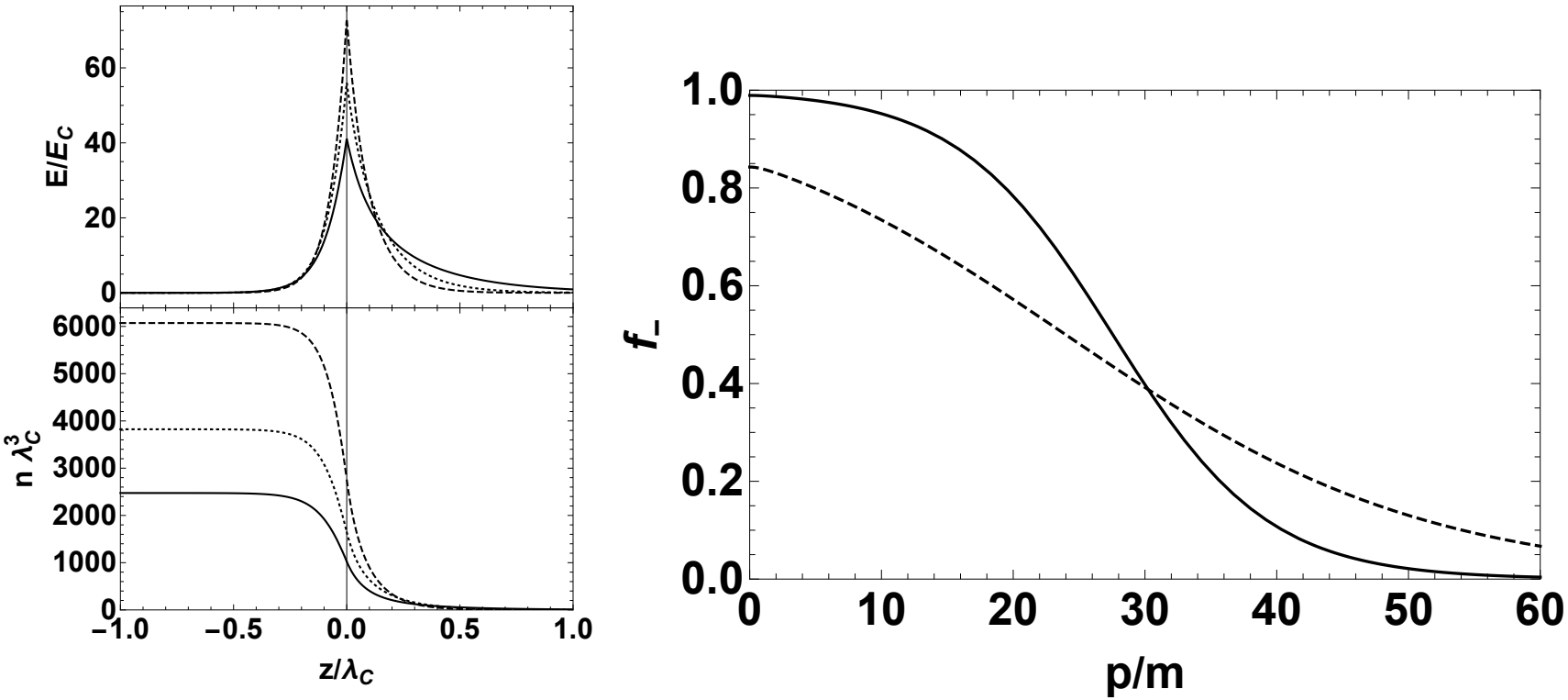


Figure: Left: electric field (top) and electron density (bottom) for $T_S = 3m_e$ (solid), $T_S = 6m_e$ (dotted), $T_S = 9m_e$ (dashed). Right: initial DF of electrons in the momentum space at the surface for $T_S = 3m_e$ (solid) and $T_S = 7m_e$ (dashed).

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

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

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

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

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

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

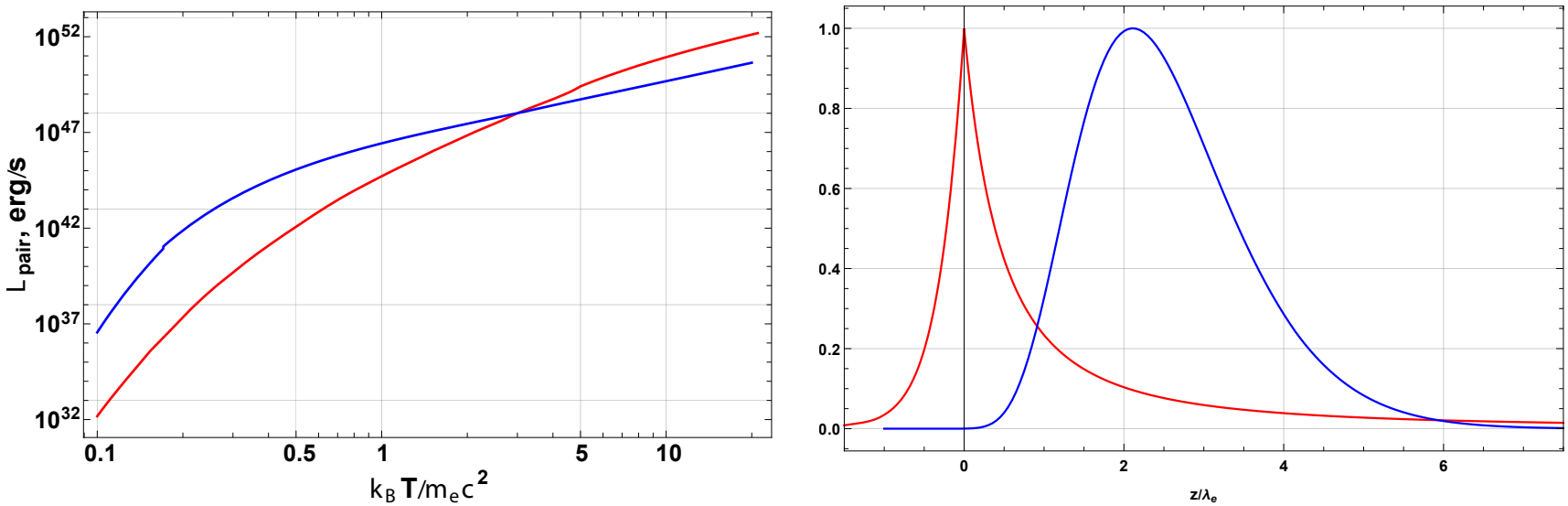
$$\frac{dn_{\pm}}{dt} = -\frac{E/E_c}{2\pi^2}\int_0^{\infty} dp_{\perp}\, p_{\perp}\,(1-f_e) \times \ln\left[1-\exp\left(-\frac{\pi(p_{\perp}^2+m_e^2)}{E/E_c}\right)\right],$$

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

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

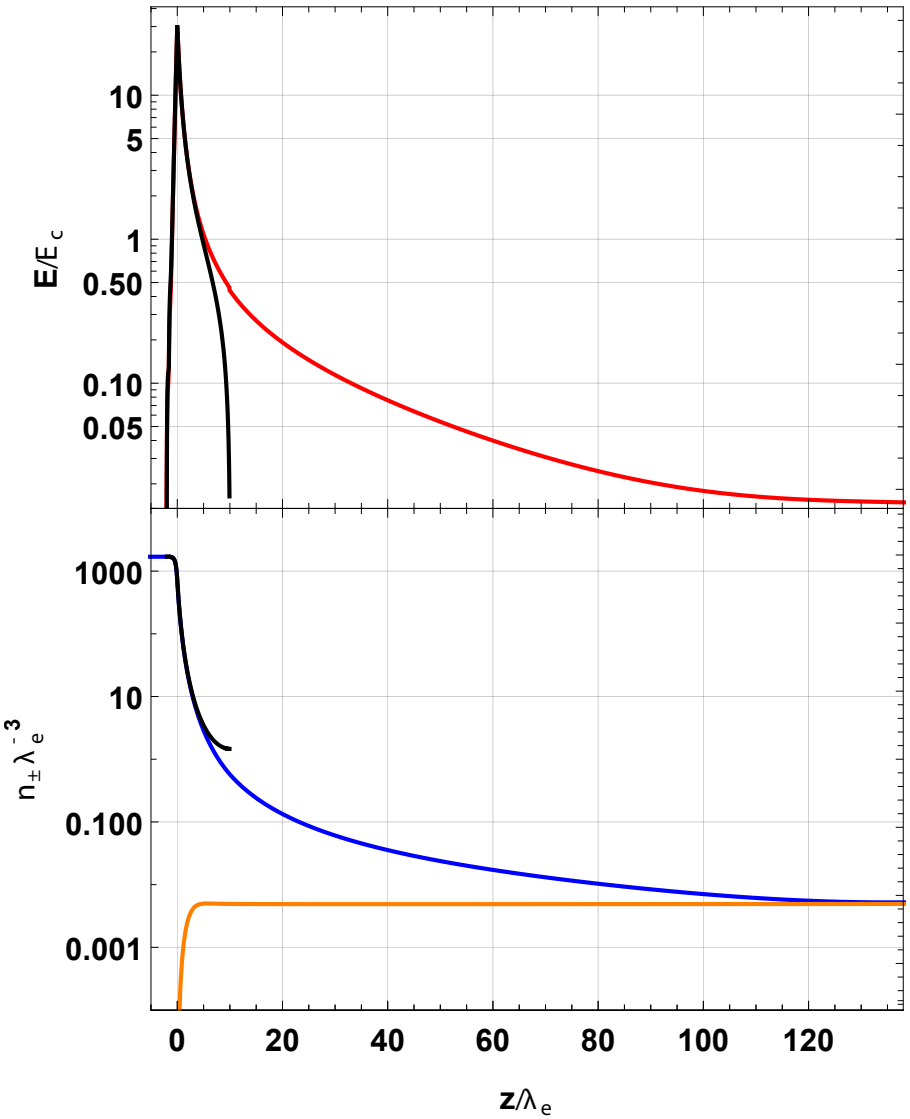
where γ is the Lorentz factor of positrons, R is the radius of the star, and z_0 is the distance from the surface where $\mu_e = m_e$.

Pair luminosity and rate [ApJ 2024]

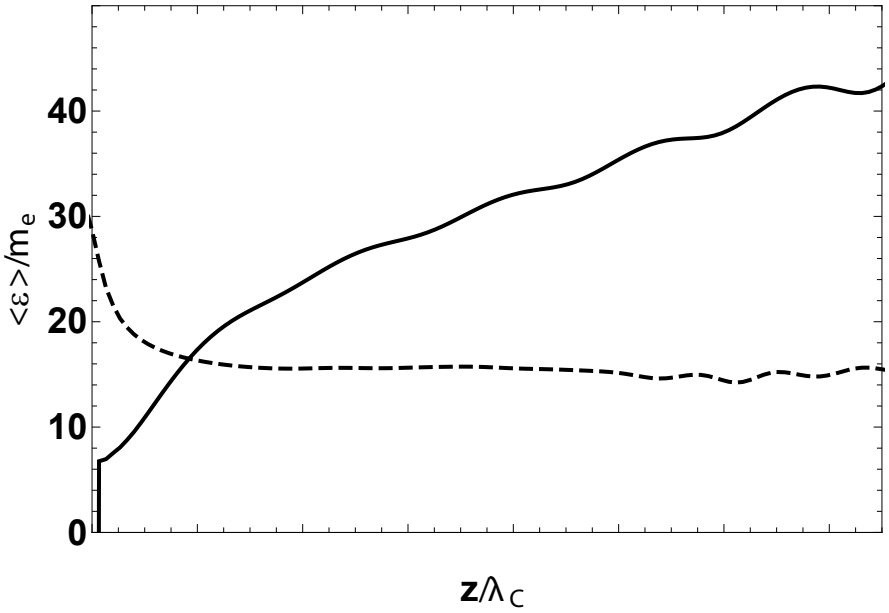


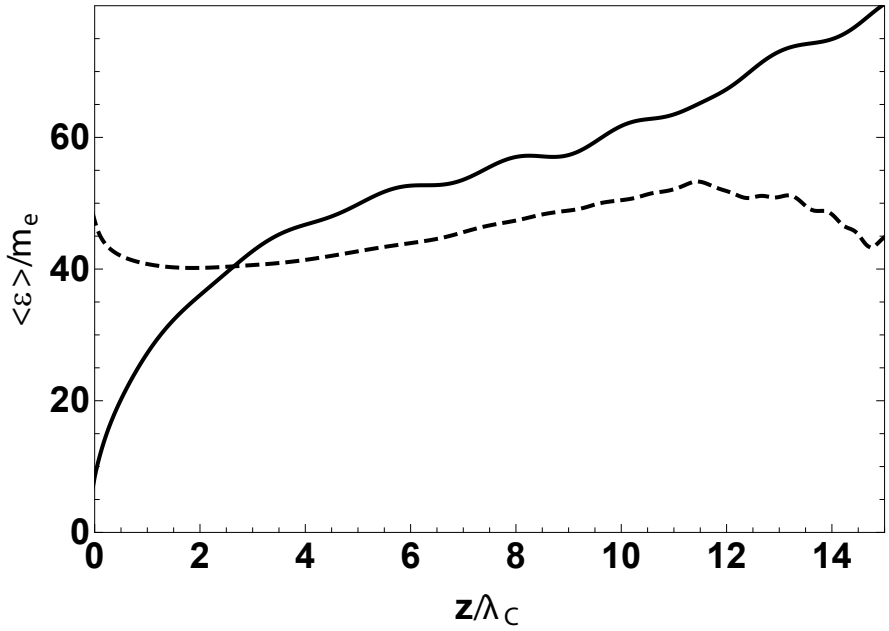
Left: Usov's rate (blue) vs our rate (red). Right: Normalized Schwinger rate (blue) and normalized electric field (red), $T = 1$ MeV.

Electrosphere at T=1 MeV

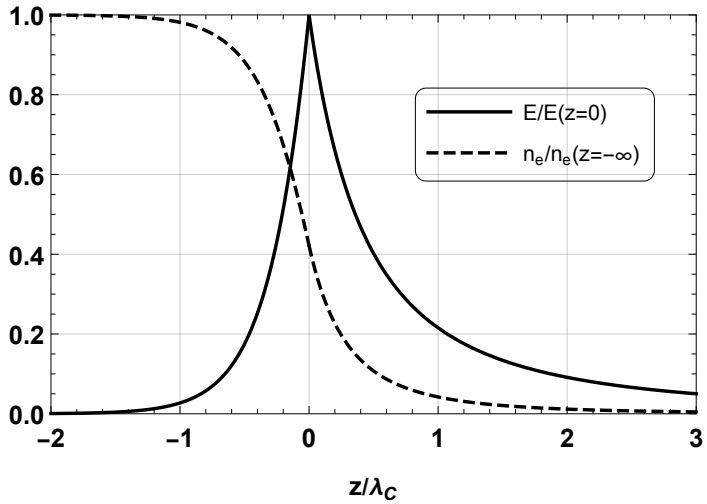


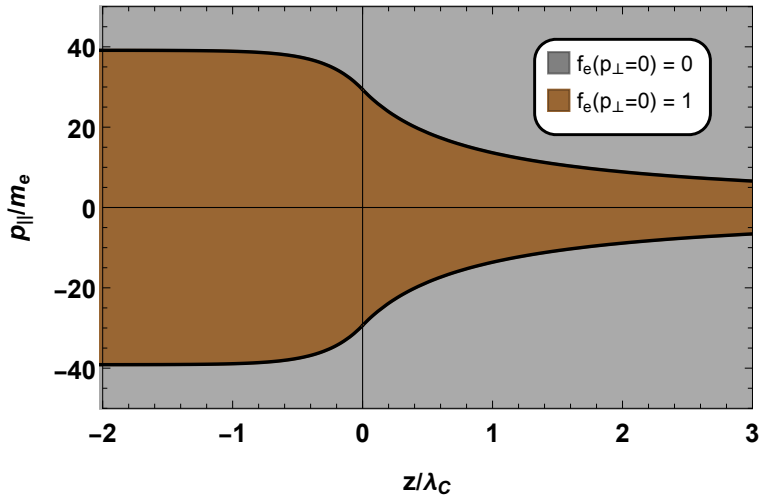
Lorentz factors: T=1.5 MeV and 3.5 MeV

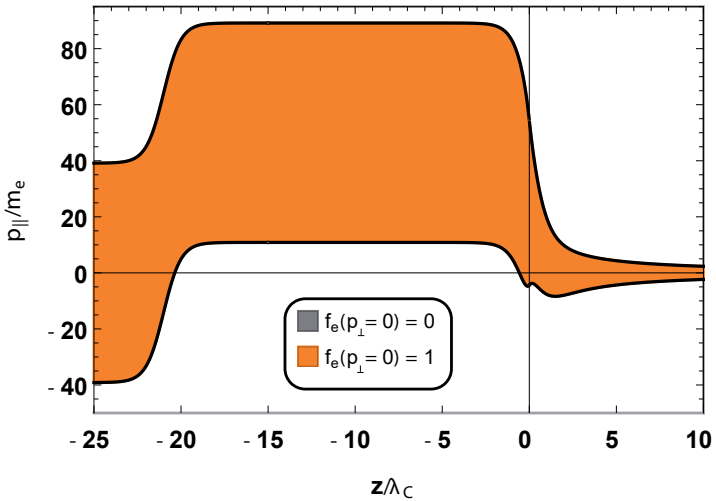




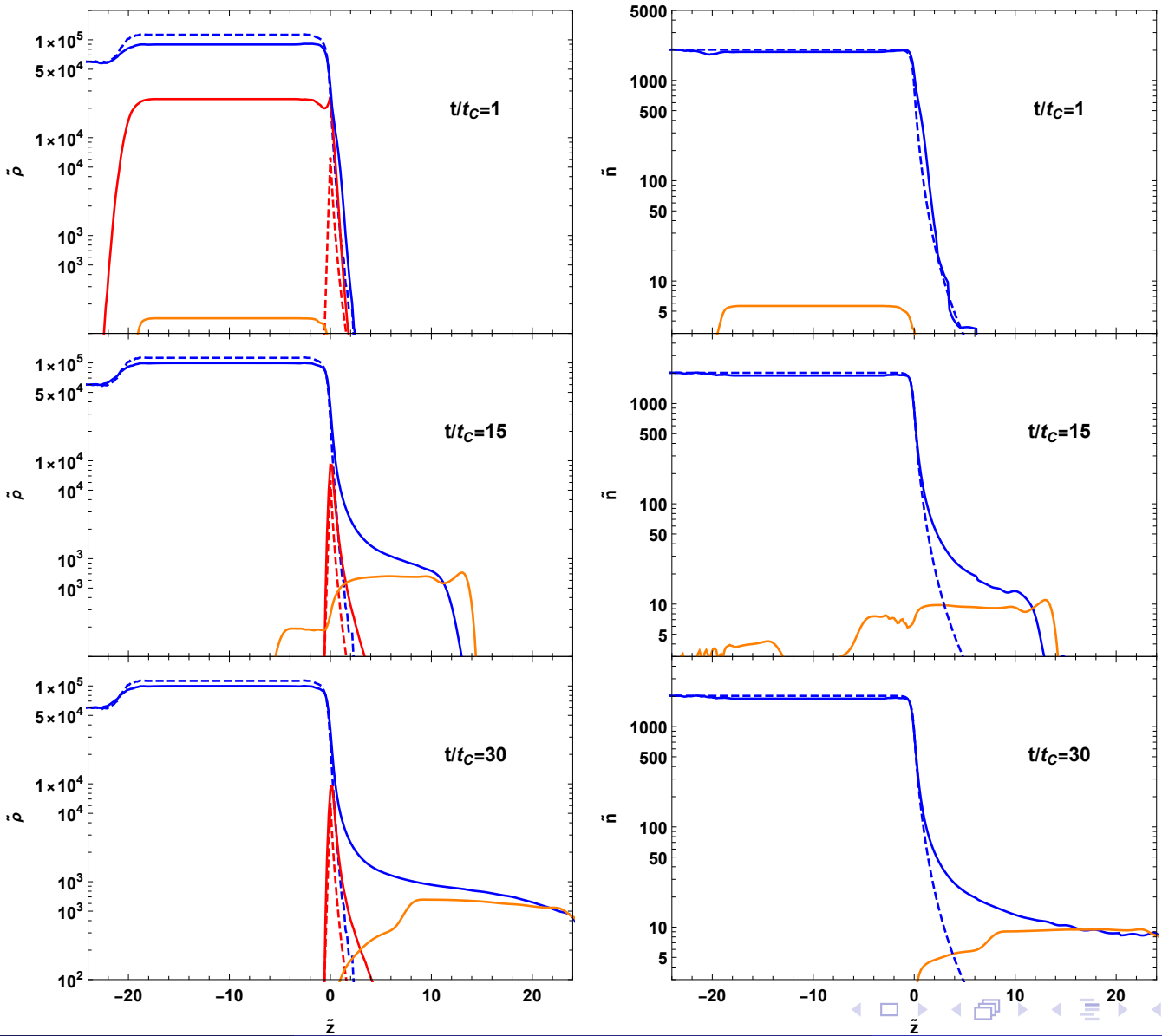
Radial perturbation: initial condition



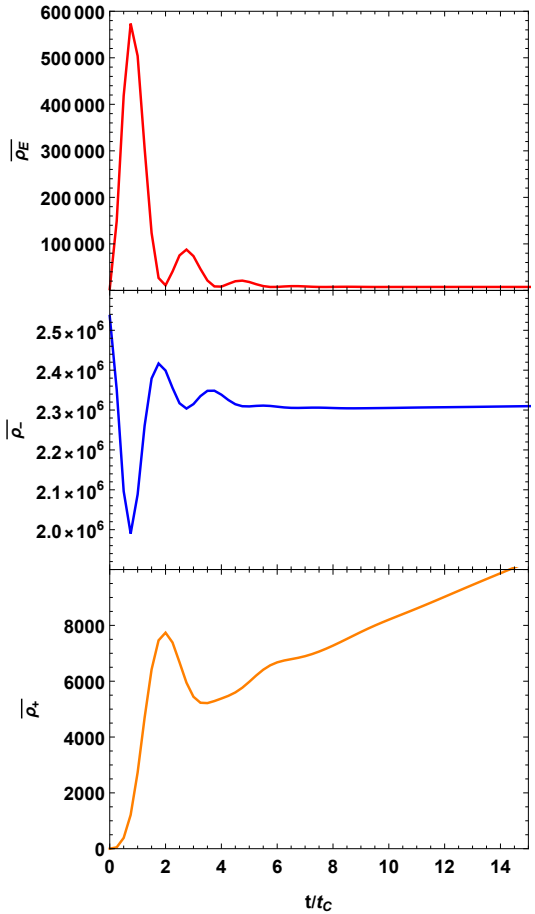


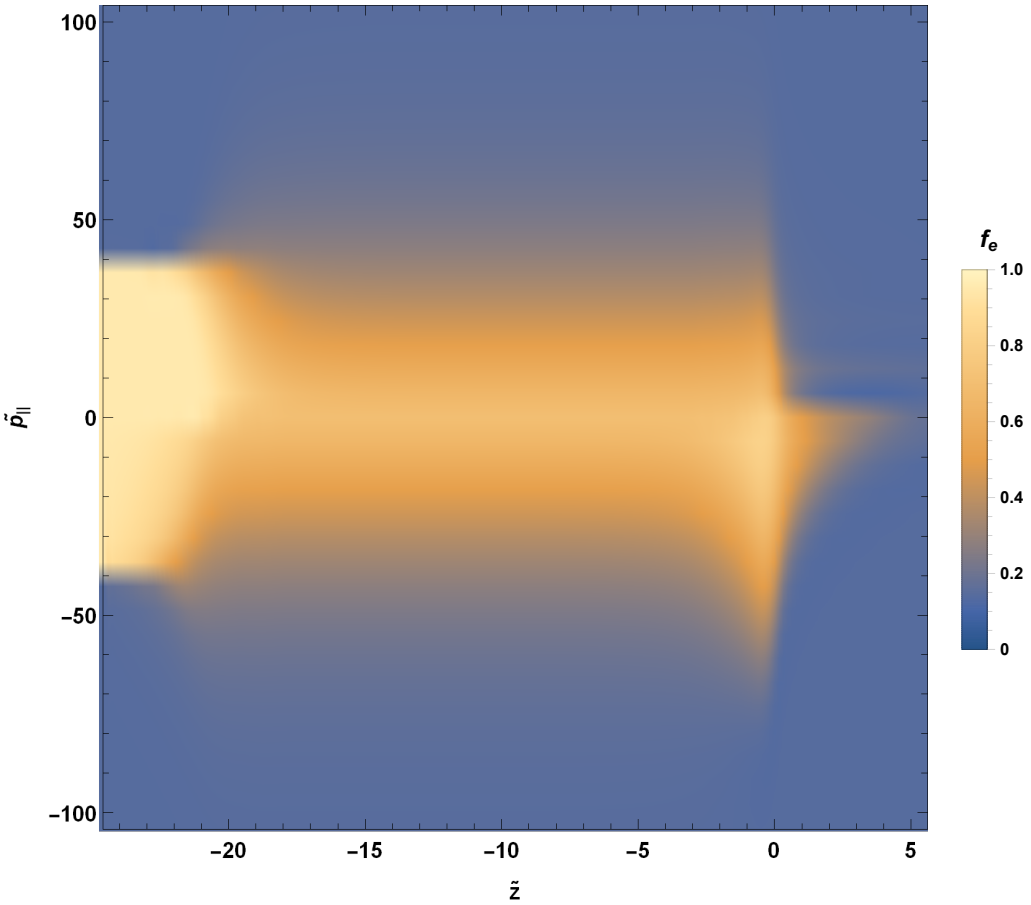


Radial perturbation: results [PRD 2025]



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

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

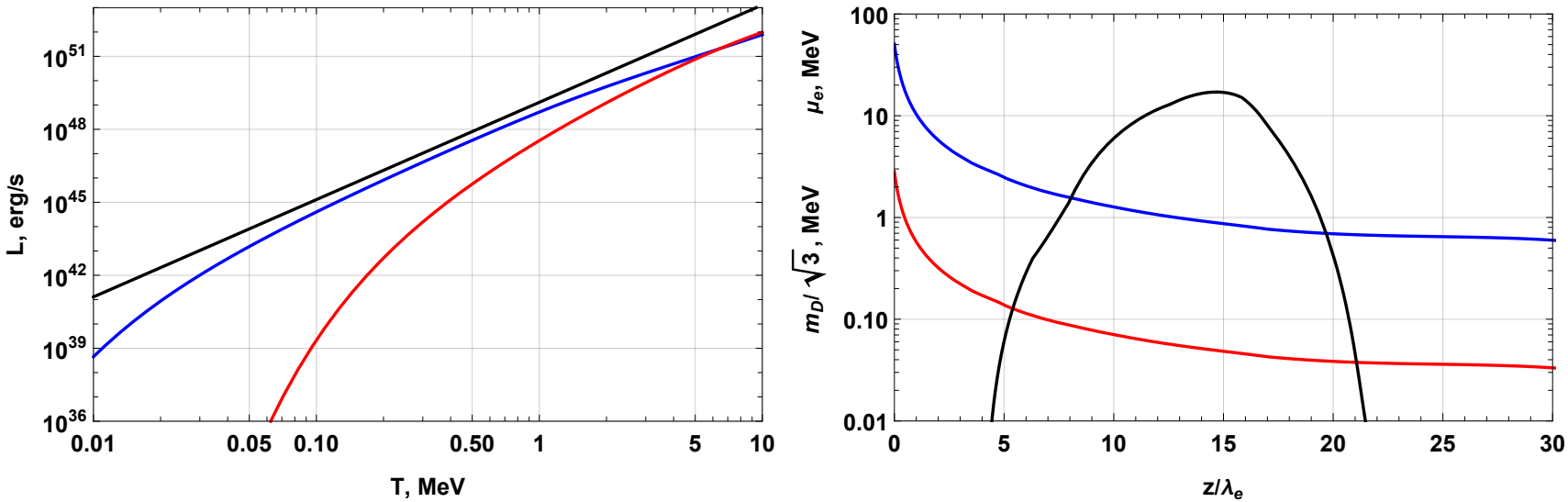
where k is photon momentum, ω is photon energy, p is electron momentum, ϵ is electron energy and $a = -2Ng_1/M$,
$b = Mg_2 - Ng_1/M$, $\chi = Np^{2/3}/(MxeEp_\perp)^{2/3}$, $g_1 = \alpha x^{-1}(1 - x + x^2/2)$,
$g_2 = \alpha 2^{-1}x^3 m_e^2 M^{-2}$, $M = px(1-x)$, $N = m_e^2 x^2 + (1-x)m_\gamma^2$, $x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

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

The photon luminosity is

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

Comparison of surface luminosities [PRD 2026c]



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 [PRD 2026a,2026b,2026c]

The heat transfer equation with the boundary conditions

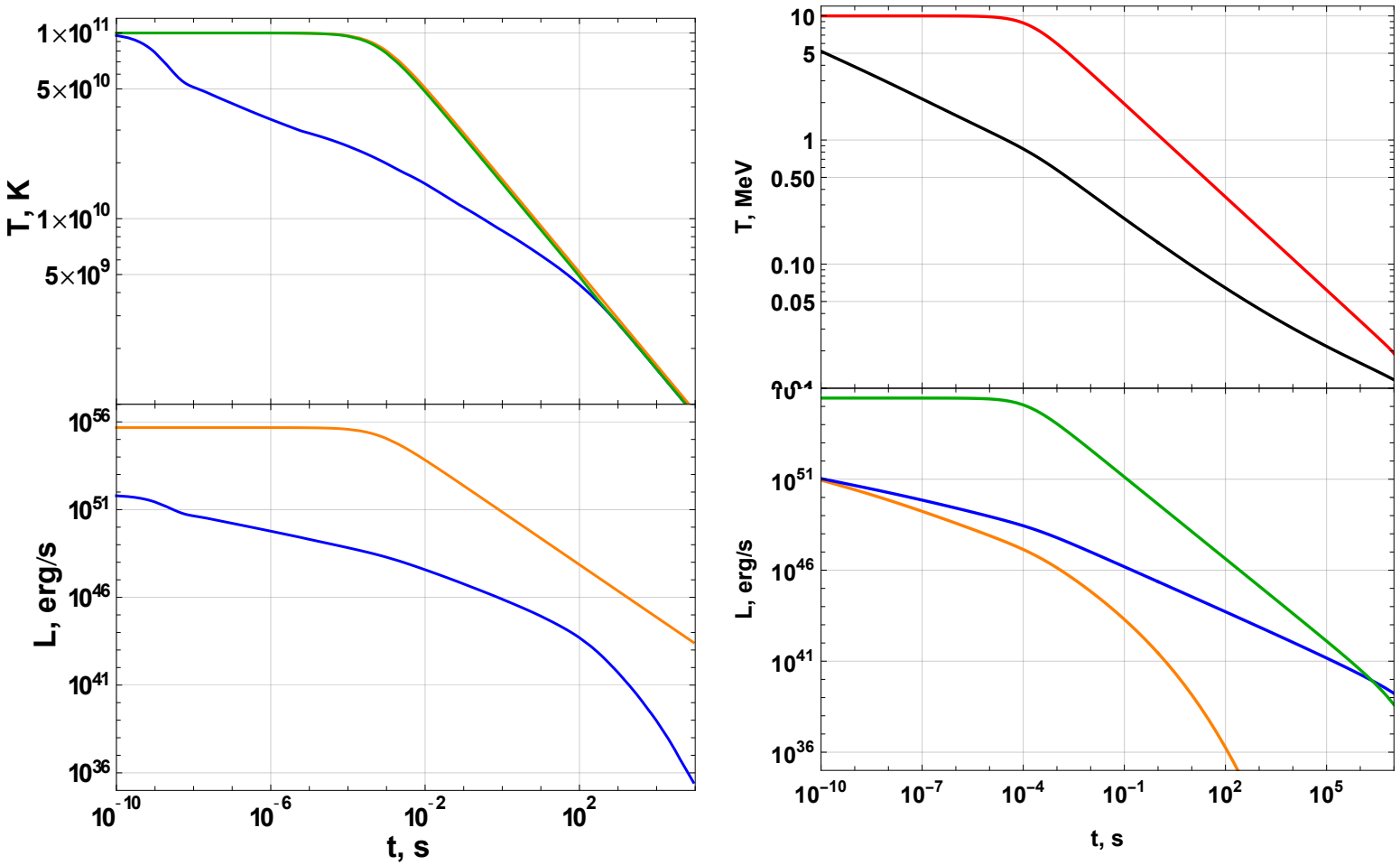
$$c_v \frac{\partial T}{\partial t} = -\frac{1}{4\pi r^2}\frac{\partial (4\pi r^2 F_r)}{\partial r} - Q_\nu, \quad F_r = -\kappa \frac{\partial T}{\partial r},$$
$$F_r|_{r=R} = (L_{\text{Schwinger}} + L_{\text{Zakharov}})/4\pi R^2, T(t=0,r) = T_0,$$

here $L_{\text{Schwinger}}$ is the luminosity in $e^{\pm}$ pairs, L_{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

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

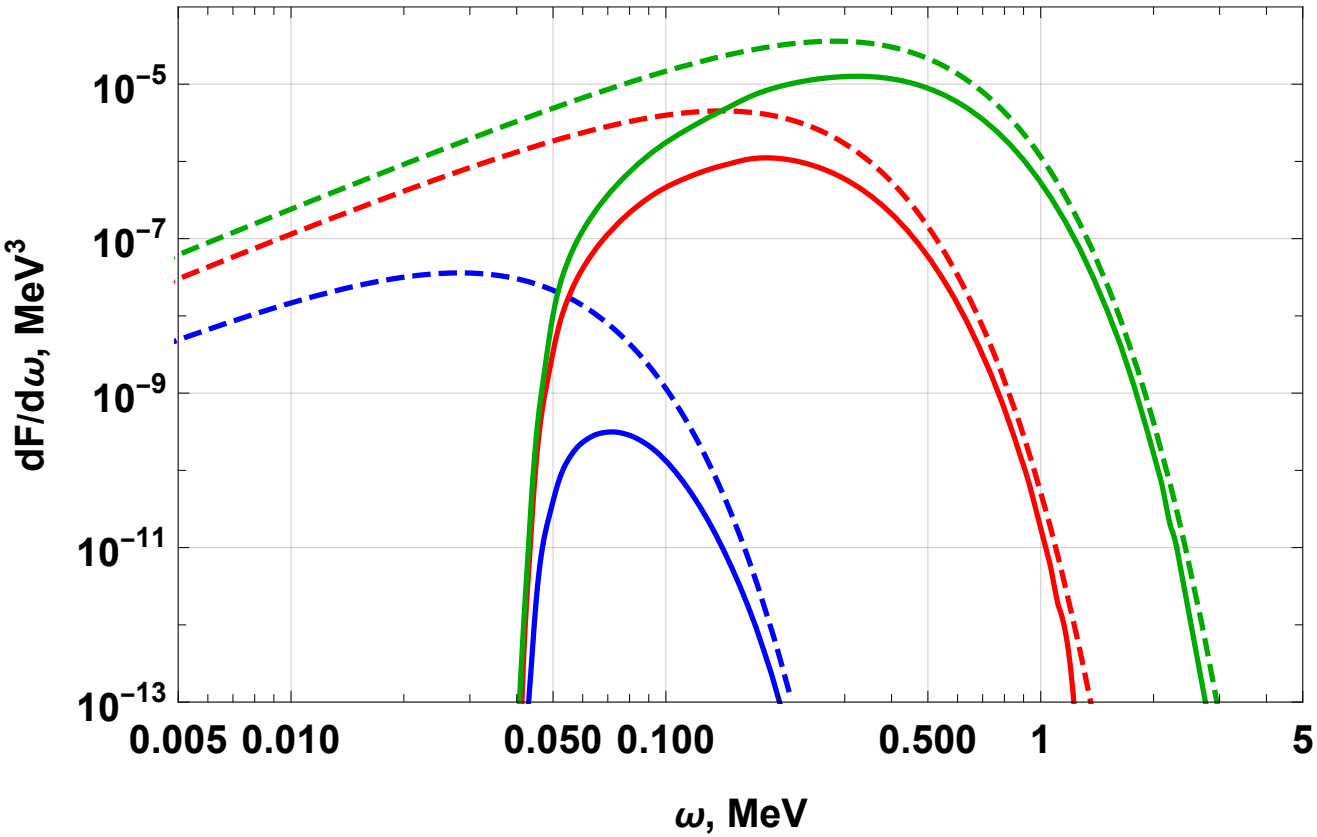
$$Q_{\nu,CFL} = 10^{20}\left(\frac{n_q}{0.22\ \text{fm}^{-3}}\right)^{1/3} T_9^8 e^{-2\Delta/k_B T}\ \frac{\text{erg}}{\text{s cm}^3}.$$

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 and solved the hierarchy of problems:
   - structure of strange stars with given EOS (TOV);
   - structure of electrosphere (Vlasov-Maxwell);
   - cooling dynamics (heat transfer).
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 produces a flash of black body radiation originating from the relativistic photosphere with temperature decreasing to 1 MeV in a ms. Further, as $T < 22$ 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 X-ray observatories will be able to detect these objects.