Gapless Color Superconductivity in Quark Matter

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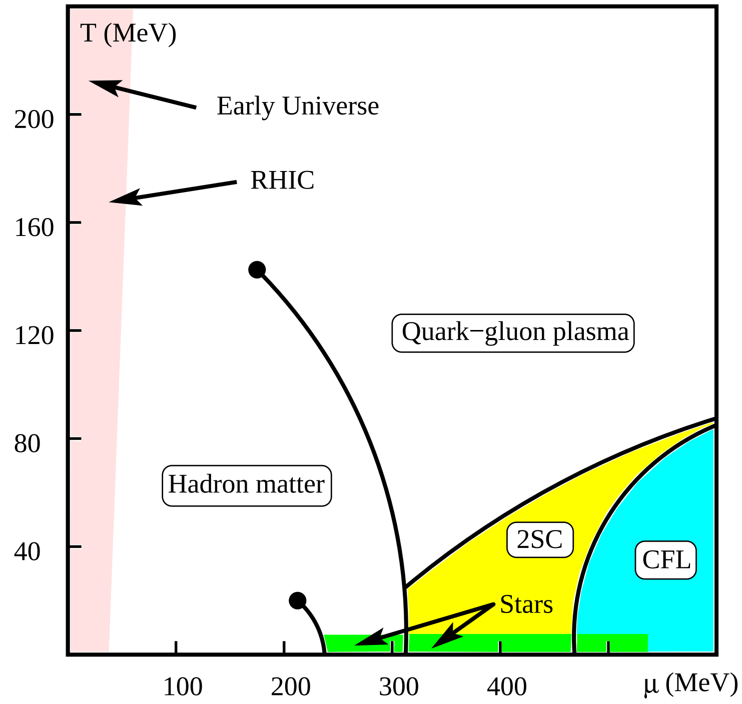
References

- I. Shovkovy and M. Huang, Phys. Lett. B **564** (2003) 205, `hep-ph/0302142`
- M. Huang and I. Shovkovy, in preparation...

Phase diagram of QCD

Dense quark matter is a color superconductor!

[Barrois,78], [Bailin & Love,84], [Alford et al.,98], [Rapp et al.,98],. . .



Where to find CSC?

- Interior of compact stars:
  M-R relation, surface temperature, neutrino flux, magnetic field, glitches, strangelets in cosmic rays, R-mode instability, etc.

- Heavy ion collisions (?)
- Cosmic strangelets (?)

Motivation: compact stars

Color superconductivity $\rightarrow$ **gap** in quasiparticle spectrum

- Thermodynamic properties (equation of state)
  - mass-radius relation
  - internal star structure
- Transport properties (conductivities, viscosities, mean free paths)
  - cooling rate
  - r-mode instability
  - glitches (crystalline phase)
- Other properties
  - magnetic field generation/penetration
  - rotational vortices

Neutrality vs. color superconductivity

- The "best" 2SC phase appears when $n_d \approx n_u$,
- but neutral matter appears when $n_d \approx 2n_u$
- Electrons do not help (!):

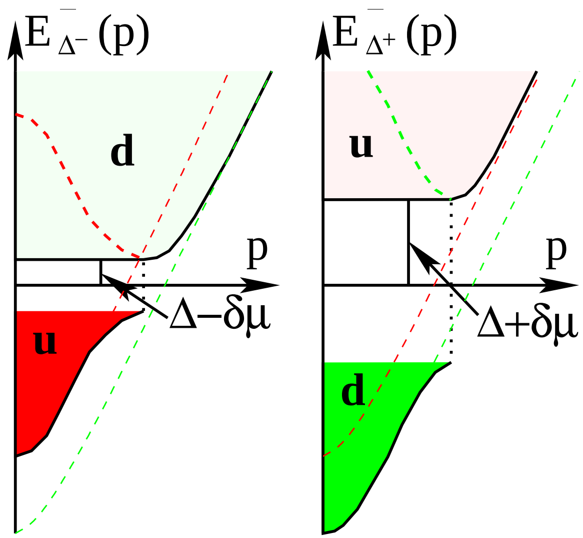
$$n_d \approx 2n_u \;\Rightarrow\; \mu_d \approx 2^{1/3}\mu_u \;\Rightarrow\; \mu_e = \mu_d - \mu_u \approx \frac{1}{4}\mu_u$$

Thus, $$n_e \approx \frac{1}{4^3}\frac{n_u}{3} \ll n_u$$

- Cooper pairing with a mismatch between Fermi surfaces of pairing quarks:

$$\mu_d - \mu_u = \mu_e$$

Gaps: $(\Delta + \mu_e/2)$ and $(\Delta - \mu_e/2)$



Gapless superconductivity

- Diquark coupling strength η

(i) "strong":

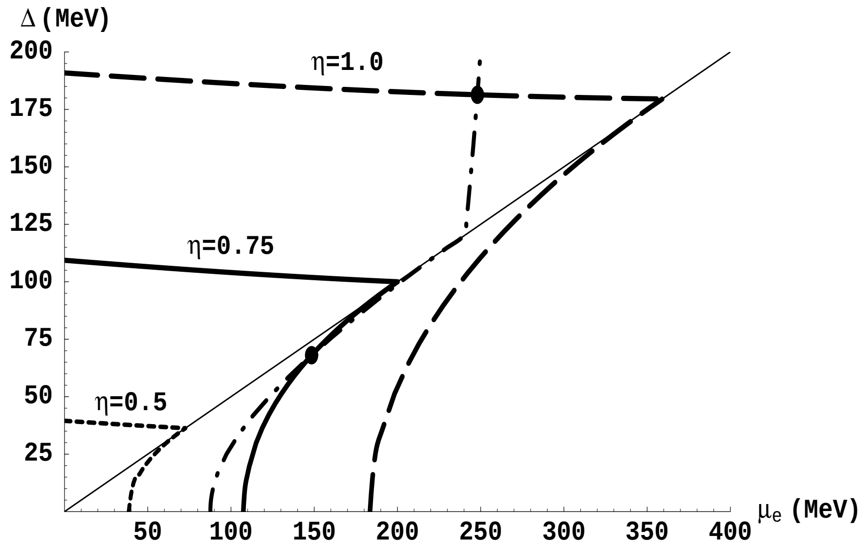
$\eta > \eta_2^{\rm cr} \longrightarrow$ 2SC

(ii) "weak":

$\eta < \eta_1^{\rm cr} \longrightarrow$ normal

(iii) "intermediate":

$\eta_1^{\rm cr} < \eta < \eta_2^{\rm cr} \longrightarrow$ g2SC



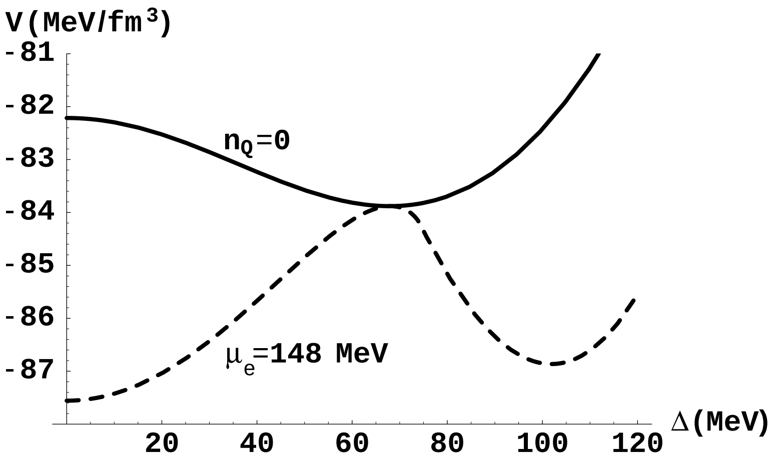
- What is g2SC?

- Is g2SC truly stable?

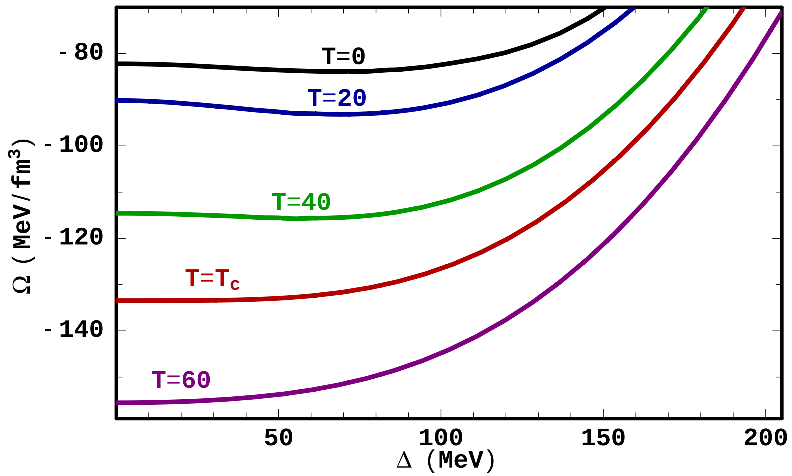
What are the physical properties of the g2SC at $T = 0$ and $T \neq 0$?

Stability

Eff. potential at $T = 0$

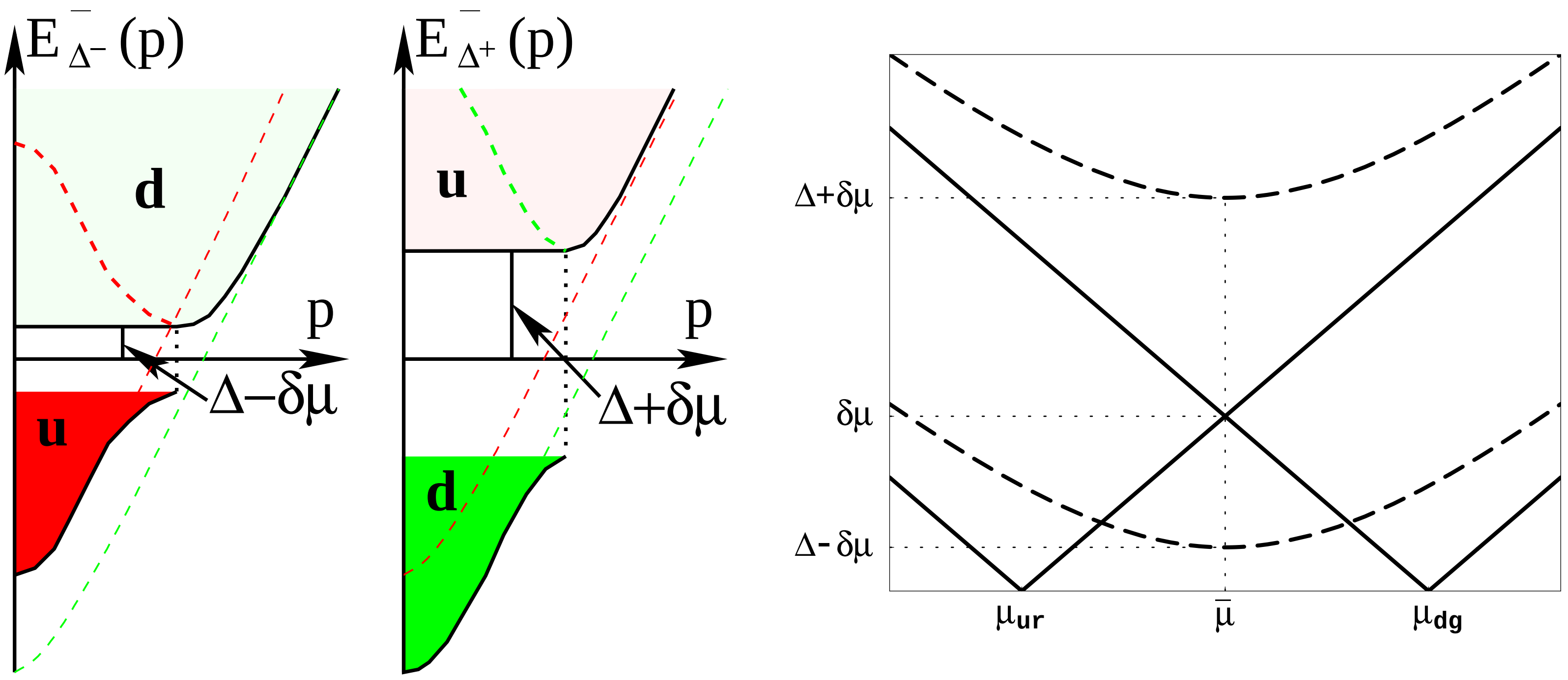


Eff. potential at $T \neq 0$

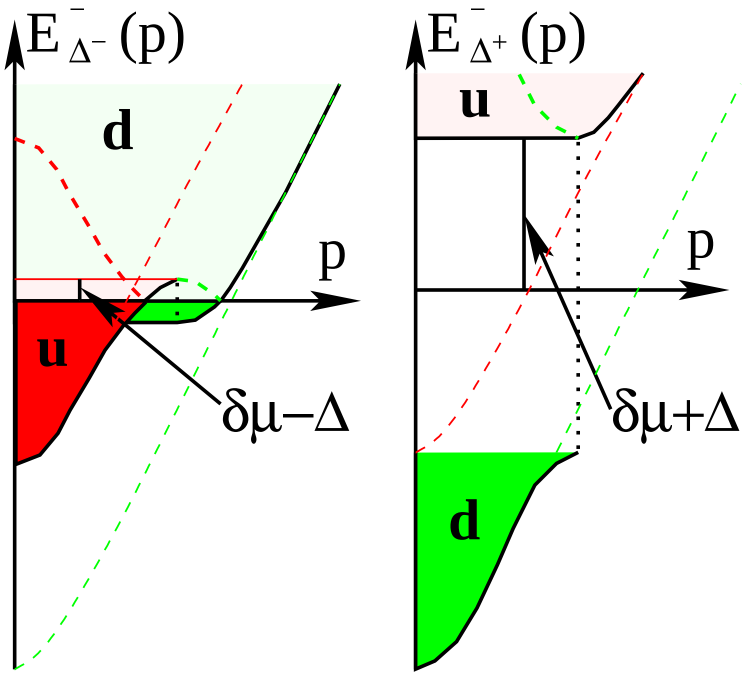


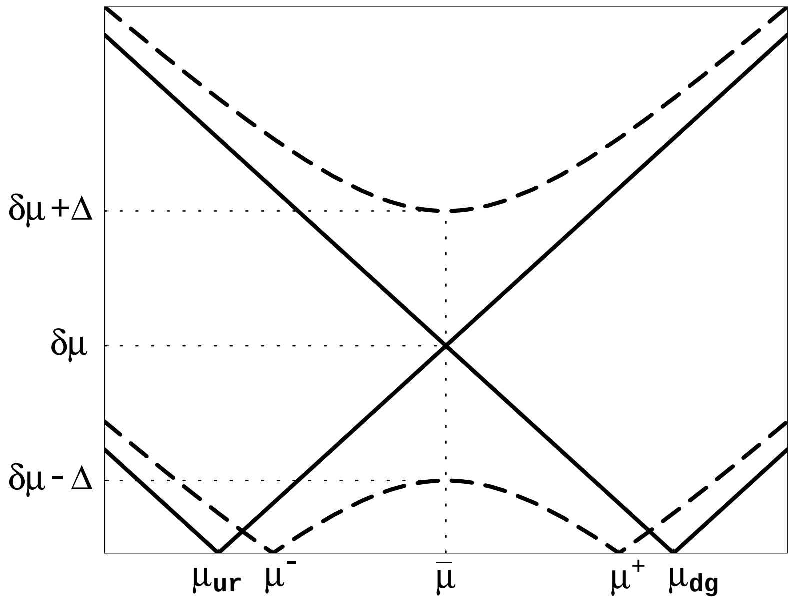
Thus, g2SC is stable provided $n_Q = 0$ is enforced *locally*

Quasiparticle spectrum in 2SC phase



Quasiparticle spectrum in g2SC phase





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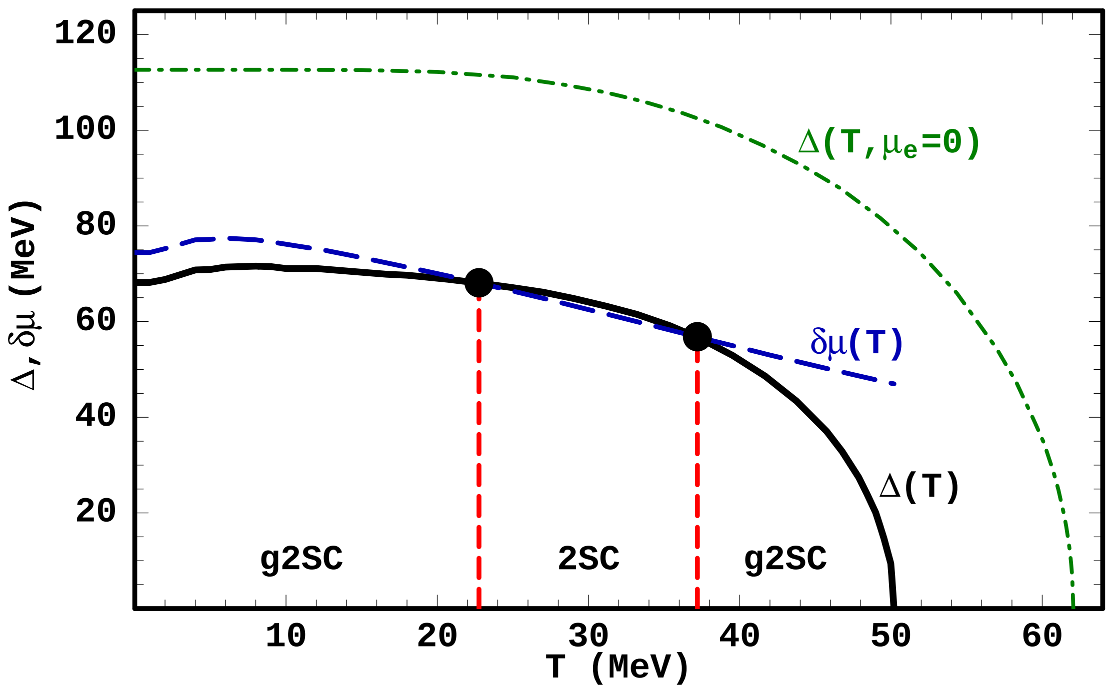
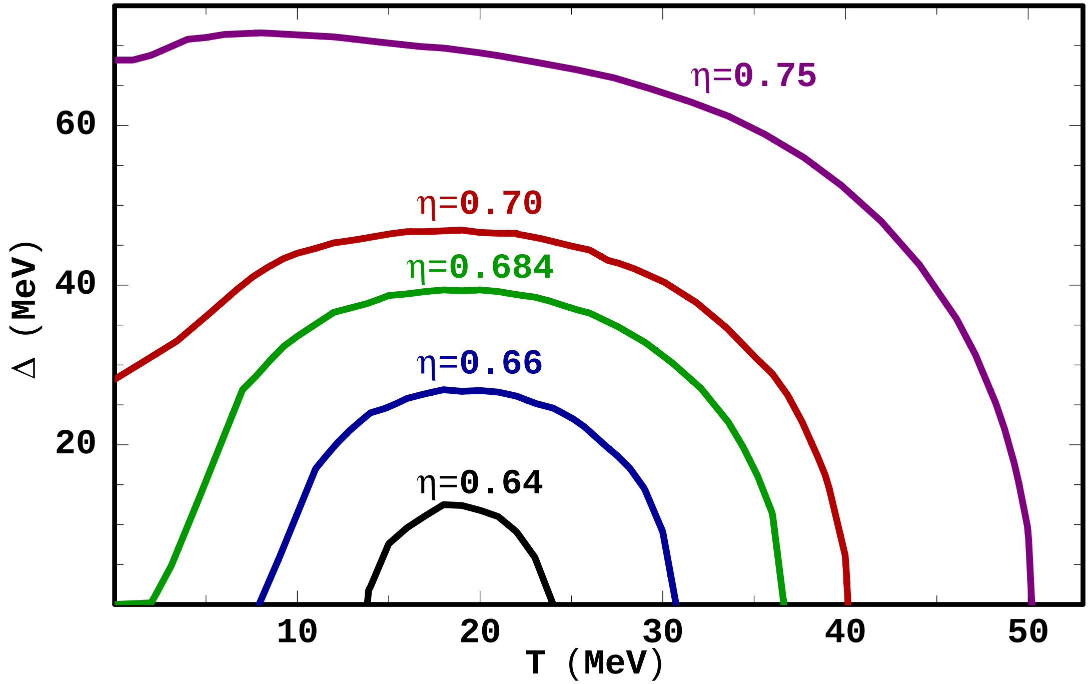
Temperature dependence of the gap. I.



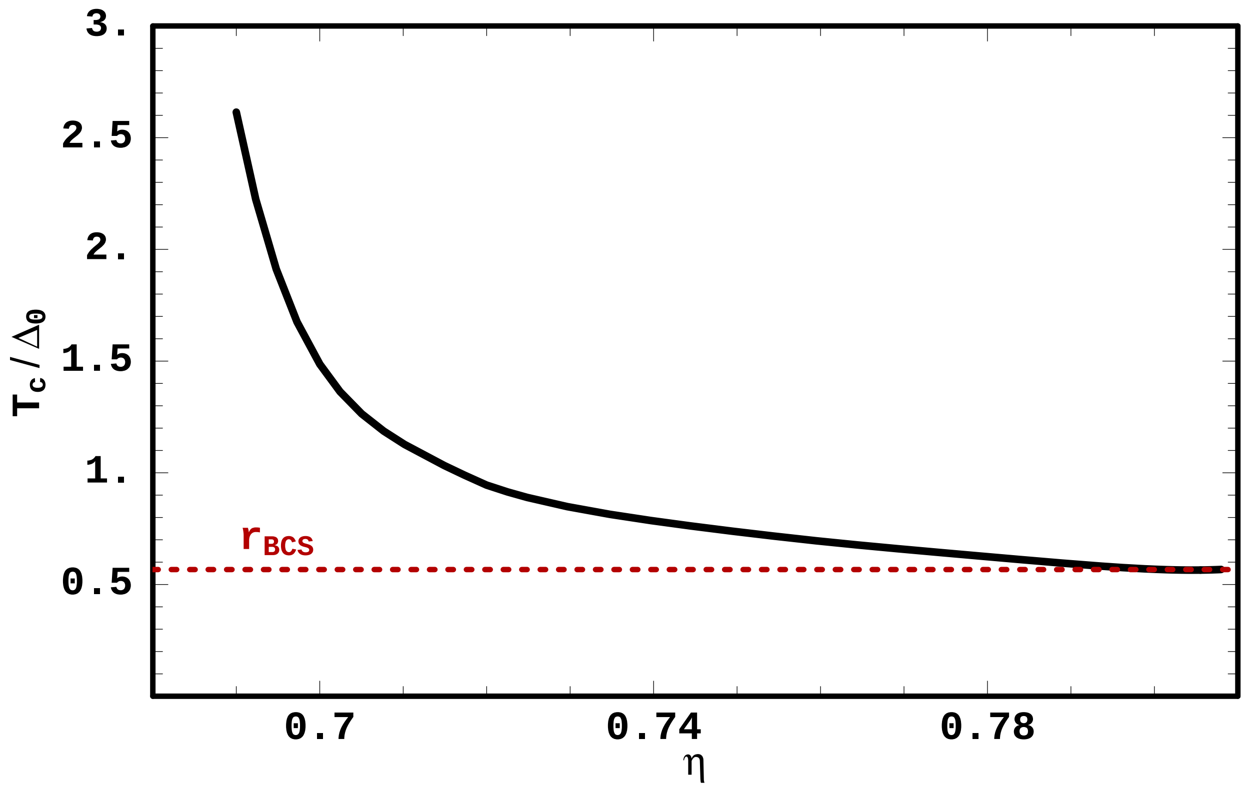
- *Nonmonotonic* temperature dependence
- Transitional behavior: g2SC → 2SC → g2SC → normal phase

Temperature dependence of the gap. II.



- Extreme *nonmonotonic* temperature dependence
- Transitional behavior: normal phase → g2SC → normal phase

Nonuniversal ratio T_c/Δ_0



- The ratio is *not universal* (unlike in BCS)
- The value of T_c/Δ_0 can be *arbitrarily* large

Summary

- Charge neutrality and β-equilibrium play very important role in studies of quark matter phases
- Gapless 2SC is a stable ground state of quark matter in a range of coupling strengths
- Gapless 2SC presents an unusual realization of the Higgs mechanism
- Temperature dependence of the gap is nonmonotonic
- Ratio T_c/Δ_0 is nonuniversal, and can be arbitrarily large
- There is more to this . . .
- Gapless quark matter may turn out to be not just a curiosity. . .