UNIVERSITY OF Southampton

Andreas Schmitt

Mathematical Sciences and STAG Research Centre
University of Southampton
Southampton SO17 1BJ, United Kingdom

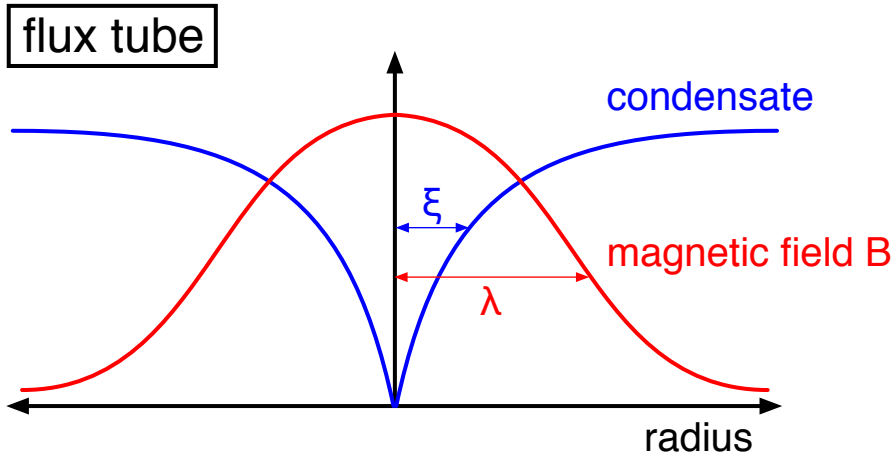
STAG RESEARCH CENTRE

(Color-)magnetic flux tubes in dense matter

A. Haber, A. Schmitt, PRD 95, 116016 (2017); EPJ Web Conf. 137, 09003 (2017)
A. Haber, A. Schmitt, arXiv:1712.08587 [hep-ph]

- two-component superconductors: unconventional type-I/type-II behavior (flux tube clusters)
- flux tubes and domain walls in superconducting quark matter

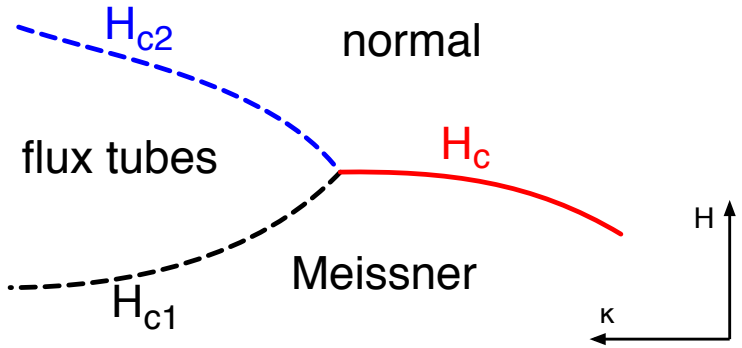
Reminder: type-I/type-II superconductivity



- Ginzburg-Landau parameter

$$\kappa = \frac{\lambda}{\xi}$$

- type-II superconductivity
  for $\kappa > 1/\sqrt{2}$: flux tube lattice
  for $H_{c1} < H < H_{c2}$
  A.A. Abrikosov, Soviet Physics JETP 5, 1174 (1957)



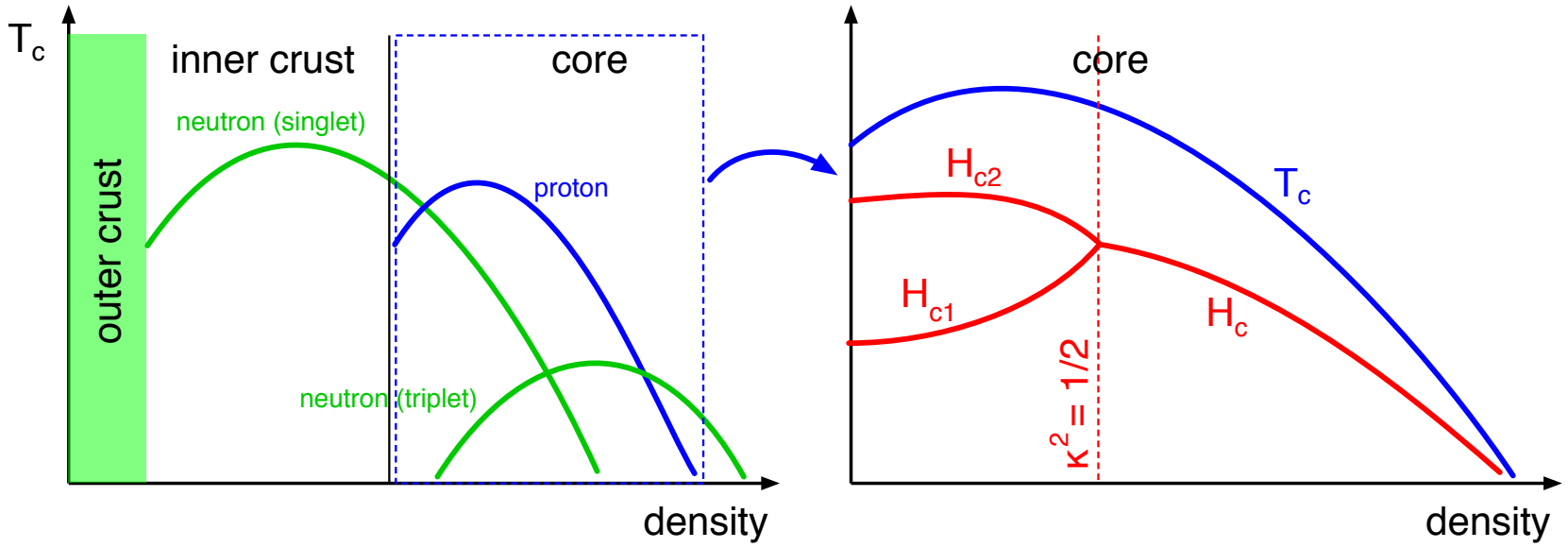
Two-component superconductors

- Ginzburg-Landau potential for two complex scalar fields with electric charges q_1, q_2 (neutron/proton: $q_1 = 2e$, $q_2 = 0$)

$$U = \frac{\mathbf{B}^2}{2} + \sum_{i=1,2} \left[|(\nabla + i q_i \mathbf{A})\phi_i|^2 - \mu_i^2 |\phi_i|^2 + \lambda_i |\phi_i|^4 \right] + 2h|\phi_1|^2 |\phi_2|^2$$

- further extensions:
  - derivative coupling ("entrainment")
    M. G. Alford, G. Good, PRB 78, 024510 (2008)
    A. Haber, A. Schmitt, PRD 95, 116016 (2017)
  - color superconductor: 3 scalar fields ϕ_1, ϕ_2, ϕ_3 and 3 gauge fields
    A. Haber, A. Schmitt, arXiv:1712.08587 [hep-ph]

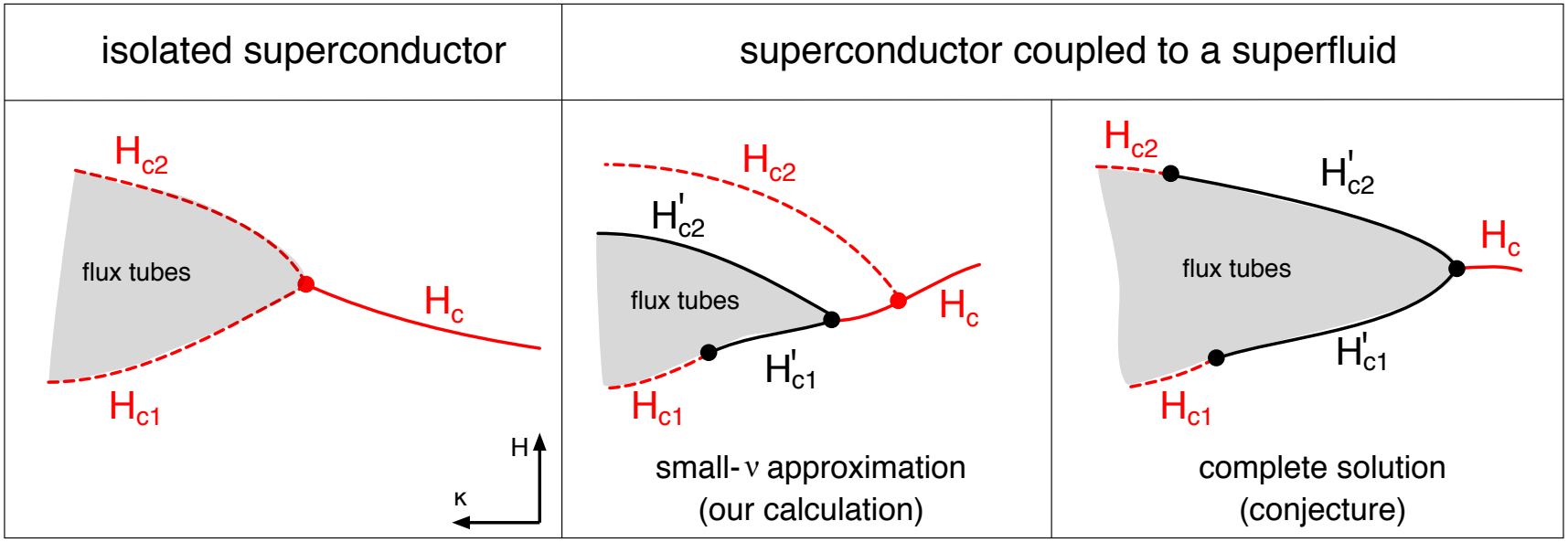
Two-component superconductors in neutron star cores



- density-dependent κ
- type-I/type-II transition in the core?
- effect of coupling to superfluid on type-I/type-II transition?

Critical magnetic fields in a two-component system

- compute flux tube profiles and flux tube interaction
  → attractive long-distance interaction in type-II regime



numerical calculation supports conjecture

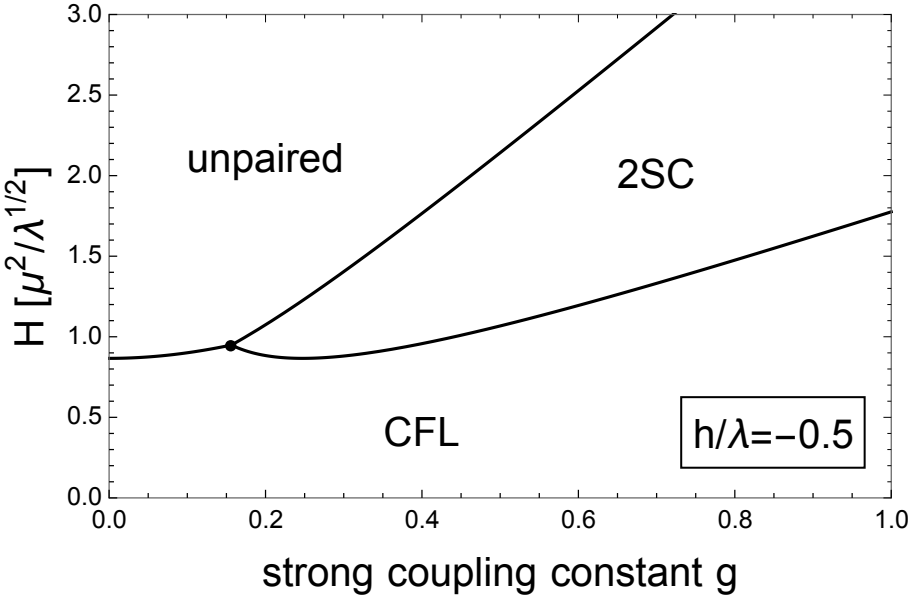
A. Haber, D. Müller, preliminary results

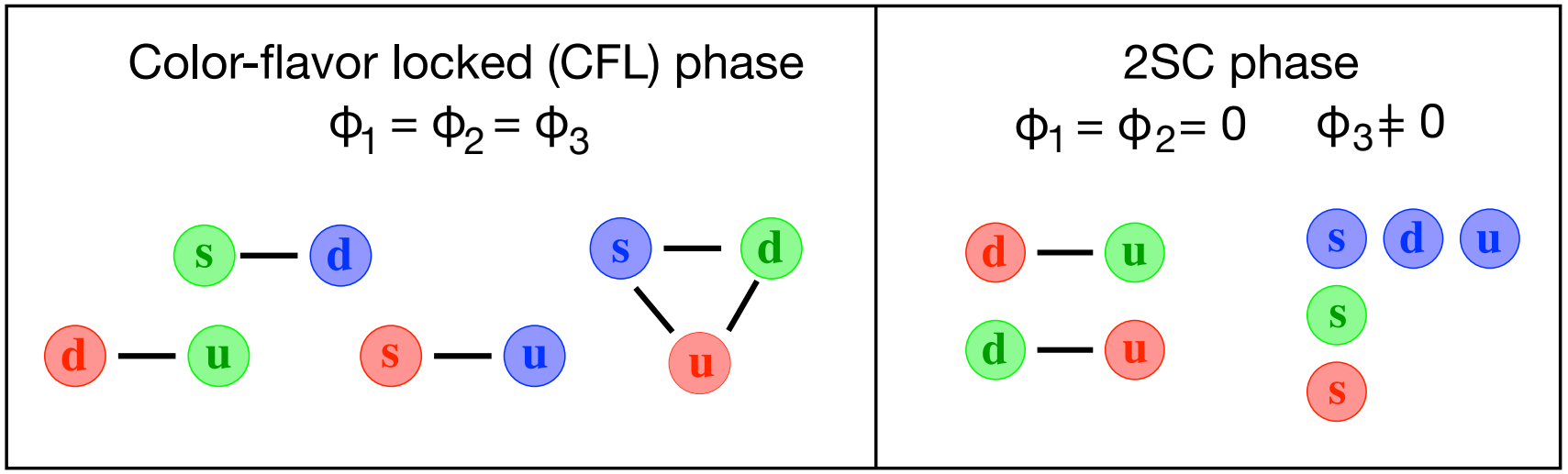
- first-order phase transition allows for flux tube clusters

see also "type-1.5" superconductors J. Carlström, J. Garaud, E. Babaev, PRB 84, 134515 (2011)

Quark matter in a magnetic field

- color-superconducting quark matter in a magnetic field
- use perturbative results for Ginzburg-Landau parameters μ, λ, h





Magnetic defects in CFL can be superfluid vortices and magnetic flux tubes at the same time!

CFL line defects	(n_1, n_2, n_3)	$\Gamma\ [\pi/3\mu_q]$	$\Phi_3\ [\pi/g]$	$\tilde{\Phi}_8\ [\pi/\tilde{g}_8]$
Global vortex Forbes, Zhitnitsky (2002)	(n, n, n)	$-n$	0	0
"Semi-superfluid" vortex Balachandran, Digal, Matsuura (2006)	$(0, 0, n)$	$-\frac{n}{3}$	0	$\frac{2n}{3}$
Magnetic flux tube T_{112} Iida (2005)	$(n, n, -2n)$	0	0	$-2n$
Magnetic flux tube T_{101} Haber, Schmitt (2017)	$(n, 0, -n)$	0	$-n$	$-n$

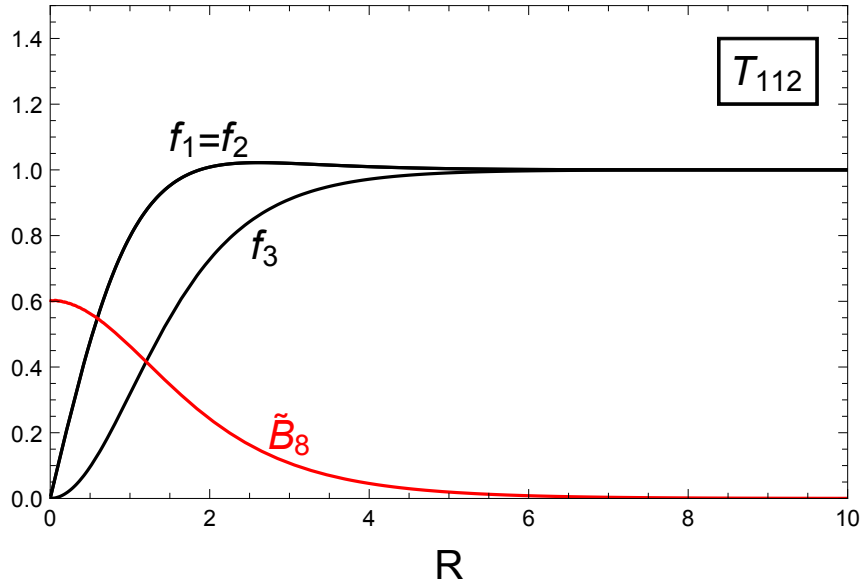
- winding numbers n_1, n_2, n_3 for three scalar fields

$$\text{baryon circulation}\ \ \Gamma \propto n_1 + n_2 + n_3$$

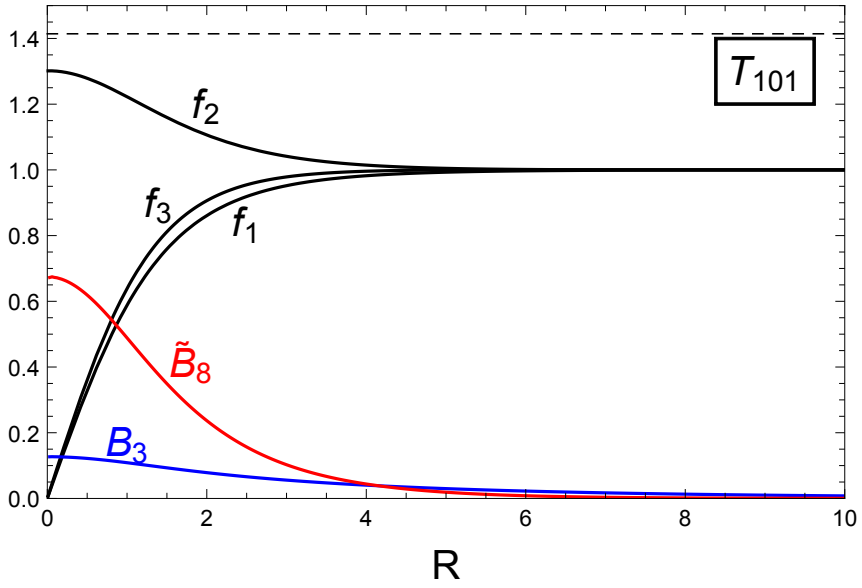
$$\text{(color-)magnetic flux}\ \ \tilde{\Phi}_8 \propto n_1 + n_2 - 2n_3$$

- photon/gluon mixing: Meissner effect for $\tilde{B}_8 = B_8 \cos\theta + B \sin\theta$

Flux tube profiles



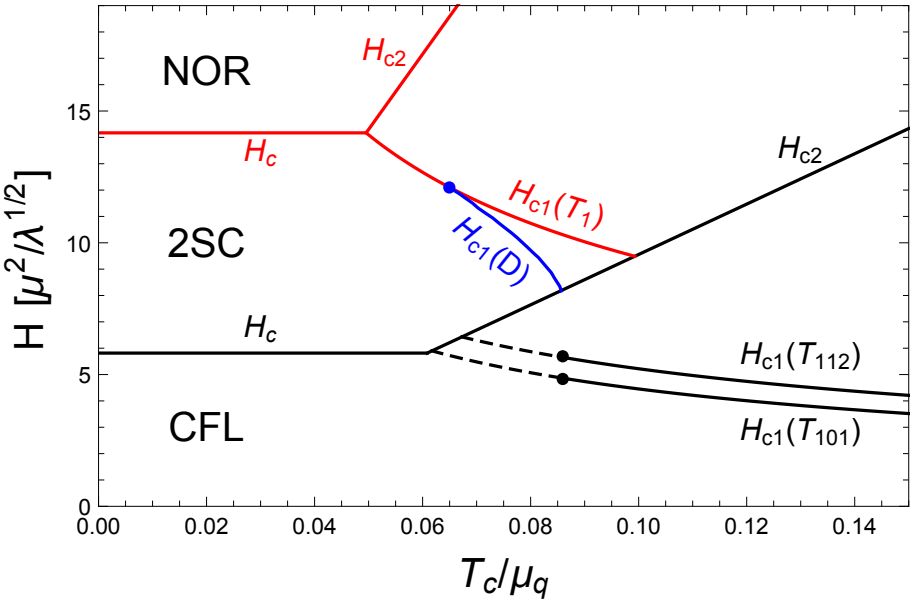
- flux tube with "unpaired core"



- flux tube with "2SC core"
  $\rightarrow$ additional B_3 field (cost in free energy)
  $\rightarrow$ non-vanishing condensate in core (gain in free energy)

Phase diagram including flux tubes

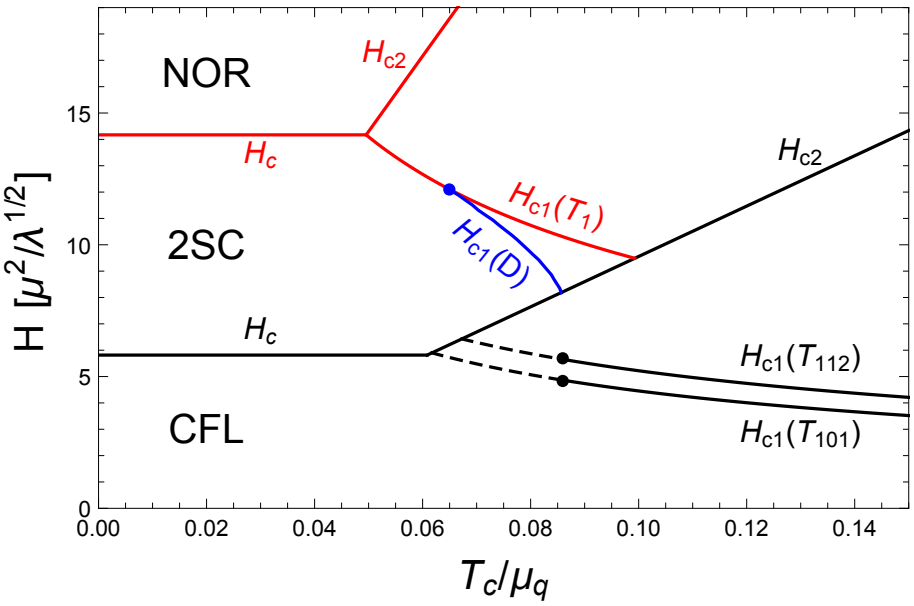
- in neutron stars
  $\mu_q \simeq 400\,\mathrm{MeV} \Rightarrow g \simeq 3.5$
- weak-coupling methods and phenomenological models:
  $T_c \simeq (10 - 50)\,\mathrm{MeV}$



- type-II regime for sufficiently large T_c/μ_q
- type-I/type-II transition complicated (multi-component structure!)

Phase diagram including flux tubes

- in neutron stars
  $\mu_q \simeq 400\,\mathrm{MeV} \Rightarrow g \simeq 3.5$
- weak-coupling methods and phenomenological models:
  $T_c \simeq (10 - 50)\,\mathrm{MeV}$



- CFL flux tubes with 2SC core (T_{101}) preferred
- critical fields $H \sim 10^{19}\,\mathrm{G} \gg H_{\mathrm{NS}}$, however:
  creation of flux tubes through cooling into superconducting phase?
- 2SC domain walls (D) preferred over ordinary 2SC flux tubes (T_1) for sufficiently large T_c/μ_q

Open questions

1. type-I/type-II transition in multi-component superconductors

   Do flux tube clusters exist in (a layer of) a neutron star?

   Do they affect transport properties/deformability?

2. magnetic flux tubes (and superfluid vortices) in quark matter

   What happens if CFL matter is rotated and placed into a magnetic field?

   Are there vortices and flux tubes (misaligned), like in neutron/proton matter?

   Do flux tubes form in the magnetic field evolution of a neutron star?

   Does the (color-)flux tube lattice ...
   ... sustain magnetic mountains? $\epsilon_{\rm CFL} \sim 10^{-7}$ vs $\epsilon_{\rm proton} \sim 10^{-9}$
   K. Glampedakis, D. I. Jones and L. Samuelsson, PRL 109, 081103 (2012)
   ... affect the tidal deformability of the star?