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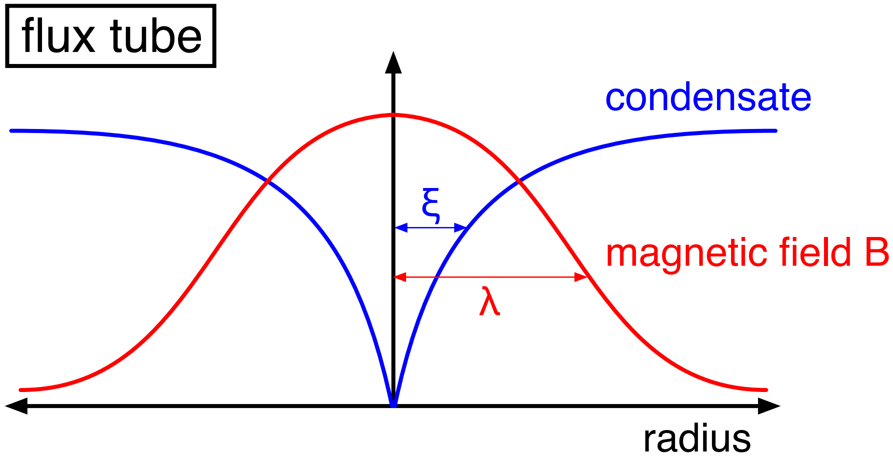
# (Color-)magnetic flux tubes in dense matter

A. Haber, A. Schmitt, PRD 95, 116016 (2017); EPJ Web Conf. 137, 09003 (2017)
A. Haber, A. Schmitt, JPG 45, 065001 (2018)

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

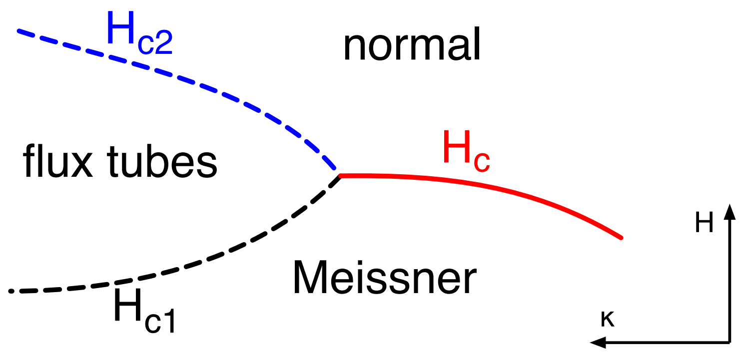
# Reminder: type-I/type-II superconductivity




- 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)



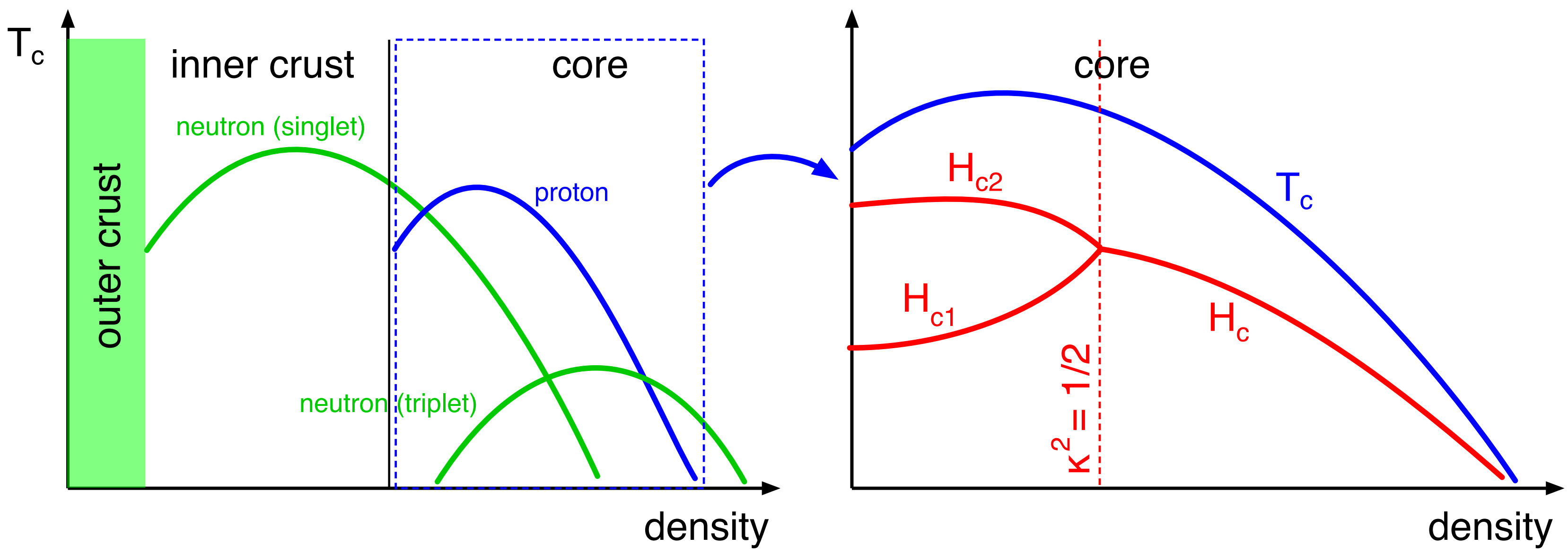
# Two-component superconductors

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

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

- 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 $\phi_1$, $\phi_2$, $\phi_3$ and 3 gauge fields
    A. Haber, A. Schmitt, JPG 45, 065001 (2018)

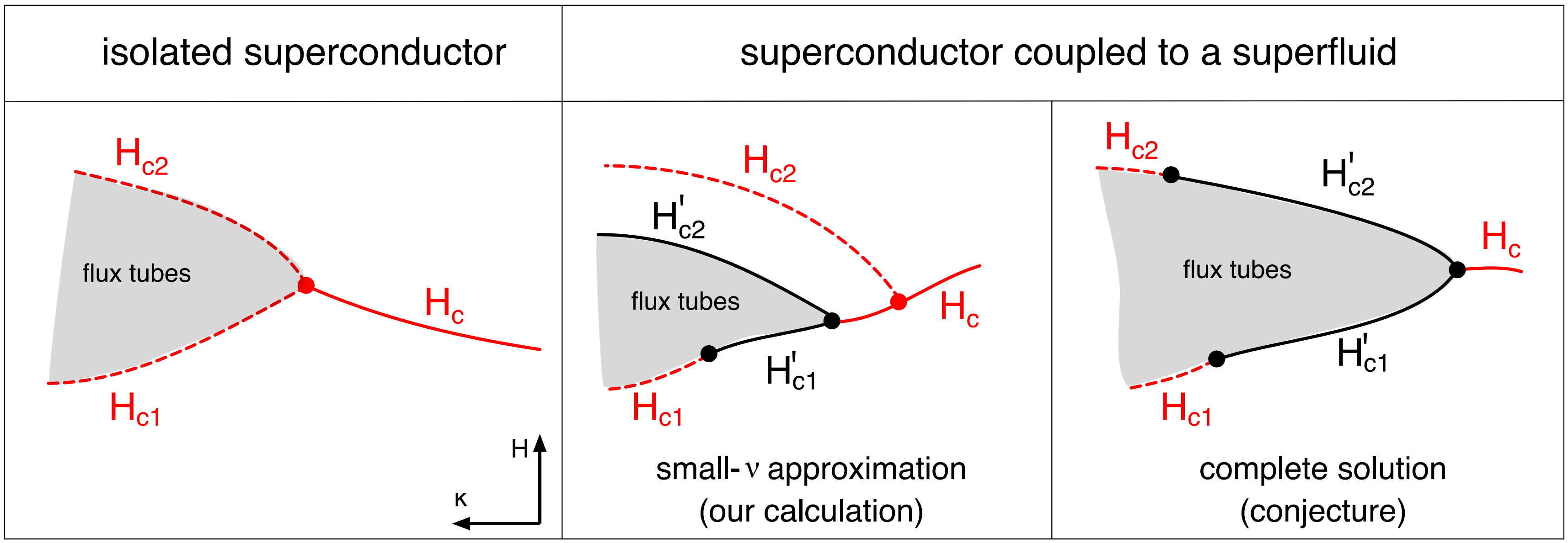
# Two-component superconductors in neutron star cores




- density-dependent $\kappa$
- 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
  $\rightarrow$ attractive long-distance interaction in type-II regime



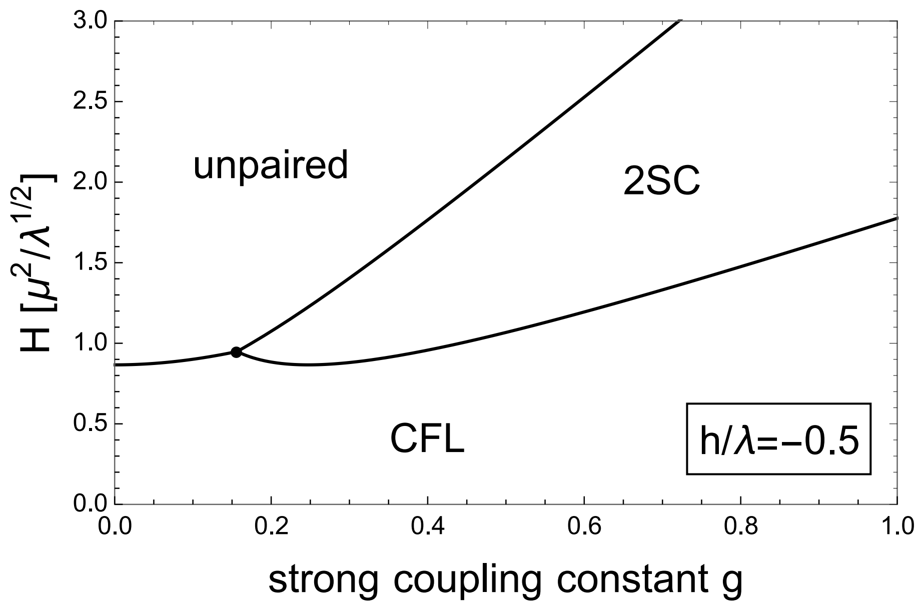

numerical calculation supports conjecture

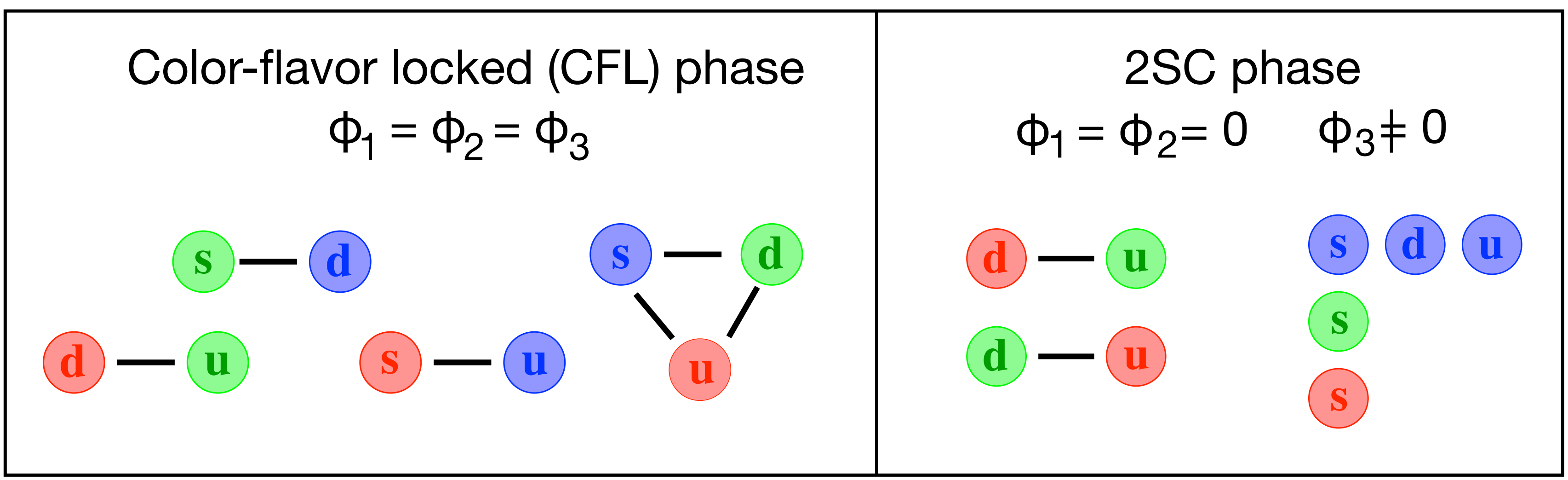
A. Haber, D. Müller, preliminary results

- 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 $\mu, \lambda, h$



| **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<br>Forbes, Zhitnitsky (2002) | $(n, n, n)$ | $-n$ | $0$ | $0$ |
| "Semi-superfluid" vortex<br>Balachandran, Digal, Matsuura (2006) | $(0, 0, n)$ | $-\frac{n}{3}$ | $0$ | $\frac{2n}{3}$ |
| Magnetic flux tube $T_{112}$<br>Iida (2005) | $(n, n, -2n)$ | $0$ | $0$ | $-2n$ |
| Magnetic flux tube $T_{101}$<br>Haber, Schmitt (2018) | $(n, 0, -n)$ | $0$ | $-n$ | $-n$ |

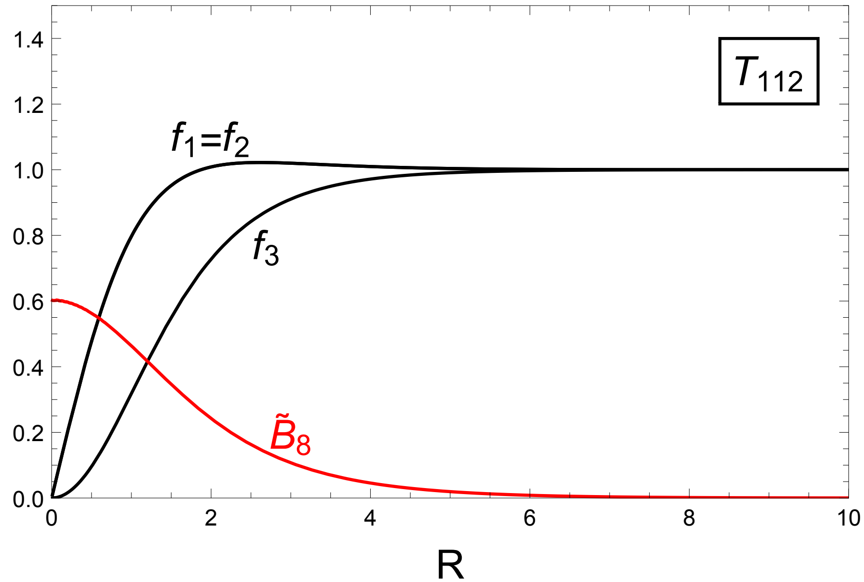
- winding numbers $n_1$, $n_2$, $n_3$ for three scalar fields

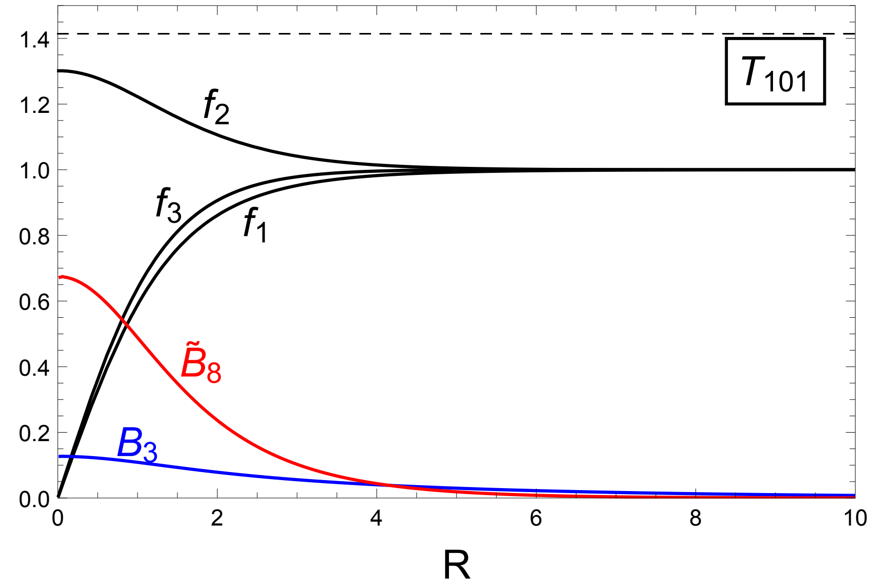
$$\text{baryon circulation} \quad \Gamma \propto n_1 + n_2 + n_3$$

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

- photon/gluon mixing: Meissner effect for $\tilde{B}_8 = B_8 \cos\theta + B \sin\theta$
- magnetic defects in CFL can be superfluid vortices and magnetic flux tubes at the same time

# Flux tube profiles



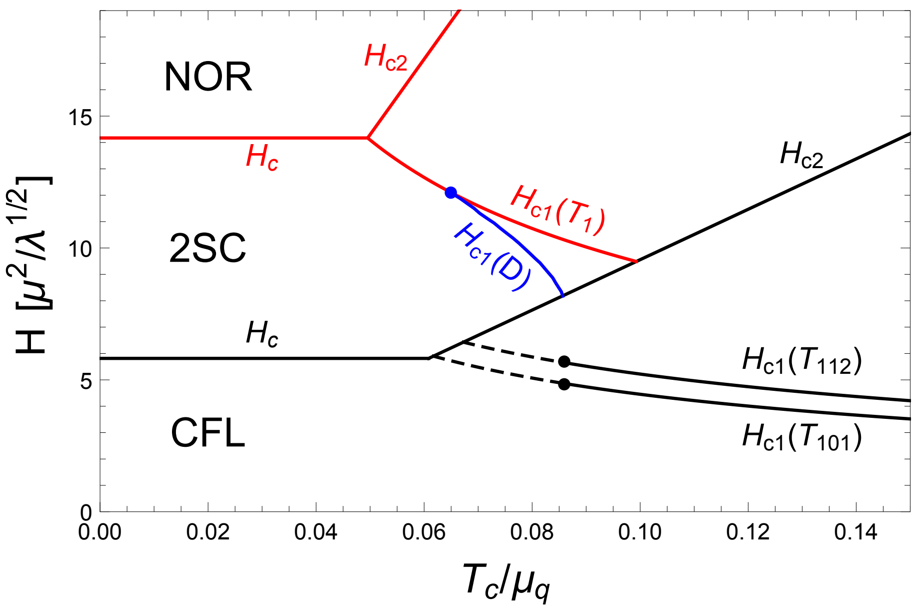




- flux tube with "unpaired core"

- flux tube with "2SC core"
  $\to$ additional $B_3$ field (cost in free energy)
  $\to$ 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 $T_c/\mu_q$
- type-I/type-II transition complicated (multi-component structure!)

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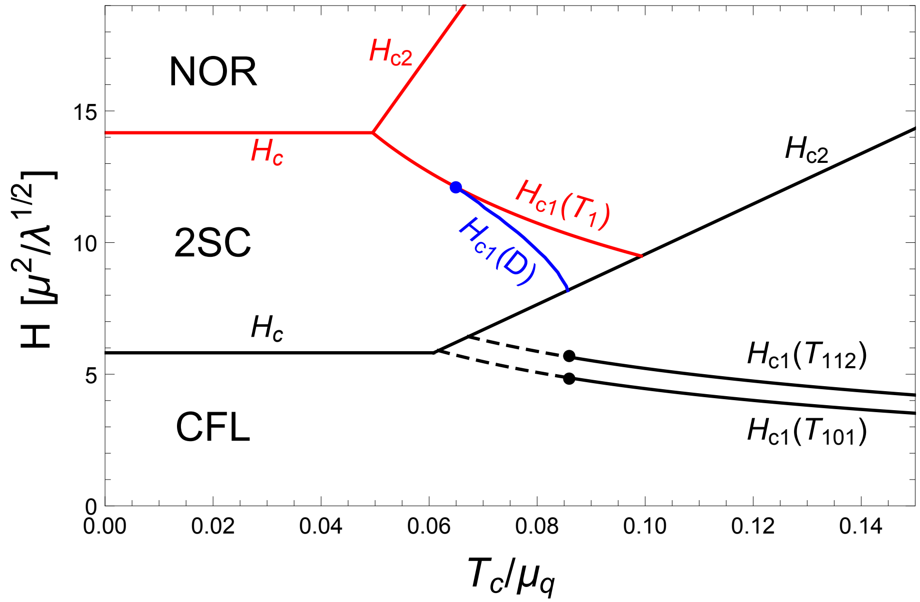


- CFL flux tubes with 2SC core ($T_{101}$) preferred
- critical fields $H \sim 10^{19}\,\mathrm{G} \gg H_{\mathrm{NS}}$, however:
  creation of flux tubes through cooling into superconducting phase?
- 2SC domain walls ($D$) preferred over ordinary 2SC flux tubes ($T_1$) for sufficiently large $T_c/\mu_q$

# Some open questions

Do flux tube clusters exist in (a layer of) a neutron star? Do they affect transport properties/deformability?

What happens if CFL is rotated and placed into a magnetic field? Are there vortices and flux tubes (misaligned), like in neutron/proton matter?

What happens to the flux tubes/vortices at a quark/hadron interface?
M. G. Alford, G. Baym, K. Fukushima, T. Hatsuda and M. Tachibana, arXiv:1803.05115 [hep-ph]
C. Chatterjee, M. Nitta and S. Yasui, arXiv:1806.09291 [hep-ph]

Does the (color-)flux tube array sustain magnetic mountains? Continuous grav. wave emission?
K. Glampedakis *et al.*, PRL 109, 081103 (2012)