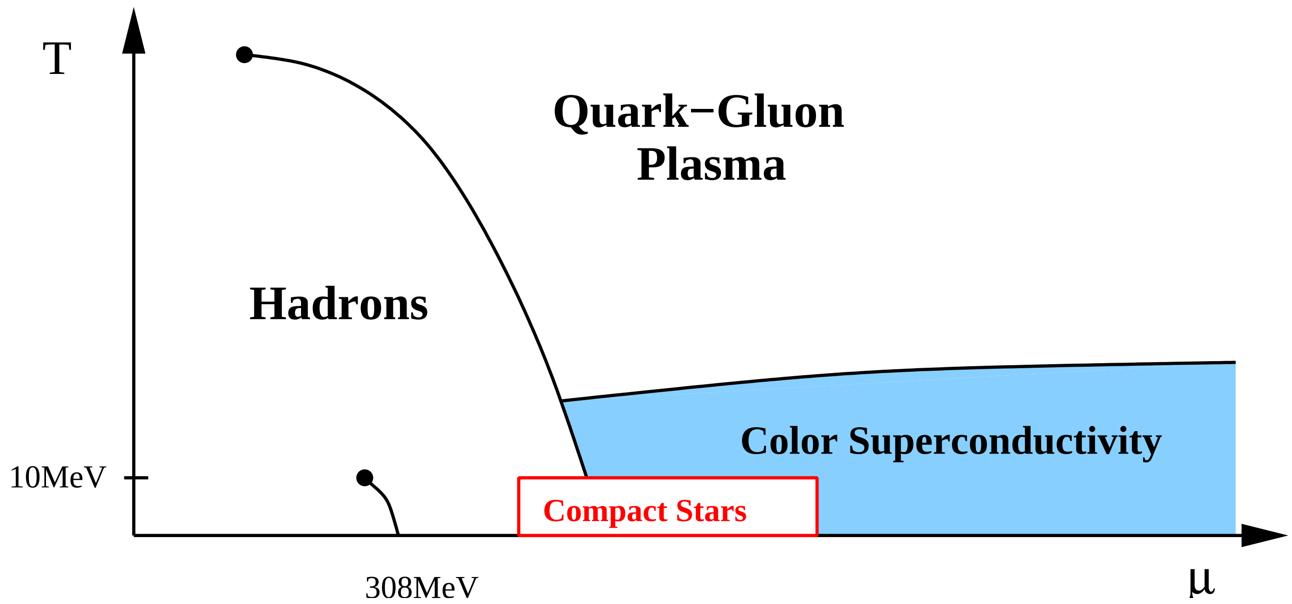
Bulk viscosity in 2SC quark matter

Mark Alford, Andreas Schmitt, J. Phys. G 34, 67-101 (2007)

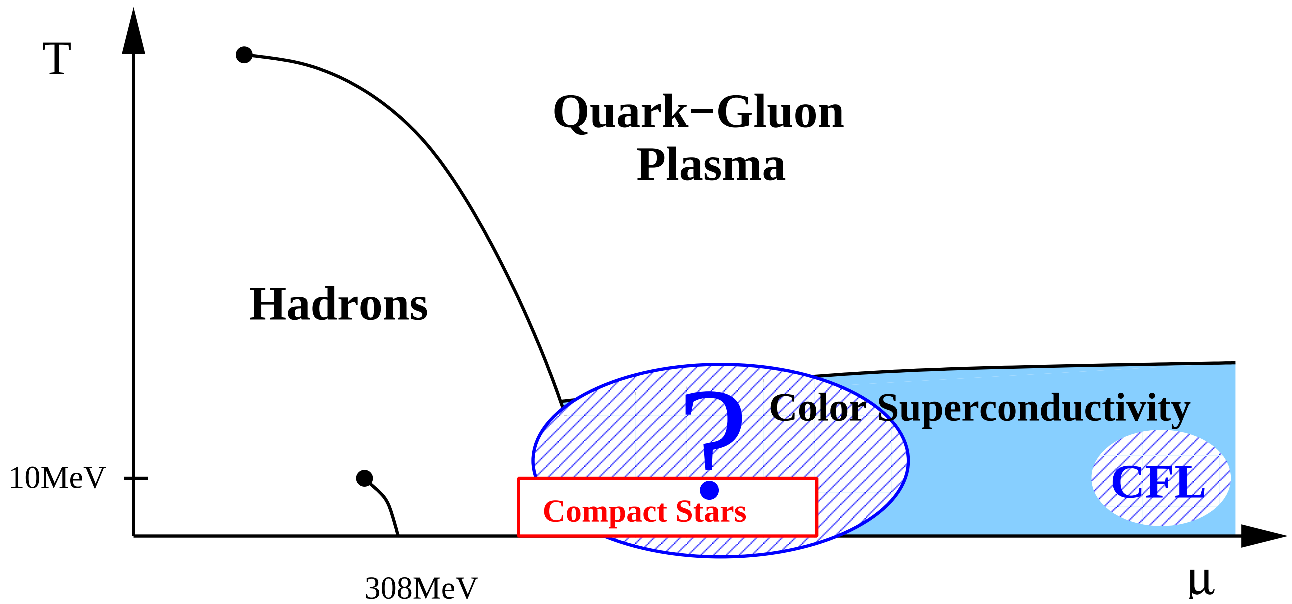
- **Color superconductivity: recent theoretical and astrophysical developments**
- **What is bulk viscosity?**
  Why is it important for compact stars?
- **Bulk viscosity in the 2SC phase**

- **QCD phase diagram (1):**
  What is color superconductivity?



	Where?	What?	Attractive force	Cooper pairs	Broken gauge group
“usual” superconductor	metals, alloys	ion lattice & electrons	phonons	electrons	$U(1)_{\text{em}}$
color superconductor	**neutron stars**	**quarks & gluons**	**gluons**	**quarks**	$SU(3)_c$

• QCD phase diagram (2): Unknown territory



Problems at moderate densities:

- perturbative QCD not valid
- strange mass not negligible
  → neutrality requirements become nontrivial

- **Different approaches**

Question:

What is the ground state of deconfined quark matter at moderate densities (in the interior of compact stars)?

1. **Theoretical approach: start from CFL and ask "what is next phase down in density?" (if not hadronic matter)**
2. **Phenomenological approach: "guess" possible phase, compute its properties and compare with astrophysical observations**

3. (Tabletop approach: learn from parallels to cold fermionic atoms in magnetic trap)

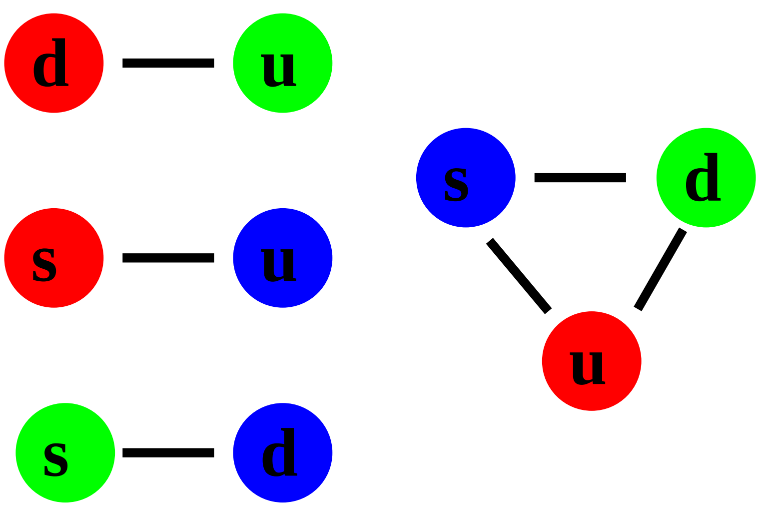
- **On safe grounds: Asymptotically large density**

$$0 \simeq m_s \simeq m_u \simeq m_d \ll \mu \qquad \text{all quark masses negligible}$$

"color-flavor locked phase (CFL)"

M. Alford, K. Rajagopal, F. Wilczek, Nucl. Phys. B537, 443 (1999)

$$SU(3)_c \times SU(3)_L \times SU(3)_R \rightarrow SU(3)_{c+L+R}$$



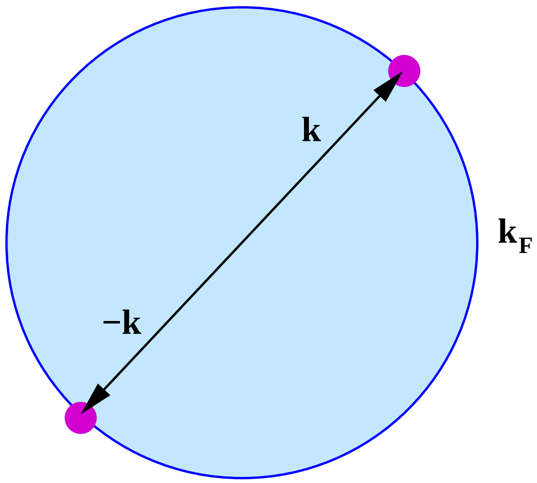
- all quarks form Cooper pairs
- state is automatically color and electrically neutral

- **Large, but not asymptotically large densities**

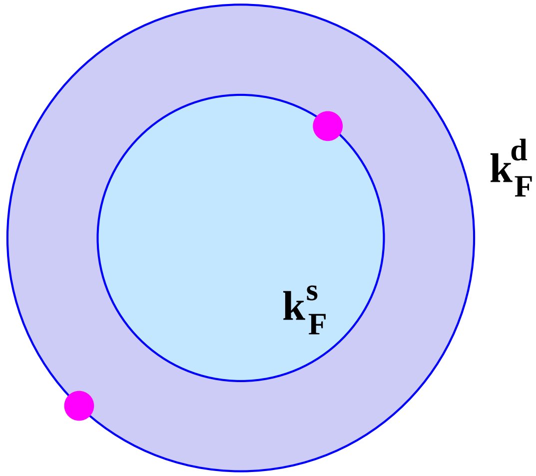
going down in density ⇔ "switching on" m_s and maintaining neutrality

→ **mismatch in Fermi momenta of pairing quarks ("stressed" pairing)**

BCS-pairing:



Neutral quark matter:

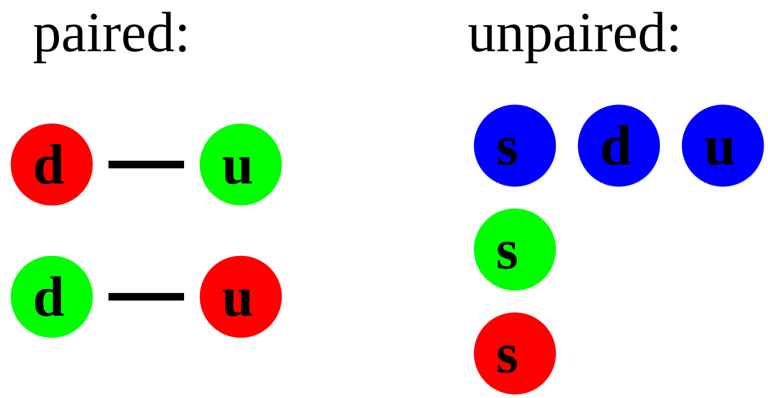


→ stressed pairing is **unavoidable**

K. Rajagopal, A. Schmitt, PRD 73, 045003 (2006)

- **Less (and less symmetric) pairing**

For instance,
2SC phase ...



... and many others

- One-flavor pairing: Color-Spin-Locking, *A*-phase, ...
  T. Schäfer, PRD 62, 094007 (2000)
  A. Schmitt, Q. Wang and D. H. Rischke, Phys. Rev. D **66**, 114010 (2002)
- Gapless superconductors: g2SC, gCFL
  I. Shovkovy, M. Huang, PLB 564, 205 (2003)
  M. Alford, C. Kouvaris, K. Rajagopal, PRL **92**, 222001 (2004)
- Counter-propagating currents: LOFF, meson current
  M. Alford, J. Bowers, K. Rajagopal, PRD 63, 074016 (2001)
  T. Schäfer, PRL 96, 012305 (2006)

- **Astrophysical approach (page 1/2)**

- **neutrino emissivity/cooling of the star**
  - **normal quark matter** N. Iwamoto, PRL 44, 1637 (1980)
  - **CFL** P. Jaikumar, M. Prakash, T. Schäfer, PRD 66, 063003 (2002)
  - **gCFL** M. Alford, P. Jotwani, C. Kouvaris, J. Kundu, K. Rajagopal, PRD, 114011 (2005)
  - **2SC** P. Jaikumar, C.D. Roberts, A. Sedrakian, PRC 73, 042801 (2006)
  - **spin-1** A. Schmitt, I.A. Shovkovy, Q. Wang, PRD 73, 034012 (2006)
  - **LOFF** R. Anglani, G. Nardulli, M. Ruggieri, M. Mannarelli, hep-ph/0607341

direct Urca processes

$$u + e \to d + \nu \, , \qquad d \to u + e + \bar{\nu}$$

ν-emissivity sensitive to **magnitude of gap**
and number and dimensionality of **ungapped modes**

tendency: need **fully gapped** phase with **not-too-large gap**
to explain observed cooling ($\to$ **CSL**?)

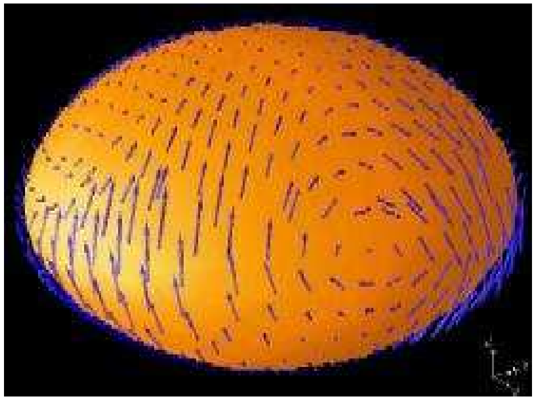
- **Astrophysical approach (page 2/2)**

- **magnetic fields**
  - **spin-0, e.g. CFL** "rotated electromagnetism"
    $\longrightarrow$ **no Meissner effect**
    M.G. Alford, J. Berges, K. Rajagopal, NPB 571, 269 (2000)
  - **spin-1 Meissner effect**
    A. Schmitt, Q. Wang, D.H. Rischke, PRL 91, 242301 (2003)
  - **precession of the star** B. Link, PRL 91, 101101 (2003)
  - **crust confinement of magnetic field**
    J.F. Perez-Azorin, J.A. Miralles, U.R.M. Geppert, A&A 451, 1009 (2006)

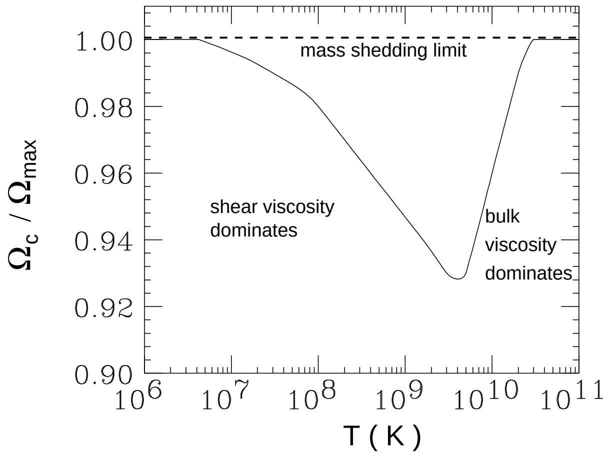
- **viscosity**
  - **shear, bulk viscosity in CFL**
    C. Manuel, A. Dobado, F.J. Llanes-Estrada, JHEP 0509, 076 (2005)
    M. Alford, M. Braby, S. Reddy, T. Schäfer, in preparation
  - **bulk viscosity in spin-1 phases**
    B.A. Sa'd, I.A. Shovkovy, D.H. Rischke, astro-ph/0607643
  - **bulk viscosity in 2SC phase**
    M.G. Alford, A. Schmitt, J. Phys. G 34, 67-101 (2007)

• Why compute bulk viscosity?

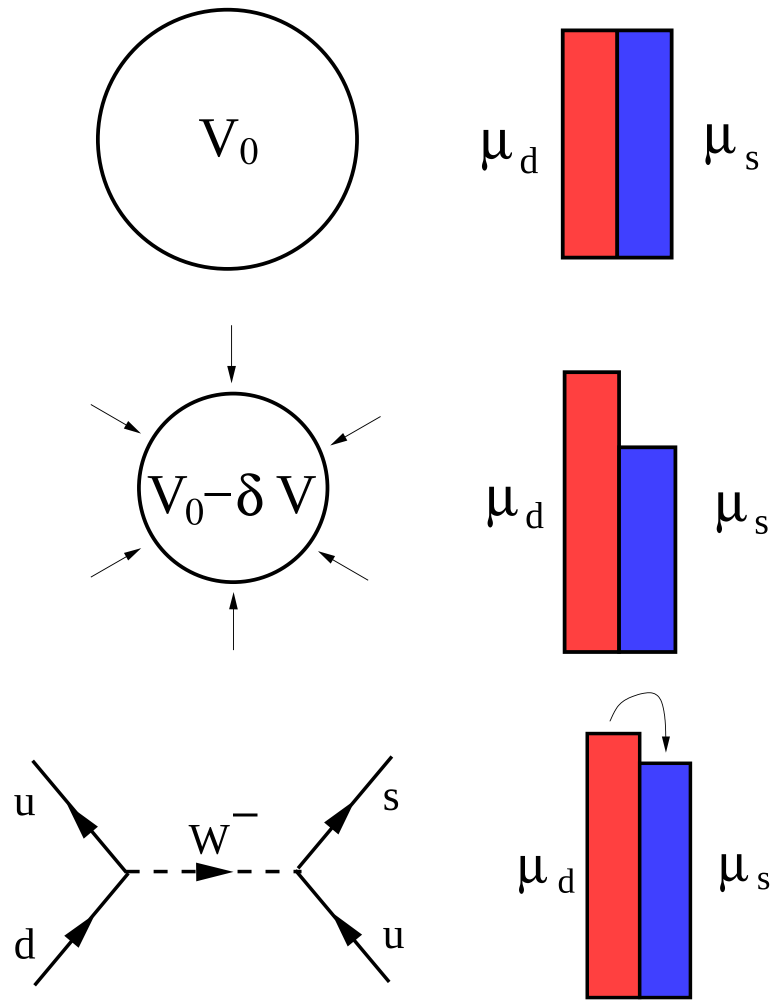
- **r-modes:** non-radial pulsation modes
- **grow unstable**
  in a perfect-fluid rotating star
  $\longrightarrow$ emission of gravitational waves
- **spin down** the star drastically and quickly (within days)



- fast rotating stars are observed!
  $\omega \simeq 1\text{ms}^{-1}$
- must be some damping mechanism
  $\longrightarrow$ **bulk/shear viscosity**
- deduce upper limit for ω from **viscosity**



- **What is bulk viscosity?**



- compression/expansion changes chemical composition
- system out of chemical equilibrium

$$\delta\mu \equiv \mu_s - \mu_d \neq 0$$

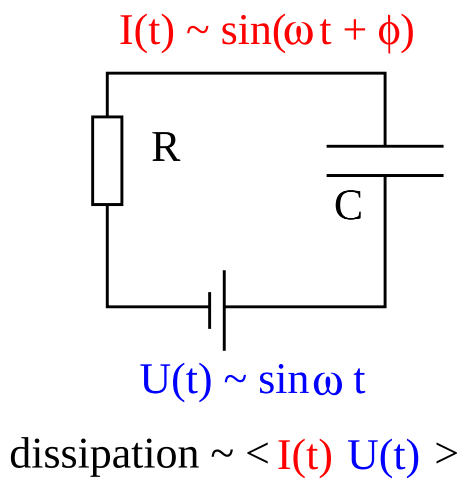
re-equilibration via

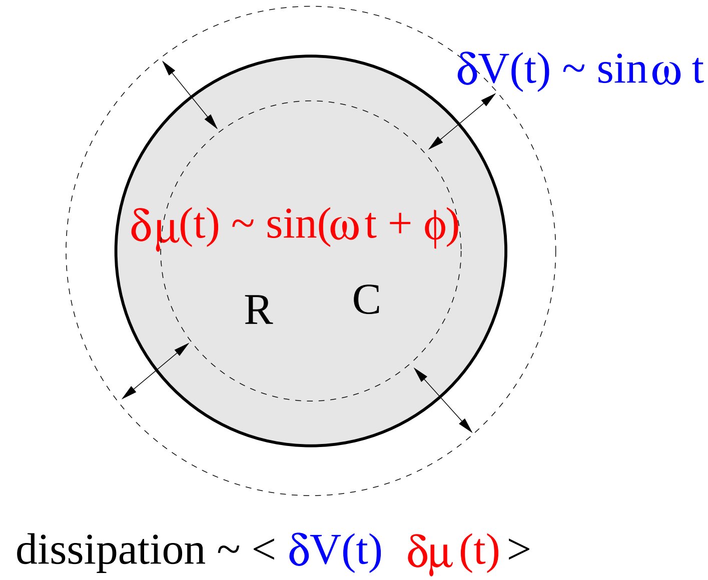
$$u + d \leftrightarrow u + s$$

- **2 time scales:**
  external oscillation ω vs. microscopic rate γ

• Bulk viscosity is a resonance phenomenon

Just like an electric circuit!





"capacitance" $C \leftrightarrow$ inverse microscopic rate γ^{-1}
(slow process $\longrightarrow$ store large chemical energy)

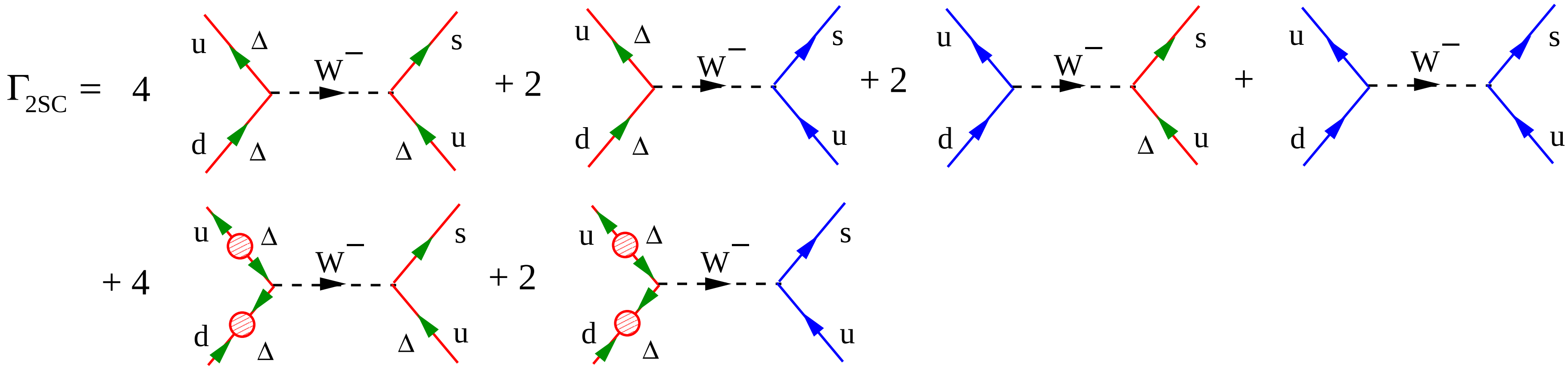
"resistance" $R \leftrightarrow \left(n_u \frac{\partial \mu_d}{\partial n_u} + n_d \frac{\partial \mu_d}{\partial n_d} - n_s \frac{\partial \mu_s}{\partial n_s} \right)^{-1}$
(same dispersion for d and s $\longrightarrow$ infinite "resistance" $\longrightarrow$ no dissipation)

Bulk viscosity

$$\zeta = \alpha \, \frac{\gamma}{\gamma^2 + \omega^2}$$

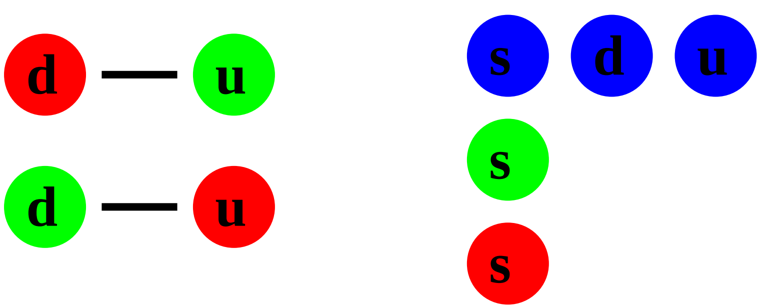
$$\alpha \equiv \frac{n_u \frac{\partial \mu_d}{\partial n_u} + n_d \frac{\partial \mu_d}{\partial n_d} - n_s \frac{\partial \mu_s}{\partial n_s}}{\frac{\partial \mu_d}{\partial n_d} + \frac{\partial \mu_s}{\partial n_s}}$$

- **Compute rate for $u + d \leftrightarrow u + s$ in 2SC**



paired:

unpaired:



small temperatures,

$$T \ll T_c \simeq 30\text{MeV}$$

$$\Gamma_{2SC} = \frac{1}{9}\Gamma_{\text{unpaired}}$$

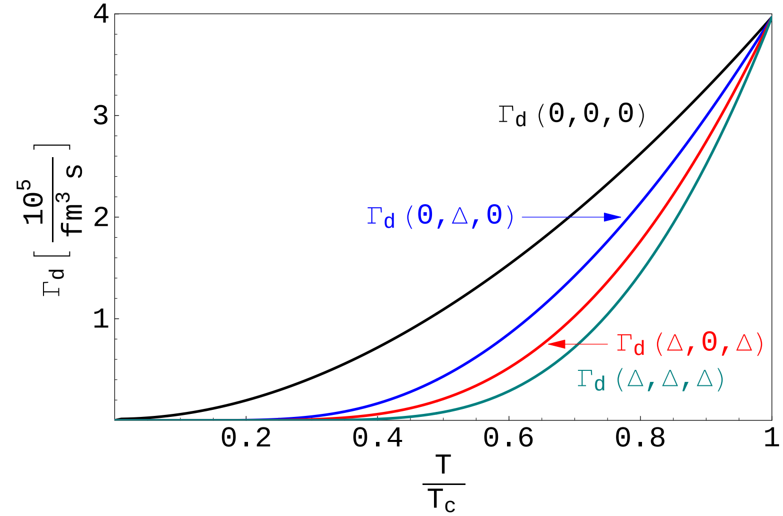
due to **exponential suppression**

$\exp(-\Delta/T)$ of gapped modes

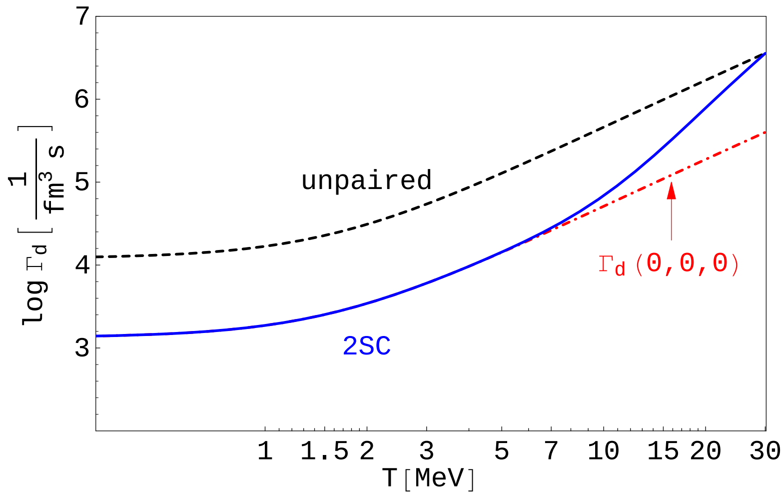
• Results for all temperatures $T < T_c$

(i) fixed $\delta\mu = \mu_s - \mu_d > 0 \rightarrow$ net production of d quarks, $\Gamma_d > 0$

- **contributions of subprocesses**



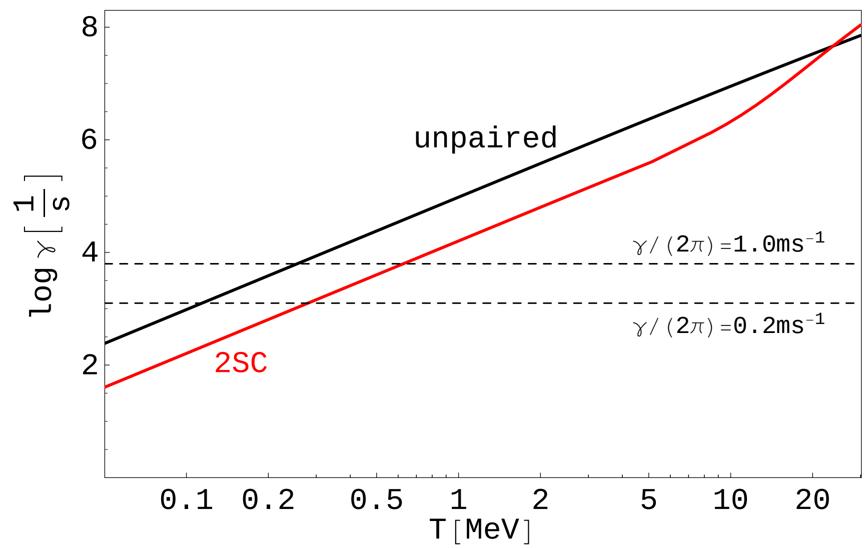
- **total rate compared to unpaired quark matter**

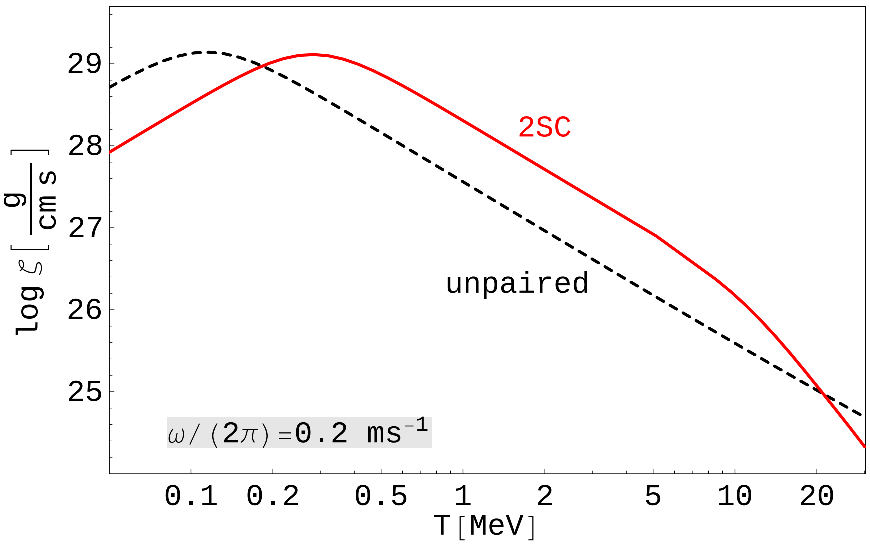


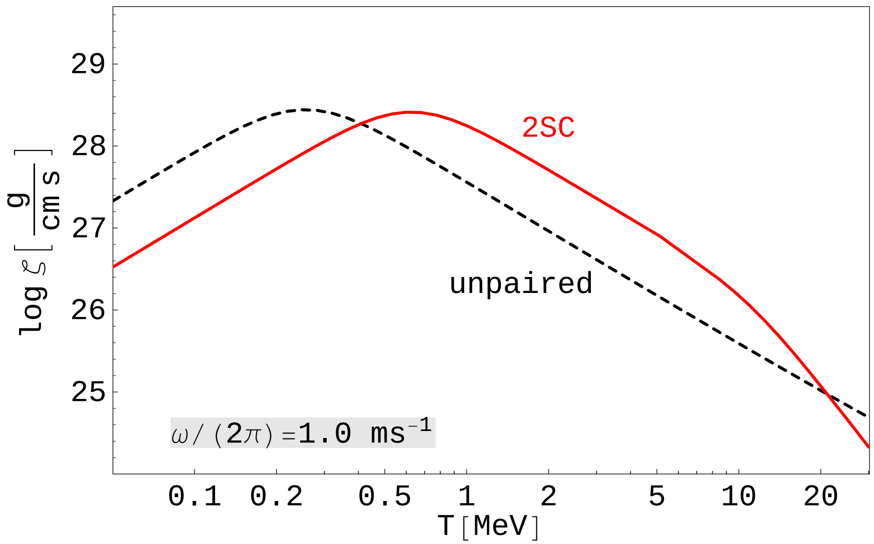
(ii) for bulk viscosity, consider $\boldsymbol{\gamma} = \dfrac{\partial \Gamma_d}{\partial \delta\mu}$

• Results for bulk viscosity

$$\zeta = \alpha \frac{\gamma}{\gamma^2 + \omega^2}$$

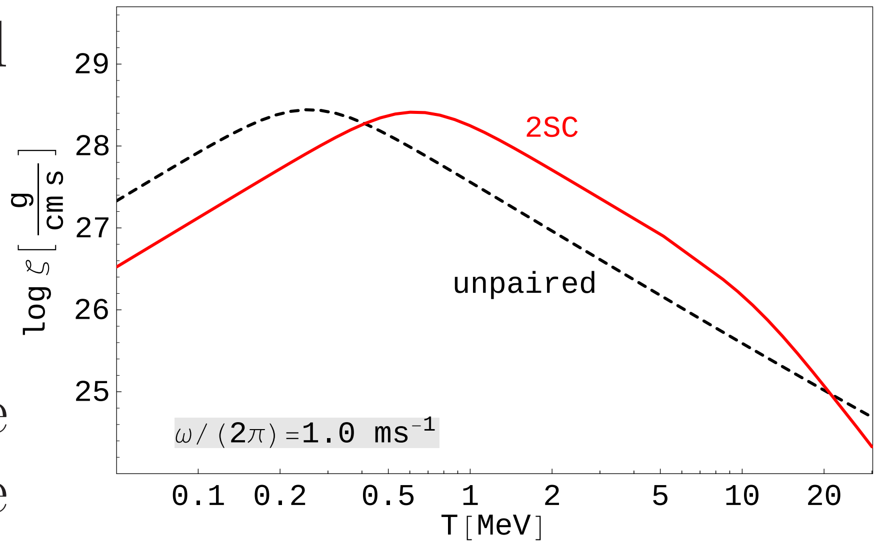


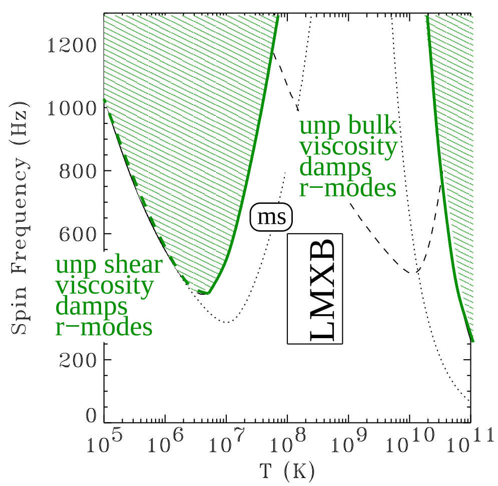




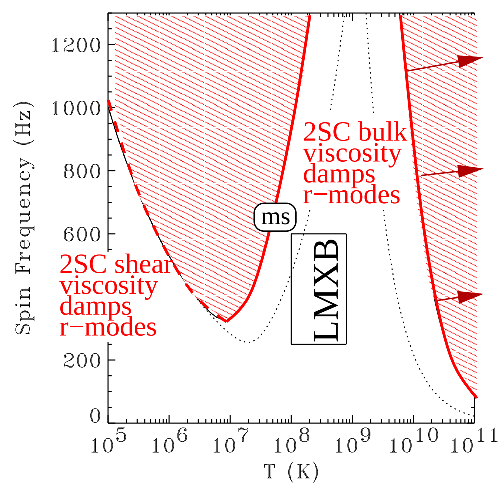
• Astrophysical implications

- bulk viscosity in superconductor can be **larger** than in normal phase
- results important for young neutron stars, $T > 1\,\mathrm{MeV}$
- $\longrightarrow$ first days of neutron star's life (potentially enough for r-mode instabilities to grow)





unpaired



2SC

J. Madsen, PRL 85, 10 (2000)

- ms = millisecond pulsars
- LMXB = low-mass x-ray binaries

• Conclusions

• Bulk viscosity

- shear and bulk viscosities damp **r-mode instabilities**
- **bulk viscosity** of quark matter in a neutron star dominated by **weak processes** (unlike heavy-ion collisions; different **external time scale**)
- **2SC quark matter** has **larger** bulk viscosity than unpaired quark matter in **very young neutron stars**

• More general

- phase(s) between **CFL** and **hadronic matter** are unknown
- use astrophysical observations to learn about these phases **(cooling curves, rotation frequencies, magnetic fields ...)**
- how does quark matter deal with **mismatched Fermi surfaces? exotic superconductors?**