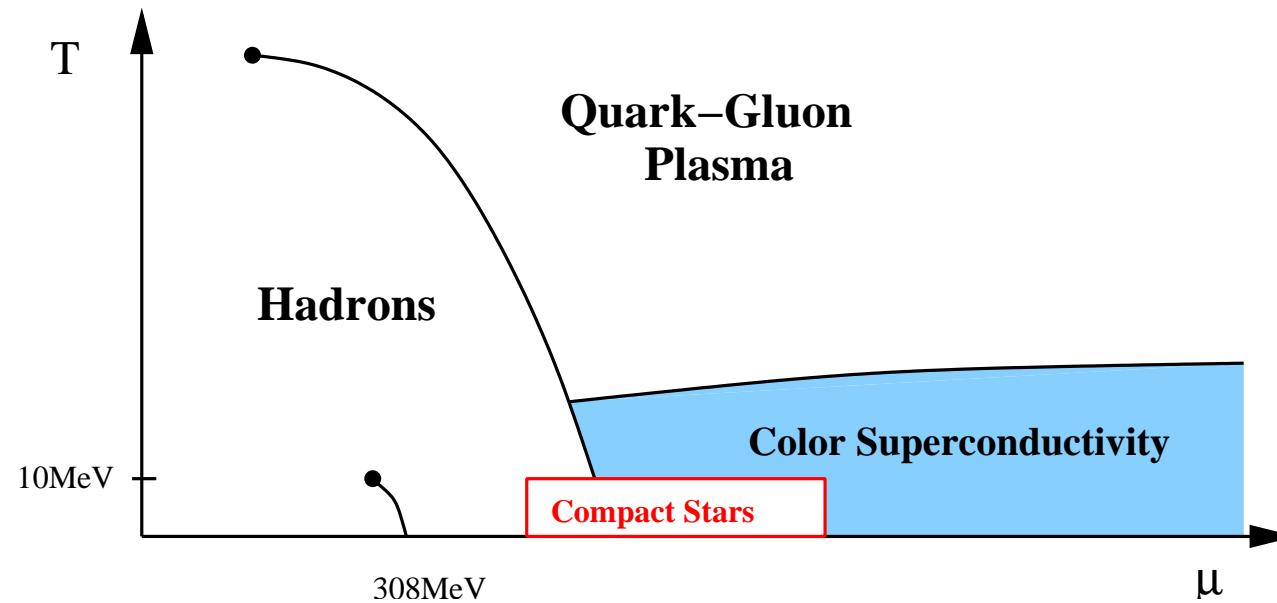


## Bulk viscosity in 2SC quark matter

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

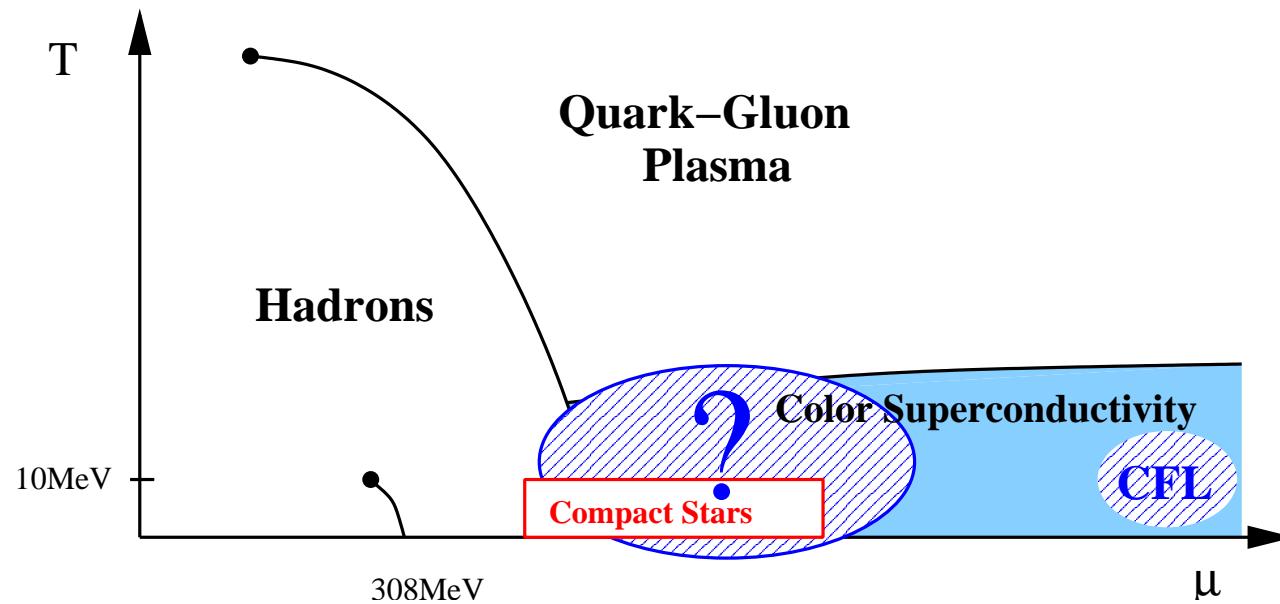
- Color superconductivity:  
state(s) of cold, dense quark matter
- What is bulk viscosity?  
Why is it important for compact stars?
- Bulk viscosity in the 2SC phase  
("2-flavor color SuperConductor")

- 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

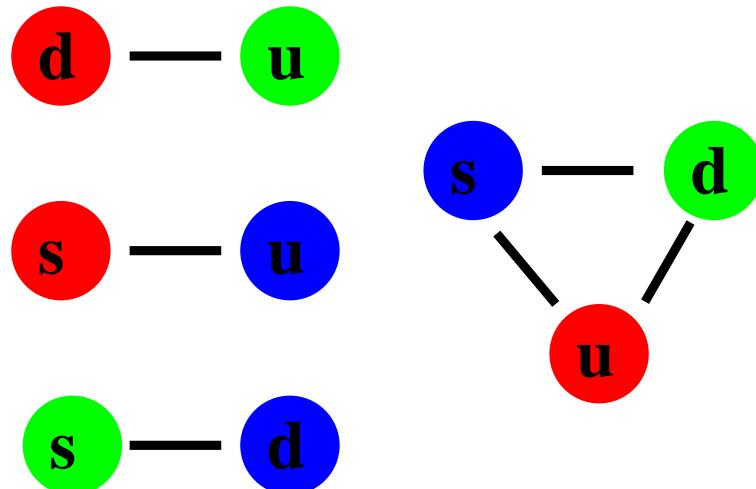
- Asymptotically large density: CFL phase

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

“color-flavor locked phase (CFL)”

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

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

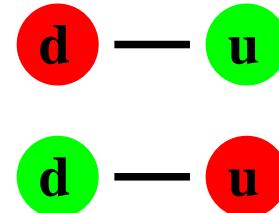


- all quarks form Cooper pairs
- state is automatically color and electrically neutral

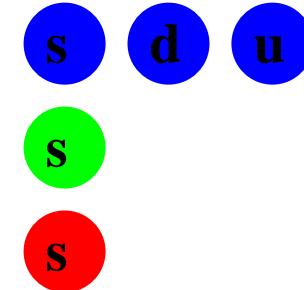
- Moderate densities: less (and less symmetric) pairing

For instance,  
2SC phase ...

paired:



unpaired:



... 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)

- Counter-propagating currents: LOFF, meson current

M. Alford, J. Bowers, K. Rajagopal, PRD 63, 074016 (2001)

T. Schäfer, PRL 96, 012305 (2006)

How do we determine the ground state ...?

## ... use astrophysical data!

- **neutrino emissivity  $\leftrightarrow$  cooling of the star**

- **CFL** P. Jaikumar, M. Prakash, T. Schäfer, PRD 66, 063003 (2002)
- **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, PRD 74, 074005 (2006)

- **rigidity of crystalline phases  $\leftrightarrow$  glitches**

- **LOFF** M. Mannarelli, K. Rajagopal, R. Sharma, hep-ph/0702021
  - M. Mannarelli's talk at this workshop

- **bulk/shear viscosity  $\leftrightarrow$  r-modes**

- **CFL** C. Manuel, A. Dobado, F.J. Llanes-Estrada, JHEP 0509, 076 (2005)  
M. Alford, M. Braby, S. Reddy, T. Schäfer, PRC 75, 055209 (2007)
  - M. Alford's talk at this workshop
- **spin-1** B.A. Sa'd, I.A. Shovkovy, D.H. Rischke, PRD 75, 065016 (2007)
- **2SC** M.G. Alford, A. Schmitt, J. Phys. G 34, 67-101 (2007)
  - remainder of this talk

- Why compute bulk viscosity?

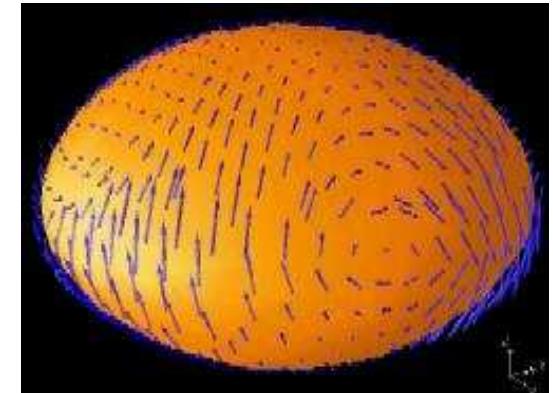
- **r-modes:** non-radial pulsation modes

- grow unstable

in a perfect-fluid rotating star

→ emission of gravitational waves

- spin down the star drastically and quickly (within days)



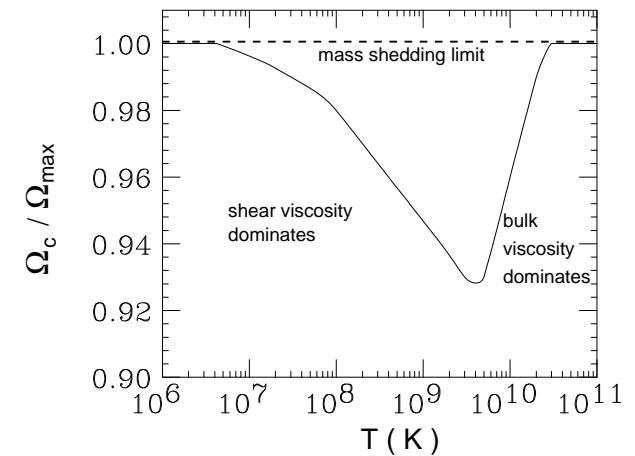
- fast rotating stars are observed!

$$\omega \simeq 1\text{ms}^{-1}$$

- must be some damping mechanism

→ **bulk/shear viscosity**

- deduce upper limit for  $\omega$  from **viscosity**

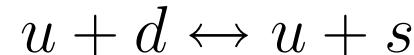


- What is bulk viscosity?

- volume oscillation  
→ chemical non-equilibrium

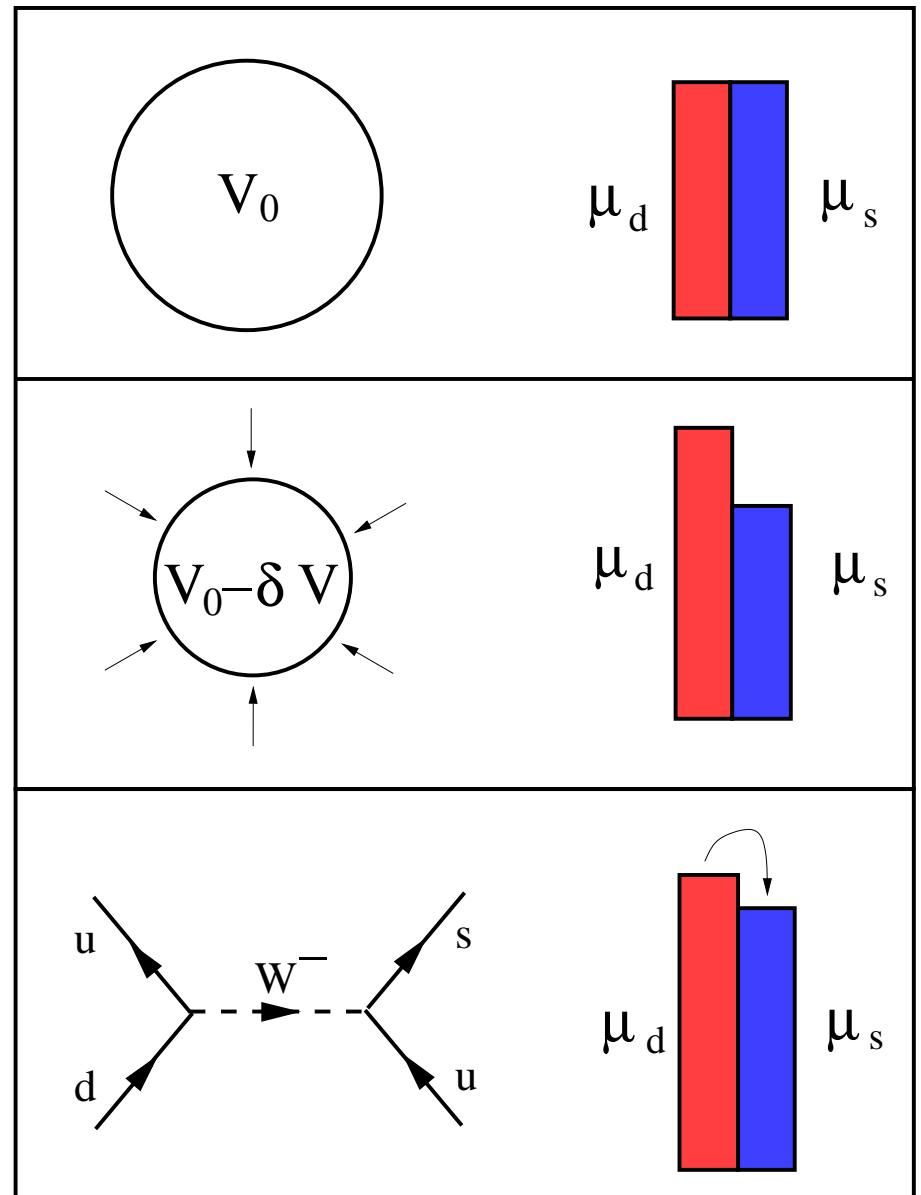
$$\delta\mu \equiv \mu_s - \mu_d \neq 0$$

- re-equilibration via



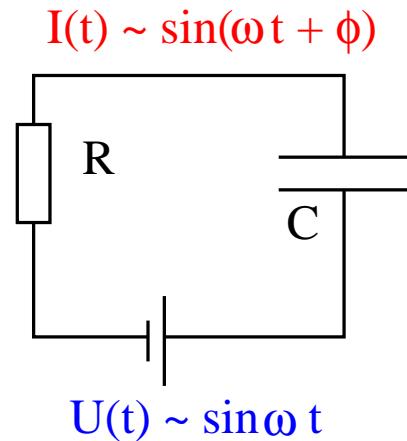
- 2 time scales:

- external oscillation  $\omega$
- microscopic rate  $\gamma$

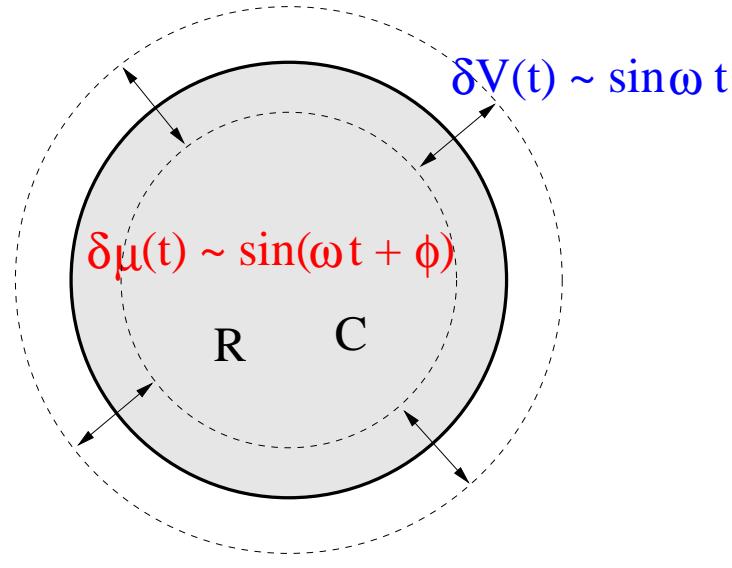


- Bulk viscosity is a resonance phenomenon

Just like an electric circuit!



$$\text{dissipation} \sim < I(t) \ U(t) >$$



$$\text{dissipation} \sim < \delta V(t) \ \delta \mu(t) >$$

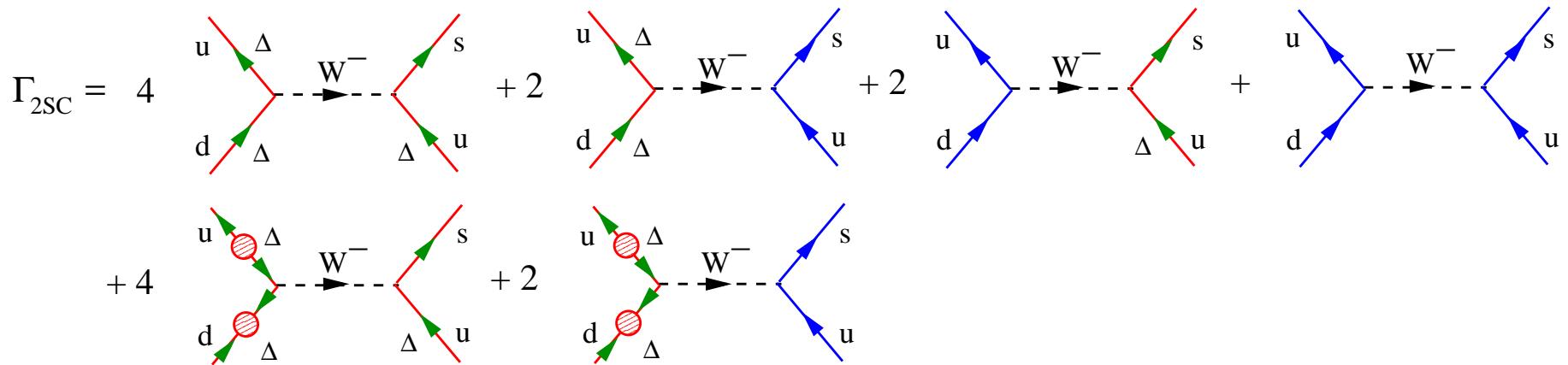
## Bulk viscosity

“capacitance”  $C \leftrightarrow$  inverse microscopic rate  $\gamma^{-1}$

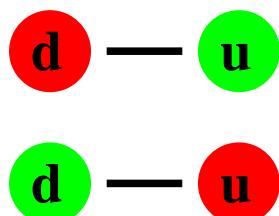
$$\zeta = \alpha \frac{\gamma}{\gamma^2 + \omega^2}$$

“resistance”  $R \leftrightarrow$  prefactor  $\alpha$

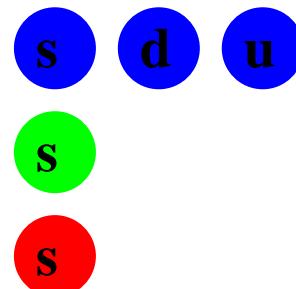
- Compute rate for  $u + d \leftrightarrow u + s$  in 2SC



paired:



unpaired:



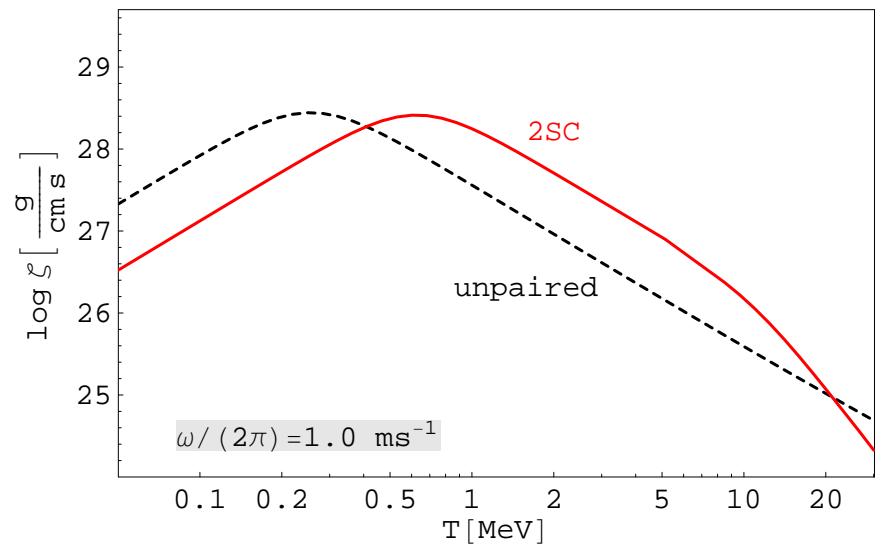
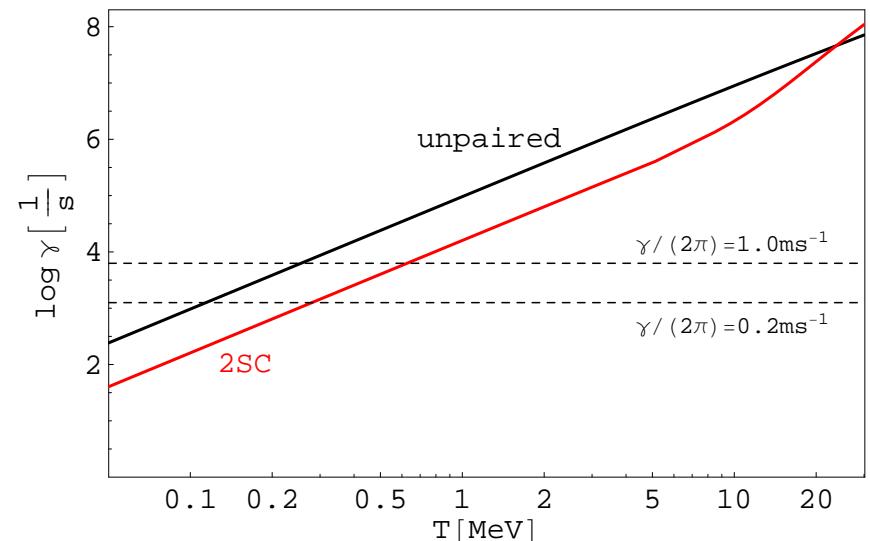
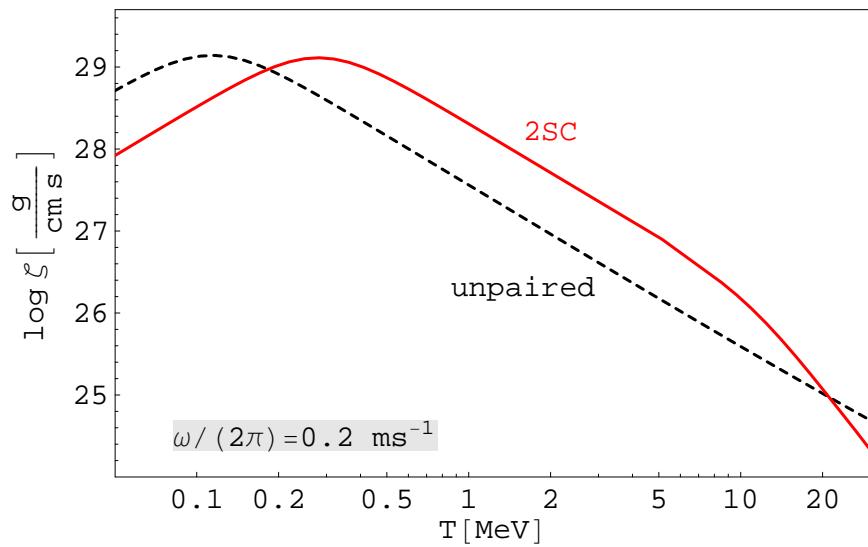
small temperatures,  
 $T \ll T_c \simeq 30 \text{ MeV}$

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

due to **exponential suppression**  
 $\exp(-\Delta/T)$  of gapped modes

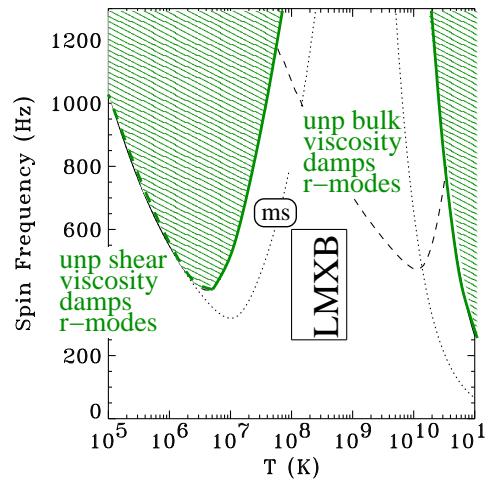
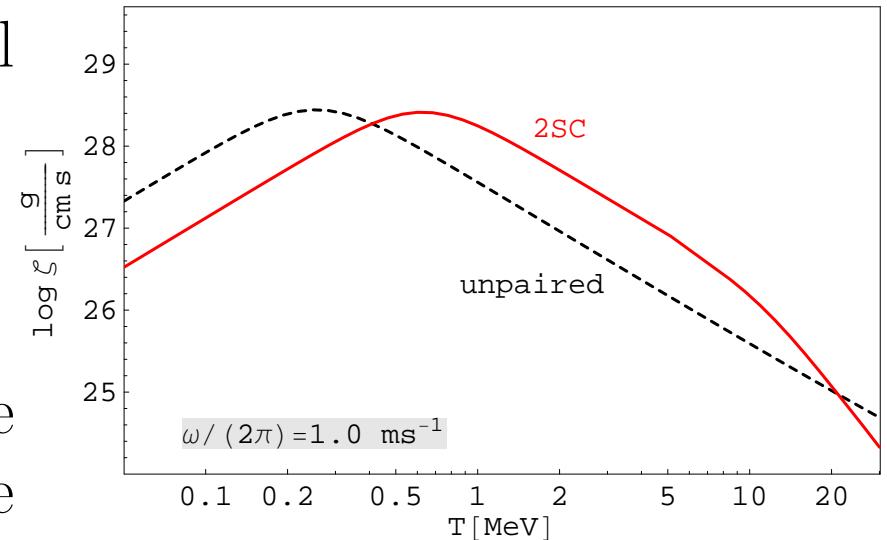
- Results for bulk viscosity

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

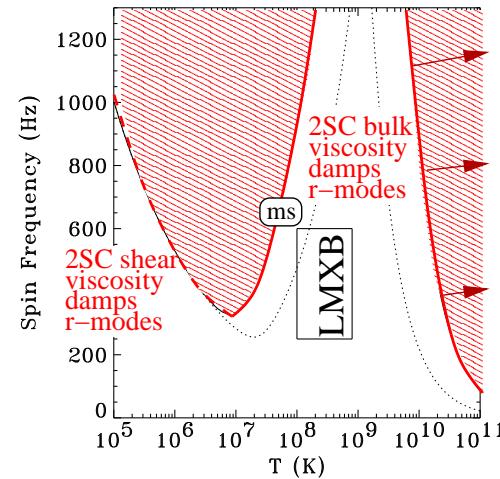


- **Astrophysical implications**

- bulk viscosity in superconductor can be **larger** than in normal phase
- results important for young neutron stars,  $T > 1 \text{ MeV}$
- → 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

- phase(s) between **CFL** and **hadronic matter** are unknown
- use astrophysical observations to learn about these phases  
**(cooling curves, rotation frequencies ...)**
- 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**