Dissipative processes in superfluid quark matter

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arXiv:0807.3264 arXiv:0904.3023 arXiv:0909.4486

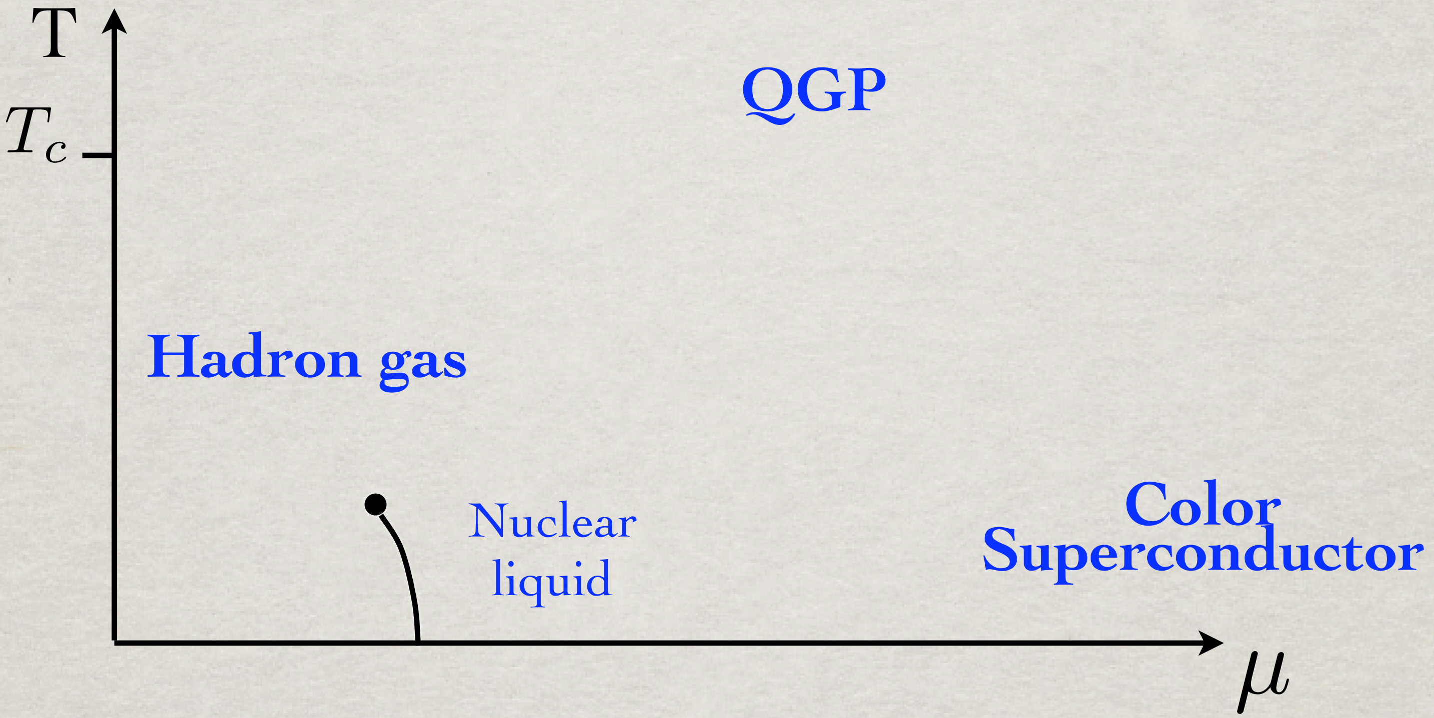
Collaborators: M.A. Escobedo, C. Manuel, B.A. Sa'd, M.Ruggieri, R.Anglani, G.Colucci

OUTLINE

- ✦ QCD phase diagram
- ✦ Color flavor locking
- ✦ Superfluids
- ✦ Dissipative processes
- ✦ R-mode oscillations

Reviews: **hep-ph/0011333, hep-ph/0102047, hep-ph/0202037, 0709.4635**

QCD PHASE DIAGRAM



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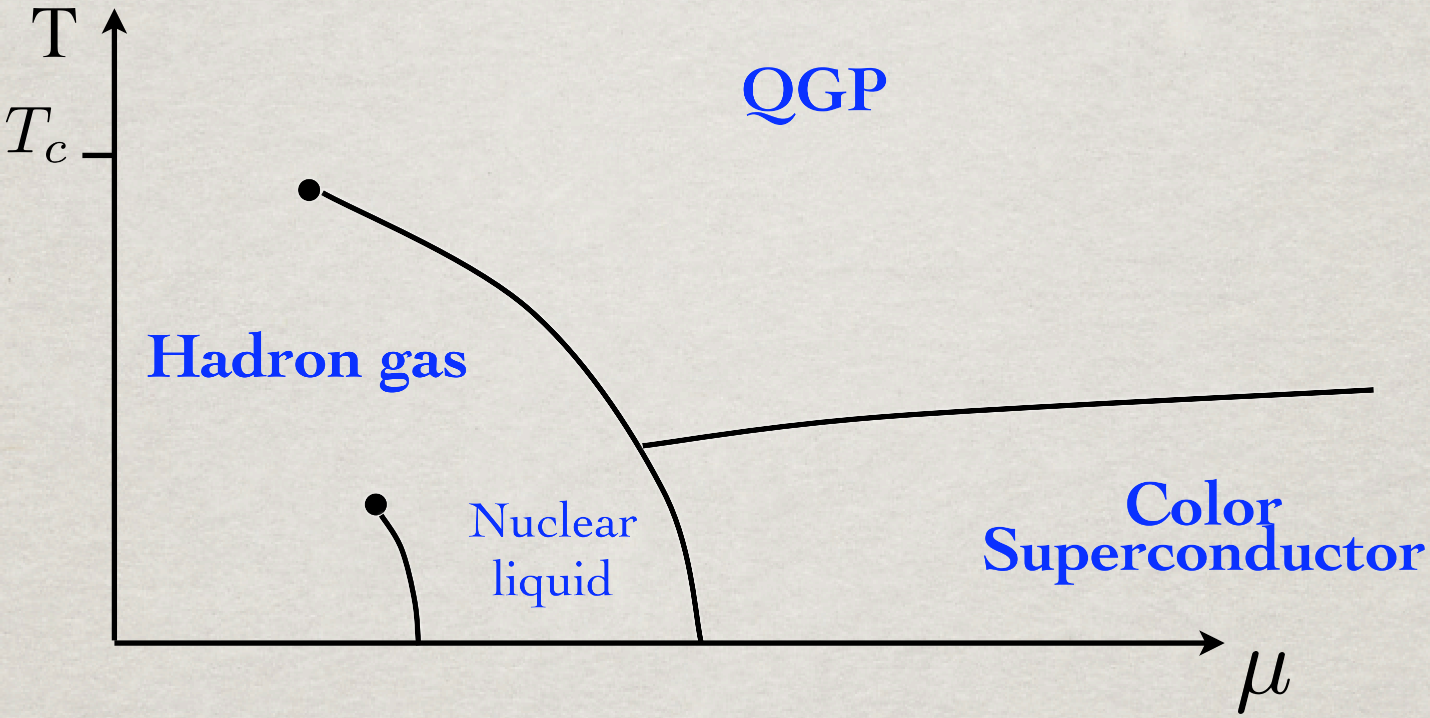

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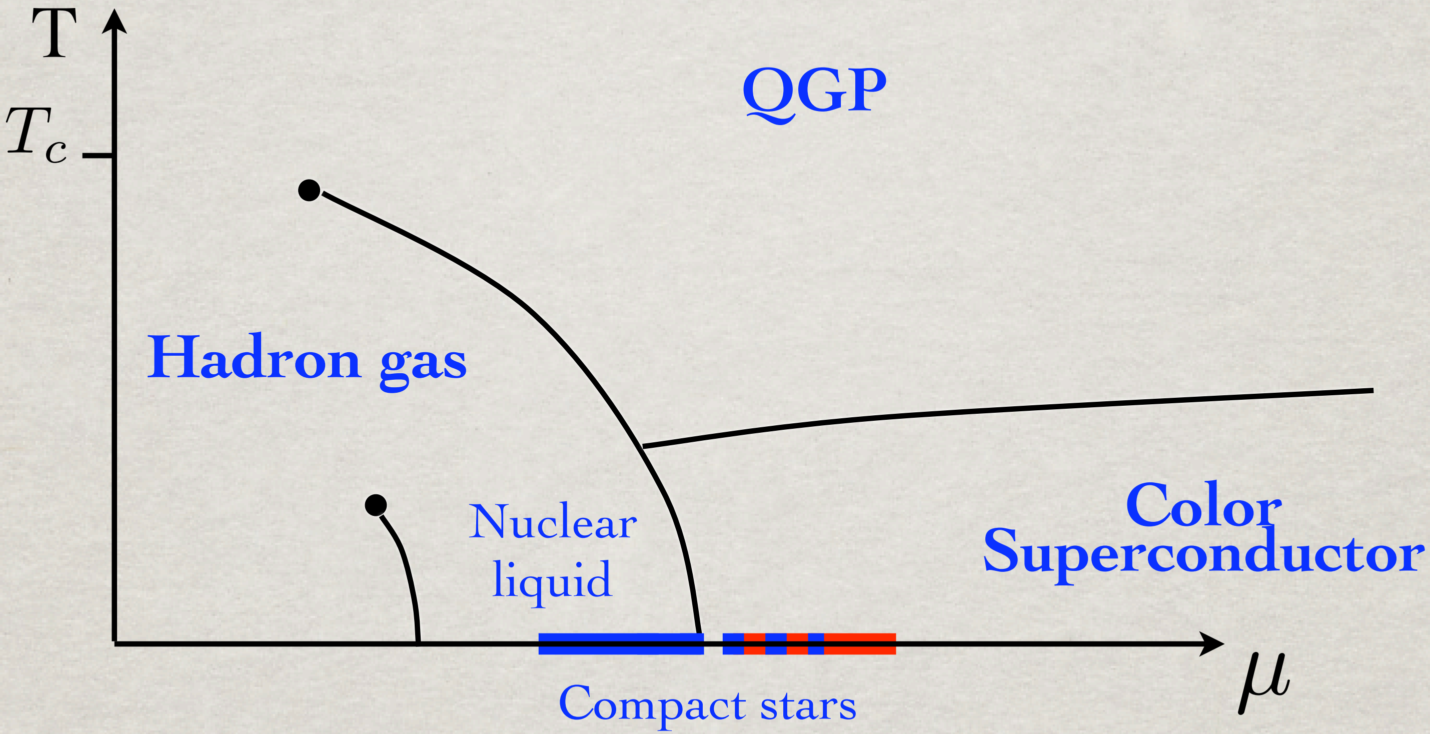

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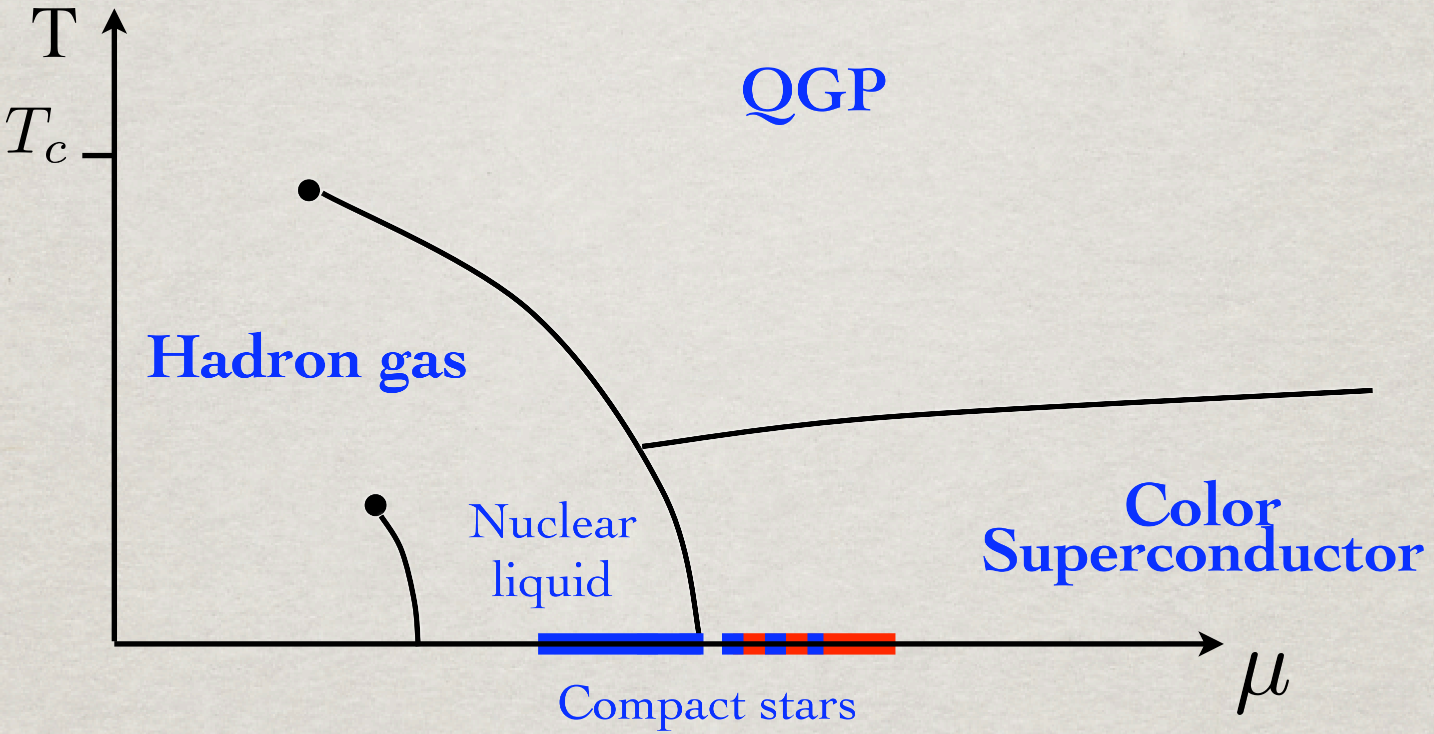

Warning: At high density ab initio calculations using QCD not available

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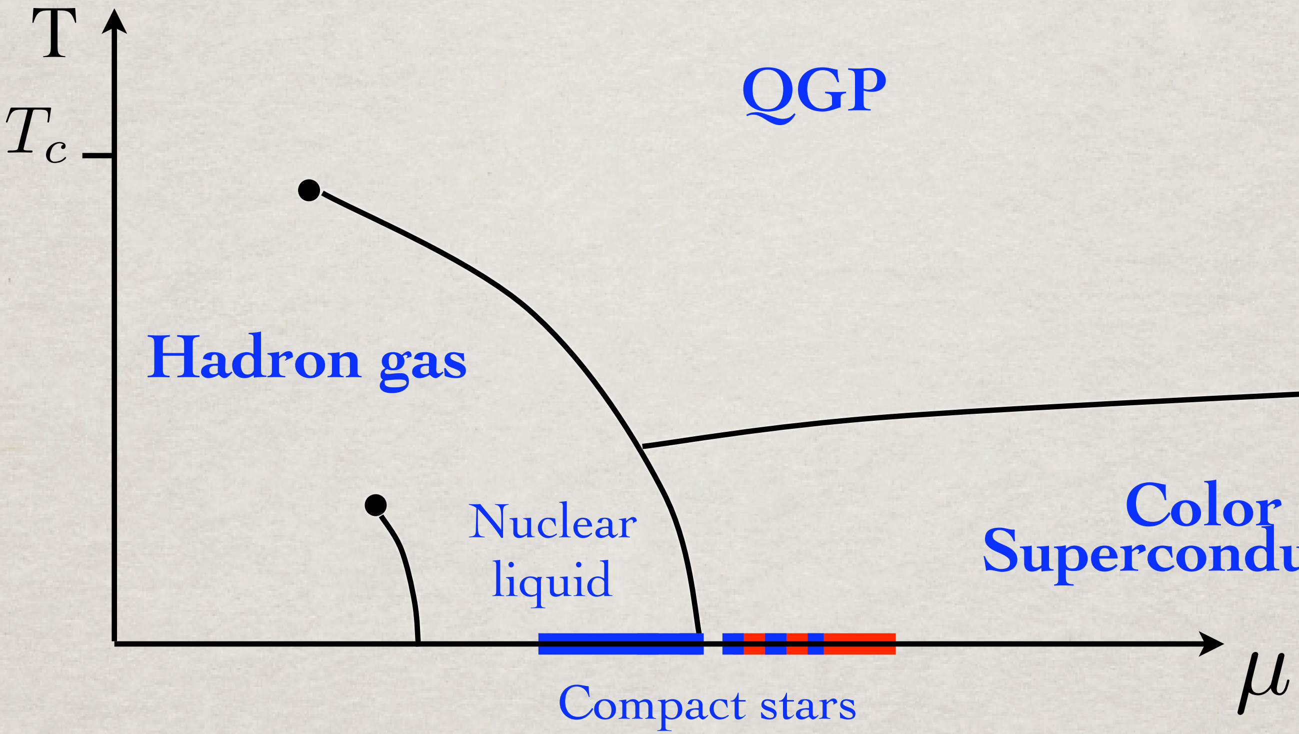

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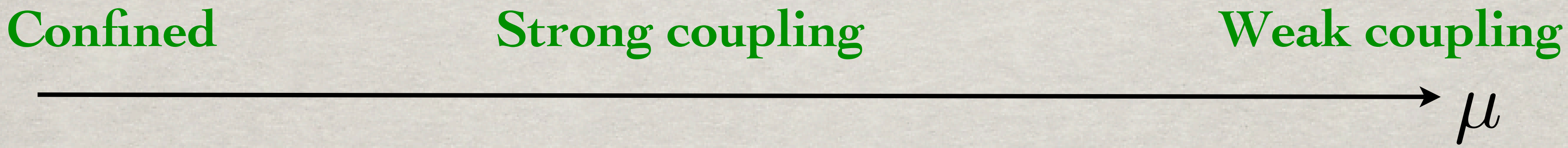

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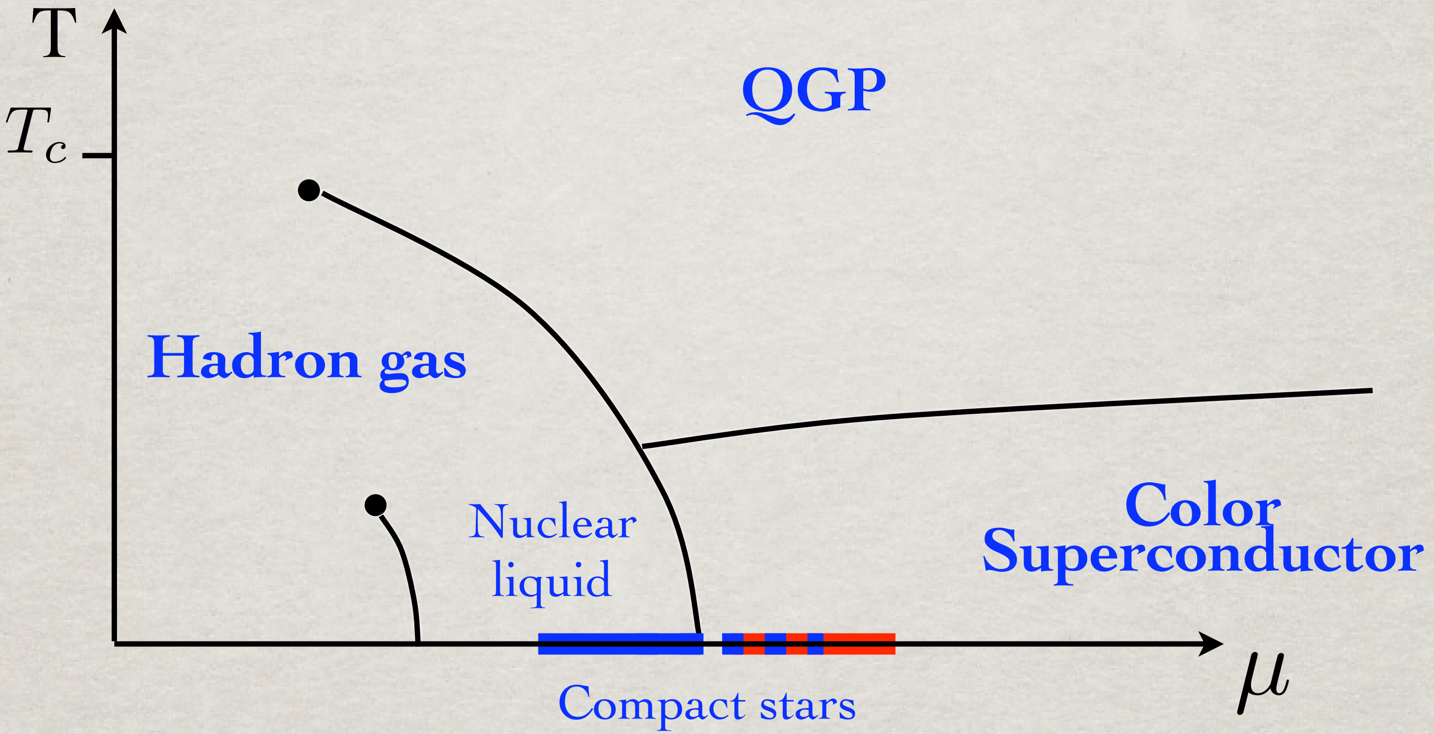

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Confined **Strong coupling** **Weak coupling**

μ

Hadrons

CSC phase?
quarkyonic phase?

CFL

COLOR SUPERCONDUCTOR

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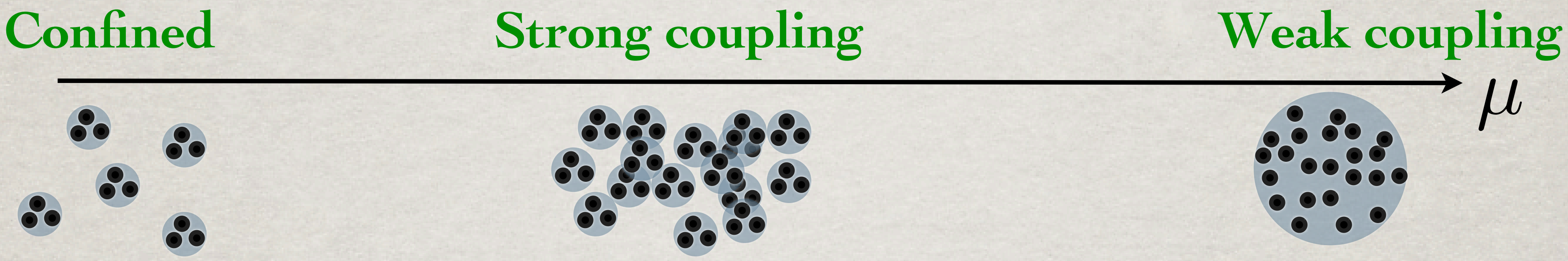

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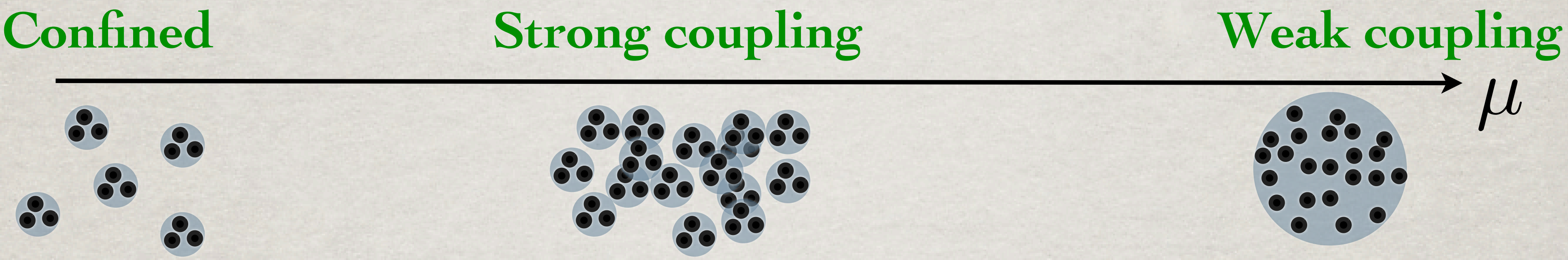
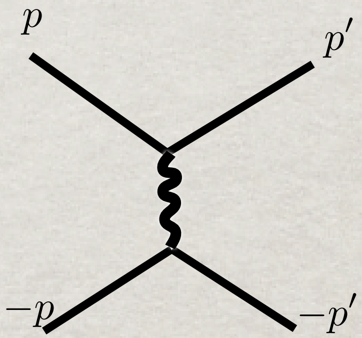


- Degenerate system of quarks
- Attractive interaction between quarks

$$3 \times 3 = \bar{3}_A + 6_S$$

↑

attractive channel



$$p, p' \simeq p_f$$

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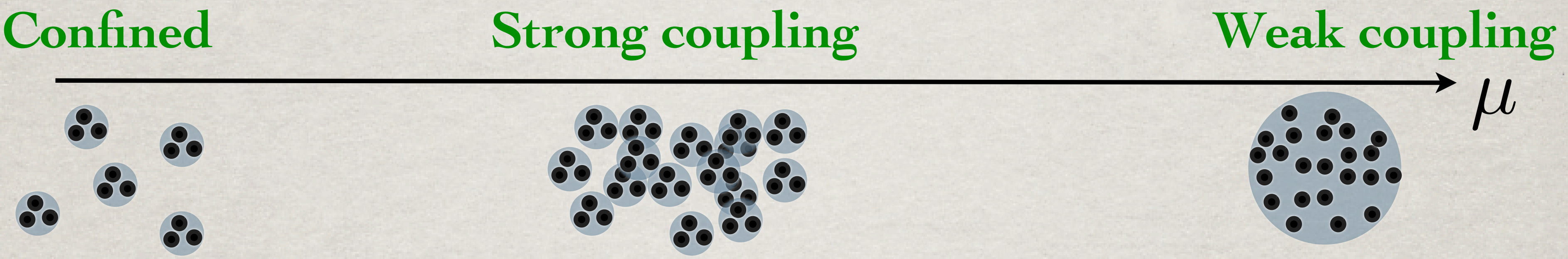

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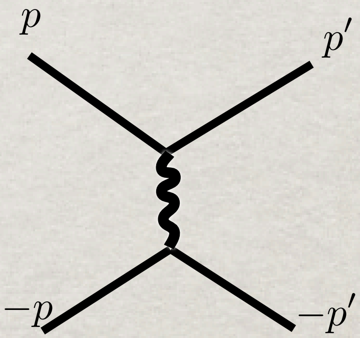

$$p, p' \simeq p_f$$

- Using quarks as building blocks, one has color, flavor as well as spin degrees of freedom: the game is complicated

- QCD, allows for a zoo of colored phases and one has to single out the one with the smallest free-energy

XTREME DENSITY

$\mu \gg m_s$

CFL phase

Alford, Rajagopal, Wilczek hep-ph/9804403

$$< \psi_{\alpha i} C \gamma_5 \psi_{\beta j} > \sim \Delta\, \epsilon_{I\alpha\beta}\epsilon_{Iij}$$

$$\boxed{SU(3)_c \times SU(3)_L \times SU(3)_R \times U(1)_B \rightarrow SU(3)_{c+L+R} \times Z_2}$$

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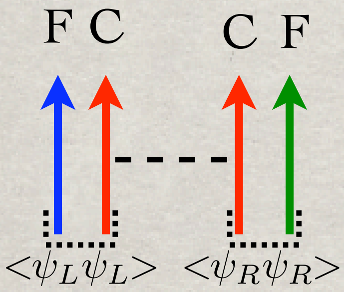

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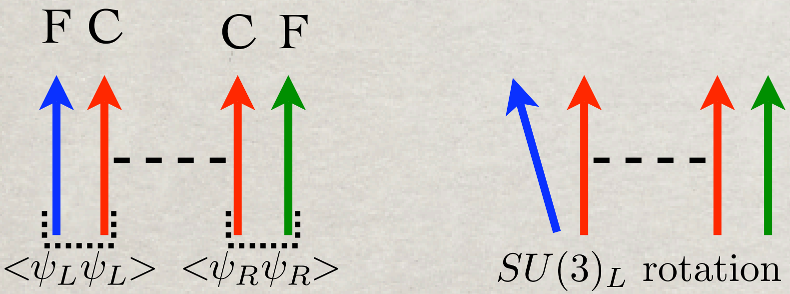

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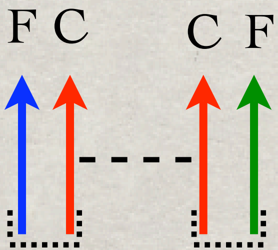
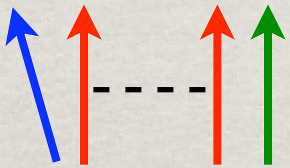
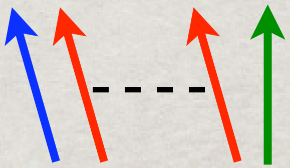


$<\psi_L \psi_L>$ $<\psi_R \psi_R>$



$SU(3)_L$ rotation



$SU(3)_c$ rotation

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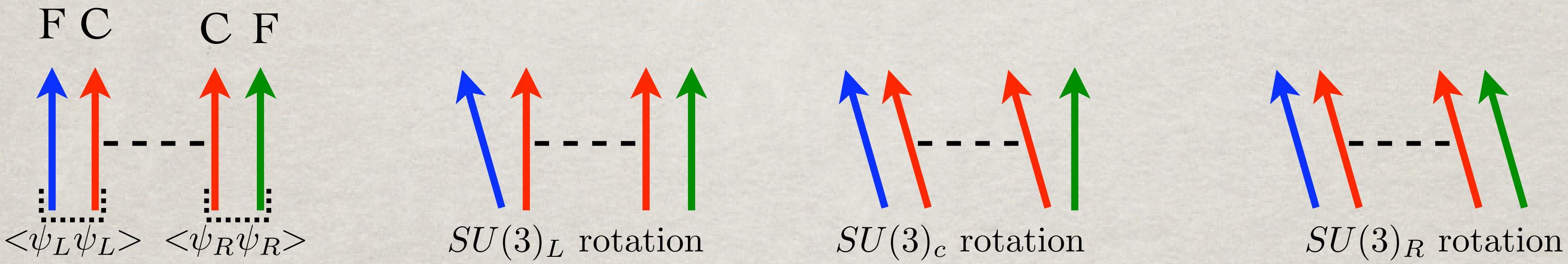

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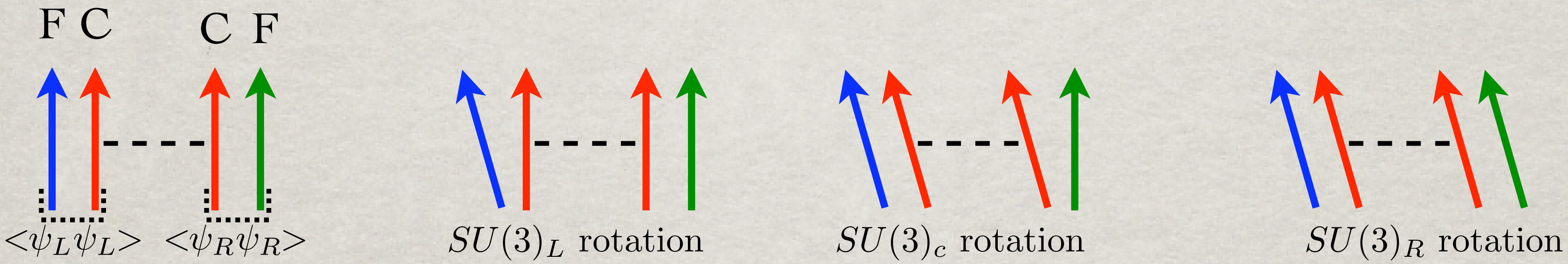
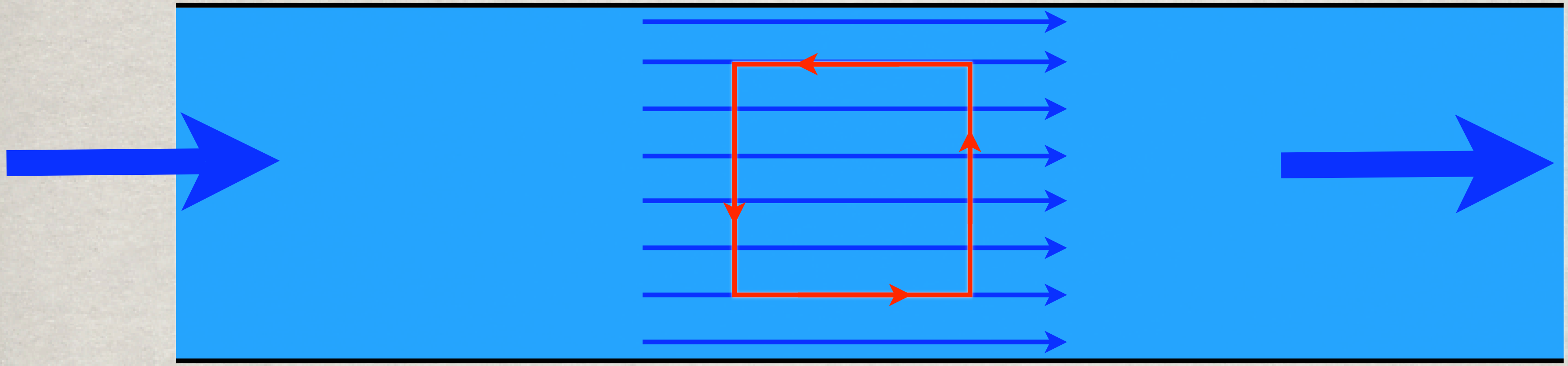


- Gluons acquire a Meissner mass by Higgs mechanism
- All quarks are paired; quasiparticles with a gapped excitation spectrum
- 8 pseudo Nambu-Goldstone bosons
- No electrons
- 1 Nambu-Goldstone boson ⟶ Superfluid

UNVISCID (DRY) FLUID



Continuity equation $$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

Euler equation $$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{\nabla \mathbf{p}}{\rho} - \nabla \phi$$

Vorticity $\boldsymbol{\Omega} = \nabla \times \mathbf{v}$

Unviscid fluid $\Omega = 0$

The flow is permanently irrotational $\mathbf{v} = \nabla \varphi$

VISCOUS (WET) FLUID

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t}+(\mathbf{v}\cdot\nabla)\mathbf{v}\right)=-\nabla p-\rho\nabla\phi+\underset{\uparrow}{\eta}\nabla^2\mathbf{v}+\left(\frac{\eta}{3}+\underset{\uparrow}{\zeta}\right)\nabla(\nabla\cdot\mathbf{v})$$

shear viscosity

bulk viscosity

- **Shear viscosity** describes reaction to shear stresses
- **Bulk viscosity** describes reaction to compression/rarefaction

Using vorticity $\frac{\partial \mathbf{\Omega}}{\partial t}+\nabla\times(\mathbf{\Omega}\times\mathbf{v})=\frac{\eta}{\rho}\nabla^2\mathbf{\Omega}$

Vorticity generated by the shear viscosity

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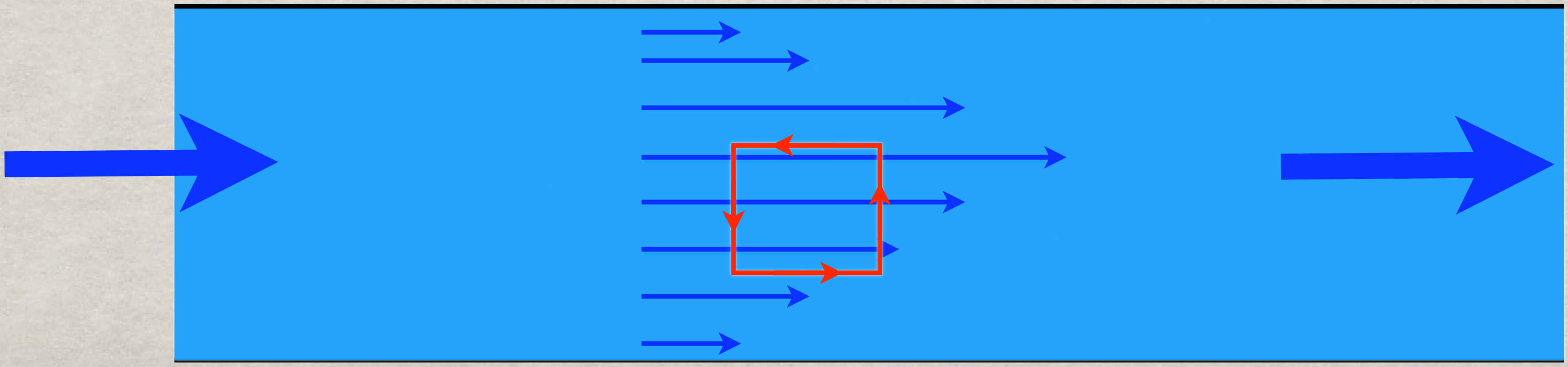
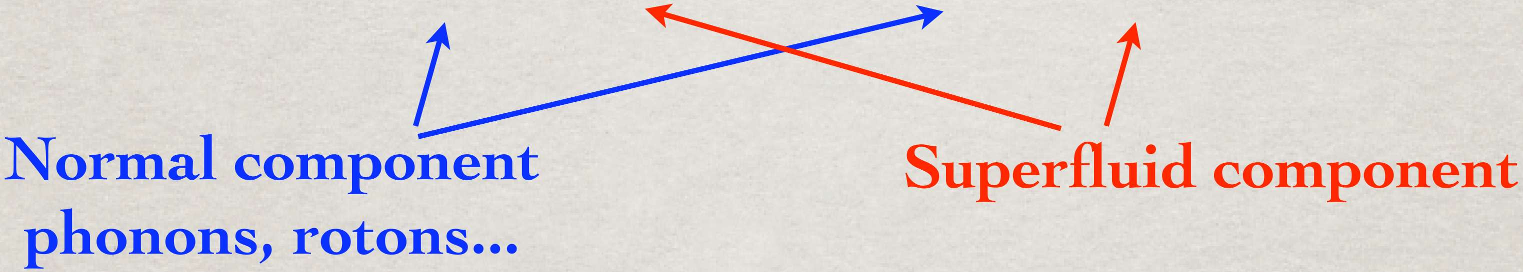


NON-RELATIVISTIC SUPERFLUIDS

Landau two-fluid theory

$$\rho = \rho_n + \rho_s \qquad \mathbf{j} = \rho_n \mathbf{v}_n + \rho_s \mathbf{v}_s$$



Normal component
phonons, rotons...

Superfluid component

$$\partial_t \rho + \mathrm{div}\mathbf{j} = 0$$

The two “components” correspond to two different motions of the fluid

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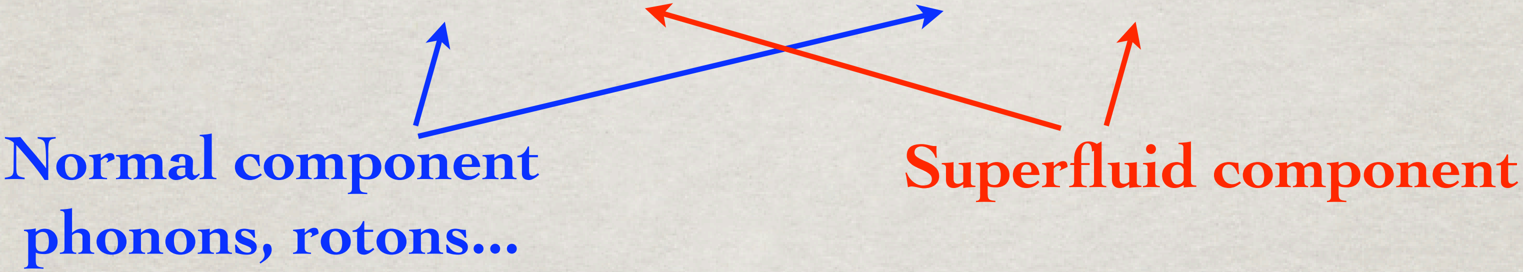

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phonons, rotons...

Superfluid component

$$\partial_t \rho + \mathrm{div}\mathbf{j} = 0$$

The two "components" correspond to two different motions of the fluid

Normal component: viscous fluid

Superfluid component: unviscid fluid

Not completely correct: neglects interactions

RELATIVISTIC HYDRODYAMICS

$$\begin{aligned} \partial_\mu n^\mu &= 0 \\ \partial_\mu (T^{\mu\nu} + T_d^{\mu\nu}) &= 0 \\ u^\mu \partial_\mu \phi + \mu + \chi &= 0 \end{aligned}$$

dissipative terms

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dissipative terms

Close to equilibrium

$$\chi = -\zeta_3 \partial_\mu (V^2 w^\mu) - \zeta_4 \partial_\mu u^\mu$$

$$\begin{aligned} T_d^{\mu\nu} &= \kappa \left(\Delta^{\mu\gamma} u^\nu + \Delta^{\nu\gamma} u^\mu\right) \left(\partial_\gamma T + T u^\delta \partial_\delta u_\gamma\right) \\ &+ \eta \Delta^{\mu\gamma} \Delta^{\nu\delta} \left(\partial_\delta u_\gamma + \partial_\gamma u_\delta + \frac{2}{3} g_{\gamma\delta} \partial_\alpha u^\alpha\right) \\ &+ \Delta^{\mu\nu} \left(\zeta_1 \partial_\gamma (V^2 w^\gamma) + \zeta_2 \partial_\gamma u^\gamma\right) \end{aligned}$$

$$w^\mu = -\left(\partial^\mu \varphi + \mu u^\mu\right)$$

where

$$\Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$$

BULK VISCOSITY IN COLOR SUPERCONDUCTORS

Bulk viscosity depends on the low energy spectrum of the theory

CFL phase

Contribution of phonons	*Manuel and LLanes*	**0705.3909**
	MM and Manuel	**0909.4486**
Contribution of kaons	*Alford et al.*	**nucl-th/0701067**
	Alford et al.	**0707.2389**

Spin 1 phase	*Sa’d et al.*	**astro-ph/0607643**
	Wang et al.	**1006.1293**

2SC phase	*Alford and Schmitt*	**nucl-th/0608019**

Large amplitude behavior of bulk viscosity: talk by Alford

PHONON EFFECTIVE ACTION

Fluid of quasiparticles (phonons) moving on the top of the superfluid background

Effective Lagrangian (low energy, asymptotic densities) Son hep-ph/0204199

$$\mathcal{L}_{\text{eff}} = \frac{3}{4\pi^2}\left[(\partial_0\varphi - \mu_q)^2 - (\partial_i\varphi)^2\right]^2$$

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$$\varphi(x) = \bar{\varphi}(x) + \phi(x)$$

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Phonon's action $$S[\phi] = \frac{1}{2}\int d^4x\sqrt{-g}\, g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$$

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Acoustic metric

$$g_{\mu\nu} = \eta_{\mu\nu} + (c_s^2 - 1)v_\mu v_\nu$$

PHONON CONTRIBUTION

phonon dispersion law $\epsilon_p = c_s p + B p^3 + \mathcal{O}(p^5)$

$$\boxed{\partial_t \mathcal{N}_{\rm ph} + {\rm div}(\mathcal{N}_{\rm ph} \mathbf{v_n}) = -\frac{\Gamma_{\rm ph}}{T} \mu_{\rm ph}}$$

$$\begin{array}{ll} B > 0 & \phi \to \phi\phi \\ B < 0 & \phi\phi \to \phi\phi\phi \end{array}$$

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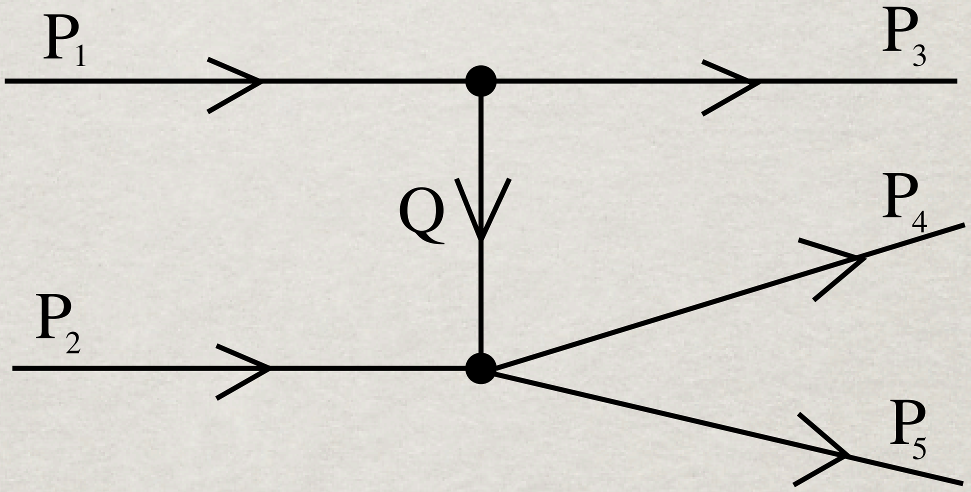
\end{aligned}$$

Notice that $\zeta_1^2 = \zeta_2\zeta_3$ the system tends toward the state where bulk viscosity does not lead to dissipation

PHONONS IN CFL

Low temperatures $T \lesssim 0.01 \text{ MeV}$

- **In CFL B<0**



Conformal limit $\zeta_1 = \zeta_2 = 0$ $\zeta_3 \sim \frac{\mu^6}{T\Delta^8}$

Conformal breaking due to m_s $\zeta_1 \sim \frac{m_s^2 \mu^7}{T\Delta^8}$ $\zeta_2 \sim \frac{m_s^4 \mu^8}{T\Delta^8}$

MUTUAL FRICTION

- Mutual friction

Force between the superfluid component and the normal component mediated by phonon-vortex interaction

$$
\begin{aligned}
\rho_s \frac{d\mathbf{v}_s}{dt} &= -\frac{\rho_s}{\rho}\nabla p - \rho_s \nabla\phi - \mathbf{F}^N \\
\rho_n \frac{d\mathbf{v}_n}{dt} &= -\frac{\rho_n}{\rho}\nabla p - \rho_n \nabla\phi + \mathbf{F}^N + \eta\nabla^2\mathbf{v}_n
\end{aligned}
$$

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- **Mutual friction**

Force between the superfluid component and the normal component mediated by phonon-vortex interaction

$$\begin{aligned}\rho_s \frac{d\mathbf{v}_s}{dt} &= -\frac{\rho_s}{\rho}\nabla p - \rho_s \nabla\phi - \mathbf{F}^N \\ \rho_n \frac{d\mathbf{v}_n}{dt} &= -\frac{\rho_n}{\rho}\nabla p - \rho_n \nabla\phi + \mathbf{F}^N + \eta\nabla^2\mathbf{v}_n\end{aligned}$$

FORCES ACTING ON A VORTEX

- **Magnus force**

  Standard hydrodynamic force

$$\mathbf{F}^M = \kappa \rho_s (\mathbf{v}_s - \mathbf{v}_L) \times \hat{\mathbf{z}}$$

- **Friction force**

  Scattering of phonons off vortices

$$\mathbf{F}^N = D(\mathbf{v}_n - \mathbf{v}_L) + D' \hat{\mathbf{z}} \times (\mathbf{v}_n - \mathbf{v}_L)$$

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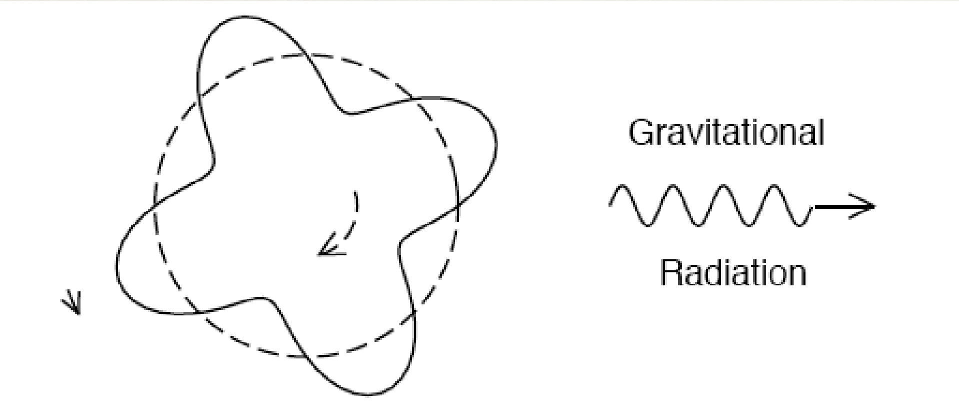
inelastic scattering on vortices

work in progress

see the talk by Anglani

DISSIPATIVE PROCESSES AND STARS OSCILLATIONS

R-mode instability



Lindblom, astro-ph/0101136

Modes retrograde in the corotating frame (but prograde in the inertial frame) are unstable.

See also Andersson, Kokkotas gr-qc/0010102

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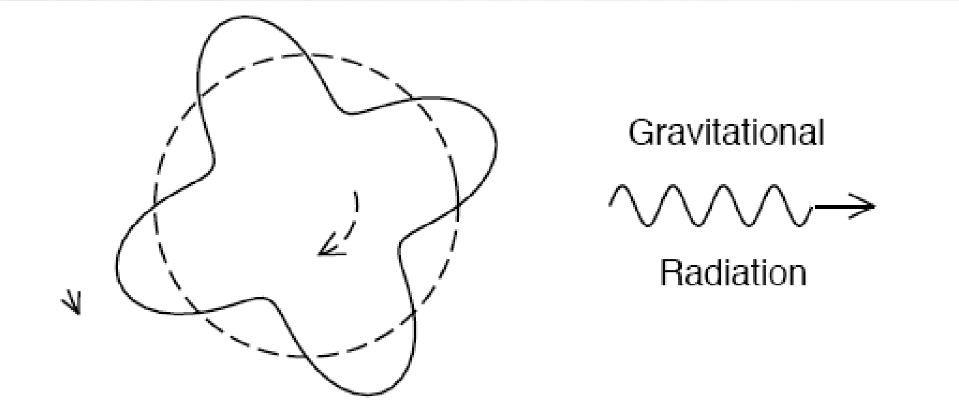

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R-mode oscillations
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Madsen, Phys. Rev. Lett. 85, 10 (2000)

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Emitting gravitational radiation
the star quickly spins down

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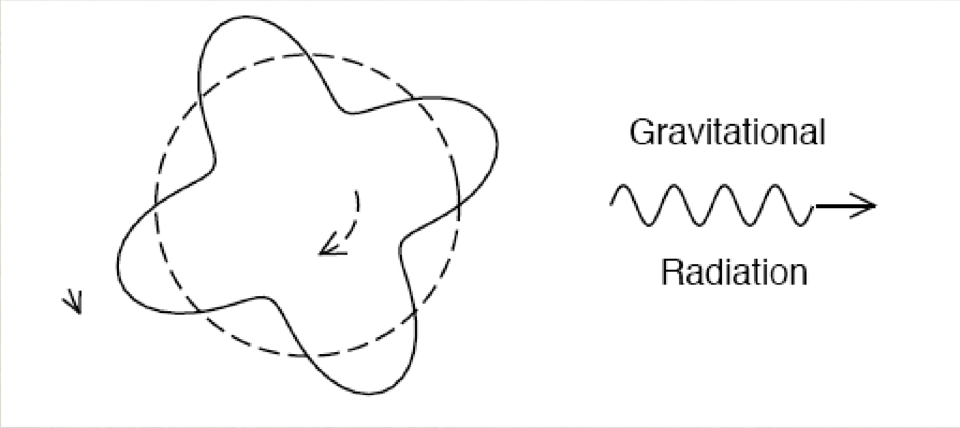

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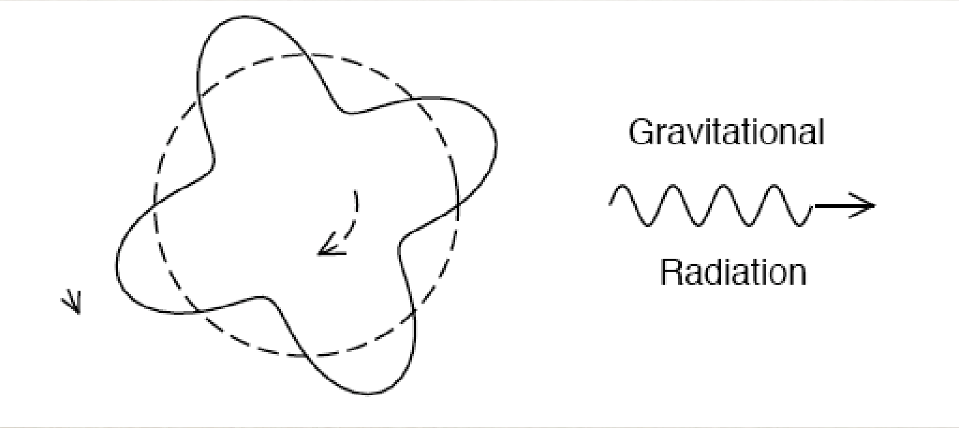

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For more details see the talk by Sedrakian

SUMMARY

- CFL is a superfluid

- Contribution of phonons to the bulk viscosity coefficients of CFL

- For rotating superfluids one has to include the mutual friction force

- Damping of star oscillations, especially gravitationally unstable r-modes


FIFA