Superfluidity of parity-doubled baryons in neutron stars

S. Yasui, M. Nitta, C. Sasaki

arXiv:2409.05670

Chihiro Sasaki

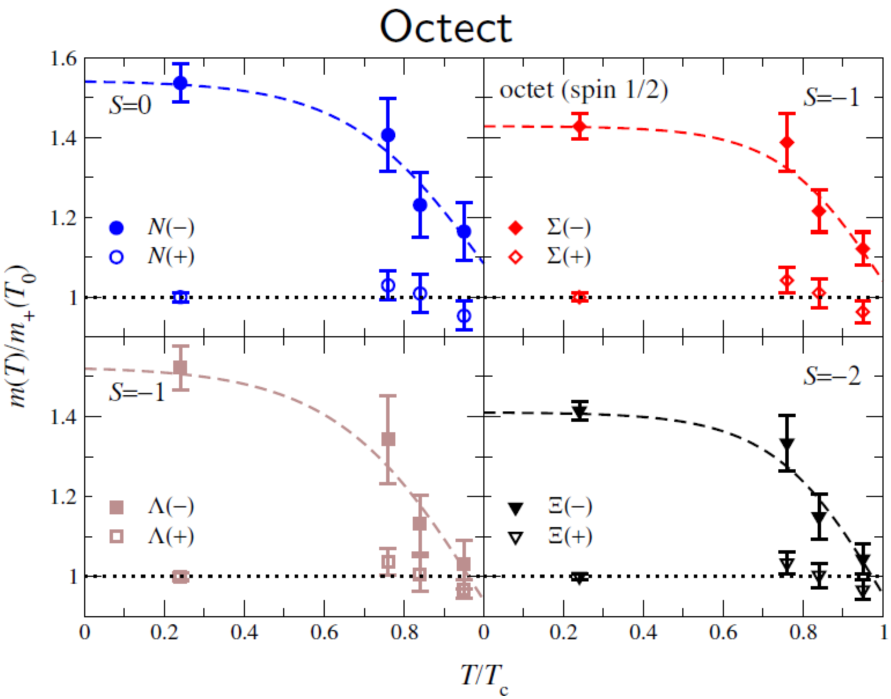
Institute of Theoretical Physics

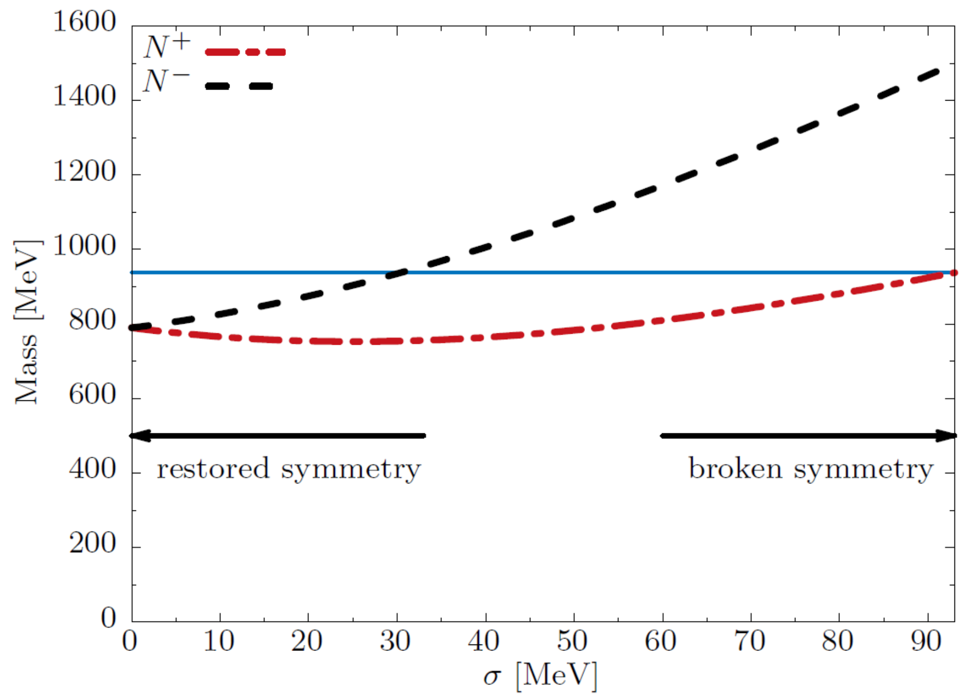
University of Wroclaw, Poland

&

SKCM², Hiroshima University, Japan

Parity doubling of baryons





- ❑ Lattice QCD at zero μ [Aarts et al., 2016-2019]
- ❑ Survival mass $m_N \approx m_0 \neq 0$ [DeTar, Kunihiro, 1989]

$$M_{\pm} = \sqrt{m_0^2 + c_1^2\sigma^2} \mp c_2\sigma \xrightarrow{\sigma \to 0} m_0$$

DeTar-Kunihiro/Parity doublet model

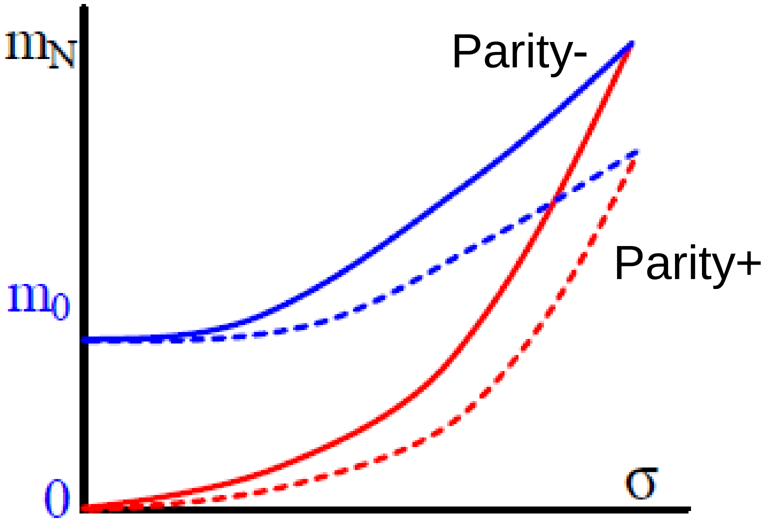
- SU(2) chiral transformation of 2 nucleons

  → how to assign 2 indep. rotation to them?

$$\psi_{1L} \to g_l\, \psi_{1L}\,, \quad \psi_{1R} \to g_r\, \psi_{1R} \;\sim\; \psi_{1L} : (1/2, 0) \quad \psi_{1R} : (0, 1/2)$$

$$\psi_{2L} \to g_r\, \psi_{2L}\,, \quad \psi_{2R} \to g_l\, \psi_{2R} \;\sim\; \psi_{2L} : (0, 1/2) \quad \psi_{2R} : (1/2, 0)$$

$$\mathcal{L}_m = m_0 \left(\bar{\psi}_2 \gamma_5 \psi_1 - \bar{\psi}_1 \gamma_5 \psi_2 \right) \;\Rightarrow\; m_{N_\pm} = \frac{1}{2} \left[\sqrt{c_1 \sigma^2 + 4 m_0^2} \mp c_2 \sigma \right]$$



[DeTar and Kunihiro, 1989]

Red: Naive

Blue: Mirror

The role of N*

- Correlations between N and N* at finite T & μ

  [Koch, Marczenko et al., 2024]

  - $\chi_2^B = \chi_2^{++} + \chi_2^{--} + 2\chi_2^{+-}$: strength & sign of χ_2^{+-}
  - Liquid-gas vs. QCD chiral transitions
  - The net-proton fluctuations do not necessarily reflect the net-baryon fluctuations at the chiral phase boundary.

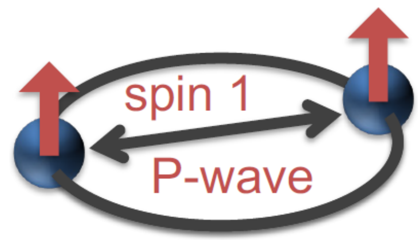
- The role of Δ(1232): correlations among (N,N*) & (Δ,Δ*) [Marczenko, PRD 2024]

S. Yasui, M. Nitta and C. Sasaki, arXiv:2409.05670

SUPERFLUIDITY IN NEUTRON STARS

Superfluidity in neutron stars

- ❑ s-wave superfluid by $^{1}S_{0}$ [Migdal, '60]
- ❑ p-wave superfluid by $^{3}P_{2}$ at $\rho/\rho_{0} > ½$ [Tabakin, '68]
  - ✓ Pulser glitches
  - ✓ Rapid cooling



$^{2S+1}L_{J}$

S: spin
L: angular momentum
J: spin+angular momentum

- ❑ This study: Cooper pairing of parity-doubled neutrons at high density → the role of N*
  - Generalized χ-sym G such that G ⊃ naïve&mirror
    $$G = U(1)_{1L} \times U(1)_{1R} \times U(1)_{2L} \times U(1)_{2R}$$
  - Common operators to the naïve & mirror assign.

Symmetries

- $U(1)_L \times U(1)_R$ chiral symmetry

$$(n, n^*) \Leftrightarrow (\psi_1, \psi_2),\ \psi_i = \psi_{iL} + \psi_{iR}$$

  - Naïve assignment

$$\psi_{1\mathrm{L}} \to U_{\mathrm{L}} \psi_{1\mathrm{L}}, \quad \psi_{2\mathrm{L}} \to U_{\mathrm{L}} \psi_{2\mathrm{L}}, \quad \psi_{1\mathrm{R}} \to U_{\mathrm{R}} \psi_{1\mathrm{R}}, \quad \psi_{2\mathrm{R}} \to U_{\mathrm{R}} \psi_{2\mathrm{R}}$$

  - Mirror assignment

$$\psi_{1\mathrm{L}} \to U_{\mathrm{L}} \psi_{1\mathrm{L}}, \quad \psi_{2\mathrm{L}} \to U_{\mathrm{R}} \psi_{2\mathrm{L}}, \quad \psi_{1\mathrm{R}} \to U_{\mathrm{R}} \psi_{1\mathrm{R}}, \quad \psi_{2\mathrm{R}} \to U_{\mathrm{L}} \psi_{2\mathrm{R}}$$

- Generalized chiral symmetry

$$G = U(1)_{1L} \times U(1)_{2L} \times U(1)_{1R} \times U(1)_{2R}$$

$$\psi_{1\mathrm{L}} \to U_{1\mathrm{L}} \psi_{1\mathrm{L}}, \quad \psi_{2\mathrm{L}} \to U_{2\mathrm{L}} \psi_{2\mathrm{L}}, \quad \psi_{1\mathrm{R}} \to U_{1\mathrm{R}} \psi_{1\mathrm{R}}, \quad \psi_{2\mathrm{R}} \to U_{2\mathrm{R}} \psi_{2\mathrm{R}}$$

Naïve: $U_{1L} = U_{2L}, U_{1R} = U_{2R}$ Mirror: $U_{1L} = U_{2R}, U_{1R} = U_{2L}$

Symmetries

Define 2 symmetries as $[\psi_L^t = (\psi_{1L}, \psi_{2L})^t]$

$$\psi_{\rm L} \to e^{i\theta_{\rm L}}\psi_{\rm L}, \quad \psi_{\rm R} \to e^{i\theta_{\rm R}}\psi_{\rm R}, \quad \text{with} \quad (e^{i\theta_{\rm L}}, e^{i\theta_{\rm R}}) \in {\rm U}(1)_{\rm L} \times {\rm U}(1)_{\rm R}$$

$$\psi_{\rm L} \to e^{i\tau_3\theta_{\rm L}}\psi_{\rm L}, \quad \psi_{\rm R} \to e^{i\tau_3\theta_{\rm R}}\psi_{\rm L}, \quad \text{with} \quad (e^{i\tau_3\theta_{\rm L}}, e^{i\tau_3\theta_{\rm R}}) \in {\rm U}(1)_{(1-2){\rm L}} \times {\rm U}(1)_{(1-2){\rm R}}$$

$${\rm U}(1)_{1{\rm L}} \times {\rm U}(1)_{2{\rm L}} = \frac{{\rm U}(1)_{\rm L} \times {\rm U}(1)_{(1-2){\rm L}}}{\mathbb{Z}'_{2{\rm L}}}, \quad {\rm U}(1)_{1{\rm R}} \times {\rm U}(1)_{2{\rm R}} = \frac{{\rm U}(1)_{\rm R} \times {\rm U}(1)_{(1-2){\rm R}}}{\mathbb{Z}'_{2{\rm R}}}$$

- Global sym G and its subgroups

$${\rm U}(1)_{\rm L} \times {\rm U}(1)_{\rm R} \subset \frac{{\rm U}(1)_{\rm L} \times {\rm U}(1)_{(1-2){\rm L}}}{\mathbb{Z}'_{2{\rm L}}} \times \frac{{\rm U}(1)_{\rm R} \times {\rm U}(1)_{(1-2){\rm R}}}{\mathbb{Z}'_{2{\rm R}}} = {\rm U}(1)_{1{\rm L}} \times {\rm U}(1)_{2{\rm L}} \times {\rm U}(1)_{1{\rm R}} \times {\rm U}(1)_{2{\rm R}}$$

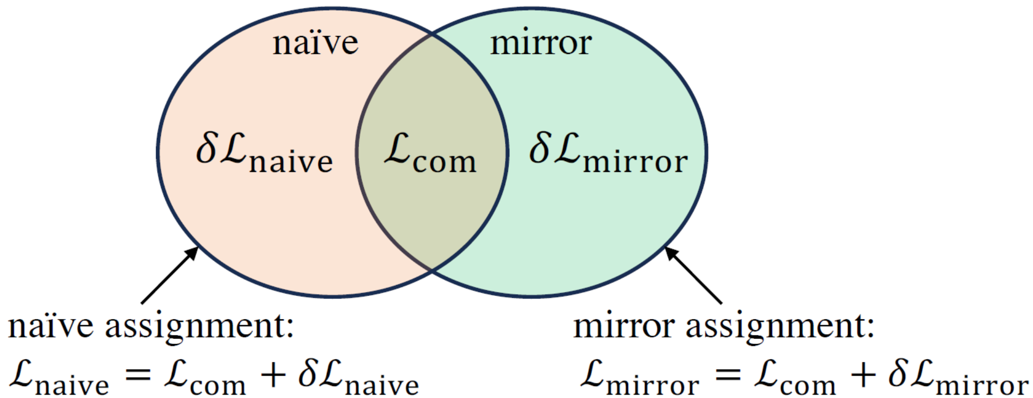
- ***Emergent chiral symmetry*** for $(\psi_1, \psi_2)^t$

$${\rm U}(1)_{(1-2){\rm L}} \times {\rm U}(1)_{(1-2){\rm R}}$$

- Both naïve & mirror as subgroups of ECS

The Lagrangian w/ ECS

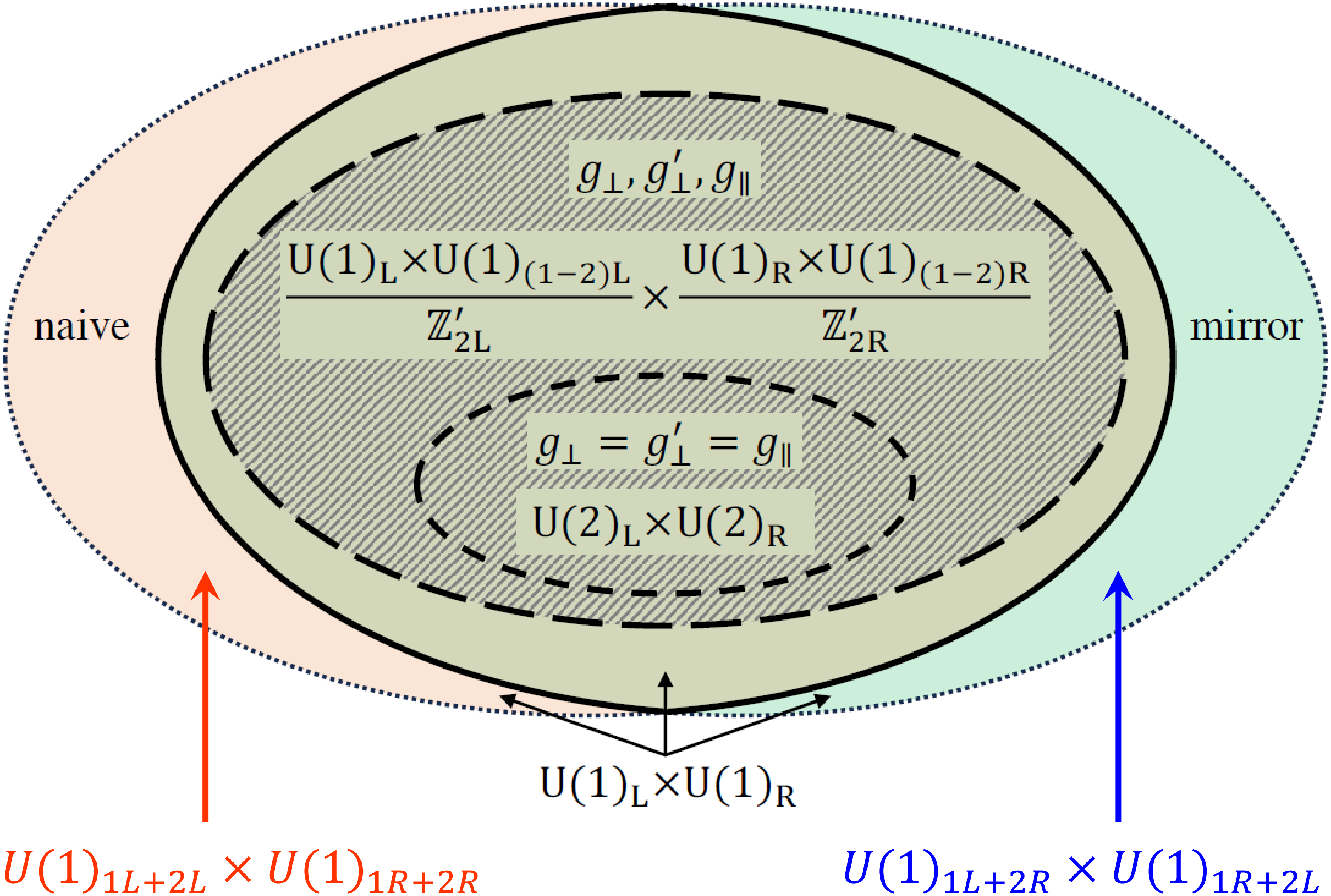
$$\mathcal{L} = \mathcal{L}_{\rm com} + \delta\mathcal{L}_{\rm naive} + \delta\mathcal{L}_{\rm mirror}$$



- ❑ Pairing formation → 4-point interactions

$$\begin{aligned}\mathcal{L}_{\rm com} &= \bar{\psi}_1 i\gamma\partial\psi_1 + \bar{\psi}_2 i\gamma\partial\psi_2 \\ &- 4g_\perp\left((\bar{\psi}_1\psi_1)^2 + (\bar{\psi}_1 i\gamma_5\psi_1)^2\right) - 4g'_\perp\left((\bar{\psi}_2\psi_2)^2 + (\bar{\psi}_2 i\gamma_5\psi_2)^2\right) \\ &- 8g_{||}\left((\bar{\psi}_1\psi_2)(\bar{\psi}_2\psi_1) + (\bar{\psi}_1 i\gamma_5\psi_2)(\bar{\psi}_2 i\gamma_5\psi_1)\right).\end{aligned}$$

- ❑ Special case: 3 equal coupling constants → $SU(2)_L \times SU(2)_R$ emergent chiral sym.



$g_\perp, g'_\perp, g_\parallel$
$\frac{U(1)_L \times U(1)_{(1-2)L}}{\mathbb{Z}'_{2L}} \times \frac{U(1)_R \times U(1)_{(1-2)R}}{\mathbb{Z}'_{2R}}$
naive
mirror
$g_\perp = g'_\perp = g_\parallel$
$U(2)_L \times U(2)_R$
$U(1)_L \times U(1)_R$
$U(1)_{1L+2L} \times U(1)_{1R+2R}$
$U(1)_{1L+2R} \times U(1)_{1R+2L}$

Mean-field analyses

- A simplified Lagrangian assuming $g_\perp = g'_\perp$

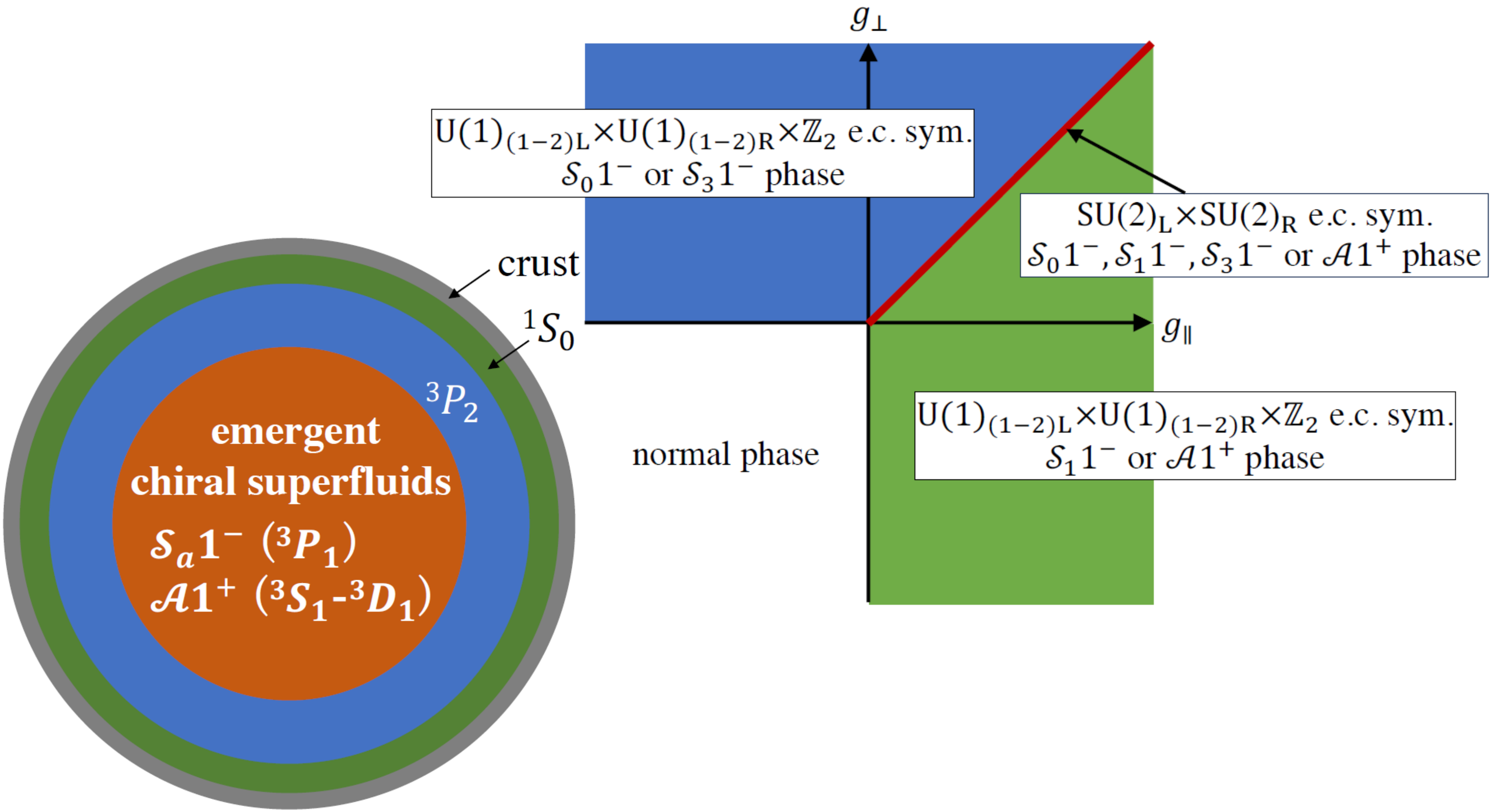
$$\mathcal{L}_{\rm com} = \bar\psi i\gamma\partial\psi - 2g_\perp\Big((\bar\psi\tau_0\psi)^2 + (\bar\psi\tau_3\psi)^2 + (\bar\psi i\gamma_5\tau_0\psi)^2 + (\bar\psi i\gamma_5\tau_3\psi)^2\Big)$$
$$- 2g_{||}\Big((\bar\psi\tau_1\psi)^2 + (\bar\psi\tau_2\psi)^2 + (\bar\psi i\gamma_5\tau_1\psi)^2 + (\bar\psi i\gamma_5\tau_2\psi)^2\Big),$$

- Nambu-Gor'kov formalism, mean-field approx. to get the thermodynamic potential

- Pairings [note: $\psi_C = C\gamma^0\psi^*, C = i\gamma^2\gamma^0$]
  - $\bar\psi_C\vec\gamma\gamma_5\tau_a\psi$: vector (a=0,1,3), symmetric → $\mathcal{S}_a 1^-$
  - $\bar\psi_C\vec\gamma\tau_2\psi$: axial-vector, anti-symmetric → $\mathcal{A}1^+$

Phase diagram

- Cooper pairs: exp. values of $\mathcal{S}_a 1^-$ and $\mathcal{A}1^+$



Dynamical symmetry breaking

$$\frac{\mathrm{U}(1)_{\mathrm{L}} \times \mathrm{U}(1)_{(1-2)\mathrm{L}}}{\mathbb{Z}'_{2\mathrm{L}}} \times \frac{\mathrm{U}(1)_{\mathrm{R}} \times \mathrm{U}(1)_{(1-2)\mathrm{R}}}{\mathbb{Z}'_{2\mathrm{R}}} \times \mathrm{SO}(3)_{\mathrm{S}}$$

- ❑ Vectorial symmetry $U(1)_{L+R}$ broken
  → superfluid phonons
- ❑ Axial symmetry $U(1)_{L-R}$ unbroken
- ❑ Emergent chiral symmetry broken to $U(1)_{(1-2)(L+R)}$ → emergent pions
- ❑ Spatial rotation symmetry broken to $SO(2)_S$
  → magnons

❖ NG bosons as sexaquark states w/ B=2: exotic

Dirac points

- Single-particle energy with a gap

$$\vec{\delta} = (0,0,\delta)$$

Dirac points (massless) at $p_z = \pm\sqrt{\mu^2 + \delta^2}$

$$\varepsilon_q \cong \sqrt{\frac{q_x^2 + q_y^2}{1 + \frac{\mu^2}{\delta^2}} + q_z^2}$$

- Propagation along x&y directions in $v \ll 1$
- Propagation along z direction in $v = c = 1$

→ Anisotropy in transport phenomena, NS cooling

SUMMARY

Conclusions

- New types of neutron superfluidity, emergent chiral symmetry breaking & its SSB
- Toward understanding of multi-quark states in dense QCD
- Specific in mirror model? Vortices? Cooling? Interface to QM?

BACKUP