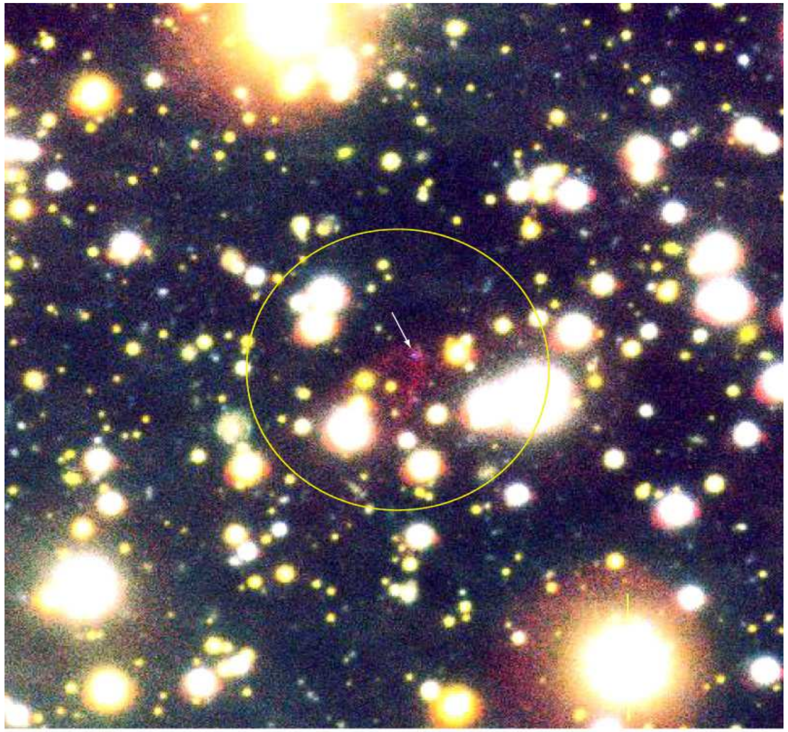
SPIN-ONE COLOR SUPERCONDUCTIVITY IN COMPACT STARS?

Deborah N. Aguilera
University of Alicante, Spain

- **QUARK MATTER EoS**

  Spin-1 color superconducting phases:
  - 2SC +"blue quark pairing"
  - Color Spin Locking phase (CSL)
- **SPIN-1 CSL CONDENSATES IN COMPACT STARS:**
  - Stable Hybrid Stars with Color Superconducting Quark Core
  - CSL gaps suitable for cooling phenomenology

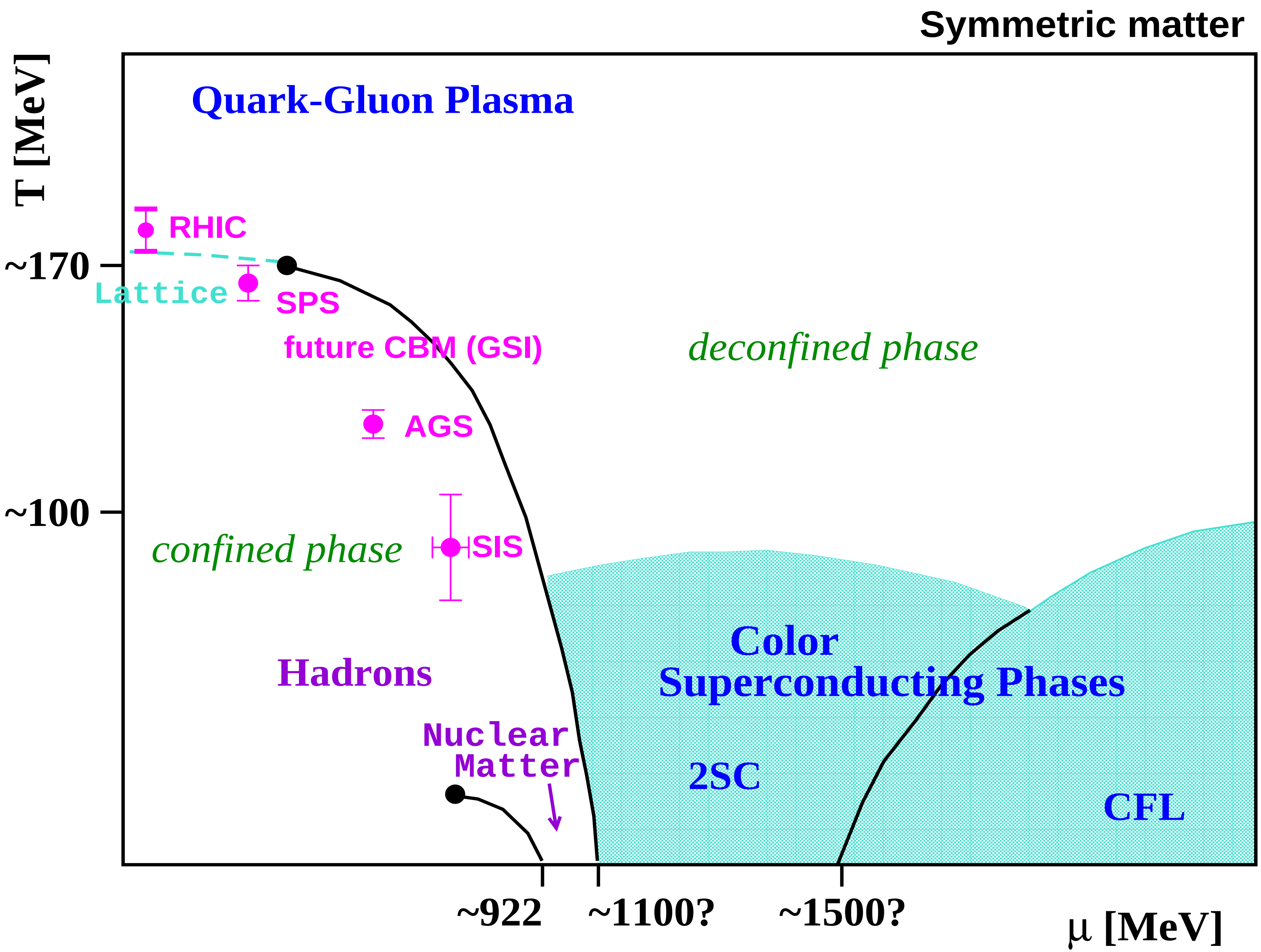


A Bowshock Nebula Near the Neutron Star RX J1856.5-3754 (Detail)
(VLT KUEYEN + FORS2)

ESO PR Photo 23b/00 (11 September 2000)

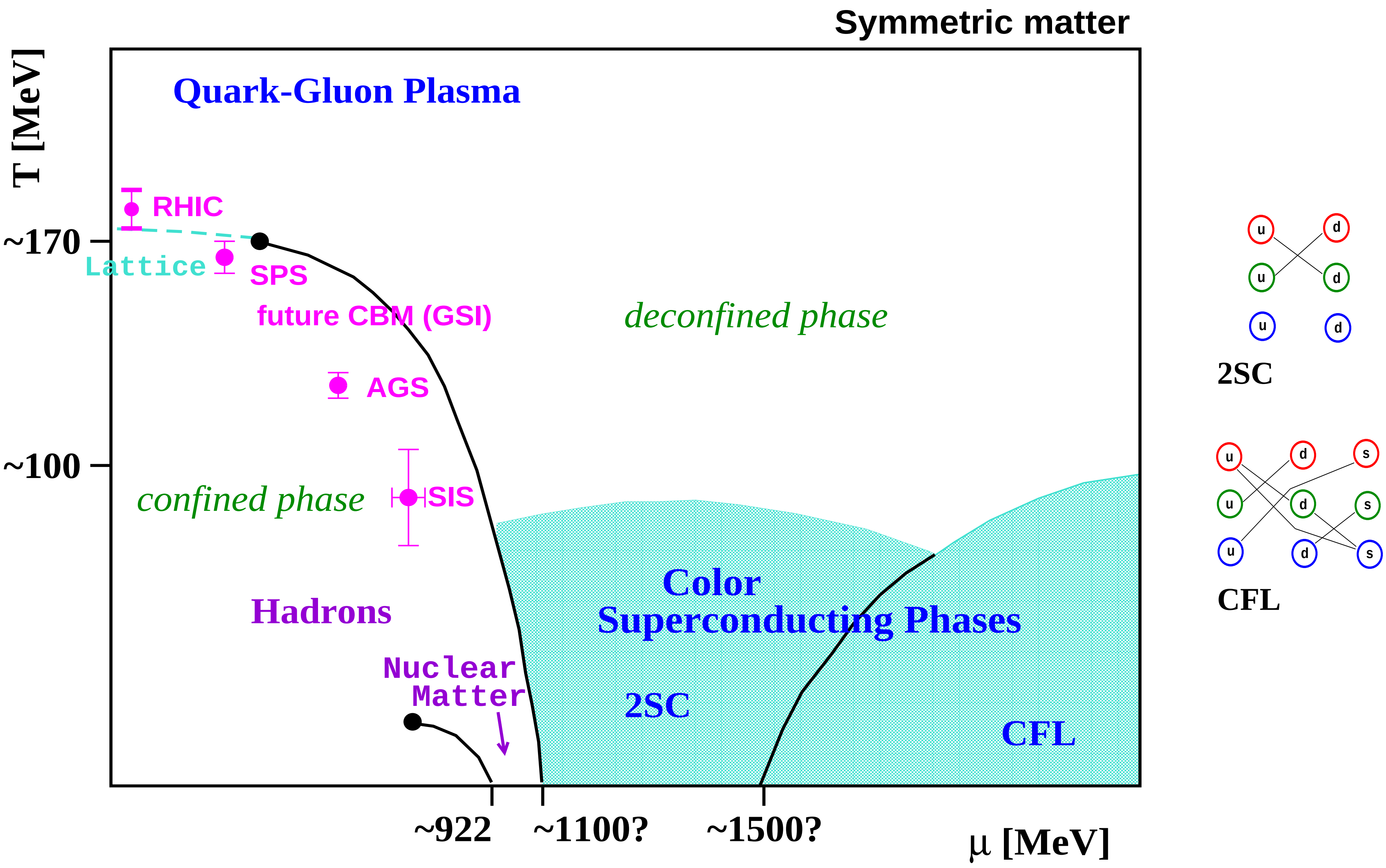
Collaborators: J.Pons, M.Buballa, D.Blaschke, H. Grigorian, N. Scoccola

QCD Phase diagram



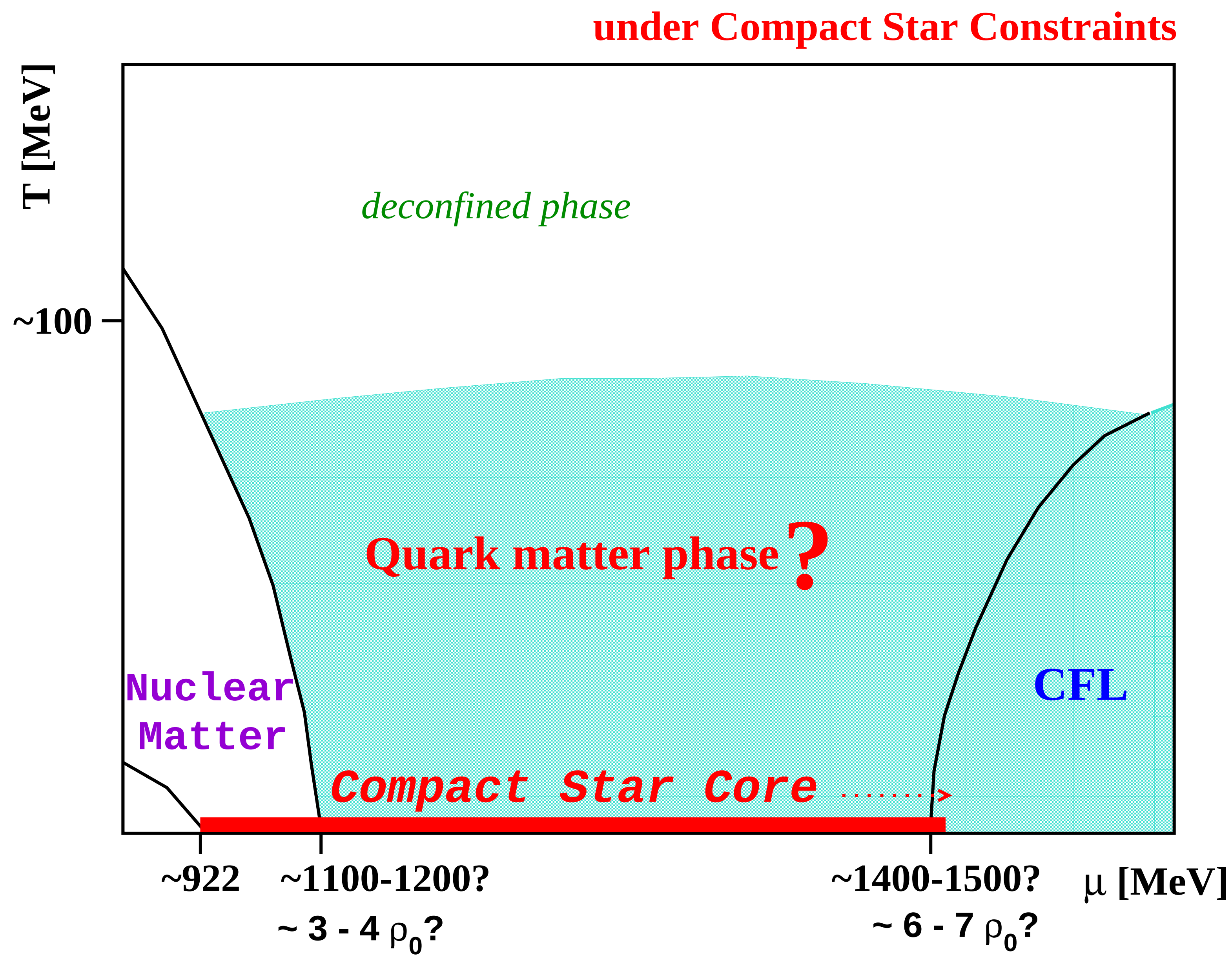
Adapted from Buballa, M. Phys.Rept. **407** (2005) 205-376,2005

QCD Phase diagram



Adapted from Buballa, M. Phys.Rept. **407** (2005) 205-376,2005

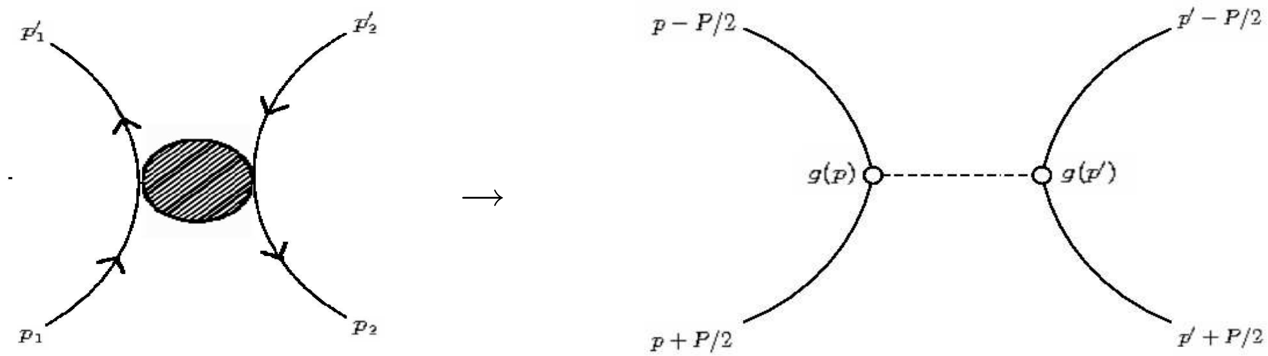
QCD Phase Diagram for Compact Stars



Nonlocal effective action

$$S[\bar\psi,\psi] \;=\; \sum_p \bar\psi(\not p - \hat m)\psi + S_{\rm int}[\bar\psi,\psi]$$

$$S_{\rm int}[\bar\psi,\psi] \;=\; -\frac{1}{2}\sum_{p_1\dots p_{2'}} [\bar\psi_1(p_1)[\lambda^a\gamma_\mu 1\!\!1_f]_{11'}\psi_{1'}(p_{1'})]g_{\mu\mu'}K(p_1,p_{1'};p_2,p_{2'})[\bar\psi_{2'}(p_{2'})[\lambda^a\gamma_{\mu'}1\!\!1_f]_{2'2}\psi_2(p_2)]$$



Separable ansatz

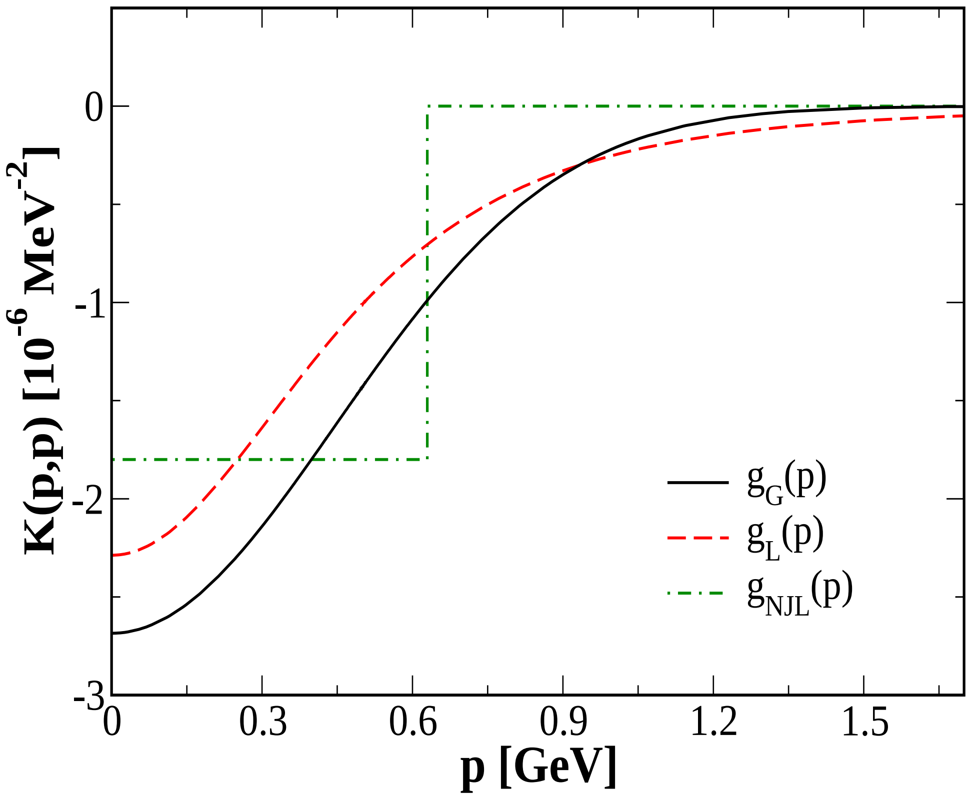
$$K(p,P,p',P') = -K_0 g(p)g(p')\delta_{P,P'}$$

NJL as particular case

$$g(p) \rightarrow \theta(1 - p/\Lambda)$$

S. Schmidt, D. Blaschke, Y. Kalinovsky, Phys. Rev. C **50** (1994) 435.

Non-local quark interactions: Form factors functions



Momentum dependent form factors:

- **Gaussian** $g_G(p) = \exp(-p^2/\Lambda^2)$
- **Lorentzian** $g_{L\alpha}(p) = [1 + (p/\Lambda)^{2\alpha}]^{-1}$
- **NJL** $g_{NJL}(p) = \theta(1 - p/\Lambda)$

Parameters Λ, G_1 **and** m **fixed by vacuum properties**
$m_\pi = 140$ **MeV,** $f_\pi = 93$ **MeV,** $M = 330$ **MeV**

	Λ **[MeV]**	$G_1\ \Lambda^2$	m **[MeV]**
g_G	891.1	3.88	2.18
g_L	703.4	2.58	2.37
g_{NJL}	629.5	2.17	5.28

S. Schmidt, D. Blaschke, Y. Kalinovsky, Phys. Rev. C **50** (1994) 435.
H. Grigorian, hep-ph/0602238

Quark condensates

- **Quark-antiquark condensates:** $\langle\, \bar{\psi}\; \hat{O}\; \psi \,\rangle$ Mesons $\rightarrow$ **Dynamical mass of quarks**
- **Quark-quark condensates:** $\langle\, \psi^T\; \hat{O}\; \psi \,\rangle$ Diquarks $\rightarrow$ **Color superconductivity**

- **Pauli principle**: $\Rightarrow$ $\hat{O}$ totally antisymmetric $\hat{O}$: operator in color, flavor, Dirac space

	antisymmetric	symmetric
Dirac	$C\,\gamma_5$, C, $C\,\gamma^\mu\,\gamma_5$ (S) (P) (V)	$C\,\gamma^\mu$, $C\,\sigma^{\mu,\nu}$ (A), (T)
$U(2)$ **flavor**	τ_2 singlet	1 , τ_1 , τ_3 triplet
$U(3)$ **color/flavor**	λ_2 , λ_5 , λ_7 antitriplet	1 , λ_1 , λ_3 , λ_4 , λ_6 , λ_8 sextet

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  – **Most attractive**: **color antitriplet channel** $\langle \psi^T\, C\, \gamma_5\, \tau_A\, \lambda_{A'}\, \psi \rangle$

Spin=0

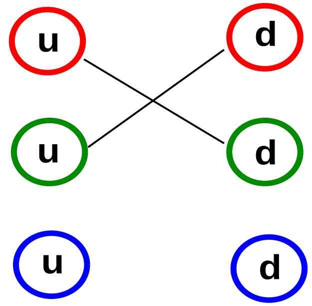
$N(f)$	τ_A	$\lambda_{A'}$	condensate	diquark pairs	phase
2	τ_2	λ_2	$\langle \psi^T\, C\, \gamma_5\, \tau_2\, \lambda_2\, \psi \rangle$	$(u_r, d_g), (u_g, d_r)$	**(2SC)**
3	τ_2	λ_2	$\langle \psi^T\, C\, \gamma_5\, \tau_2\, \lambda_2\, \psi \rangle$	$(u_r, d_g), (u_g, d_r)$	**(CFL)**
	τ_5	λ_5	$\langle \psi^T\, C\, \gamma_5\, \tau_5\, \lambda_5\, \psi \rangle$	$(d_g, s_b), (d_b, s_g)$	
	τ_7	λ_7	$\langle \psi^T\, C\, \gamma_5\, \tau_7\, \lambda_7\, \psi \rangle$	$(s_b, u_r), (s_r, u_b)$	

2SC phase

Interaction channels:

Mesonic $\phi = -2G_1\varphi \qquad \varphi = \langle\, \psi^T\, \psi \,\rangle$

2SC $\Delta = -2G_2\delta \qquad \delta = \langle\, \psi^T\, C\, \gamma_5\, \tau_2\, \lambda_2\, \psi \,\rangle$



Thermodynamical potential

$$\Omega(T,\mu) \;=\; \frac{\phi^2}{4G_1} + \frac{|\Delta|^2}{4G_2} - 4\sum_{i=1}^{3}\int \frac{d^3p}{(2\pi)^3}\left[\frac{E_i^- + E_i^+}{2} + T\ln(1+e^{-E_i^-/T}) + T\ln(1+e^{-E_i^+/T})\right] - \Omega_{\rm vac}$$

the dynamical mass

$$M(p) \;=\; m + g(p)\phi$$

the dispersion laws

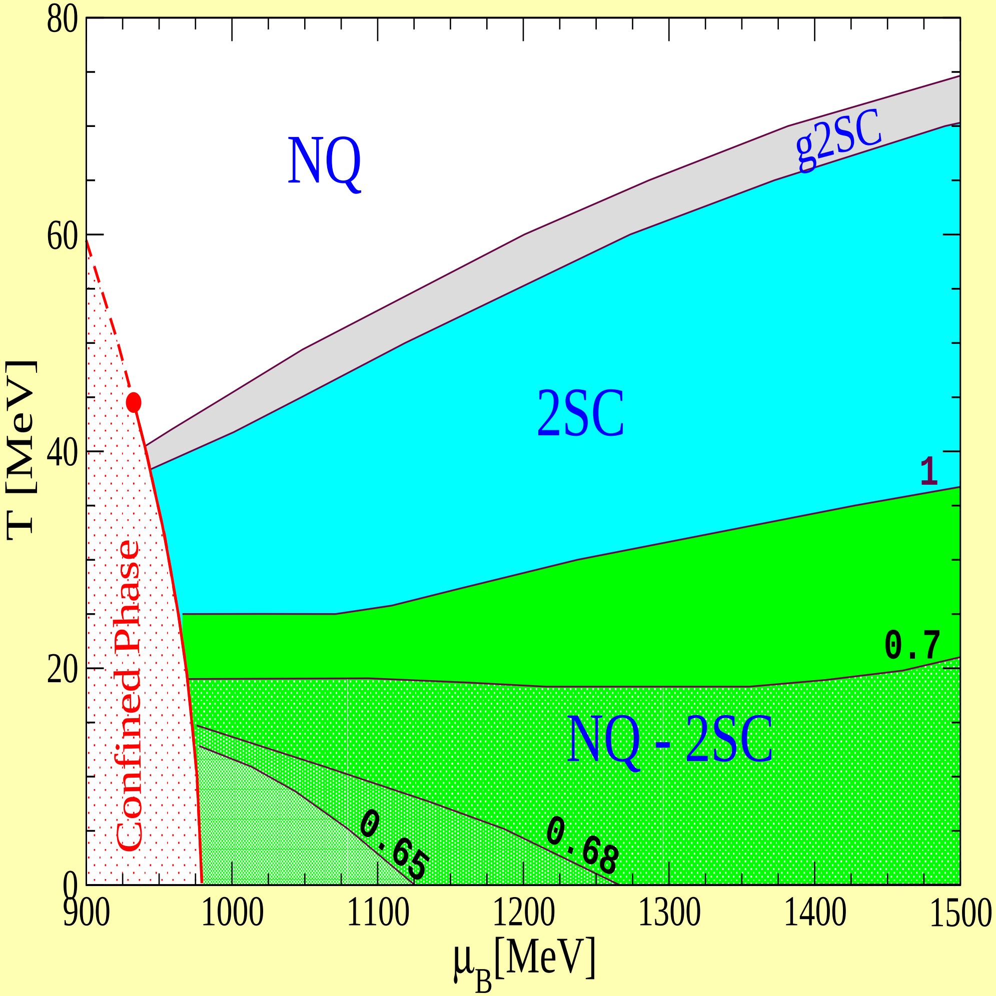
$$E_1^{\mp}(\vec{p}) = E_2^{\mp}(\vec{p}) \;=\; \sqrt{(\varepsilon(\vec{p}) \mp \mu)^2 + g(p)^2|\Delta|^2}$$ **for rg paired quarks**

$$E_3^{\mp}(\vec{p}) \;=\; \varepsilon(\vec{p}) \mp \mu$$ **for the b unpaired quarks**

where $\varepsilon(\vec{p}) = \sqrt{\vec{p}^2 + M(p)}$ **Coupling constants ratio** $\eta = G_2/G_1$

QCD Phase diagram under compact star contraints

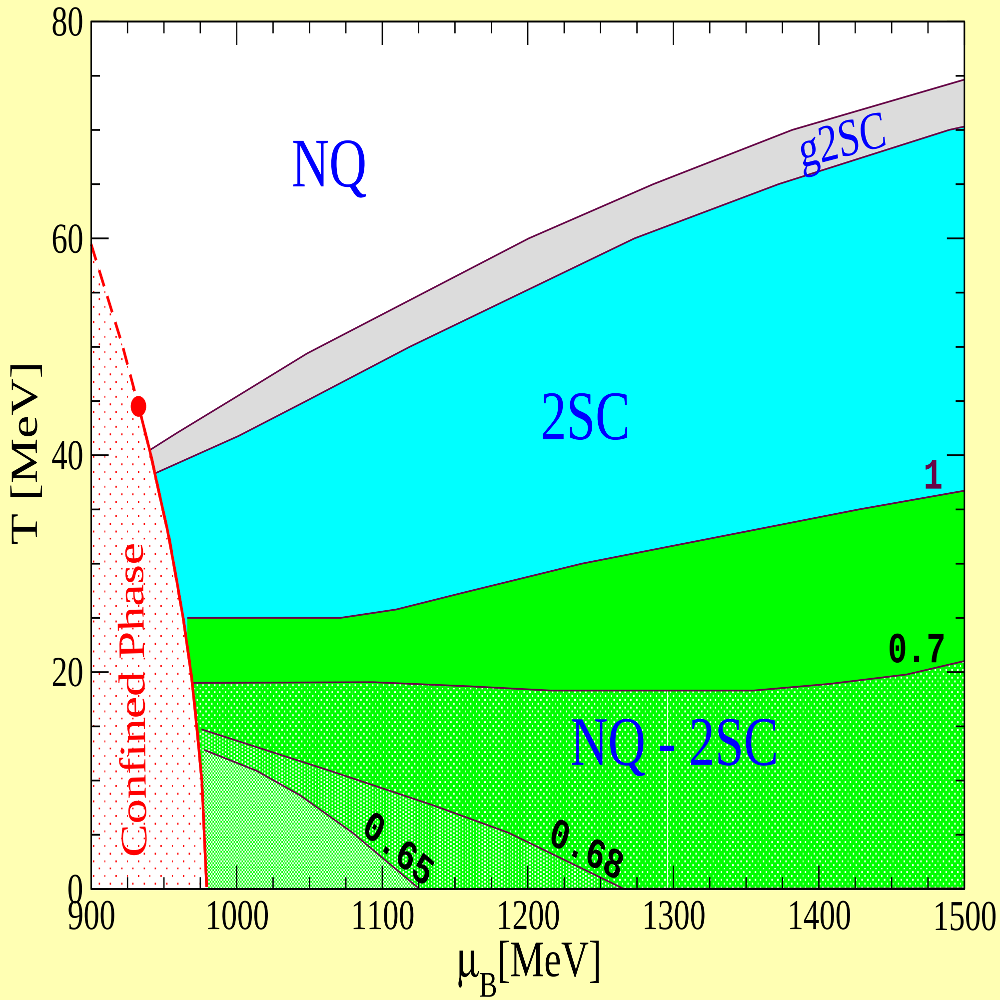
Strong coupling $\eta = 1$



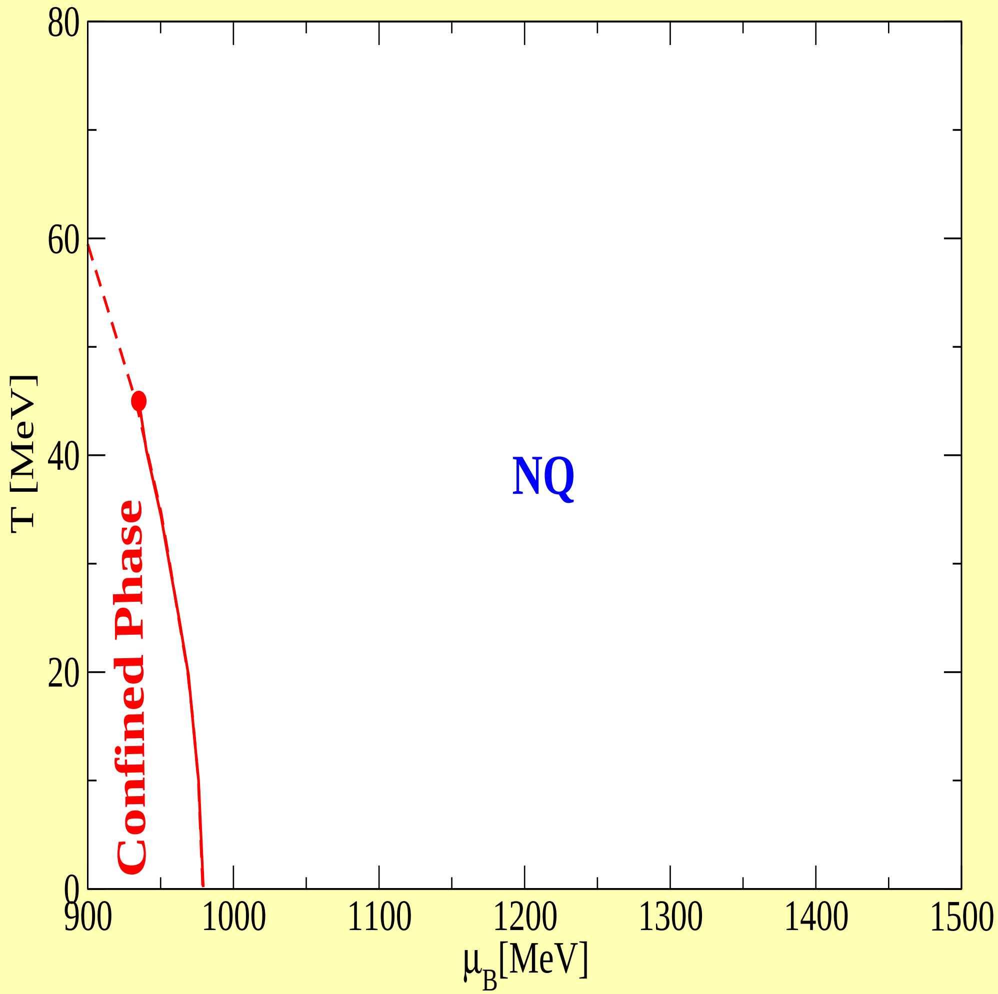
D. N. Aguilera, D. Blaschke and H. Grigorian, Nucl. Phys. A **757** (2005), 527.

Gaussian form factor

Strong coupling $\eta = 1$



Usual coupling $\eta = 0.75$



D. N. Aguilera, D. Blaschke and H. Grigorian, Nucl. Phys. A **757** (2005), 527.

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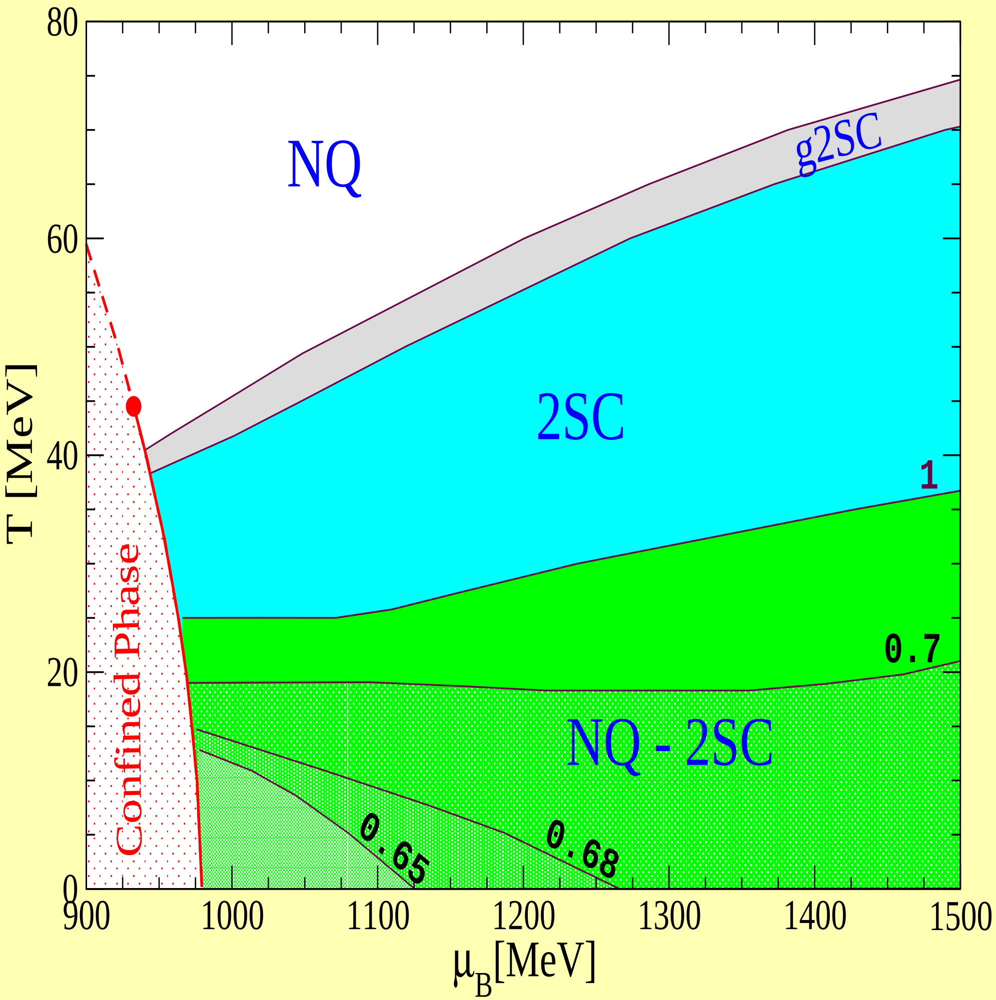

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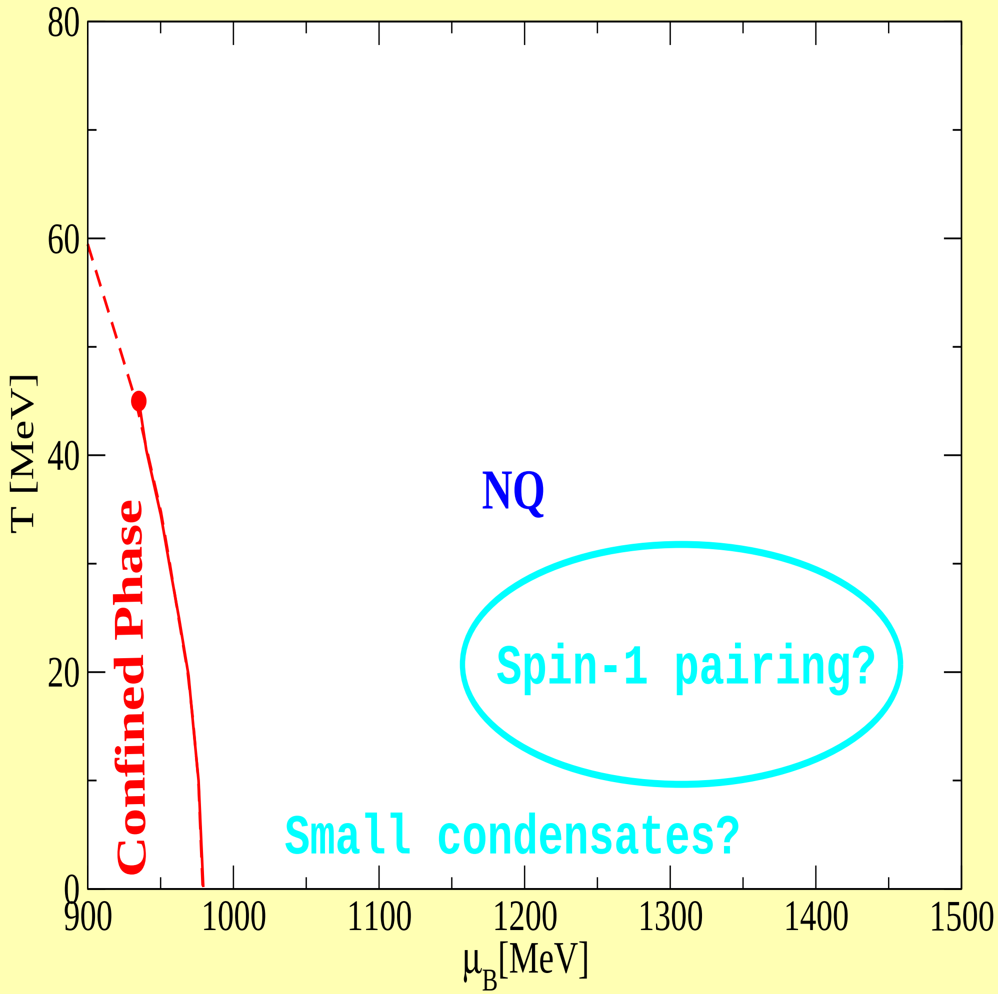
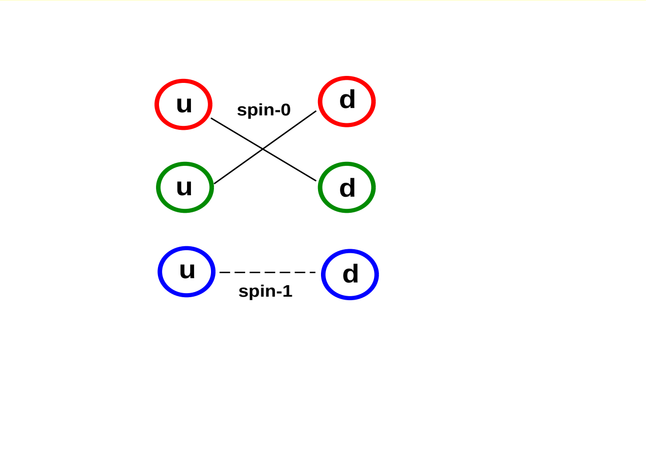
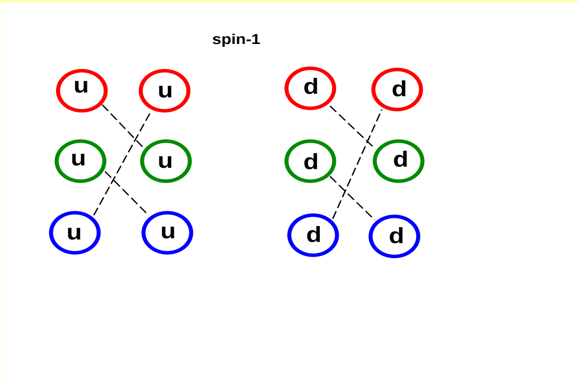
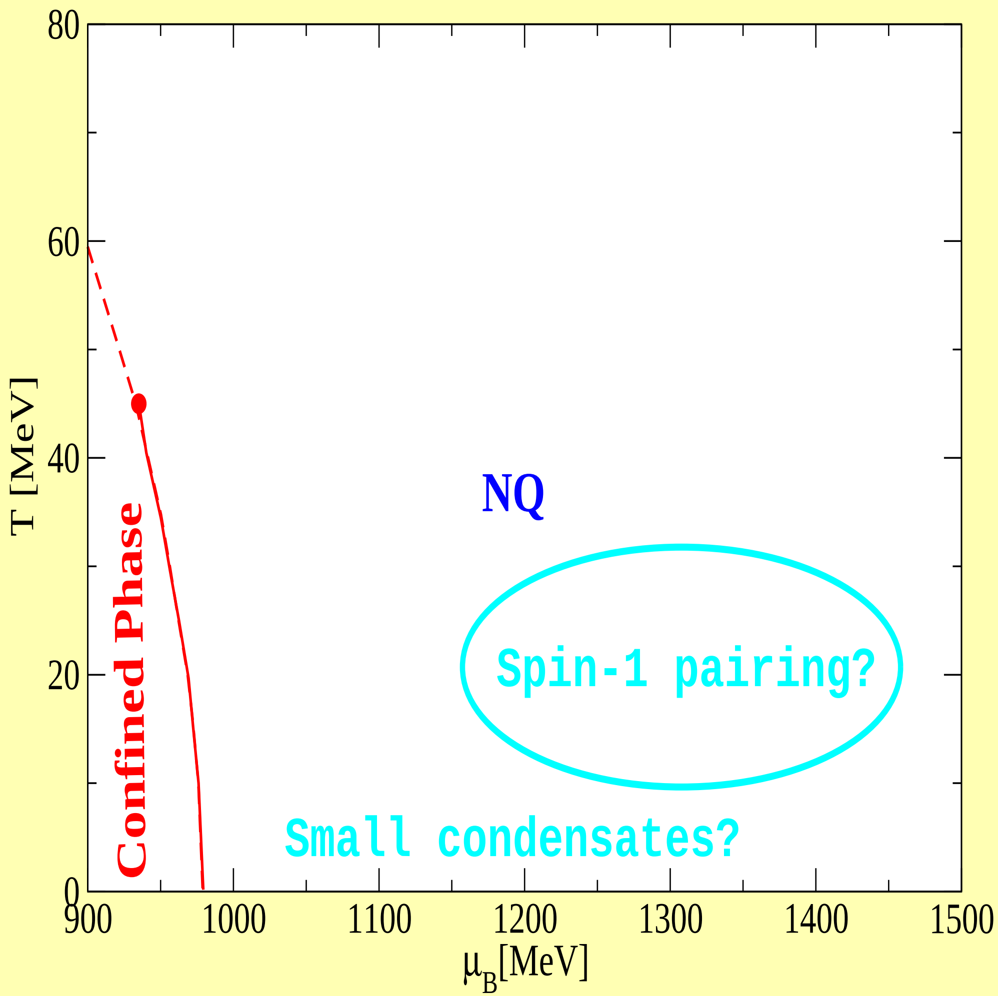


D. N. Aguilera, D. Blaschke and H. Grigorian, Nucl. Phys. A **757** (2005), 527.



2SCb	2SC+ spin-1 blue quarks *destroyed by asymmetry*
CSL	Color Spin Locking *independent of asymmetry*





T. Schaefer, Phys. Rev. D **62**, 094007. A. Schmitt et al., Phys. Rev. D **66**, 114010
D. N. Aguilera and D. Blaschke, hep-ph/0512001.

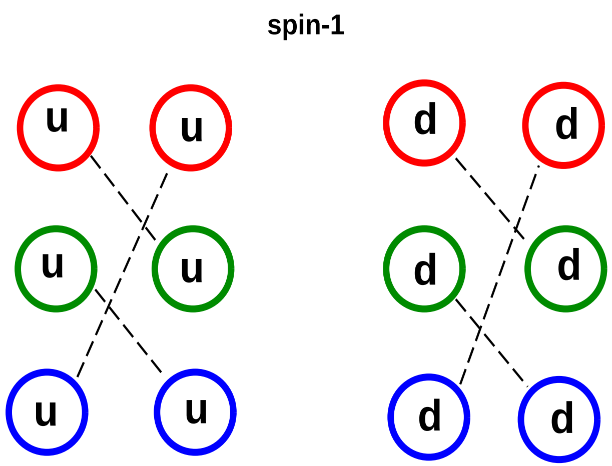
CSL - Color Spin Locked phase

Interaction channels:

Mesonic $\phi = -2G_1\varphi$ $\quad\varphi = \langle\, \psi^T\, \psi\,\rangle$

Spin-1 CSL $\Delta'_f = -H_v \eta_f$

$$\eta_f \;=\; \langle\, q_f{}^T\, C\, \gamma^3\, \lambda_2\, q_f\,\rangle = \langle\, q_f{}^T\, C\, \gamma^1\, \lambda_7\, q_f\,\rangle = \langle\, q_f{}^T\, C\, \gamma^2\, \lambda_5\, q_f\,\rangle$$

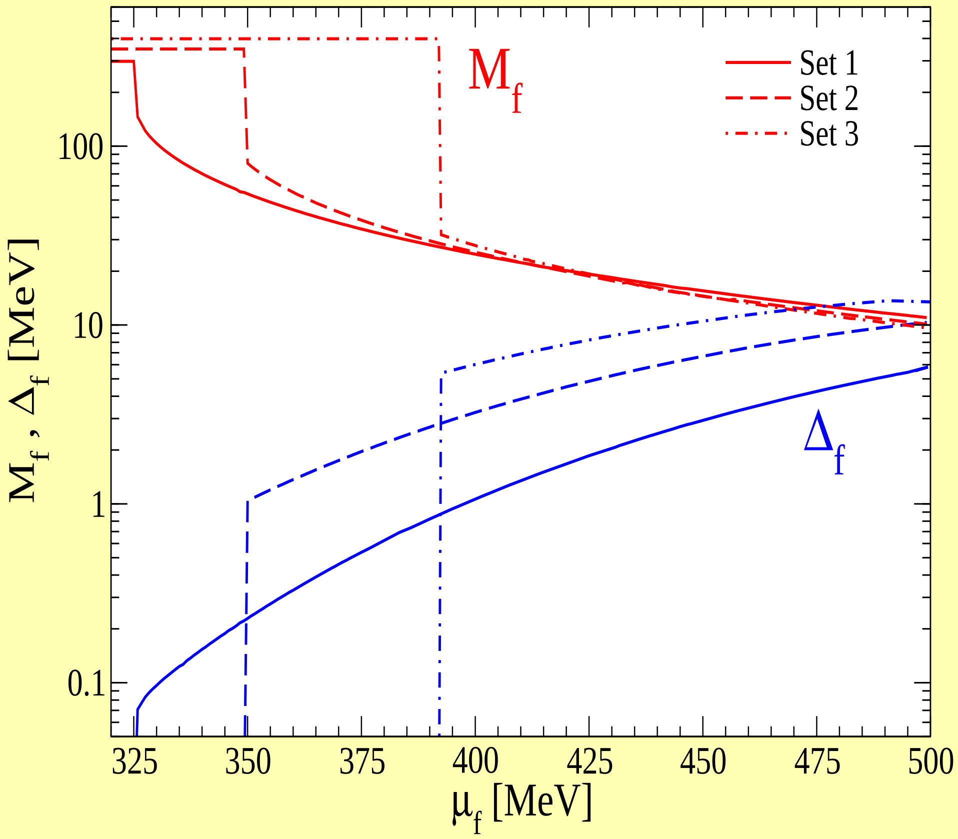


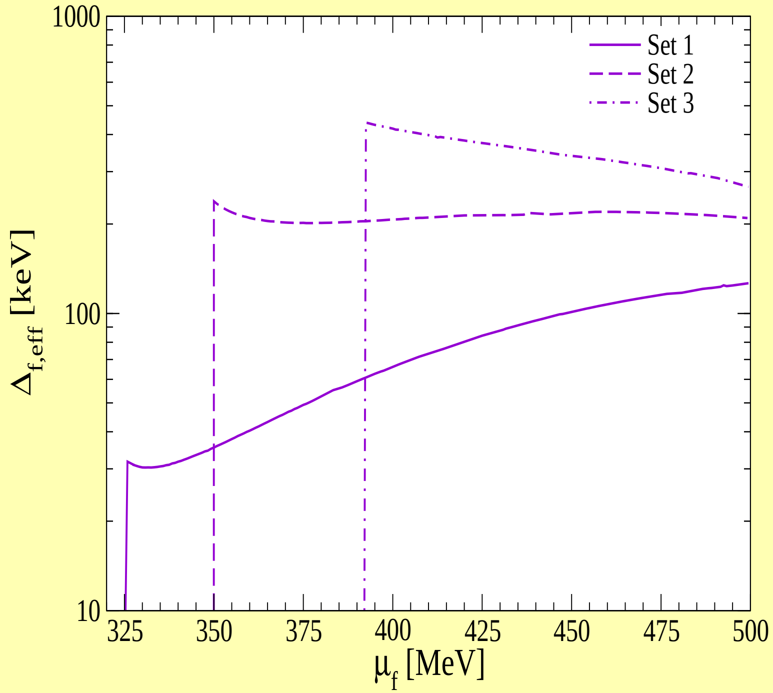
Color and spin are locked, flavors decouple

Thermodynamical potential $\Omega = \sum_f \Omega_f$

$$\Omega_f(T,\mu_f) \;=\; \frac{\phi_f{}^2}{8G_1} + 3\frac{|\Delta'_f|^2}{8G_3} - \sum_{k=1}^{6}\int \frac{d^3p}{(2\pi)^3}\left(E_{f,k} + 2T\ln\left(1+e^{-E_{f,k}/T}\right)\right)$$

D. Aguilera, D. Blaschke, M. Buballa and V. Yudichev, Phys. Rev. D **72** (2005), 034008.



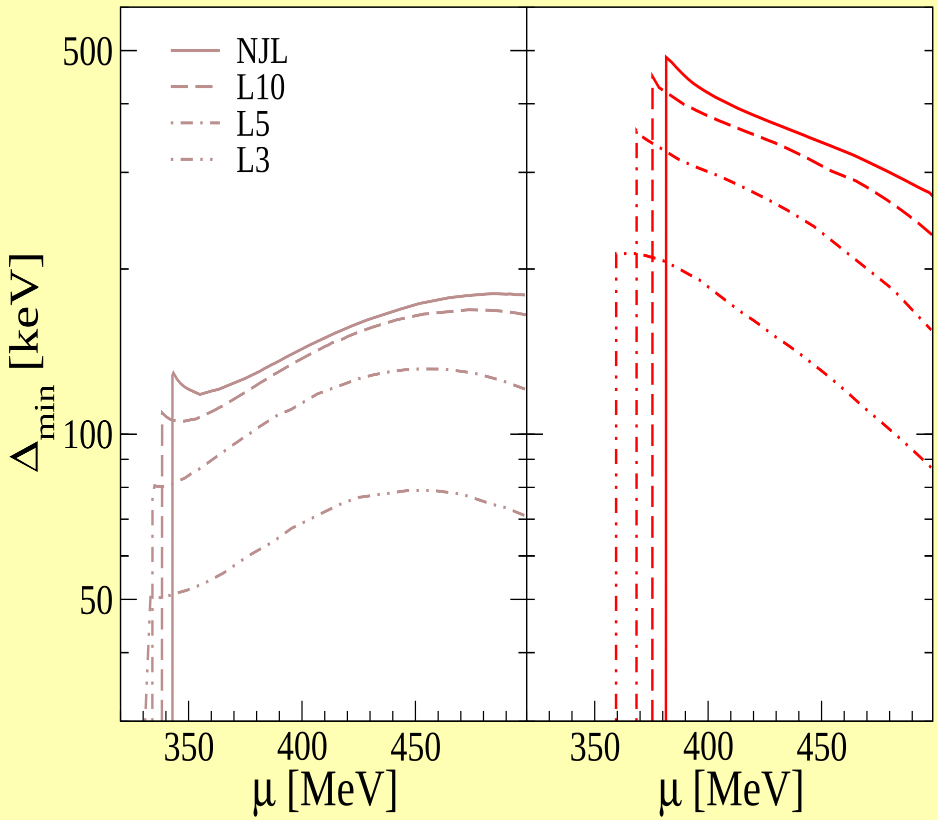


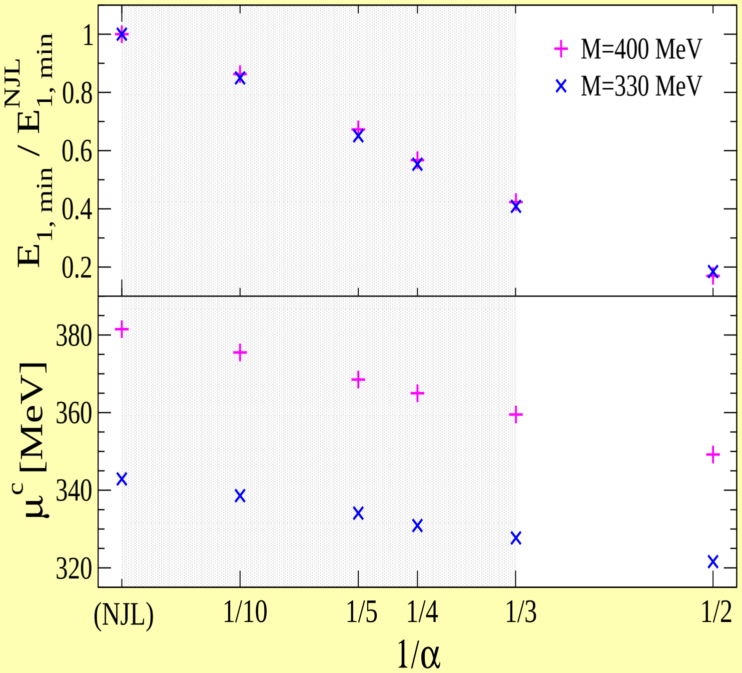
- *Δ_{eff} corresponds to expectations from cooling phenomenology*

CSL not affected by asymmetry → *Could support compact stars constraints!*

D. Aguilera, D. Blaschke, M. Buballa and V. Yudichev, Phys. Rev. D **72** (2005), 034008.

Gap Equation solutions for CSL - Nonlocal models





Nonlocal interactions affect CSL condensates:

- **lowering of the onset of color superconductivity**
  may help to stabilize quark cores in NS
- **reduction of the minimum gaps**
  may help to suppress direct URCA in the cooling of NS

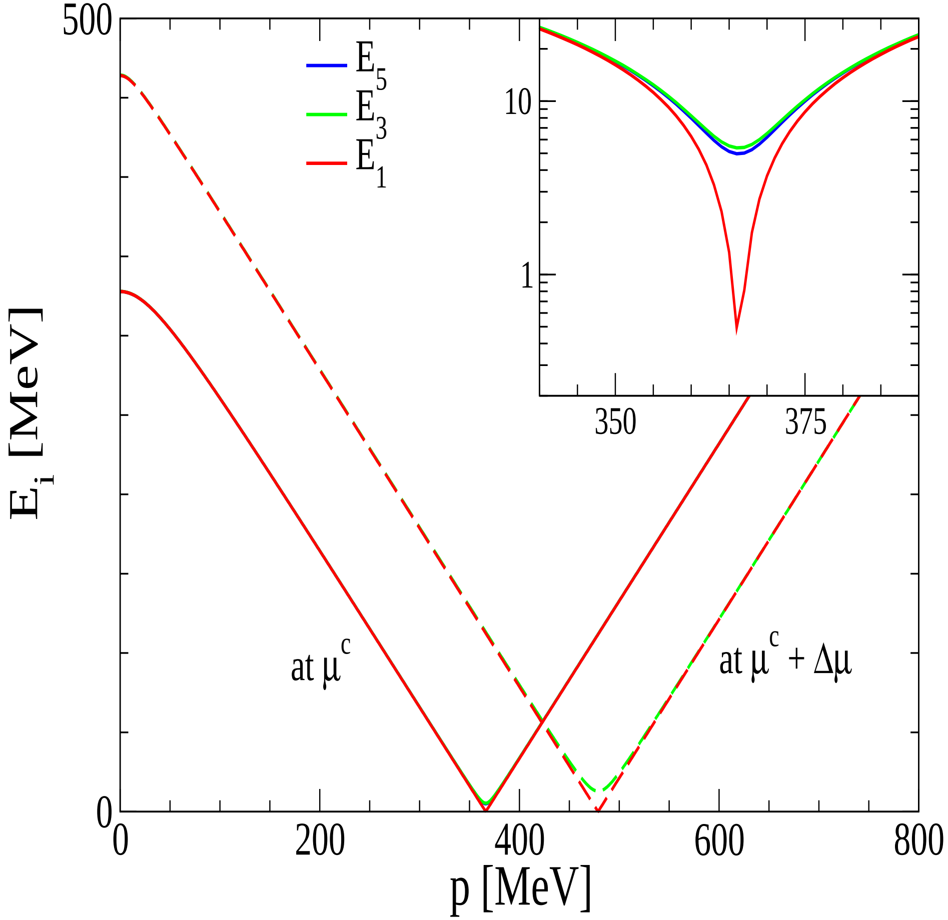
D. Aguilera, D. Blaschke, H. Grigorian and N. Scoccola, hep-ph/0604196

Energy dispersion relations

$$E^2_{f1,2} = (\varepsilon_{f,\mathrm{eff}} \mp \mu_{f,\mathrm{eff}})^2 + |\Delta_{f,\mathrm{eff}}|^2$$

$$E^2_{f3,5} = (\varepsilon_f - \mu_f)^2 + a_{f3,5}|\Delta_f|^2$$
$$E^2_{f4,6} = (\varepsilon_f + \mu_f)^2 + a_{f4,6}|\Delta_f|^2$$

$$\varepsilon^2_{f,\mathrm{eff}} = \vec{p}^{\,2} + M^2_{f,\mathrm{eff}}$$
$$M_{f,\mathrm{eff}} = \frac{\mu_f}{\mu_{f,\mathrm{eff}}} M_f$$
$$\mu^2_{f,\mathrm{eff}} = \mu^2_f + |\Delta_f|^2$$
$$|\Delta_{f,\mathrm{eff}}|^2 = |\Delta_f|^2 \frac{M^2_f}{\mu^2_{f,\mathrm{eff}}}$$

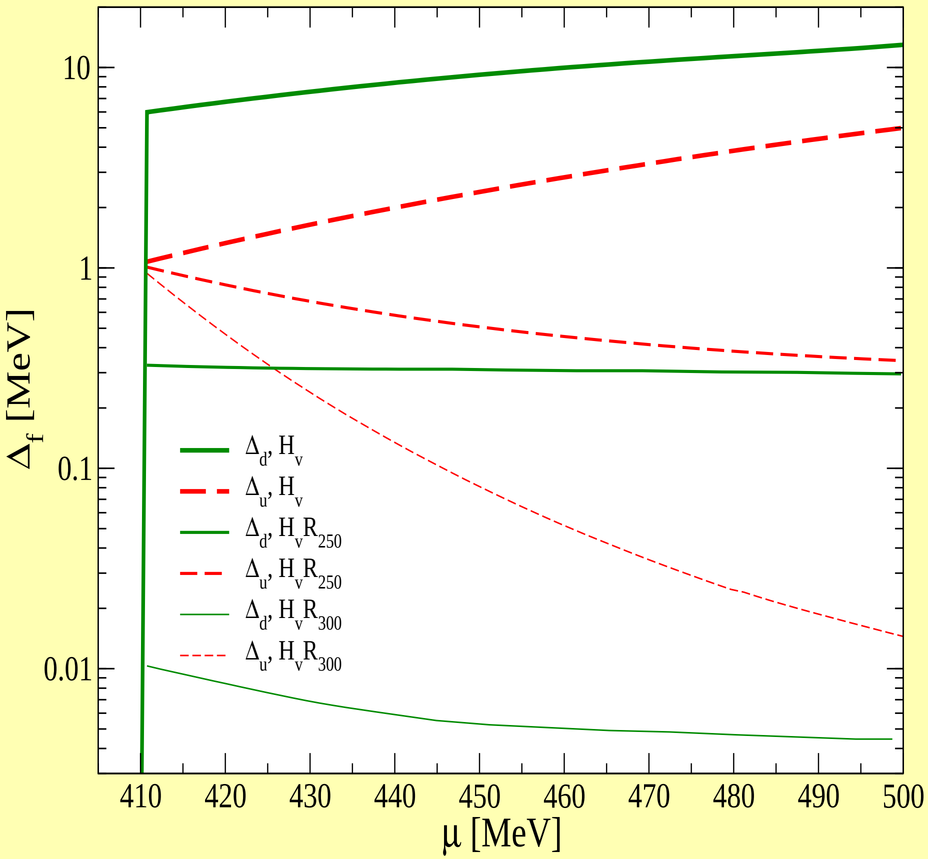


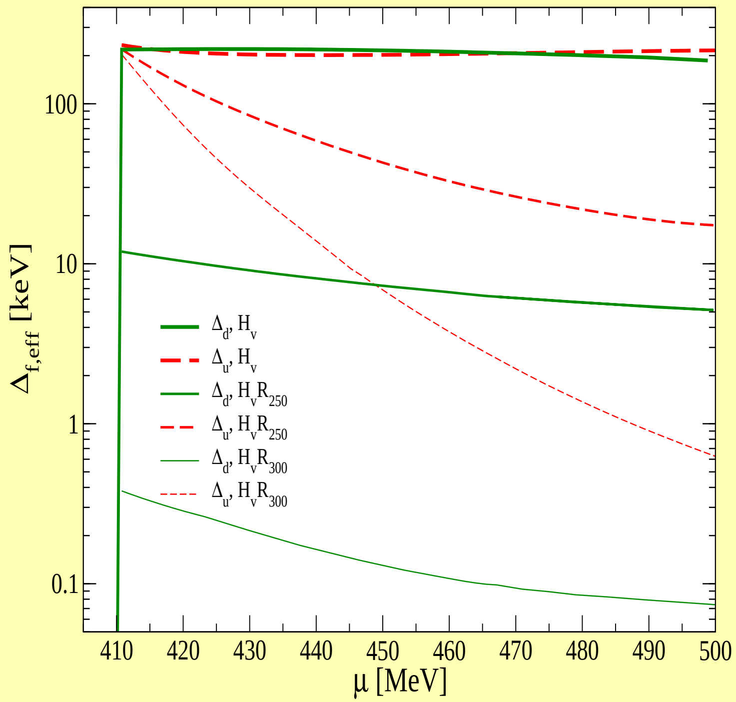
No gapless modes ⇒ suppression of direct URCA!

For NJL: D. Aguilera, D. Blaschke, M. Buballa and V. Yudichev, Phys. Rev. D **72** (2005), 034008.
Recently for nonlocal models: D. Aguilera, D. Blaschke, H. Grigorian and N. Scoccola, hep-ph/0604196

CSL phase under compact stars constraints

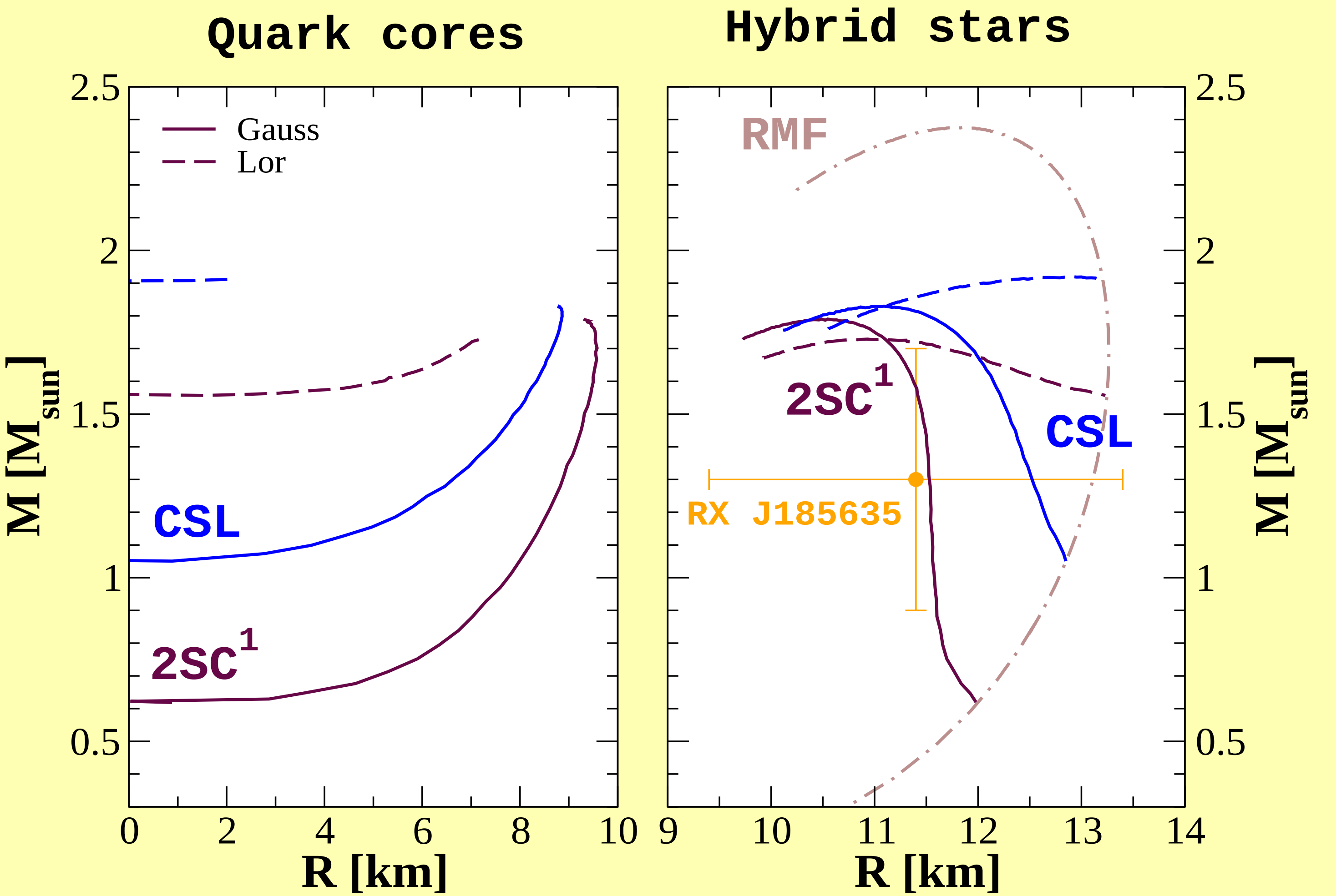
- Color neutrality is automatically satisfied
- Flavors decouple ⇒ Charge neutrality can be easily be constructed: $\mu_u = \mu - \frac{2}{3}\mu_e \quad \mu_d = \mu + \frac{1}{3}\mu_e$





CSL pairing is a good candidate for cooling phenomenology

Stable Hybrid stars Confi gurations - *PRELIMINARY RESULTS*

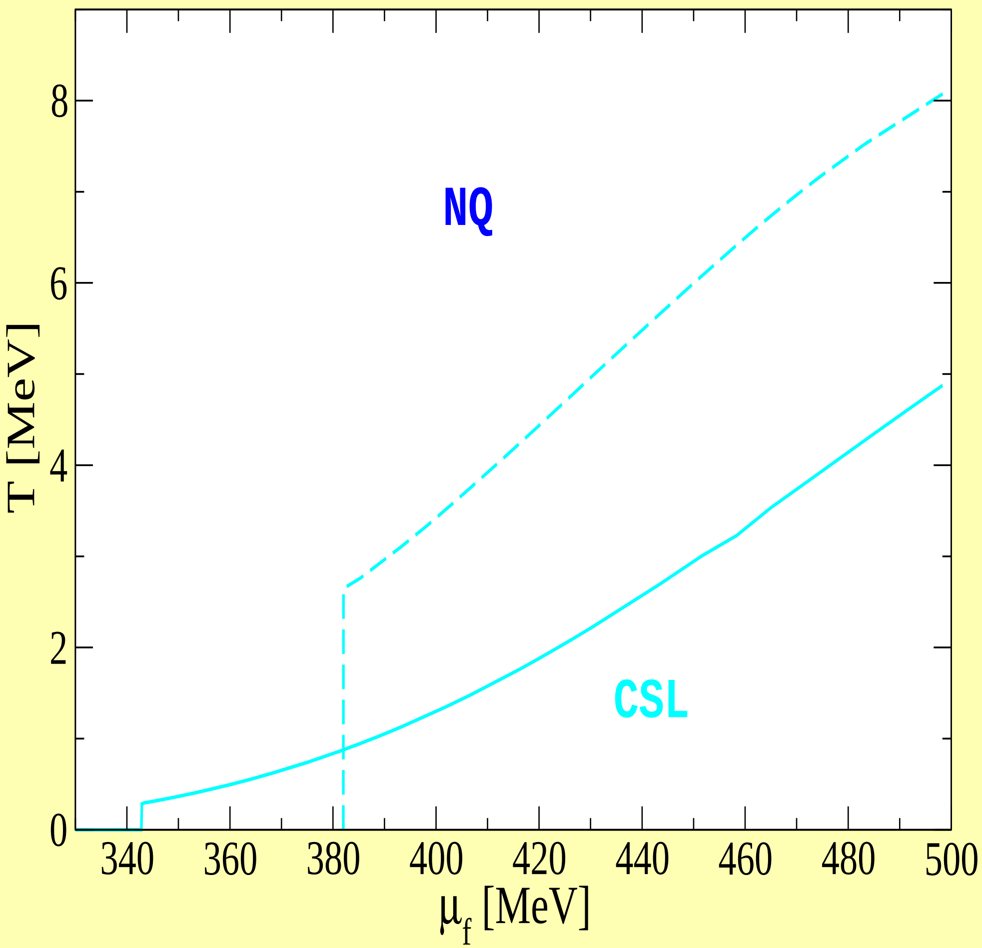


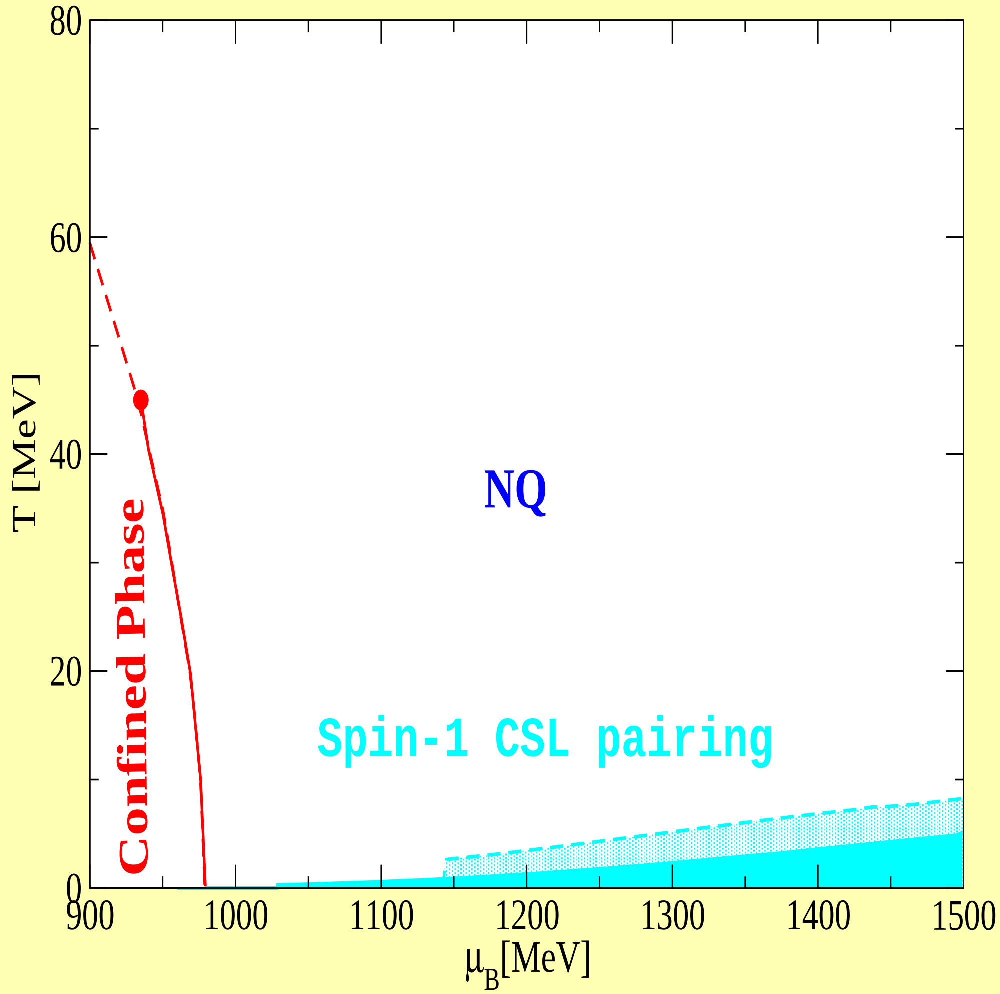
Model in accordance with e.g. (M, R) observational constraints of RX J185635-3754

- $2SC^1$ **means for** η =**1 strong diquark coupling**

D. N. Aguilera et al., in preparation

CSL critical temperatures - *PRELIMINARY RESULTS*





CSL phase could be relevant in the early evolution of NS

D. N. Aguilera et al., in preparation

- **RESULTS**
  - Big effect of compact star constraints in quark matter phases:
    * *Pure 2SC unlikely* for intermediate coupling constants ($\eta = 0.75$).
  - Phases with small gaps but single flavor pairing become important:
    * Spin-1 *Color Spin Locked (CSL)* investigated.

- **CONSEQUENCES in the observables:**
  - **Hybrid stars:**
    Stable configurations for hybrid stars. Model obeys the observational constraints of the compact object RX J185635-3754.
  - **Cooling of compact stars:**
    CSL gaps are compatible with neutron star cooling phenomenology.
    CSL quark matter phase is a *good candidate* for the superdense matter in the interior of compact stars.

THANKS

- Collaborators:
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  - U. Alicante (Spain)
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