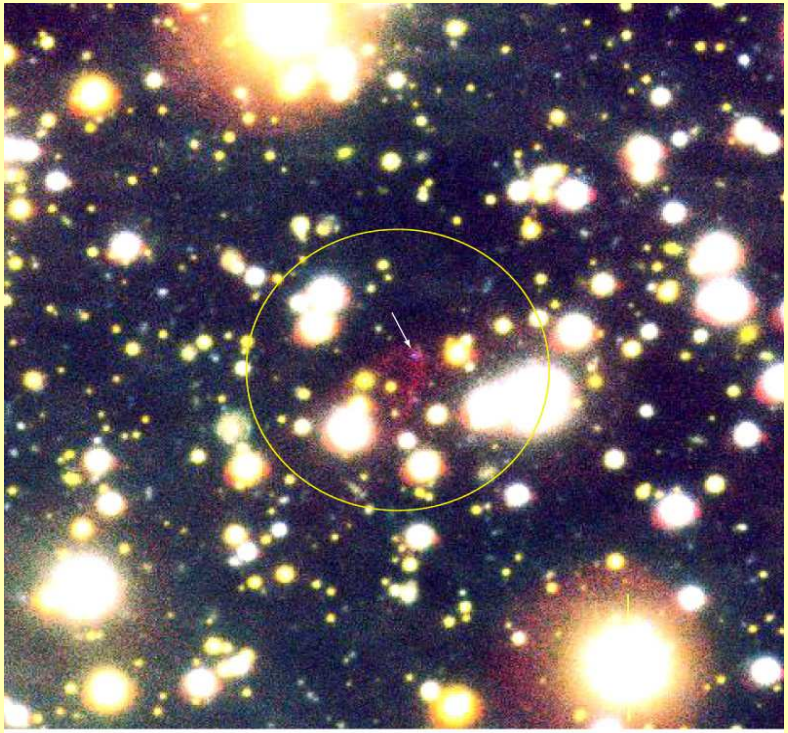
COLOR-SPIN LOCKING PHASE IN TWO-FLAVOR QUARK MATTER FOR COMPACT STAR PHENOMENOLOGY

Deborah N. Aguilera **(University of Rostock)**

Collaborators:
D. Blaschke (GSI), H. Grigorian (U. Rostock),
M. Buballa (TU Darmstadt)

- **QUARK MATTER EoS FOR COMPACT STARS**
  - Spin-0: 2 flavor color SuperConducting phase (2SC)?
  - Spin-1: 2SC +"X", Color Spin Locking phase (CSL)
- **RESULTS:**
  - Stable configurations for hybrid stars with superconducting quark core
  - CSL gaps for cooling phenomenology



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

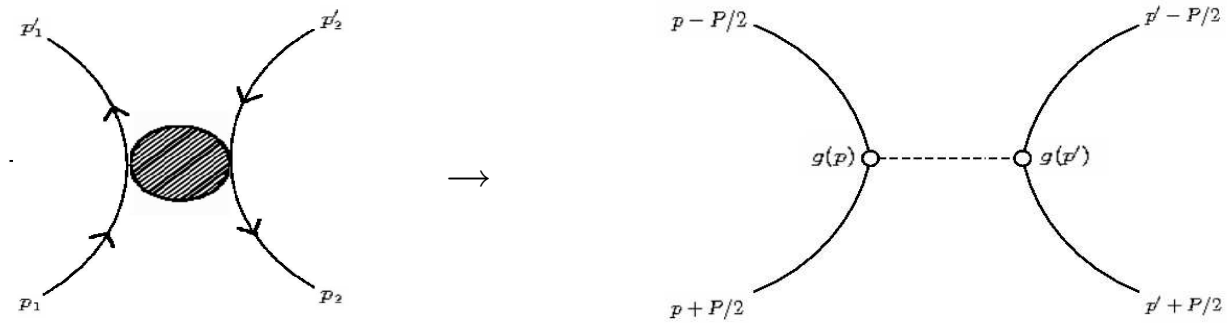
ESO PR Photo 23b/00 (11 September 2000) ©European Southern Observatory

Dynamical separable model

Nonlocal effective action

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

$$S_{\rm int}[\bar{\psi},\psi] \;=\; -\frac{1}{2}\sum_{p_1\cdots p_{2'}} [\bar{\psi}_1(p_1)[\lambda^a\gamma_\mu \mathbb{1}_f]_{11'}\psi_{1'}(p_{1'})]g_{\mu\mu'}K(p_1,p_{1'};p_2,p_{2'})[\bar{\psi}_{2'}(p_{2'})[\lambda^a\gamma_{\mu'}\mathbb{1}_f]_{2'2}\psi_2(p_2)]$$



Separable ansatz

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

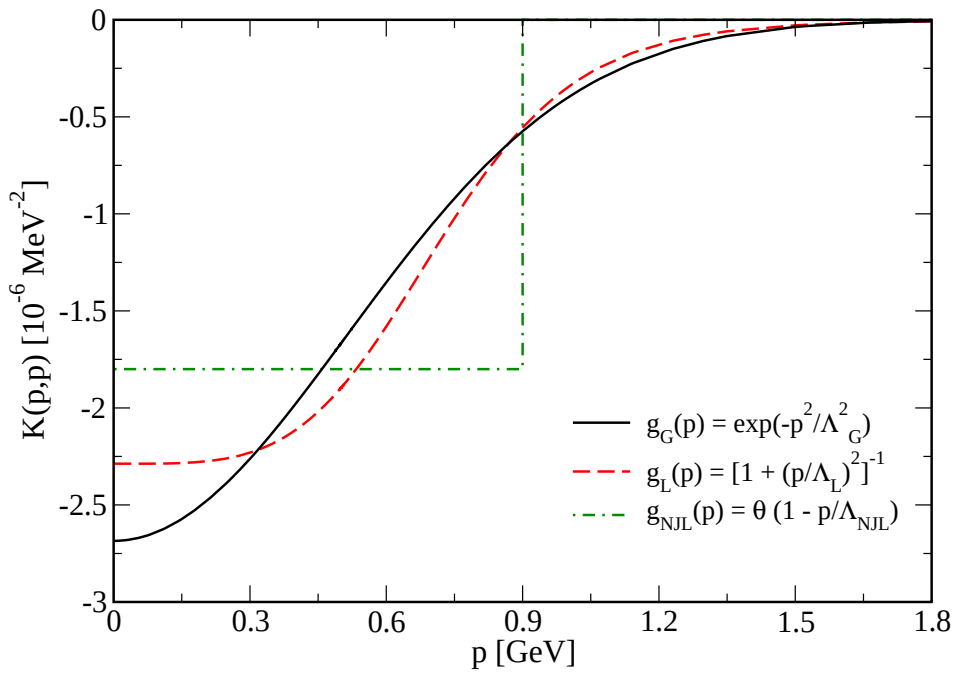
NJL as particular case

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

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

Non-local quark interactions: Form factors functions

- **3-D momentum dependent form factors:**
  - **Gaussian** $g_G(p) = \exp(-p^2/\Lambda^2)$
  - **Lorentzian** $g_L(p) = [1 + (p^2/\Lambda^2)]^{-1}$
  - **NJL cutoff** $g_{NJL}(p) = \theta(1 - p/\Lambda)$
- **Parameters**
  Λ, G_1 **and** m **fixed by vacuum properties**
  $m_\pi = 140$ **MeV,** $f_\pi = 93$ **MeV,**
  $\phi(0) = 330$ **MeV at** $T = \mu = 0$



	Λ **[GeV]**	$G_1\ \Lambda^2$	m **[MeV]**	$T_c(\mu=0)$ **[MeV]**	$\mu_c^{(S)}(T=0)$ **[MeV]**	$\mu_c^{(N)}(T=0)$ **[MeV]**
g_G	1.025	3.780	2.41	174	965	991
g_L	0.893	2.436	2.34	188	999	1045
g_{NJL}	0.900	1.944	5.10	212	1030	1100

S. Schmidt, D. Blaschke, Y. Kalinovsky, Phys. Rev. C **50** (1994) 435.
H. Grigorian, D. Blaschke and D. N. Aguilera, Phys. Rev. C **69** (2004) 065802, arXiv:astro-ph/0303518.

Thermodynamical potential and gap equations

The total thermodynamical potential (q: quarks, l: leptons)

$$\Omega(\phi,\Delta;\{\mu_{fc}\},T;\mu_l) = \Omega_q(\phi,\Delta;\{\mu_{fc}\},T) + \sum_{l\in\{e,\bar{\nu}_e,\nu_e\}} \Omega^{id}(\mu_l,T)\ , \qquad \Omega^{id} \text{ ideal Fermi gas}$$

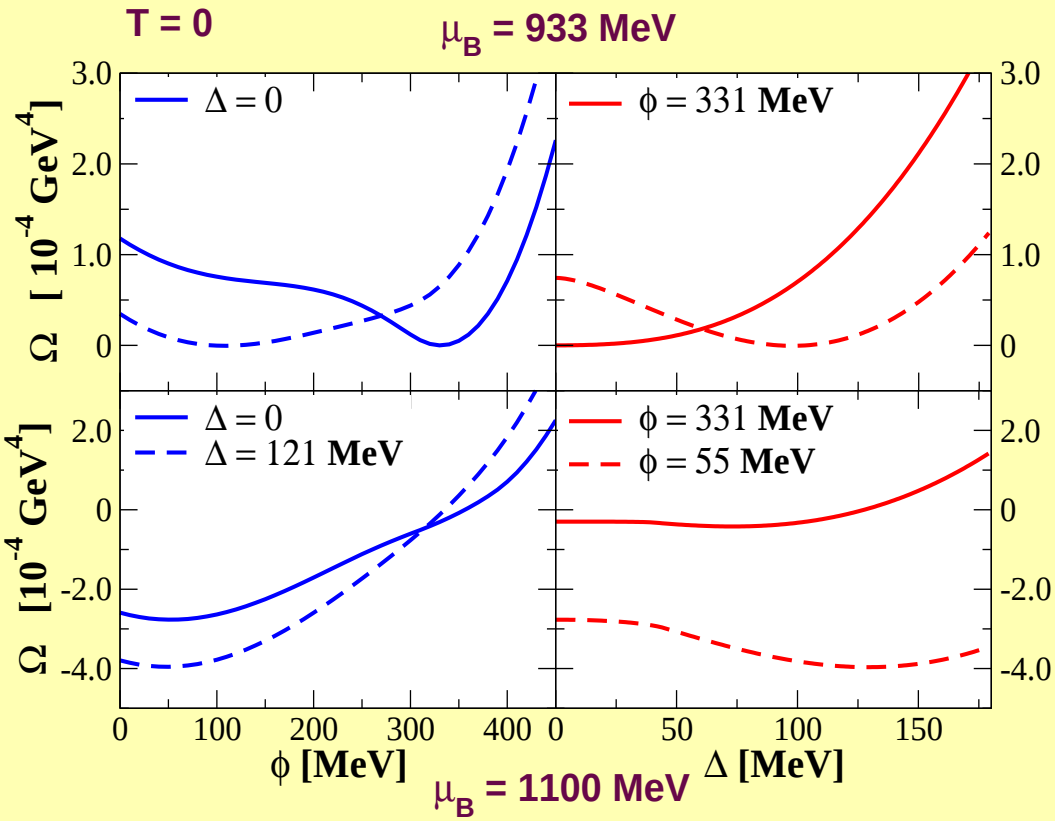
Local extrema of Ω $\leftrightarrow$ Gap equations:

$$\left.\frac{\partial\Omega}{\partial\phi}\right|_{\phi=\phi_0;\Delta=\Delta_0} = \left.\frac{\partial\Omega}{\partial\Delta}\right|_{\phi=\phi_0;\Delta=\Delta_0} = 0$$

Global minimum of Ω $\rightarrow$ Thermodynamics

$$\Omega(\phi_0,\Delta_0;\{\mu_{fc}\},T) = \epsilon - Ts - \sum_{f,c} n_{fc}\mu_{fc} = -P$$

number densities $\quad n_j = \left.\frac{\partial\Omega}{\partial\mu_j}\right|_{\phi_0,\Delta_0;T,\{\mu_i,i\neq j\}}$



Constraints for Quark Matter in Compact Stars

CONSTRAINT	CONSERVED QUANTITY	NEW CHEMICAL POTENTIAL
• β-equilibrium $d \longrightarrow u + e^- + \bar{\nu}_e$ $u + e^- \longrightarrow d + \nu_e$	$\mu_{dc} - \mu_{uc} = \mu_e + \mu_{\bar{\nu}_e}$	$\mu_{qcc'} = (\mu_{uc} + \mu_{dc'})/2$ **quark** $\mu_I = (\mu_{uc} - \mu_{dc})/2$ **Isospin asymmetry**
• **Neutral electric charge density**	$Q = \frac{2}{3}\sum_c n_{uc} - \frac{1}{3}\sum_c n_{dc} - n_e = 0$	$\mu_Q = -\mu_e$
• **Neutral color charge density**	$n_8 = \frac{1}{3}\sum_f (n_{fr} + n_{fg} - 2n_{fb}) = 0$	$\mu_{qcc'} = \mu_q \delta_{cc'} + \mu_8 (\lambda_8)_{cc'}$
• **Conserved baryon number density**	$n_B = \frac{1}{3}\sum_{f,c} n_{fc} =$ **const.**	$\mu_B = 3\mu_q - \mu_I$ **Baryon**

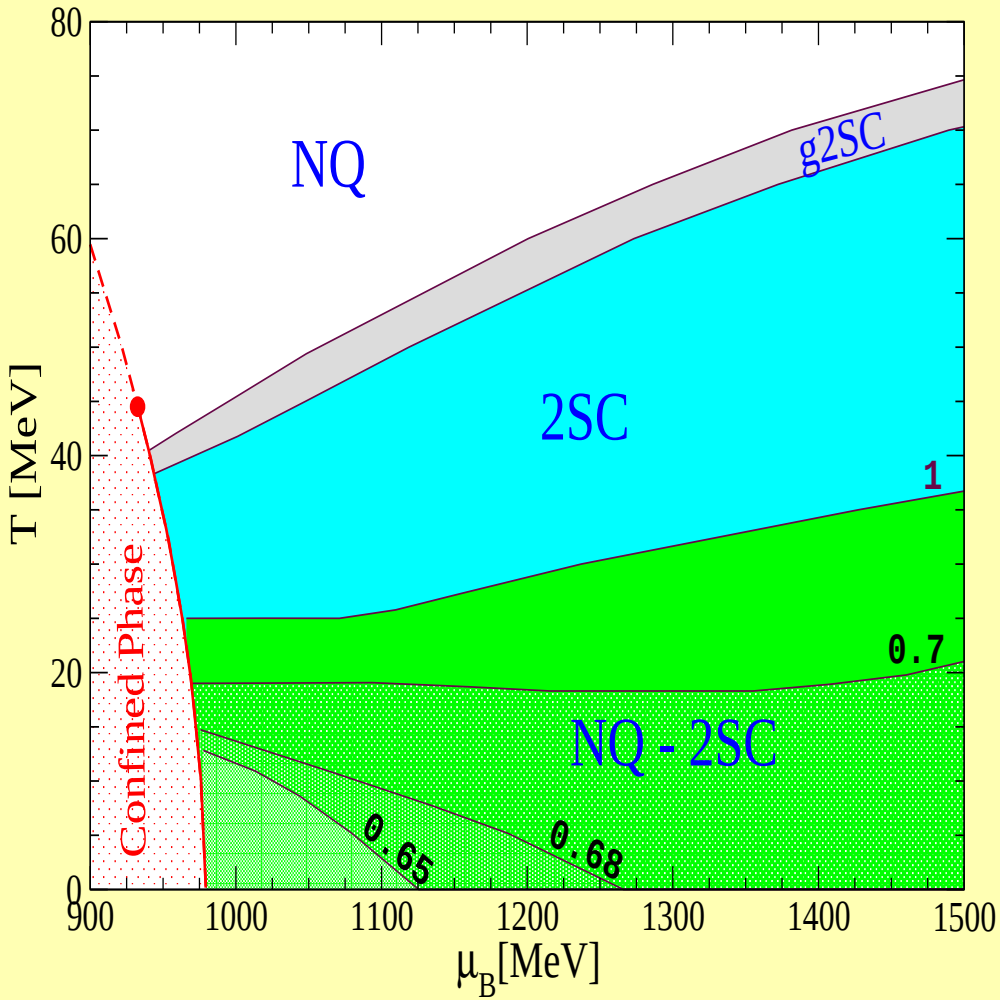
Gibbs free enthalpy density

$$G = \sum_{f,c} \mu_{fc} n_{fc} + \mu_e n_e = \mu_Q\, Q + \mu_8\, n_8 + \mu_B\, n_B$$

Strong conditions for diquark paring!

QCD Phase diagram under compact star contraints

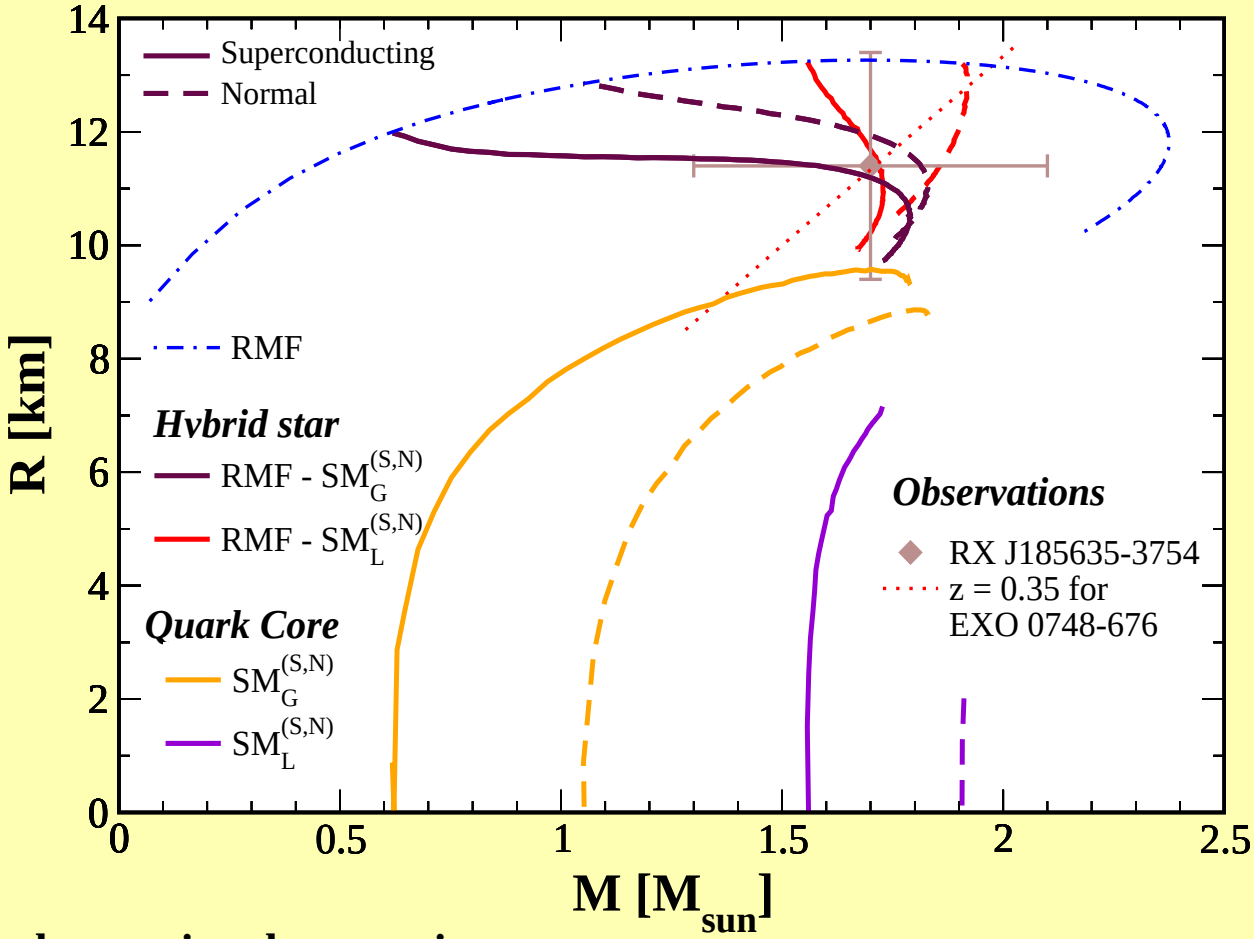
Strong coupling $\eta = 1$



D. N. Aguilera, D. Blaschke and H. Grigorian, Nucl. Phys. A (2005), in press.

Stable Hybrid stars Configurations

Strong coupling $\eta = 1$



Model obeys the observational constraints

- (M, R) **for isolated NS RX J185635-3754** **S. Zane, R. Turolla and J. Drake, astro-ph/0302197**
- $z = 0.35$ **for CS in EXO 0748-676** **J. Cottam, F. Paerels and M. Mendez, Nature 420, 51 (2002)**

H. Grigorian, D. Blaschke and D. N. Aguilera, Phys. Rev. C **69** (2004) 065802, arXiv:astro-ph/0303518.

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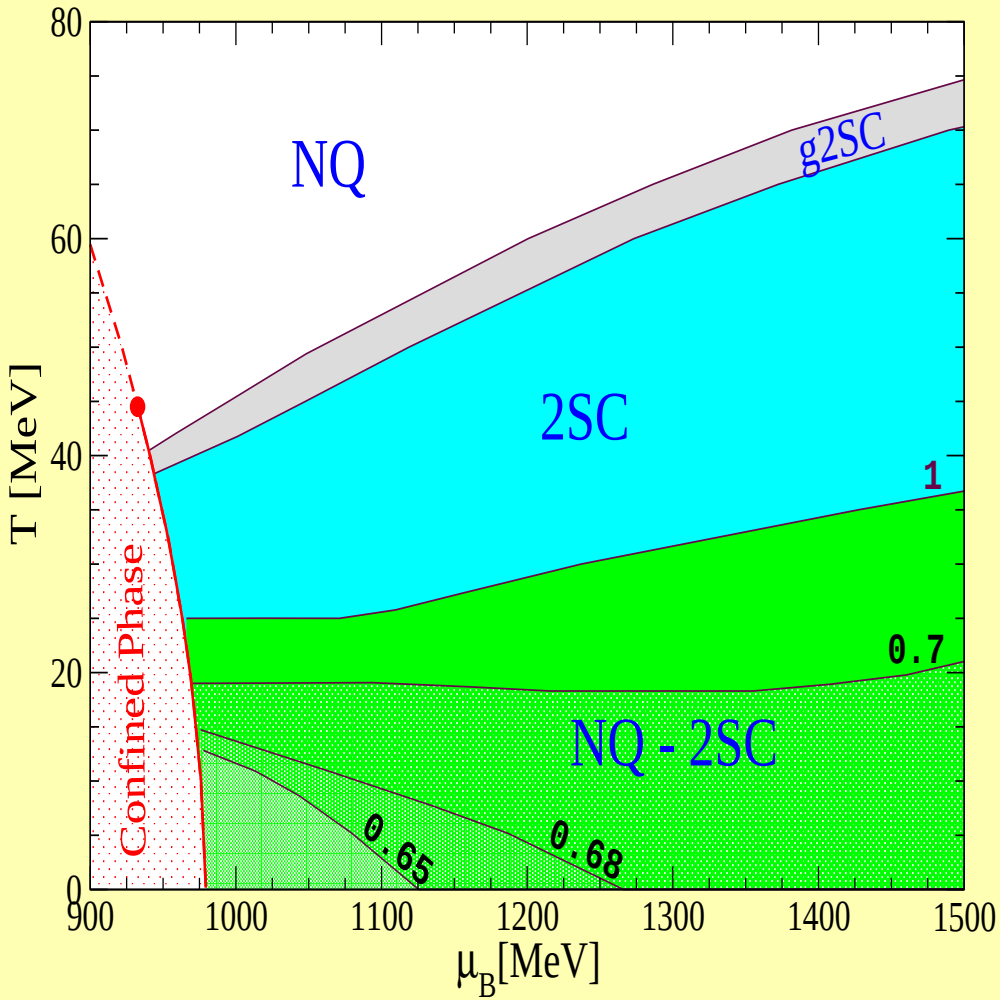
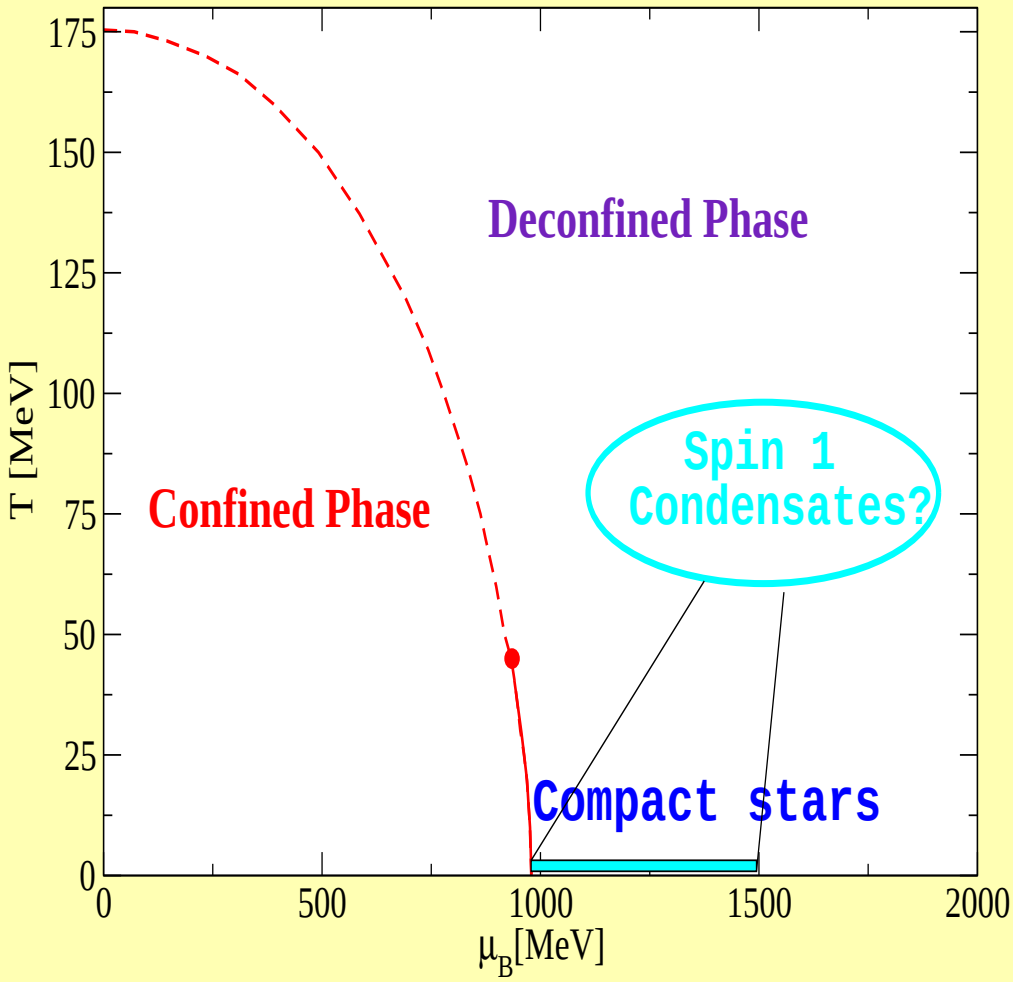


Usual coupling $\eta = 0.75$



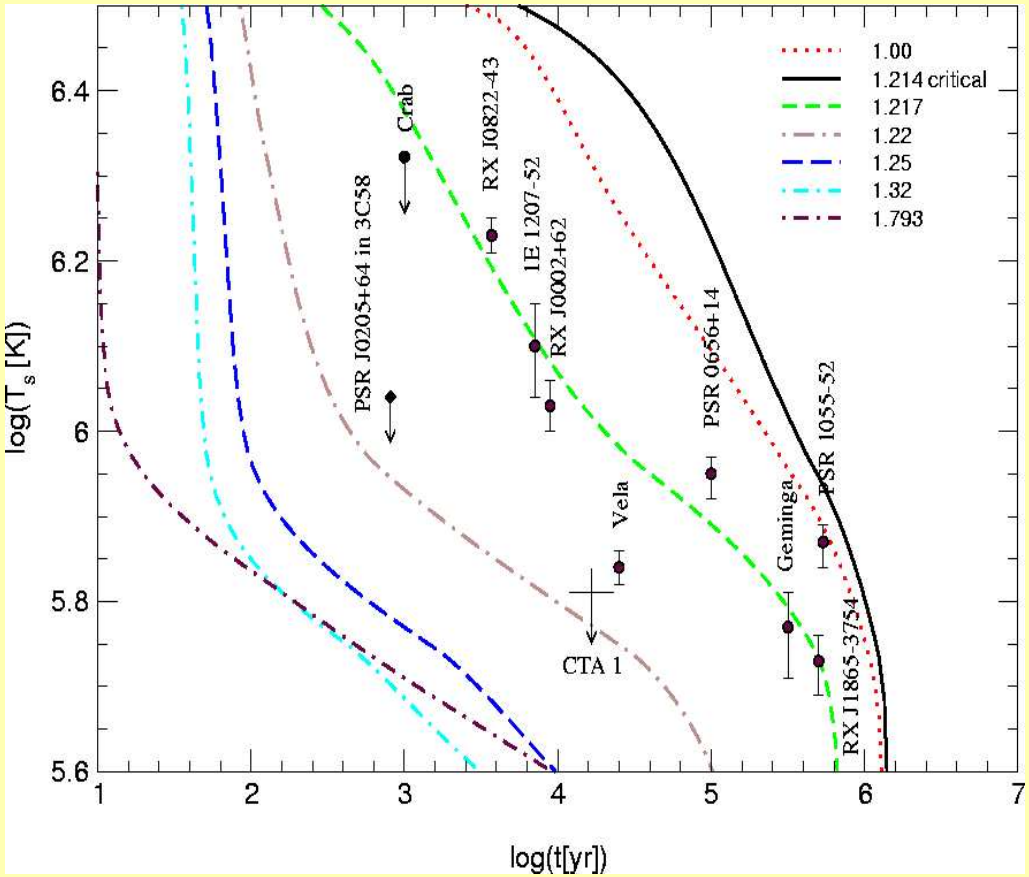
D. N. Aguilera, D. Blaschke and H. Grigorian, Nucl. Phys. A (2005), in press.

BUT important changes in the cooling evolution of compact stars could occur if

- **ALL QUARKS ARE PAIRED** $\Rightarrow$ **prevention of the direct URCA-process** $\Rightarrow$ **prevents the star to cool too fast**
- **GAPS ARE NOT TOO LARGE (**$10 \leq \Delta' \leq 100$ **KeV)** $\Rightarrow$ **processes are effective enough**

Neutron star cooling phenomenology: Hybrid stars with 2SC quark matter cores

- **pure 2SC ($\Delta_{rg} \simeq 100$ MeV)**
  - b **quarks unpaired** $\Delta' = 0$



URCA process allowed $\Rightarrow$ *Cooling is too fast*

H. Grigorian, D. Blaschke and D. Voskresensky, Phys. Rev. C **71** (2005) 045801, arXiv:astro-ph/0411619.

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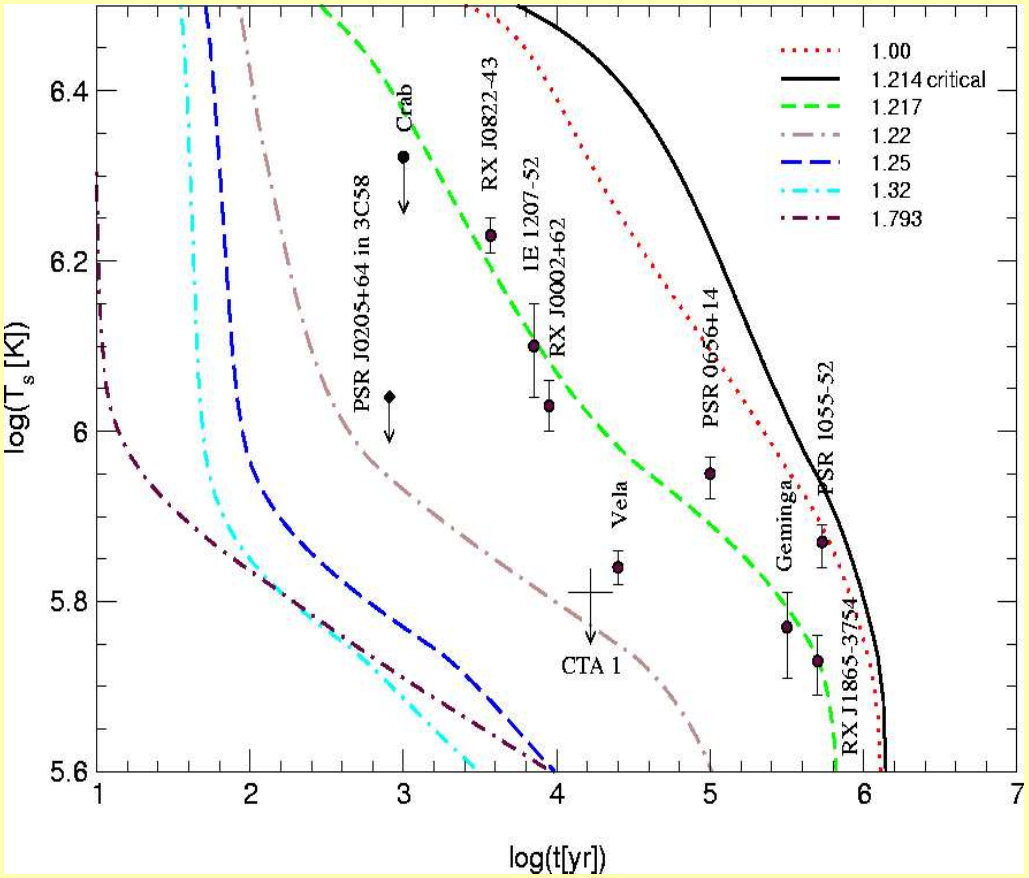
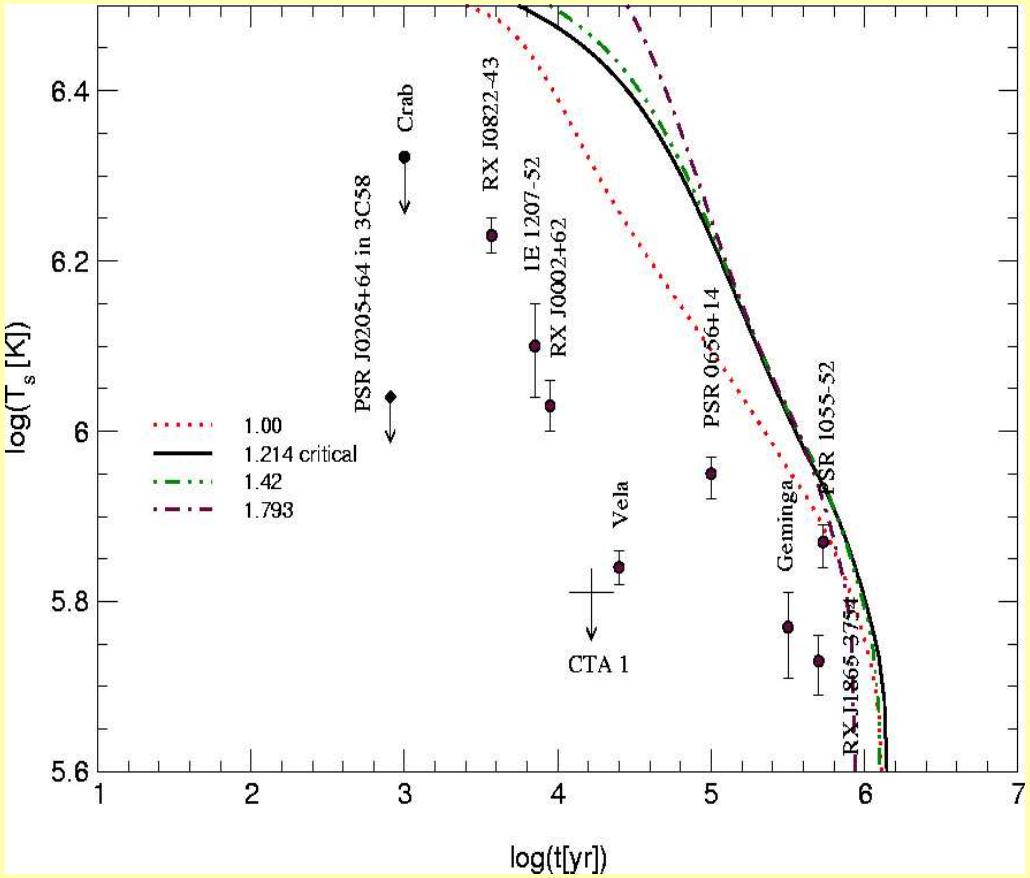


URCA process allowed $\Rightarrow$ *Cooling is too fast*

- **2SC + X**
  - **X-pairing channel** $\Delta' \simeq 1$ **MeV**



Processes no effective enough $\Rightarrow$ *Cooling is too slow*

H. Grigorian, D. Blaschke and D. Voskresensky, Phys. Rev. C **71** (2005) 045801, arXiv:astro-ph/0411619.

Neutron star cooling phenomenology: Hybrid stars with 2SC quark matter cores II

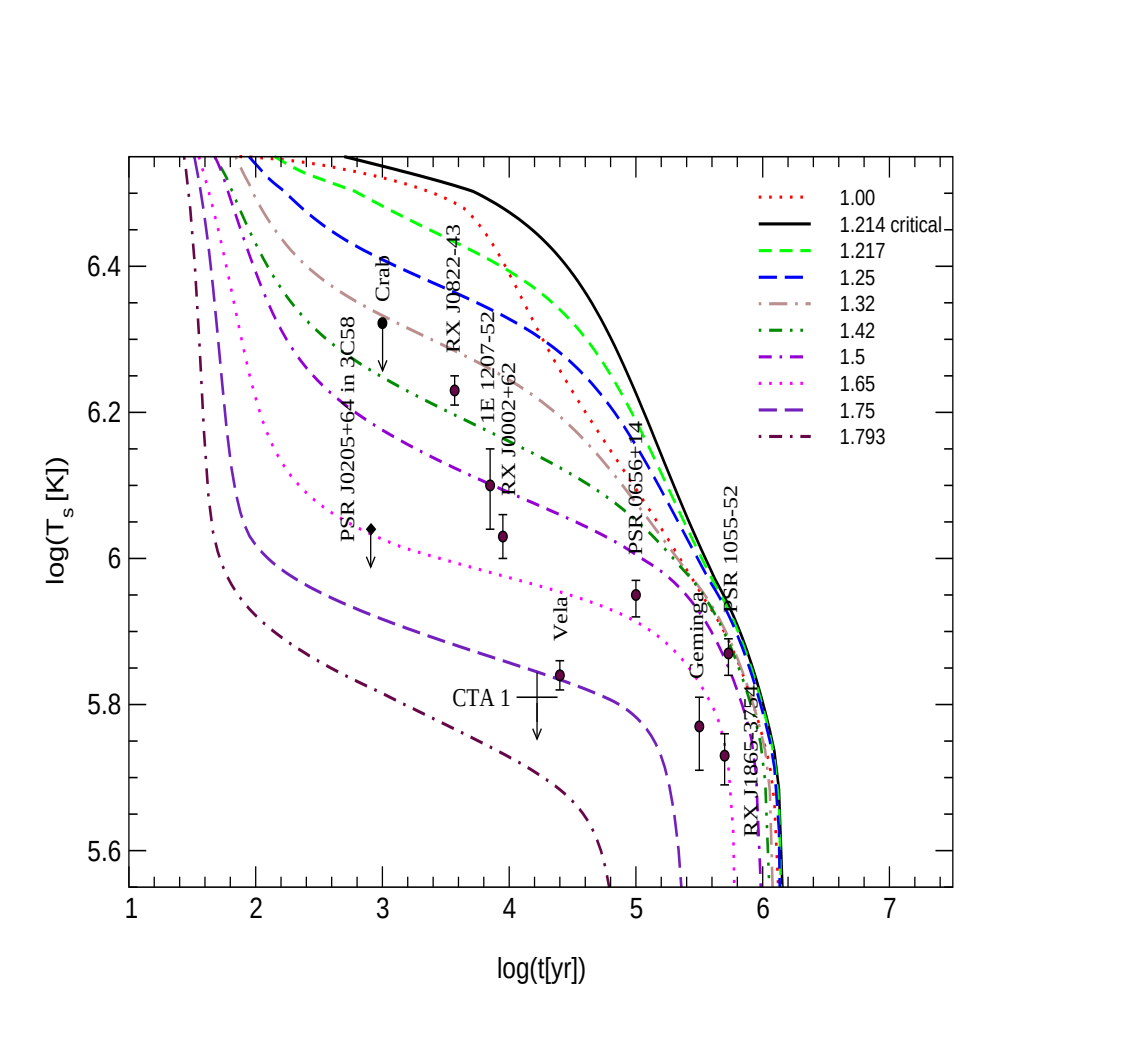
- **2SC + X**
  - **X-pairing channel with**

    μ-dependent gap $\Delta'(\mu) = \Delta_c[e^{-\alpha\frac{(\mu-\mu_c)}{\mu_c}}]$

    $\Delta' \simeq 1$ **MeV -** 10 **keV**

Then, processes are effective enough $\Rightarrow$

Observational data could be explained



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- **GAPS ARE NOT TOO LARGE** ($10 \leq \Delta' \leq 100$ **KeV**) $\Rightarrow$ processes are effective enough

POSSIBLE PAIRING PATTERNS

3-flavor	CFL		gaps are too large appears at very high densities
2-flavor	2SC+ X	X = spin-1 blue quarks	correct order of Δ' $\Leftarrow$ RESULTS destroyed by asymmetry
		X = $\Delta'[e^{-\alpha\frac{(\mu-\mu_c)}{\mu_c}}]$	no microscopic explanation
	CSL*		correct order of Δ' $\Leftarrow$ RESULTS independent of asymmetry

* T. Schfer, Phys. Rev. D **62**, 094007.
A. Schmitt, Q. Wang and D. H. Rischke, Phys. Rev. D **66**, 114010 (2002).

CSL - Color Spin Locked phase

Interaction channels:

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

Spin-1 CSL $\Delta' = -H_v\eta \quad \eta_u = \langle\, u^T\, C\, \gamma^3\, \lambda_2\, u\, \rangle \;\; = \langle\, u^T\, C\, \gamma^1\, \lambda_7\, u\, \rangle \;\; = \langle\, u^T\, C\, \gamma^2\, \lambda_5\, u\, \rangle$
$(u \to d)$

Thermodynamical potential $\Omega(T,\mu) = \Omega_u(T,\mu_u) + \Omega_d(T,\mu_d) + \Omega_{leptons}(T,\mu_Q)$

$$\Omega_f(T,\mu_f) \;=\; \frac{\phi_f^2}{8G_1} + 3\frac{|\Delta_f'|^2}{8G_3} - T\sum_n \int \frac{d^3p}{(2\pi)^3}\frac{1}{2}\mathrm{Tr}\ln(\frac{1}{T}S_f^{-1}(i\omega_n,\vec{p}))$$

$$S_f^{-1}(p) \;=\; \begin{pmatrix} \not{p} + \mu_f\gamma^0 - M_f & \Delta_f(\gamma^3\lambda_2 + \gamma^1\lambda_7 + \gamma^2\lambda_5) \\ \Delta_f^\star(\gamma^3\lambda_2 + \gamma^1\lambda_7 + \gamma^2\lambda_5) & \not{p} - \mu_f\gamma^0 - M_f \end{pmatrix} .$$

then

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

D. Aguilera, D. Blaschke, M. Buballa and V. Yudichev, Phys. Rev. D (2005), in press.

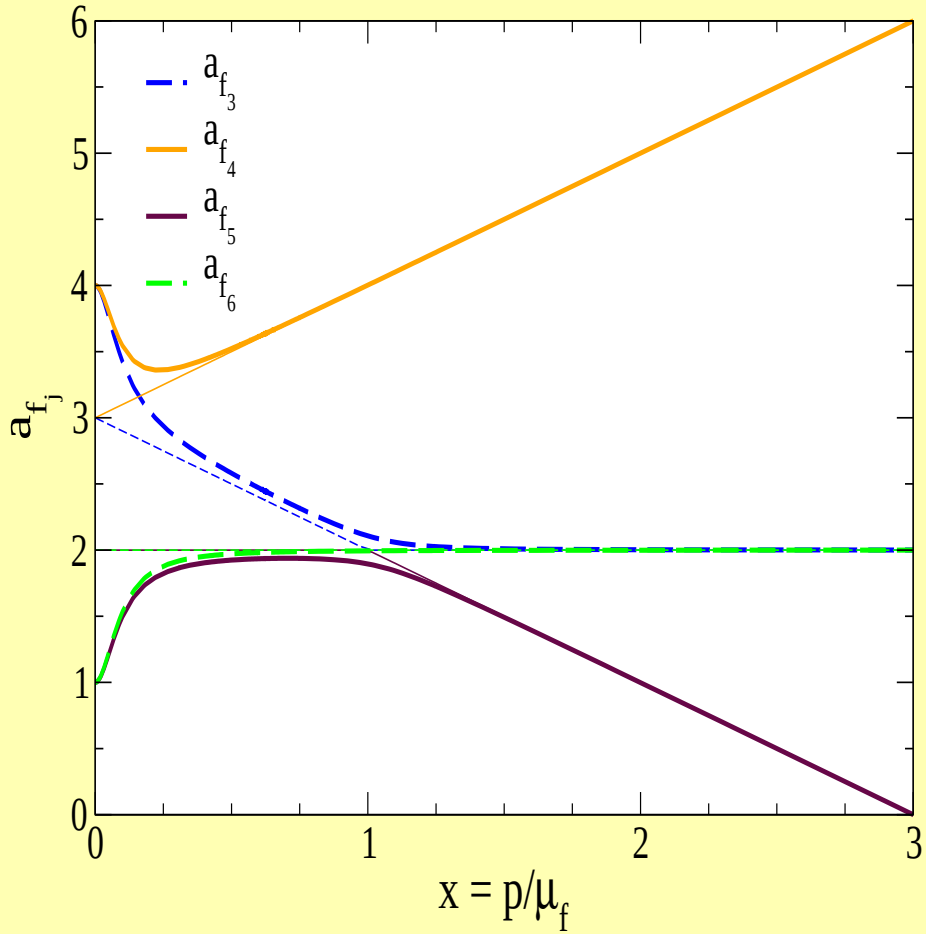
Dispersion relations for CSL phase

Energy dispersion relations

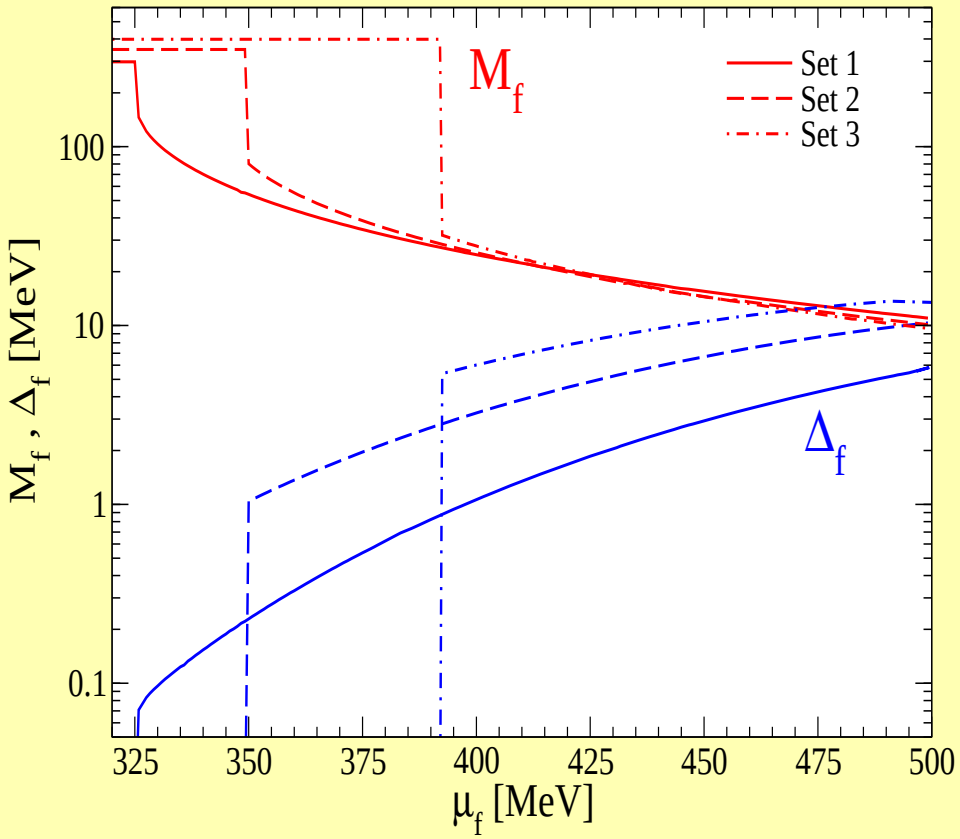
$$E^2_{f_{1,2}} = (\varepsilon_{f,\text{eff}} \mp \mu_{f,\text{eff}})^2 + |\Delta_{f,\text{eff}}|^2$$

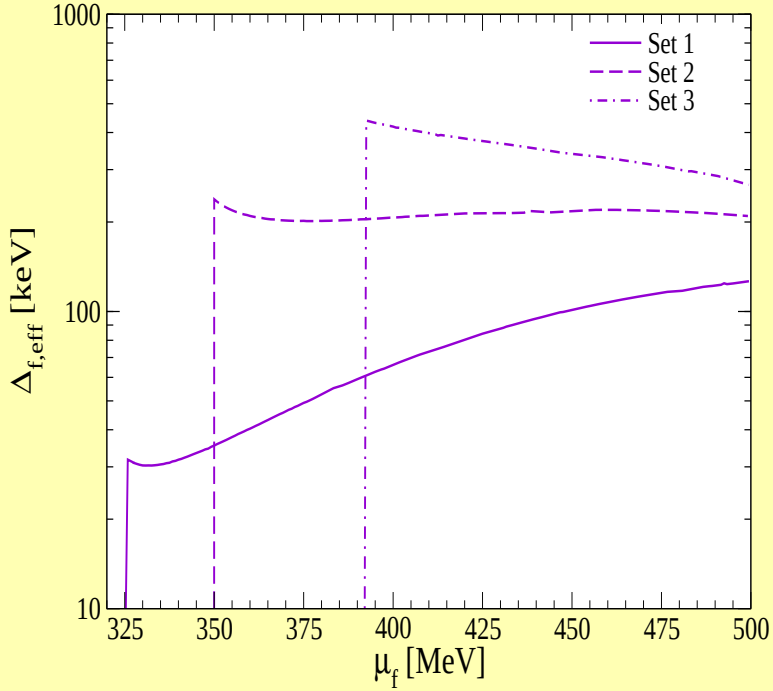
$$E^2_{f_{3,5}} = (\varepsilon_f - \mu_f)^2 + a_{f_{3,5}}|\Delta_f|^2$$
$$E^2_{f_{4,6}} = (\varepsilon_f + \mu_f)^2 + a_{f_{4,6}}|\Delta_f|^2$$

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



Gap Equation solutions for CSL - NJL models



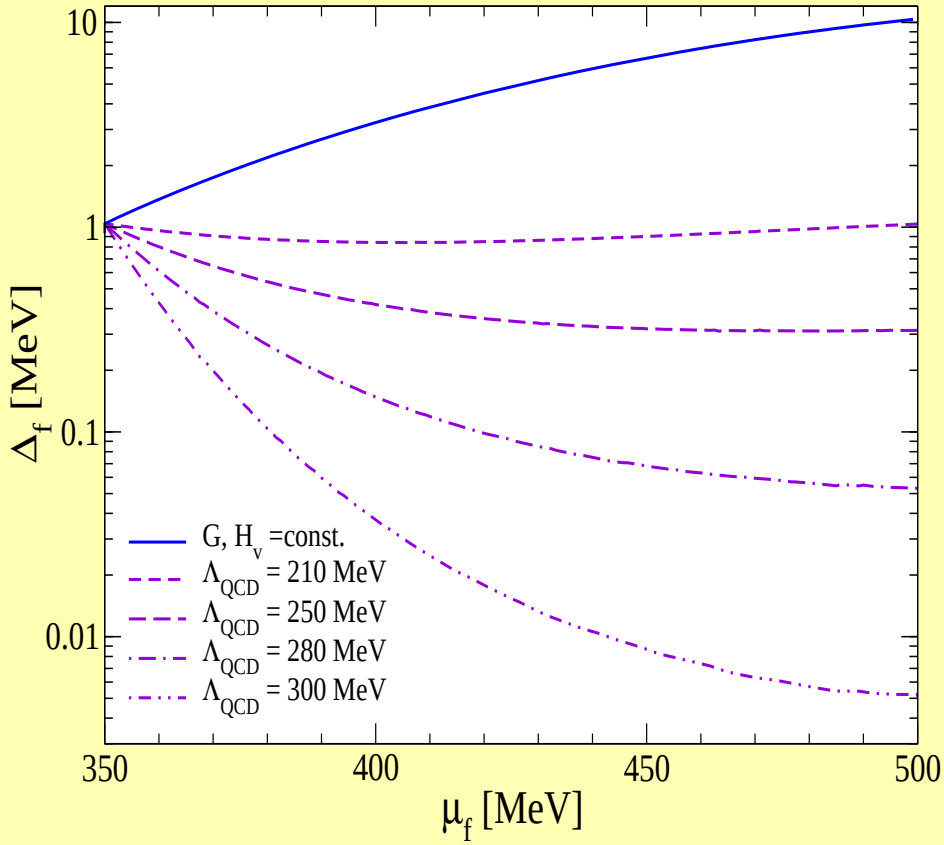


- *Δ_{eff} corresponds to expectations from cooling phenomenology*

CSL not affected by asymmetry $\longrightarrow$ *Could support compact stars constraints!*

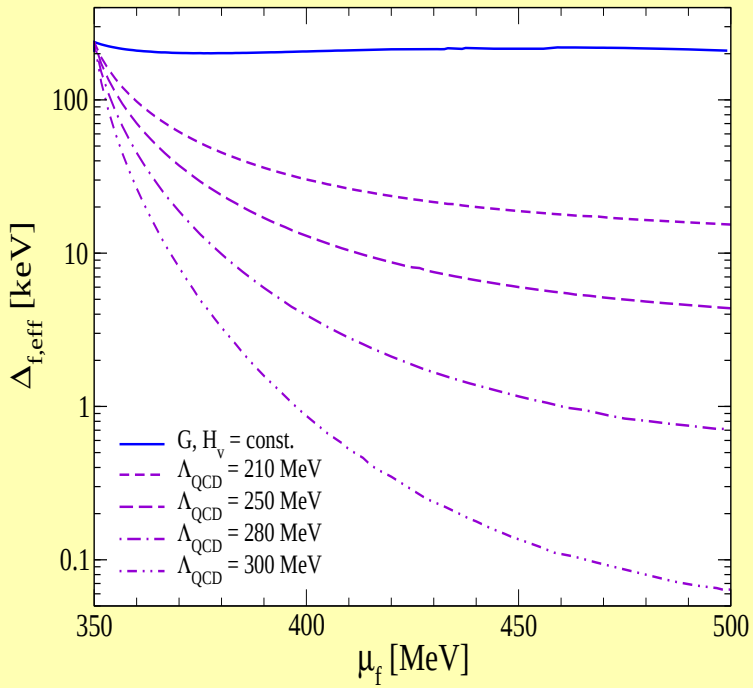
D. Aguilera, D. Blaschke, M. Buballa and V. Yudichev, Phys. Rev. D (2005), in press.
Set 1, Set 3 from M. Buballa, Habilitationsschrift - arXiv:hep-ph/0402234.

Gap Equation solutions for CSL - density dependent coupling



Density dependent coupling constant

$$R_{\Lambda_{\rm QCD}}(\mu) = \frac{\alpha(\mu)}{\alpha(\mu_{\rm crit})} = \frac{\ln(\mu_{\rm crit}/\Lambda_{\rm QCD})}{\ln(\mu/\Lambda_{\rm QCD})}$$



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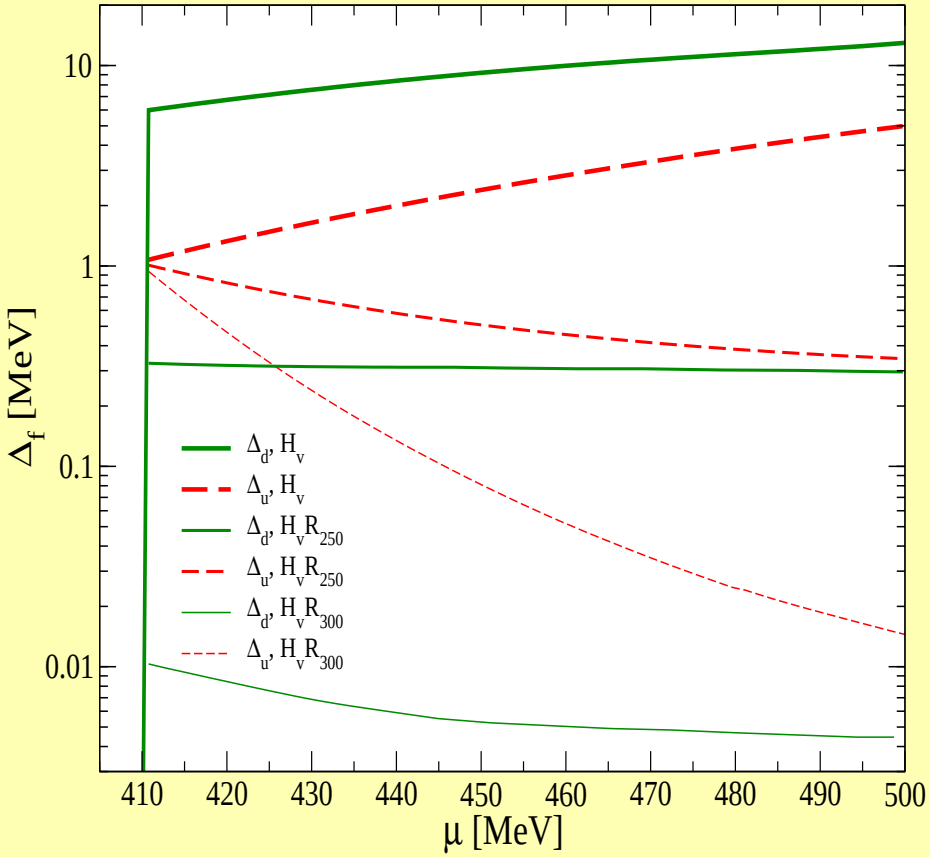

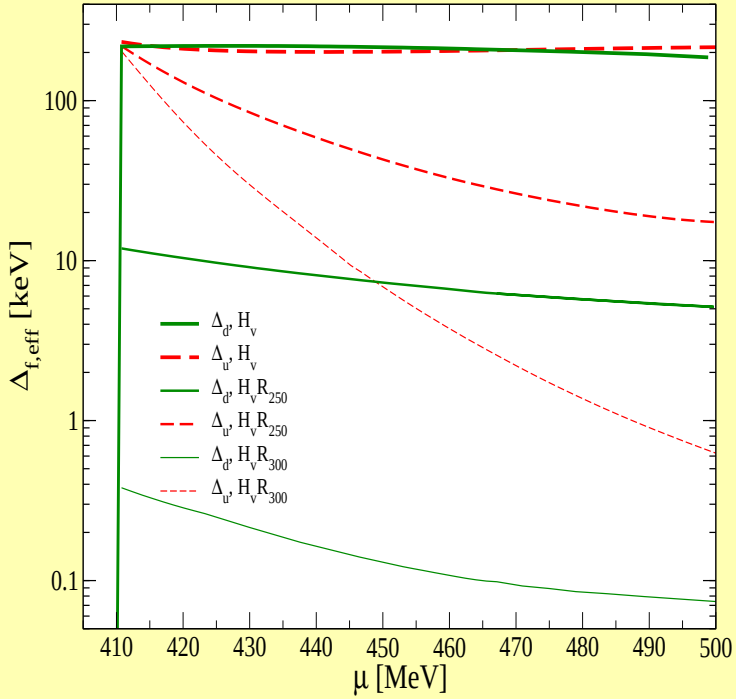

Summary

- **RESULTS**

  Under compact stars constraints

  – *Pure 2SC unlikely* for usual coupling constants.

  – Spin-1 channels like *Color Spin Locked (CSL)* phase seem likely to occur.

- **CONSEQUENCES in the observables:**

  – **Hybrid stars:**
  Stable configurations for hybrid stars. Model obeys the observational constraints of compact object like RX J185635-3754.

  – **Cooling of compact stars:**
  CSL compatible with neutron star cooling phenomenology

  $*$ independent of asymmetry

  $\hookrightarrow$ *could fulfill compact stars constraints*