Massive neutron stars with quarks
Vector–interaction–enhanced bag model

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The Dyson–Schwinger equation formalism

In–medium quark propagator

$$S(p^2,\tilde{p}_4)^{-1} = i\vec{\gamma}\vec{p}A(p^2,\tilde{p}_4) + i\gamma_4\tilde{p}_4 C(p^2,\tilde{p}_4) + B(p^2,\tilde{p}_4),$$

The Dyson–Schwinger equation for the quark propagator

$$S(p^2,\tilde{p}_4)^{-1} = i\vec{\gamma}\vec{p} + i\gamma_4\tilde{p}_4 + m + \Sigma(p^2,\tilde{p}_4),$$

with $\tilde{p}_4 = p_4 + i\mu$, and the self–energy term

$$\Sigma(p^2,\tilde{p}_4) = \int \frac{d^4q}{(2\pi)^4} g^2(\mu) D_{\rho\sigma}(p-q,\mu)\frac{\lambda_\alpha}{2}\gamma_\rho S(q^2,\tilde{q}_4)\Gamma^\alpha_\sigma(q,p,\mu),$$

Truncations:

$$g^2 D_{\rho\sigma}(p-q) = \frac{1}{m_G^2}\theta(\Lambda^2 - \vec{q}^2)\delta^{\rho\sigma},$$

$$\Gamma^\alpha_\sigma(q,p,\mu) = \frac{\lambda^\alpha}{2}\gamma_\sigma.$$

Derived gap equations:

$$\tilde{p}_4^2 C(p^2,\tilde{p}_4) = \tilde{p}_4^2 + \frac{8}{3m_G^2}\int \frac{d^4q}{(2\pi)^4}\frac{\tilde{p}_4\tilde{q}_4 C(q^2,\tilde{q}_4)}{\vec{q}^2A^2(q^2,\tilde{q}_4) + \tilde{q}_4^2C^2(q^2,\tilde{q}_4) + B^2(q^2,\tilde{q}_4)},$$

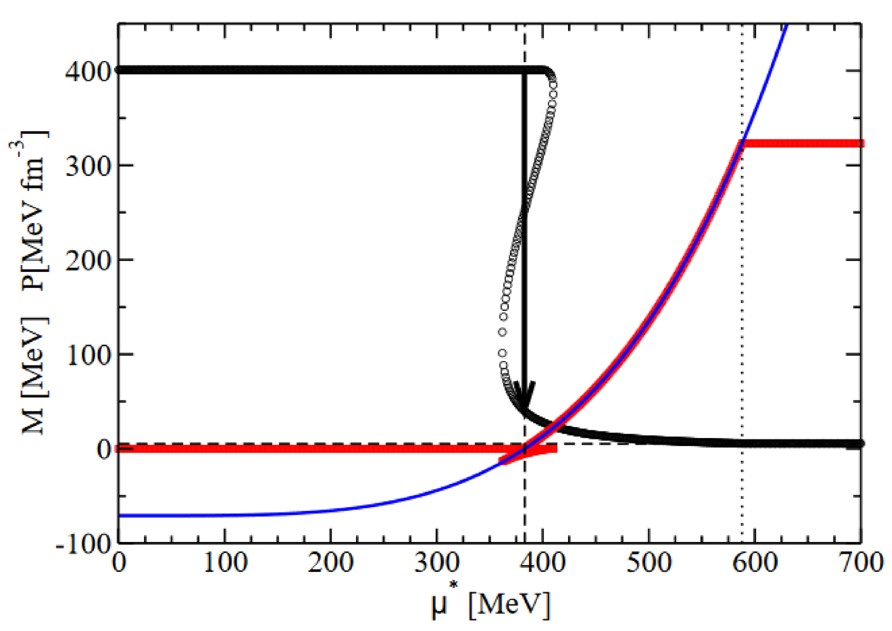
$$B(p^2,\tilde{p}_4) = m + \frac{16}{3m_G^2}\int \frac{d^4q}{(2\pi)^4}\frac{B(q^2,\tilde{q}_4)}{\vec{q}^2A^2(q^2,\tilde{q}_4) + \tilde{q}_4^2C^2(q^2,\tilde{q}_4) + B^2(q^2,\tilde{q}_4)}$$

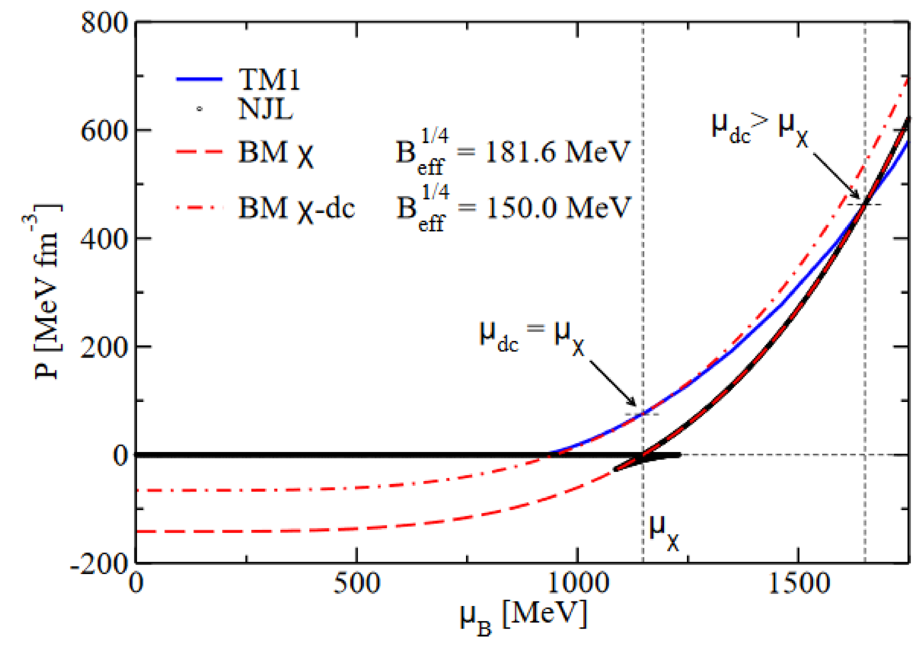
The DSE–derived single flavor pressure (left picture, red line or right picture, black line)

$$P_{FG} = TrLnS^{-1} = 2N_c\int_\Lambda \frac{d^4q}{(2\pi)^4} Ln\left(\vec{p}^2 + \tilde{p}_4^2 + B^2\right),$$

and

$$P_I = -\frac{1}{2}Tr\Sigma S = \frac{3}{4}m_G^2(\mu-\mu^*)^2 - \frac{3}{8}m_G^2(B-m)^2.$$

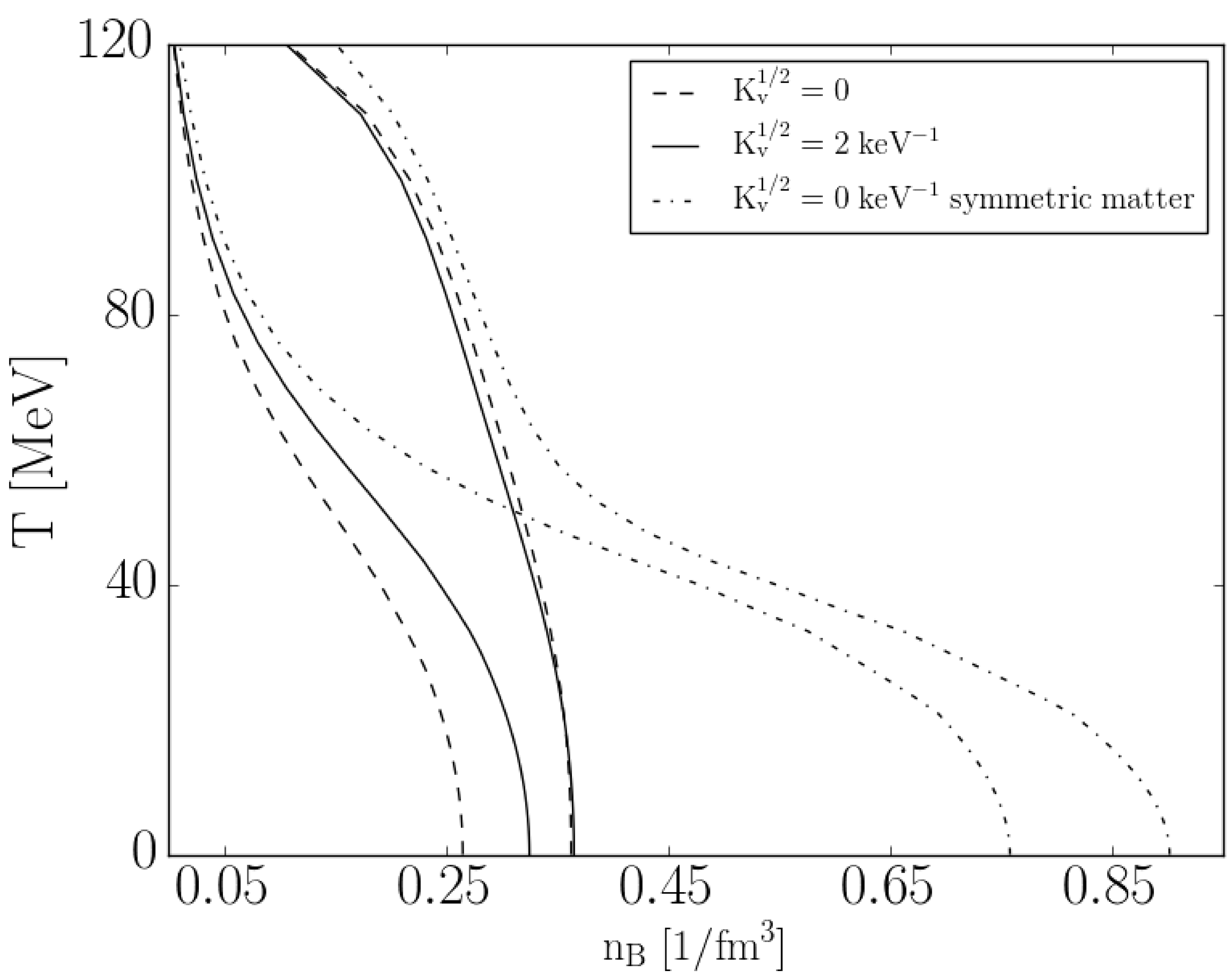




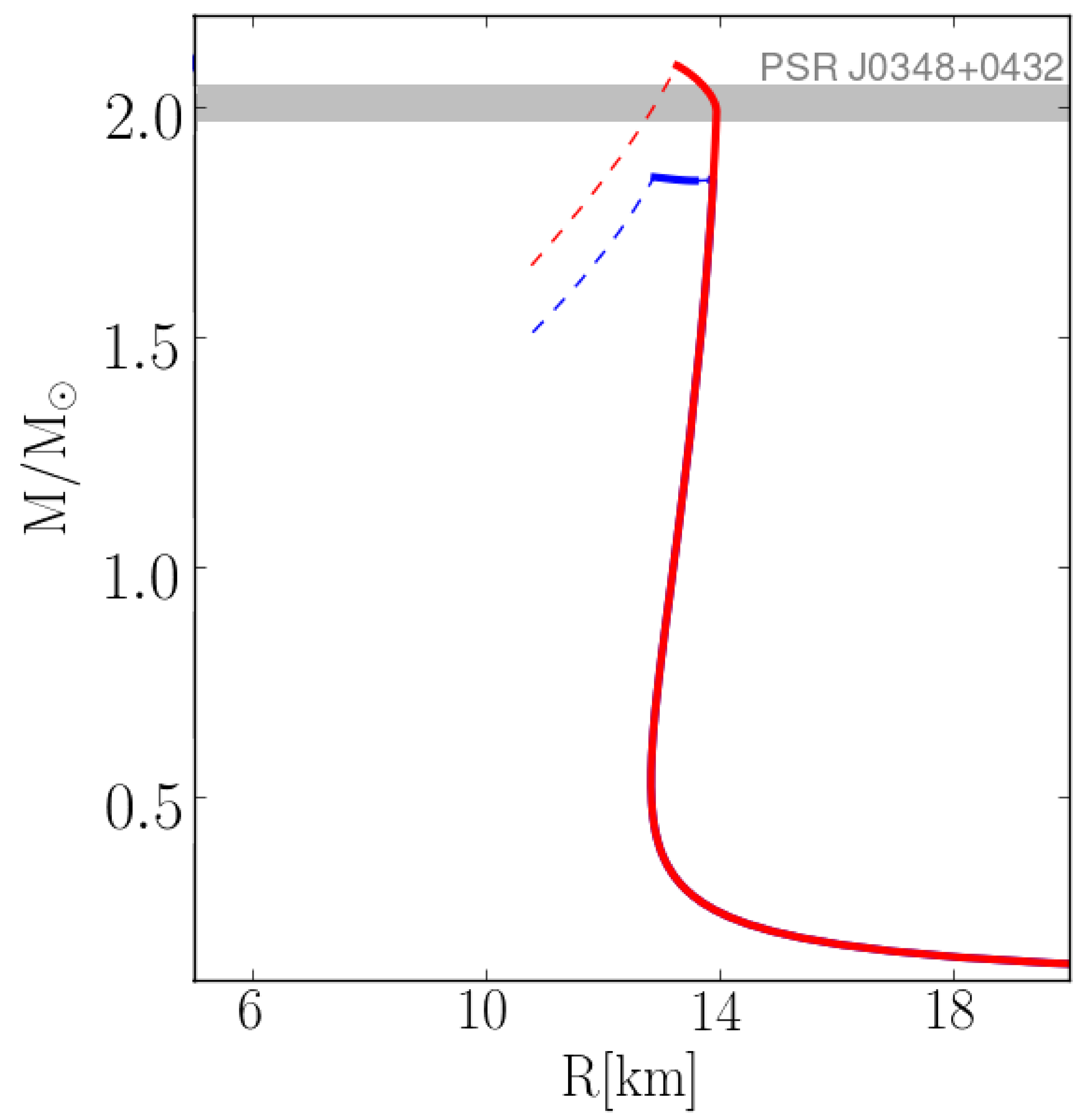
$$P_f(\mu_f) = P^{kin}_{FG,f}(\mu_f^*) - B_{\chi,f}.$$
$$\mu_f = \mu_f^* + K_v n_{FG,f}(\mu^*)$$

$$P^Q = \sum P_f(\mu_f) + B_{dc}$$
$$\mu_B = \mu_u + 2\mu_d$$

Phase diagram



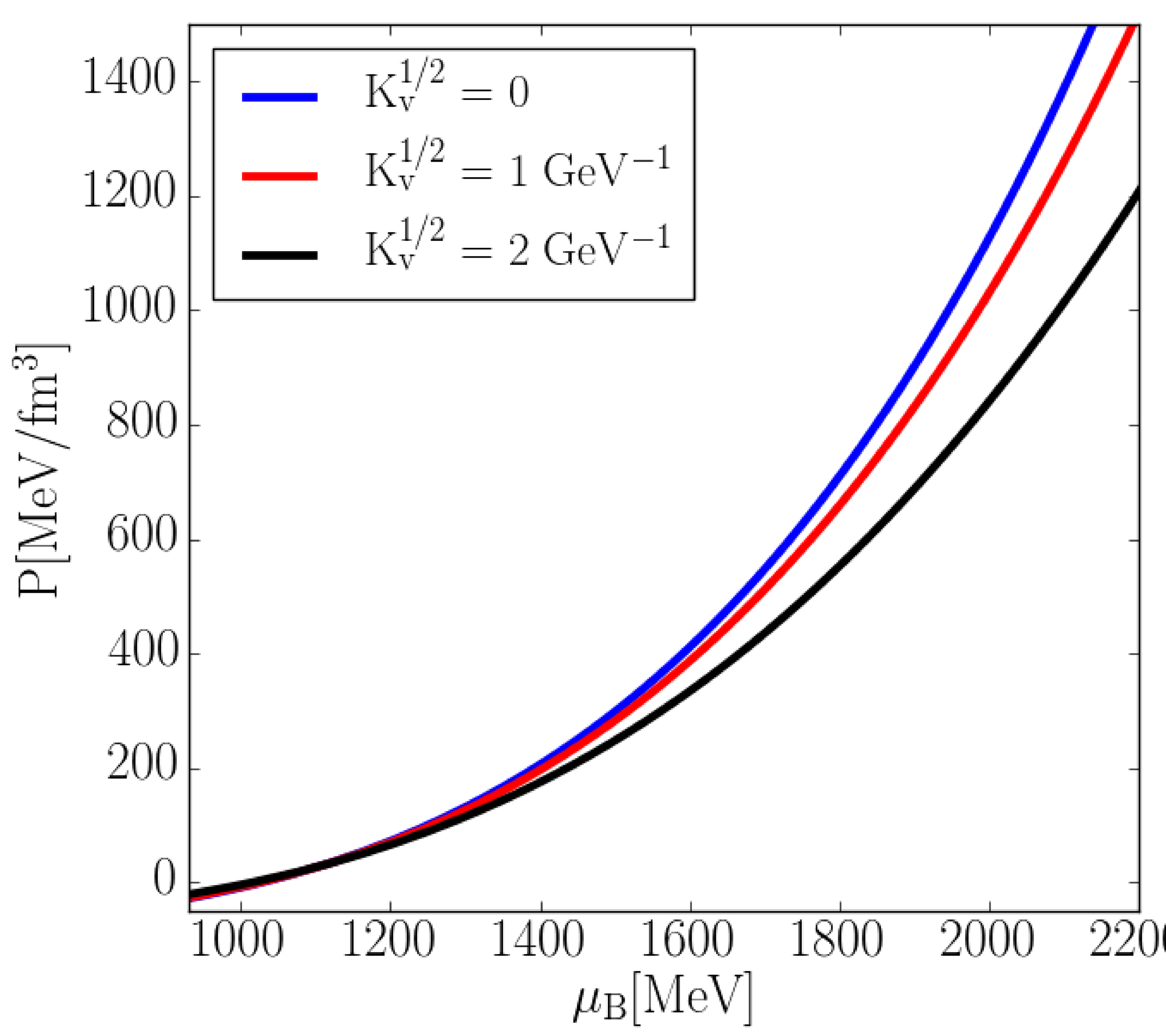
Neutron star mass–radius relation



Repulsive vector interaction essential for the presence of massive hybrid neutron stars is realised by redefining the pressure as

$$P_f(\mu_f) = P^{kin}_{FG,f}(\mu_f^*) + \frac{K_v}{2}n^2_{FG,f}(\mu_f^*) - B_{\chi,f}.$$

The impact on the single flavor EoS:



vBag equation of state

Single flavor chemical potential	$\mu_f = \mu_f^* + K_v n_{FG,f}(\mu^*)$
Baryochemical potential	$\mu_B = \mu_u + 2\mu_d$
Charge chemical potential	$\mu_C = \mu_u - \mu_d$
Particle number density	$n_f(T,\mu_f) = n_{FG,f}(T,\mu_f^*)$
Baryon density	$n_B = \sum_f \frac{1}{3}n_f(T,\mu_f^*)$
Single flavor pressure	$P_f(T,\mu_f) = P^{kin}_{FG,f}(T,\mu_f^*) + \frac{K_v}{2}n^2_{FG,f}(\mu_f^*) - B_{\chi,f}$
Total pressure	$P^Q = \sum_f P_f(T,\mu_f) + B_{dc}(T,\mu_C)$
Single flavor energy density	$\epsilon_f(T,\mu_f) = \epsilon^{kin}_{FG,f}(T,\mu_f^*) + \frac{K_v}{2}n^2_{FG,f}(\mu_f^*) + B_{\chi,f}$
Total energy density	$\epsilon^Q = \sum_f \epsilon_f(T,\mu_f^*) - B_{dc}(T,\mu_C) + T\frac{\partial B_{dc}(T,\mu_C)}{\partial T} + \mu_C\frac{\partial B_{dc}(T,\mu_C)}{\partial \mu_C}$
Single flavor entropy	$s_f(T,\mu_f) = s^{kin}_{FG,f}(T,\mu_f^*)$
Total entropy	$s^Q = \sum_f s_f(T,\mu_f) + \frac{\partial B_{dc}(T)}{\partial T}$

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