Dense hadronic matter and astrophysics of massive compact stars

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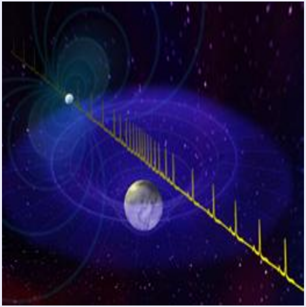
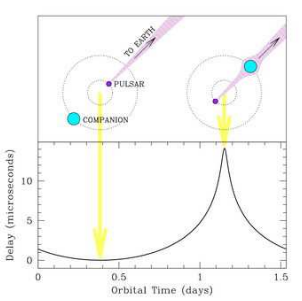
Dense hadronic matter

Observed massive pulsars in binaries with WD $M \sim 2M_{\odot}$





- Compatibility of hyperonization with large masses of pulsars - “hyperon puzzle”
- Microscopic hypernuclear BHF calculations produce max $M \leq 1.5\, M_{\odot}$
- Quark deconfinement softens the EOS as well
- Are new degrees of freedom compatible with observations?

DF includes hadronic degrees of freedom

$$\boxed{\underbrace{p, n, \Lambda, \Sigma^{\pm,0}, \Xi^{-,0}}_{Baryons} \quad \underbrace{\sigma, \boldsymbol{\rho}_\mu, \omega_\mu}_{Mesons} \quad \underbrace{e, \mu}_{Leptons} \quad \underbrace{\nu_f}_{T\neq 0}}$$

$$\begin{aligned}\mathcal{L} &= \sum_B \bar\psi_B \Big[\gamma^\mu \Big(i\partial_\mu - g_{\omega BB}\omega_\mu - \frac{1}{2} g_{\rho BB}\boldsymbol{\tau}\cdot\boldsymbol{\rho}_\mu\Big) - (m_B - g_{\sigma BB}\sigma)\Big]\psi_B \\ &+ \frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{4}\omega^{\mu\nu}\omega_{\mu\nu} + \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu - \frac{1}{4}\boldsymbol{\rho}^{\mu\nu}\boldsymbol{\rho}_{\mu\nu} + \frac{1}{2}m_\rho^2\boldsymbol{\rho}^\mu\cdot\boldsymbol{\rho}_\mu \\ &+ \sum_\lambda \bar\psi_\lambda(i\gamma^\mu\partial_\mu - m_\lambda)\psi_\lambda - \frac{1}{4}F^{\mu\nu}F_{\mu\nu},\end{aligned}$$

- Nuclear DF: DD-ME2 parametrization P. Ring et al. Phys. Rev. C 71, 024312 (2005).
- Hypernuclear DF extension SU(3) couplings + variations in the coupling $\sigma - \Lambda$ and $\sigma - \Sigma^-$

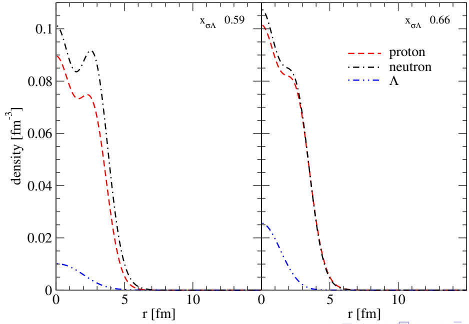
- Parameters of nuclear functional:

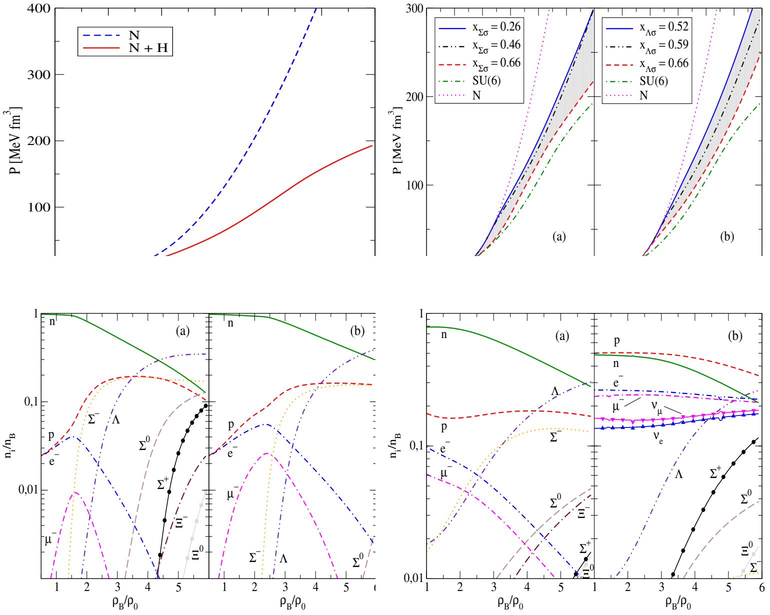
$$\rho_0 = 0.152\text{fm}^{-3}, \quad E/A = -16.14\text{MeV} \quad K_0 = 250.90\text{MeV}, \tag{1}$$

$$J = 32.30\text{MeV}, \quad L = 51.24\text{MeV}, \quad K_{sym} = -87.19\text{MeV} \tag{2}$$

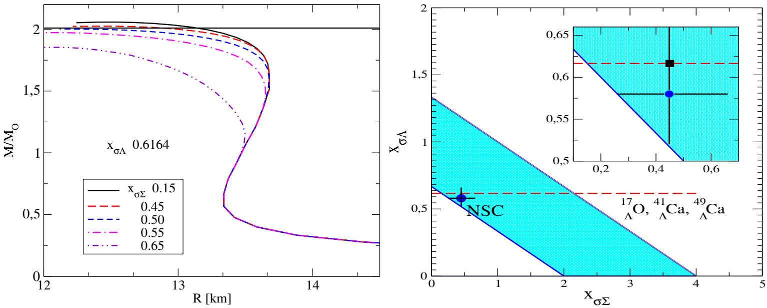
	$E_{Mass}[\Lambda\ 1s_{1/2}]$ [MeV]	$E[\Lambda\ 1s_{1/2}]$ [MeV]	E/A [MeV]	r_p [fm]	r_n [fm]	r_Λ [fm]
${}^{17}_{\Lambda}$O	-12.109	-11.716	-8.168	2.592	2.562	2.458
^{16}O	–	–	-8.001	2.609	2.579	–
${}^{41}_{\Lambda}$C	-17.930	-17.821	-8.788	3.362	3.309	2.652
^{40}Ca	–	–	-8.573	3.372	3.320	–
${}^{49}_{\Lambda}$Ca	-19.215	-19.618	-8.858	3.379	3.562	2.715
^{48}Ca	–	–	-8.641	3.389	3.576	–

Single-particle energies of the $\Lambda\ 1s_{1/2}$ states, binding energies, and rms radii of the Λ-hyperon, neutron, and proton of ${}^{17}_{\Lambda}$O, ${}^{41}_{\Lambda}$C, and ${}^{49}_{\Lambda}$Ca are presented for optimal model. In addition, single-particle energies of the $\Lambda\ 1s_{1/2}$ states, i.e. separation energies of the Λ-particle, obtained from the mass formula are given for these Λ-hypernuclei. Furthermore, the properties of ^{16}O, ^{40}Ca, and ^{48}Ca are given for the optimal model; (van Dalen, Colucci, Sedrakian, PLB 734, 383 (2014)).





Left panel: $T = 0$, soft vs hard EOS, right panel: $T = 50$ MeV, neutrino-less vs neutrino-full matter



- blue region - allowed by the inequality, NSC value - the blue dot - red line - Λ-hypernuclei, - left of square (inset) along red line – constraint from stars - best values of parameters:

$$\boxed{x_{\sigma\Lambda} = 0.6164, \qquad 0.15 \leq x_{\sigma\Sigma} \leq 0.45.}$$

Proof of principle of bracketing parameters by *combination* of NS and hyper-nuclei.

II. Dense QCD and compact stars

General form of order parameter

$$\Delta \propto \langle 0|\psi^a_{\alpha\sigma}\psi^b_{\beta\tau}|0\rangle$$

- Antisymmetry in spin σ, τ for the BCS mechanism to work
- Antisymmetry in color a, b for attraction
- Antisymmetry in flavor to avoid Pauli blocking

At low densities 2SC phase (Bailin and Love '84)

$$\boxed{\Delta(2SC) \propto \Delta\epsilon^{ab3}\epsilon_{\alpha\beta}}$$

At high densities we expect 3 flavors of u, d, s massless quarks. The ground state is the color-flavor-locked phase (Alford, Rajagopal, Wilczek '99)

$$\boxed{\Delta(CFL) \propto \langle 0|\psi^a_{\alpha L}\psi^b_{\beta L}|0\rangle = -\langle 0|\psi^a_{\alpha R}\psi^b_{\beta R}|0\rangle = \Delta\epsilon^{abC}\Delta\epsilon_{\alpha\beta C}}$$

Important variations on 2SC phase (crystalline-color-superconductor)

$$\boxed{\Delta(CSC) \propto \Delta\epsilon^{ab3}\epsilon_{\alpha\beta}, \qquad \delta\mu \neq 0, \qquad m_s \neq 0.}$$

Color-superconductivity within the NJL model

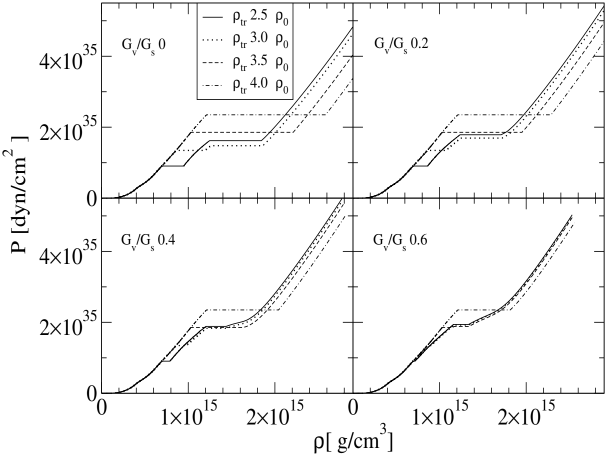
$$
\begin{aligned}
\mathcal{L}_Q &= \bar{\psi}(i\gamma^\mu\partial_\mu - \hat{m})\psi + G_V(\bar{\psi}i\gamma^0\psi)^2 + G_S\sum_{a=0}^{8}[(\bar{\psi}\lambda_a\psi)^2 + (\bar{\psi}i\gamma_5\lambda_a\psi)^2] \\
&+ G_D\sum_{\gamma,c}[\bar{\psi}^a_\alpha i\gamma_5\epsilon^{\alpha\beta\gamma}\epsilon_{abc}(\psi_C)^b_\beta][(\bar{\psi}_C)^r_\rho i\gamma_5\epsilon^{\rho\sigma\gamma}\epsilon_{rsc}\psi^8_\sigma] \\
&- K\left\{\det{}_f[\bar{\psi}(1+\gamma_5)\psi] + \det{}_f[\bar{\psi}(1-\gamma_5)\psi]\right\},
\end{aligned}
$$

quark spinor fields ψ^a_α, color $a = r, g, b$, flavor ($\alpha = u, d, s$) indices, mass matrix $\hat{m} = \mathrm{diag}_f(m_u, m_d, m_s)$, λ_a $a = 1, ..., 8$ Gell-Mann matrices. Charge conjugated $\psi_C = C\bar{\psi}^T$ and $\bar{\psi}_C = \psi^T C$ $C = i\gamma^2\gamma^0$.

Simple but efficient model to treat CSC phases:

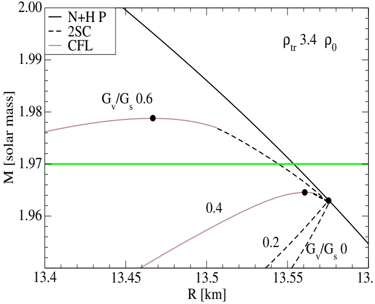
- a sum is over the 8 gluons
- G_S is the scalar coupling fixed from vacuum physics
- G_D is the di-quark coupling, which is related to the G_S via Fierz transformation
- G_V and ρ_{tr} are treated as a free parameter

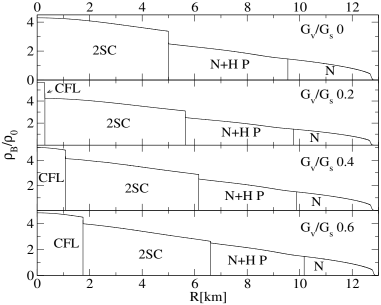
EOS w



- Phase equilibrium is constructed via Maxwell prescription
- Sequential phase transition $NM \rightarrow 2SC \rightarrow CFL$

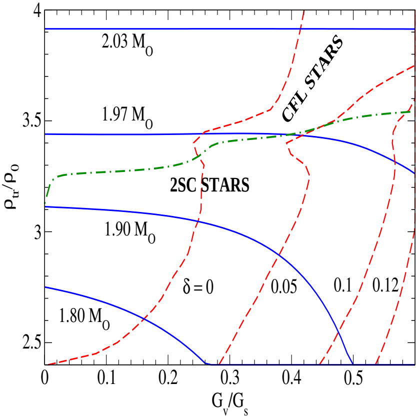
Mass vs Radius relationship





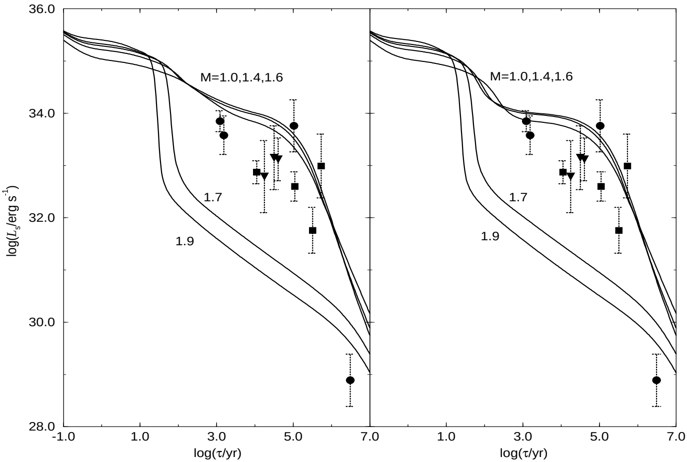
- Dashed only 2SC, grey includes CFL.
- Stability is achieved for $G_V > 0.2$ and transition densities few ρ_0

Stability diagram in



- Below dashed-dotted: 2SC stars are stable
- To the right of dashed curves CFL stars are stable few ρ_0

Cooling simulations of neutron stars (surface photon luminosity vs age)



Transport of thermal energy and energy balance equations ($T' = Te^{\Phi}$)

$$\frac{dT'}{dr} = \frac{-3\kappa\rho}{16\sigma T^3}\frac{L_\gamma e^{\Phi}}{4\pi r^2\sqrt{1-\frac{2Gm}{rc^2}}}, \qquad \frac{d}{dr}\left(Le^{2\Phi}\right) = \frac{-4\pi r^2}{\sqrt{1-\frac{2Gm}{rc^2}}}nT'\frac{ds}{dt}.$$

L is the total luminosity (neutrino + photon)

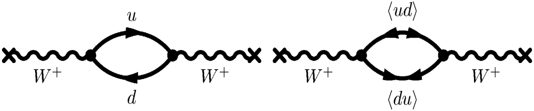
$$\left(\int_0^{R_c} nc_v dV_p\right)\frac{dT'}{dt} = -(L_\nu + L_\gamma)e^{2\Phi_c}.$$

The final equation to solve

$$\boxed{\left(\int_0^{R_c} nc_v(r,T)dV_p\right)\frac{dT'}{dt} = -\int_0^{R_c} n\mathcal{Q}_\nu(r,T)e^{2\Phi}dV_p + 4\pi\sigma R^2T_S^4e^{2\Phi_c}}$$

Quark cores of NS emit neutrons via: $d \to u + e + \bar{\nu}_e \quad u + e \to d + \nu_e$. The rate of the process is

$$\epsilon_{\nu\bar{\nu}} \quad \propto \quad \Lambda^{\mu\lambda}(q_1, q_2) \Im\, \Pi^R_{\mu\lambda}(q).$$



(a) (b)

via the response function

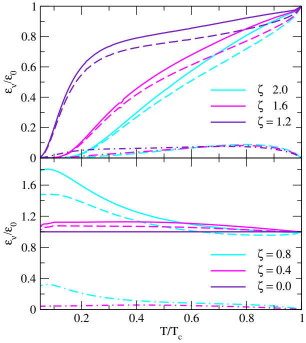
$$\Pi_{\mu\lambda}(q) = -i \int \frac{d^4p}{(2\pi)^4} \mathrm{Tr}\left[(\Gamma_-)_\mu S(p)(\Gamma_+)_\lambda S(p+q)\right], \quad \Gamma_\pm(q) = \gamma_\mu(1-\gamma_5) \otimes \tau_\pm$$

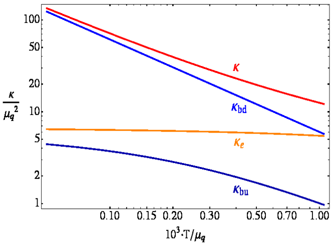
with propagators

$$S_{f=u,d} = i\delta_{ab} \frac{\Lambda^+(p)}{p_0^2 - \epsilon_p^2}(\not{p} - \mu_f \gamma_0), \quad F(p) = -i\epsilon_{ab3}\epsilon_{fg}\Delta \frac{\Lambda^+(p)}{p_0^2 - \epsilon_p^2}\gamma_5 C$$

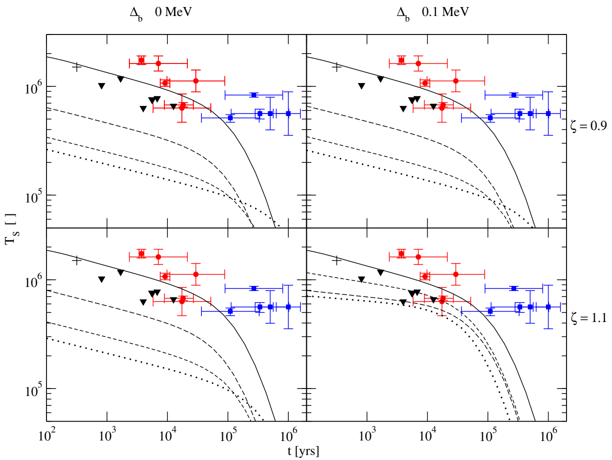
CSC phases show non-trivial dependence on gap: $\zeta = \Delta/\delta\mu$

$$\zeta > 1 \quad \text{gapped} \qquad \zeta \leq 1 \quad \text{un-gapped}$$

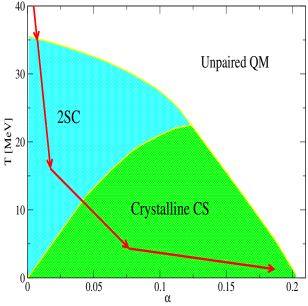


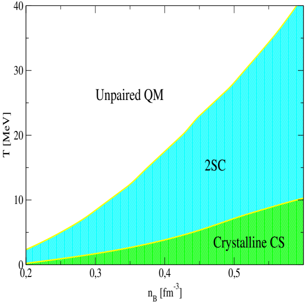


- Two-flavor phase (2SC) - No gapless excitations - suppressed emissivities
- Crystalline (LOFF) phase - Gapless excitations - unsuppressed emissivities

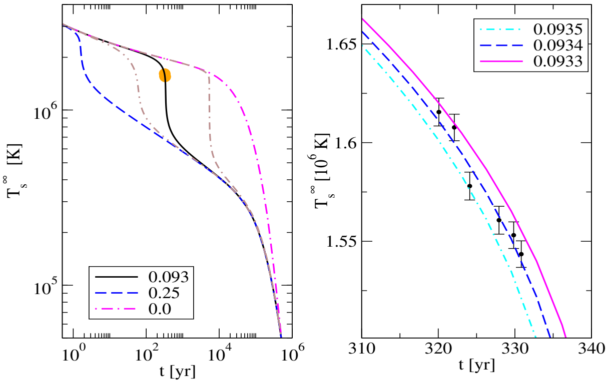


Cooling simulation of stars with quark matter cores, (D. Hess, A. Sedrakian, Phys. Rev. D 84, 063015 (2011))





- Can Cas A be a massive compact star with a quark core?
- Cas A cooling can be explained by a $1.4 M_\odot$ star using as a cooling agent the pair-breaking processes.



- Two-parameter fit to the Cas A: w - the width of the transition and T^* the temperature of the transition
- The blue quark gap is a further parameter.