Rapid cooling of Cas A as a phase transition in dense QCD

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I. Dense Matter Equation of State and Neutron Stars

Equation of state of hypernuclear matter: impact of hyperon–scalar-meson couplings
Giuseppe Colucci, A. S.
Phys. Rev. C 87, 055806 (2013), arXiv:1302.6925

Composition and stability of hybrid stars with hyperons and quark color-superconductivity
Luca Bonanno, A. S.
Astron. Astrophys. 539, A16 (2012), arXiv:1108.0559

Relativistic covariant Lagrangians for hypernuclear matter

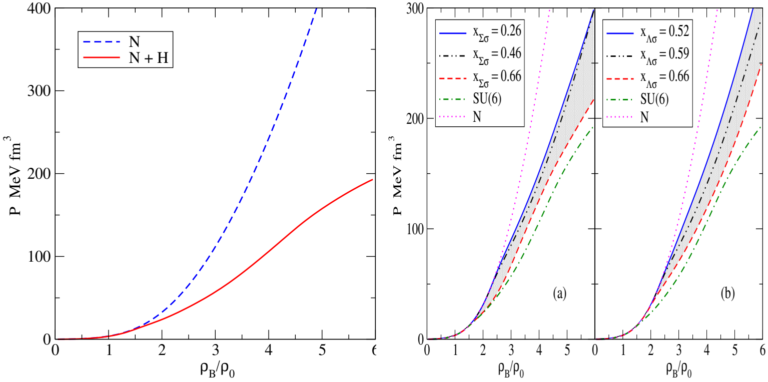
Lagrangian for effective fields:

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

(1) (2)

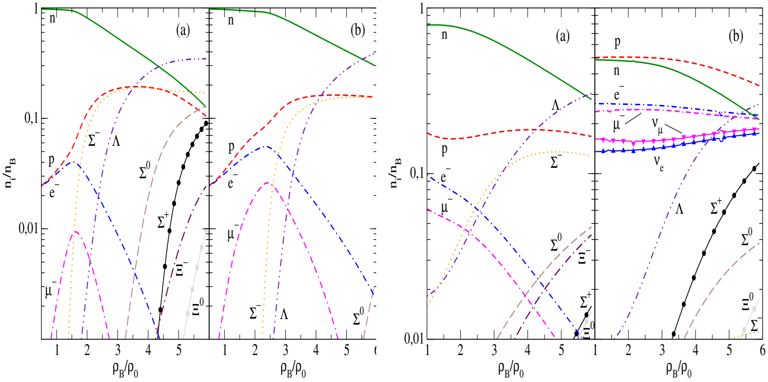
- B-sum is over the baryonic octet $B \equiv p, n, \Lambda, \Sigma^{\pm,0}, \Xi^{-,0}$
- N-meson sector: density-dependent coupling according to the DD-ME2
- H-meson couplings weaker by factors 2/3 according to the SU(6) quark model.

EOS Nuclear vs Hypernuclear Matter



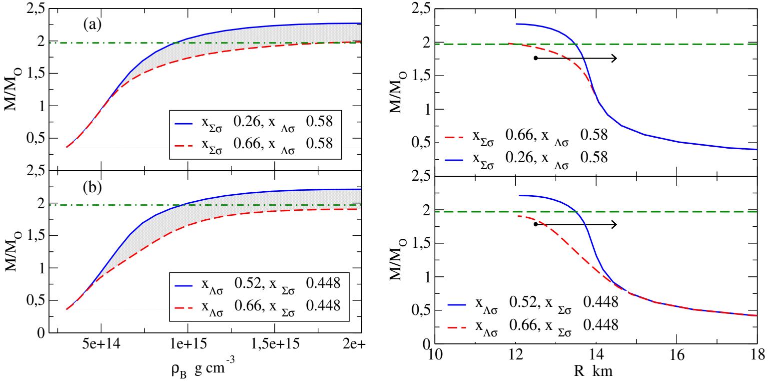
- Dashed - nuclear
- Full - hypernuclear + variation of the scalar σ meson - hypernuclear couplings

Abundances of hyperons



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

Mass vs Radius relationship



Quark phases

Nambu-Jona-Lasinio Lagrangian:

$$\begin{aligned} \mathcal{L}_Q &= \bar{\psi}(i\gamma^\mu\partial_\mu - \hat{m})\psi + G_V(\bar{\psi}i\gamma^0\psi)^2 + G_S\sum_{a=0}^{8}[(\bar{\psi}\lambda_a\psi)^2 + (\bar{\psi}i\gamma_5\lambda_a\psi)^2] \\ &+ G_D\sum_{\gamma,c}[\bar{\psi}^a_\alpha i\gamma_5\epsilon^{\alpha\beta\gamma}\epsilon_{abc}(\psi_C)^b_\beta][(\bar{\psi}_C)^r_\rho i\gamma_5\epsilon^{\rho\sigma\gamma}\epsilon_{rsc}\psi^8_\sigma] \\ &- K\left\{\det_f[\bar{\psi}(1+\gamma_5)\psi] + \det_f[\bar{\psi}(1-\gamma_5)\psi]\right\} + G_V(\bar{\psi}i\gamma^\mu\psi)^2, \end{aligned} \tag{3}$$

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 $a = 1, \ldots, 8$ Gell-Mann matrices. Charge conjugated $\psi_C = C\bar{\psi}^T$ and $\bar{\psi}_C = \psi^T C$ $C = i\gamma^2\gamma^0$.

- a sum is over the 8 gluons
- G_S is the scalar coupling fixed from vacuum physics; G_D is the scalar coupling, which is related to the G_S via Fierz transformation
- Vector coupling G_V and transition density are the free parameters

Quark phases

Pairing patterns: 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

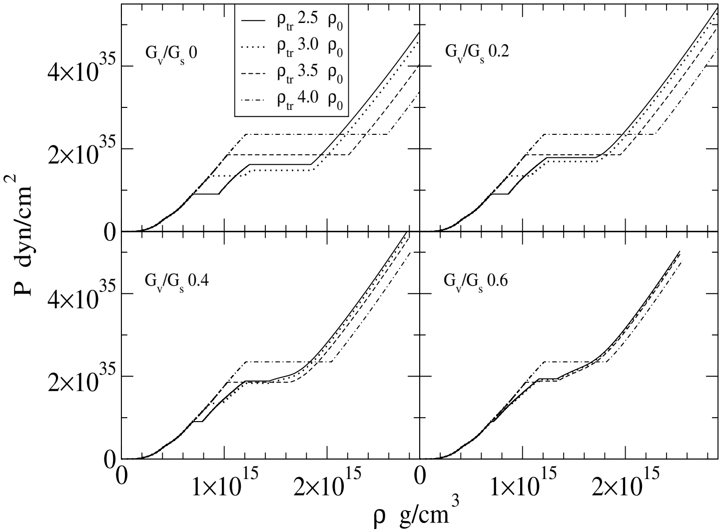
At low densities 2SC phase (Bailin and Love '84)

$$\Delta \propto= \Delta\epsilon^{ab3}\epsilon_{\alpha\beta}$$

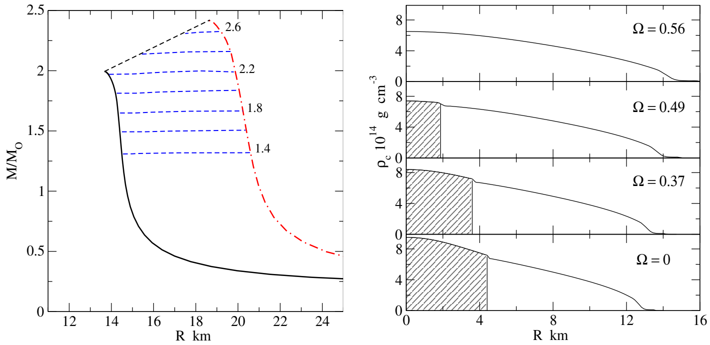
At high densities we expect 3 flavors of u, d, s massless quarks. The ground state is the color-flavor-locked phase (Alford, Rajagopal, Wilczek '99)

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

EoS with equilibrium among nuclear, hyperonic, 2SC- and CFL-quark phases

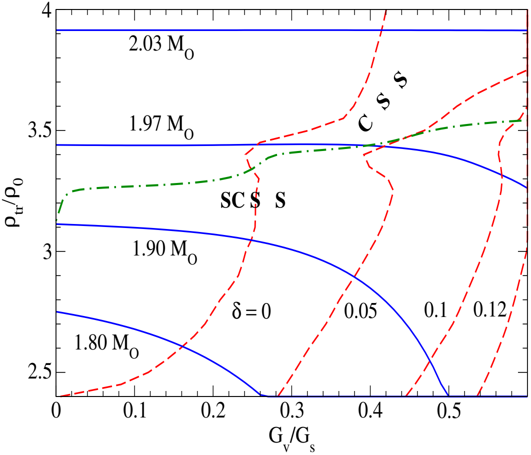


Mass vs Radius relationship



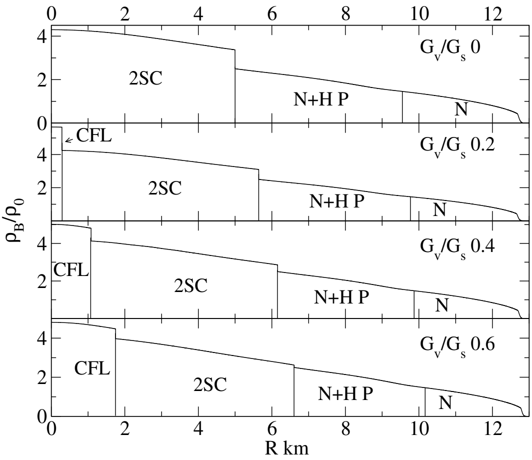
- Hypermassive configurations + evolutionary sequences
- New type of sequences featuring phase transition *Transitional sequences!*

Parameter space



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

Composition: multilayer stars with quark, hyperonic, nuclear matters



- Fix transition density $2.5 \times \rho_0$.
- Increasing G_V stabilizes the stars + “exotic matter”

II. Cassiopea A

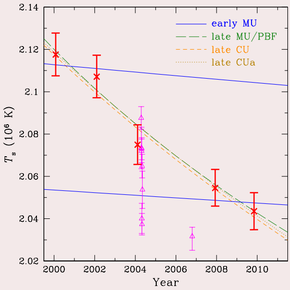
Rapid cooling of the compact star in Cassiopea A as a phase transition in dense QCD

A. S.

Astron. Astrophys. 555, L10 (2013)

Cas A remnant, cooling in course

This extraordinarily deep Chandra image shows Cassiopeia A (Cas A, for short), the youngest supernova remnant in the Milky Way.



NASA's Chandra X-ray Observatory has discovered the first direct evidence for a superfluid. (Conclusions drawn from cooling simulations of the neutron stars).

Energy balance equation (Thorne '77)

$$\frac{d}{dr}\left(Le^{2\Phi}\right) = \frac{-4\pi r^2}{\sqrt{1-\frac{2Gm}{rc^2}}} ne^{\Phi} T \frac{ds}{dt}. \tag{4}$$

L is the total luminosity (neutrino + photon) The gradients of neutrino luminosity

$$\frac{d}{dr}\left(L_\nu e^{2\Phi}\right) = \frac{4\pi r^2}{\sqrt{1-\frac{2Gm}{rc^2}}} ne^{2\Phi} q_\nu, \quad L_\nu e^{2\Phi_c} = \int_0^{R_c} nq_\nu e^{2\Phi} dV_p. \tag{5}$$

Transport of thermal energy

$$\frac{d}{dr}\left(Te^{\Phi}\right) = \frac{-3\kappa\rho}{16\sigma T^3} \frac{L_\gamma e^{\Phi}}{4\pi r^2 \sqrt{1-\frac{2Gm}{rc^2}}} \tag{6}$$

In isothermal core approximation $T' = Te^{\Phi} = \text{const}$.

$$\frac{dT'}{dt} = -\frac{Le^{2\Phi_c}}{\int_0^{R_c} nc_v dV_p}. \tag{7}$$

Combination gives

$$\frac{dT'}{dt} = -\frac{\int_0^{R_c} nq_\nu(r,T) e^{2\Phi} dV_p + 4\pi\sigma R^2 T_S^4 e^{2\Phi_c}}{\int_0^{R_c} nc_v(r,T) dV_p}. \tag{8}$$

Key processes

- Hadronic matter
  - Modified Urca process + Pair-breaking process

$$n + n \to n + p + e + \bar{\nu}, \quad [NN] \to [NN] + \nu + \bar{\nu}.$$

  - Crust bremsstrahlung

$$e + (A, Z) \to e + (A, Z) + \nu + \bar{\nu},$$

- Quark matter
  - Quark Urca process + Pair-breaking

$$d \to u + e + \bar{\nu}, \quad (dd) \to (dd) + \nu + \bar{\nu} \tag{9}$$

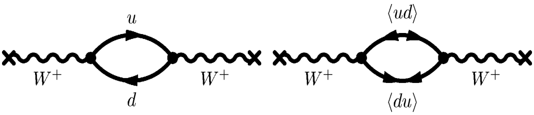
- Surface photo-emission

$$L_\gamma = 4\pi\sigma R^2 T^4$$

Cooling processes in quark matter

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)

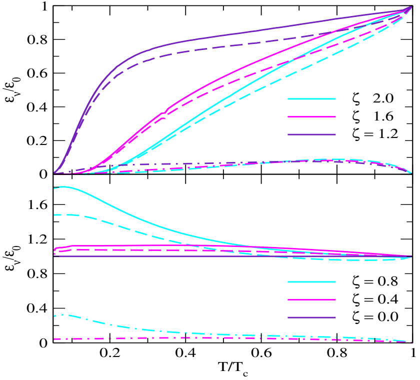
via the response function

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

with propagators

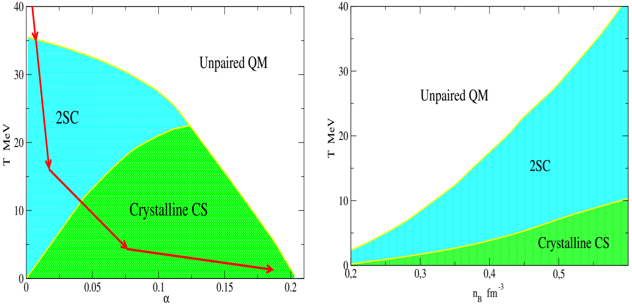
$$S_{f=u,d} = i\delta_{ab} \frac{\Lambda^+(p)}{p_0^2 - \epsilon_p^2}(\not{p} - \mu_f \gamma_0), \quad F(p) = -i\epsilon_{ab3}\epsilon_{fg}\Delta \frac{\Lambda^+(p)}{p_0^2 - \epsilon_p^2}\gamma_5 C$$

CSC phases show non-trivial dependence on gap



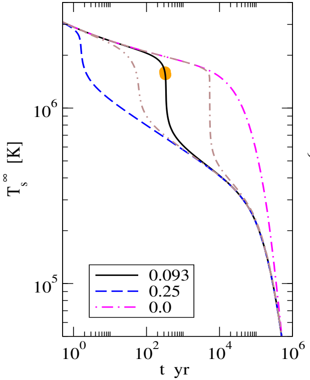
- Two-flavor phase (2SC) - No gapless excitations - suppressed emissivities
- Crystalline (LOFF) phase - Gapless excitations - unsuppressed emissivities

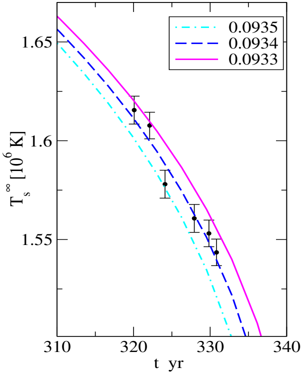
Phase diagram



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

CAS A: a cooling quark star?





- 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.

Conclusions

- Massive compact stars can still feature exotic matter

- Cooling simulations (Cas A case) remain a sensitive probe of the physics of neutron star interiors (more information on mass etc needed)