CONSTRAINTS FOR PROPARTIES OF NUCEAR MATTER FROM NEUTRON STAR COOLING

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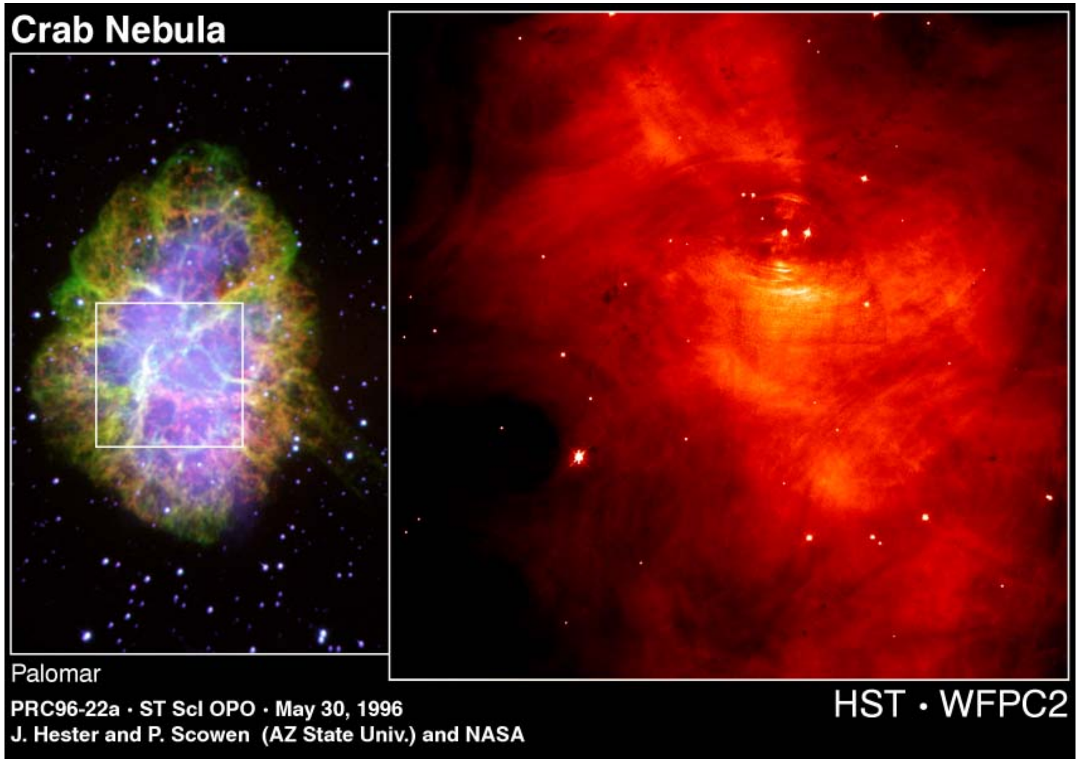
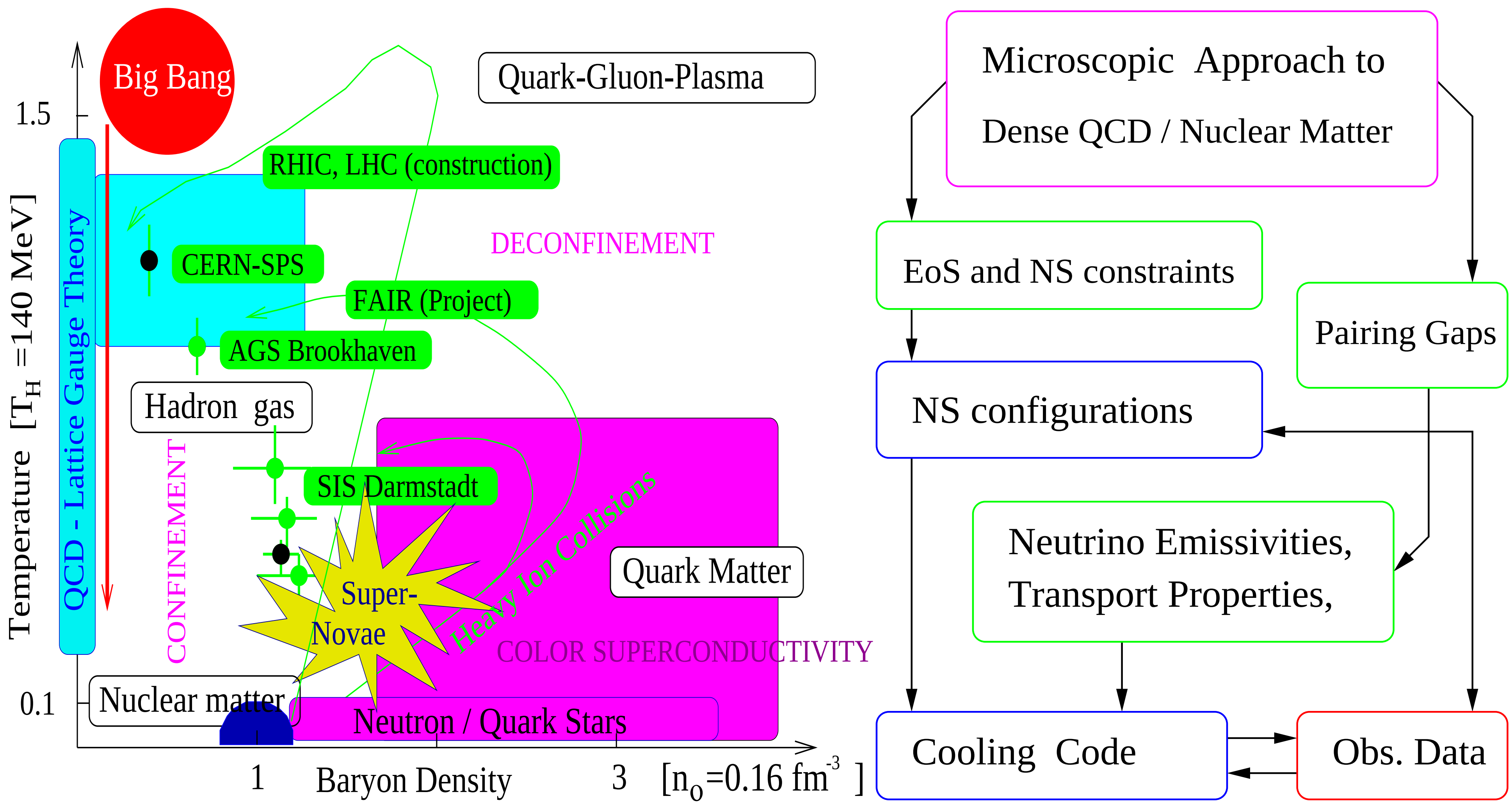
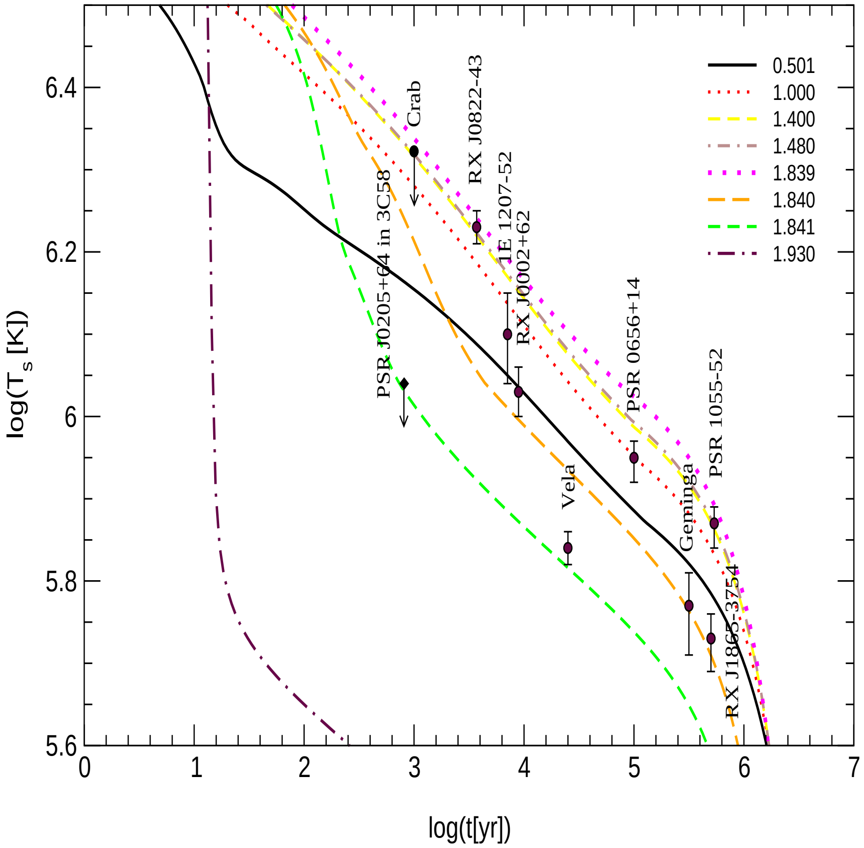
- General schem for cooling simulations
- Compact object
- Temperature-Age diagram
- Observational Constraints



QCD Phase Diagram & Compact Stars



Cooling of a Neutron Star



Evolution of the surface temperature T_s of a hadronic star

$$\frac{dU}{dt} = \sum_i C_i \frac{dT}{dt} = -\varepsilon_\gamma - \sum_j \varepsilon_\nu^j$$

Data taken from:
Yakovlev et al.,
A & A **389** (2002) L24;

Calculation:
D. Blaschke, H. Grigorian and D. N. Voskresensky, Astron. Astrophys. **424** (2004) 979.

BOLTZMANN EQUATION IN CURVED SPACE - TIME

The Boltzmann equation for massless particles
Lindquist, R.W. 1966, Ann. Phys., 37, 478

$$p^\beta\left(\frac{\partial f}{\partial x^\beta} - \Gamma^\alpha_{\beta\gamma} p^\gamma \frac{\partial f}{\partial p^\alpha}\right) = \left(\frac{df}{d\tau}\right)_{coll} \tag{1}$$

- f is the invariant neutrino distribution function
- p^α is the neutrino 4-momentum
- $\Gamma^\alpha_{\beta\gamma}$ are the Christoffel symbols for the metric

$$ds^2 = -e^{2\phi}dt^2 + e^{2\Lambda}dr^2 + r^2 d\theta^2 + r^2\sin^2\theta\, d\Phi^2 \tag{2}$$

The BE in the comoving basis

$$p^b\left(e_b^\beta \frac{\partial f}{\partial x^\beta} - \Gamma^a_{bc} p^c \frac{\partial f}{\partial p^a}\right) = \left(\frac{df}{d\tau}\right)_{coll} \tag{3}$$

The non-zero Ricci coefficients are

$$\Gamma^1_{00} = \Gamma^0_{01} = e^{-\phi}e^{-\Lambda}\left(\frac{\partial(\gamma e^\phi)}{\partial r} + \frac{\partial(\gamma v e^\Lambda)}{\partial t}\right), \quad \Gamma^0_{11} = \Gamma^1_{10} = e^{-\phi}e^{-\Lambda}\left(\frac{\partial(\gamma e^\Lambda)}{\partial t} + \frac{\partial(\gamma v e^\phi)}{\partial r}\right),$$

$$\Gamma^2_{20} = \Gamma^0_{22} = \Gamma^3_{30} = \Gamma^0_{33} = -v\Gamma^1_{22} = v\Gamma^2_{21} = -v\Gamma^1_{33} = v\Gamma^3_{31} = \frac{\gamma v e^{-\Lambda}}{r}, \Gamma^2_{33} = -\Gamma^3_{32} = -\frac{\cot\theta}{r}. \tag{4}$$

Heat transport and Neutrino diffusion

The neutrino 4-momentum is

$$p^a = \left(\omega, \omega\mu, \omega(1-\mu^2)^{1/2}\cos\Phi, \omega(1-\mu^2)^{1/2}\sin\Phi\right)$$

- μ is the cosine of the angle between the neutrino momentum and the radial direction
- ω is the neutrino energy in a comoving frame

The BE in the spherically symmetric case

$$\begin{aligned}\omega(e_0^t + \mu e_1^t)\frac{\partial f}{\partial t} \; &+ \; \omega(e_0^r + \mu e_1^r)\frac{\partial f}{\partial r} - \omega^2\left(\mu\Gamma^1_{00} + \mu^2\Gamma^1_{10} + (1-\mu^2)\Gamma^2_{20}\right)\frac{\partial f}{\partial \omega} \\ &- \; \omega(1-\mu^2)\left(\Gamma^1_{00} + \Gamma^1_{22} + \mu\Gamma^1_{10} - \mu\Gamma^2_{20}\right)\frac{\partial f}{\partial \mu} = \left(\frac{df}{d\tau}\right)_{coll} . \end{aligned} \quad (5)$$

Applying the operator to equation (5) and defining the i^{th} moment
Thorne, K. S. 1981, MNRAS 194, 439

$$\frac{1}{2}\int_{-1}^{+1} d\mu\,\mu^i, \quad i = 0,1,2,\cdots, \quad M_i = \frac{1}{2}\int_{-1}^{+1} d\mu\,\mu^i f, \quad Q_i = \frac{1}{2}\int_{-1}^{+1} d\mu\,\mu^i \left(\frac{df}{d\tau}\right)_{coll} .$$

Heat transport and Neutrino diffusion

Let us introduce N_ν, F_ν, and S_N are the number density, number flux and number source term, respectively, while J_ν, H_ν, P_ν, and S_E are the neutrino energy density, energy flux, pressure, and the energy source term:

$$N_\nu = \int_0^\infty \frac{d\omega}{2\pi^2} M_0 \omega^2 \,, \quad F_\nu = \int_0^\infty \frac{d\omega}{2\pi^2} M_1 \omega^2 \,, \quad S_N = \int_0^\infty \frac{d\omega}{2\pi^2} Q_0 \omega \tag{6}$$

$$J_\nu = \int_0^\infty \frac{d\omega}{2\pi^2} M_0 \omega^3 \,, \quad H_\nu = \int_0^\infty \frac{d\omega}{2\pi^2} M_1 \omega^3 \,, \quad P_\nu = \int_0^\infty \frac{d\omega}{2\pi^2} M_2 \omega^3 \,, \quad S_E = \int_0^\infty \frac{d\omega}{2\pi^2} Q_0 \omega^2 \,. \tag{7}$$

- integrating over the neutrino energy
- utilizing the continuity equation
- assumption of a quasi-static evolution

The neutrino transport equation Burrows, A., & Lattimer, J. M. 1986, ApJ, 307, 178

$$\frac{\partial(N_\nu/n_B)}{\partial t} + \frac{\partial(e^\phi 4\pi r^2 F_\nu)}{\partial a} = e^\phi \frac{S_N}{n_B}$$

$$\frac{\partial(J_\nu/n_B)}{\partial t} + P_\nu \frac{\partial(1/n_B)}{\partial t} + e^{-\phi} \frac{\partial(e^{2\phi} 4\pi r^2 H_\nu)}{\partial a} = e^\phi \frac{S_E}{n_B}$$

Heat transport and Neutrino diffusion

The distribution function in the diffusion approximation:

$$f(\omega,\mu) = f_0(\omega) + \mu f_1(\omega)\,, \quad f_0 = [1 + e^{\left(\frac{\omega-\mu_\nu}{kT}\right)}]^{-1} \tag{8}$$

- f_0 is the distribution function at equilibrium ($T = T_{mat}$, $\mu_\nu = \mu_\nu^{eq}$)
- ω and μ_ν are the neutrino energy and chemical potential

The moments M_i of f are

$$M_0 = f_0\,,\ M_1 = \frac{1}{3} f_1\,,\ M_2 = \frac{1}{3} f_0\,, \quad \text{and} \quad M_3 = \frac{1}{5} f_1\,. \tag{9}$$

The equation (**??**) is now

$$e^{-\Lambda}\left(\frac{\partial f_0}{\partial r} - \omega \frac{\partial \phi}{\partial r}\frac{\partial f_0}{\partial \omega}\right) = 3\frac{Q_1}{\omega}\,. \tag{10}$$

The collision term Q_1 can be represented as

$$\left(\frac{df}{d\tau}\right)_{coll} = \omega\left(j_a(1-f) - \frac{f}{\lambda_a} + j_s(1-f) - \frac{f}{\lambda_s}\right) \tag{11}$$

- j_a is the emissivity
- λ_a is the absorptivity
- j_s and λ_s are the scattering contributions

Heat transport and Neutrino diffusion

The explicit form of the diffusion coefficient D

$$D(\omega) = \left(j + \frac{1}{\lambda_a} + \kappa_1^s \right)^{-1} . \tag{12}$$

Using the relation ($\eta_\nu = \mu_\nu / T$ is the neutrino degeneracy parameter)

$$\frac{\partial f_0}{\partial r} = - \left(T \frac{\partial \eta_\nu}{\partial r} + \frac{\omega}{T} \frac{\partial T}{\partial r} \right) \frac{\partial f_0}{\partial \omega} , \tag{13}$$

we obtain

$$f_1 = -D(\omega) e^{-\Lambda} \left[T \frac{\partial \eta}{\partial r} + \frac{\omega}{T e^{\phi}} \frac{\partial (T e^{\phi})}{\partial r} \right] \left(- \frac{\partial f_0}{\partial \omega} \right) . \tag{14}$$

Now the energy-integrated lepton and energy fluxes are

$$\begin{aligned} F_\nu &= - \frac{e^{-\Lambda} e^{-\phi} T^2}{6\pi^2} \left[D_3 \frac{\partial (T e^{\phi})}{\partial r} + (T e^{\phi}) D_2 \frac{\partial \eta}{\partial r} \right] \\ H_\nu &= - \frac{e^{-\Lambda} e^{-\phi} T^3}{6\pi^2} \left[D_4 \frac{\partial (T e^{\phi})}{\partial r} + (T e^{\phi}) D_3 \frac{\partial \eta}{\partial r} \right] . \end{aligned} \tag{15}$$

Heat transport and Neutrino diffusion

The coefficients D_2, D_3, and D_4 are defined through ($x = \omega/T$)

$$D_n = \int_0^\infty dx\, x^n D(\omega) f_0(\omega)(1 - f_0(\omega)) \,,$$

The explicit expression for the absorption mean free path

$$\frac{1}{\lambda_a} = \frac{G_F^2}{\pi^2} \int_0^\infty dE_e\, E_e^2\, [1 - f_{eq}(E_e)] \int_{-1}^{+1} d\cos\theta\, \frac{(\cos\theta - 1)}{1 - e^{-z}} [AR_1 + R_2 + BR_3] \tag{16}$$

$$R_s^{out} = 4G_F^2 \frac{(\cos\theta - 1)}{1 - e^{-z}} [AR_1 + R_2 + BR_3] \tag{17}$$

The polarization functions

$$R_1 = (\mathcal{V}^2 + \mathcal{A}^2)\, [\mathrm{Im}\, \Pi_L^R(q_0, q) + \mathrm{Im}\, \Pi_T^R(q_0, q)] \tag{18}$$

$$R_2 = (\mathcal{V}^2 + \mathcal{A}^2)\, \mathrm{Im}\, \Pi_T^R(q_0, q) - \mathcal{A}^2\, \mathrm{Im}\, \Pi_A^R(q_0, q) \quad R_3 = 2\mathcal{V}\mathcal{A}\, \mathrm{Im}\, \Pi_{VA}^R(q_0, q)\,. \tag{19}$$

- $\mathcal{V} = Cg_V$ and $\mathcal{A} = Cg_A$ for the absorption, C is the Cabibbo factor
- $\mathcal{V} = g_V/2$ and $\mathcal{A} = g_A/2$ for the scattering

To include all six neutrino types, one can redefine the diffusion coefficients

$$D_2 = D_2^{\nu_e} + D_2^{\bar\nu_e}\,, \quad D_3 = D_3^{\nu_e} - D_3^{\bar\nu_e}\,, \quad D_3 = D_4^{\nu_e} + D_4^{\bar\nu_e} + 4D_4^{\nu_\mu}\,. \tag{20}$$

Using the equation for the electron fraction and the matter energy equation

$$\frac{\partial Y_e}{\partial t} = -e^{\phi}\frac{S_N}{n_B}, \qquad Y_L = \frac{N_\nu}{n_B} + Y_e \tag{21}$$

$$\frac{\mathrm{d}(E/N_B)}{\mathrm{d}t} + P\frac{\mathrm{d}(V/N_B)}{\mathrm{d}t} = -e^{\phi}\frac{S_N}{n_B} \tag{22}$$

$$Te^{\phi}\frac{\partial \mathbf{s}}{\partial t} + \mu_\nu e^{\phi}\frac{\partial \mathbf{Y_L}}{\partial t} + \frac{\partial(e^{2\phi}4\pi r^2 \mathbf{H}_\nu)}{\partial a} = 0 \tag{23}$$

we obtain

$$\frac{\partial N_\nu/n_B}{\partial t} + \frac{\partial Y_e}{\partial t} + \frac{\partial(e^{\phi}4\pi r^2 F_\nu)}{\partial a} = 0 \tag{24}$$

$$\frac{\partial \mathbf{Y_L}}{\partial t} + \frac{\partial(e^{\phi}4\pi r^2 \mathbf{F}_\nu)}{\partial a} = 0 \tag{25}$$

(26)

$$F_\nu = -\frac{e^{-\Lambda}e^{-\phi}T^2}{6\pi^2}\left[\mathbf{D_3}\frac{\partial(Te^{\phi})}{\partial r} + (Te^{\phi})\mathbf{D_2}\frac{\partial\eta}{\partial r}\right]$$

$$H_\nu = -\frac{e^{-\Lambda}e^{-\phi}T^3}{6\pi^2}\left[\mathbf{D_4}\frac{\partial(Te^{\phi})}{\partial r} + (Te^{\phi})\mathbf{D_3}\frac{\partial\eta}{\partial r}\right]. \tag{27}$$

Quasi-equilibrate Evolution of Compact Object

The structure equations are

$$\frac{\partial r}{\partial a} = \frac{1}{4\pi r^2 n_B e^{\Lambda}}, \qquad \frac{\partial m}{\partial a} = \frac{\rho}{n_B e^{\Lambda}} \tag{28}$$

$$\frac{\partial \phi}{\partial a} = \frac{e^{\Lambda}}{4\pi r^4 n_B}\left(m + 4\pi r^3 P\right), \tag{29}$$

$$\frac{\partial P}{\partial a} = -(\rho + P)\frac{e^{\Lambda}}{4\pi r^4 n_B}\left(m + 4\pi r^3 P\right) \tag{30}$$

with the boundary conditions

$$\begin{aligned} r(a=0) &= 0; \qquad m(a=0) = 0, \\ \phi(a=a_s) &= \frac{1}{2}\log\left[1 - \frac{2m(a=a_s)}{r(a=a_s)}\right]; \qquad P(a=a_s) = P_s \end{aligned} \tag{31}$$

COOLING EVOLUTION WITHOUT NEUTRINO TRAPPING

- The flux energy per unit time $l(r)$ through a spherical slice at distance r from the center is:

$$\mathbf{l}(r) = -4\pi r^2 \mathbf{k}(r) \frac{\partial(\mathbf{T}(r)e^{\Phi})}{\partial r} e^{-\Phi} \sqrt{1 - \frac{2M}{r}}.$$

The factor $e^{-\Phi}\sqrt{1 - \frac{2M}{r}}$ corresponds to the relativistic correction of the time scale and the unit of thickness.

- The equations for energy balance and thermal energy transport are:

$$\frac{\partial}{\partial N_B}(\mathbf{l}e^{2\Phi}) = -\frac{1}{n}(\epsilon_\nu e^{2\Phi} + \mathbf{c_V}\frac{\partial}{\partial t}(\mathbf{T}e^{\Phi}))$$

$$\frac{\partial}{\partial N_B}(\mathbf{T}e^{\Phi}) = -\frac{1}{\mathbf{k}}\frac{\mathbf{l}e^{\Phi}}{16\pi^2 r^4 n}$$

where $n = n(r)$ is the baryon number density, $N_B = N_B(r)$ is the total baryon number in the sphere with radius r and

$$\frac{\partial N_B}{\partial r} = 4\pi r^2 n \left(1 - \frac{2M}{r}\right)^{-1/2}$$

D. Blaschke, H. Grigorian and D. N. Voskresensky, Astronomy and Astrophysics **368**, 561 (2001).

Stellar matter under Compact star conditions

The stellar matter including the quark core of compact stars consists of neutrons protons, up, down quarks, electrons and neutrinos in beta equilibrium and with the charge neutrality condition.

- β-equilibrium $n \longleftrightarrow p + e^- + \bar{\nu}_e$;–in nuclear matter

  $d \longleftrightarrow u + e^- + \bar{\nu}_e$–in quark matter

$$\mu_n = \mu_p + \mu_e + \mu_{\nu_e}$$

$$\mu_d = \mu_u + \mu_e + \mu_{\nu_e}$$

where μ_e, μ_{ν_e} are the electrons and the neutrino chemical potentials.

- Charge neutrality $n_p - n_e = 0$: –in nuclear matter

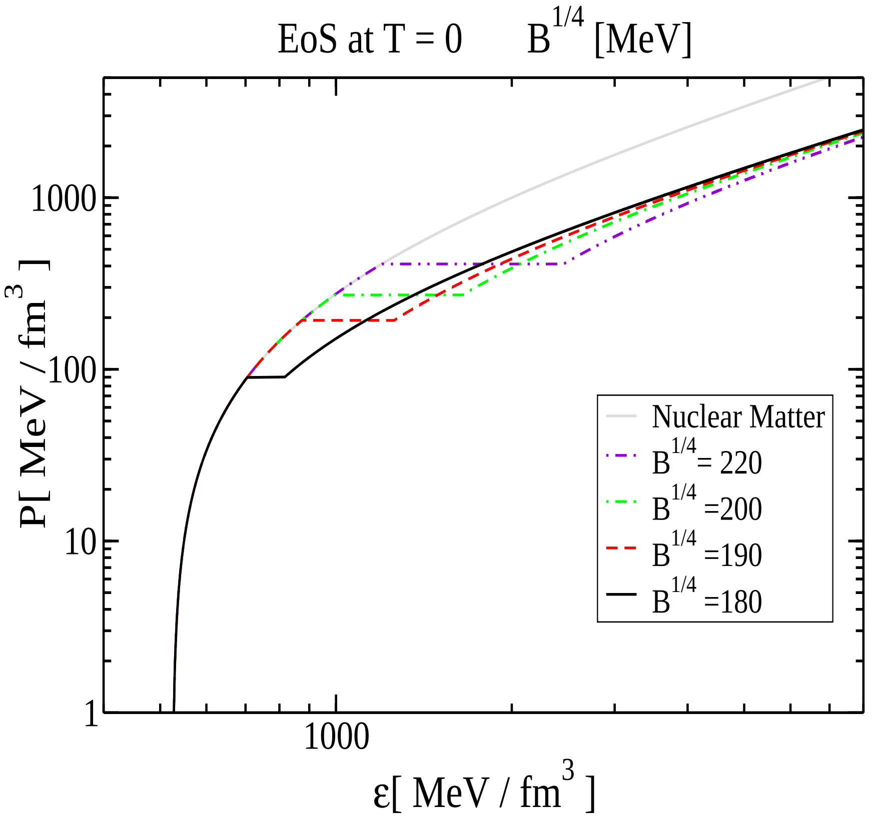
  $\frac{2}{3}n_u - \frac{1}{3}n_d - n_e = 0$ –in quark matter

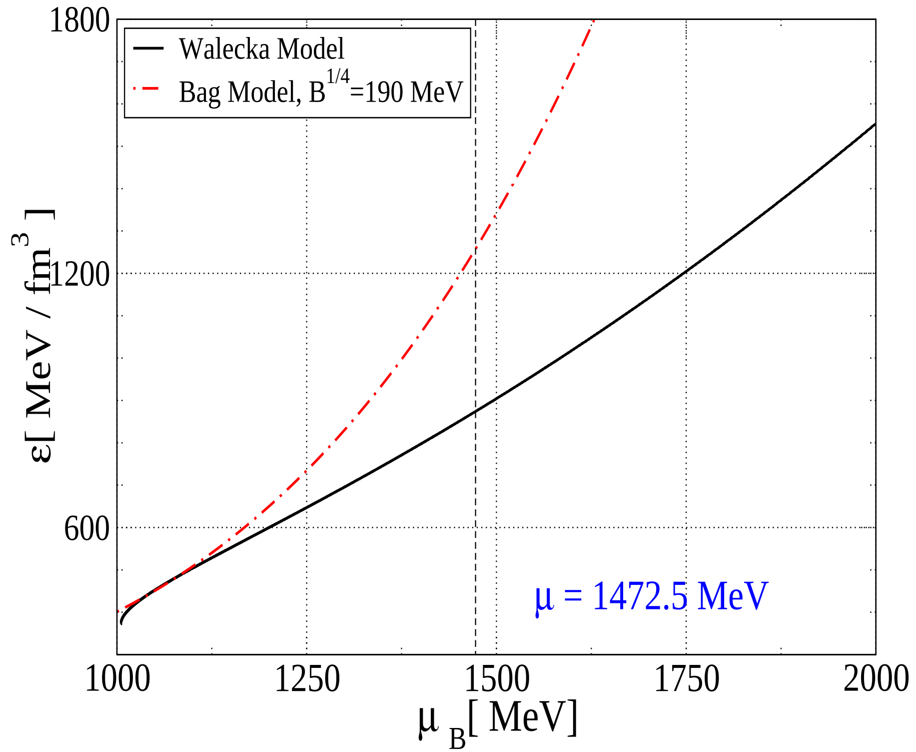
The contribution from the leptons should be added to the thermodynamical potential Ω_q:

$$\Omega(\phi, \Delta; \mu_q, \mu_I, \mu_e, T) = \Omega_q(\phi, \Delta; \mu_q, \mu_I, T) + \Omega_e(\mu_e, T) + \Omega_{\nu_e}(\mu_{\nu_e}, T)$$

Phase transition: Nuclear matter ⟶ Quark matter

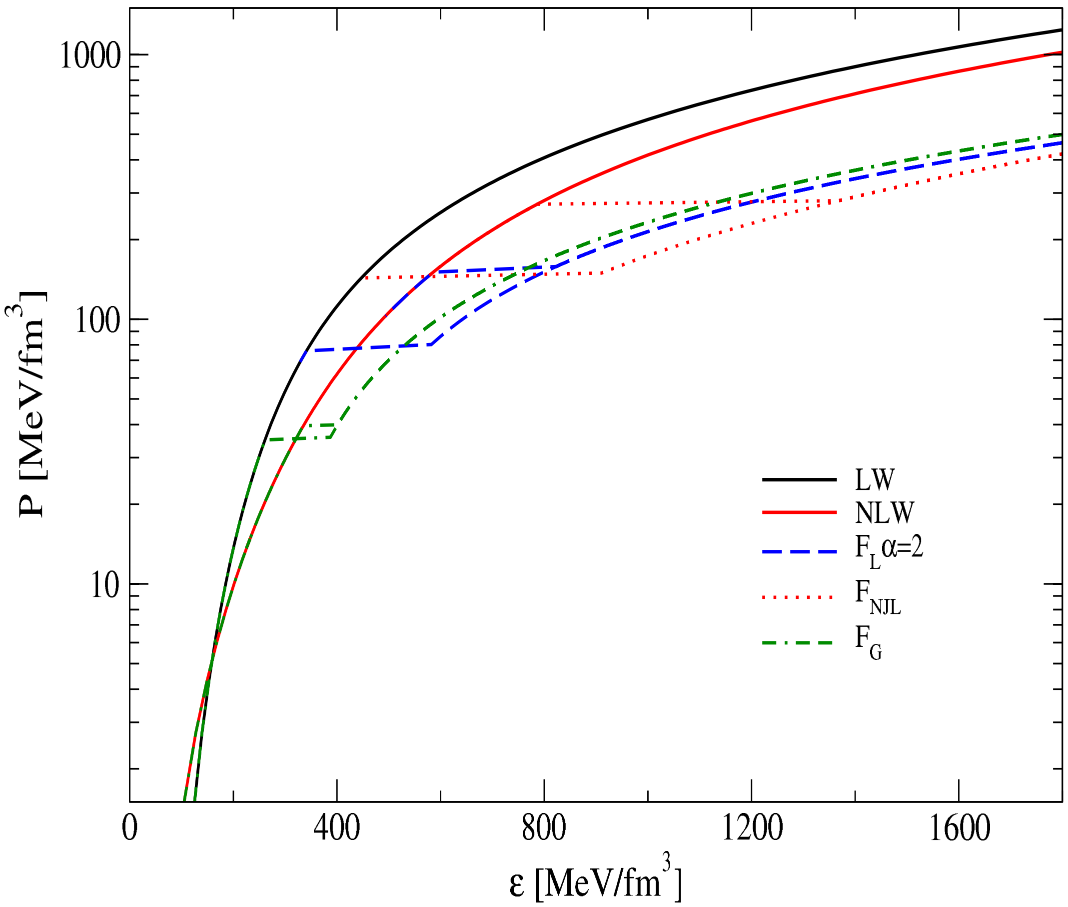
- Walecka model (p,n,e)+(σ,ω) $\longrightarrow$ Bag model (u,d,e)
- Maxwell construction: $P^{Had} = P^{Quark} \quad \mu_B^{Had} = \mu_B^{Quark}$





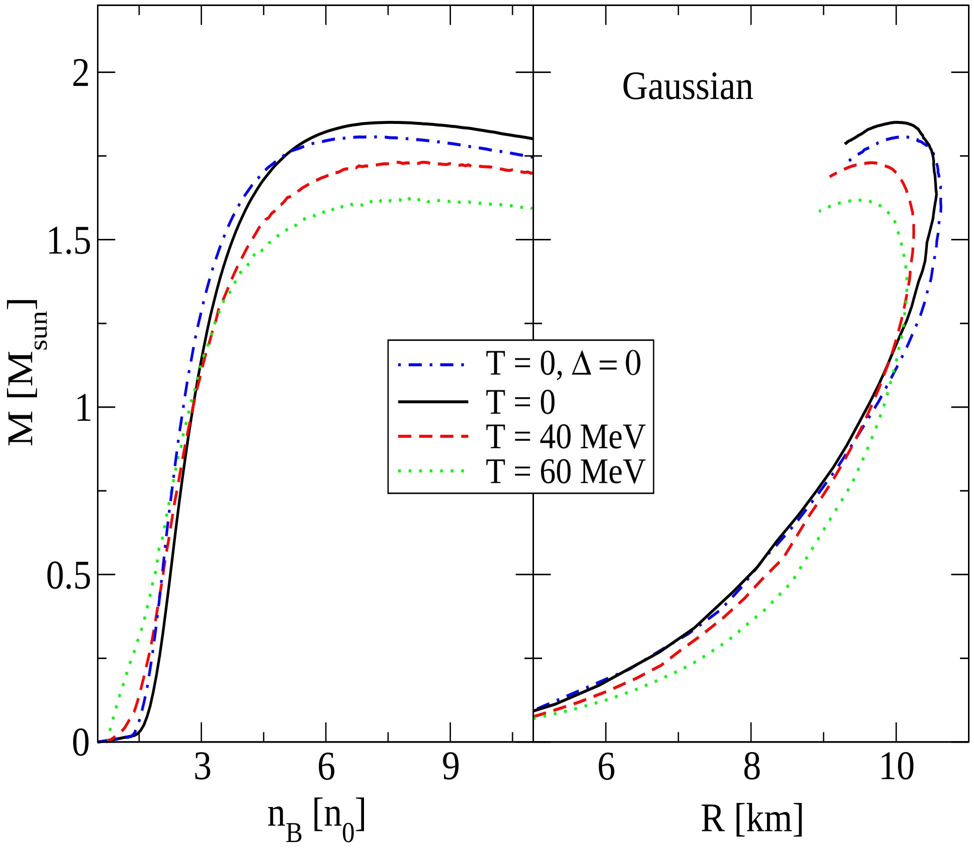
EoS for Quark Star with Shell

Phase Transitions



- In order to consider then quark stars with a possible hadronic shell we made the phase transition between the quark matter EoS and a hadron EoS: linear (LW) and nonlinear Walecka model (NLW).
- The phase transition is calculated via the Maxwell construction (P constant for equal μ_q)

Configuration of Compact Stars without Shell
Condensate and Temperature effect



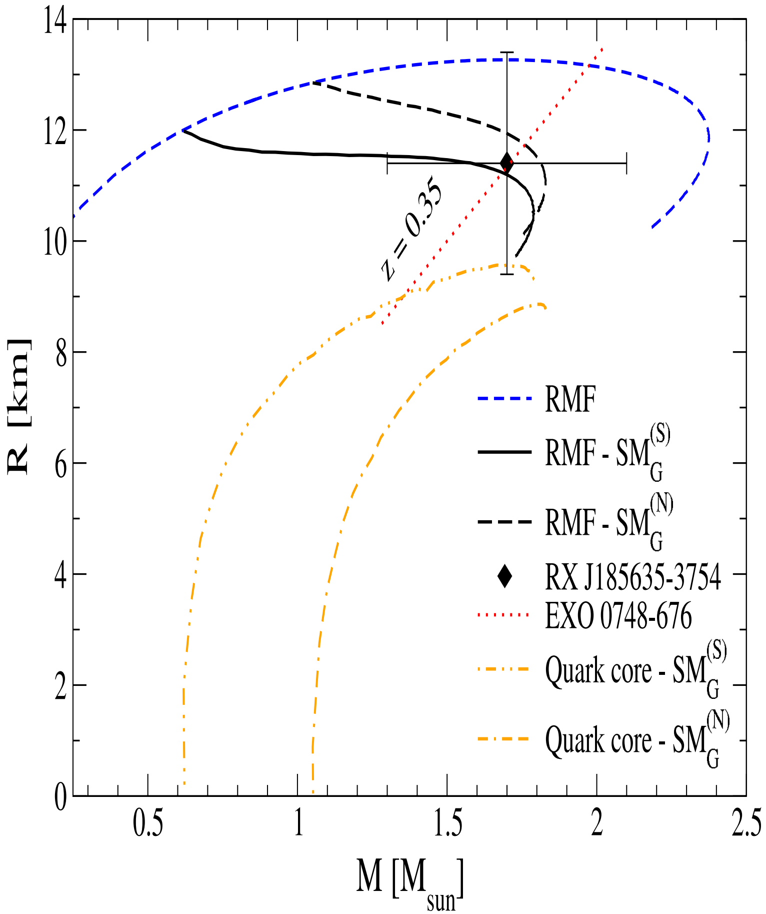
The star configuration could be defined from the **Tolman-Oppenheimer-Volkoff equations**

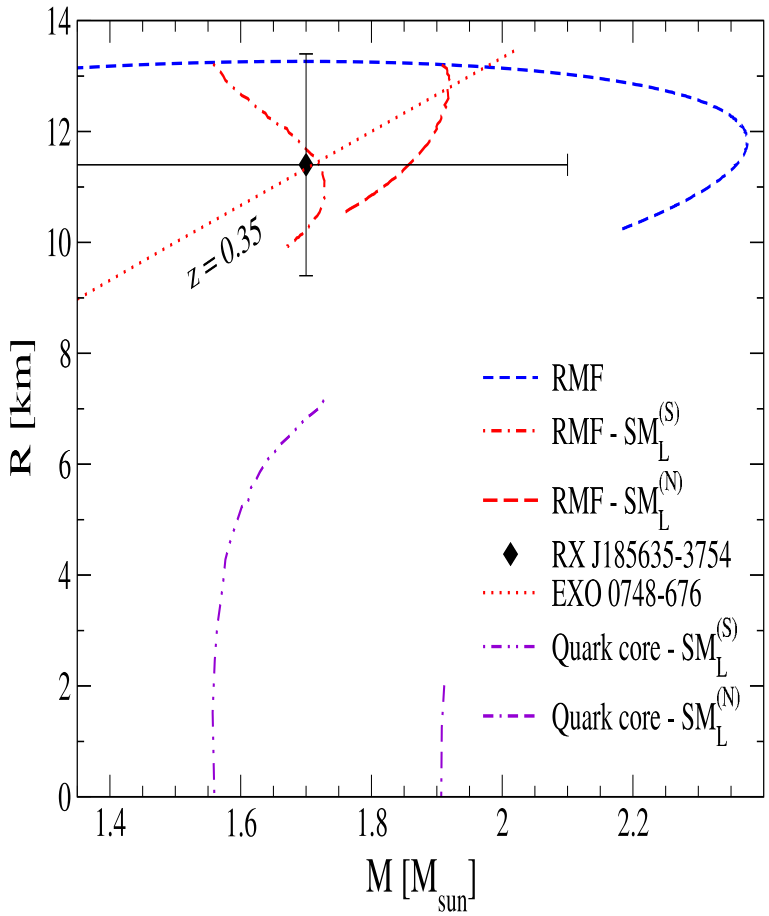
$$\frac{dP}{dr} = -\frac{[\epsilon(r) + P(r)][m(r) + 4\pi r^3 P(r)]}{r[r - 2m(r)]}$$

$$m = 4\pi \int_0^r r^2 \epsilon(r) dr$$

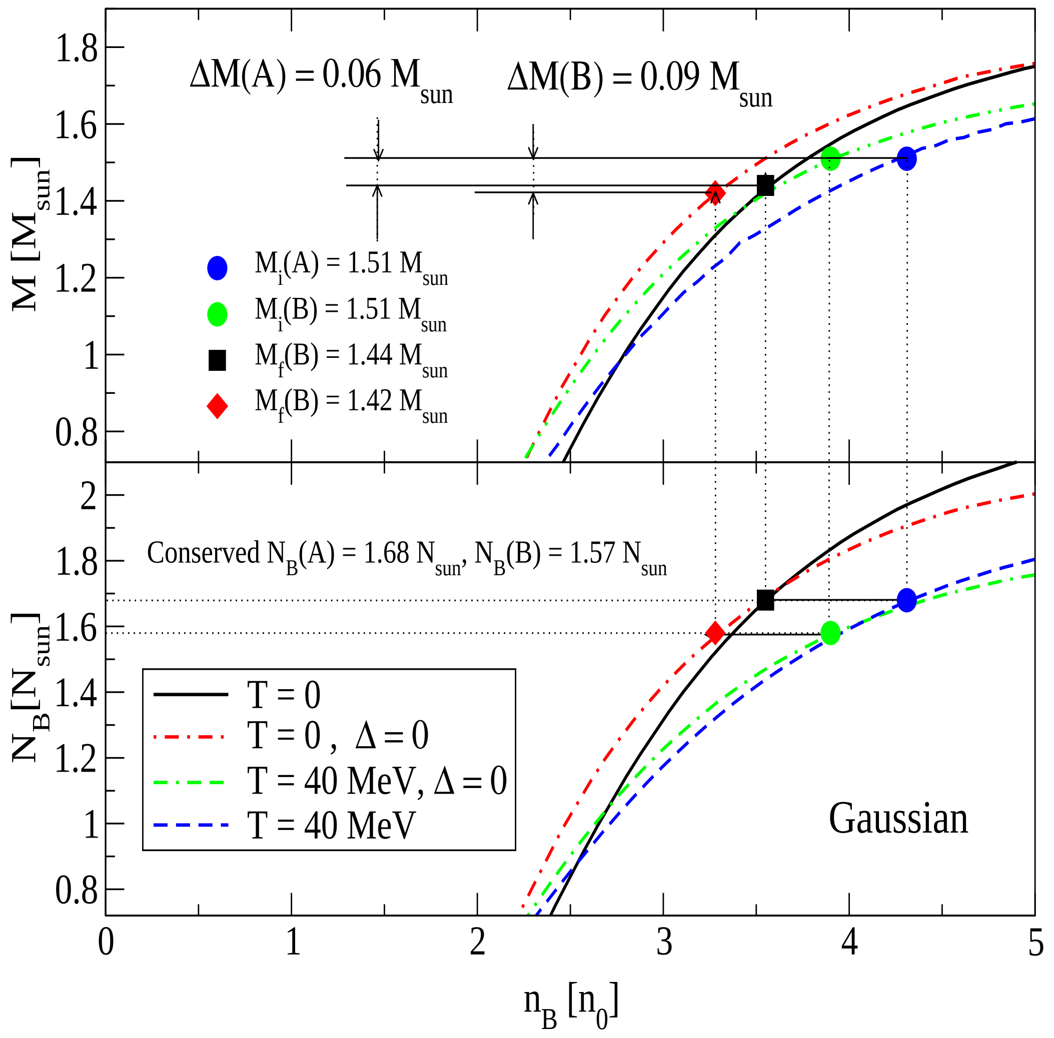
The equations are solved for the set of central densities $n_q(0)$ for which the stars are stable. The total mass $M = m(r)$ of the star is defined on the radius r so that $P(r) = 0$.
The integral parameters M and R feel the existence of the diquark condensation: the EoS becames softer. Also are sensitive on temperature variations. Both are decresing the values of the M_{max} and R_{max} of the core approximately 10% from their values of the $T = 0$ and $\Delta = 0$ cases.

STABILITY OF HADRONIC AND HYBRID STARS





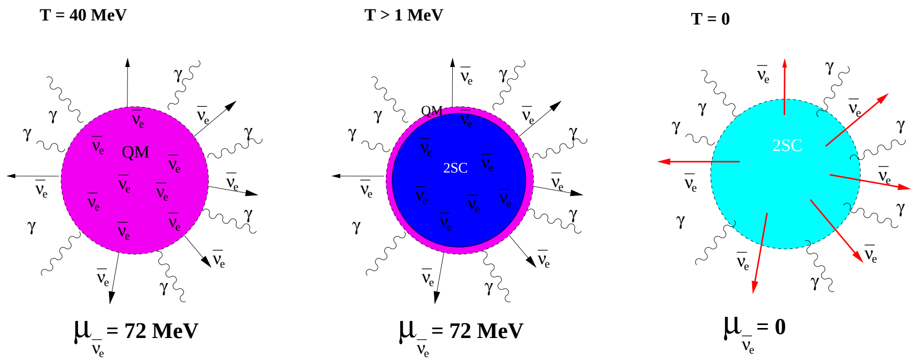
MASS DEFECT - ESTIMATION OF ENERGY

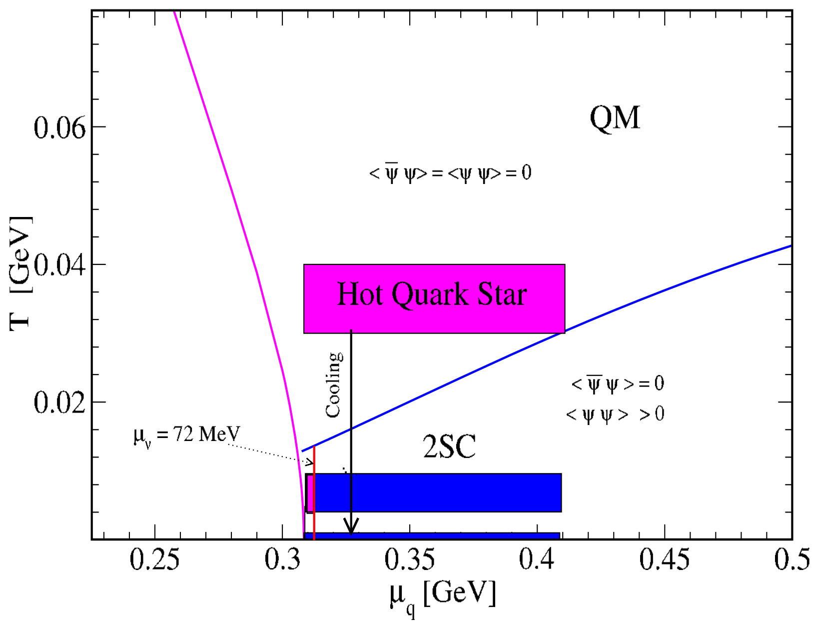


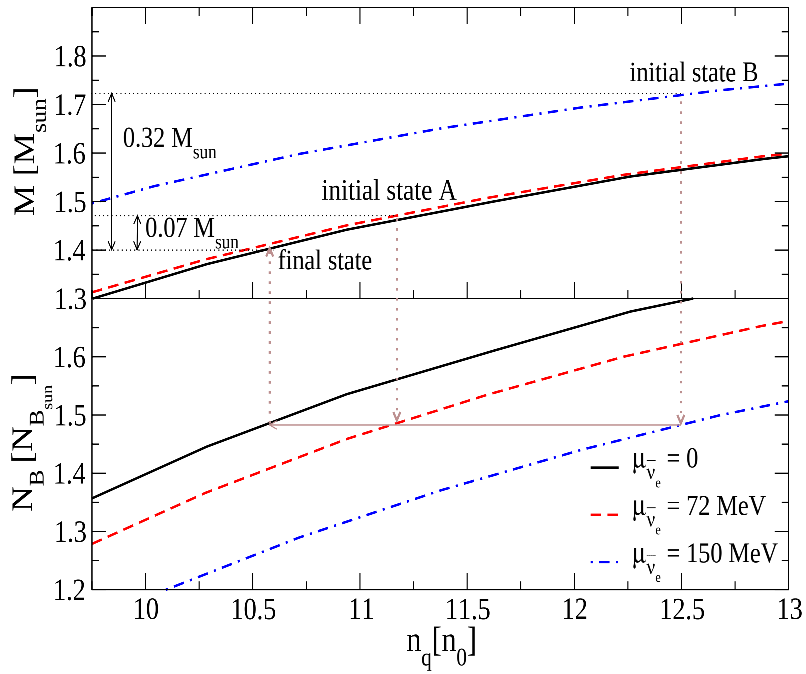
- During the cooling evolution the star must loose an amount of energy: the energy release will have an equivalent in a mass defect. We estimated this from the diquark condensation as about 0.1 M$_\odot$. It corresponds to the estimated energy $(\Delta/\mu)^2 \simeq 10^{52}$ erg of the diquark condensate, see Ref. [*].

* D. K. Hong, S. D. Hsu and F. Sannino, Phys. Lett. **B516**,362 (2001).

PNS Evolution with Neutrino Trapping





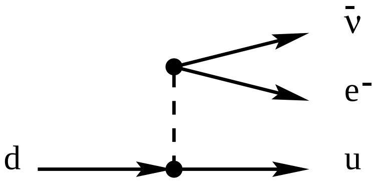


- Mass defect $\Delta M \sim 0.05 \div 0.4\ M_\odot \Rightarrow 10^{53} \div 10^{54}$ erg
- Effect due to Un-Trapping of (Anti-)Neutrinos
- Explosion possible: Phase transition 1st Order
- GRB with time delay $\Rightarrow$ Cannon Ball Model

D. N. Aguilera, D. Blaschke, H. Grigorian, arXiv:astro-ph/0212237

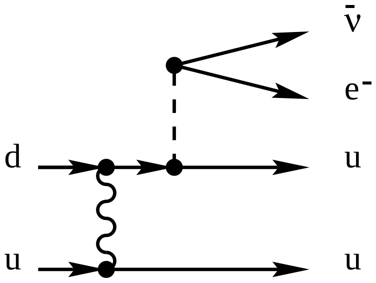
NEUTRINO PROCESSES IN QUARK MATTER: EMISSIVITIES

- Quark direct Urca (QDU) the most efficient processes
  $d \to u + e + \bar{\nu}$ and $u + e \to d + \nu$
  $\epsilon_\nu^{\rm QDU} \simeq 9.4 \times 10^{26} \alpha_s u Y_e^{1/3} \zeta_{\rm QDU}\, T_9^6$ erg cm^{-3} s^{-1},
  Compression $u = n/n_0 \simeq 2$, strong coupling $\alpha_s \approx 1$



- Quark Modified Urca (QMU) and Quark Bremsstrahlung (QB)
  $d + q \to u + q + e + \bar{\nu}$ and $q_1 + q_2 \to q_1 + q_2 + \nu + \bar{\nu}$
  $\epsilon_\nu^{\rm QMU} \sim \epsilon_\nu^{\rm QB} \simeq 9.0 \times 10^{19} \zeta_{\rm QMU}\, T_9^8$ erg cm^{-3} s^{-1}.

- Suppression due to the pairing
  QDU : $\zeta_{\rm QDU} \sim \exp(-\Delta_q/T)$
  QMU and **QB** : $\zeta_{\rm QMU} \sim \exp(-2\Delta_q/T)$ for $T < T_{{\rm crit},q} \simeq 0.4\, \Delta_q$



- $e + e \to e + e + \nu + \bar{\nu}$
  $\epsilon_\nu^{ee} = 2.8 \times 10^{12}\, Y_e^{1/3} u^{1/3} T_9^8$ erg cm^{-3} s^{-1},
  becomes important for $\Delta_q/T >> 1$

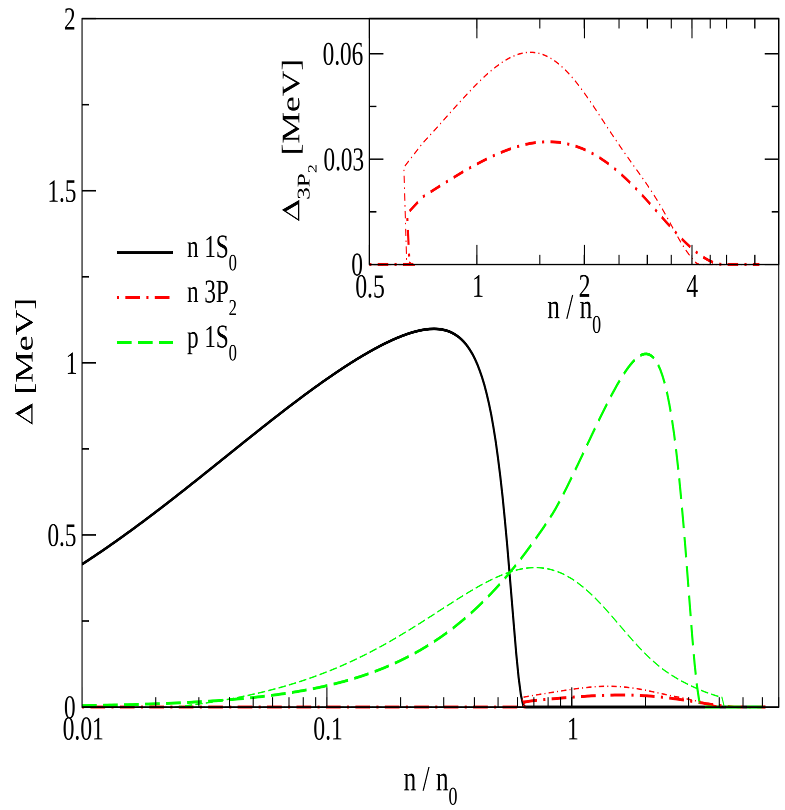
D. Blaschke, H. Grigorian, D.N. Voskresensky , Astron. & Astrophys. 368 (2001) 561

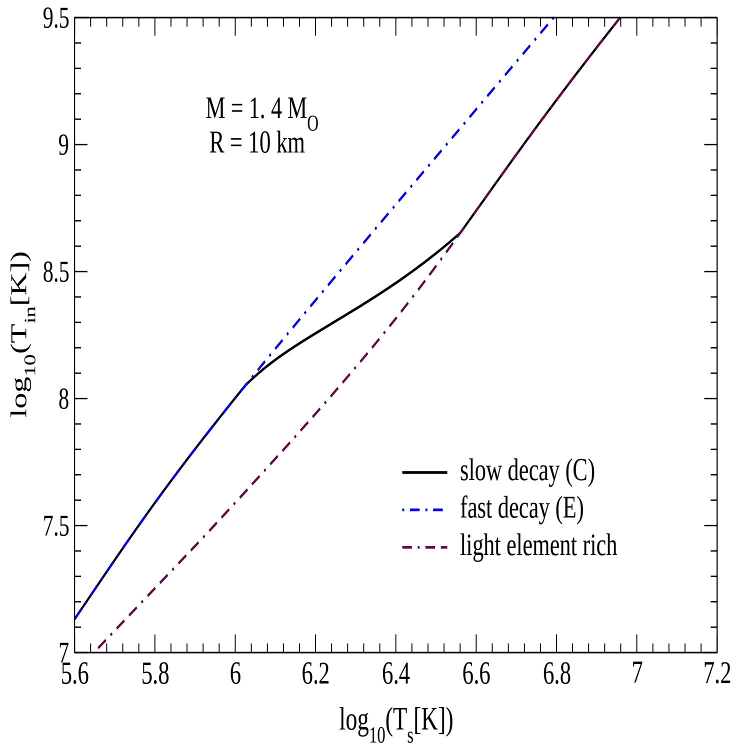
Flowers, Itoh, ApJ 250 (1981) 750; Schaab, Voskresensky, Sedrakian, Weber, Weigel, A & A 321 (1997)591

Yakovlev, Levenfish, Shibanov, Phys. Usp. 169 (1999) 825; Baiko, Haensel, Acta Phys. Polon. B 30 (1999) 1097

Hadron matter: Pairing Gaps and Crust of Stars

- Neutron and Proton pairing gaps
- Crust model



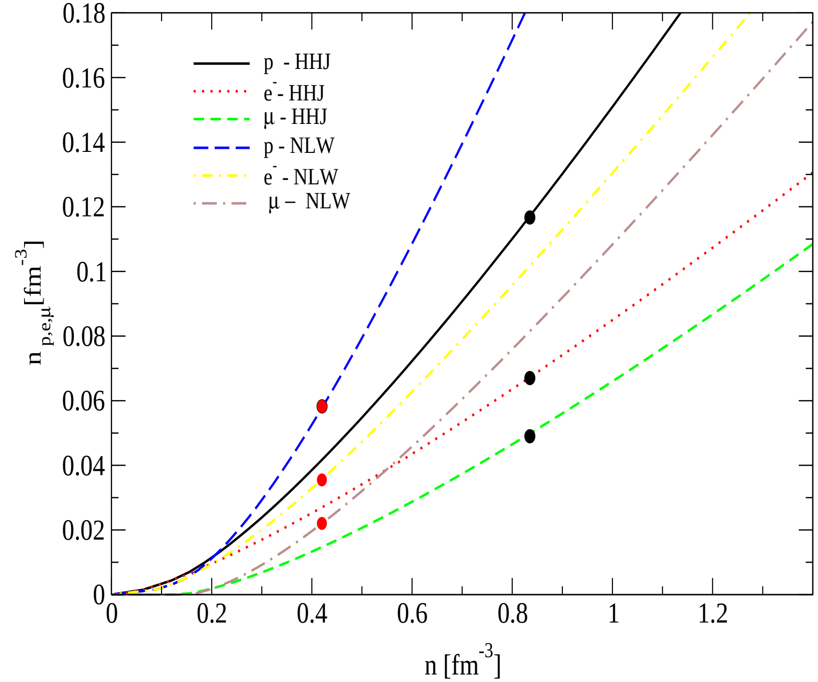


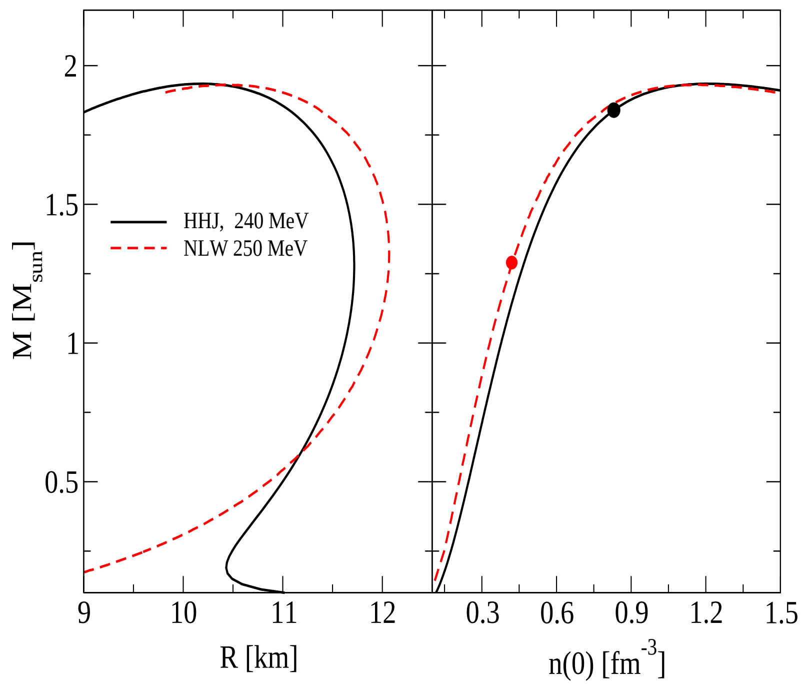
Yakovlev, D.G., Gnedin, O.Y., Kaminker, A.D., Levenfish, K.P., Potekhin, A.Y. 2003, [arXiv:astro-ph/0306143]; Yakovlev,D.G., Levenfish, K.P., Potekhin, A.Y., Gnedin, O.Y., Chabrier, G., [arXiv:astro-ph/0310259]
Takatsuka, T., Tamagaki, R. 2004, [arXiv: nucl-th/0402011].

HADRON MATTER: DU CRITICAL DENSITIES AND CRITICAL MASSES OF STARS

- DU critical densities
  $n_c = 2.7\ n_0$ non linear Walecka (NLW)
  $n_c = 5.0\ n_0$ Heiselberg, Hjorth-Jenson HHJ;

- DU critical masses
  $M_c = 1.25\ M_\odot$ - NLW
  $M_c = 1.84\ M_\odot$ - HHJ

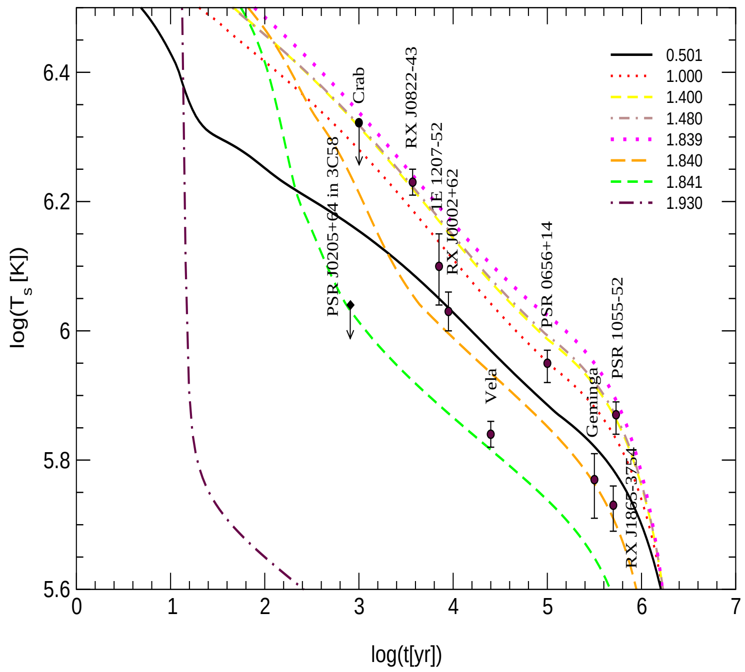




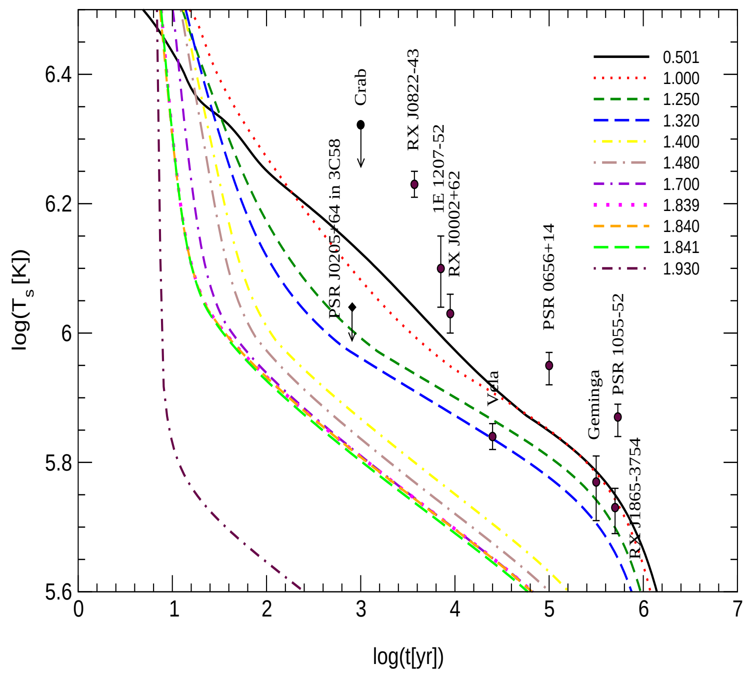
Heiselberg, H., Hjorth-Jensen, M. 1999, [arXiv:astro-ph/9904214]

COOLING CURVES: HADRONS (NORMAL) STARS

- our fit for crust



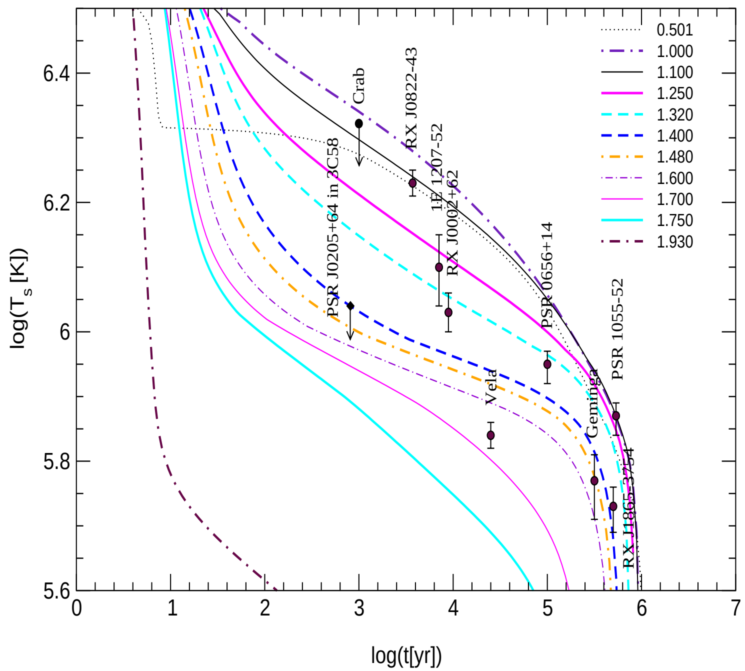
- including π -condensate and medium modification of MU



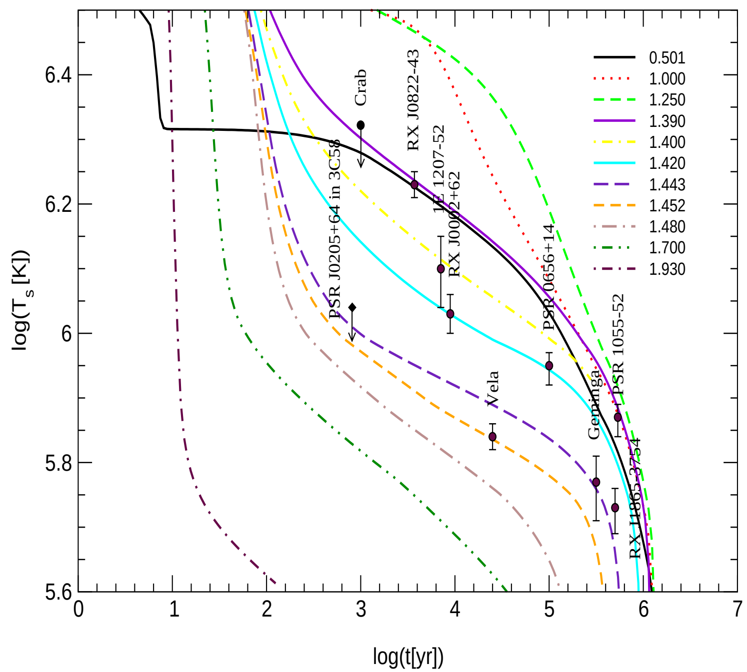
D. Blaschke, H. Grigorian, and D.N. Voskresensky, (2004). arXiv:astro-ph/0403170

Cooling curves: Hadrons (superconducting) Stars

- with AV18 gaps, π -condensate, MMU ($3P_2$ - suppressed)



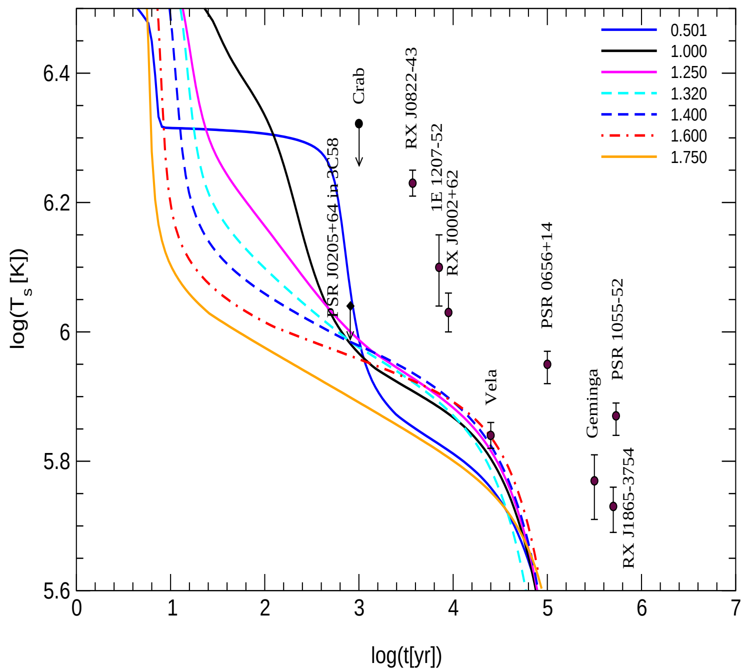
- with Gaps from Yakovlev at al. 2003

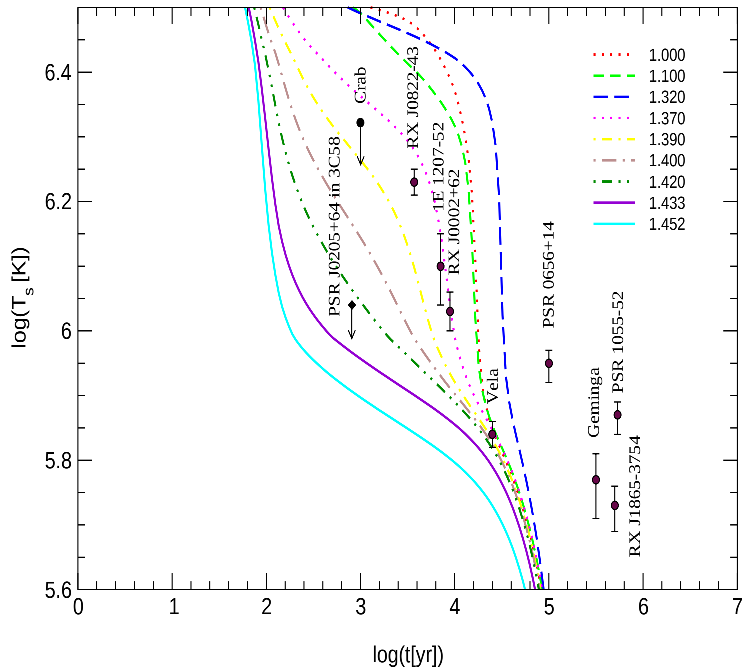


H. Grigorian, and D.N. Voskresensky, (2005). arXiv:astro-ph/0501678

COOLING CURVES: HADRONS (SUPERCONDUCTING - ANOMALIES) STARS

- with AV18 gaps, π -condensate, MMU ($3P_2$ - is **NOT** suppressed)
- with Gaps from Yakovlev at al. 2003

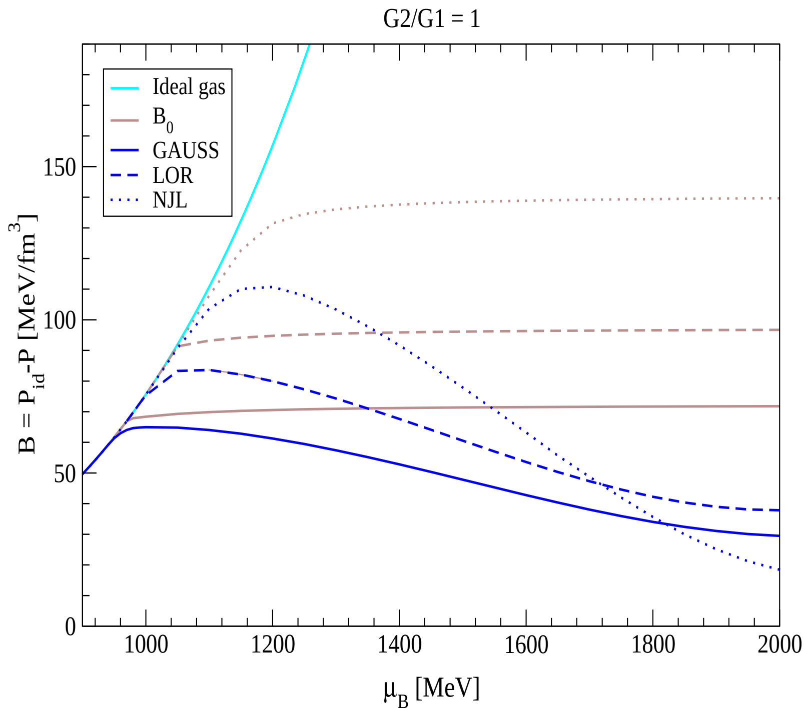




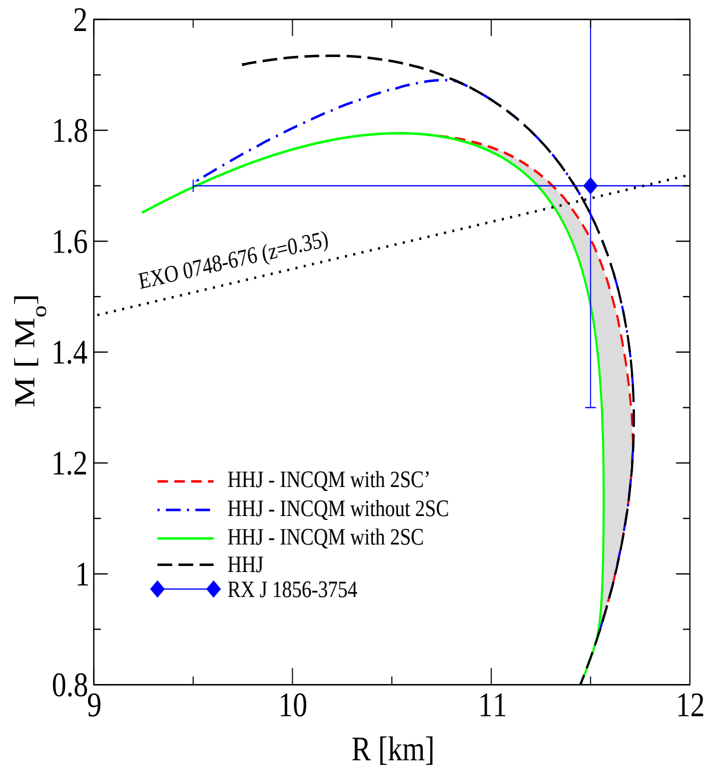
D. Blaschke, H. Grigorian, and D.N. Voskresensky, (2004). arXiv:astro-ph/0403170

Hybrid Star Model with 2SC Quark matter core

- Density dependent Bag Pressure for Separable Model (SM)

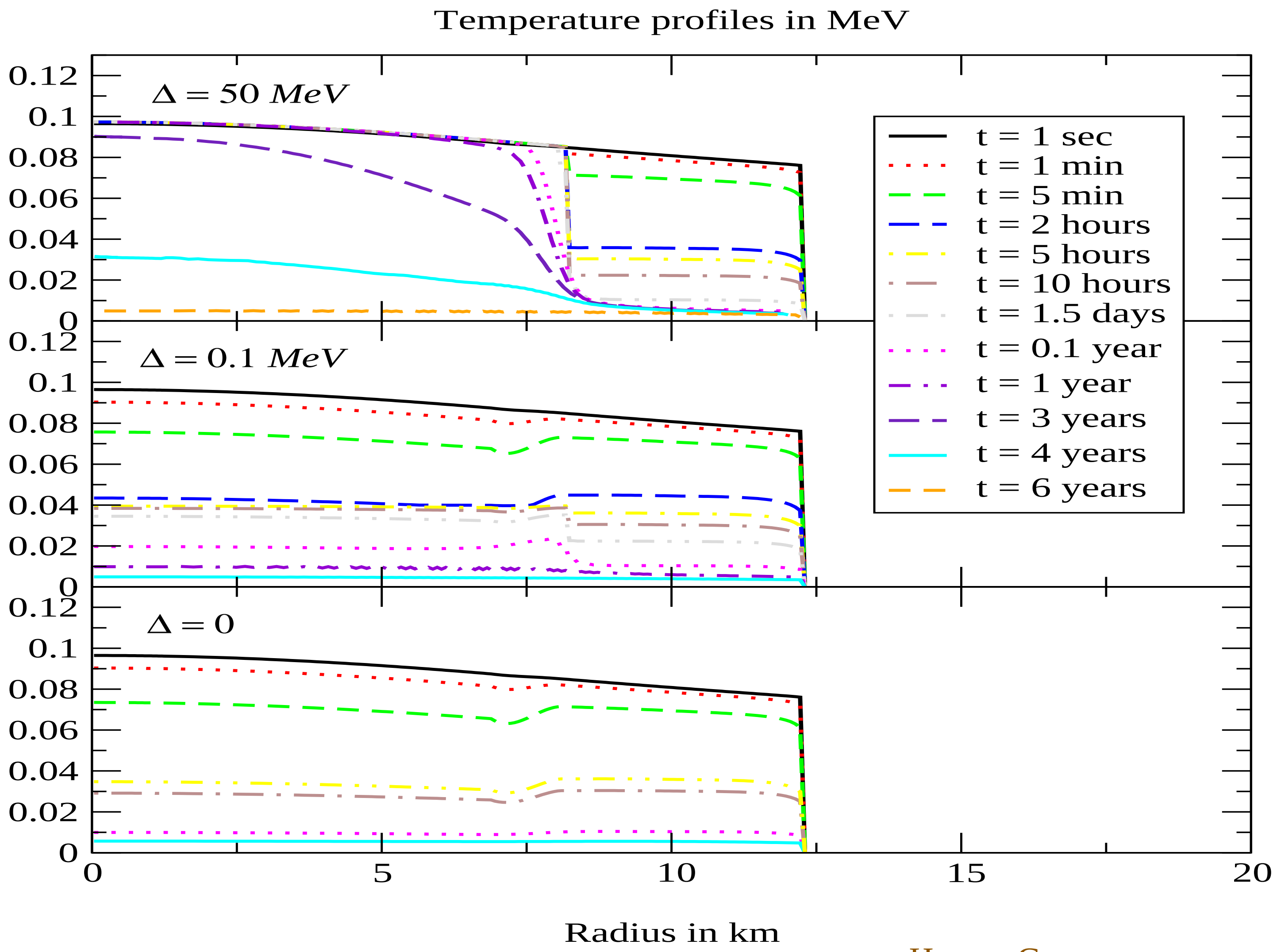


- Critical masses for phase transition
  $M_c = 1.2\ M_\odot$ HHJ - INCQM (Gaussian)with 2SC
  $M_c = 1.82\ M_\odot$ - without 2SC



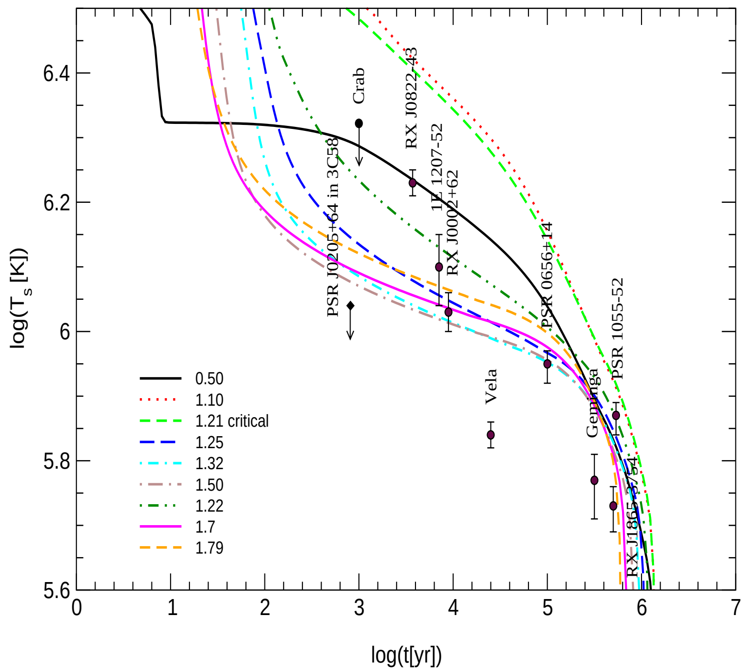
H. Grigorian , D. Blaschke , D.N. Aguilera. Phys.Rev.C **69** (2004) 065802 [arXiv:astro-ph/0303518]

Temperature Evolution in the Interior of the Star

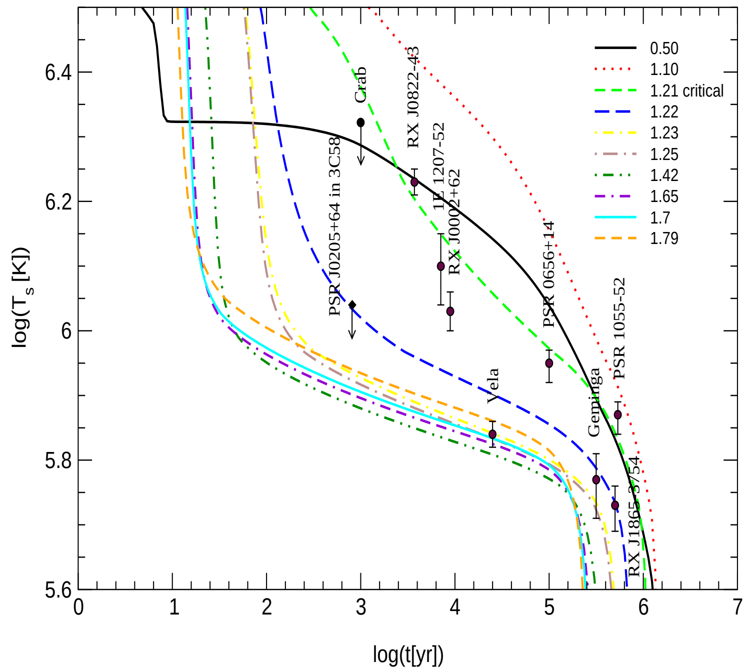


COOLING CURVES: HYBRID STARS WITH 2SC QUARK MATTER

- 2SC + X phase, $\Delta_X = 100$ keV



- 2SC + X phase, $\Delta_X = 30$ keV

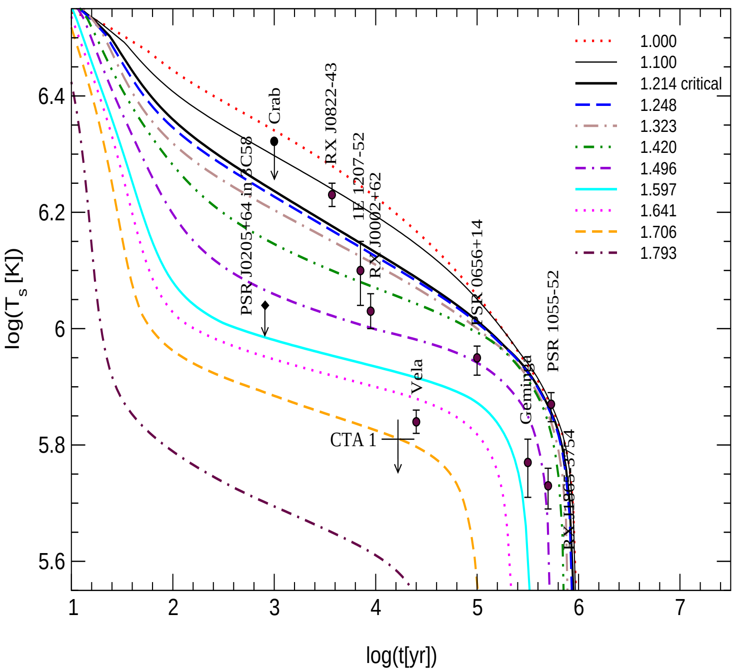


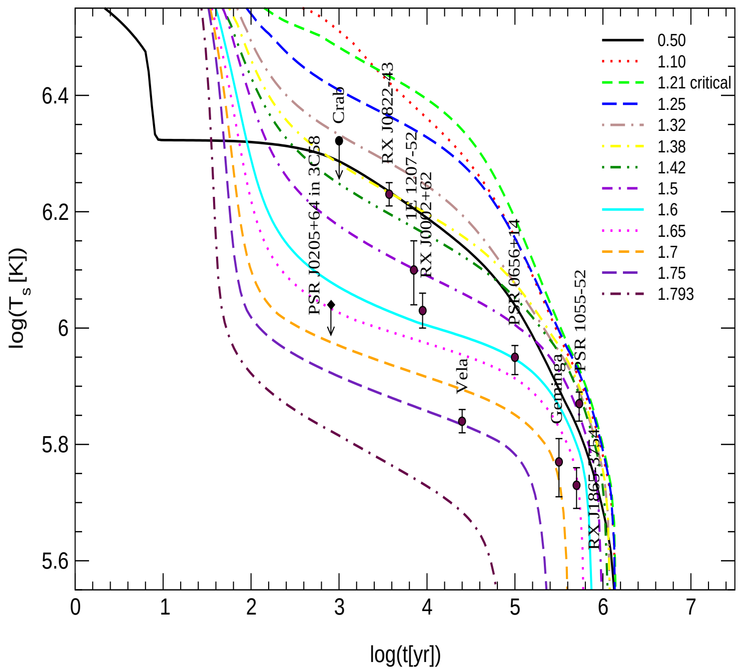
Blascke, Voskresensky, Grigorian, [arXiv:astro-ph/0403171],

Cooling curves: Hybrid Stars with 2SC quark matter

- 2SC + X phase, $\Delta_X = 1.0$ Exp$(-\alpha(1-\mu/\mu_c))$ MeV

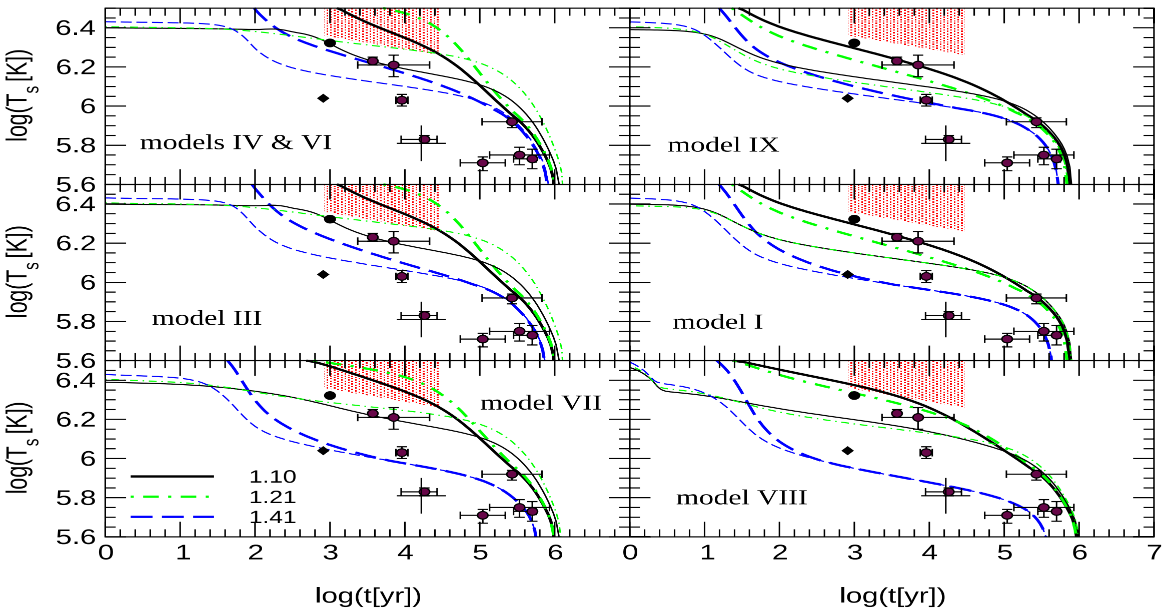
- the gaps in hadron shell by TT and Yak.





H. Grigorian, D. Blaschke, and D.N. Voskresensky, (2004) [arXiv:astro-ph//0411619];
H. Grigorian (2005) [arXiv:astro-ph/0502576];

Selection of scenario with Brightness Constraint



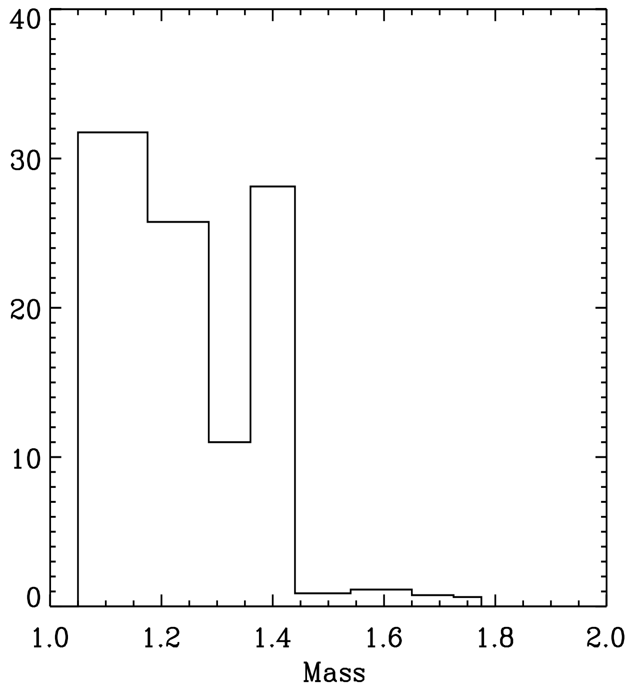
Class of model	Models with π-condensate	Models without π-condensate	Gaps
A	I	IX	Tsuruta law n-$^3P_2$*0.1
B	III	IV & VI[a]	Yakovlev et al. :2003 n-$^3P_2$*0.1
B'	VII	-	p-$^1P_0$*0.5; n-$^3P_2$*0.1
B"	VIII	-	p-$^1P_0$*0.2; n-$^1P_0$*0.5; n-$^3P_2$*0.1

[a] The model VI is the same as model IV, which was already calculated with crust (E) in Ref. D. Blaschke, H. Grigorian and D. N. Voskresensky, Astron. Astrophys. **424** (2004) 979.

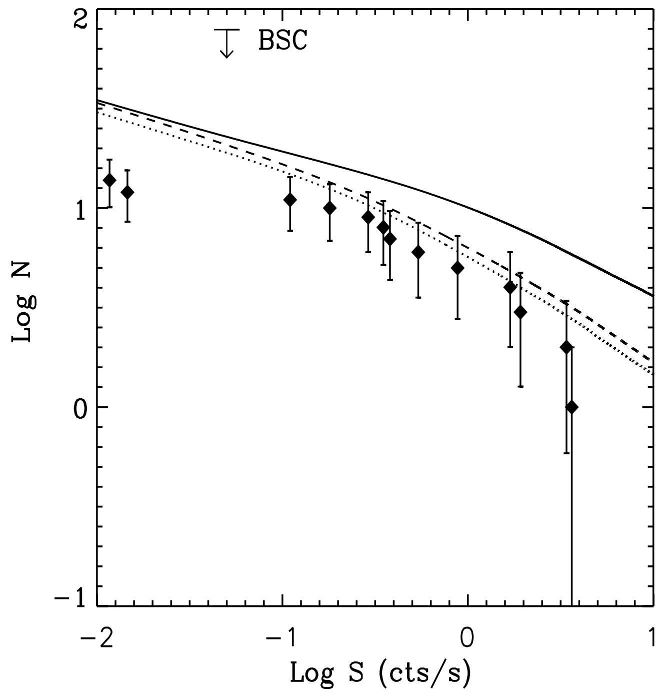
H. Grigorian, [arXiv:astro-ph/0507052]

Selection of scenario with LogN-LogS Constraint

The mass distribution



Simulation for model IX (test pass: positive)



Log N-Log S of isolated neutron stars is effective in discriminating among cooling models.

S. Popov, H. Grigorian, R. Turolla and D. Blaschke arXiv:astro-ph/0411618 (2004).