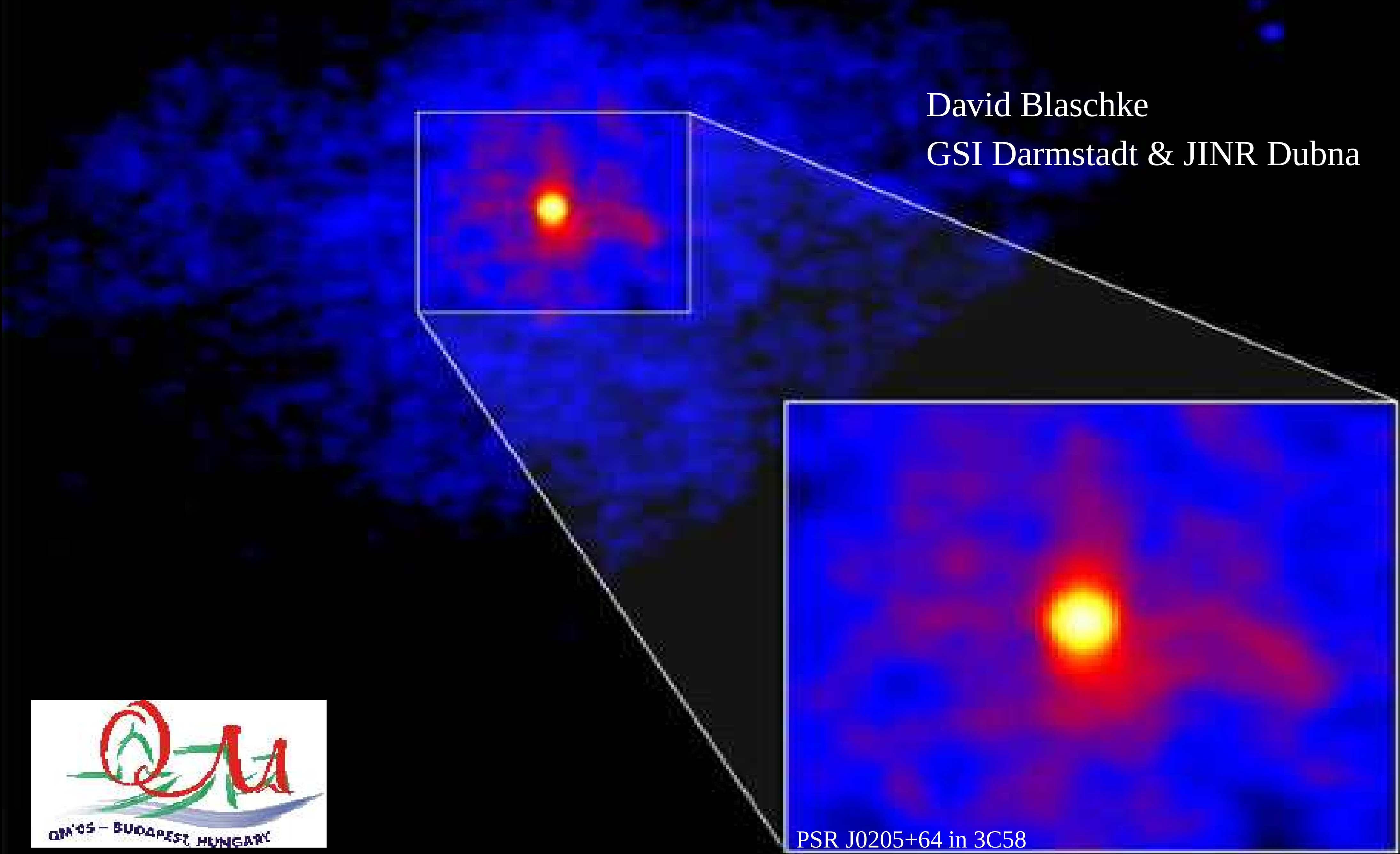
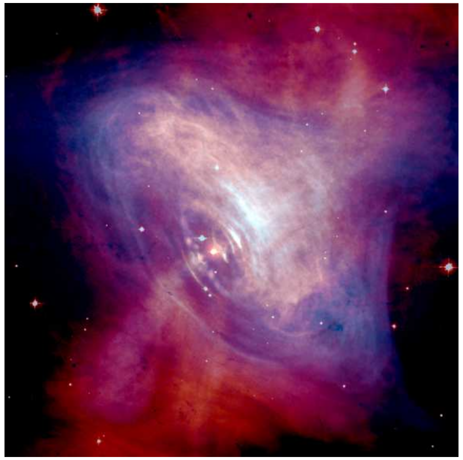
Cooling of Neutron Stars with Color Superconducting Quark Cores

David Blaschke
GSI Darmstadt & JINR Dubna

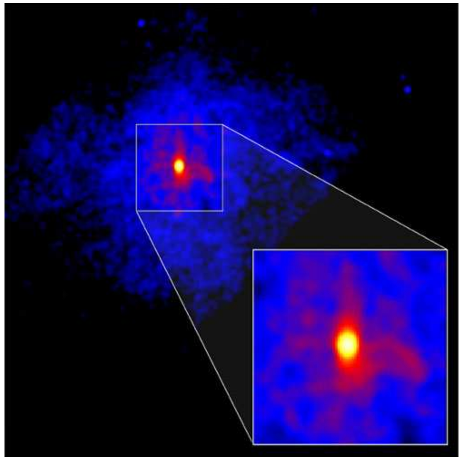


Compact Star Cooling - Introduction

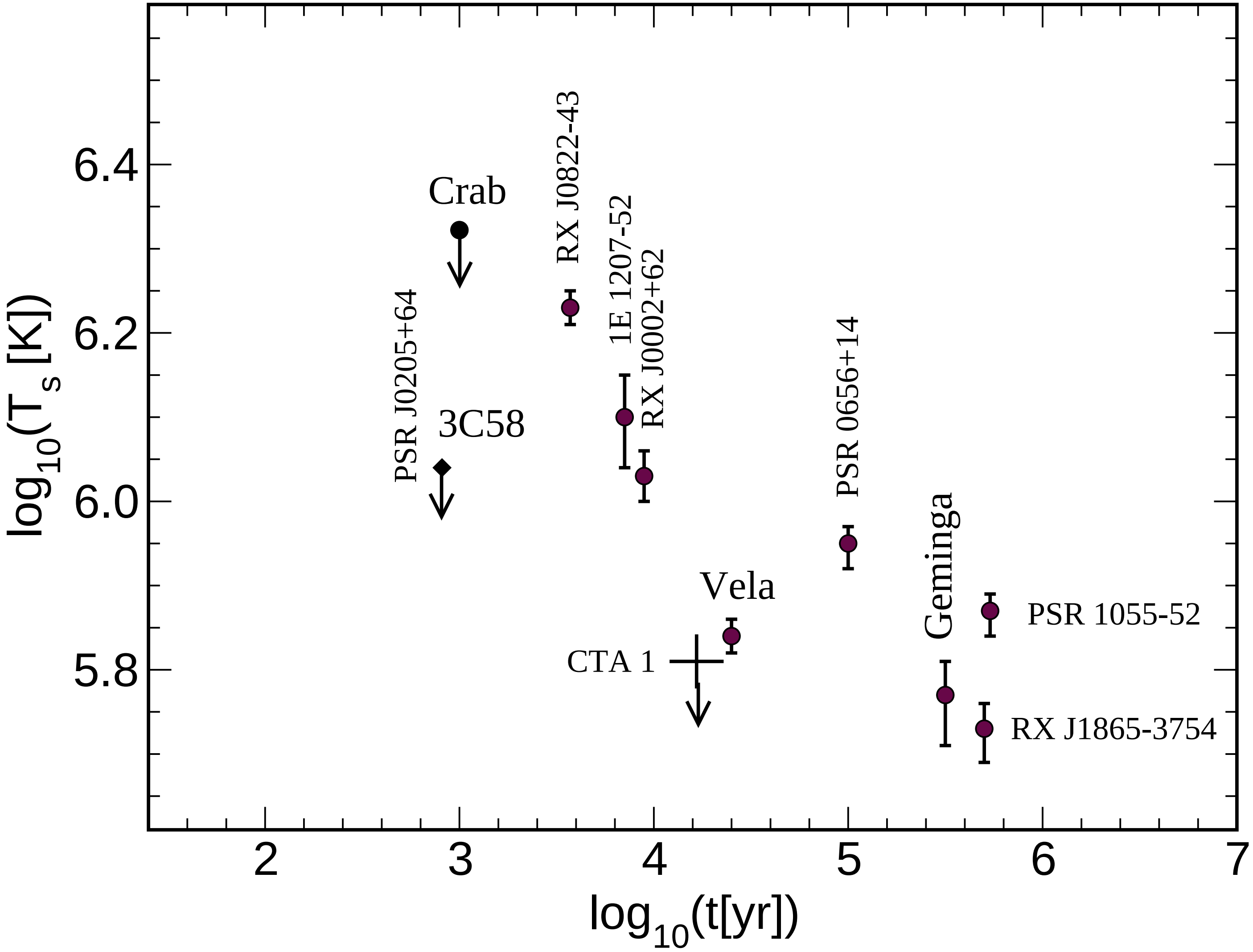
Pulsars in SN remnants:
1054 - Crab



1181 - 3C58

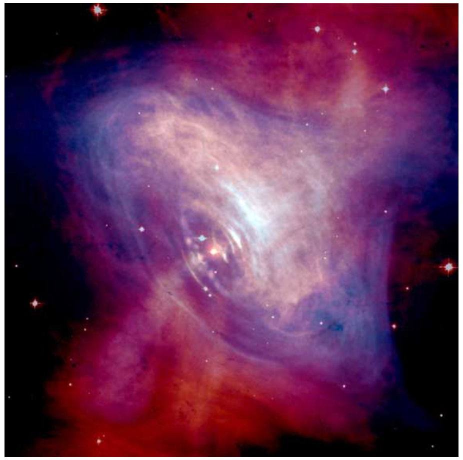


Temperature - age plot: characterizes compact star matter properties

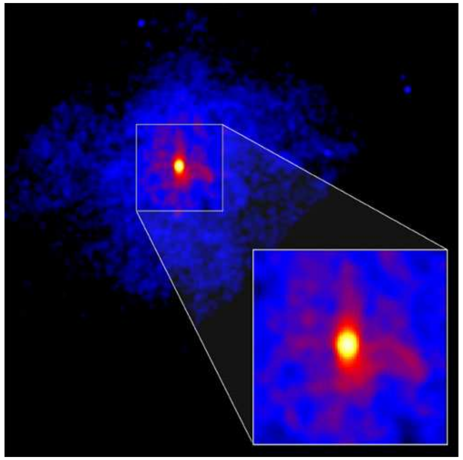


Compact Star Cooling - Introduction

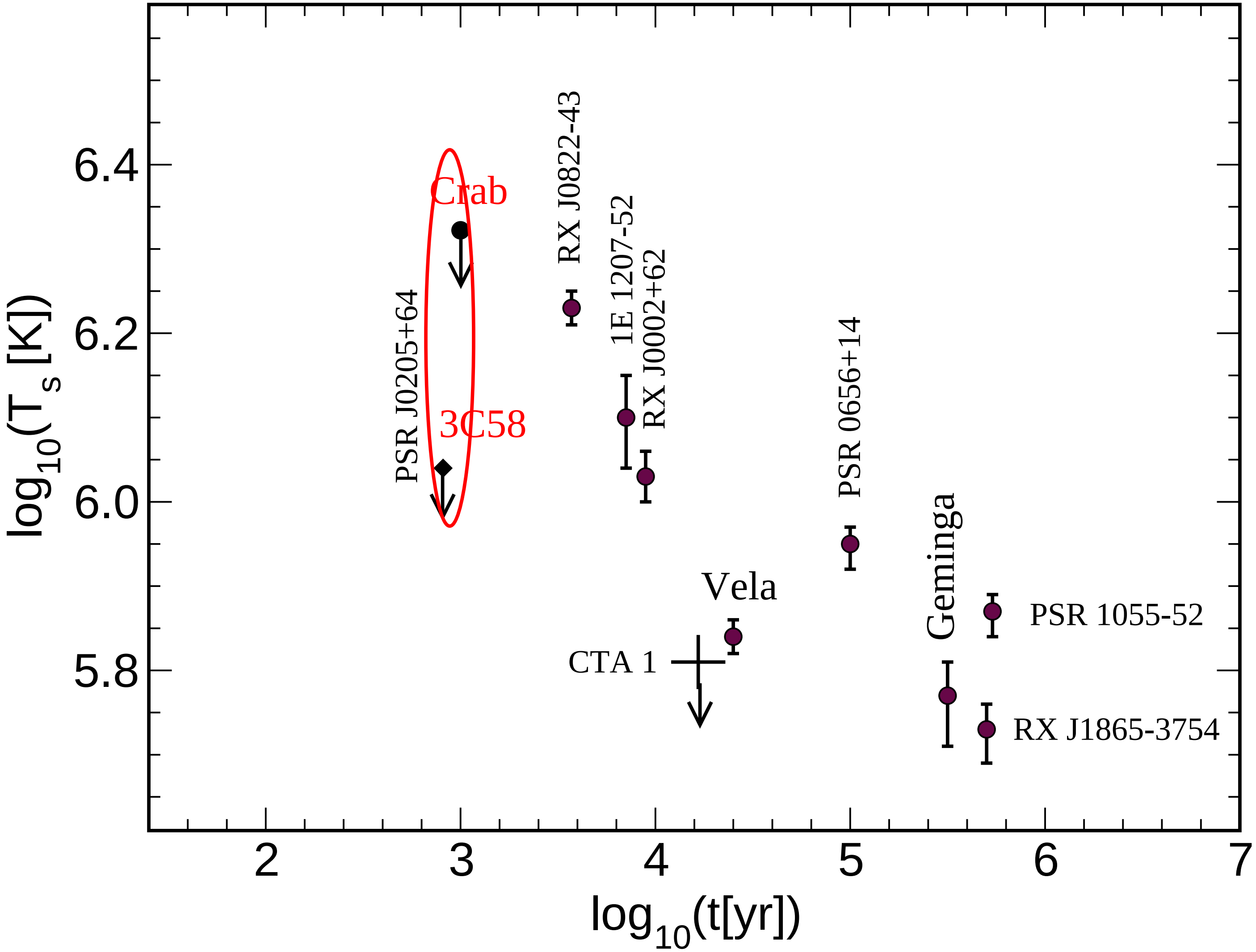
Pulsars in SN remnants:
1054 - Crab



1181 - 3C58

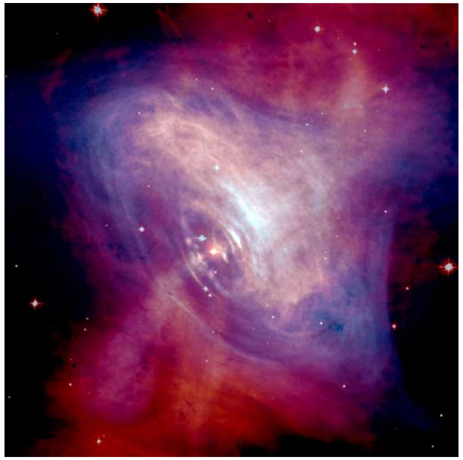


Too cool for its age: Quark matter in PSR J0205+64 ? (NASA 2002)

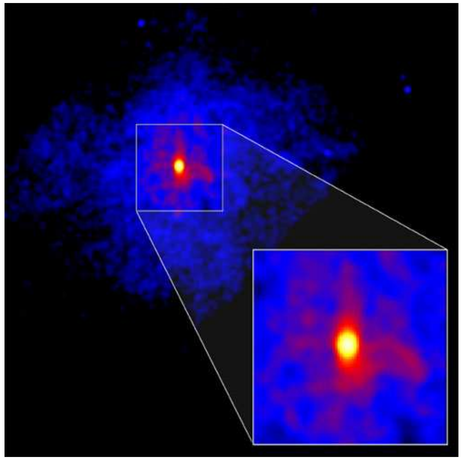


Compact Star Cooling - Phenomenology

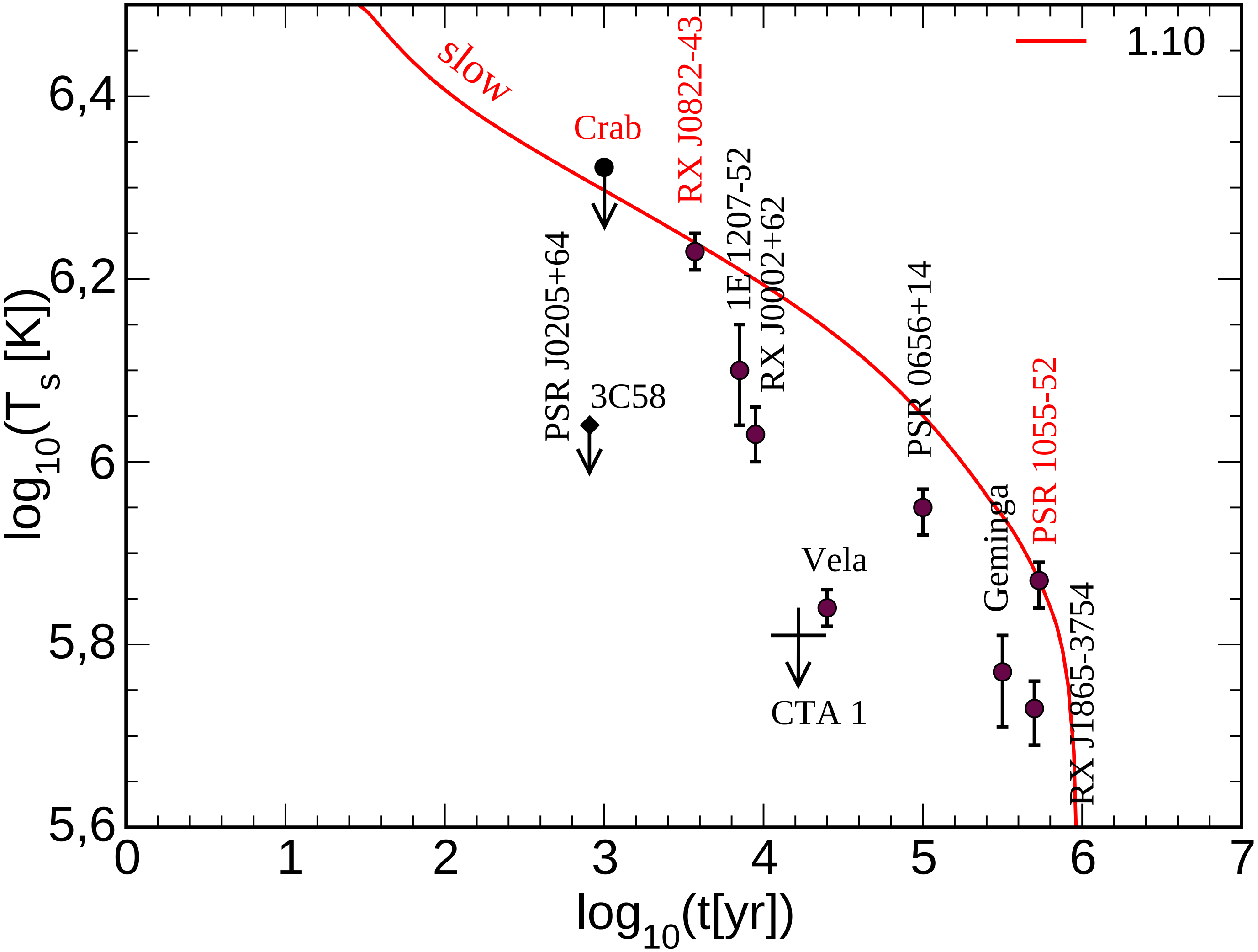
Pulsars in SN remnants:
1054 - Crab



1181 - 3C58

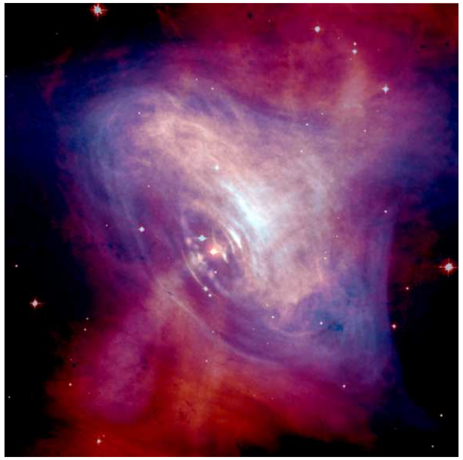


Temperature - age plot: characterizes compact star matter properties

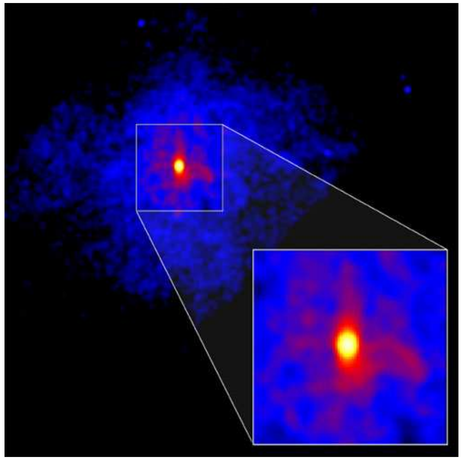


Compact Star Cooling - Introduction

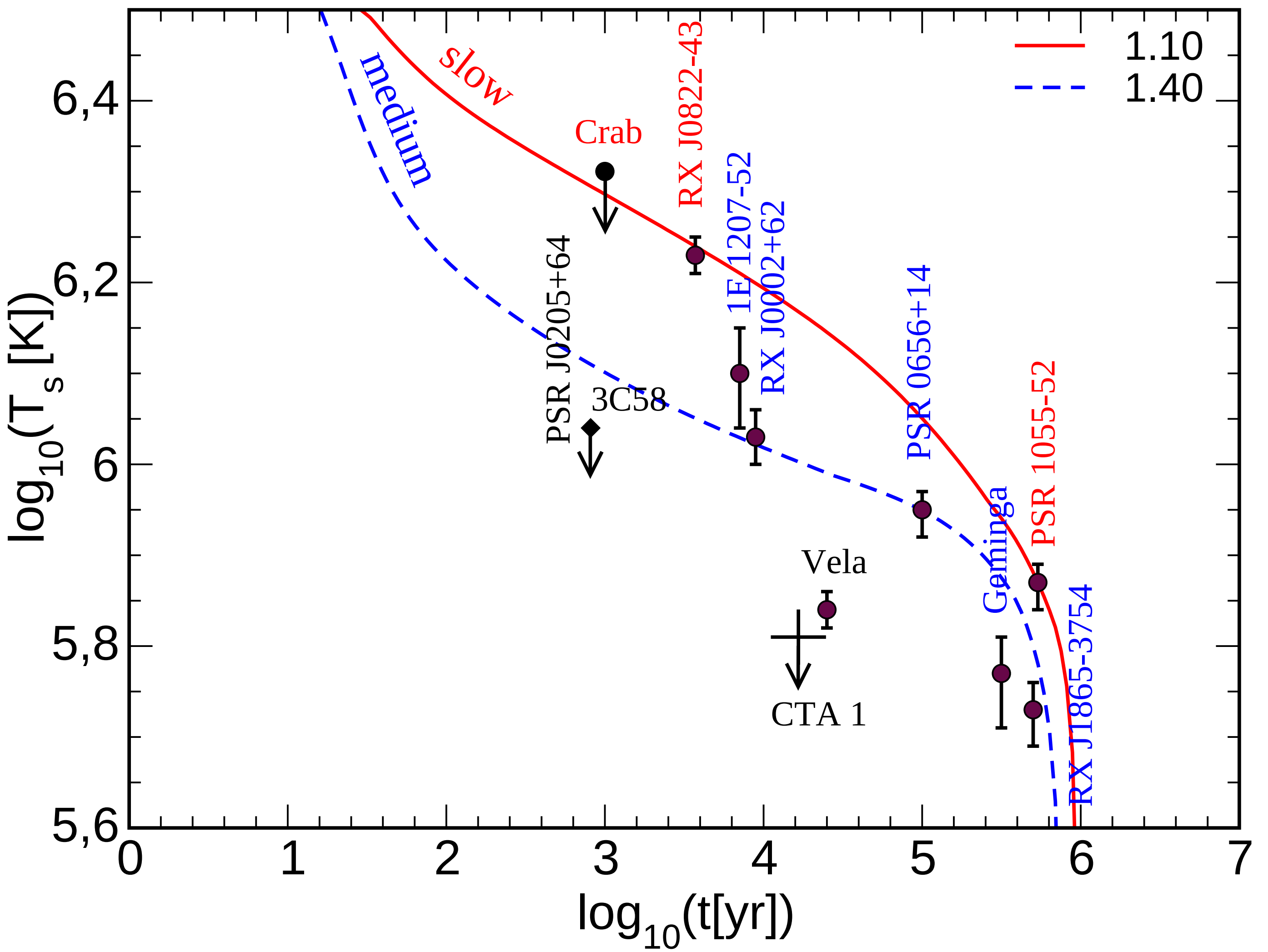
Pulsars in SN remnants:
1054 - Crab



1181 - 3C58



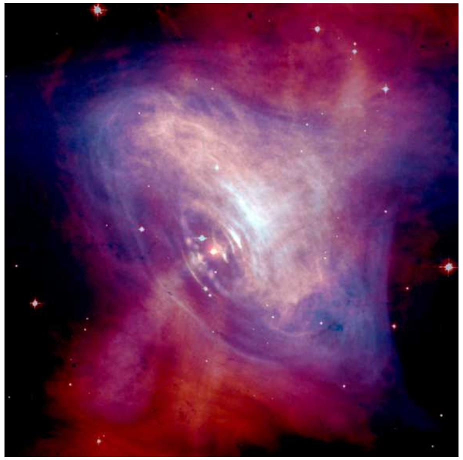
Temperature - age plot: characterizes compact star matter properties



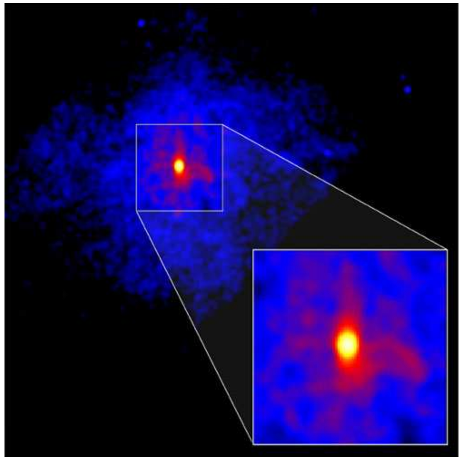
Compact Star Cooling - Introduction

Pulsars in SN remnants:

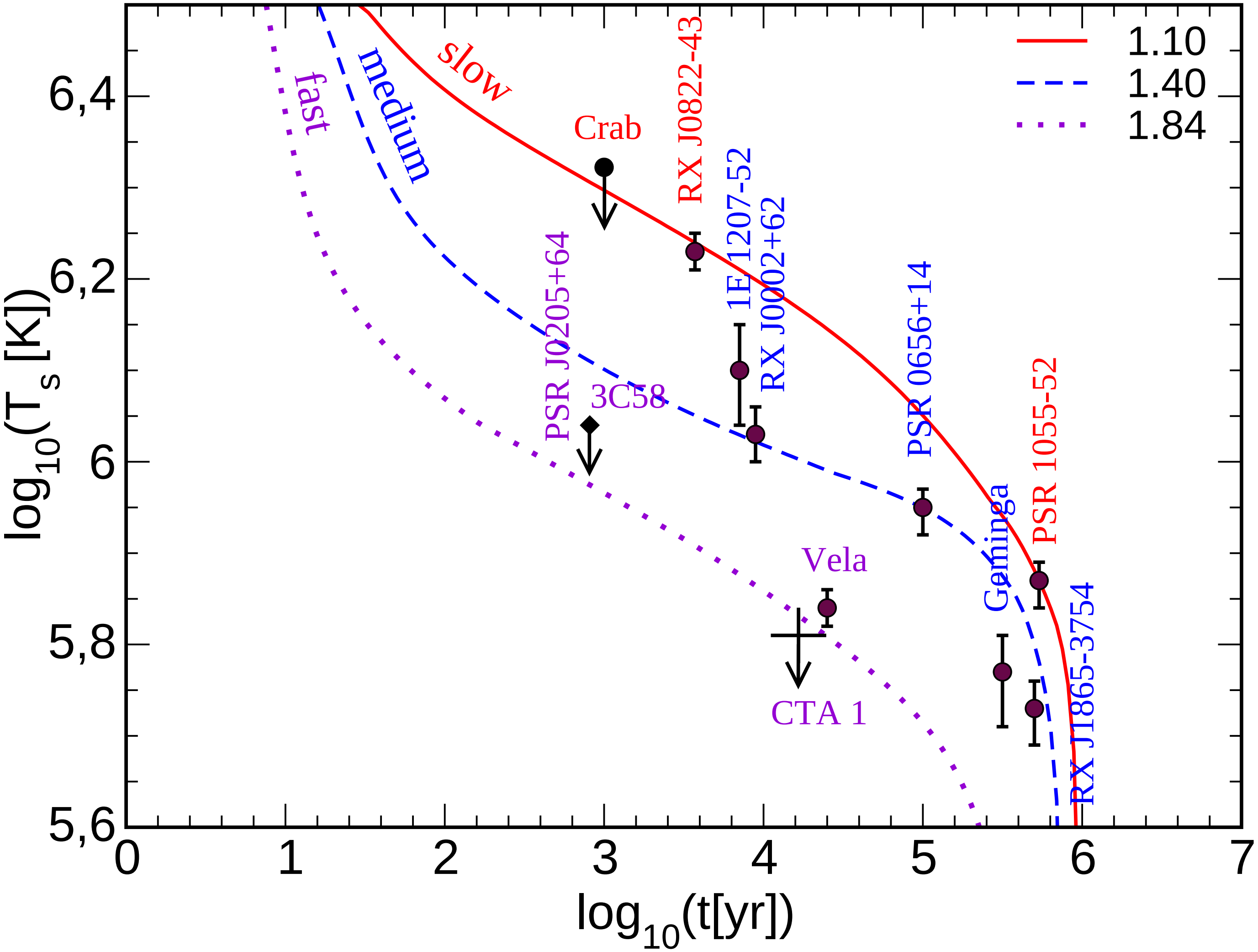
1054 - Crab



1181 - 3C58



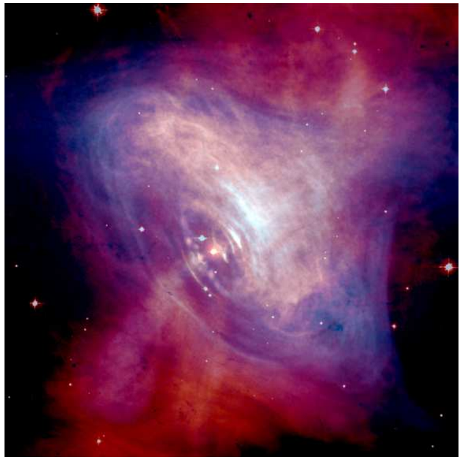
Classification of cooling compact stars



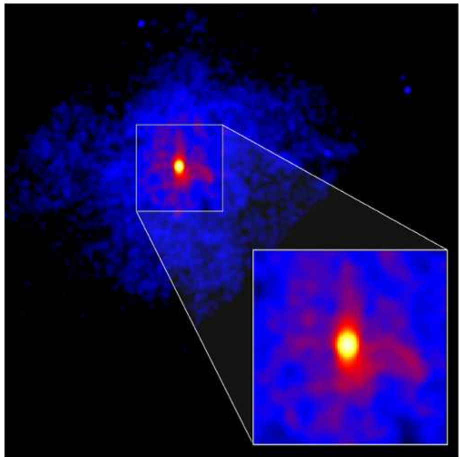
Compact Star Cooling - Hadronic Scenario

Pulsars in SN remnants:

1054 - Crab

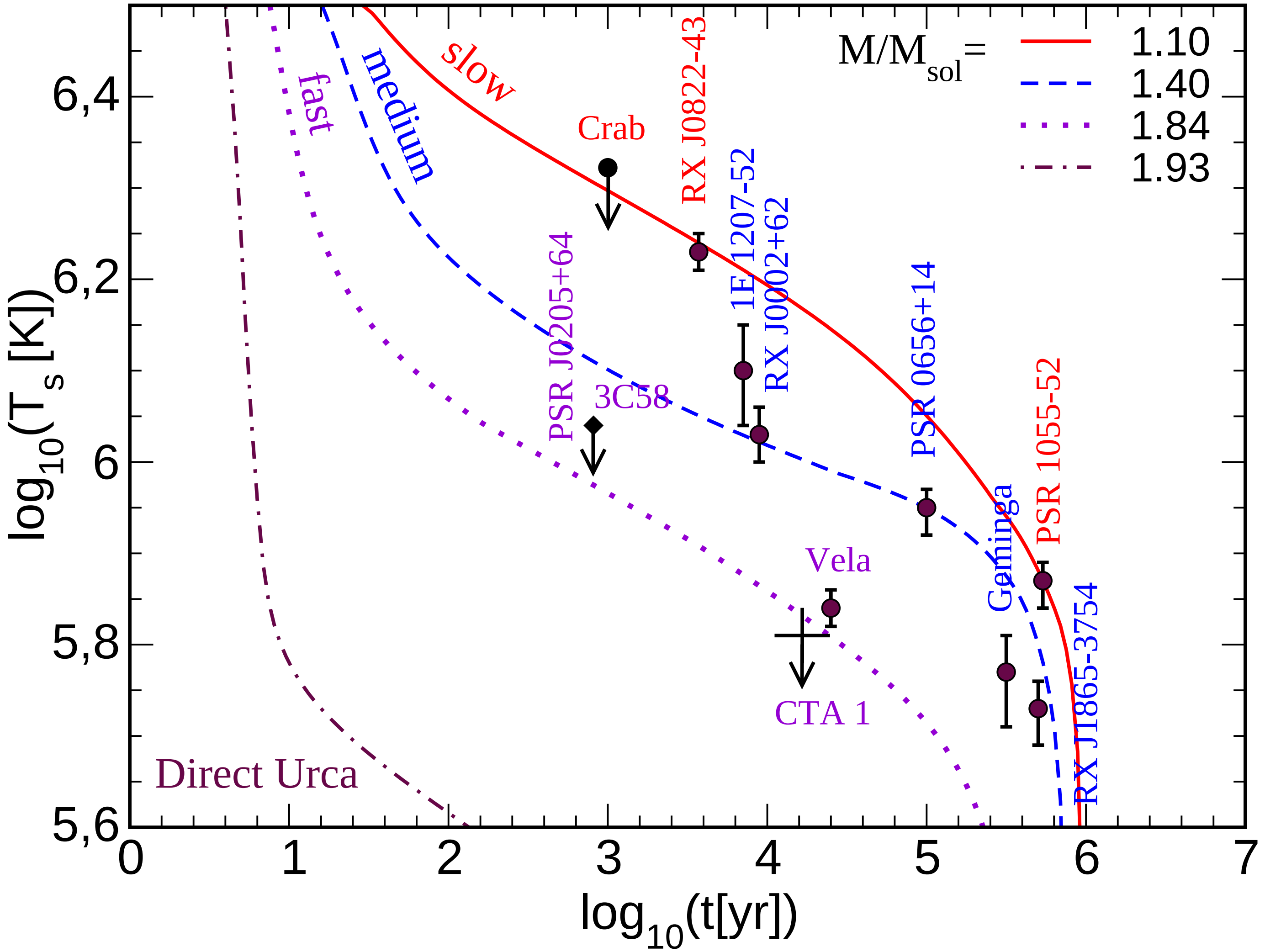


1181 - 3C58



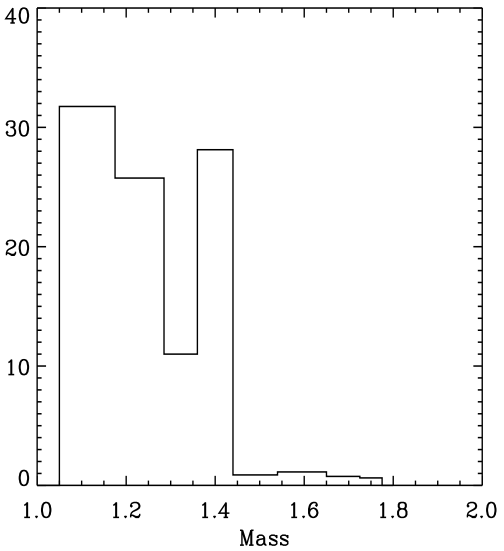
Classification of cooling compact stars: parameter - mass

D.B., Grigorian, Voskresensky, A& A 424, 979 (2004)

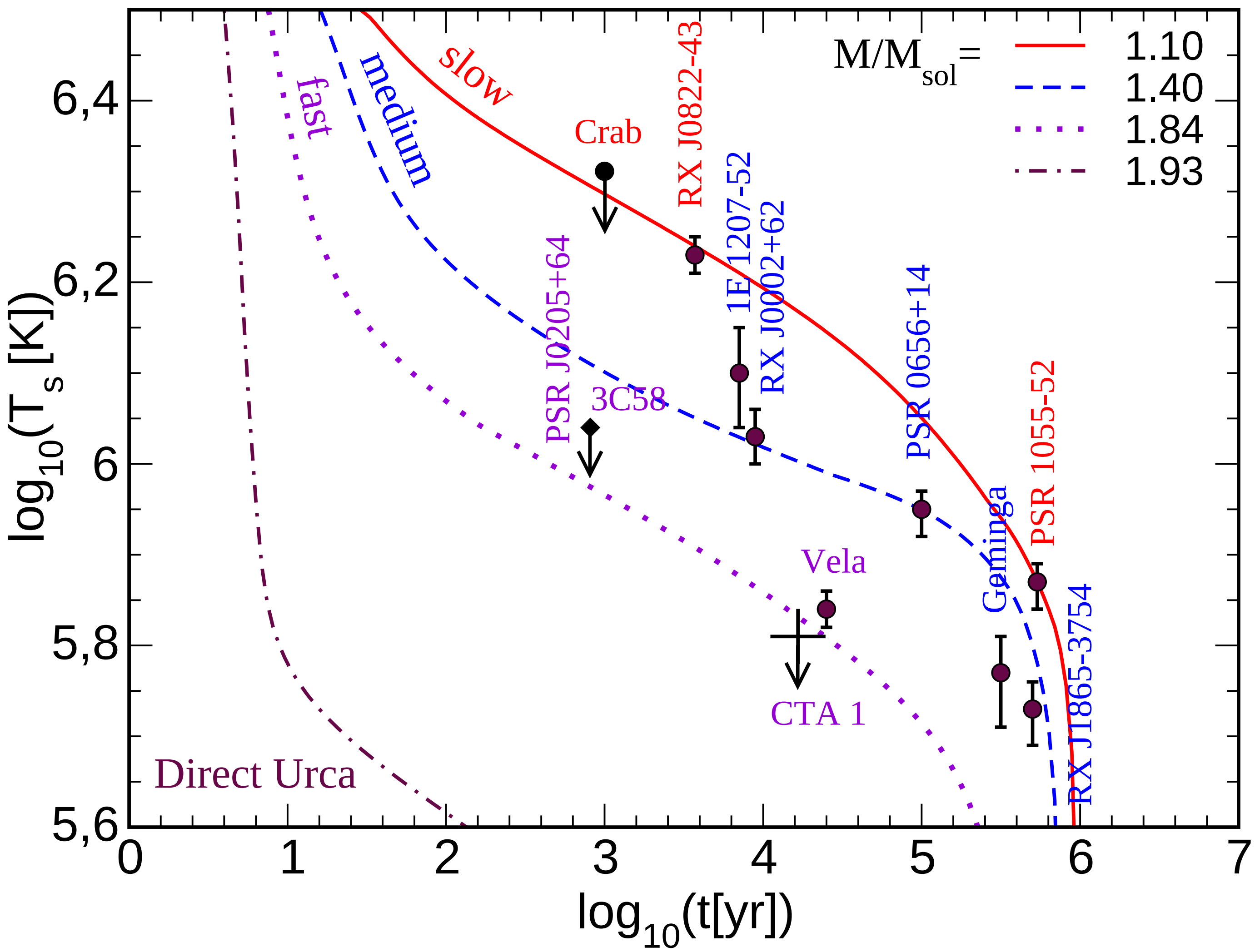


Compact Star Cooling - Hadronic Scenario

Mass distribution from population synthesis models for the solar vicinity



Classification of cooling compact stars: parameter - mass



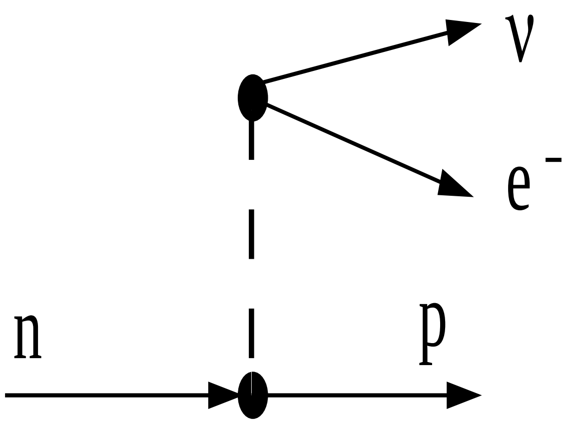
Popov et al: astro-ph/0411618

Radiopulsar masses ($1.4\ M_\odot$) not reliable for isolated pulsars
- evolutionary effects in binaries

Caution: Beware of the direct Urca process!

Casino DE URCA today ...

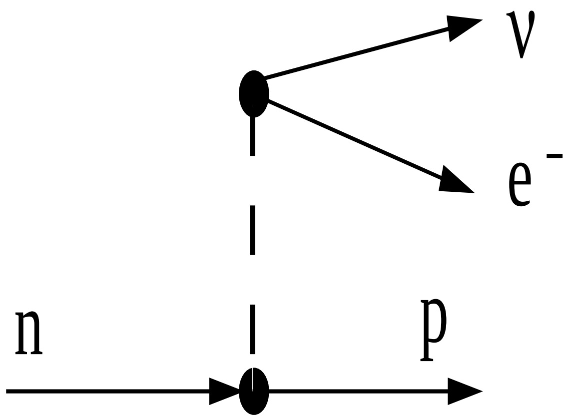
First studied by Gamov and Schönberg (≈ 1940)



$$\varepsilon_\nu[DU] \sim 10^{27}\, T_9^6 \text{ erg cm}^{-3}\text{s}^{-1}$$

Huge emissivity → cools the star too fastly!!

Direct Urca process constraint



DU process w/o neutrino trapping ($\lambda_\nu \gg R$, $\mu_\nu = 0$):

β-Equilibrium: $\mu_n = \mu_p + \mu_e$

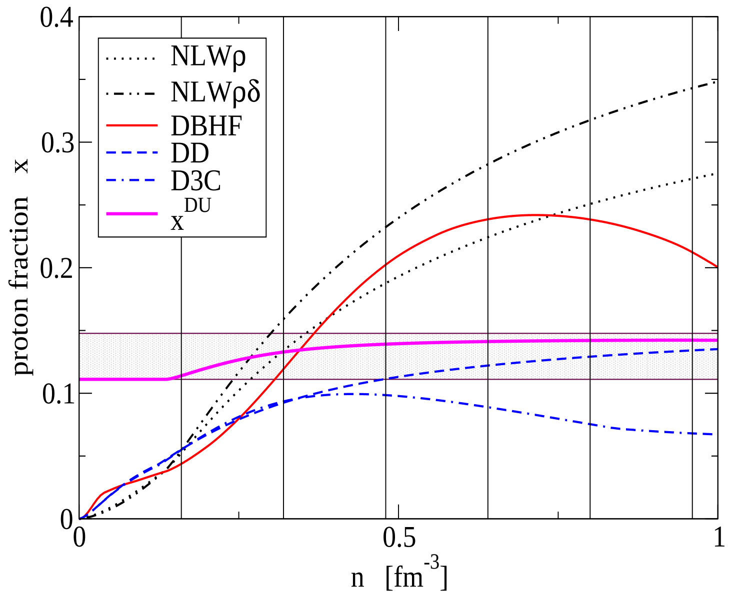
Charge neutrality: $n_p = n_e + n_\mu \Leftrightarrow p_{F,p}^3 = p_{F,e}^3 + p_{F,\mu}^3$

Momentum conservation:

$\vec{p}_{F,n} = \vec{p}_{F,p} + \vec{p}_{F,e} \Leftrightarrow |\vec{p}_{F,n}| \leq |\vec{p}_{F,p}| + |\vec{p}_{F,e}|$

$p_{F,n} \leq p_{F,p}[1 + (1 - n_\mu/n_p)^{1/3}] \Rightarrow n_n \leq 8\, n_p - 4 n_\mu$

$$\Rightarrow \boxed{\frac{n_p}{n_p + n_n} = x_p \geq \frac{1}{9} + \frac{4}{9} x_\mu}$$

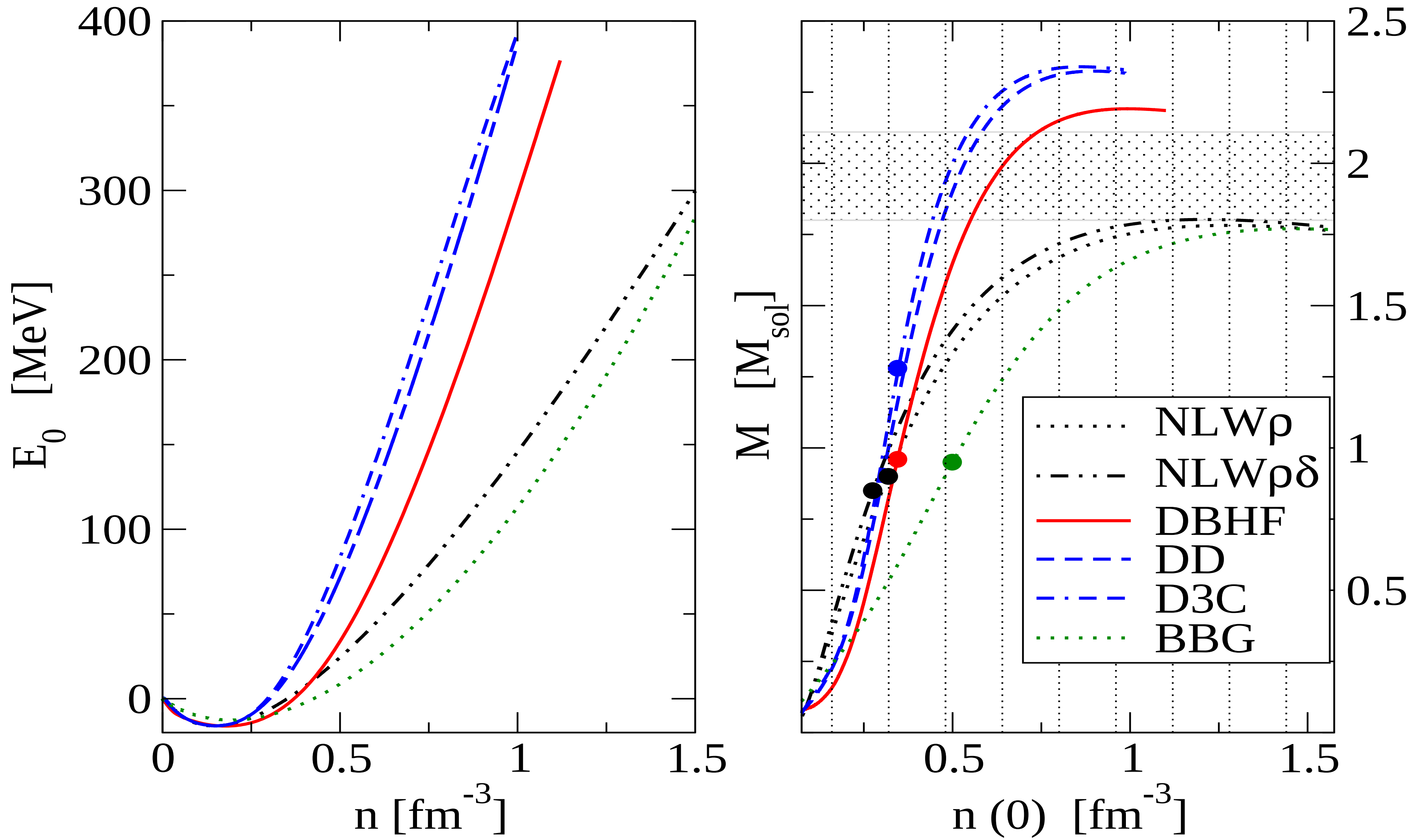


Luminosity:

$$L_\nu = (2\pi)^4 \int \frac{d^3 p_n}{(2\pi)^3 2E_n} \ldots \int \frac{d^3 p_\nu}{(2\pi)^3 2E_\nu}\, \delta^3(\vec{p}_i)\delta(E_i)\, |M_{fi}|^2\, f_n(1 - f_p)(1 - f_e)$$

Emissivity: $\epsilon_\nu = \frac{L_\nu}{V} \sim 10^{27} \left(\frac{m_n^* m_p^*}{m_N^2}\right) \left(\frac{n_e}{n_0}\right)^{1/3} \left(\frac{T}{10^9 K}\right)^6 \frac{\text{erg}}{\text{cm}^3 s}$

DU constraint eliminates most hadronic EoS



RMF EoS violate DU constraint unless couplings and masses are density dependent !

Kolomeitsev, Voskresensky, nucl-th/0410063; Klähn, et al., in prep.

Quark Matter Phase Diagram

$$\begin{aligned}\Omega(T,\mu) &= \frac{\phi_u^2+\phi_d^2+\phi_s^2}{8G_S}+\frac{|\Delta_{ud}|^2+|\Delta_{us}|^2+|\Delta_{ds}|^2}{4G_D}\\ &- T\sum_n\int\frac{d^3p}{(2\pi)^3}\frac{1}{2}\mathrm{Tr}\ln\left(\frac{1}{T}S^{-1}(i\omega_n,\vec{p})\right)\\ &+ \Omega_e-\Omega_0.\end{aligned}$$

Inverse propagator of Nambu-Gorkov spinors

$$S^{-1}(i\omega_n,\vec{p}) = \begin{bmatrix}\gamma_\mu p^\mu - M+\mu\gamma^0 & \widehat{\Delta}\\ \widehat{\Delta}^\dagger & \gamma_\mu p^\mu - M - \mu\gamma^0\end{bmatrix},$$

with diquark gaps ($\Delta_{ur}=\Delta_{ds},\dots$)

$$\Delta_{k\gamma}=2G_D\langle\bar{q}_{i\alpha}i\gamma_5\epsilon_{\alpha\beta\gamma}\epsilon_{ijk}q^C_{j\beta}\rangle.$$

as elements of the gap matrix

$$\widehat{\Delta} = i\gamma_5\epsilon_{\alpha\beta\gamma}\epsilon_{ijk}\Delta_{k\gamma}.$$

Fermion determinant (Tr ln D = ln det D)

$$\mathrm{lndet}\left(\frac{1}{T}S^{-1}(i\omega_n,\vec{p})\right)=2\sum_{a=1}^{18}\ln\left(\frac{\omega_n^2+\lambda_a(\vec{p})^2}{T^2}\right).$$

Result for thermodynamic potential

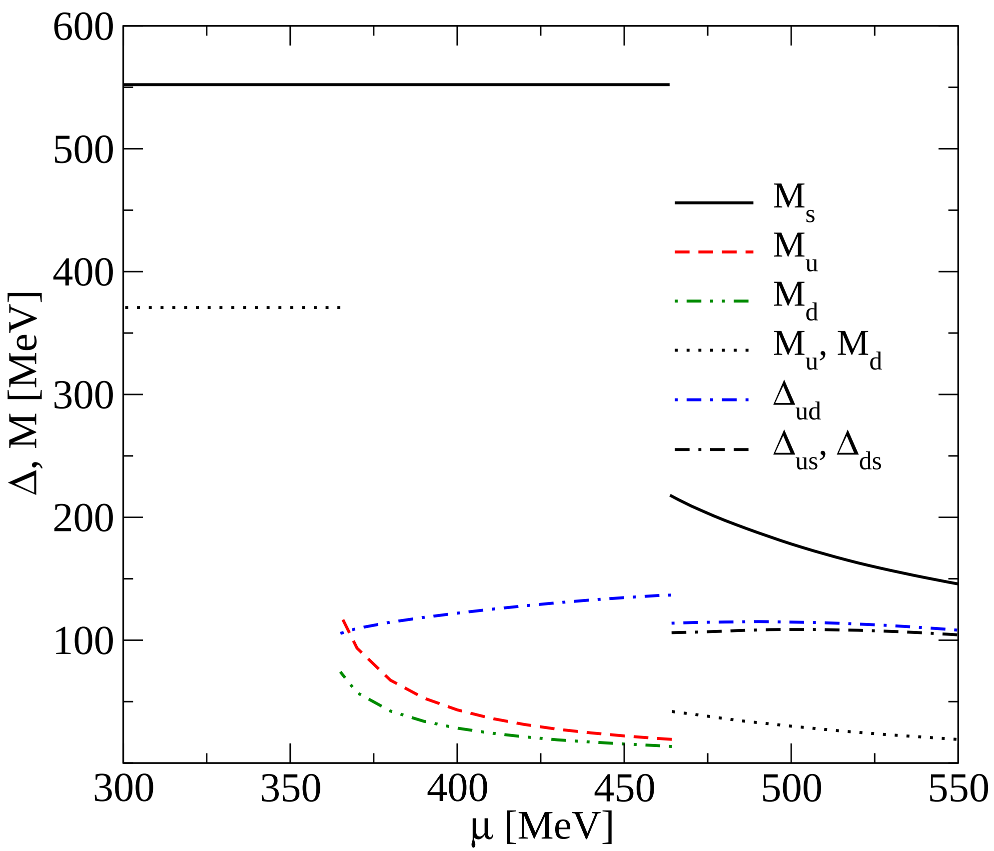
$$\begin{aligned}\Omega(T,\mu) &= \frac{\phi_u^2+\phi_d^2+\phi_s^2}{8G_S}+\frac{|\Delta_{ud}|^2+|\Delta_{us}|^2+|\Delta_{ds}|^2}{4G_D}\\ &- \int\frac{d^3p}{(2\pi)^3}\sum_{a=1}^{18}\left(\lambda_a+2T\ln\left(1+e^{-\lambda_a/T}\right)\right)\\ &+ \Omega_e-\Omega_0.\end{aligned}$$

Neutrality conditions: $n_Q=n_8=n_3=0$,

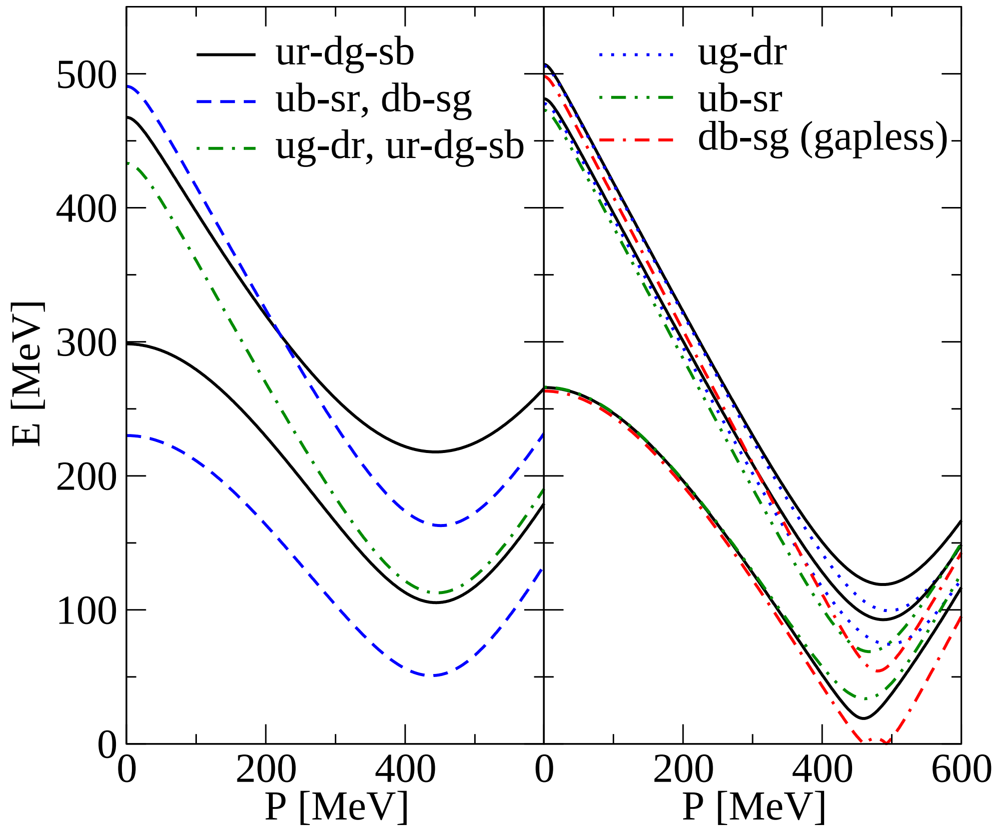
$$n_i = -\frac{\partial\Omega}{\partial\mu_i}=0,$$

Equation of state: $P=-\Omega$, etc.

Quark Masses, Diquark Gaps, Gapless Modes



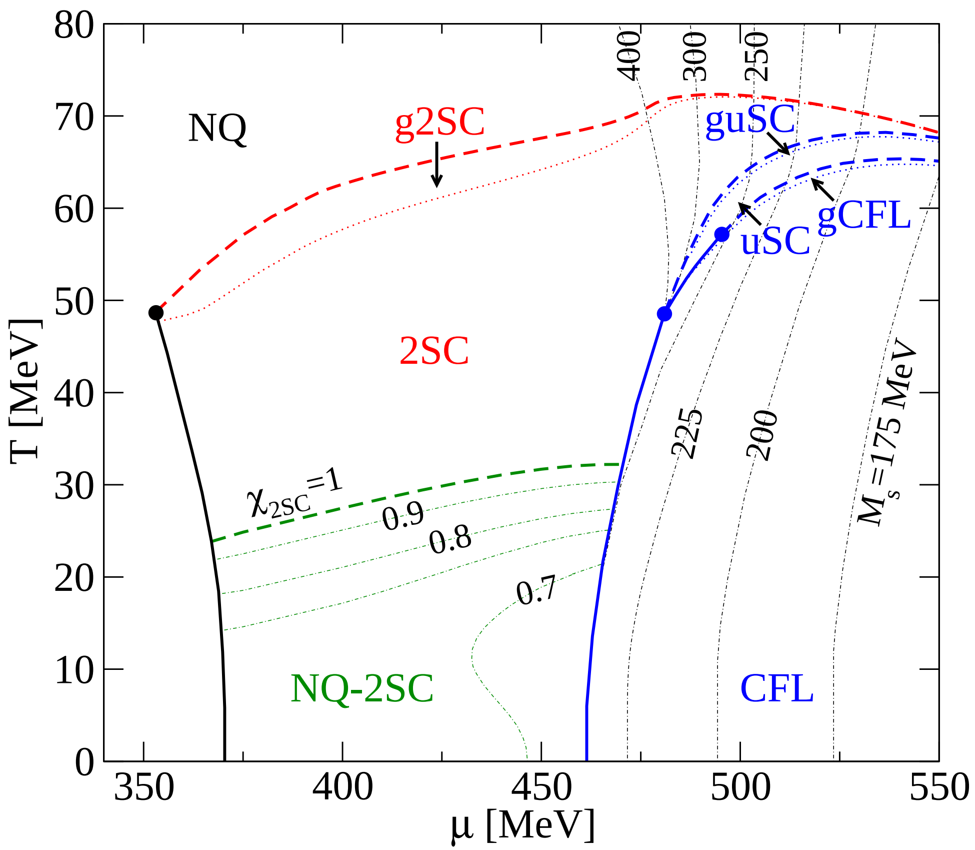
Dynamical quark masses and diquark gaps at $T = 0$ for intermediate diquark coupling $G_D = 0.75\ G_S$



Dispersion relations for $G_D = 0.75\ G_S$, $T = 0$, $\mu = 465$ MeV (left), $G_D = 1.0\ G_S$, $T = 59$ MeV, $\mu = 500$ MeV (right)

Rüster et al: hep-ph/0502184, Blaschke et al: hep-ph/0502194

Three-flavor Quark Matter Phase Diagram



Rüster et al: hep-ph/0503184
Blaschke et al: hep-ph/0503194

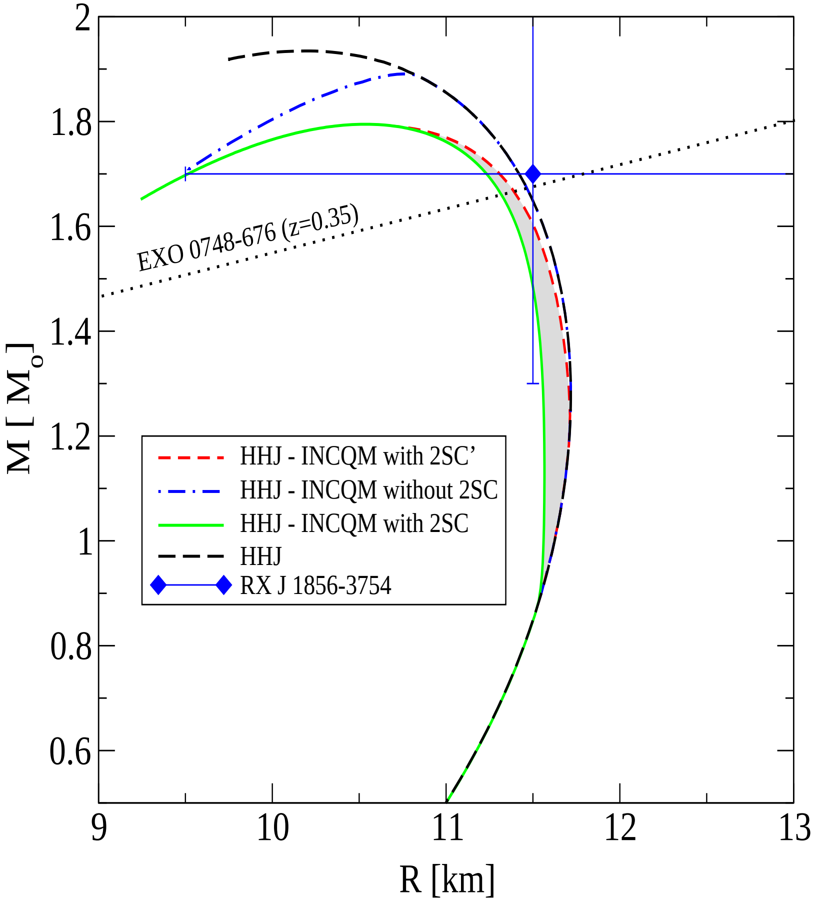
The phases are:

- NQ: $\Delta_{ud} = \Delta_{us} = \Delta_{ds} = 0$;
- NQ-2SC: $\Delta_{ud} \neq 0$, $\Delta_{us} = \Delta_{ds} = 0$, $0 \leq \chi_{2SC} \leq 1$;
- 2SC: $\Delta_{ud} \neq 0$, $\Delta_{us} = \Delta_{ds} = 0$;
- uSC: $\Delta_{ud} \neq 0$, $\Delta_{us} \neq 0$, $\Delta_{ds} = 0$;
- CFL: $\Delta_{ud} \neq 0$, $\Delta_{ds} \neq 0$, $\Delta_{us} \neq 0$;

Result:

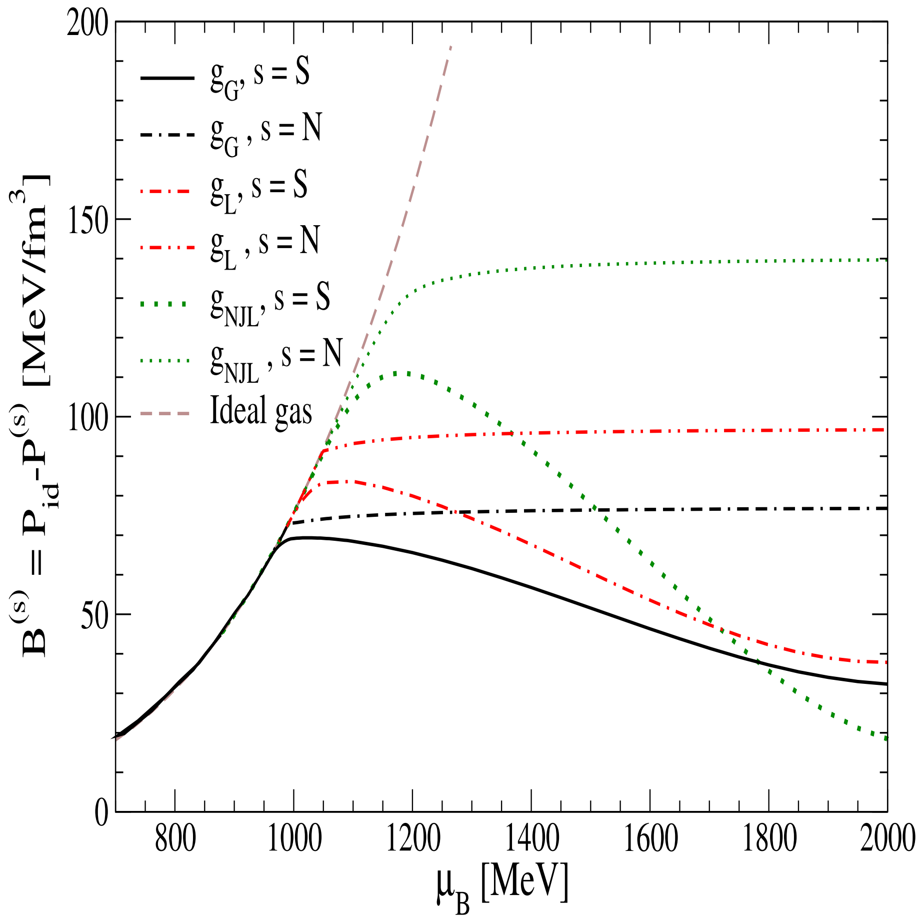
- Gapless phases only at high T,
- CFL only at high chemical potential,
- At T $\leq$25-30 MeV: mixed NQ-2SC phase,
- Critical point (T_c,μ_c)=(48 MeV, 353 MeV),
- Strong coupling, $G_D = G_S$, similar, no NQ-2SC mixed phase.

Hybrid Star Configurations



Mass-radius relation for hybrid star with HHJ and instantaneous nonlocal chiral quark model.

Grigorian et al, PRC 71 (2005)



Density dependent bag constant corresponding to the INCQM for Gaussian, Lorentzian and NJL formfactors.

Grigorian et al, PRC 69 (2004)

General Relativistic Cooling Equations

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

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

The factor $e^{-\Phi}\sqrt{1 - \frac{2M}{r}}$ corresponds to relativistic corrections of time and distance scales.
The equations for energy balance and thermal energy transport are:

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

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

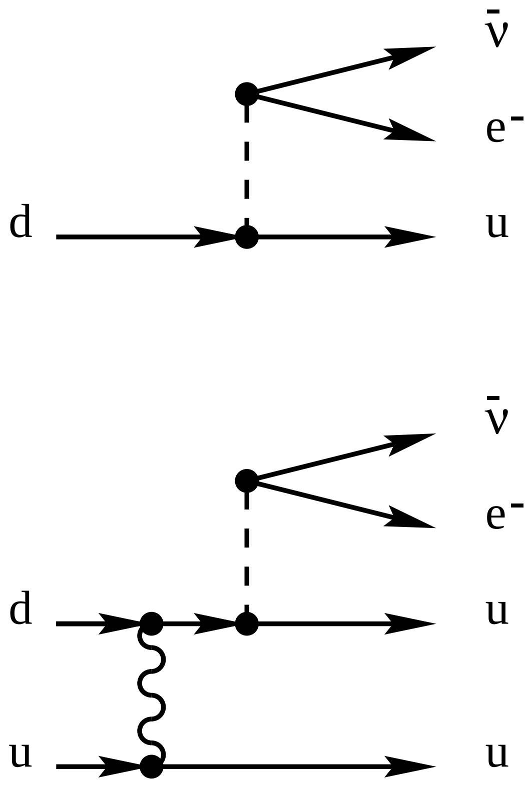
where $n = n(r)$ is the baryon number density, $N_B = N_B(r)$ is the total baryon number in the sphere with radius r and

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

F. Weber: Pulsars as Astrophys. Labs ... (1999); D.B., Grigorian, Voskresensky, A& A 368 (2001) 561.

Neutrino processes in quark matter: Emissivities

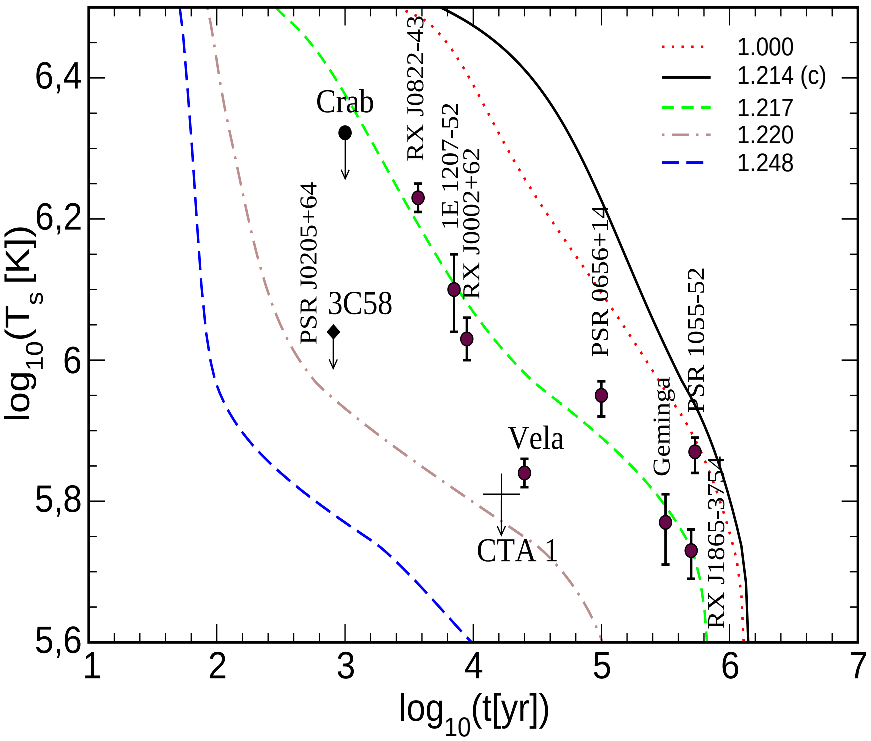
- Quark direct Urca (QDU) the most effi cient processes
  $d \to u + e + \bar{\nu}$ and $u + e \to d + \nu$
  $\epsilon_\nu^{\rm QDU} \simeq 9.4 \times 10^{26} \alpha_s u Y_e^{1/3} \zeta_{\rm QDU}\, T_9^6$ erg cm^{-3} s^{-1},
  Compression $u = n/n_0 \simeq 2$, strong coupling $\alpha_s \approx 1$
- Quark Modifi ed 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 $T < T_{{\rm crit},q} \simeq 0.57\, \Delta_q$
- $e + e \to e + e + \nu + \bar{\nu}$
  $\epsilon_\nu^{ee} = 2.8 \times 10^{12}\, Y_e^{1/3} u^{1/3} T_9^8$ erg cm^{-3} s^{-1},
  becomes important for $\Delta_q/T >> 1$

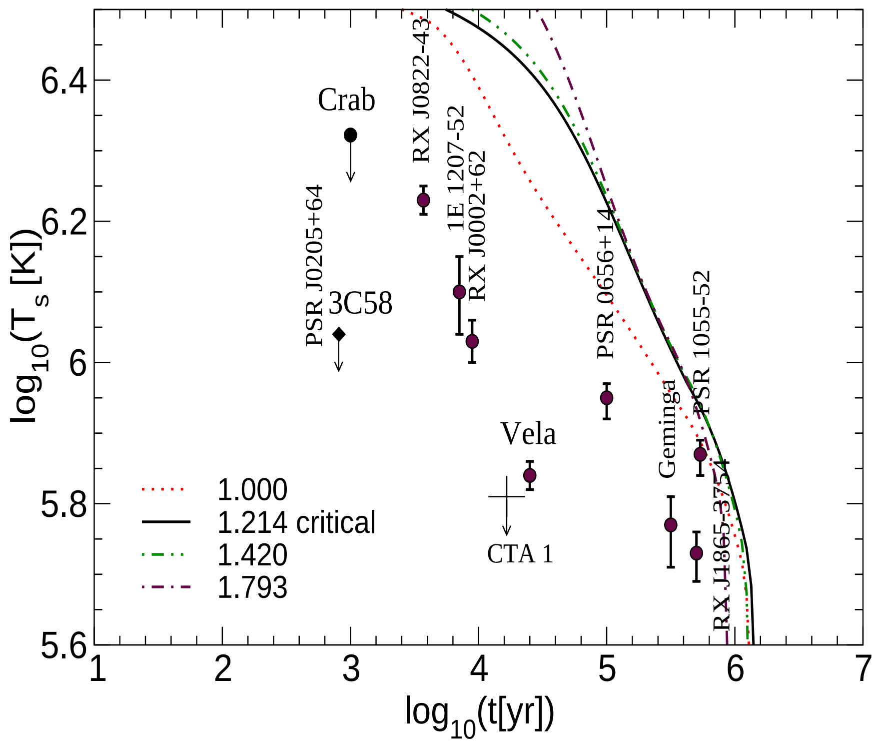


Quark PBF

BLASCHKE, GRIGORIAN, VOSKRESENSKY , ASTRON. & ASTROPHYS. 368 (2001) 561; JAIKUMAR, PRAKASH, PLB 516 (2001) 345
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

Hybrid Star Cooling with 2SC Quark Matter



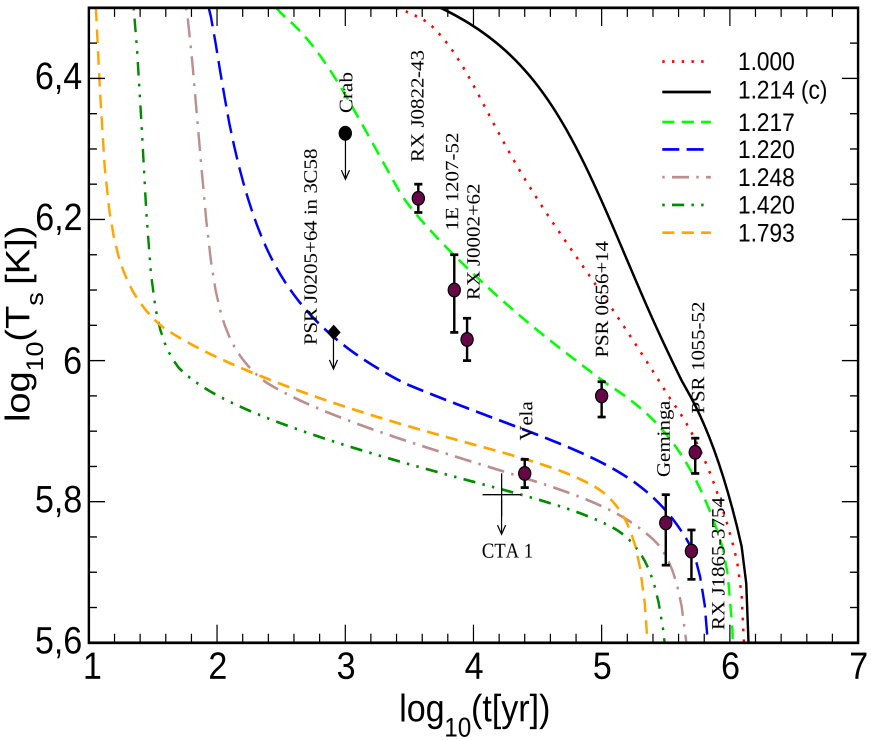


2SC phase - 1 color is unpaired
(mixed superconductivity)

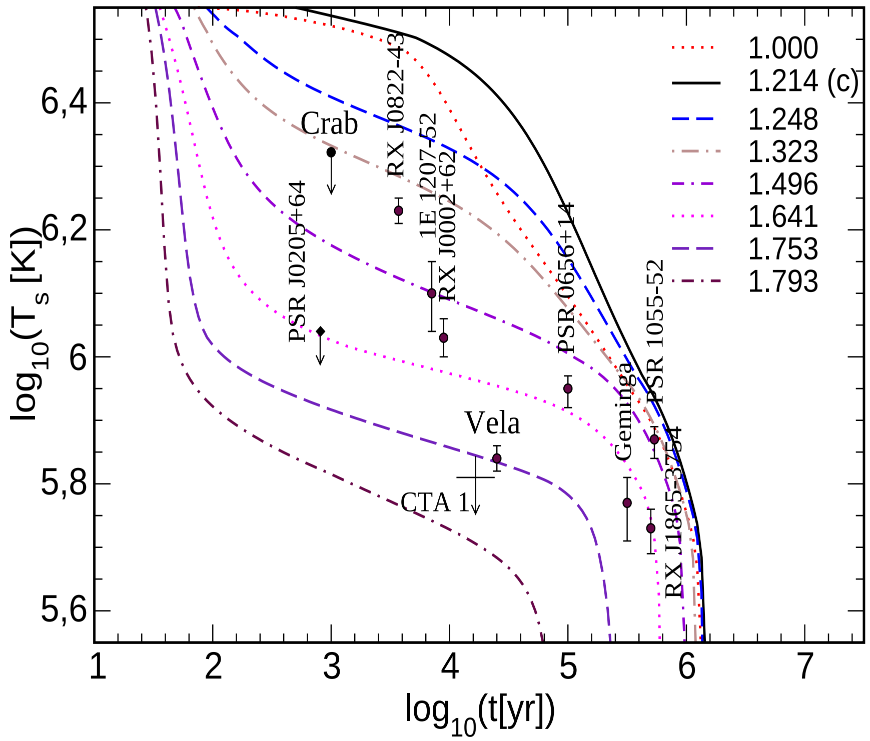
2SC + X phase,
$\Delta_X = 1$ MeV

Grigorian, D.B., Voskresensky, PRC 71 (2005)

Hybrid Star Cooling with 2SC Quark Matter



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

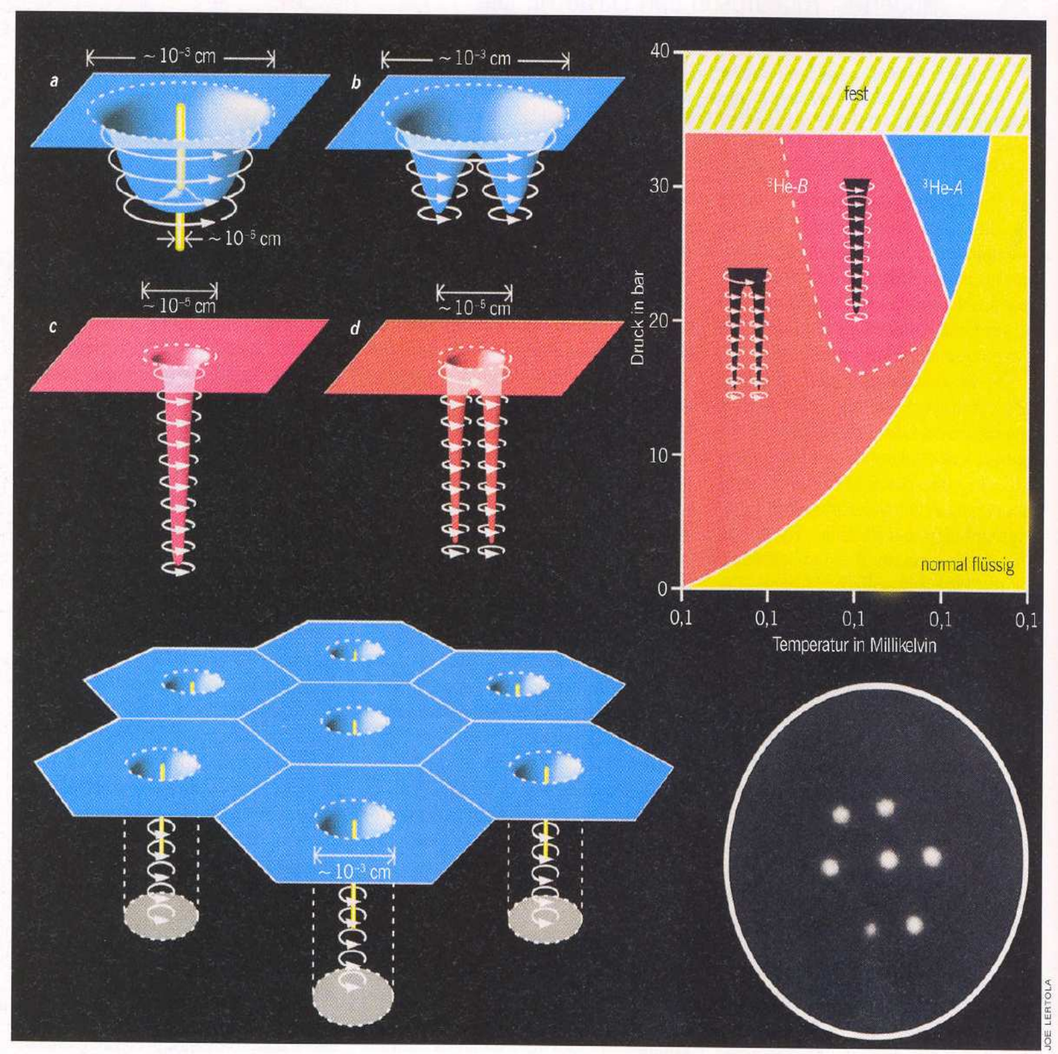


2SC + X phase, - μ dependent gap

$\Delta_X(\mu) = 1\ \mathbf{MeV}\ \exp(10(1 - \mu/\mu_c))$

Grigorian, D.B., Voskresensky, PRC 71 (2005)

Spin-1 (CSL) Phase for Compact Stars

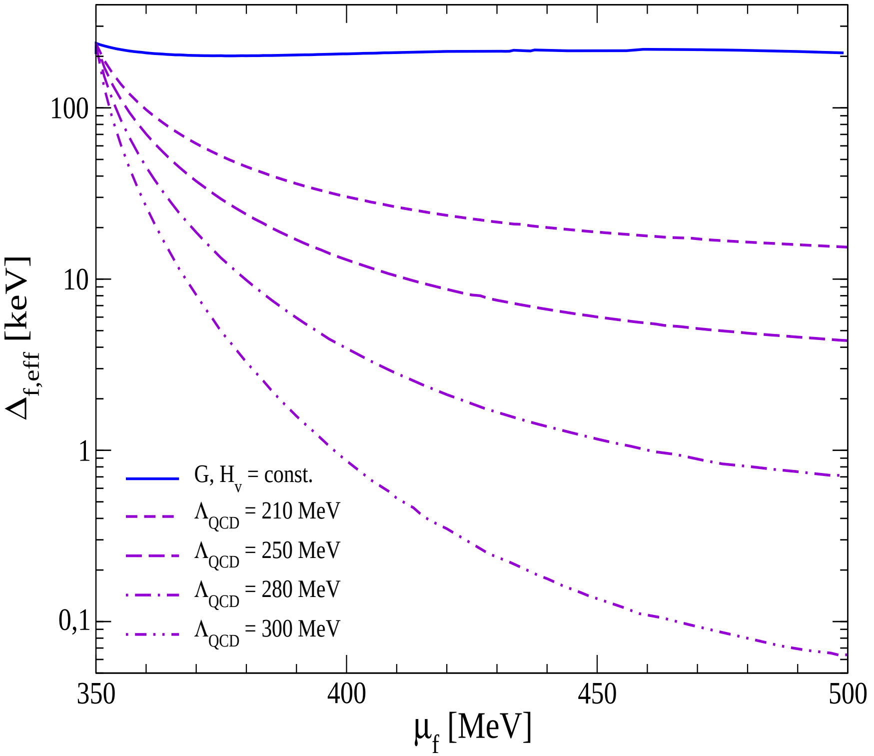


Phases of superfluid ^{3}He

Color-spin-locking (CSL) condensate

Aguilera et al., hep-ph/0503288 $\rightarrow$ PRD

$$\langle q_f^T \; C\gamma^3\lambda_2 \; q_f\rangle = \langle q_f^T \; C\gamma^1\lambda_7 \; q_f\rangle = \langle q_f^T \, C\gamma^2\lambda_5 \, q_f\rangle \equiv \eta_f \; ,$$



Conclusions

Theory of EoS with Constraints

- Nuclear Matter - Quark Matter Phase transition depends on details of the modeling, e.g. Coupling Constants, Form Factors $\Rightarrow$ Improve by using DSE Models
- Stable Neutron Stars with 2-Flavor Quark Matter Core possible

Experimental Observables

- **Observation of Compact Star Configurations:**

  $\Rightarrow$ A very massive star ($M > 2M_\odot$) makes quark core configurations implausible

  $\Rightarrow$ A very compact star ($R < 10$ km) makes corresponding hadronic stars very unlikely

- **Cooling Evolution:**

  $\Rightarrow$ Hadronic EoS should not support DU process ($x > 11$ %) for typical star masses $M \leq 1.4\ M_\odot$

  $\Rightarrow$ Medium effects are required; ${}^3P_2$ neutron pairing gap has to be suppressed

  $\Rightarrow$ Quark matter core $\Rightarrow$ all quarks gapped, $\Delta_{\rm min} \approx 30$ keV, $\Rightarrow$ 2SC+X oder CSL phase?

  $\Rightarrow$ CFL phase unlikely, critical density (and gaps) too large, gCFL only at $T > 50$ MeV

  $\Rightarrow$ Decreasing $\Delta(n)$ would explain cooling by hybrid stars

THANK YOU

COLLABORATION

- Virtual Institute ’Dense Hadronic Matter and QCD Phase Transition’ at GSI Darmstadt, with the Color Superconductivity Seminar at Frankfurt and Darmstadt
- Deborah Aguilera, Jens Berdermann, Michael Buballa, Hovik Grigorian, Thomas Klähn, Sergei Popov, Fredrik Sandin, Roberto Turolla, Valery Yudichev, Dmitry Voskresensky, ...

ECT* WORKSHOP

’The New Physics of Compact Stars’, Trento, Sept. 12-16, 2005

Virtual Institute of the Helmholtz−Association

Dense Hadronic Matter and QCD Phase Transition