NEUTRON STAR COOLING

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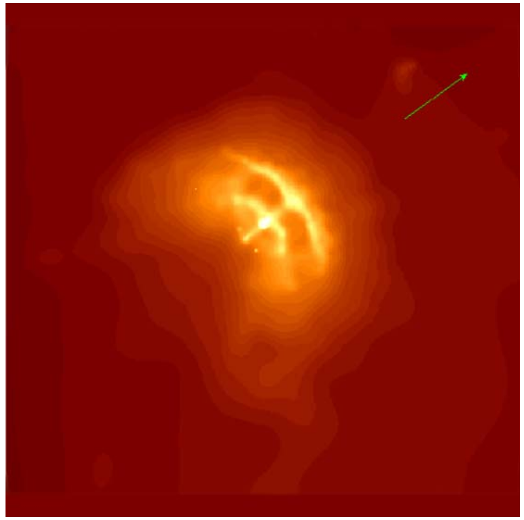
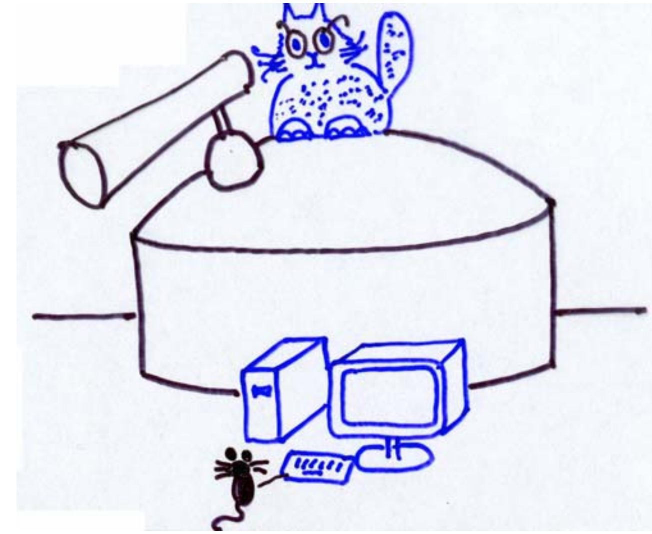
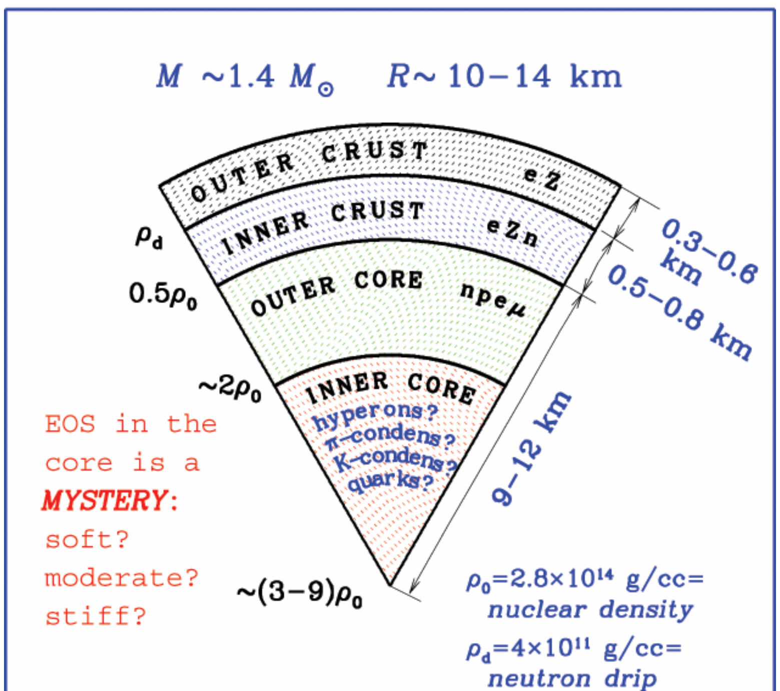
- **Introduction**
- **Theory**
- **Theory versus observations**
- **Conclusions and the end**

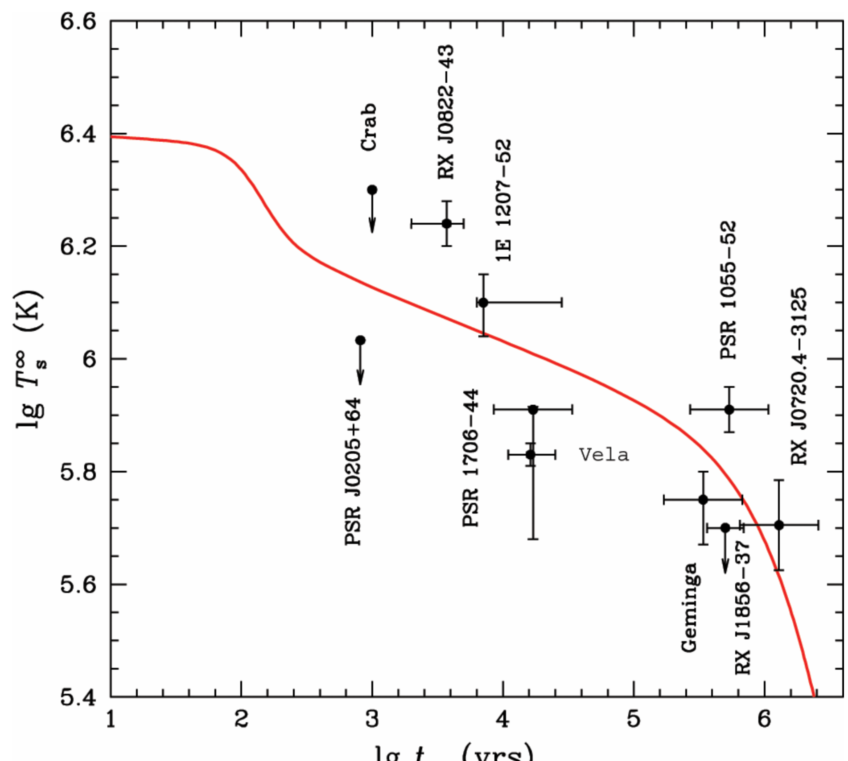
MSU, September, 2004,

Chandra image of the Vela pulsar wind nebula NASA/PSU Pavlov et al









Basic concepts of the cooling theory

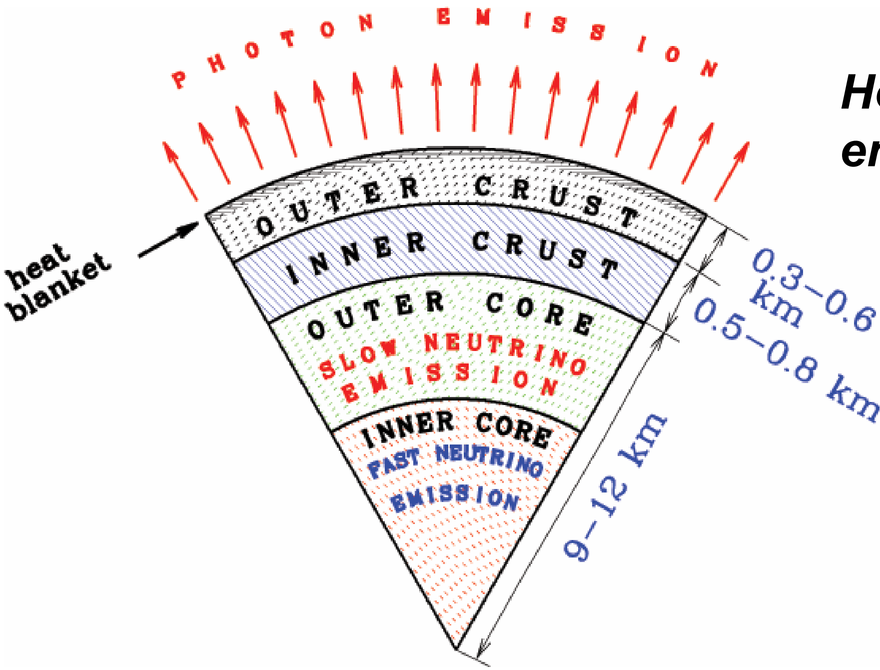
Thermal balance:

$$C(T)\frac{dT}{dt} = -L_\nu(T) - L_\gamma(T_s)$$

Photon luminosity: $L_\gamma = 4\pi\sigma R^2 T_s^4$

Heat blanketing envelope: $T_s = T_s(T)$

Heat content: $U_T \sim 10^{48}\ T_9^2\ \ ergs$



Neutrino emission: slow and/or fast?

Main cooling regulators:

1. EOS
2. Neutrino emission
3. Superfluidity
4. Magnetic fields
5. Light elements on the surface

HISTORY

Old

Stabler 1960

Chiu 1964

Morton 1964

Chiu & Salpeter 1964

Bahcall & Wolf 1965

Tsuruta & Cameron 1966

New

Lattimer, Pethick, Prakash & Haensel 1991

Page & Applegate 1992

Schaab, Voskresensky, Sedra-kian, Weber & Weigel 1997

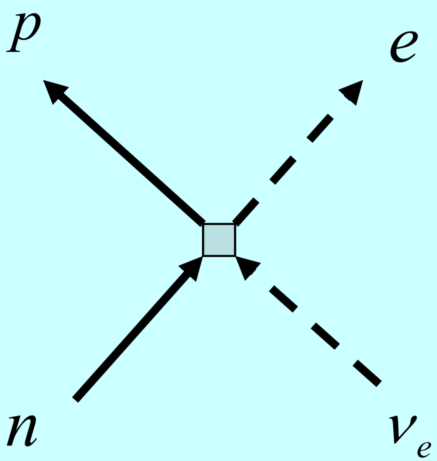
Page 1998

Direct Urca (Durca) process

Lattimer, Pethick, Prakash, Haensel (1991)

$$n \to p + e + \bar{\nu}_e \quad , \quad p + e \to n + \nu_e$$

$$n \to n + \bar{\nu}_e + \nu_e$$



$$Q = 2\int w_{i\to f}\,\varepsilon_\nu\, f_n\,(1-f_p)(1-f_e)\,d\Gamma$$

$$Q = \frac{457\pi}{10080} G^2 (1+3g_A^2) \frac{m_n^* m_p^* m_e^*}{\hbar^{10} c^3} T^6 \Theta_{npe}$$

$$Q \sim 3\times 10^{27}\, T_9^6 \quad erg\ cm^{-3}\ s^{-1} \quad \Rightarrow \quad L_\nu \sim 10^{46}\ T_9^6 \quad erg\ s^{-1}$$

Threshold: $p_{Fn} \le p_{Fp} + p_{Fe}$ ⇒ $\rho \gtrsim 2\rho_0$ ⇒ **in the inner cores of massive stars**

Similar processes with muons : produce ν_μ

Similar processes with hyperons, e.g.: $n \to \Lambda$

Inner cores of massive neutron stars:

Nucleons, hyperons	$n \to p + e + \bar{\nu}_e$ $p + e \to n + \nu_e$	$Q \sim 3 \times 10^{27}\, T_9^6 \ \frac{erg}{cm^3\ s}$	$L_\nu \sim 10^{46}\, T_9^6 \ \frac{erg}{s}$
Pion condensates	$\tilde{n} \to \tilde{p} + e + \bar{\nu}_e$ $\tilde{p} + e \to \tilde{n} + \nu_e$	$Q \sim 10^{24-26}\, T_9^6 \ \frac{erg}{cm^3\ s}$	$L_\nu \sim 10^{42-44}\, T_9^6 \ \frac{erg}{s}$
Kaon condensates	$\tilde{q} \to \tilde{q} + e + \bar{\nu}_e$ $\tilde{q} + e \to \tilde{q} + \nu_e$	$Q \sim 10^{23-24}\, T_9^6 \ \frac{erg}{cm^3\ s}$	$L_\nu \sim 10^{41-42}\, T_9^6 \ \frac{erg}{s}$
Quark matter	$d \to u + e + \bar{\nu}_e$ $u + e \to d + \nu_e$	$Q \sim 10^{23-24}\, T_9^6 \ \frac{erg}{cm^3\ s}$	$L_\nu \sim 10^{41-42}\, T_9^6 \ \frac{erg}{s}$

Everywhere in neutron star cores

Modified Urca (Murca)	$n + N \to p + e + N + \bar{\nu}_e$ $p + e + N \to n + N + \nu_e$	$Q \sim 10^{20-22}\, T_9^8 \ \frac{erg}{cm^3\ s}$	$L_\nu \sim 10^{38-40}\, T_9^8 \ \frac{erg}{s}$
Brems-strahlung	$N + N \to N + N + \nu + \bar{\nu}$ ⇩ $\nu_e,\ \nu_\mu,\ \nu_\tau$	$Q \sim 10^{18-20}\, T_9^8 \ \frac{erg}{cm^3\ s}$	$L_\nu \sim 10^{36-38}\, T_9^8 \ \frac{erg}{s}$

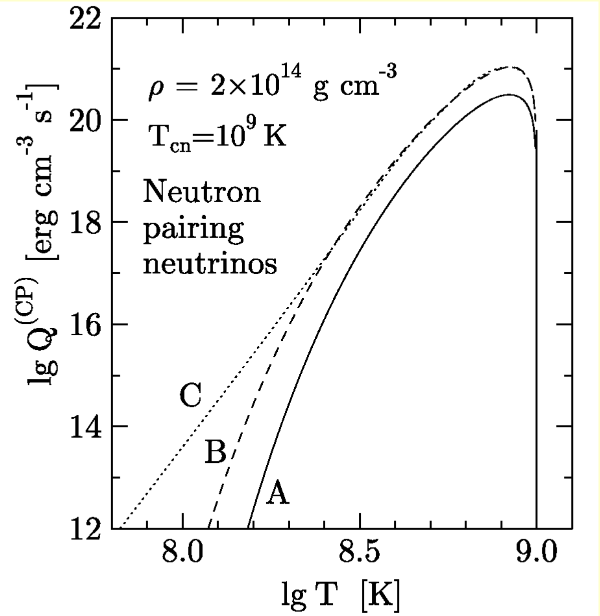
Effects of superfluidity

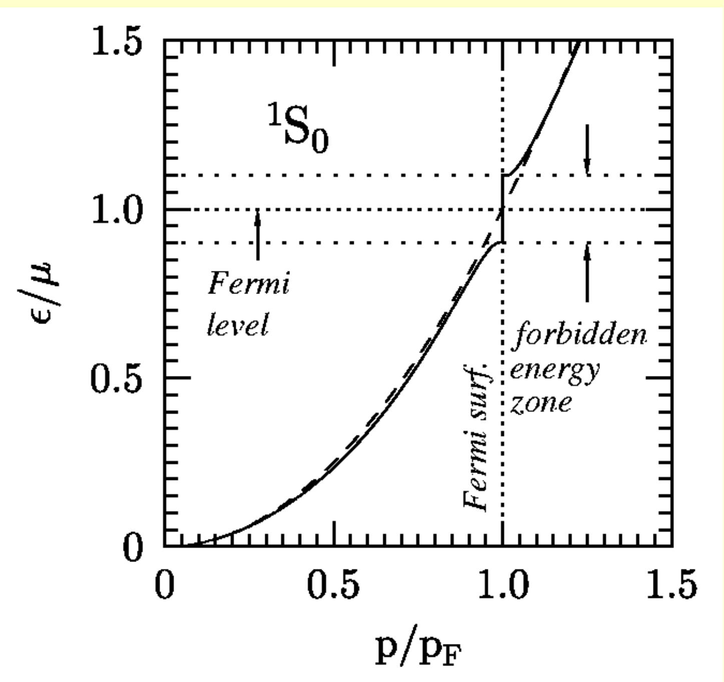
Cooper pairing at $T<T_c$

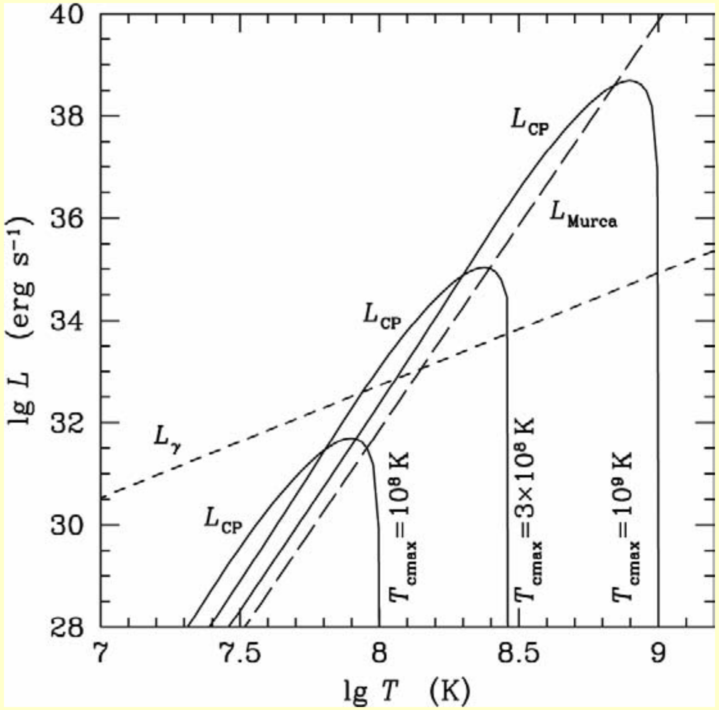
- **suppresses familiar neutrino processes**
- **creates a new process: neutrino emission due to Cooper pairing**

Flowers, Ruderman and Sutherland 1976

$$L_\nu^{Cooper} \sim (10-100)\ L_\nu^{Murca} \propto T^8$$







Welcome to the Urca World

1. Gamow and Shoenberg: Casino da Urca in Rio de Janeiro

   Neutrino theory of stellar collapse, Phys. Rev. 59, 539, 1941:

   Unrecordable cooling agent

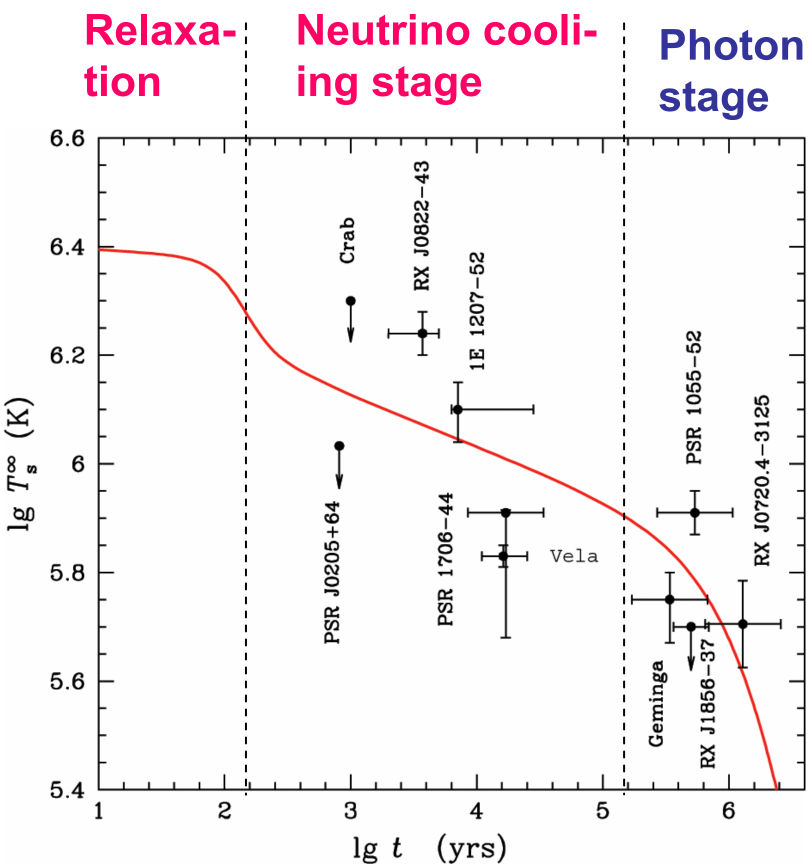
2. Kseniya Levenfish: St.-Petersburg

   Direct Urca -- Durca

   Modified Urca -- Murca

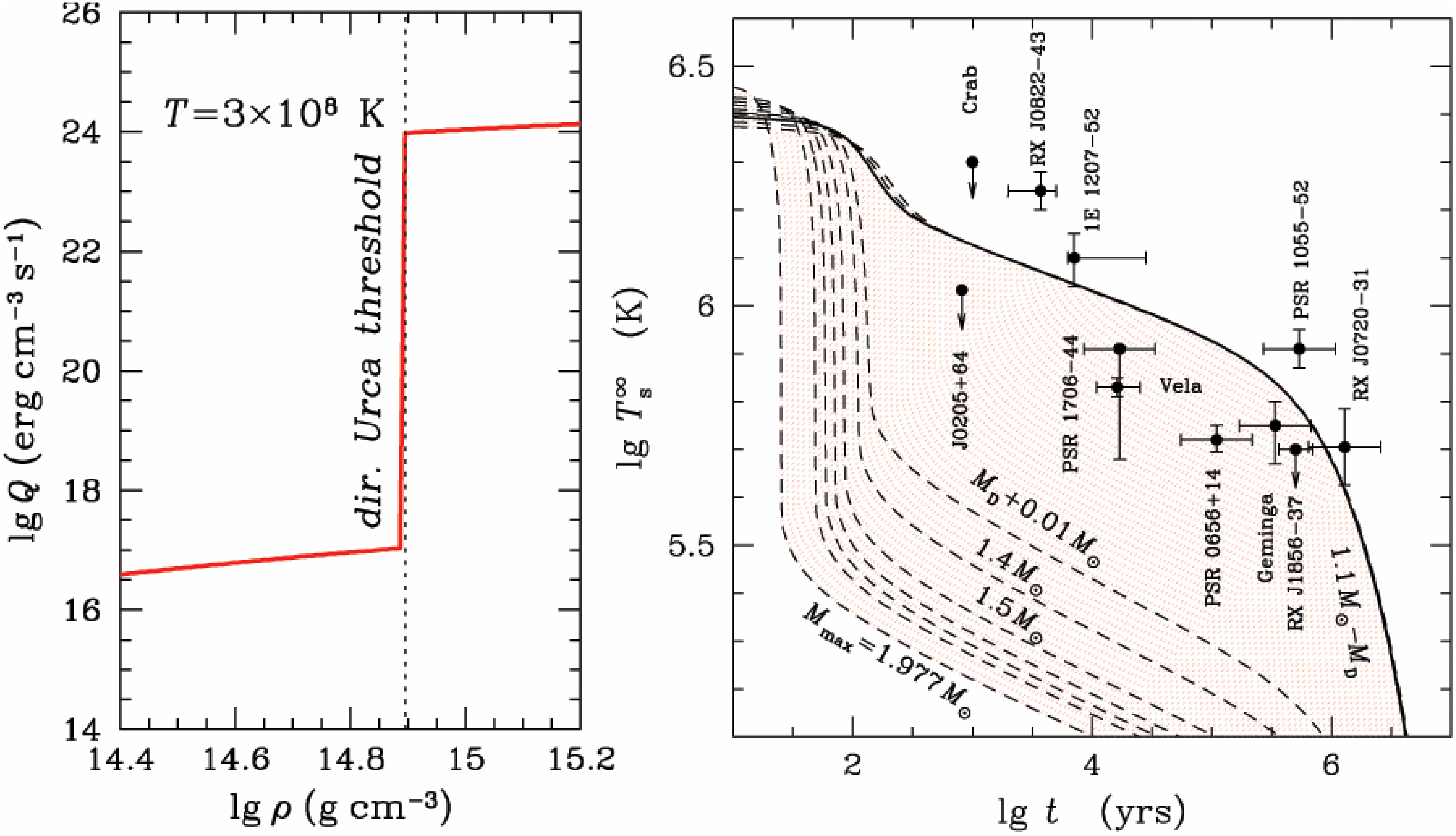
OBSERVATIONS AND BASIC COOLING CURVE

Nonsuperfluid star
Murca neutrino emission:
slow cooling



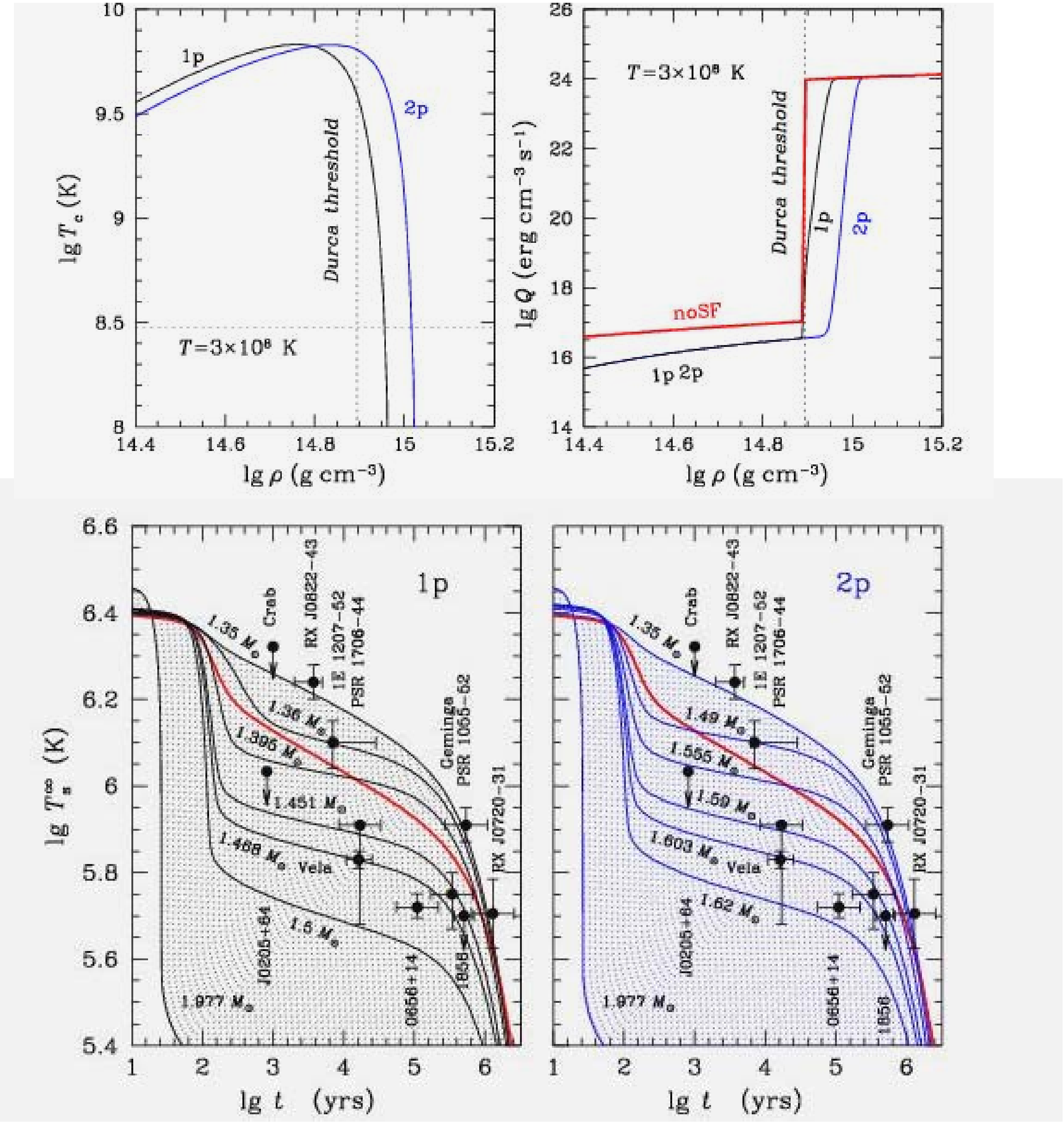
Yakovlev & Pethick 2004

NONSUPERFLUID STARS: MURCA VERSUS DURCA

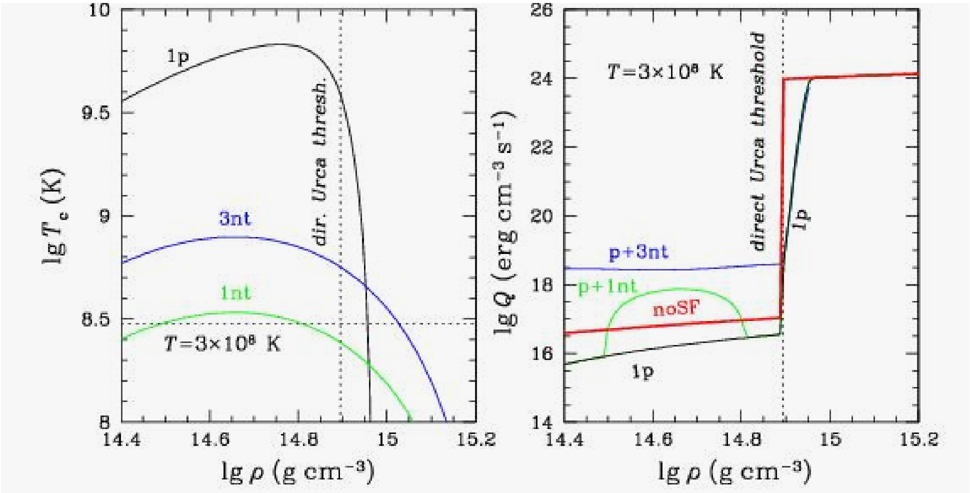


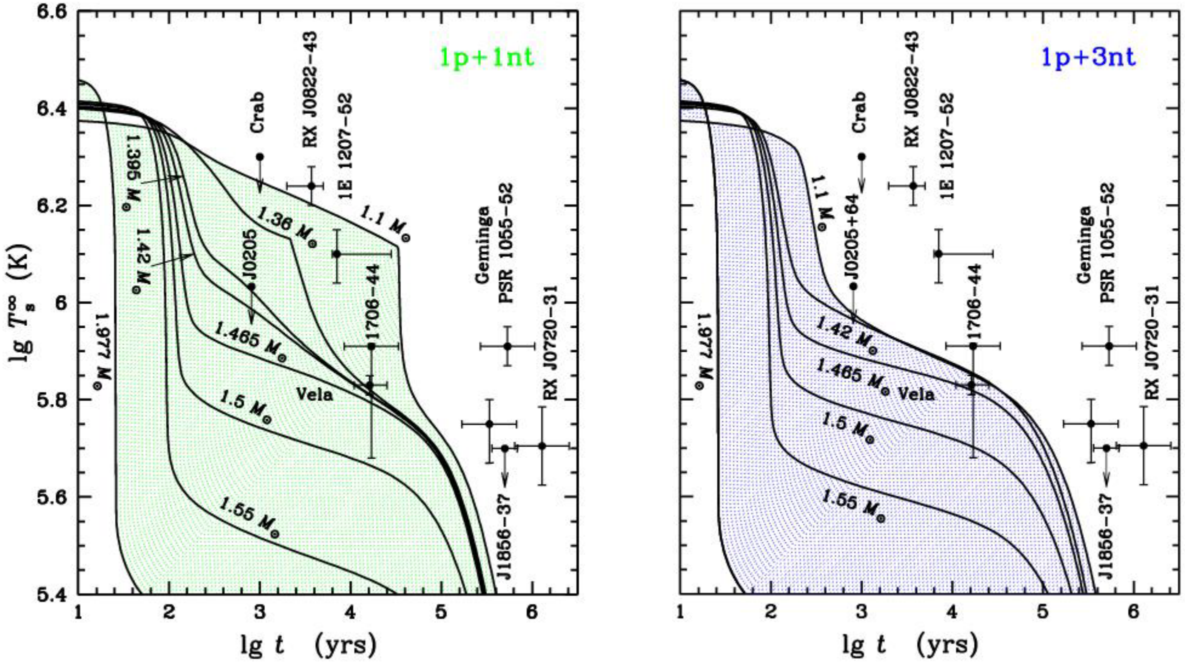
Yakovlev & Pethick 2004

Neutron stars with proton superfluidity in the cores



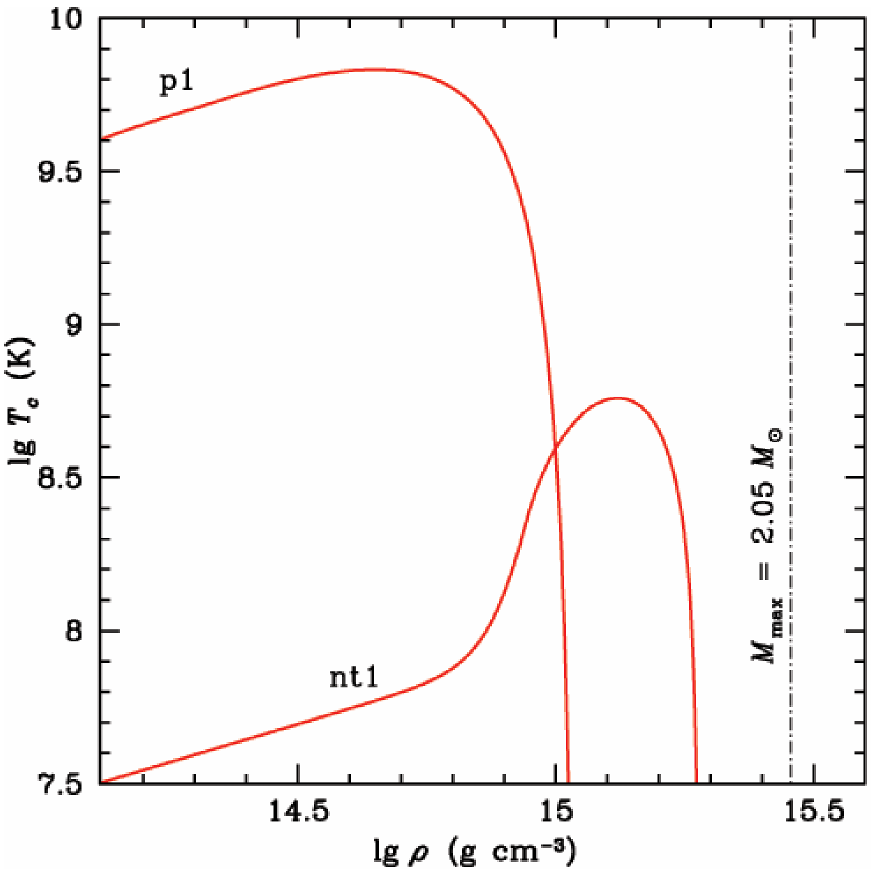
Neutron stars with proton and mild neutron superfluidities in the cores

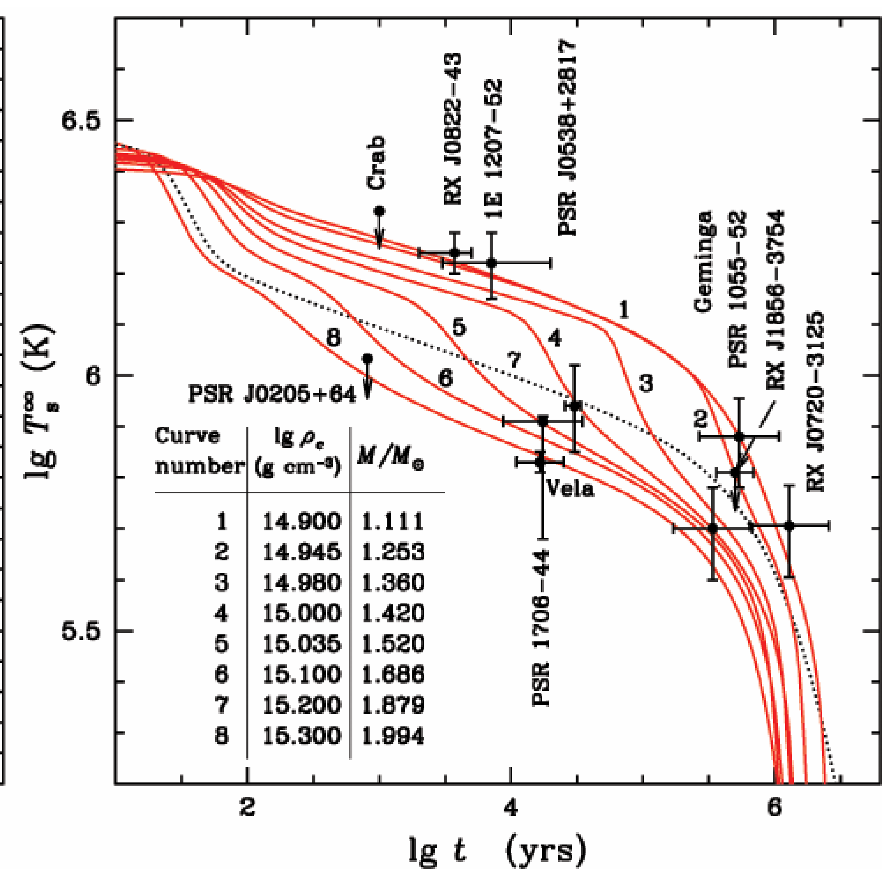




Harmful mild neutron pairing

SUPERFLUID NUCLEON STARS WITHOUT DURCA



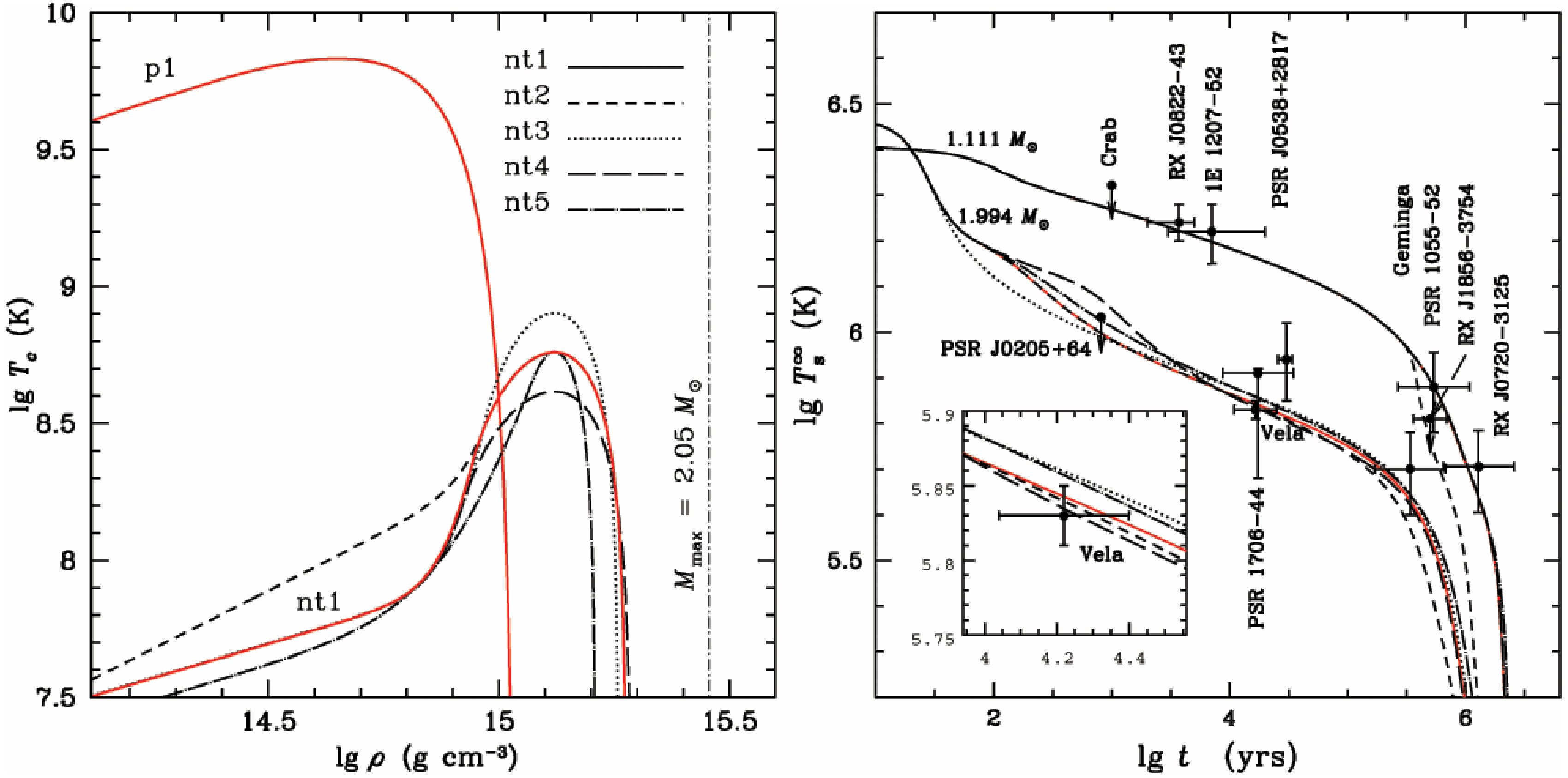


EOS: Douchin & Haensel 2001

Gusakov, Kaminker, Yakovlev, Gnedin 2004
Page, Lattimer, Prakash, Steiner 2004 – minimal cooling model

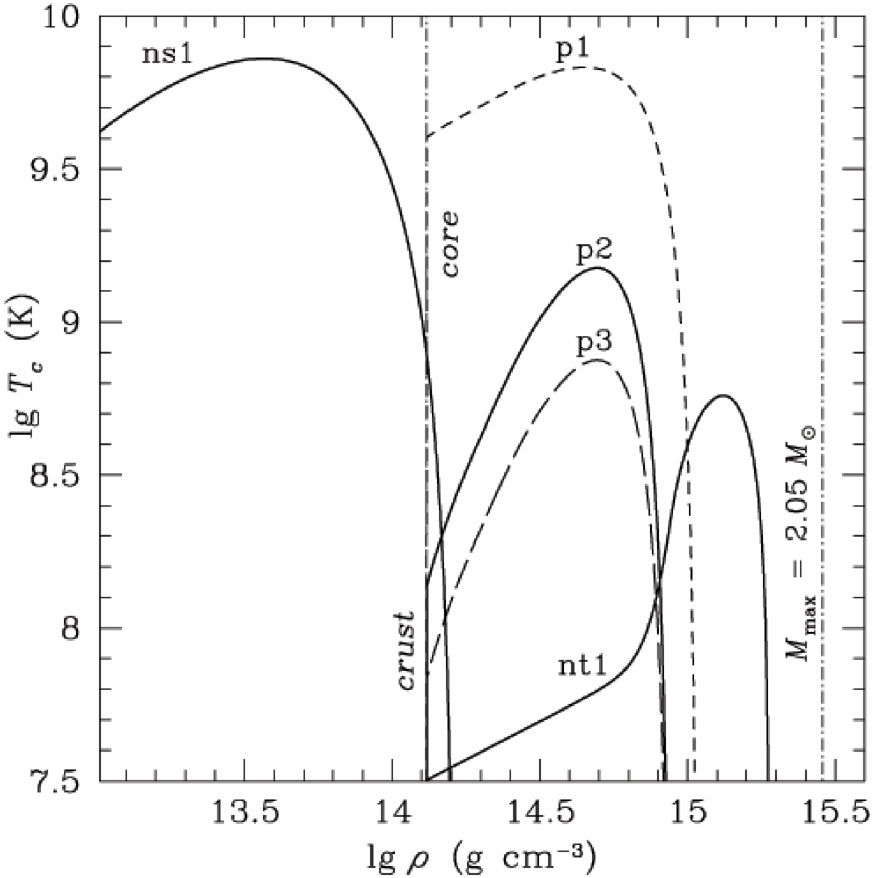
Useful mild neutron pairing

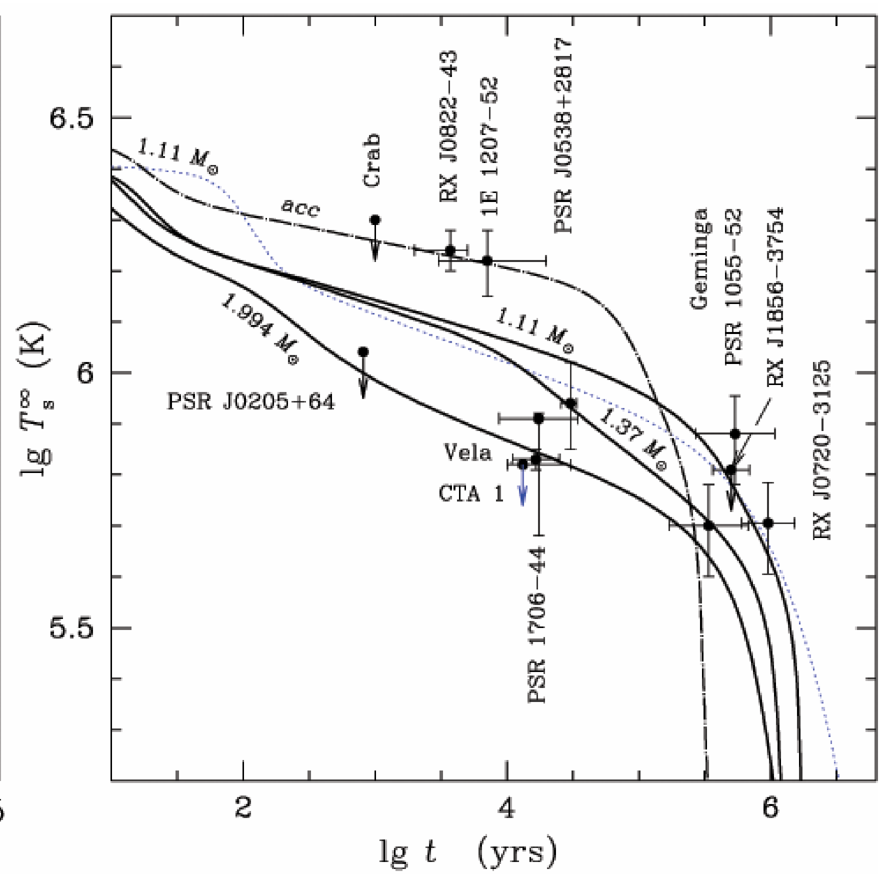
TESTING COOLING MODELS WITHOUT DURCA



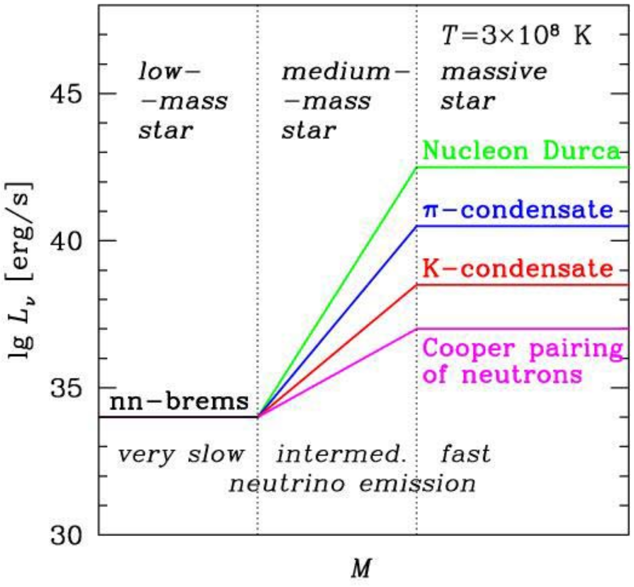
Gusakov, Kaminker, Yakovlev, Gnedin 2004

SUPERFLUID NEUTRON STARS WITHOUT DURCA BUT WITH ACCRETED ENVELOPES

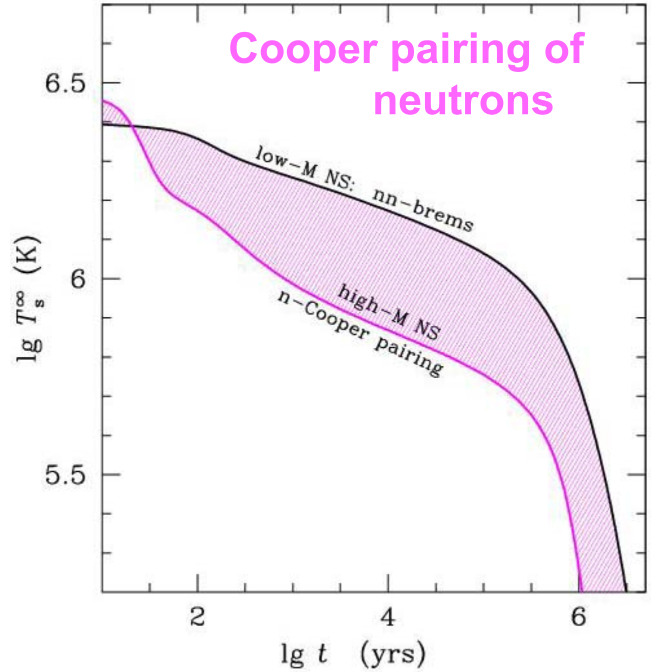


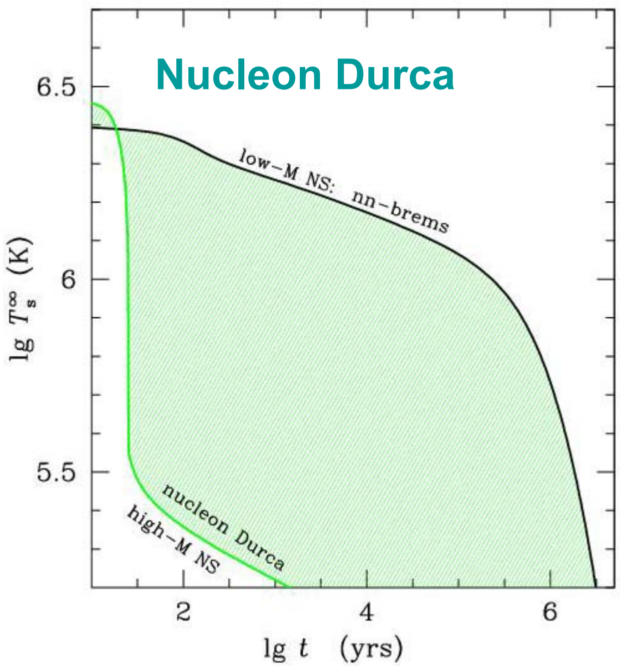


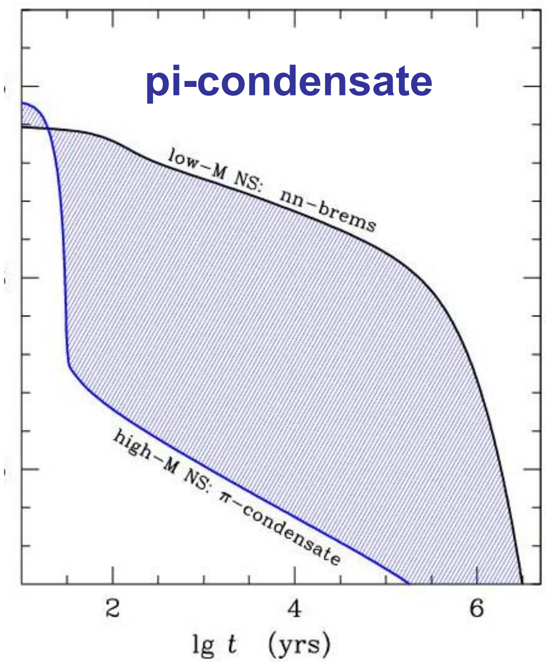
Kaminker, Gusakov, Yakovlev, Gnedin 2004

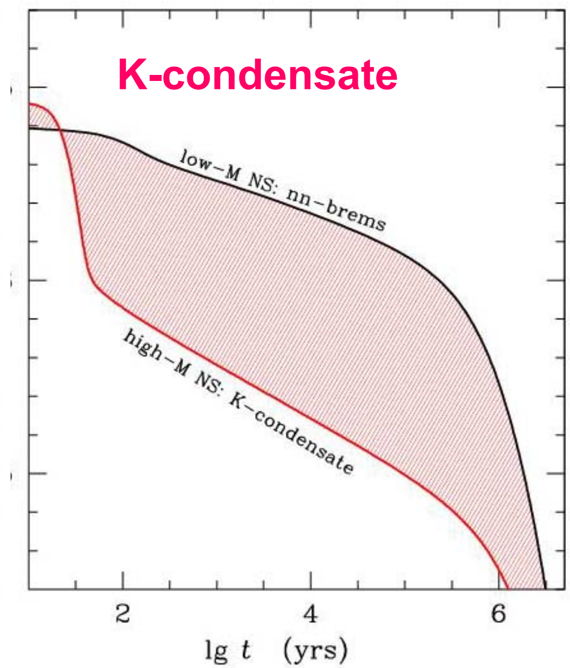


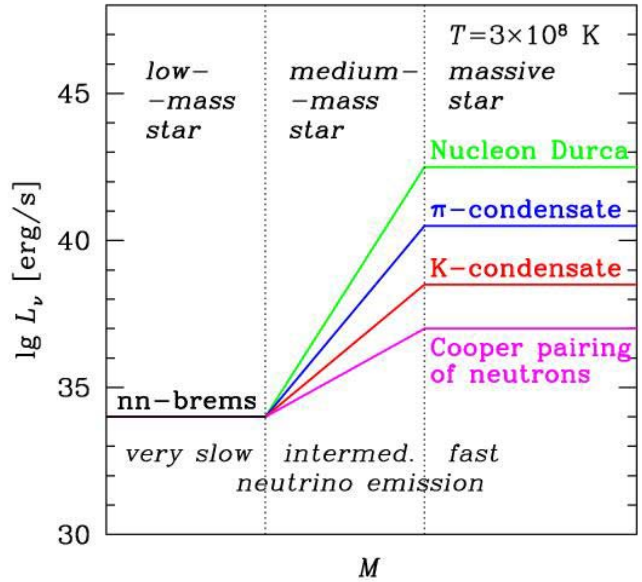
SIMILAR THEORY OF SXRTs



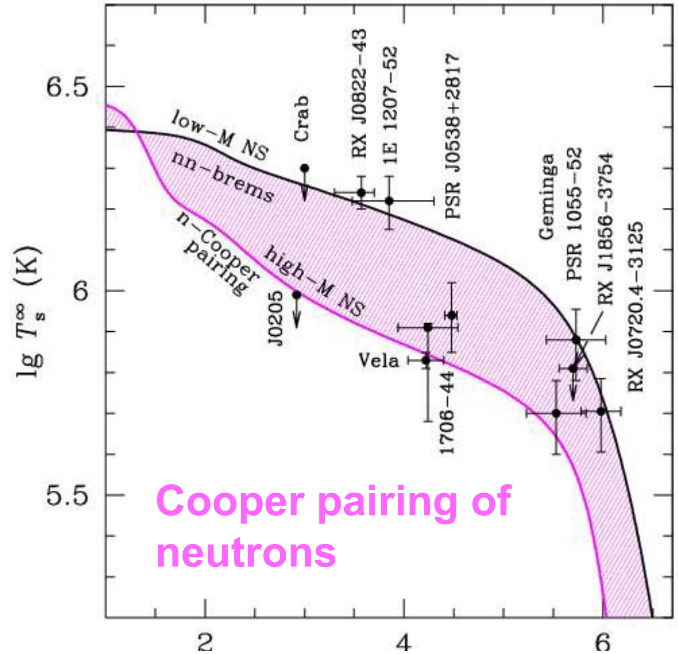


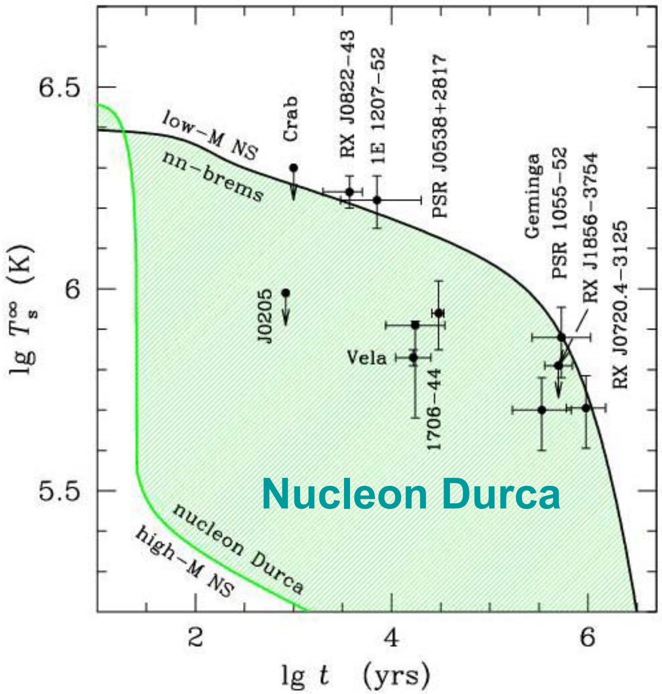


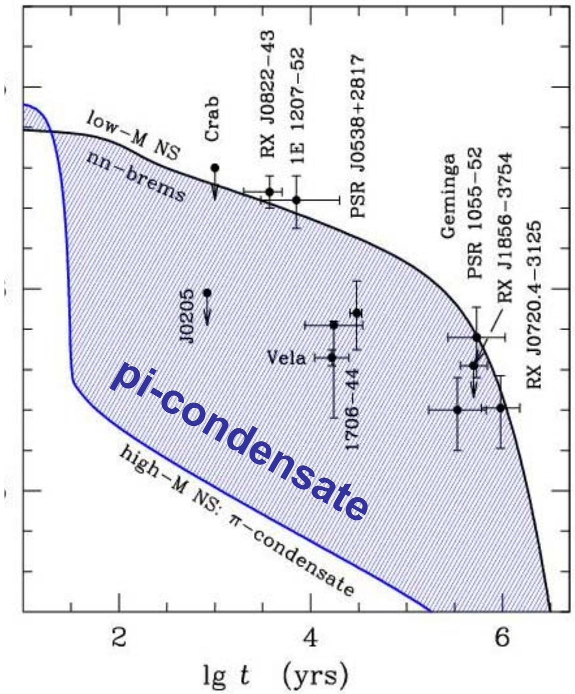


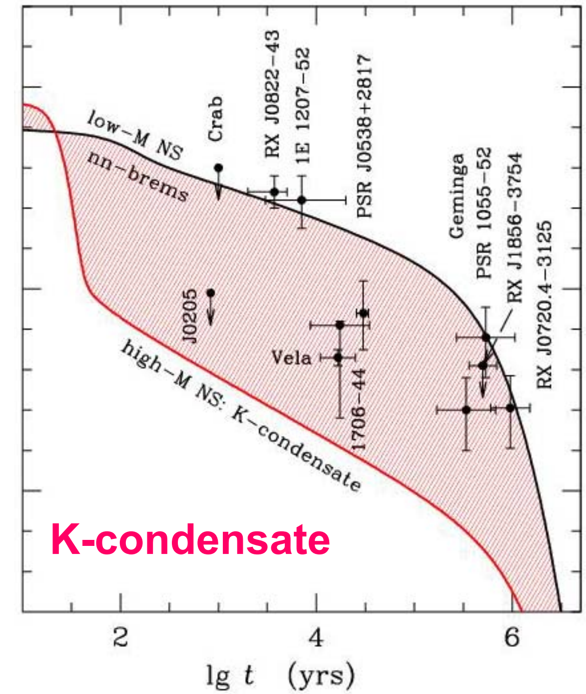


THEORY versus OSERVA- TIONS



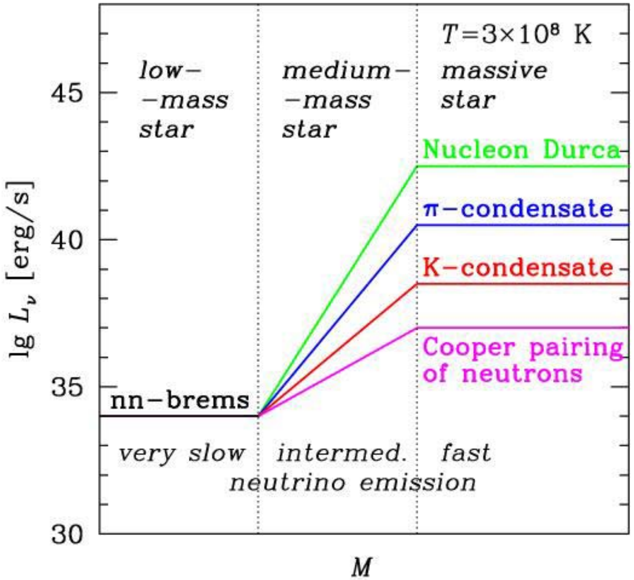


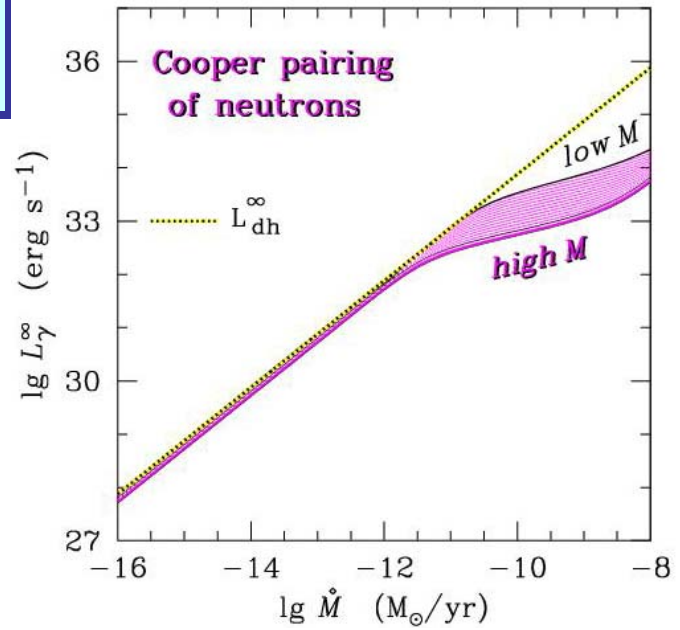


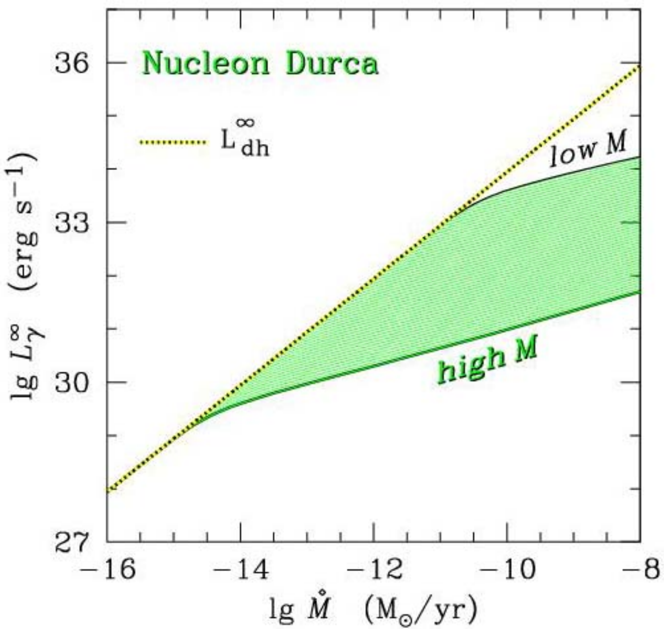


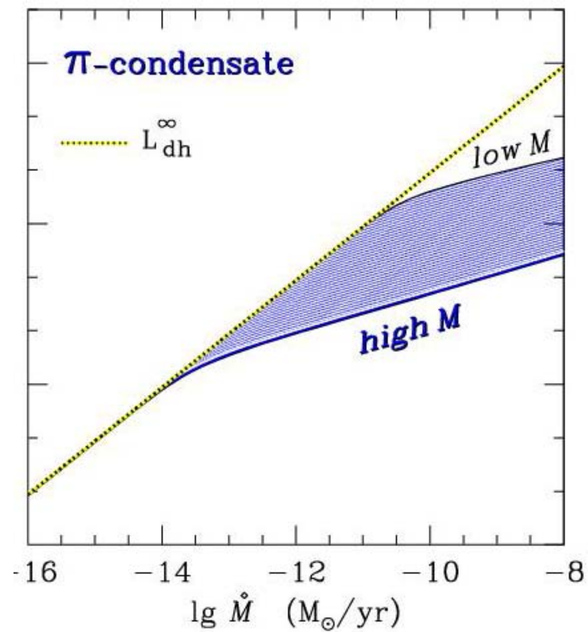
Theory of thermal states of SXRTs

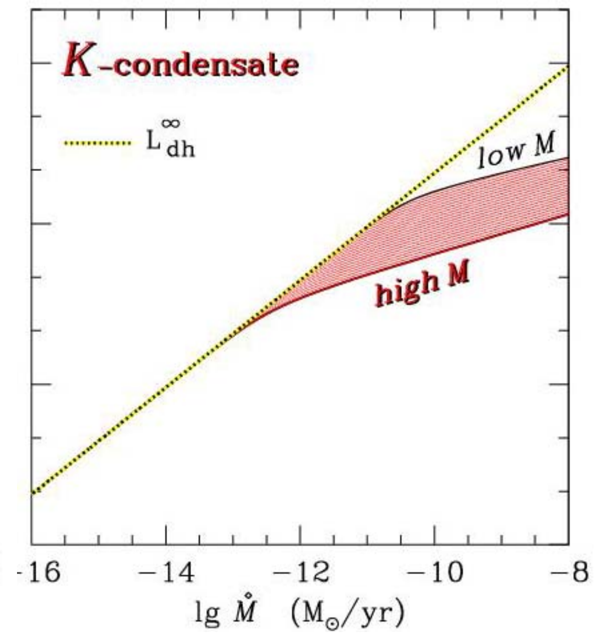
Yakovlev, Levenfish & Haensel, 2003



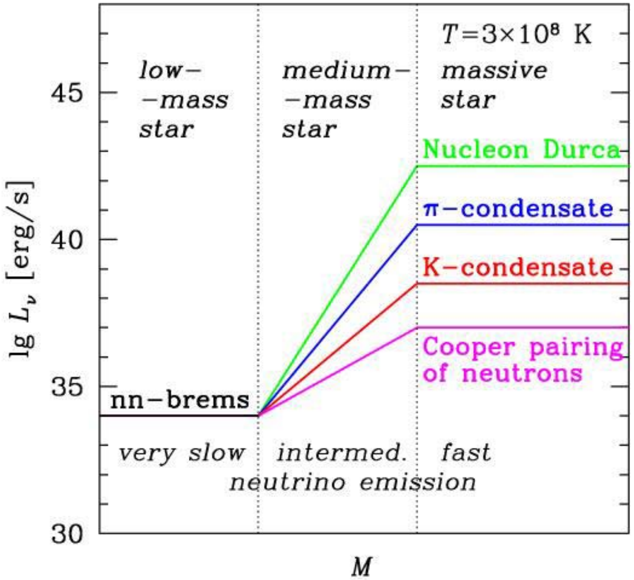


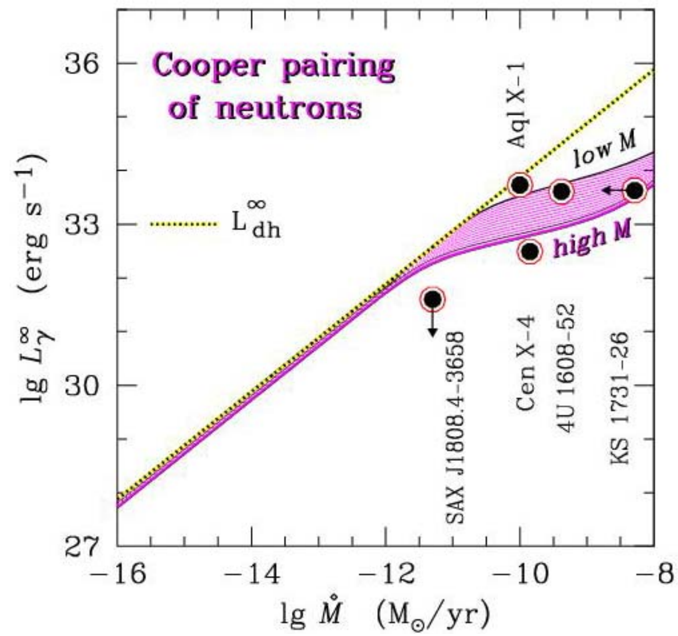


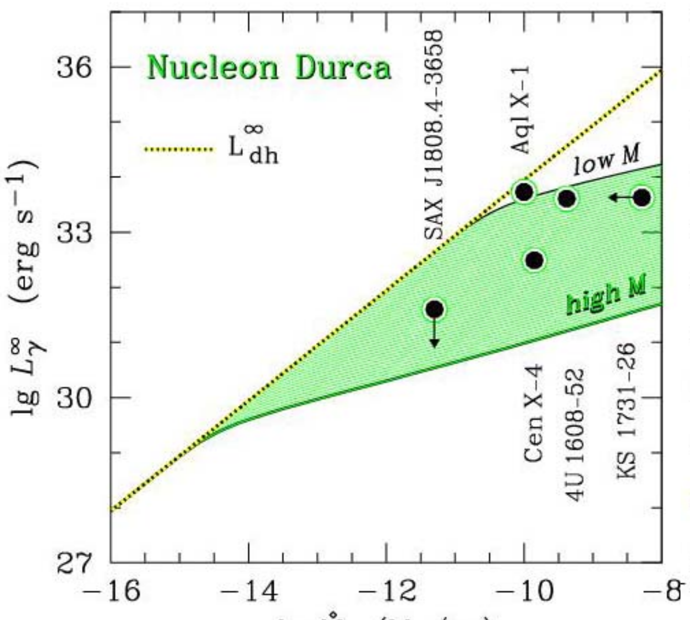


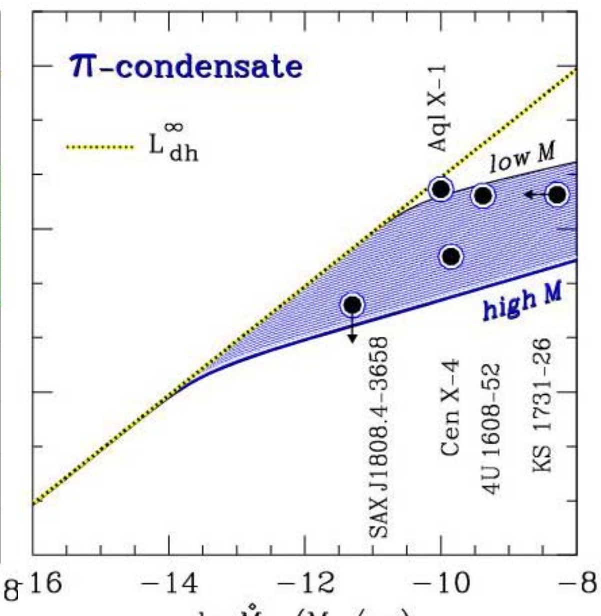


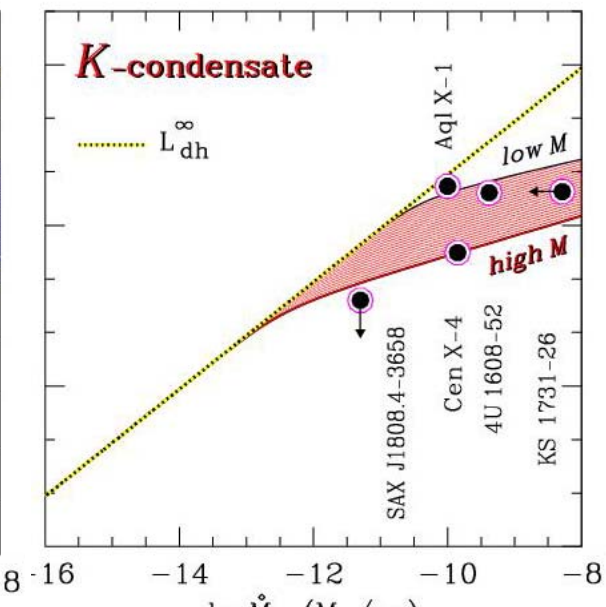
THEORY VERSUS OBSERVATIONS











LEFT BEHIND

Sophisticated EOSs and models: strange stars, color superconductivity, localized protons, etc

Cooling of young stars (thermal relaxation stage, t<100 years; the physics of the matter of subnuclear density) – Lattimer et al. 1994; Gnedin et al. 2001

Cooling of old stars (t>1 Myr; reheating mechanisms) – Alpar et al. 1987, Shibazaki & Lamb 1989

Cooling of neutron stars with magnetic fields and accreted envelopes – thermal evolution combined with the evolution of magnetic field and burning of light elements in the surface layers

Symmetry of cooling behavior with respect to exchanging proton and neutron superfluidities – Kaminker et al. 2004

The effects of crustal superfluidity

Cooling of accreting neutron stars – e.g., in soft X-ray transients with deep crustal heating of accreted matter – Haensel & Zdunik 1990, Brown et al. 1998

CONCLUSIONS

There are several very different cooling scenarios. All require enhanced neutrino cooling and can explain the observations.

All scenarios predict the acceleration of cooling with increasing neutron-star mass – mass ordering

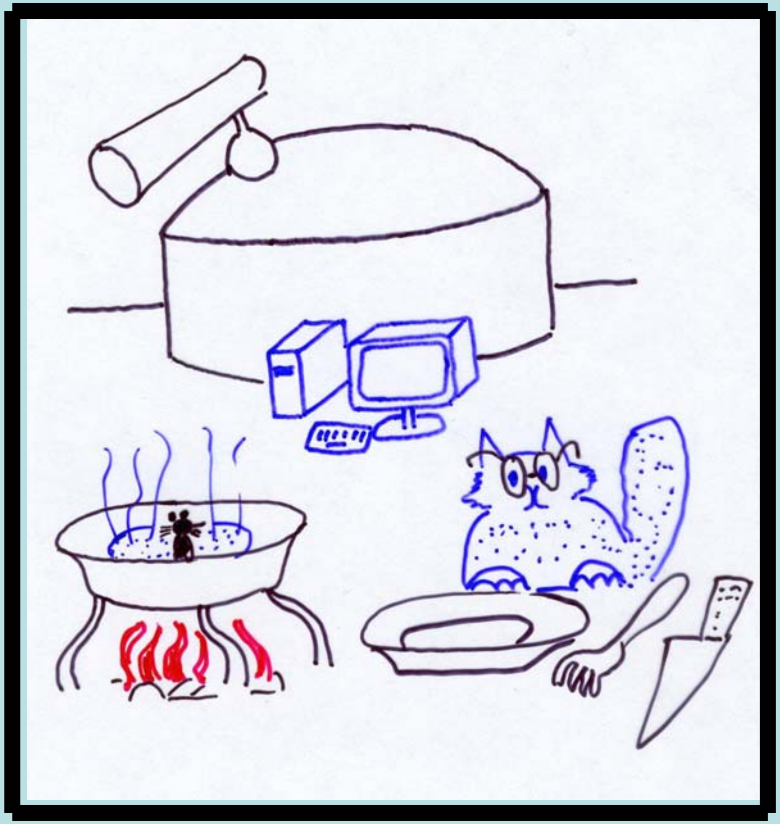
The cooling of middle-aged stars is strongly regulated by EOS and superfluidity

There should be no mild superfluidity in outer neutron star cores

New observations of the coldest and hottest neutron stars are most important

Other observational evidences (cold isolated neutron stars; transiently accreting neutron stars, measurements of masses and radii, spectral lines, etc) would be helpful

New theoretical results (EOS, superfluidity, etc) are welcome



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