Neutron Stars and Pulsars: about 40 Years after their Discovery

363th Heraeus-Seminar, Bad Honnef, May 14-19, 2006

Thermal Emission

from

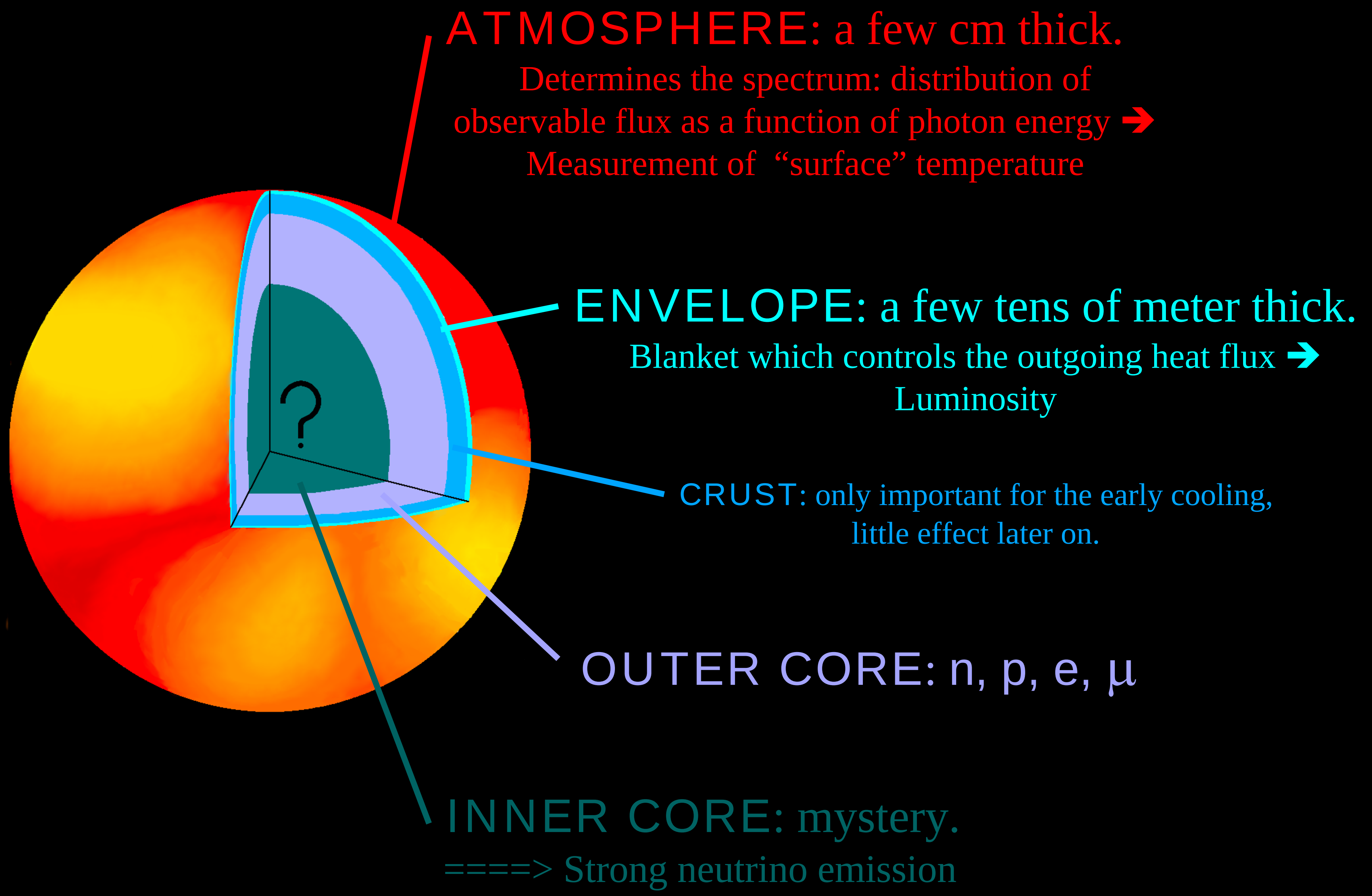
Cooling Neutron Stars

Dany Page

Instituto de Astronomía, UNAM, Mexico

PART I

Neutron Star Cooling in a nutshell


ATMOSPHERE: a few cm thick.
Determines the spectrum: distribution of observable flux as a function of photon energy ➔ Measurement of "surface" temperature
ENVELOPE: a few tens of meter thick.
Blanket which controls the outgoing heat flux ➔ Luminosity
CRUST: only important for the early cooling, little effect later on.
OUTER CORE: n, p, e, μ
INNER CORE: mystery.
====> Strong neutrino emission
?

The Equations of Neutron Star Cooling

Schwarzschild metric:

$$ds^2 = -e^{2\Phi}\, c^2 dt^2 + \frac{dr^2}{1 - 2Gm/c^2 r} + r^2 d\Omega^2.$$

Gravitational mass:

$$\frac{dm}{dr} = 4\pi r^2 \rho, \qquad m(r=0) = 0$$

Gravitational potential:

$$\frac{d\Phi}{dr} = \frac{Gmc^2 + 4\pi G r^3 P}{c^4 r^2 (1 - 2Gm/c^2 r)}, \qquad e^{\Phi(R)} = \sqrt{1 - \frac{2GM}{c^2 R}},$$

Hydrostatic equilibrium:

(Tolman-Oppenheimer-Volkov)

$$\frac{dP}{dr} = -(\rho c^2 + P)\frac{d\Phi}{dr} = -\frac{(\rho + P/c^2)(Gm + 4\pi G r^3 P/c^2)}{r^2(1 - 2Gm/c^2 r)}. \qquad P(r=0) = P_c$$

Energy conservation:

$$\frac{d(Le^{2\Phi})}{dr} = -\frac{4\pi r^2 n e^{\Phi}}{\sqrt{1 - 2Gm/c^2 r}} \left(\frac{d\epsilon}{dt} + e^{\Phi}(q_\nu - q_h)\right) \qquad L(r=0) = 0$$

$$\frac{d\epsilon}{dt} = \frac{d\epsilon}{dT} \cdot \frac{dT}{dt} = c_v \cdot \frac{dT}{dt}$$

Heat transport:

$$\frac{d(Te^{\Phi})}{dr} = -\frac{3}{16\sigma_{SB}} \frac{\kappa\rho}{T^3} \frac{Le^{\Phi}}{4\pi r^2 \sqrt{1 - 2Gm/c^2 r}} \qquad T_b = T_b(L_b)$$

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STRUCTURE

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The Equations of Neutron Star Cooling

Most of it is just energy balance:

$$\frac{dE_{th}}{dt} = C_V \frac{dT}{dt} = -L_\nu - L_\gamma$$

E_{th} = Total thermal energy content [erg]

C_V = specific heat [erg K^{-1}]

L_ν = neutrino luminosity [erg s^{-1}]

L_γ = photon luminosity [erg s^{-1}]

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L_{ν} = neutrino luminosity [erg s^{-1}]

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$$\frac{dE_{th}}{dt} = C_{\mathrm{V}} \frac{dT}{dt} = -L_{\nu} - L_{\gamma} + H$$

H = Heating rate [erg s^{-1}]

Neutrino Emission Scenarios

Some Core Neutrino Emission Processes and Their Emissivities

Process Name	Process	Emissivity Q_ν[a] (ergs s^{-1} cm^{-3})	Emissivity References
Modified Urca	$\begin{cases} n + n' \to n' + p + e^- + \overline{\nu_e} \\ n' + p + e^- \to n' + n + \nu_e \end{cases}$	$\sim 10^{20} T_9^8$	Friman & Maxwell 1979
Kaon condensate	$\begin{cases} n + K^- \to n + e^- + \overline{\nu_e} \\ n + e^- \to n + K^- + \nu_e \end{cases}$	$\sim 10^{24} T_9^6$	Brown et al. 1988
Pion condensate	$\begin{cases} n + \pi^- \to n + e^- + \overline{\nu_e} \\ n + e^- \to n + \pi^- + \nu_e \end{cases}$	$\sim 10^{26} T_9^6$	Maxwell et al. 1977
Direct Urca	$\begin{cases} n \to p + e^- + \overline{\nu_e} \\ p + e^- \to n + \nu_e \end{cases}$	$\sim 10^{27} T_9^6$	Lattimer et al. 1991
Quark Urca	$\begin{cases} d \to u + e^- + \overline{\nu_e} \\ u + e^- \to d + \nu_e \end{cases}$	$\sim 10^{26} \alpha_c T_9^6$	Iwamoto 1980

[a] T_9 is the temperature in units of 10^9 K.

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Kaon condensate	$\begin{cases} n + K^- \to n + e^- + \bar{\nu}_e \\ n + e^- \to n + K^- + \nu_e \end{cases}$	$\sim 10^{24} T_9^6$	FAST
Pion condensate	$\begin{cases} n + \pi^- \to n + e^- + \bar{\nu}_e \\ n + e^- \to n + \pi^- + \nu_e \end{cases}$	$\sim 10^{26} T_9^6$	
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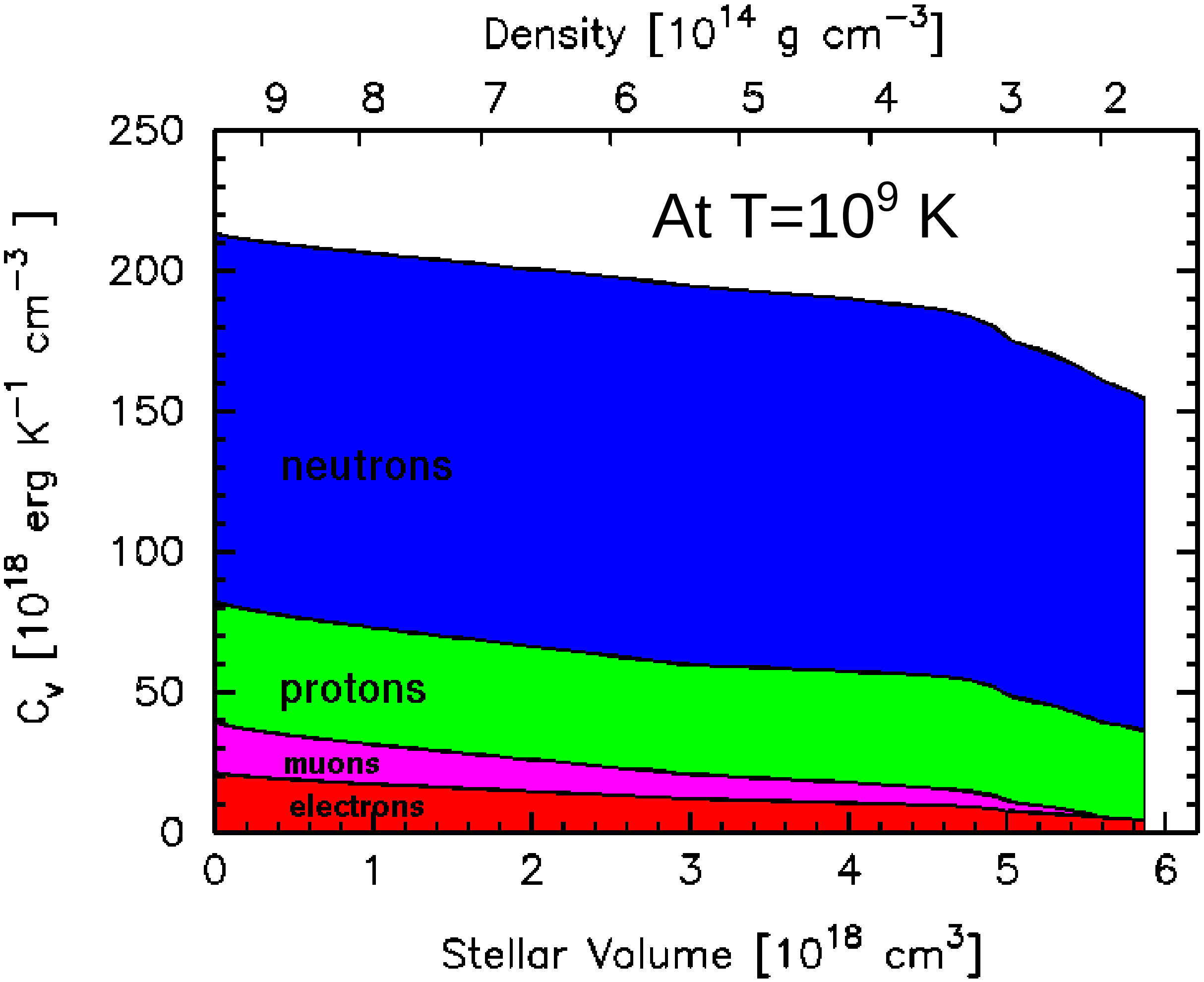
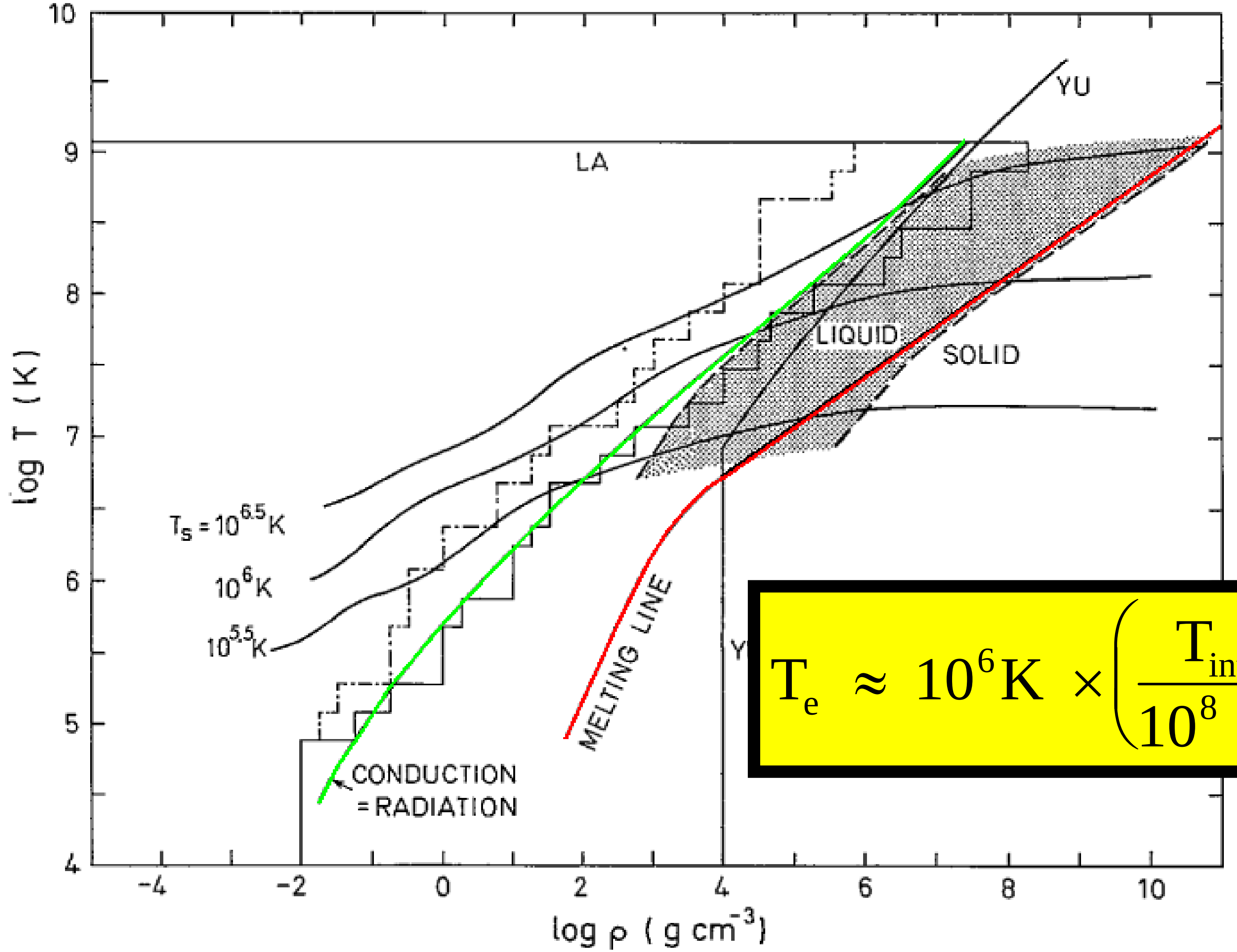
[a] T_9 is the temperature in units of 10^9 K.

Distribution of C_v in the core among constituents

$$C_V = N(0)\frac{\pi^2}{3}k_B^2 T \qquad N(0) = \frac{m^* p_F}{\pi^2 \hbar^3}$$



Surface vs Interior Temperature: the ENVELOPE

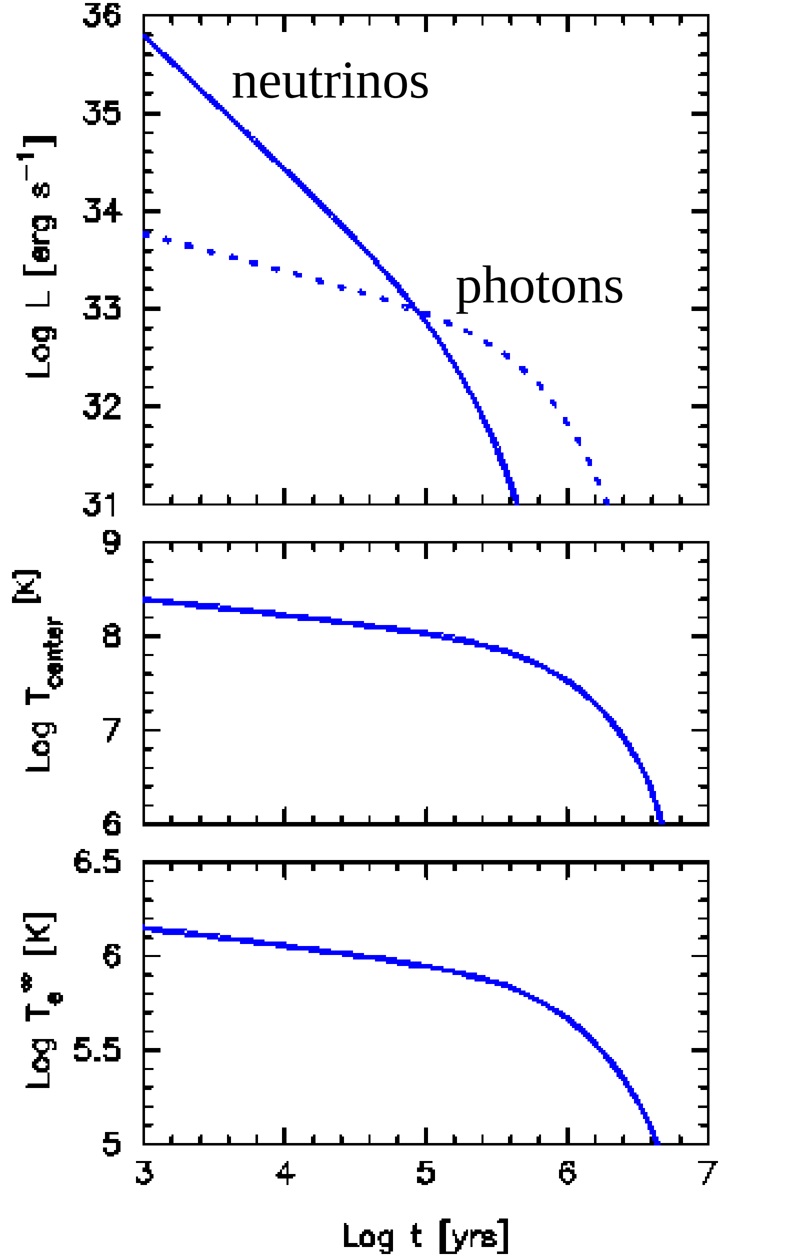


$$T_e \approx 10^6 \mathrm{K} \times \left(\frac{T_{int}}{10^8\ \mathrm{K}} \right)^{1/2}$$

Gudmundsson, Pethick & Epstein, Ap. J. 259 (1982), L19 and Ap. J. 272 (1983) 286

Basic Cooling: neutrino vs photon cooling eras

$$\frac{dE_{th}}{dt} = C_V \frac{dT}{dt} = -L_\nu - L_\gamma$$



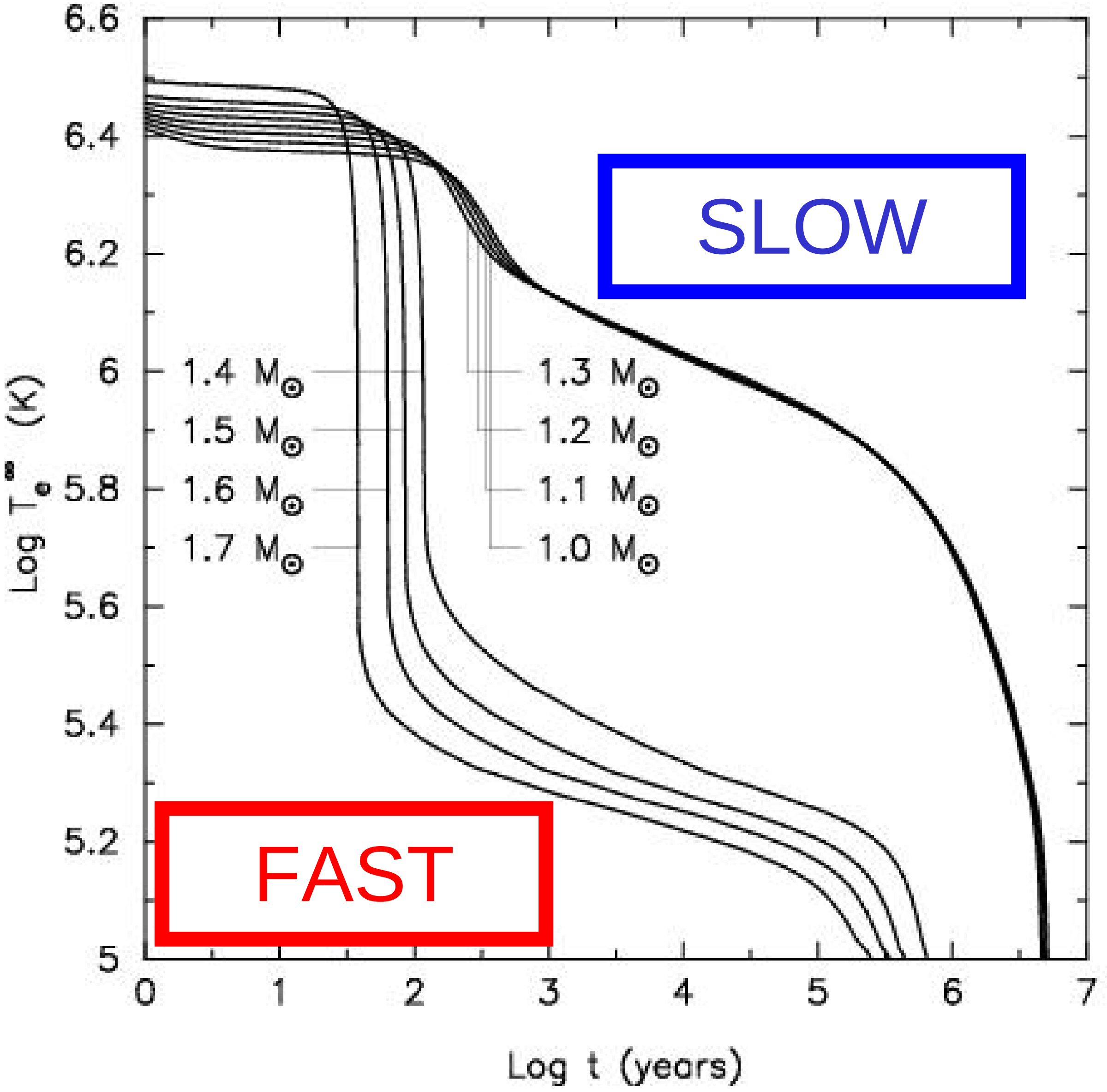
Neutrino Cooling era: $L_\nu >> L\gamma$

$$\frac{dT}{dt} = -\frac{q_{\nu 0}}{c_{V0}} \times T^7 \Rightarrow t - t_0 = A\left[\frac{1}{T^6} - \frac{1}{T_0^6}\right] \Rightarrow \quad T \propto t^{-1/6}$$

Photon Cooling era: $L_\nu << L\gamma$

$$\frac{dT}{dt} \propto -T^{1+\alpha} \Rightarrow t - t_0 = B\left[\frac{1}{T^\alpha} - \frac{1}{T_0^\alpha}\right] \Rightarrow \quad T \propto t^{-1/\alpha}$$

Fast Cooling with Direct Urca Process



"The Cooling of Neutron Stars by the Direct Urca Process", Page & Applegate, ApJ 394, L17 (1992)

PART II

Neutron Star Cooling:

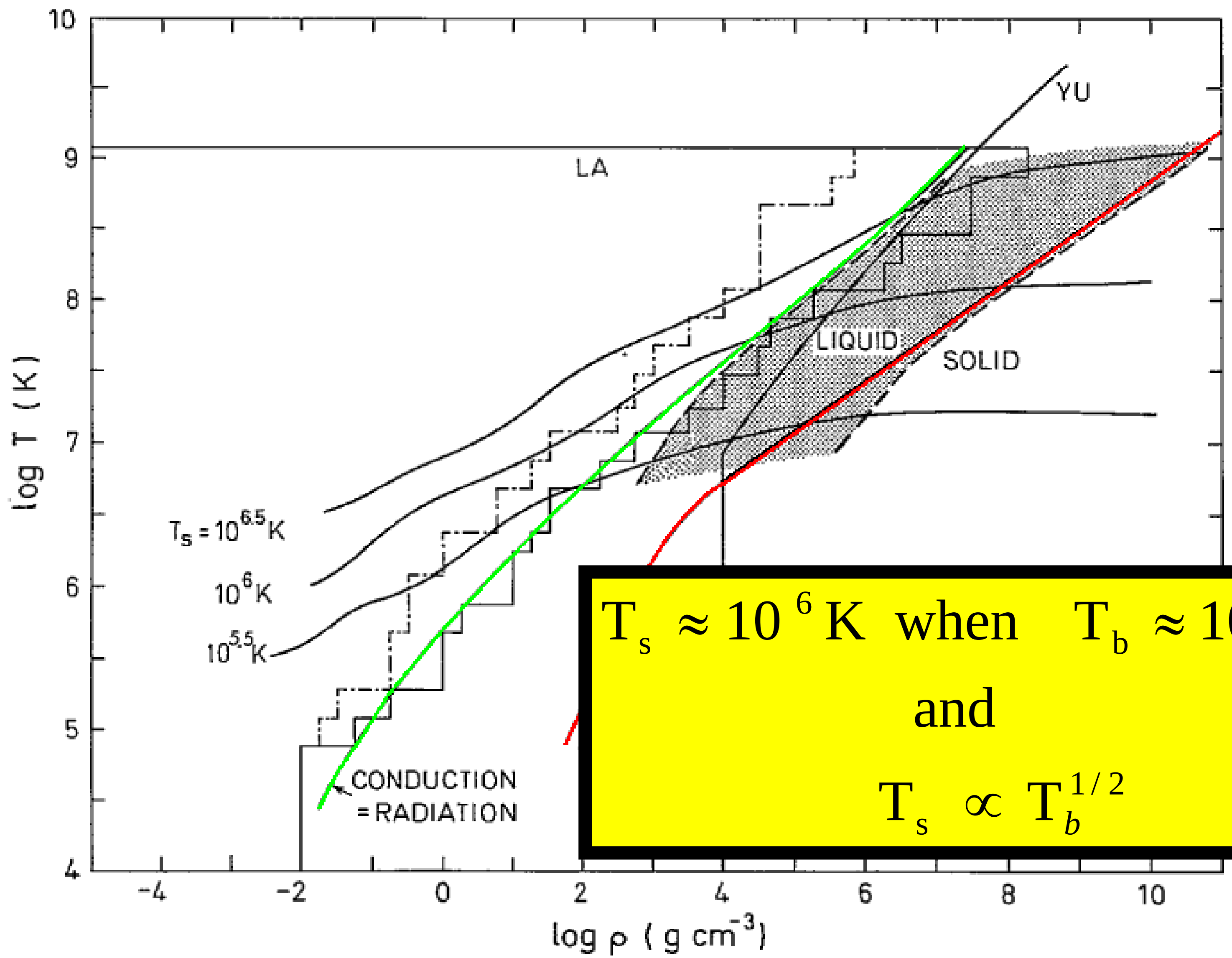
more "realistic" models

The Envelope:

more sophisticated models

- Magnetic fields ... part 1 !
- Chemical composition

Temperature profile in the envelope: the "sensivity strip"



$$T_s \approx 10^6\ \mathrm{K} \ \text{ when } \ T_b \approx 10^8\ \mathrm{K}$$

and

$$T_s \propto T_b^{1/2}$$

Gudmundsson, Pethick & Epstein, Ap. J. 259 (1982), L19 and Ap. J. 272 (1983) 286

Surface Temperature Distribution with a Magnetic Field:

Considering the effect of the magnetic field only in the envelope

$$T_s^4(\Theta_B) = T_s^4(\Theta_B = 0)\sin^2\Theta_B + T_s^4(\Theta_B = 90)\cos^2\Theta_B$$

Greenstein & Hartke, 1983

Best present version: Potekhin & Yakovlev, 2001

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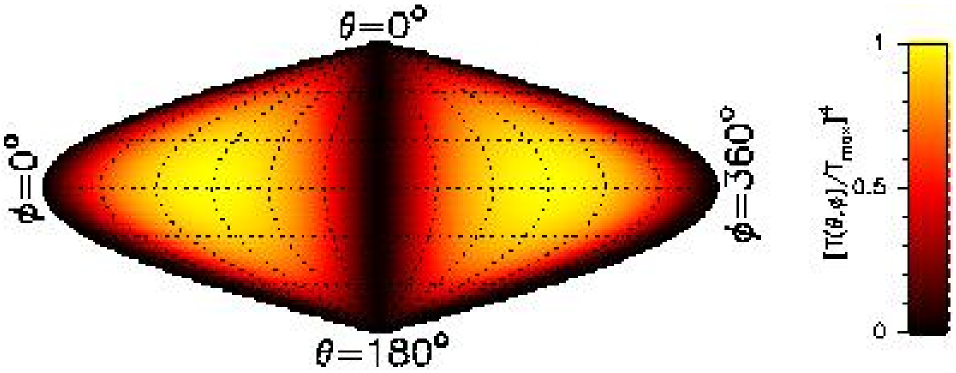
Purely Dipolar Field



D. Page "*Surface temperature distribution in magnetized neutron stars. I. dipolar fields*", 1995

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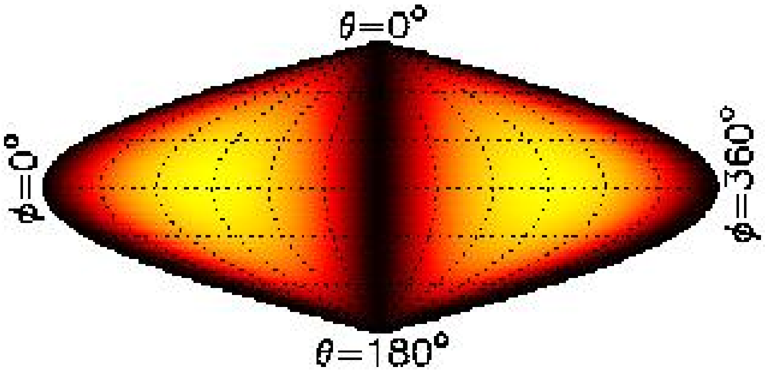
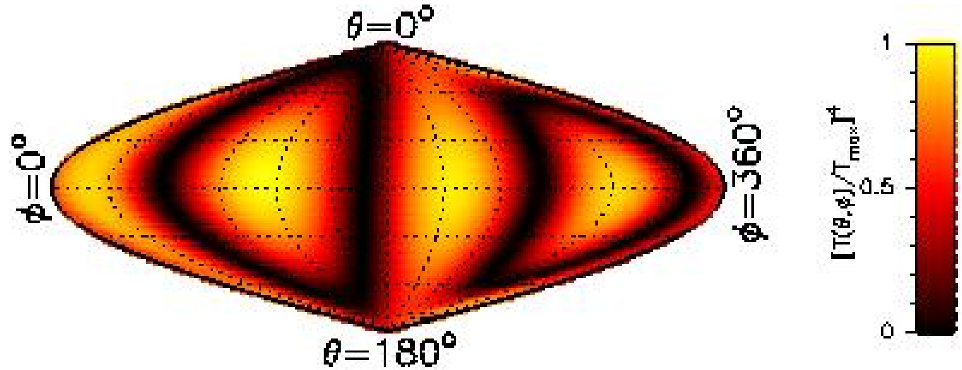


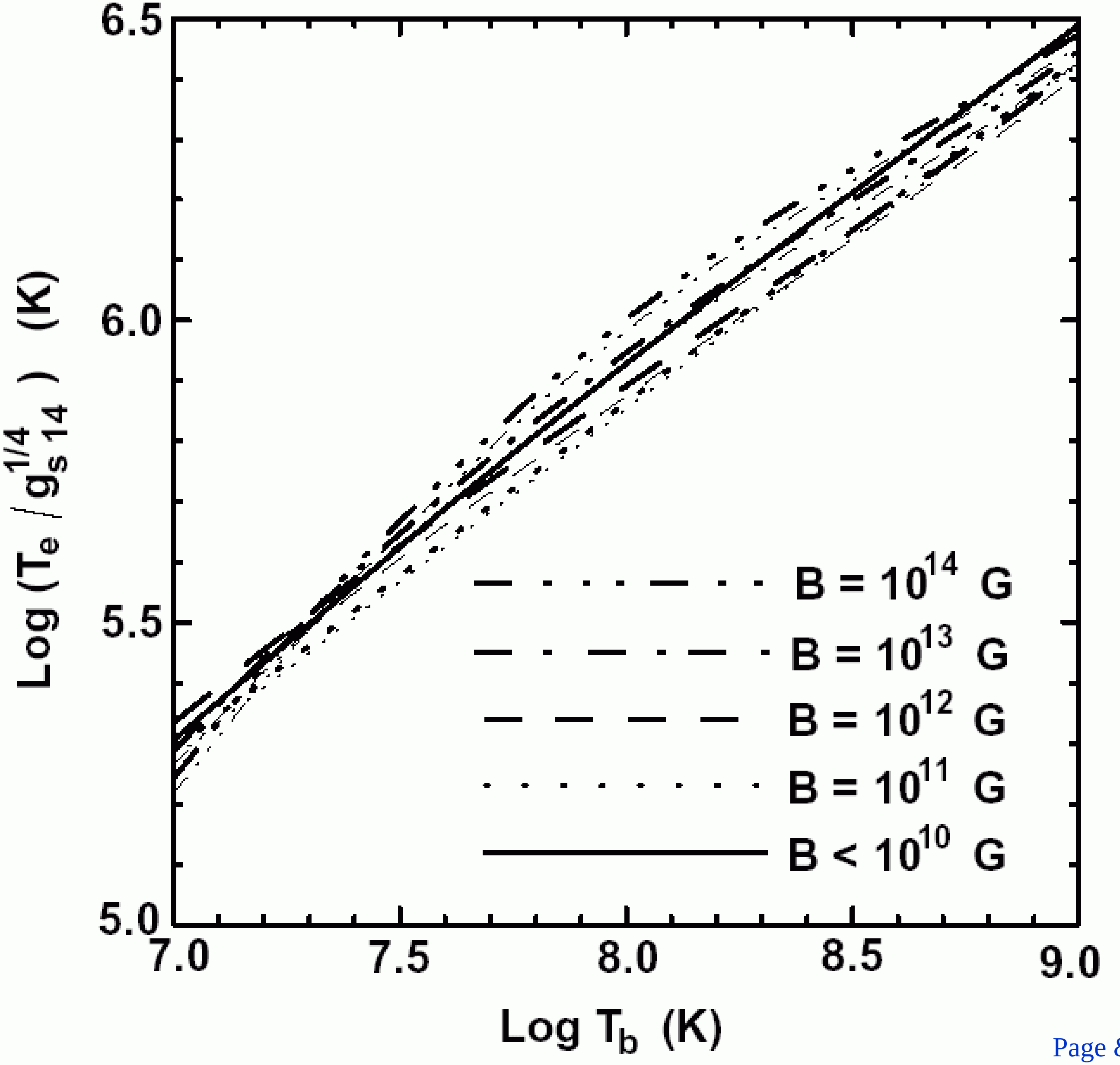
Dipole + Quadrupole Field



D. Page "*Surface temperature distribution in magnetized neutron stars. I. dipolar fields*", 1995

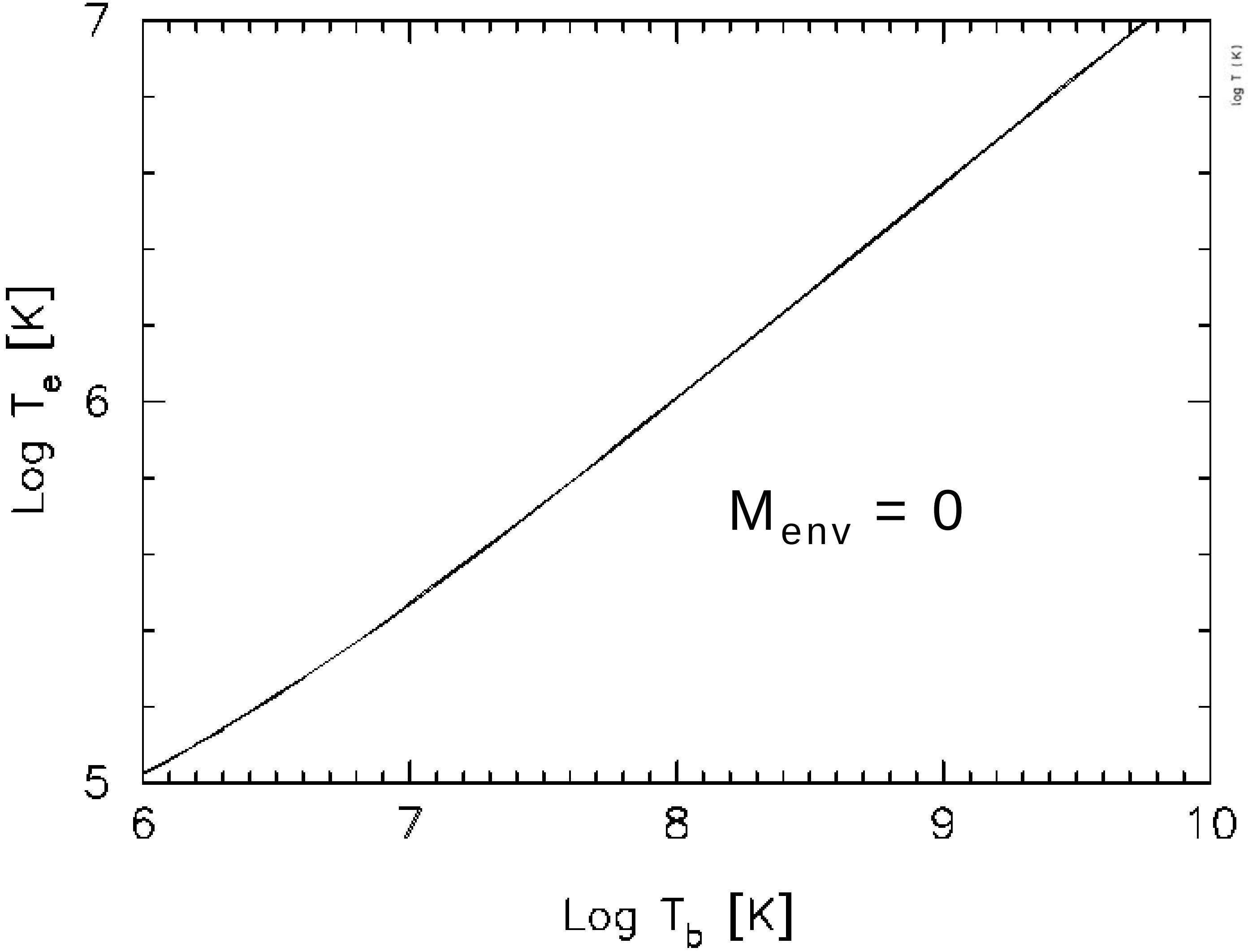
D. Page & A. Sarmiento,"*Surface temperature distribution in magnetized neutron stars. II*" 1996

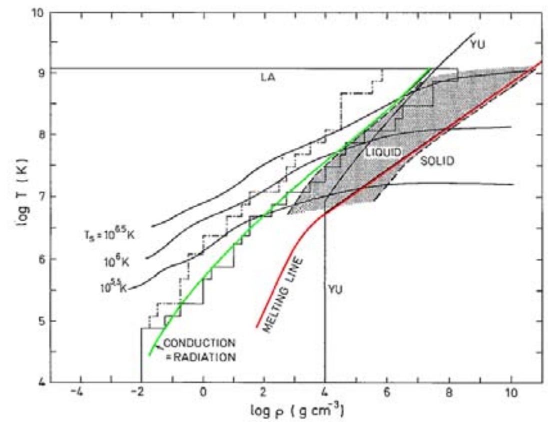
“$T_e - T_b$ relationship” for dipolar and dipolar+quadrupolar fields



Page & Sarmiento, 1996

Light elements in the envelope





Chabrier, Potekhin & Yakovlev, ApJ 477 (1997), L99

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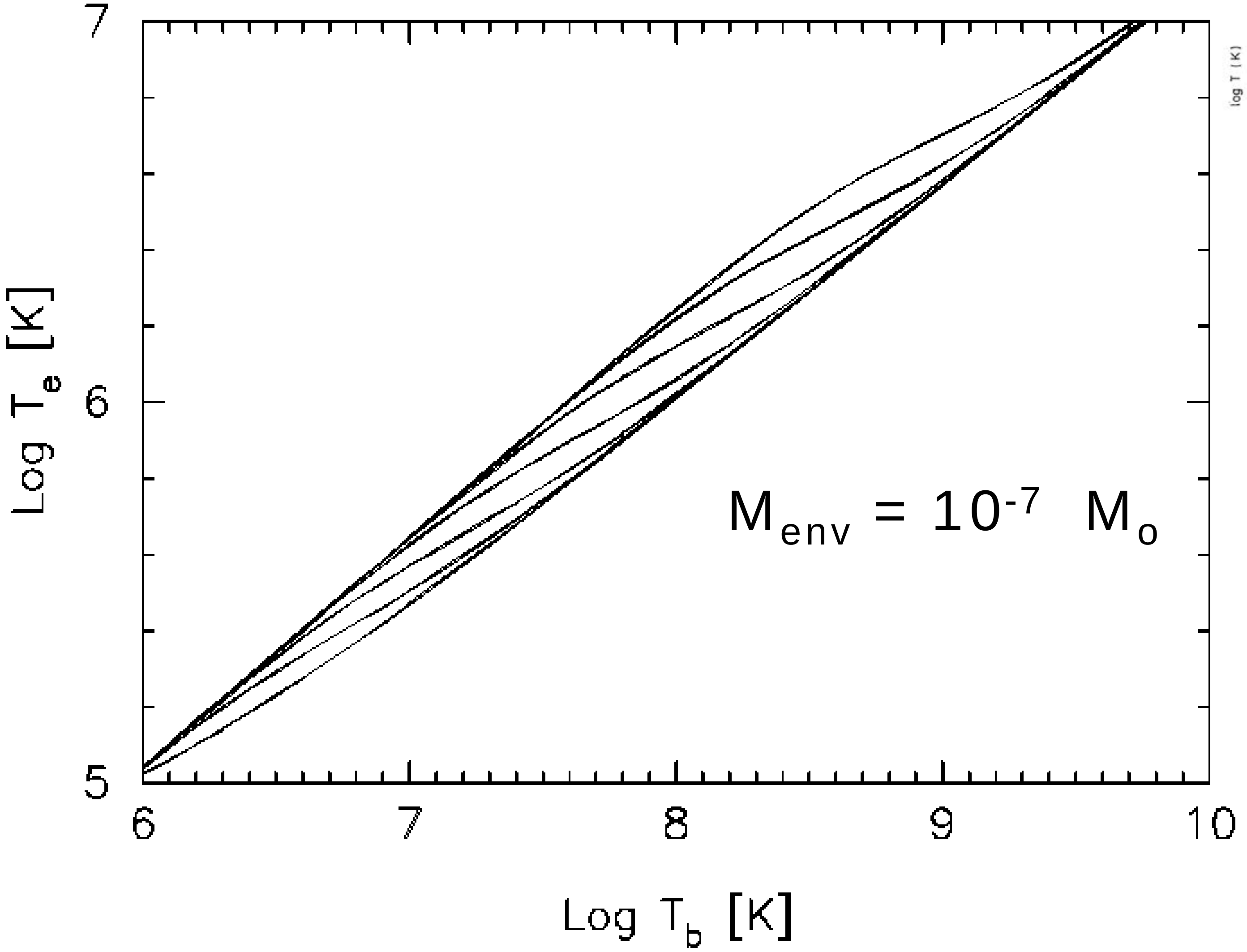
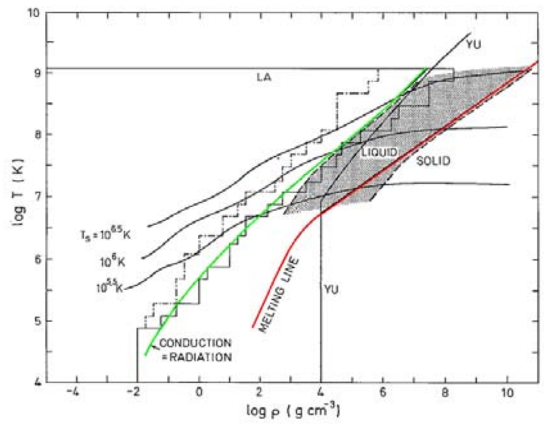


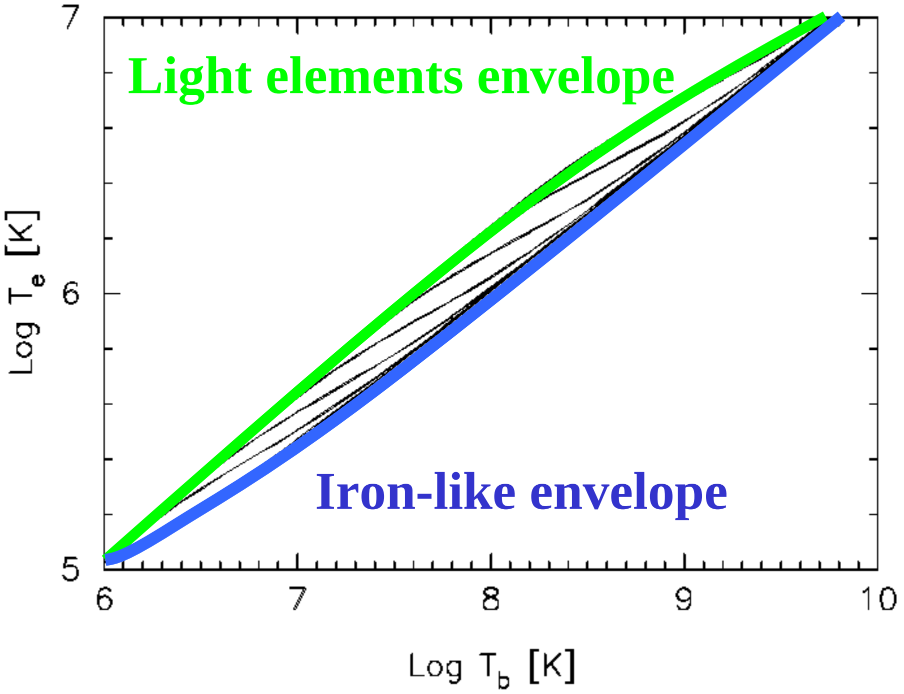


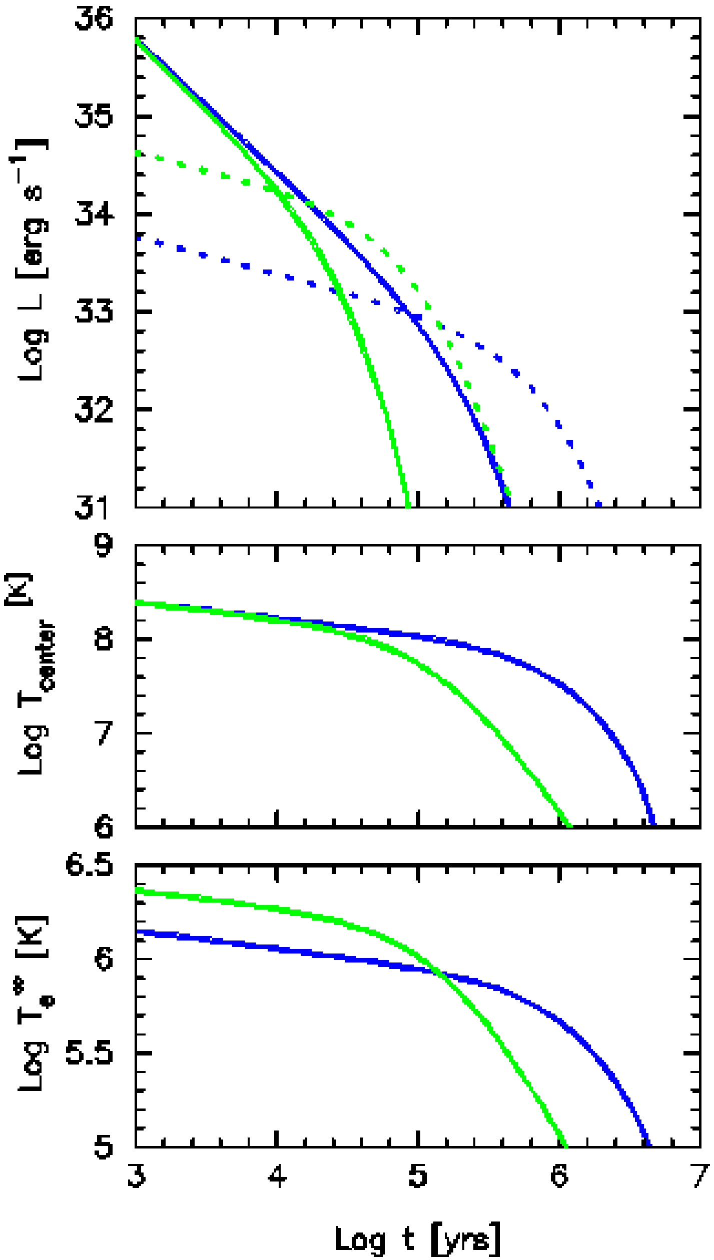
Chabrier, Potekhin & Yakovlev, ApJ 477 (1997), L99

Effect of envelope chemical compositions

$$T_e = T_e(T)$$

$$L_\gamma = 4\pi R^2 \; T_e^4 \propto T^{2+\alpha}$$





Neutron and Proton Pairing:

(superfluidity & superconductivity)

- **Supression of Specific Heat**
- **Supression of Neutrino Emission**
- **Opening of a NEW Neutrino Process**

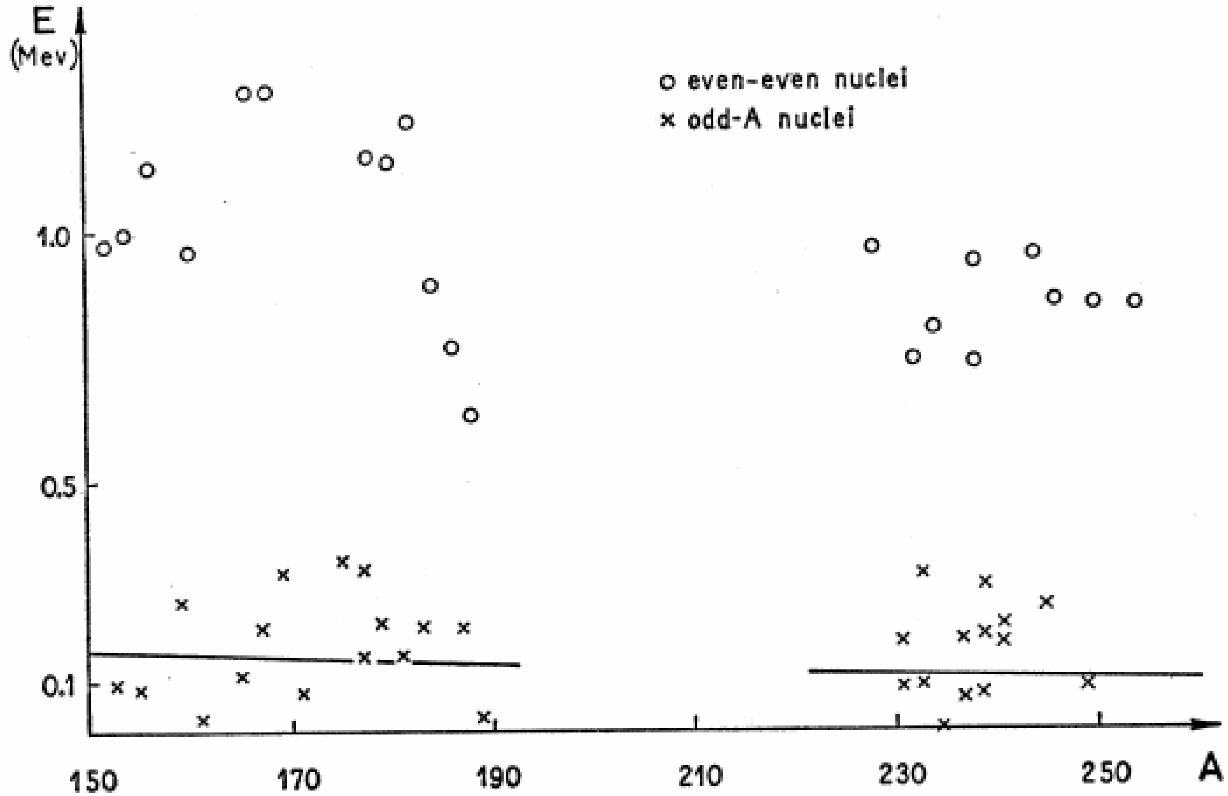
Pairing between nucleons in nuclei

EXCITATION SPECTRA OF NUCLEI 937

FIG. 1. Energies of first excited intrinsic states in deformed nuclei, as a function of the mass number. The experimental data may be found in *Nuclear Data Cards* [National Research Council, Washington, D. C.] and detailed references will be contained in reference 1 above. The solid line gives the energy $\delta/2$ given by Eq. (1), and represents the average distance between intrinsic levels in the odd-A nuclei (see reference 1).

The figure contains all the available data for nuclei with $150 < A < 190$ and $228 < A$. In these regions the nuclei are known to possess nonspherical equilibrium shapes, as evidenced especially by the occurrence of rotational spectra (see, e.g., reference 2). One other such region has also been identified around $A = 25$; in this latter region the available data on odd-A nuclei is still represented by Eq. (1), while the intrinsic excitations in the even-even nuclei in this region do not occur below 4 Mev.

We have not included in the figure the low lying $K=0$ states found in even-even nuclei around Ra and Th. These states appear to represent a collective odd-parity oscillation.



Possible Analogy between the Excitation Spectra of Nuclei and Those of the Superconducting Metallic State
Bohr, A.; Mottelson, B. R.; Pines, D. (1958), Phys. Rev. 110, p.936

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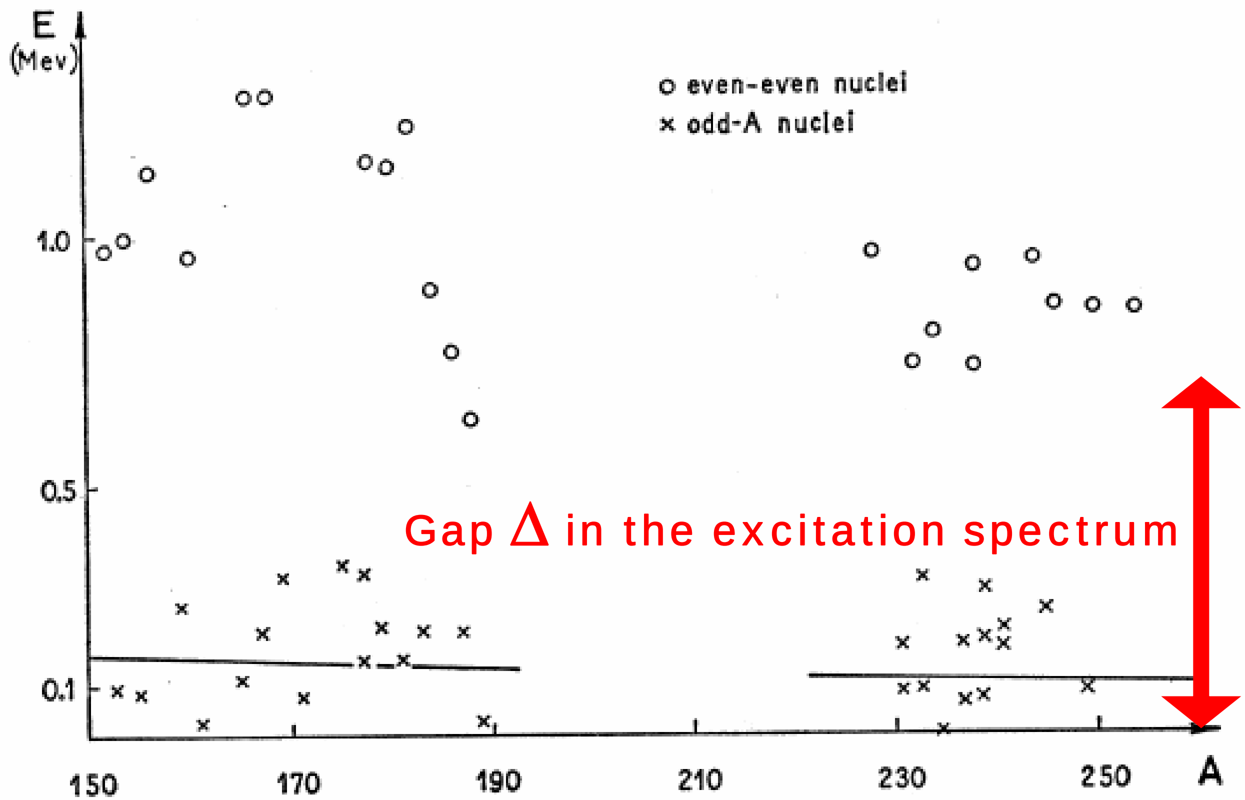
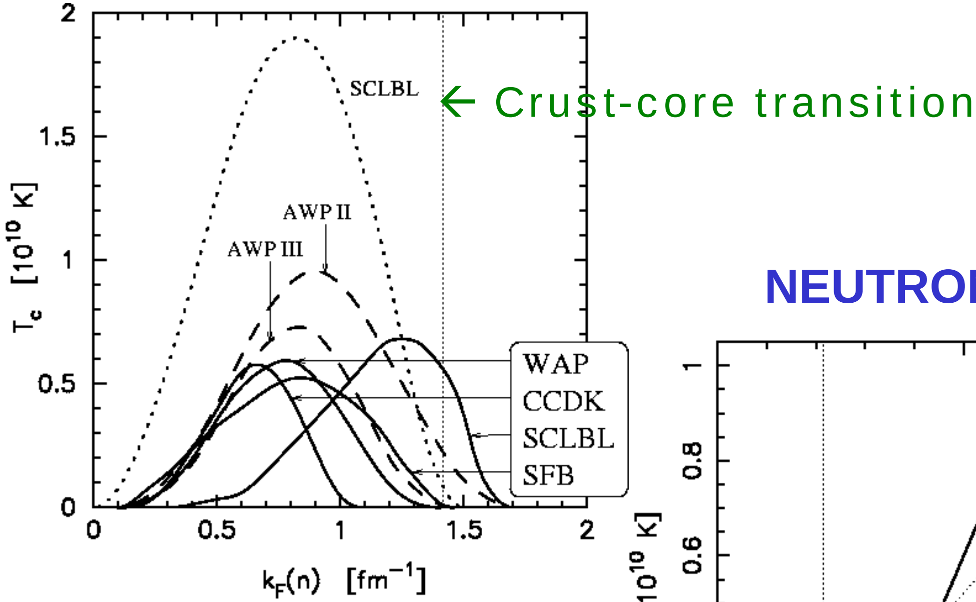


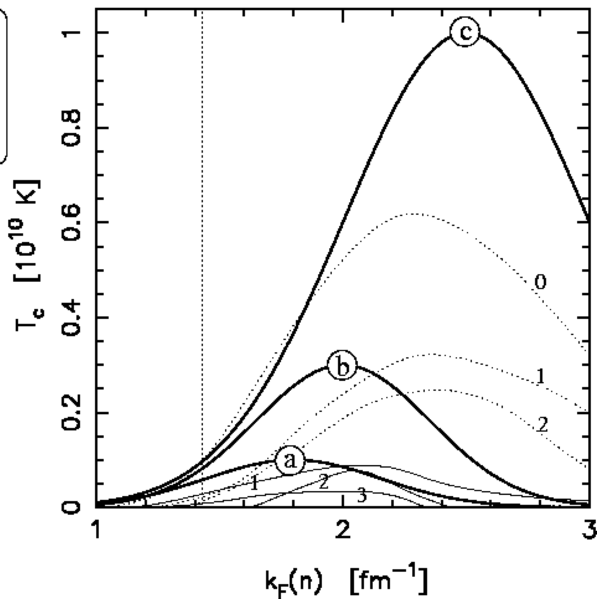
⇒ Excitations are suppressed by a factor ~ exp(- Δ/kT)

Predictions for the nucleon pairing gaps

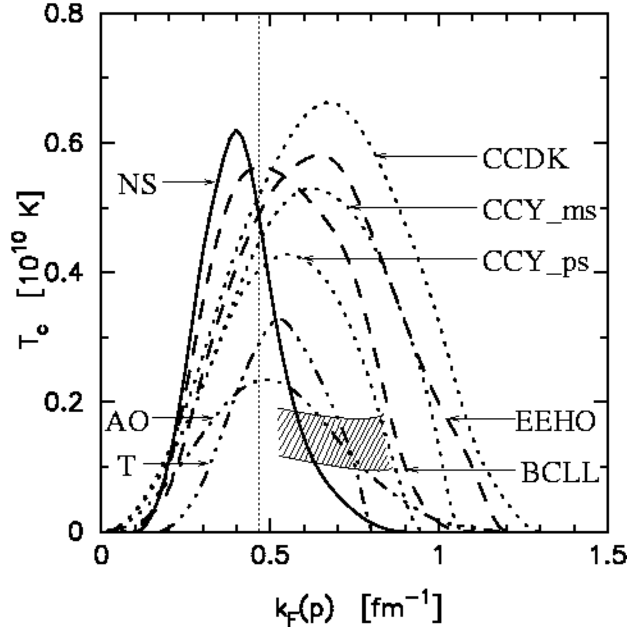
NEUTRON $^1S_0$ gap



NEUTRON $^3P_2$ gap

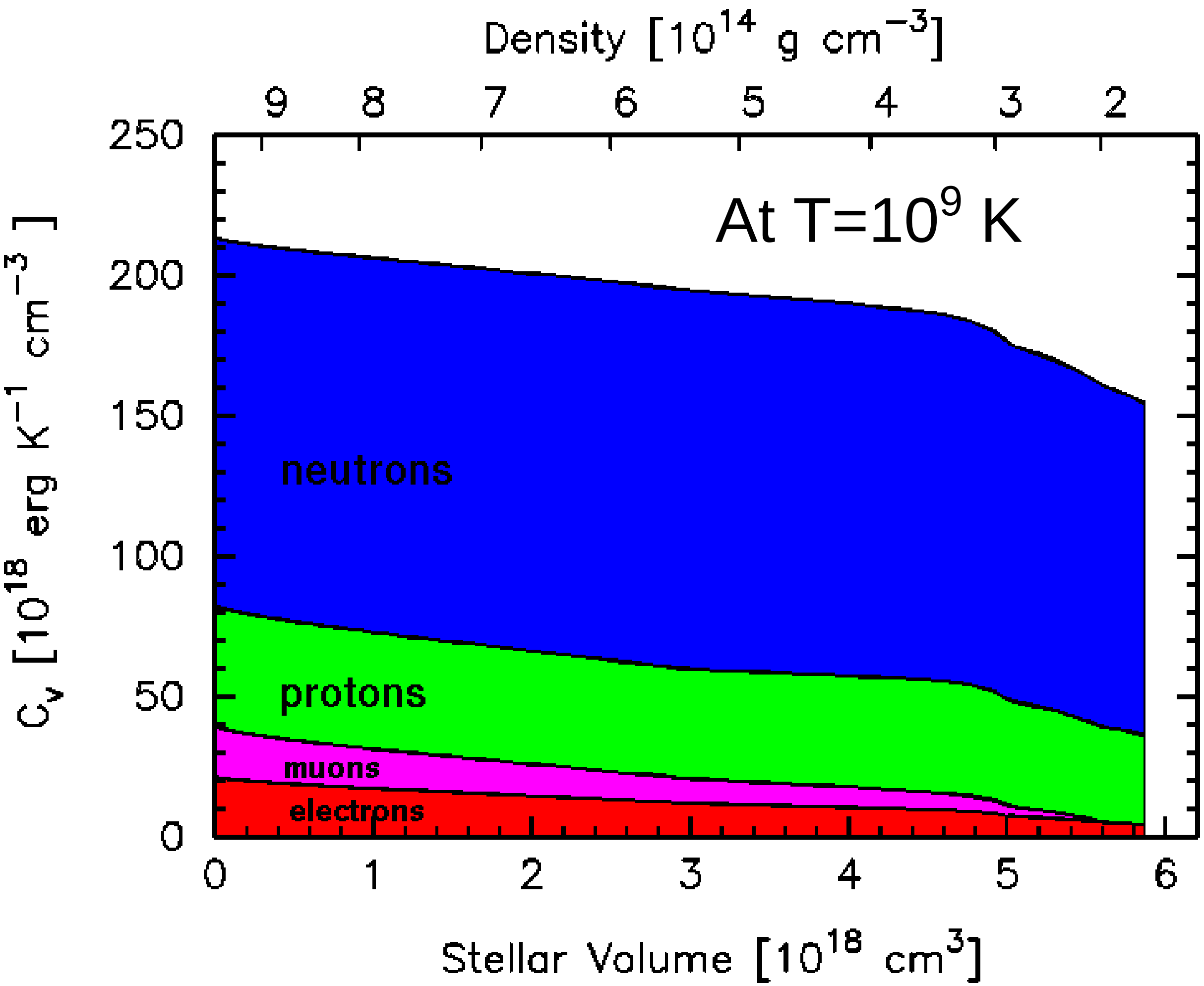


PROTON $^1S_0$ gap

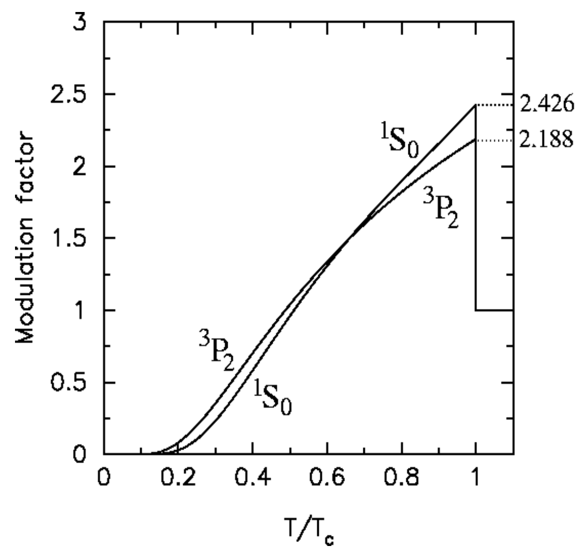


Suppression C_v by pairing

$$C_V = N(0)\frac{\pi^2}{3}k_B^2 T \qquad N(0) = \frac{m^* p_F}{\pi^2 \hbar^3}$$

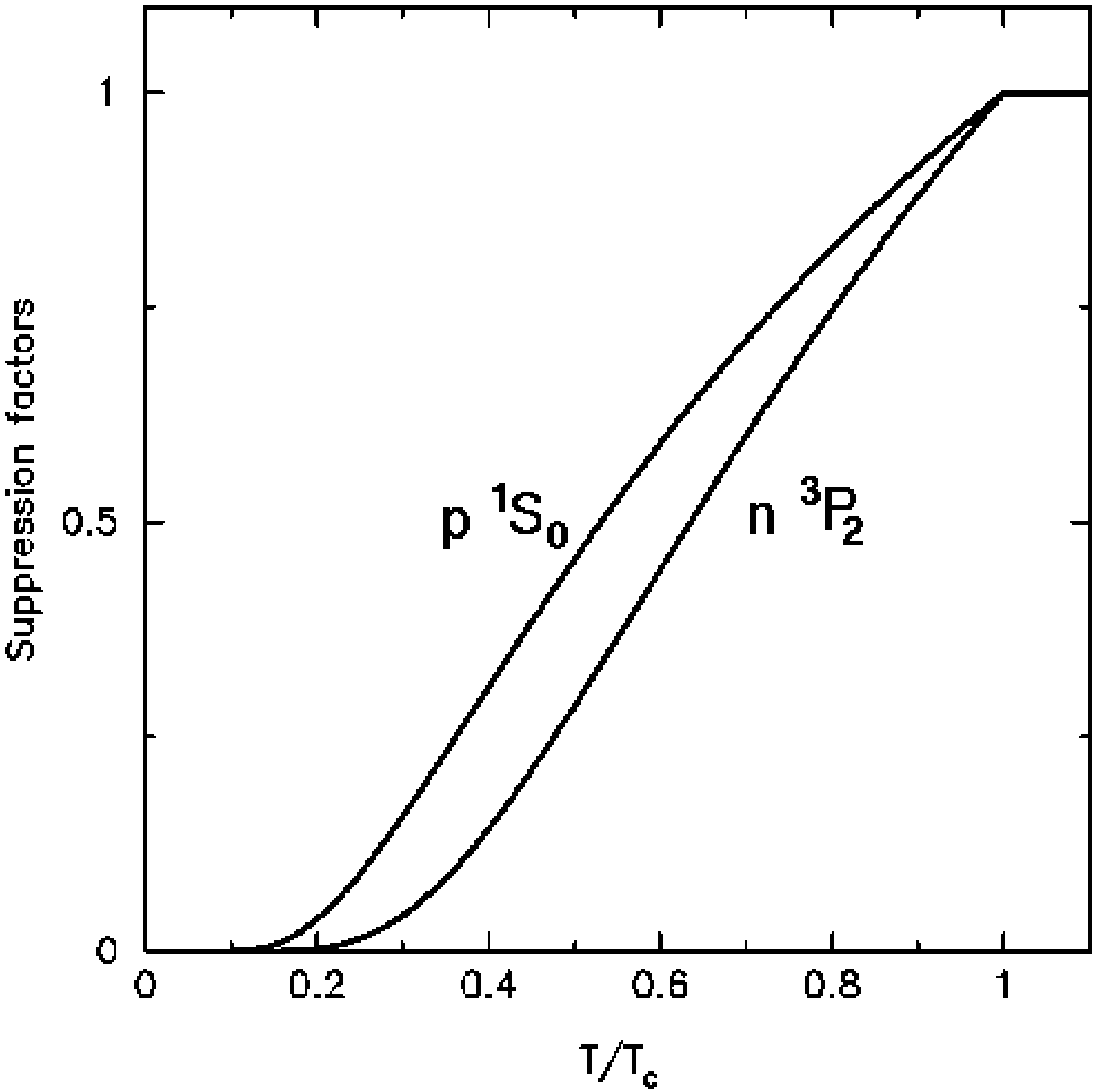


$$C_V^{paired} = C_V^{normal} \times M(T/T_c) \approx C_V^{normal} \times e^{-\Delta(T)/kT}$$

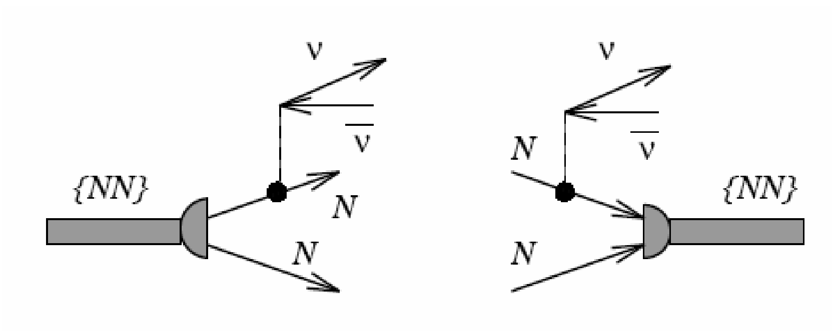


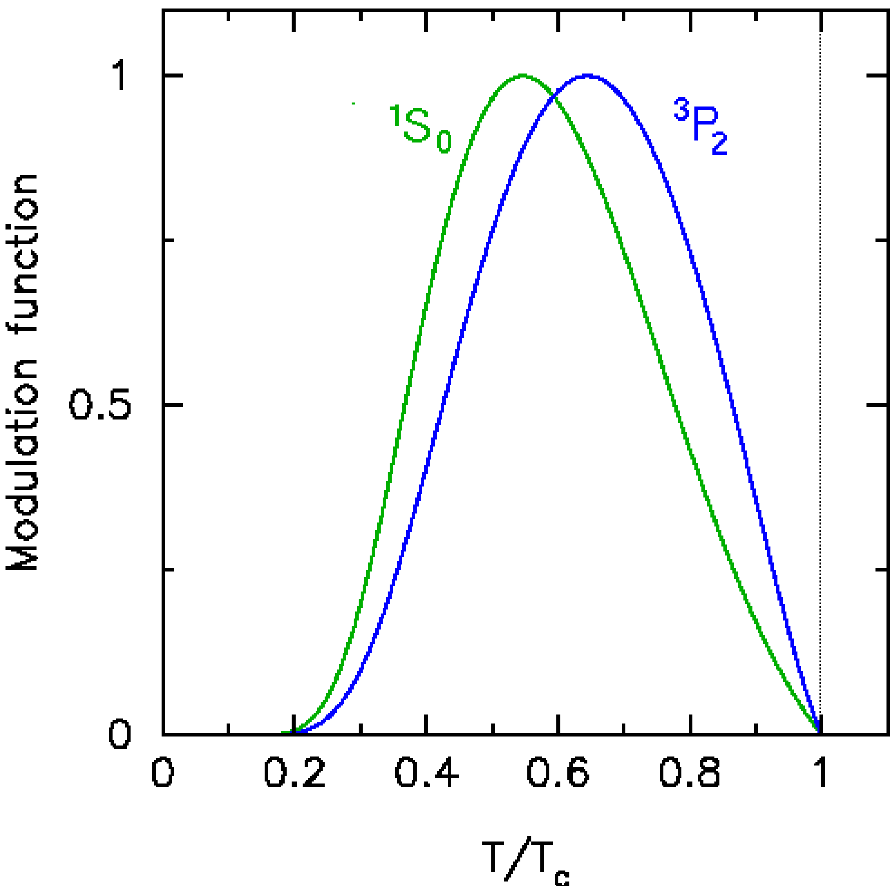
Suppression of MURCA *et al.* by pairing

$$q_\nu^{\text{paired}} = S(T/Tc;\text{phase})\, q_\nu^{\text{normal}}$$



Neutrino emission through the formation and breaking of Cooper pairs ("PBF")





$$q_\nu^{\text{Coop}} \approx 10^{22}\ F(T/Tc; \text{phase})\, T_9^7$$

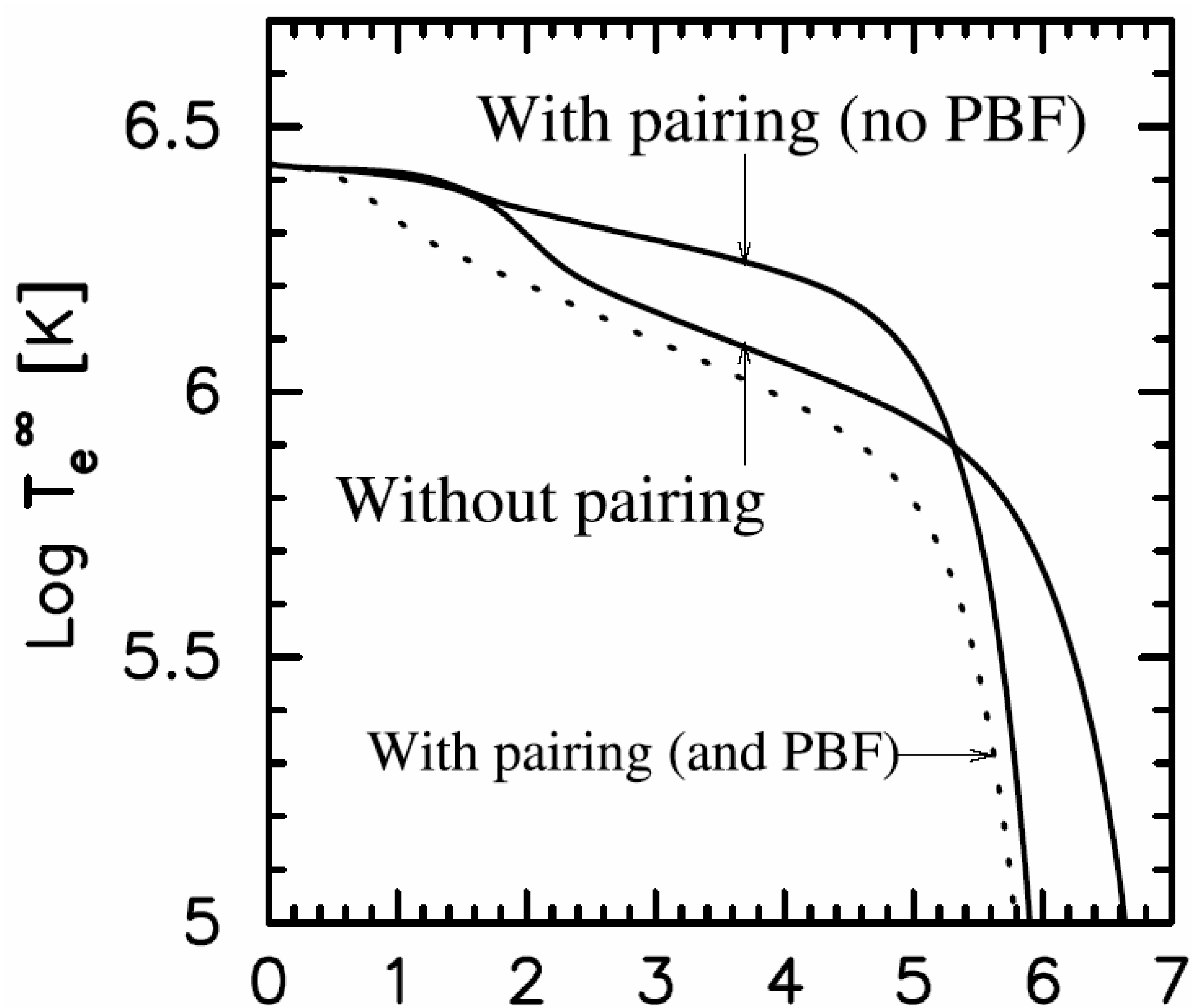
$$q_\nu^{\text{MUrca}} \approx 10^{21}\ T_9^8$$

Flowers, Ruderman & Sutherland, Ap. J. 205 (1976), 541

Voskresenskii & Senatorov, Zh. Eksp. Teor. Fiz. 90 (1986), 1505 [JETP 63 (1986), 885]

Voskresenskii & Senatorov, Yad. Fiz. 45 (1987), 657 [Sov. J. Nucl. Phys. 45 (1987), 411]

Basic Effects of Pairing on the Cooling



PART III

Minimal Cooling
of
Neutron Stars

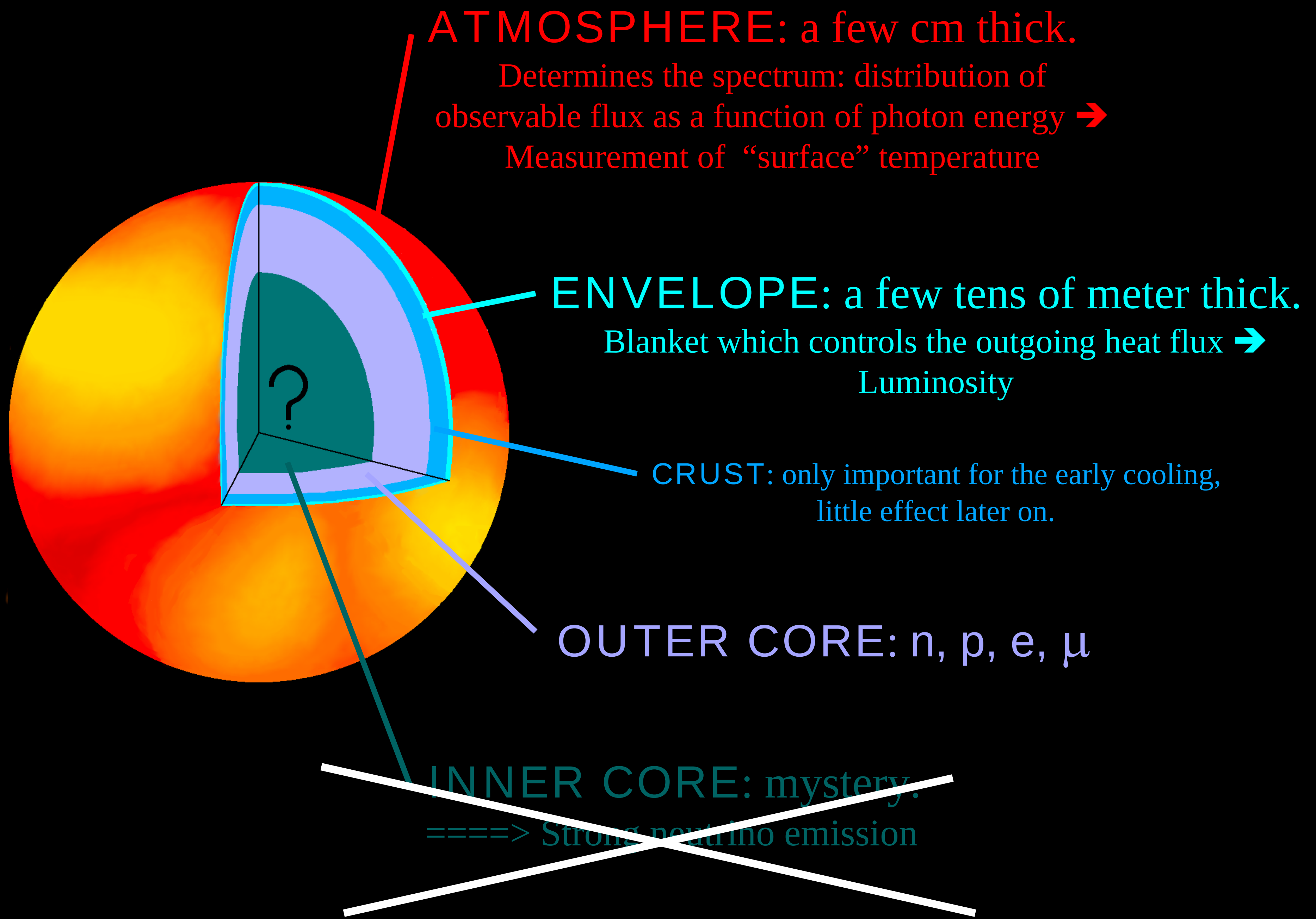
Revised version of the "Standard Model"

Dany Page

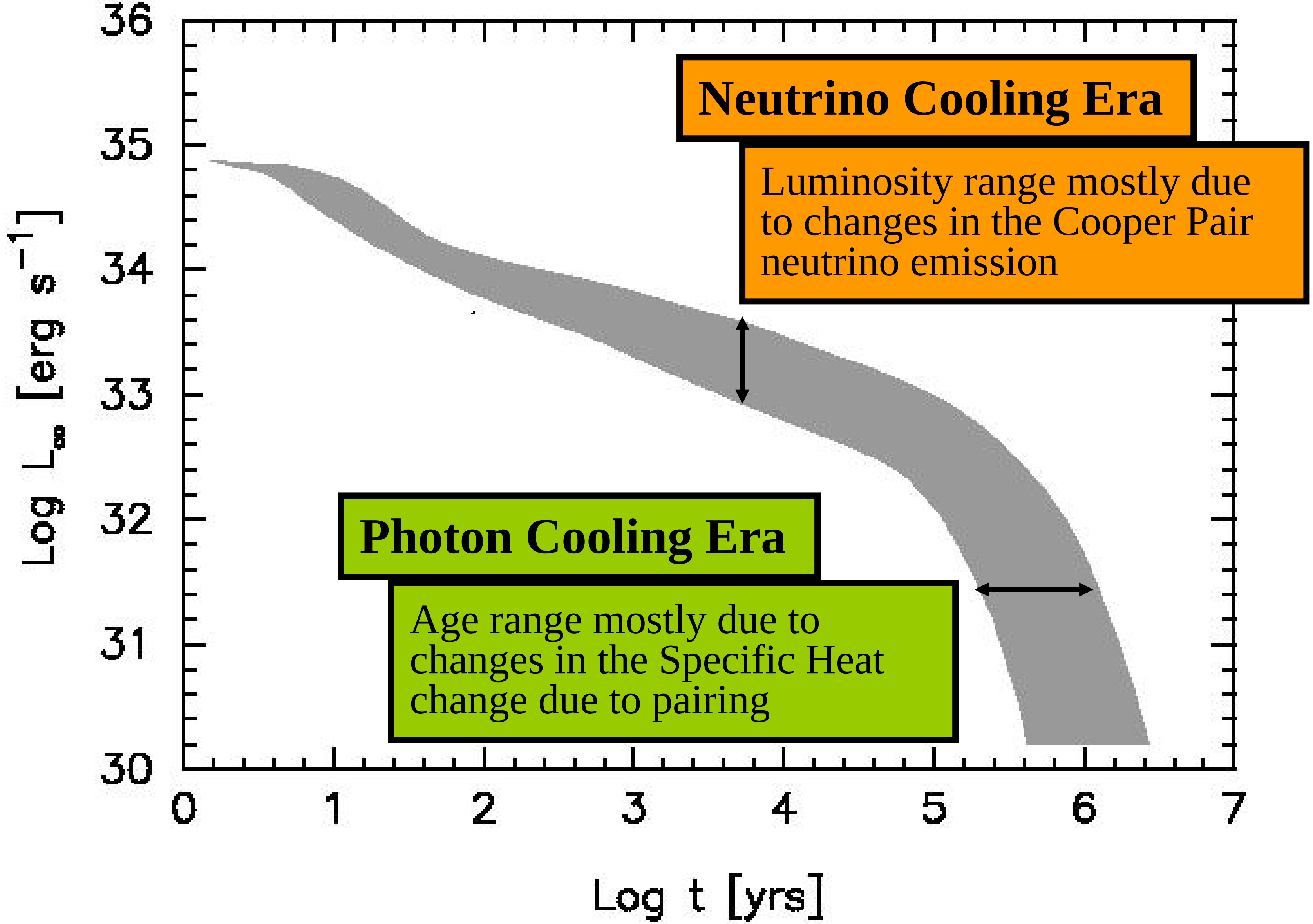
Instituto de Astronomía, UNAM

In collaboration with:

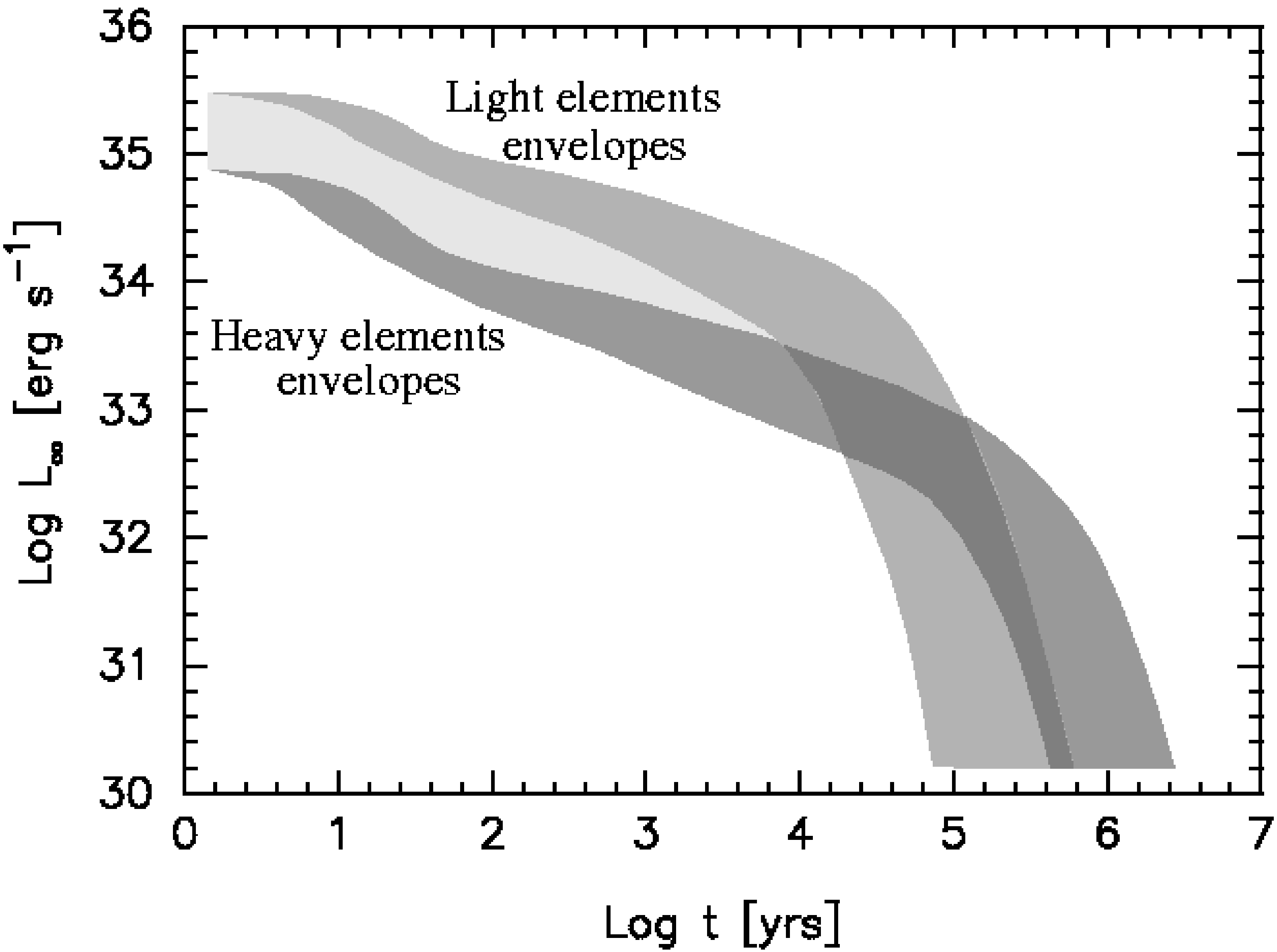
- **J.H. Lattimer** (SUNY Stony Brook)
- **M. Prakash** (SUNY Stony Brook)
- **A. Steiner** (UM, Mineapolis)


ATMOSPHERE: a few cm thick.
Determines the spectrum: distribution of observable flux as a function of photon energy ➔ Measurement of "surface" temperature
ENVELOPE: a few tens of meter thick.
Blanket which controls the outgoing heat flux ➔ Luminosity
?
CRUST: only important for the early cooling, little effect later on.
OUTER CORE: n, p, e, μ
INNER CORE: mystery:
====> Strong neutrino emission

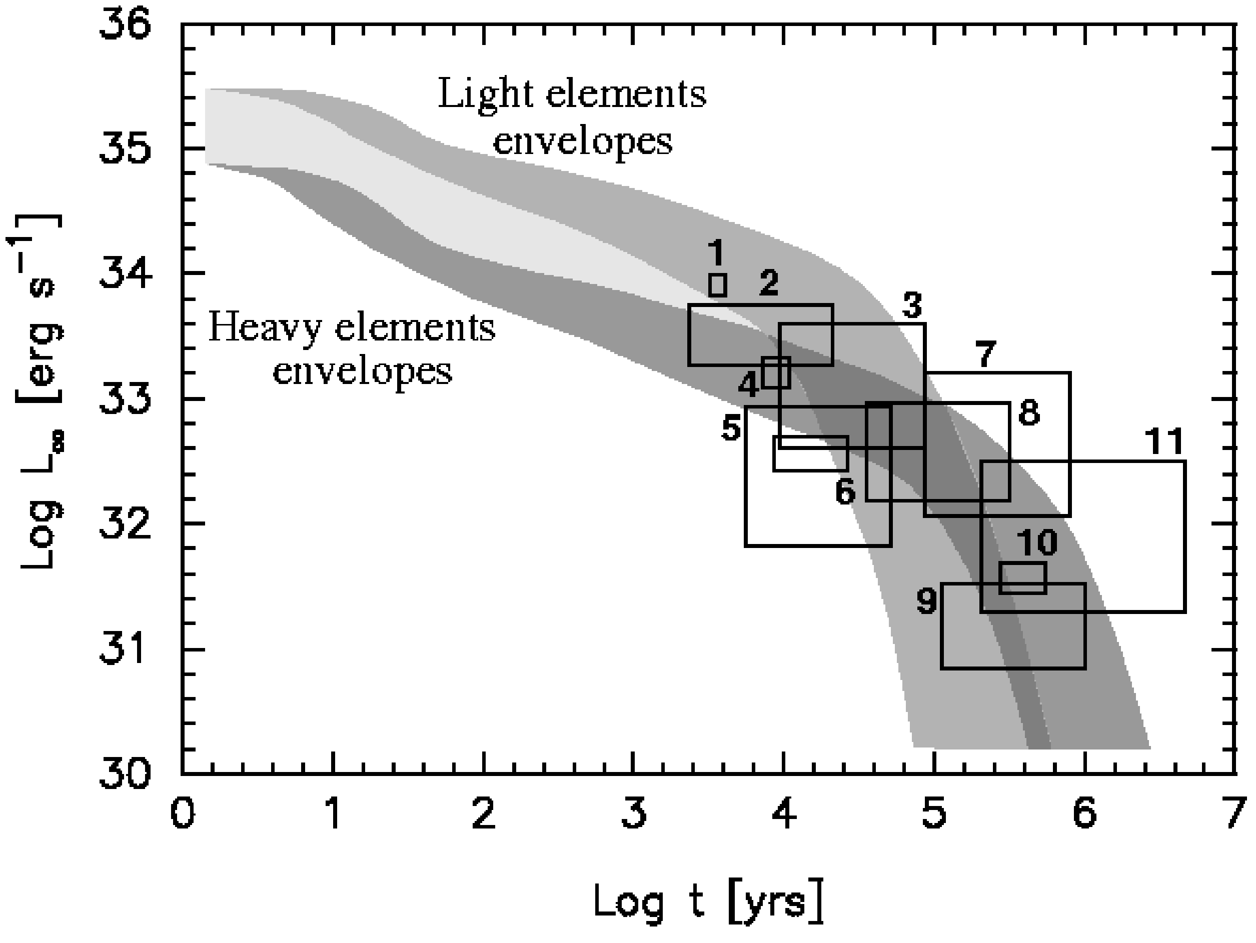
Minimal Cooling



Minimal Cooling



Comparison with Data



Mag H fits:

1) RX J0822-4247 (in Puppis A)

2) 1E 1207.4-5209 (in PKS 1209-52)

3) PSR 0538+2817

4) RX J0002+6246 (in CTB 1)

5) PSR 1706-44

6) PSR 0933-45 (in Vela)

BB fits:

7) PSR 1055-52

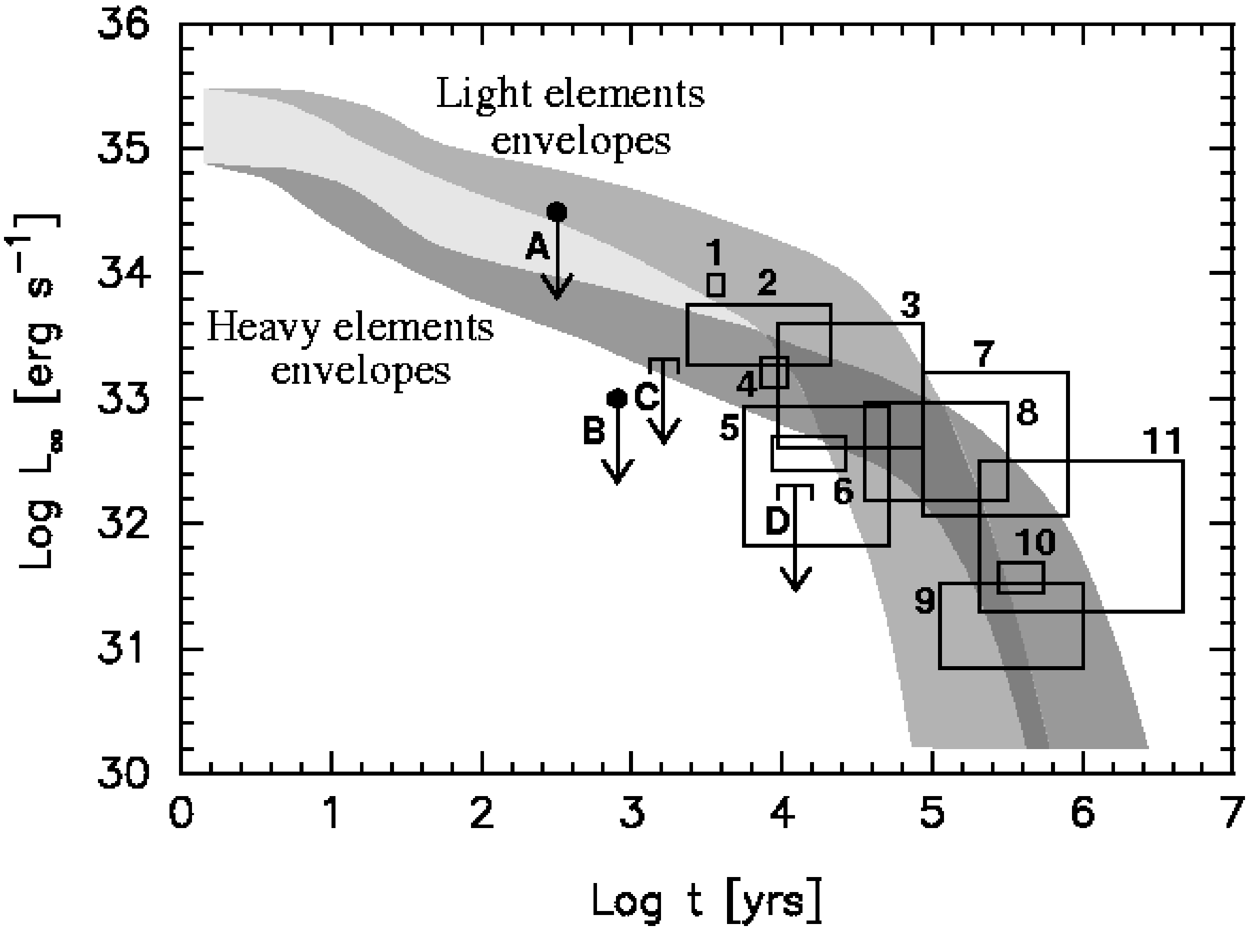
8) PSR 0656+14

9) PSR 0633+1748 "Geminga"

10) RX J1856.5-3754

11) RX J0720.4-3125

Comparison with Data



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10) RX J1856.5-3754

11) RX J0720.4-3125

Upper limits:

A) CXO J232327.8+584842 (in Cas A)

B) PSR J0205+6449 (in 3C58)

C) PSR J1124-5916 (in G292.0+1.8)

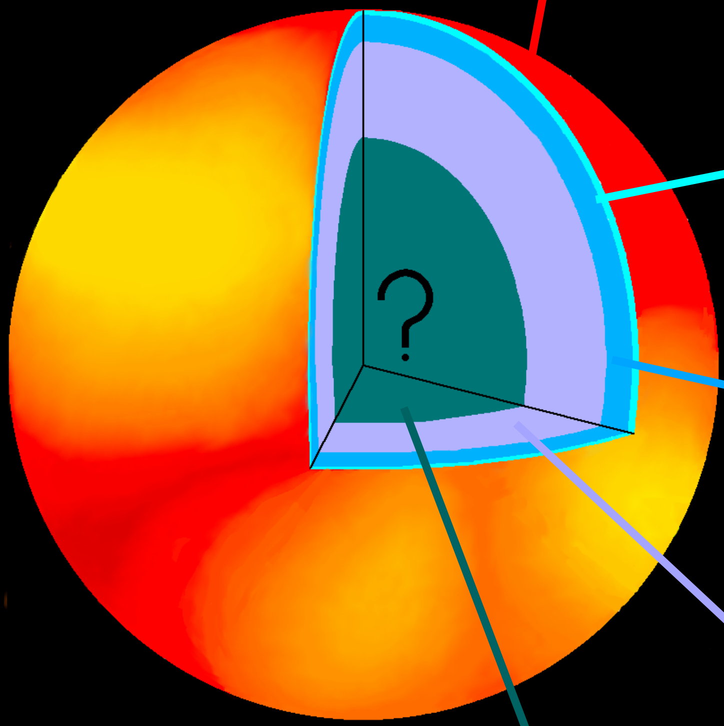
D) RX J0007.0+7302 (in CTA 1)

PART III

Fast Cooling

of

Neutron Stars



ATMOSPHERE: a few cm thick.

Determines the spectrum: distribution of observable flux as a function of photon energy ➔ Measurement of "surface" temperature

ENVELOPE: a few tens of meter thick.

Blanket which controls the outgoing heat flux ➔ Luminosity

CRUST: only important for the early cooling, little effect later on.

OUTER CORE: n, p, e, μ

INNER CORE: mystery.

====> Strong neutrino emission

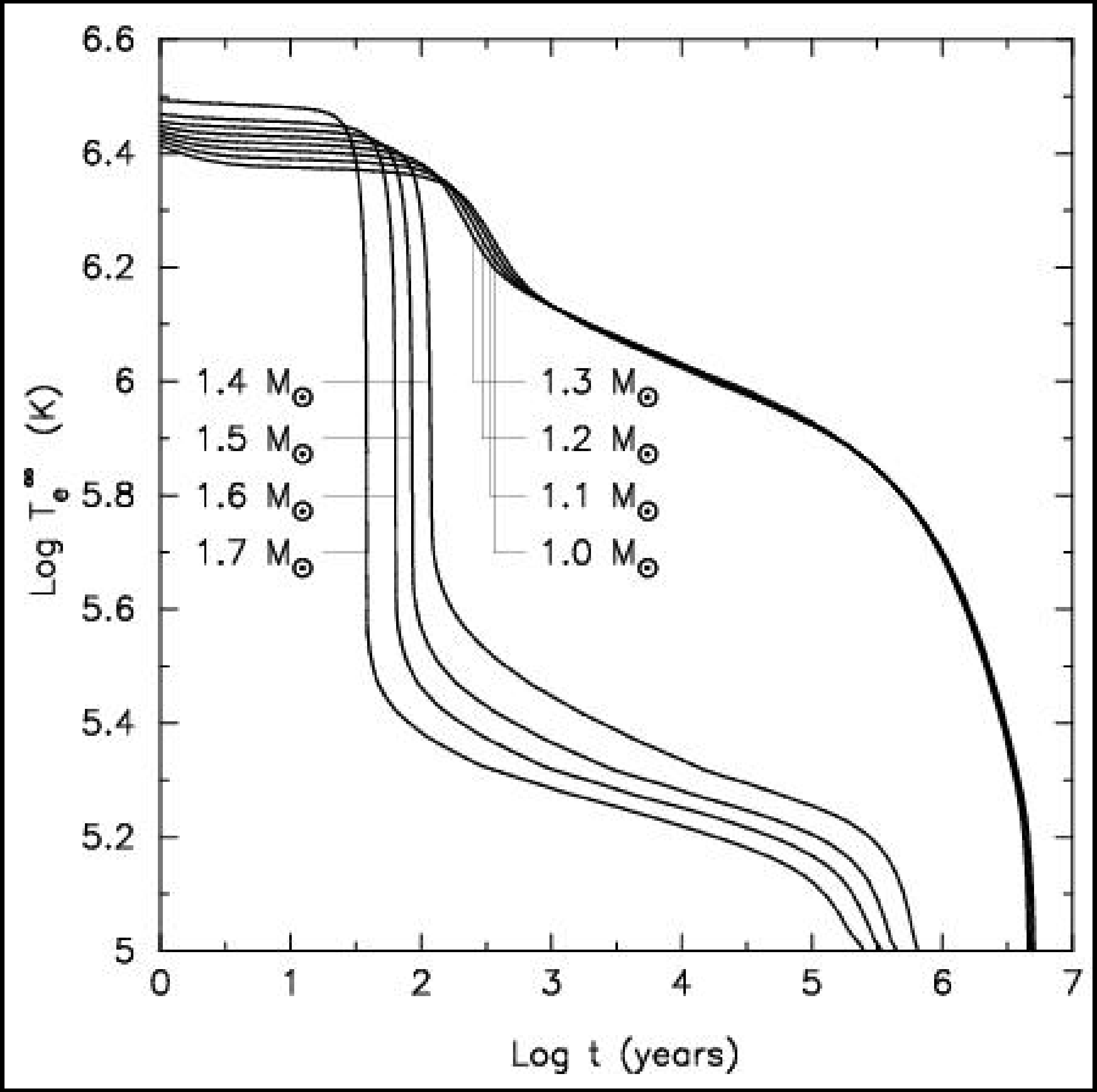
Neutrino Emission Scenarios

Some Core Neutrino Emission Processes and Their Emissivities

Process Name	Process	Emissivity Q_ν[a] (ergs s^{-1} cm^{-3})	Emissivity References
Modified Urca	$\begin{cases} n + n' \rightarrow n' + p + e^- + \bar{\nu}_e \\ n' + p + e^- \rightarrow n' + n + \nu_e \end{cases}$	$\sim 10^{20} T_9^8$	Friman & Maxwell 1979
Kaon condensate	$\begin{cases} n + K^- \rightarrow n + e^- + \bar{\nu}_e \\ n + e^- \rightarrow n + K^- + \nu_e \end{cases}$	$\sim 10^{24} T_9^6$	Brown et al. 1988
Pion condensate	$\begin{cases} n + \pi^- \rightarrow n + e^- + \bar{\nu}_e \\ n + e^- \rightarrow n + \pi^- + \nu_e \end{cases}$	$\sim 10^{26} T_9^6$	Maxwell et al. 1977
Direct Urca	$\begin{cases} n \rightarrow p + e^- + \bar{\nu}_e \\ p + e^- \rightarrow n + \nu_e \end{cases}$	$\sim 10^{27} T_9^6$	Lattimer et al. 1991
Quark Urca	$\begin{cases} d \rightarrow u + e^- + \bar{\nu}_e \\ u + e^- \rightarrow d + \nu_e \end{cases}$	$\sim 10^{26} \alpha_c T_9^6$	Iwamoto 1980

[a] T_9 is the temperature in units of 10^9 K.

Fast Cooling with Direct Urca Process



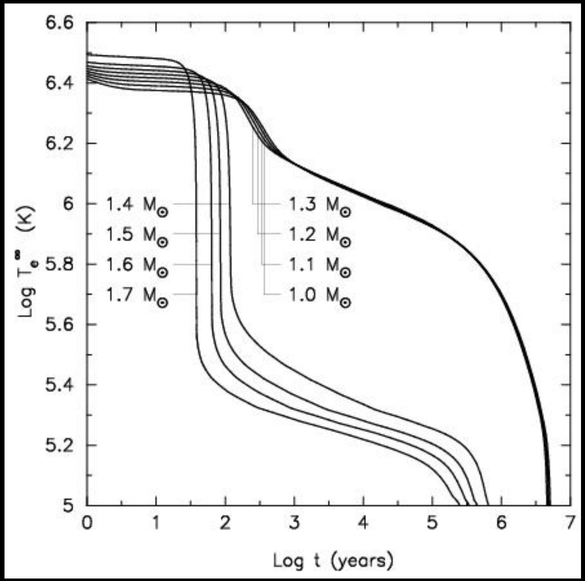
Critical mass for Durca:

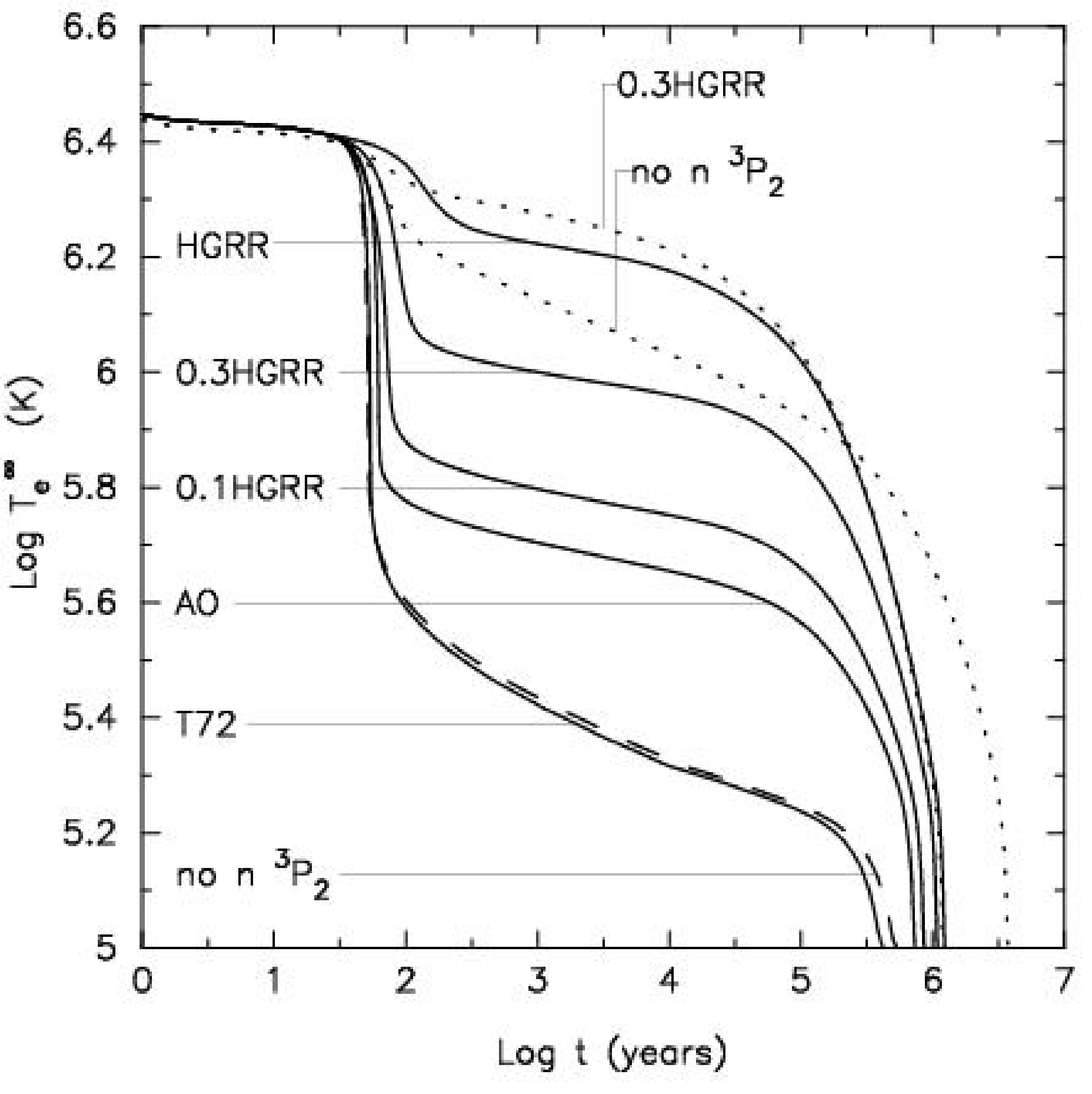
1.35 M_o <- Arbitrary, we DO NOT KNOW what it really is

Notice: the 1.4 M_o star has a "Durca pit" of 0.04 M_o !

“The Cooling of Neutron Stars by the Direct Urca Process”, Page & Applegate, ApJ 394, L17 (1992)

Fast Cooling with Direct Urca Process



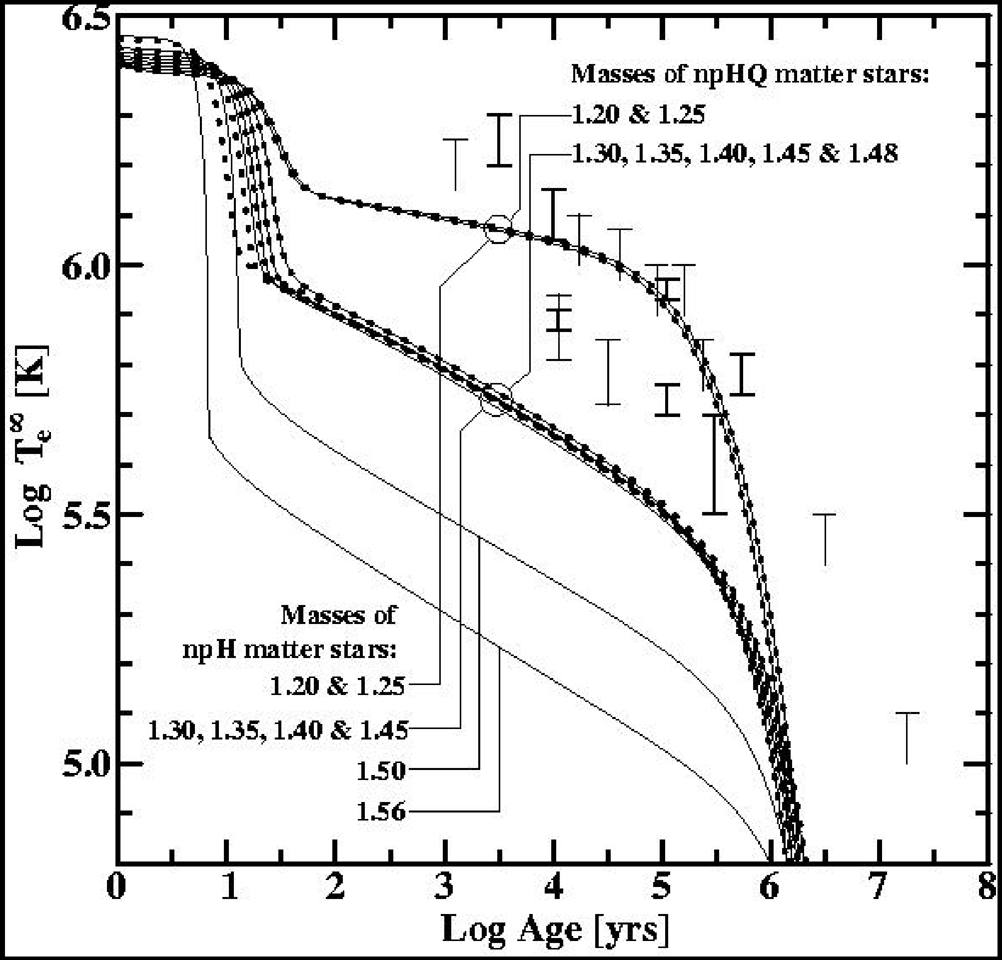


With pairing (e.g., n $^3P_2$) the cooling can be temporarily stopped at practically any temperature, depending on the value of T_c in the "Durca pit"

"The Cooling of Neutron Stars by the direct Urca Process", Page & Applegate, ApJ 394, L17 (1992)

A "Maximal Model"

Direct Urcas with Nucleons, Hyperons and Quarks



"Prospects of Detecting Baryon and Quark Superfluidity from Cooling Neutron Stars",
Page, Prakash, Lattimer & Steiner, PRL 85, 2048 (2000)

PART IV

Neutron Star Cooling

with

Strong Toroidal Magnetic Fields

Dany Page

Instituto de Astronomía, UNAM

In collaboration with:

- **U. Geppert (MPE, Garching)**
- **M. Kuecker (AIP, Potsdam)**

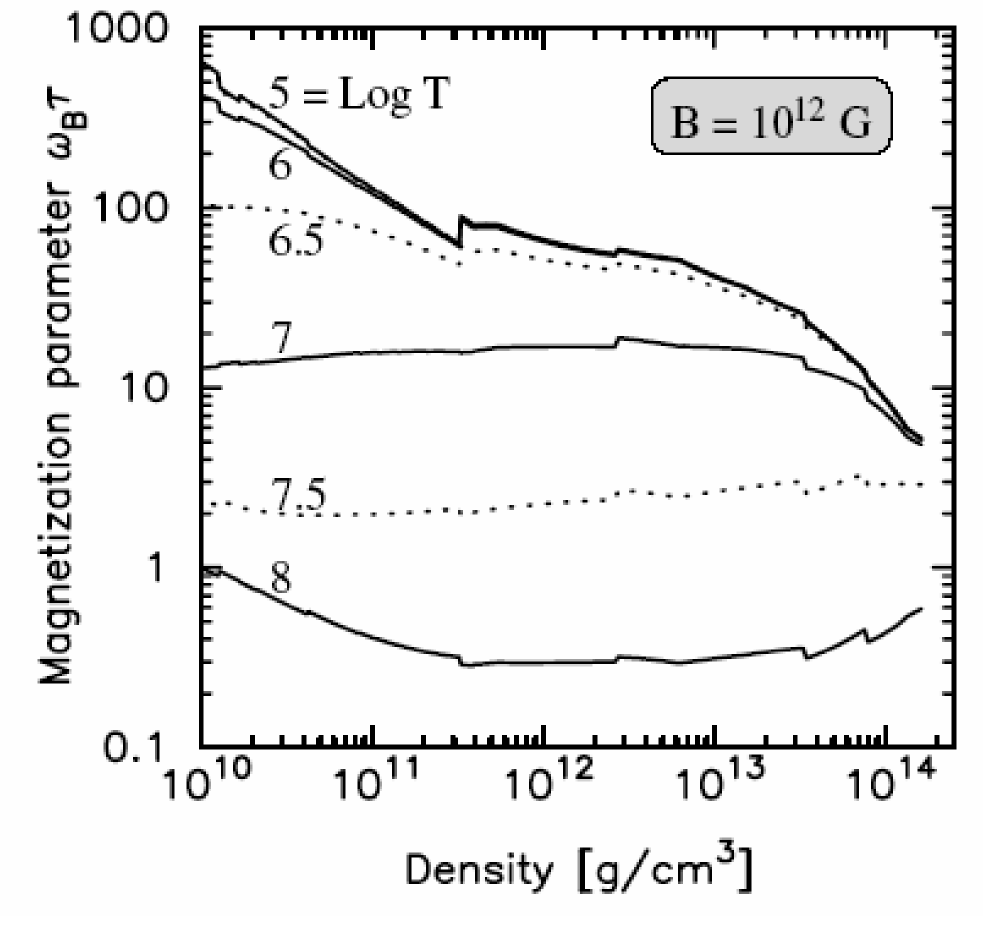
Anisotropy of heat transport: magnetic field effects deep in the crust

Electron thermal conductivity

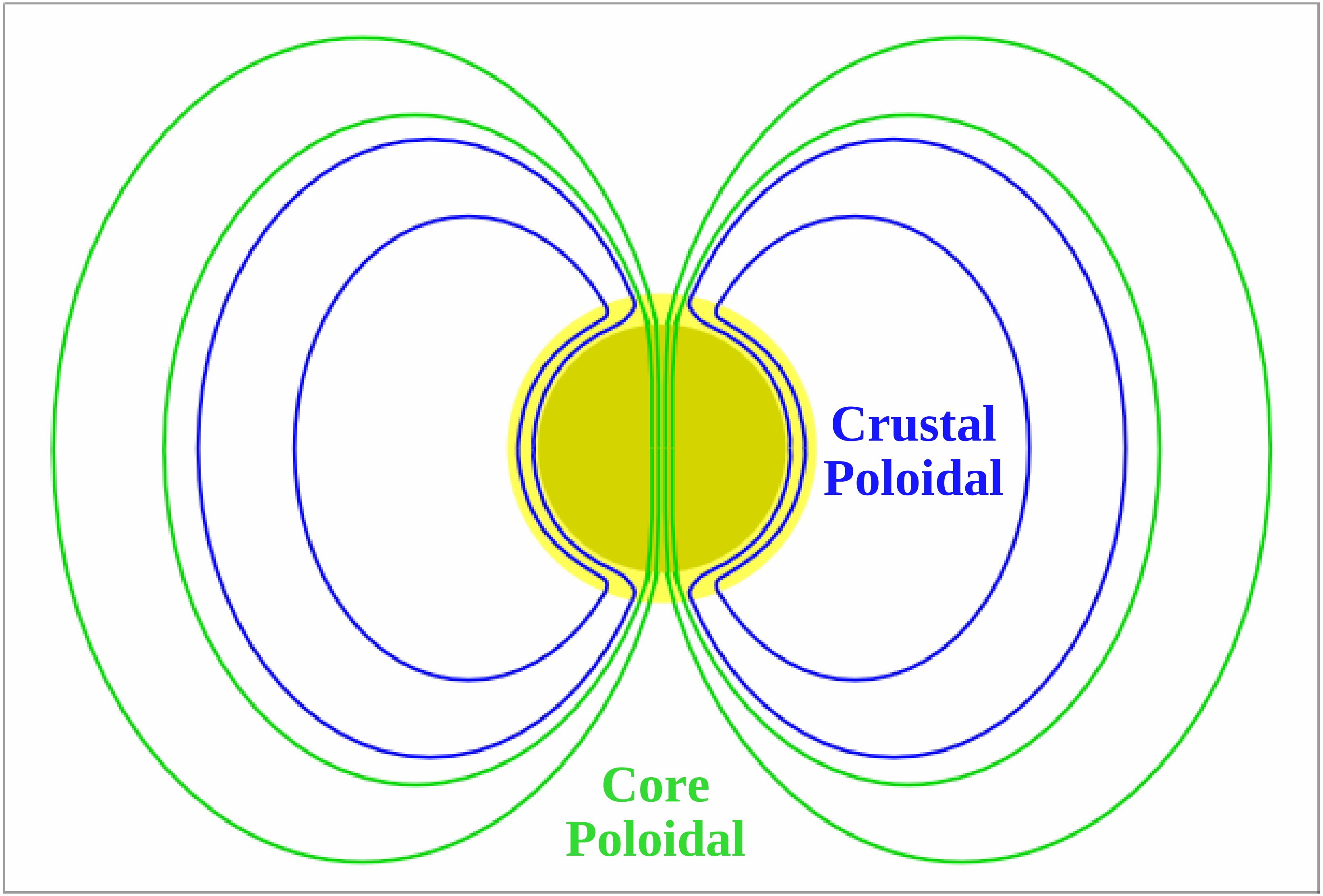
$$\kappa_{||} = \kappa_0$$

$$\kappa_{\perp} = \frac{\kappa_0}{1+(\Omega_b \tau)^2}$$

Electron gyrofrequency $$\omega_B = \frac{eB}{m^* c}$$



Dipolar Fields: Crust + Core Currents



Anisotropy of heat transport:
magnetic field effects deep in the crust

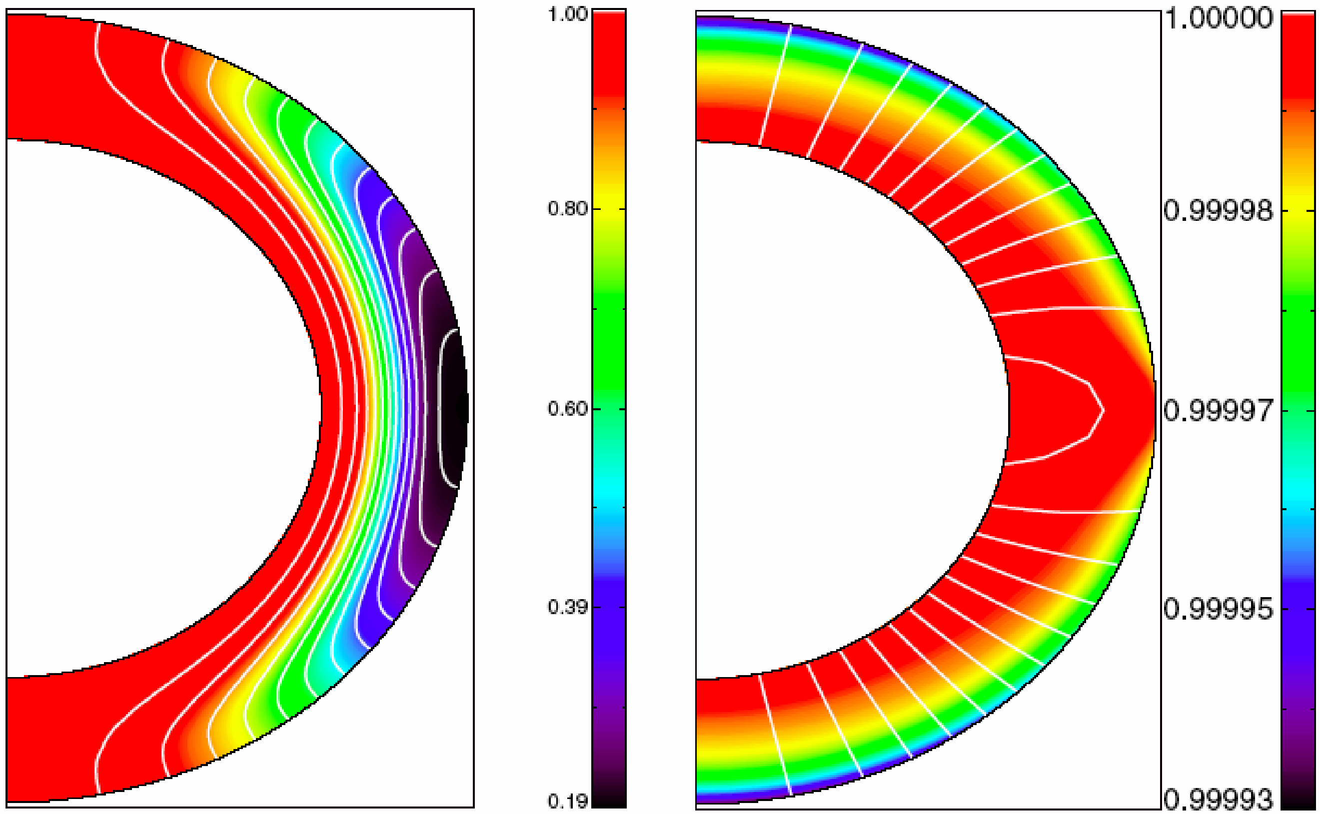
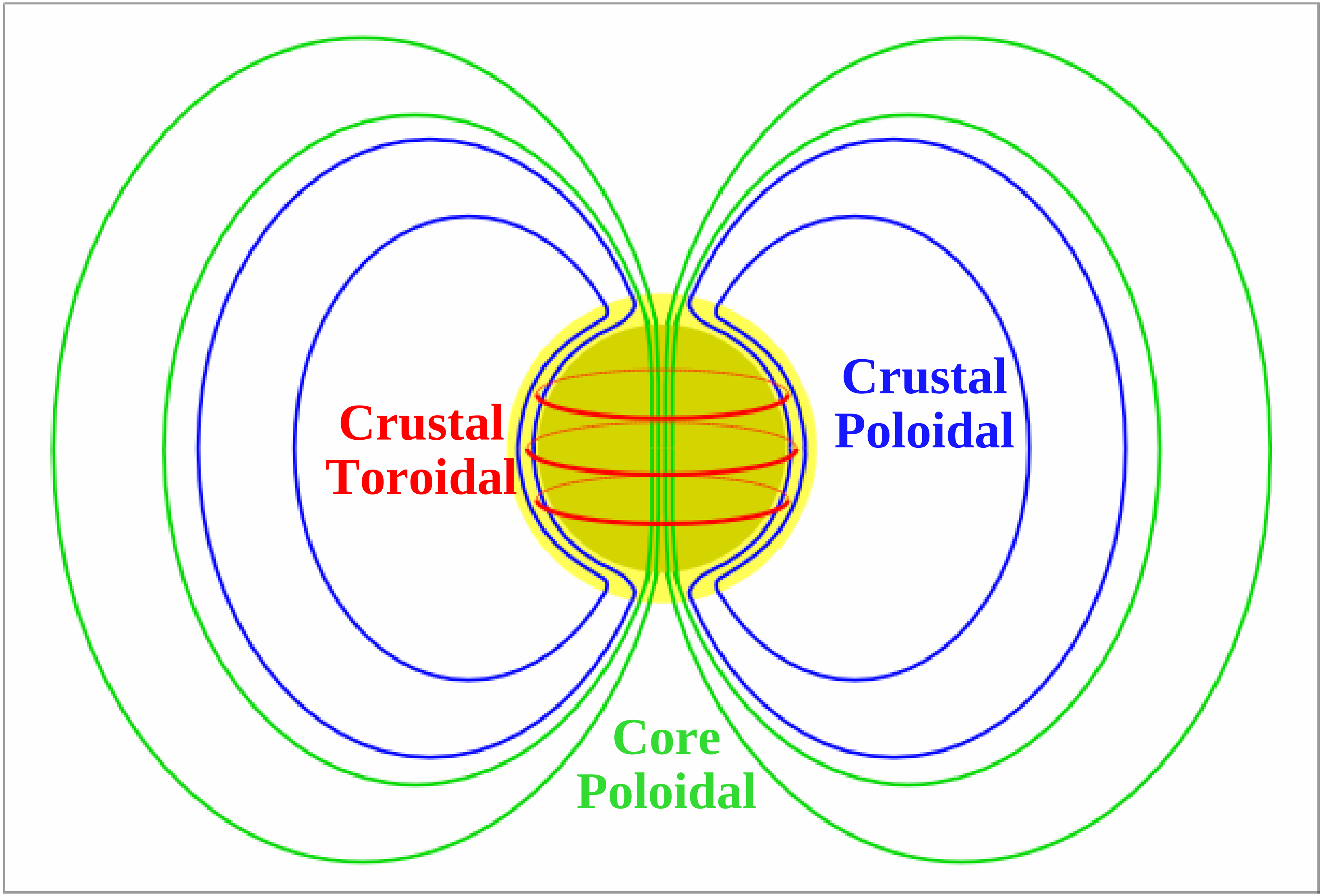


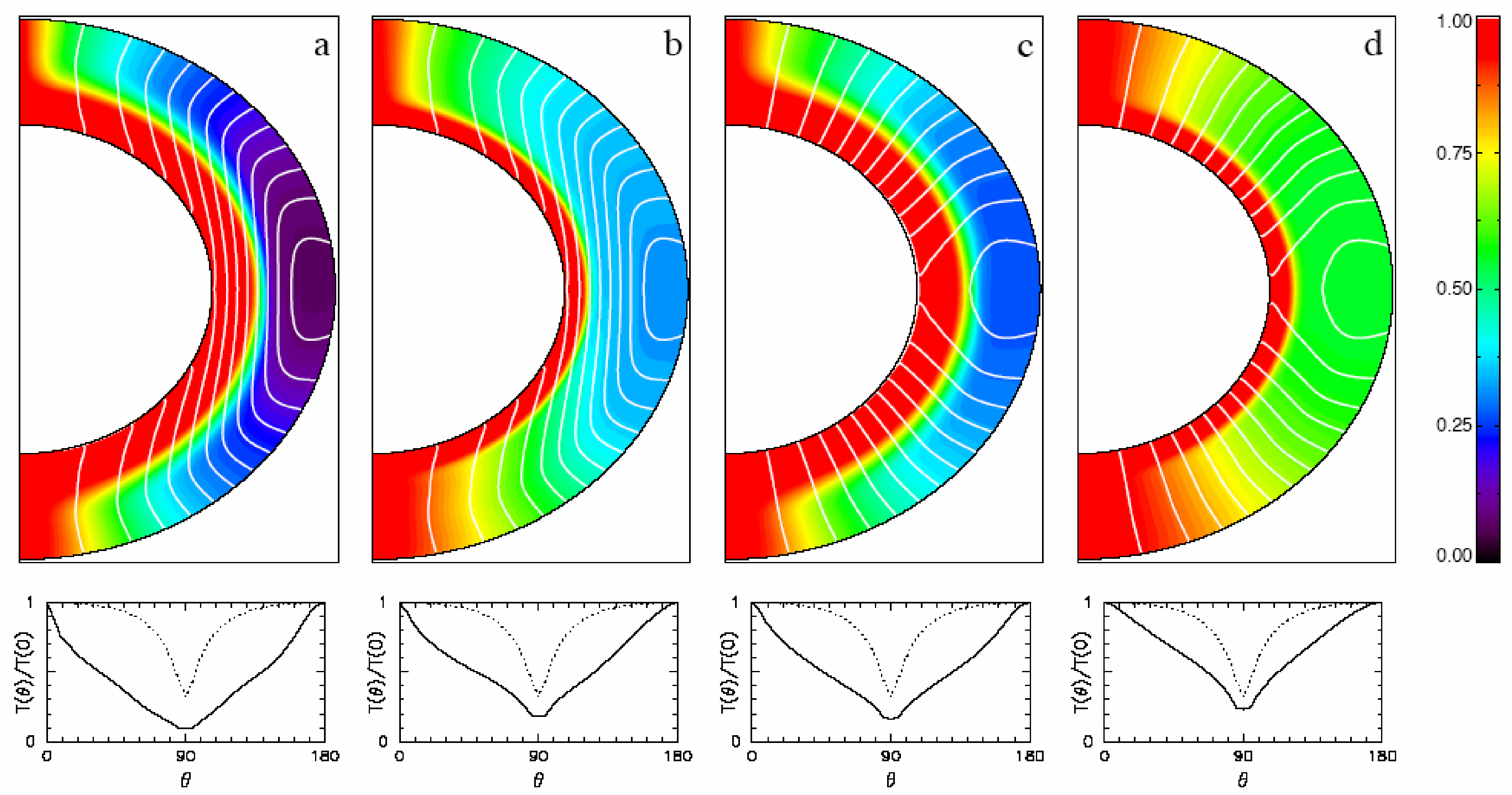
Fig. 7. Representation of both field lines and temperature distribution in the crust whose radial scale ($r(\rho_n) \leq r \leq r(\rho_b)$) is stretched by a factor of 5, assuming $B_0 = 3 \times 10^{12}$ G and $T_{core} = 10^6$ K. Left panel corresponds to a crustal field, right panel to a star-centered core field. Bars show the temperature scales in units of T_{core}.

Geppert, Kueker & Page, 2004

Poloidal + Toroidal Components

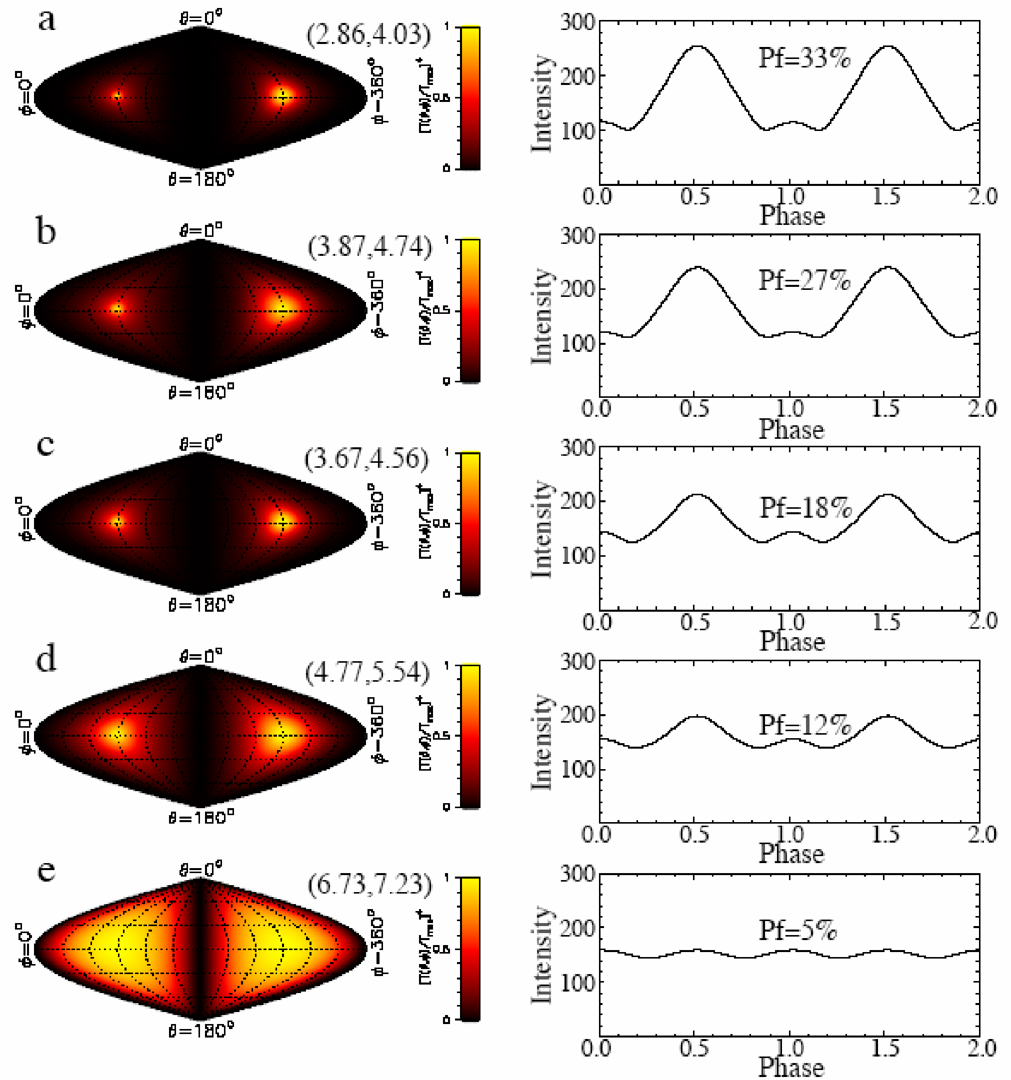


Anisotropy of heat transport: magnetic field effects deep in the crust

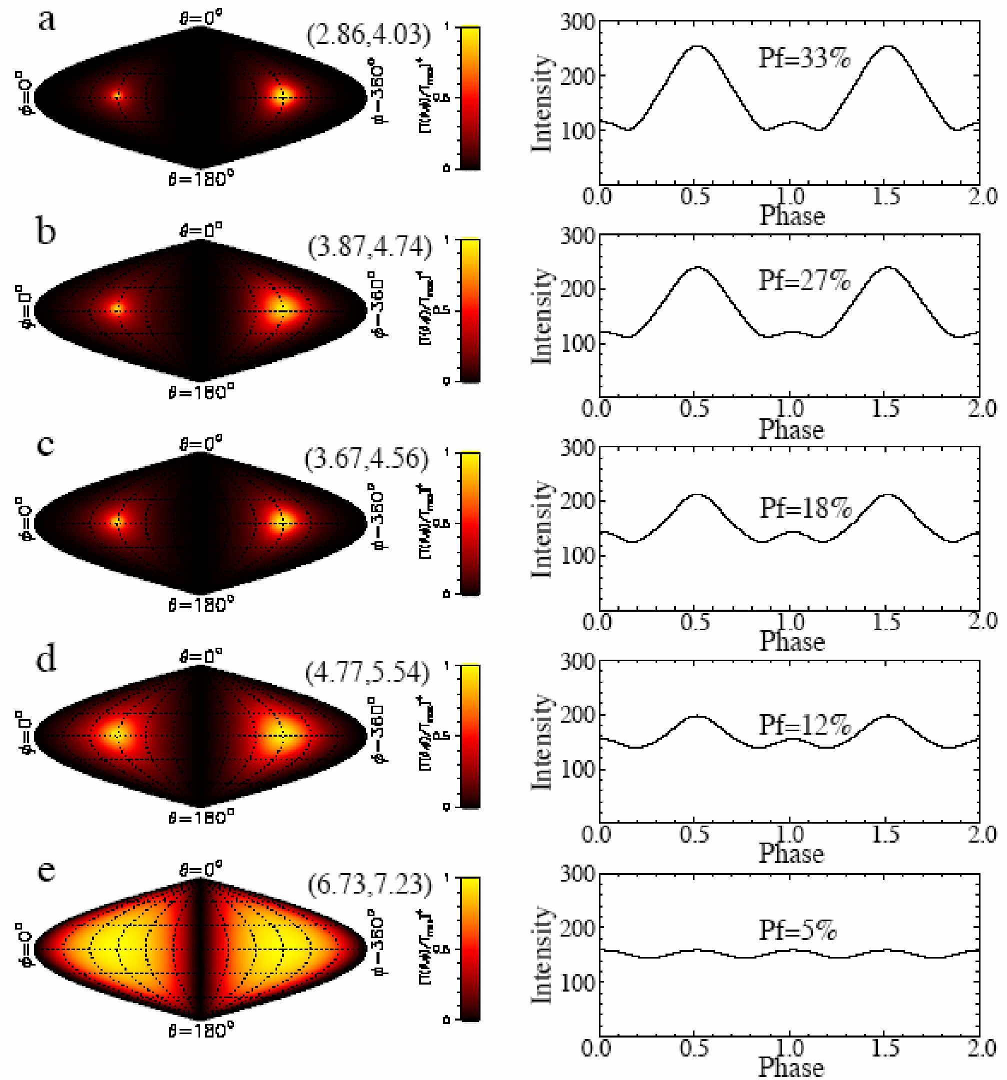


Geppert, Kueker & Page, 2006

Surface temperatures and Blackbody pulse profiles



Surface temperatures and Blackbody pulse profiles



Fit of RX J1856.5-3754 optical and X-ray spectrum

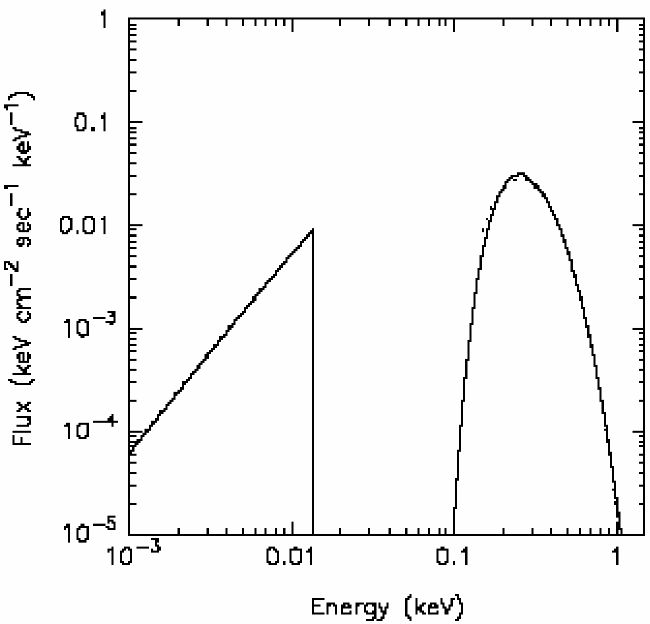
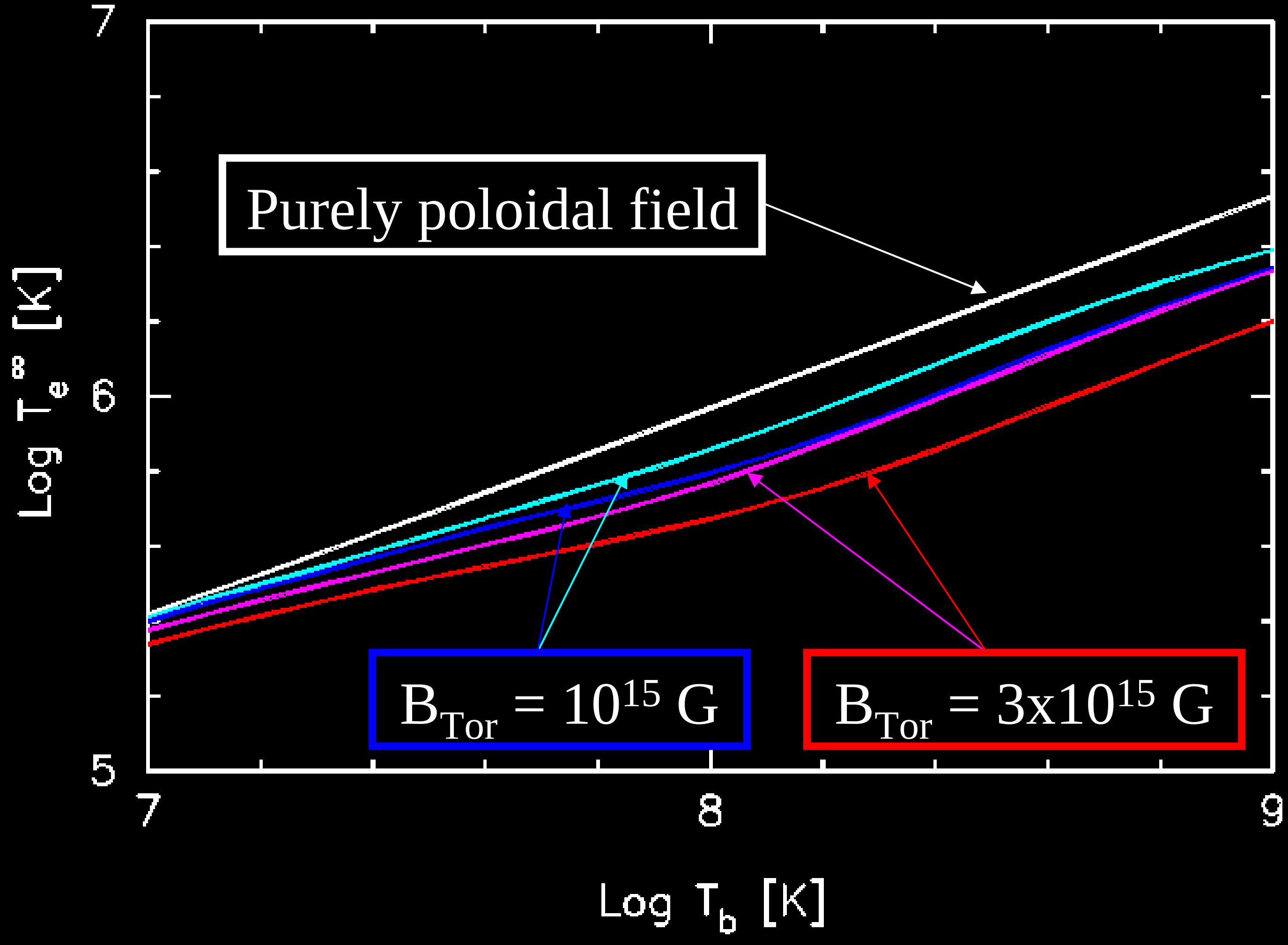
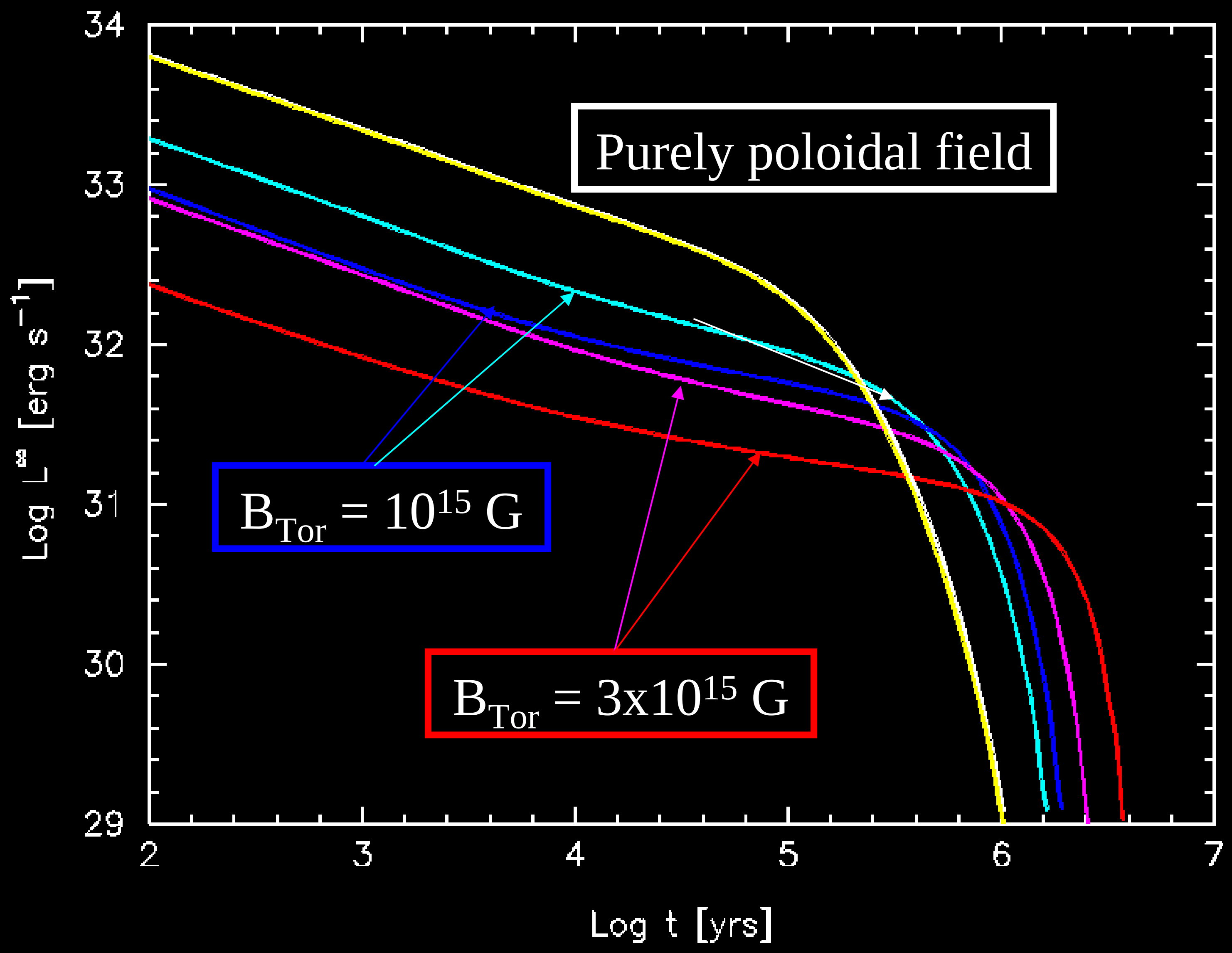


Fig. 10. Fit of the spectrum of RX J1856.5-3754. Dotted lines show the two blackbodies fit to the data from Trümper *et al.* (2004). The continuous line show our results: the star has a radius R = 14.4 km and R_∞ = 17.06 km for a 1.4 $M_\odot$, at a distance of 122 pcs ($N_H = 1.6 \times 10^{20}$ cm^{-2} for interstellar absorption) and the observer is assumed to be aligned with the rotation axis. The magnetic field structure corresponds to model c of Figure 6 adjusted to the 14.4 km radius with $T_b = 6.8 \times 10^7$ K, resulting in $T_{\rm eff}^\infty = 4.62 \times 10^5$ K and $T_{\rm max}^\infty = 8.54 \times 10^5$ K

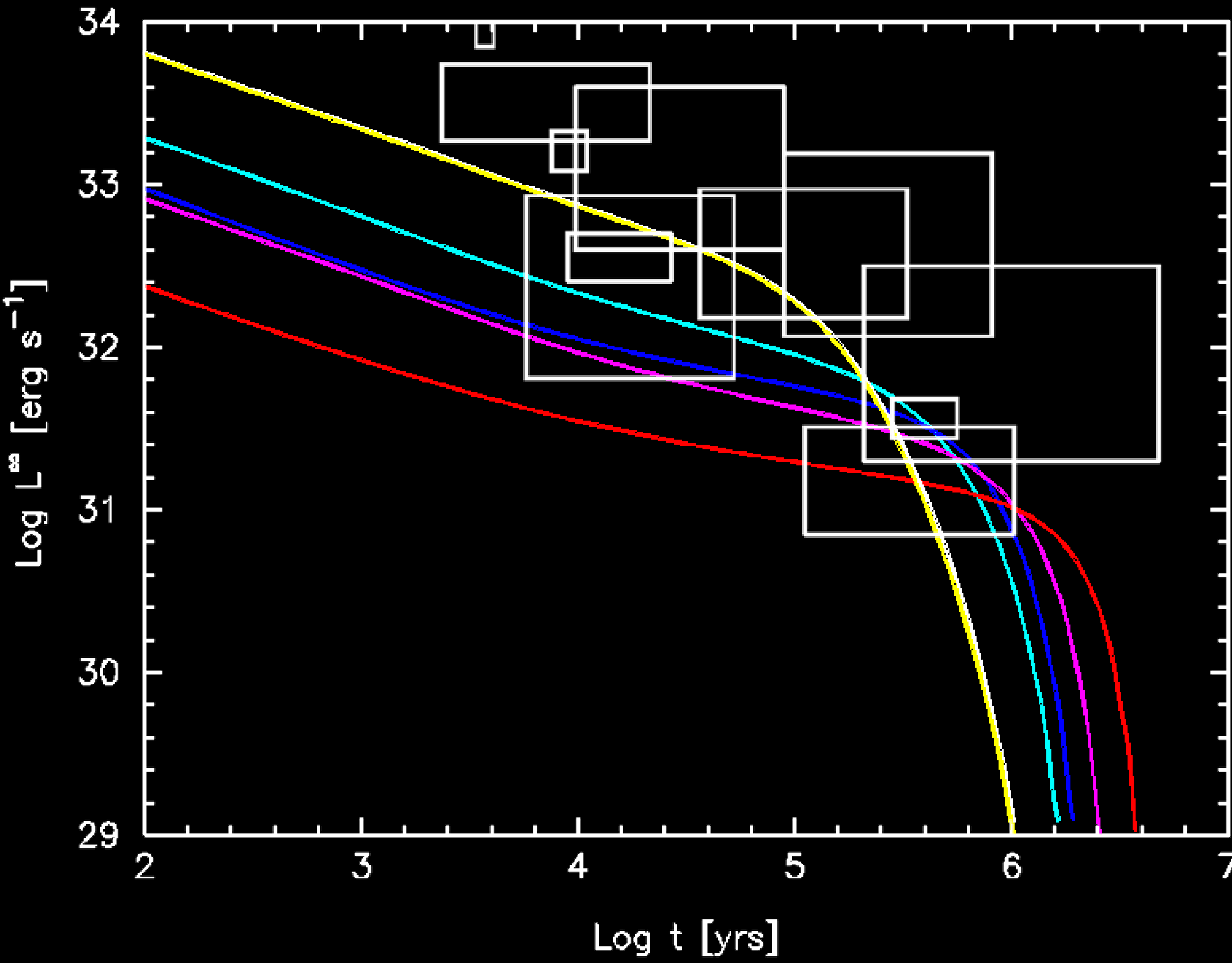
"T_e – T_b relationship"
Poloidal + Toroidal Fields



Cooling of NSs with Strong Toroidal Fields



Cooling of NSs with Strong Toroidal Fields



CONCLUSIONS

- Isolated Neutron Stars with clearly identified thermal spectrum seem to be compatible with "minimal" cooling scenarios: no clear evidence for presence of "exotic" matter.
- Some cases, barely detected, or even undetected, point toward "non-minimal" stars.

- A STRONG toroidal field in the crust can channel heat toward very small hot spots on the stellar surface: "natural" explanation of the 2-Temperature fits of the XDINS optical+X-ray spectra.
- Cooling histories of such star are quite differrent from the ones of stars without toroidal fields:

They are much less luminous

but

survive much longer before diving into oblivion.


"That's all Folks!"

11th Marcel Grossmann Meeting

Thermal Behaviour of Compact Stars

Eleventh Marcel Grossmann Meeting on General Relativity
at the Freie Universität of Berlin
July 23 - 29, 2006

Scope:

Modelling of the thermal behavior of compact stars (either neutron, in their many possible forms, or strange stars) is a very powerfull tool to study the nature of matter at supra-nuclear densities. This session will focus on two complementary approaches to this problem: isolated cooling compact stars and accreting ones. Review talks will present critical observational data and the essential theory.

Some compact stars in LMXBs (Low-Mass X-ray Binaries) may be much heavier than isolated ones and together they allow to study an extended range of masses. Transiently accreting systems make it possible to study the short-time thermal response of the star while superbursting systems directly probe the interior physical conditions. Moreover, recent observations seriously challenge our standard view of neutron stars.

The later merging of the compact star and its companion (probably a white dwarf for descendants of LMXBs) is a possible central engine for short gamma-ray bursts and certainly a strong source of gravitational waves.

Invited Speakers:
Dima Yakovlev, Sergei Popov, Andrew Cumming, Jean in't Zand, Peter Jonker

National Institute for Nuclear Theory, Seattle

Summer 2007INT-07-2a

The Neutron Star Crust and Surface

June 18 to July 20, 2007

Organizers: D. Page, G. Pavlov, M. Prakash, & R. Rutledge