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Thermal Evolution of Neutron Stars

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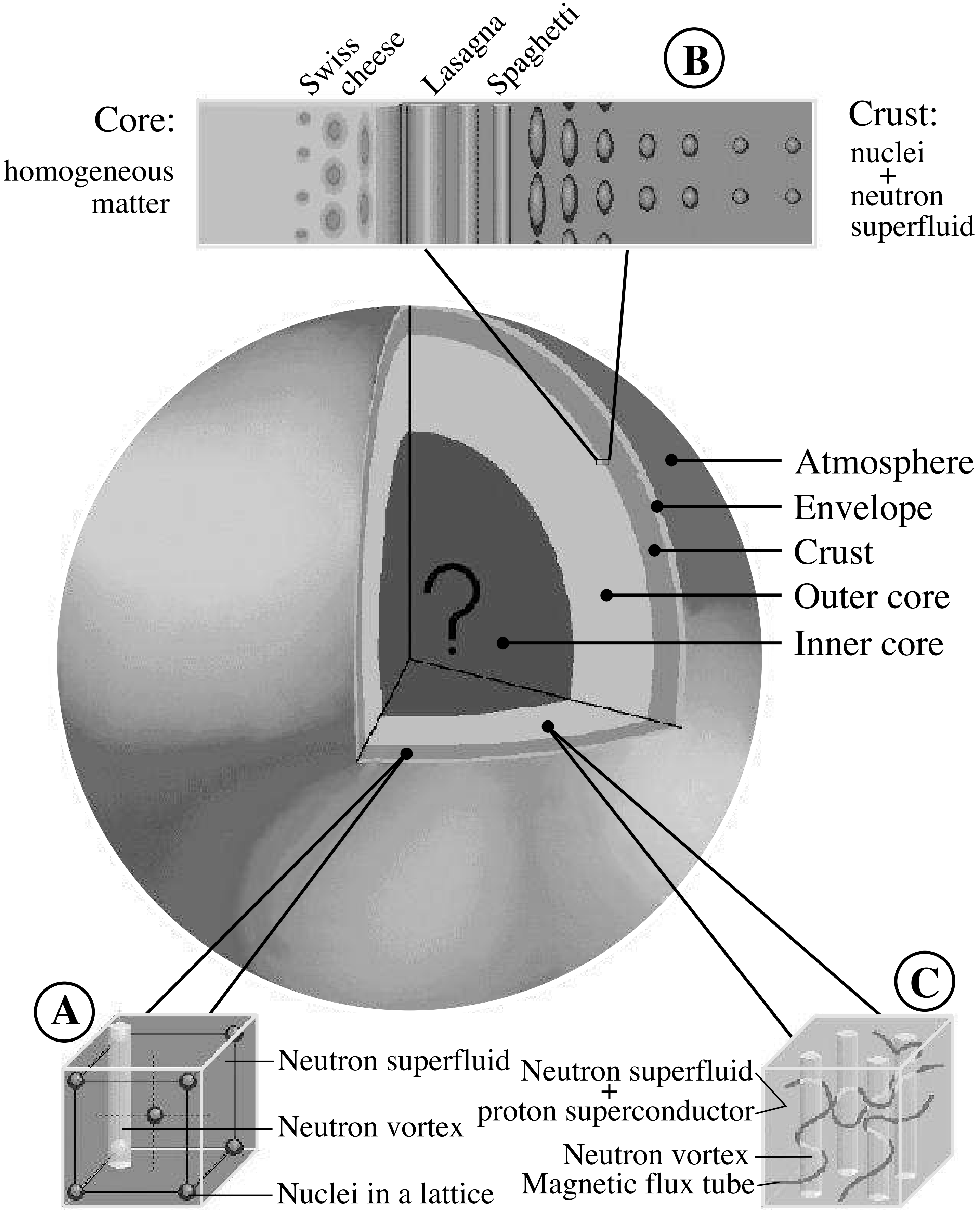
Thermal Evolution of Neutron Stars

- **Overview of neutron star structure and a simple analytical cooling model**
- URCA processes
- Problem 1: pairing
- Problem 2: envelope chemical composition and magnetic fields
- Minimal Cooling
- Problem 3: data interpretation
- Examples of fast cooling scenarios
- Conclusion and prospects



“Dense Matter in Compact Stars: Theoretical Developments and Observational Constraints”, Page D. & Reddy S., 2006ARNPS..56..327P

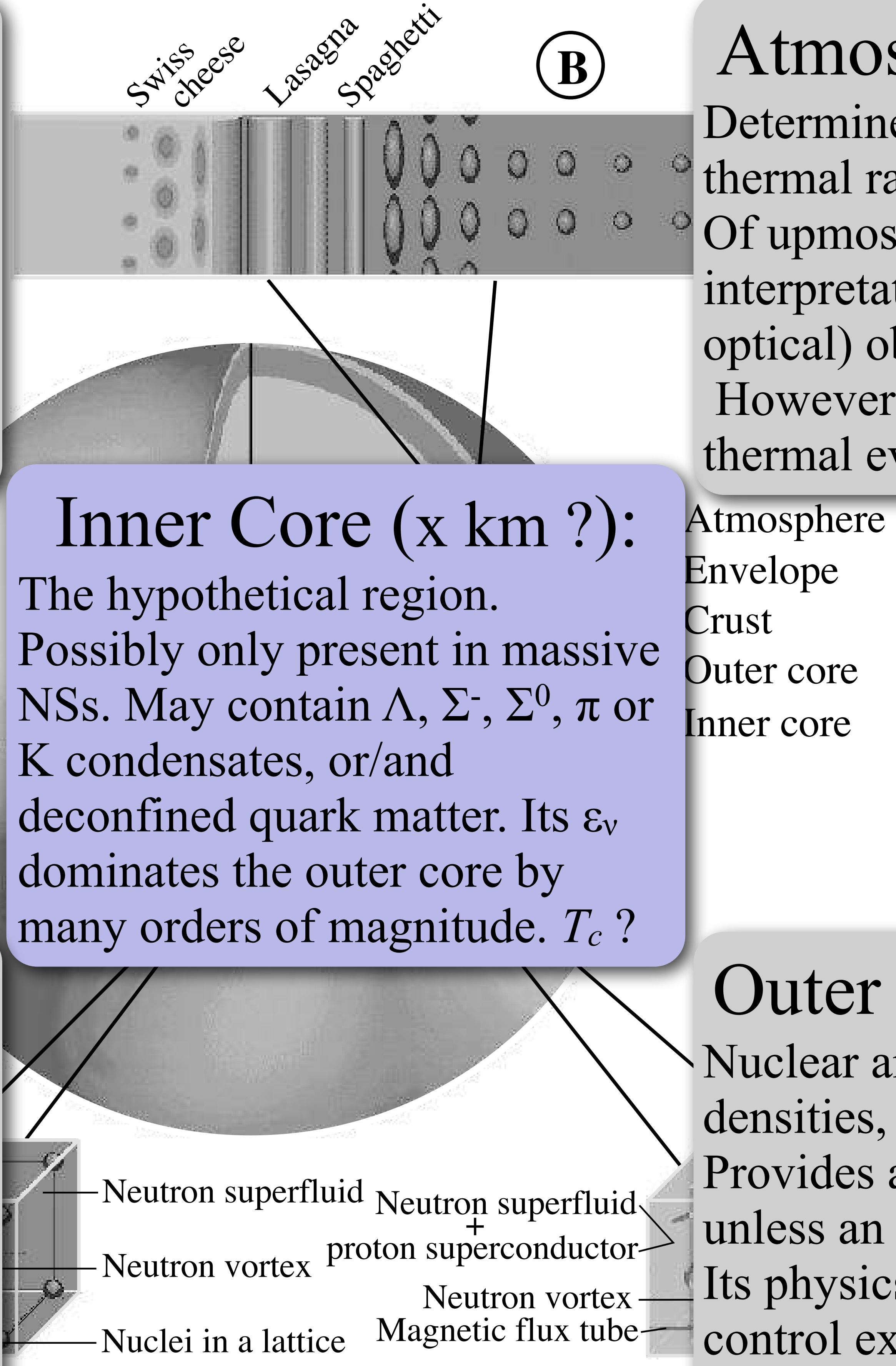
Envelope (100 m):

Contains a huge temperature gradient: it determines the relationship between T_{int} and T_e. Extremely important for the cooling, strongly affected by magnetic fields and the presence of “polluting” light elements.

Atmosphere (10 cm):

Determines the shape of the thermal radiation (the spectrum). Of upmost importance for interpretation of X-ray (and optical) observation.

However it as NO effect on the thermal evolution of the star.



Inner Core (x km ?):

The hypothetical region. Possibly only present in massive NSs. May contain Λ, Σ^-, Σ^0, π or K condensates, or/and deconfined quark matter. Its ϵ_ν dominates the outer core by many orders of magnitude. T_c ?

Crust (1 km):

Little effect on the long term cooling. BUT: may contain heating sources (magnetic/ rotational, pycnonuclear under accretion). Its thermal time is important for very young star and for quasi-persistent accretion

Outer Core (10-x km):

Nuclear and supranuclear densities, containing n, p, e & μ. Provides about 90% of c_v and ϵ_ν unless an inner core is present. Its physics is basically under control except pairing T_c which is essentially unknown.

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Neutron star cooling on a napkin

Assume the star's interior is isothermal and neglect GR effects.

Thermal Energy, E_{th} ,balance:

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

⇒ 3 essential ingredients are needed:

- C_v = total stellar specific heat
- L_γ = total surface photon luminosity
- L_ν = total stellar neutrino luminosity

H = "heating", from B field decay, friction, etc ...

Surface photon emission on a napkin

$$L_\gamma = 4\pi R^2 \sigma_{\mathrm{SB}} T_e^4$$

L_γ: erg s^{-1}

T_e: effective temperature, is *defined* by this relation

(in analogy to blackbody emission)

Relationship between T_e and $T=T_{int}$ (interior T): provided by an envelope model.

Simple ("rule of thumb") formula:

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

A sample of neutrino emission processes

Name	Process	Emissivity ($\mathrm{erg\ cm^{-3}\ s^{-1}}$)	
Modified Urca cycle (neutron branch)	$n+n \to n+p+e^- + \bar{\nu}_e$ $n+p+e^- \to n+n+\nu_e$	$\sim 2{\times}10^{21}\ R\ T_9^8$	Slow
Modified Urca cycle (proton branch)	$p+n \to p+p+e^- + \bar{\nu}_e$ $p+p+e^- \to p+n+\nu_e$	$\sim 10^{21}\ R\ T_9^8$	Slow
Bremsstrahlung	$n+n \to n+n+\nu+\bar{\nu}$ $n+p \to n+p+\nu+\bar{\nu}$ $p+p \to p+p+\nu+\bar{\nu}$	$\sim 10^{19}\ R\ T_9^8$	Slow
Cooper pair formations	$n+n \to [nn]+\nu+\bar{\nu}$ $p+p \to [pp]+\nu+\bar{\nu}$	$\sim 5{\times}10^{21}\ R\ T_9^7$ $\sim 5{\times}10^{19}\ R\ T_9^7$	Medium
Direct Urca cycle	$n \to p+e^- + \bar{\nu}_e$ $p+e^- \to n+\nu_e$	$\sim 10^{27}\ R\ T_9^6$	Fast
π^- condensate	$n+ <\pi^-> \to n+e^- + \bar{\nu}_e$	$\sim 10^{26}\ R\ T_9^6$	Fast
K^- condensate	$n+ <K^-> \to n+e^- + \bar{\nu}_e$	$\sim 10^{25}\ R\ T_9^6$	Fast

A simple analytical solution

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

$$C_v = CT \quad L_\nu = NT^8 \quad L_\gamma = ST^{2+4\alpha}$$

$L_\gamma = 4\pi R^2 \sigma T_e^4$ using $T_e \propto T^{0.5+\alpha}$ with $\alpha \ll 1$

- **Neutrino Cooling Era:** $L_\nu >> L_\gamma$

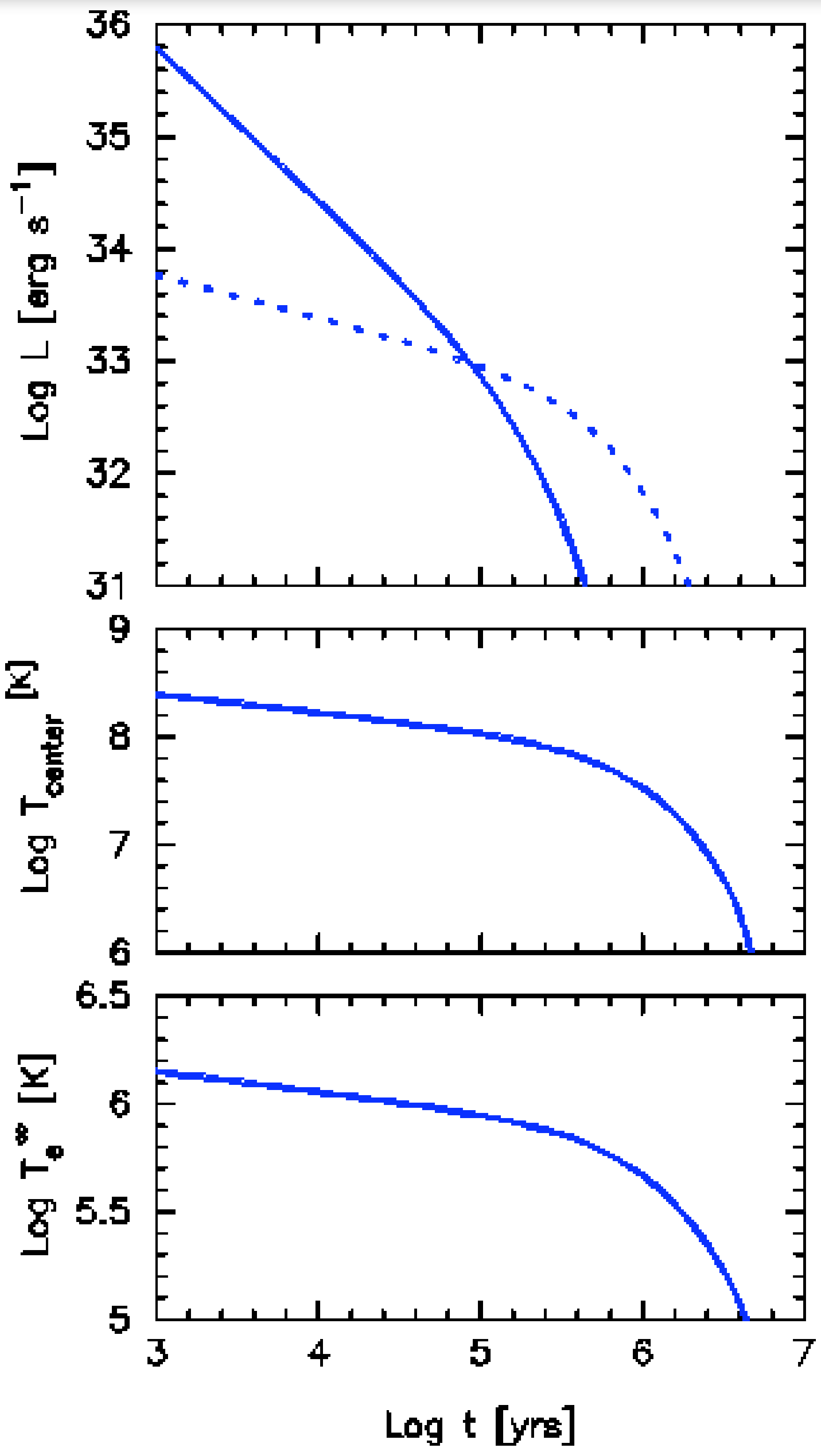
$$\frac{dT}{dt} = -\frac{N}{C} T^7 \Rightarrow t - t_0 = \frac{C}{6N}\left[\frac{1}{T^6} - \frac{1}{T_0^6}\right]$$

$T \propto t^{-1/6}$ and $T_e \propto t^{-1/12}$

- **Photon Cooling Era:** $L_\gamma >> L_\nu$

$$\frac{dT}{dt} = -\frac{N}{S} T^{1+\alpha} \Rightarrow t - t_0 = \frac{C}{4\alpha S}\left[\frac{1}{T^\alpha} - \frac{1}{T_0^\alpha}\right]$$

$T \propto t^{-1/\alpha}$ and $T_e \propto t^{-1/2\alpha}$



Neutrino cooling time scales

$$\frac{dE_{th}}{dt} = C_v \frac{dT}{dt} = -L_\nu \qquad C_v = CT \quad \text{and} \quad L_\nu^{\text{slow}} = N^{\text{slow}} T^8 \quad \text{or} \quad L_\nu^{\text{fast}} = N^{\text{fast}} T^6$$

- **Slow neutrino cooling:** $L_\nu^{\text{slow}} = \iiint \epsilon_\nu^{\text{slow}} dV = 10^{38} - 10^{40} \times T_9^8 \ \text{erg s}^{-1} \equiv N_9^{\text{slow}} T_9^8$

(lowest value corresponds to the case where extensive pairing in the core suppresses its neutrino emission and only the crust e-ion bremsstrahlung process is active)

$$\frac{dT}{dt} = -\frac{N}{C} T^7 \Rightarrow t - t_0 = \frac{C}{6N^{\text{slow}}}\left[\frac{1}{T^6} - \frac{1}{T_0^6}\right]$$

$$\tau_\nu^{\text{slow}} \sim \frac{6 \text{ months}}{T_9^6} \times \left[\frac{C_9/10^{39}}{6 \ N_9^{\text{slow}}/10^{40}}\right]$$

- **Fast neutrino cooling:** $L_\nu^{\text{sfast}} = \iiint \epsilon_\nu^{\text{sfast}} dV = 10^{44} - 10^{45} \times T_9^6 \ \text{erg s}^{-1} \equiv N_9^{\text{fast}} T_9^6$

$$\frac{dT}{dt} = -\frac{N}{C} T^5 \Rightarrow t - t_0 = \frac{C}{4N^{\text{fast}}}\left[\frac{1}{T^\alpha} - \frac{1}{T_0^\alpha}\right]$$

$$\tau_\nu^{\text{fast}} \sim \frac{4 \text{ minutes}}{T_9^4} \times \left[\frac{C_9/10^{39}}{4 \ N_9^{\text{fast}}/10^{45}}\right]$$

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The direct URCA process

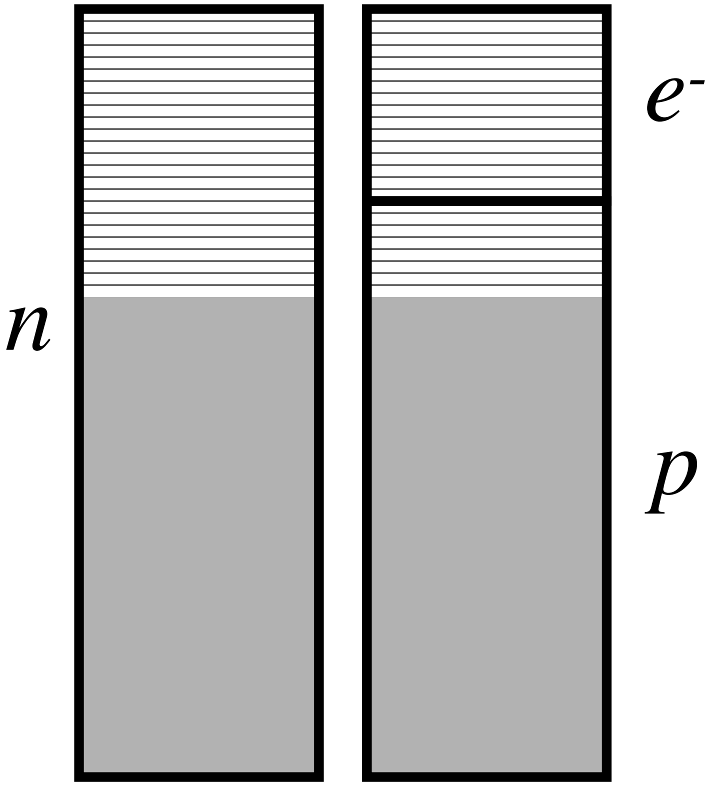
Basic mechanism: β and inverse β decays:

$$n \longrightarrow p + e^- + \bar{\nu}_e \quad \text{and} \quad p + e^- \longrightarrow n + \nu_e$$

Energy conservation:

Momentum conservation:

$E_{Fn} = E_{Fp} + E_{Fe}$



"Triangle rule": $p_{Fn} < p_{Fp} + p_{Fe}$

$$n_i = \frac{k_{F\,i}^3}{3\pi^2} \Rightarrow n_n^{1/3} \le n_p^{1/3} + n_e^{1/3} = 2n_p^{1/3}$$

$$\boxed{x_p \equiv \frac{n_p}{n_n + n_p} \ge \frac{1}{9} \approx 11\%}$$

"Direct URCA process in neutron stars", JM Lattimer, CJ Pethick, M Prakash & P Haensel, 1991 PhRvL 66, 2701

A sample of neutrino emission processes

Name	Process	Emissivity (erg cm^{-3} s^{-1})	
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Modifie (proton	$^- + \bar{\nu}_e$ $+ \nu_e$	$\sim 10^{21}\ R\ T_9^8$	Slow
Bremsst	$+ \bar{\nu}$ $\bar{\nu}$ $+ \bar{\nu}$	$\sim 10^{19}\ R\ T_9^8$	Slow
Cooper formatic	$\bar{\nu}$ $\bar{\nu}$	$\sim 5{\times}10^{21}\ R\ T_9^7$ $\sim 5{\times}10^{19}\ R\ T_9^7$	Medium
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π^- condensate	$n + < \pi^- > \to n + e^- + \bar{\nu}_e$	$\sim 10^{26}\ R\ T_9^6$	Fast
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Modified URCA vs. Direct URCA:

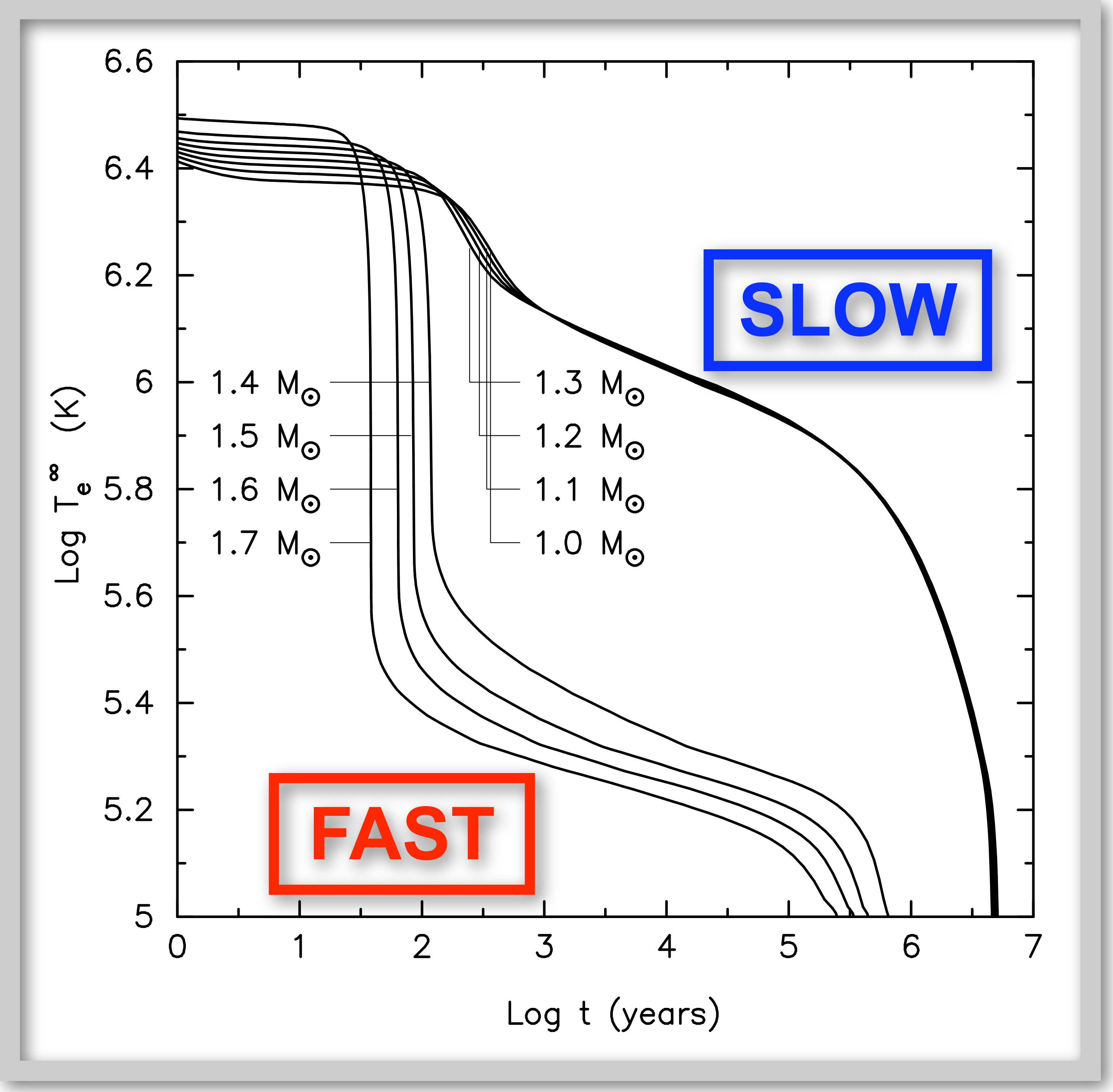
$$n + n' \longrightarrow p + n' + e + \bar{\nu}$$

$$n \longrightarrow p + e + \bar{\nu}$$

3 vs 5 fermions phase space:

$$\left(\frac{k_B T}{E_F}\right)^2 \sim \left(\frac{0.1\,\mathrm{MeV}\cdot T_9}{100\,\mathrm{MeV}\cdot E_{F\,100}}\right)^2 \sim 10^{-6}$$

Direct vs modified URCA cooling



Models based on the PAL EOS:

adjusted (by hand) so that DURCA becomes allowed (triangle rule !) at M > 1.35 M_{Sun}.

This value is arbitrary:
we DO NOT know the value of this critical mass, and hopefully observations will, some day, tell us what it is !

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

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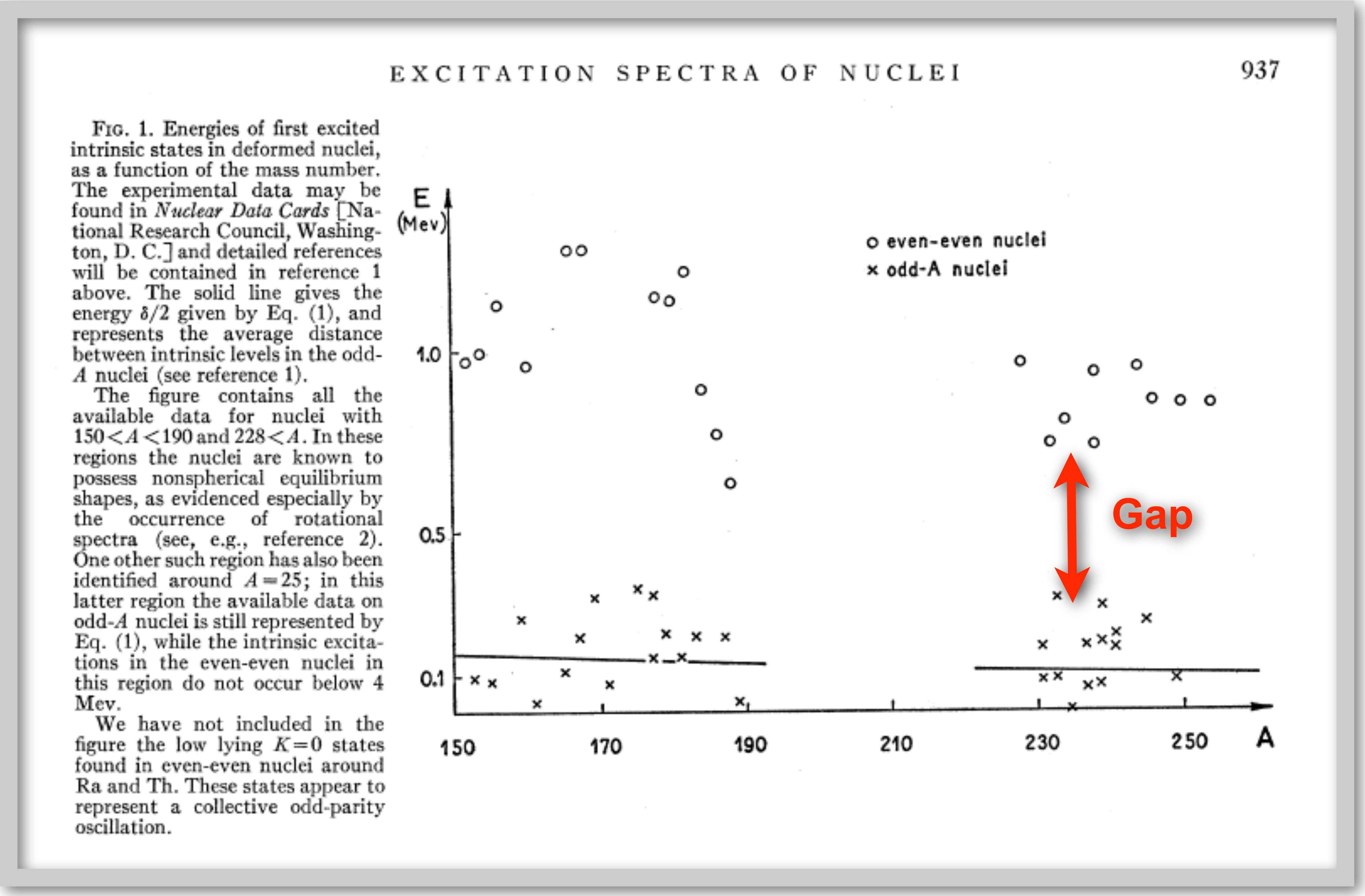
Nucleon pairing



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, Mottelson, Pines, 1958 Phys. Rev. 110, 936

Suppression of c_v and ε_ν by pairing

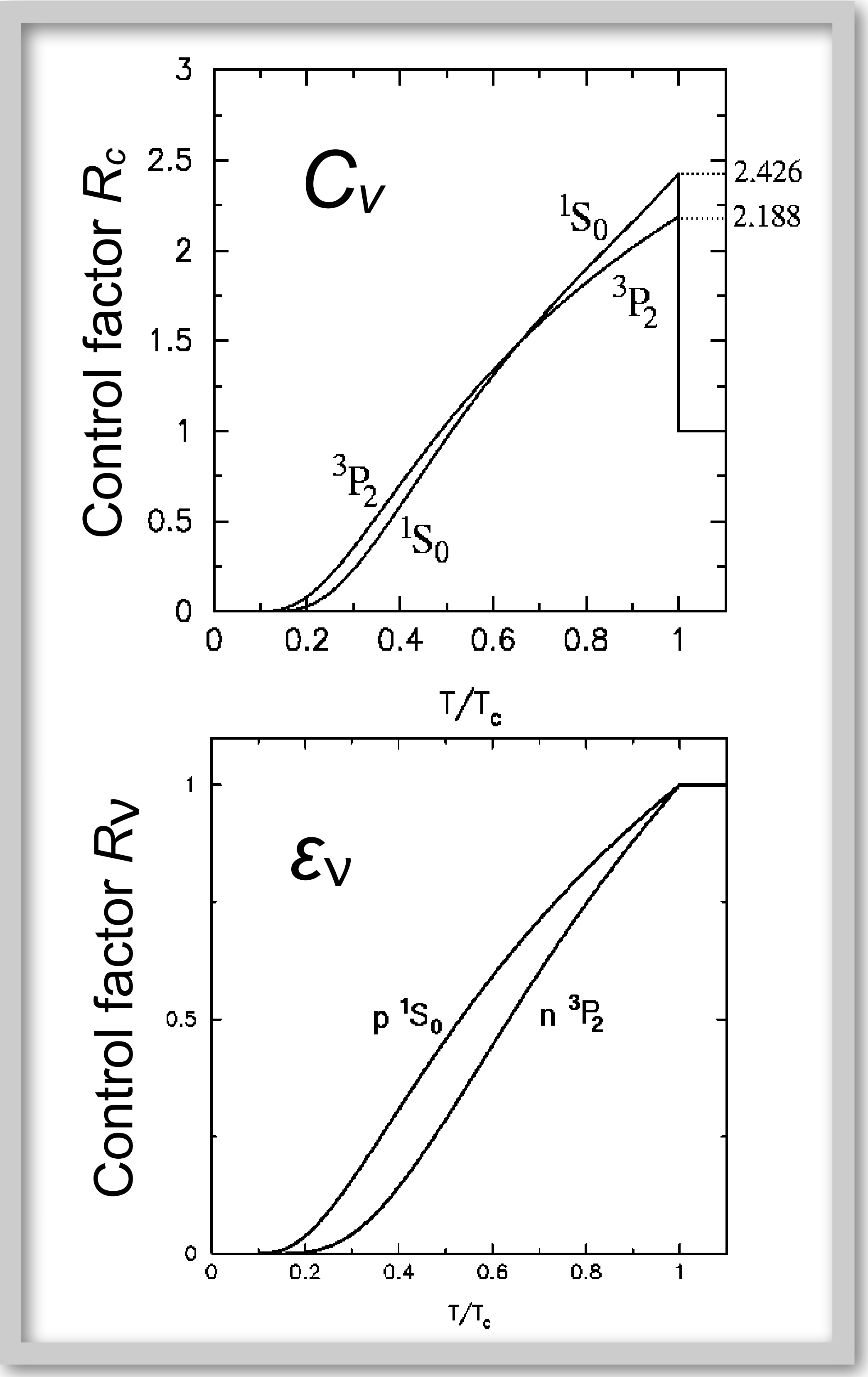
The presence of a pairing gap in the single particple excitation spectrum results in a Boltzmann-like

$\sim\exp(-\Delta/k_B T)$

suppression of c_v and ε_ν:

$$c_v \to c_v^{\text{Paired}} = R_c c_v^{\text{Normal}}$$

$$\epsilon_\nu \to \epsilon_\nu^{\text{Paired}} = R_\nu \epsilon_\nu^{\text{Normal}}$$



Phase shifts: presumption for pairing channels

Possible channels:

- Low momentum: ${}^1S_0$
- Larger momentum: ${}^3P_2$

${}^3P_2$ is mixed with ${}^3F_2$ by the tensor interaction

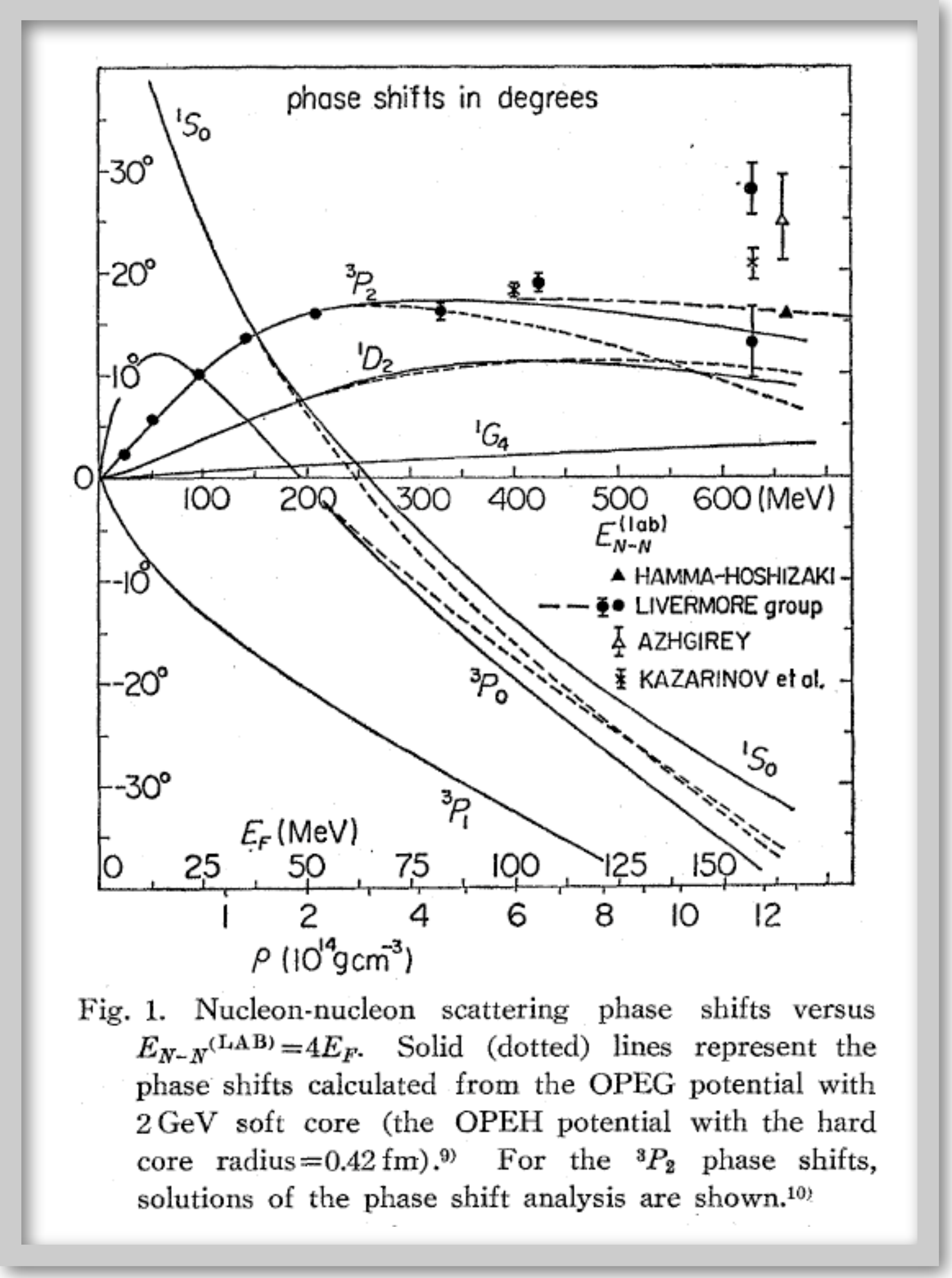
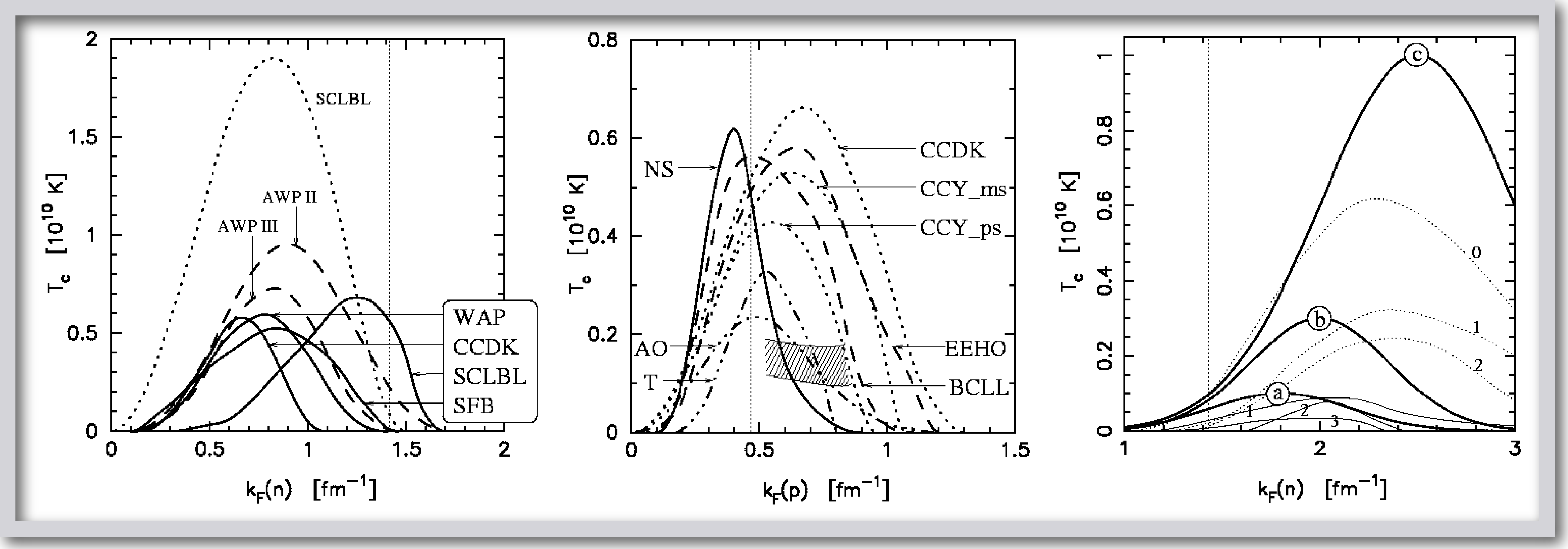


Fig. 1. Nucleon-nucleon scattering phase shifts versus $E_{N-N}{}^{(\mathrm{LAB})}=4E_F$. Solid (dotted) lines represent the phase shifts calculated from the OPEG potential with 2 GeV soft core (the OPEH potential with the hard core radius=0.42 fm).[9] For the ${}^3P_2$ phase shifts, solutions of the phase shift analysis are shown.[10]

"Superfluid State in Neutron Star Matter. I Generalized Bogoliubov Transformation and Existence of ${}^3P_2$ Gap at High Density", Tamagaki, R., 1970 PThPh..44..905T

Pairing T_c models



Neutron $^1S_0$ Proton $^1S_0$ Neutron $^3P_2$

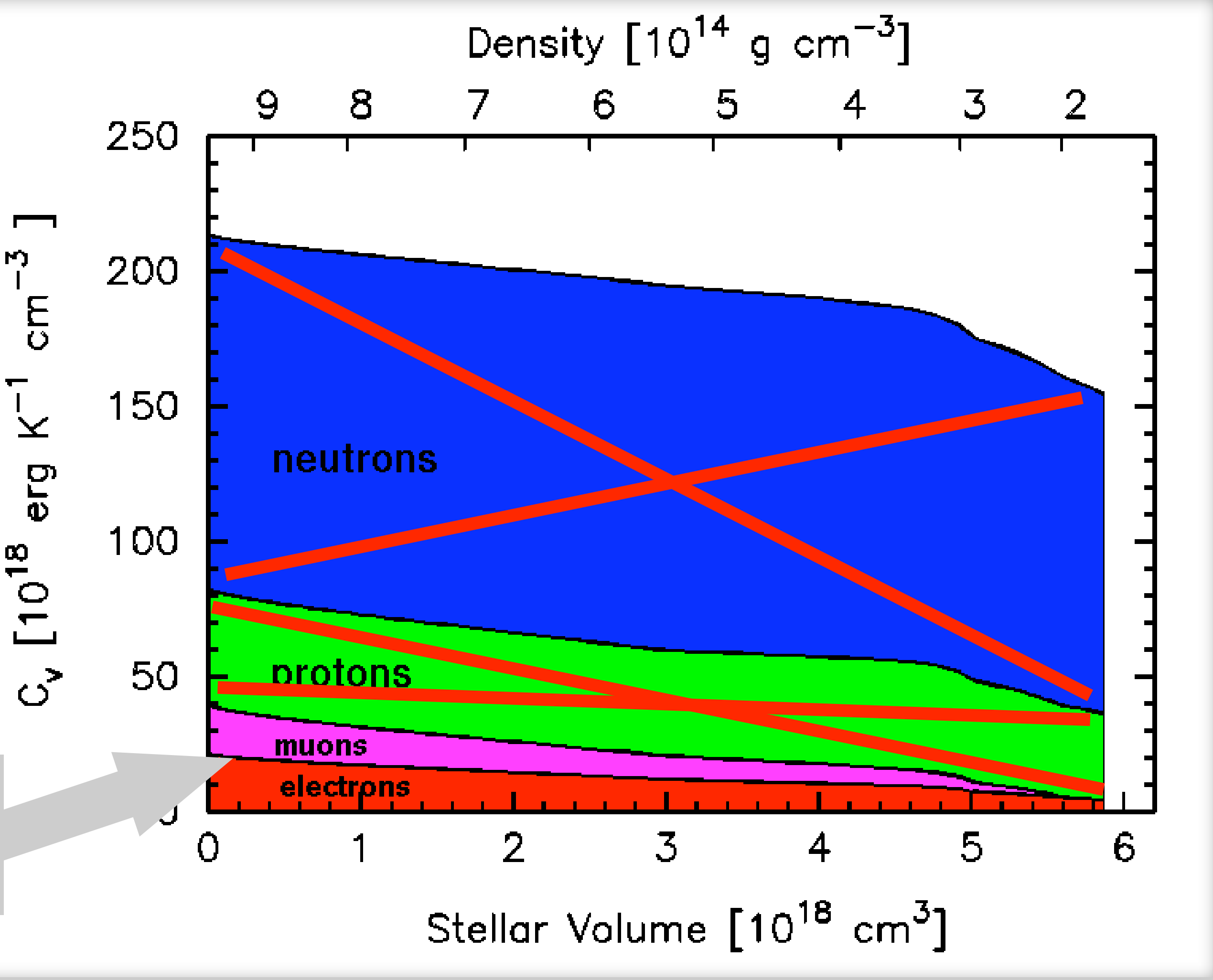
Size and extent of pairing gaps is highly uncertain

Specific heat on a napkin

Sum over all degenerate fermions: $c_V = \sum_i c_{V\,i}$ $\quad c_{V\,i} = N(0)\frac{\pi^2}{3}k_B^2 T$ with $N(0) = \frac{m^* p_F}{\pi^2 \hbar^3}$

$$\boxed{C_V = \iiint c_V dV \simeq 10^{38} - 10^{39} \times T_9 \;\; \text{erg K}^{-1} \equiv C_9 T_9}$$

(lowest value corresponds to the case where extensive pairing of baryons in the core suppresses their c_V and only the leptons, e & μ, contribute)



Distribution of c_V in the core of a 1.4 M_{Sun} neutron star build with the APR EOS (Akmal, Pandharipande, & Ravenhall, 1998), at

T = 10^9 K

Lepton c_V will always be present

Slow vs fast cooling with pairing

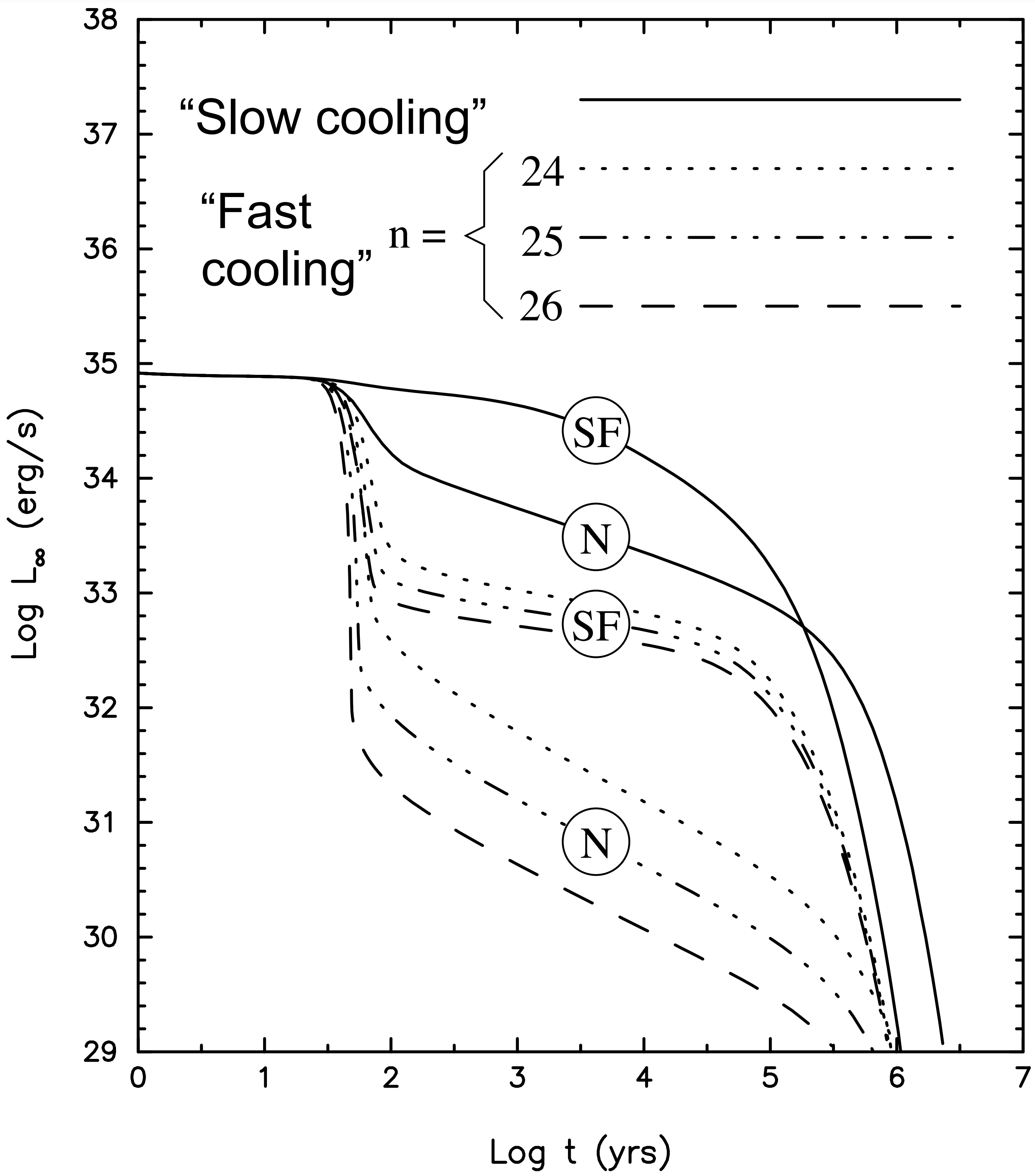
Slow neutrino emission
(modified URCA process)

$$\epsilon_\nu^{\mathrm{slow}} \sim 10^{21}\, T_9^8 \ \ \mathrm{erg\ cm^{-3}\ s^{-1}}$$

Fast neutrino emission
(almost anything else)

$$\epsilon_\nu^{\mathrm{fast}} \sim 10^{n}\, T_9^6 \ \ \mathrm{erg\ cm^{-3}\ s^{-1}}$$

- n = 24 ~ Kaon condensate
- n = 25 ~ Pion condensate
- n = 26 ~ Direct Urca



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Envelope models

Ingredients:

Thin plane parallel layer with

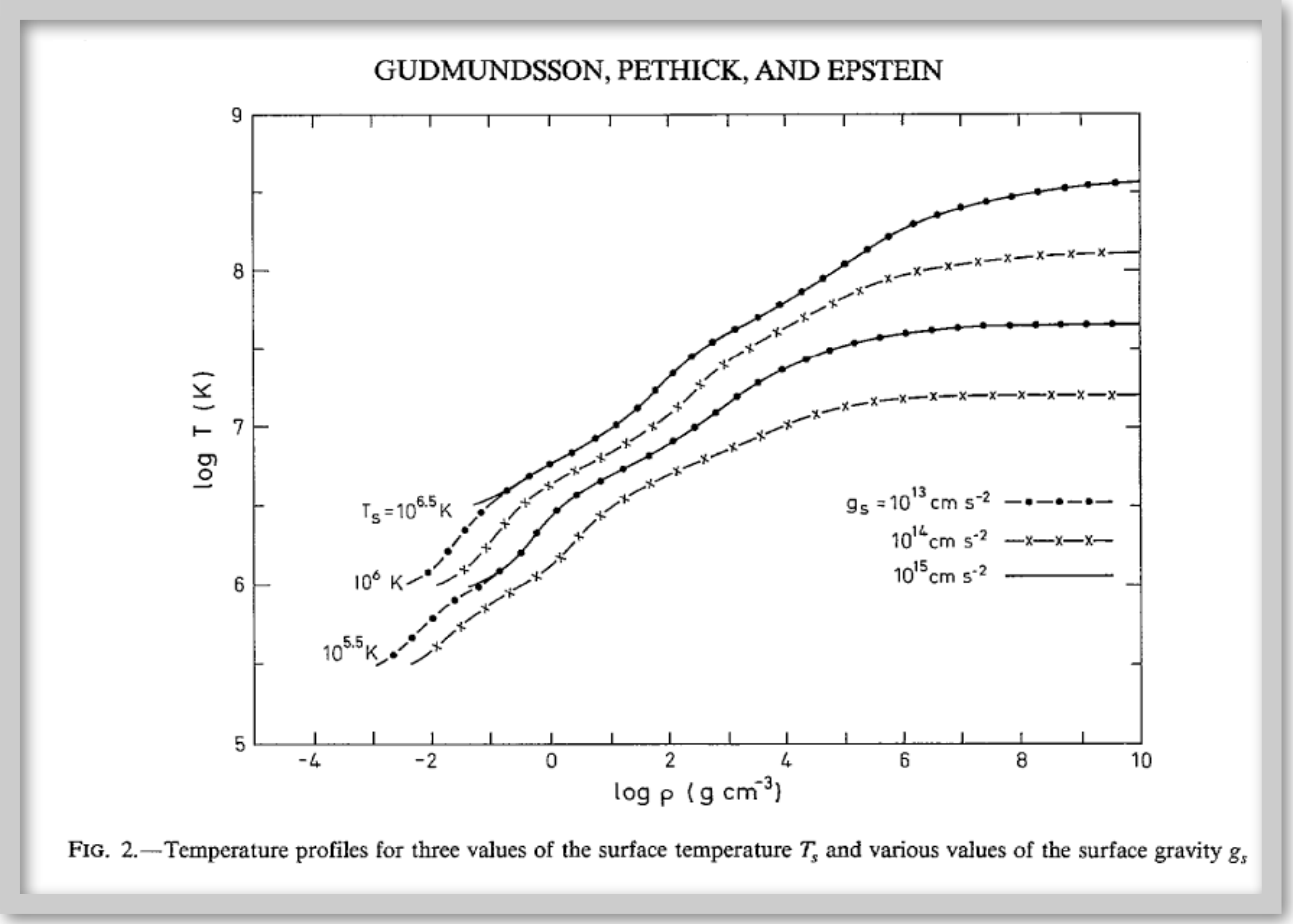
$m=M$, $r=R$

$L=4\pi R^2 \sigma T_e^4$ uniform in the envelope

$$\frac{dT}{dP} = \frac{3}{16}\frac{\kappa}{T^3}\frac{T_e^4}{g_s}$$

$$g_s = \frac{GM}{R^2}\frac{1}{\sqrt{1-2GM/c^2R}}$$

Los Alamos opacity tables and equation of state for pure iron



GUDMUNDSSON, PETHICK, AND EPSTEIN

FIG. 2.—Temperature profiles for three values of the surface temperature T_s and various values of the surface gravity g_s

RESULT: "T_b - T_e" relationship. T_b = T at $\rho_B = 10^{10}$ g cm^{-3}

Neutron star envelopes
Gudmundsson, E. H.; Pethick, C. J.; Epstein, R. I., 1982ApJ...259L..19G

Structure of neutron star envelopes
Gudmundsson, E. H.; Pethick, C. J.; Epstein, R. I. 1983ApJ...272..286G

Envelope models

Ingredients:

Thin plane parallel layer with

r

L

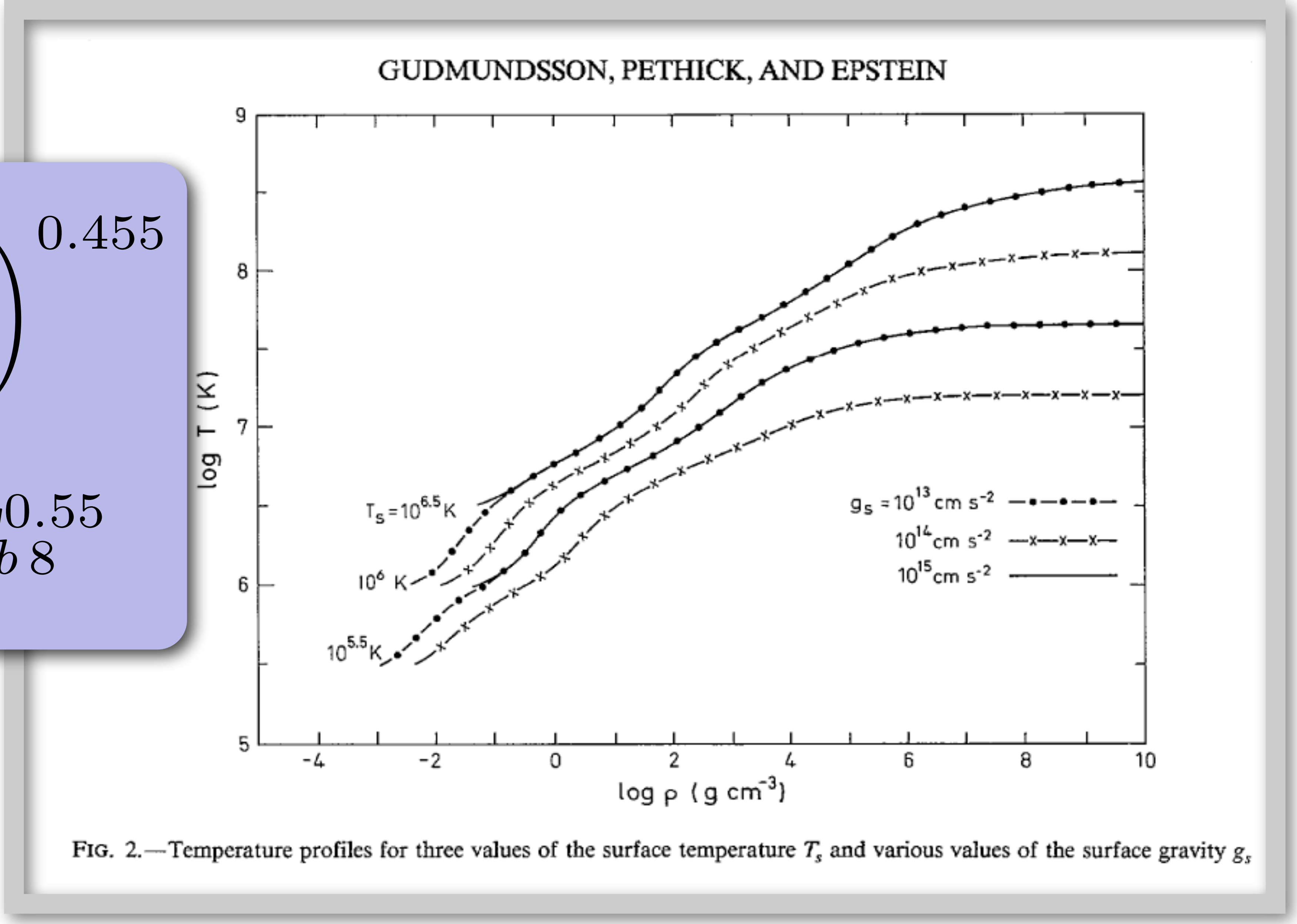
$\frac{d}{d}$

$$T_{b\,8} = 1.288 \left(\frac{T_{s\,6}^4}{g_{s\,14}} \right)^{0.455}$$

$$T_{s\,6} = 0.87\, g_{s\,14}^{1/4}\, T_{b\,8}^{0.55}$$

$g_s = \frac{\quad}{R^2 \sqrt{1 - 2GM/c^2R}}$

Los Alamos opacity tables and equation of state for pure iron



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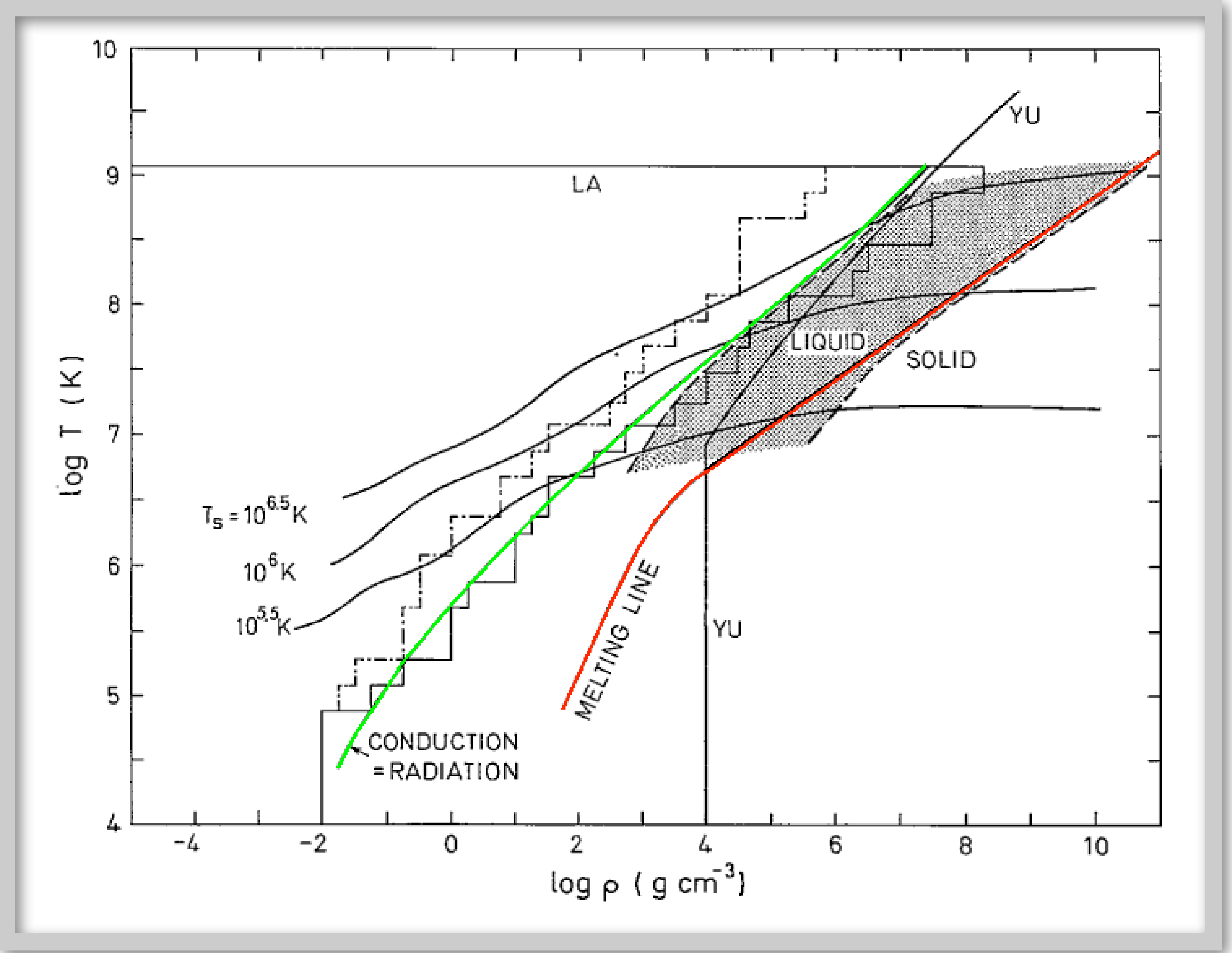
The sensitivity strip



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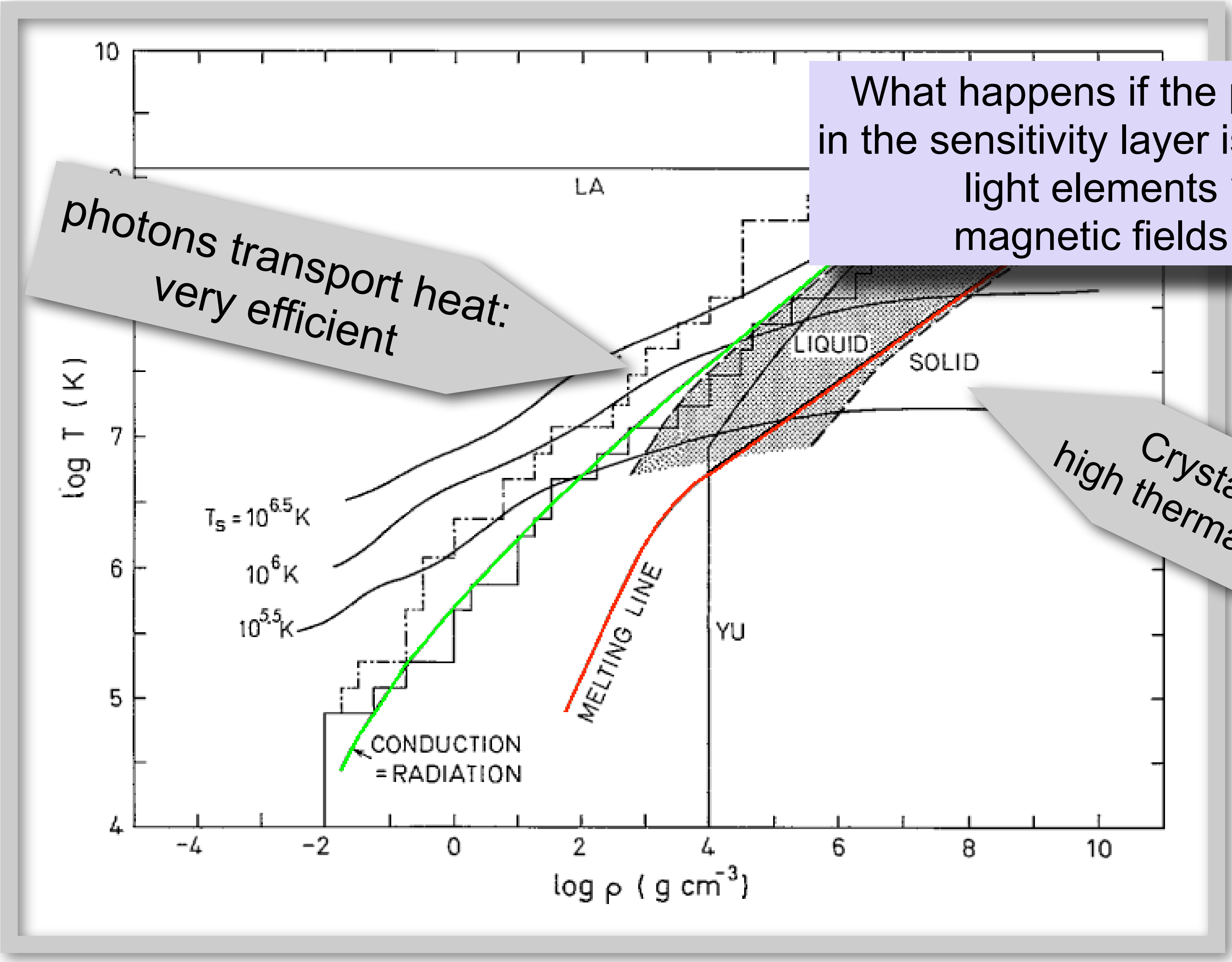


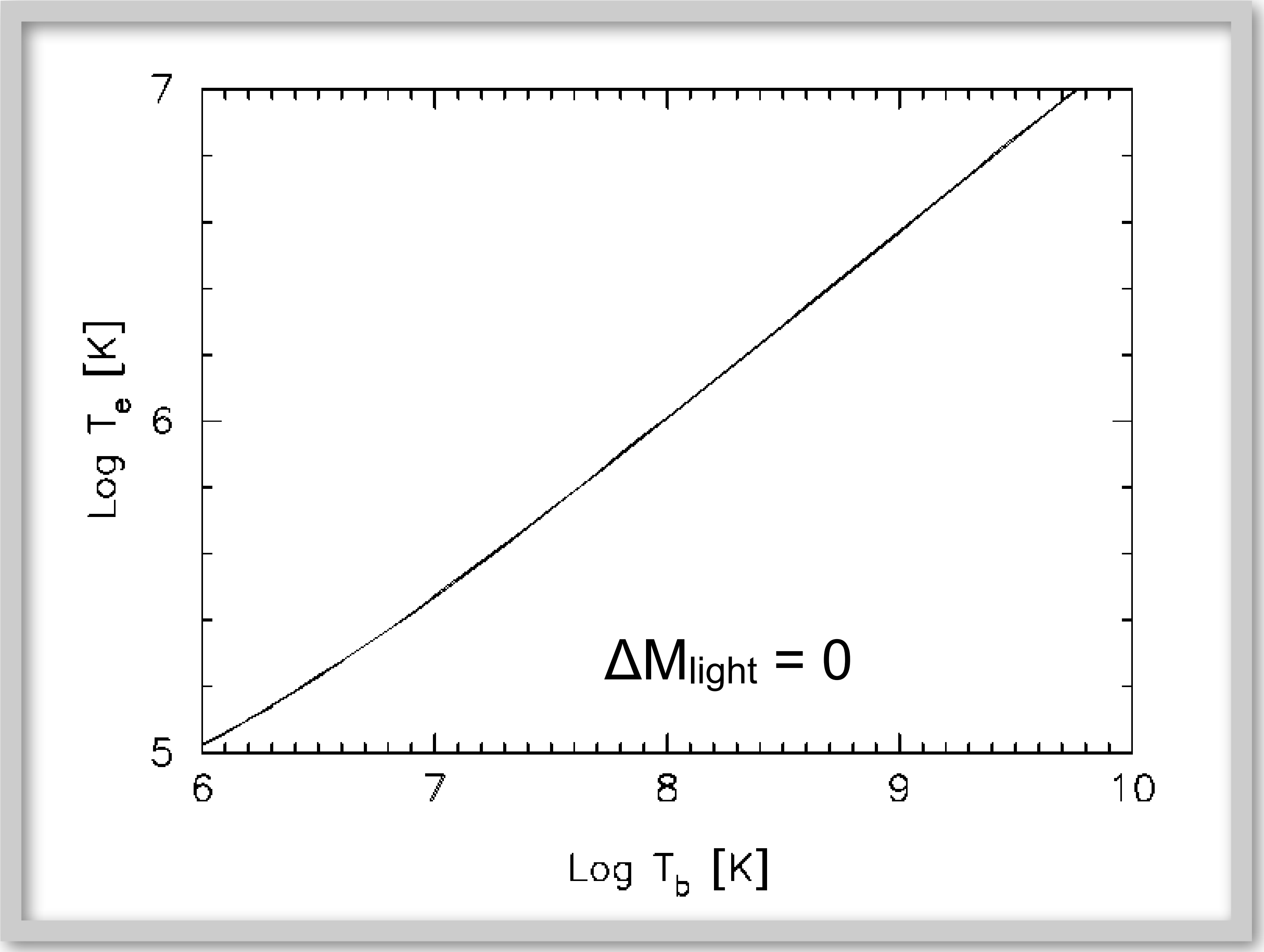
What happens if the physics in the sensitivity layer is altered:
light elements ?
magnetic fields ?

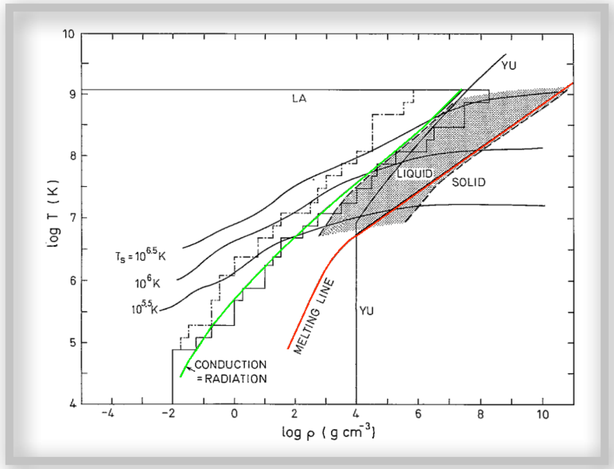
photons transport heat:
very efficient

Crystalized ions:
high thermal conductivity

Structure of neutron star envelopes
Gudmundsson, E. H.; Pethick, C. J.; Epstein, R. I. 1983ApJ...272..286G

Light element envelopes

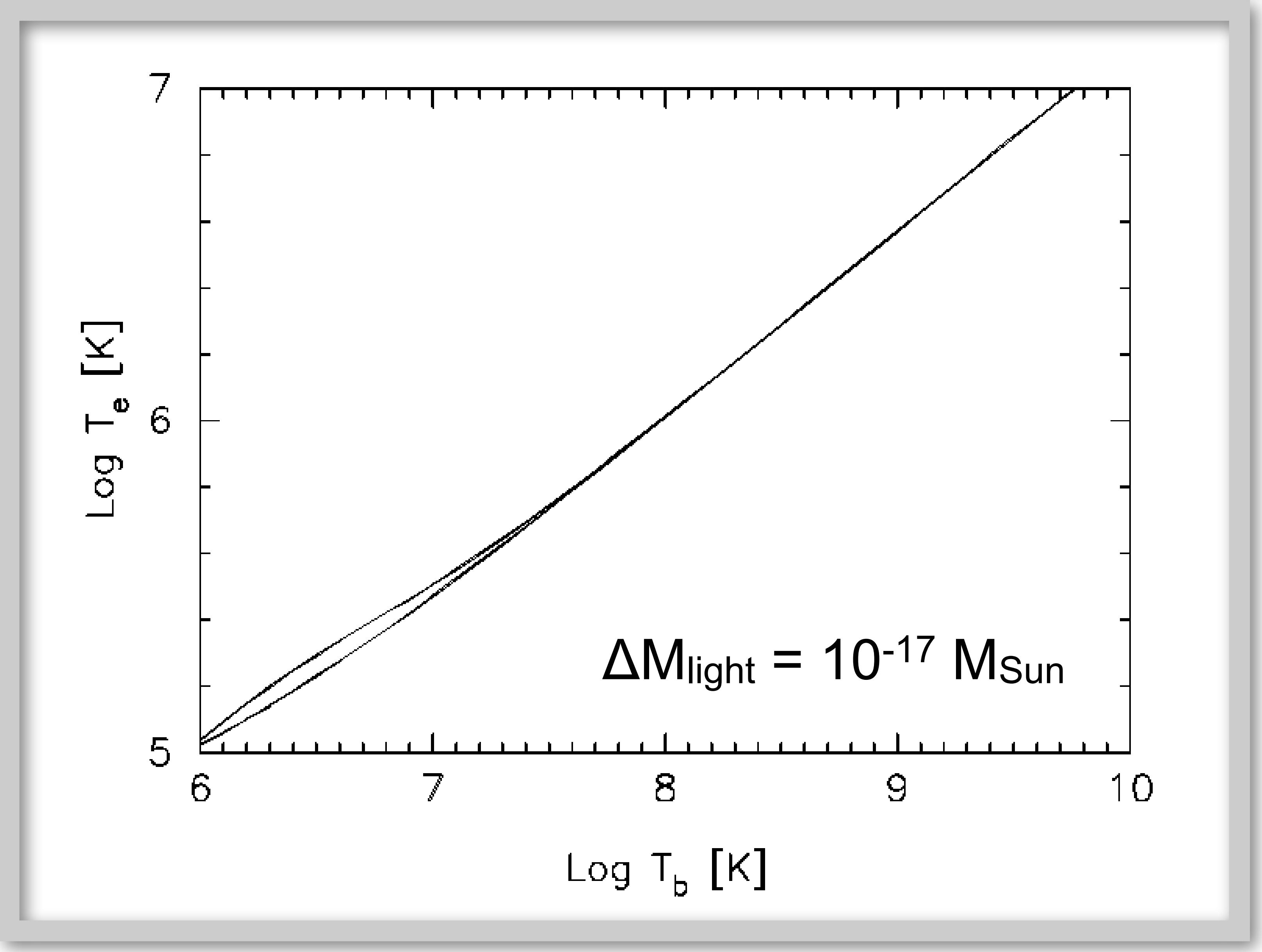




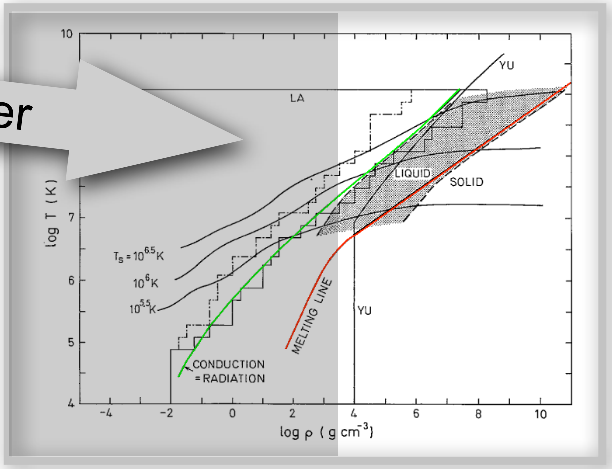
ΔM_{light} = mass of light in the upper envelope

Cooling Neutron Stars with Accreted Envelopes
Chabrier, Gilles; Potekhin, Alexander Y.; Yakovlev, Dmitry G., 1997ApJ...477L..99C

Light element envelopes



$\Delta M_{light} = 10^{-17}\ M_{Sun}$



Thickness of light elements layer

Electron thermal conductivity, due to e-ion scattering in the liquid sensitivity layer:

$$\lambda_{\text{liquid}} \propto \frac{1}{Z}$$

ΔM_{light} = mass of light in the upper envelope

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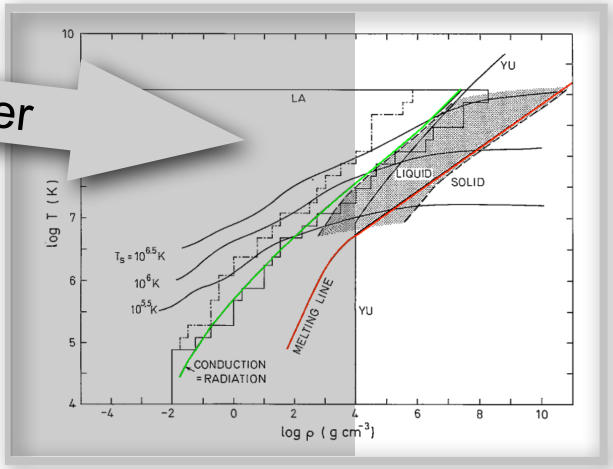

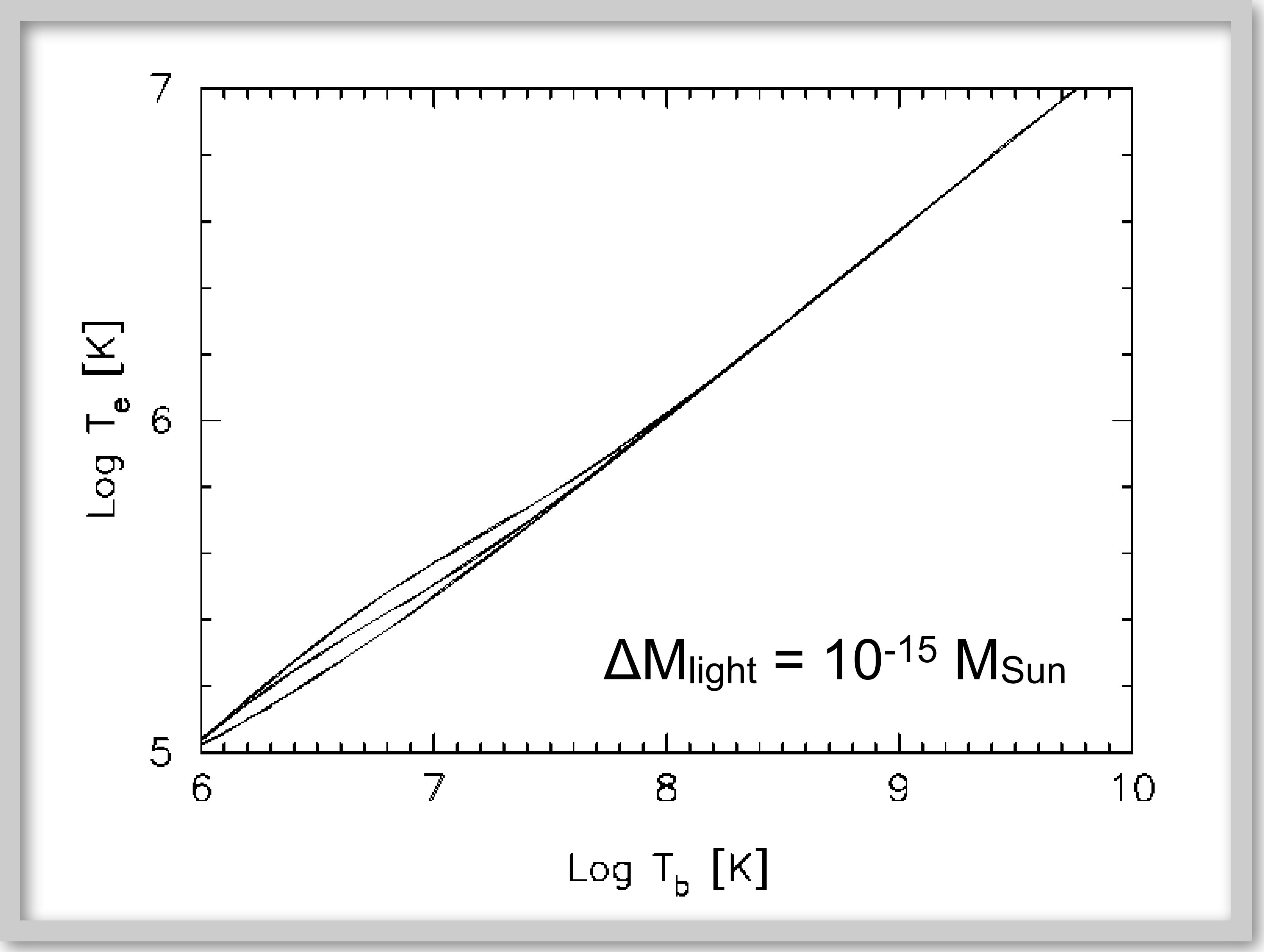

$\Delta M_{\rm light} = 10^{-15}\ M_{\rm Sun}$

Electron thermal conductivity, due to e-ion scattering in the liquid sensitivity layer:

$$\lambda_{\rm liquid} \propto \frac{1}{Z}$$

$\Delta M_{\rm light}$ = mass of light in the upper envelope

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Chabrier, Gilles; Potekhin, Alexander Y.; Yakovlev, Dmitry G., 1997ApJ...477L..99C

Light Element Envelopes

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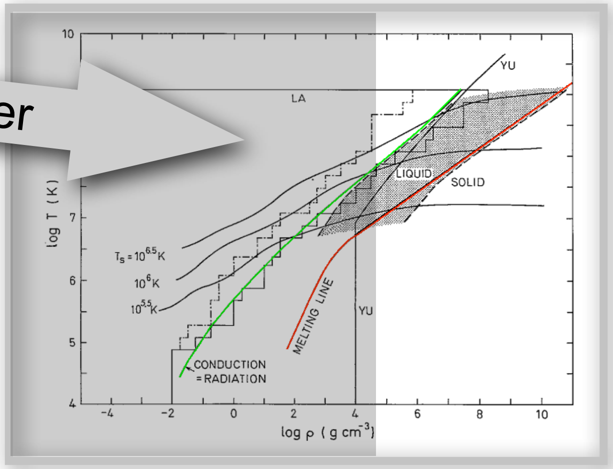

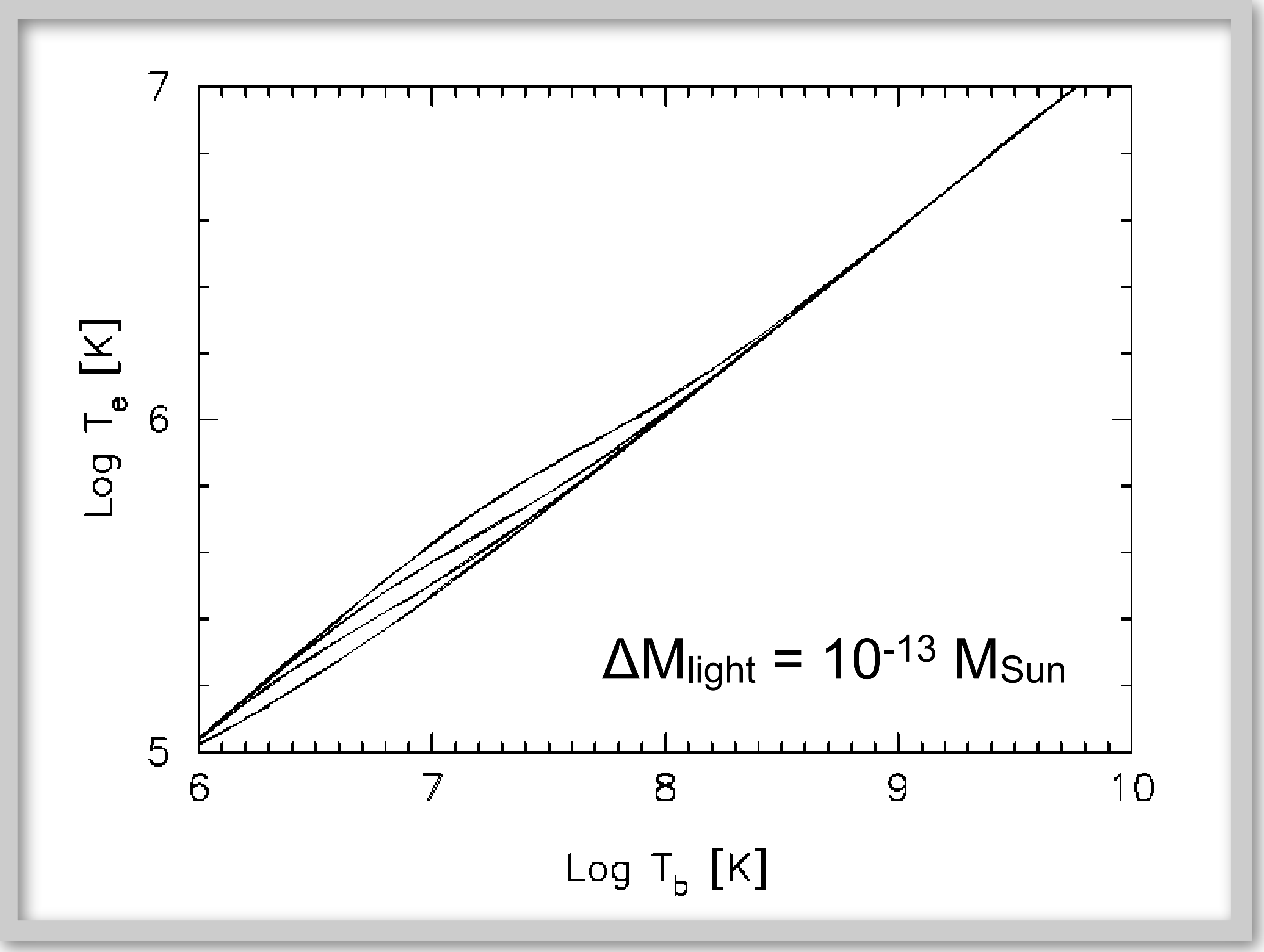

$\Delta M_{light} = 10^{-13}\ M_{Sun}$

Electron thermal conductivity, due to e-ion scattering in the liquid sensitivity layer:

$$\lambda_{\text{liquid}} \propto \frac{1}{Z}$$

ΔM_{light} = mass of light in the upper envelope

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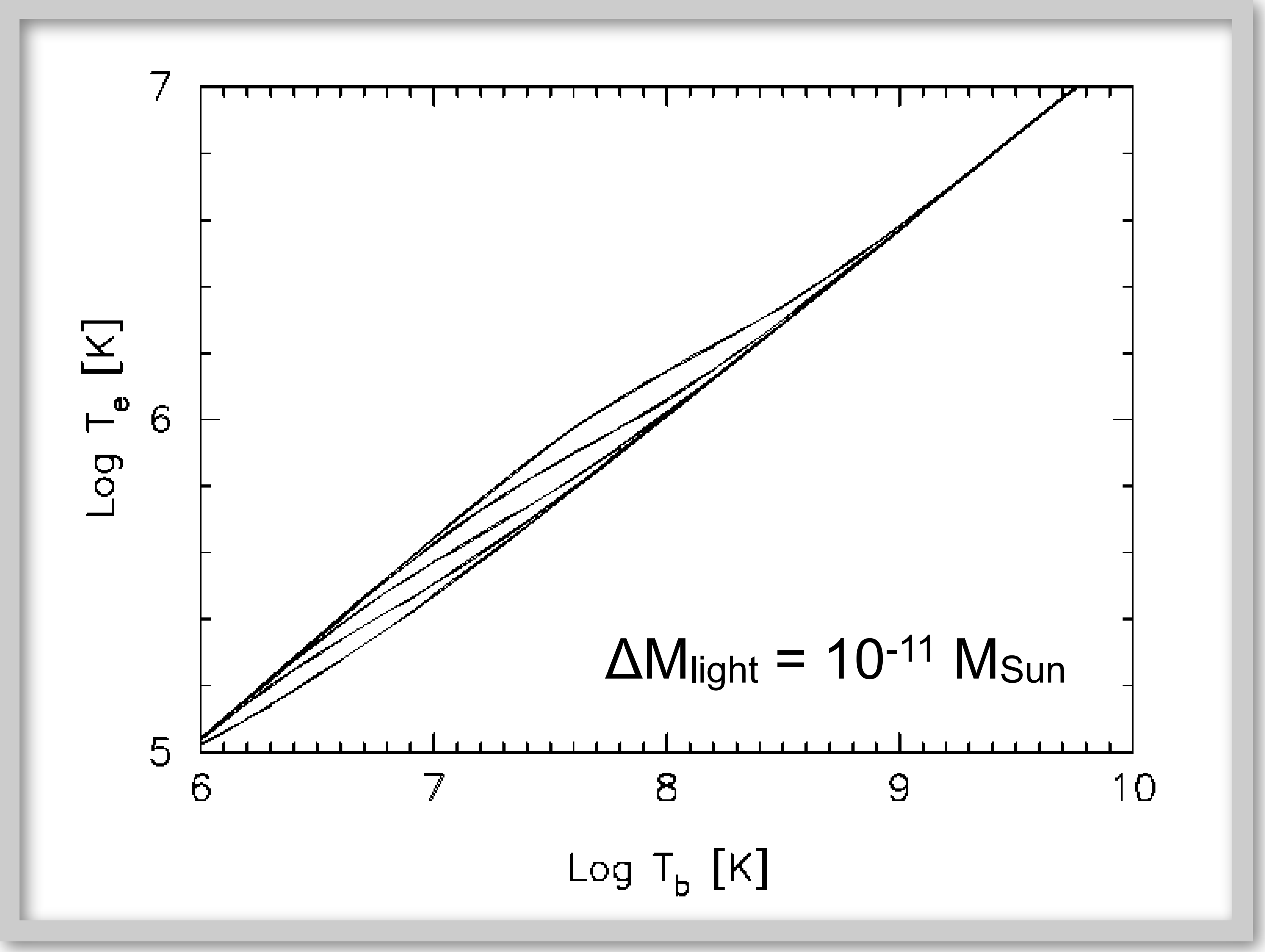
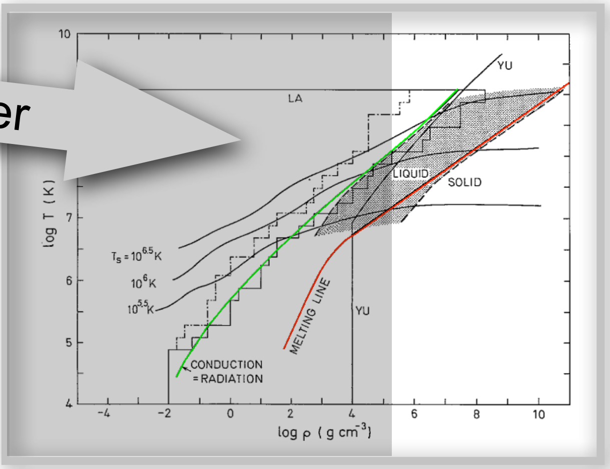
Light element envelopes



$\Delta M_{\rm light} = 10^{-11}\ M_{\rm Sun}$

Thickness of light elements layer



Electron thermal conductivity, due to e-ion scattering in the liquid sensitivity layer:

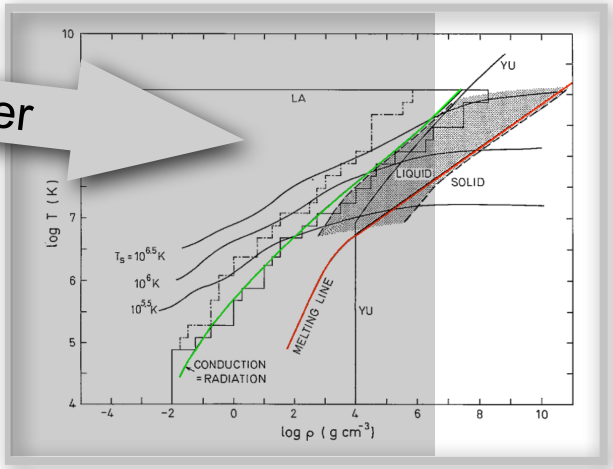
$$\lambda_{\rm liquid} \propto \frac{1}{Z}$$

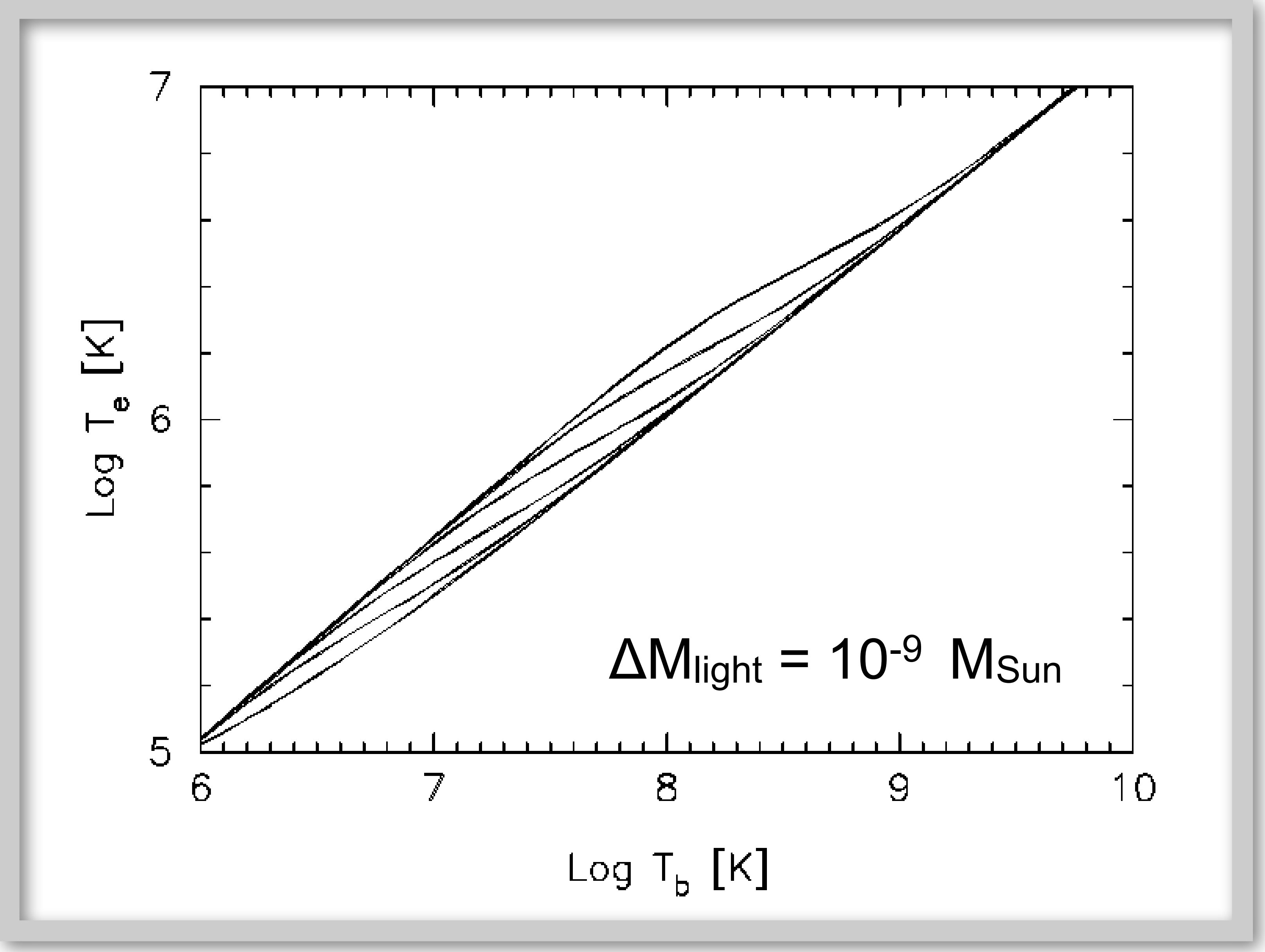
$\Delta M_{\rm light}$ = mass of light in the upper envelope

Cooling Neutron Stars with Accreted Envelopes
Chabrier, Gilles; Potekhin, Alexander Y.; Yakovlev, Dmitry G., 1997ApJ...477L..99C

Light element envelopes

Thickness of light elements layer





$\Delta M_{\rm light} = 10^{-9}\ M_{\rm Sun}$

Electron thermal conductivity, due to e-ion scattering in the liquid sensitivity layer:

$$\lambda_{\rm liquid} \propto \frac{1}{Z}$$

$\Delta M_{\rm light}$ = mass of light in the upper envelope

Cooling Neutron Stars with Accreted Envelopes
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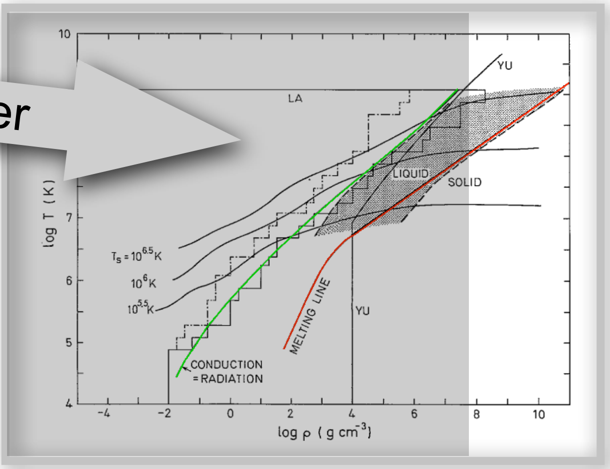
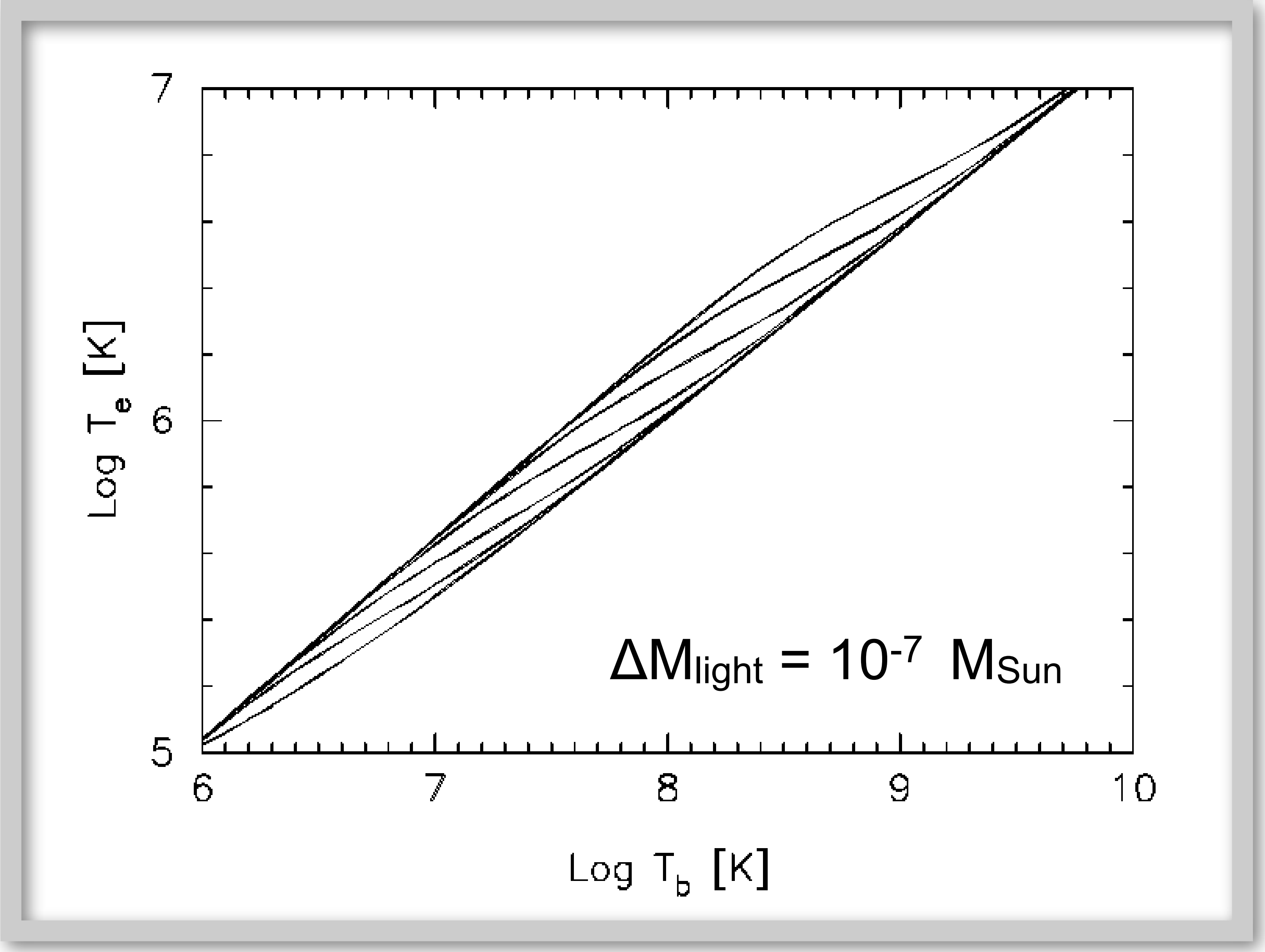
Thickness of light elements layer





$\Delta M_{\rm light} = 10^{-7}\ M_{\rm Sun}$

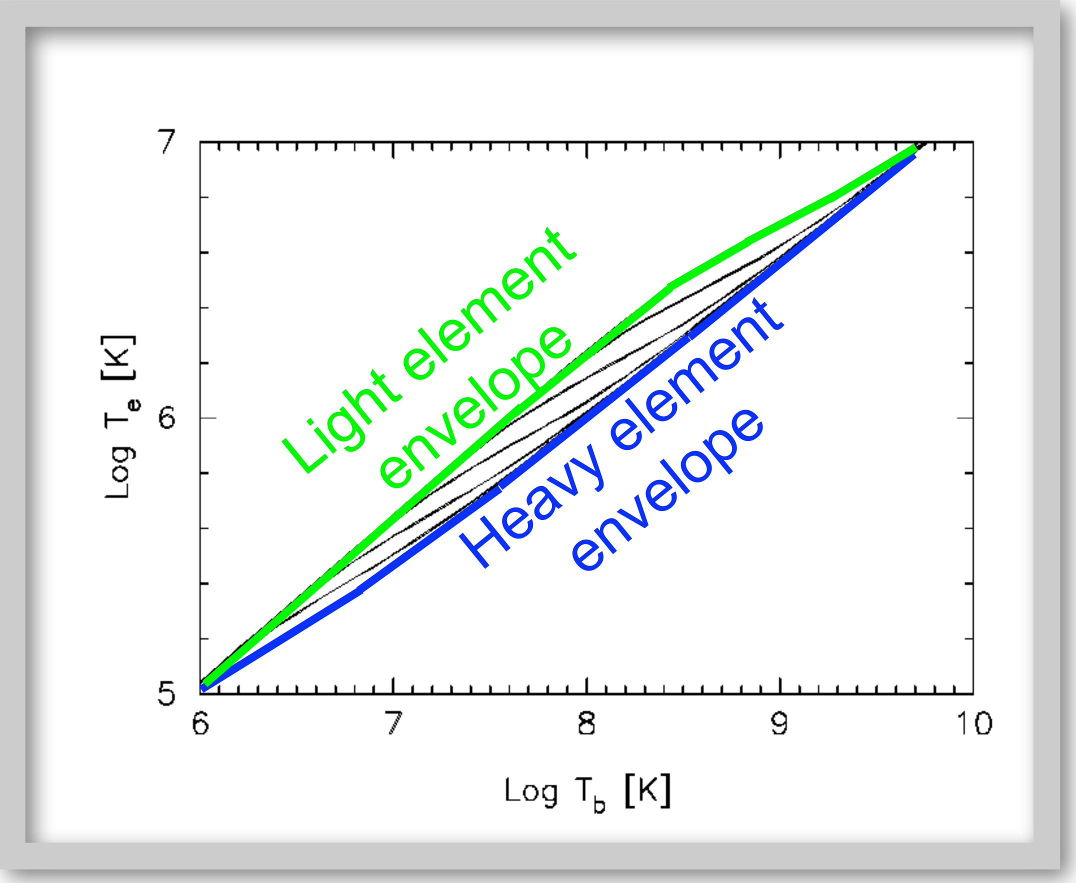
Electron thermal conductivity, due to e-ion scattering in the liquid sensitivity layer:

$$\lambda_{\rm liquid} \propto \frac{1}{Z}$$

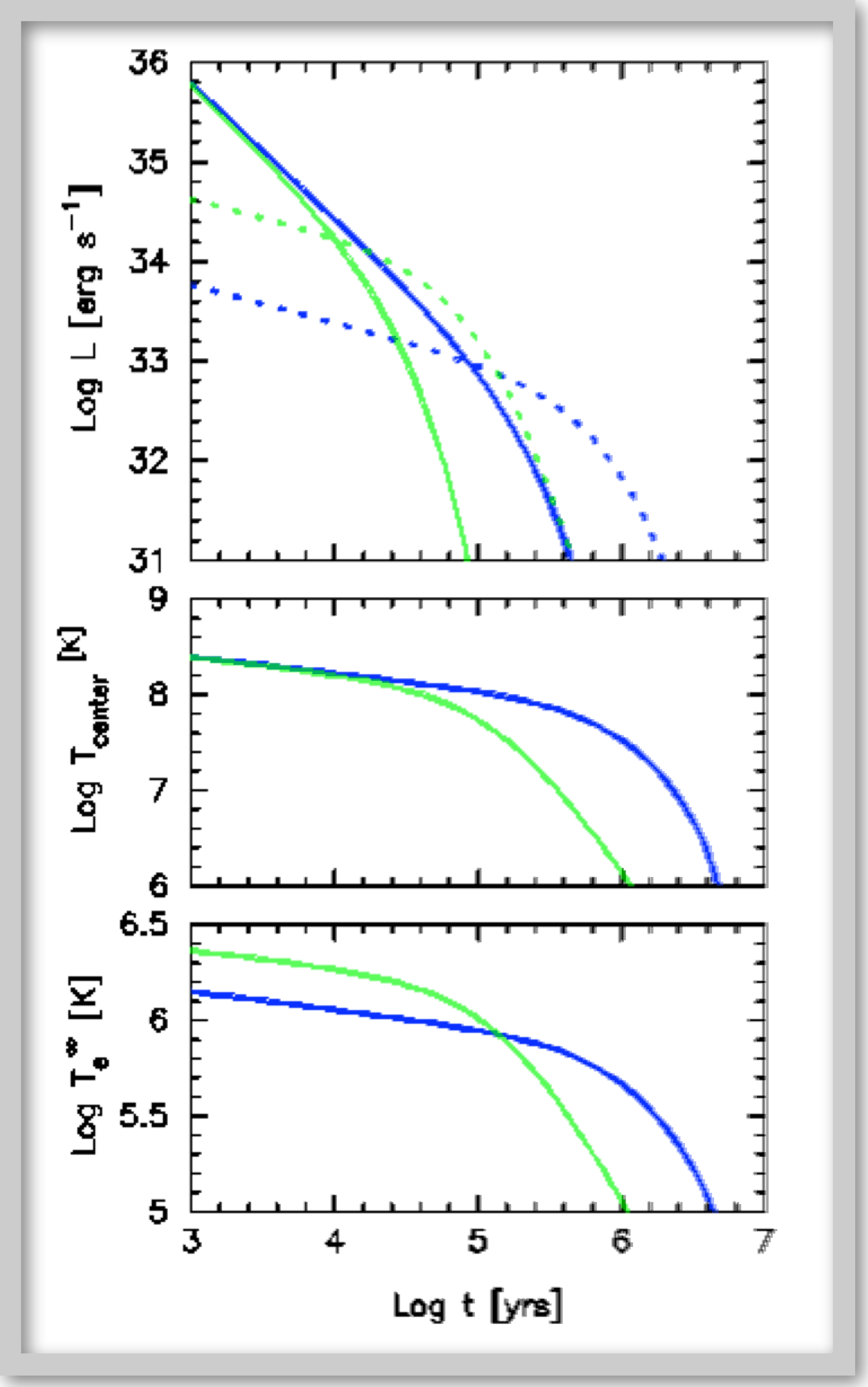
$\Delta M_{\rm light}$ = mass of light in the upper envelope

Cooling Neutron Stars with Accreted Envelopes
Chabrier, Gilles; Potekhin, Alexander Y.; Yakovlev, Dmitry G., 1997ApJ...477L..99C

Effect of light element envelopes



Light element envelopes:
- star looks warmer during neutrino cooling era, but
- cools faster during photon cooling era



Heat transport with magnetic field

$$\vec{F} = -\kappa \cdot \vec{\nabla} T$$

$$\kappa_0 = \frac{1}{3} c_{\mathrm{v}} \overline{\mathrm{v}}^2 \tau \quad = \quad \frac{\pi^2 k_{\mathrm{B}}^2 T n_e}{3 m_e^*} \tau$$

τ = electron relaxation time

In the presence of a strong magnetic field κ becomes a tensor:

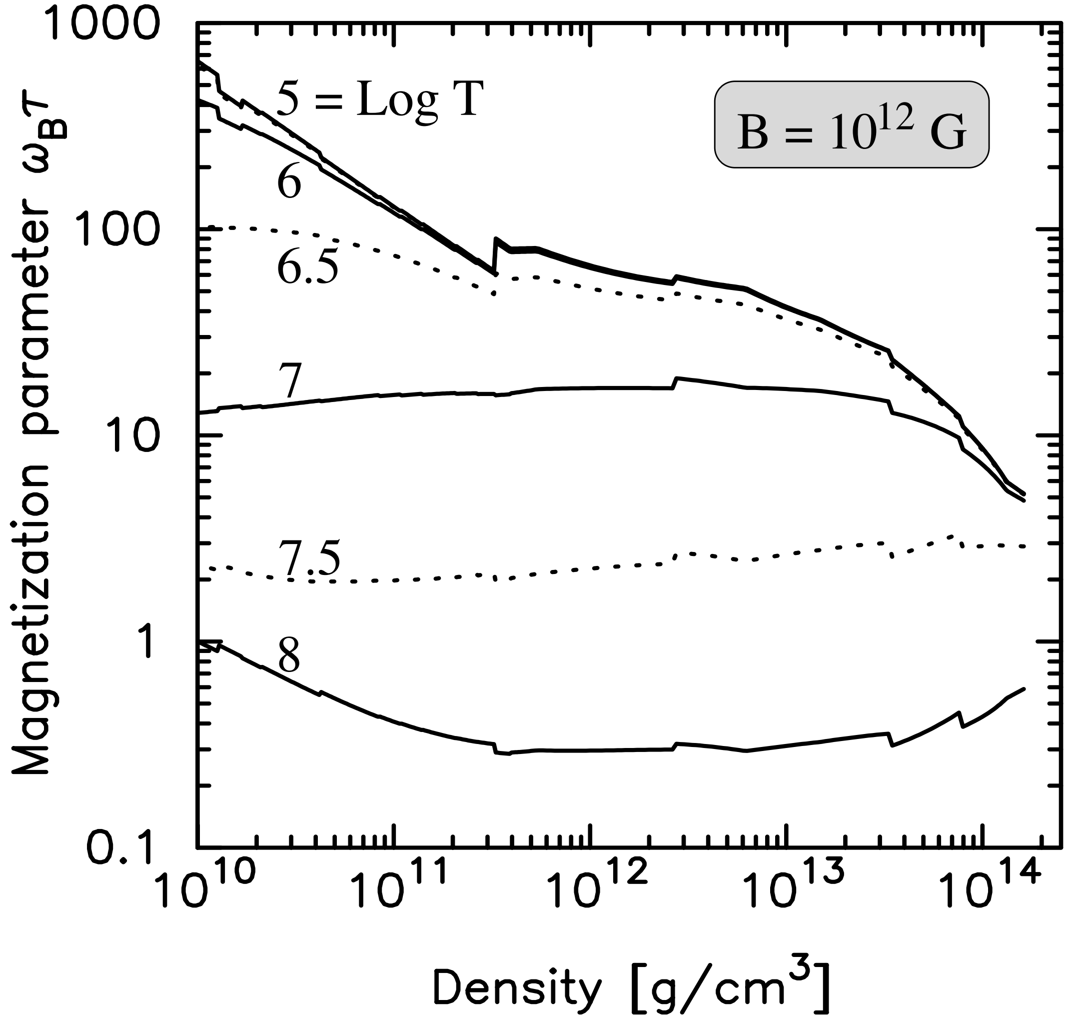
$$\kappa = \begin{pmatrix} \kappa_\perp & \kappa_\wedge & 0 \\ -\kappa_\wedge & \kappa_\perp & 0 \\ 0 & 0 & \kappa_\parallel \end{pmatrix}$$

$$\kappa_\parallel = \kappa_0$$

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

$$\kappa_\wedge = \frac{\kappa_0 \, \omega_B \tau}{1 + (\omega_B \tau)^2}$$

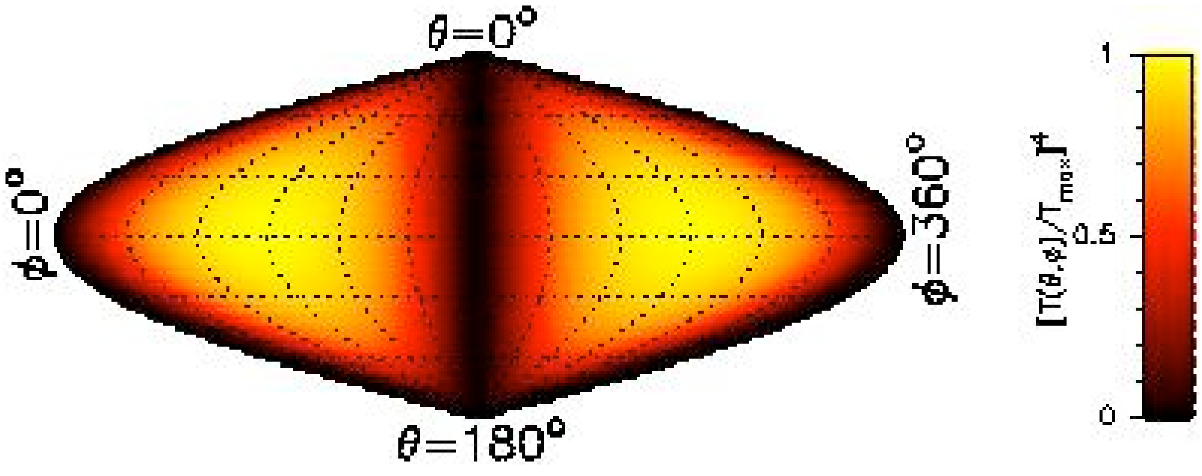
$\omega_B = \dfrac{eB}{m_e^* c}$ = electron cyclotron frequency



Temperature distribution in magnetized neutron star crusts
U Geppert, M Kueker & D Page, 2004A&A...426..267G

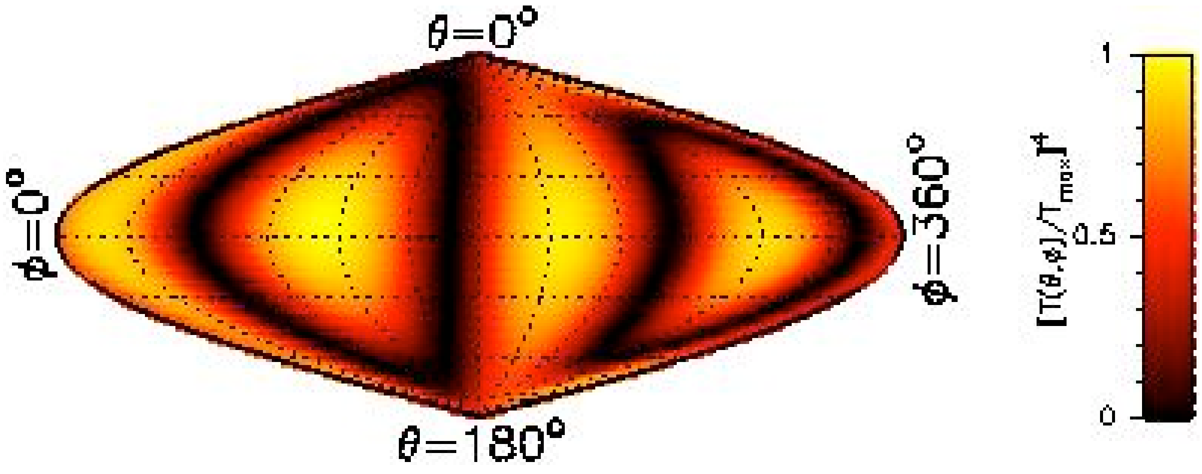
Surface temperature distributions

With the Greenstein-Hartke interpolation formula one can take any field geometry at the surface (envelope) and calculate the surface temperature distribution:



Purely dipolar field

(oriented on the equatorial plane
to make a prettier picture !)



Dipolar +
quadrupolar field

Surface temperature of a magnetized neutron star and interpretation of the ROSAT data.
I. Dipolar fields
D Page, ApJ 442, 273 (1995)

Surface temperature of a magnetized neutron star and interpretation of the ROSAT data. II.
D Page & A Sarmiento, ApJ 473, 1067 (1996)

Magnetized T_b - T_e relationships

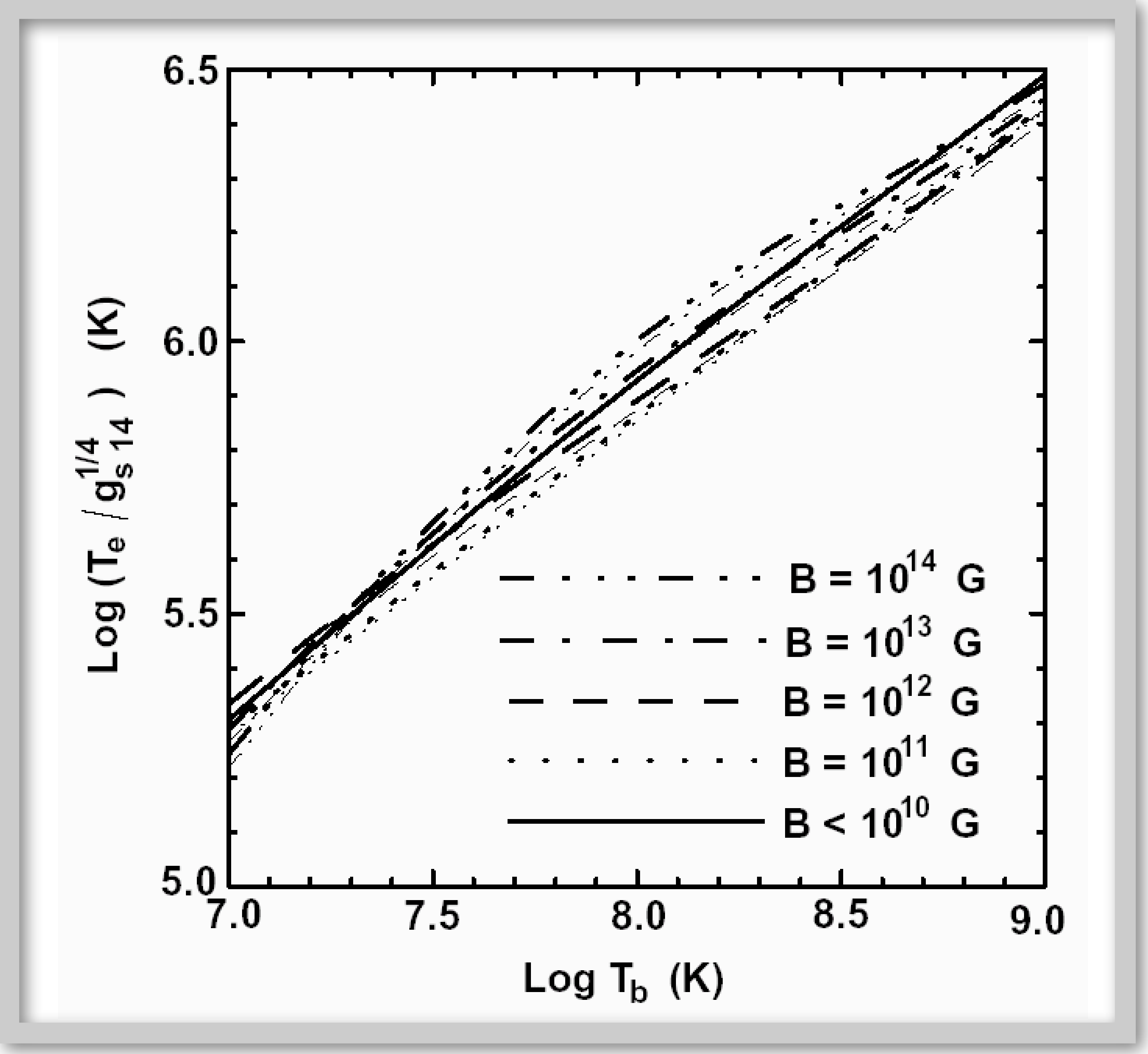
The star's effective temperature is then easily calculated:

$$L = \iint \sigma_B T_s(\theta,\phi)^4 dS \;=\; 4\pi R^2 \sigma T_e^4$$

$$(dS \;=\; R^2 \cdot d\Omega)$$

$$T_e^4 = \frac{1}{4\pi}\iint T_s(\theta,\phi)^4\, d\Omega$$

This directly generates a T_b - T_e relationship for any surface magnetic field geometry



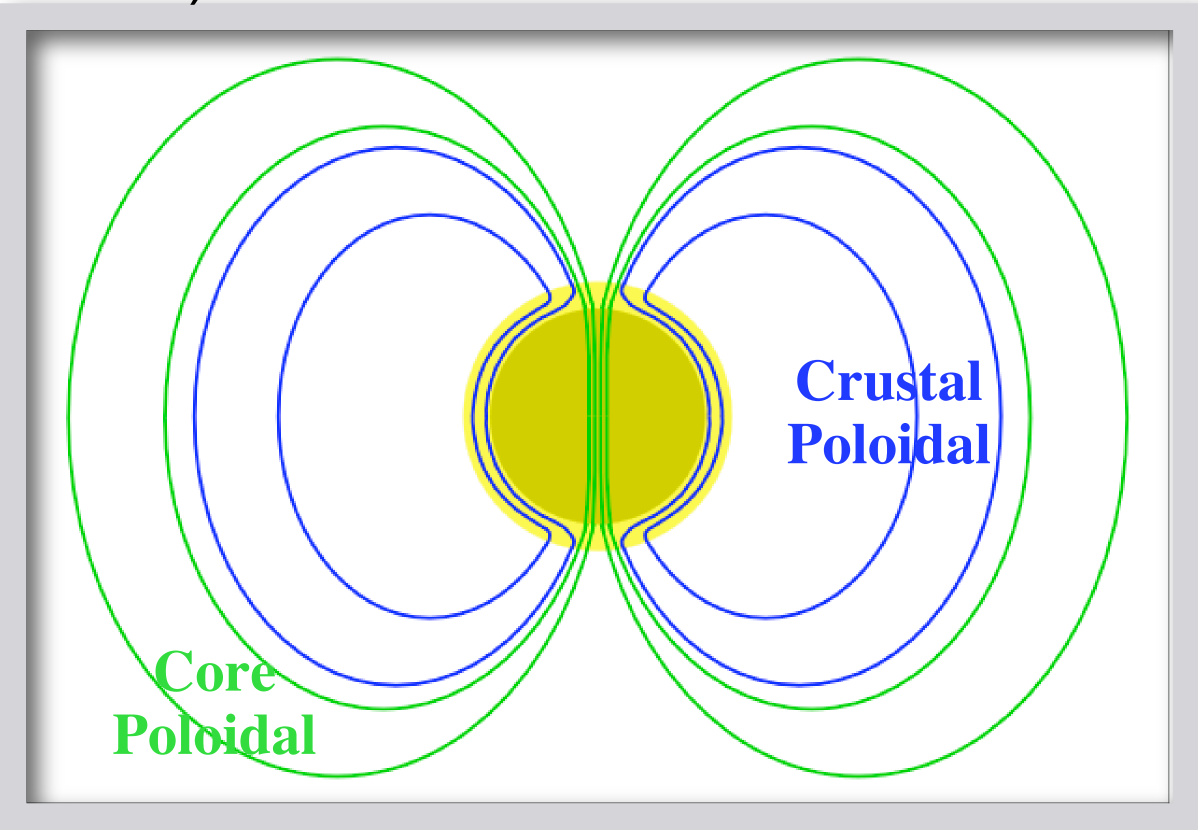
Surface temperature of a magnetized neutron star and interpretation of the ROSAT data. II.
D Page & A Sarmiento, ApJ 473, 1067 (1996)

Structure of the field in the crust ?

$$\vec{\nabla} \wedge \vec{B} = \frac{4\pi}{c}\vec{j} \quad \Longrightarrow$$

Choosing a field geometry means choosing where the currents are !

First natural choice: separate currents in the **crust** from currents in the **core** (“crustal” versus “core” field)



Magnetic field lines are isothermal

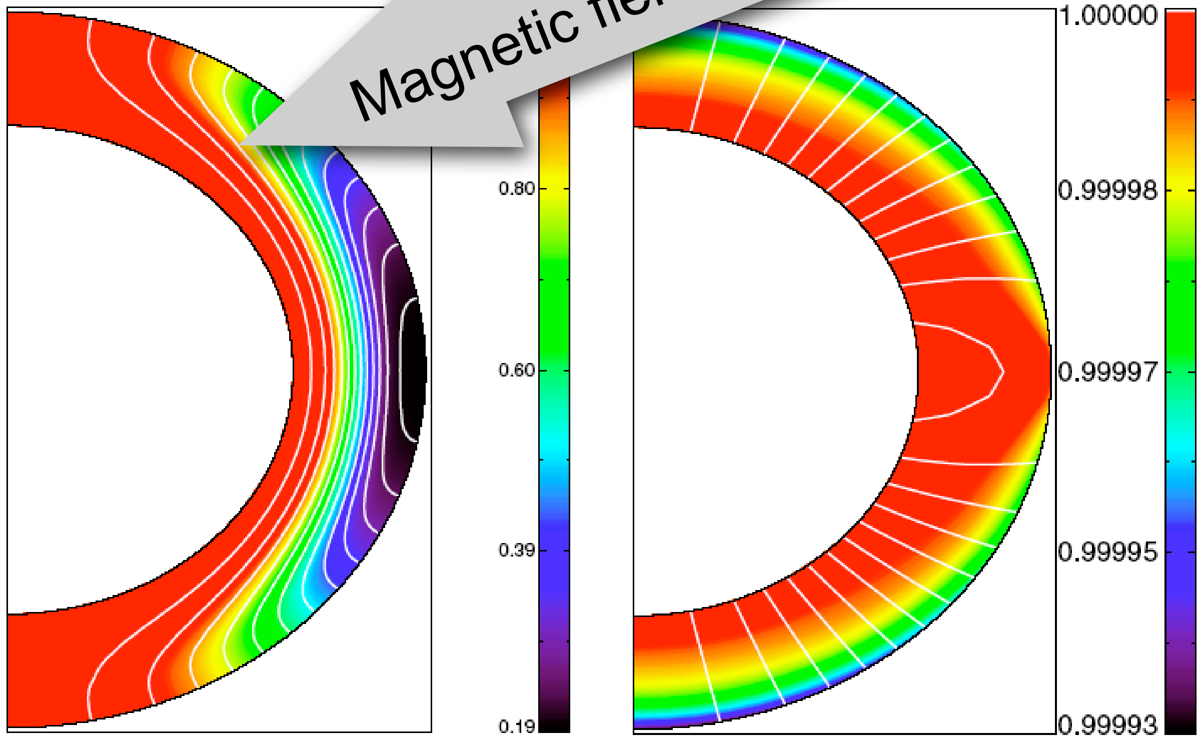
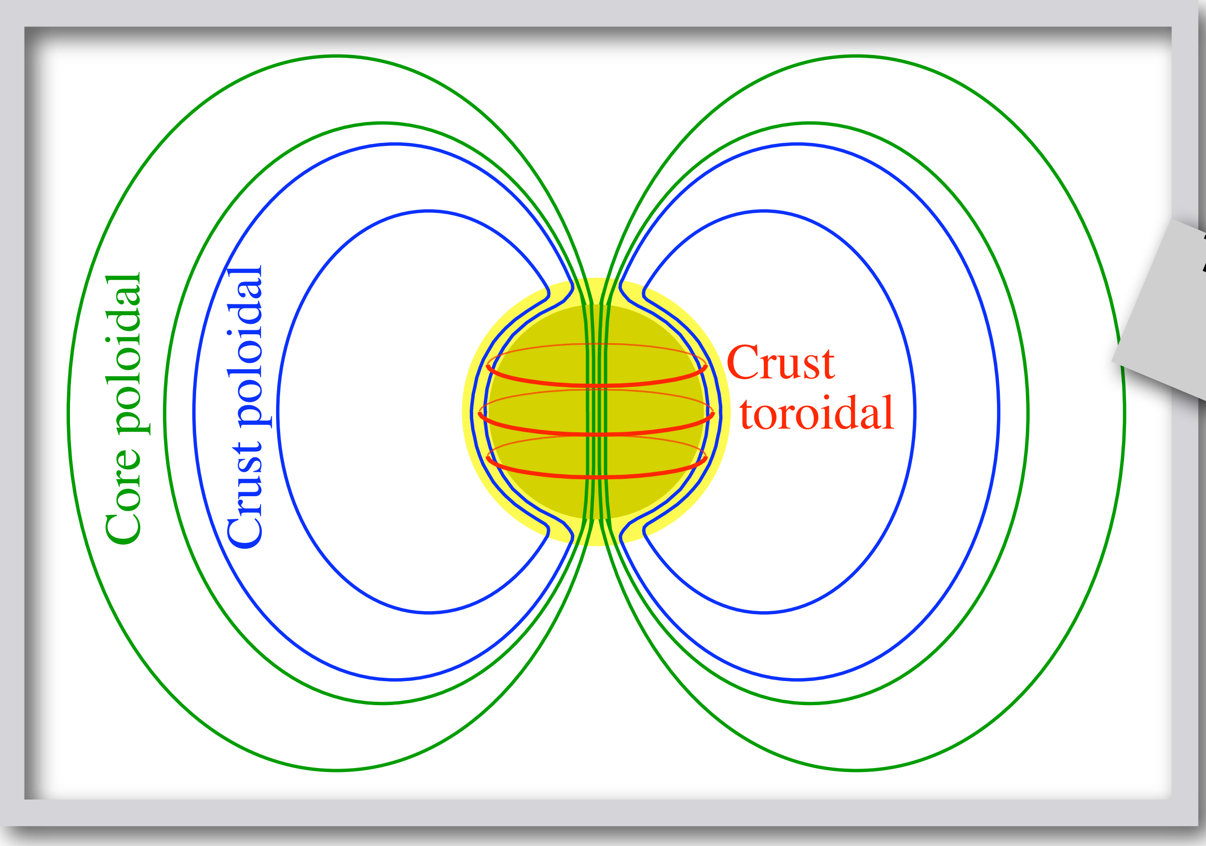


Fig. 7. Representation of both field lines and temperature distribution in the crust whose radial scale ($r(\rho_n) \leq r \leq r(\rho_b)$) is stretched by a factor of 5, assuming $B_0 = 3 \times 10^{12}$ G and $T_{\rm core} = 10^6$ K. Left panel corresponds to a crustal field, right panel to a star-centered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

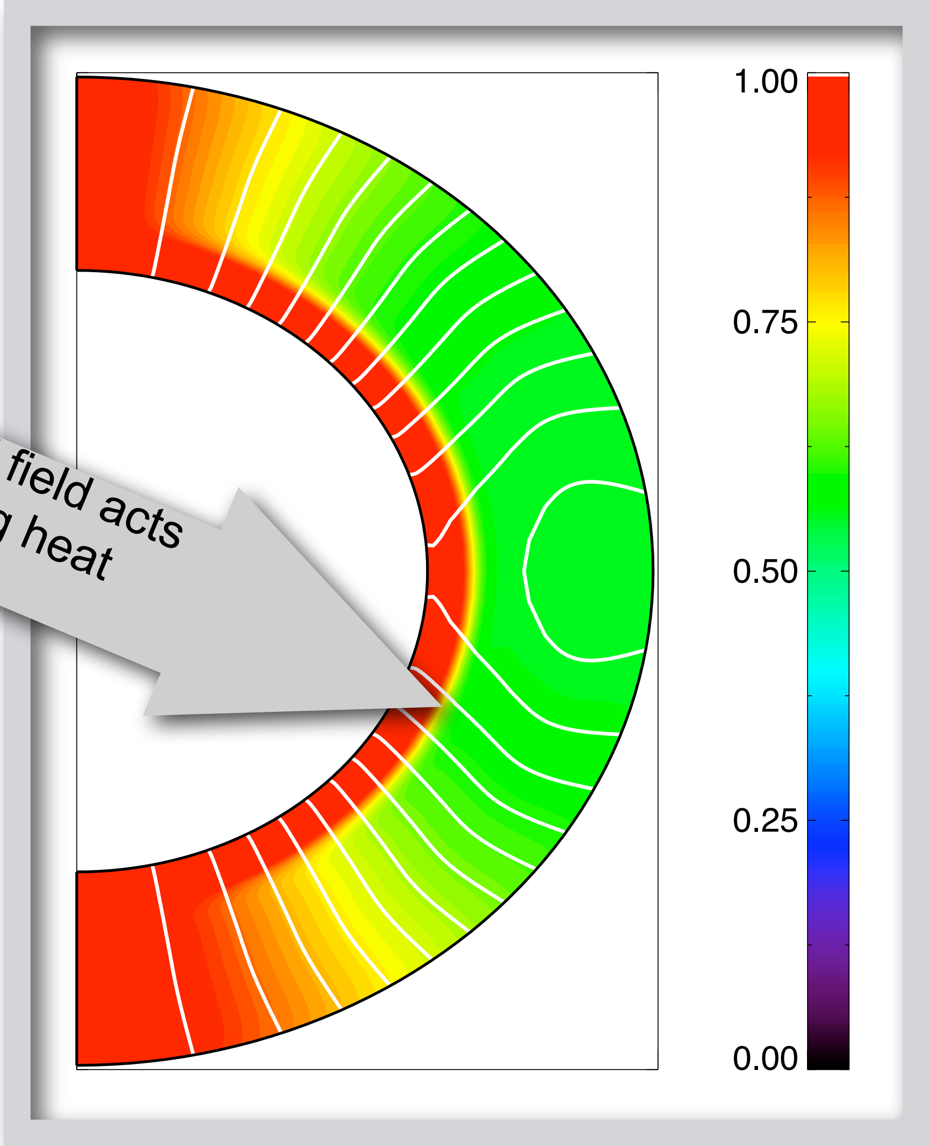
Temperature distribution in magnetized neutron star crusts,
Geppert, Küker & Page, 2004 A&A 426, 267

Addition of a toroidal component

Toroidal field: winded as a dotnut inside the star.
Unseen from outside but may leave an imprint at the surface through its effect on the heat transport



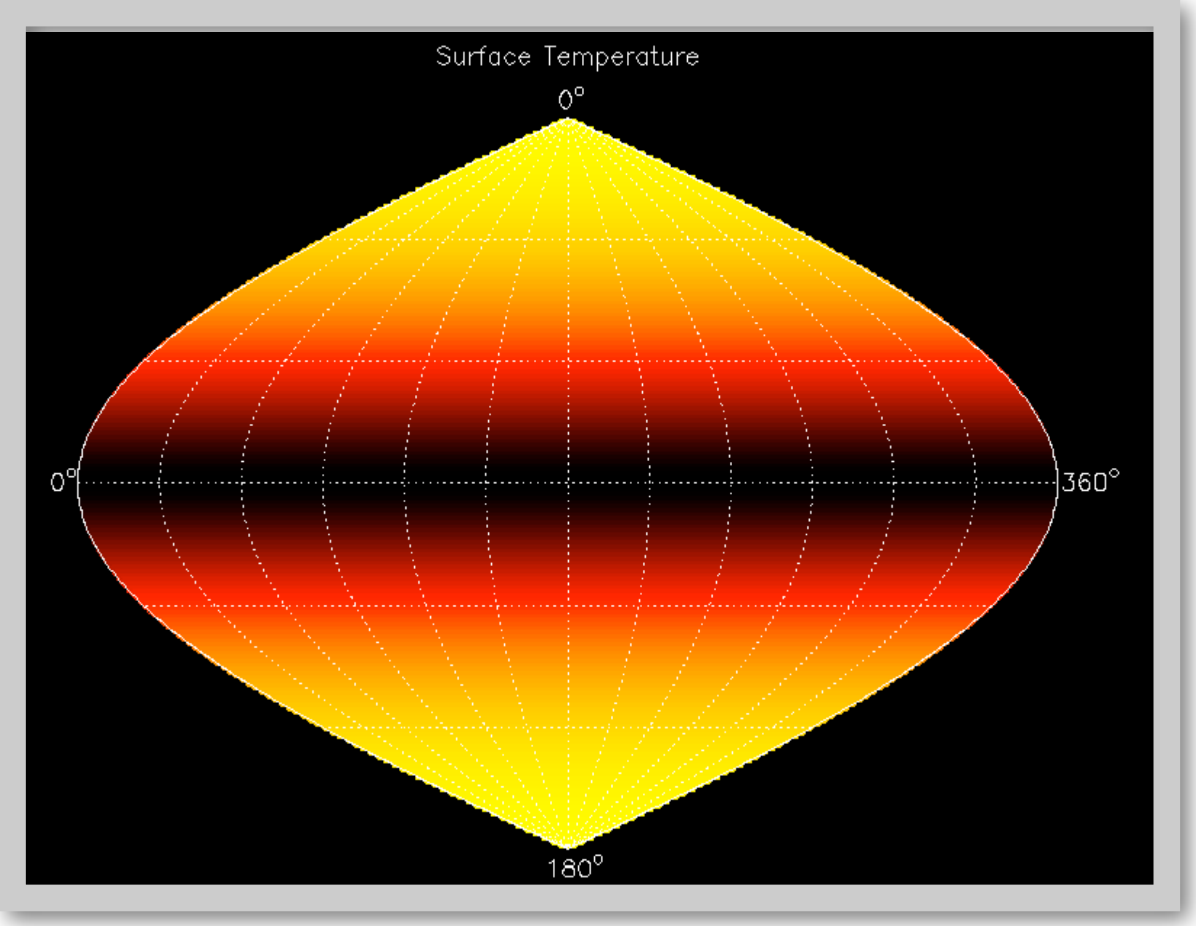
The toroidal field acts as a strong heat barrier



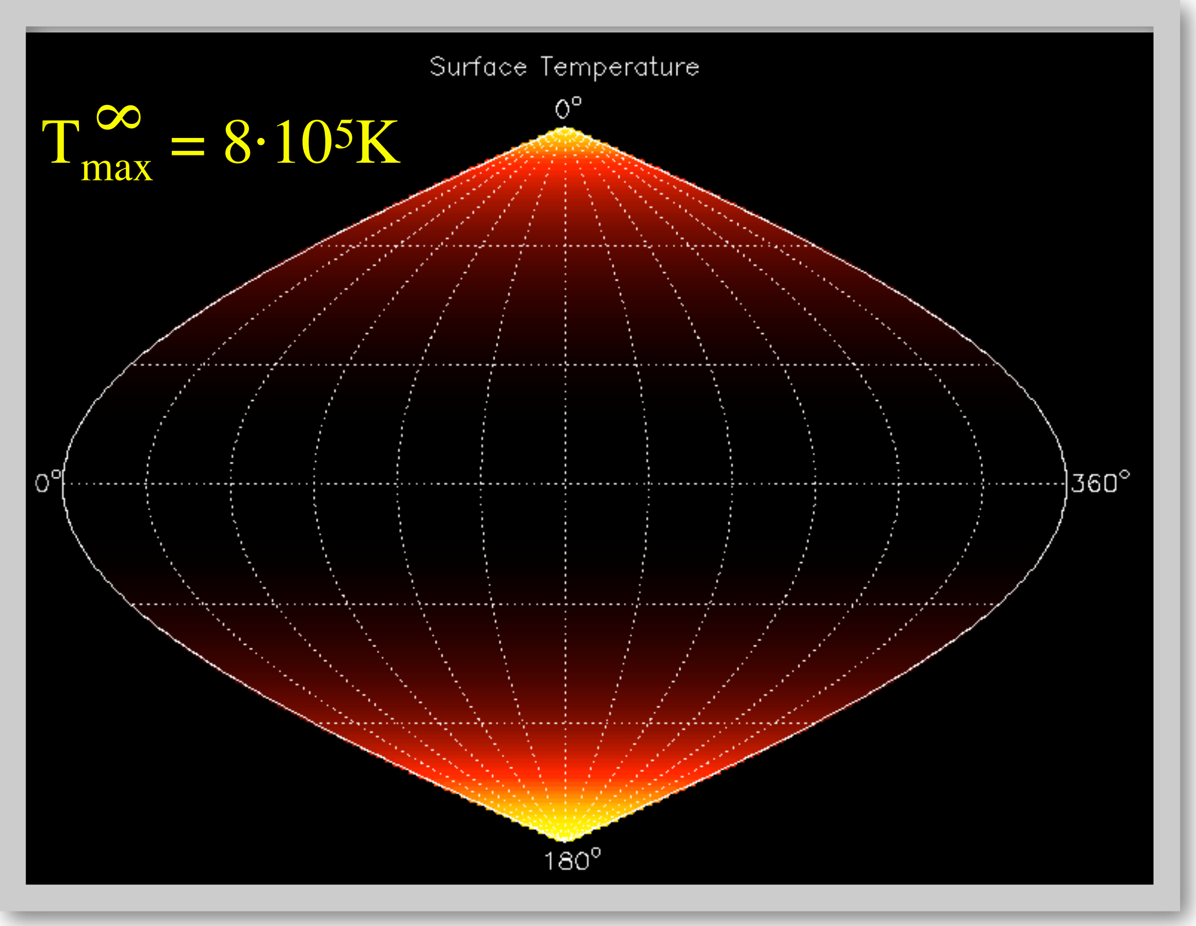
Temperature distribution in magnetized neutron star crusts. II. The effect of a strong toroidal component, Geppert, Küker & Page, 2006 A&A 457, 937

Surface temperatures with toroidal fields

Dipolar poloidal field (10^{13} G) with only envelope effects taken into account



Same dipolar poloidal field (10^{13} G) with only a strong toroidal field in the crust



$T^{\infty}_{max} = 8 \cdot 10^5 K$

High field PSR J1119-6127

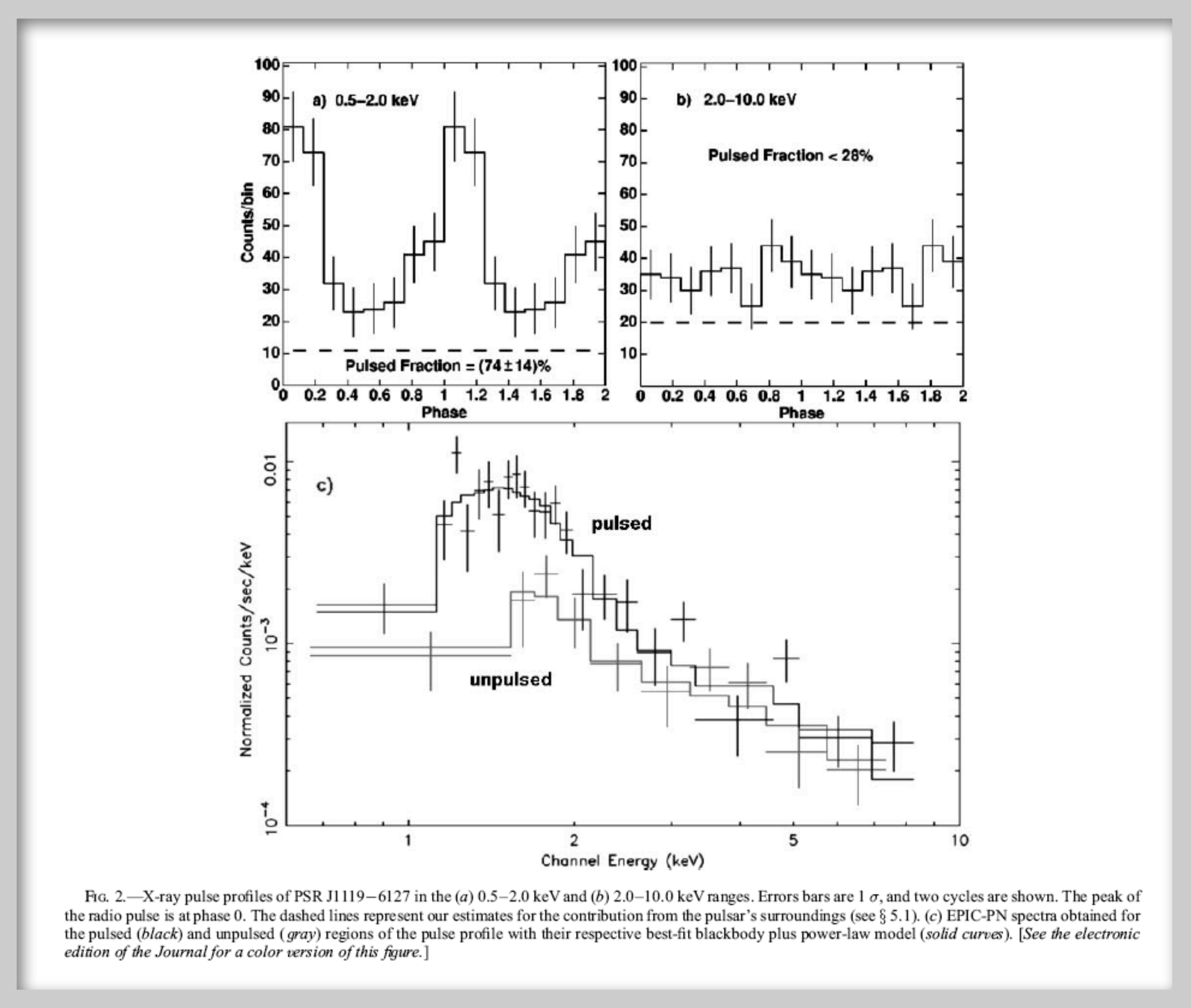
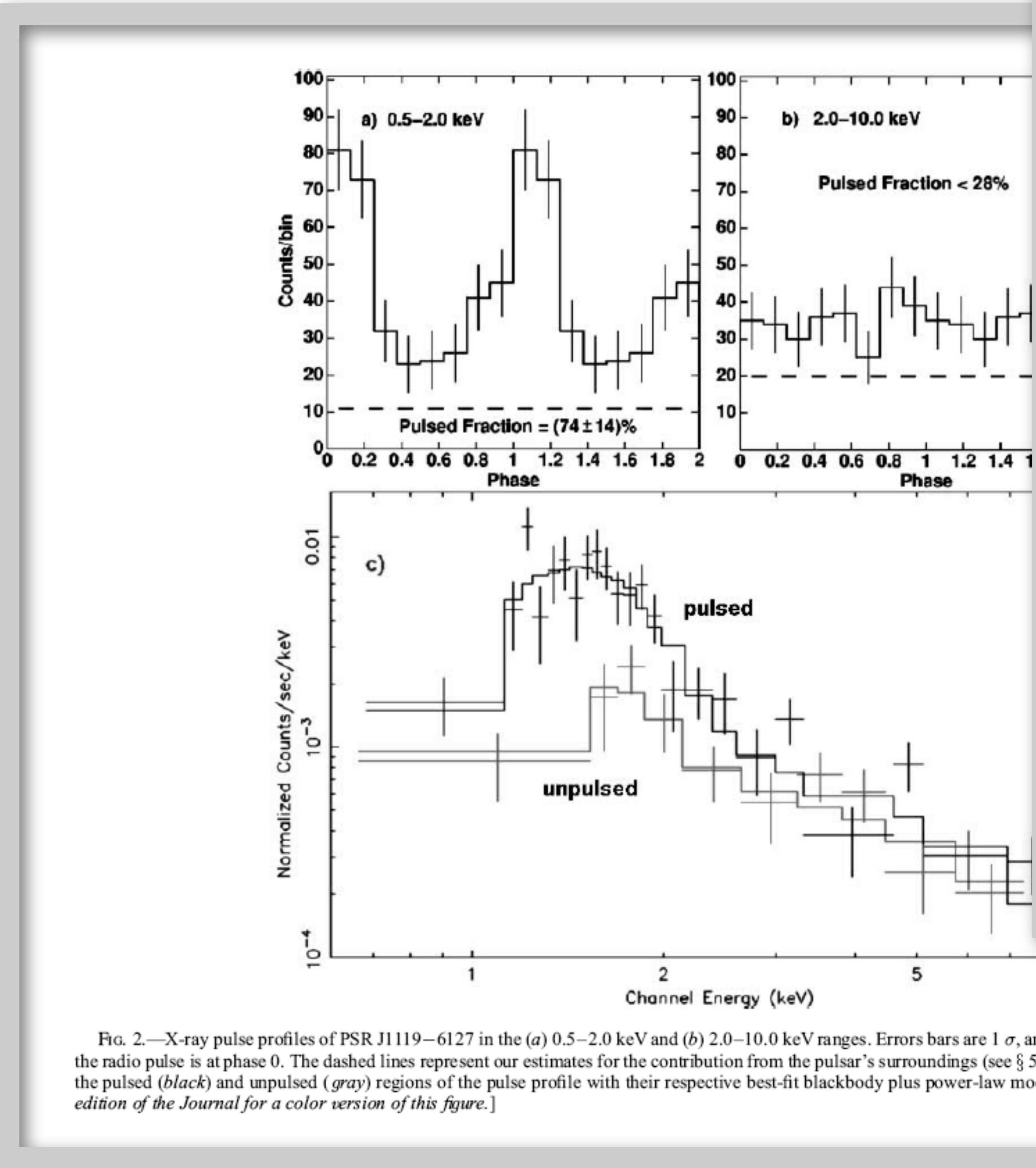


FIG. 2.—X-ray pulse profiles of PSR J1119−6127 in the (*a*) 0.5–2.0 keV and (*b*) 2.0–10.0 keV ranges. Errors bars are 1 σ, and two cycles are shown. The peak of the radio pulse is at phase 0. The dashed lines represent our estimates for the contribution from the pulsar's surroundings (see § 5.1). (*c*) EPIC-PN spectra obtained for the pulsed (*black*) and unpulsed (*gray*) regions of the pulse profile with their respective best-fit blackbody plus power-law model (*solid curves*). [*See the electronic edition of the Journal for a color version of this figure.*]

"Unusual Pulsed X-Ray Emission from the Young, High Magnetic Field Pulsar PSR J1119-6127"
Gonzalez, M. E.; Kaspi, V. M.; Camilo, F.; Gaensler, B. M.; Pivovaroff, M. J.
2005ApJ...630..489G

High field PSR J1119-6127



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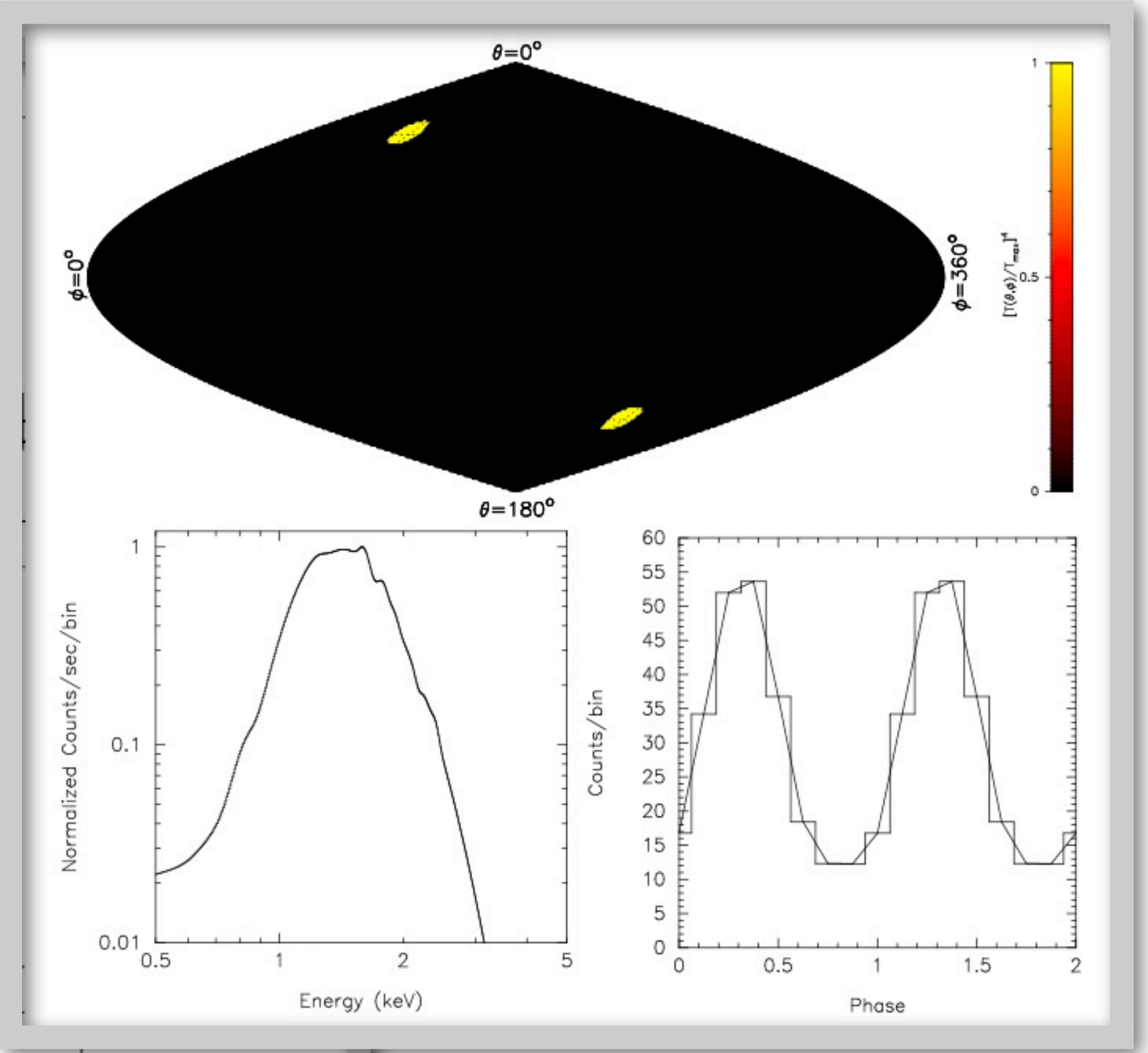

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2005ApJ...630..489G

Thermal Evolution of Neutron Stars

- Overview of neutron star structure and a simple analytical cooling model
- URCA processes
- Problem 1: pairing
- Problem 2: envelope chemical composition and magnetic fields
- **Minimal Cooling**
- Problem 3: data interpretation
- Examples of fast cooling scenarios
- Conclusion and prospects

Minimal Cooling or, do we need fast cooling ?

Minimal Cooling assumes:
nothing special happens in the core, i.e.,
no direct URCA, no π^- or K^- condensate,
no hyperons, no deconfined quark matter, no ...

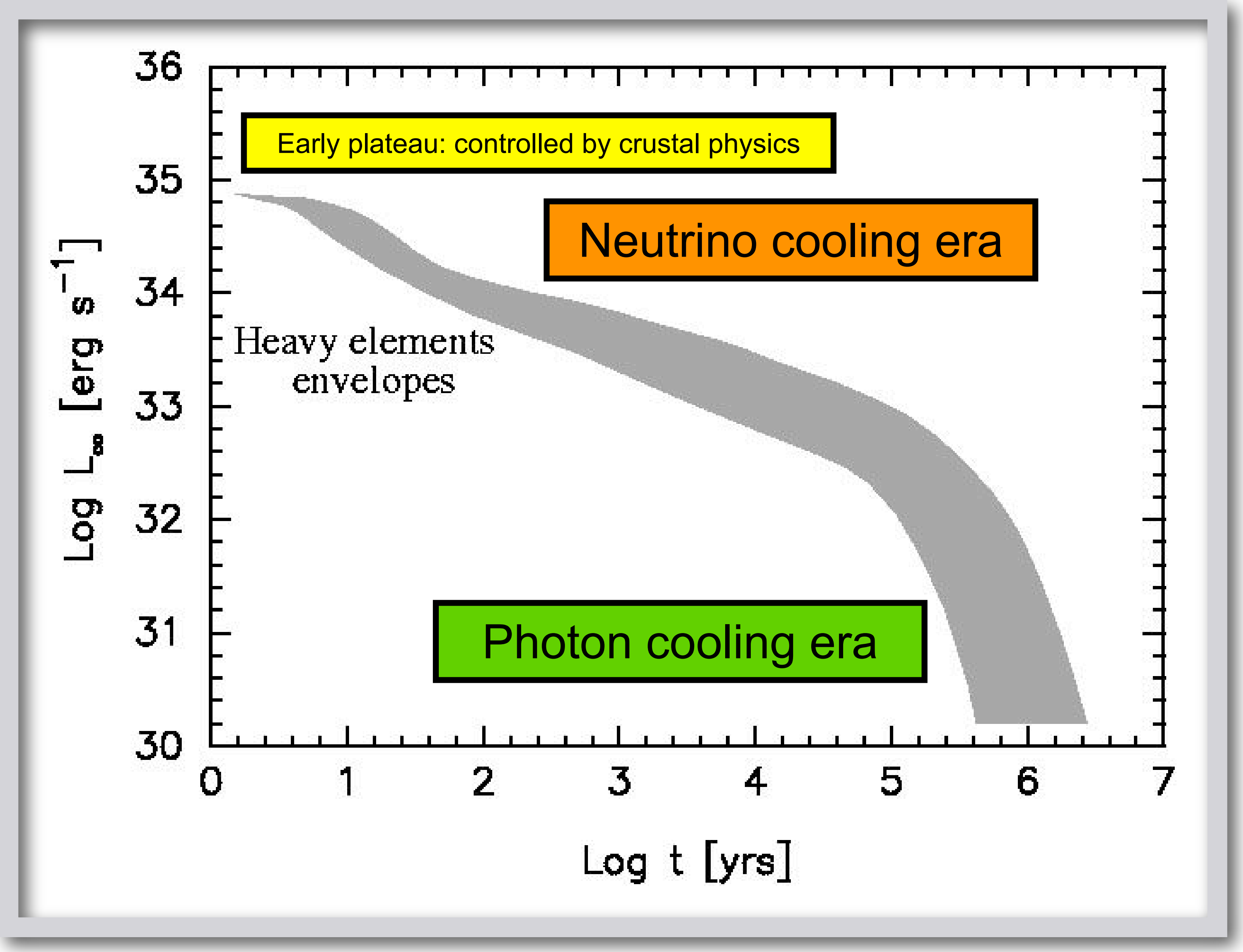
(and no medium effects enhance the
modified URCA rate beyond its standard value)

Minimal Cooling is not naive cooling:

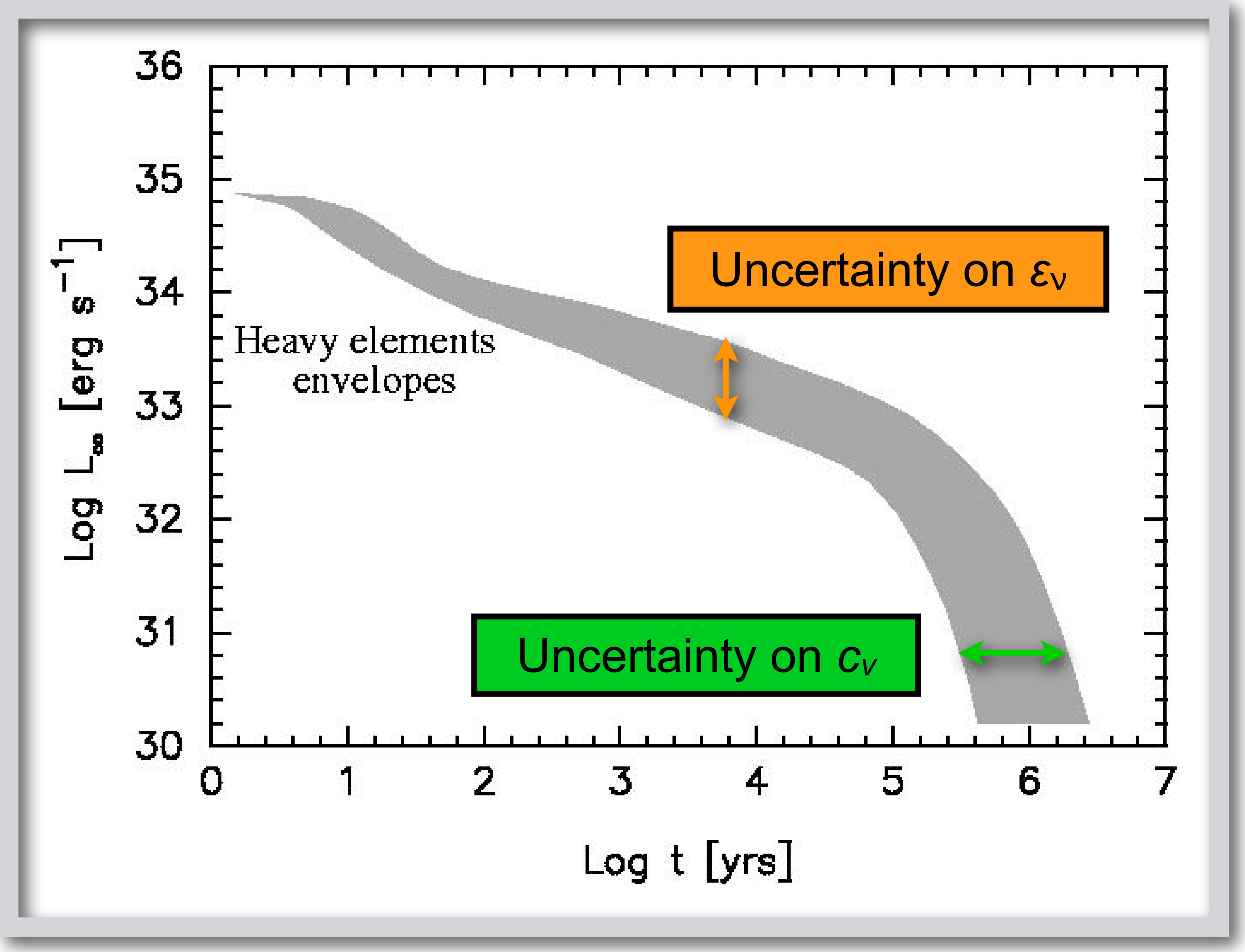
it takes into account uncertainties due to

- Large range of predicted values of T_c for n & p.
- Enhanced neutrino emission at $T \leq T_c$ from the Cooper pair formation mechanism.
- Chemical composition of upper layers (envelope), i.e., iron-peak elements or light (H, He, C, O, ...) elements, the latter significantly increasing T_e for a given T_b.
- Equation of state.
- Magnetic field.

Minimal Cooling: neutrino vs photon eras

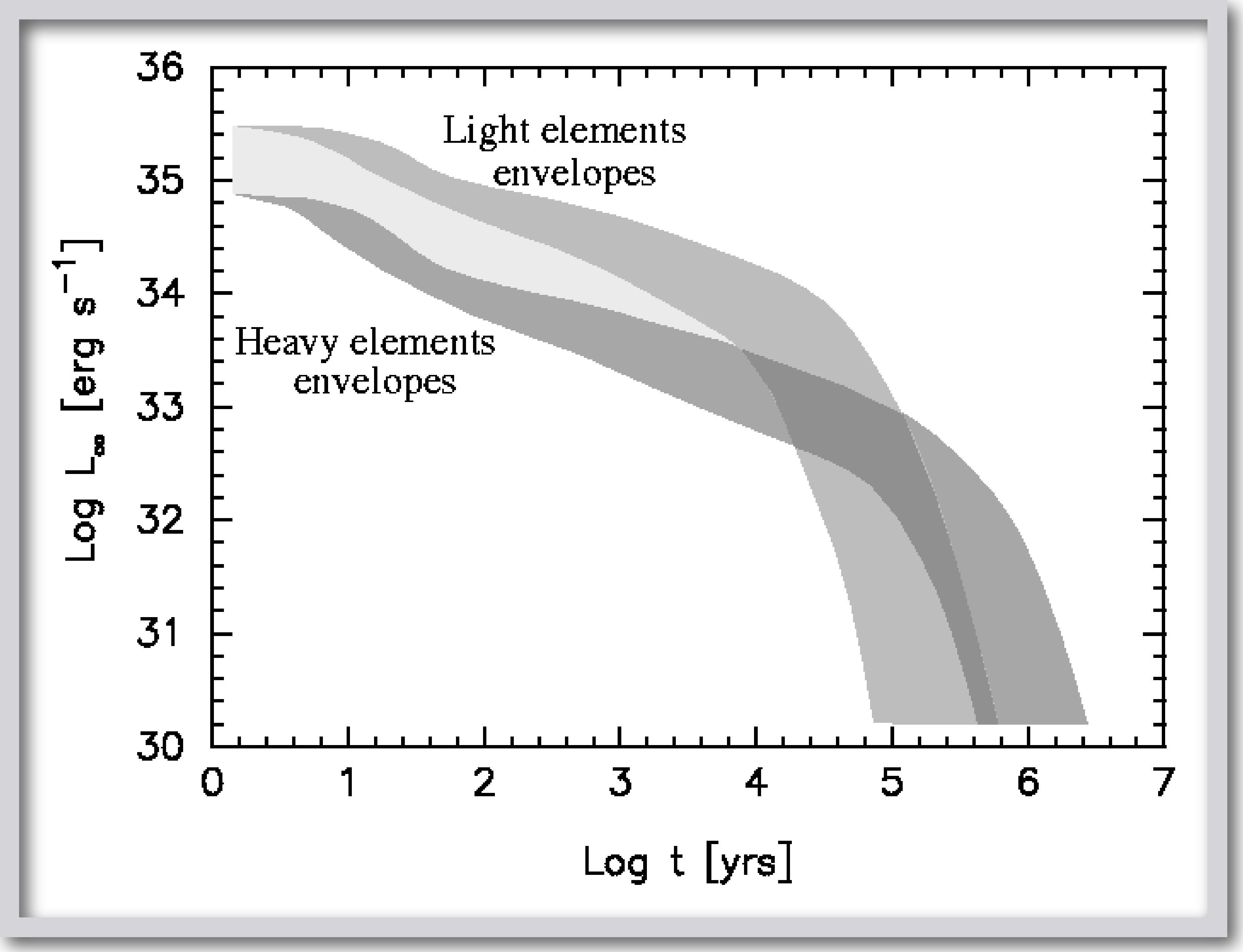


Minimal Cooling: effects of gap uncertainty



Range of predicted luminosities mostly due to uncertainties on T_c for n $^3P_2$ pairing

Minimal Cooling: envelope composition



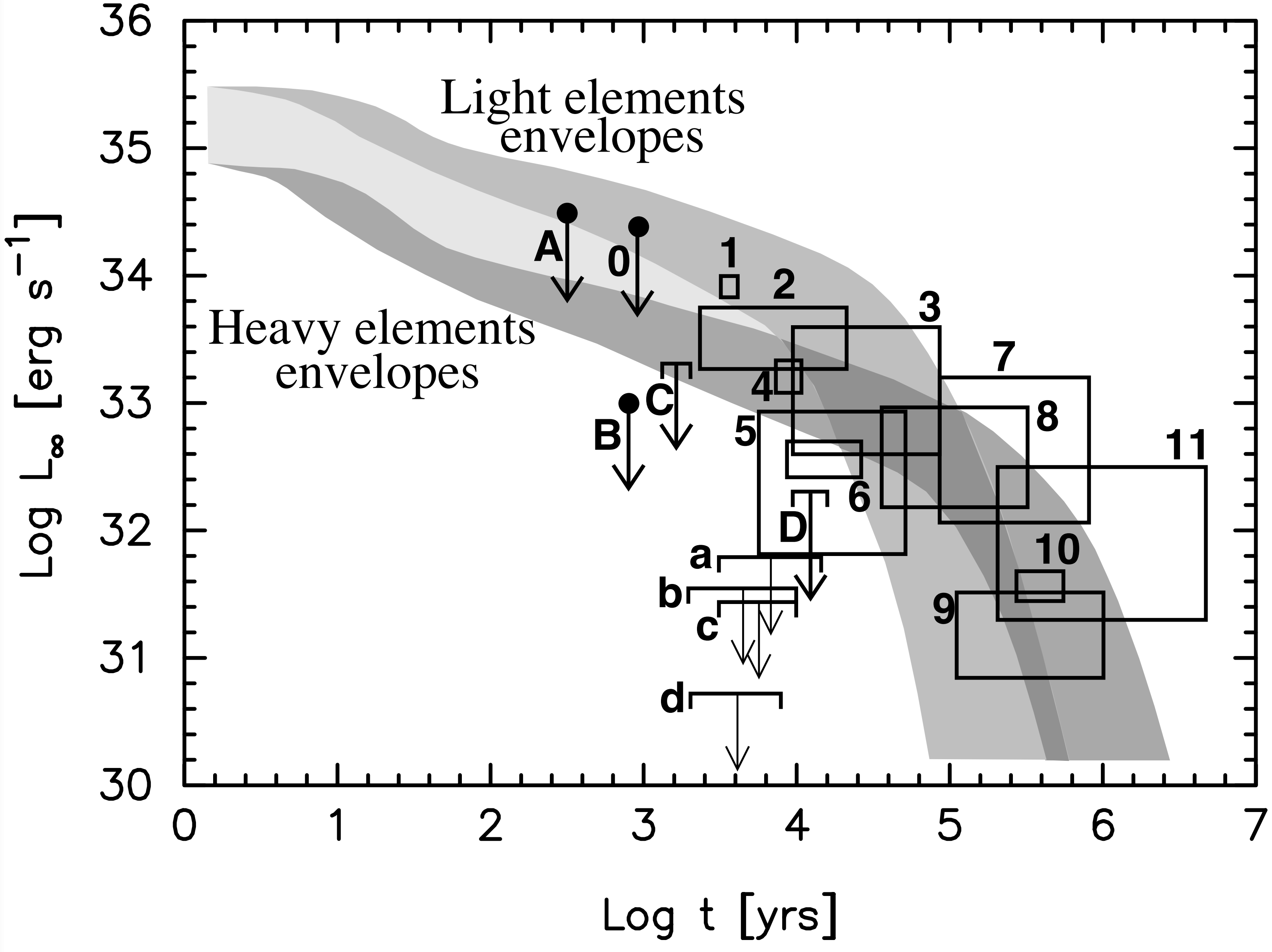
Range of predicted luminosities due to uncertainties on envelope chemical composition

Minimal Cooling versus data

1. RX J0822-4247 (in SNR Puppis A)
2. 1E 1207.4-5209 (in SNR PKS 1209-52)
3. PSR 0538+2817
4. RX J0002+6246 (in SNR CTB 1)
5. PSR 1706-44
6. PSR 0833-45 (in SNR ``Vela")
7. PSR 1055-52
8. PSR 0656+14
9. PSR 0633+1748 (``Geminga")
10. RX J1856.5-3754
11. RX J0720.4--3125

0. PSR 0531+21(in Crab)
A. CXO J232327.8+584842 (in SNR Cas A)
B. PSR J0205+6449 (in SNR 3C58)
C. PSR J1124--5916 (in SNR G292.0+1.8)
D. RX J0007.0+7302 (in SNR CTA 1)

a. ? (in SNR G315.4--2.3)
b. ? (in SNR G093.3+6.9)
c. ? (in SNR G084.2--0.8)
d. ? (in SNR G127.1+0.5)



Neutron star initial mass function

Agreement of most observed isolated cooling neutron stars with predictions of the “minimal cooling” paradigm may be due to the range of initial mass

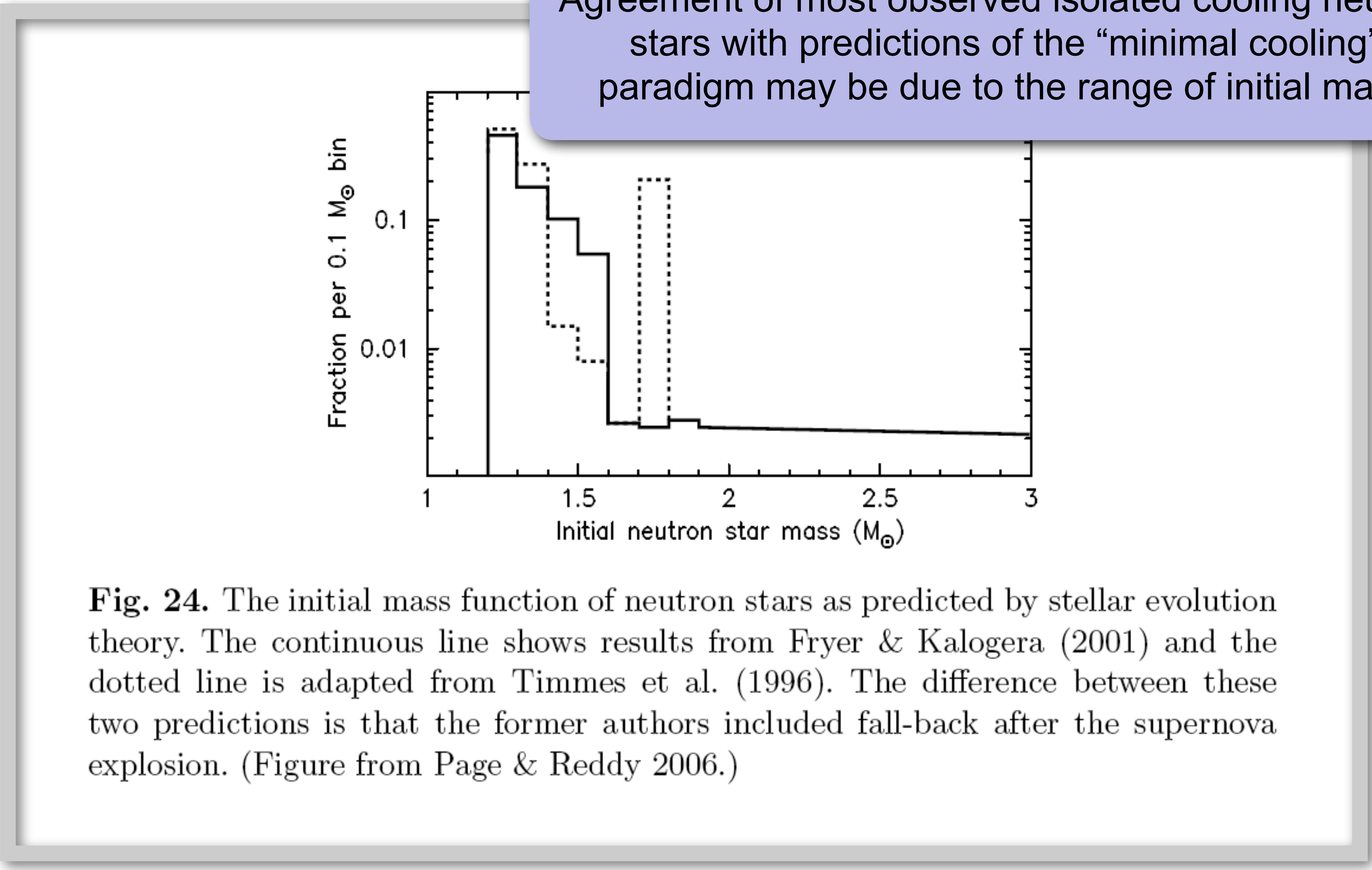


Fig. 24. The initial mass function of neutron stars as predicted by stellar evolution theory. The continuous line shows results from Fryer & Kalogera (2001) and the dotted line is adapted from Timmes et al. (1996). The difference between these two predictions is that the former authors included fall-back after the supernova explosion. (Figure from Page & Reddy 2006.)

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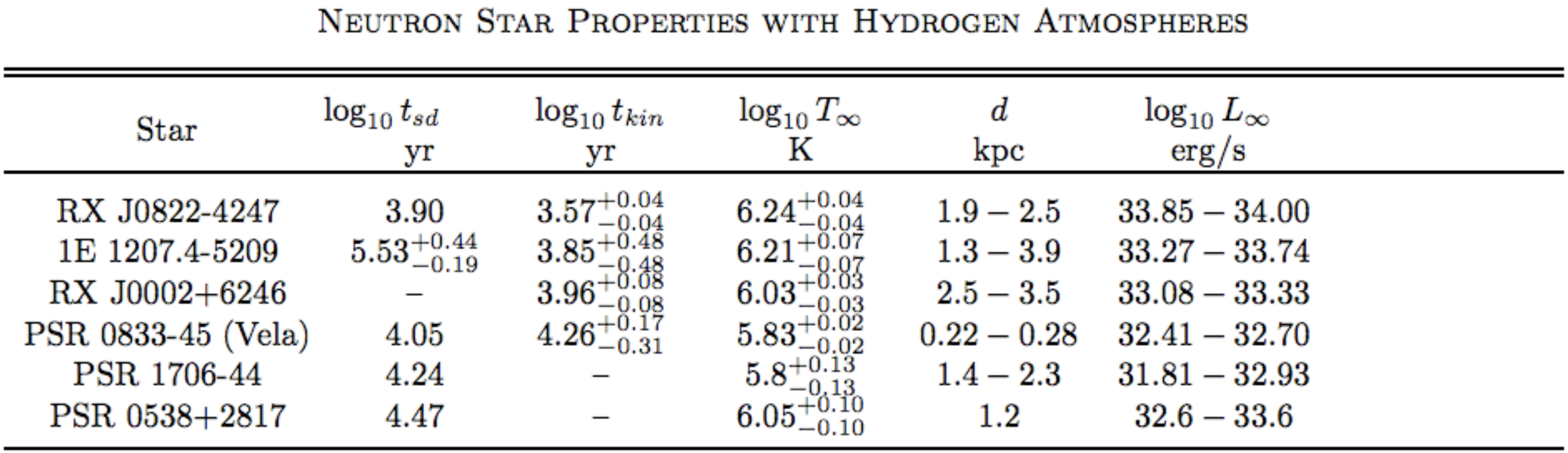
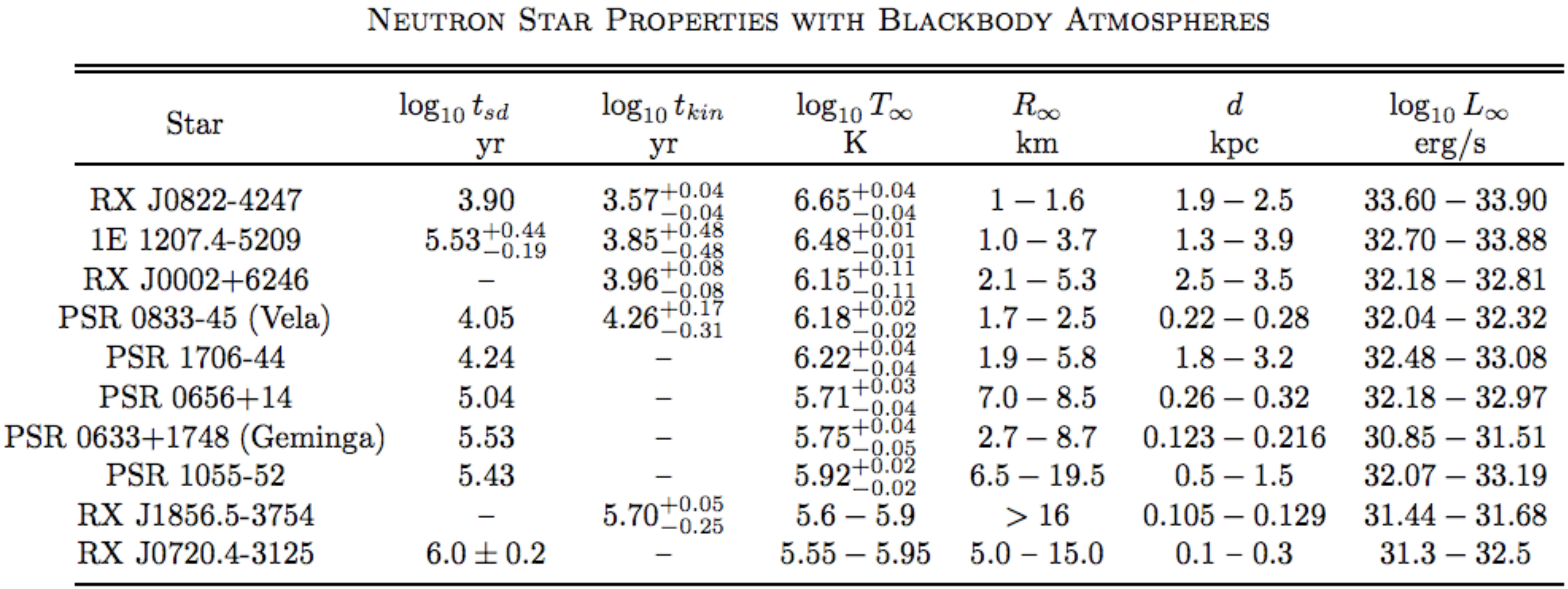
Data: with H atmosphere spectral fits



NEUTRON STAR PROPERTIES WITH HYDROGEN ATMOSPHERES

Star	$\log_{10} t_{sd}$ yr	$\log_{10} t_{kin}$ yr	$\log_{10} T_\infty$ K	d kpc	$\log_{10} L_\infty$ erg/s
RX J0822-4247	3.90	$3.57^{+0.04}_{-0.04}$	$6.24^{+0.04}_{-0.04}$	1.9 – 2.5	33.85 – 34.00
1E 1207.4-5209	$5.53^{+0.44}_{-0.19}$	$3.85^{+0.48}_{-0.48}$	$6.21^{+0.07}_{-0.07}$	1.3 – 3.9	33.27 – 33.74
RX J0002+6246	–	$3.96^{+0.08}_{-0.08}$	$6.03^{+0.03}_{-0.03}$	2.5 – 3.5	33.08 – 33.33
PSR 0833-45 (Vela)	4.05	$4.26^{+0.17}_{-0.31}$	$5.83^{+0.02}_{-0.02}$	0.22 – 0.28	32.41 – 32.70
PSR 1706-44	4.24	–	$5.8^{+0.13}_{-0.13}$	1.4 – 2.3	31.81 – 32.93
PSR 0538+2817	4.47	–	$6.05^{+0.10}_{-0.10}$	1.2	32.6 – 33.6

Data: with blackbody spectral fits



Neutron Star Properties with Blackbody Atmospheres

Star	$\log_{10} t_{sd}$ yr	$\log_{10} t_{kin}$ yr	$\log_{10} T_\infty$ K	R_∞ km	d kpc	$\log_{10} L_\infty$ erg/s
RX J0822-4247	3.90	$3.57^{+0.04}_{-0.04}$	$6.65^{+0.04}_{-0.04}$	1 – 1.6	1.9 – 2.5	33.60 – 33.90
1E 1207.4-5209	$5.53^{+0.44}_{-0.19}$	$3.85^{+0.48}_{-0.48}$	$6.48^{+0.01}_{-0.01}$	1.0 – 3.7	1.3 – 3.9	32.70 – 33.88
RX J0002+6246	–	$3.96^{+0.08}_{-0.08}$	$6.15^{+0.11}_{-0.11}$	2.1 – 5.3	2.5 – 3.5	32.18 – 32.81
PSR 0833-45 (Vela)	4.05	$4.26^{+0.17}_{-0.31}$	$6.18^{+0.02}_{-0.02}$	1.7 – 2.5	0.22 – 0.28	32.04 – 32.32
PSR 1706-44	4.24	–	$6.22^{+0.04}_{-0.04}$	1.9 – 5.8	1.8 – 3.2	32.48 – 33.08
PSR 0656+14	5.04	–	$5.71^{+0.03}_{-0.04}$	7.0 – 8.5	0.26 – 0.32	32.18 – 32.97
PSR 0633+1748 (Geminga)	5.53	–	$5.75^{+0.04}_{-0.05}$	2.7 – 8.7	0.123 – 0.216	30.85 – 31.51
PSR 1055-52	5.43	–	$5.92^{+0.02}_{-0.02}$	6.5 – 19.5	0.5 – 1.5	32.07 – 33.19
RX J1856.5-3754	–	$5.70^{+0.05}_{-0.25}$	5.6 – 5.9	> 16	0.105 – 0.129	31.44 – 31.68
RX J0720.4-3125	6.0 ± 0.2	–	5.55 – 5.95	5.0 – 15.0	0.1 – 0.3	31.3 – 32.5

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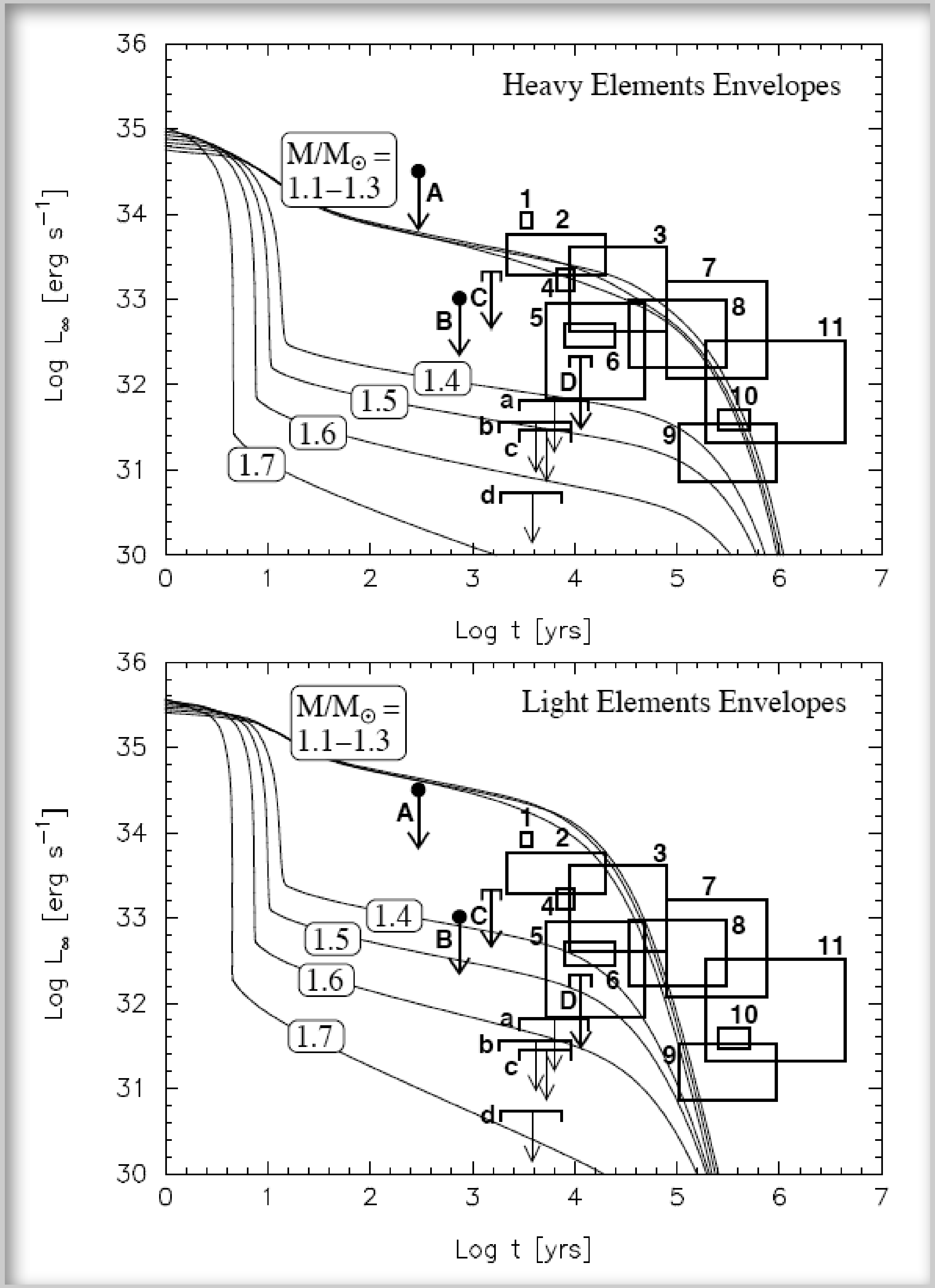
Direct URCA with pairing vs data

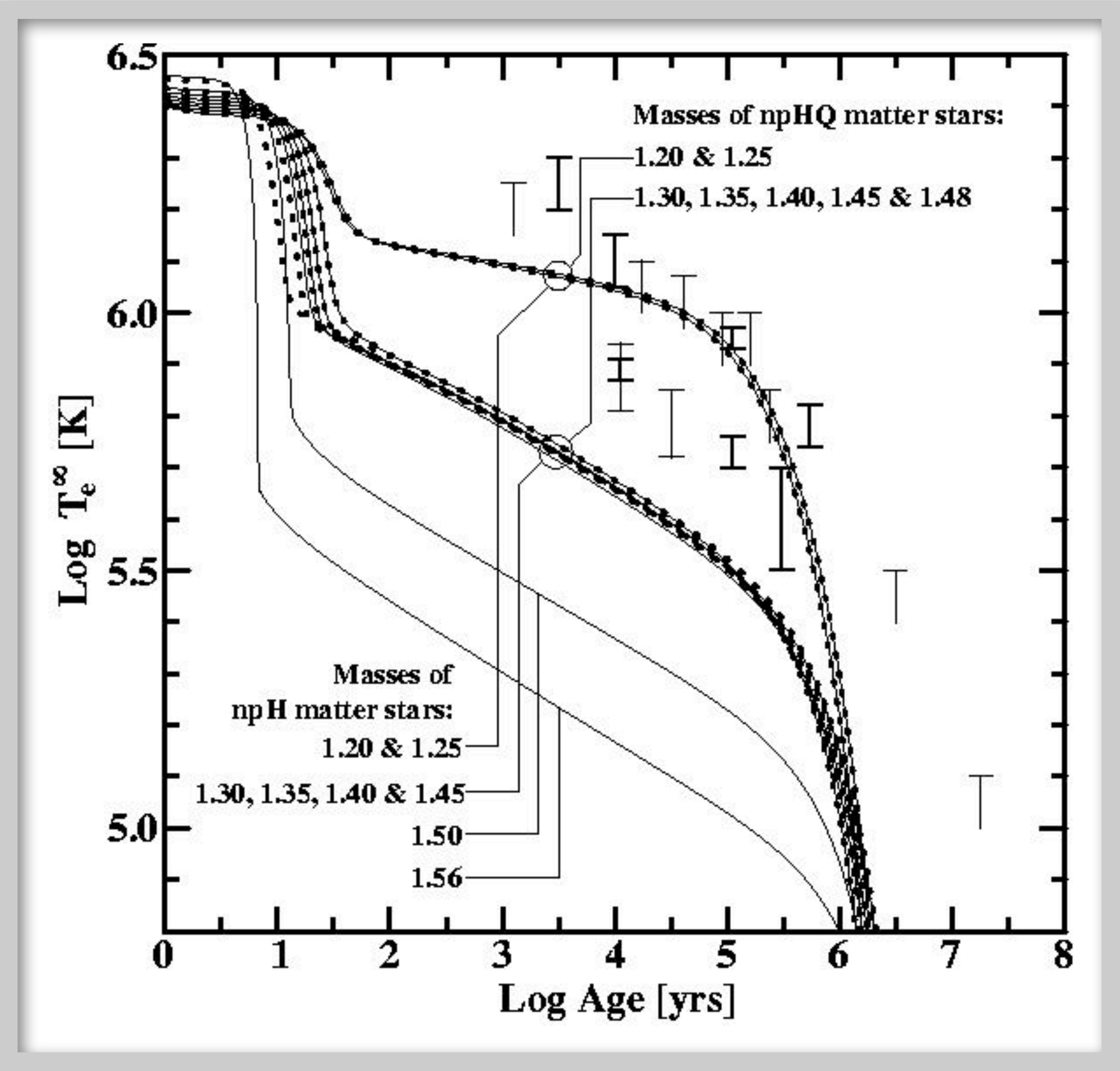
EOS: PAL
$M_{cr} = 1.35\ M_{Sun}$

Pairing gaps:

Neutron $^1S_0$: “SFB”
Neutron $^3P_2$: “b”
Proton $^1S_0$: “T73”



A “Maximal” cooling model (?)



Comparison of two models with n, p & hyperons (ΛDUURCA with Λ is controlled by its $^1S_0$ gap) and n, p, hyperons + quarks (Quark DURCAs are strongly suppress by a very large gap)

Because of the strong suppression of neutrino emission by large gaps, there is little difference between the two models.

“Prospects of Detecting Baryon and Quark Superfluidity from Cooling Neutron Stars”, D Page, M Prakash, JM Lattimer & AW Steiner, 2000PhRvL..85.2048P

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Conclusions and . . .

- Many possibilities for fast neutrino emission.
- Neutrino emission can be strongly suppressed by pairing.
- Minimal Cooling: most observed isolated cooling neutron star are OK.
- A few serious candidates for neutrino cooling beyond minimal.

. . . prospects

HELP !

From nuclear physicists:

- Reliable pairing gaps (for nucleons, hyperons, quarks: !?!)
- Medium effects on the modified URCA process

From astrophysicists:

- Better atmosphere models with strong magnetic fields
- Better models of T_{surf} distribution with magnetic fields.

From astronomers:

- More reliable estimates of ages
- X-ray polarimetry to determine the surface magnetic field geometry (?)


"That's all Folks!"