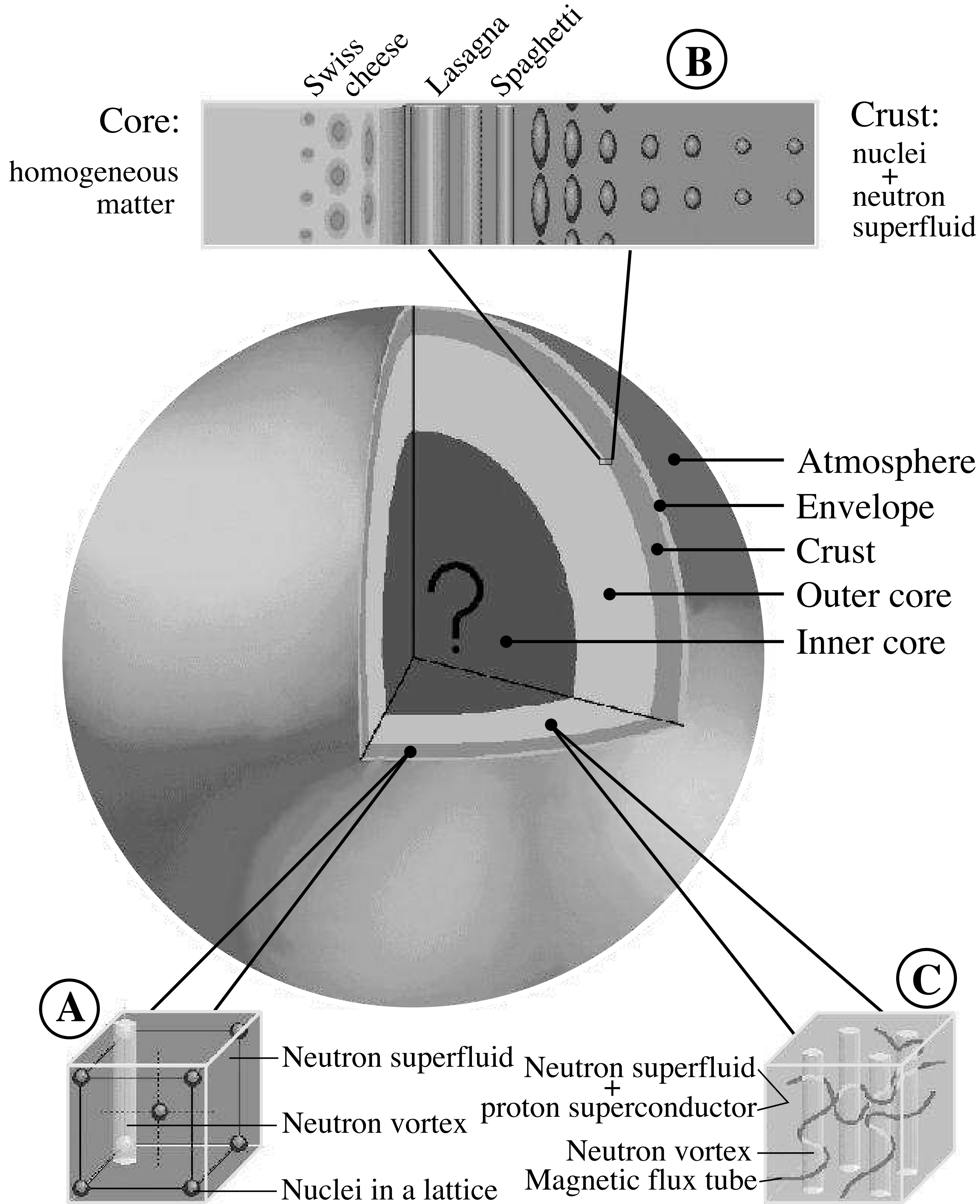
Instituto de Astronomía UNAM

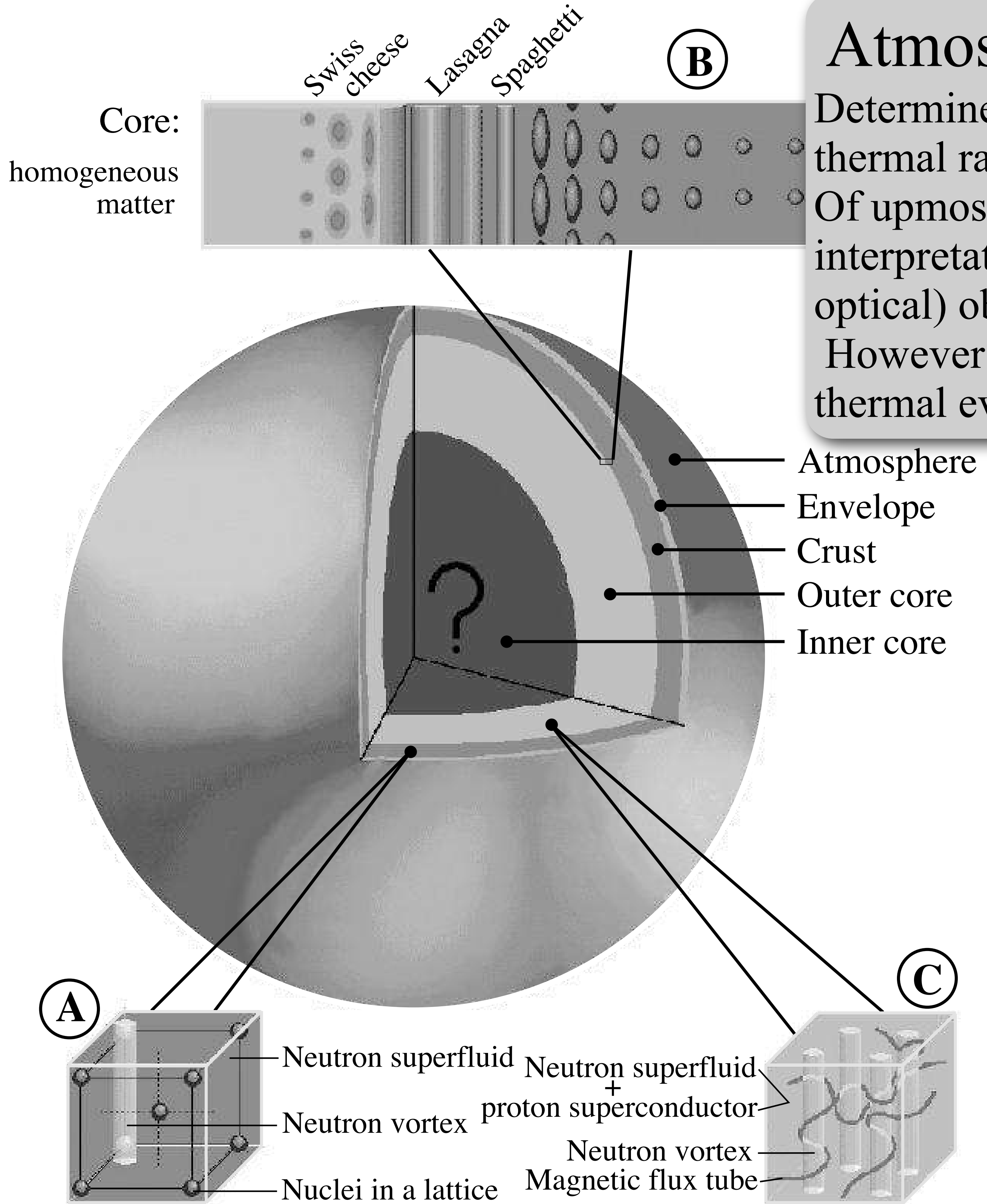
Neutron Star Cooling

Dany Page

Instituto de Astronomía
Universidad Nacional Autónoma de México



Dense Matter in Compact Stars: Theoretical Developments and Observational Constraints, Page D. & Reddy S., 2006, Annu. Rev. Nucl. Part. Sci. 56, 327



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.

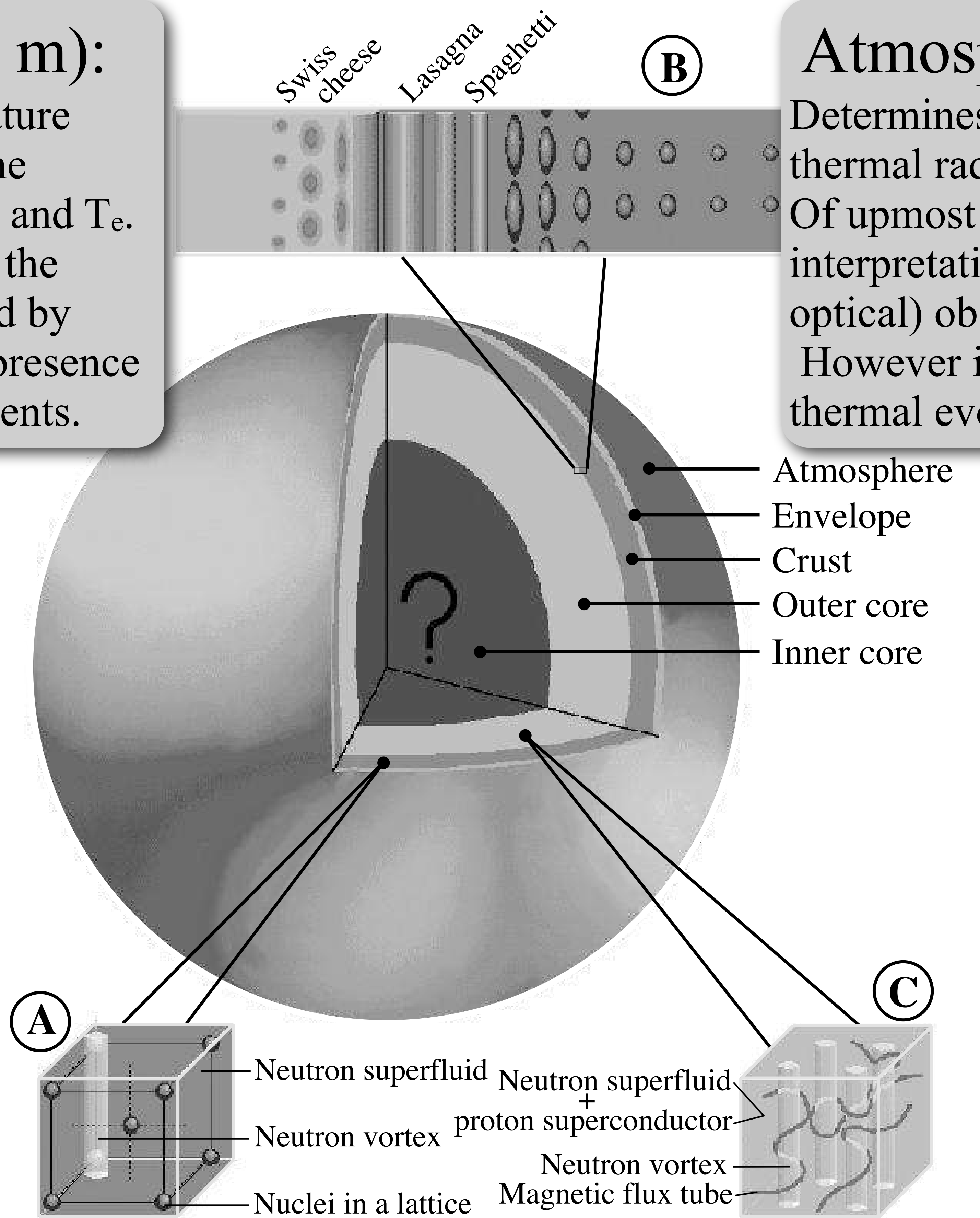
Dense Matter in Compact Stars: Theoretical Developments and Observational Constraints, Page D. & Reddy S., 2006, Annu. Rev. Nucl. Part. Sci. 56, 327

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.



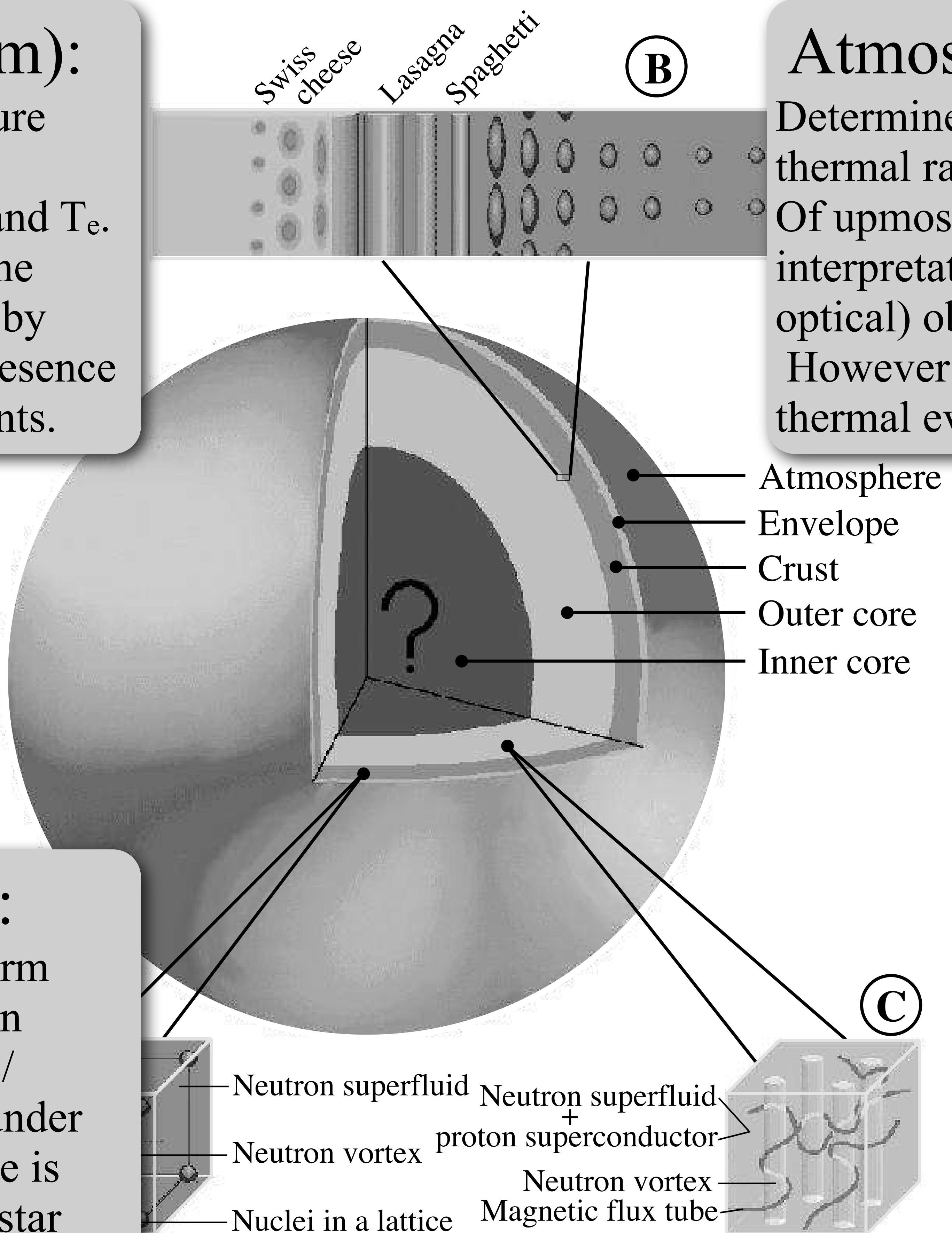
Dense Matter in Compact Stars: Theoretical Developments and Observational Constraints, Page D. & Reddy S., 2006, Annu. Rev. Nucl. Part. Sci. 56, 327

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.



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

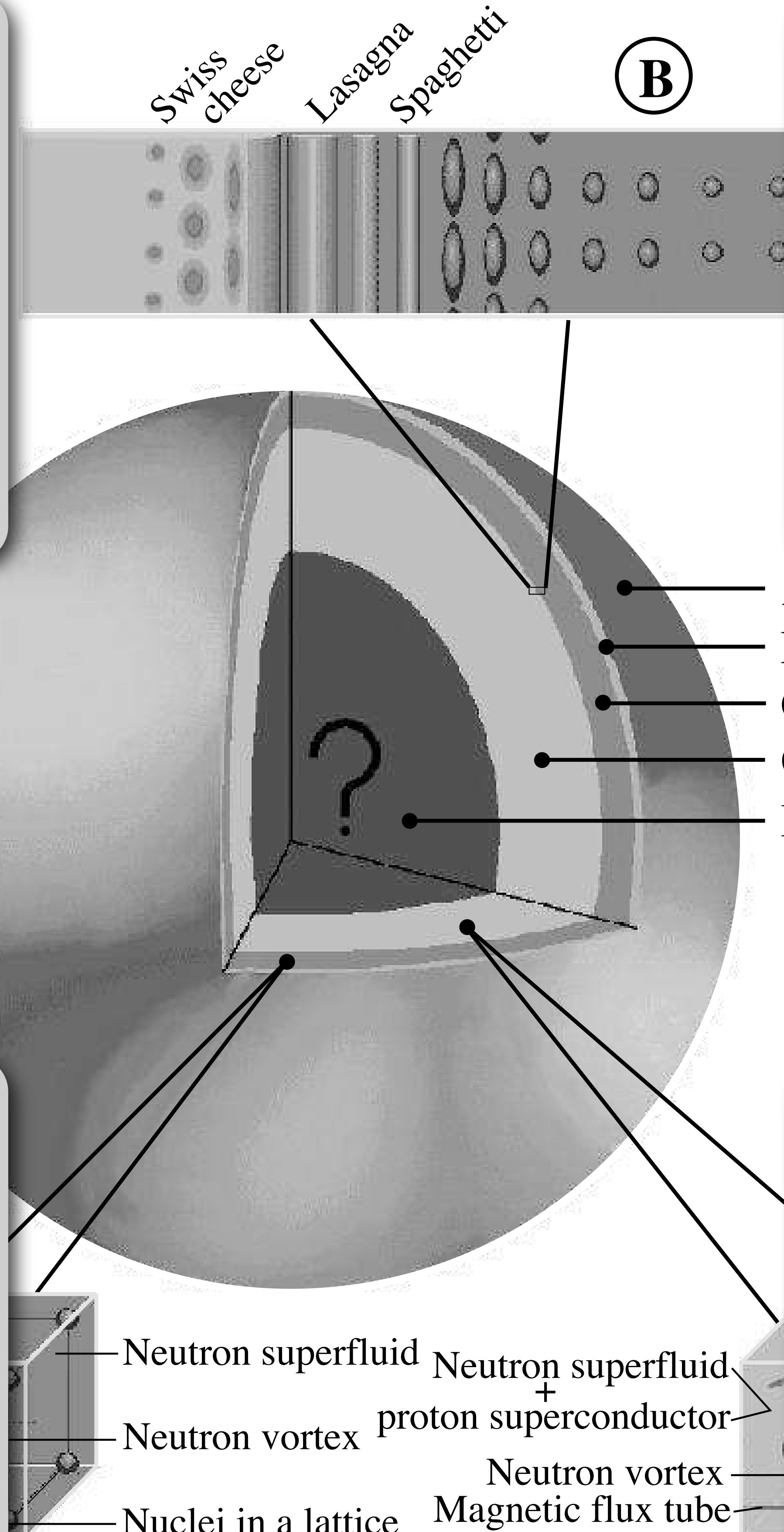
Dense Matter in Compact Stars: Theoretical Developments and Observational Constraints, Page D. & Reddy S., 2006, Annu. Rev. Nucl. Part. Sci. 56, 327

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.



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_v unless an inner core is present. Its physics is basically under control except pairing T_c which is essentially unknown.

Dense Matter in Compact Stars: Theoretical Developments and Observational Constraints, Page D. & Reddy S., 2006, Annu. Rev. Nucl. Part. Sci. 56, 327

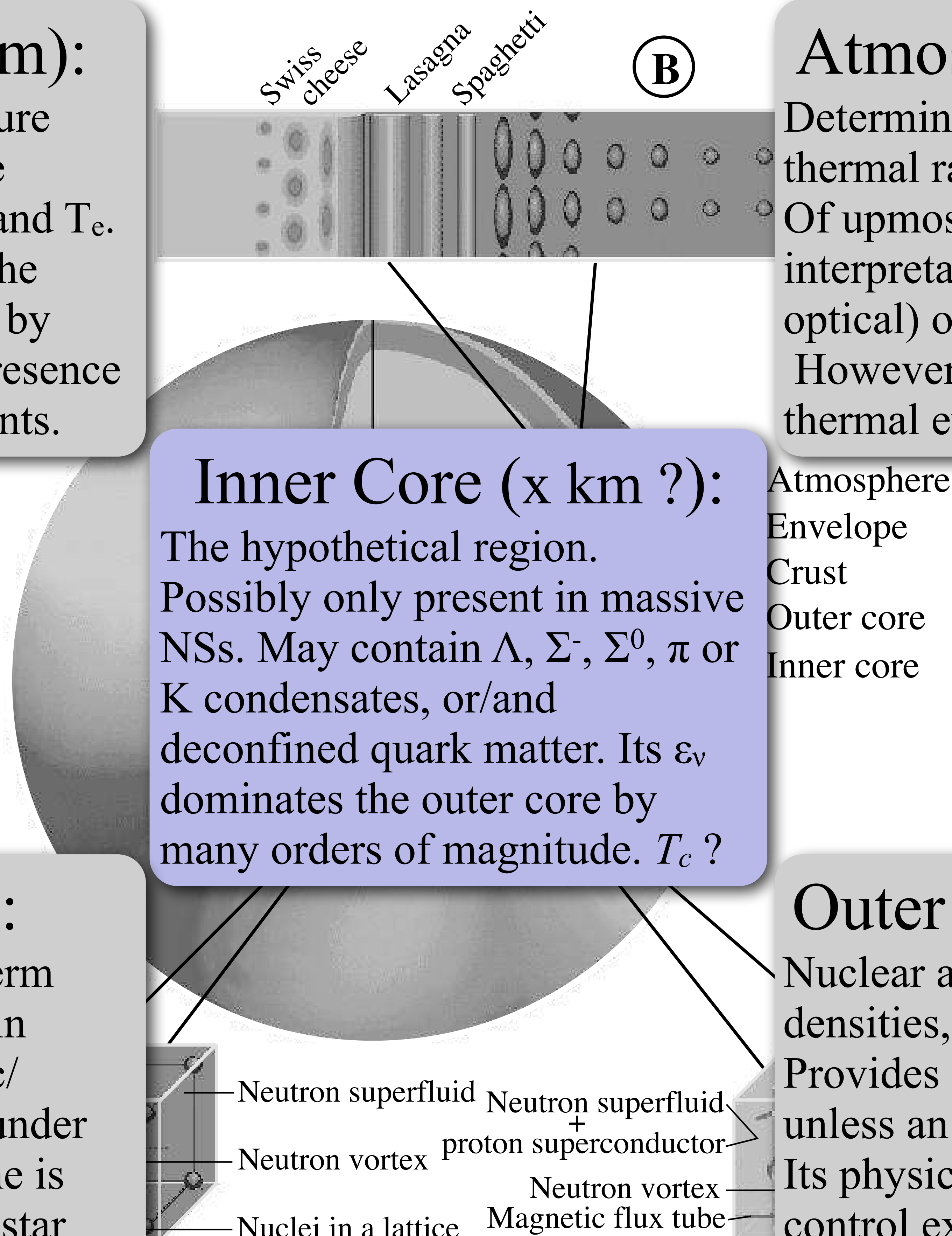
Envelope (100 m):

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.

Dense Matter in Compact Stars: Theoretical Developments and Observational Constraints, Page D. & Reddy S., 2006, Annu. Rev. Nucl. Part. Sci. 56, 327

Neutron star cooling on a napkin

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

Thermal Energy, E_{th} ,balance:

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

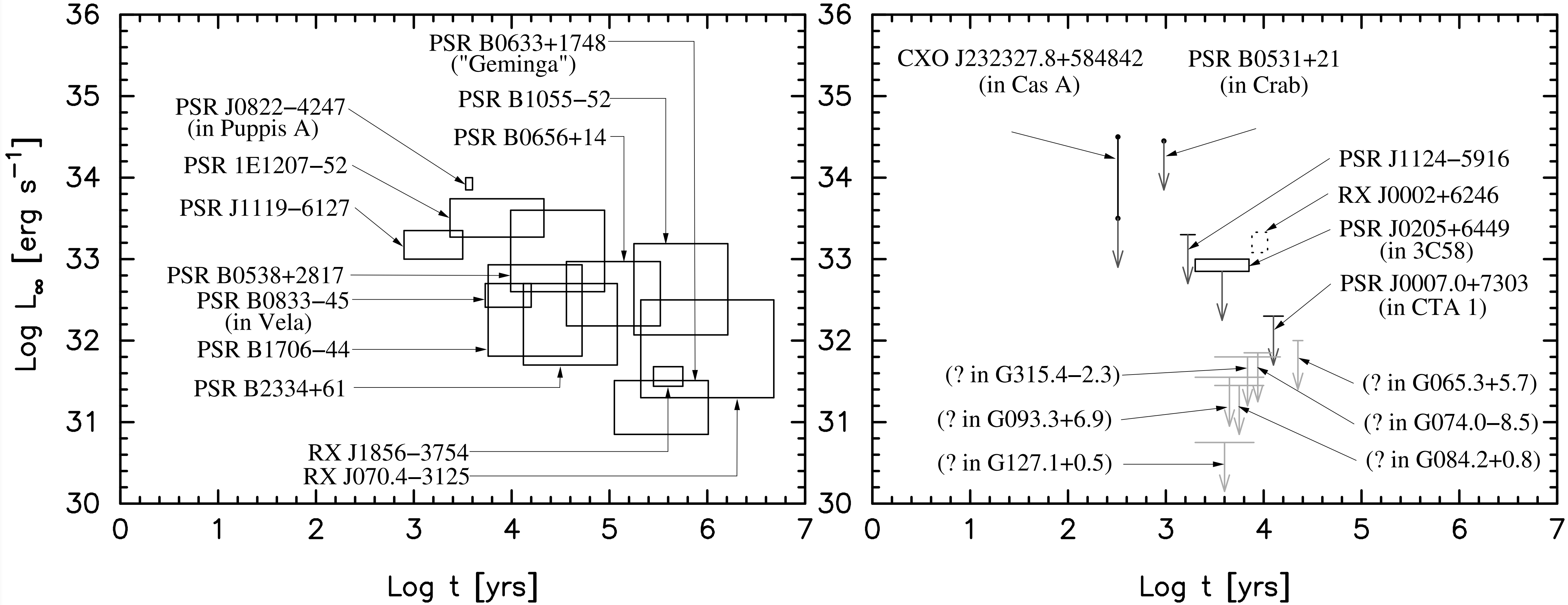
⇒ 3 essential ingredients are needed:

- 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 ...

Observational Data

Observational data



Specific Heat

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

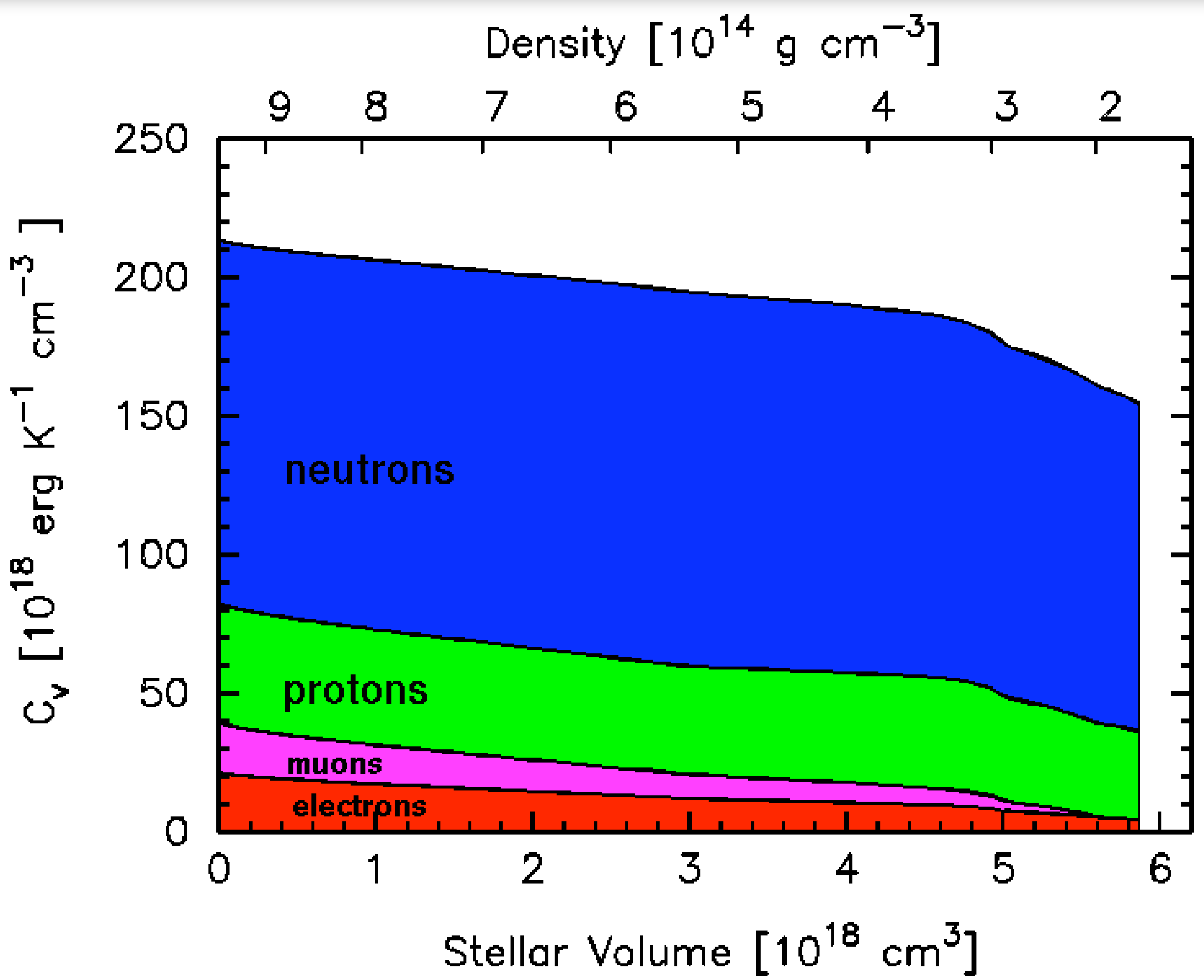
H = "heating", from B field decay, friction, etc ...

Specific heat on a napkin

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

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

(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

Neutrinos

The direct Urca process

Basic mechanism: β and inverse β decays:

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

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

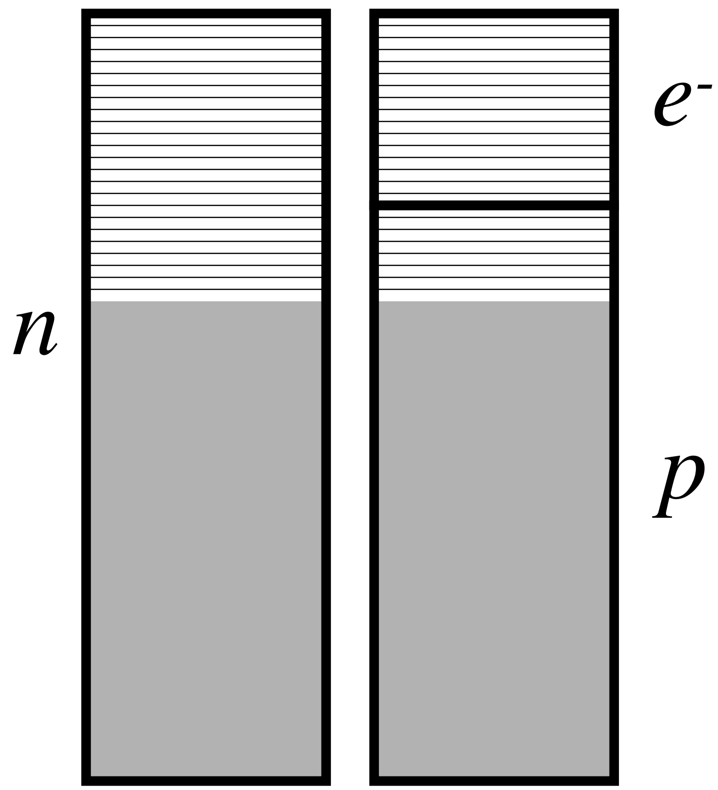
The direct Urca process

Basic mechanism: β and inverse β decays:

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

Energy conservation:

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



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

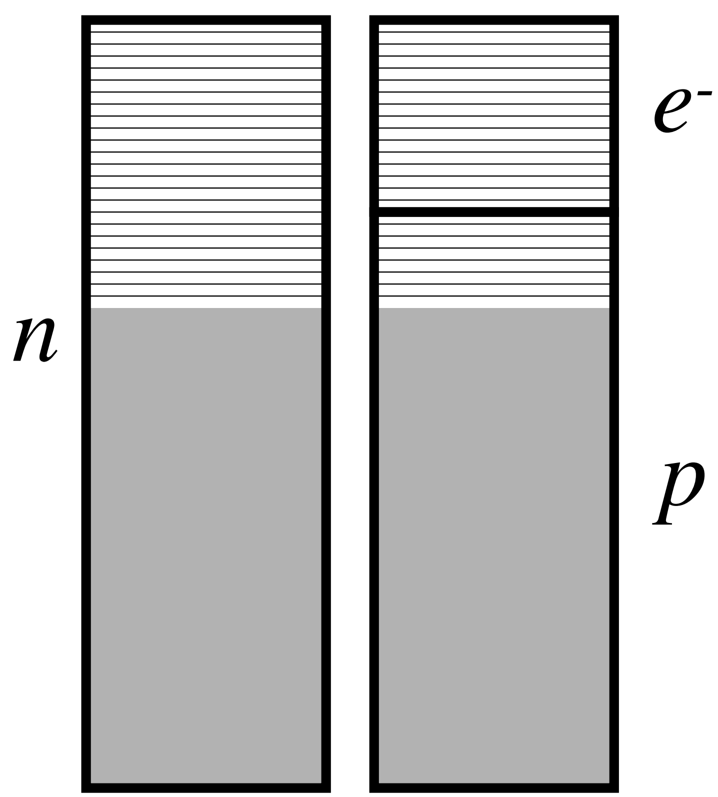
The direct Urca process

Basic mechanism: β and inverse β decays:

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

Energy conservation:

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



Momentum conservation:

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

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

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

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

The modified URCA process

If the direct Urca process:
$$\begin{cases} n & \longrightarrow & p + e^- + \overline{\nu}_e \\ p + e^- & \longrightarrow & n + \nu_e \end{cases}$$

is forbidden because of momentum conservation, add a spectator neutron:

Modified Urca process:
$$\begin{cases} n + n' & \longrightarrow & p + n' + e^- + \overline{\nu}_e \\ p + n' + e^- & \longrightarrow & n + n' + \nu_e \end{cases}$$

Momentum conservation is automatic, but the price to pay is:

3 vs 5 fermions phase space:
$$\left(\frac{k_B T}{E_F}\right)^2 \sim \left(\frac{0.1\,\mathrm{MeV}\cdot T_9}{100\,\mathrm{MeV}\cdot E_{F\,100}}\right)^2 \sim 10^{-6}\cdot T_9^2$$

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

Neutrino emission on a napkin (I)

The Murca-Bremsstrahlung family and Durca

Name	Process	Emissivity (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
Direct Urca cycle	$n \to p + e^- + \bar{\nu}_e$ $p + e^- \to n + \nu_e$	$\sim 10^{27}\ R\ T_9^6$	Fast

Hyperons in neutron stars (I)

Hyperons, as Λ and Σ⁻ can be produced through reactions as, e.g.

$$\begin{cases} p + e^- & \longrightarrow & \Lambda + \nu_e \\ \Lambda & \longrightarrow & p + e^- + \overline{\nu}_e \end{cases}$$

$$\begin{cases} n + e^- & \longrightarrow & \Sigma^- + \nu_e \\ \Sigma^- & \longrightarrow & n + e^- + \overline{\nu}_e \end{cases}$$

Energy conservation requires: $\mu_\Lambda = \mu_n$ and $\mu_{\Sigma^-} = \mu_n + \mu_e$

Momentum conservation: very easily satisfied for Λ and not very difficult to satisfy for Σ^-

Hyperons will result in DUrca processes if they can be present

Charged mesons (π^- & K^-) in neutron stars

Hyperons, as π^- and K^- can be produced through reactions as, e.g.

$$\begin{cases} n + e^- & \longrightarrow & n + \pi^- + \nu_e \\ n + \pi^- & \longrightarrow & n + e^- + \overline{\nu}_e \end{cases}$$

$$\begin{cases} n + e^- & \longrightarrow & n + K^- + \nu_e \\ n + K^- & \longrightarrow & n + e^- + \overline{\nu}_e \end{cases}$$

Energy conservation requires: $m^*_\pi = \mu_e$ or $m^*_K = \mu_e$

Momentum conservation: trivially satisfied because mesons condense (they are bosons) and the condensate can absorb *any* extra needed momentum

Charged mesons will result in DUrca processes if they can be present

Neutrino emission on a napkin (III)

Name	Process	Emissivity (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 (nucleons)	$n \to p + e^- + \bar{\nu}_e$ $p + e^- \to n + \nu_e$	$\sim 10^{27}\ R\ T_9^6$	Fast
Direct Urca cycle (Λ hyperons)	$\Lambda \to p + e^- + \bar{\nu}_e$ $p + e^- \to \Lambda + \nu_e$	$\sim 10^{27}\ R\ T_9^6$	Fast
Direct Urca cycle (Σ^- hyperons)	$\Sigma^- \to n + e^- + \bar{\nu}_e$ $n + e^- \to \Sigma^- + \nu_e$	$\sim 10^{27}\ R\ T_9^6$	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

Neutrino emission on a napkin (III)

Name	Process	Emissivity (erg cm^{-3} s^{-1})	
Modified Urca cycle (neutron branch)	$n + n \to n + p + e^- + \bar{\nu}_e$ $n + p + e^- \to n + n + \nu_e$	$\sim 2\times 10^{21}$ …	Slow
Modified Urca cycle (proton branch)	$p + n \to p + p + e^- + \bar{\nu}_e$ $p + p + e^- \to p + n$ …	…	Slow
Bremsstrahlung	$n + n \to n + n$ … $n + p \to$ … p …	…	Slow
Cooper pair formations	…	…$\times 10^{21}\ R\, T_9^7$ $\sim 5\times 10^{19}\ R\, T_9^7$	Medium
Direct Urc… (nucle…	… e	$\sim 10^{27}\ R\, T_9^6$	Fast
Direct U… (Λ hypero…	… $e^- + \bar{\nu}_e$ … $+ e^- \to \Lambda + \nu_e$	$\sim 10^{27}\ R\, T_9^6$	Fast
Direct Urc… (Σ^- hyperon…	$\Sigma^- \to n + e^- + \bar{\nu}_e$ $n + e^- \to \Sigma^- + \nu_e$	$\sim 10^{27}\ R\, T_9^6$	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

Anything beyond just neutrons and protons
(and only a small amount of them)
results in enhanced neutrino emission

Dominant neutrino processes in the crust

Plasmon decay process

$$\Gamma \longrightarrow \nu + \overline{\nu}$$

Bremsstrahlung processes:

$$e^- + {}^AZ \longrightarrow e^- + {}^AZ + \nu + \overline{\nu}$$

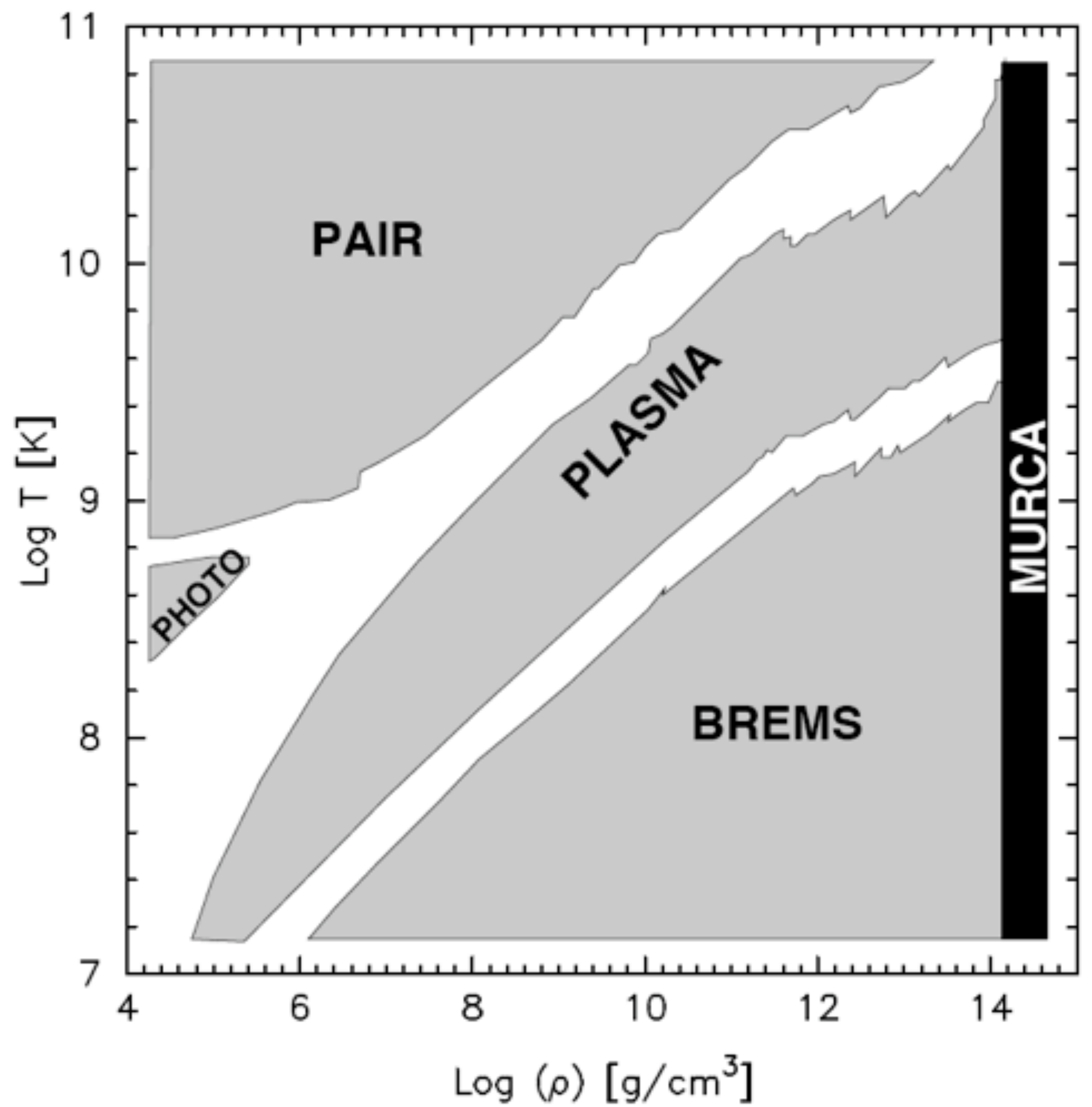
$$n + n \longrightarrow n + n + \nu + \overline{\nu}$$

Pair annihilation process:

$$\gamma + \gamma \leftrightarrow e^- + e^+ \longrightarrow \nu + \overline{\nu}$$

Photo-neutrino process:

$$\gamma + e^- \longrightarrow e^- + \nu + \overline{\nu}$$



Regions where the indicated neutrino emission process contributes more than 90% of the total.

Simple Models

A simple analytical solution

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

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

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

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

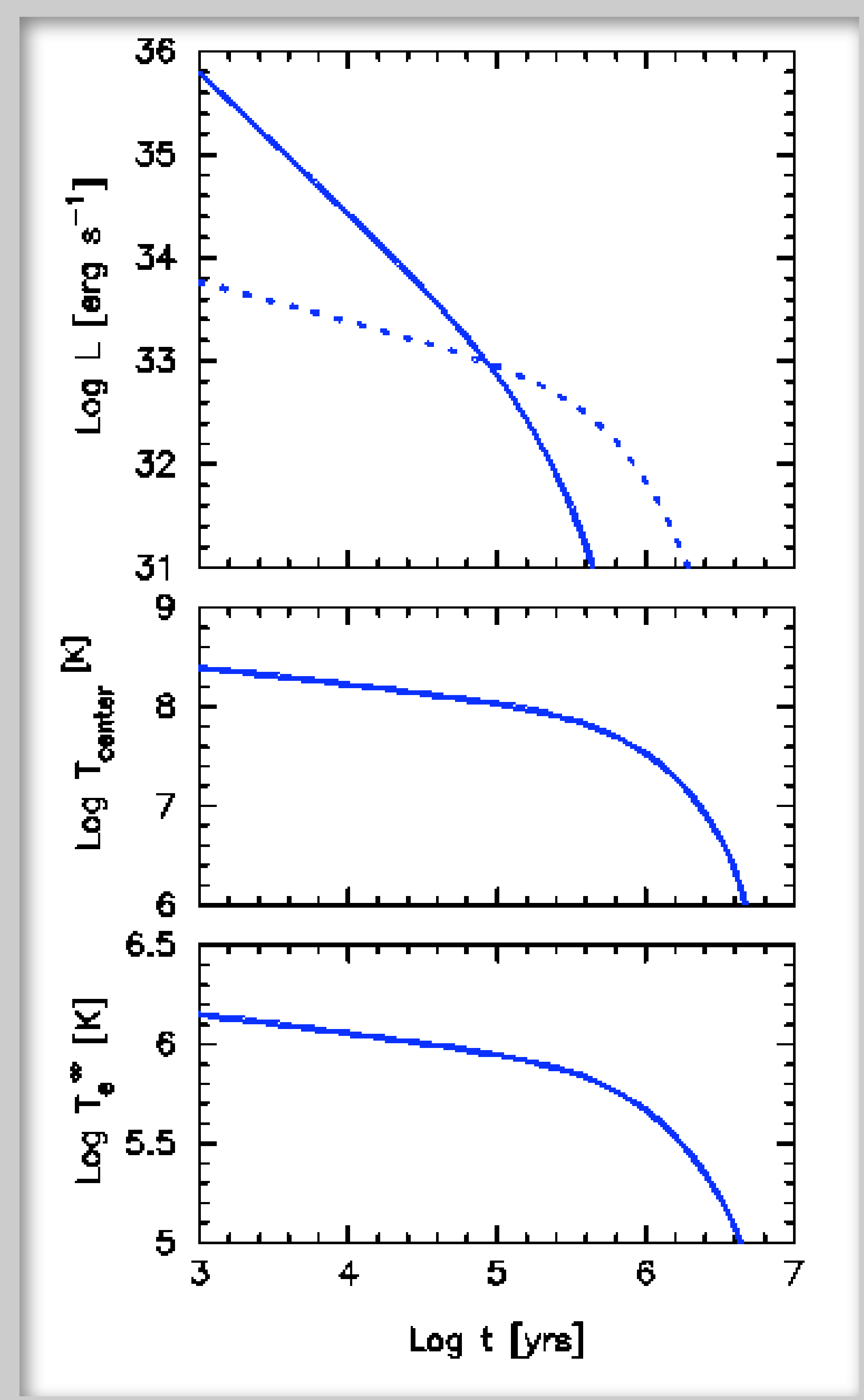
$$\frac{dT}{dt} = -\frac{N}{C} T^7 \Rightarrow t - t_0 = \frac{C}{6N}\left[\frac{1}{T^6} - \frac{1}{T_0^6}\right]$$

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

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

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

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



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)

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

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

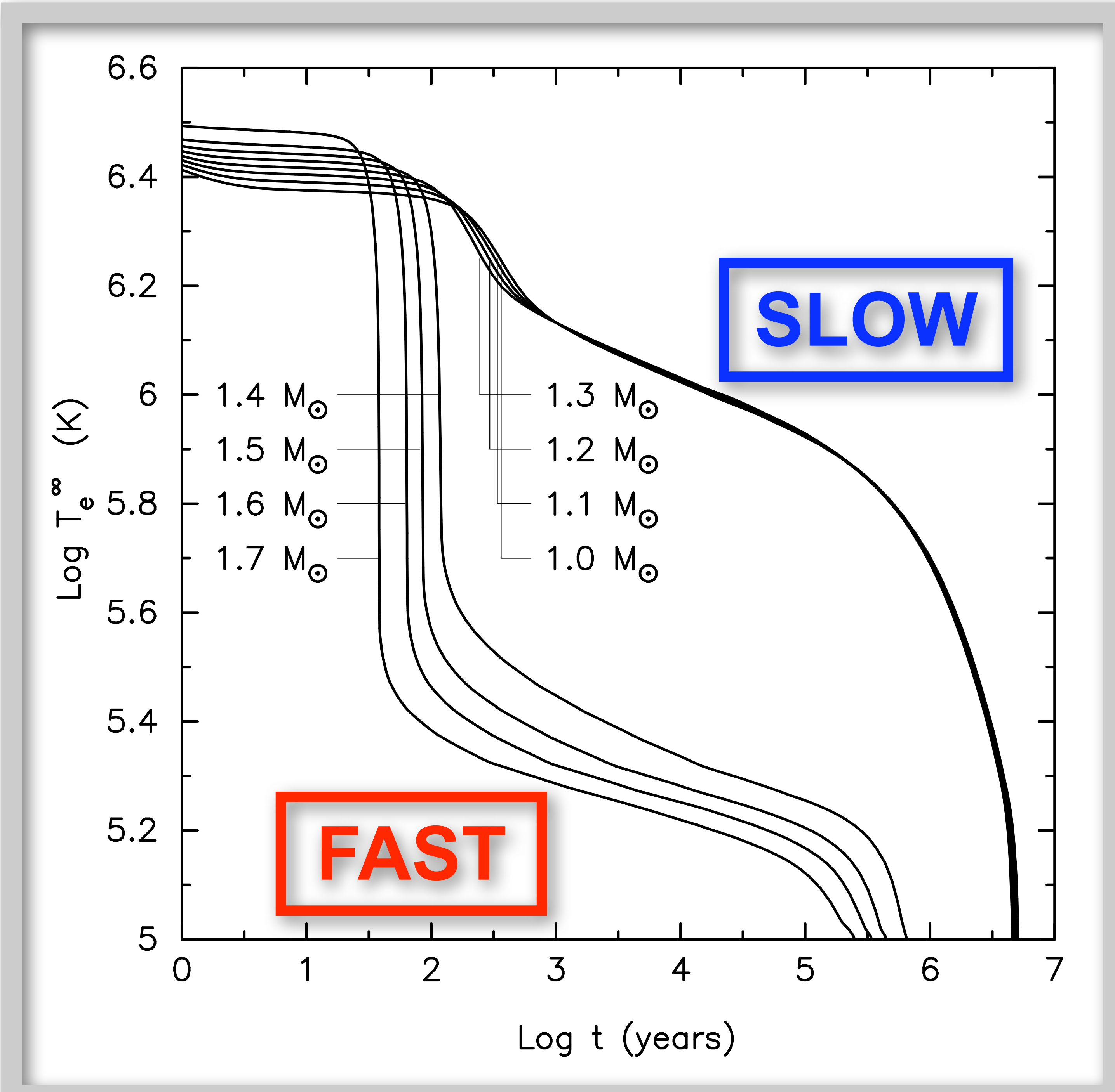
- **Fast neutrino cooling:** $L_\nu^{\text{sfast}} = \iiint \epsilon_\nu^{\text{sfast}} dV = 10^{44} - 10^{45} \times T_9^6 \ \text{erg s}^{-1} \equiv N_9^{\text{fast}} T_9^6$

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

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

MUrca vs DUrca

Direct vs modified Urca cooling

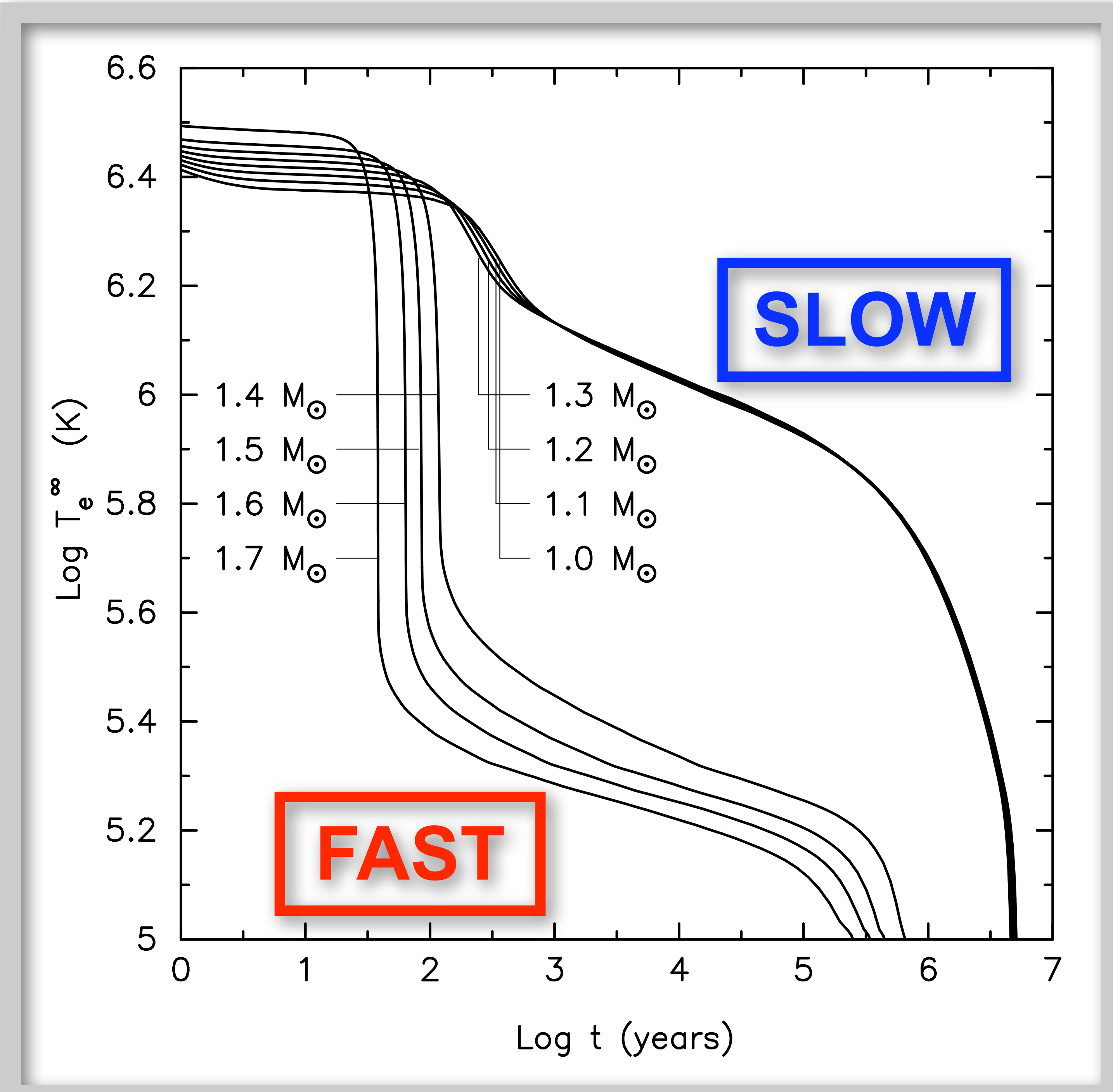


Models based on the PAL EOS:

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

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

Direct vs modified Urca cooling



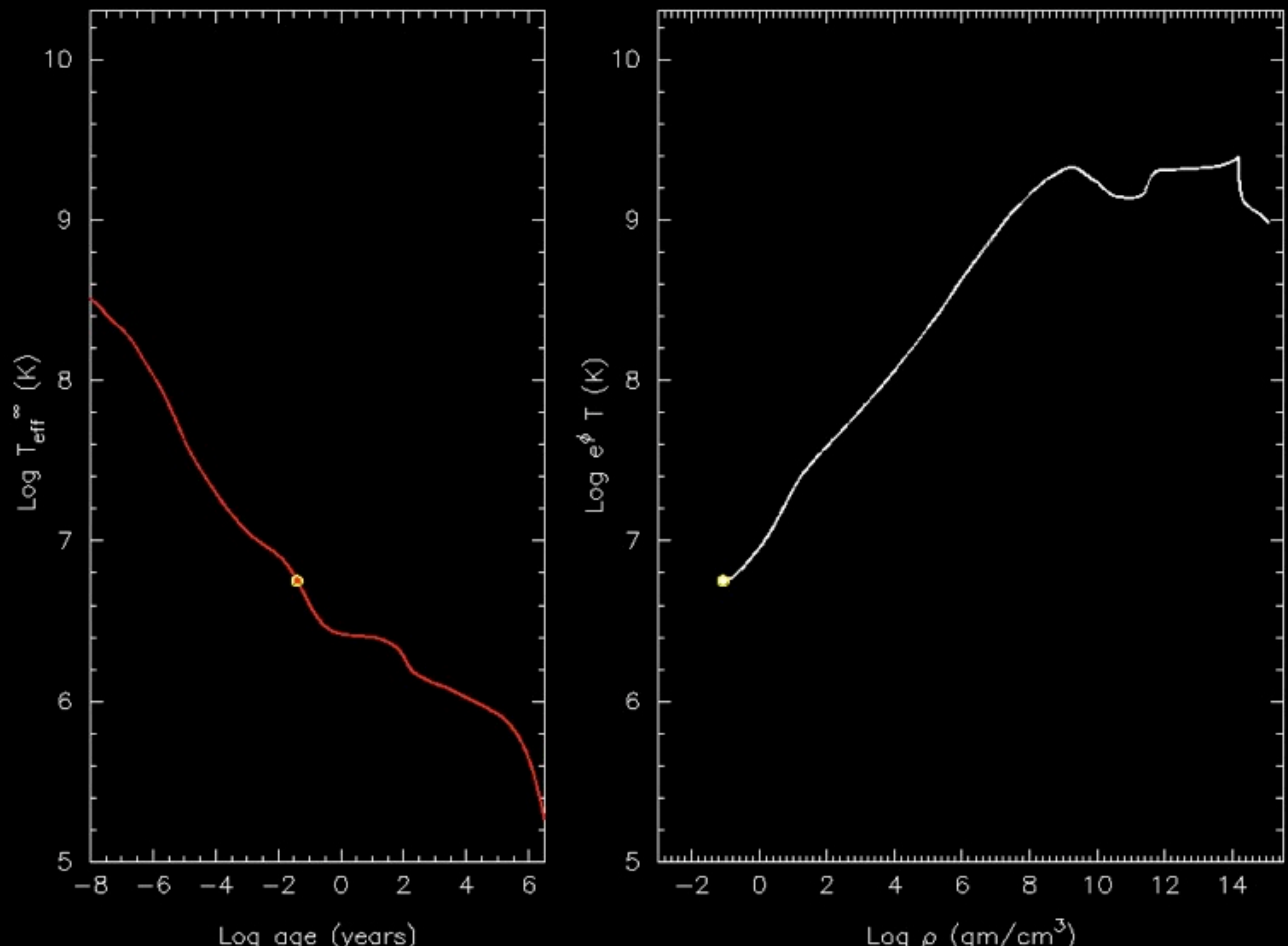
Models based on the PAL EOS:

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

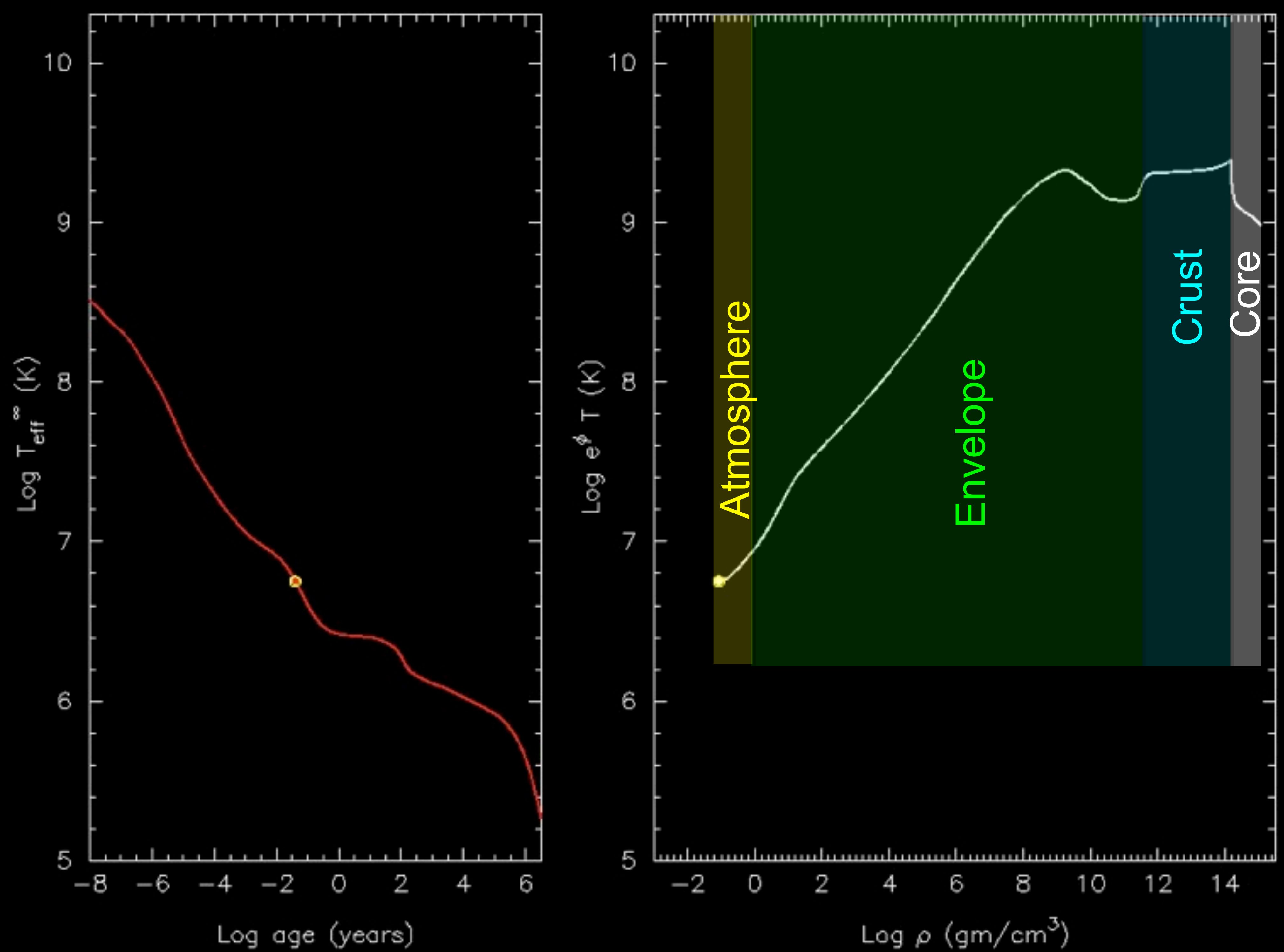
This value is arbitrary:
we DO NOT know the value of this critical mass, and hopefully observations will, some day, tell us what it is !

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

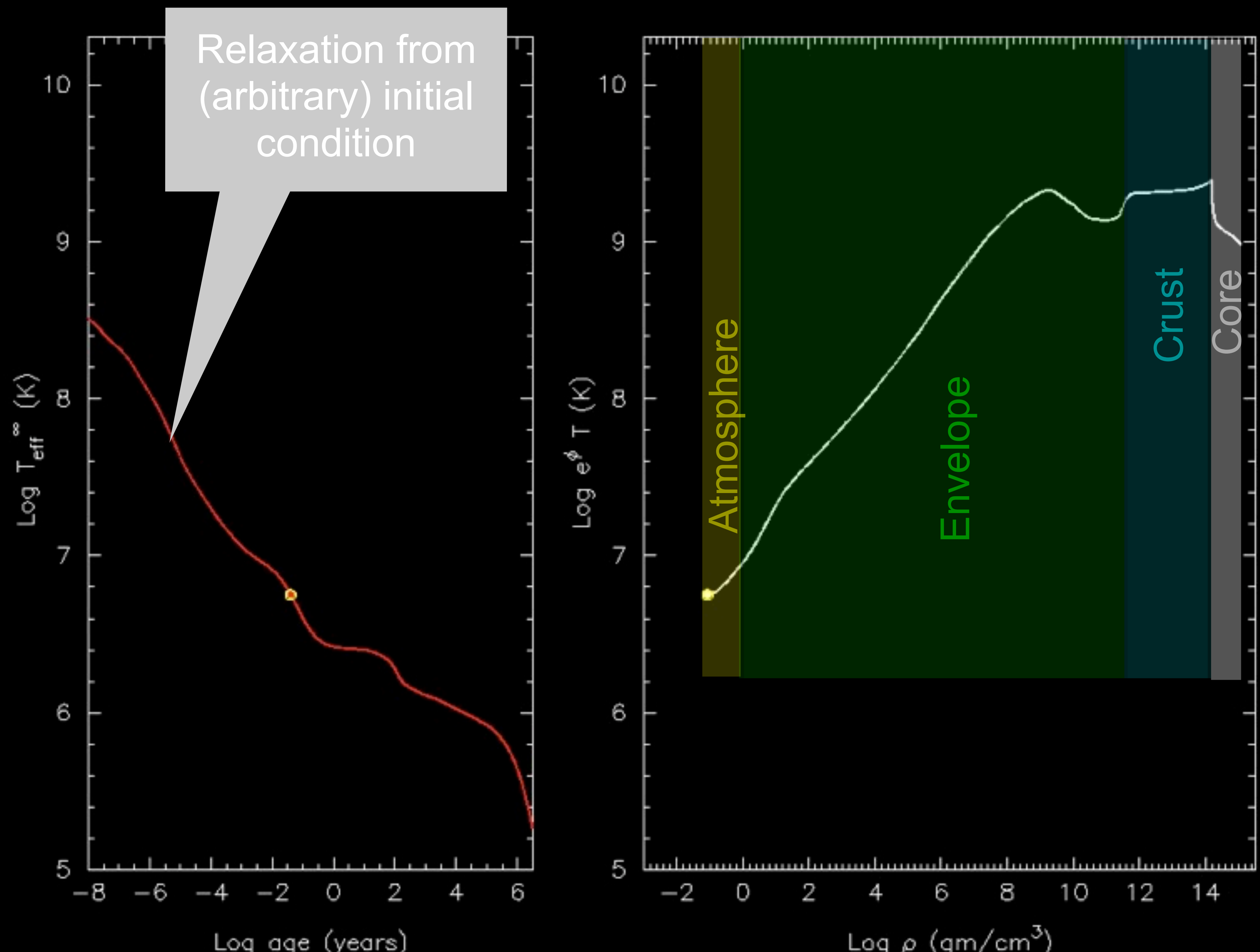
Standard cooling of a 1.3 M⊙ neutron star



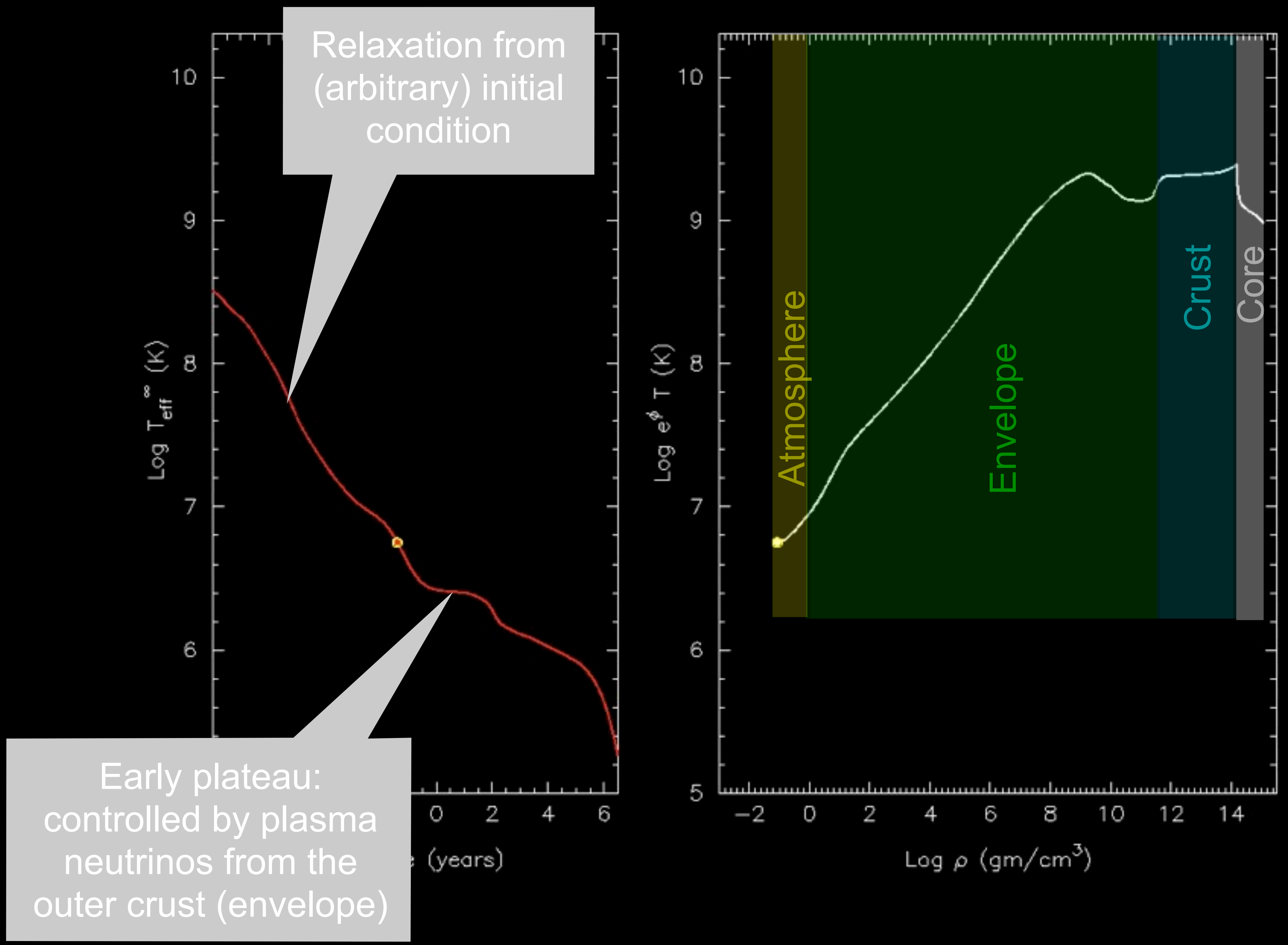
Standard cooling of a 1.3 M⊙ neutron star



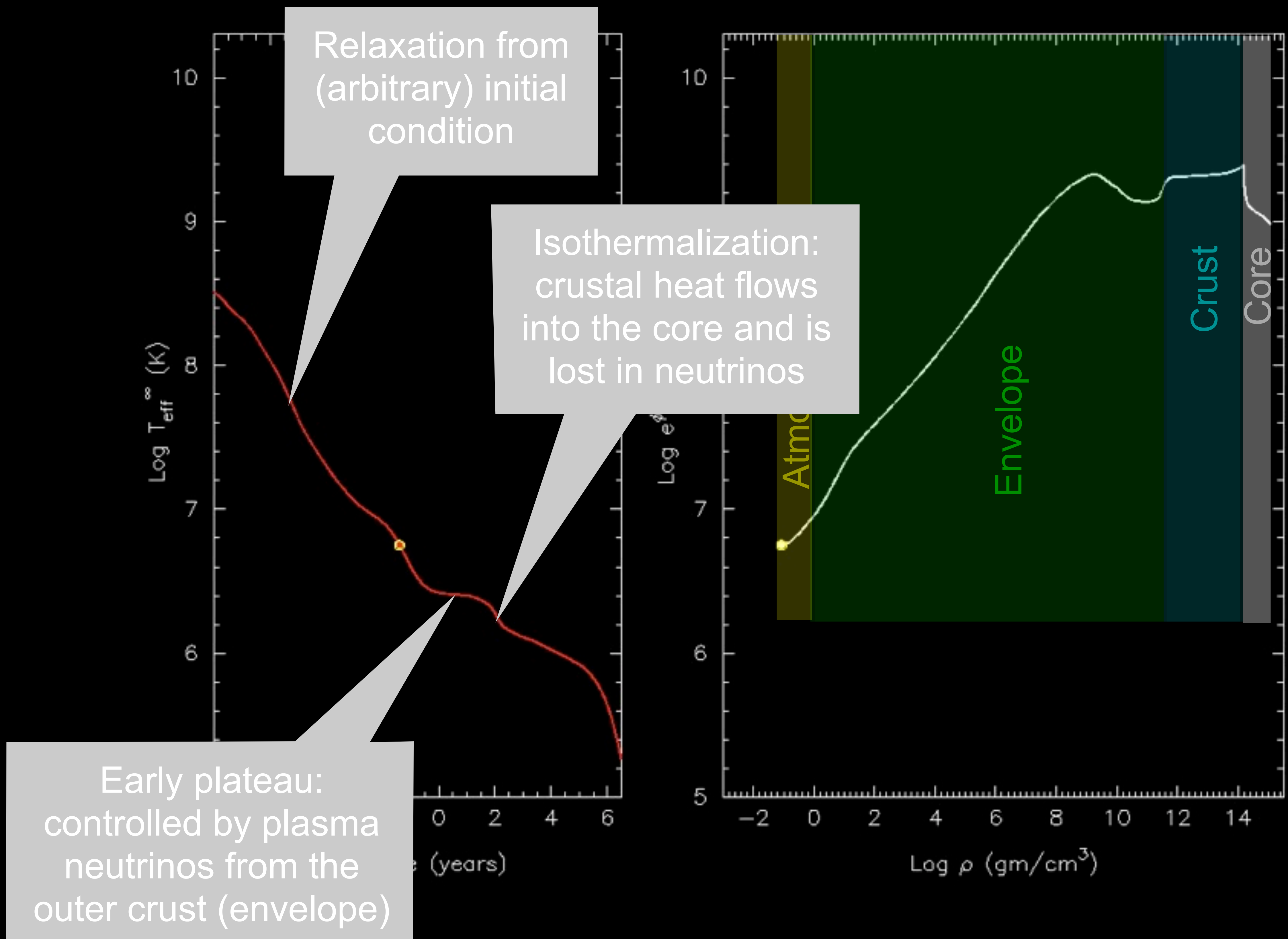
Standard cooling of a 1.3 M⊙ neutron star



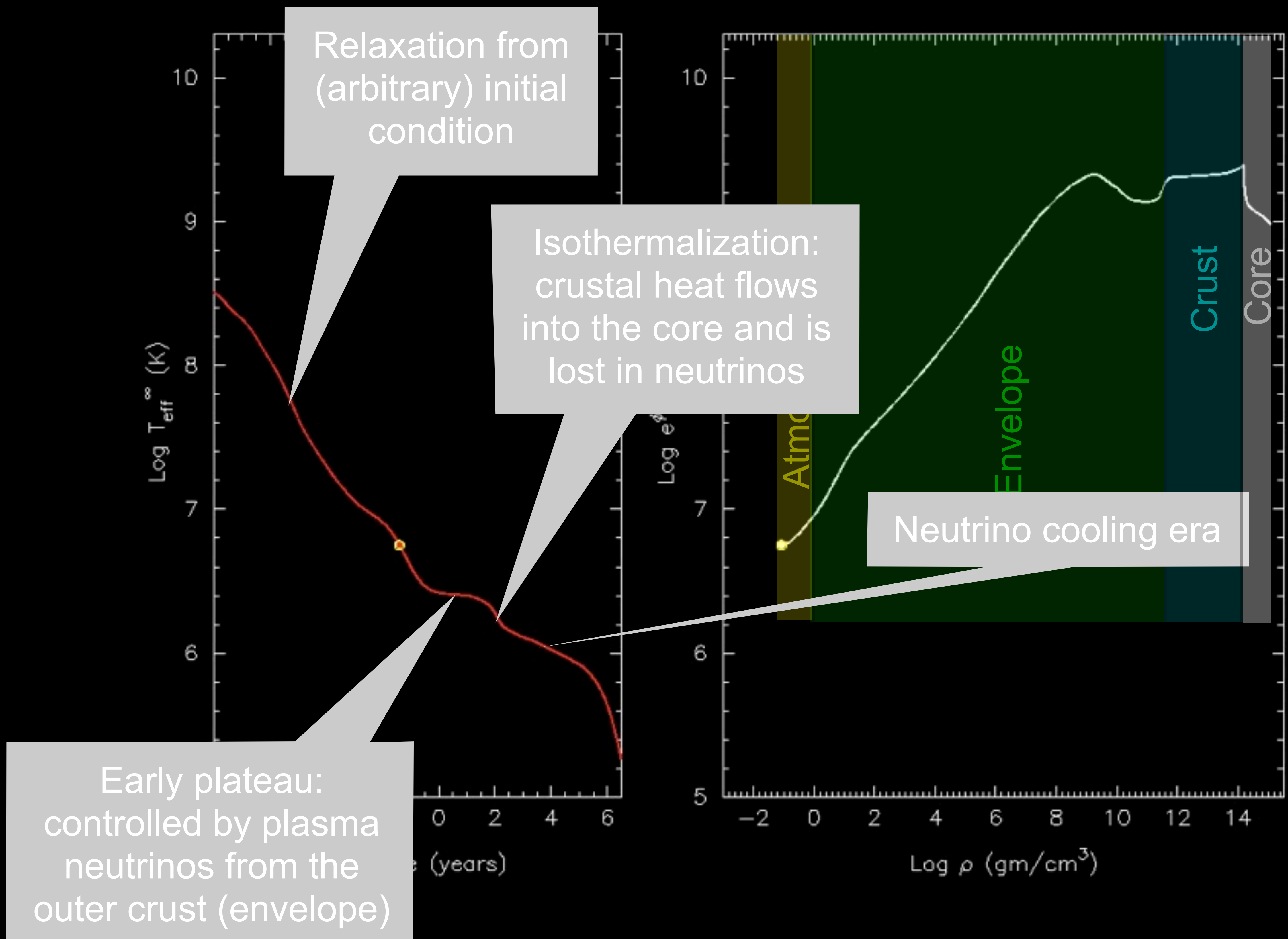
Standard cooling of a 1.3 M⊙ neutron star



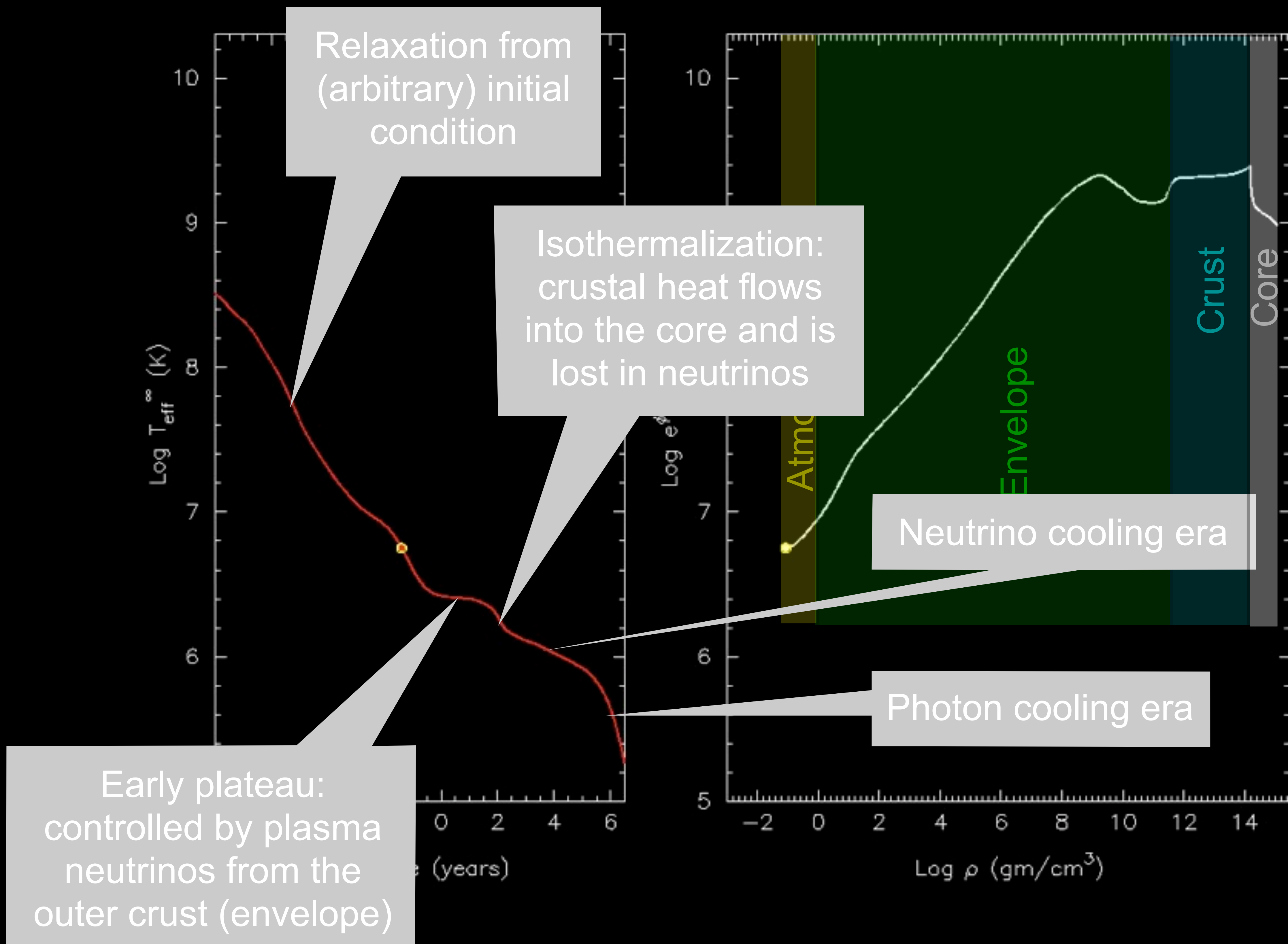
Standard cooling of a 1.3 M⊙ neutron star



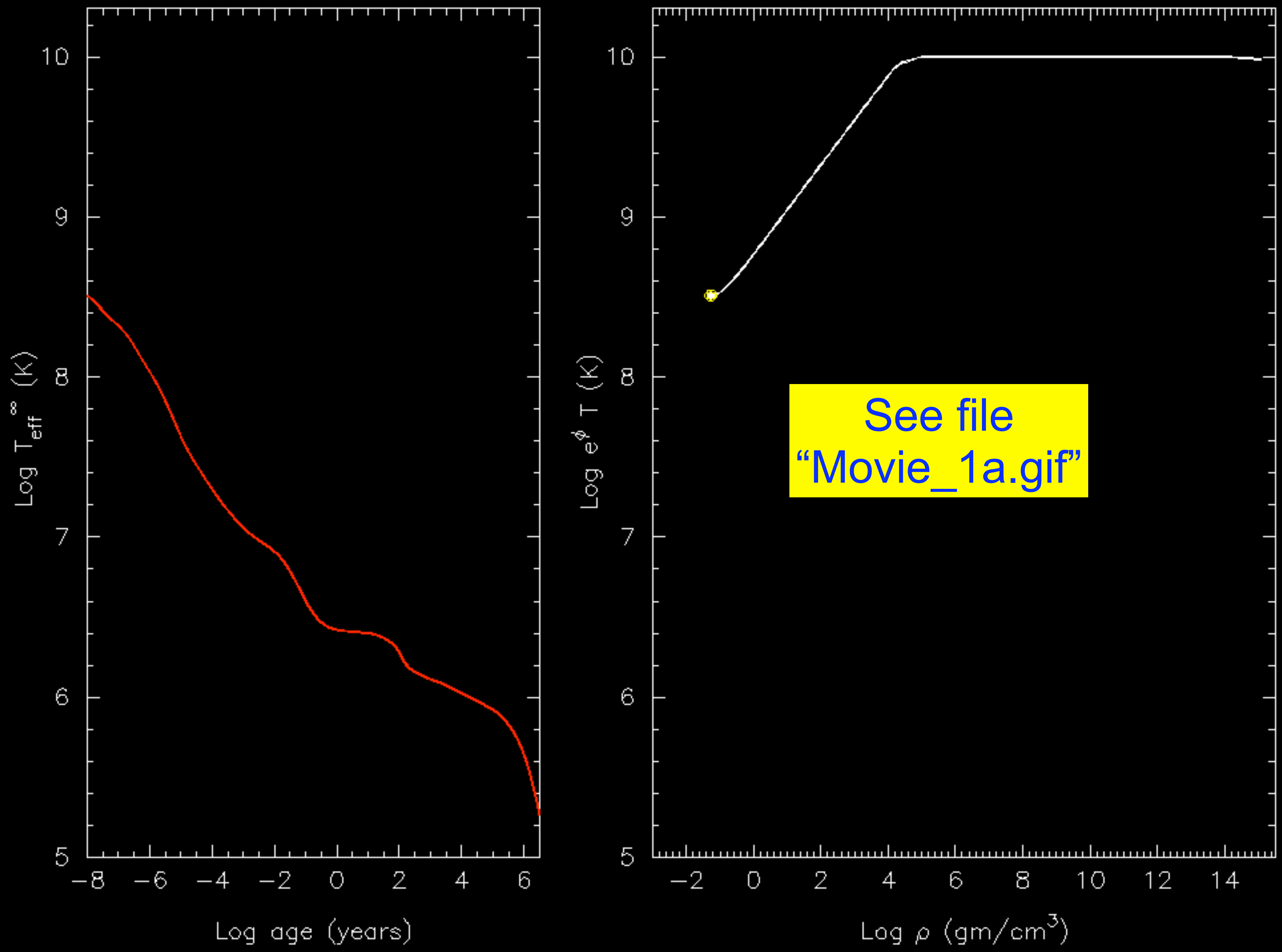
Standard cooling of a 1.3 M⊙ neutron star



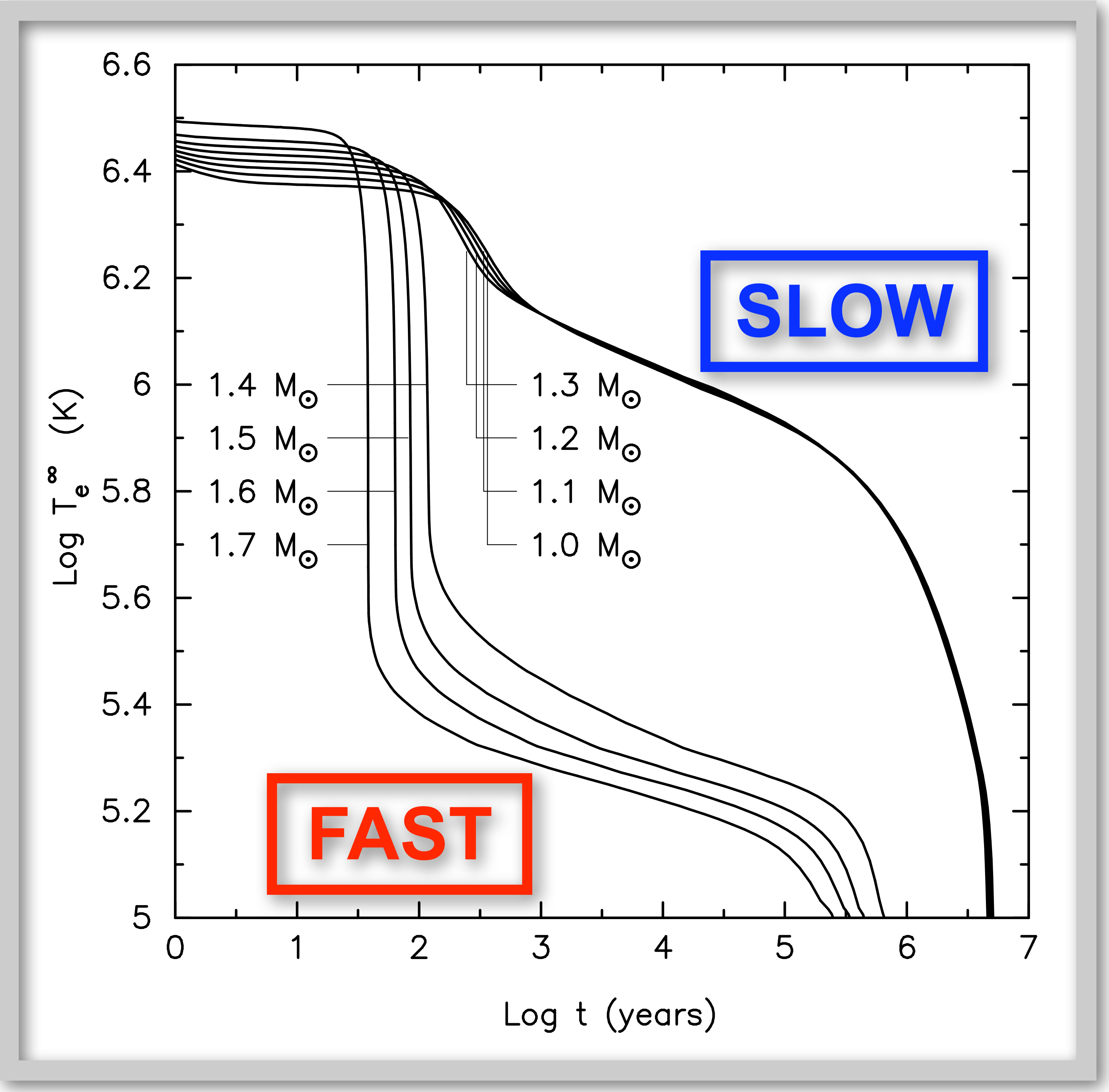
Standard cooling of a 1.3 M⊙ neutron star



Standard cooling of a 1.3 M⊙ neutron star



Direct vs modified Urca cooling



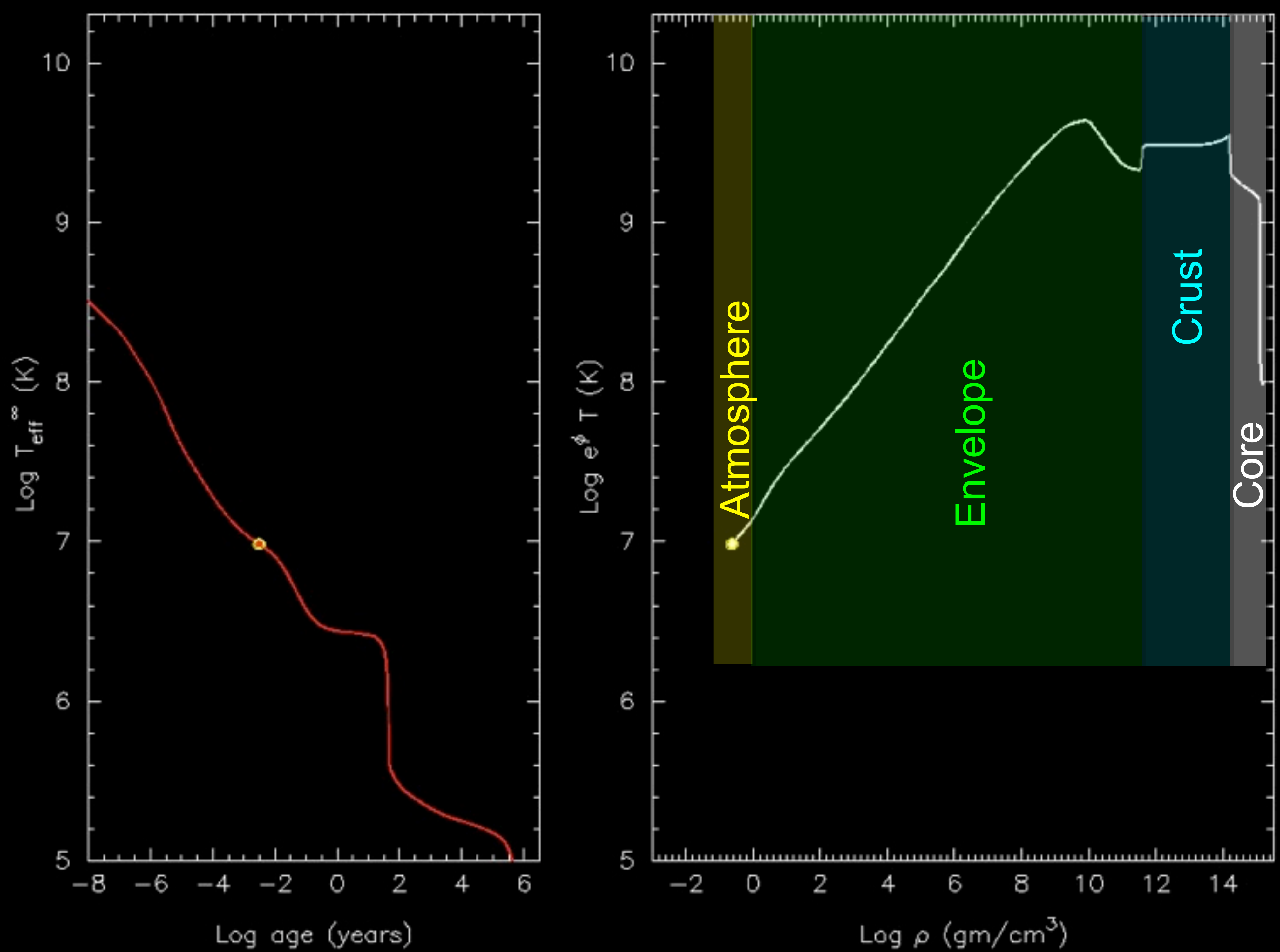
Models based on the PAL EOS:

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

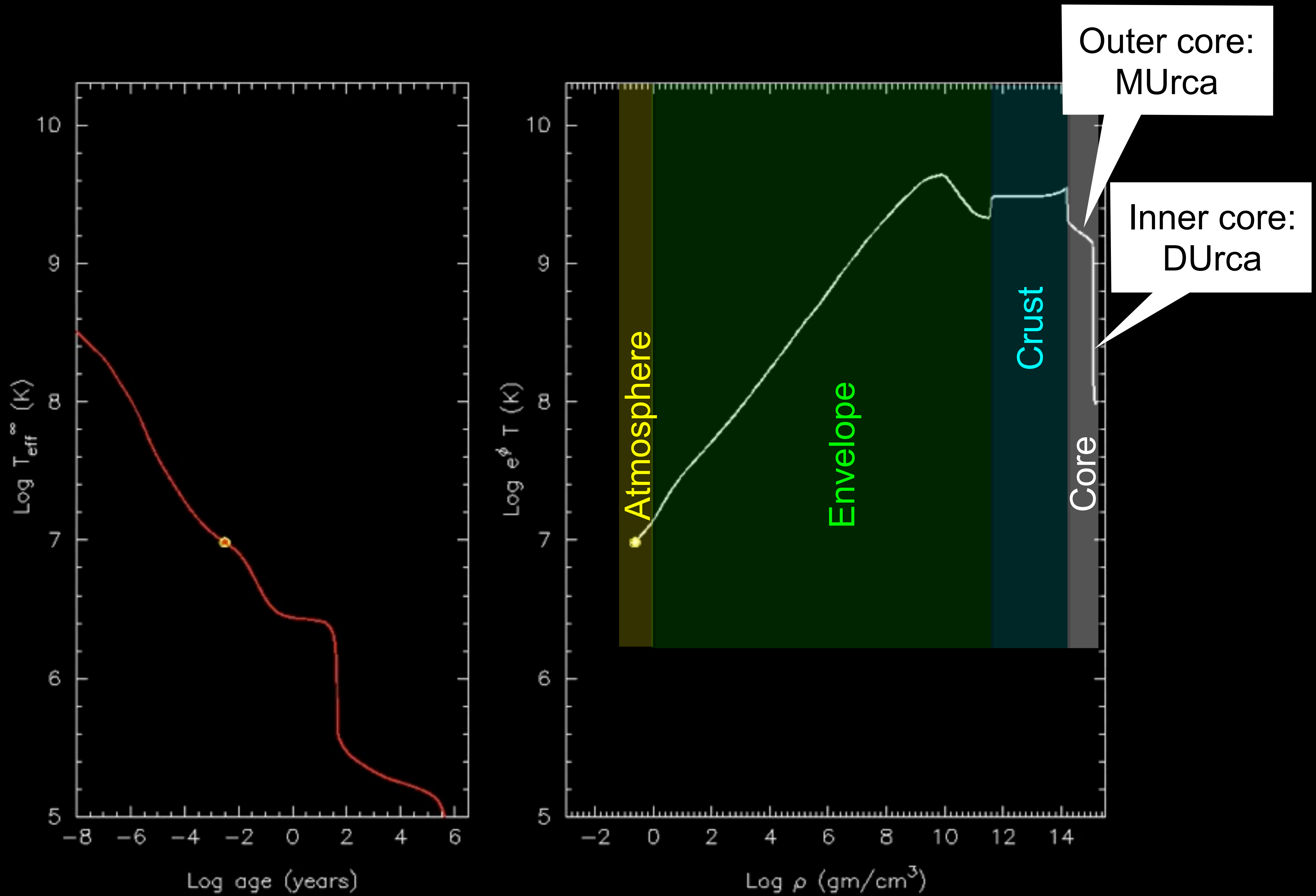
This value is arbitrary:
we DO NOT know the value of this critical mass, and hopefully observations will, some day, tell us what it is !

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

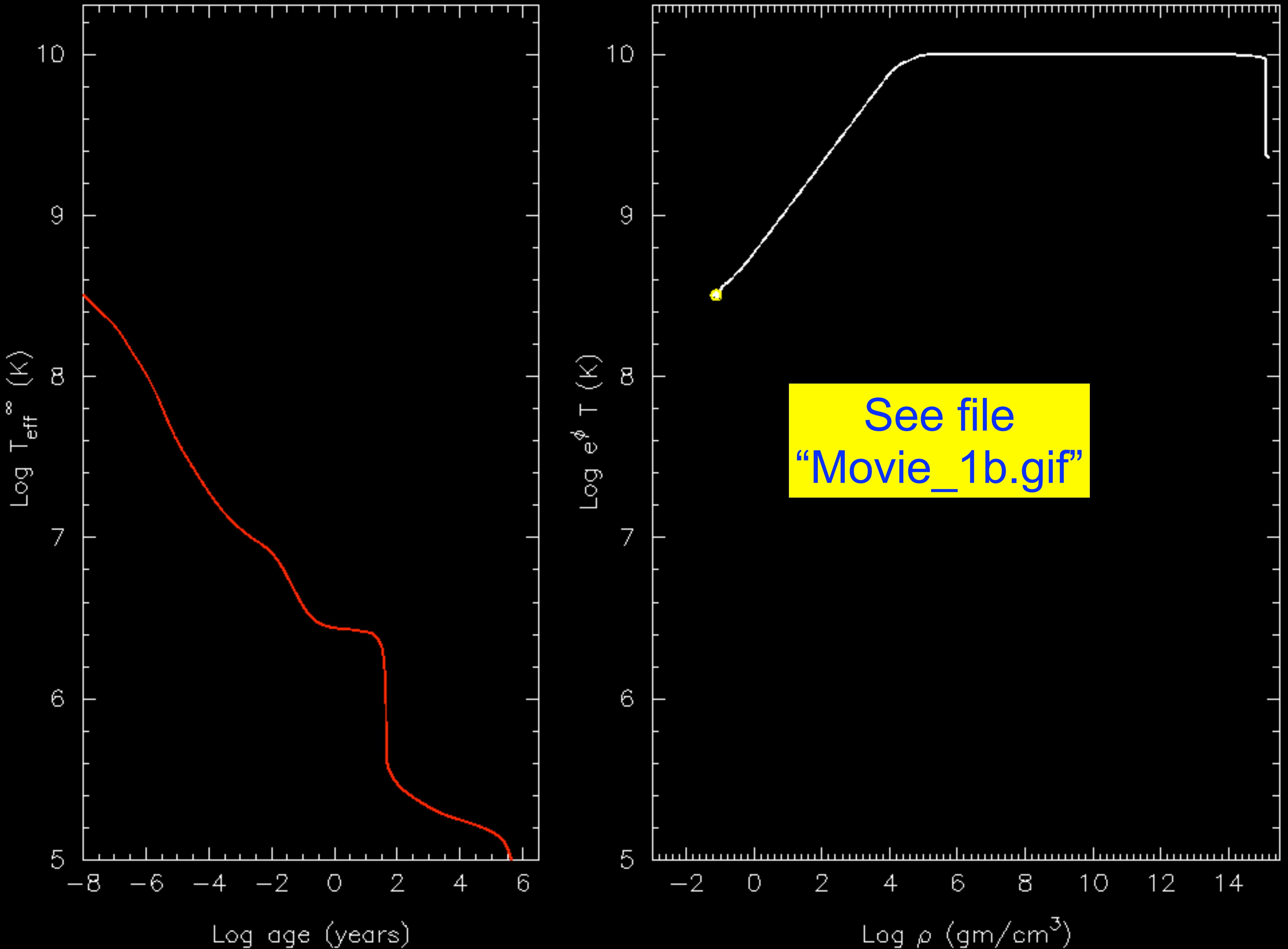
Enhanced cooling of a 1.5 M⊙ neutron star



Enhanced cooling of a 1.5 M⊙ neutron star



Enhanced cooling of a 1.5 M⊙ neutron star



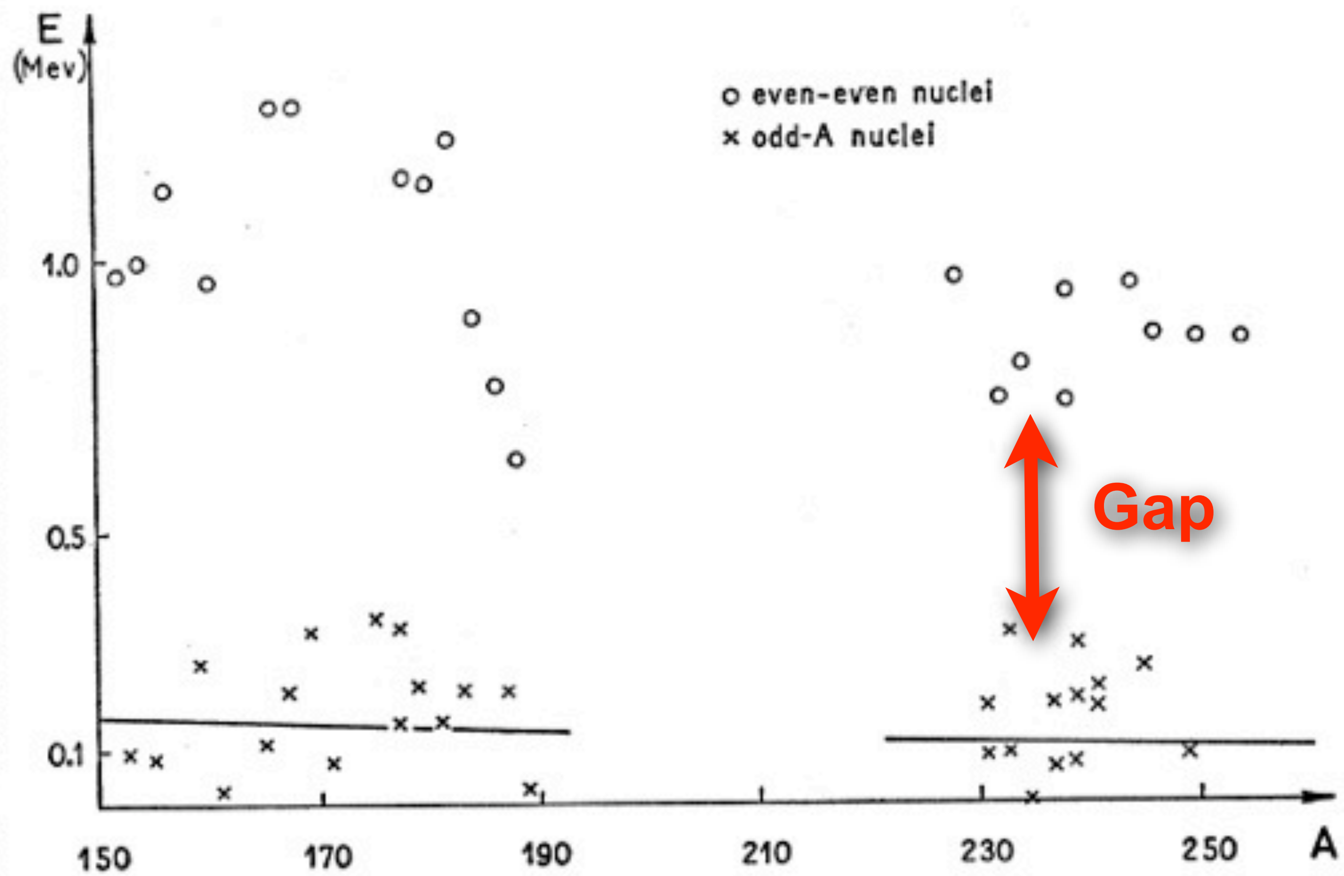
Pairing

Nucleon pairing

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

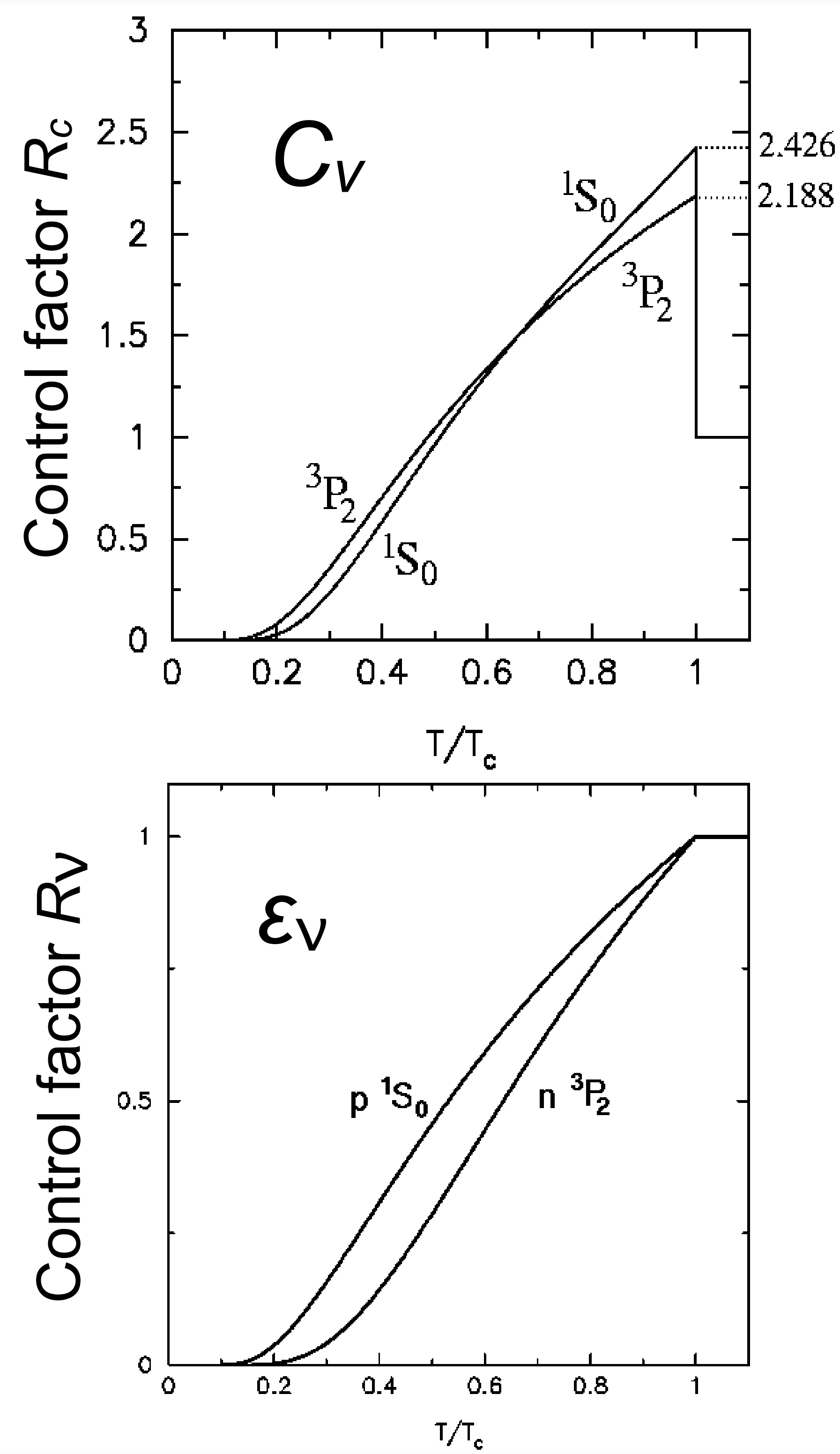
The presence of a pairing gap in the single particple excitation spectrum results in a Boltzmann-like

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

suppression of c_v and ε_ν:

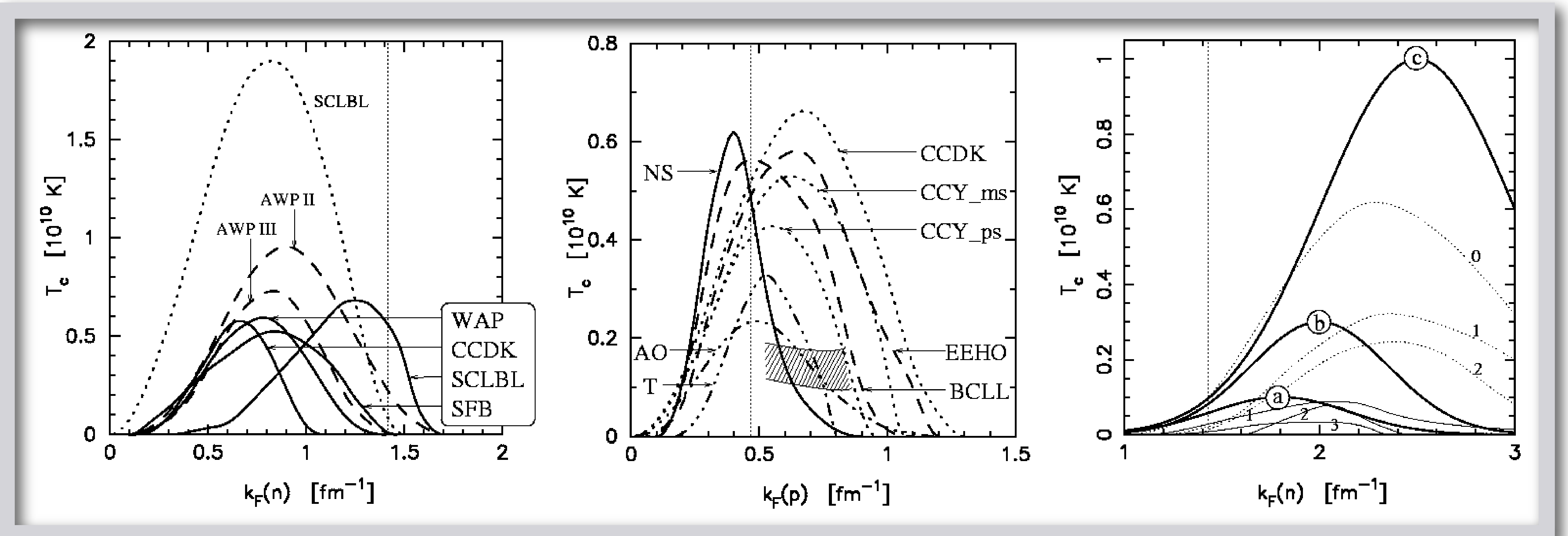
$$c_v \to c_v^{\text{Paired}} = R_c c_v^{\text{Normal}}$$

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



Pairing T_c models

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



Size and extent of pairing gaps is highly uncertain

Slow vs fast cooling with pairing

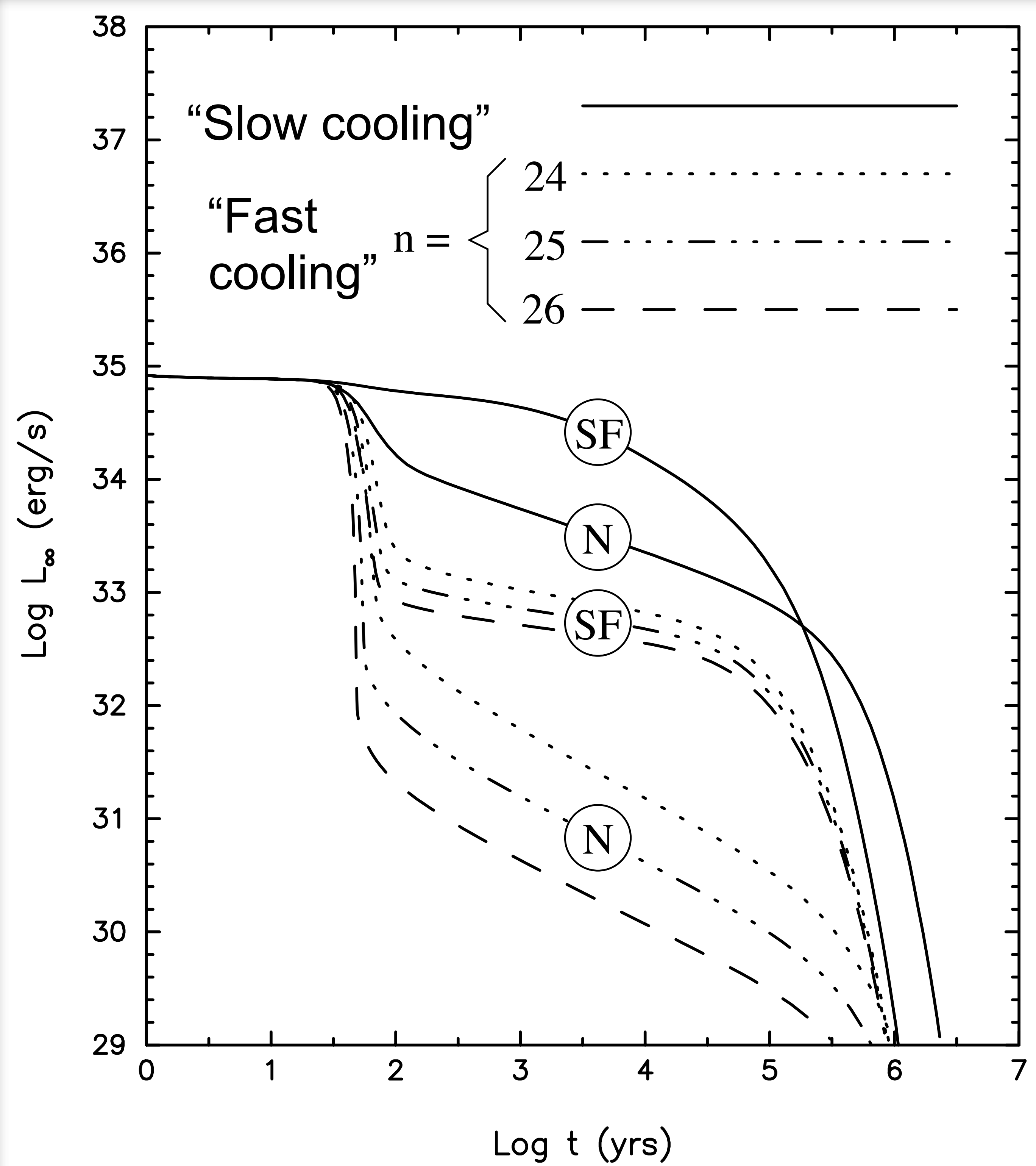
Slow neutrino emission
(modified URCA process)

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

Fast neutrino emission
(almost anything else)

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

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



Slow vs fast cooling with pairing

Slow neutrino emission
(modified URCA process)

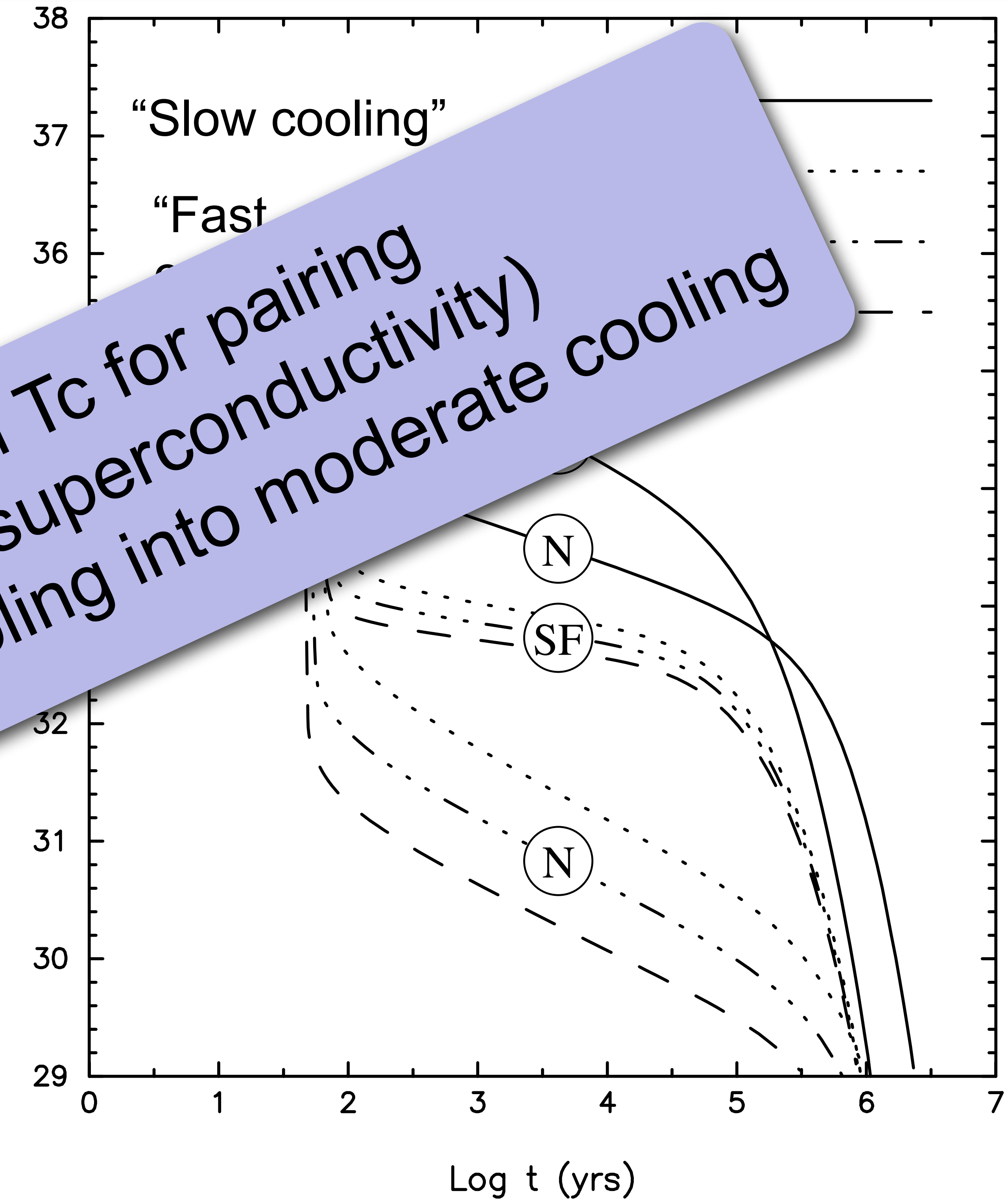
$$\epsilon_\nu^{\rm slow} \sim 10^{21}\ T_9^8\ \ {\rm erg\ cm^{-3}\ s^{-1}}$$

Fast neutrino emission
(almost anything else)

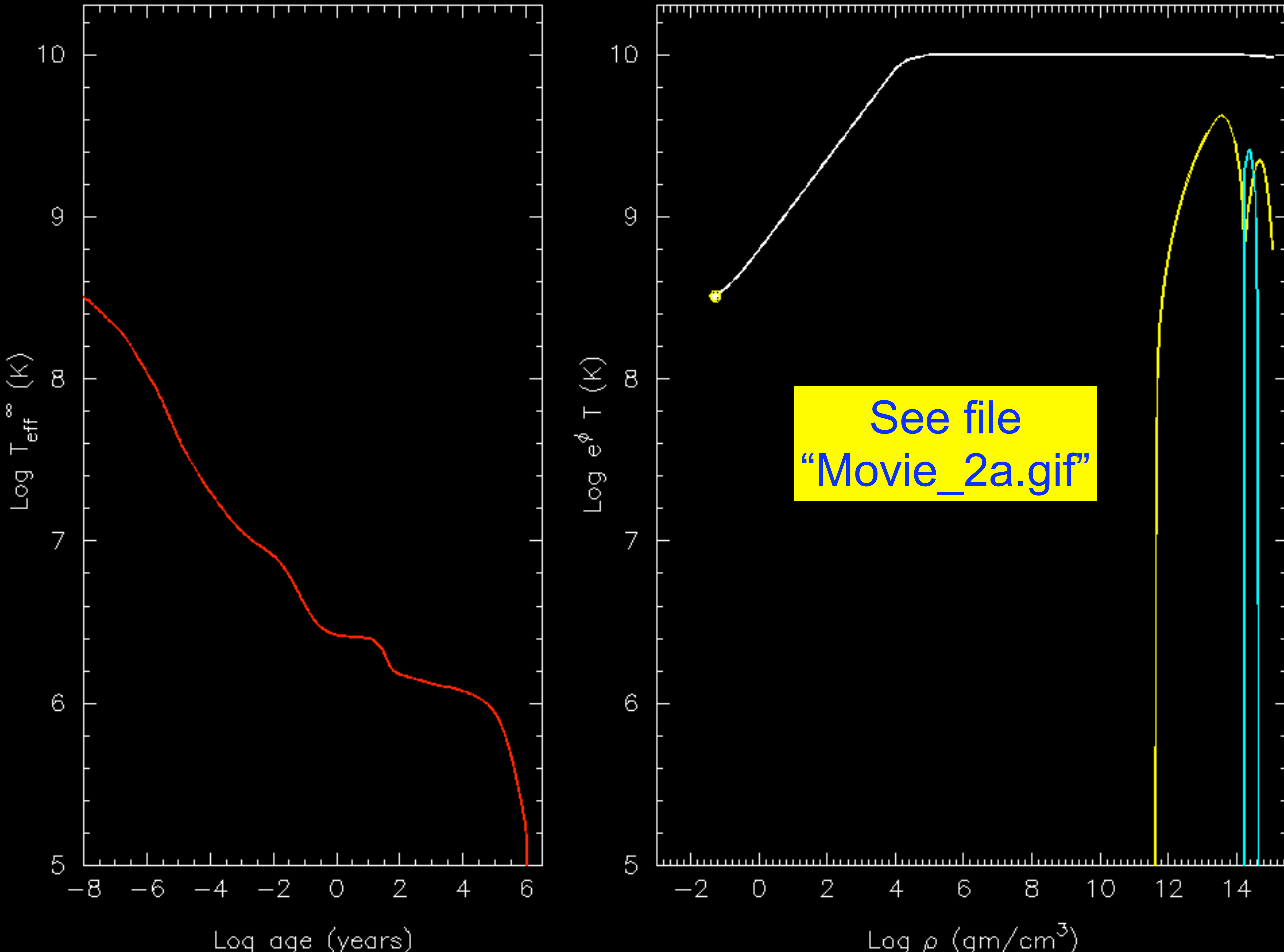
$$\epsilon_\nu^{\rm fast} \sim 10^{n}\ T_9^6\ \ {\rm erg}$$ …

- n = 2… …sate
- n = 25… …ndensate
- n = 26 … Direct Urca

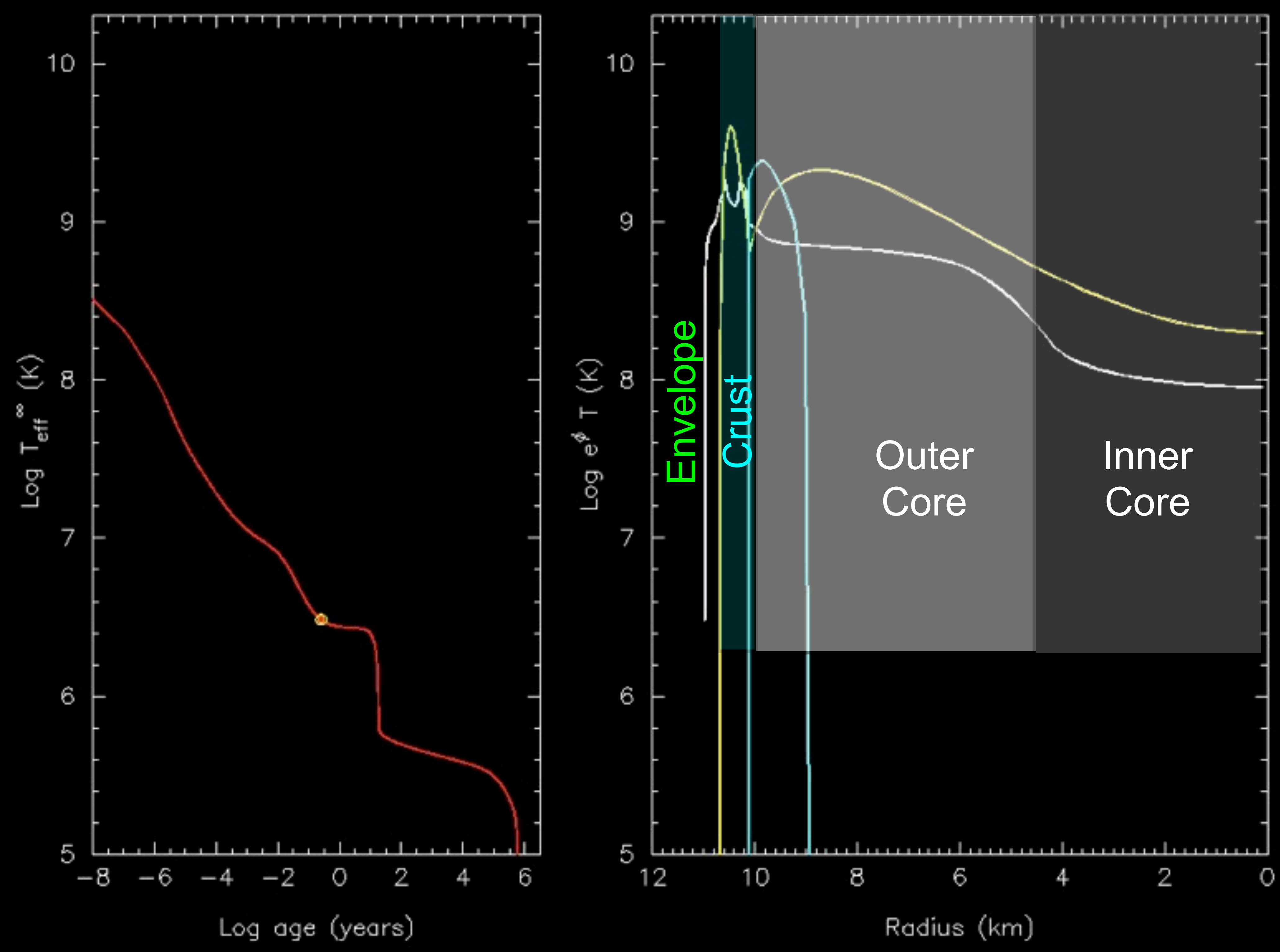
A large enough Tc for pairing
(superfluidity or superconductivity)
can transform fast cooling into moderate cooling



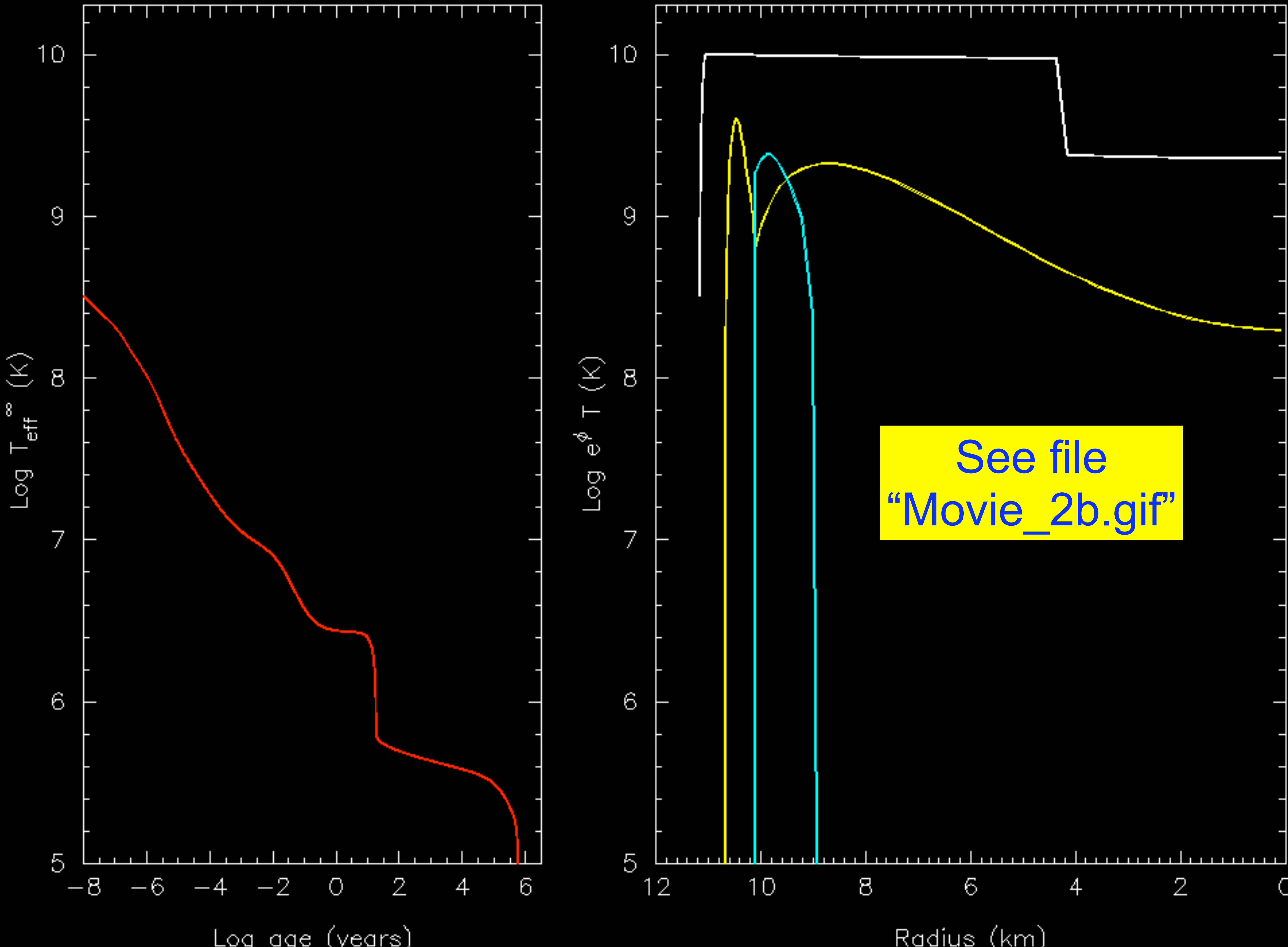
Standard cooling of a 1.3 M⊙ neutron star with pairing



Enhanced cooling of a 1.5 M⊙ neutron star with pairing



Enhanced cooling of a 1.5 M⊙ neutron star moderated pairing



Envelopes:

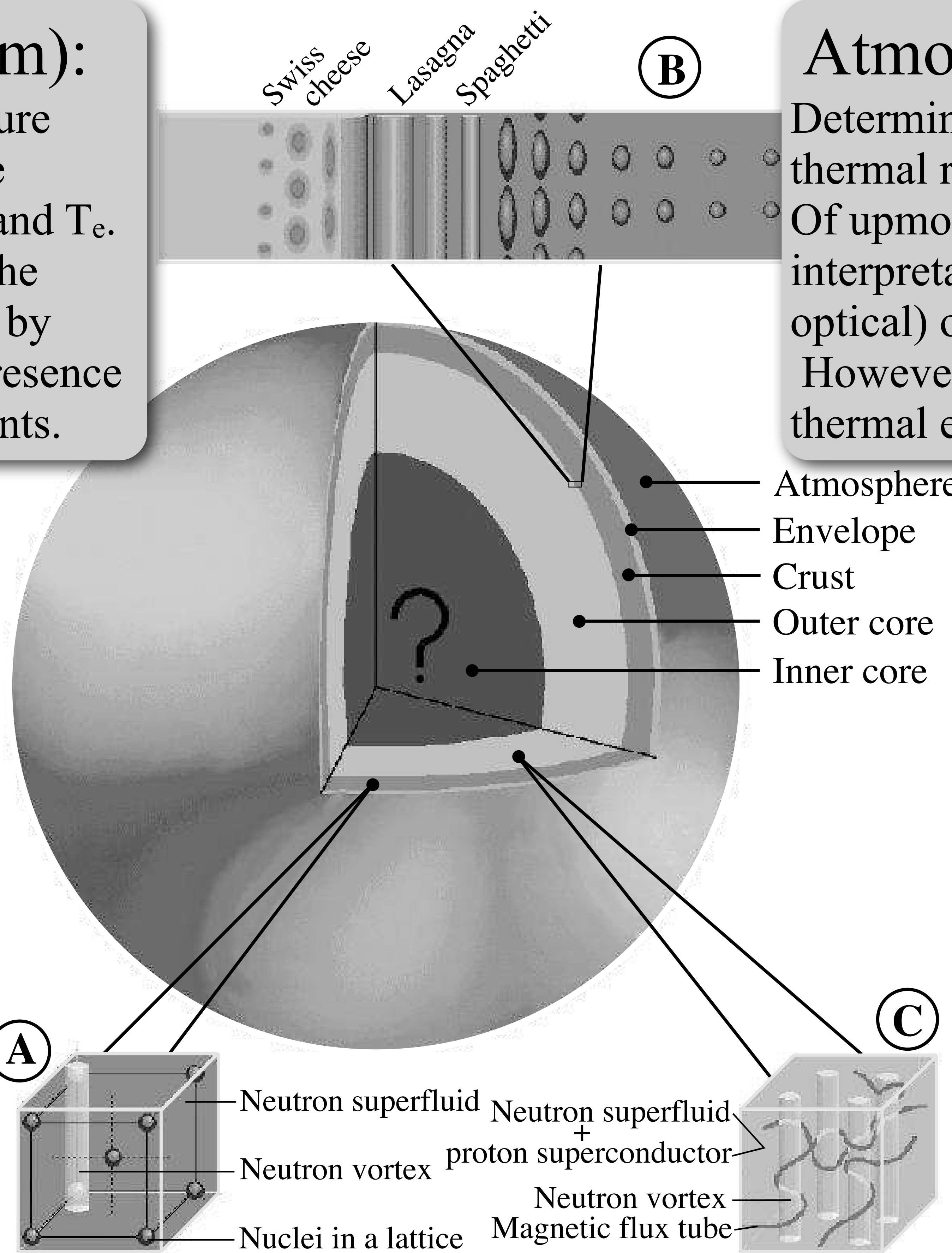
Heavy vs light elements
Magnetic fields

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.



Dense Matter in Compact Stars: Theoretical Developments and Observational Constraints, Page D. & Reddy S., 2006, Annu. Rev. Nucl. Part. Sci. 56, 327

Envelope models

GUDMUNDSSON, PETHICK, AND EPSTEIN

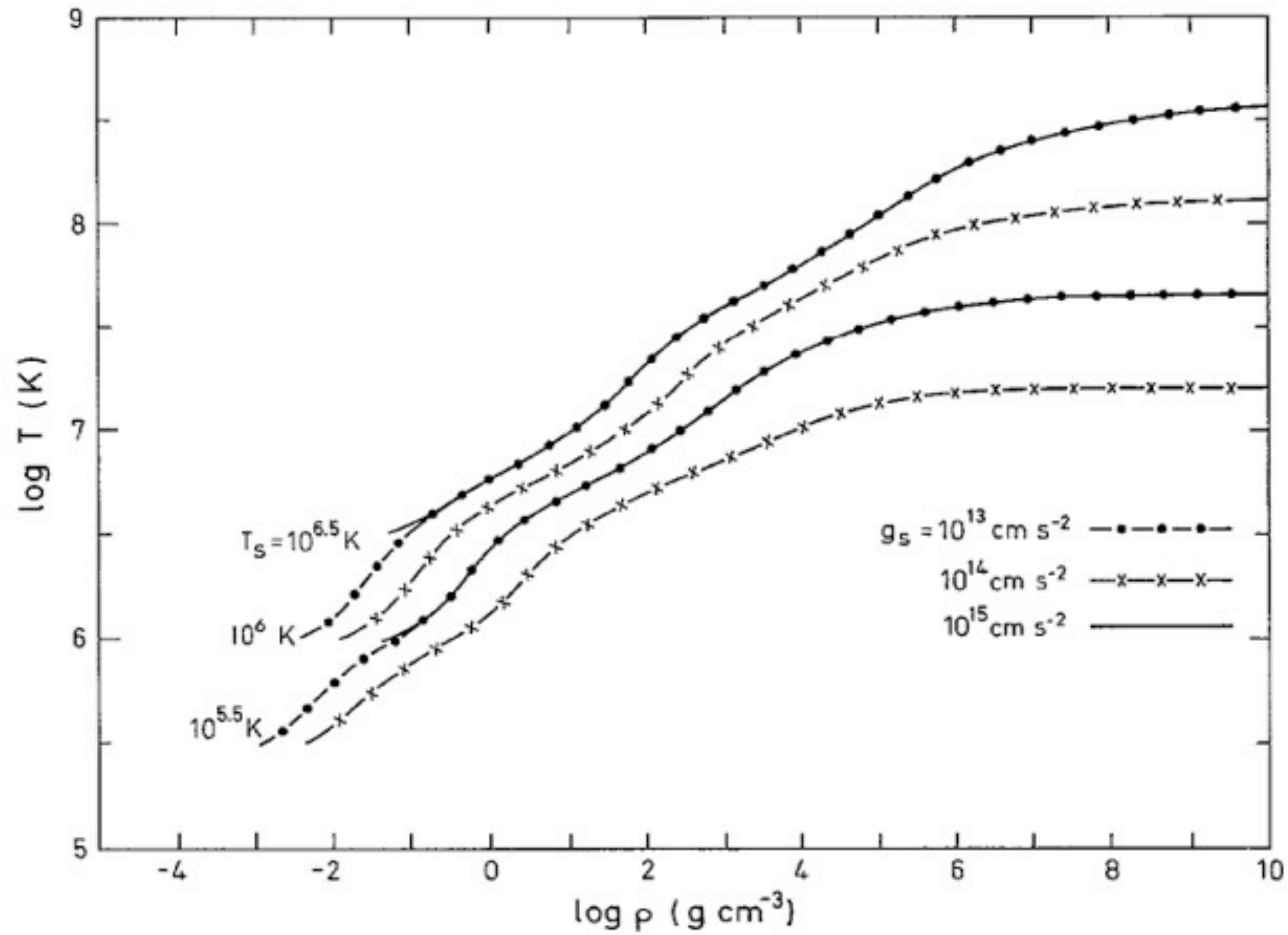
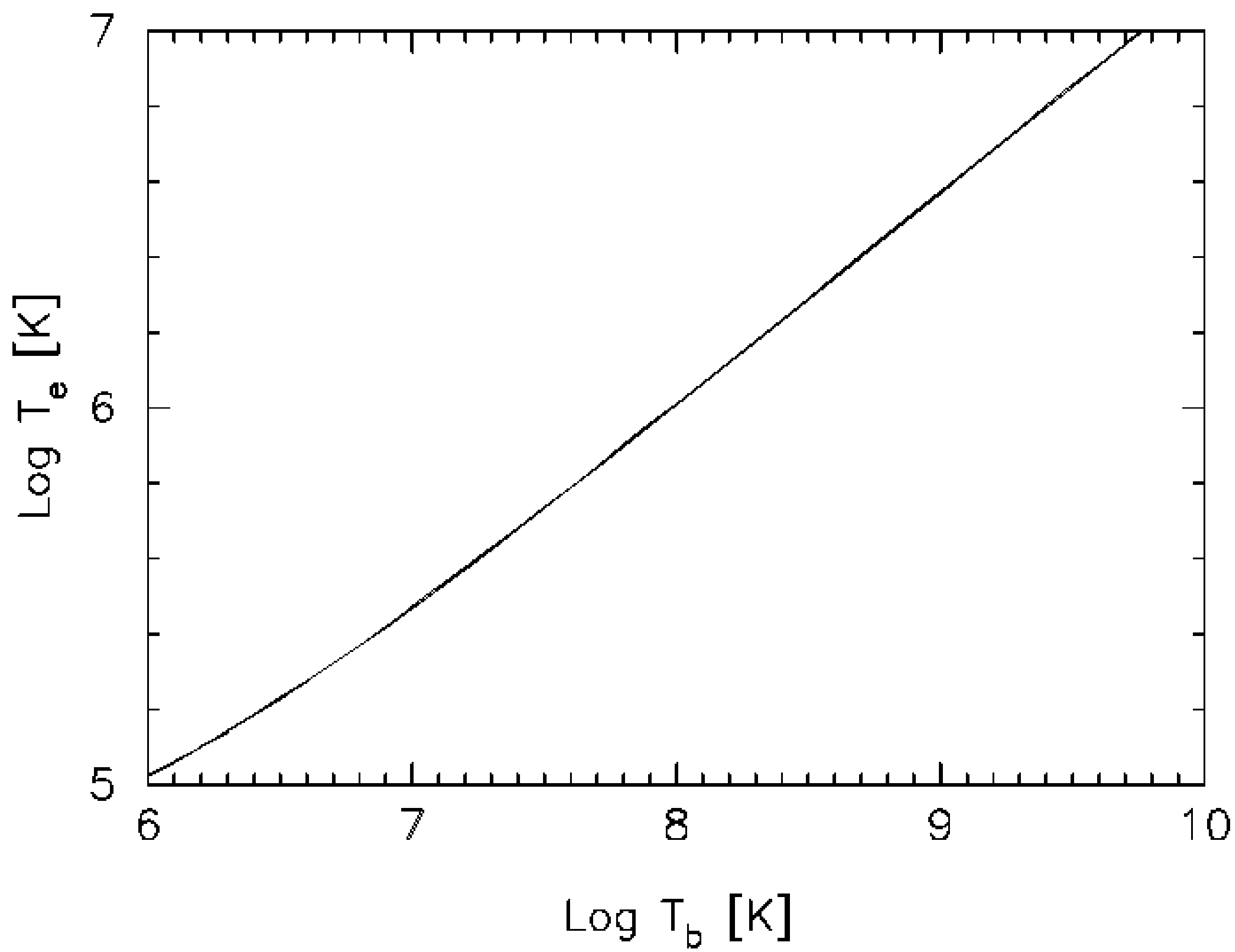


FIG. 2.—Temperature profiles for three values of the surface temperature T_s and various values of the surface gravity g_s

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

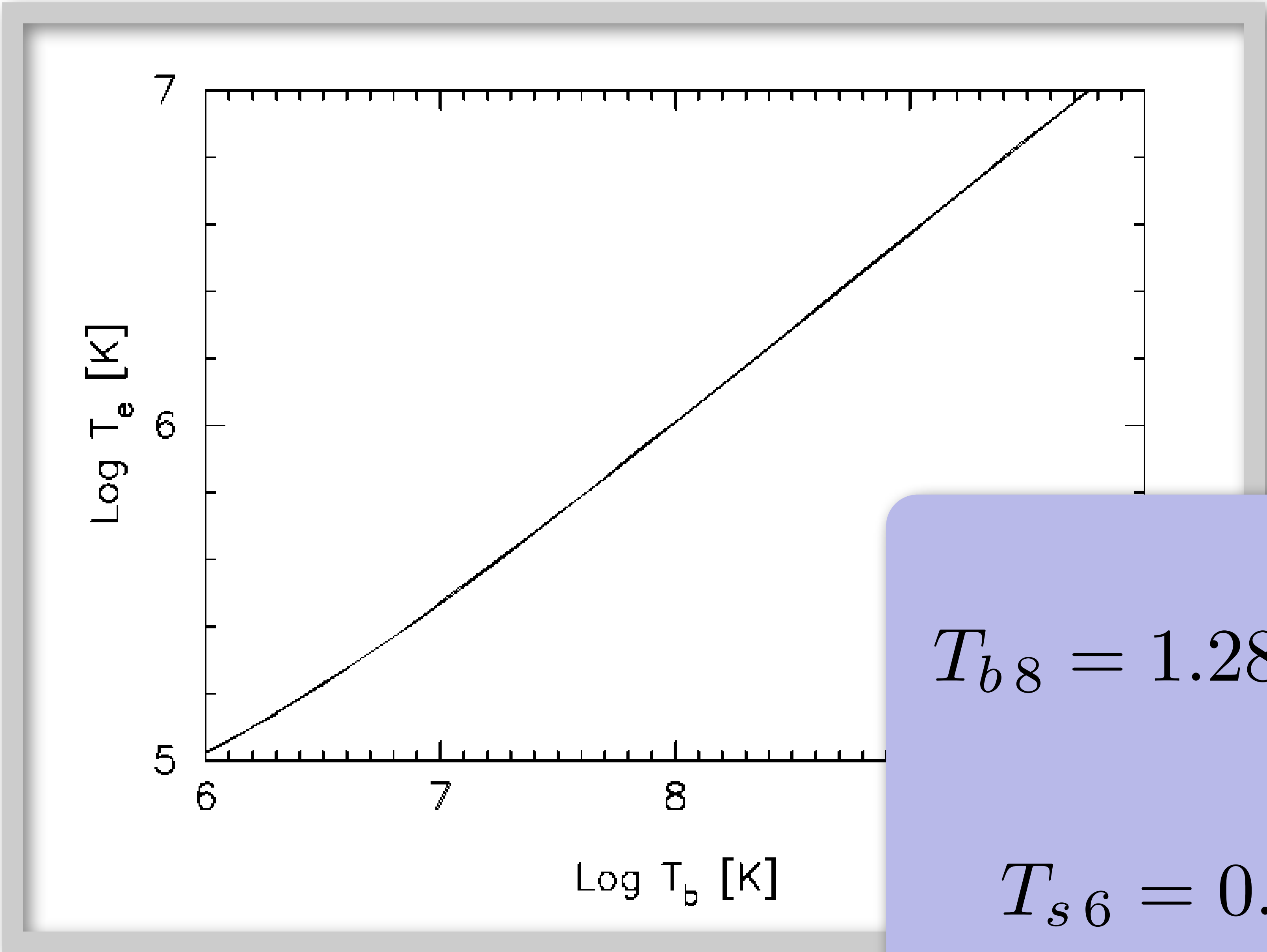
Structure of neutron star envelopes
Gudmundsson, E. H.; Pethick, C. J.; Epstein, R. I. 1983ApJ...272..286G

T_b - T_e relationship for heavy elements



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

T_b - T_e relationship for heavy elements

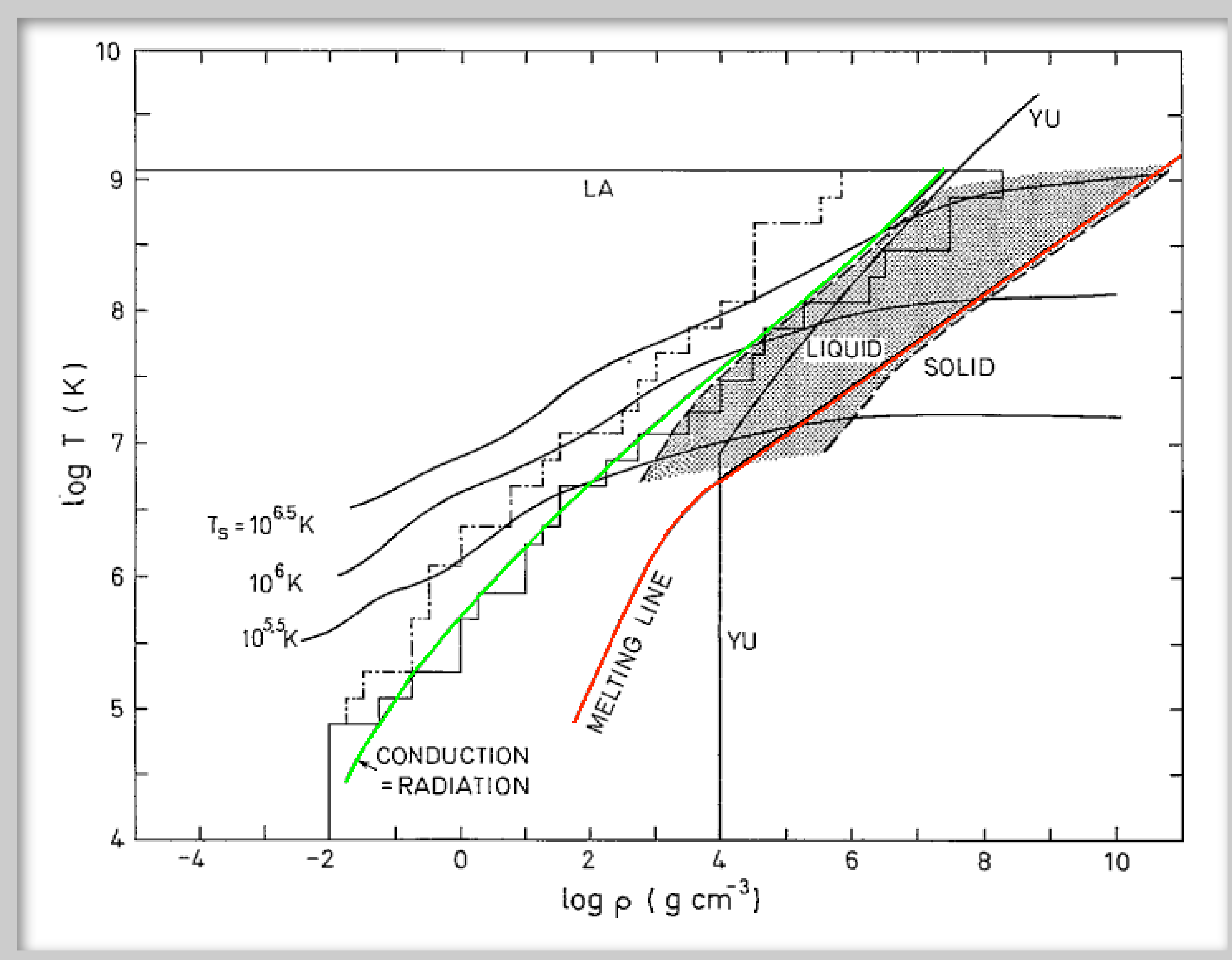


$$T_{b\,8} = 1.288 \left(\frac{T_{s\,6}^4}{g_{s\,14}} \right)^{0.455}$$

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

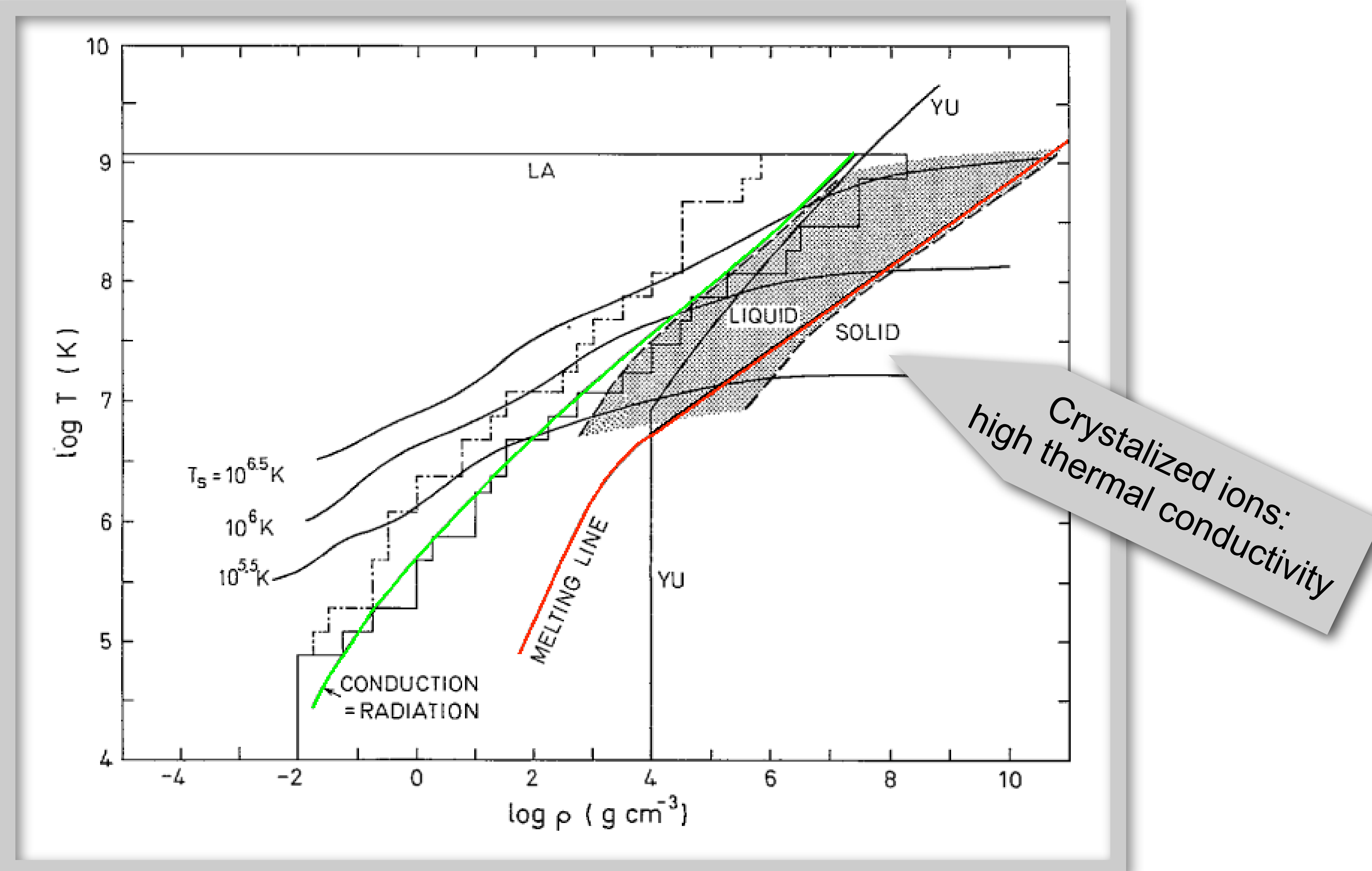
Cooling Neutron Stars with Accreted Envelopes
Chabrier, Gilles; Potekhin, Alexander Y.; Yakovlev, Dmitry G., 1997ApJ...477L..99C

The sensitivity strip



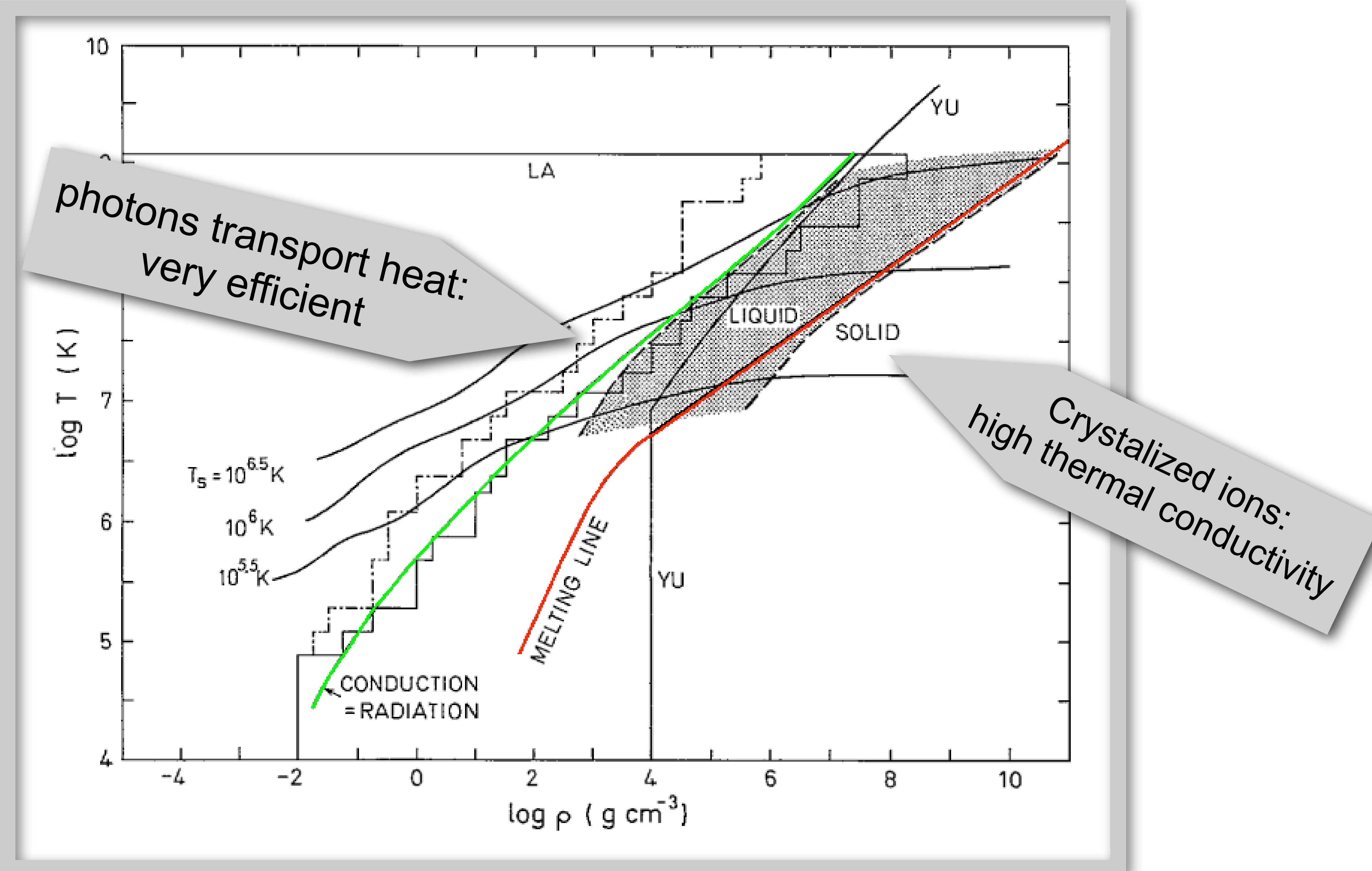
Structure of neutron star envelopes
Gudmundsson, E. H.; Pethick, C. J.; Epstein, R. I. 1983ApJ...272..286G

The sensitivity strip



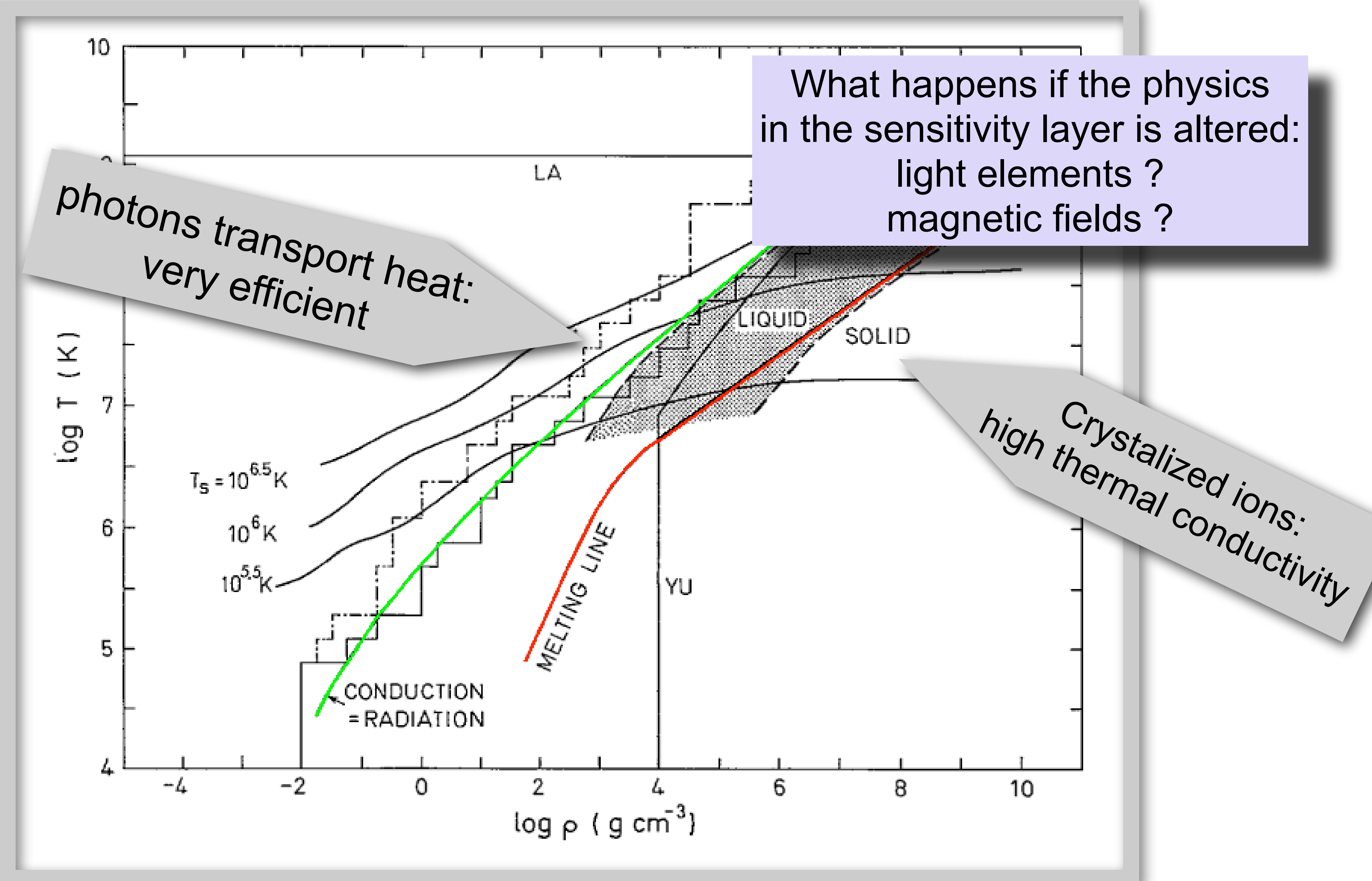
Structure of neutron star envelopes
Gudmundsson, E. H.; Pethick, C. J.; Epstein, R. I. 1983ApJ...272..286G

The sensitivity strip



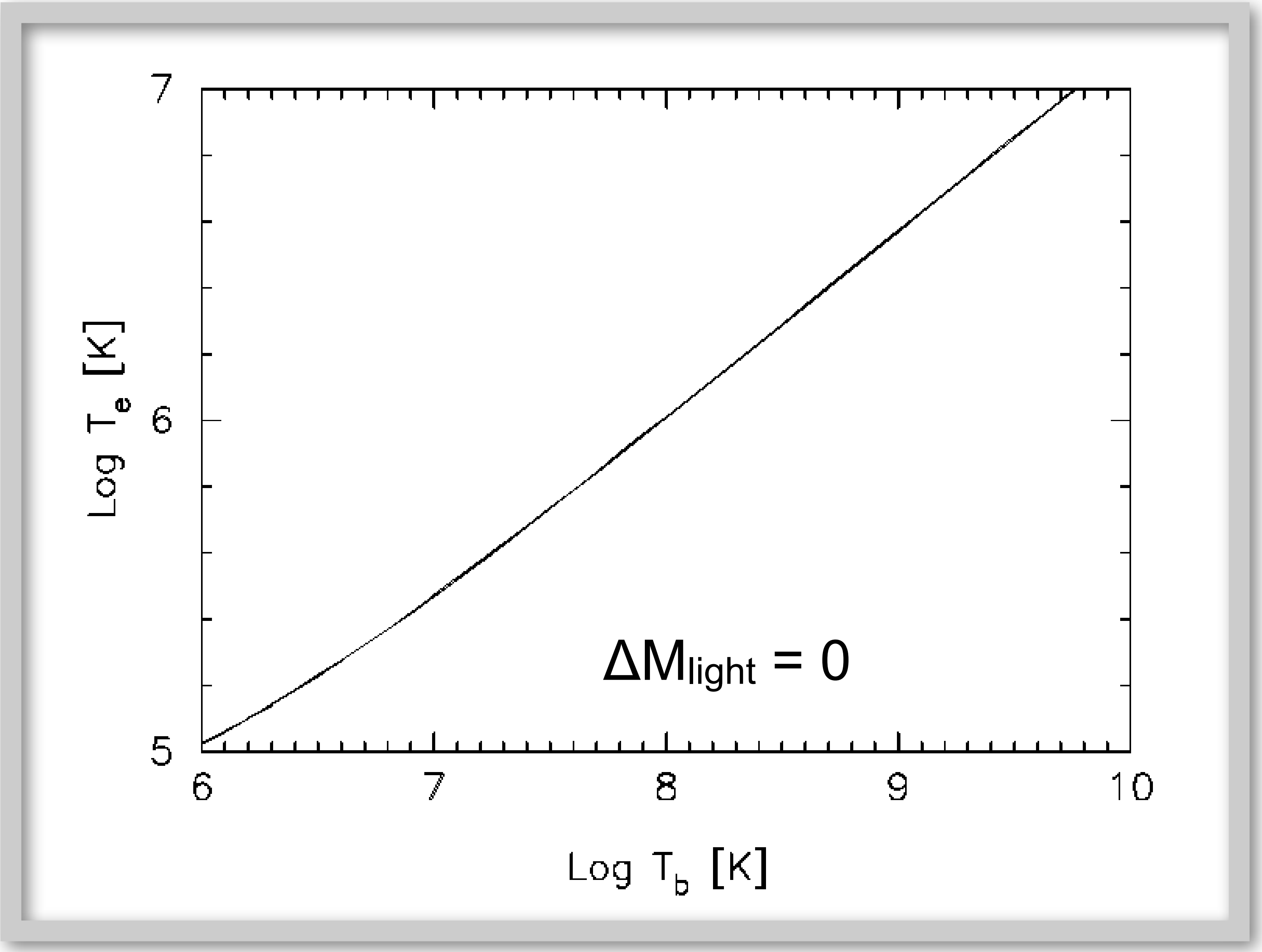
Structure of neutron star envelopes
Gudmundsson, E. H.; Pethick, C. J.; Epstein, R. I. 1983ApJ...272..286G

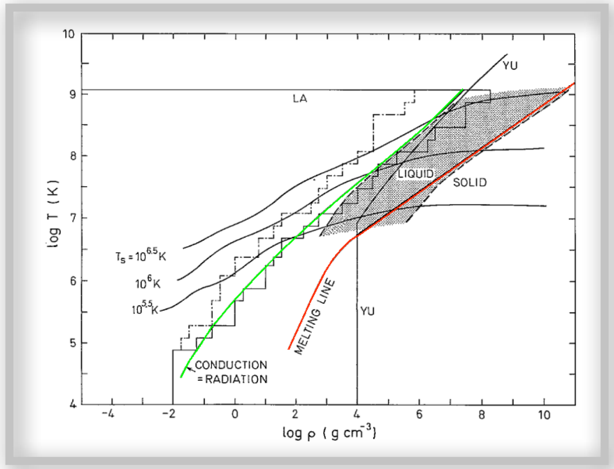
The sensitivity strip



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

Light element envelopes



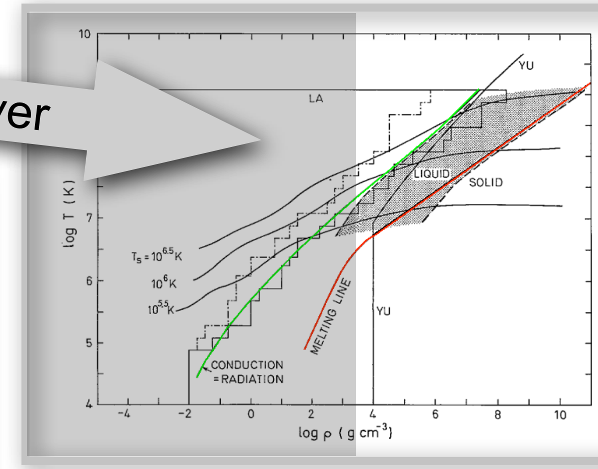


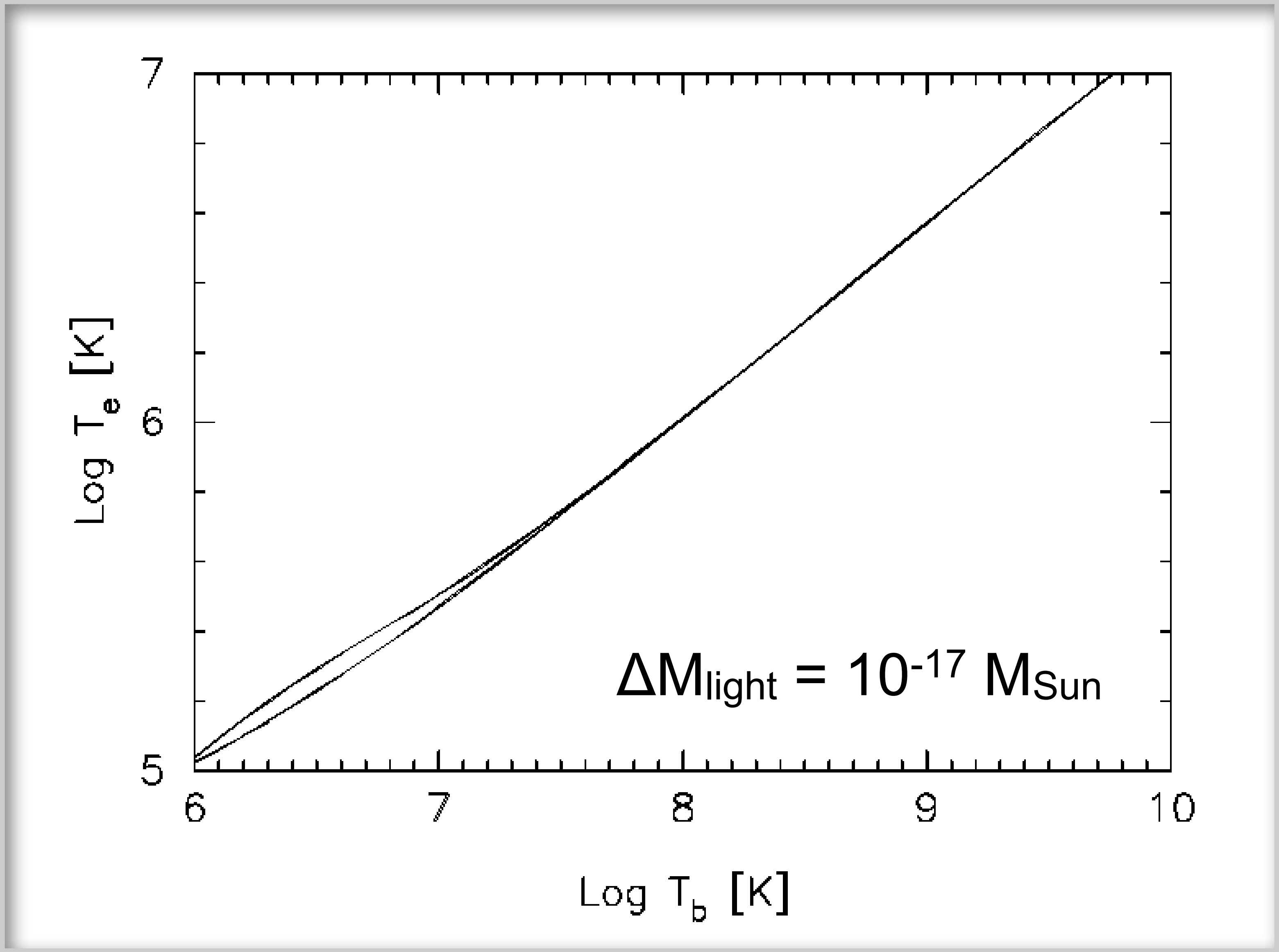
ΔM_{light} = mass of light elements in the upper envelope

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





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

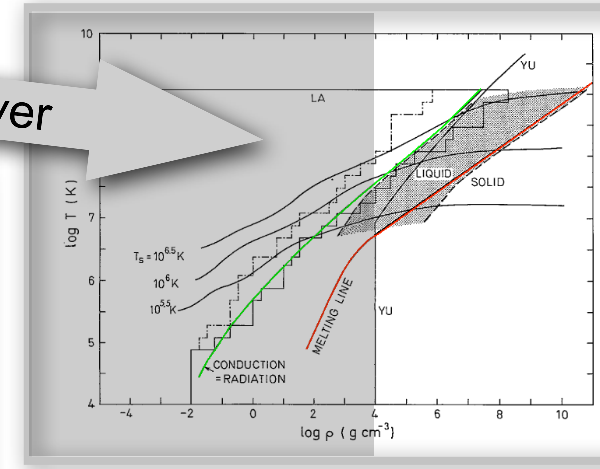
$$\lambda_{\text{liquid}} \propto \frac{1}{Z}$$

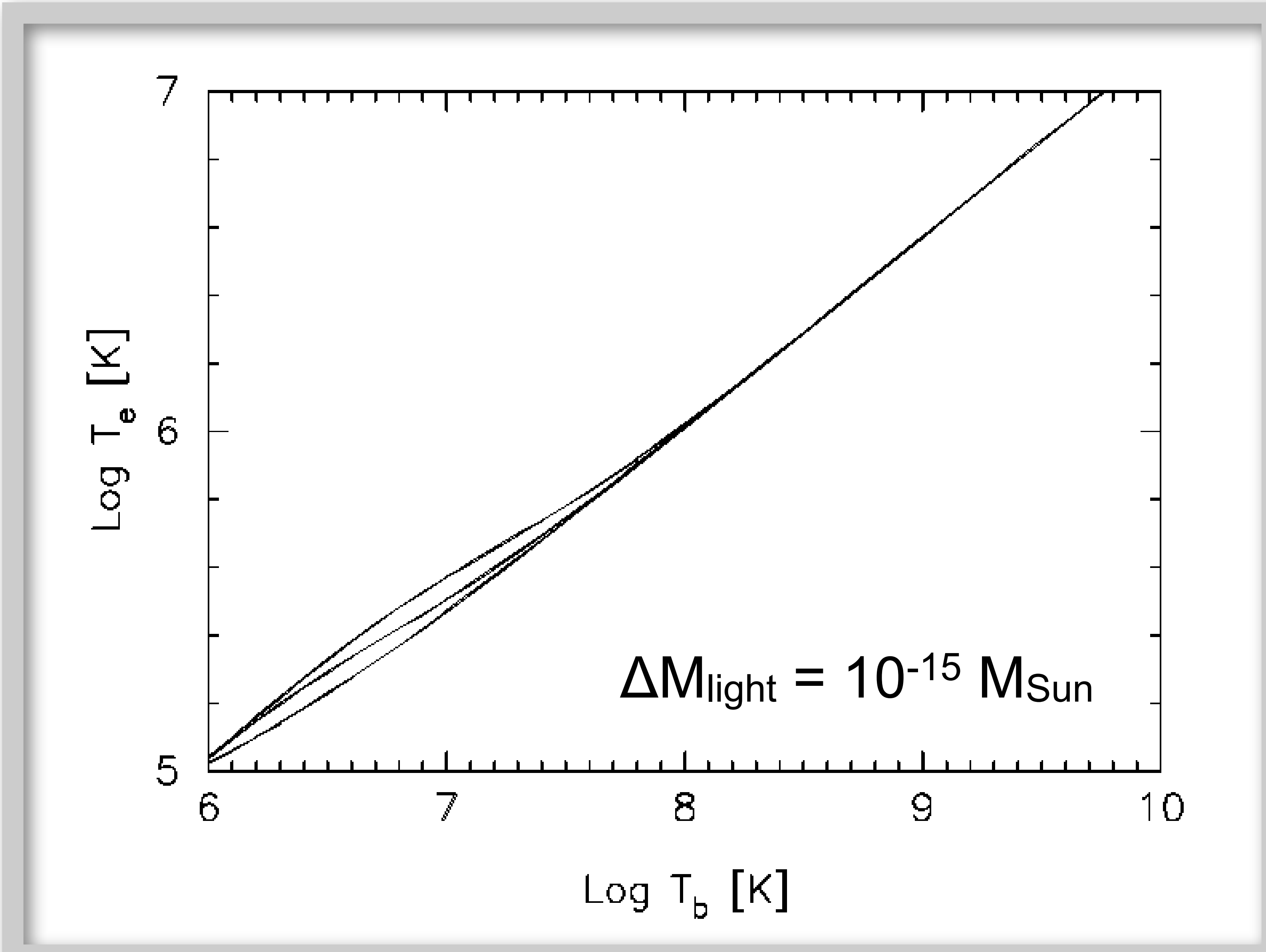
ΔM_{light} = mass of light elements in the upper envelope

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





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

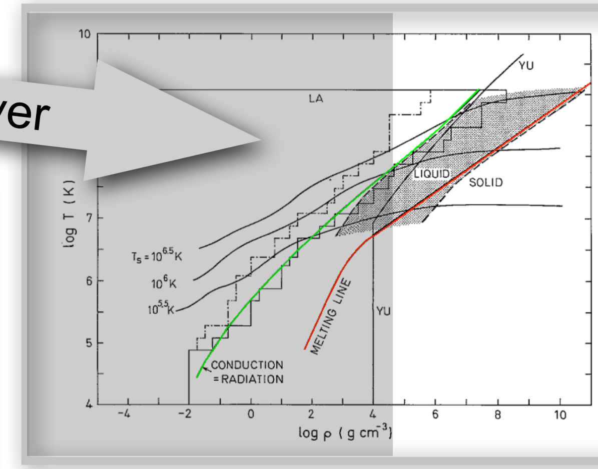
$$\lambda_{\text{liquid}} \propto \frac{1}{Z}$$

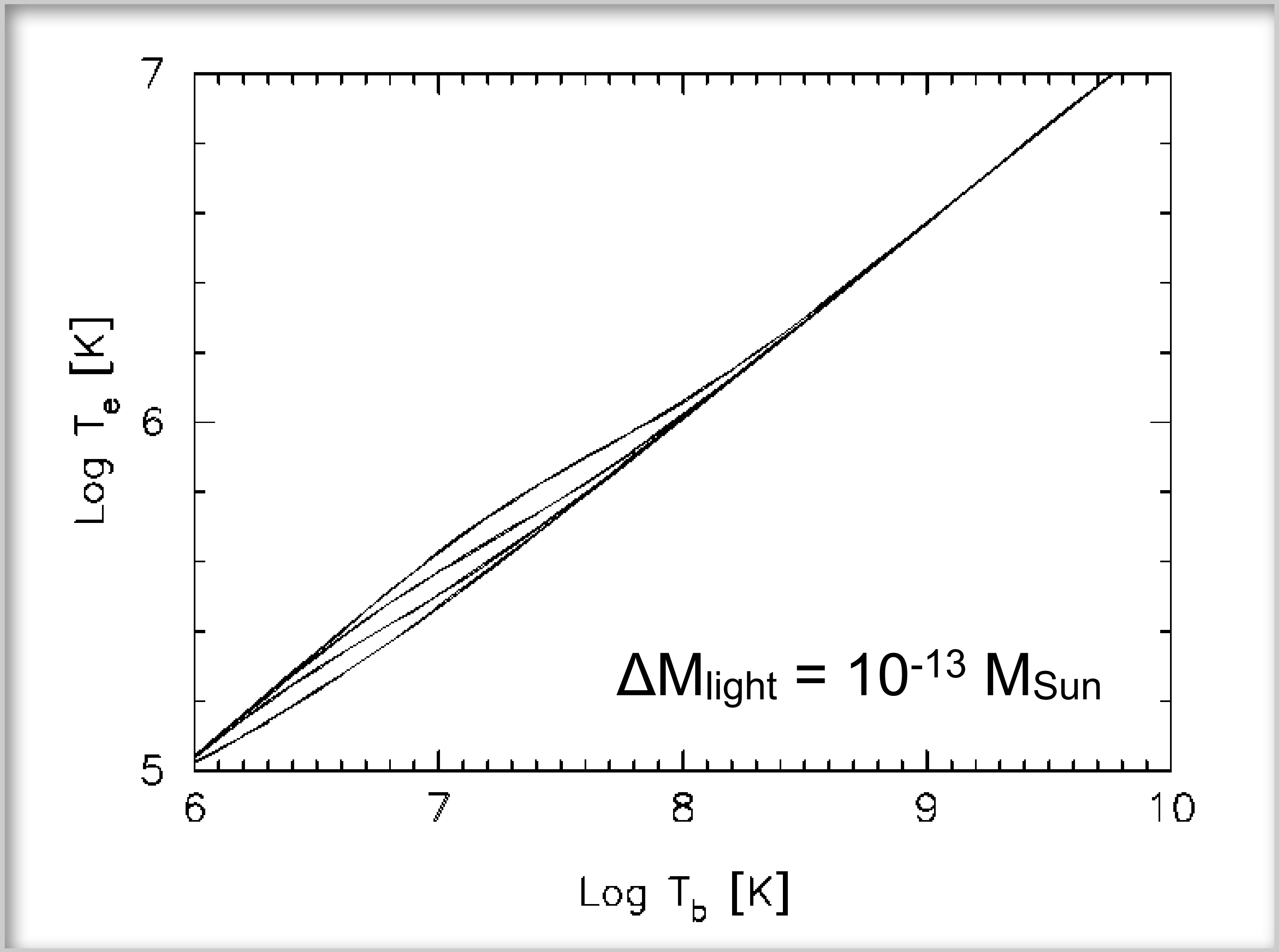
ΔM_{light} = mass of light elements in the upper envelope

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





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

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

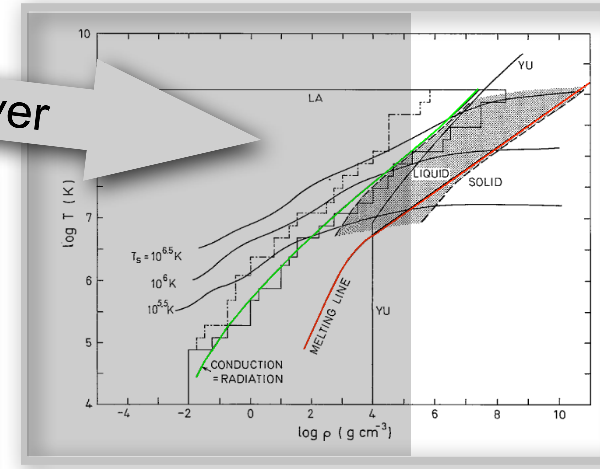
$$\lambda_{\text{liquid}} \propto \frac{1}{Z}$$

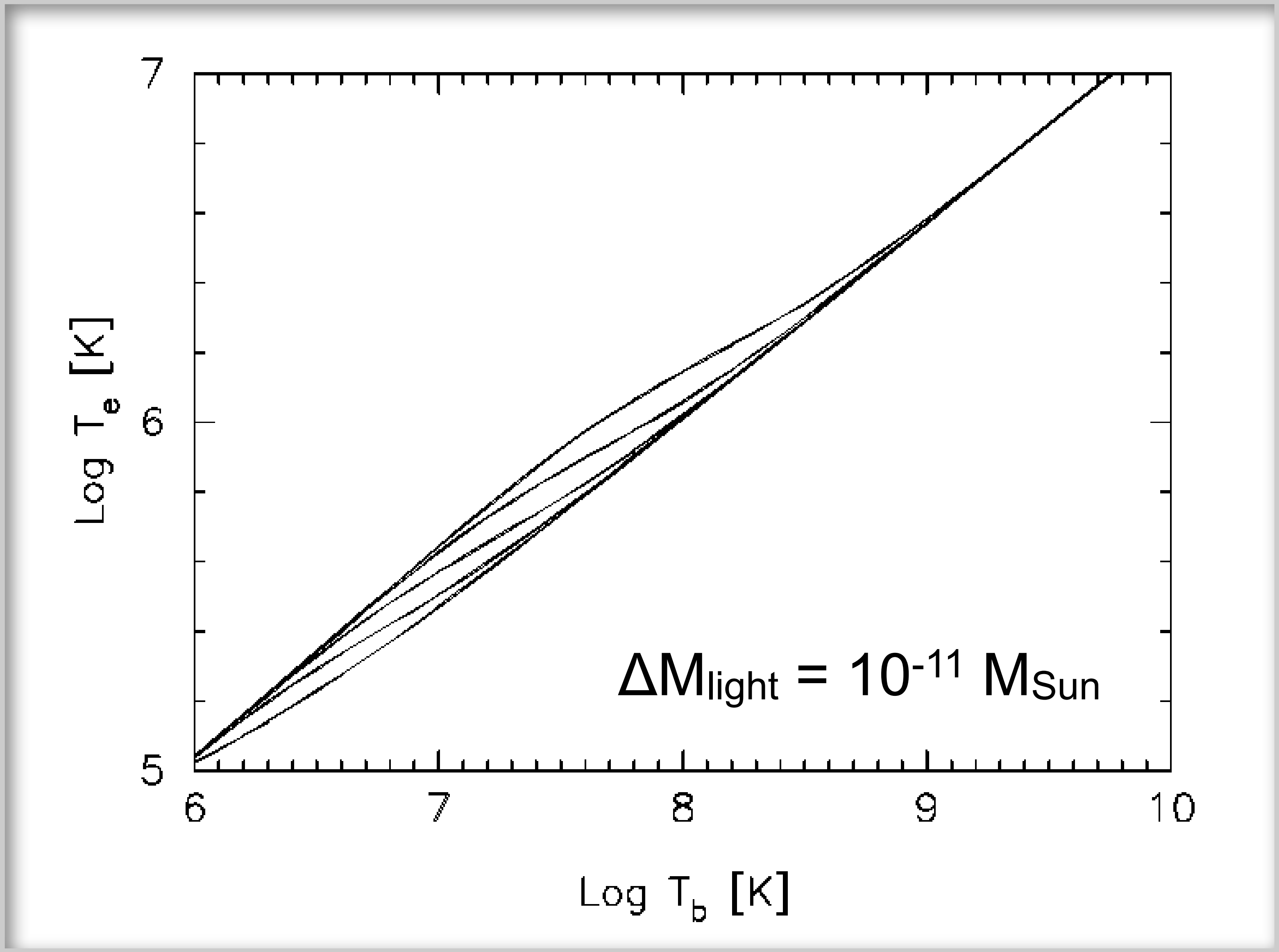
ΔM_{light} = mass of light elements in the upper envelope

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





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

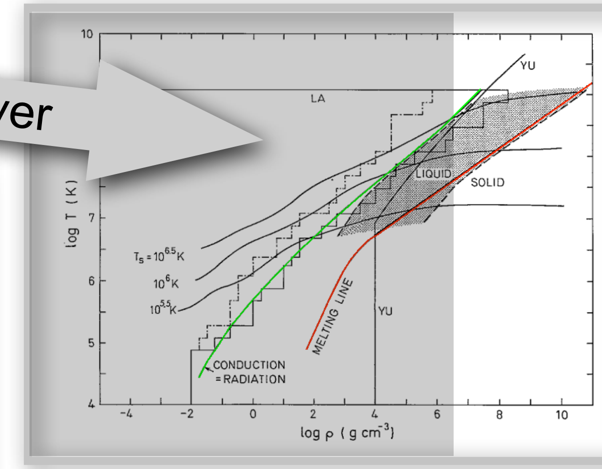
$$\lambda_{\text{liquid}} \propto \frac{1}{Z}$$

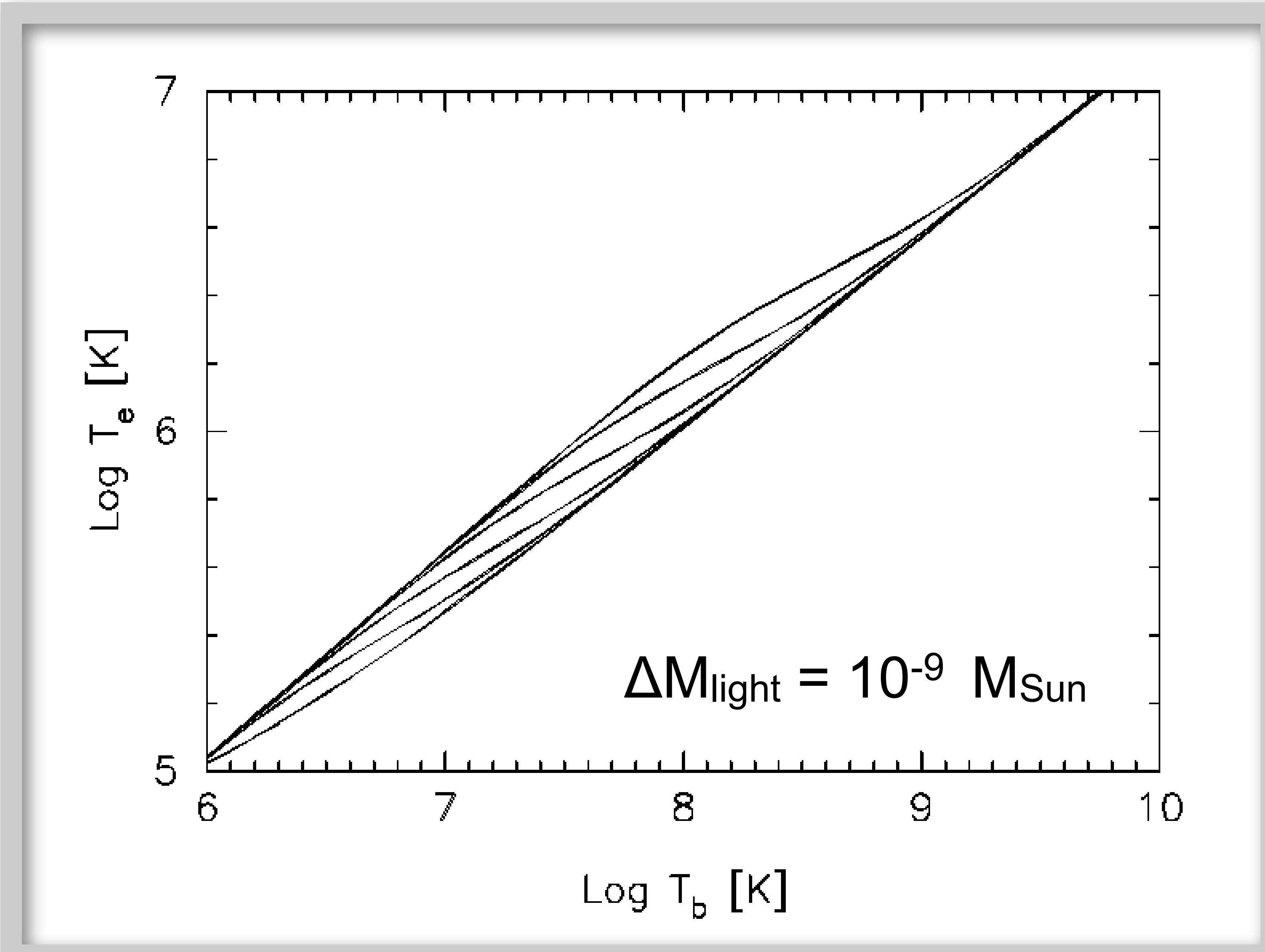
ΔM_{light} = mass of light elements in the upper envelope

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





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

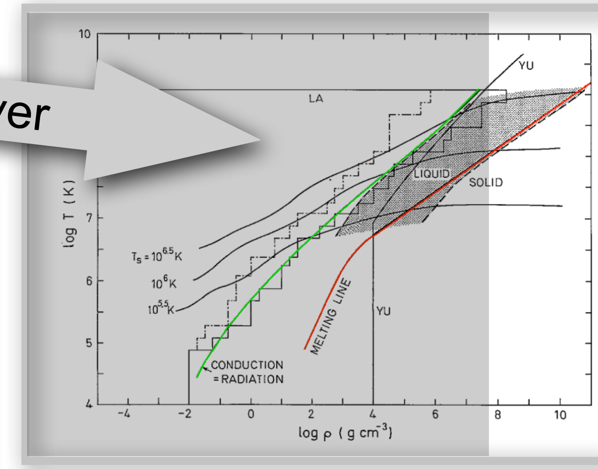
$$\lambda_{\text{liquid}} \propto \frac{1}{Z}$$

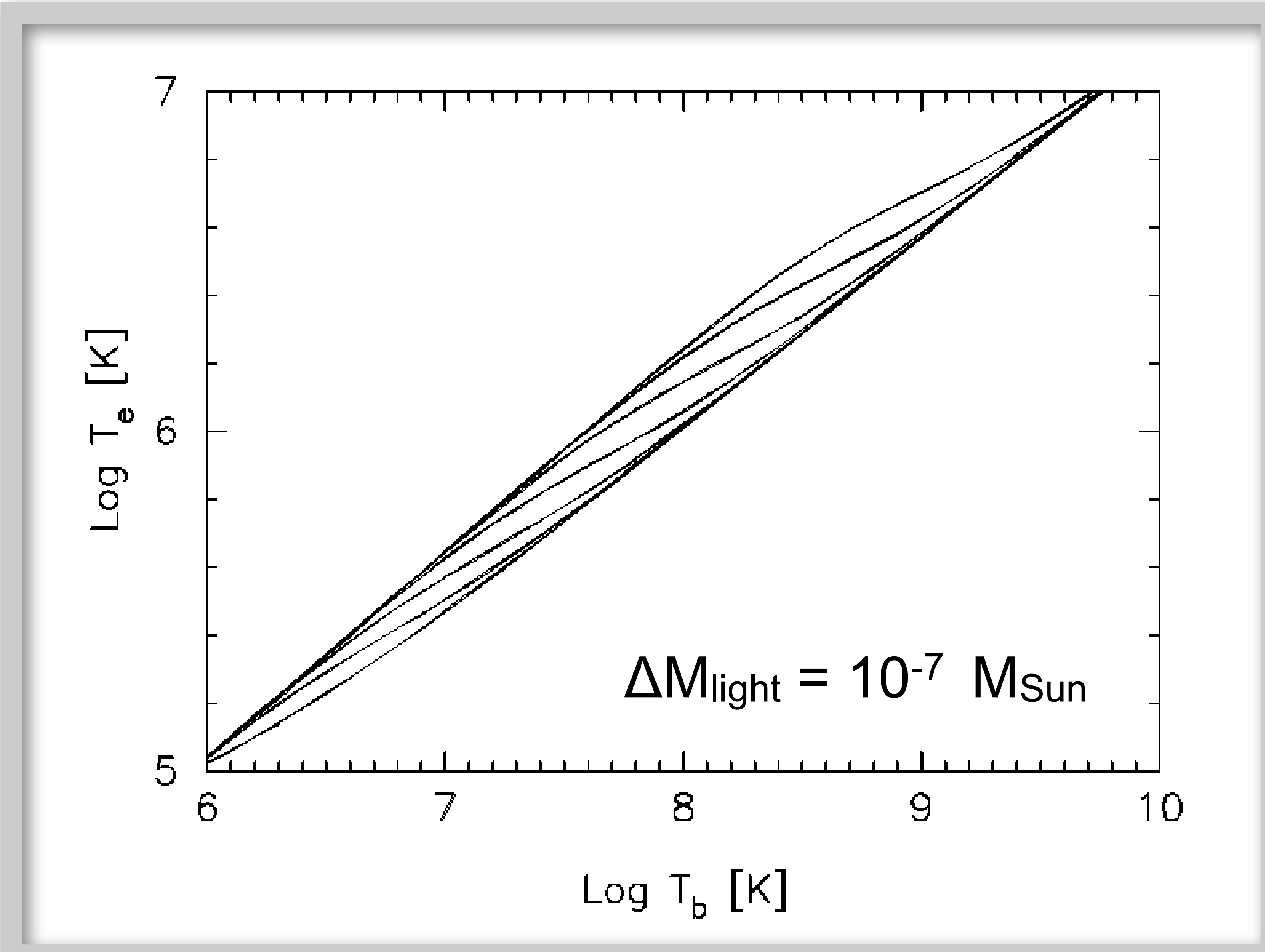
ΔM_{light} = mass of light elements in the upper envelope

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





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

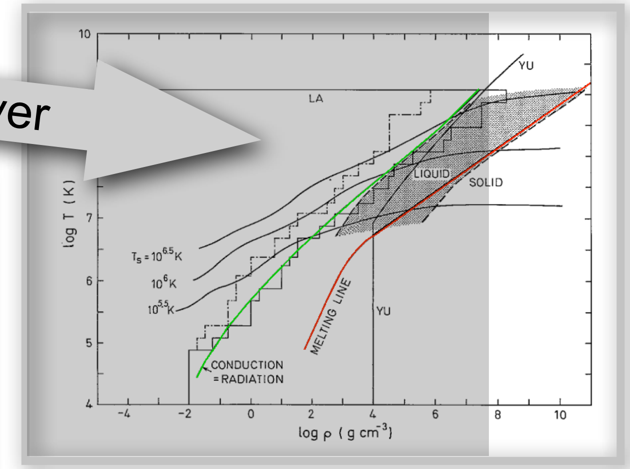
$$\lambda_{\rm liquid} \propto \frac{1}{Z}$$

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

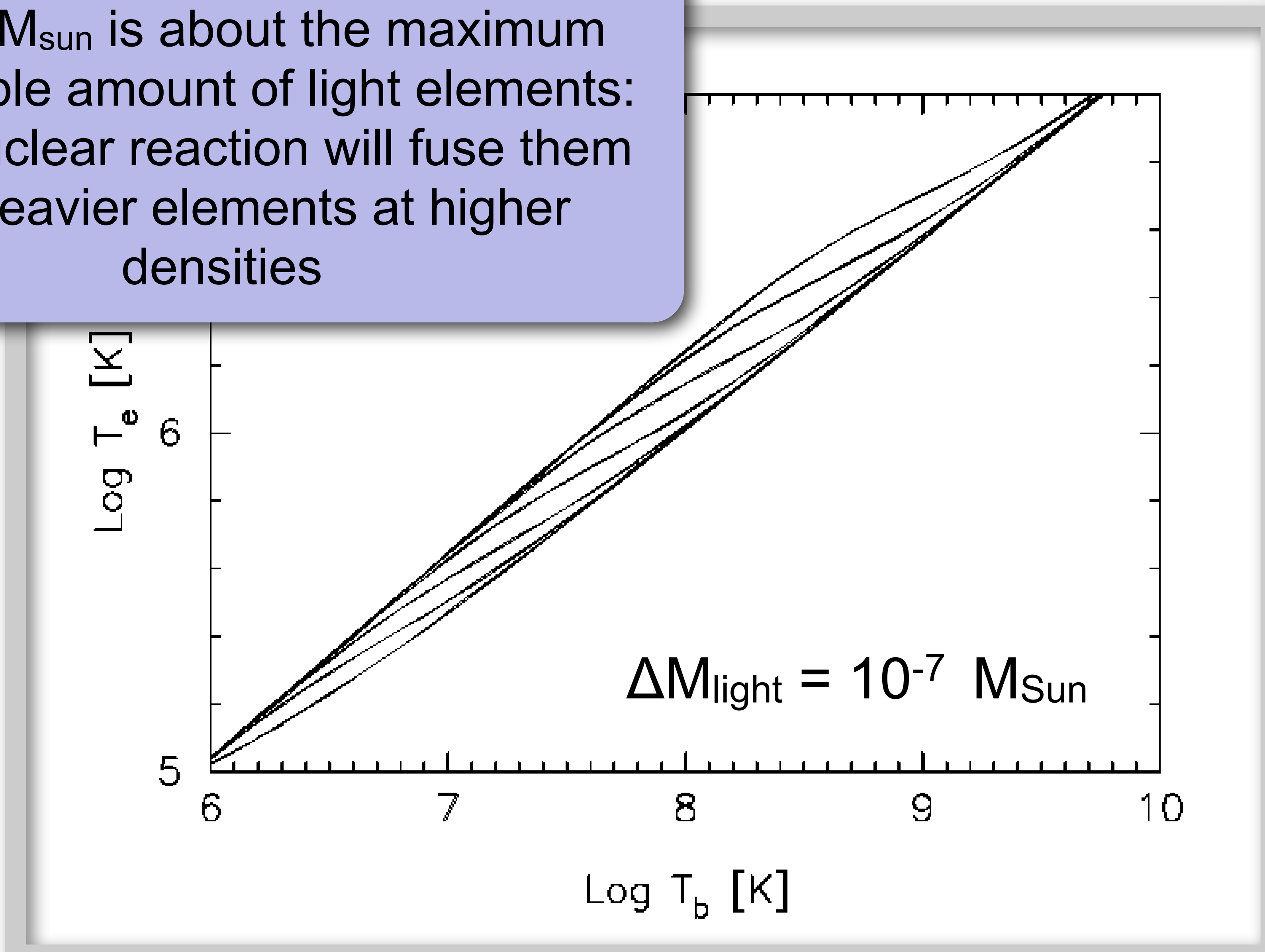
Cooling Neutron Stars with Accreted Envelopes
Chabrier, Gilles; Potekhin, Alexander Y.; Yakovlev, Dmitry G., 1997ApJ...477L..99C

Light element envelopes

Thickness of light elements layer



10^{-7} M_{sun} is about the maximum possible amount of light elements: pycnonuclear reaction will fuse them into heavier elements at higher densities



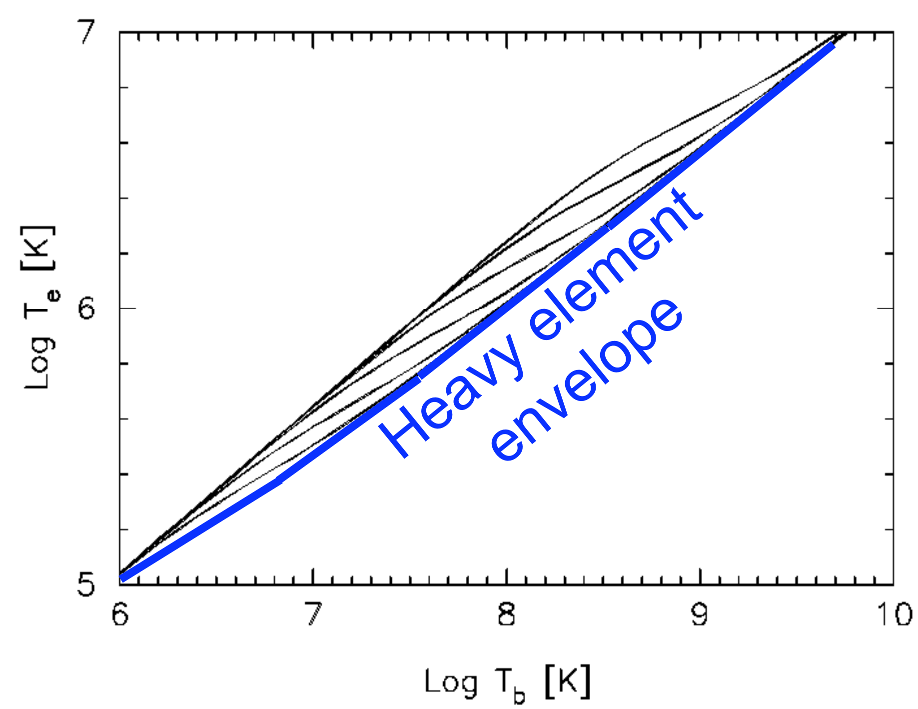
Electron thermal conductivity, due to e-ion scattering in the liquid sensitivity layer:

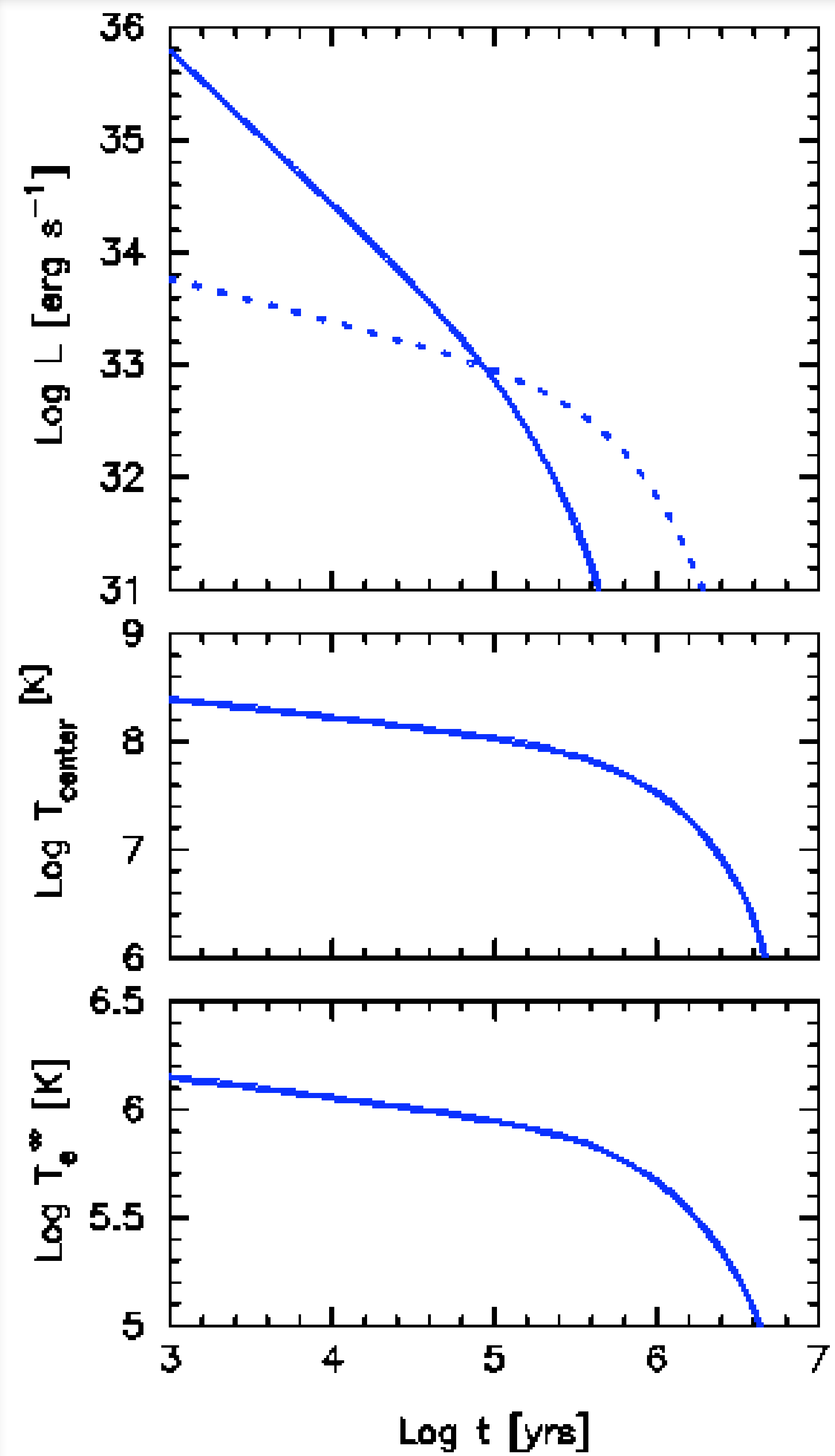
$$\lambda_{\text{liquid}} \propto \frac{1}{Z}$$

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

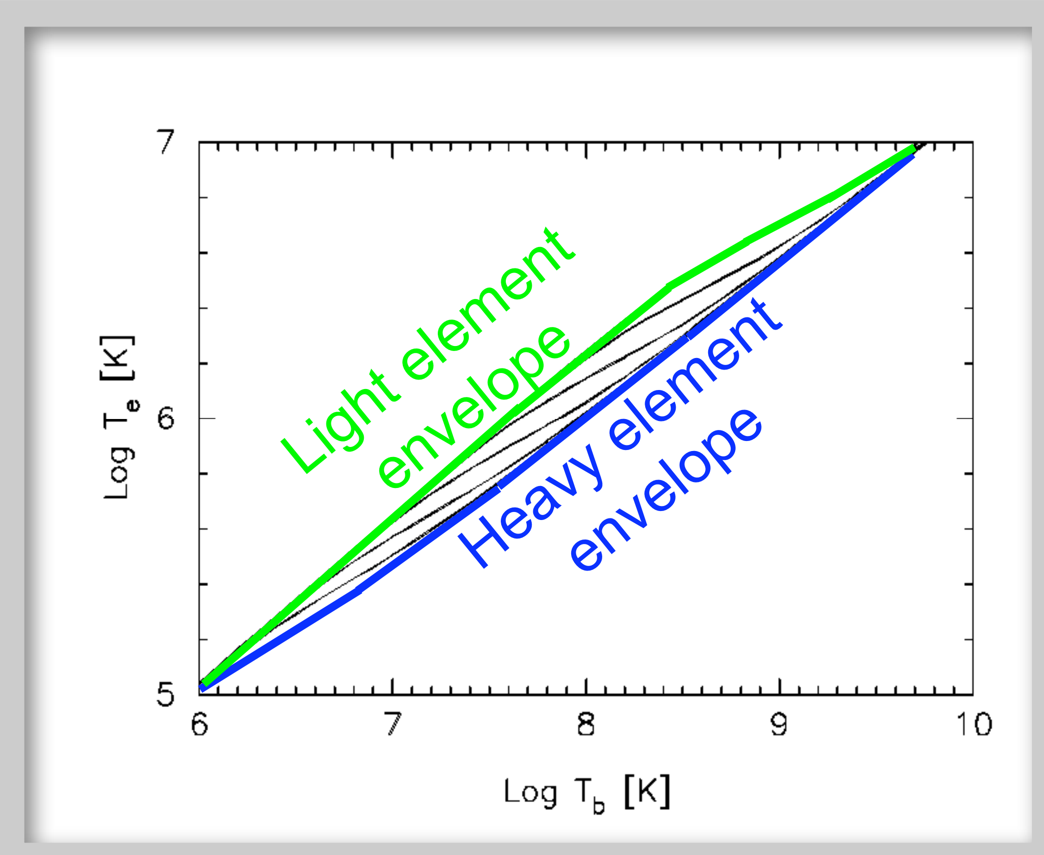
Cooling Neutron Stars with Accreted Envelopes
Chabrier, Gilles; Potekhin, Alexander Y.; Yakovlev, Dmitry G., 1997ApJ...477L..99C

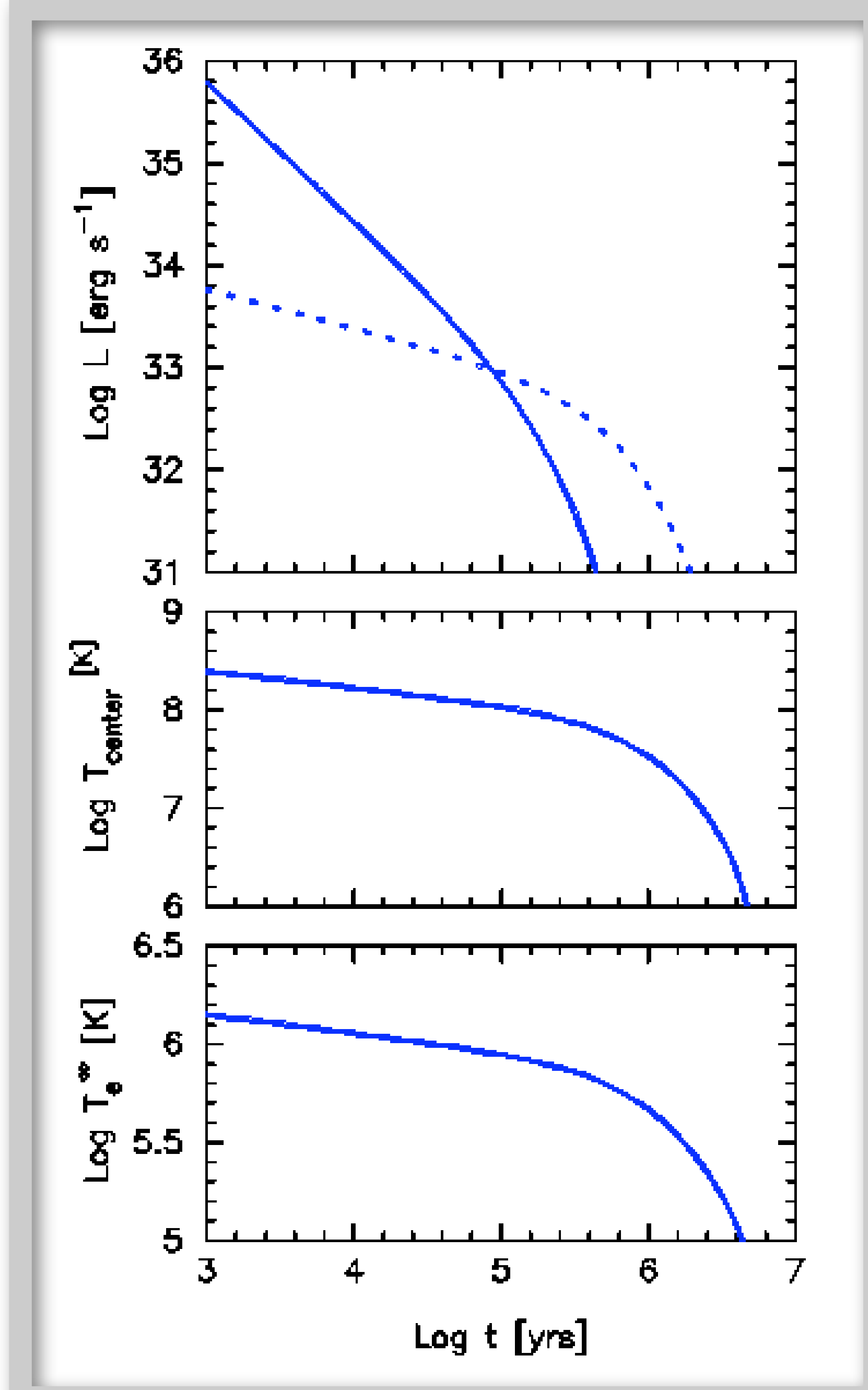
Effect of light element envelopes



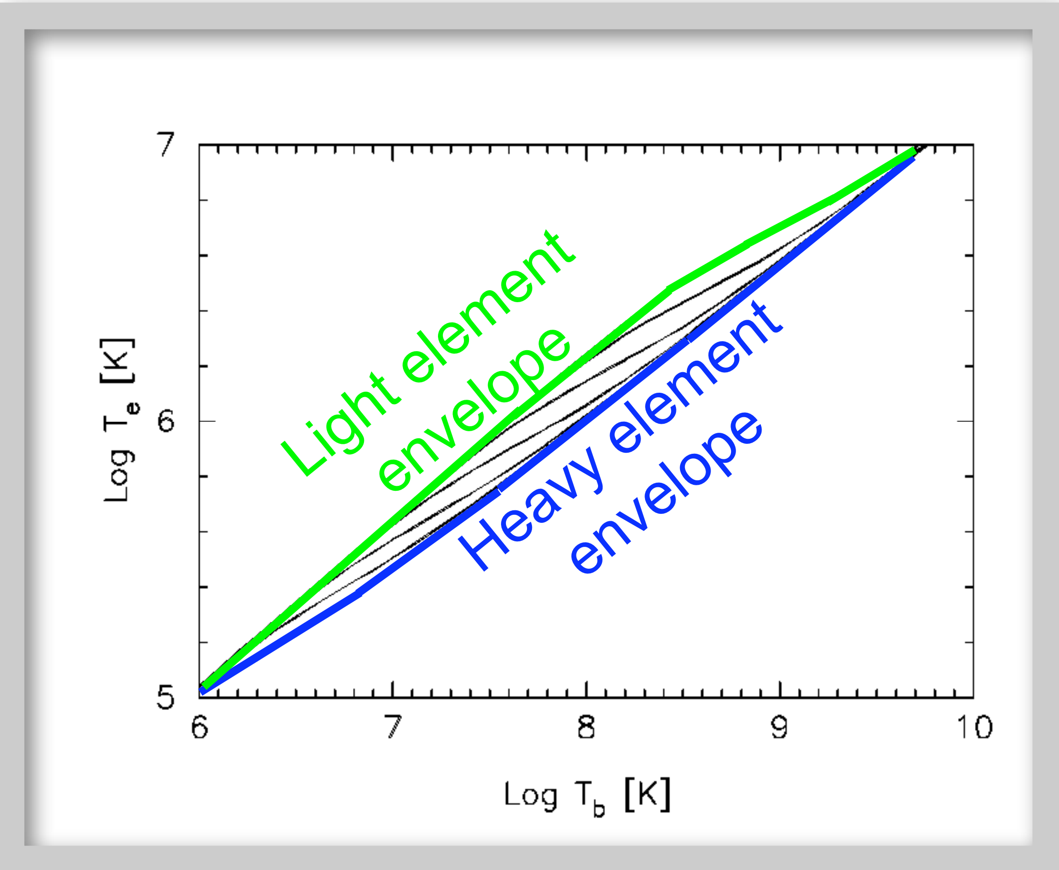


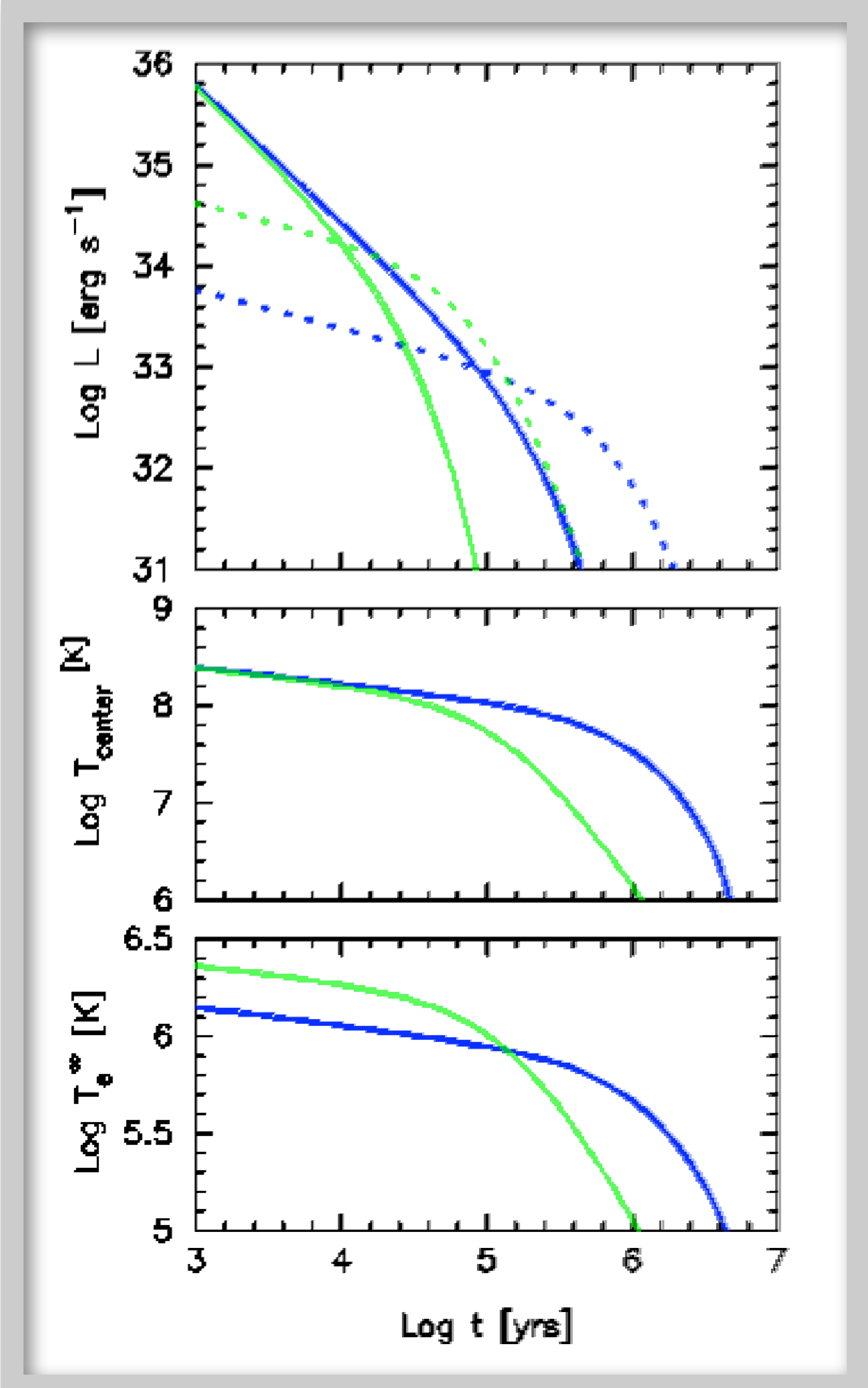
Effect of light element envelopes



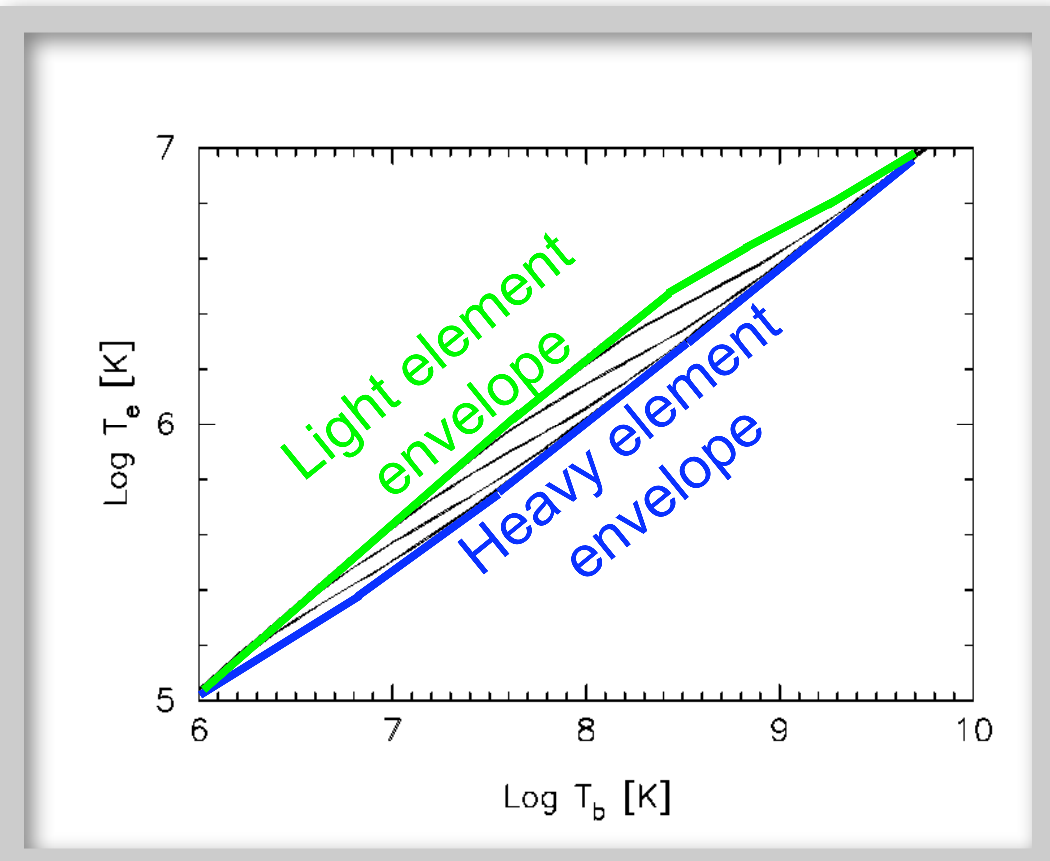


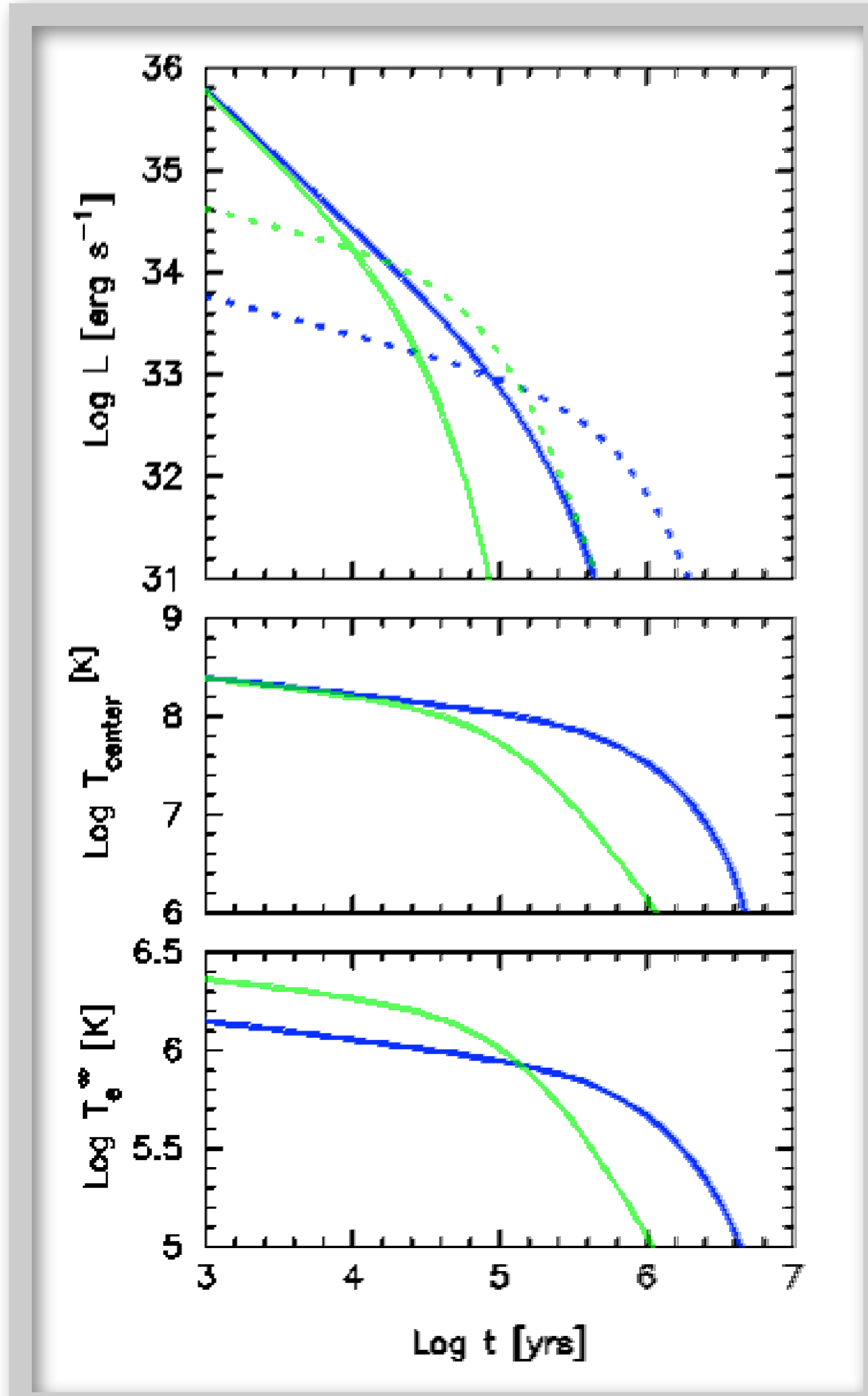
Effect of light element envelopes





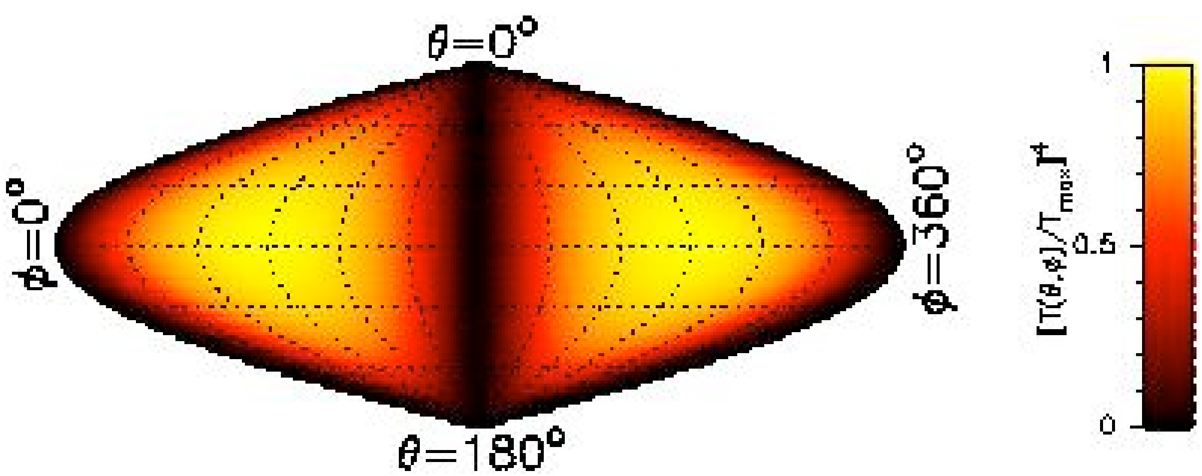
Effect of light element envelopes



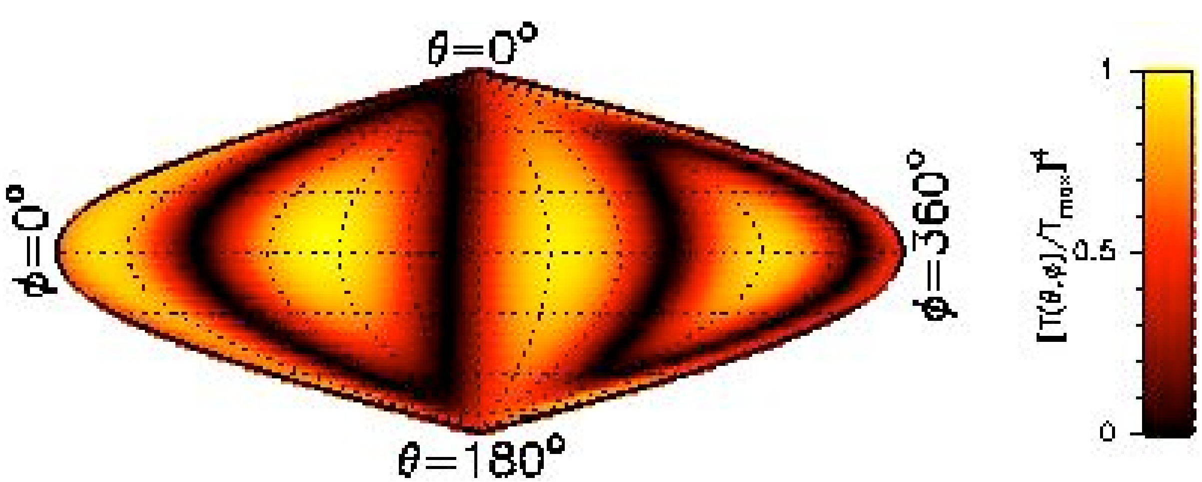


Light element envelopes:
- star looks warmer during neutrino cooling era, but
- cools faster during photon cooling era

Magnetized envelopes: surface temperature distributions



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)

Magnetized T_b - T_e relationships

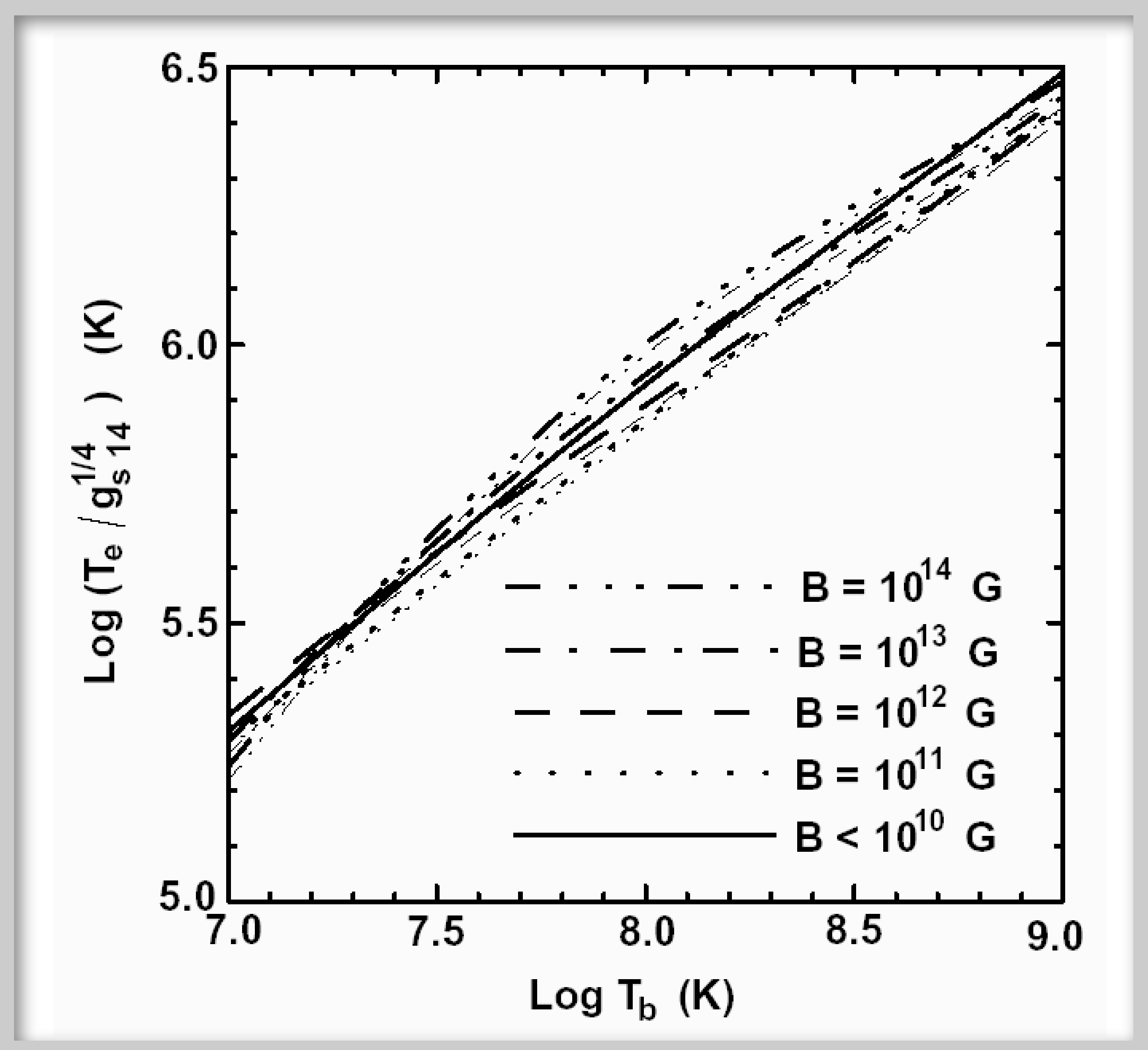
The star's effective temperature is then easily calculated:

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

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

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

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)

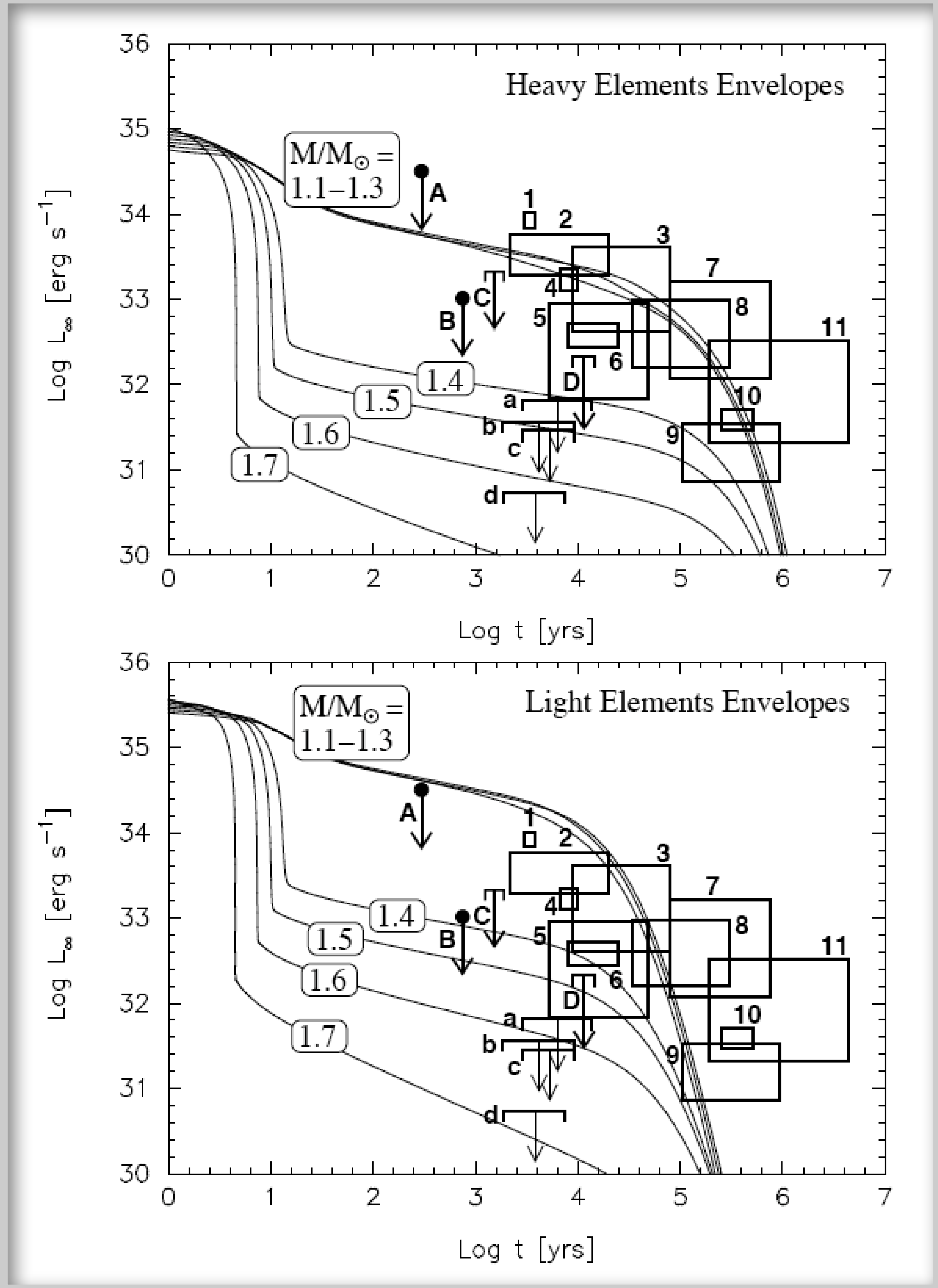
Comparison with Data

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"



Minimal Cooling

Minimal Cooling or, do we need fast cooling ?

Motivation:

Many new observations of cooling neutron stars with CHANDRA and XMM-NEWTON

Do we have any strong evidence for the presence of some "exotic" component in the core of some of these neutron stars ?

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 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 ...

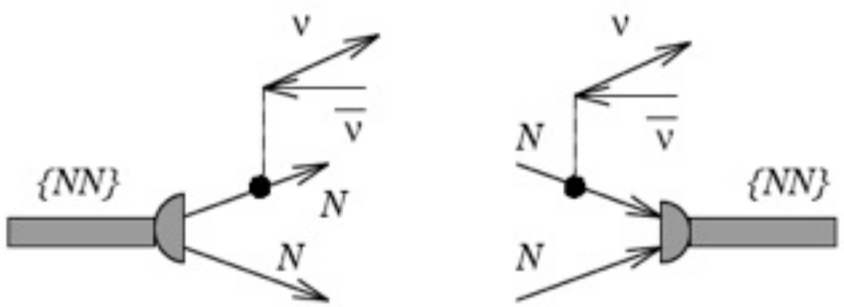
(and no medium effects enhance the
modified URCA rate beyond its standard value)

Minimal Cooling is not naive cooling:

it takes into account uncertainties due to

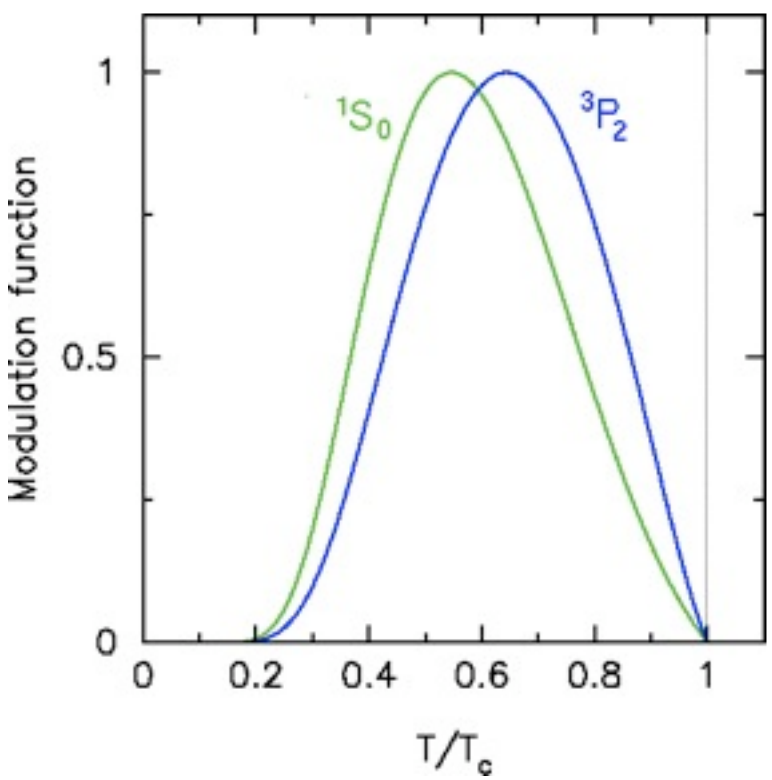
- Large range of predicted values of T_c for n & p.
- Enhanced neutrino emission at $T \leq T_c$ from the Cooper pair formation mechanism.
- Chemical composition of upper layers (envelope), i.e., iron-peak elements or light (H, He, C, O, ...) elements, the latter significantly increasing T_e for a given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

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



$$Q = \frac{4G_F^2 m_i^* p_{F,i}}{15\pi^5 \hbar^{10} c^6} (k_B T)^7 \mathcal{N}_\nu a_{i,j} F_j [\Delta_i(T)/T]$$

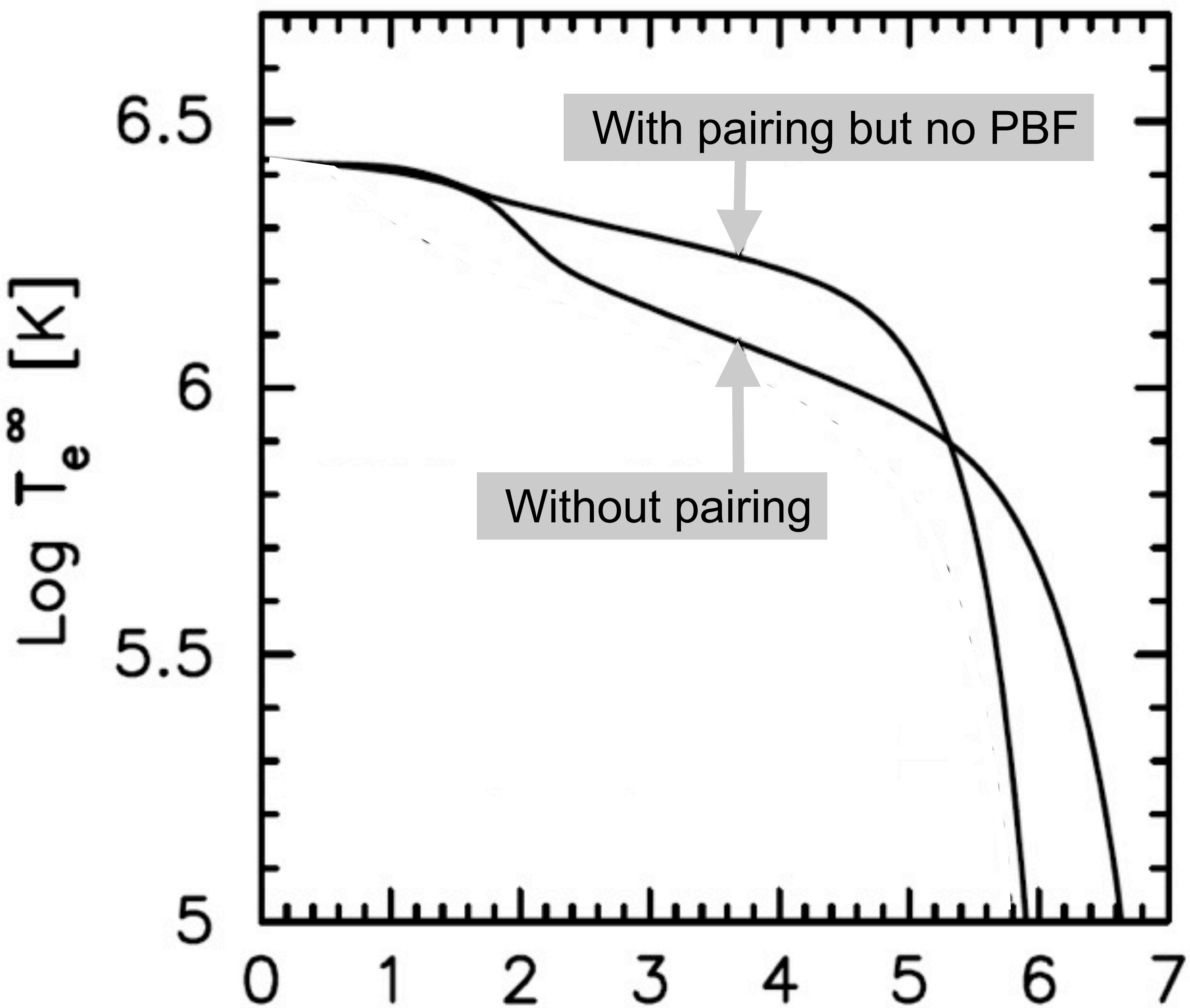
$$= 3.51 \times 10^{21} \frac{\text{erg}}{\text{cm}^3 \text{ s}} \left(\frac{m_i^*}{m_i}\right) \left(\frac{p_{F,i}}{m_i c}\right) \times T_9^7 a_{i,j} F_j [\Delta(T)/T]$$



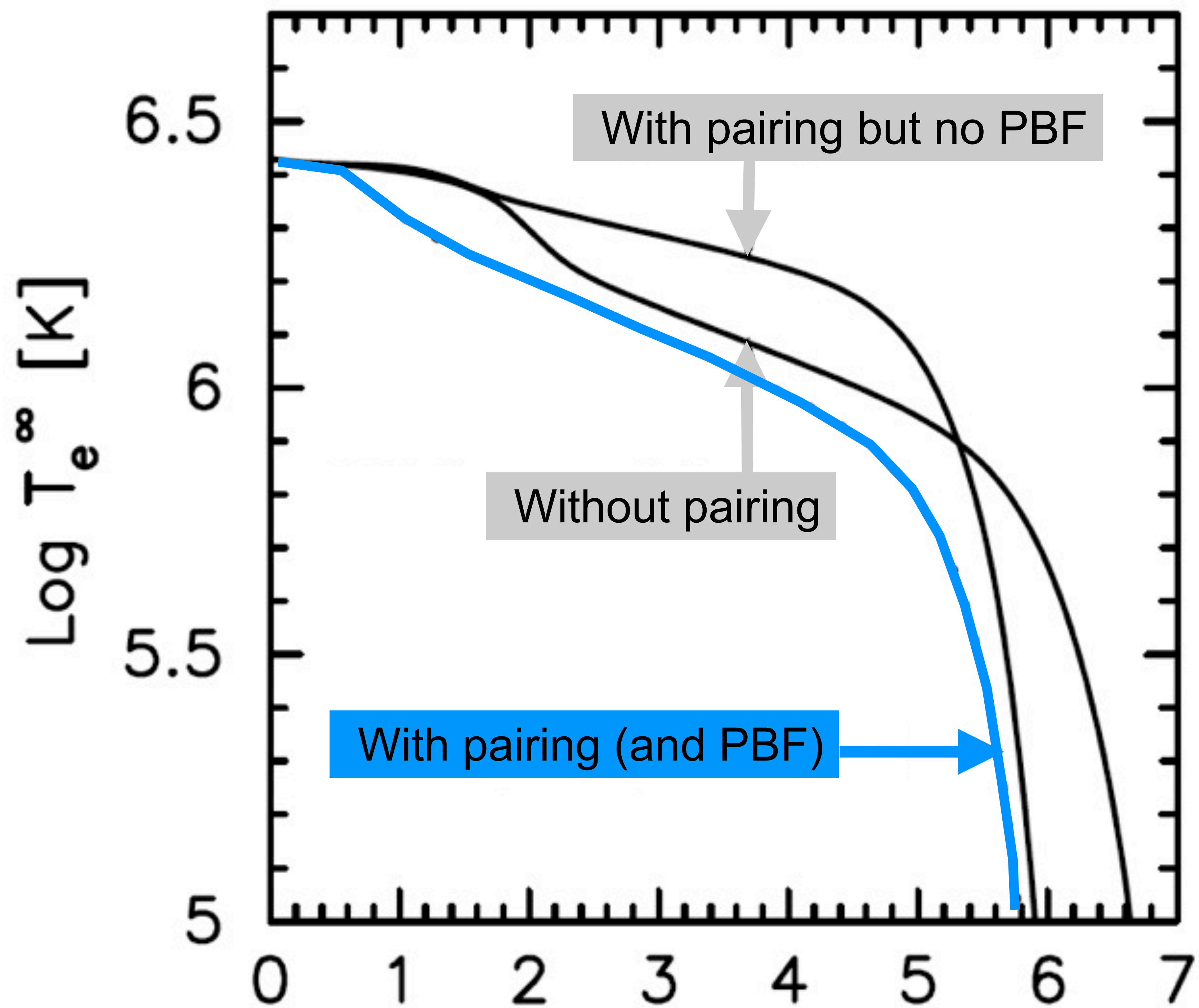
Neutrino pair emission from finite-temperature neutron superfluid and the cooling of neutron stars
E Flowers, M Ruderman & P Sutherland, 1976ApJ...205..541F

Voskresensky D., Senatorov A., 1986, Sov. Phys.–JETP 63, 885

Basic effects of pairing on the cooling

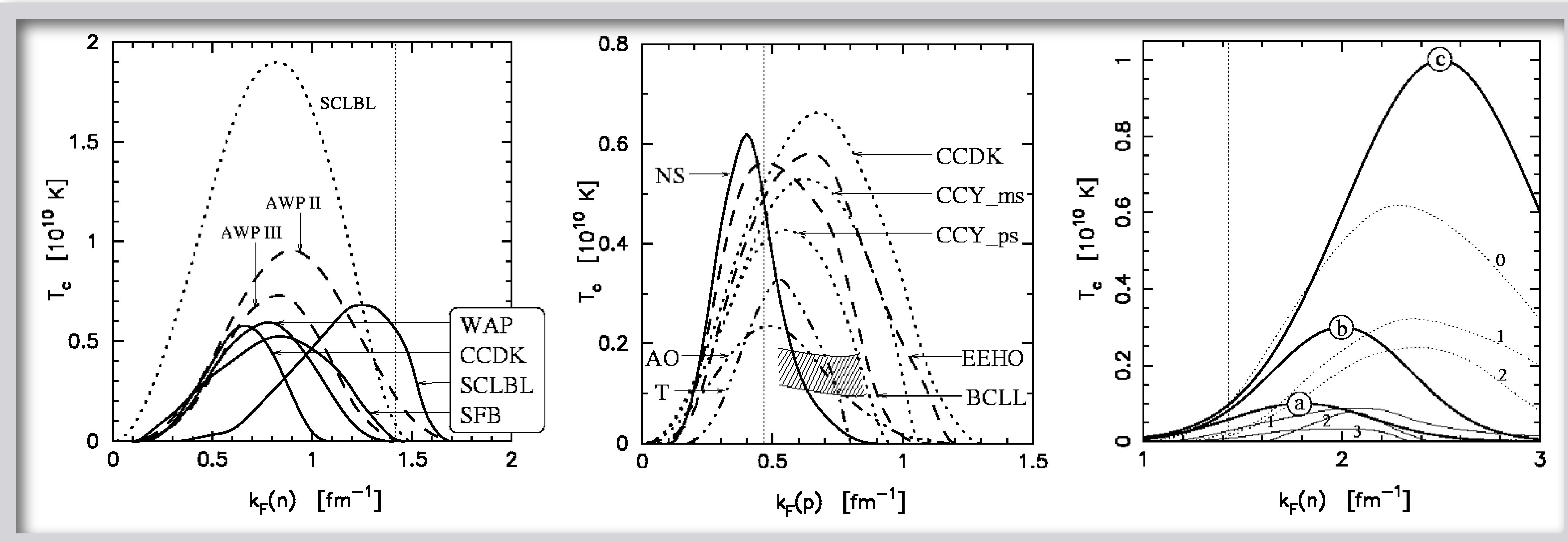


Basic effects of pairing on the cooling



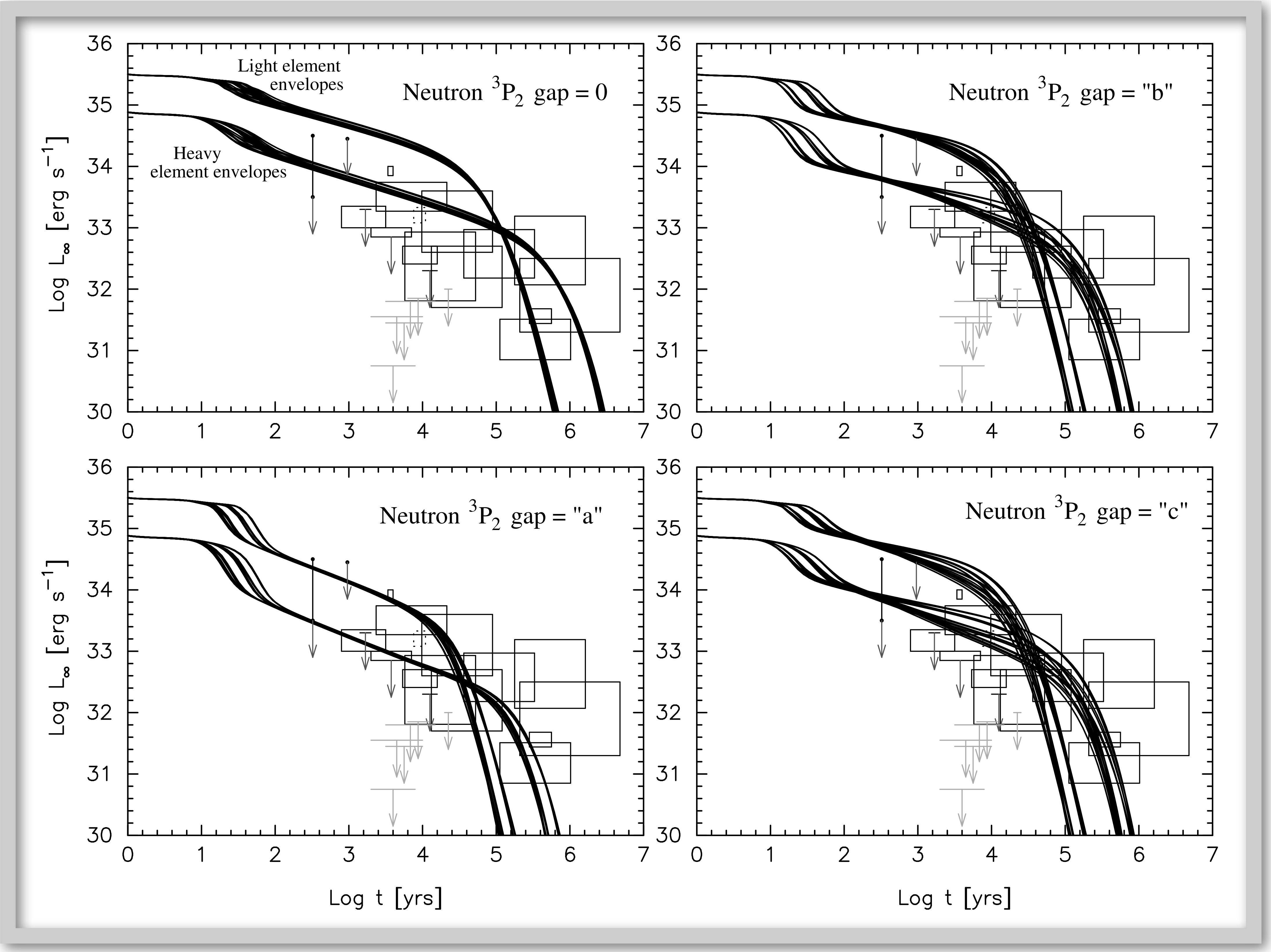
Pairing T_c models

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

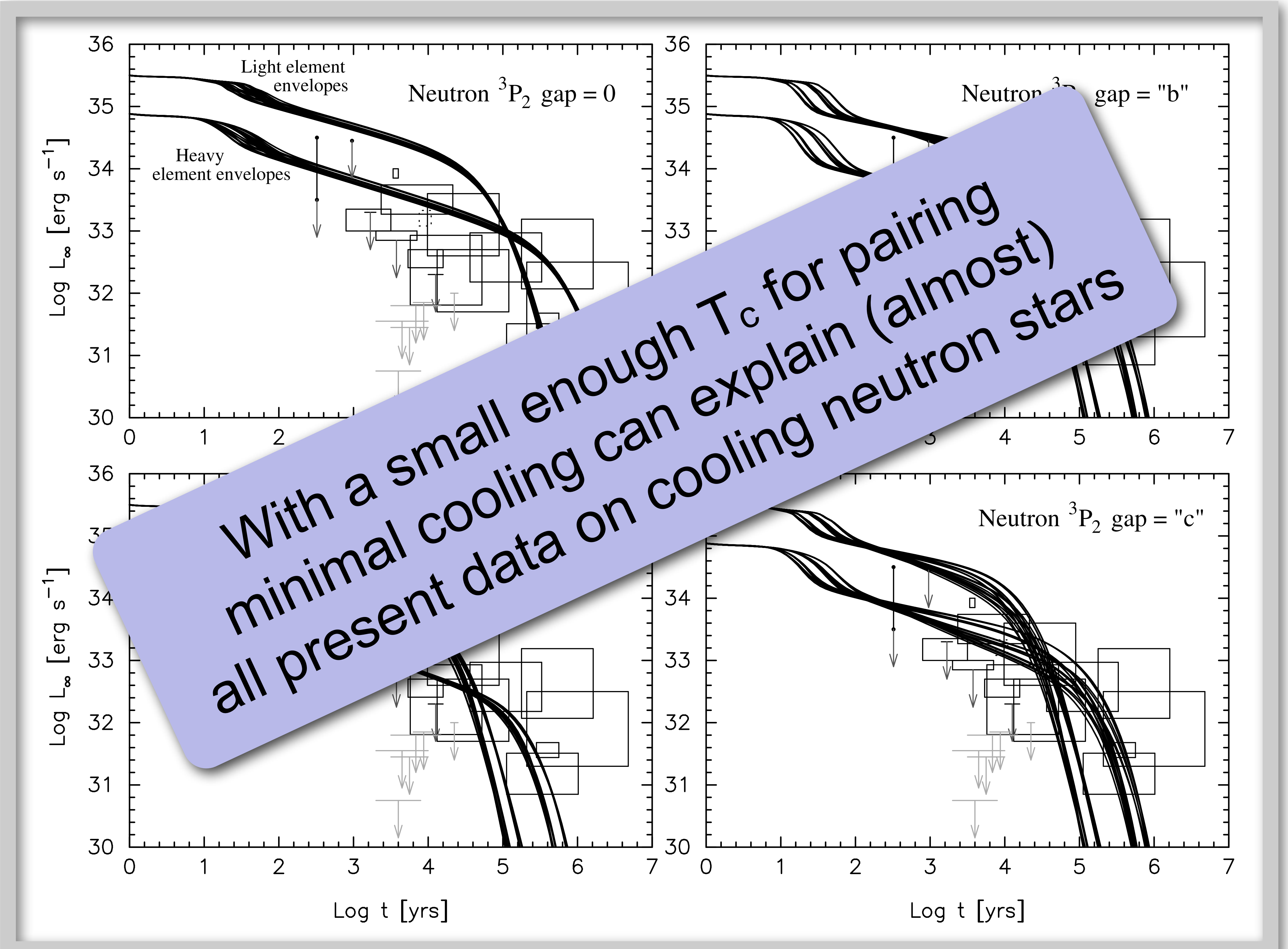


Size and extent of pairing gaps is highly uncertain

Minimal cooling versus data



Minimal cooling versus data



Conclusions

Conclusions

- Many possibilities for fast neutrino emission.
- Neutrino emission can be strongly suppressed by pairing.
- Fast cooling scenarios are compatible with if T_c for pairing is large enough.
- Minimal Cooling: most observed isolated cooling neutron stars are OK.
- A few serious candidates for neutrino cooling beyond minimal.