**Institute of Astronomy, National Autonomous University of Mexico**

# Thermal evolution of neo-neutron stars.

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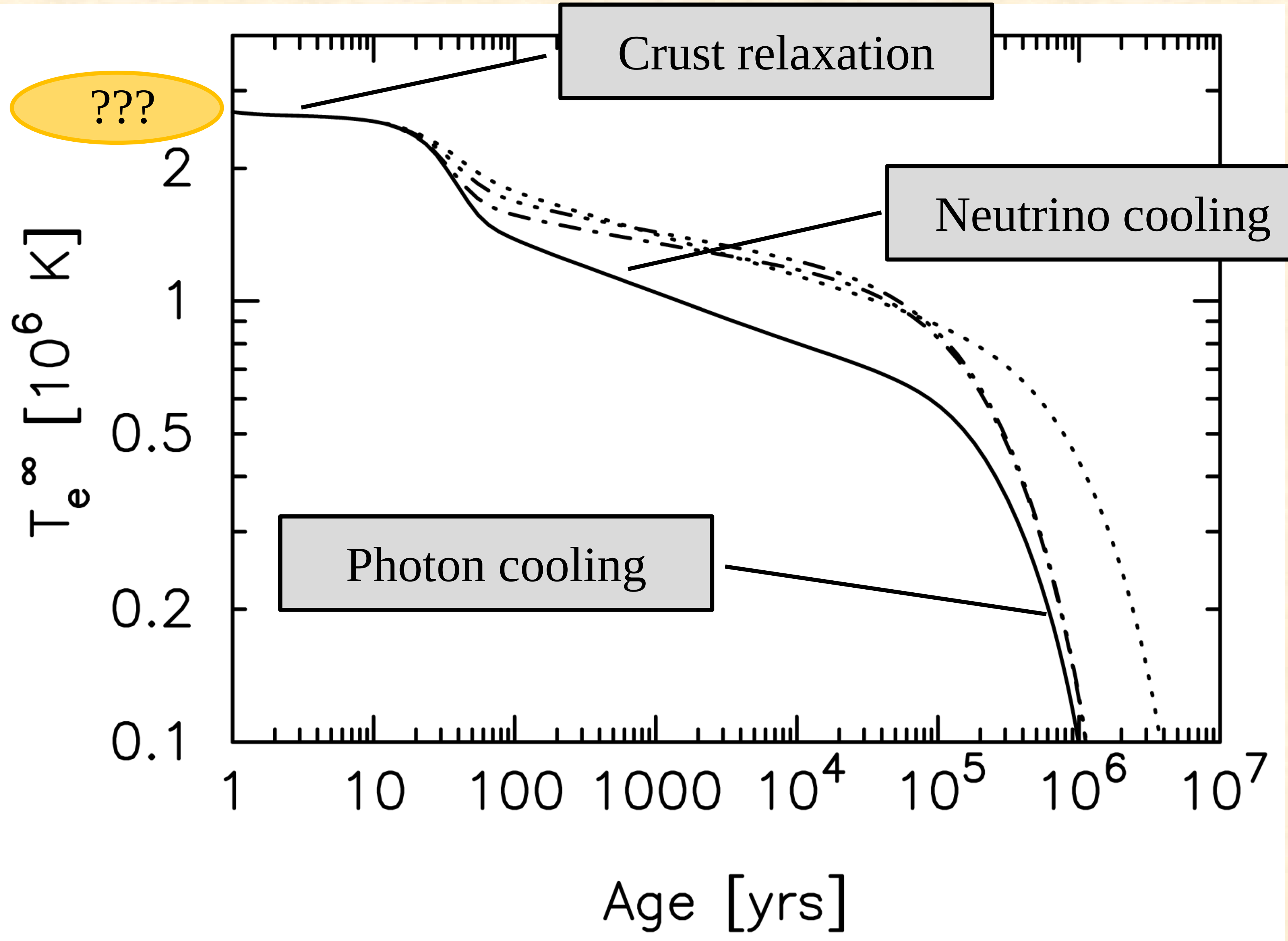
# Outline



## Thermal evolution of neo-neutron stars

- **Introduction.** Neo-neutron stars & Governing equations
- **Results**
- **Conclusions & Discussion**

# Long-term cooling of isolated neutron stars



Now we want to focus on what is happening at the initial relaxation stage.

1

- Proto-neutron star, $0 \leq t \lesssim 30 - 60$ s
- Opaque to neutrinos
- T ~ $10^{11}$ K

2

- Neo-neutron star, $30 - 60 \lesssim t \lesssim 1$ day
- Transparent to neutrinos
- The crust is being formed
- T $\ll 10^{11}$ K

# Governing equations

## Governing equations

Spherically symmetric metric for a nonrotating neutron star:

$$\mathrm{d}s^2 = c^2\mathrm{d}t^2\mathrm{e}^{2\Phi} - \mathrm{e}^{2\lambda}\mathrm{d}r^2 - r^2\left(\mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\varphi^2\right)$$

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Lagrange radial variable *a* – enclosed baryon number.
Convenient when the star structure evolves in time.

$$a = \int_0^r 4\pi r'^2 n(r')\mathrm{e}^{\lambda(r')}\mathrm{d}r'$$

Mechanical structure equations (*almost* temperature-independent)

$$\frac{\partial r}{\partial a} = \frac{1}{4\pi r^2 n e^{\lambda}}$$

$$\frac{\partial P}{\partial a} = -\frac{G\left(\rho + u/c^2 + P/c^2\right)\left(m + 4\pi r^3 P/c^2\right)}{4\pi r^4 n} e^{\lambda}$$

$$\frac{\partial \Phi}{\partial a} = \frac{G\left(m + 4\pi r^3 P/c^2\right)}{4\pi r^4 n c^2} e^{\lambda}$$

$$\frac{\partial m}{\partial a} = \frac{\rho + u/c^2}{n e^{\lambda}}$$

Thermal evolution equations:

$$\tilde{L} = -\kappa\left(4\pi r^2\right)^2 \mathrm{e}^{\Phi} n \frac{\partial \tilde{T}}{\partial a}$$

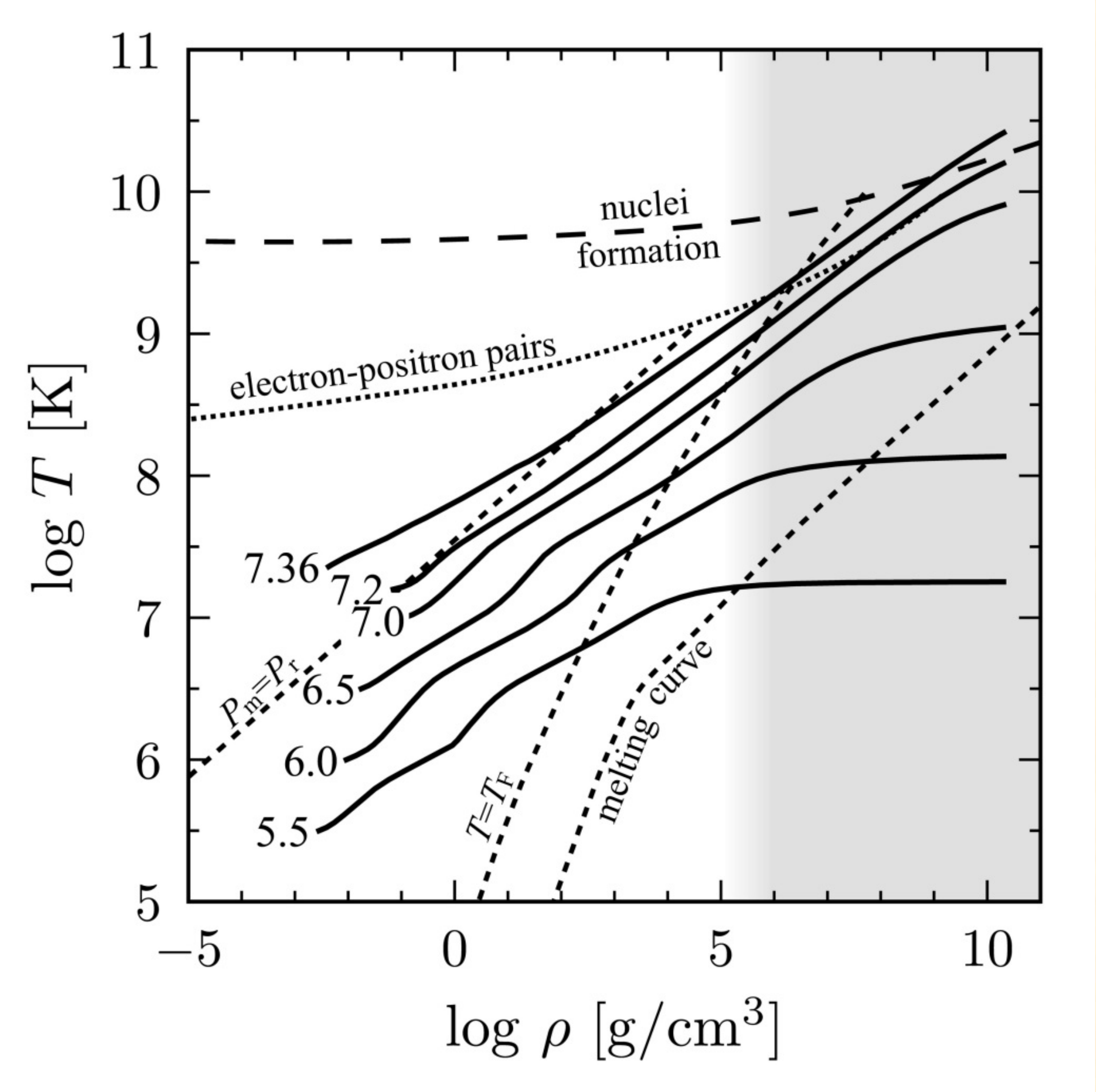
$$\mathrm{e}^{\Phi} \frac{\partial\left(\tilde{T}\mathrm{e}^{-\Phi}\right)}{\partial t} = -\frac{1}{C_V}\left(\tilde{Q}_L + \tilde{Q}_\nu + \tilde{Q}_V\right)$$

Here

$$\tilde{L} = L\mathrm{e}^{2\Phi},\ \tilde{T} = T\mathrm{e}^{\Phi}$$

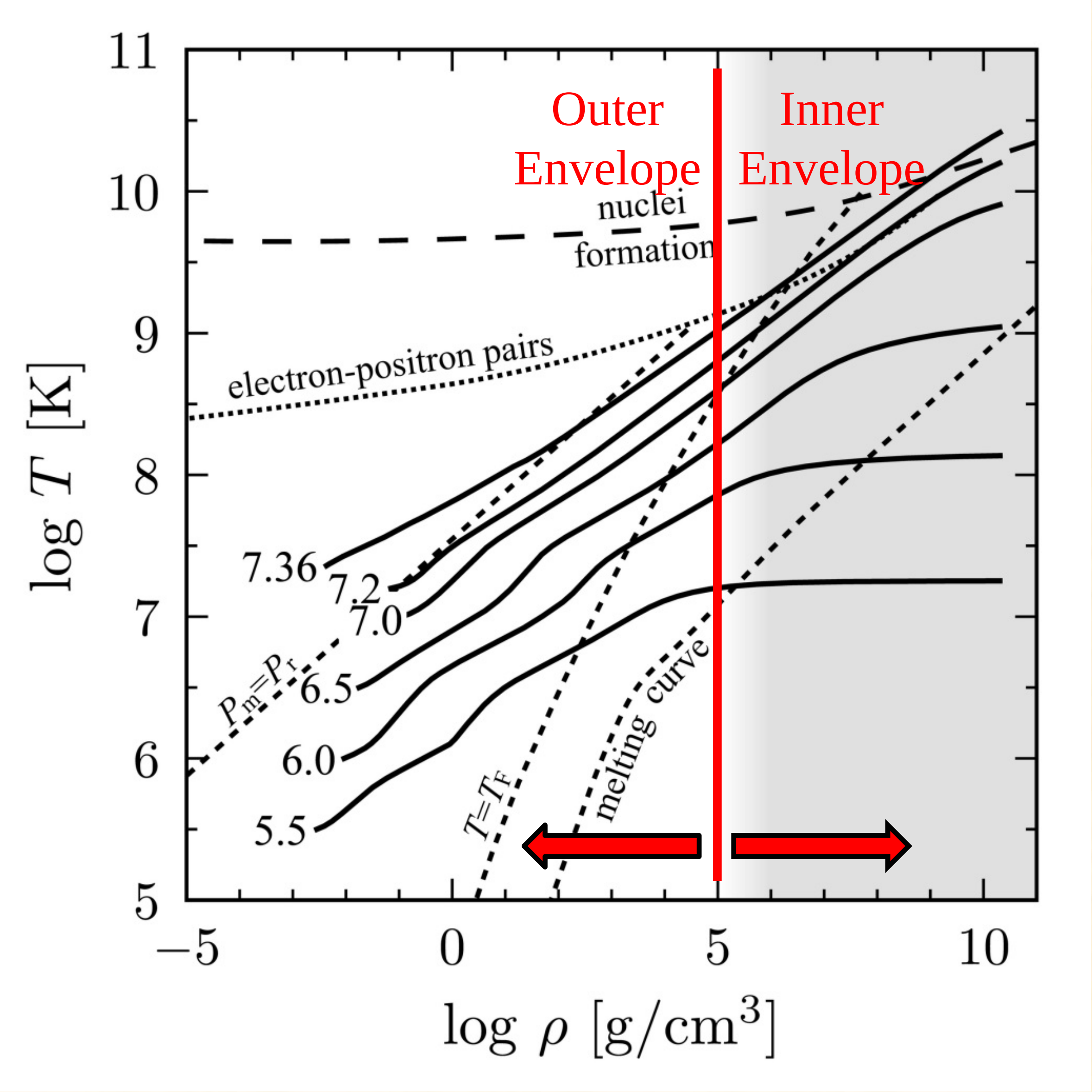
$$\tilde{Q}_L \equiv n\frac{\partial \tilde{L}}{\partial a},\ \tilde{Q}_\nu \equiv \mathrm{e}^{2\Phi} Q_\nu,\ \tilde{Q}_V \equiv -\tilde{T}\left(\frac{\partial P}{\partial T}\right)\Bigg|_n \frac{\partial \ln n}{\partial t}$$

# Stationary iron outer envelope: physical regimes.




$g_s = 10^{14}$ cm/s$^2$

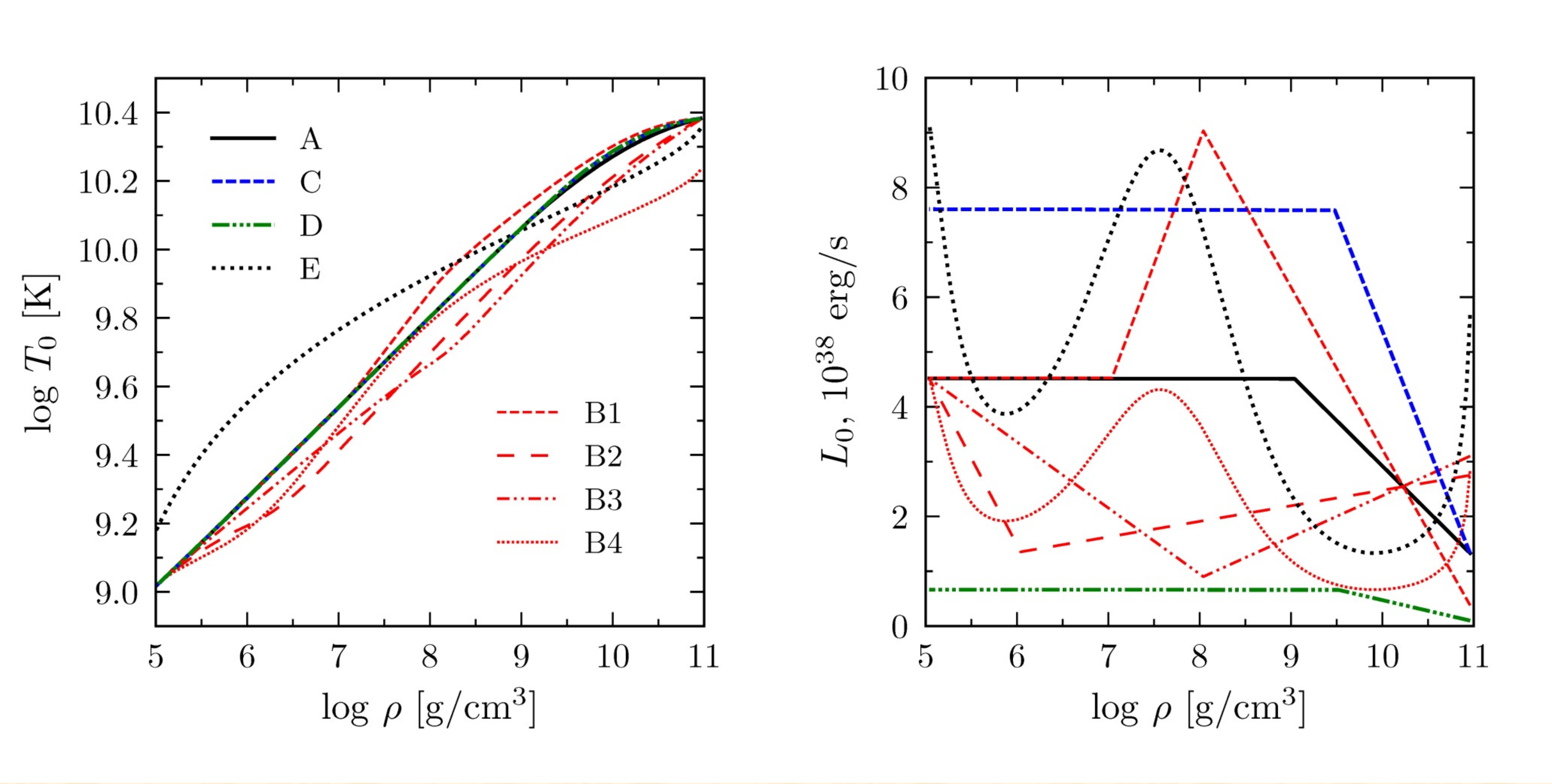
# Stationary iron outer envelope: physical regimes.



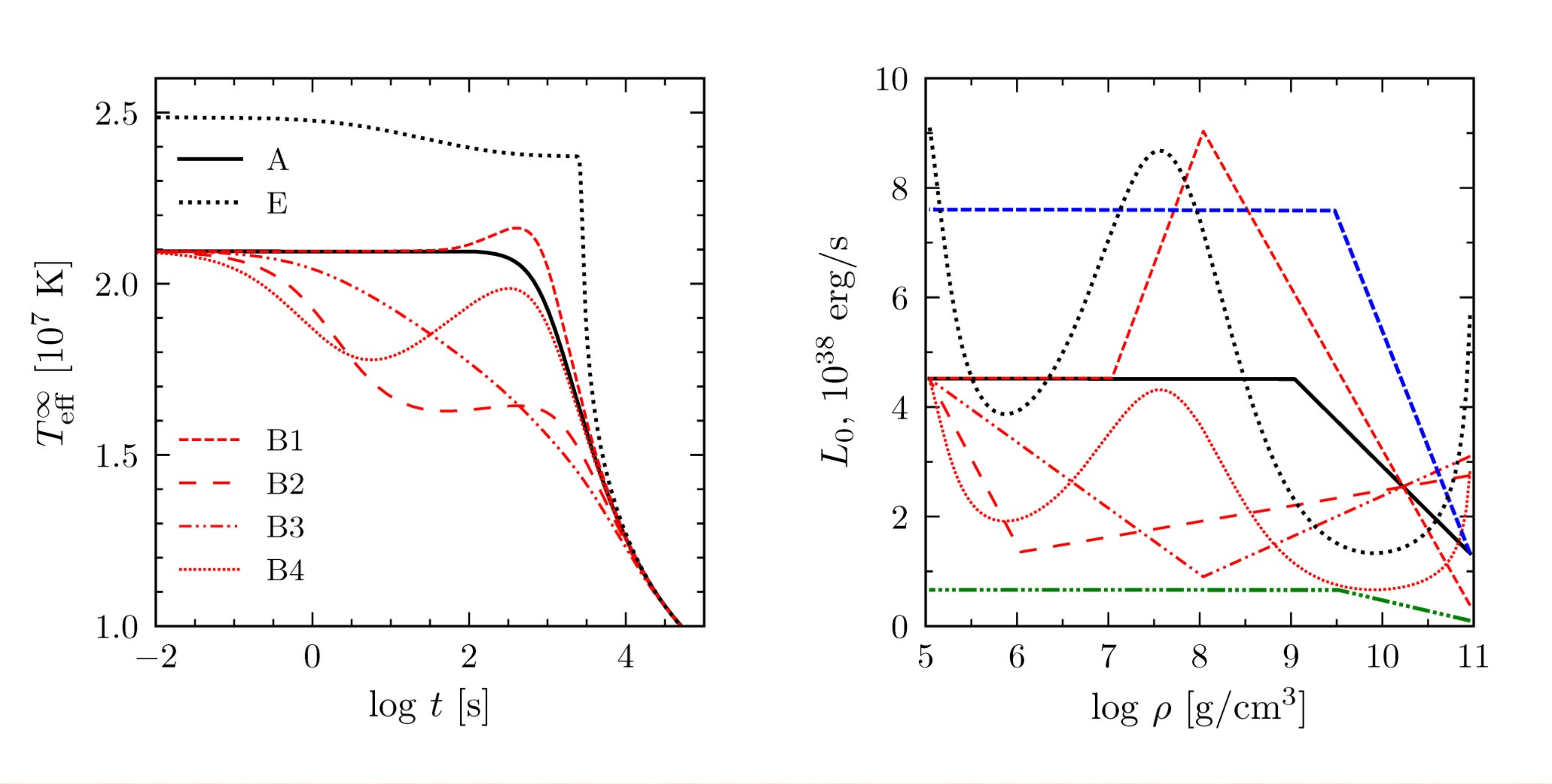

$g_s = 10^{14}$ cm/s$^2$

# Results

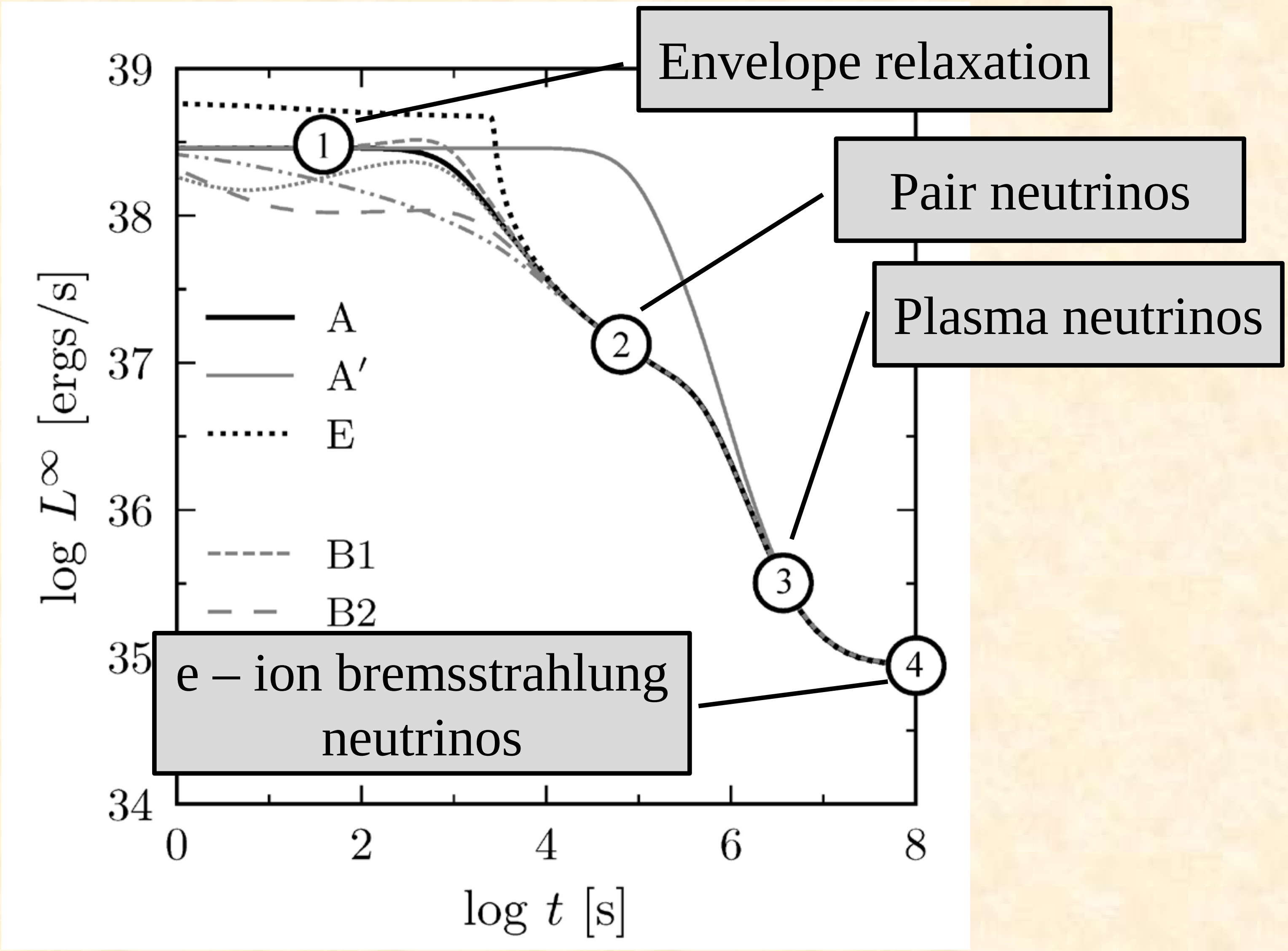
We have considered thermal evolution of neutron stars of the following masses: 0.25 $M_\odot$ (model D), 1.4 $M_\odot$ (models A, B1 – B4 and E) and 2.0 $M_\odot$ (model C). Initial conditions:



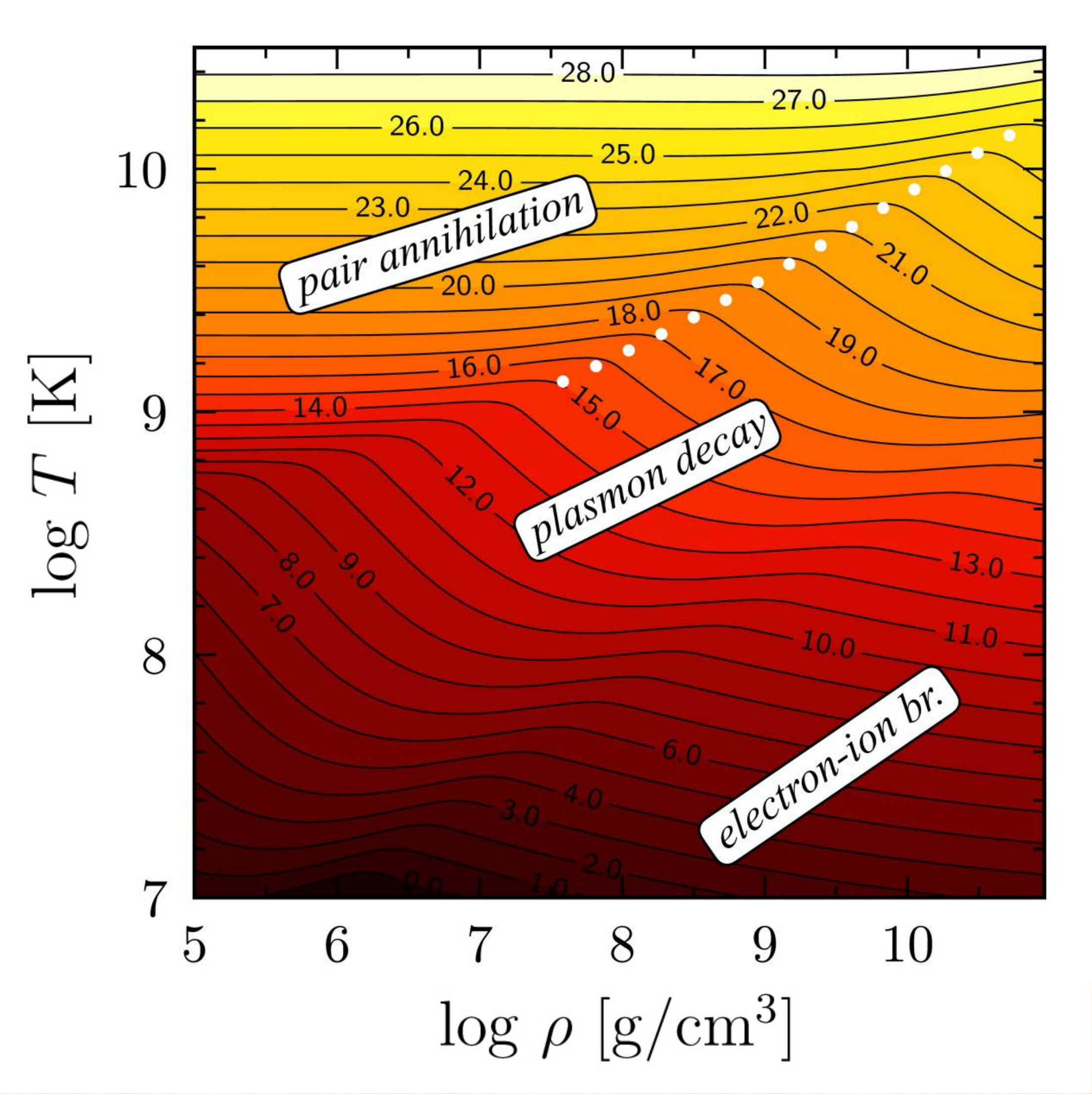
Cooling curves (left) and comparison with initial conditions (right):



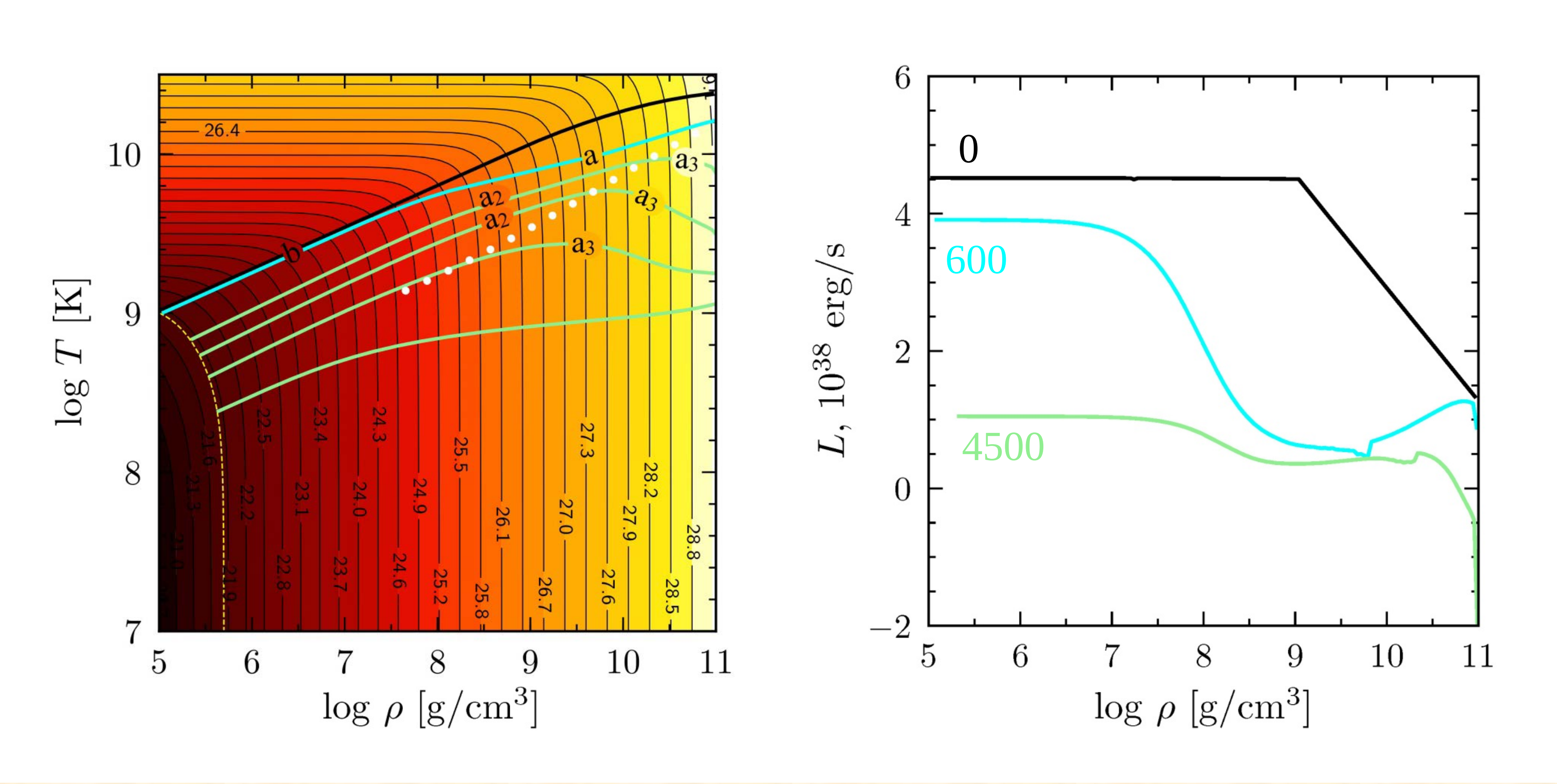
# Early cooling phases details



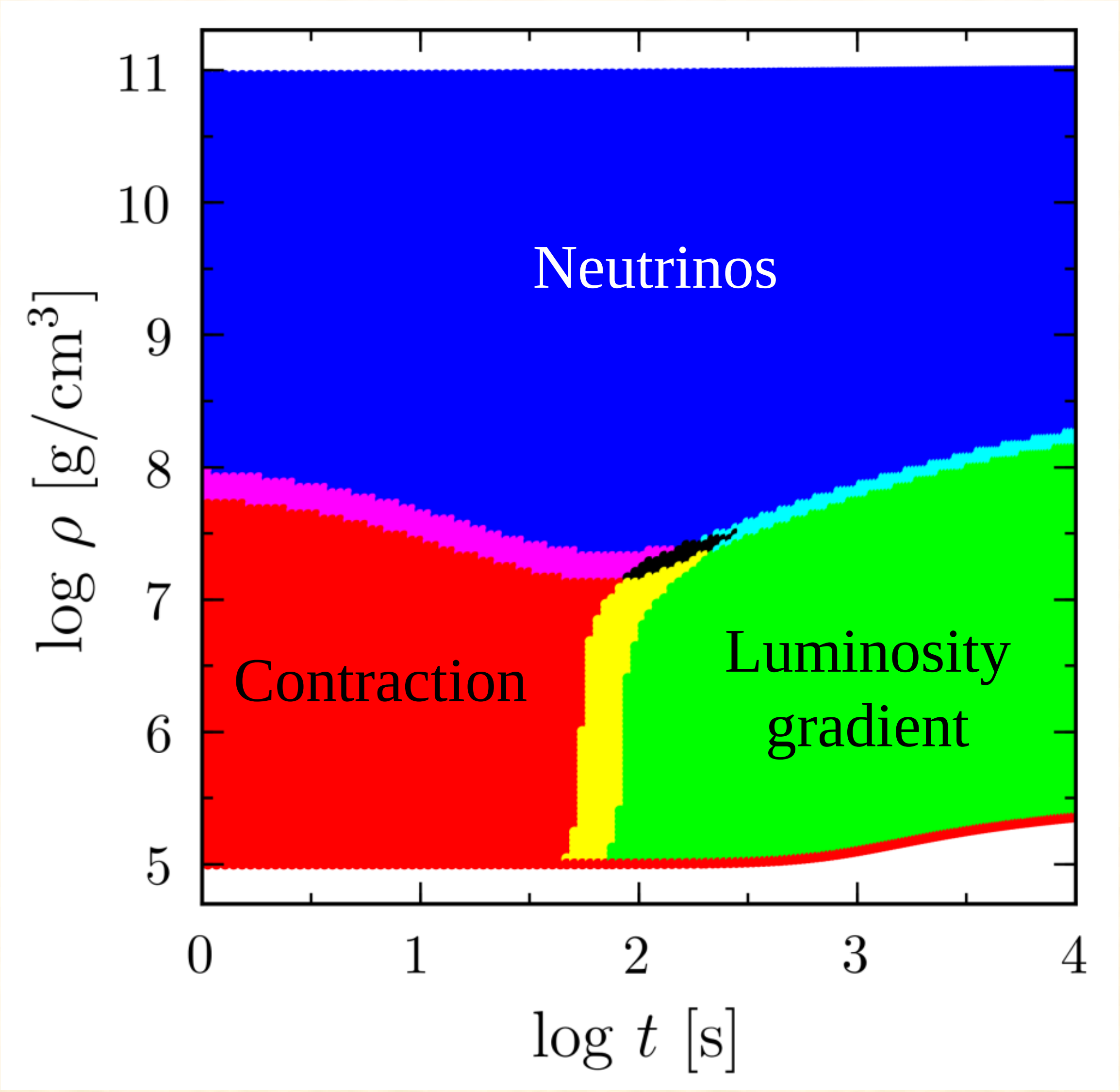
# Neutrino emission mechanisms



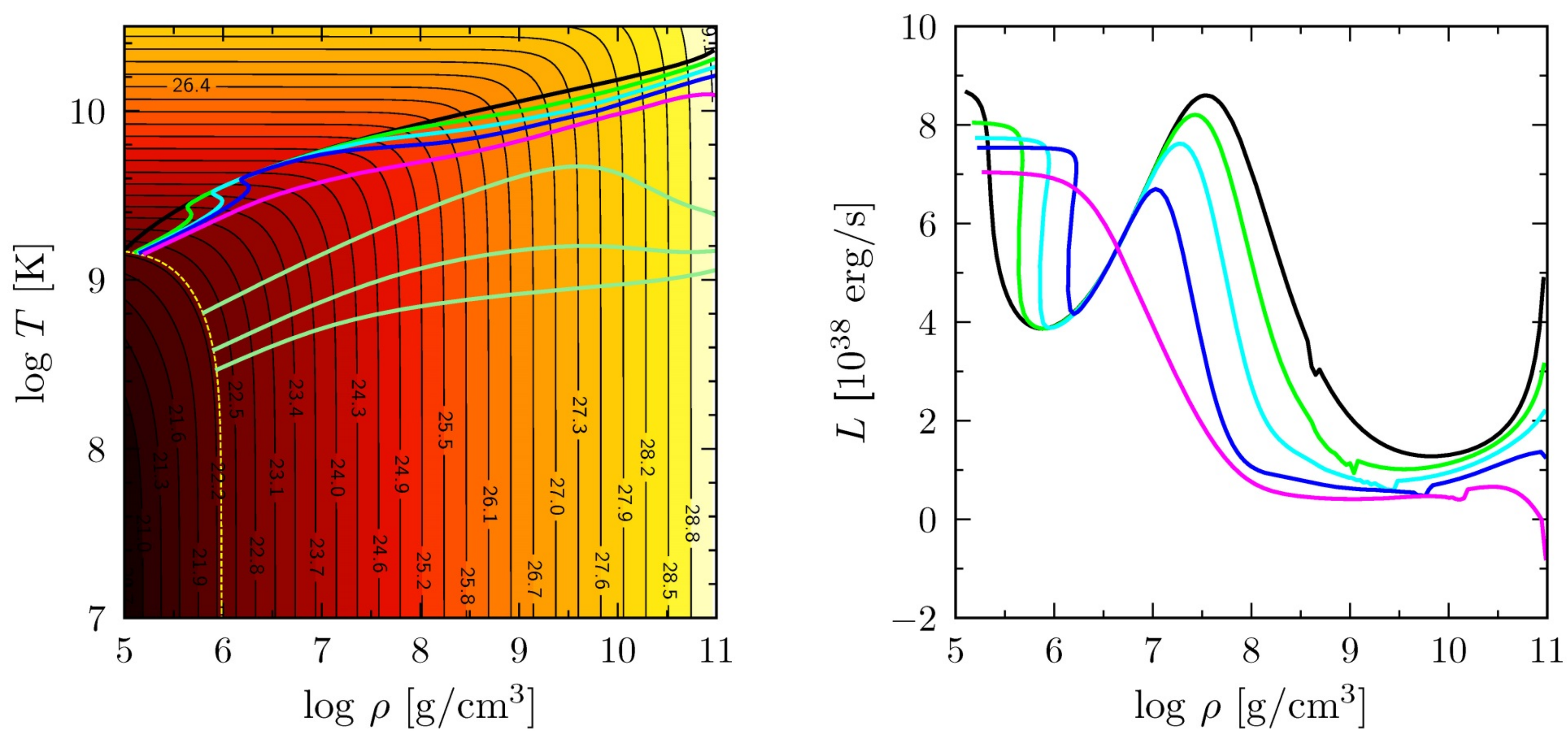
Temperature (left) and luminosity (right) profiles for model A:



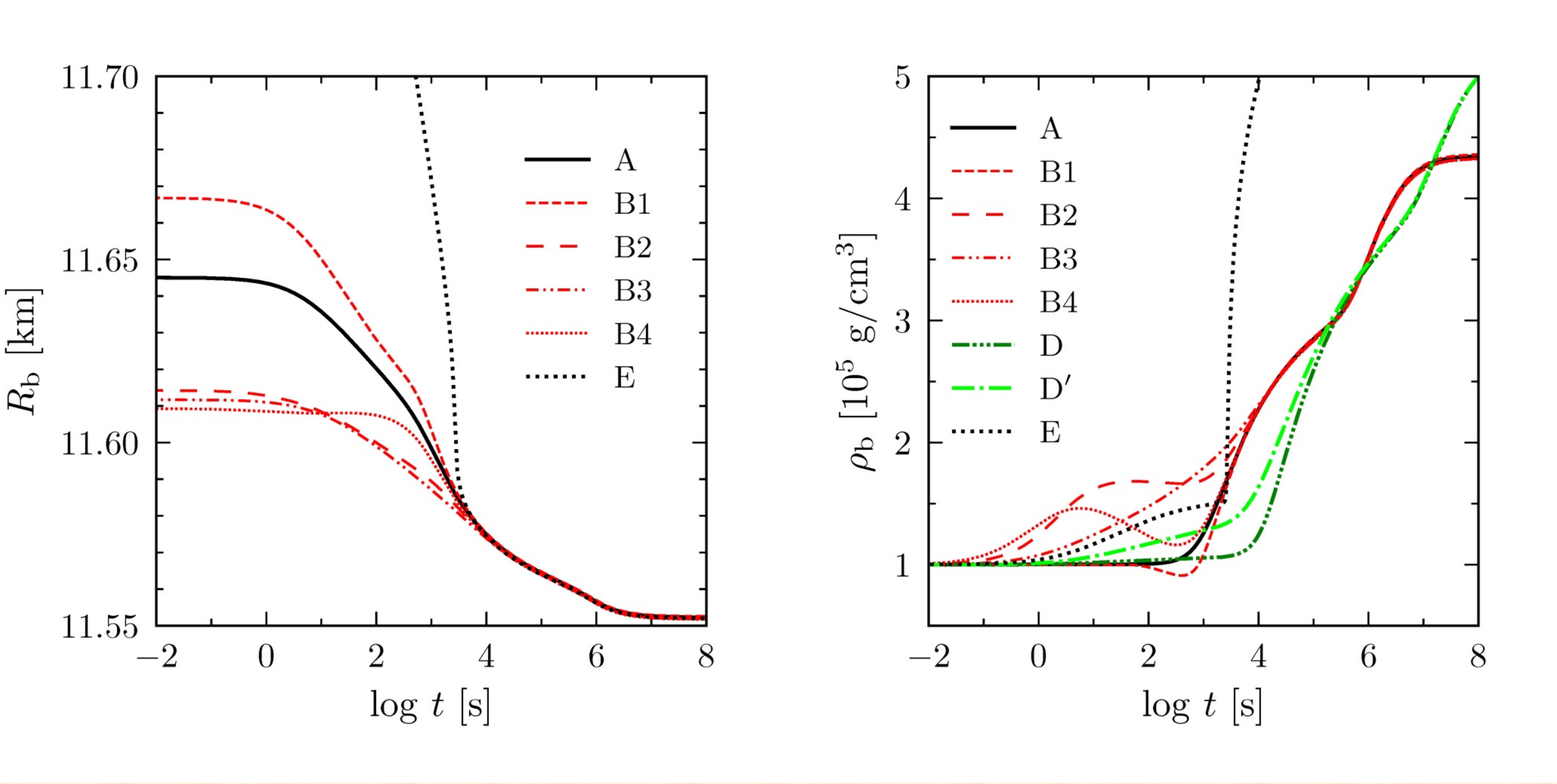
Dominant mechanism of energy release and/or energy loss. Model A.



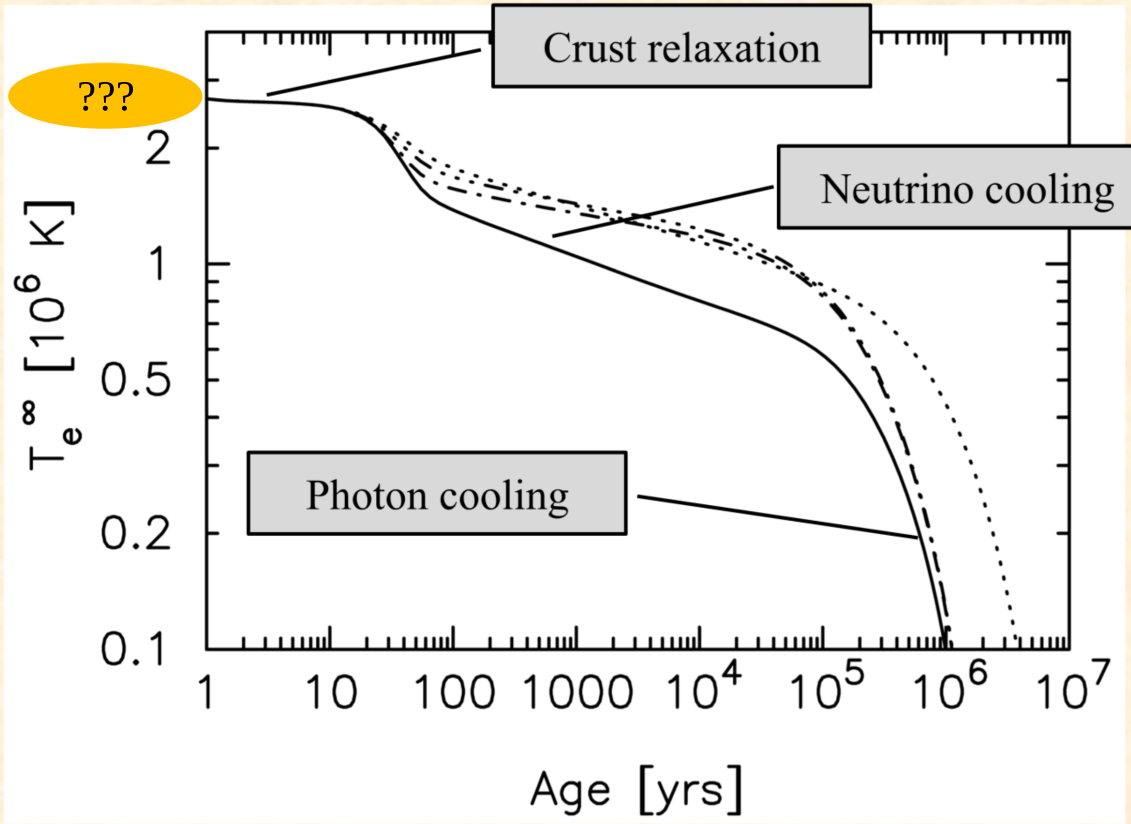
Temperature (left) and luminosity (right) profiles for model E:



Time evolution of the boundary between outer and inner envelopes. Radius is on the left and density is on the right



# Conclusions & Discussion



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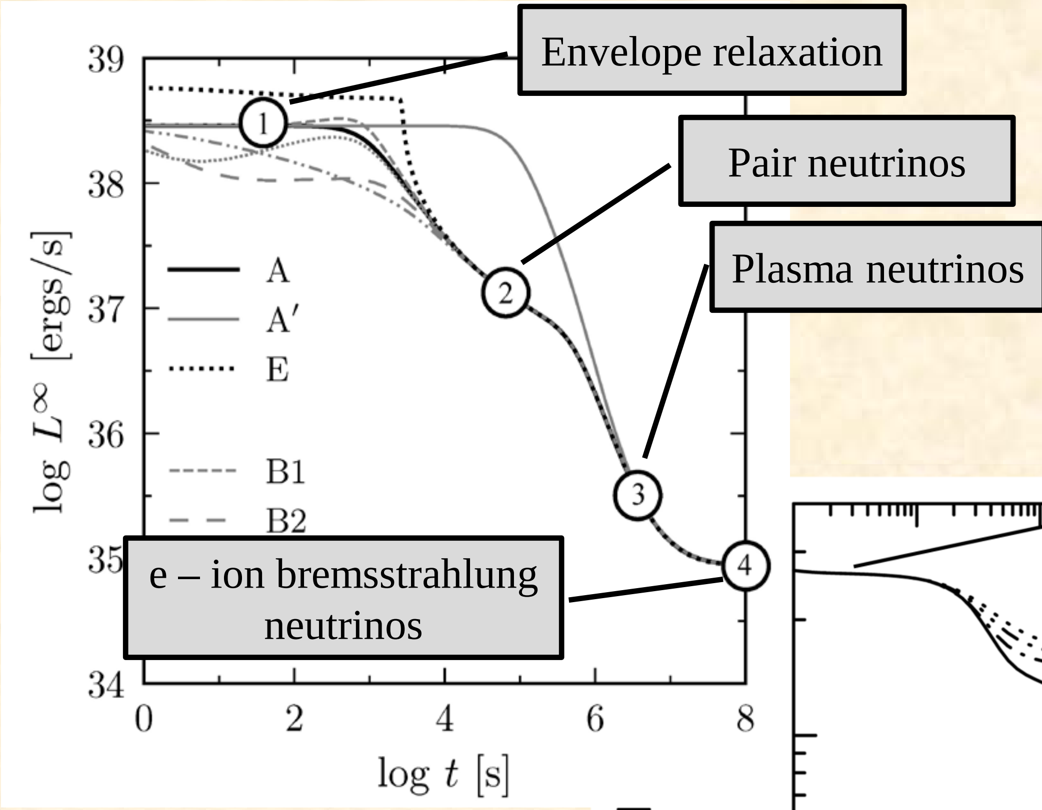
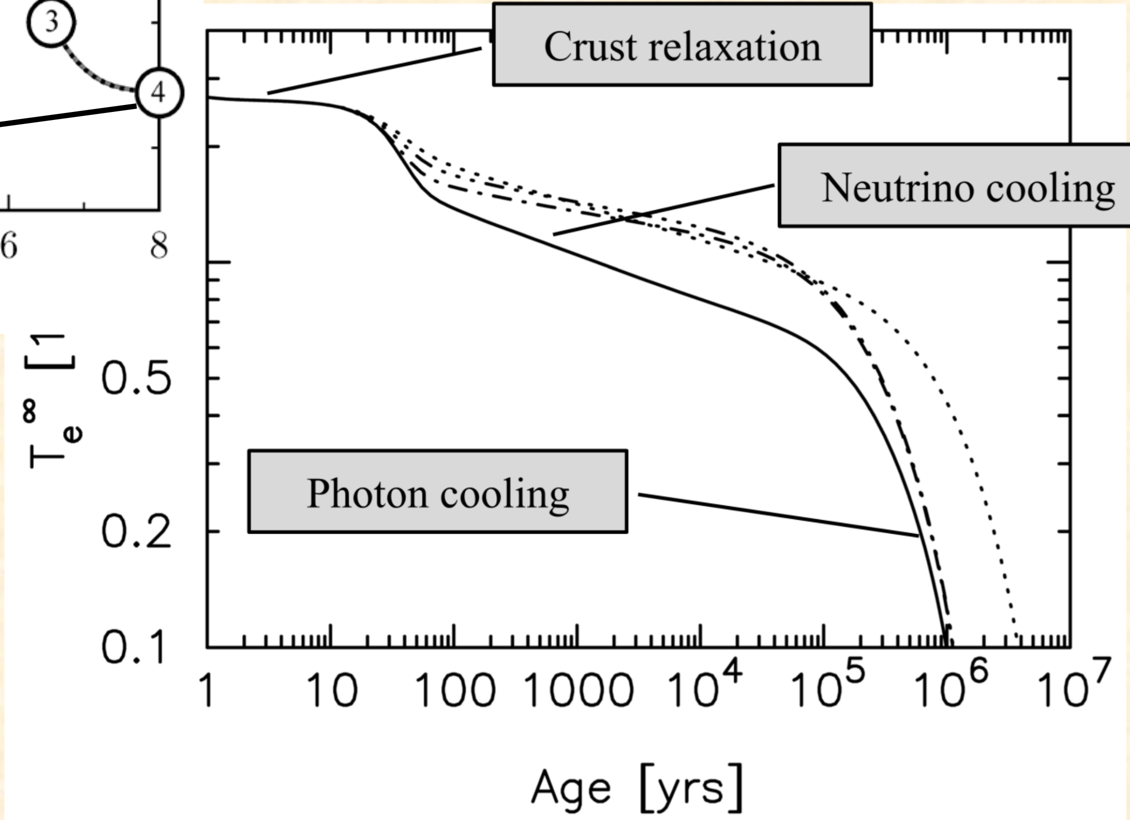
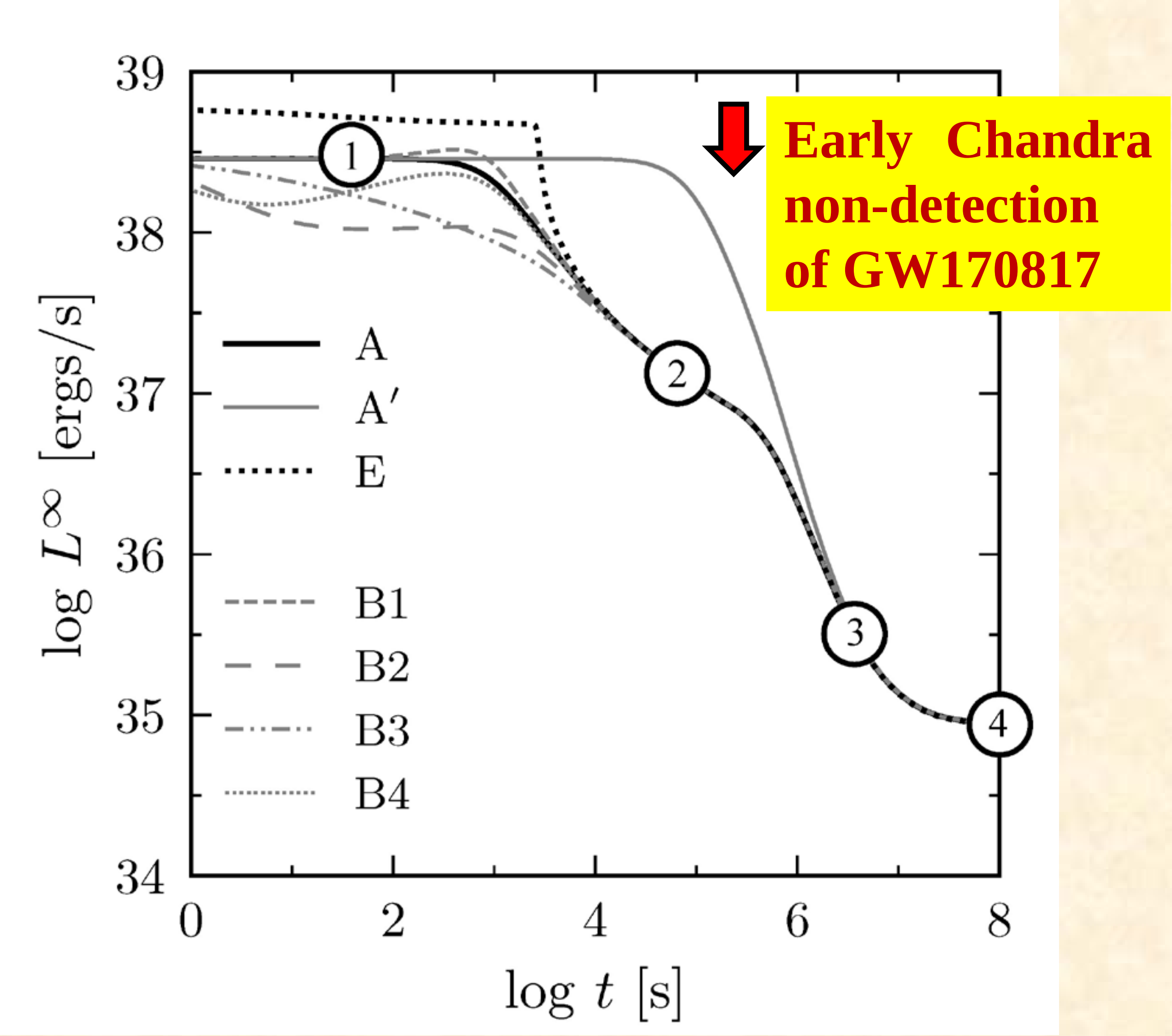


## **Conclusions & Discussion**

- We have modified the standard long-term cooling calculation to handle the thermal evolution of neo-neutron stars and computed early cooling phases in details. To achieve this we had to modify both physical ingredients and solver algorithms.
- The results clearly demonstrate that the initial configuration is very important for the neo-neutron stars thermal evolution. In particular, it was shown how surface temperature maps the initial temperature/luminosity profile. Thus, a question of finding the proper initial conditions arises.
- We have also demonstrated that small change in the initial conditions allows the star to stay at super-Eddington luminosity for ~ 2600 s. This implies noticeable mass loss (equivalent to the mass of the whole outer envelope or more, i.e. $M \sim 10^{-12}\,M_\odot$).

**Conclusions & Discussion**




Thank you for your attention!