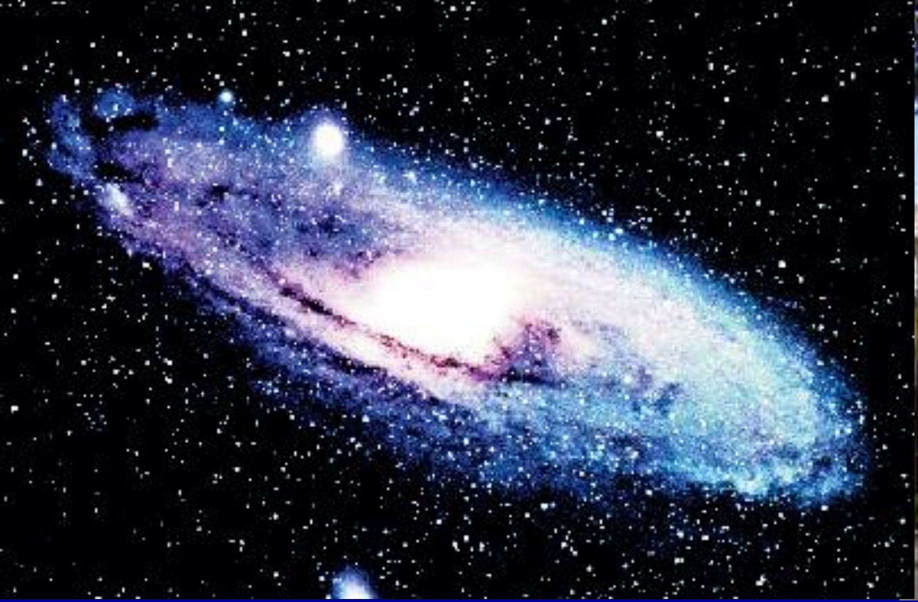


# *Thermal emission of neutron stars with internal heaters*


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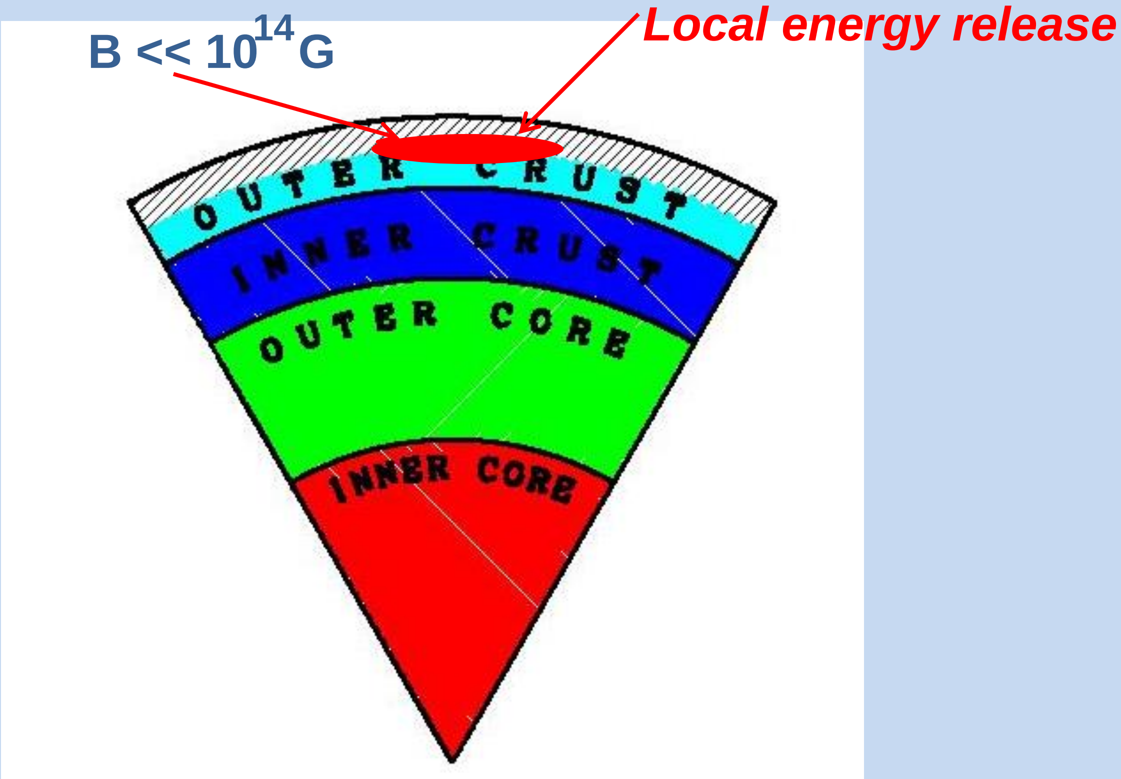
# Specific features

- *Kaminker et al. (2006, 2009) -- what's the news?*

- *Comparison the results of 2D and 1D codes.*
- *Consideration NSs with typical field $B \sim 10^{12}$ G in outer layers including a heat blaketing envelope.*
- *Detailed consideration of heat fux and neutrino emissivities*
- *Dependence on EOS of NS matter*



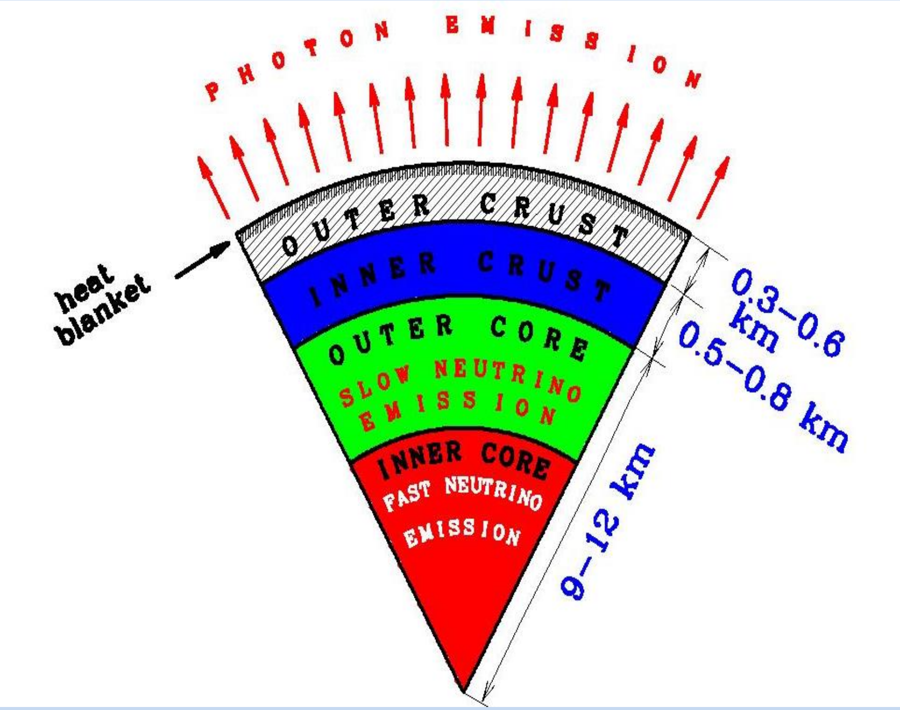
# Heating and cooling of neutron stars

***Oversimplified*** ***equation of thermal diffusion with account of neutrino emissivity*** $Q_\nu$ ***and heating power per unit volume*** $H$**:**

$$c_v \frac{\partial T}{\partial t} = \mathrm{div}\,(\kappa\, \nabla T) - Q_\nu + H$$

(a) The thermal balance equation **(GR)**
(b) The heat transport equation **(GR)**

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




Heat blanketing envelope

Including $Q_\nu$ : $T_s = T_s(T_b)$

$\rho_b = 10^{10}$ g cm$^{-3}$ ; thickness ~ 100 m;
mass of the envelope < $10^{-6}\, M_{Sun}$

Heat content of NS: $U_T \sim 10^{48}\, T_9^2$ *ergs*

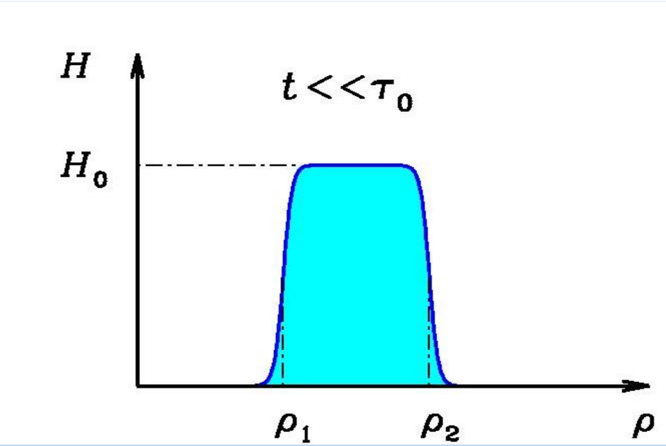
---

**1D** code: $L_r(r) = 4\pi r^2 F_r(r,t),\ T(r,t)$

**2D** code: $F_{r,\theta}(r, \theta, t),\quad T(r, \theta, t)$

# *Phenomenological heater and calculations*

**Radial heat power distribution:**




$$H(\rho,t) = H_0\ \Theta(\rho_1,\rho_2)\ \exp(-t/\tau_0)$$

Four parameters: $\rho_1,\ \rho_2,\ H_0,\ \tau_0$

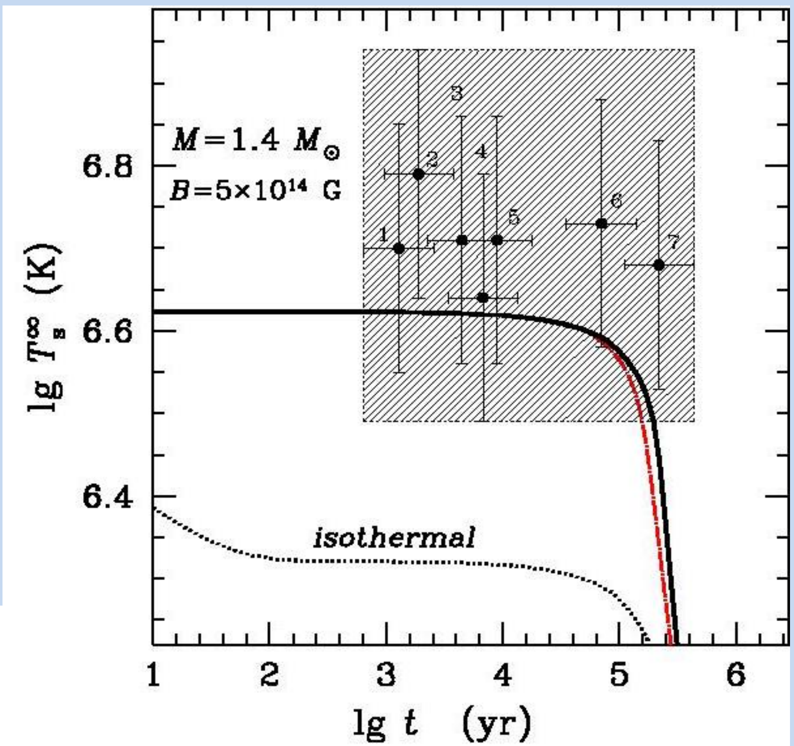
$\tau_0 = 5\times10^4$ yr

***Angular heat power distribution:***

**Either hot "blob" – 2D code,**
***then additional parameter $\theta_0$***

**Or hot spherical layer – 1D code**

$$\rho_1 \le \rho \le \rho_2$$




**Total redshifted heat power :**

$$W^\infty(t) = \int \mathrm{d}V\, e^{2\Phi}\, H,$$

**Run cooling code: in about ~ 10000 years → quasi-stationary temperature distribution determined by the heat source.**

# Two equations of state and model parameters

(1) Toy-model equation of state (EOS):
parametrization -- Heiselberg & Hjorth-Jensen (1999) ⟷ (HHJ)

$$\mathcal{E} = \mathcal{E}_0 u \frac{u - 2 - s}{1 + su} + S_0 u^{\gamma} (1 - 2x_{\rm p})^2.$$

− energy per baryon; HHJ (s, γ )

$u = n / n_0$, $n_0 = 0.16$ fm , $\mathcal{E}_0 = 15.8$ MeV, $S_0 = 32$ *MeV* , *s* & *γ* − *parameters* .

To fit the EOS by Akmal, Pandharipand & Ravenhall (1998) − (APR)

s = 0.2, *γ* = 0.6 − HHJ (0.2, 0.6)

This work: s = 0.1, *γ* = 0.7 − HHJ (0.1, 0.7) in the NS core − $M_{max} = 2.16\, M_{Sun}$

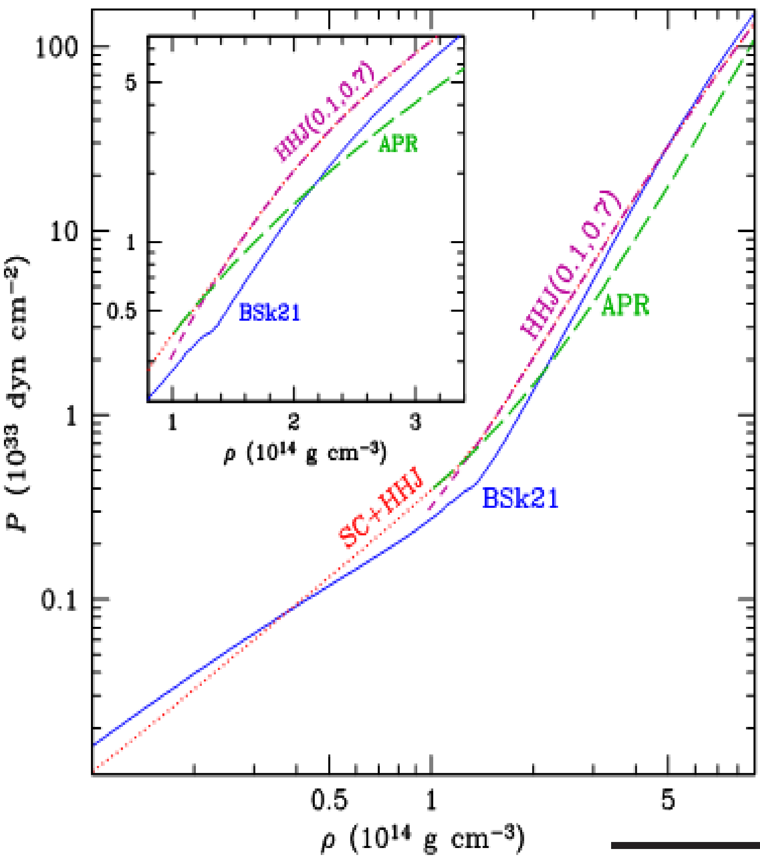
in combination with
smooth composition SC in the NS crust : SC + HHJ (0.1, 0.7)

(2) Analytical parametrizations of the family BSk EOSs: Potekhin et al. (2013)

We use one representative of the BSk − family: BSk 21
by Goriely et al. (2010), Chamel et al. (2010), Pearson et al. (2011, 2012)

with maximum NS mass: $M_{max} = 2.28\ M_{Sun}$

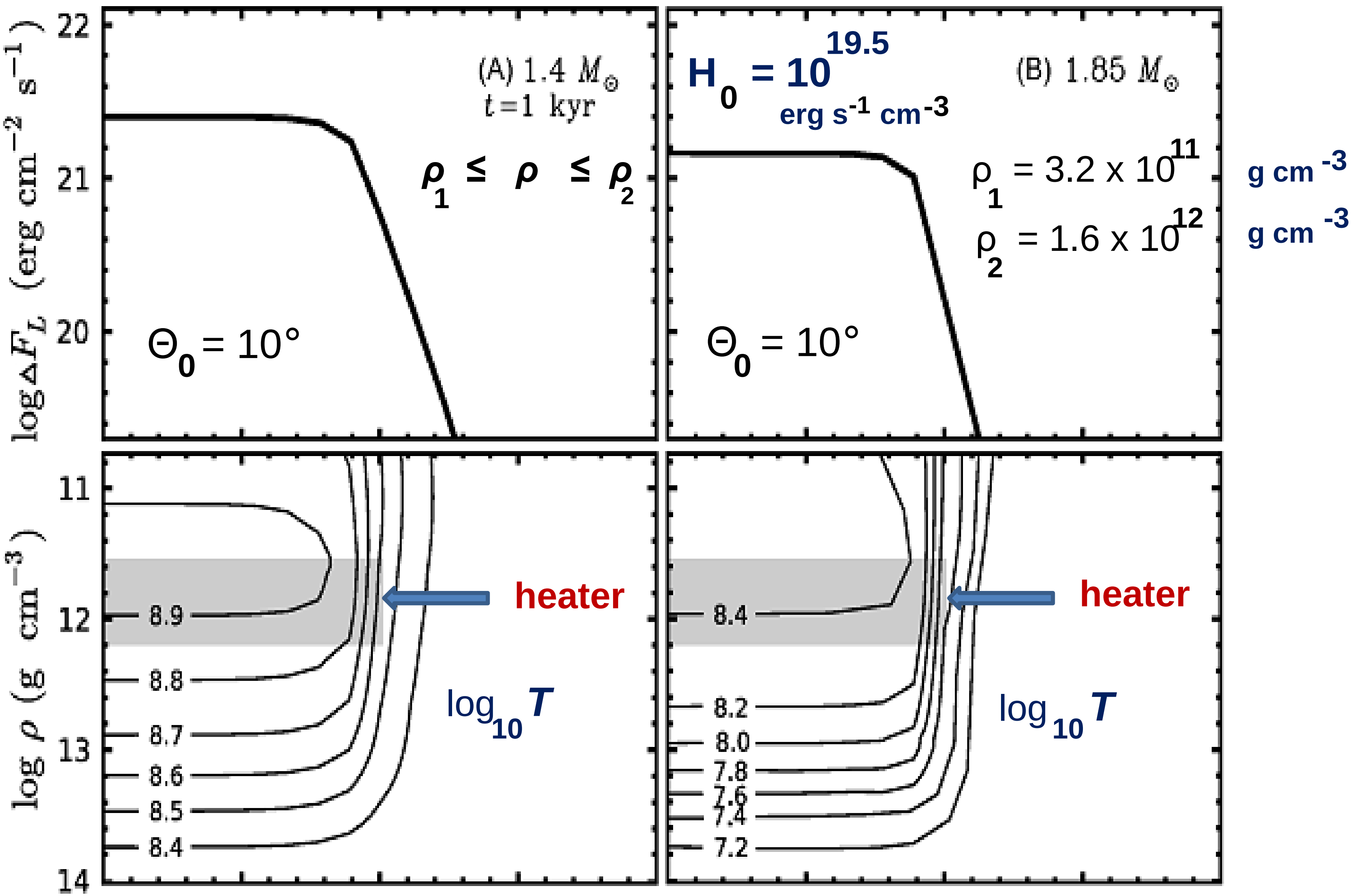
# Equations of state and NS models




| Star model | $M/M_\odot$ | | $R$ (km) | | $\rho_{c14}$ | |
|---|---|---|---|---|---|---|
| | HHJ | BSk | HHJ | BSk | HHJ | BSk |
| Maximum mass | 2.16 | 2.28 | 10.84 | 11.07 | 24.5 | 22.9 |
| Fast cooler | 1.85 | | 12.32 | 12.46 | 11.34 | 9.98 |
| Durca onset | 1.77 | 1.57 | 12.46 | 12.58 | 10.5 | 8.09 |
| Standard cooler | 1.4 | | 12.74 | 12.57 | 7.78 | 7.3 |

# Results of 2D code

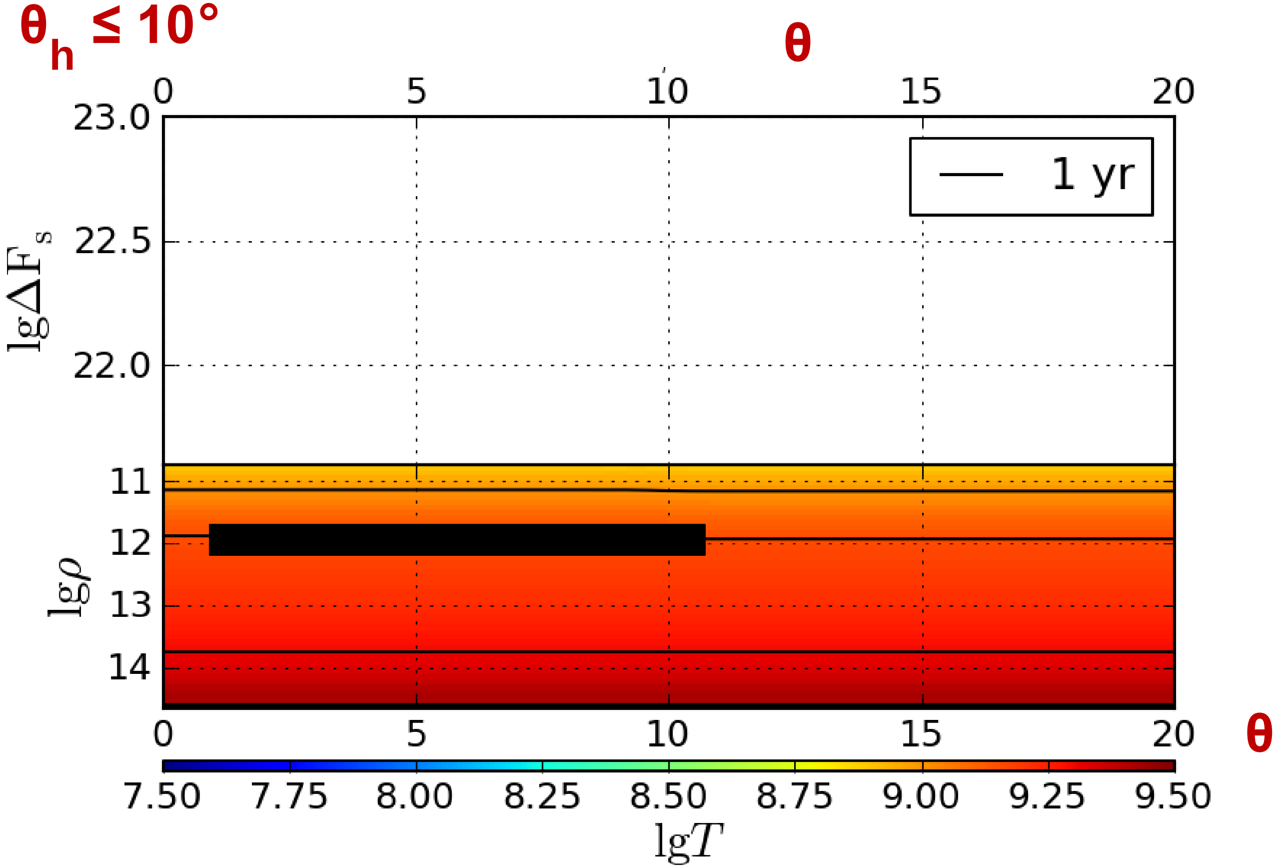
**Excess** heat flux density : $\Delta F_L = F_L - F_{L0}$ ; $F_{L0}$ – heat flux without heater



# Results of 2D code as series of snapshots

**Heater: angular distribution**

**$\theta_h \leq 10°$**




**Heater:**
***~ 400 m under surface***
***~ 80 m width***

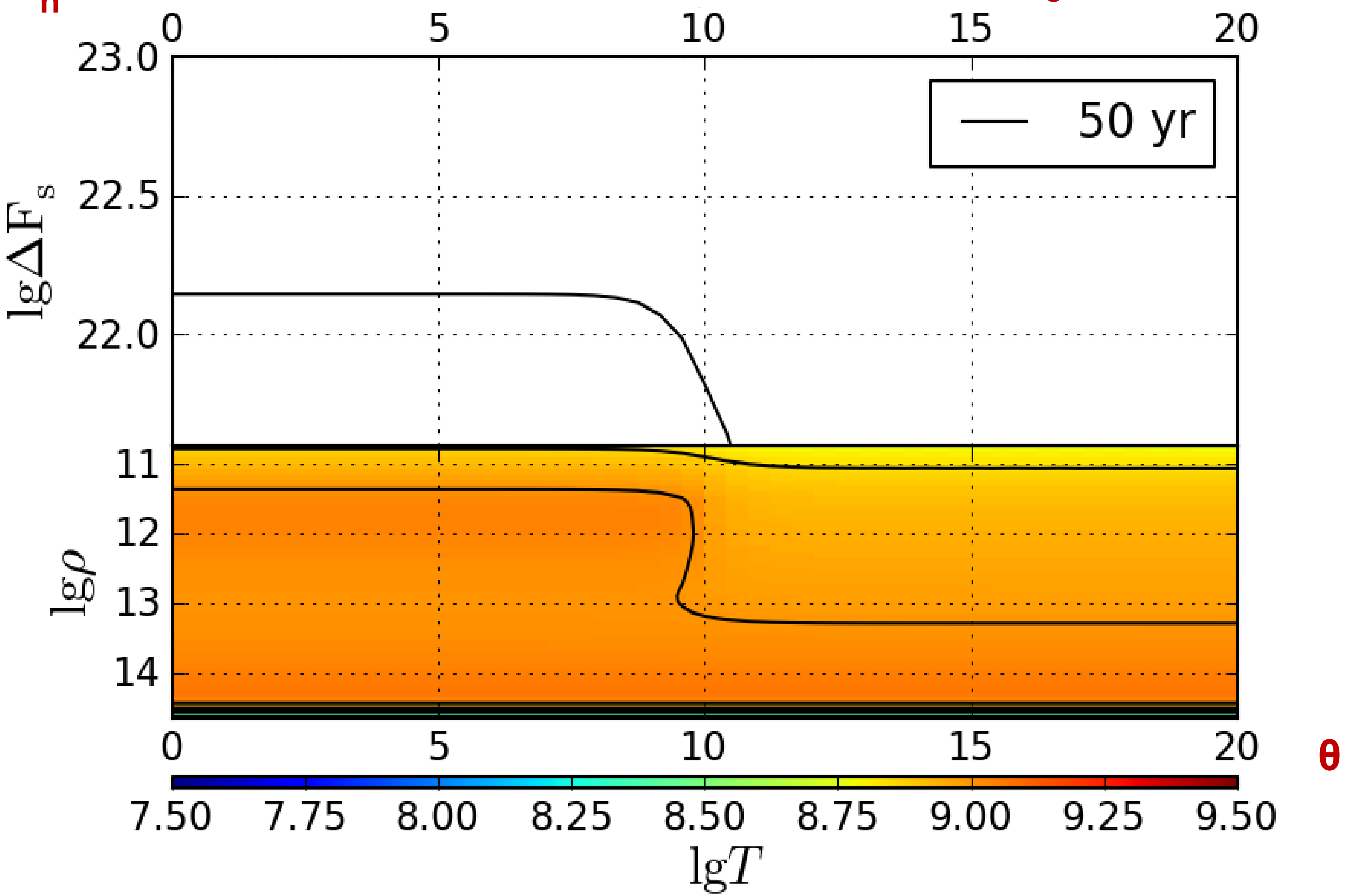
$$\rho_1 = 3.2 \times 10^{11} \text{ g cm}^{-3}$$

$$\rho_2 = 1.6 \times 10^{12} \text{ g cm}^{-3}$$

$$H_0 = 10^{19.5} \text{ erg cm}^{-3} \text{ s}^{-1}$$

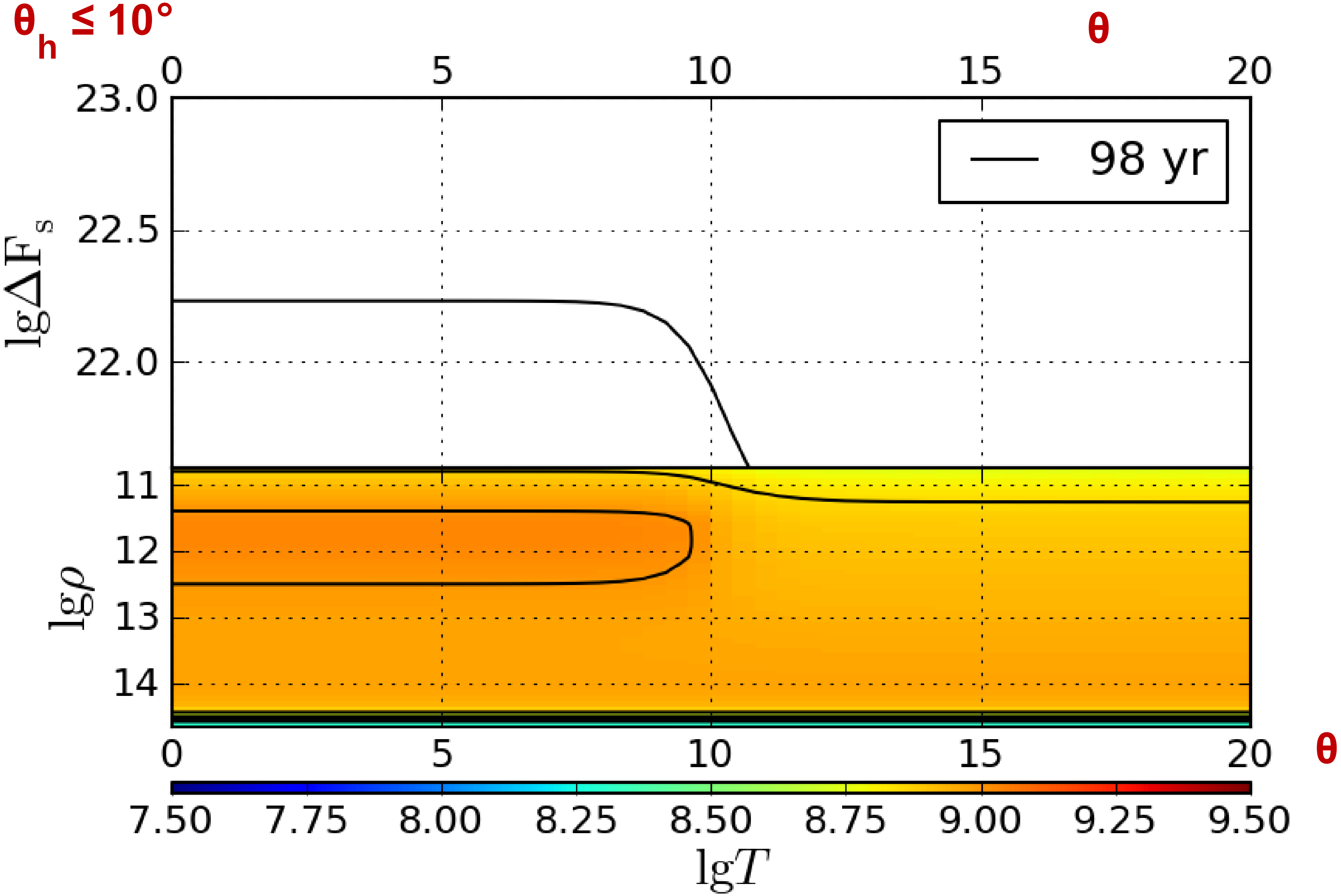
**Heater: angular distribution**

$\theta_h \leq 10°$



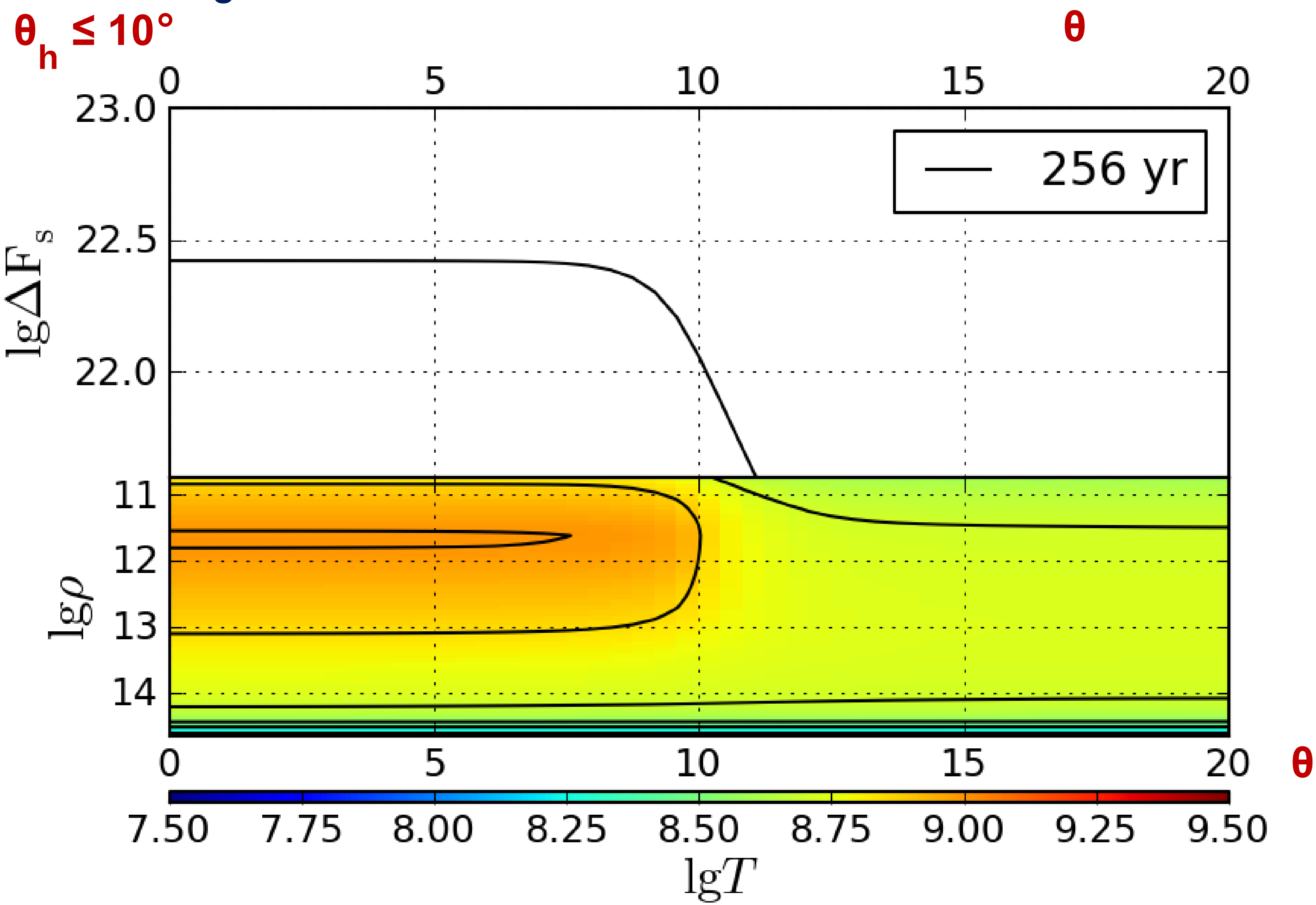
## Heater: angular distribution

$\theta_h \leq 10°$



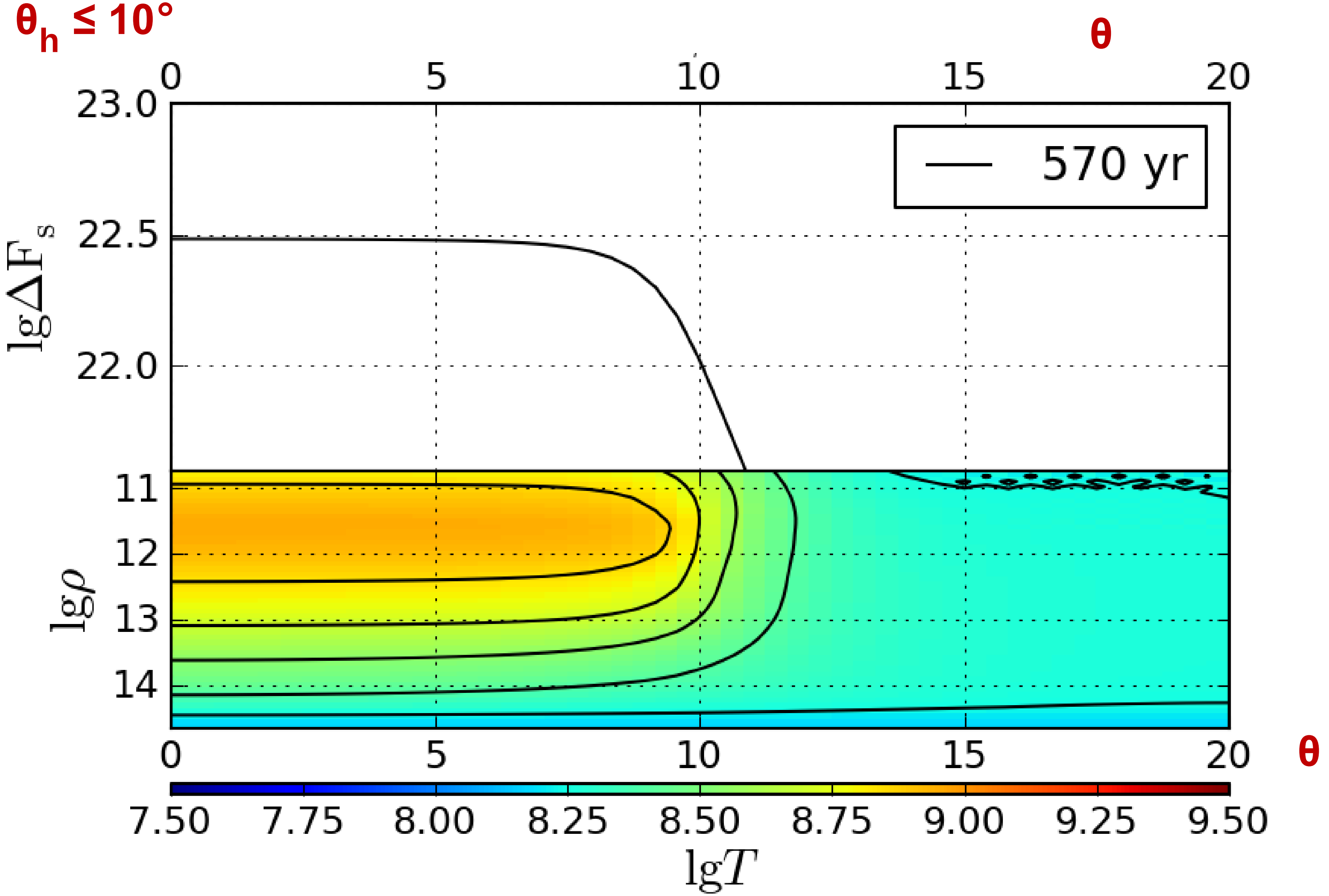
**Heater: angular distribution**

$\theta_h \leq 10°$

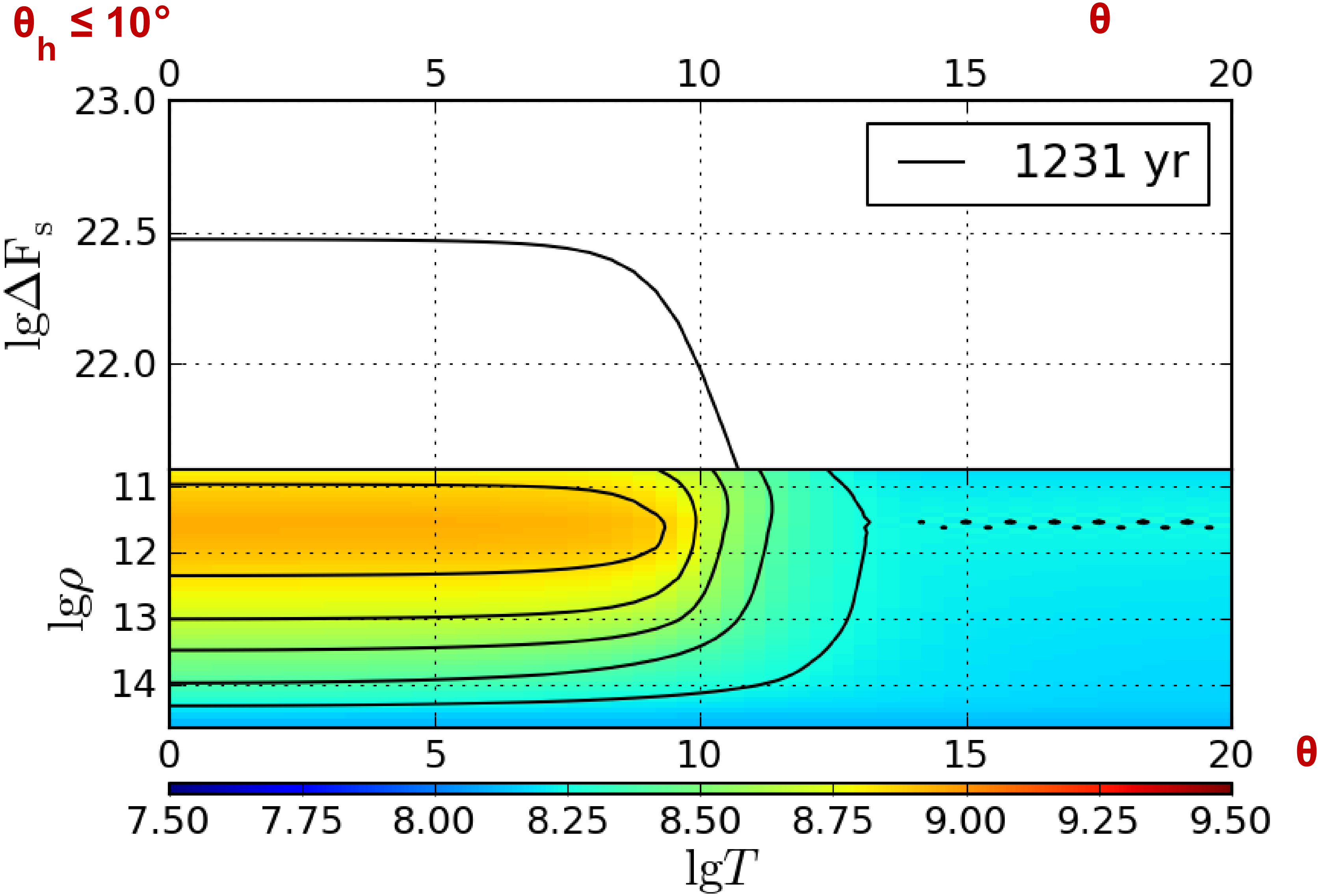


**Heater: angular distribution**

**$\theta_h \leq 10°$**

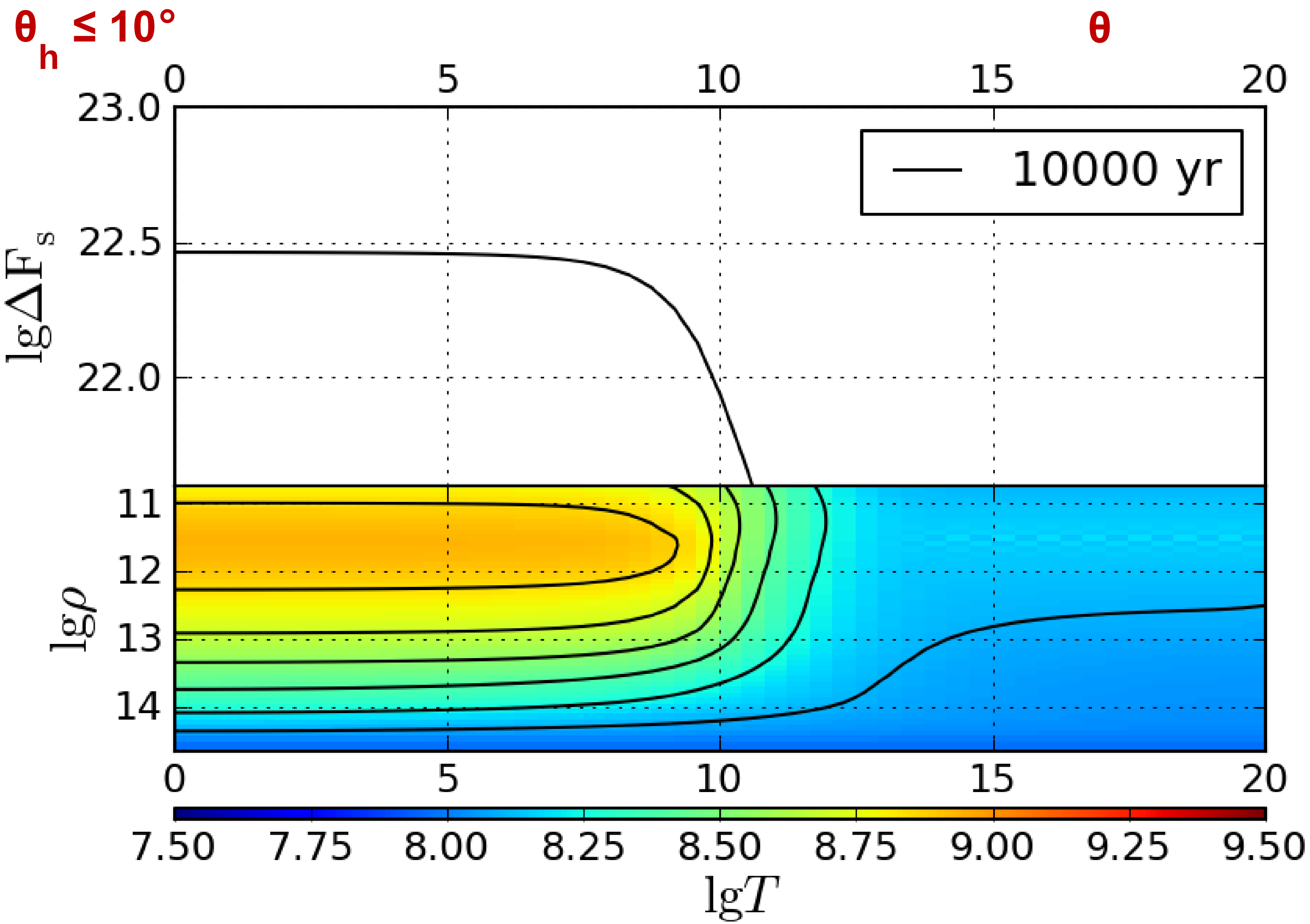


## Heater: angular distribution



# Weak heat spreading along the surface

**Heater: angular distribution**

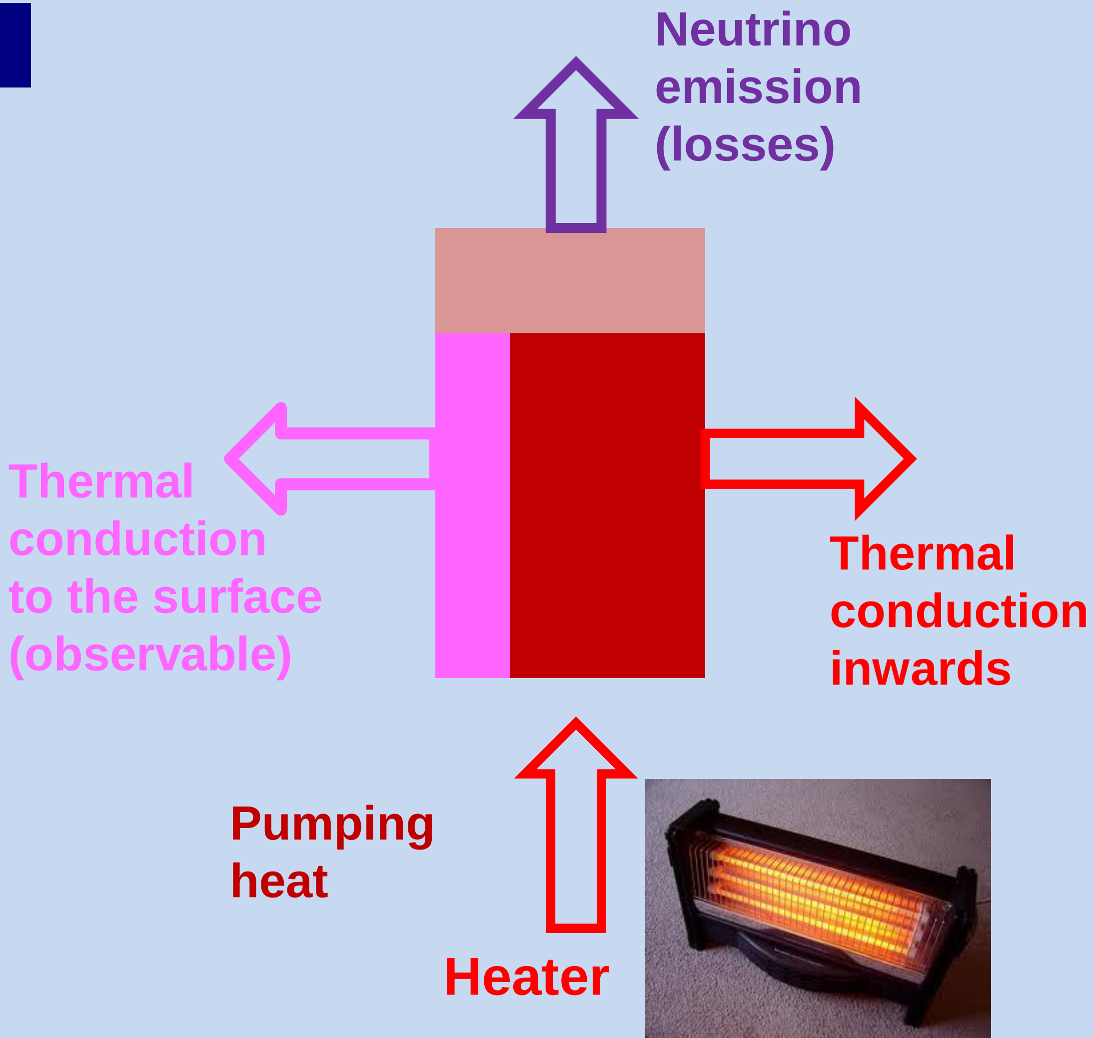


# Weak heat spreading along the surface

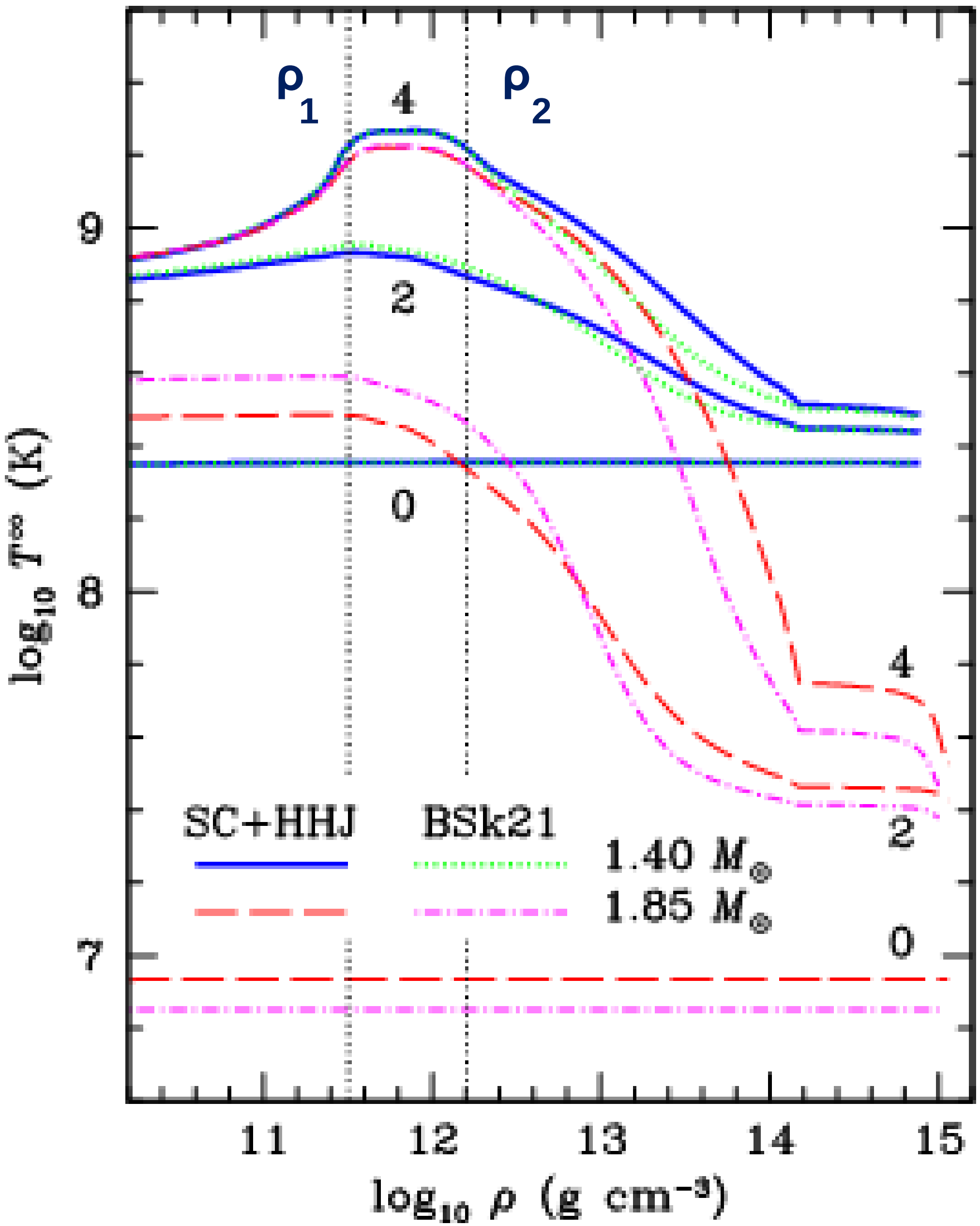
**Heat does not spread along the surface:**
**heater's area is projected on the surface**
**1D and 2D codes give similar results**

***Pons and Rea (2012)***
***but see:***
***Pons, Miralles, Geppert (2009)***
***Vigano et al. (2013)***

## Carrying away pumped heat:



# Temperature profiles inside 1.4 $M_{Sun}$ and 1.85 $M_{Sun}$ stars




$T^{\infty}(\rho) = T(\rho)\, e^{\Phi}$

$\rho_1 = 3.2 \times 10^{11}$ g cm$^{-3}$

$\rho_2 = 1.6 \times 10^{12}$ g cm$^{-3}$

0 – $H_0 = 0$; erg s$^{-1}$ cm$^{-3}$

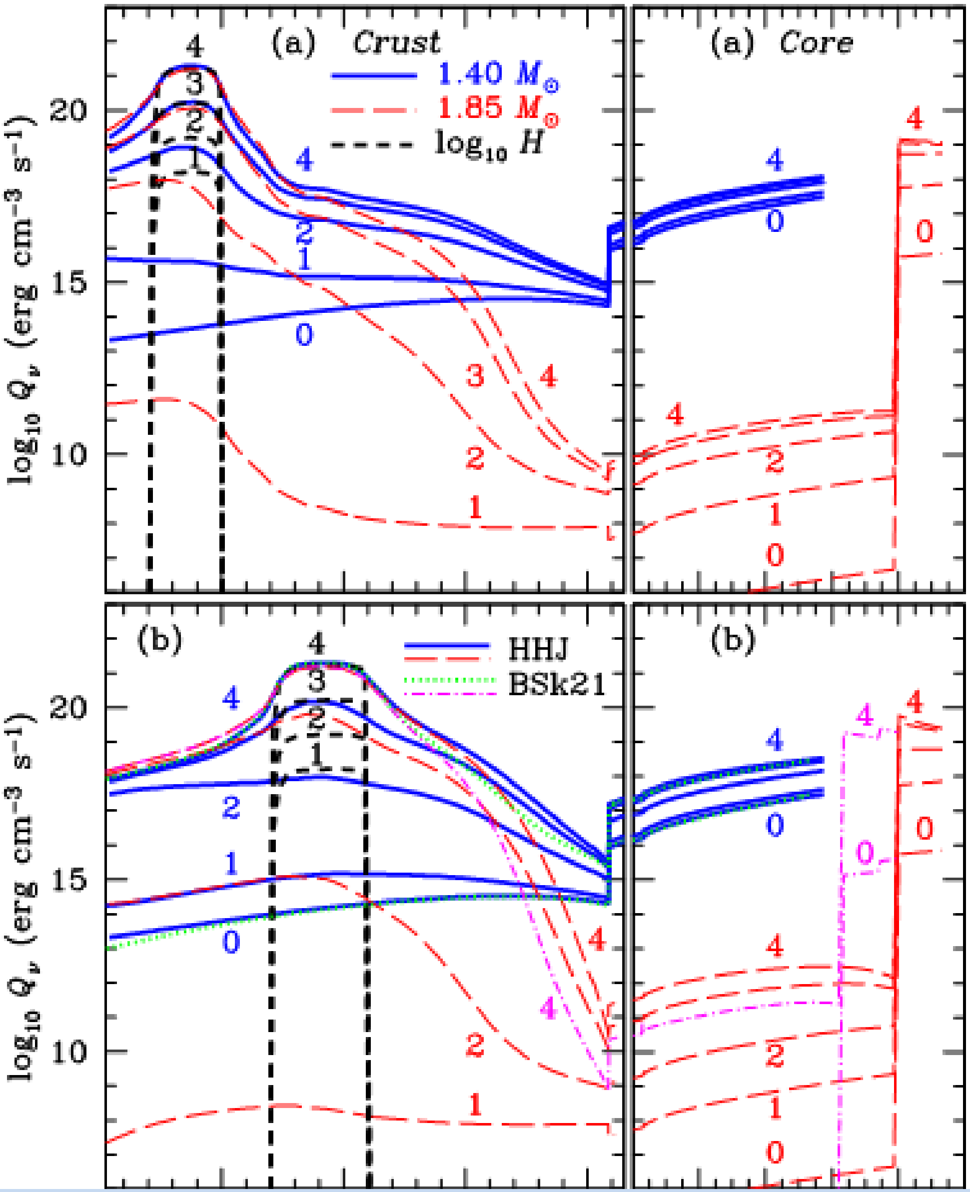
1 – $H_0 = 10^{18.5}$

2 – $H_0 = 10^{19.5}$

3 – $H_0 = 10^{20.5}$

4 – $H_0 = 10^{21.5}$

# Neutrino emissivity and heat density profiles




11 12 13 14

$\log_{10}\rho$ (g cm$^{-3}$)

4 6 8 10

$\rho$ ($10^{14}$ g cm$^{-3}$)

(a) $\rho_1 = 3.20 \times 10^{10}$ g cm$^{-3}$

$\rho_2 = 9.20 \times 10^{10}$ $M = 1.4\ M_{Sun}$

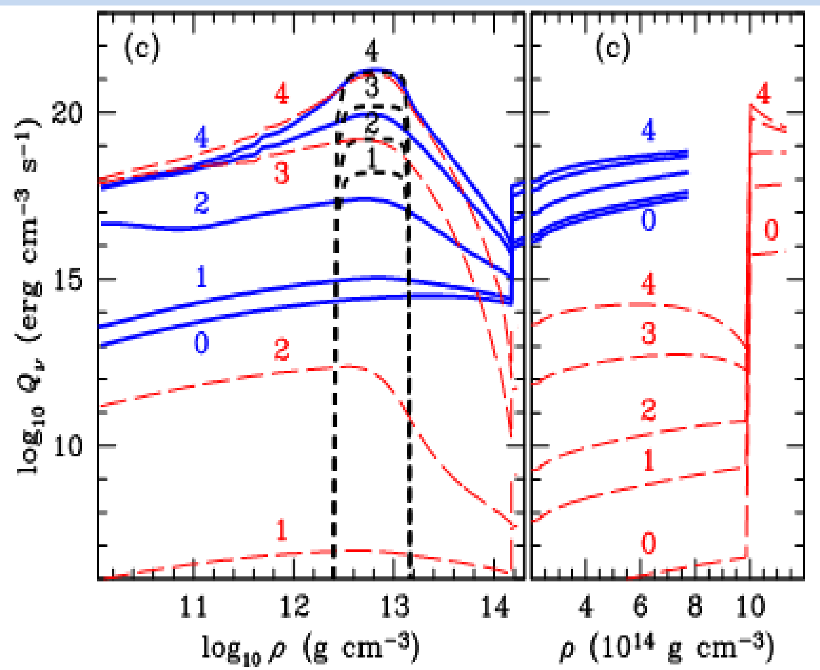
$\rho_2 = 9.34 \times 10^{10}$ $M = 1.85\ M_{Sun}$

(b) $\rho_1 = 3.20 \times 10^{11}$ g cm$^{-3}$

$\rho_2 = 1.60 \times 10^{12}$

(c) $\rho_1 = 3.20 \times 10^{12}$ g cm$^{-3}$

$\rho_2 = 1.27 \times 10^{13}$



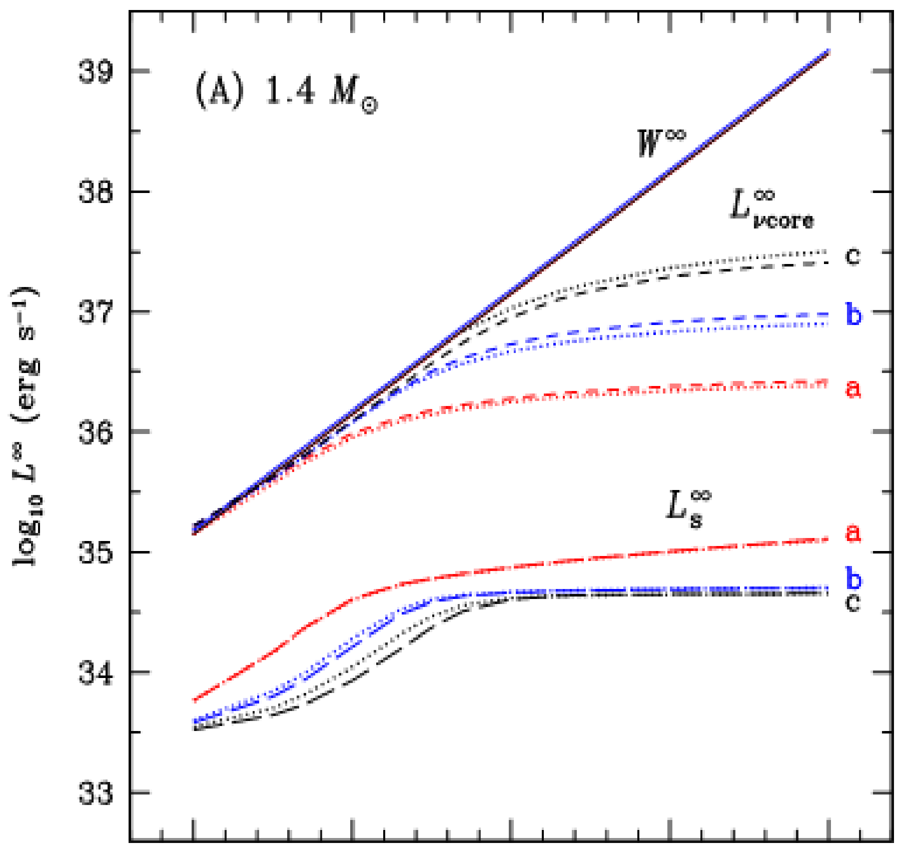
# Total heat flux vs. surface photon luminosity and heat flux towards NS core

$W^{\infty}$ – *total redshift heat power,*

Efficiency: $L_s^{\infty} / W^{\infty}$ ~ a few %

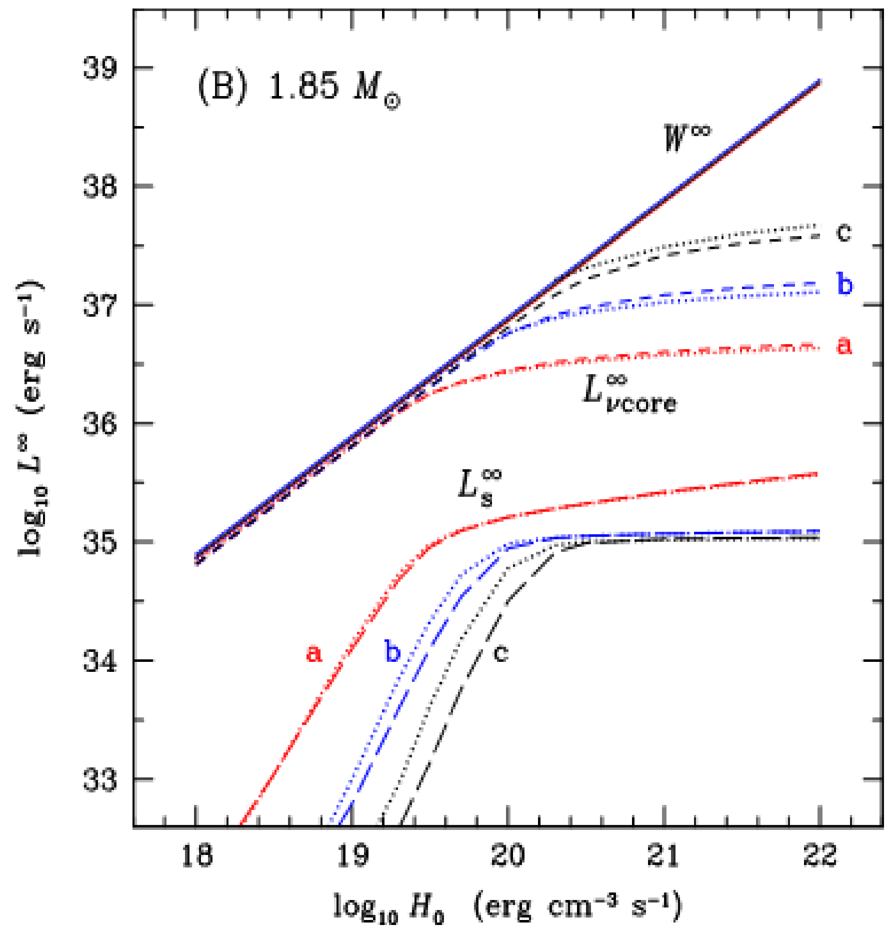
$L^{\infty}_{\nu core}$ – neutrino luminosity of the core

$L_s^{\infty}$ – surface thermal luminosity




18 19 20 21 22

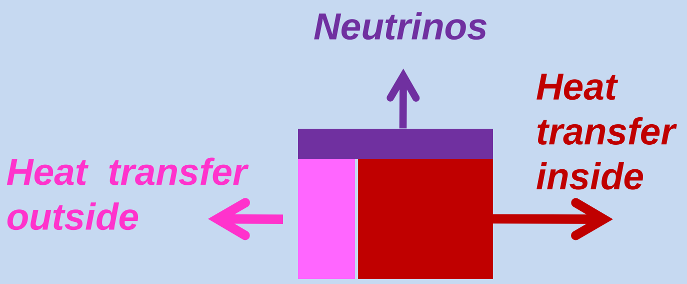
$\log_{10} H_0$ (erg cm$^{-3}$ s$^{-1}$)



# Heating regimes

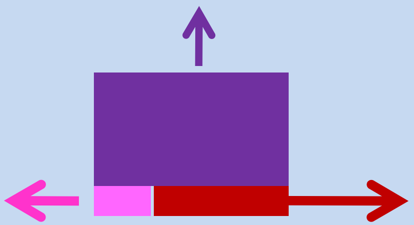
**1** $T < 10^9$ K, $H_0 < 10^{20}$ erg cm$^{-3}$ s$^{-1}$

***Conduction outflow regime:***




**2** $T > 10^9$ K, $H_0 > 10^{20}$ erg cm$^{-3}$ s$^{-1}$

***Neutrino outflow regime:***



# Non-economical heater

***What is observed as quasi-persistent emission is basically a small fraction of input energy***

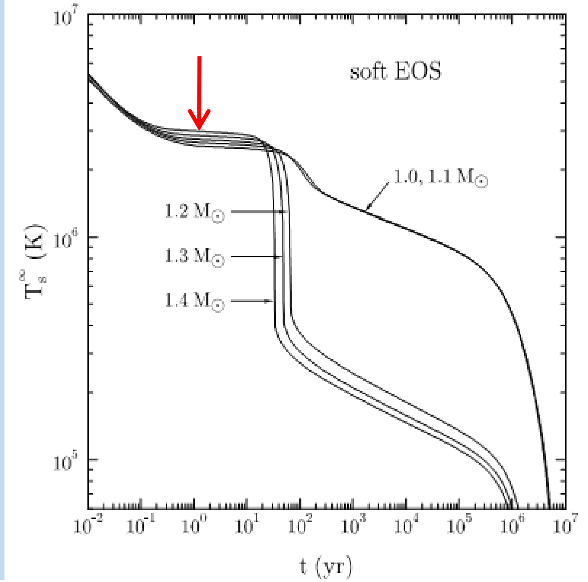
# Most economical heater

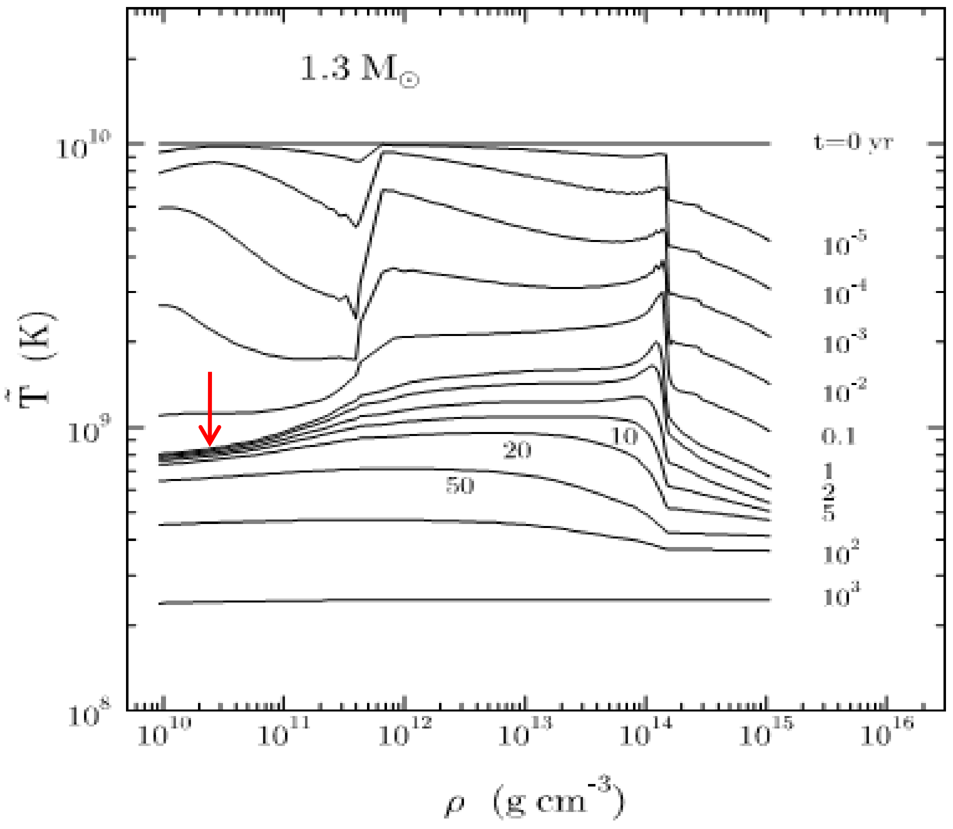
| | |
|---|---|
| ***Position:*** | ***Outer crust*** |
| ***Heat power:*** | $H_0 < 10^{20}$ erg cm$^{-3}$ s$^{-1}$ |
| ***Efficiency to heat surface:*** | ***<3%*** |
| ***Angular distribution:*** | ***Hot spot*** |

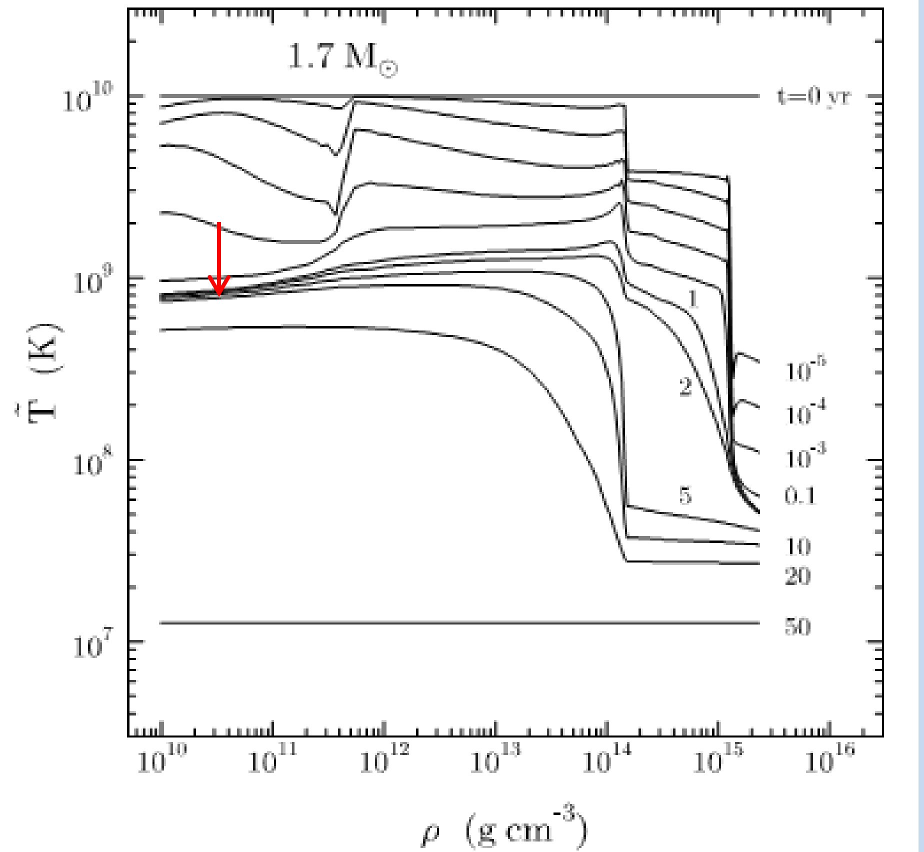
# Thermal relaxation of the neutron star crust

Energy **storage** in the crust of young NS is analogous to the hot layer heater: the **neutrino** outflow regime $T \geq 10^9$ K .

**Thermal decoupling of NS crust and core at t < 10 – 100 years**

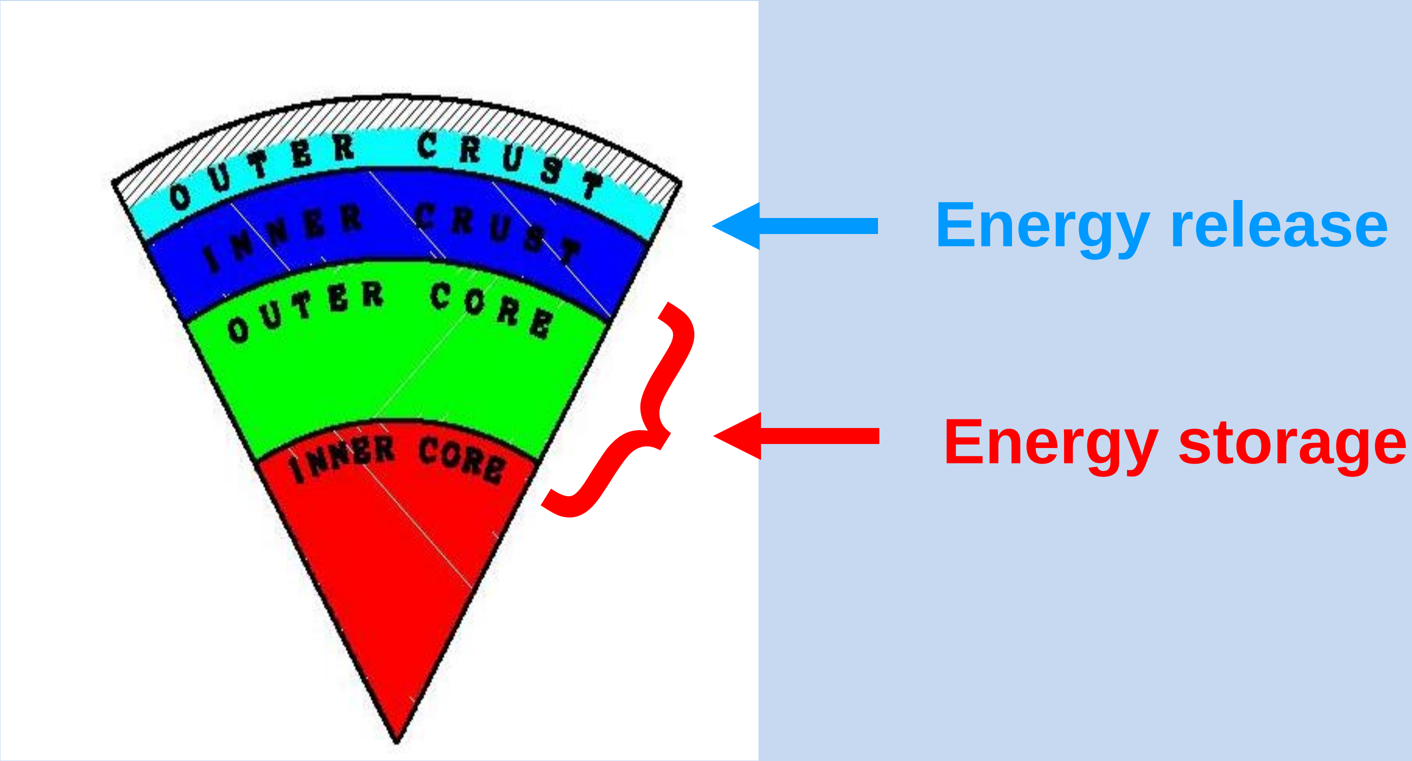


# Features of internal heating

***The energy can be stored in the entire star or in inner crust but released in the outer crust***



# CONCLUSIONS

- Comparison of 2D and 1D calculations : the heat **mainly** diffuses **radially** inwards ⟹ **neutrinos** from the NS core.
  Small fraction of the heat ⟹ outwards ⟹ thermal surface **radiation.**
  **Heater** is located in a **blob** ⟹ a hot spot **radiates.**
  **Heater** is distributed in a **layer** ⟹ the whole surface **radiates.**

- **Two** <u>regimes</u> of heating:
  (a) *The* ***conduction*** *outflow* *<u>regime</u>*: $H < 10^{20}$ erg cm$^{-3}$ s$^{-1}$, $T < 10^{9}$ K;
  The thermal **emission** is regulated by the **heater's power** and the **neutrino emission** in the NS core;
  Strong ***thermal coupling*** : the outer crust ⟺ the core;

  (b) *The* ***neutrino*** *outflow* *<u>regime</u>*: $H > 10^{20}$ erg cm$^{-3}$ s$^{-1}$, $T > 10^{9}$ K;
  **Thermal decoupling** : the outer crust ⟺ the core.

- The most economical heater is **intermediate:** $H \sim 10^{20}$ erg cm$^{-3}$ s$^{-1}$, it's placed in the outer crust .
  Efficiency of surface $T$ – radiation $L_s^\infty / W^\infty$ *does* ***not exceed*** *a few* **%.**

- Efficiency of the heater in **more massive** stars (with **fast cooling**) is **higher**

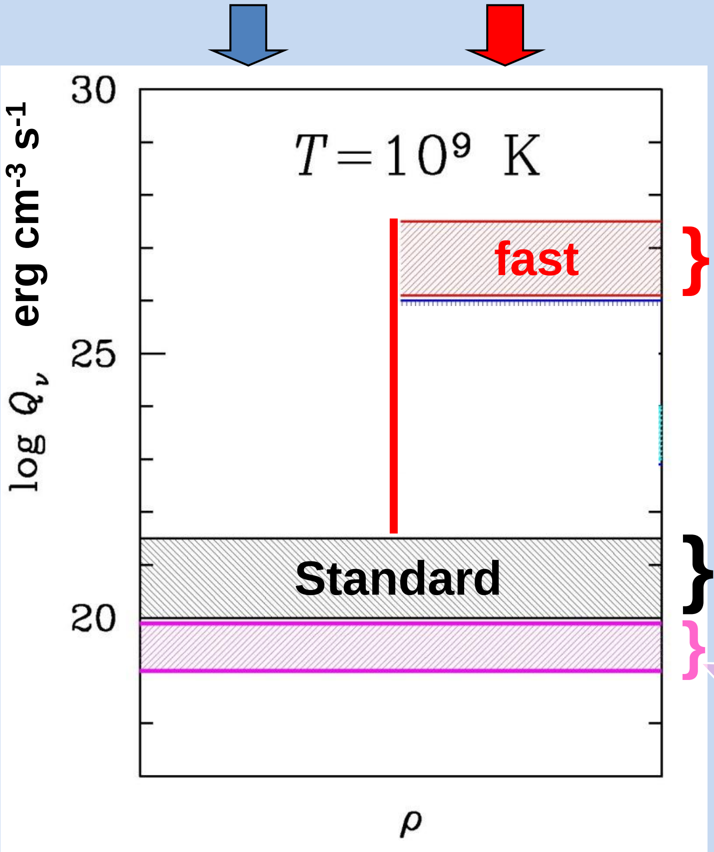
- Weak dependence results on **EOS** of NS matter

# Neutrino emission from NS core

**Outer core**
**Standard cooling**

**Inner core**
**Fast cooling**

***Nucleon composition:***
***N=n, p***




**Direct Urca**

$n \rightarrow p + e + \bar{\nu}_e \qquad p + e \rightarrow n + \nu_e$

**Modified Urca**

$nN \rightarrow pNe\bar{\nu} \qquad pNe \rightarrow nN\nu$

**NN bremsstrahlung**

$N + N \rightarrow N + N + \nu + \bar{\nu}$

$$\left\{ \begin{bmatrix} n+n \\ n+p \\ p+p \end{bmatrix} \right\}$$

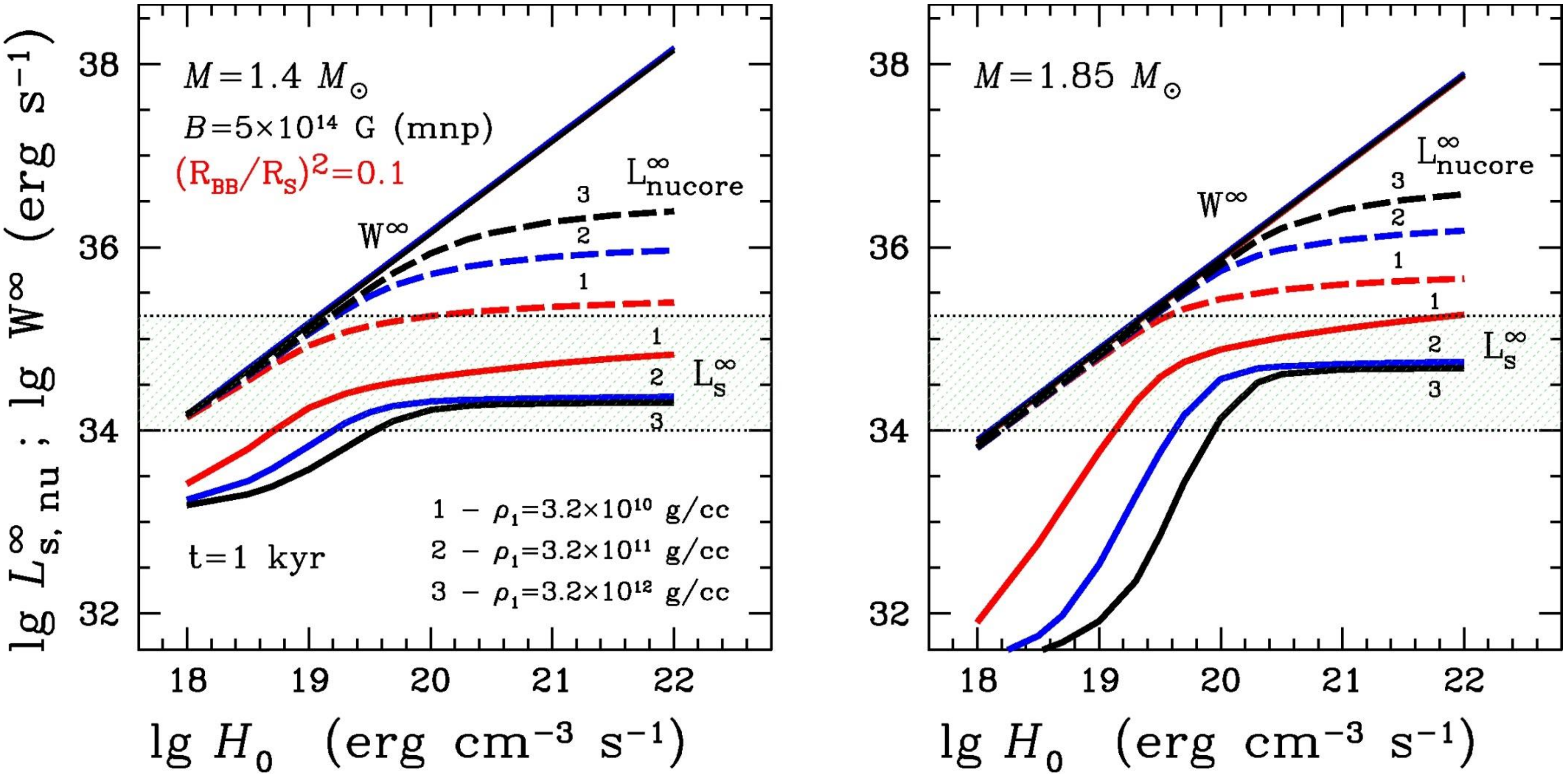
**Amlified neutrino emission in the internal core of NS:**

$$Q_{\mathrm{FAST}} = Q_{0\mathrm{F}} T^6 \qquad L_{\mathrm{FAST}} = L_{0\mathrm{F}} T^6$$

**Neutrino emision from the entier stellar body:**

$$Q_{\mathrm{SLOW}} = Q_{0\mathrm{S}} T^8 \qquad L_{\mathrm{SLOW}} = L_{0\mathrm{S}} T^8$$

# Total heat power vs. surface photon luminosity and heat flux towards NS core




**Hot spot**

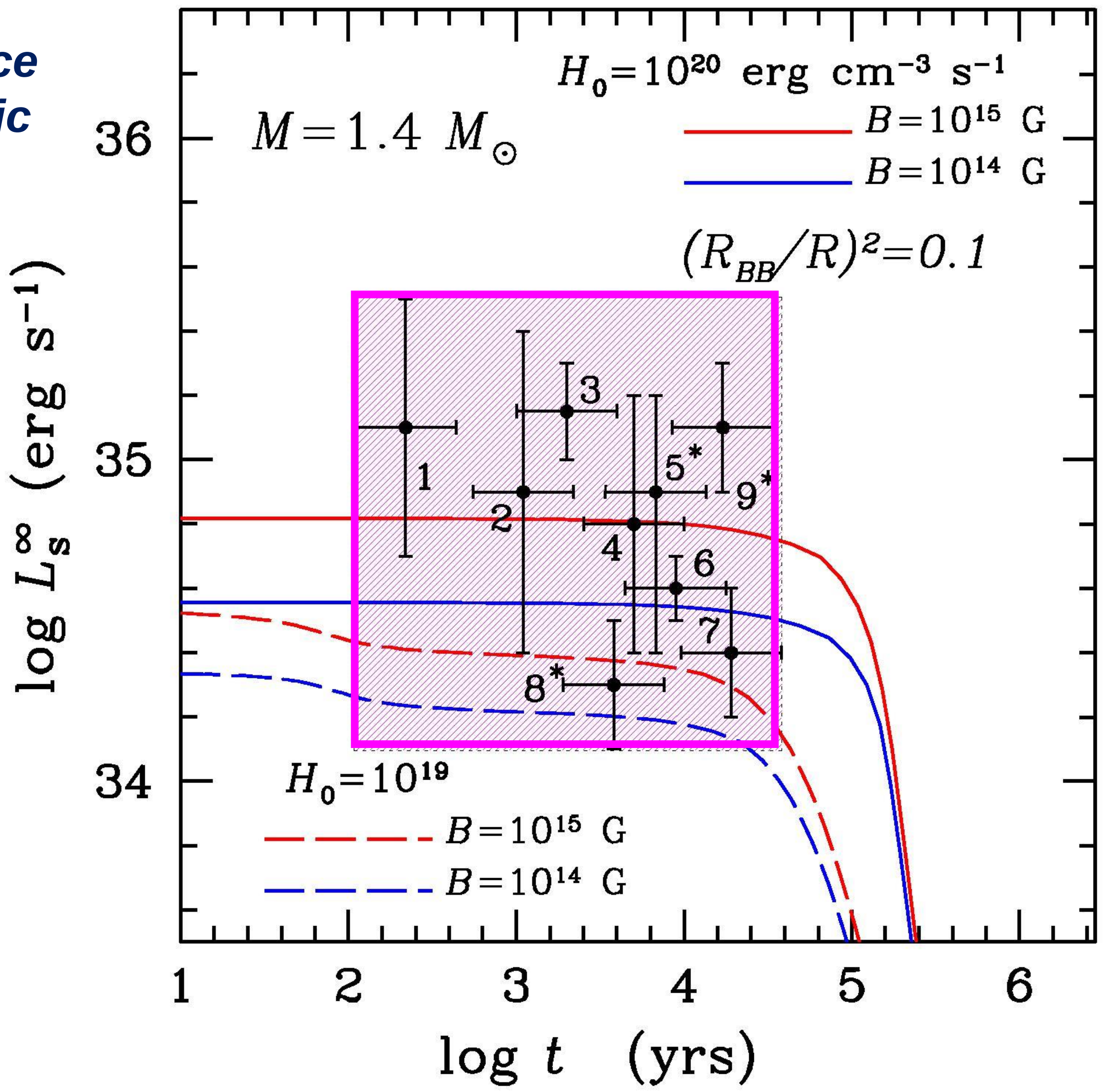
***"Eddington" limit:***

*Kaminker et al. 2006*

*Pons and Rea 2012*

# Toy-model: thermal radiation of magnetars

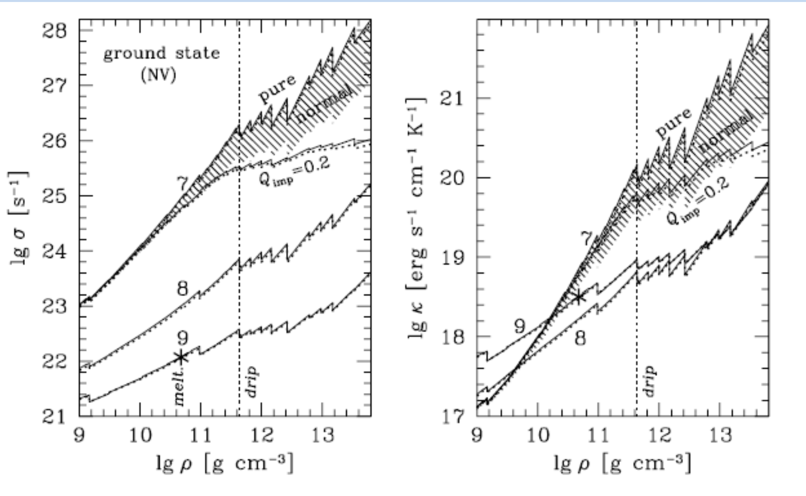
***Hot spot under the surface is heated , e.g., by Ohmic dissipation***




**Light elements in the outer envelopes increase efficiency of the thermal radiation**
**Kaminker et al. (2009)**

# Nature of heating: Ohmic dissipation

## Numerical example




**Ohmic dissipation heat rate**

***High temperature is needed:***

- ***Low electric conduction***
- ***Low thermal conduction***

***Similar matters:***

***Aguilera, Pons, Miralles 2008***

***Pons, Miralles, Geppert 2009***

$$H \sim \frac{j^2}{\sigma} \sim \frac{c^2 B^2}{\sigma h^2 (4\pi)^2}$$

$$\text{For } B \sim 10^{15}\ \text{G}, \quad \sigma \sim 10^{22}\ \text{s}^{-1}, \quad h \sim 30\ \text{m} \quad \Rightarrow \quad H \sim 6\times10^{19}\ \text{erg cm}^{-3}\ \text{s}^{-1}$$

$$\text{For } (R_{BB}/R)^2 \sim 0.1 \quad \Rightarrow \quad W_{\text{OHMIC}} \sim 10^{36}\ \text{erg s}^{-1}, \quad L_S \sim 3\times10^{34}\ \text{erg s}^{-1}$$

$$\text{HEAT EFFICIENCY: } L_S / W_{\text{OHMIC}} \sim 1/30$$

$$\text{TOTAL ENERGY NEEDED: } W_{\text{OHMIC}}\tau \sim 10^{44} - 10^{45}\ \text{erg}$$

$$(\tau \sim 5\times10^4\ \text{yr})$$