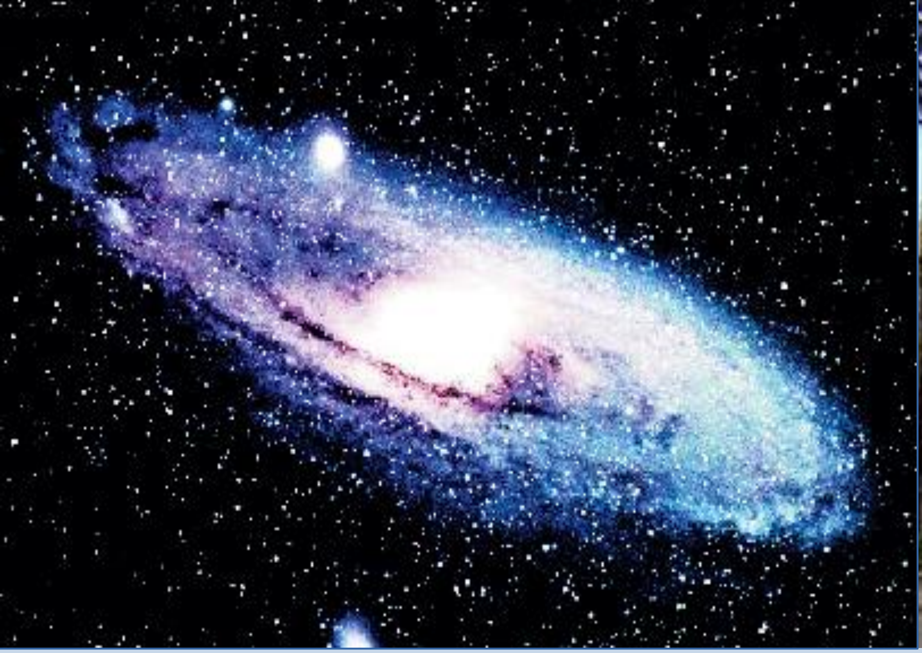

Radiation from neutron stars with internal variable heating

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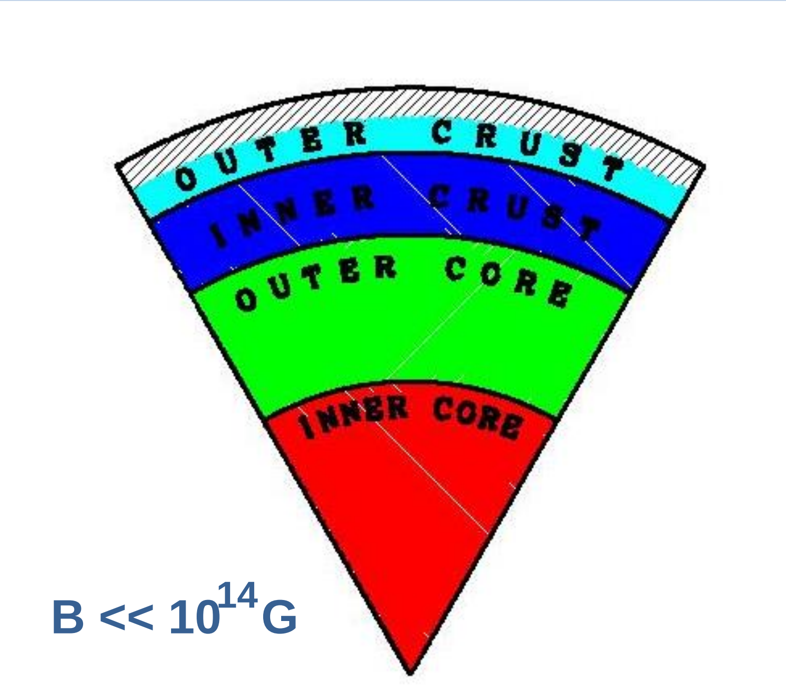
Outline

- *Heating and cooling of neutron stars: general equations*
- *Stationary heaters: general remarks*
- *Variable heaters: basic remarks and parameters*
- *Variations of luminosities: heat peaks and heat drops*
- *Effects of neurton superfluidity (SF) in the crust*
- *Variations of accreted crust depth*
- *Conclusions*



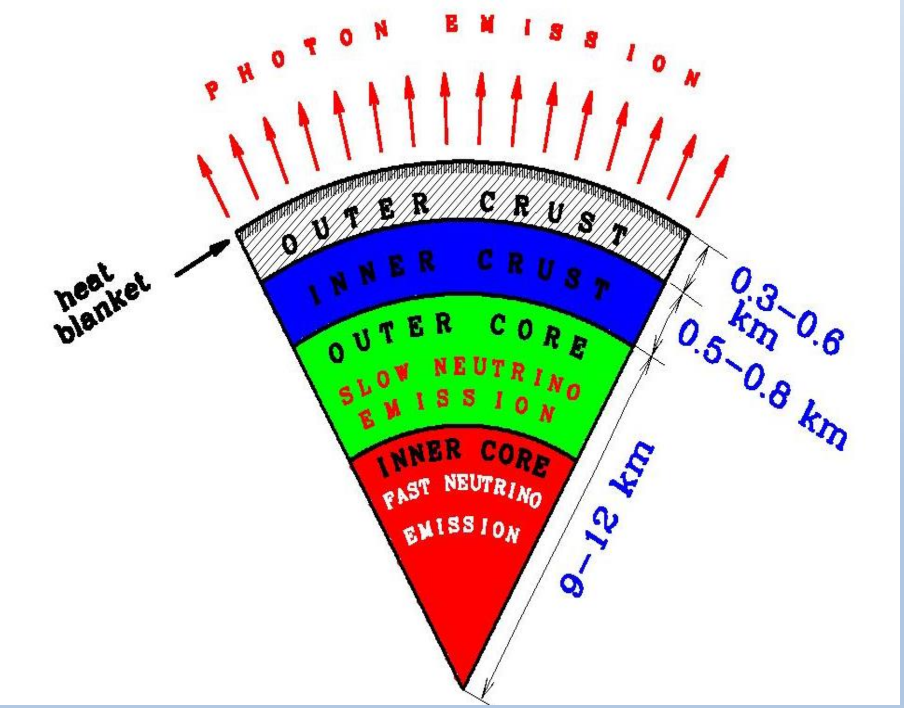
Heating and cooling of neutron stars

Oversimplified *equation of thermal diffusion with account of neutrino emissivity* Q_ν *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 $T_s = T_s(T_b)$

Including Q_ν **:**

$\rho_b = 10^{10}$ 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: $L_r\,(r) = 4\,\pi\,r^2\,F_r\,(r\,,t\,)$,

$T\,(r\,,t\,)$

$$\tilde{T}(\rho) = T(\rho)\exp(\Phi) - \text{ redshifted } T$$

Equation of state and model parameters

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: $M_{\mathrm{max}} = 2.28\ M_{Sun}$

$M = 1.40\ \mathrm{M}_\odot \qquad R = 12.60\ \mathrm{km} \qquad \rho_{\mathrm{b}} = 10^{9}\ \mathrm{g\ cm^{-3}}$ - standard cooling

$M = 1.85\ \mathrm{M}_\odot \qquad R = 12.25\ \mathrm{km} \qquad \rho_{\mathrm{b}} = 10^{10}\ \mathrm{g\ cm^{-3}}$ - fast cooling: direct URCA

Stationary heaters

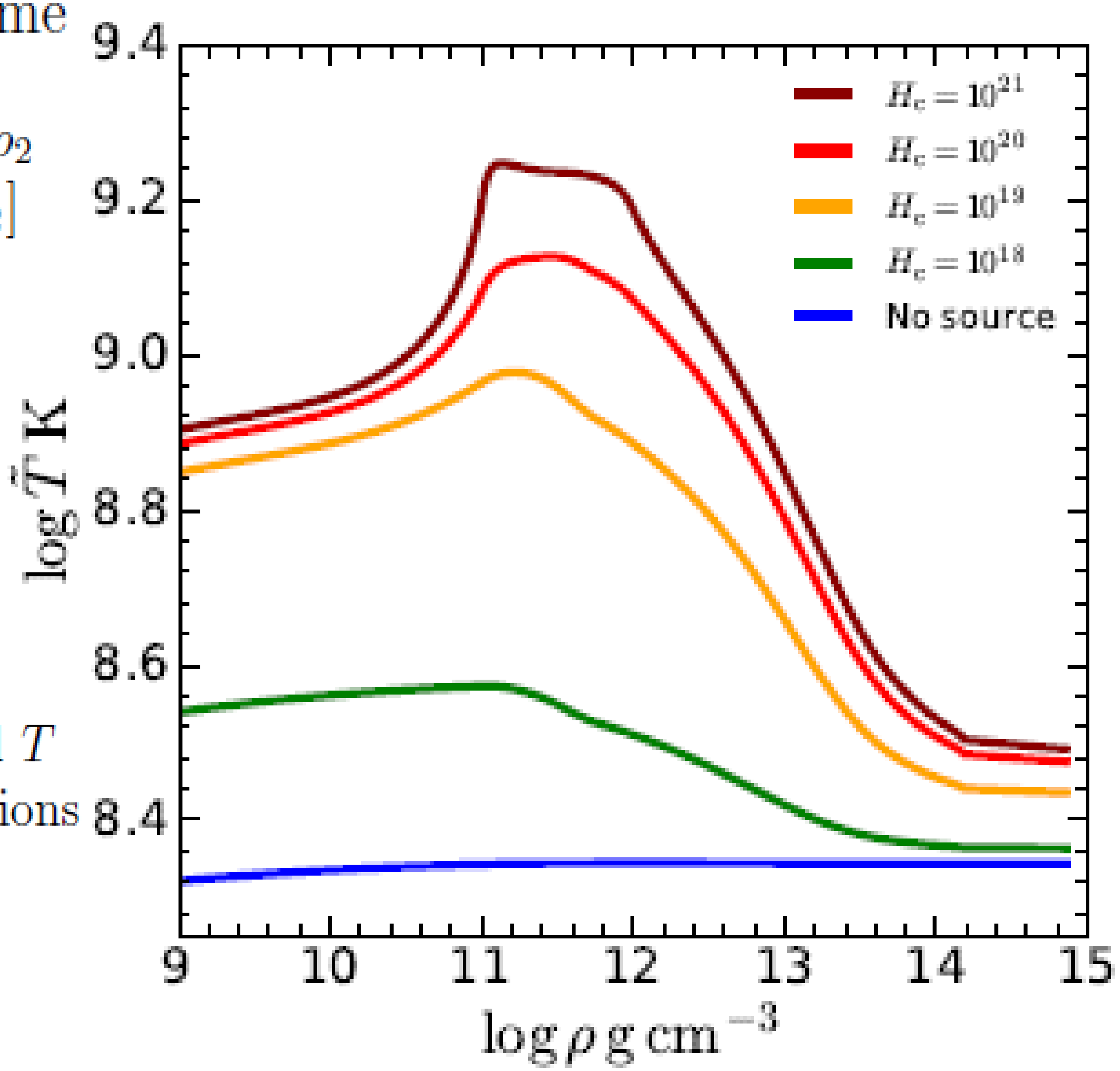
Initially NS cools down up to the moment when a const. heating is switched on

At the first stage -- constant heat power H_c $(\mathrm{erg\ cm^{-3}\ s^{-1}})$

$t_c = t_1;$ $t_c -$ cooling time

$$Q_{hc} = \begin{cases} H_c, & \text{if} \quad \rho_1 \le \rho \le \rho_2 \\ 0, & \text{if} \quad \rho \notin [\rho_1, \rho_2] \end{cases}$$

$$\rho_1 = 10^{11}\ \mathrm{g\ cm^{-3}}$$
$$\rho_2 = 10^{12}\ \mathrm{g\ cm^{-3}}$$



$\tilde{T}(\rho) = T(\rho)\exp(\Phi) -$ redshifted T

$\tilde{T}(\rho) = const_\rho$ in isothermal regions

Quasi-stationary state:

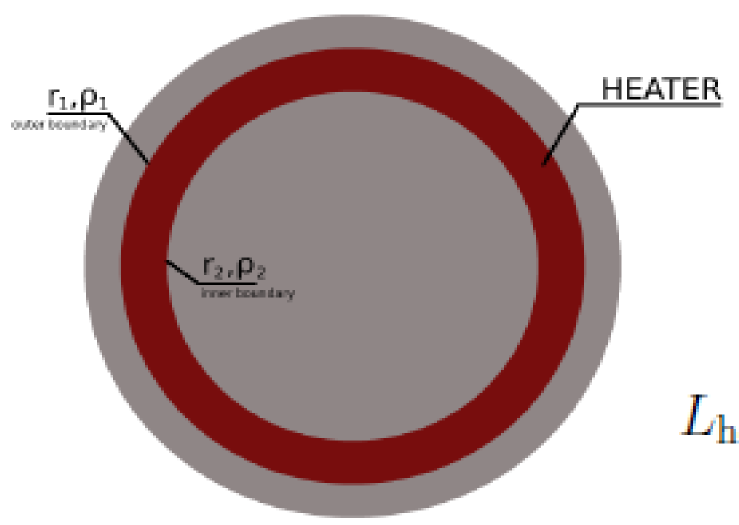
$$\frac{\partial \tilde{T}}{\partial t} = 0$$

Variable heaters: basic positions

At the second stage – variable heat power $Q_{\rm h}(\rho,t)$ $(\rm erg\ cm^{-3}\ s^{-1})$

$t_{\rm c}=t_2;$ $t_2>t_1;$ $t_{\rm c}-$ cooling time;

$$Q_{\rm h}(\rho,\,t)=\begin{cases} H_{\rm c}+(H_0-H_{\rm c})\sin^2\left(\frac{\pi\ t}{\Delta t}\right), & \text{if} \quad \rho_1\le\rho\le\rho_2, \ \text{and} \quad 0\le t\le\Delta t, \\ H_{\rm c}, & \text{if} \quad \rho_1\le\rho\le\rho_2, \ \text{and} \quad t\notin[0,\Delta t], \\ 0, & \text{if} \quad \rho\notin[\rho_1,\,\rho_2], \ \text{and} \quad t\notin[0,\Delta t] \end{cases}$$



H_0- is the variation amplitude,

$\Delta t-$ is the variation duration,

Redshifted heat power $(\rm erg\ s^{-1})$:

$$L^{\infty}_{\rm h,\ hc}(t)=\int Q_{\rm h,\ hc}(\rho,t)\ \exp(2\Phi){\rm d}V,$$

$L_{\rm hc}\equiv L_{\rm c}$

${\rm d}V-$ a proper volume element (GR)

$\Phi-$ metric function

Variable heaters: basic parameters

Redshifted heat power (erg s^{-1}):
A variable heater may increase or decrease its power and produce a peak of a dip in the thermal surface emission.

At which parameters these variations become observable ?

Two types of variations:

- peaks – $H_0 = 10H_c \quad Q_h = H_c + 9H_c \, \sin^2\,(\pi t/\Delta t)$
- drops – $H_0 = 0 \quad Q_h = H_c - H_c \, \sin^2\,(\pi t/\Delta t)$

Parameters of variable heaters at the second stage:

- stationary heat intensities –

$H_c = 5 \times 10^{17}$ (A), 5×10^{18} (B), 5×10^{19} erg $\mathrm{cm^{-3}\,s^{-1}}$ (C)

- corresponding steady heat powers –

$L_c^\infty = 1.7 \times 10^{35}$ (A), 1.7×10^{36} (B), 1.7×10^{37} erg s^{-1} (C)

- variation durations – $\Delta t = 1, \quad 10, \quad 100$ yr

- two positions of the heater:

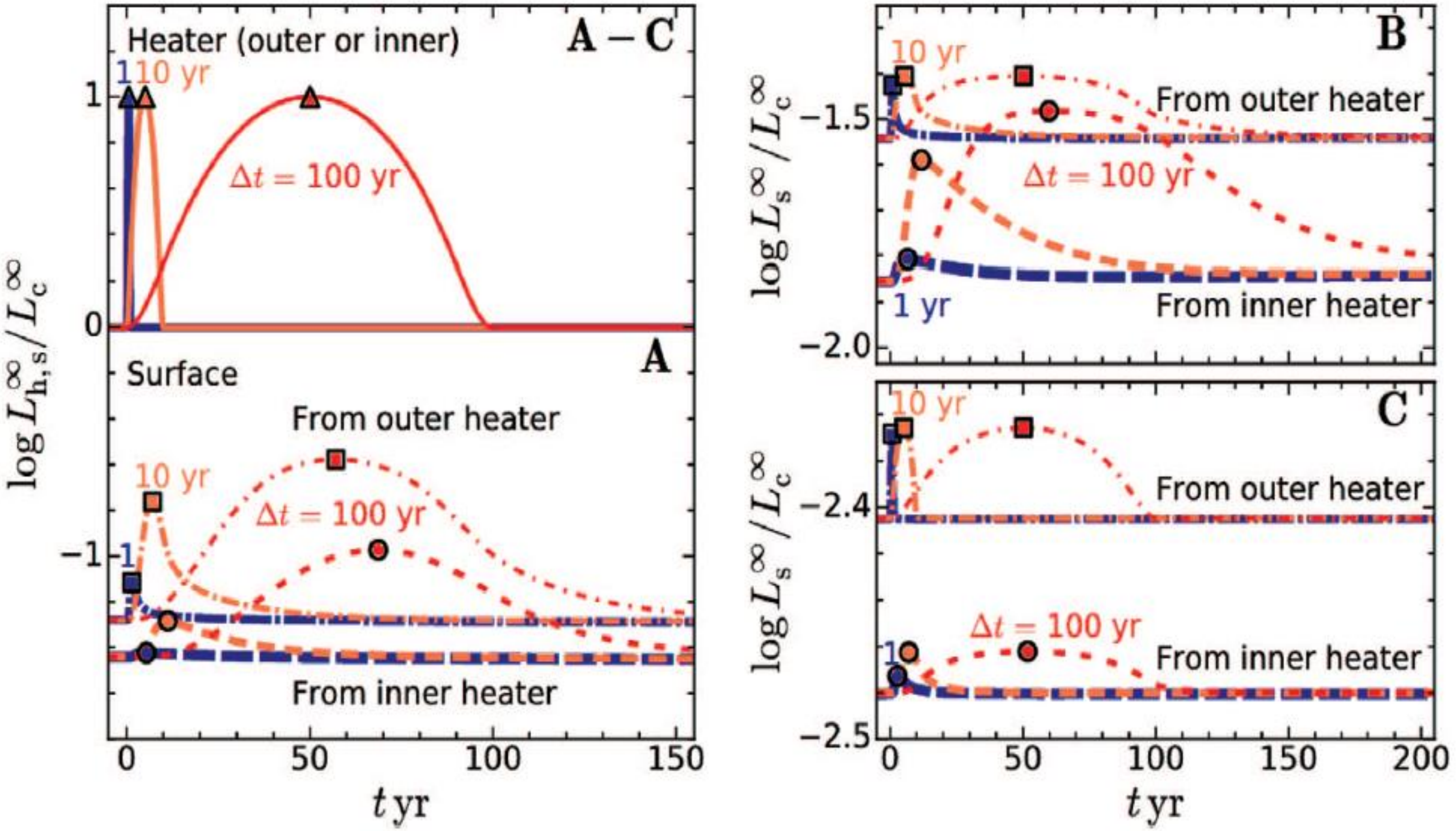
outer heater – $\rho_1 = 10^{11}$ g $\mathrm{cm^{-3}}$, $\rho_2 = 10^{12}$ g $\mathrm{cm^{-3}}$
inner heater – $\rho_1 = 10^{12}$ g $\mathrm{cm^{-3}}$, $\rho_2 = 1.27 \times 10^{12}$ g $\mathrm{cm^{-3}}$

Variable heaters: heat peaks

- two positions of the heater:

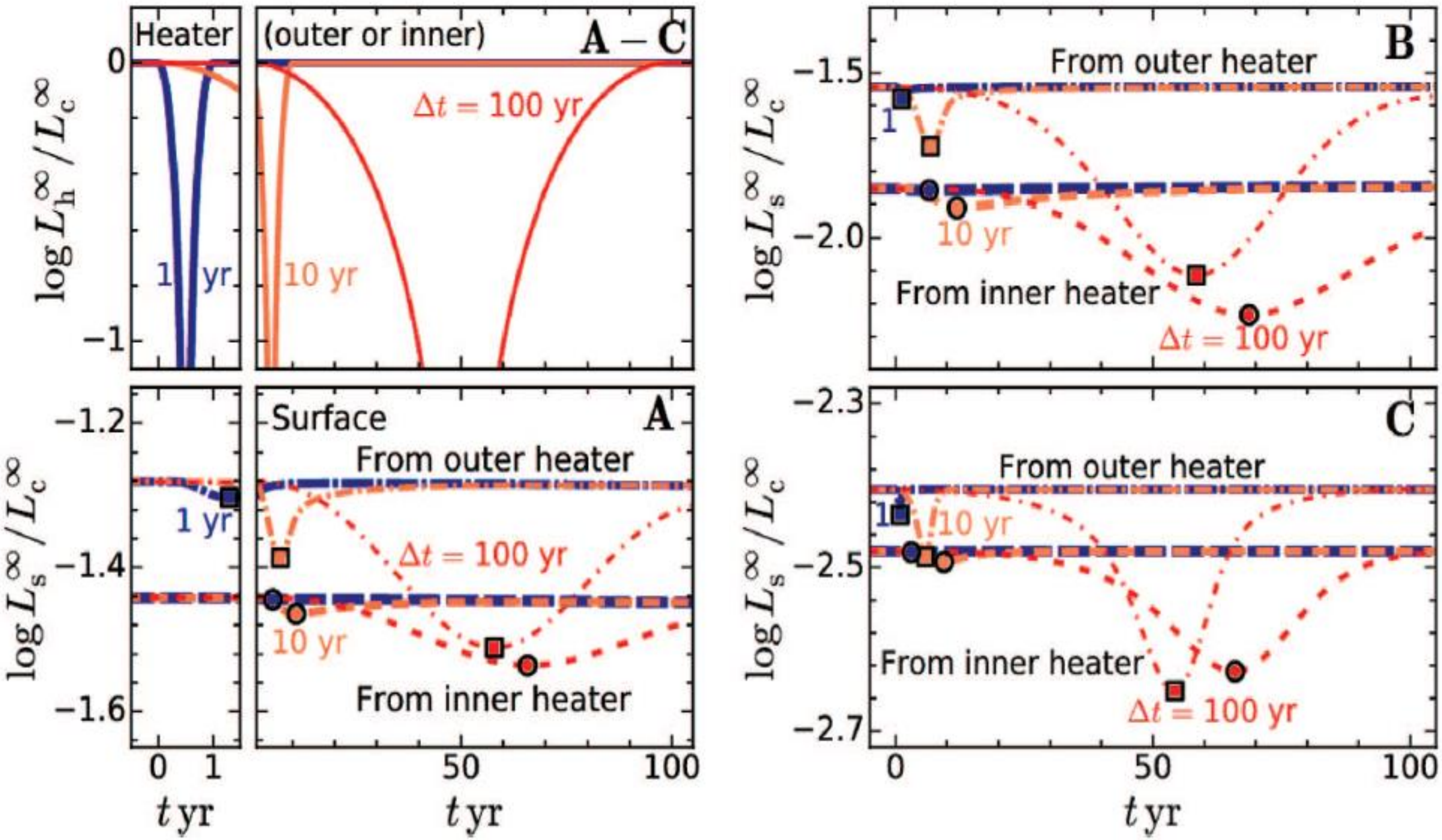
outer heater – $\rho_1 = 10^{11}$ g cm^{-3}, $\rho_2 = 10^{12}$ g cm^{-3}

inner heater – $\rho_1 = 10^{12}$ g cm^{-3}, $\rho_2 = 1.27 \times 10^{12}$ g cm^{-3}



Variable heaters: heat drops

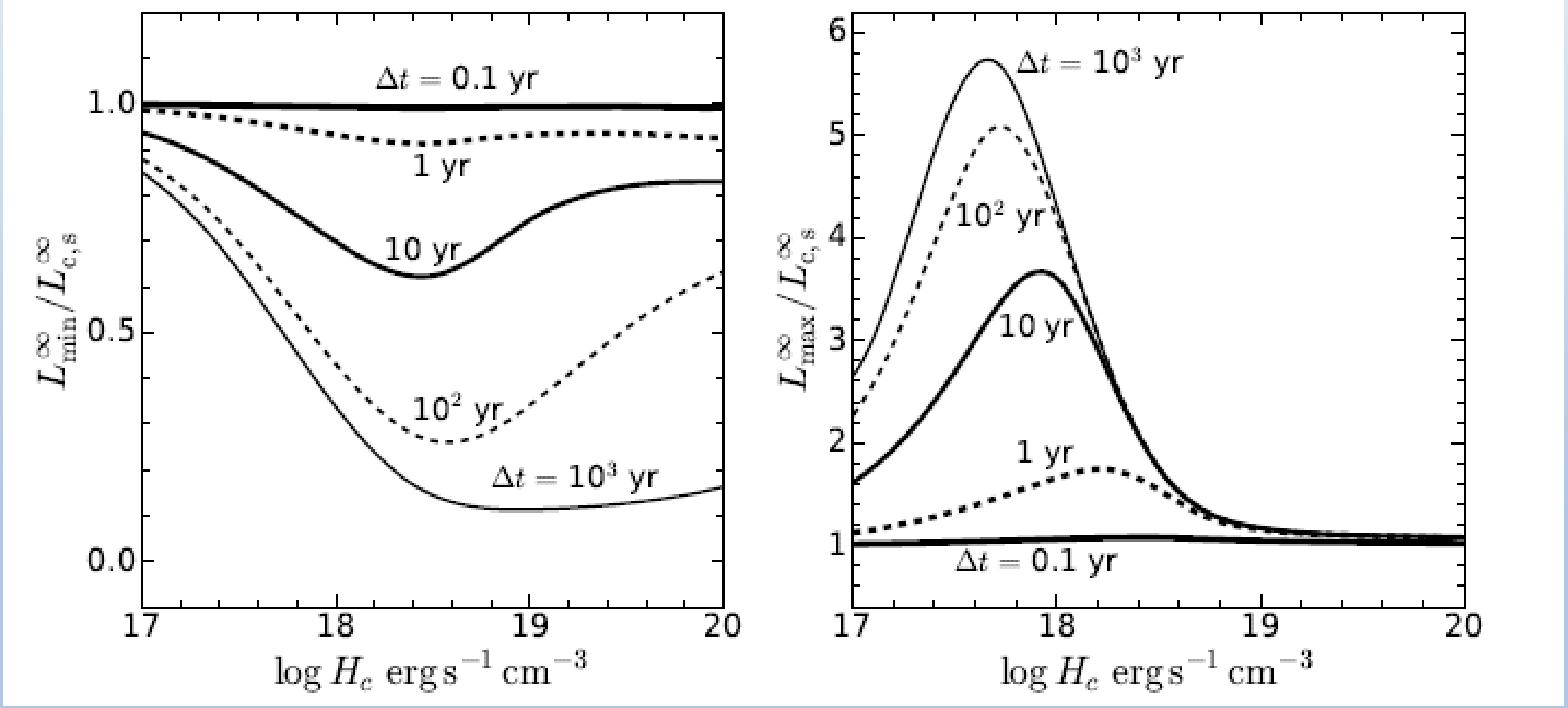
drops $-$ $H_0 = 0$ $\quad Q_\mathrm{h} = H_\mathrm{c} - H_\mathrm{c}\,\sin^2\,(\pi t/\Delta t)$



Maximum of peaks and minimum of dips

ratios of $L^{\infty}_{\rm max}/L^{\infty}_{\rm c}$ vs. $H_{\rm c}$ at $H_0 = 10\ H_{\rm c}$ for maximums of peaks
ratios of $L^{\infty}_{\rm min}/L^{\infty}_{\rm c}$ vs. $H_{\rm c}$ at $H_0 = 0$ for minimums of dips

for five values $\Delta t = 0.1,\ 1,\ 10,\ 100$ and 1000 yr



To obtain noticeable variations of the surface emission we need:
an intermediate heater – $H_{\rm c} \sim (1-5) \times 10^{18}$ erg cm^{-3} $^{-1}$
and sufficiently long energy input $\Delta t \gtrsim 10$ yr

Intermediate conclusions

We introduce t_{diff} – characteristic diffusion time
($t_{\mathrm{diff}} \sim C_V\ l^2/\kappa$),
l – characteristic length scale,
κ – thermal conductivity (erg cm^{-1} s^{-1} K^{-1}),
Δt_{s} – characteristic time scale of the surface emission
and T_{h} – typical heater's temperature

Three main regimes of the surface variability:

1) *dynamic response* to an internal rapid energy input
($\Delta t \lesssim t_{\mathrm{diff}}$)
at not too hot star ($T_{\mathrm{h}} \lesssim 10^9$ K):

rapid rise and longer decay
$\Delta t_{\mathrm{s}} \sim t_{\mathrm{diff}}$.

2) *quasi-stationary response* at not too hot star
($T_{\mathrm{h}} \lesssim 10^9$ K) to a slow energy release
($\Delta t \gtrsim t_{\mathrm{diff}}$):
the surface emission approximately follows the internal energy release.

3) *efficient neutrino cooling* in a hot star
($T_{\mathrm{h}} \gtrsim 10^9$ K):
weak variations of the surface emission.

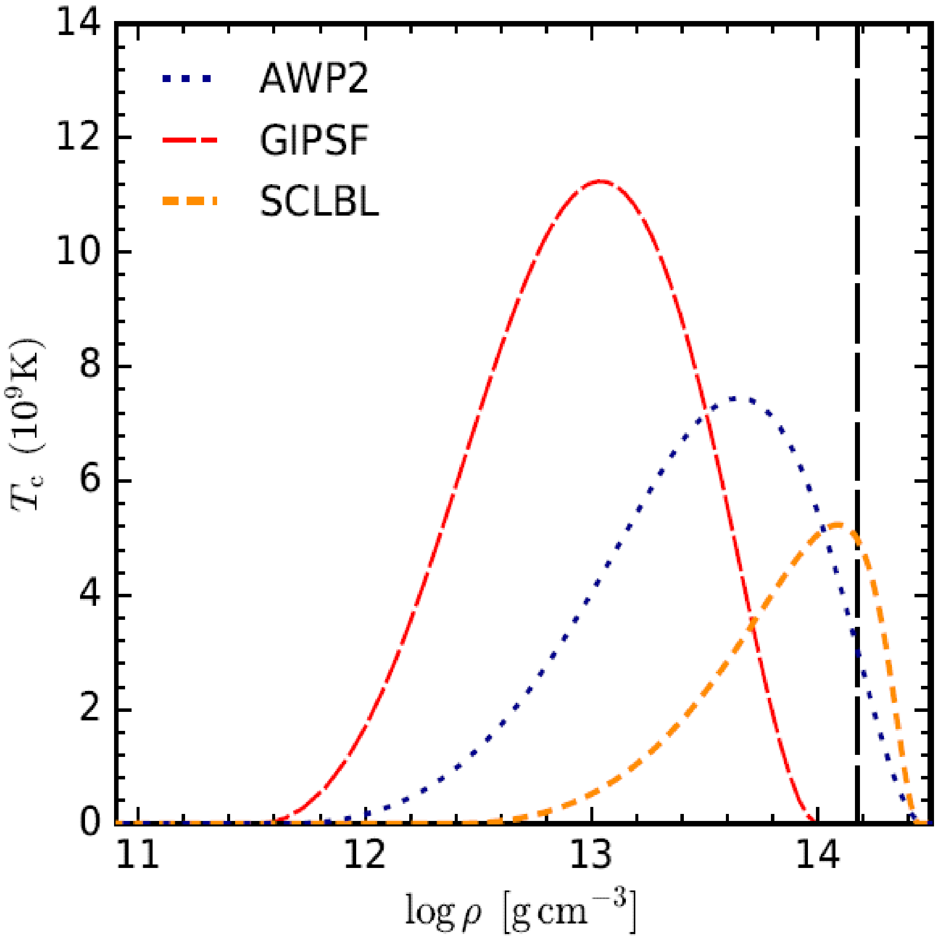
Superfluidity (SF) and heat capacity

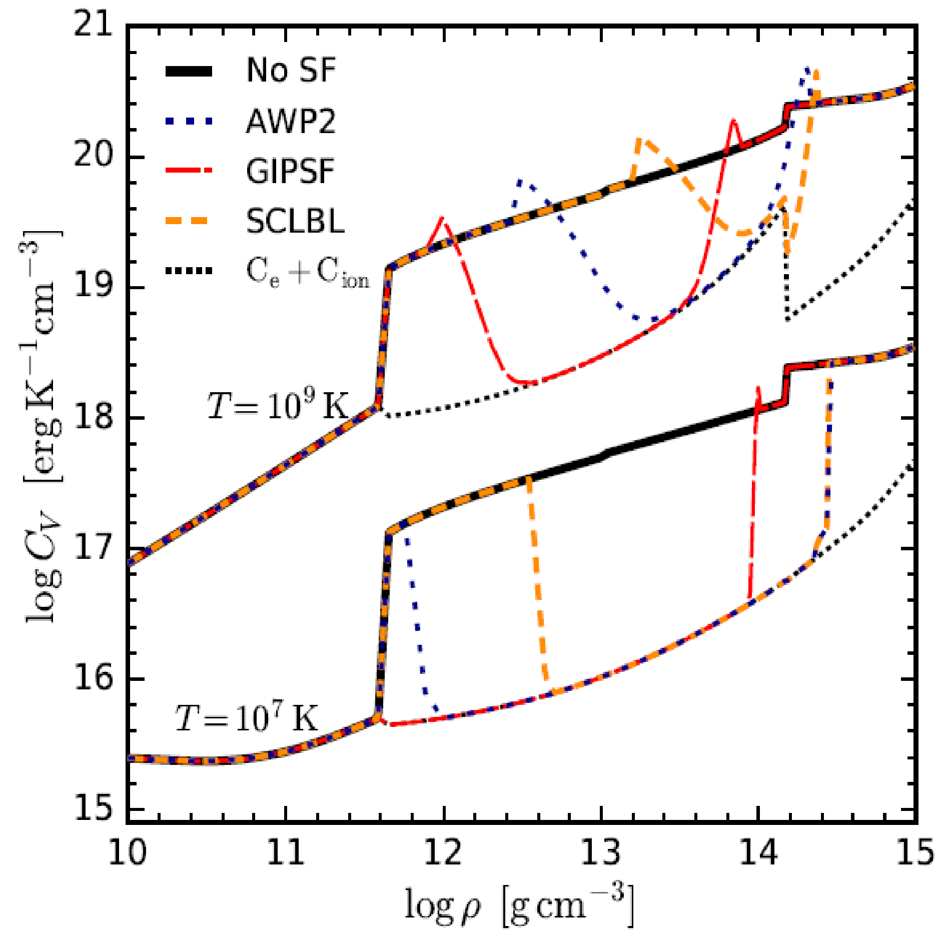
Neutron superfluidity in the crust $^1S_0$– type.

The main effect – suppression of the heat capacity (erg cm^{-3} K^{-1}):

$$C_{\mathrm{n},\,V} \propto C^0_{\mathrm{n},\,V}\ \exp\left(-\frac{b\,T_\mathrm{c}}{T}\right),$$

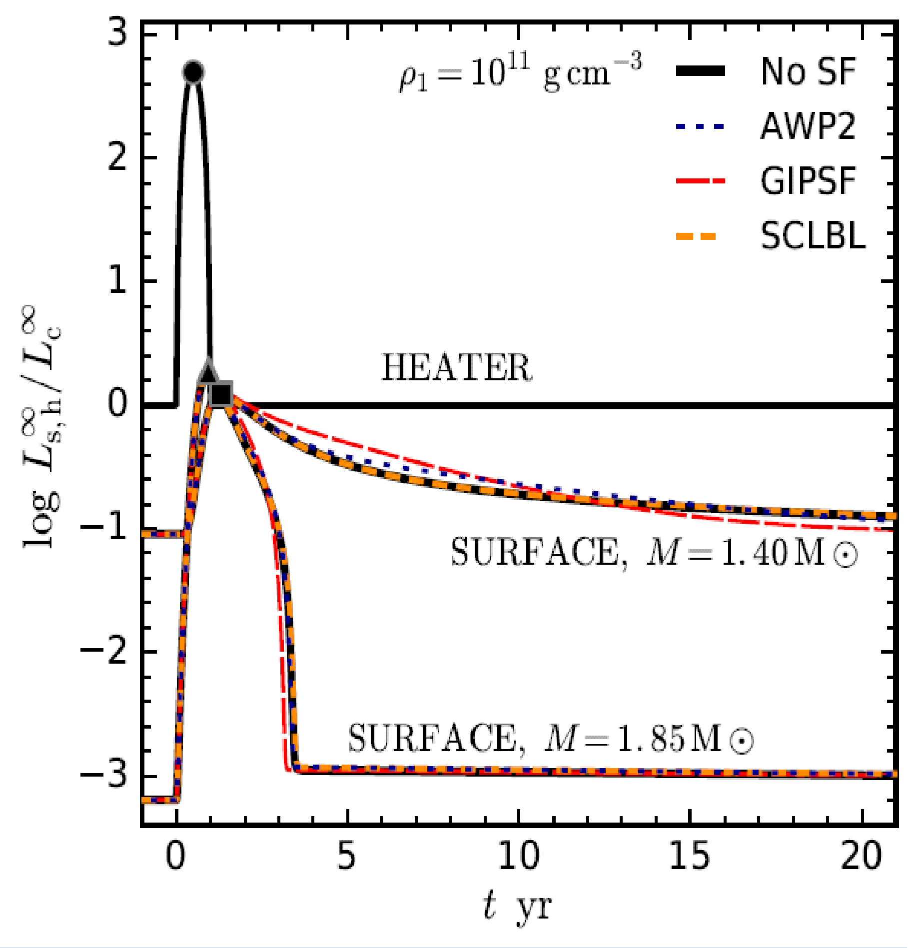
where T_c– critical temperature, b– const.

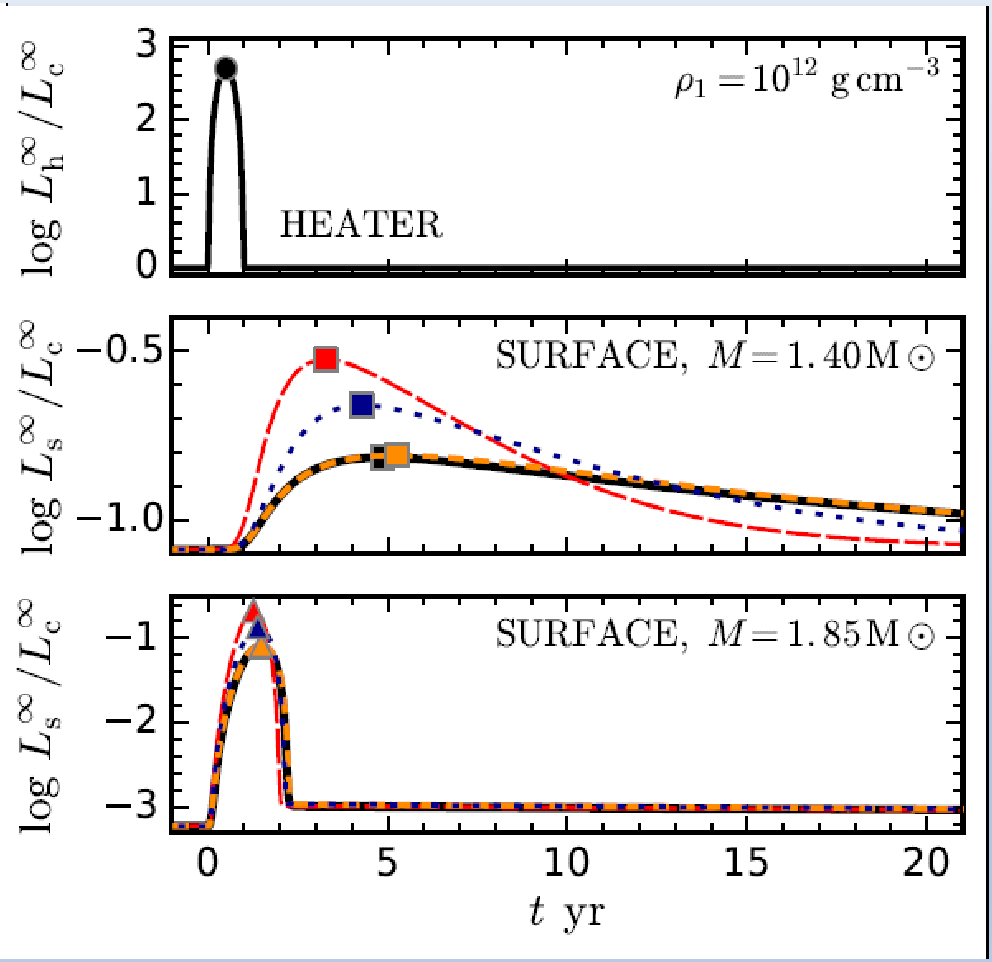




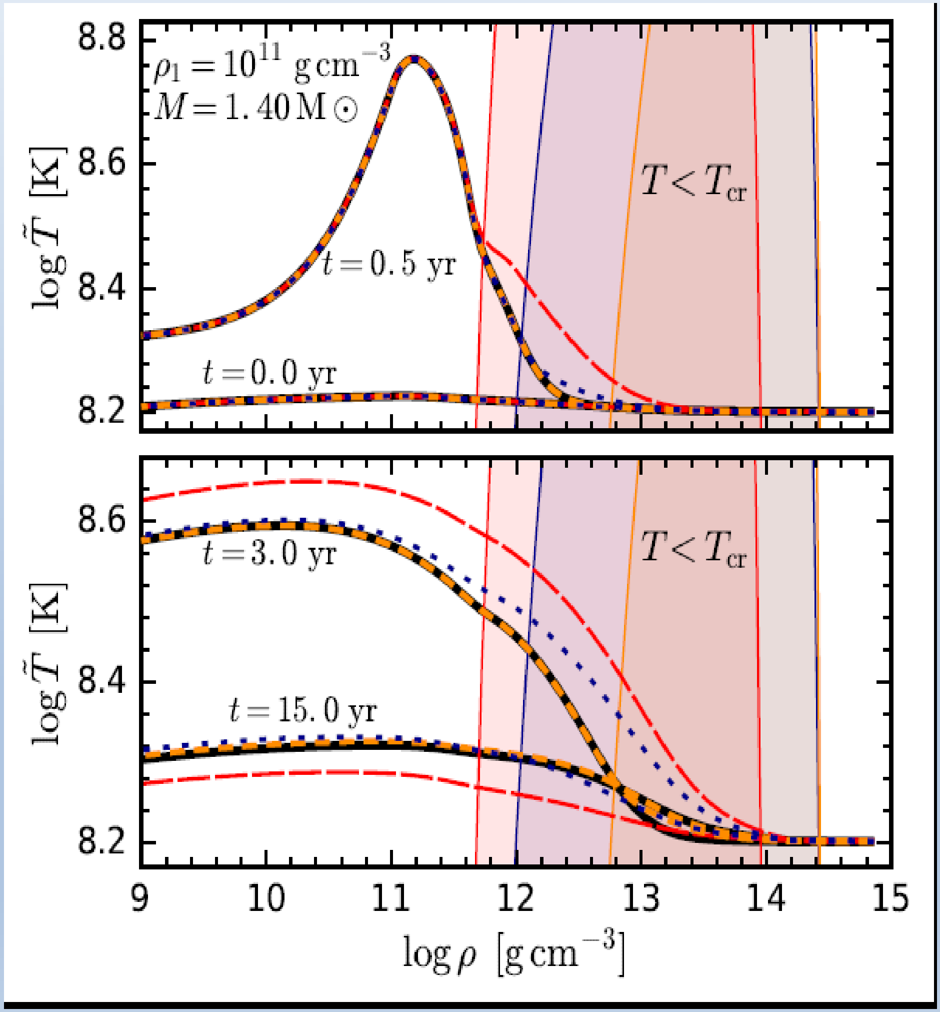
AWP2 – Ainsworth et al. (1989); GIPSF – Gandolfi et al. (2009); SCLBL – Schulze et al. (1996)

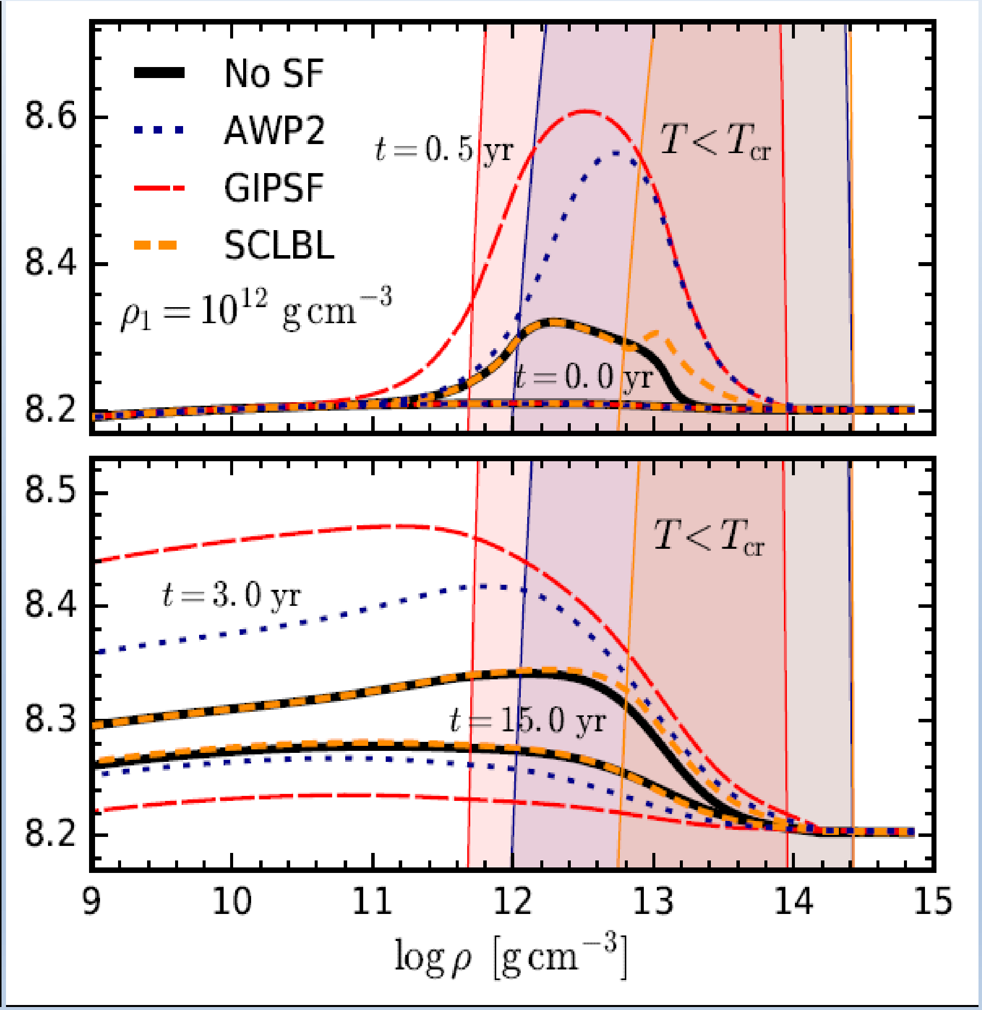
Peaks: heat power versus surface luminosities



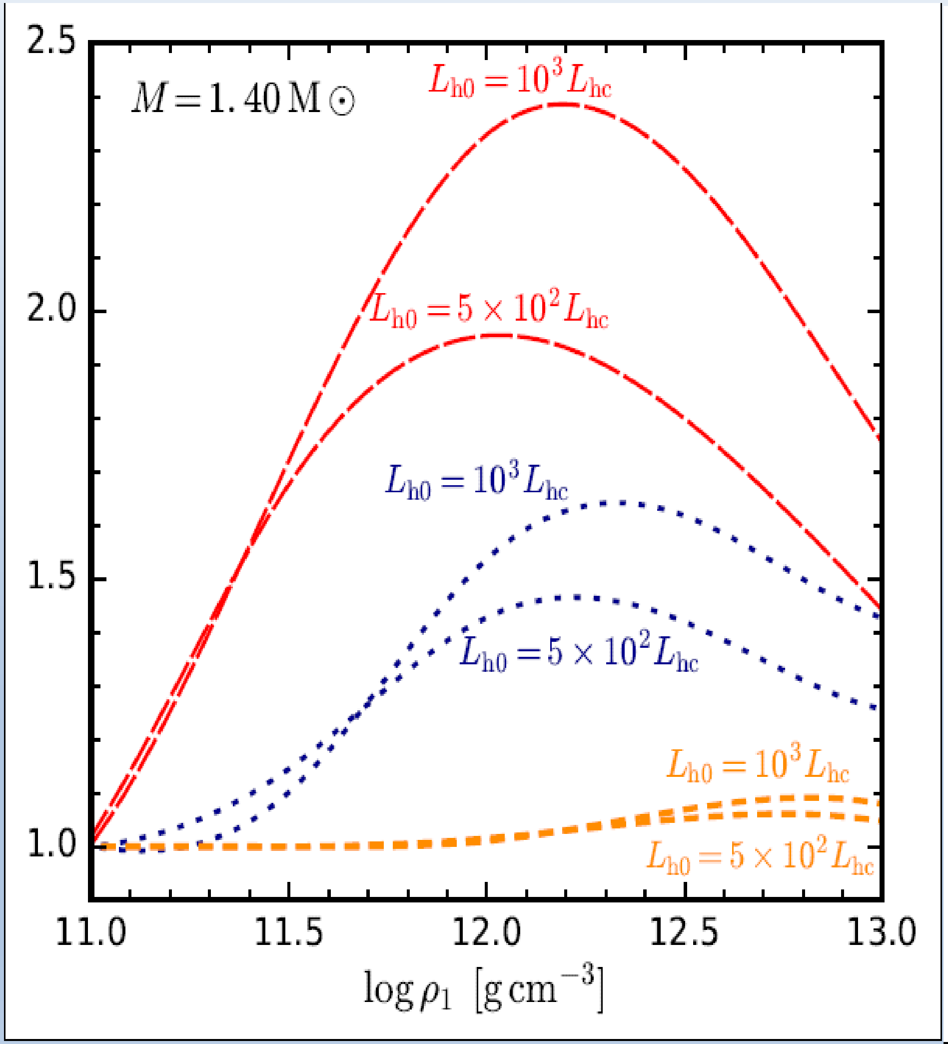


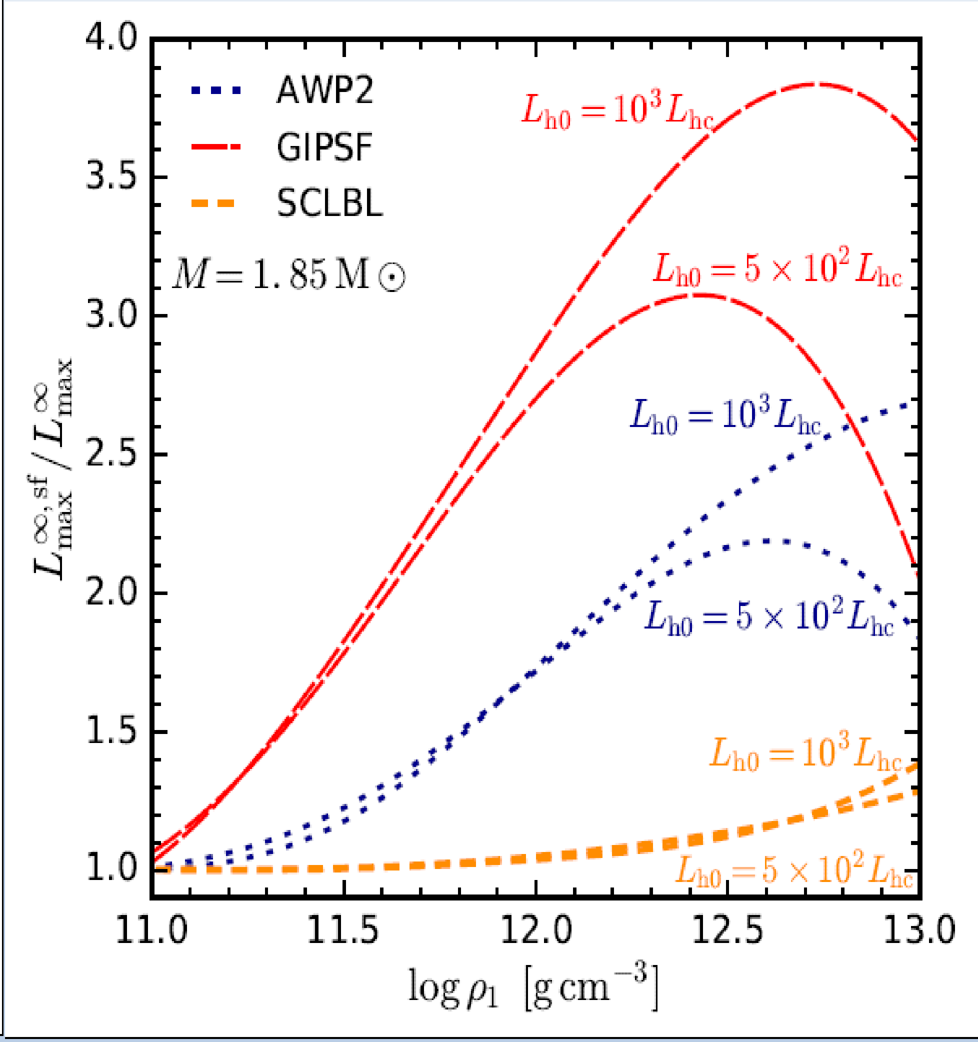
Temperature profiles





Enhancement of luminosity by SF

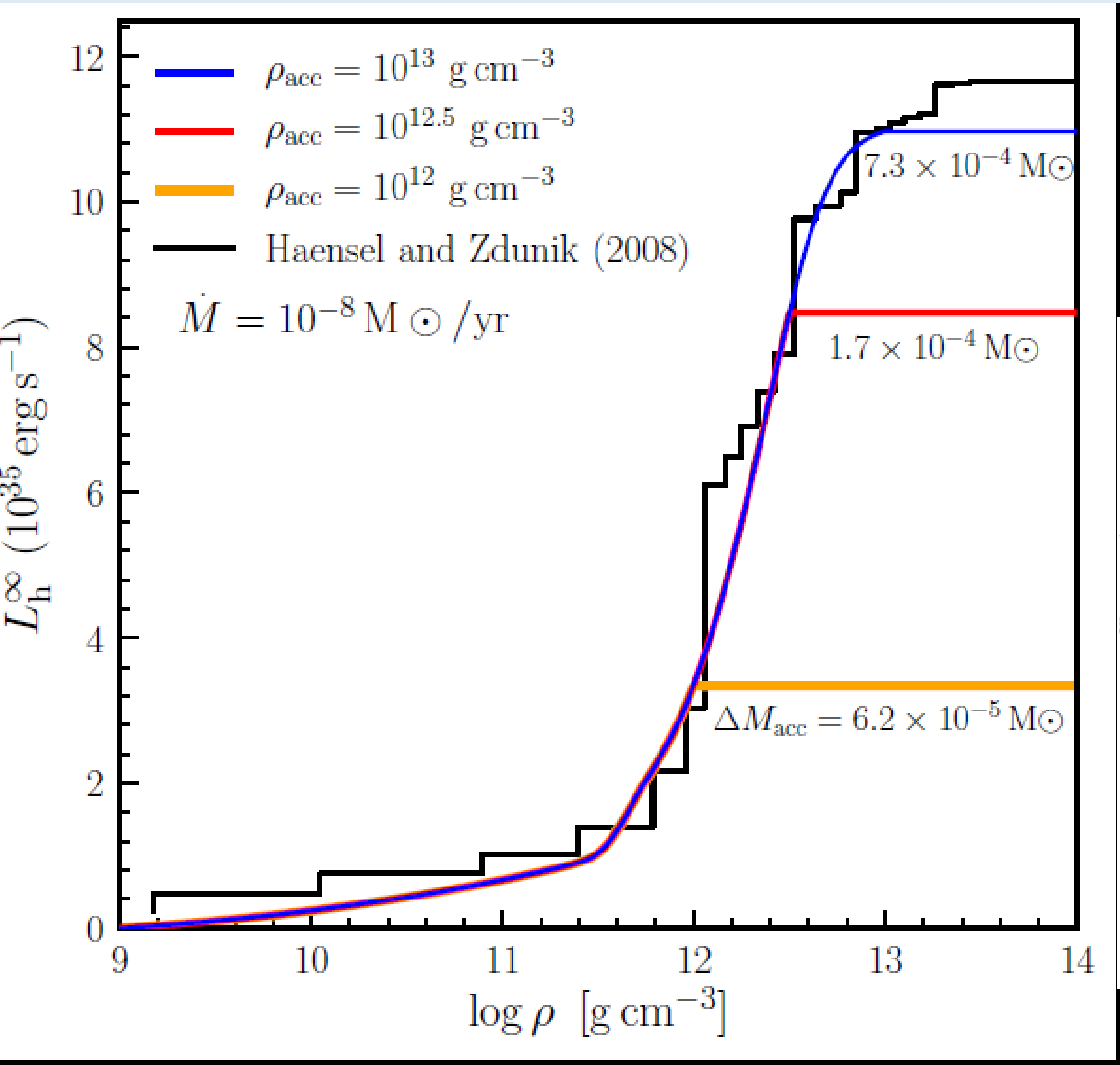




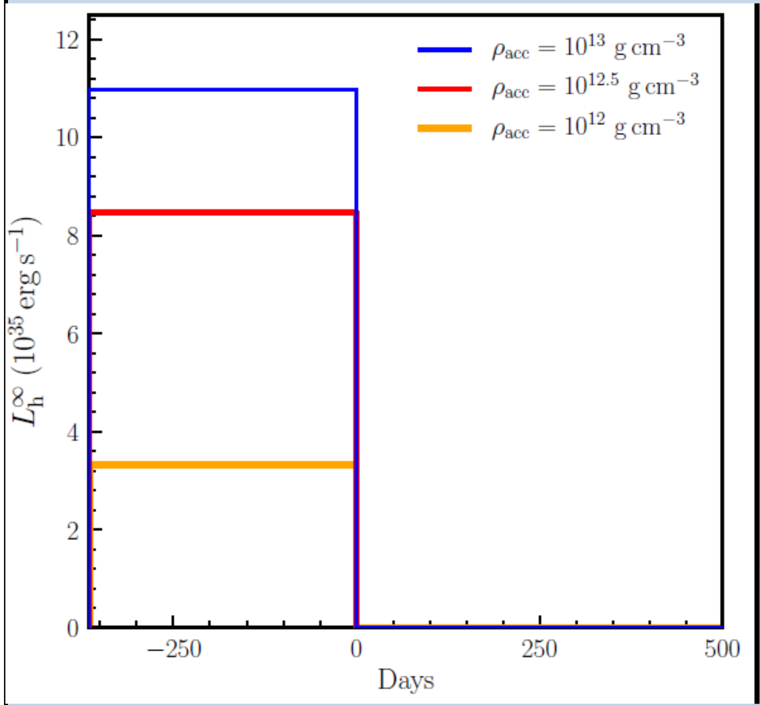
Integrated heat release in the crust : fully and not fully accreted crust

Transient accretion

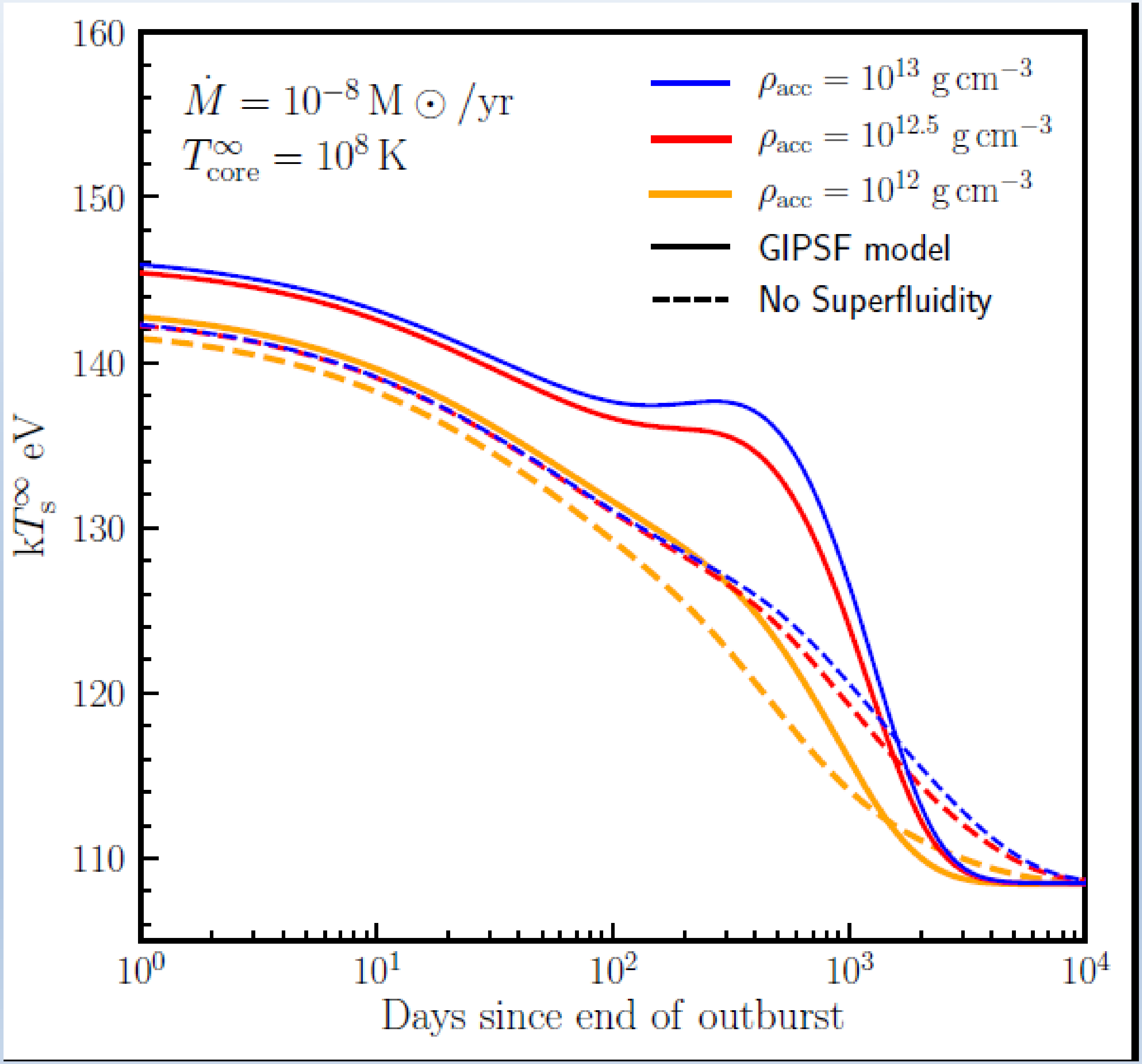
LMXB – active period – bright X-ray sources



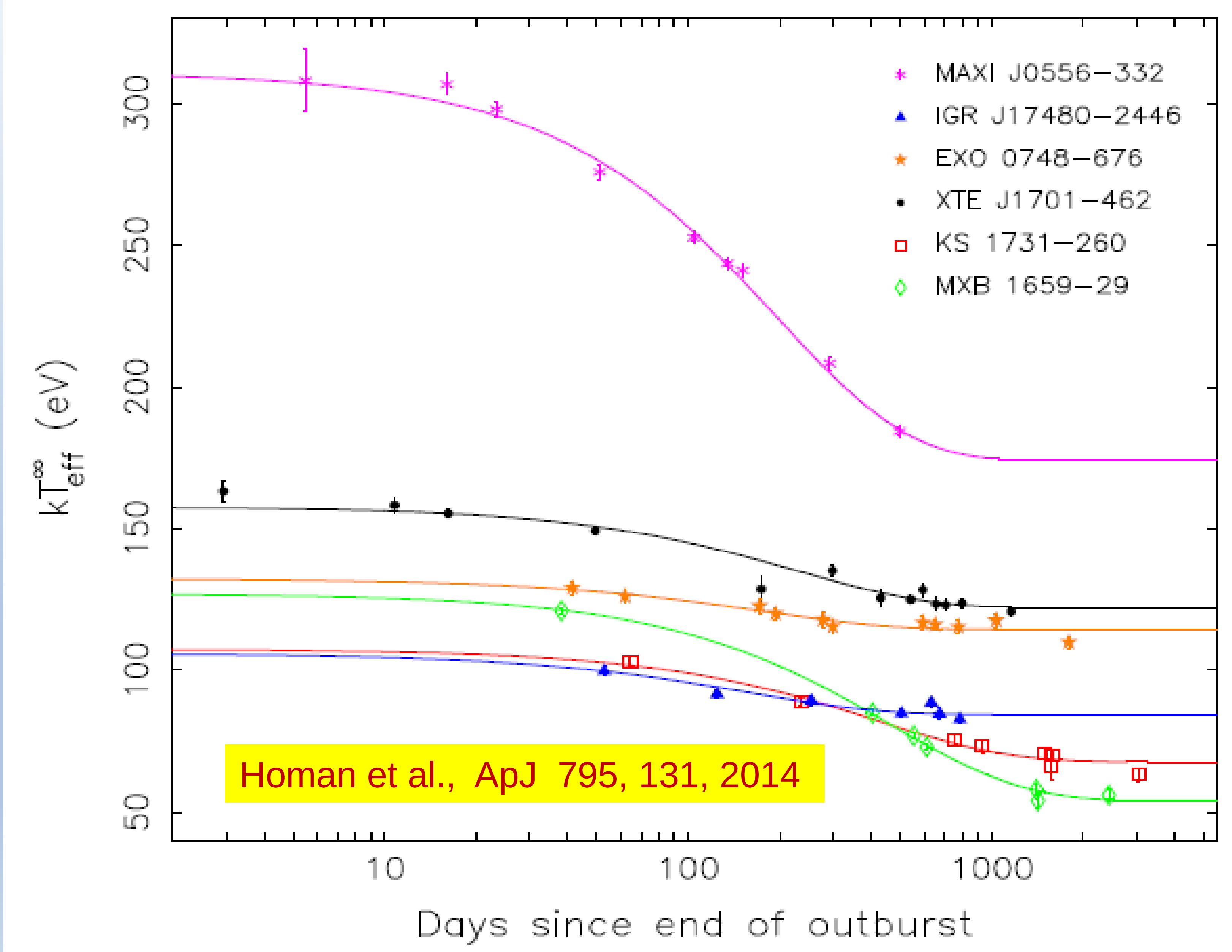
Deep crustal heating --
nuclear transformations
In the crust
Energy release 1- 2 MeV



Partly accreted crusts: transitions to a quiescent state



Six quasi-persistent LMXBs in quiescence



Homan et al., ApJ 795, 131, 2014

Conclusions

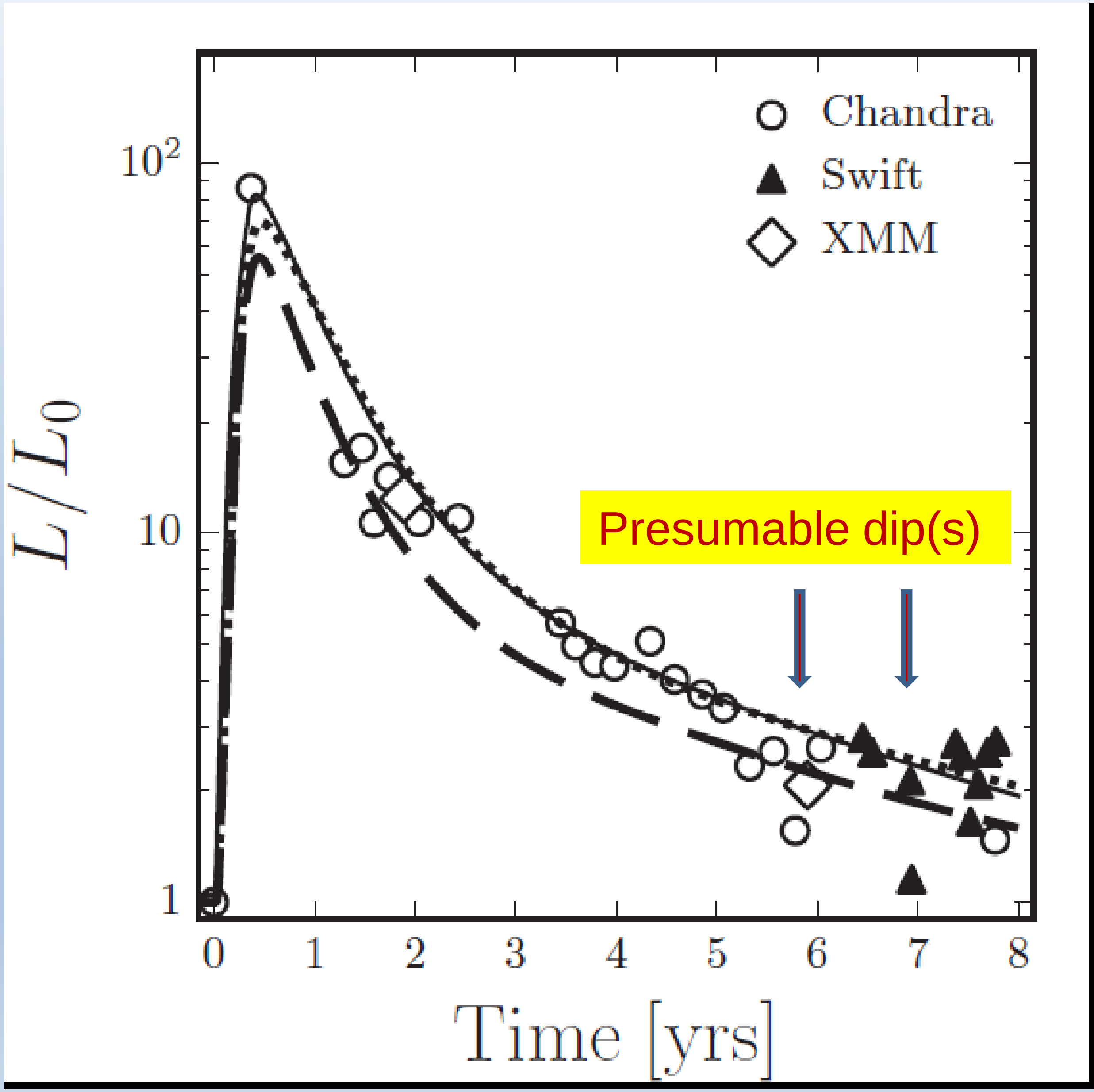
- Neutron stars tends to hide their internal activity:
  the surface luminosities are smaller, broader and asymmetrical

- To obtain noticeable variations of the surface emission one needs
  intermediate heater $H_c \sim (1\text{-} 5) \times 10^{18}$ erg cm^{-3}s^{-1}
  and suficiently long ~ 10 yr

- The heater has to be rather close to the surface

- Neutron superfluidity in the crust enhances surface luminosities and makes them steeper in time – decreases relaxation time

Simulated X-ray luminosities L(t) versus observational data 1E 161348-5055 in RCW 103

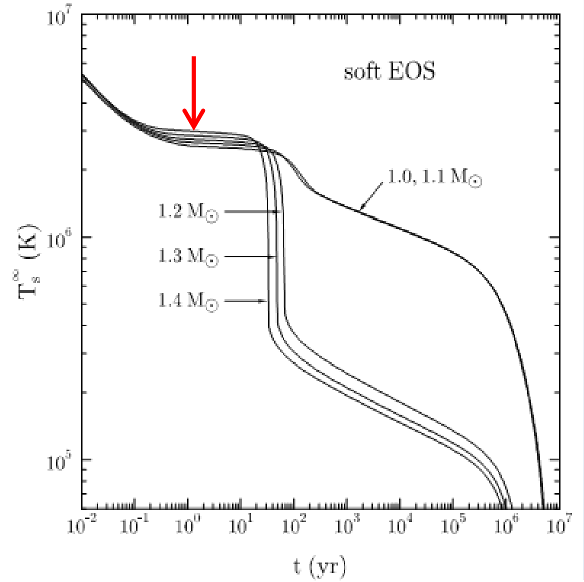


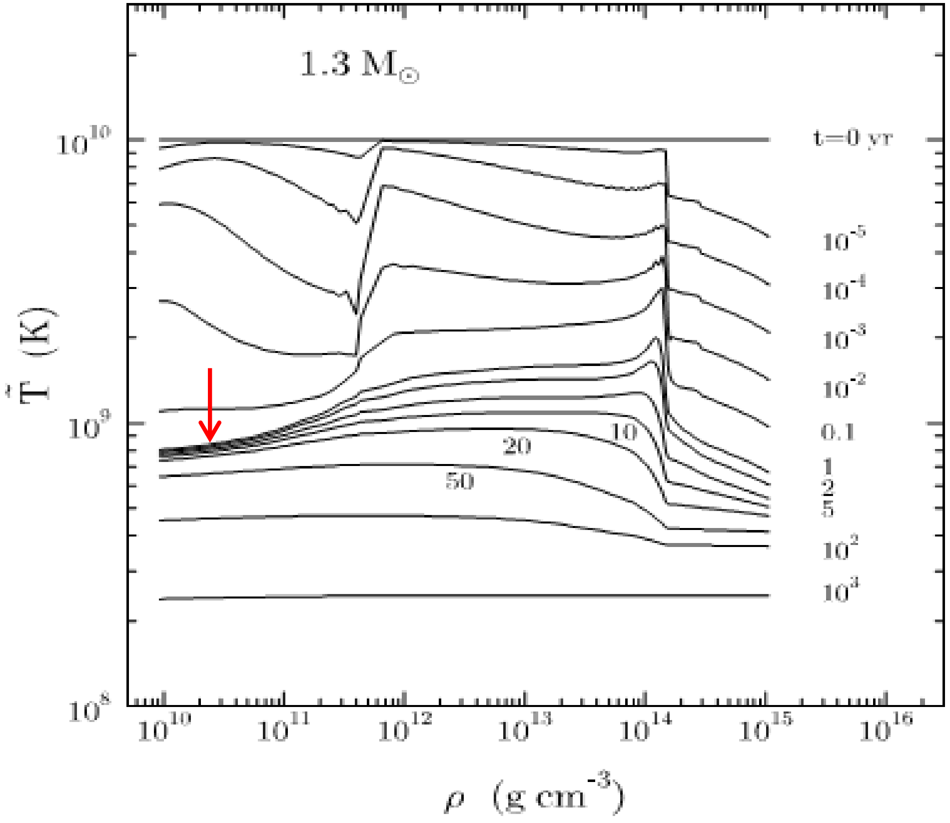
Presumable dip(s)

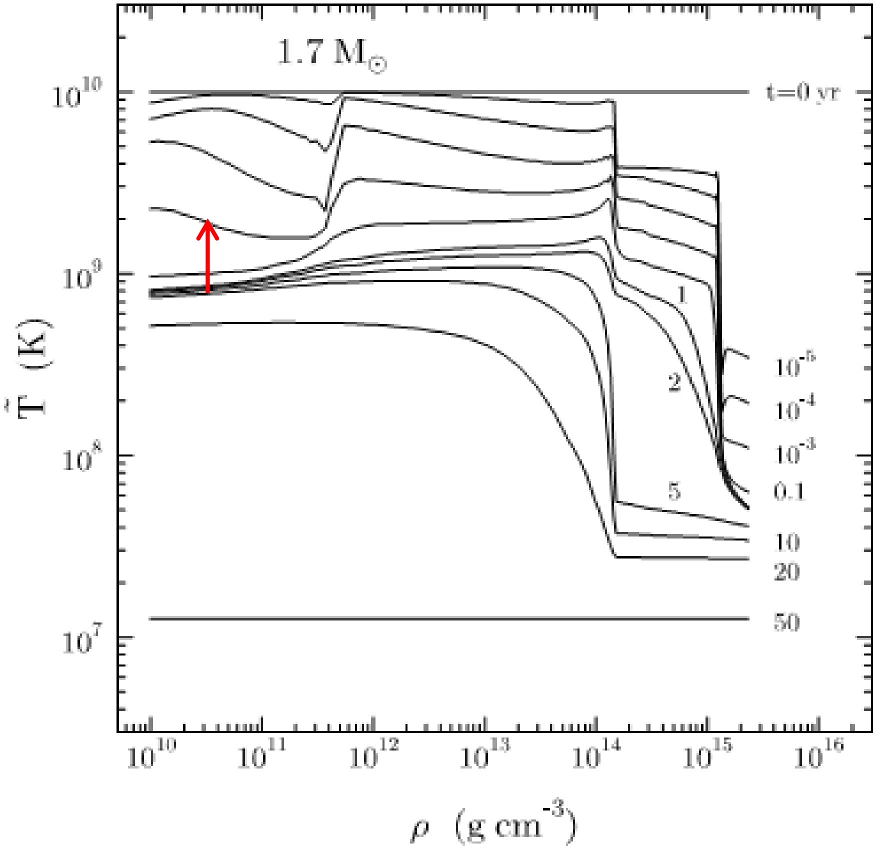
Thermal relaxation of the neutron star crust

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

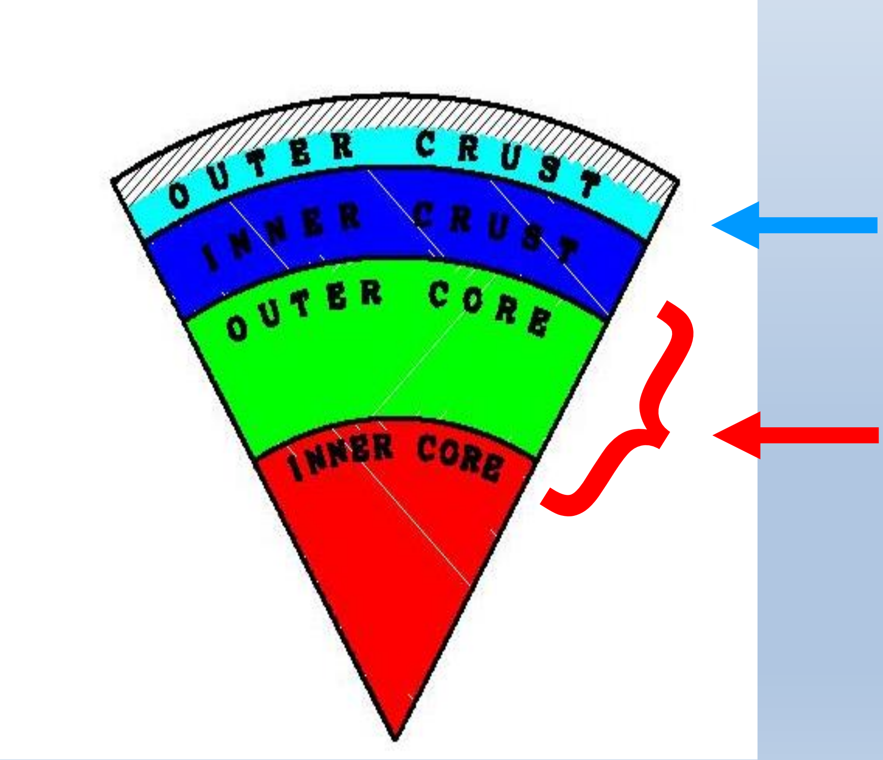






Features of internal heating

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



Energy release

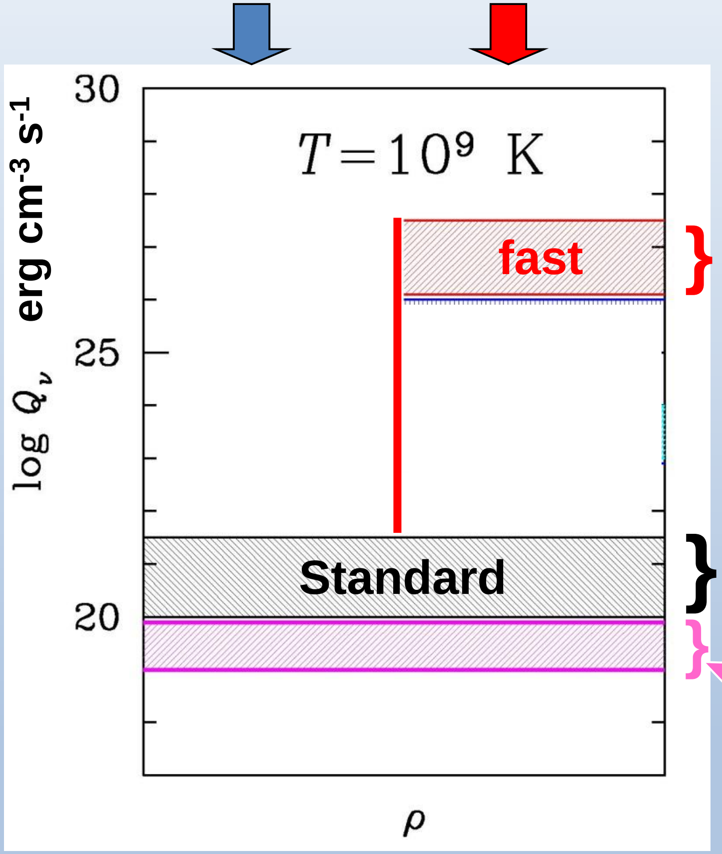
Energy storage

Neutrino emission from NS core

Outer core
Standard cooling

Inner core
Fast cooling

Nucleon composition:
N=n, p



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

Modified Urca

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

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

NN bremsstrahlung

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

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:

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