



MAGNETARS AS COOLING NEUTRON STARS WITH INTERNAL HEATING

**A.D. Kaminker, D.G. Yakovlev, A.Y. Potekhin, N. Shibazaki*,
P. Sternin, and O.Y. Gnedin****

Ioffe Physical Technical Institute, St.-Petersburg, Russia

**Rikkyo University, Tokyo 171-8501, Japan*

***Ohio State University, 760 1/2 Park Street, Columbus, OH 43215, USA*

- **Introduction**
- **Physics input**
- **Games with cooling code**
- **Conclusions**

Cooling theory with internal heating

Thermal balance:

$$C(T) \frac{dT}{dt} = W - L_\nu - L_\gamma$$

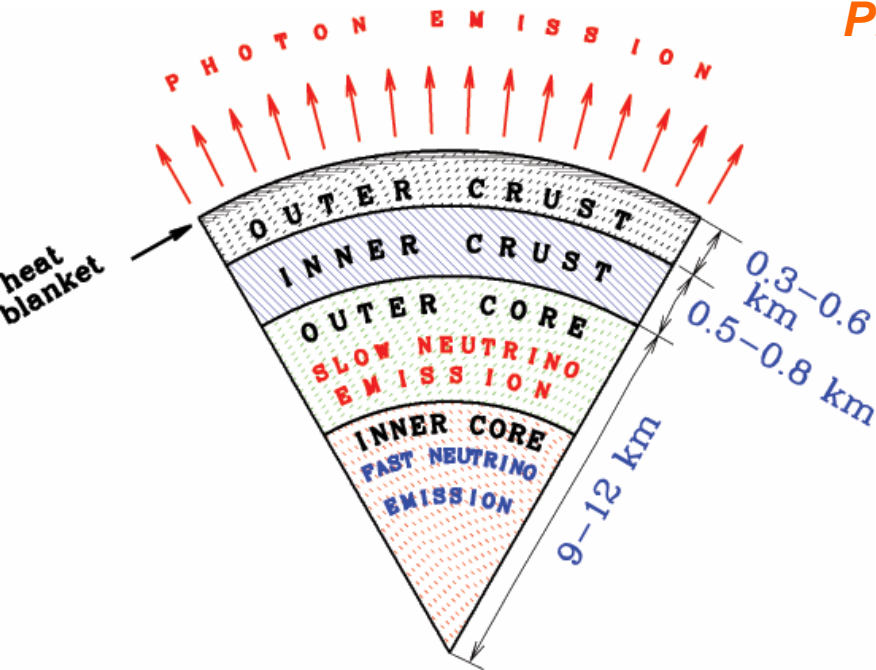
Heat transport:

$$F = -\kappa \frac{dT}{dr}; \quad \kappa - \text{effective thermal conductivity}$$

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

Heat blanketing envelope: $T_s = T_s(T)$

Heat content: $U_T \sim 10^{48} T_9^2 \text{ ergs}$



Main cooling regulators:

1. EOS
2. Neutrino emission
3. Reheating processes
4. Superfluidity
5. Magnetic fields
6. Light elements on the surface

1. **EOS: APR III** (n, p, e, μ) **Gusakov et al. (2005)**
Akmal-Pandharipande-Ravenhall (1998) -- neutron star models

Parametrization: Heiselberg & Hiorth-Jensen (1999)

$$M_{\max} = 1.93M_{\odot},$$

$$M_D = 1.7M_{\odot},$$

$$\rho_{\max} = 2.7 \times 10^{15} \text{g cm}^{-3},$$

$$\rho_D = 1.3 \times 10^{15} \text{g cm}^{-3},$$

$$R = 10.4 \text{ km},$$

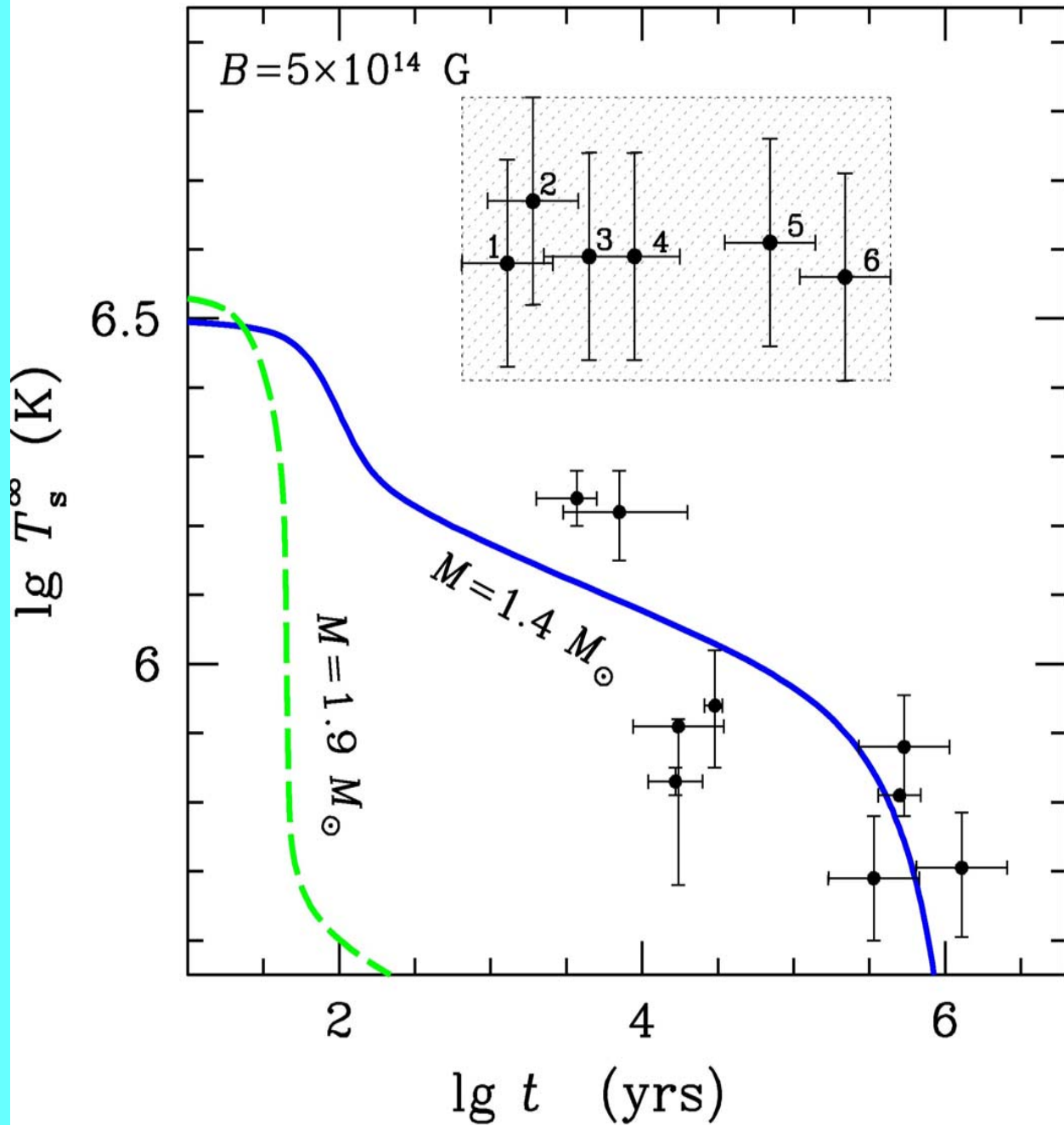
$$R = 11.83 \text{ km}$$

2. **Heat blanketing envelope:** $\rho \leq \rho_b = 10^{10} \text{ g / cm}^3$

$$T_b - T_s \text{ -- relation; } T_b = T(\rho_b)$$

T_{eff} -- effective temperature; $T_s(\mathcal{G})$ -- surface temperature,

$$4\pi\sigma R^2 T_{\text{eff}}^4 = L_{\gamma} = \sigma \int T_s^4 d\Sigma; \quad d\Sigma \text{ -- surface element}$$



1- SGR 1900+14

2- SGR 0526-66

3- AXP 1E 1841-045

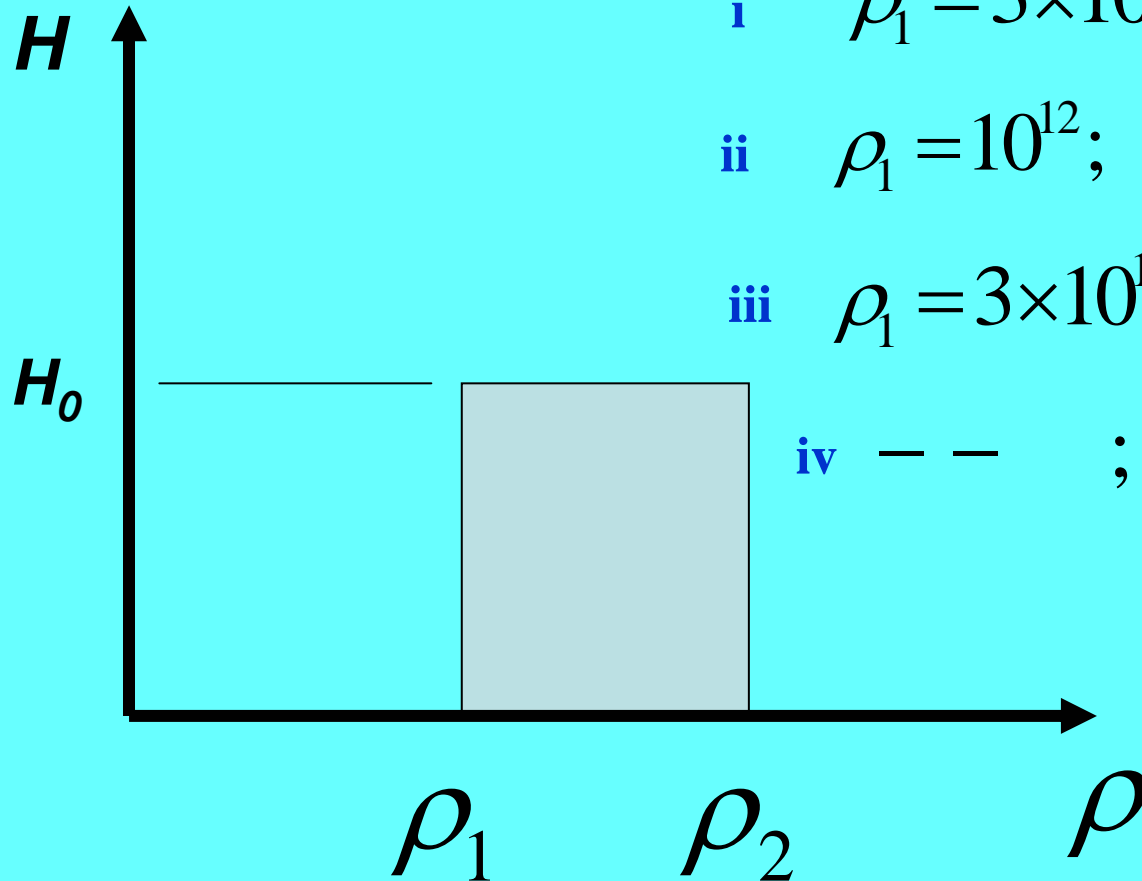
4- AXP 1RXS J170849-400910

5- AXP 4U 0142+61

6- AXP 1E 2259+586

3. Model of heating: $H(\rho, t) = H_0 f_1 f_2 \exp(-\frac{t}{\tau})$

$$f_1(\rho) = \frac{1}{1 + \exp(\frac{\rho - \rho_1}{\Delta\rho_1})}; \quad f_2(\rho) = \frac{1}{1 + \exp(\frac{\rho - \rho_2}{\Delta\rho_2})} \quad \text{at} \quad \rho_1 \leq \rho \leq \rho_2$$



i $\rho_1 = 3 \times 10^{10}$; $\rho_2 = 10^{11} \text{ g cm}^{-3}$;

ii $\rho_1 = 10^{12}$; $\rho_2 = 3 \times 10^{12} \text{ g cm}^{-3}$;

iii $\rho_1 = 3 \times 10^{13}$; $\rho_2 = 10^{14} \text{ g cm}^{-3}$;

iv - - ; $\rho_2 = 9 \times 10^{14} \text{ g cm}^{-3}$;

$$t = 10^3 \text{ yr}$$

No *isothermal* stage

Core — crust decoupling

Only *outer layers* of heating are appropriate for *hottest NSs*

1- SGR 1900+14

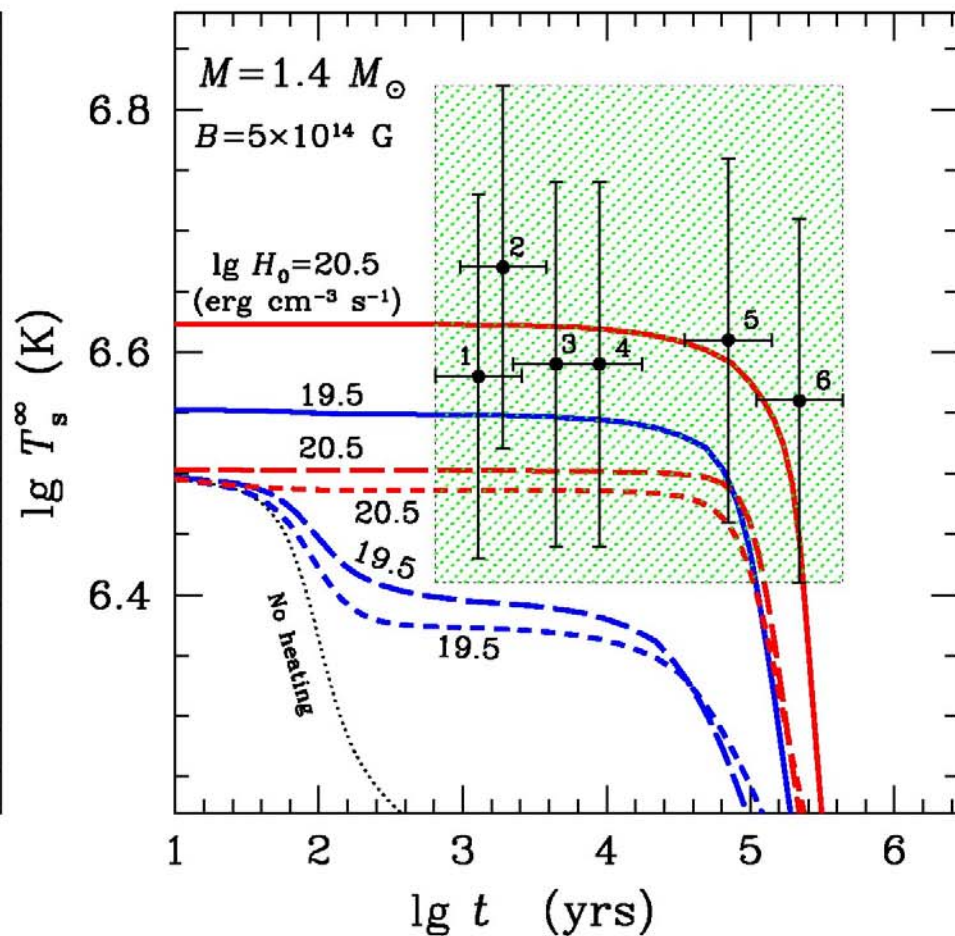
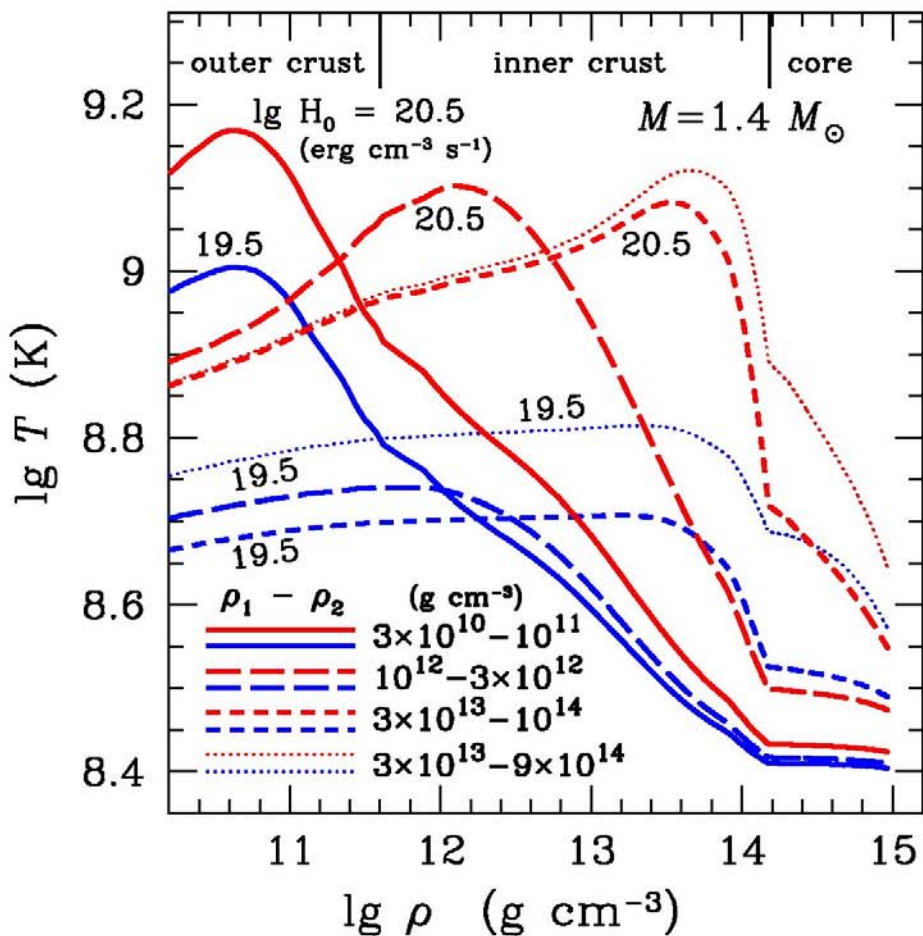
2- SGR 0526-66

3- AXP 1E 1841-045

4- AXP 1RXS J170849-400910

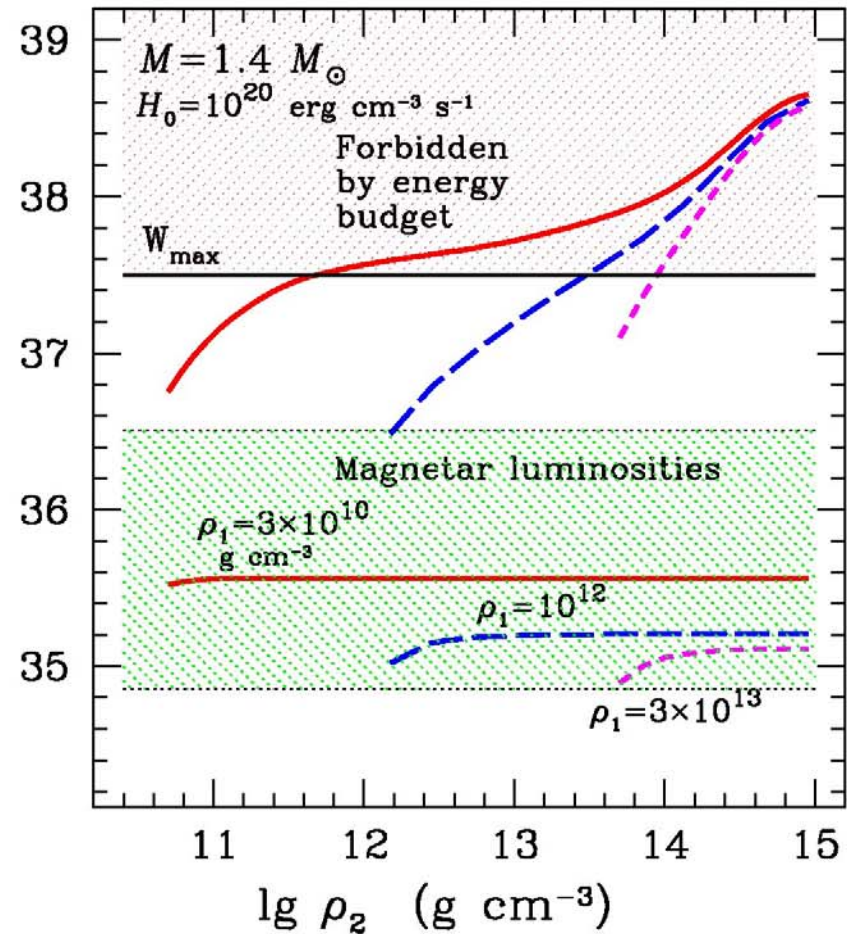
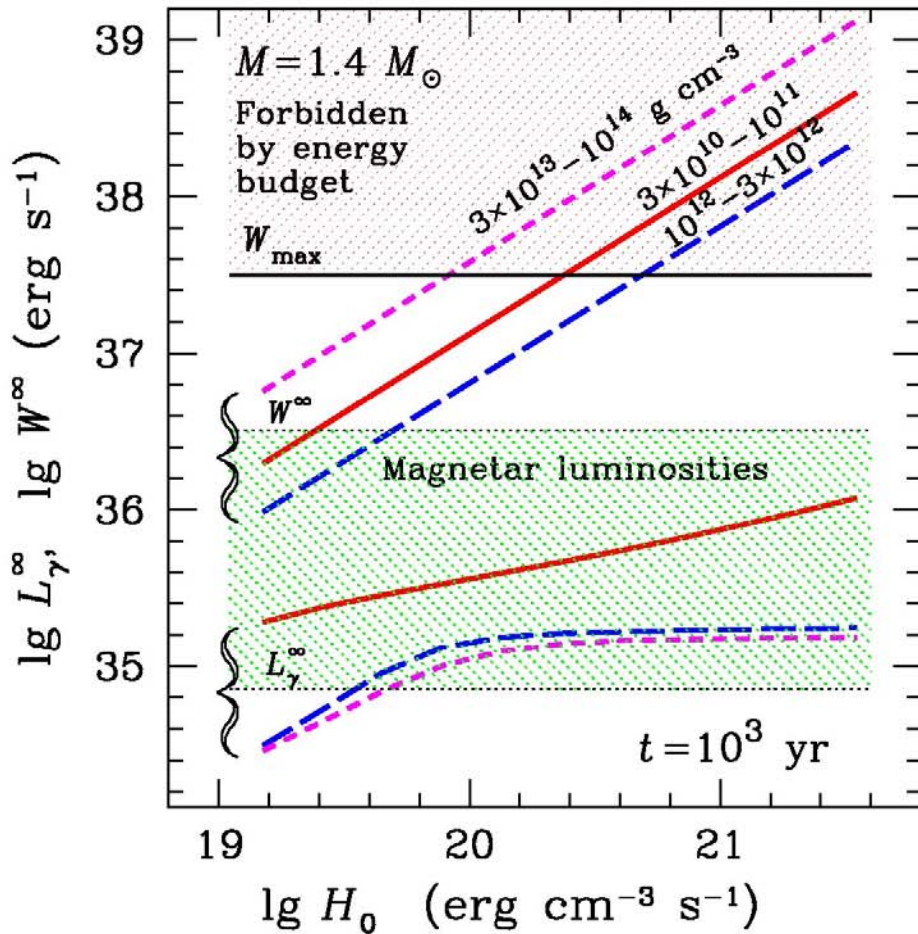
5- AXP 4U 0142+61

6- AXP 1E 2259+586



Necessary energy input vrs. photon luminosity

$$W^\infty \left(\frac{\text{erg}}{s} \right) \quad \underline{\text{into the layer}} \quad \rho_1 \leq \rho \leq \rho_2$$

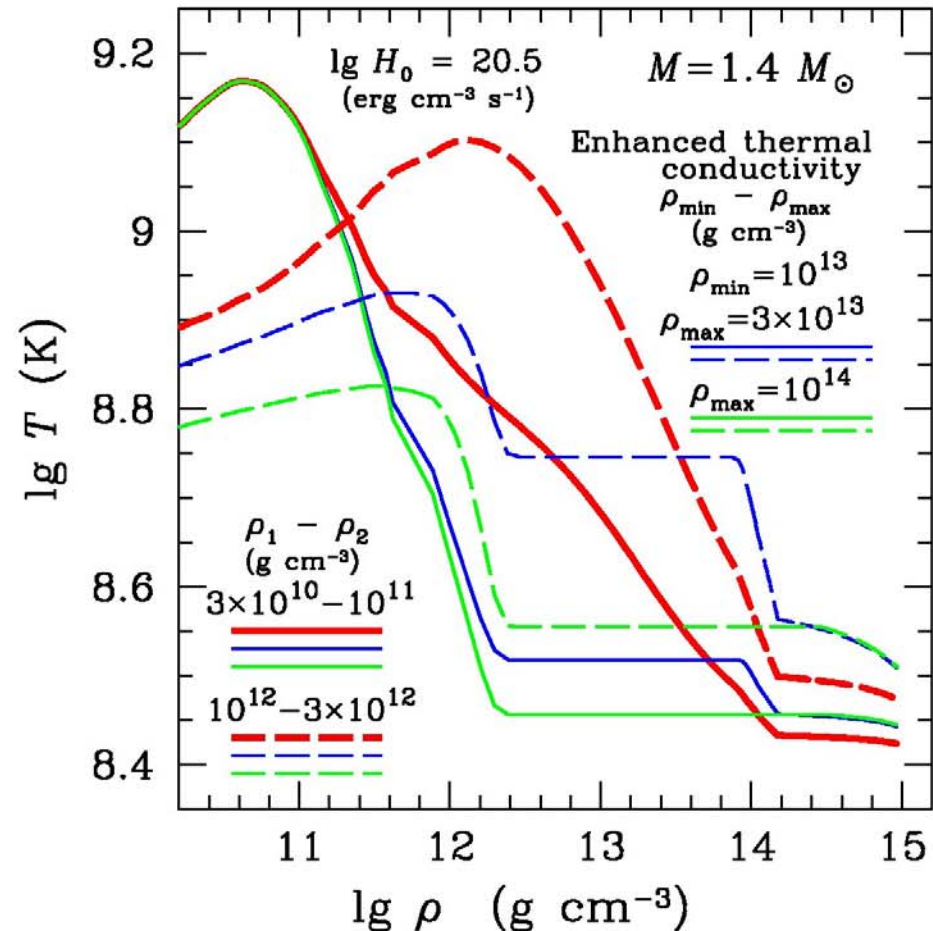
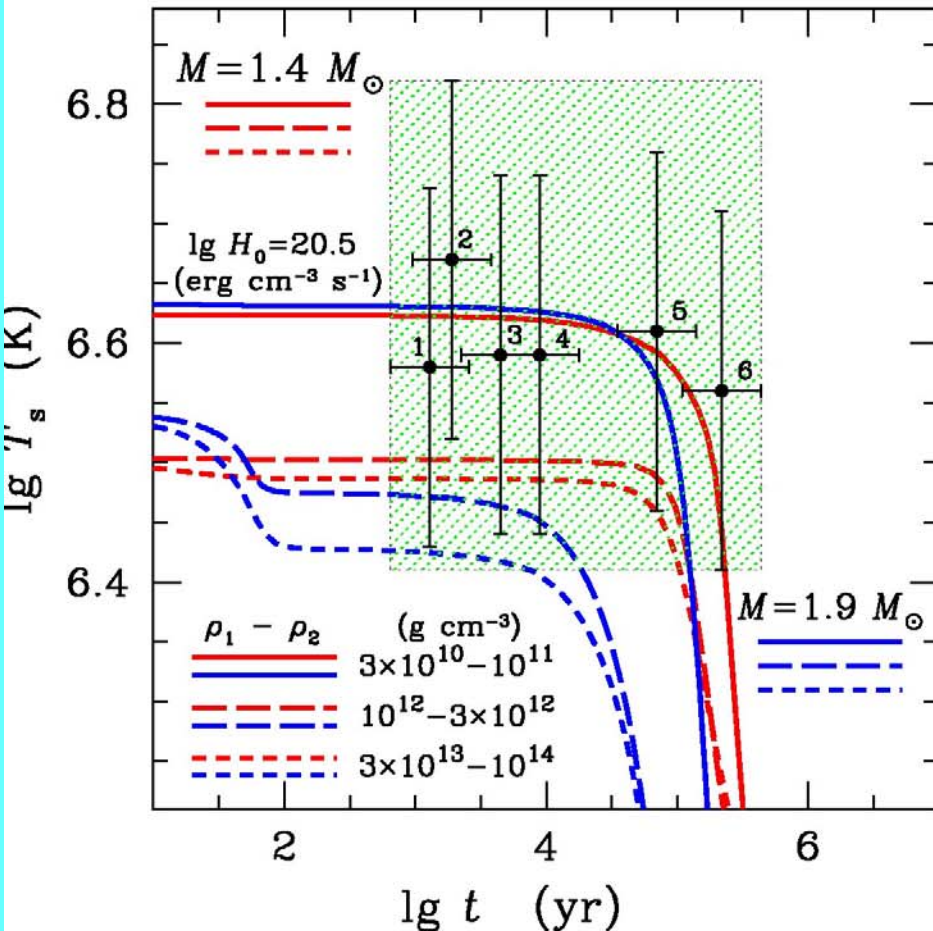


Direct Urca process included

Enhanced thermal conductivity

from ρ_{\min} to ρ_{\max}

Appearance of isothermal layers



Conclusions

1. High thermal state of **magnetars** demand a powerful **reheating**
2. The heating should be located in a thin layer at : $\rho \leq 5 \times 10^{11} \text{ g cm}^{-3}$
in the **outer crust**. The **heat intensity** H_0 should range
from $\square 3 \times 10^{19}$ to $3 \times 10^{20} \text{ erg cm}^{-3} \text{ s}^{-1}$.
Deeper heating would be extremely inefficient due to neutrino radiation
3. Only **~ 1%** of the **total energy** released in the heat layer can be spent to heat the **NS surface**
4. Pumping **huge energy** into deeper layers can not increase -- T_{eff}^{∞}
5. Temperature distributions within **NS** are **strongly nonuniform** due to thermal decoupling of the **outer crust** from the **inner parts** of the star