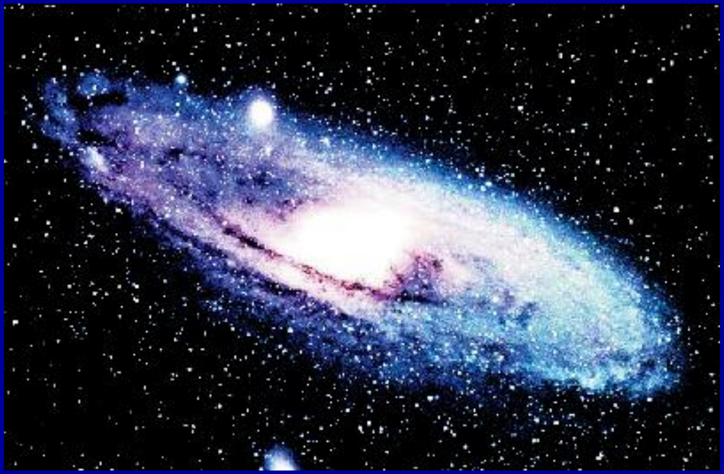


THERMAL EVOLUTION OF ORDINARY NEUTRON STARS AND MAGNETARS

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Ioffe Physical Technical Institute, Saint-Petersburg, Russia

- **Introduction**
- **Thermal evolution of ordinary neutron stars**
- **Thermal evolution of magnetars**
- **Comparison of ordinary neutron stars and magnetars**
- **Conclusions**

Rikkyo University,Tokyo, September 1, 2012

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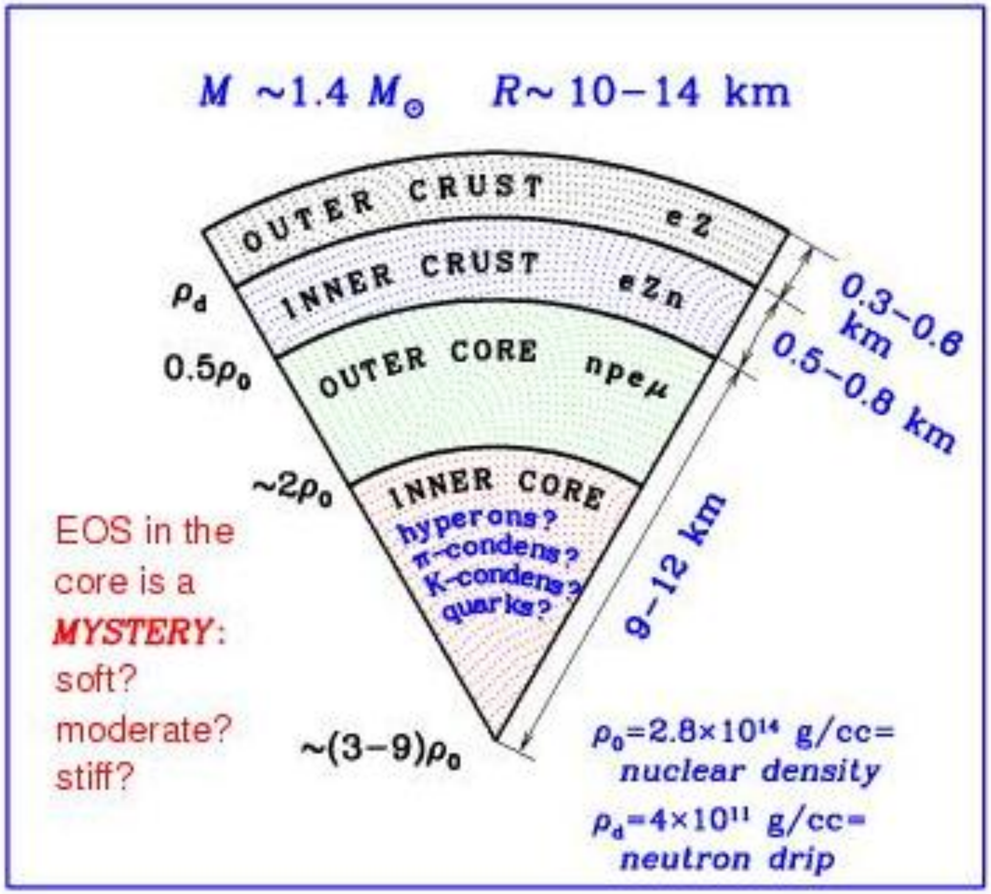
HARD WORK ON MAGNETAR PHYSICS

Neutron star structure

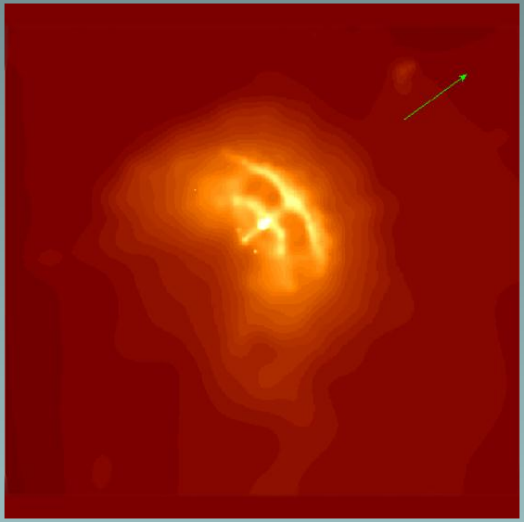


Mystery:
EOS of superdense matter
in the core

For simplicity, consider nucleon core:
neutrons
protons
electrons
muons
EOS=?
Superlfuidity=?

Cooling of ordinary neutron stars

Chandra image of the Vela pulsar wind nebula NASA/PSU Pavlov et al

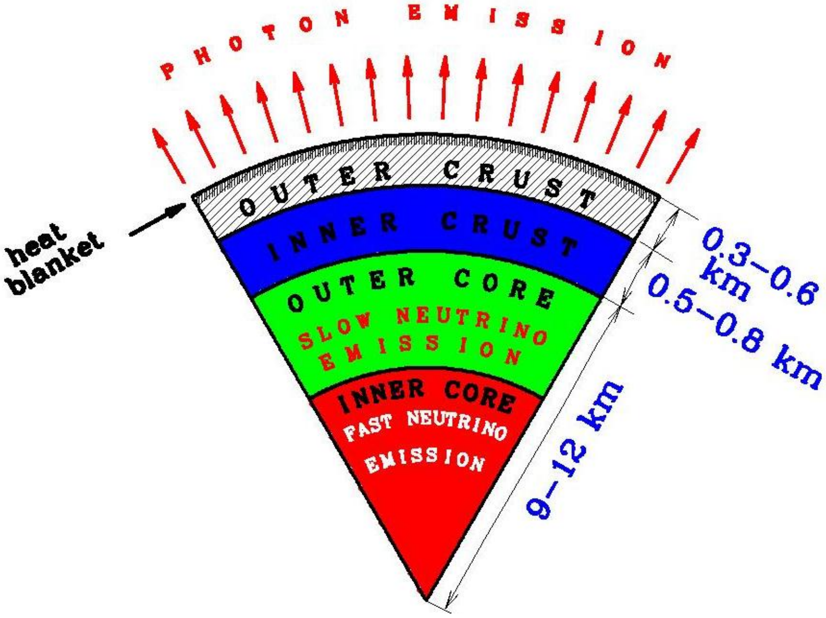


Ordinary neutron stars:

- ***Isolated neutron stars which cool by loosing their internal heat***
- ***Middle-aged (t < 1 Myr)***
- ***Show surface thermal radiation (mainly in X-rays)***

Cooling of ordinary neutron stars

Heat diffusion with neutrino and photon losses



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

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

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

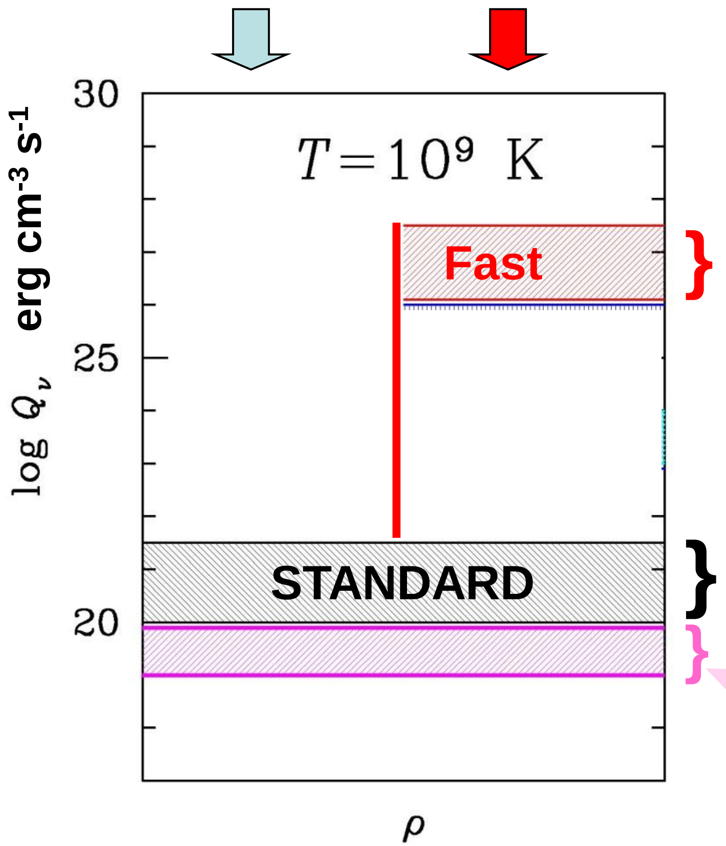
Main cooling regulators:

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

Testing: **Internal structure of neutron stars**

Neutrino emission from cores of non-superfluid NSs

Outer core	**Inner core**
Slow emission	**Fast emission**



NS with nucleon core:
N=n, p

Direct Urca

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

Modified Urca

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

NN bremsstrahlung

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

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

Enhanced emission in inner cores of massive neutron stars:

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

Everywhere in neutron star cores:

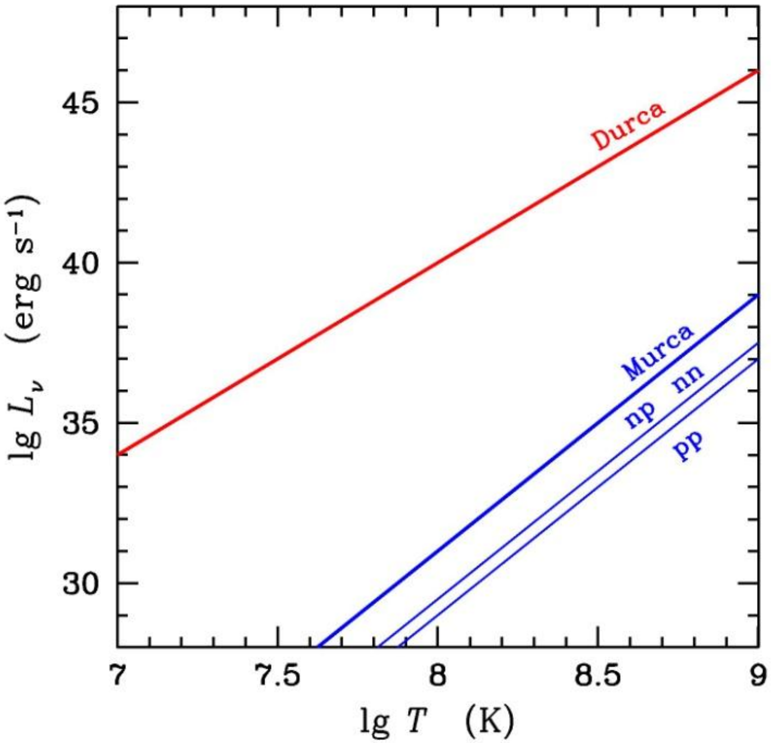
$$Q_{\rm SLOW} = Q_{\rm 0S} T^8 \qquad L_{\rm SLOW} = L_{\rm 0S} T^8$$

Neutrino emission of non-superfluid Neutron star

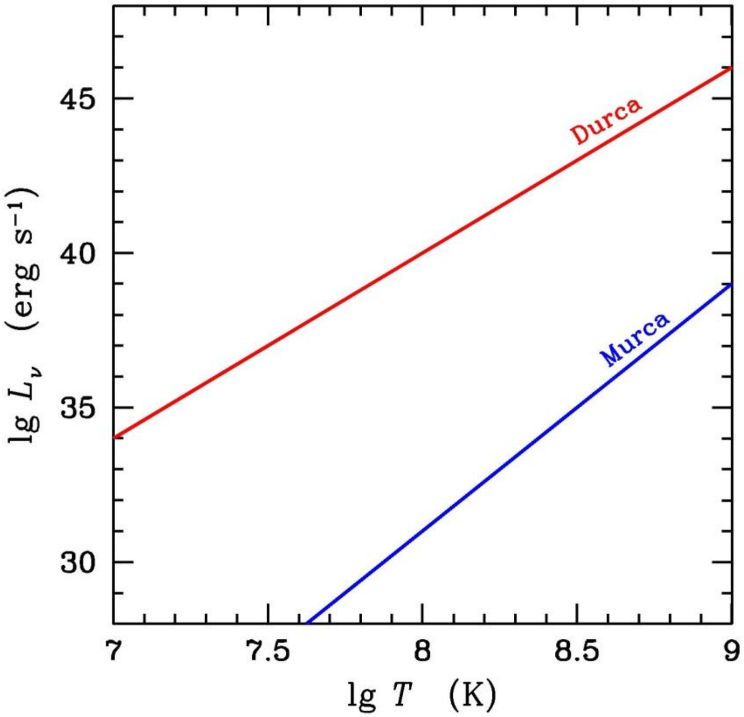
Casino da Urca – Urca – Durca – Murca – Kurca

K.P. Levenfish

G.A. Gamow

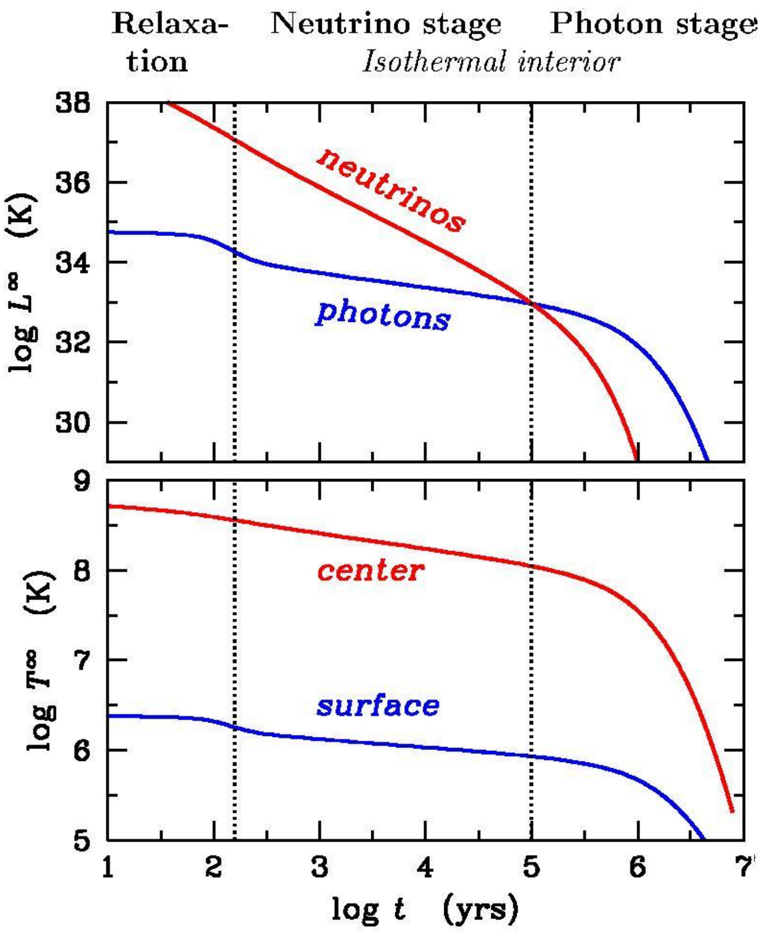


Main neutrino mechanisms



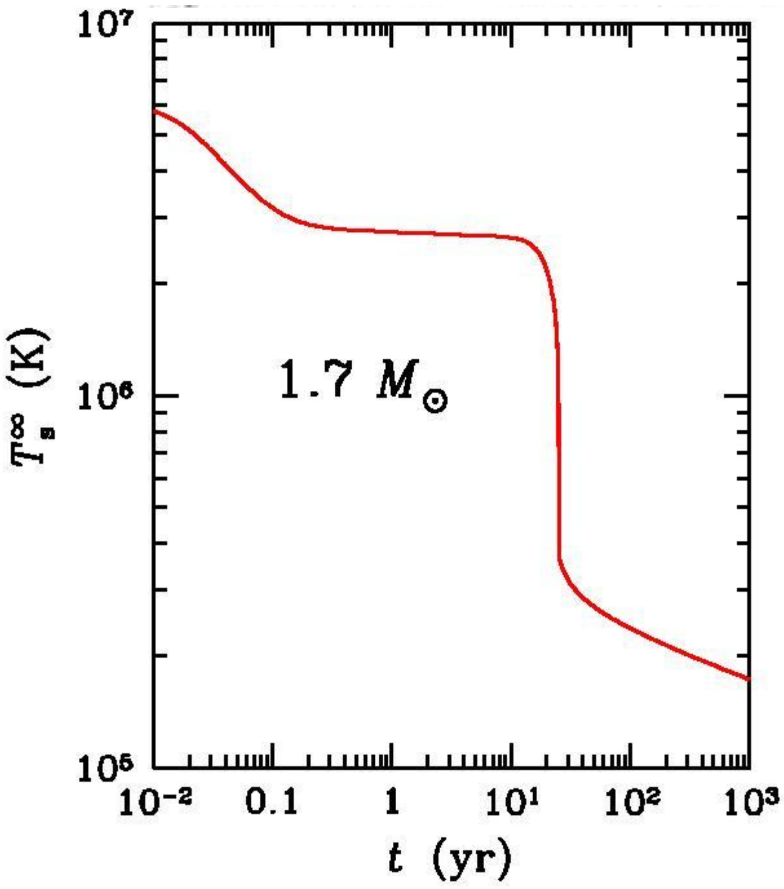
Neutrino emission levels

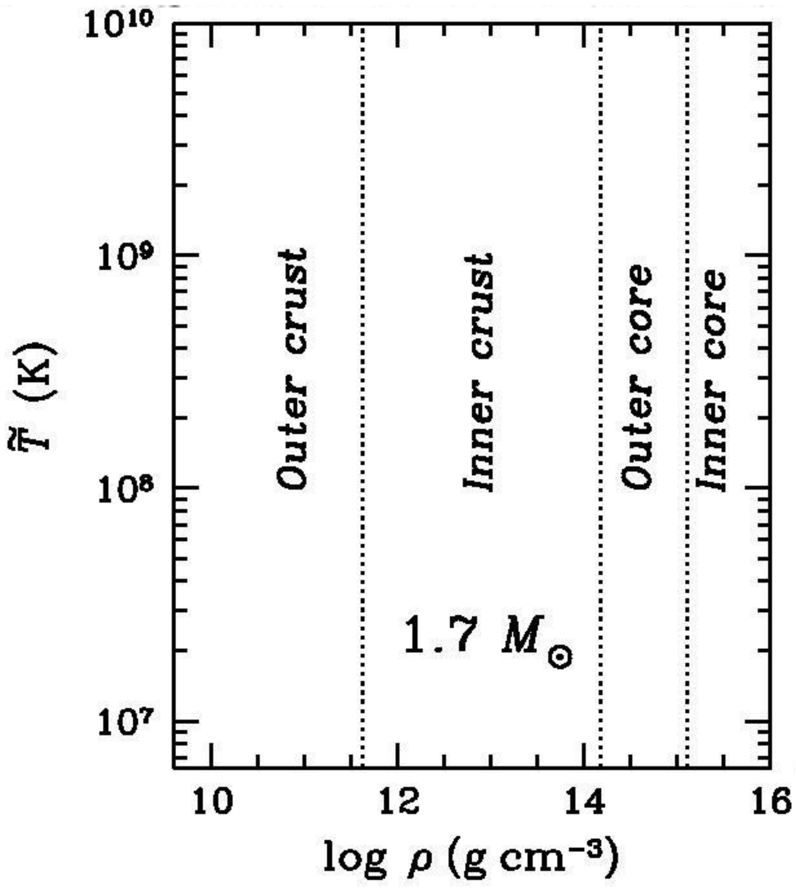
THREE COOLING STAGES



Stage	Duration	Physics
Relaxation	10—100 yr	Crust
Neutrino	10-100 kyr	Core, surface
Photon	Infinite	Surface, core, Reheating

THERMAL RELAXATION
Look From Inside and Outside

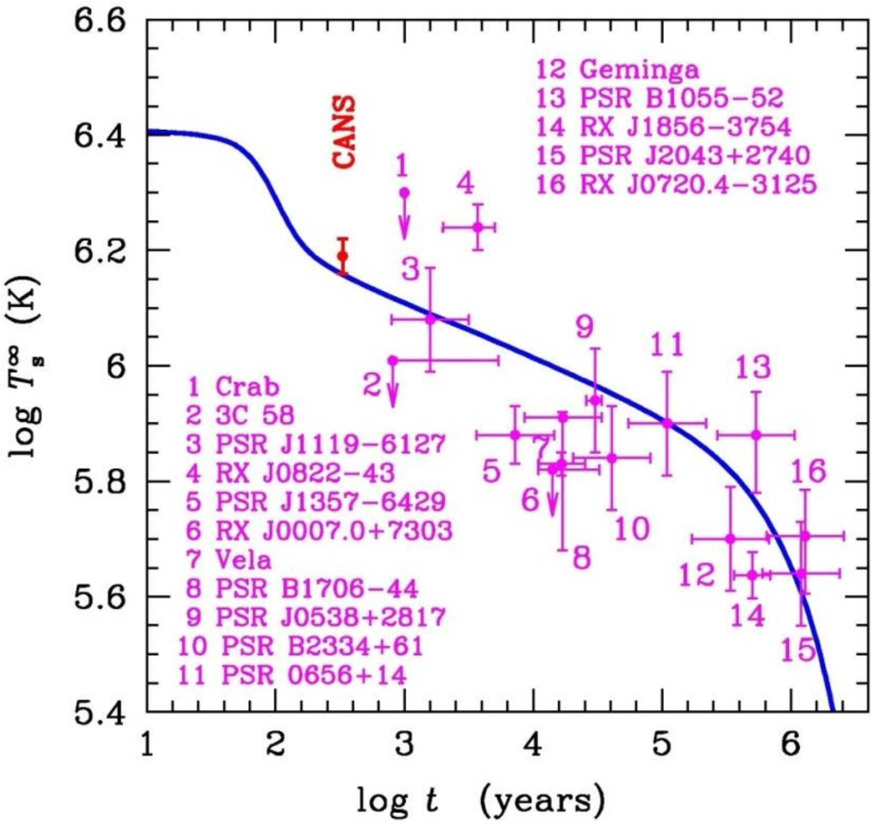




Gnedin et al. (2001)

OBSERVATIONS OF ORDINARY COOLING NEUTRON SRARS

1=Crab
2=PSR J0205+6449
3=PSR J1119-6127
4=RX J0822-43
5=1E 1207-52
6=PSR J1357-6429
7=RX J0007.0+7303
8=Vela
9=PSR B1706-44
10=PSR J0538+2817
11=PSR B2234+61
12=PSR 0656+14
13=Geminga
14=RX J1856.4-3754
15=PSR 1055-52
16=PSR J2043+2740
17=PSR J0720.4-3125



Interpretation of all observations of ordinary neutron stars

1=Crab
2=PSR J0205+6449
3=PSR J1119-6127
4=RX J0822-43
5=1E 1207-52
6=PSR J1357-6429
7=RX J0007.0+7303
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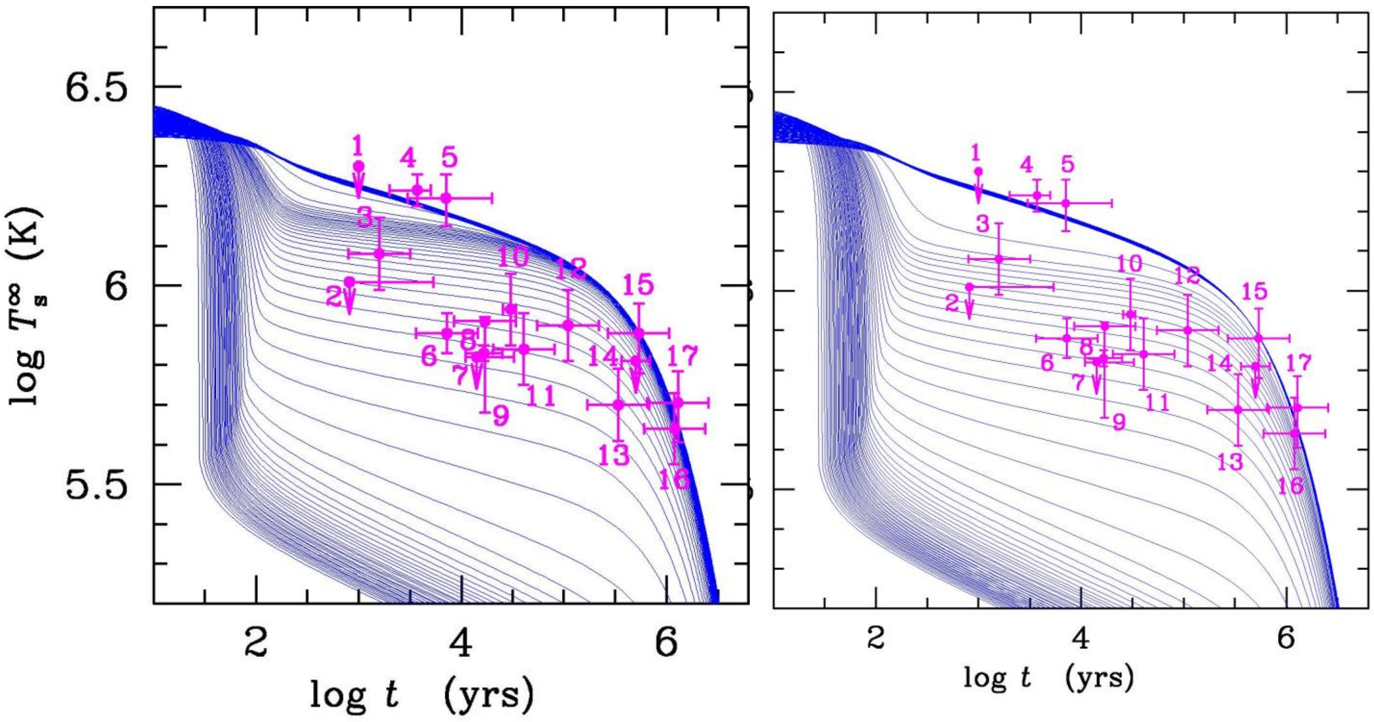
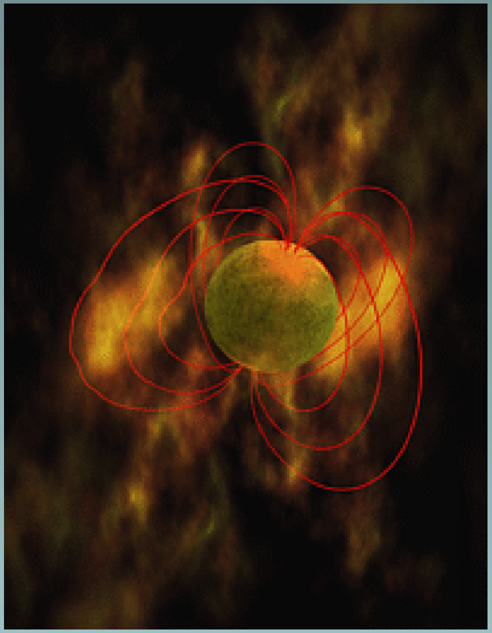


Models of cooling neutron stars with different masses for two models of proton superfluidity

- *Observed middle-aged ordinary cooling NSs are mainly on neutrino cooling stage*
- *They cool from inside via neutrino emission; powered by internal thermal energy*
- *They have isothermal interiors = cores and surface are thermally coupled*
- *Good natural laboratories of superdense cores (neutrinos + superfluidity)*
- *They are just cooling; no extra heat sources required*

Thermal evolution of magnetars



Magnetars:

•AXPs + SXRs
•Neutron stars which are powered neither by accretion nor by rotation
•Possibly are powered by strong magnetic fields
•Activity: quasi-persistent thermal emission, flares and giant flares, QPOs
•Magnetospheric activity (twisted magnetospheres)

Main problem:

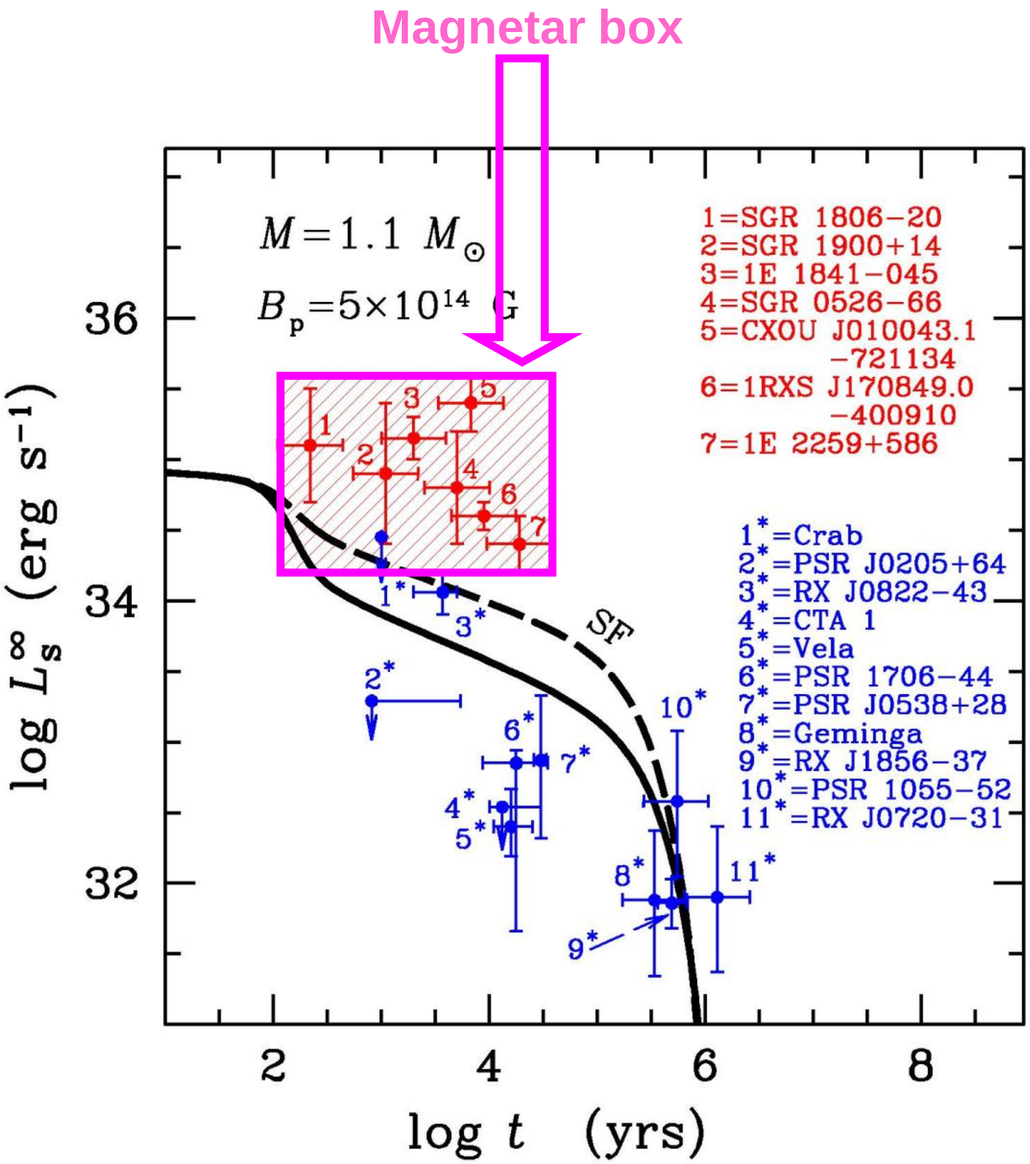
•Are spending a lot of energy
•Could be the energy of superstrong B-field within the star (in the core)

Main question:

•Where is this energy released and how?

Example: Supergiant flare of SGR 1806 – 20 on Dec. 27, 2004: $W_X \sim 10^{46}$ erg $\Rightarrow W_{\text{INPUT}} \sim 10^{50}$ erg

Magnetars versus ordinary cooling neutron stars
The need for heating: Luminosity representation



Two assumptions:

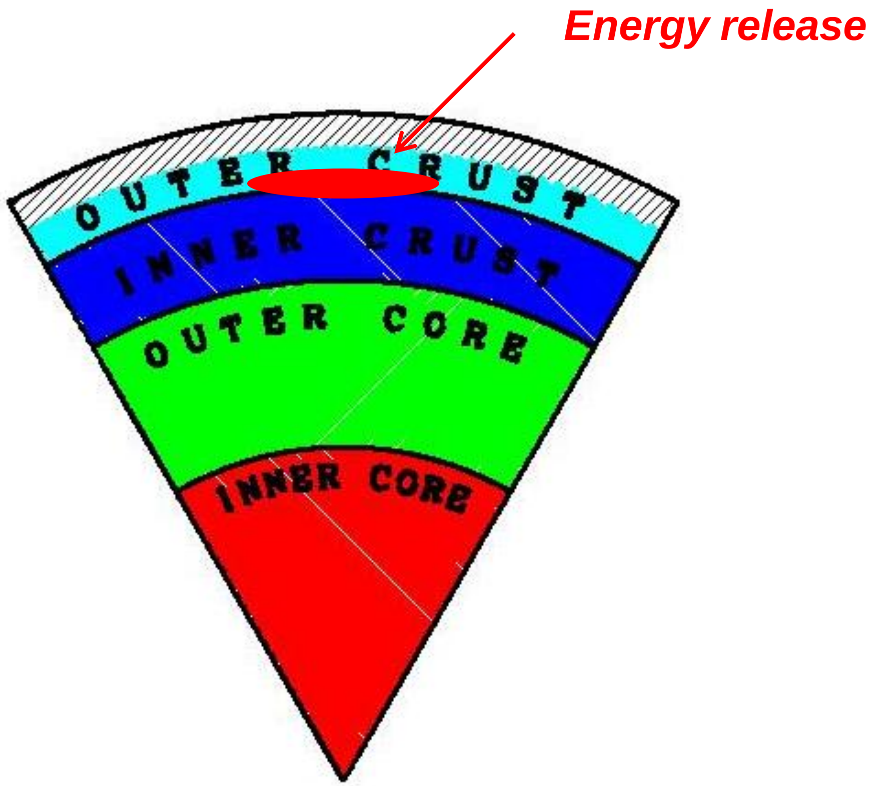
(1) The magnetar data reflect persistent thermal surface emission

(2) Magnetars are cooling neutron stars

There should be a HEATING!
Which we assume to be INTERNAL

Statement of the Problem

- *To explain quasi-persistent thermal emission of magnetars*
- *Assume: the emission is powered by internal heat sources*
- *The maximum stored energy $E_{TOT}=10^{49}$—10^{50} erg can be the energy of internal magnetic field $B=(1—3)\times10^{16}$ G in the magnetar core*
- *The stored energy is released in the crust*

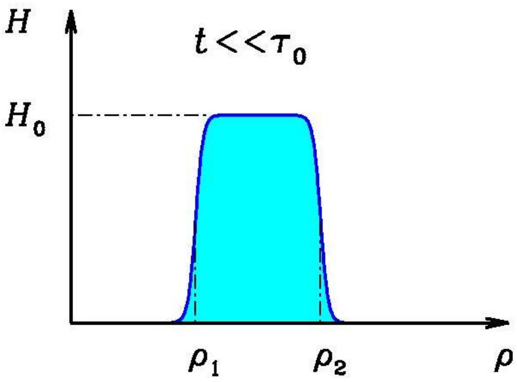


Neutron star model

- *EOS: Akmal, Pandharipande, Ravenhall (APR III); neutrons, protons, electrons, and muons in NS cores*
- *Direct Urca: central density* > 1.275×10^{15} g/cc, $M > 1.685\ M_{SUN}$
- *Maximum mass:* $M_{MAX} = 1.929\ M_{SUN}$
- *Example of slow cooling:* $M = 1.4\ M_{SUN}$, $R = 12.27$ km, *central density* = 9.280×10^{14} g/cc
- *Effects of superfluidity are neglected*
- *Iron heat blanketing envelopes (densities* $< 10^{10}$ g/cc)
- *Radial magnetic field* $B = 5 \times 10^{14}$ G *above hot spots*
- *Cooling codes: either 2D, or 1D*

Phenomenological heater and calculations

Radial heat power distribution:



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

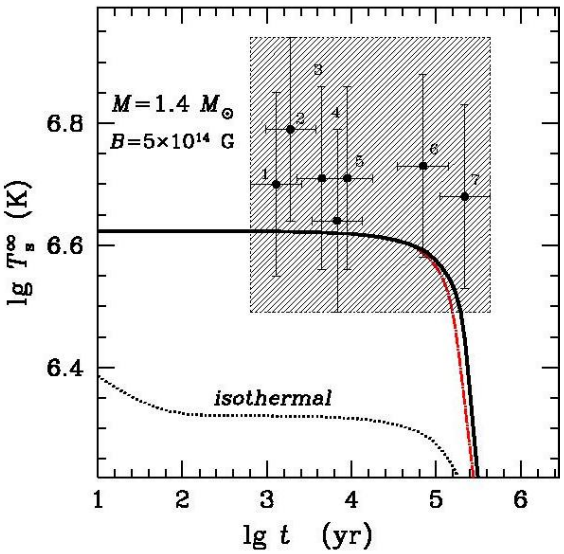
Four parameters: $\rho_1,\ \rho_2,\ H_0,\ \tau_0$

$\tau_0 = 5\times10^4$ yr

Angular heat power distribution:

Either hot spot: 2D code

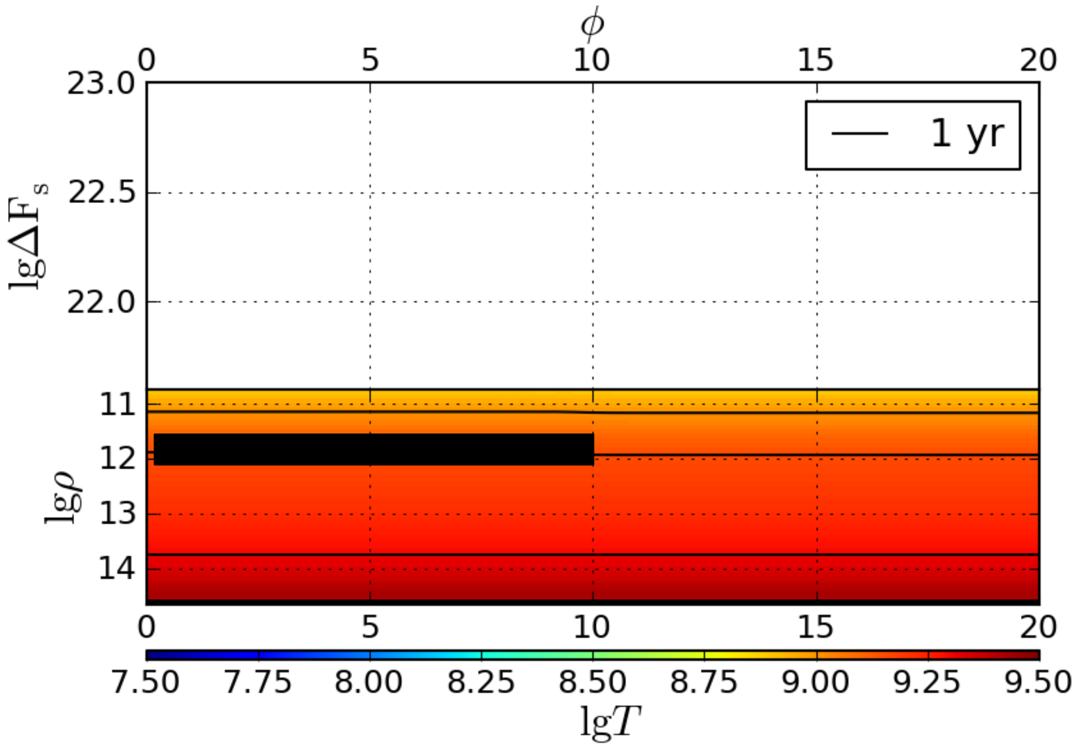
Or spherical layer: 1D code



Run cooling code: in about 100 years – quasi-stationary temperature distribution determined by the heat source

Results of 2D code

Heater: angles $\phi < 10^o$



Heater:

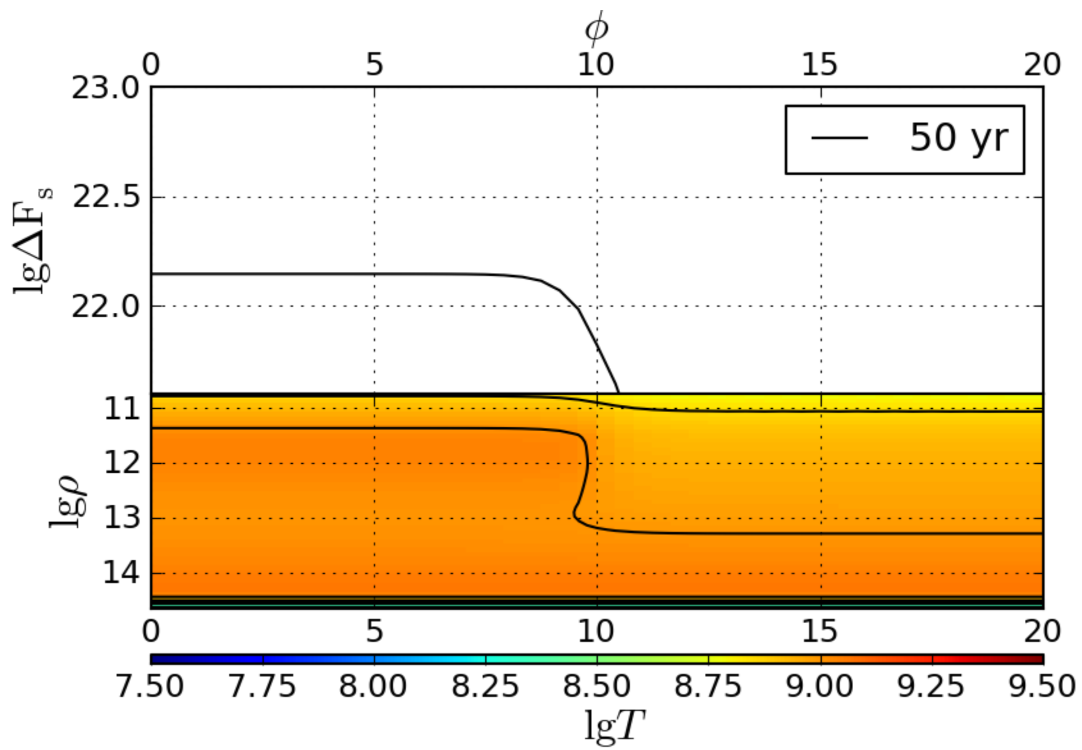
~400 m under surface

~80 m width

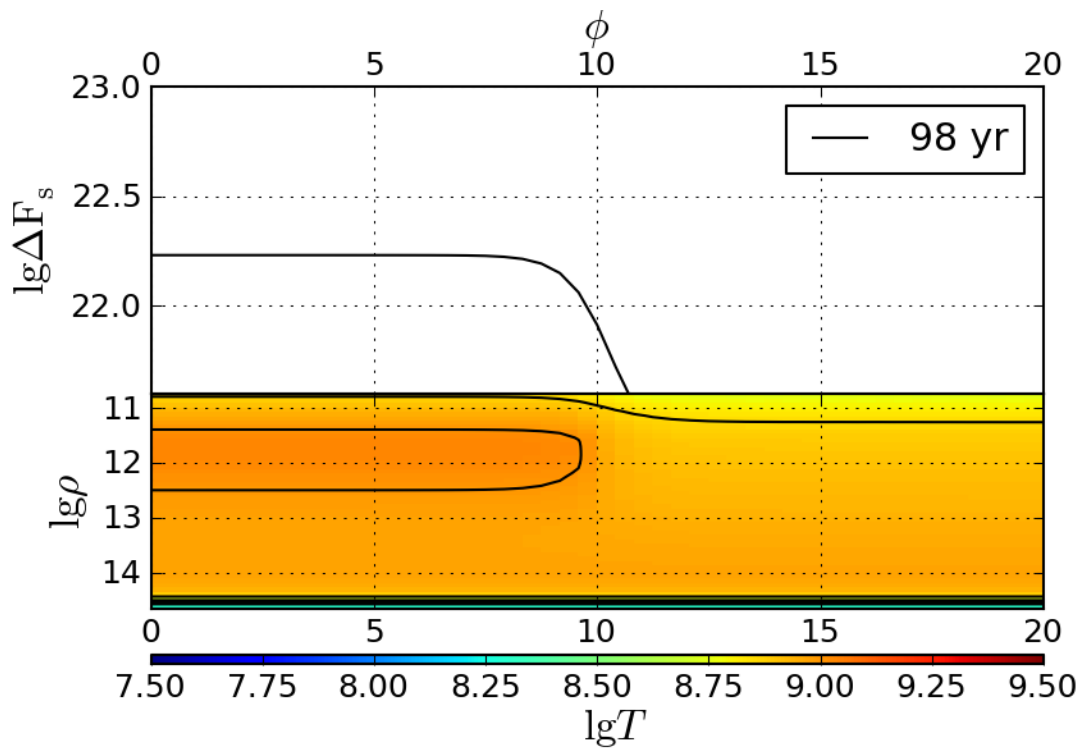
$$\rho_1 = 3.2 \times 10^{11} \text{ g cm}^{-3}$$

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

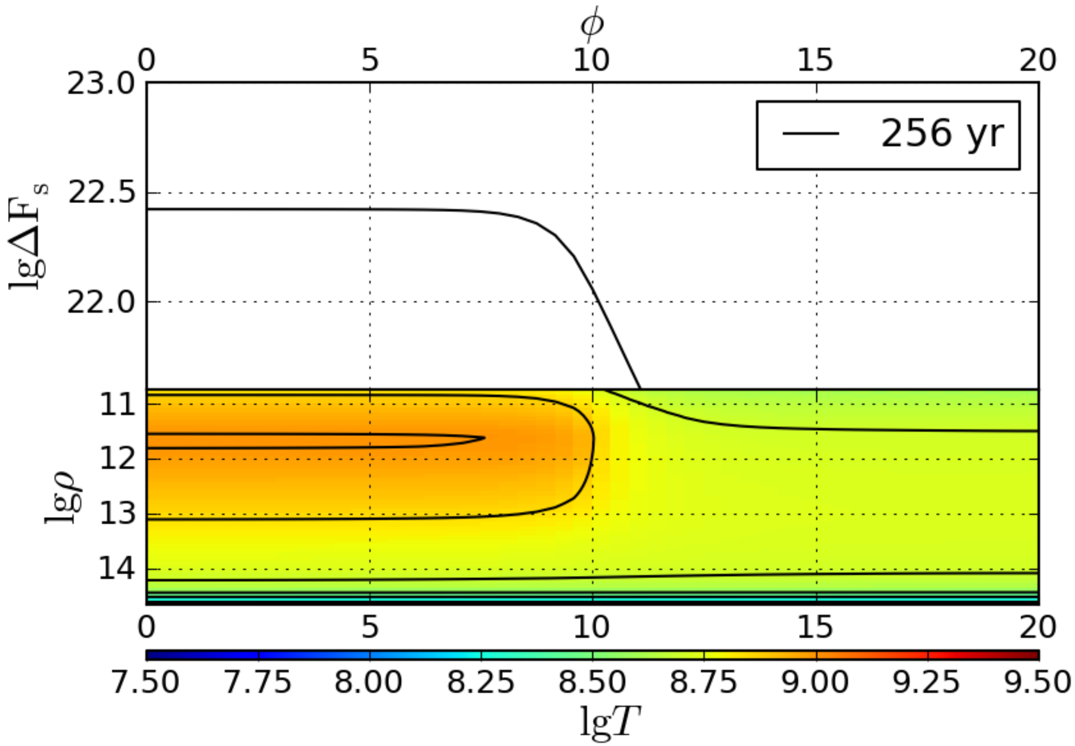
$$H_0 = 10^{19.5} \text{ erg cm}^{-3} \text{ s}^{-1}$$



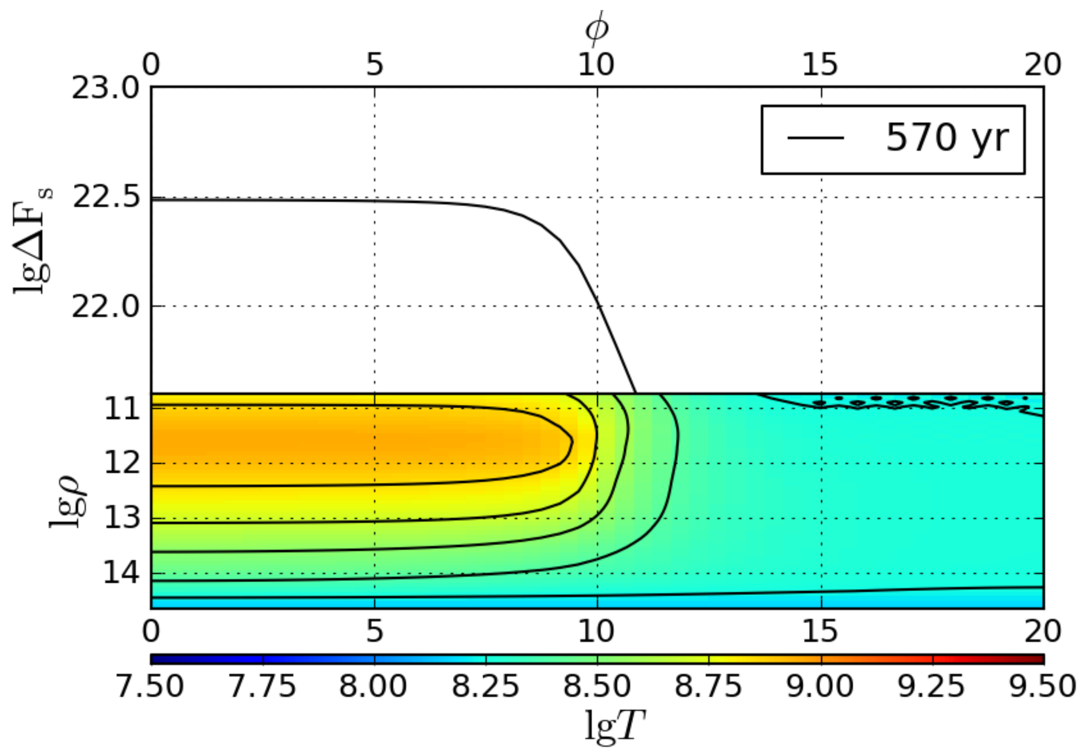
ϕ
0
5
10
15
20
23.0
22.5
22.0
$\lg \Delta F_s$
50 yr
11
12
13
14
$\lg \rho$
0
5
10
15
20
7.50
7.75
8.00
8.25
8.50
8.75
9.00
9.25
9.50
$\lg T$



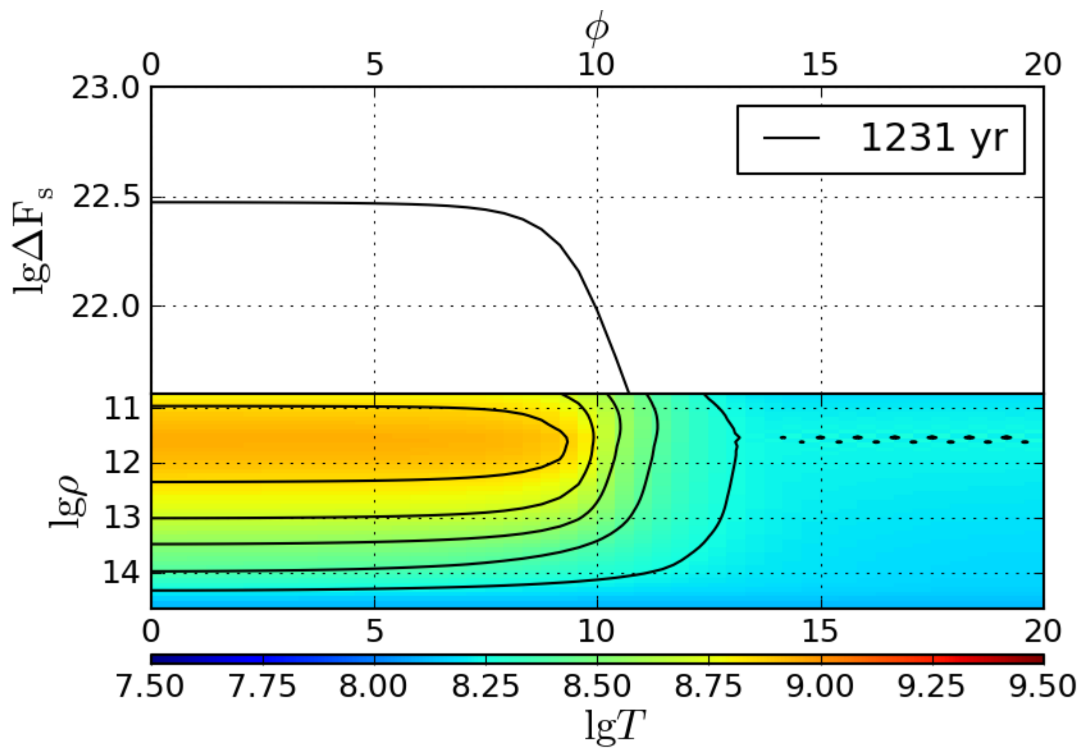
ϕ
0
5
10
15
20
23.0
22.5
22.0
lgΔF_s
98 yr
11
12
13
14
lgρ
7.50
7.75
8.00
8.25
8.50
8.75
9.00
9.25
9.50
lgT



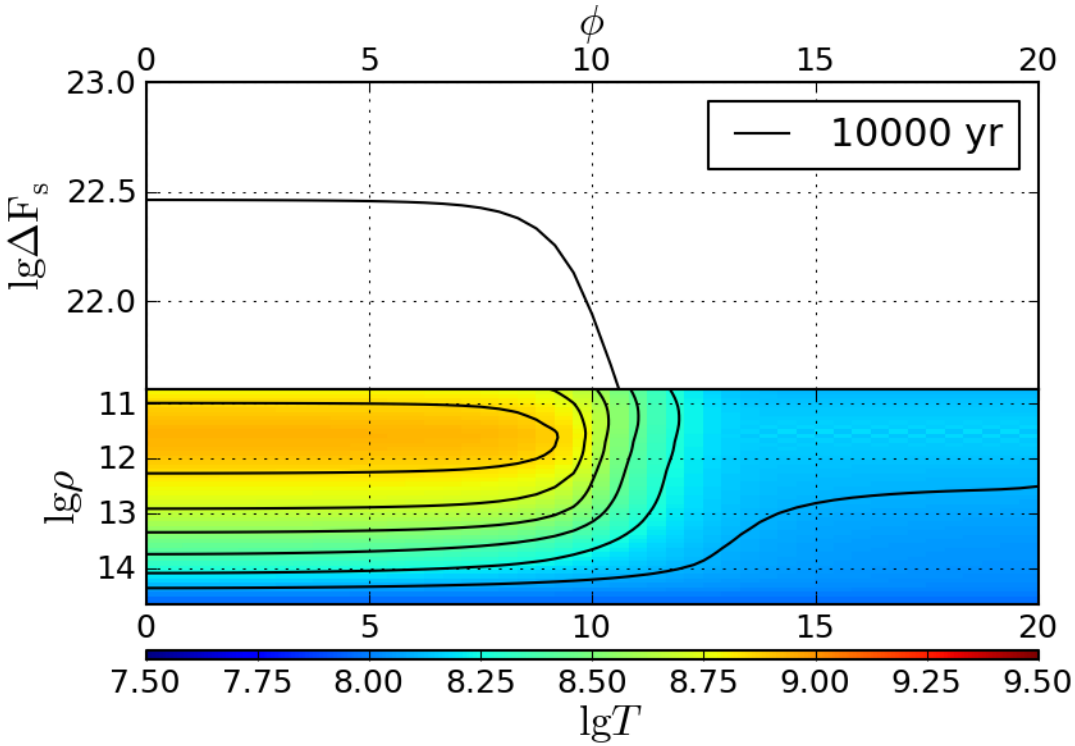
ϕ
0
5
10
15
20
23.0
22.5
22.0
$\lg\Delta F_s$
256 yr
11
12
13
14
$\lg\rho$
0
5
10
15
20
7.50
7.75
8.00
8.25
8.50
8.75
9.00
9.25
9.50
$\lg T$



ϕ
0
5
10
15
20
23.0
22.5
22.0
$\lg \Delta F_s$
570 yr
11
12
13
14
$\lg \rho$
0
5
10
15
20
7.50
7.75
8.00
8.25
8.50
8.75
9.00
9.25
9.50
$\lg T$



ϕ
0
5
10
15
20
23.0
22.5
22.0
$\lg \Delta F_s$
1231 yr
11
12
13
14
$\lg \rho$
0
5
10
15
20
7.50
7.75
8.00
8.25
8.50
8.75
9.00
9.25
9.50
$\lg T$



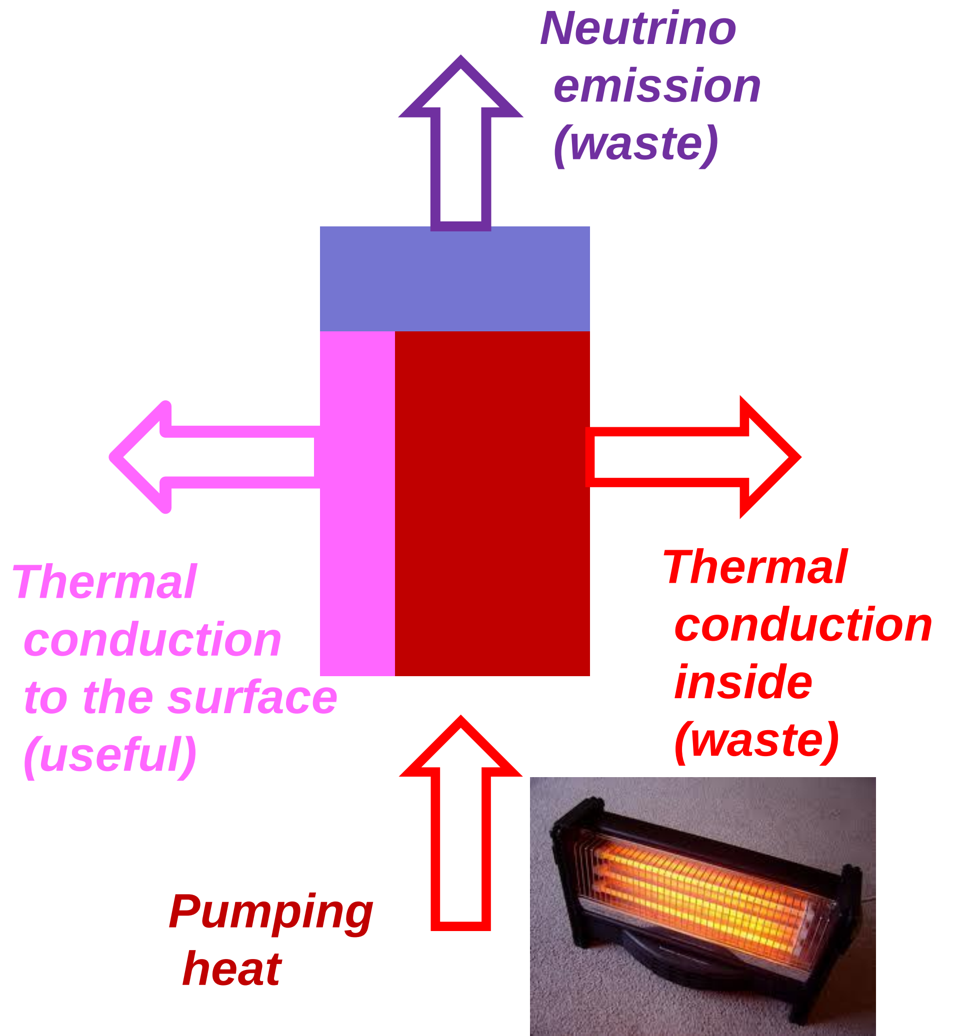
ϕ
0
5
10
15
20
23.0
22.5
22.0
$\lg\Delta F_s$
10000 yr
11
12
13
14
$\lg\rho$
0
5
10
15
20
7.50
7.75
8.00
8.25
8.50
8.75
9.00
9.25
9.50
$\lg T$

Weak heat spreading along the surface

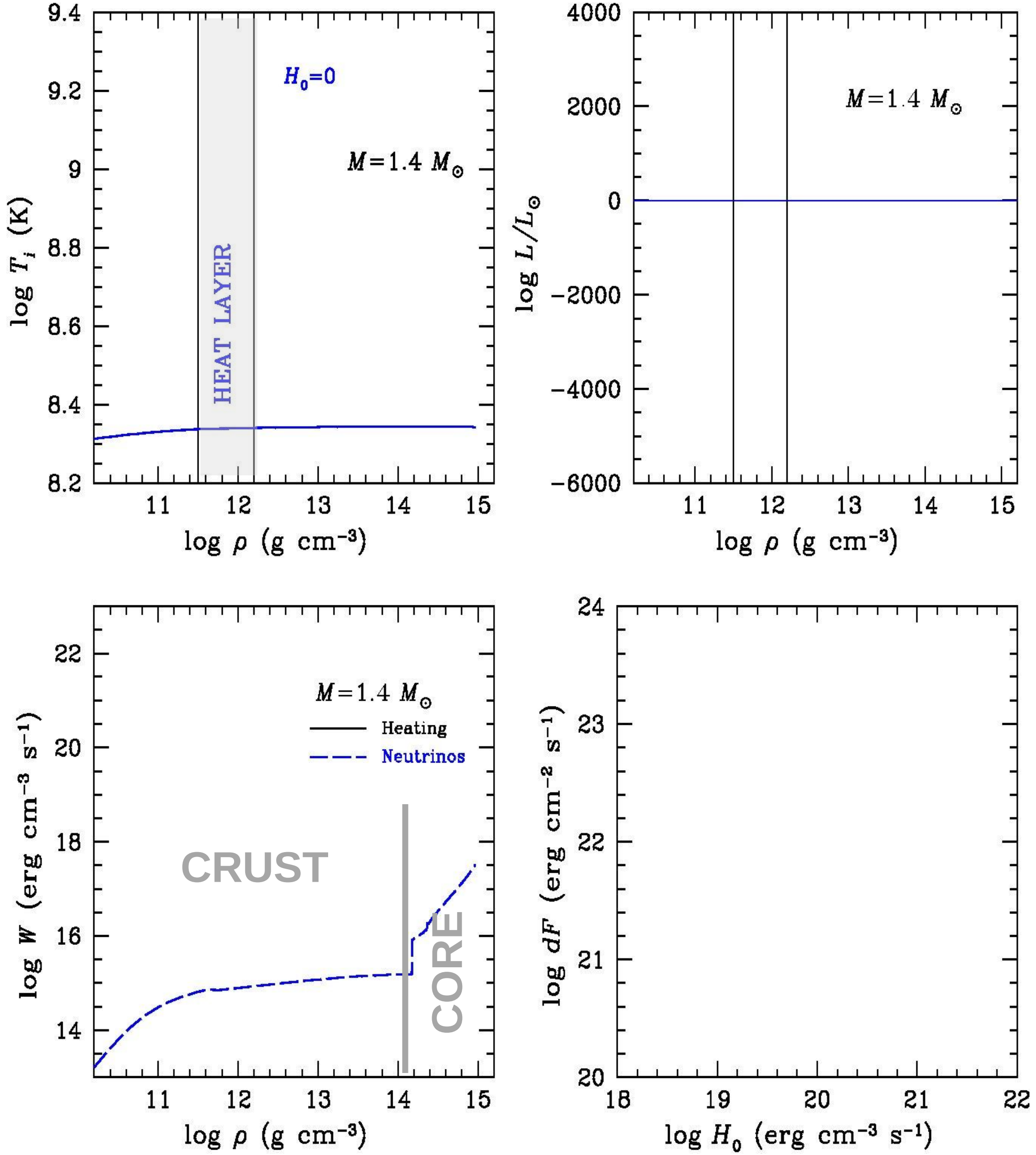
Heat does not want to spread along the surface:
Heater's area is projected on the surface
1D and 2D codes give similar results

As in
Pons and Rea 2012
but see
Pons, Miralles, Geppert 2009

Carrying away pumped heat



HEATING ONE LAYER WITH DIFFERENT INTENSITY



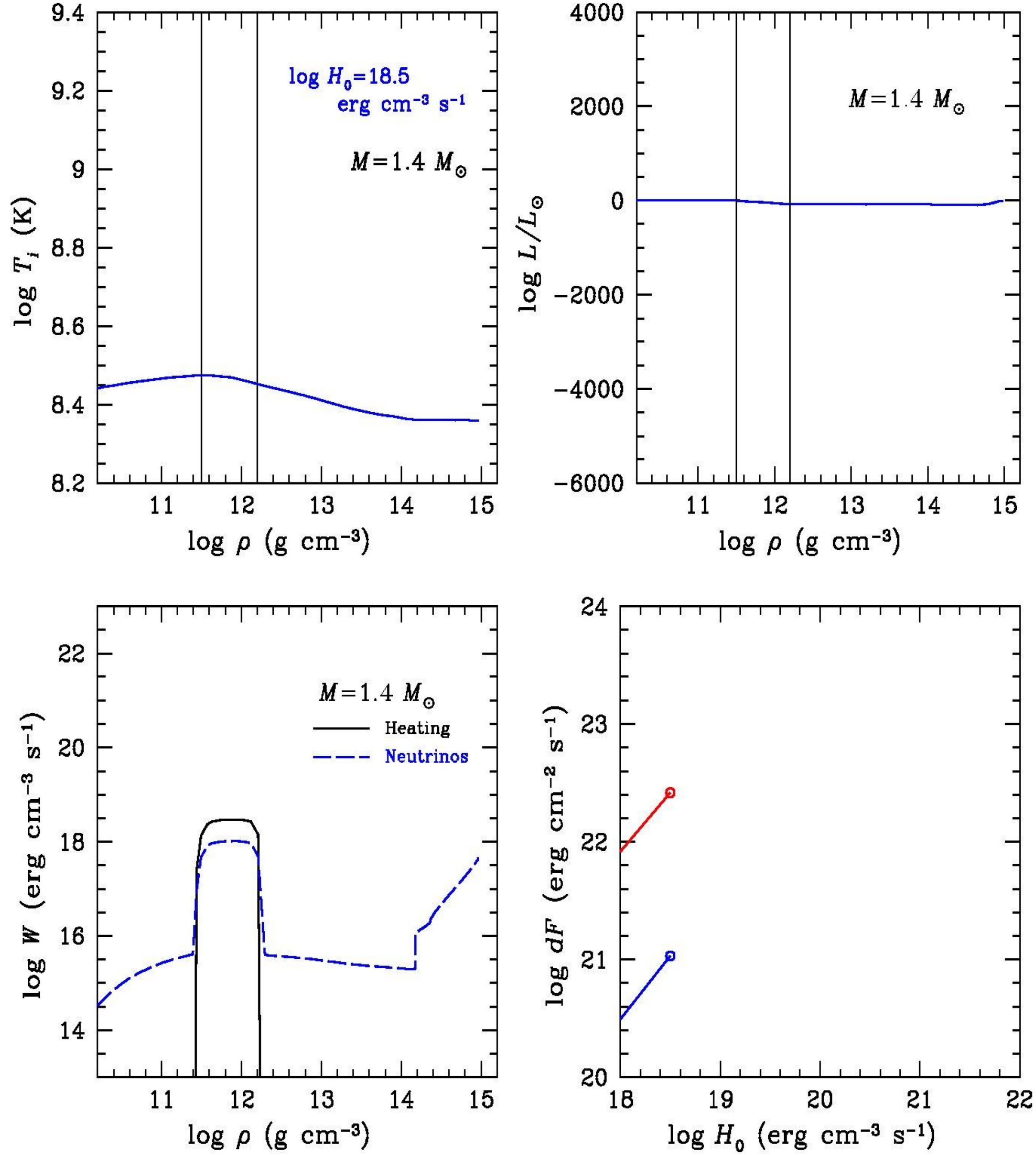
$$H_0 = 0$$

$$\rho_1 = 3.2\times10^{11}\ \text{g cm}^{-3}$$

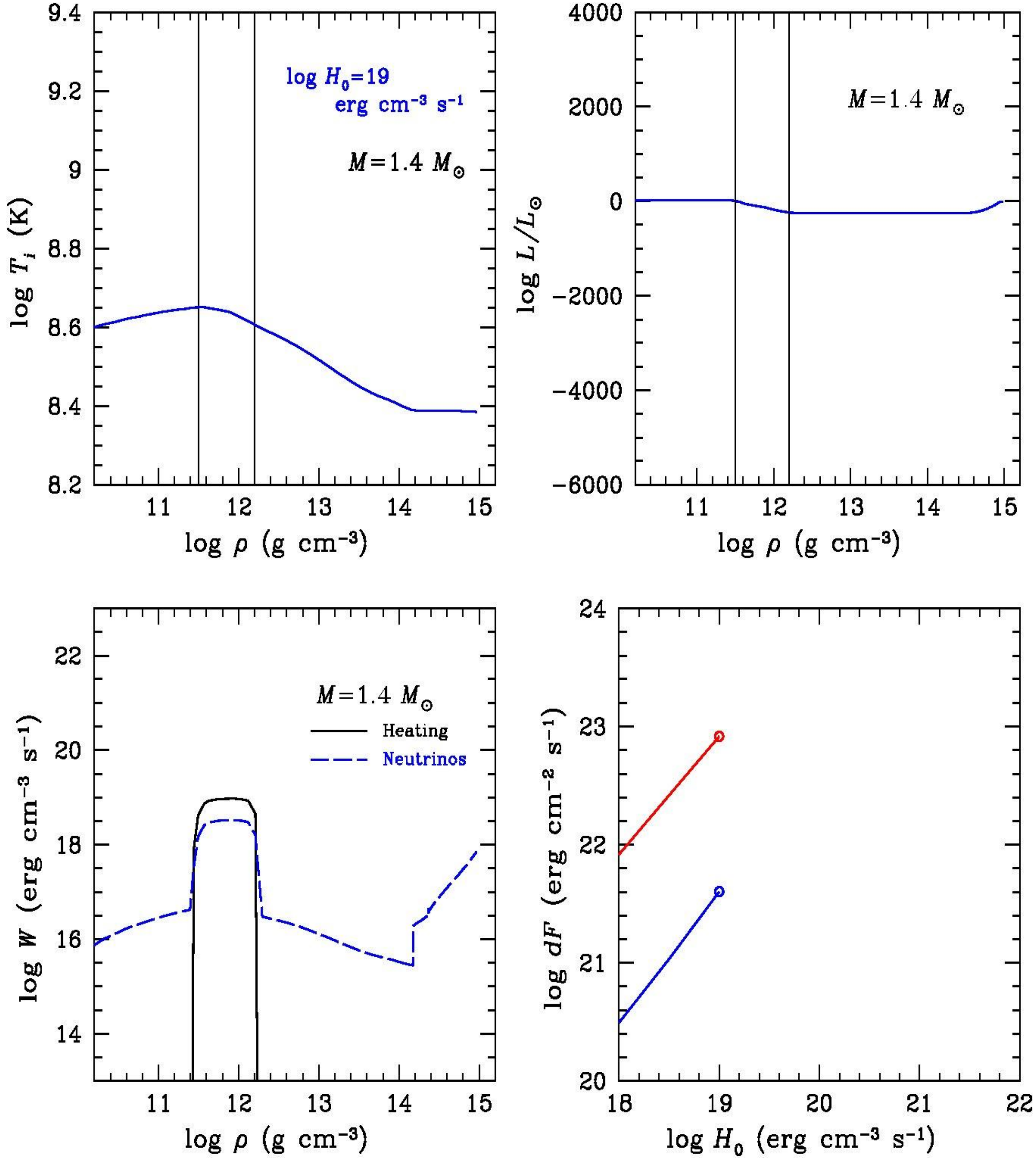
$$\rho_2 = 1.6\times10^{12}\ \text{g cm}^{-3}$$

Heat layer:
~400 m under surface
~80 m width

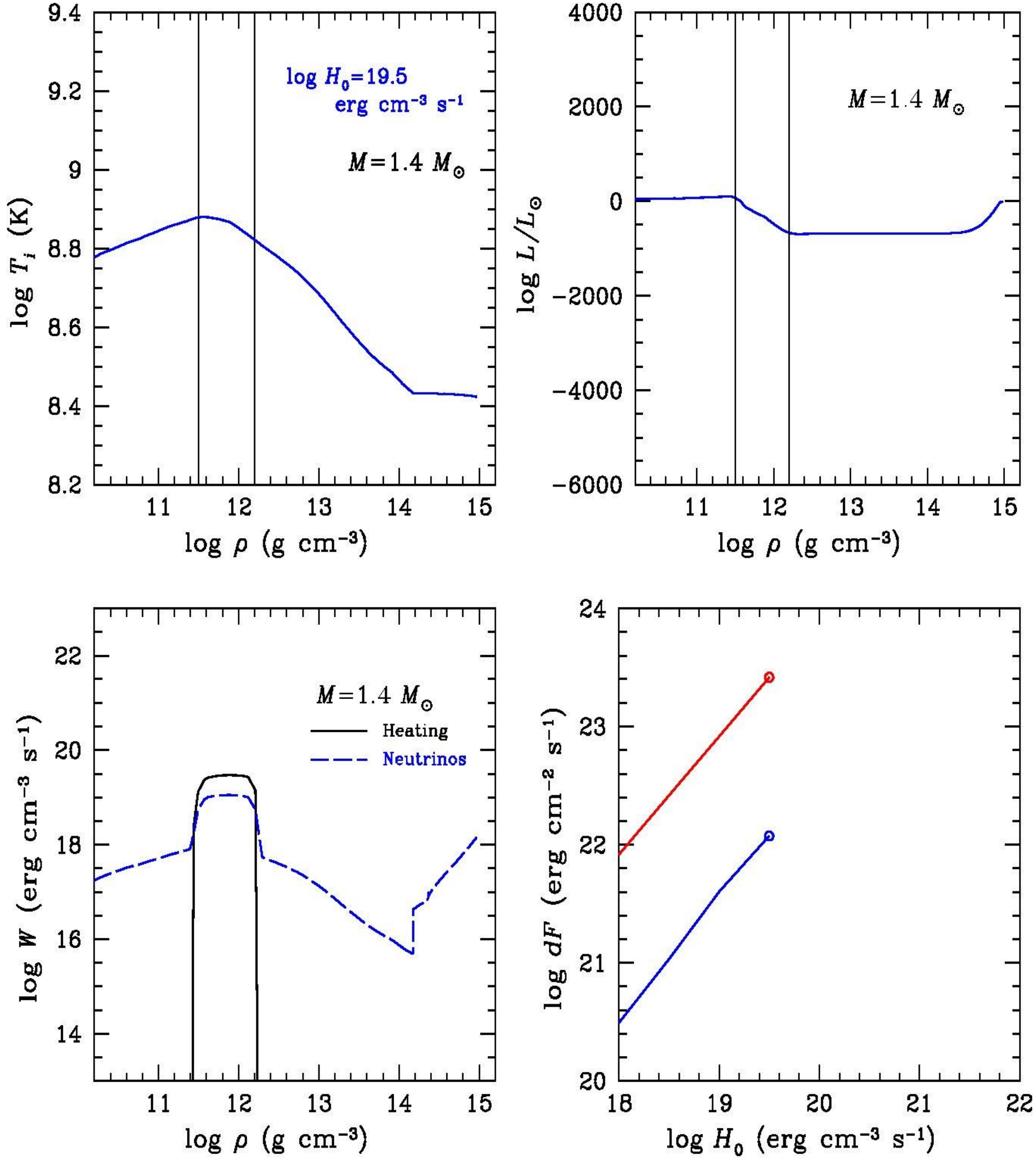
Age = 1000 yrs



$$H_0 = 10^{18.5}\ \mathrm{erg\ cm^{-3}\ s^{-1}}$$



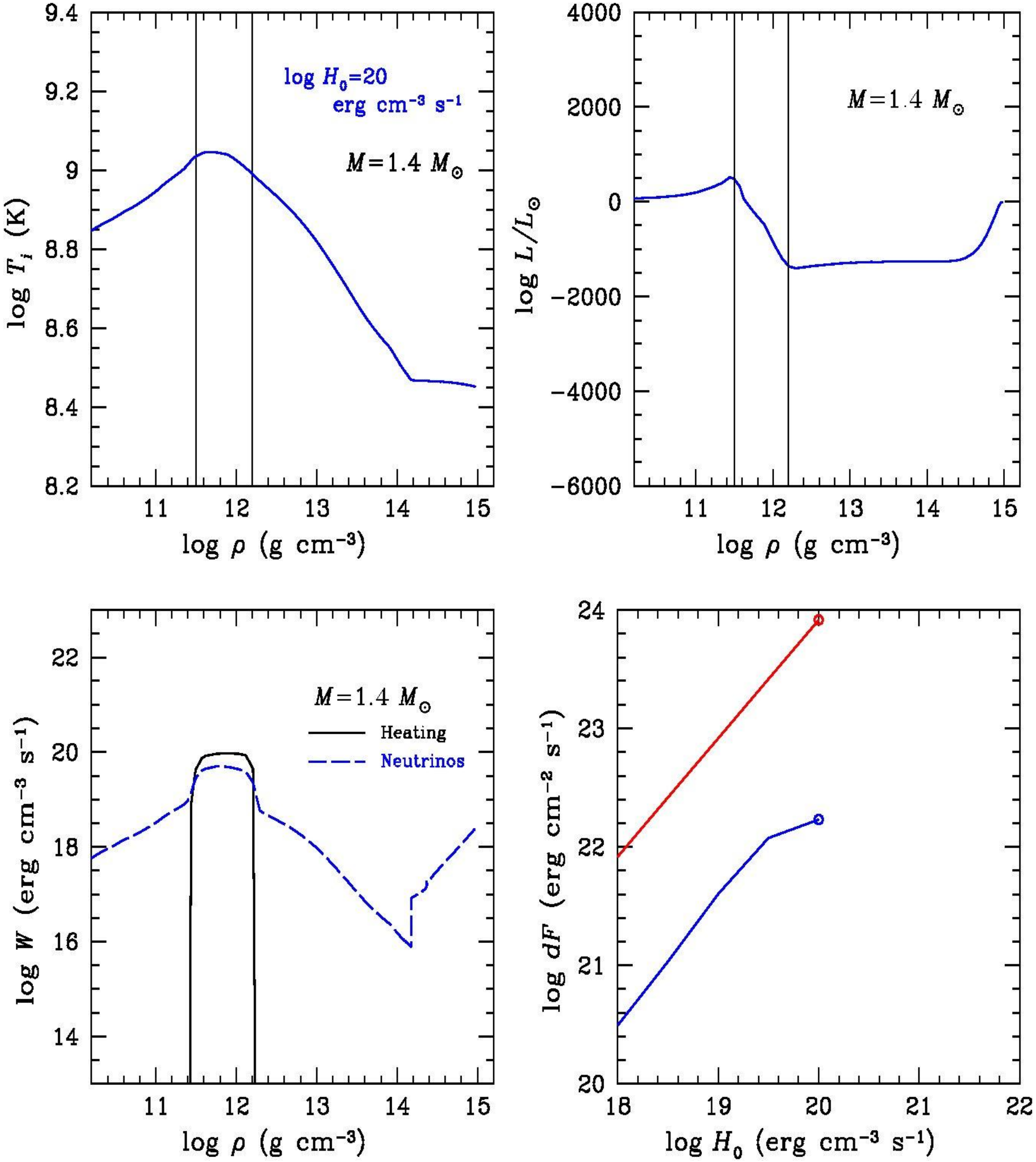
$$H_0 = 10^{19}$$
$$\text{erg cm}^{-3}\ \text{s}^{-1}$$

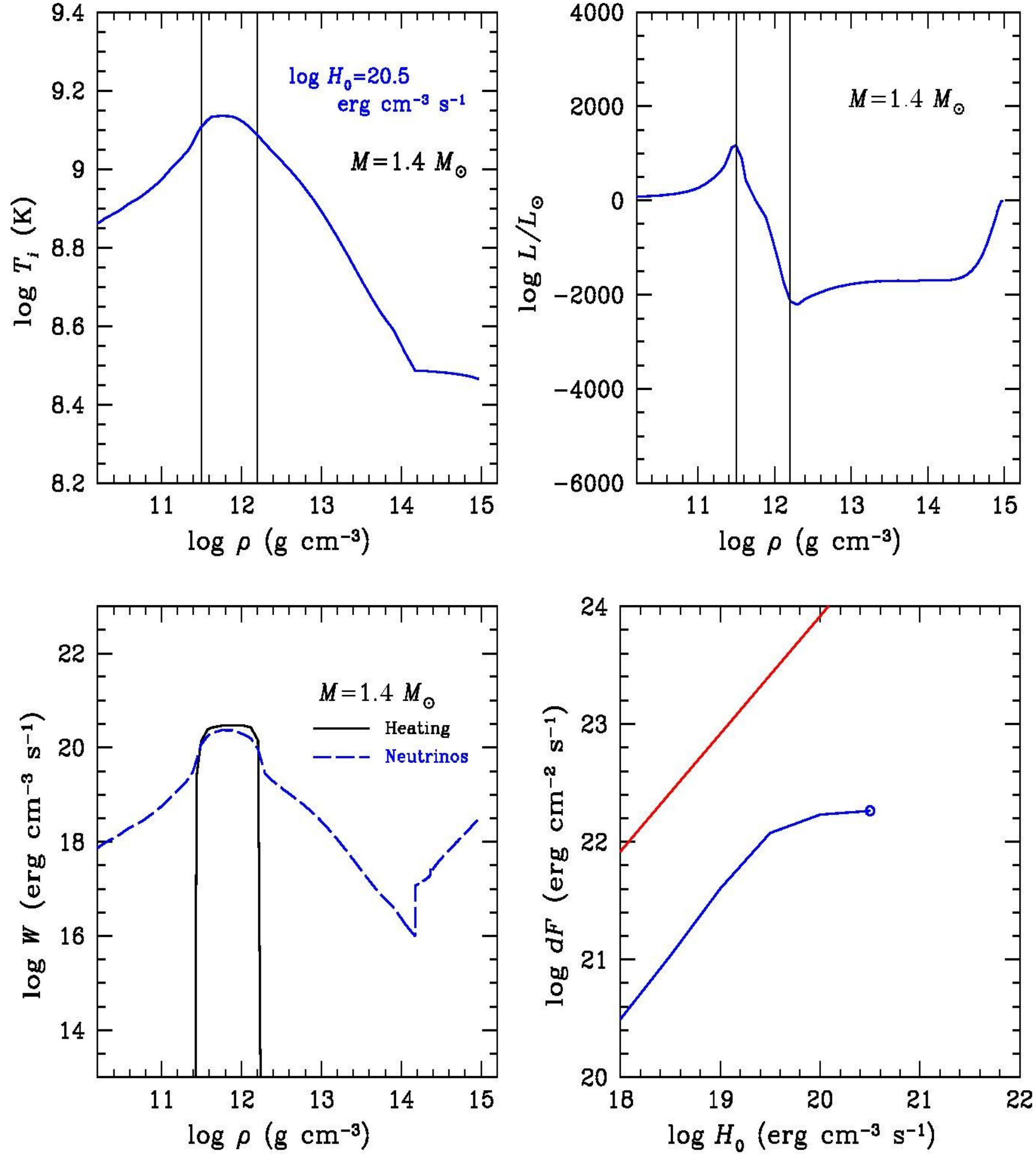


$$H_0 = 10^{19.5}$$

$$\mathrm{erg\ cm^{-3}\ s^{-1}}$$

$$H_0 = 10^{20} \text{ erg cm}^{-3} \text{ s}^{-1}$$

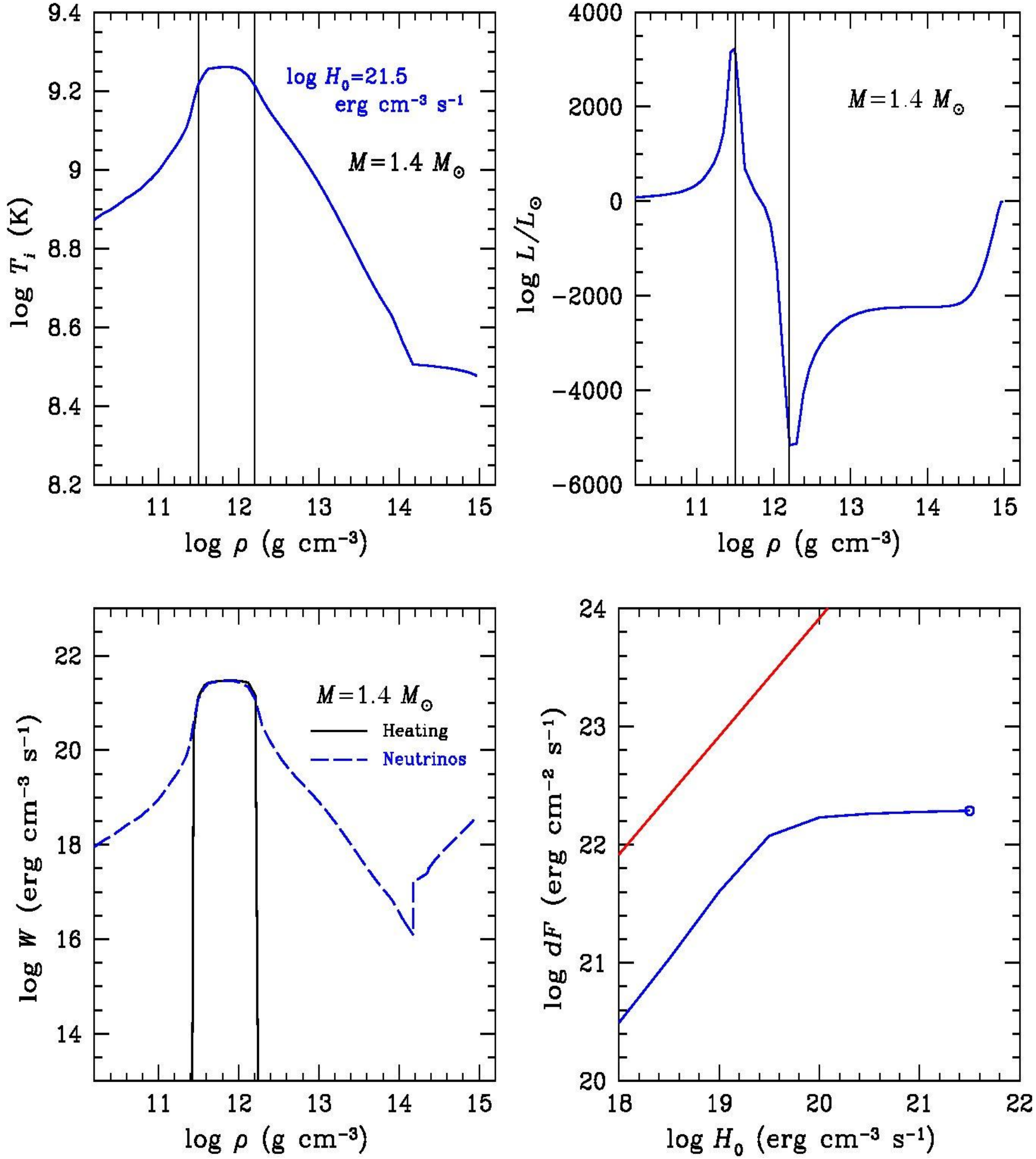


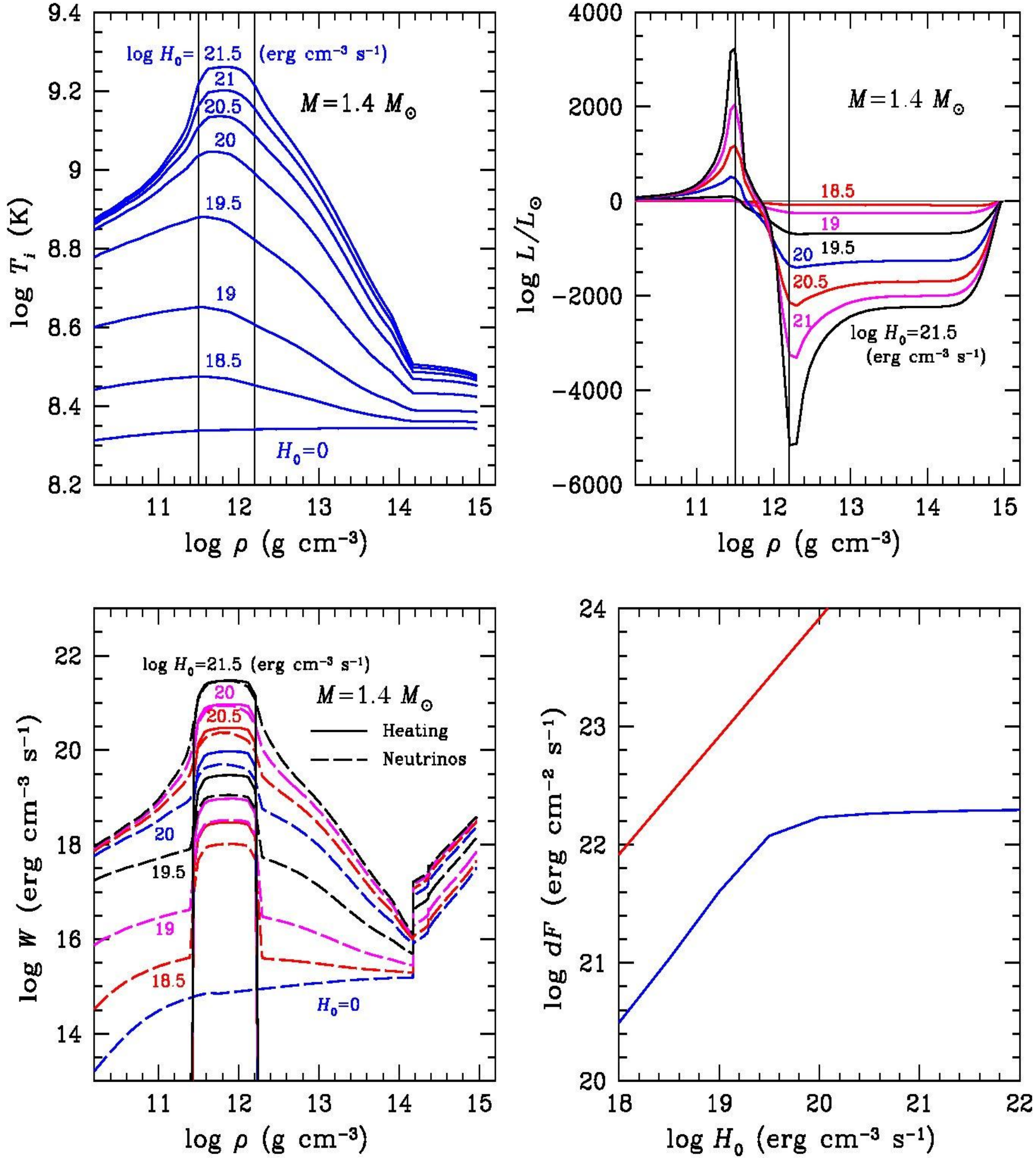


$$H_0 = 10^{20.5}$$

$$\text{erg cm}^{-3}\ \text{s}^{-1}$$

$H_0 = 10^{21.5}$ $\mathrm{erg\ cm^{-3}\ s^{-1}}$

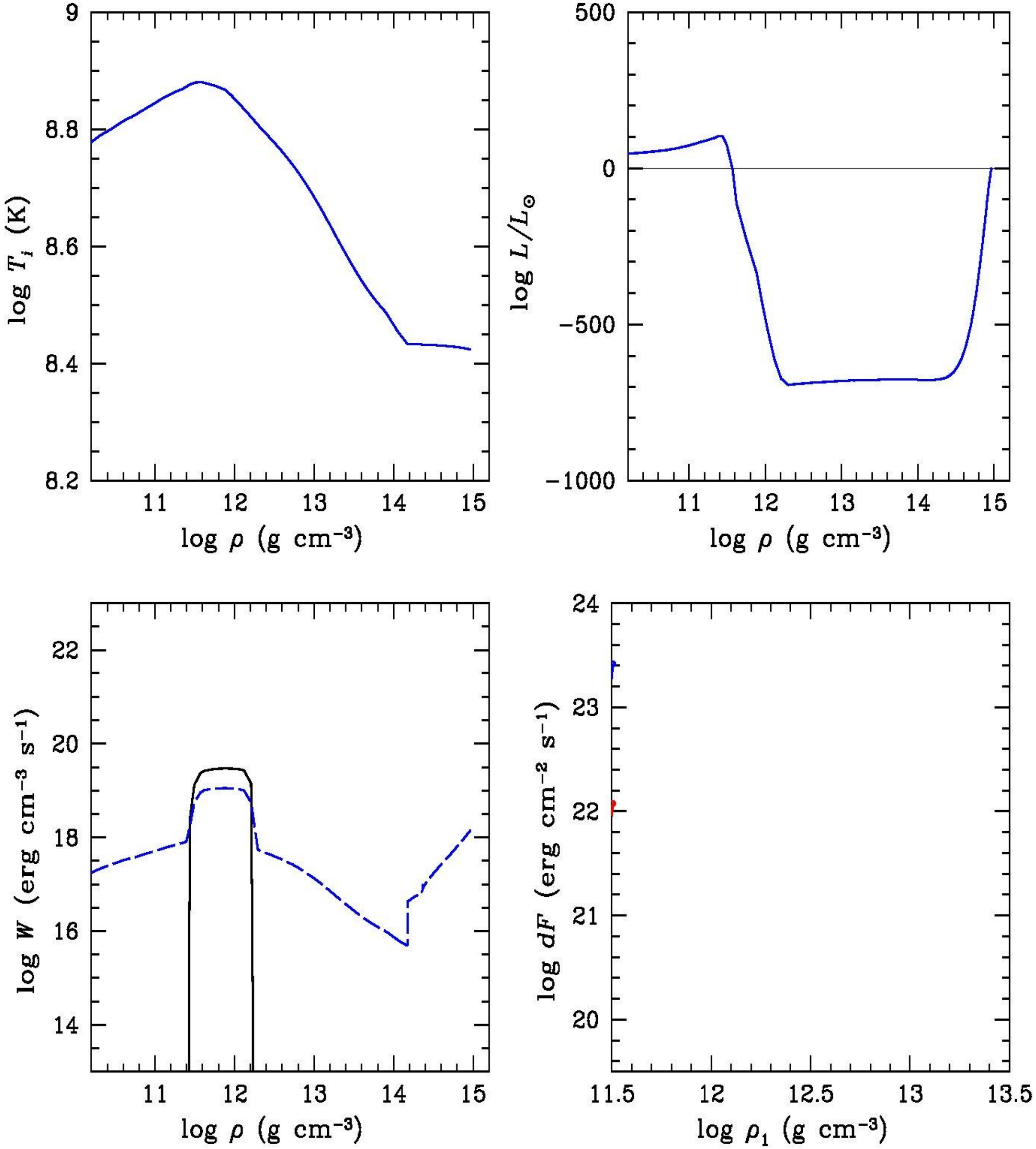




"Eddington" limit:

Kaminker et al. 2006
Pons and Rea 2012

STANDARD HEATER IN DIFFERENT PLACES



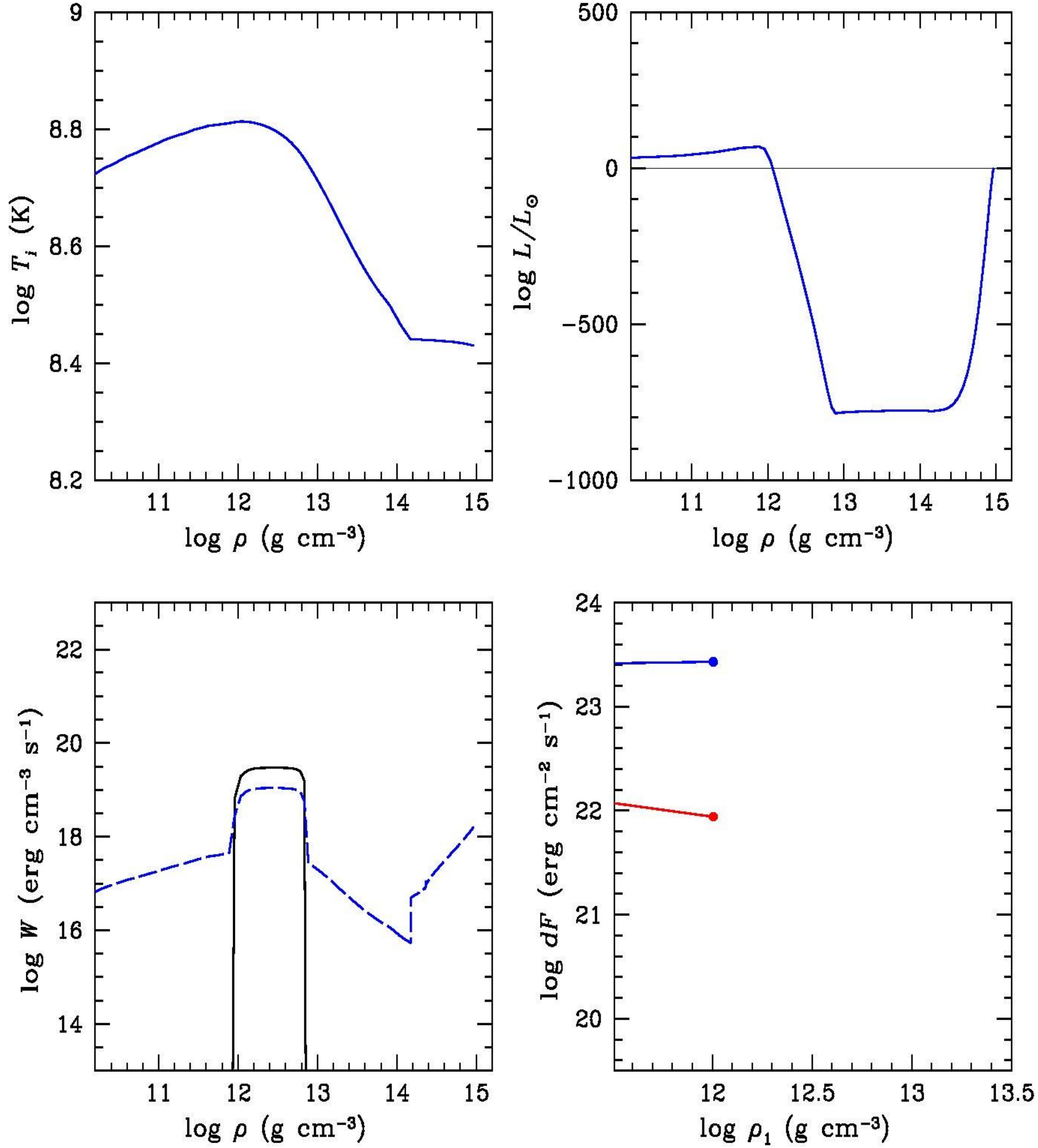
$$\rho_1 = 3.2\times10^{11}\ \text{g cm}^{-3}$$

$$\rho_2 = 1.6\times10^{12}\ \text{g cm}^{-3}$$

FIXED HEATER:

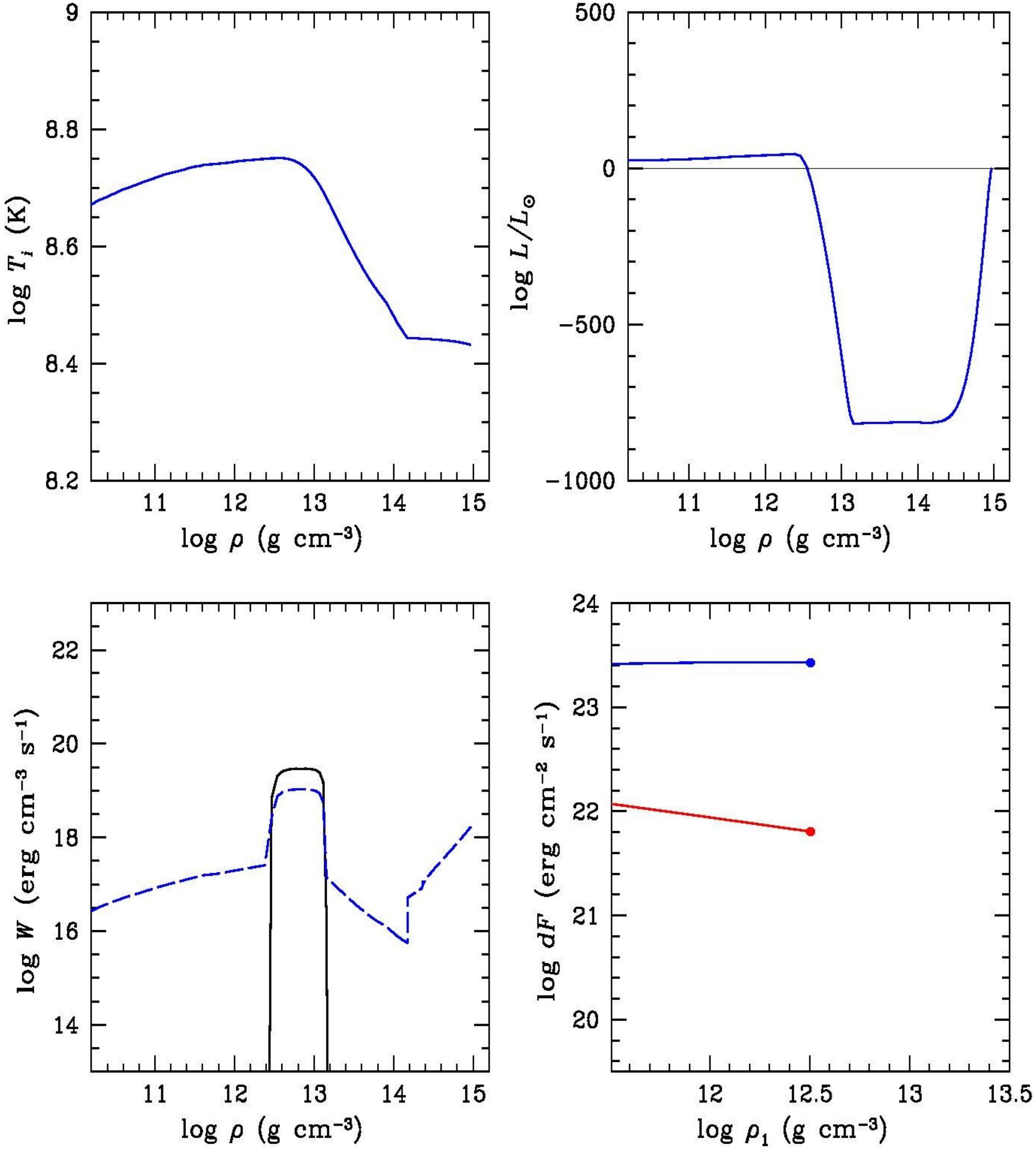
$$W^\infty = 2.6\times10^{23}\ \text{erg cm}^{-2}\ \text{s}^{-1}$$

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



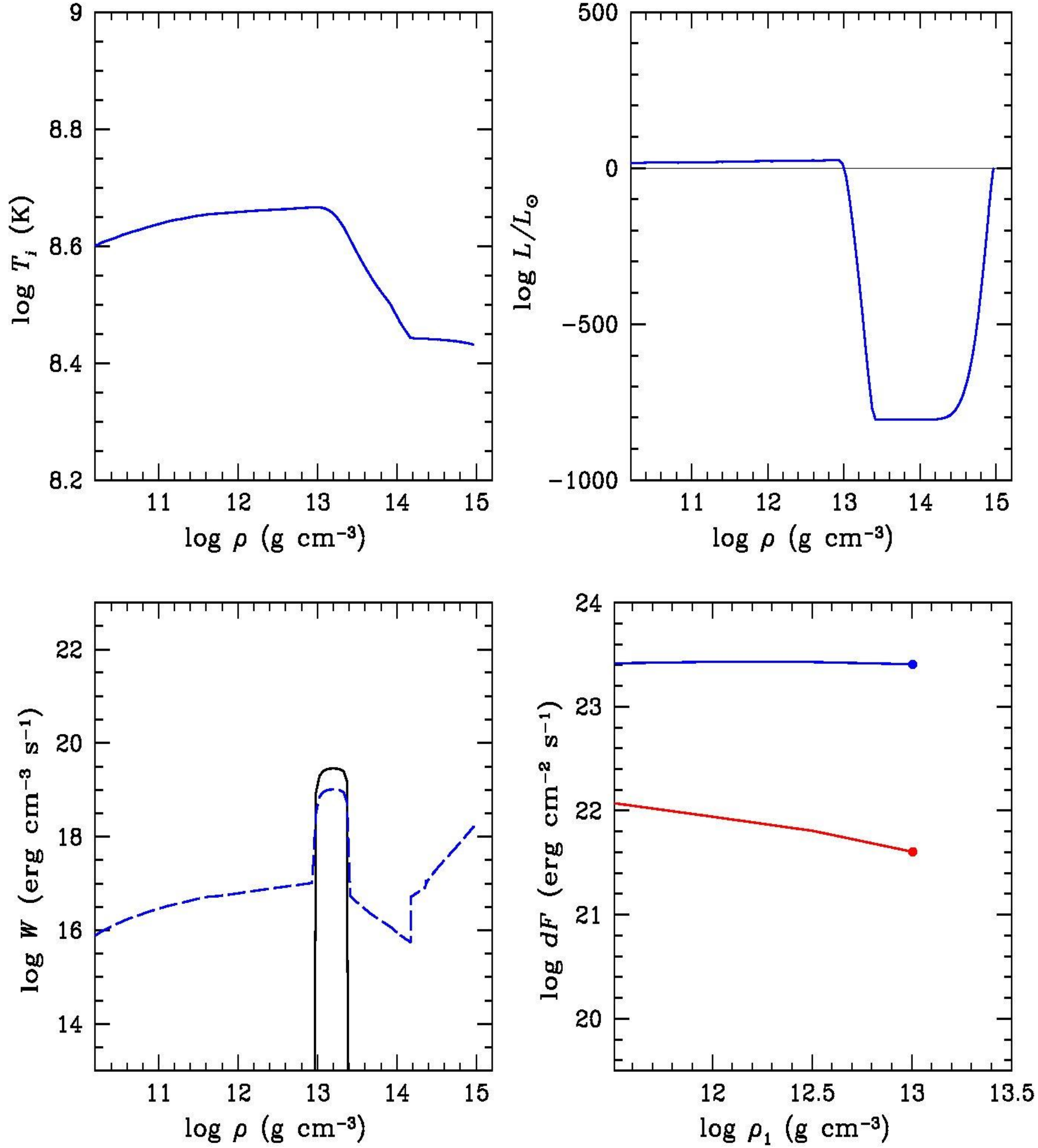
$$\rho_1 = 1.0 \times 10^{12} \text{ g cm}^{-3}$$

$$\rho_2 = 6.9 \times 10^{12} \text{ g cm}^{-3}$$



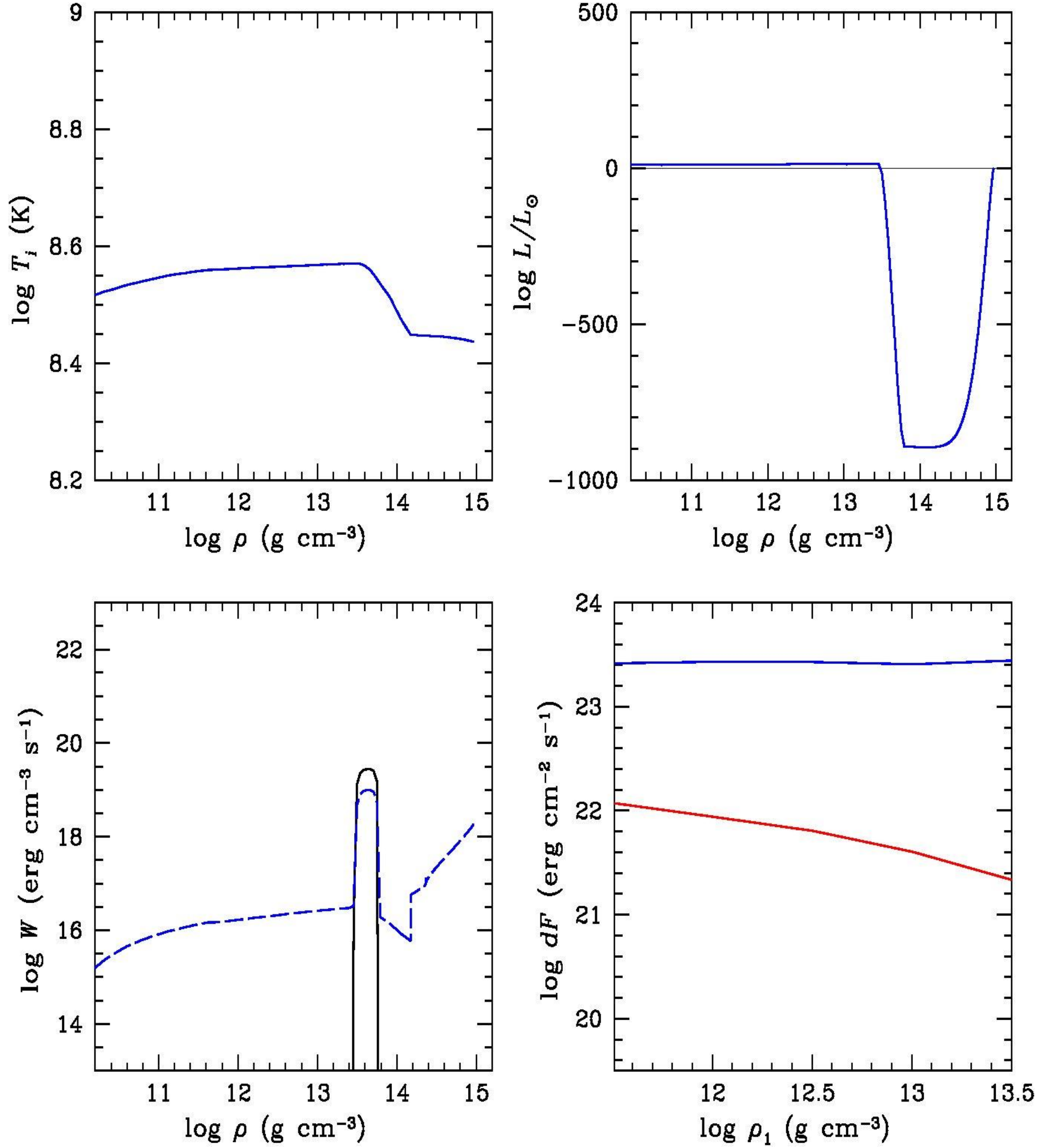
$$\rho_1 = 3.2\times10^{12}\ \mathrm{g\ cm^{-3}}$$

$$\rho_2 = 1.3\times10^{13}\ \mathrm{g\ cm^{-3}}$$



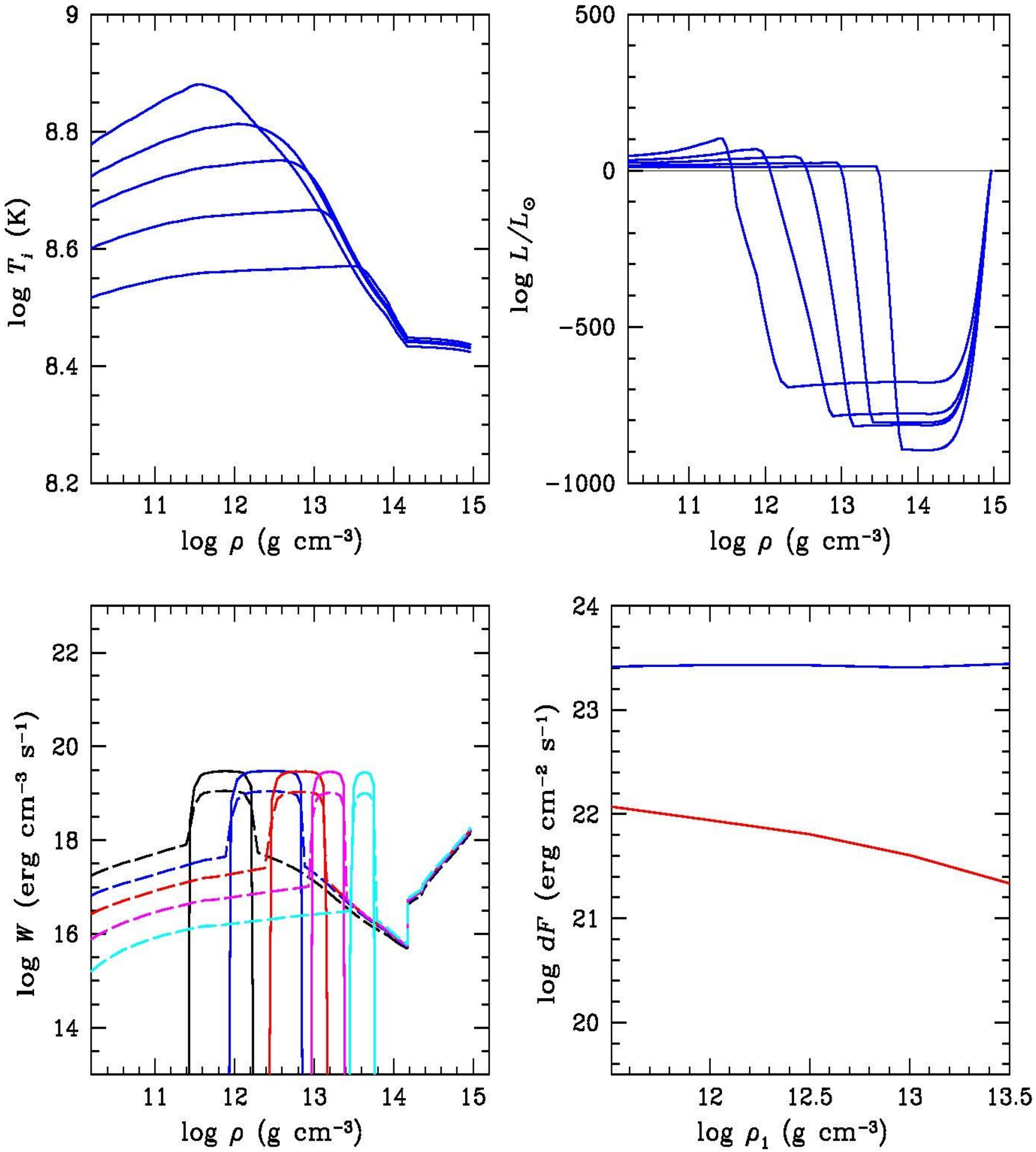
$$\rho_1 = 1.0 \times 10^{13} \text{ g cm}^{-3}$$

$$\rho_2 = 2.4 \times 10^{13} \text{ g cm}^{-3}$$



$$\rho_1 = 3.2 \times 10^{13} \text{ g cm}^{-3}$$

$$\rho_2 = 5.6 \times 10^{13} \text{ g cm}^{-3}$$

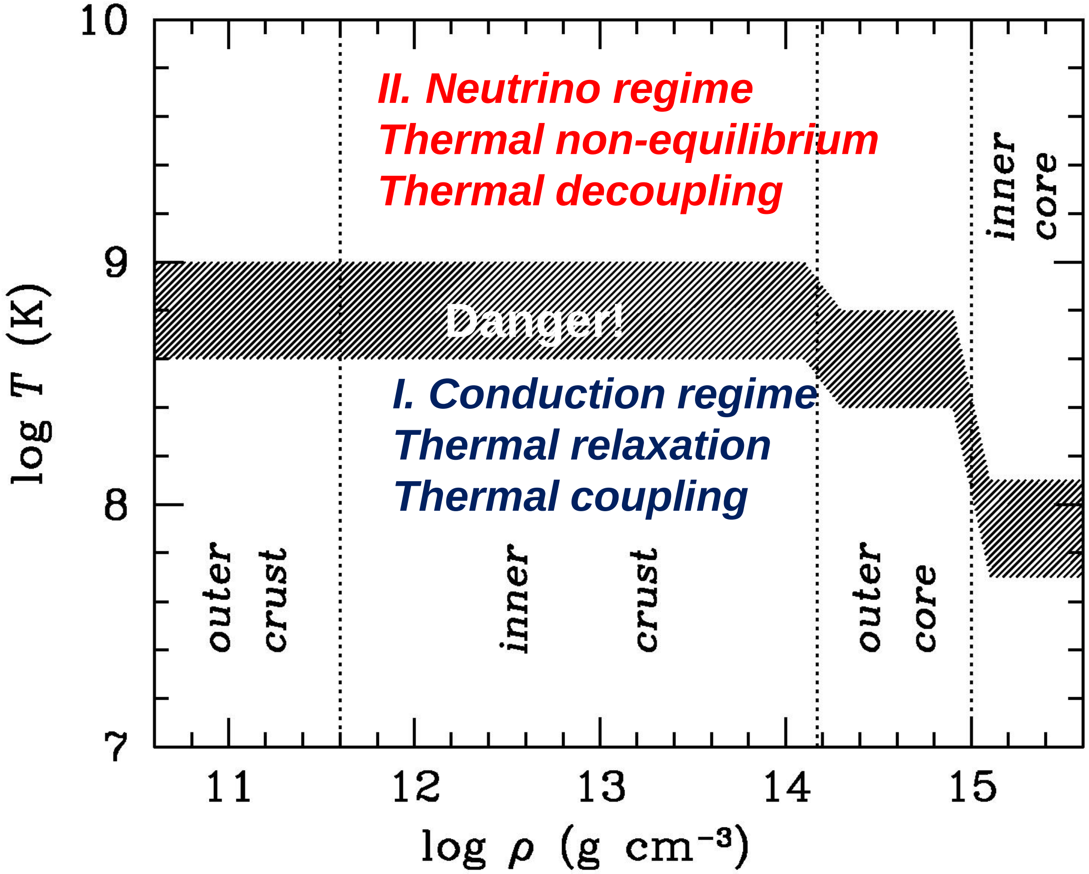


Moving heater towards core reduces efficiency

Kaminker et al. 2006
Pons and Rea 2006

TWO THERMAL REGIMES

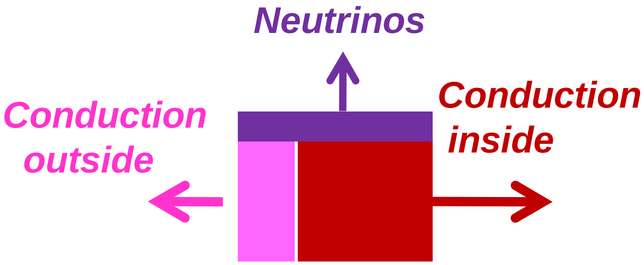
$$C \frac{\partial T}{\partial t} = \mathrm{div}\,(\kappa\,\nabla T) - Q_\nu + H$$



HEATING REGIMES

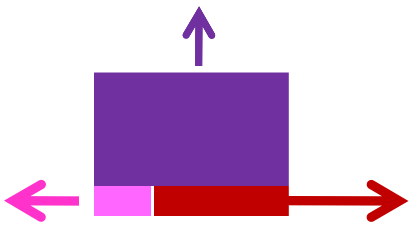
1 $T < 10^9$ K, $H_0 < 10^{20}$ erg cm^{-3} s^{-1}

Regulated by thermal conduction



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

Regulated by neutrino emission



BASICALLY NON-ECONOMICAL HEATER

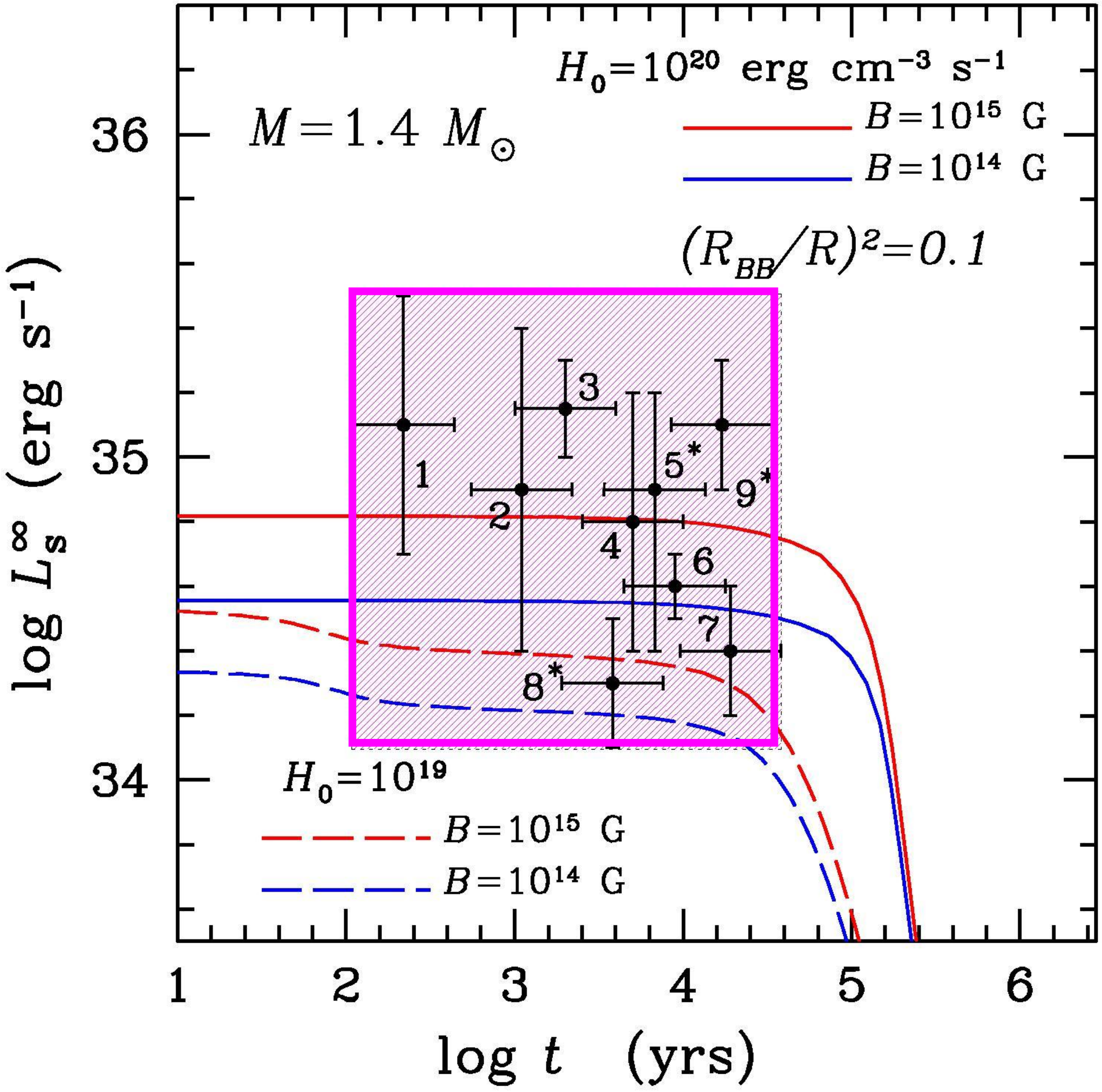
What is observed as quasi-persistent emission is basically a small fraction of input energy

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*

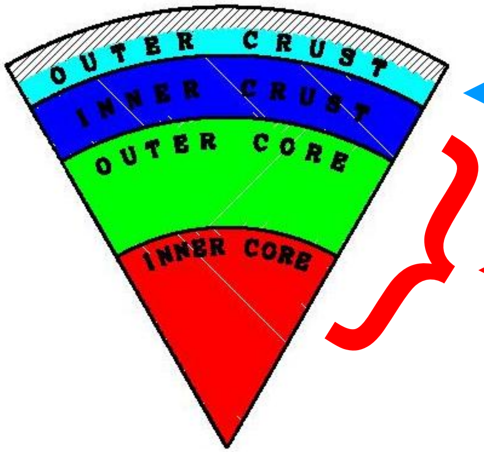
Most economical model of magnetars

Magnetic spots under surface heated by Ohmic dissipation



THE NATURE OF INTERNAL HEATING

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

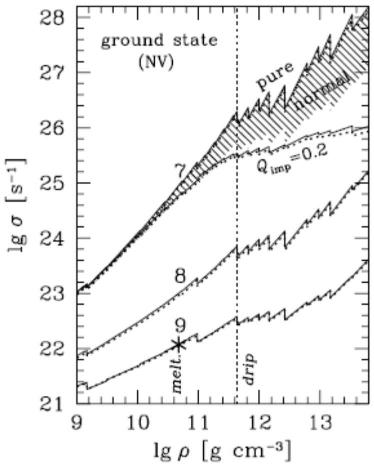


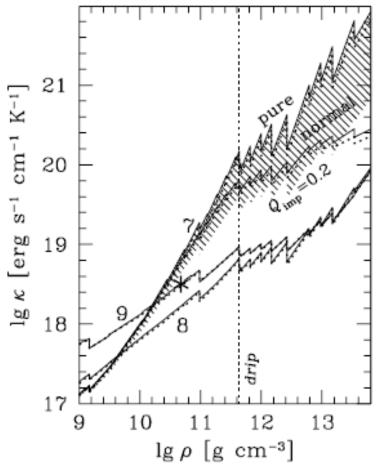
Energy release

Energy storage

Nature of heating: Ohmic dissipation

Numerical example





High temperature is needed:
- ***Low electric conduction***
- ***Low thermal conduction***

Similar matters:
Aguilera, Pons, Miralles 2008
Pons, Miralles, Geppert 2009

Ohmic dissipation heat rate

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

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

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

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

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

$(\tau \sim 5\times10^4$ yr$)$

Energy deposition to heater?

Mechanism:* *Unknown

Possibilities:

- ***Hall drift (and instability),*** ***e.g. Geppert and Rheinhardt (2002), Aguilera et al. (2008), Pons and Geppert (2010), Price et al. (2012)***
- ***Thermomagnetic effects (thermopower) at large temperature gradients***
- ***Instability (e.g., loss of mechanical stability due to magnetic forces); emission of hydromagnetic waves, etc.***

Main features of magnetars

- Magnetars may be cooling neutron stars with internal heating.
- It is economical to place heat sources in the outer crust.
- The heat rate in the outer crust can be $H \sim 10^{20}$ erg s^{-1} cm^{-3}, the total heat rate exceeding the thermal surface luminosity with by a factor of >=30.
- The outer crust is thermally decoupled from deeper interior; the thermal radiation tests the physics of the outer crust.
- The heating may be supported by Ohmic decay under hot spots.
- Mechanism of magnetic field deposition to the heater is not clear

Ordinary cooling neutron stars versus magnetars

Objects	*Ordinary stars*	*Magnetars*
Interiors	*Isothermal*	*Non-isothermal*
Powered by	*Thermal energy of core*	*Heat sources in crust*
Thermal coupling	*Surface and core*	*Surface and heater*
Natural laboratories of	*Superdense core*	*Heater*
Allow to study of	*Neutrino emission and superfluidity in core*	*Energy release in heater (Ohmic dissipation?)*