Thermal radiation of magnetars

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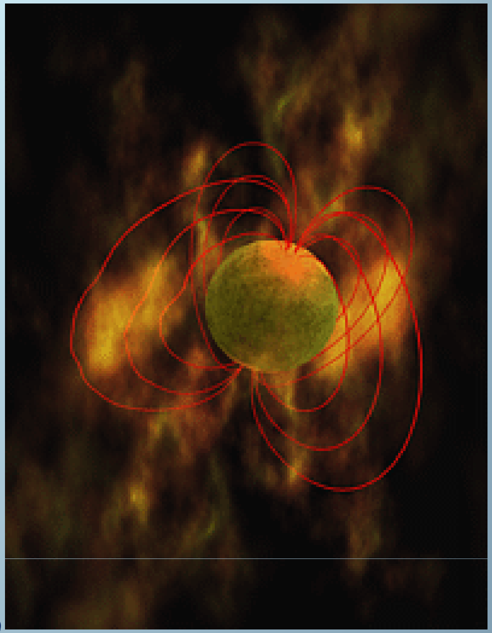
Thermal evolution of magnetars



Magnetars:

- SXRs + AXPs -- neutron stars with ultrahigh magnetic field : $B \gtrsim 10^{14}$ G.
- Majority of data evidence -- they are powered neither by accretion nor by rotation
- Most probably -- they are driven by ultrahigh B-fields
- Activity: quasi-persistent thermal and non-thermal emission, X-ray and gamma-ray bursts, flares and giant flares, glitches, QPOs, etc.
- Sources: wild processes of magnetic energy release in neutron stars interiors or magnetospheres

Main problem:

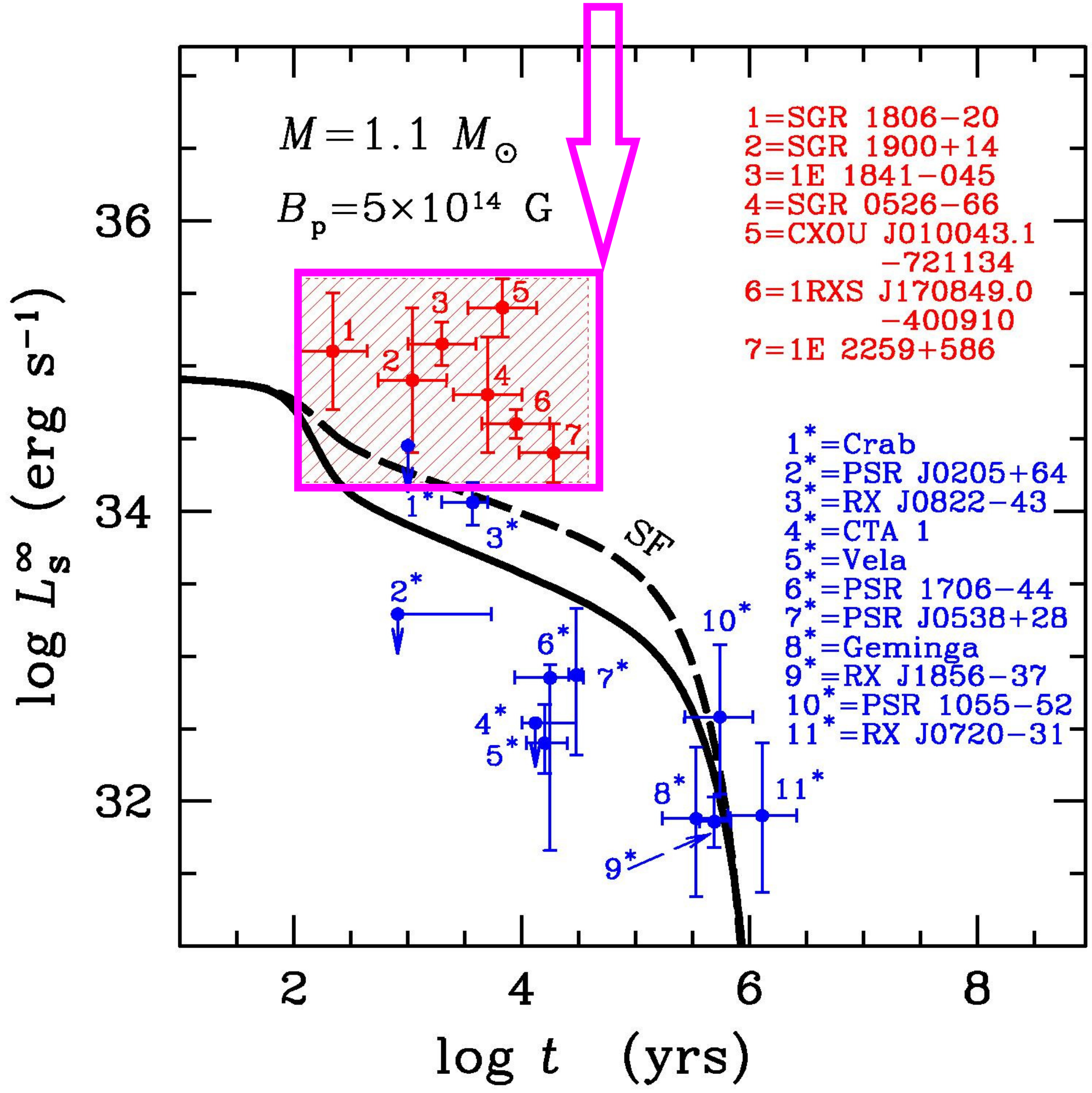
- SXRs + AXPs are spending a lot of energy: up to $W_{tot} \lesssim 10^{50}$ erg
- Whether it could be the energy of ultrahigh B-field within the star (in the crust or core)

Main question:

- Where is this energy released and how? What are mechanisms?

Magnetars versus ordinary cooling neutron stars

Magnetar box (not complete)



Two assumptions:

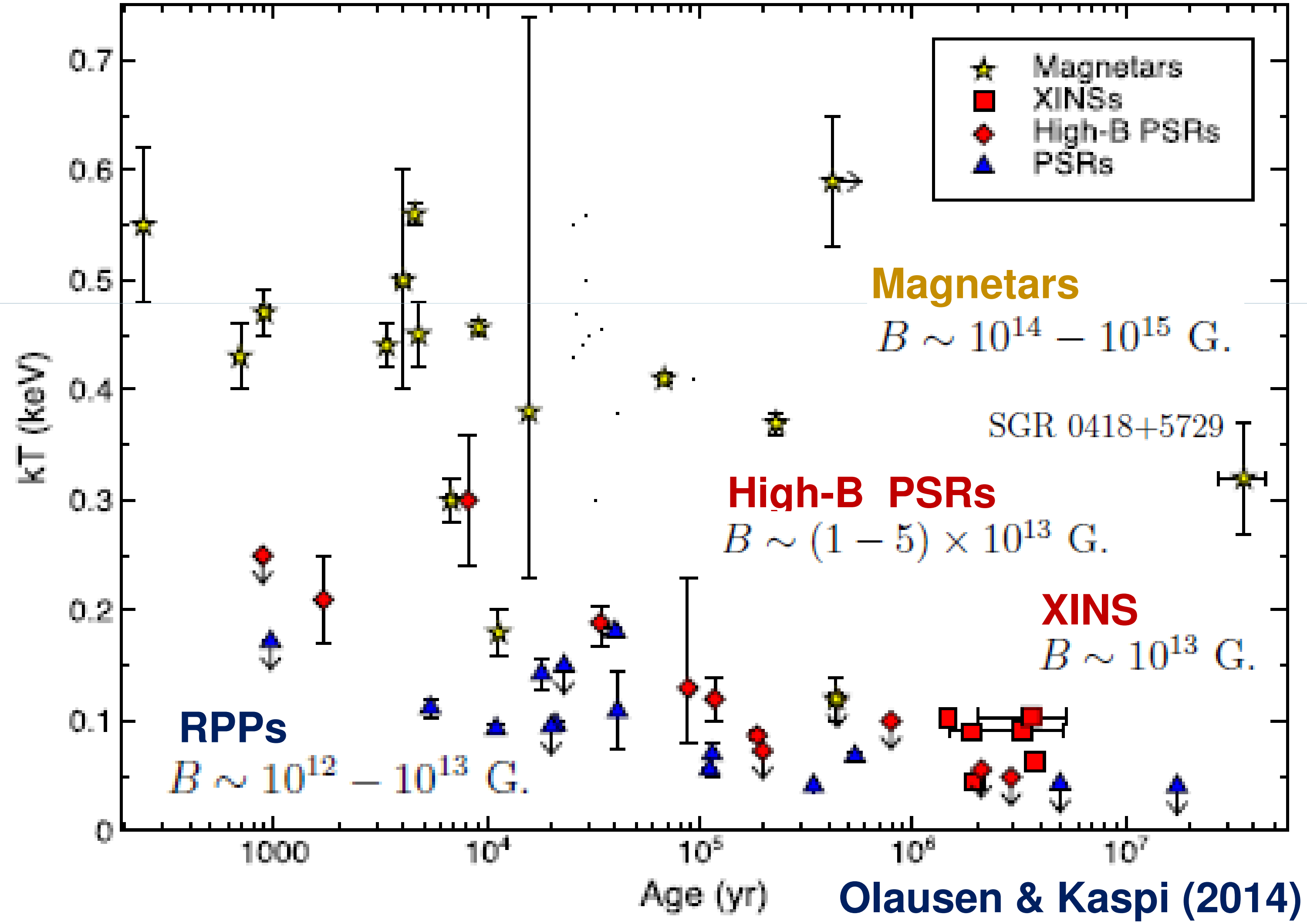
1. The magnetar data reflect persistent thermal surface emission
2. Magnetars may be regarded as cooling neutron stars

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

Main trends: BB-temperatures vs. ages

Characteristic age: $t_c = P/2\dot{P}$

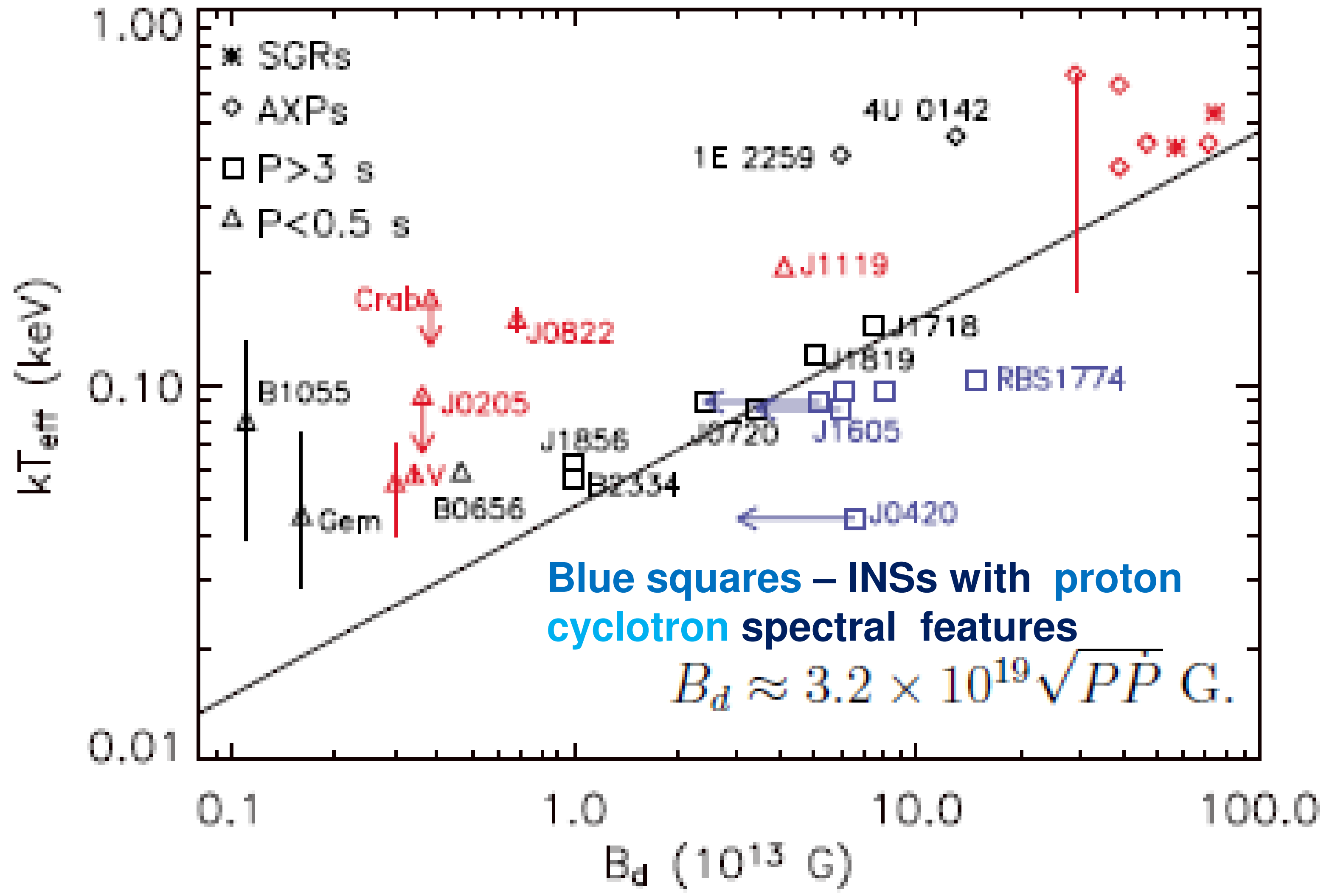
Inferred dipole magnetic field : $B_d \approx 3.2 \times 10^{19}\sqrt{P\dot{P}}$ G.



Olausen & Kaspi (2014)

Correlations: BB- temperatures vs. B-fields

Red symbols – **young NSs (< 10^4yr)**



Blue squares – INSs with proton cyclotron spectral features

$$B_d \approx 3.2 \times 10^{19} \sqrt{P\dot{P}}\ \mathrm{G}.$$

Pons et al. (2007)

Phenomenological approach

The aim is *to explain thermal emission of magnetars*

Basic assumption: *internal heating is inherent feature of ultrahigh B-fields*:

B-fields ⟹ *heater* ⟹ *quasi-persistent thermal emission*

Phenomenological points: *the emission is powered by internal heat sources*

- *The maximum stored energy* $E_{tot} \simeq 10^{49} - 10^{50}$ *erg can be the energy of internal magnetic field* $B \simeq (1-3) \times 10^{16}$ *G in the magnetar internal crust and/or core*

- *The stored energy is released in the crust*

This approach has been confirmed recently:

by series of 2D- calculations of magneto-thermal evolution:
Pons, Miralles, Geppert 2009, Pons & Rea 2012, Vigano et al. 2013, Perna et al. 2013

Our approach is much more primitive, but it allows to set a few principal points which we believe to be useful .

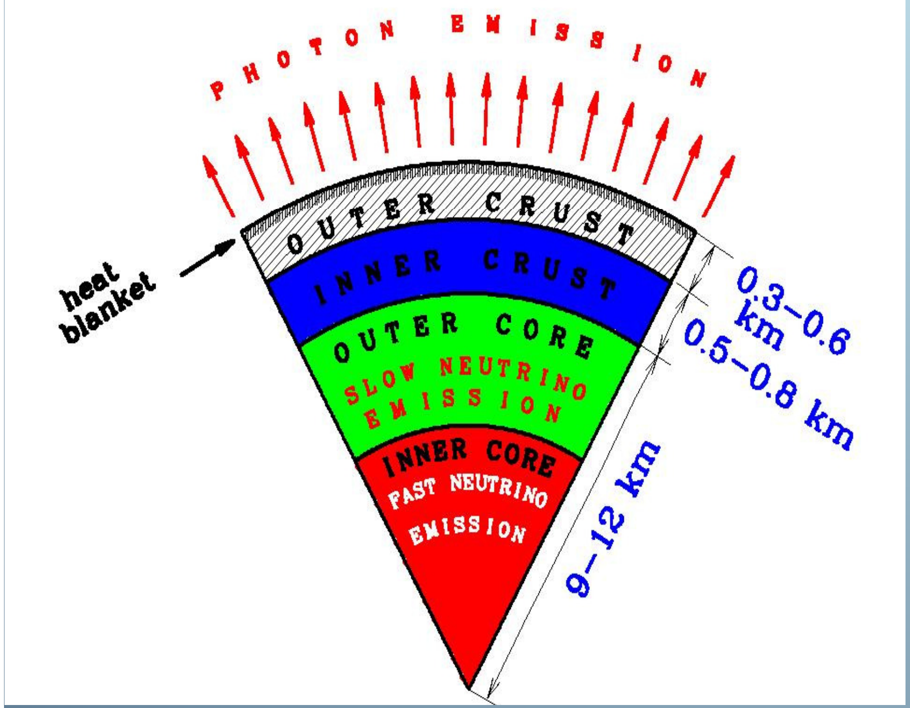
Heating and cooling of neutron stars

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

Including Q_ν :

$$T_s = T_s(T_b)$$

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

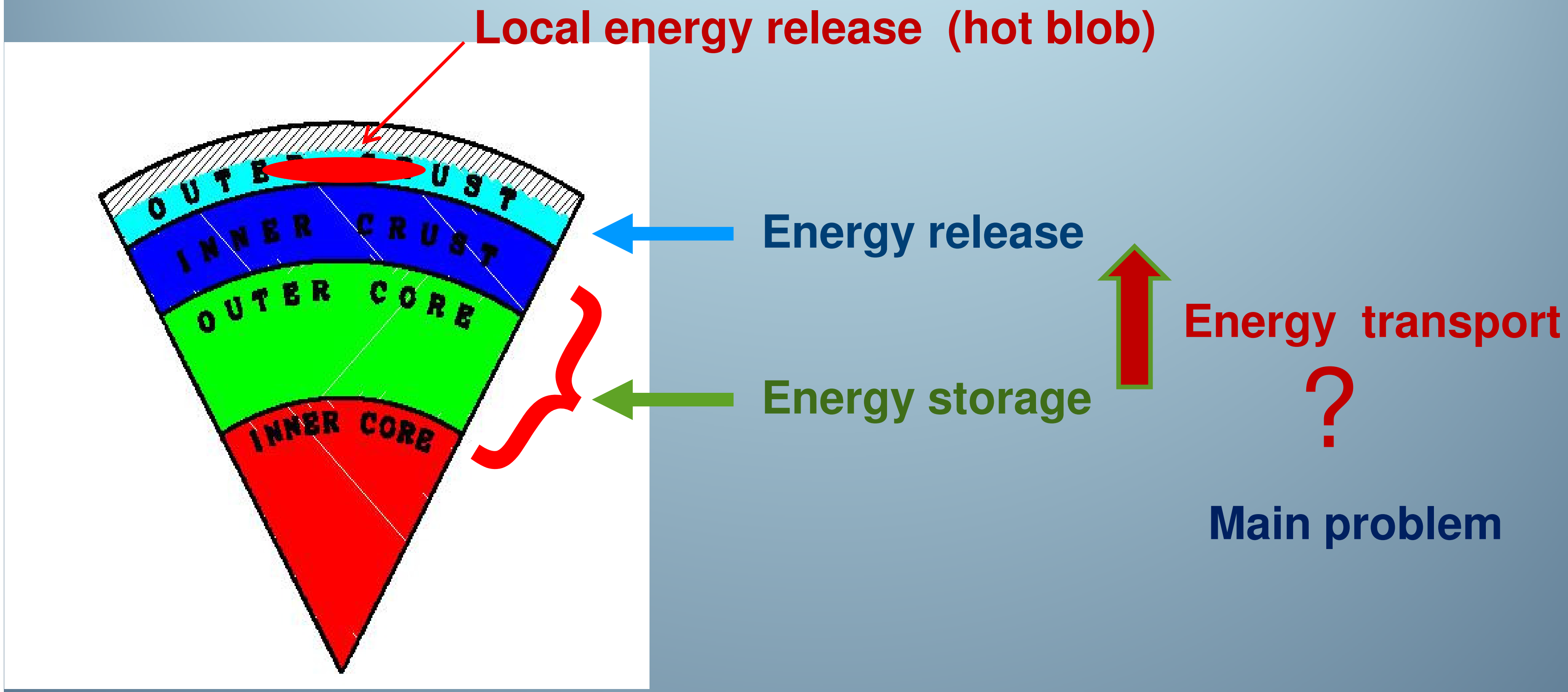
Heat content of NS: $U_T \sim 10^{48}\ T_9^2\ \ ergs$

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

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

Features of internal heating

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



Local energy release (hot blob)

Energy release

Energy storage

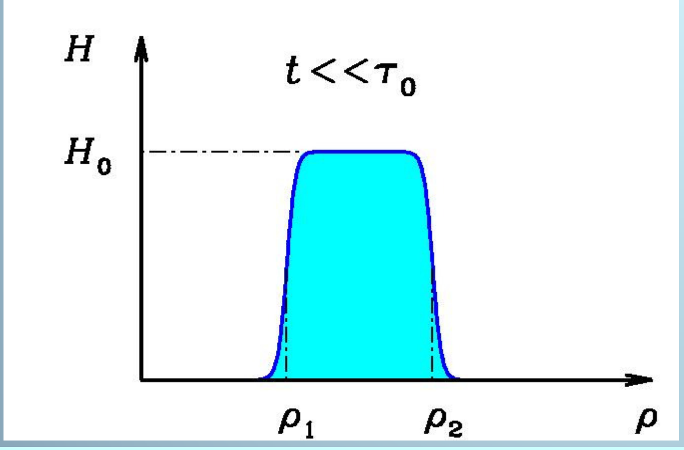
Energy transport

?

Main problem

Phenomenological heater and calculations

Radial heat power distribution:



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

Four parameters: ρ_1, ρ_2, H_0, τ_0

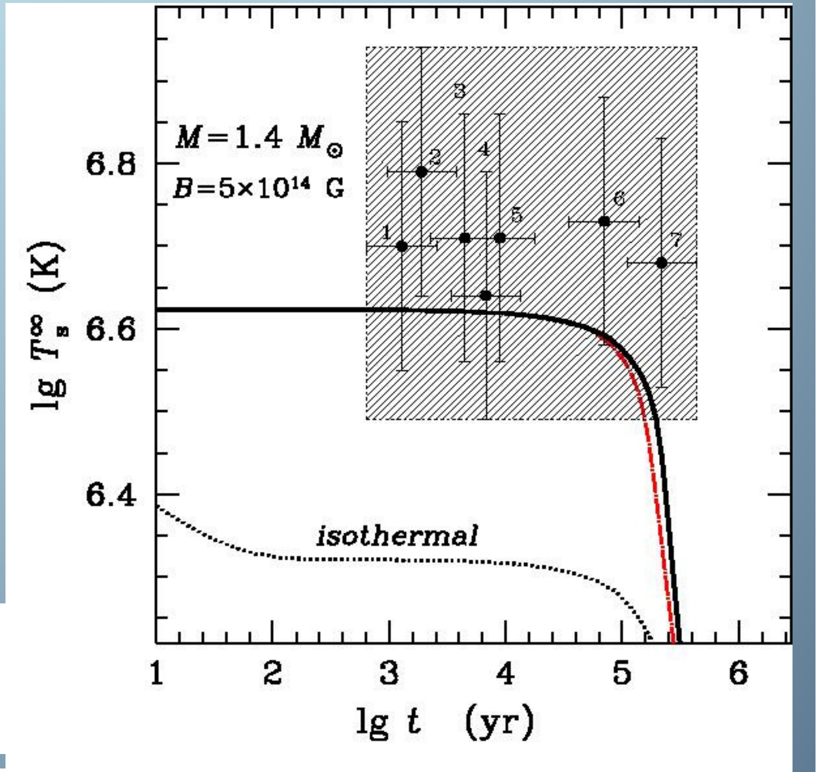
$$\tau_0 = 5\times10^4\ \ \text{yr}$$

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

Angular heat power distribution:

Either hot "blob" – 2D code,
then additional parameter θ_0

Or hot spherical layer – 1D code



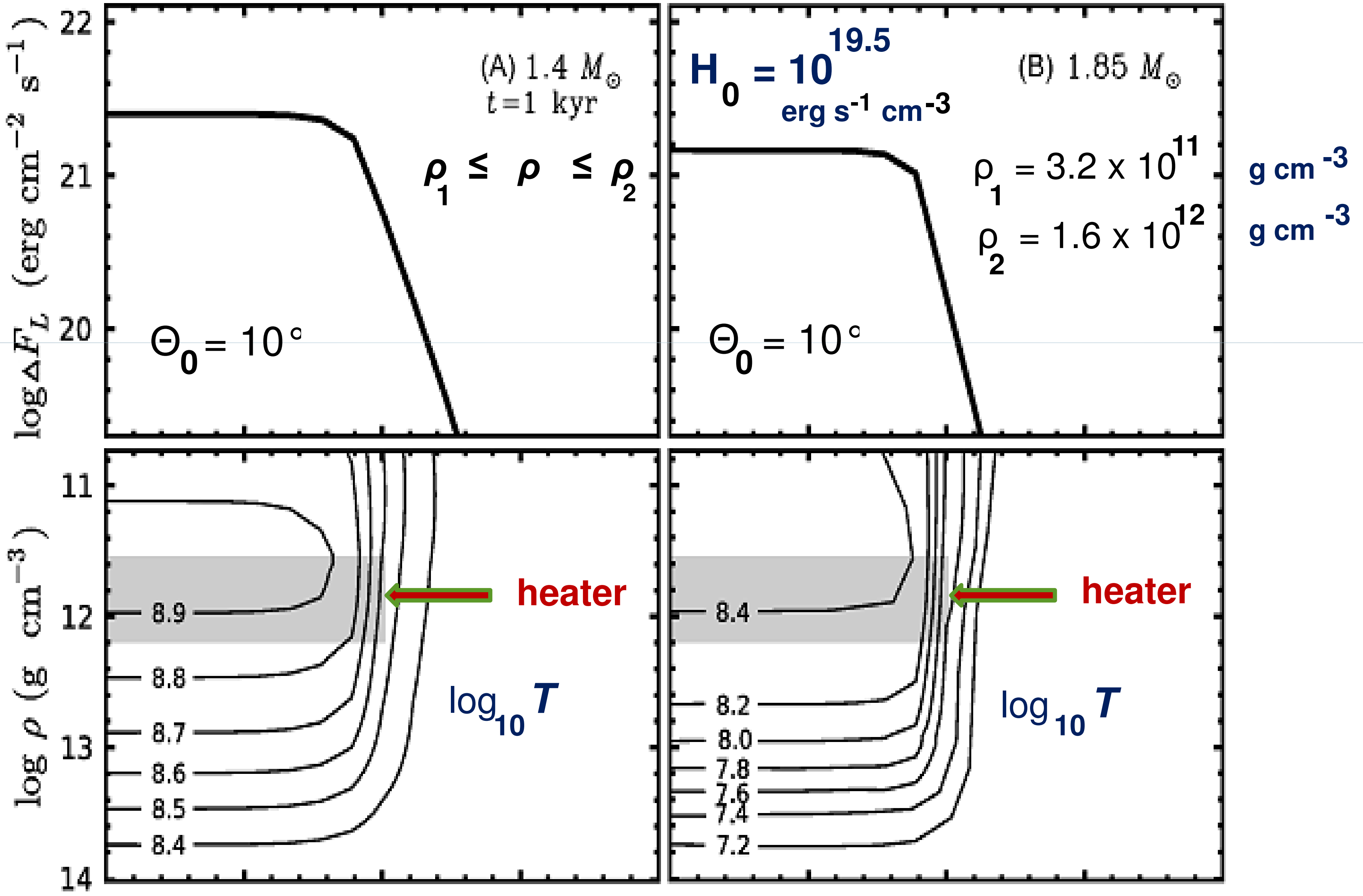
Total redshifted heat power :

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

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

Results of 2D code

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



$\rho_1 \leq \rho \leq \rho_2$

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

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

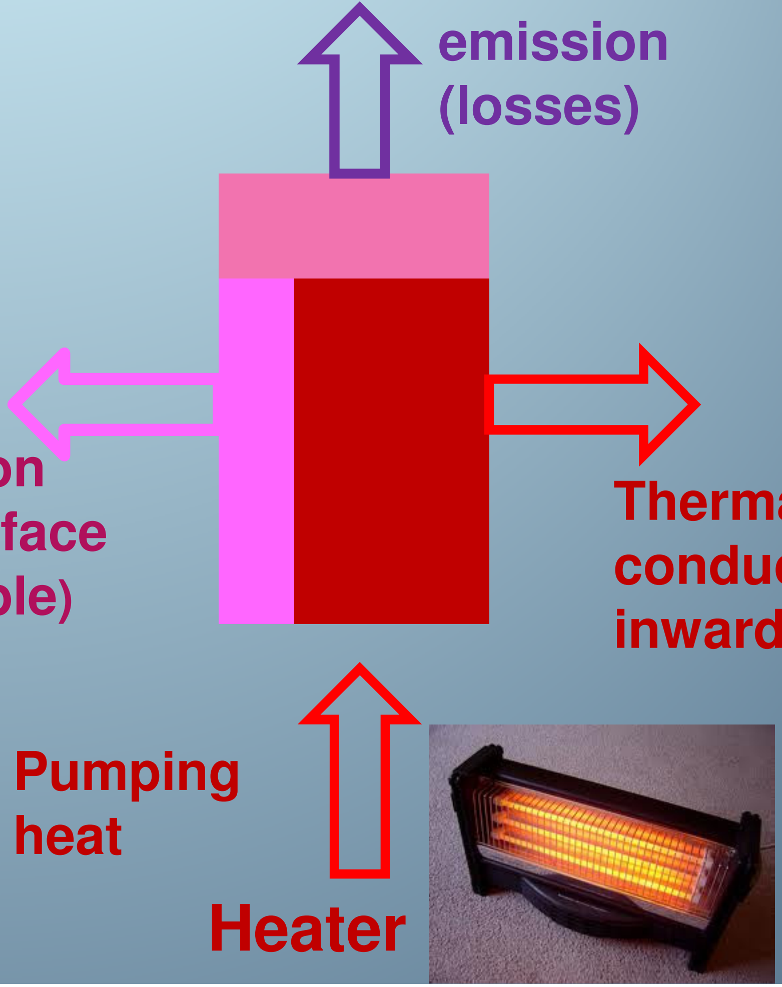
$\rho_2 = 1.6 \times 10^{12}$ g cm^{-3}

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 more general approach:
Pons, Miralles, Geppert (2009)
Vigano et al. (2013)

Carrying away pumped heat:



Neutrino emission (losses)

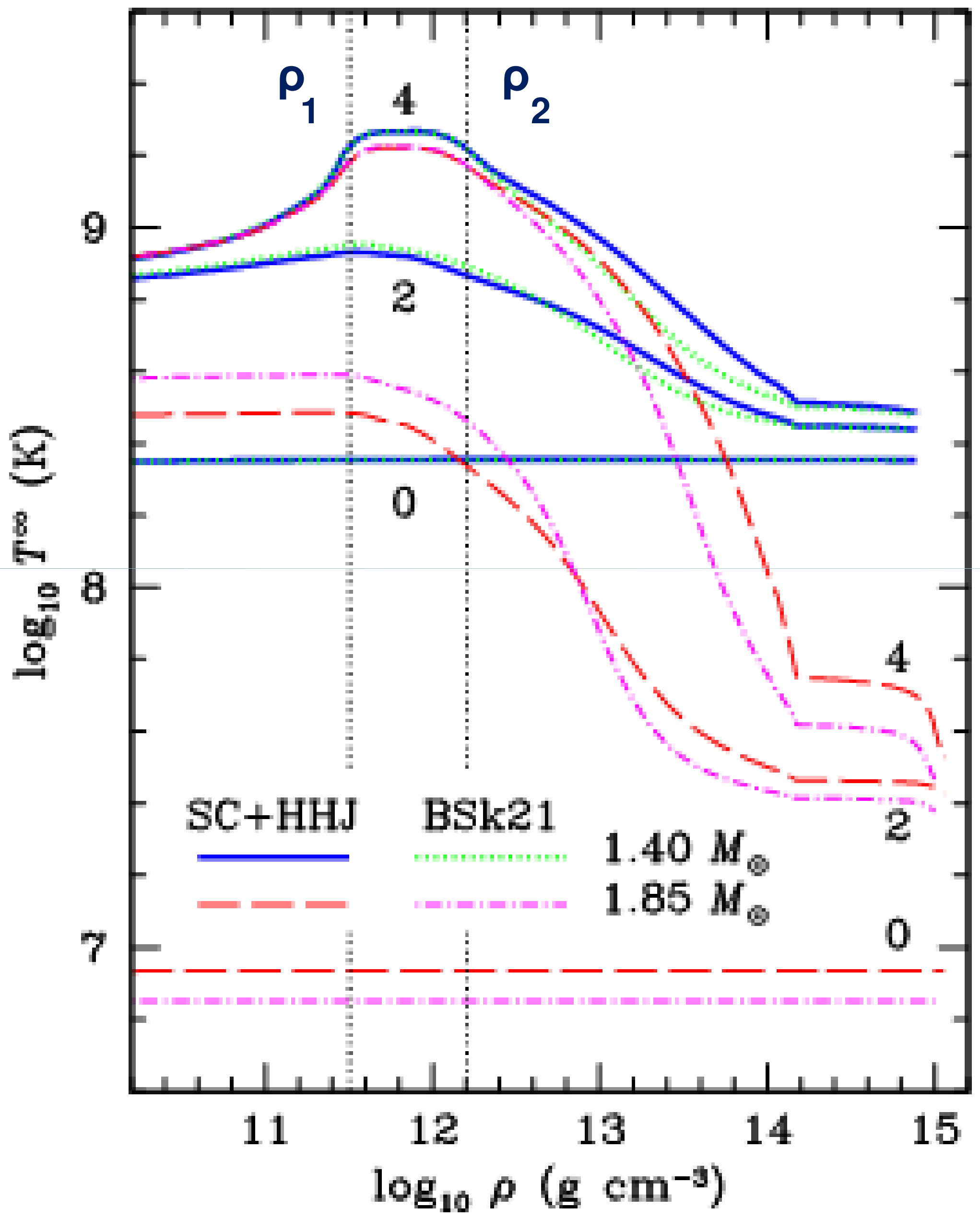
Thermal conduction to the surface (observable)

Thermal conduction inwards

Pumping heat

Heater

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



1D - calculations

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

$$B = 10^{12} \text{ G}$$

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

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

0 – $H_0 = 0$;

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

2 – $H_0 = 10^{19.5}$ erg s^{-1}cm^{-3}

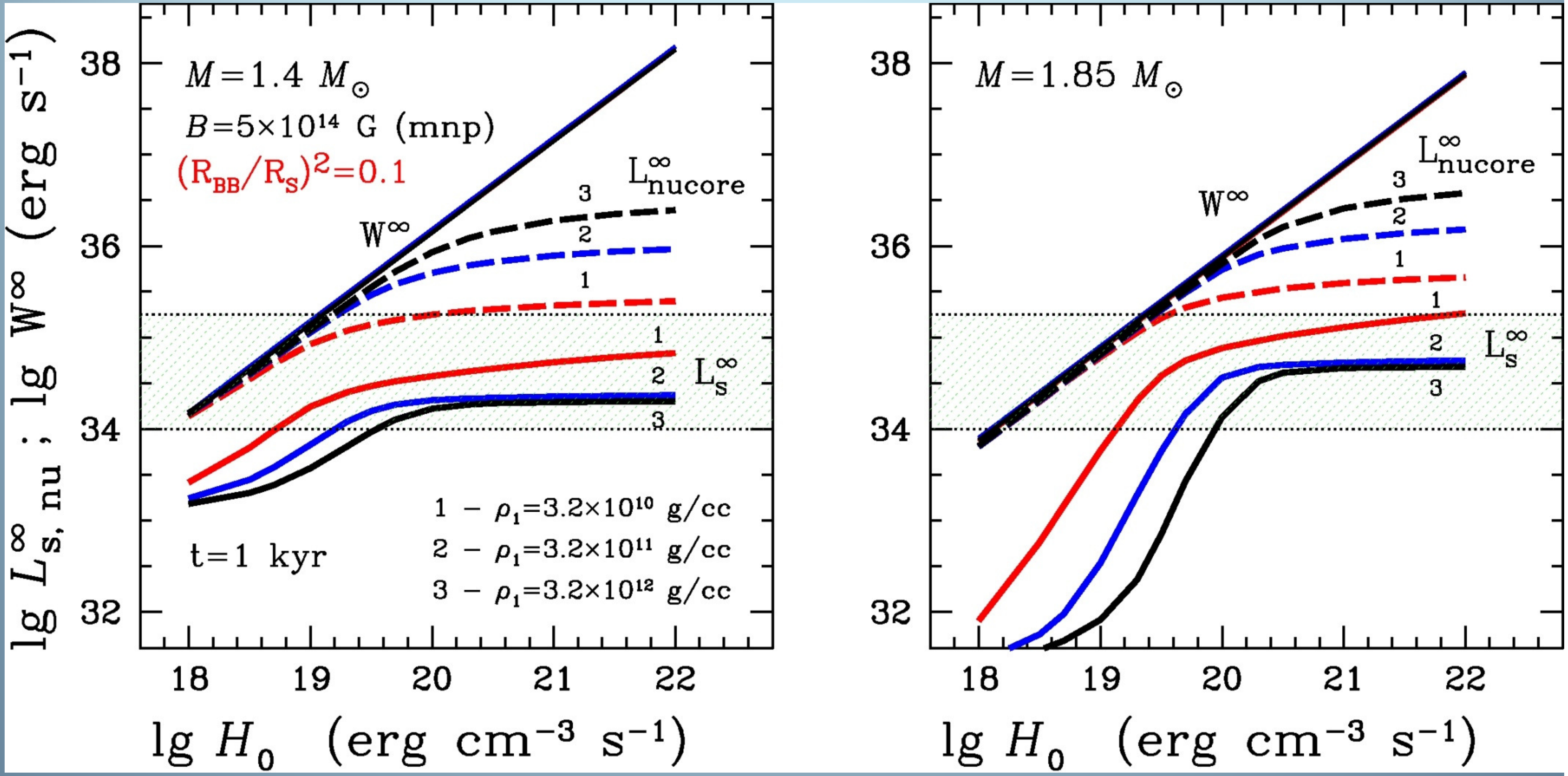
3 – $H_0 = 10^{20.5}$ erg s^{-1}cm^{-3}

4 – $H_0 = 10^{21.5}$ erg s^{-1}cm^{-3}

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

L_s^∞ (erg/s)

L_{nucore}^∞ (erg/s)



Hot spot $\Delta\Omega/4\pi = 0.1$

"Eddington" limit:
Kaminker et al. 2006
Pons and Rea 2012

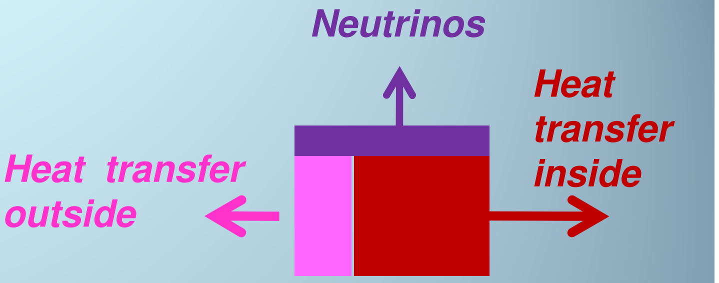
$$W^\infty(t) = \int V\, e^{2\Phi} H,$$

Heating regimes

1

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

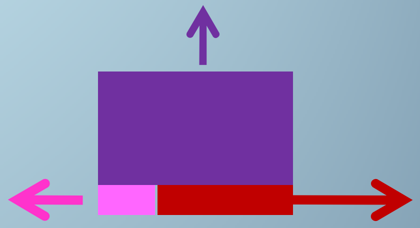
Conduction outflow regime:



2

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

Neutrino outflow regime:



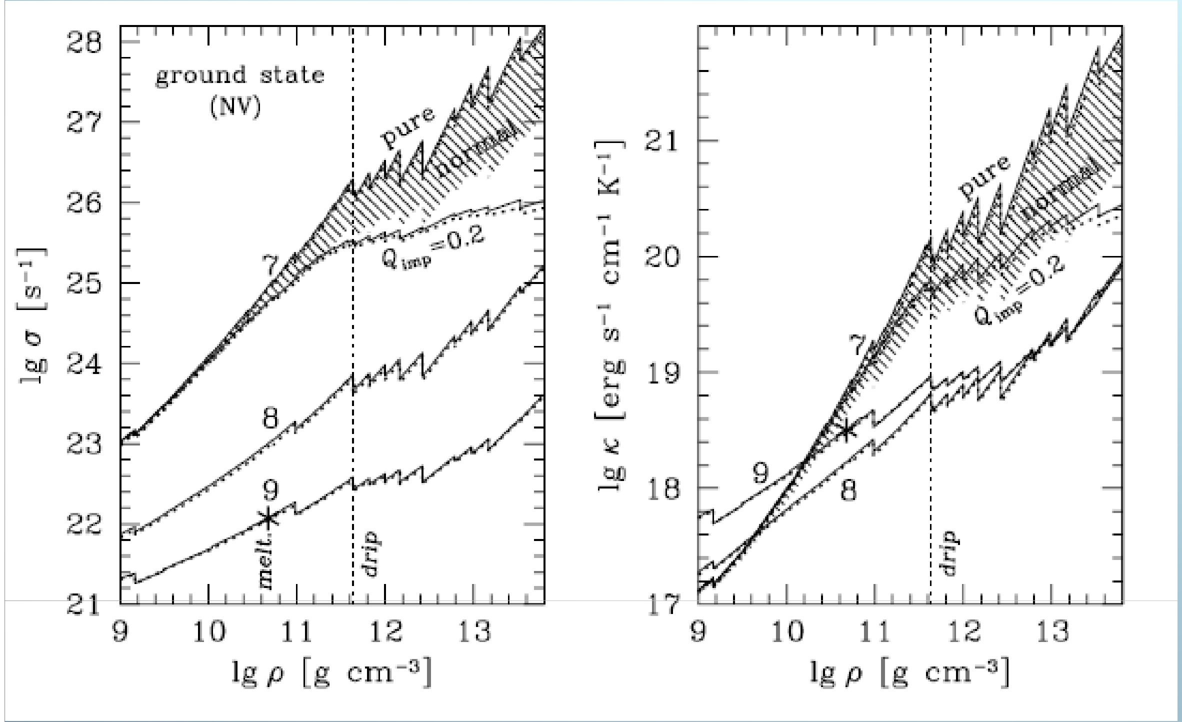
Non-economical heater

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***

Nature of heating: Ohmic dissipation



High temperature is needed:

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

Similar matters:

Aguilera, Pons, Miralles 2008

Pons, Miralles, Geppert 2009

Heat rate :

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

Ohmic dissipation; electrical conducticity ; Heat rate :

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

$$\text{For } \Delta\Omega/4\pi = (R_{BB}/2R)^2 \sim 0.1 \ \Rightarrow\ W_{\rm Ohmic} \sim 10^{36}\ \text{erg s}^{-1},$$

$$\text{Heat efficiency:}\quad L_s/W_{\rm Ohmic} \sim 1/30 \ \Rightarrow L_s \sim 3\times 10^{34}\ \text{erg s}^{-1}$$

$$\text{Total energy needed:}\quad W_{\rm Ohmic}\tau \sim 10^{47} - 10^{48}\ \text{erg}$$

$$(\tau \sim 5\times 10^4\ \text{yr})$$

Main features of magnetars

- *Magnitars -- SGRs and AXPs : neutron stars with ultrahigh B-fields -- exhibit strong persistent thermal and non-thermal emission.*
- ***Magnetars may be treated as cooling neutron stars with internal heating.***
- *Internal heating is probably inherent feature of ultrahigh B-fields.*
- ***The heating may be supported by Ohmic decay, e.g., inside local domains in the outer crust under hot spots.***
- ***Mechanism of B-field-energy transport to the heater is not clear.***

Main features of heating

- ***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 over a layer ⟹ the whole surface radiates.

- ***Two <u>regimes</u> of heating:***

  (a) The conduction outflow regime:

  $H < 10^{20}$ 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 with 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 and the core.

The most economical heater is intermediate: $H \sim 10^{20}\ \mathrm{erg\ cm^{-3}\ s^{-1}},\quad T \sim 10^{9}\ \mathrm{K}$

Efficiency of surface *T* – radiation *L / W* *does not exceed a few %.*

Quiesent Luminosity vs. B-field

Inferred dipole B-field:

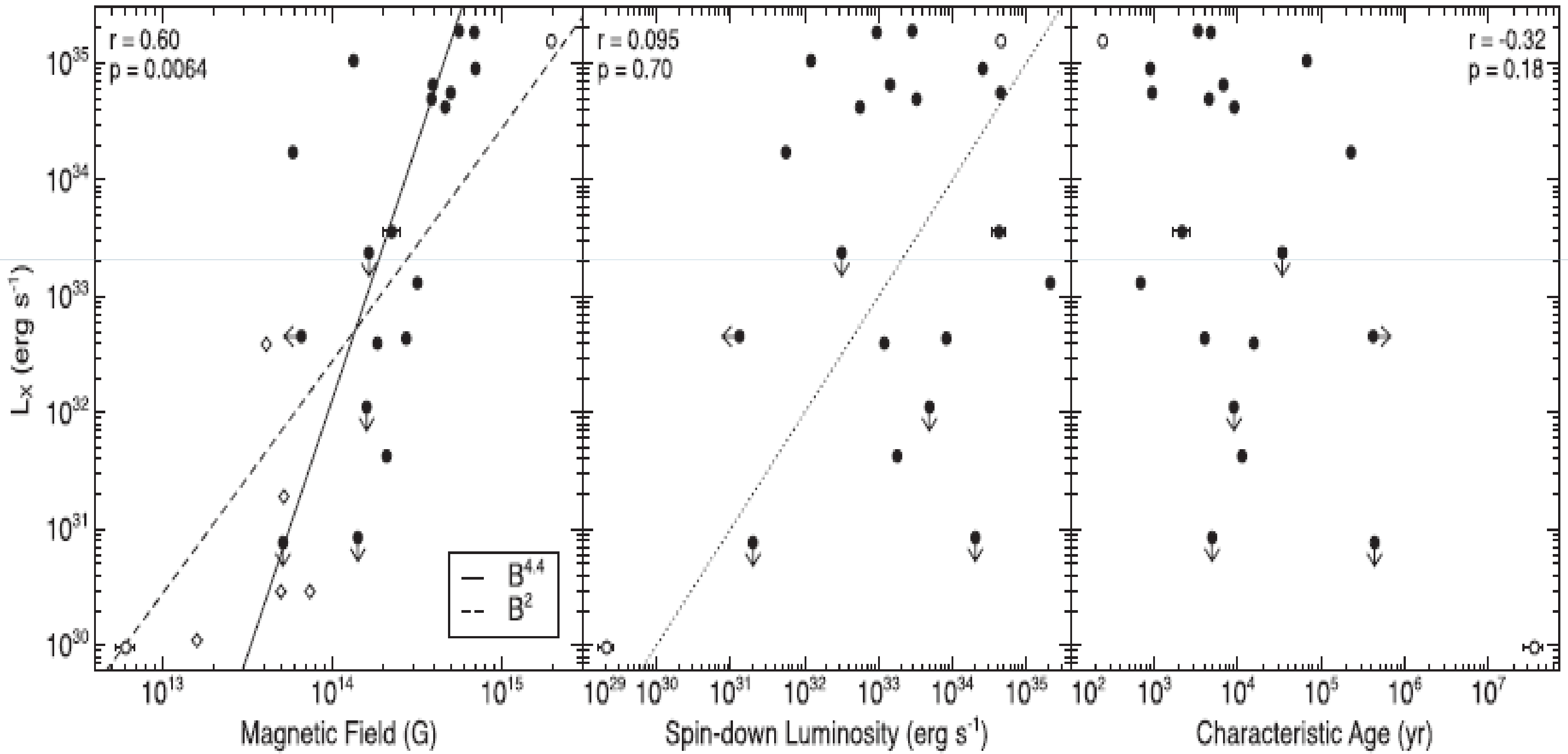
$$B_d \approx 3.2 \times 10^{19} \sqrt{P\dot{P}}\ \mathrm{G}.$$

Spin-down energy:

$$\dot{E} = I\Omega\dot{\Omega} = -(2\pi)^2 I\dot{P}/P^3$$

Characteristic age:

$$t_c = P/2\dot{P}$$



Olausen & Kaspi (2014)

Neutron star model

- *EOS (APR IV): Akmal, Pandharipande, Ravenhall 1998, Heiselberg & Hjorth-Jensen 1999; neutrons, protons, electrons, and muons in NS cores*

  *Maximum mass: MMAX=*2.16 *MSUN , R=*10.84 km ,
  central density = 2.45x1015 g/cc
  *Example of slow cooling: M=*1.4 *MSUN, R=*12.74 km,
  *central density = 7.*755x1014 g/cc

  Direct Urca: central density > 1.05x1015 g/cc, *M>*1.77 *MSUN*

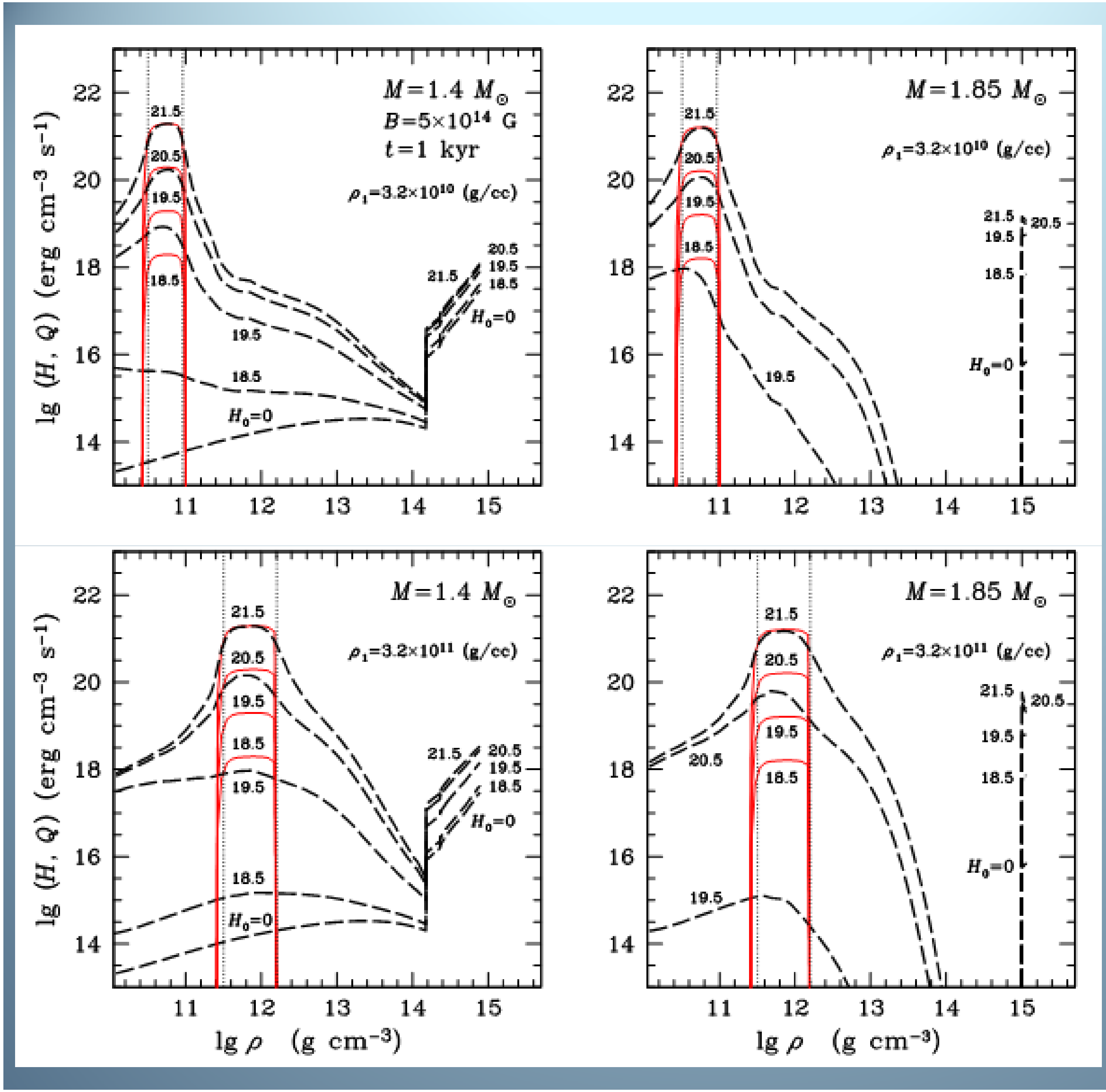
- *Effects of superfluidity are neglected*

- *Iron heat blanketing envelopes (densities* <1010 g/cc),
  but role of light elements on the surface – Kaminker et al. 2009

- *Radial magnetic field B=*5x1014 G *above hot spots:*
  synchrotron neutrino emission in the crust +
  anisotropic thermal conductivity and neutrino emission
  in the blanketing envelopes

- *Cooling codes: either 2D, or 1D*

Neutrino emissivity *Q* and heat intensity *H* vs. density



Direct Urca kernel of high neutrino emission