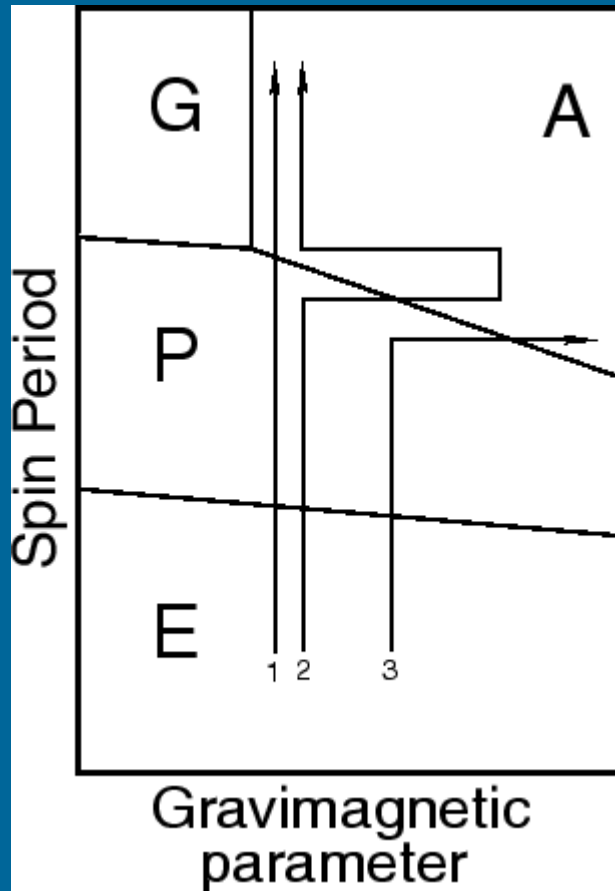


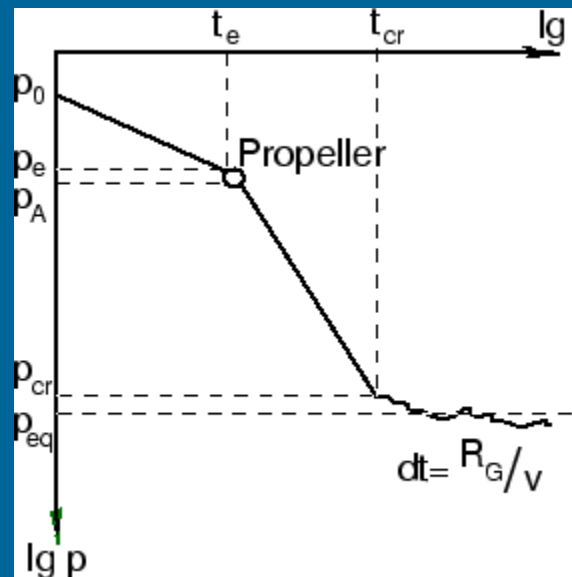
# Thermal evolution of neutron stars

# Evolution of neutron stars. I.: rotation + magnetic field

Ejector  $\rightarrow$  Propeller  $\rightarrow$  Accretor  $\rightarrow$  Georotator



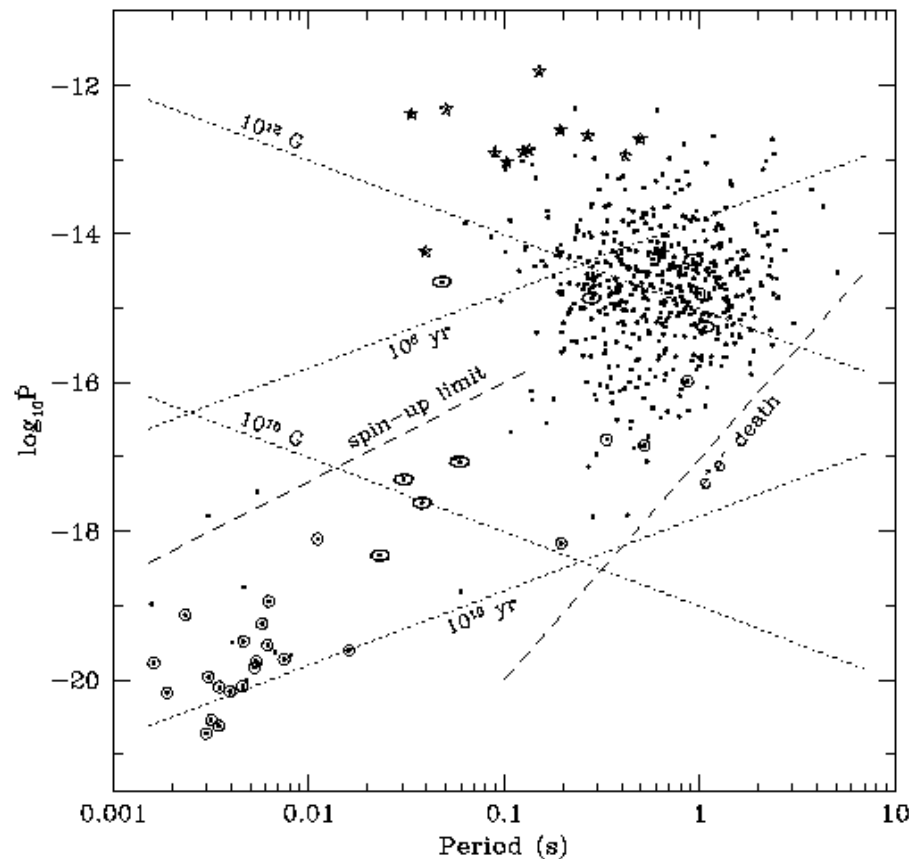
- 1 – spin down
- 2 – passage through a molecular cloud
- 3 – magnetic field decay



astro-ph/0101031

See the book by Lipunov (1987, 1992)

# Magnetorotational evolution of radio pulsars



$$L_m = \frac{2}{3} \frac{\mu^2 \omega^4}{c^3} \sin^2 \beta = \kappa_t \frac{\mu^2}{R_t^3} \omega,$$

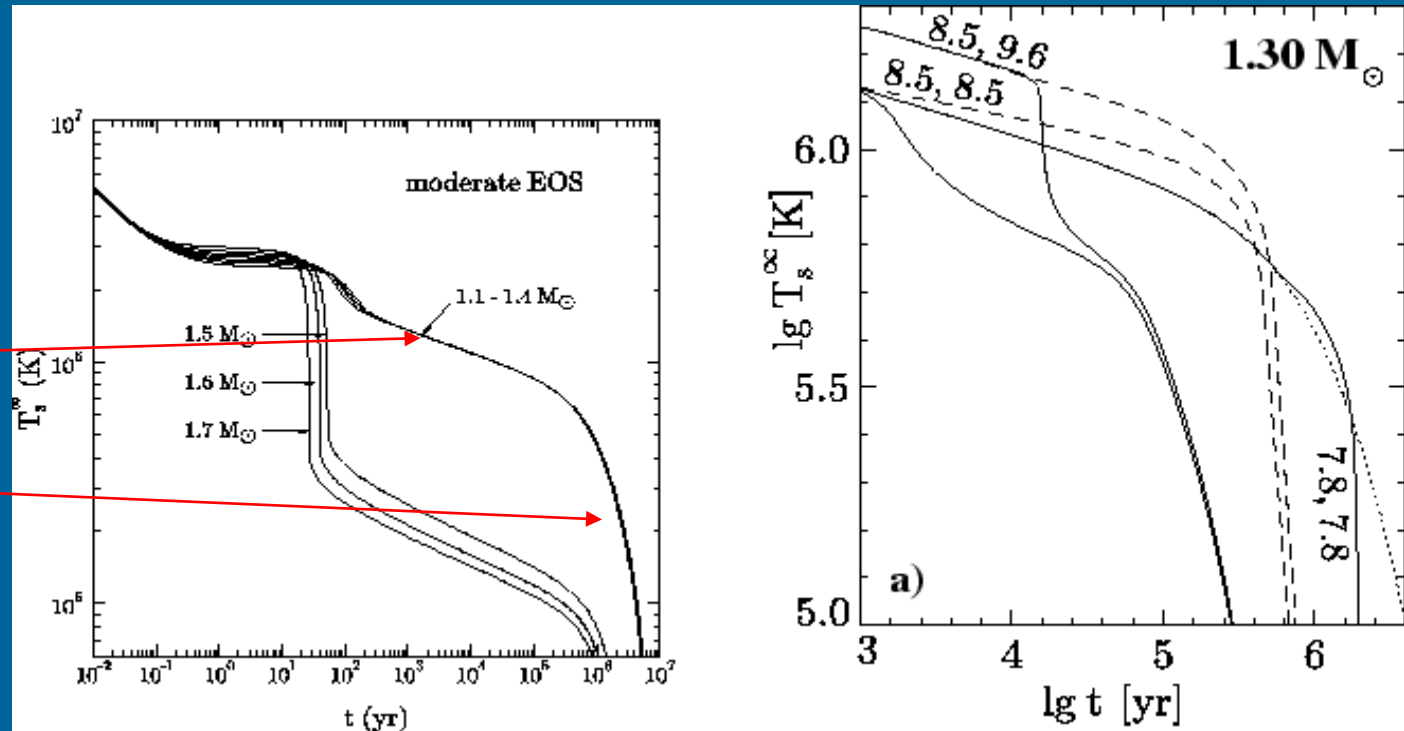
$$B \sim 3.2 \times 10^{19} (P dP/dt)^{1/2} \text{ G.}$$

Spin-down.  
Rotational energy is released.  
The exact mechanism is still unknown.

# Evolution of NSs. II.: temperature

Neutrino  
cooling stage

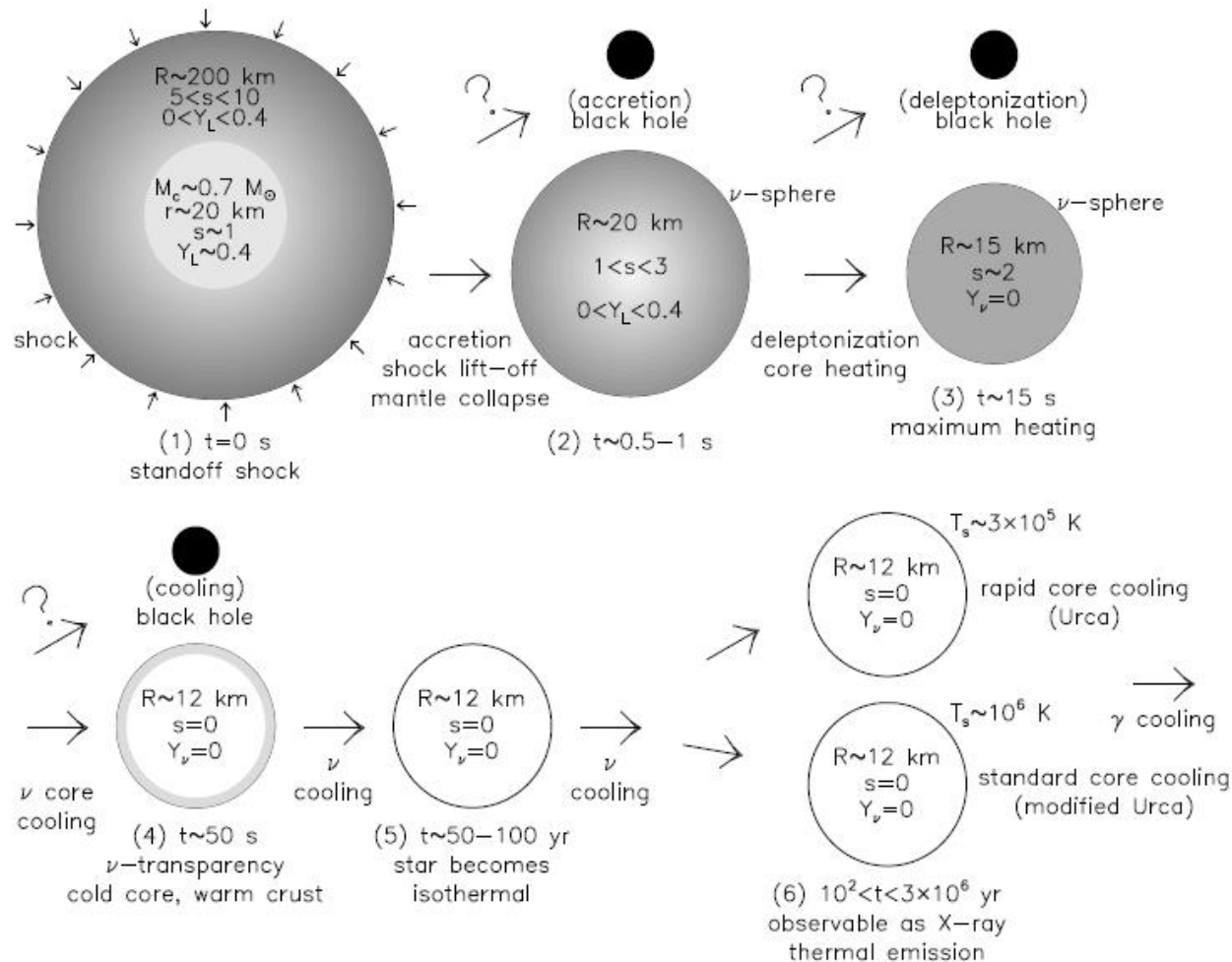
Photon  
cooling stage



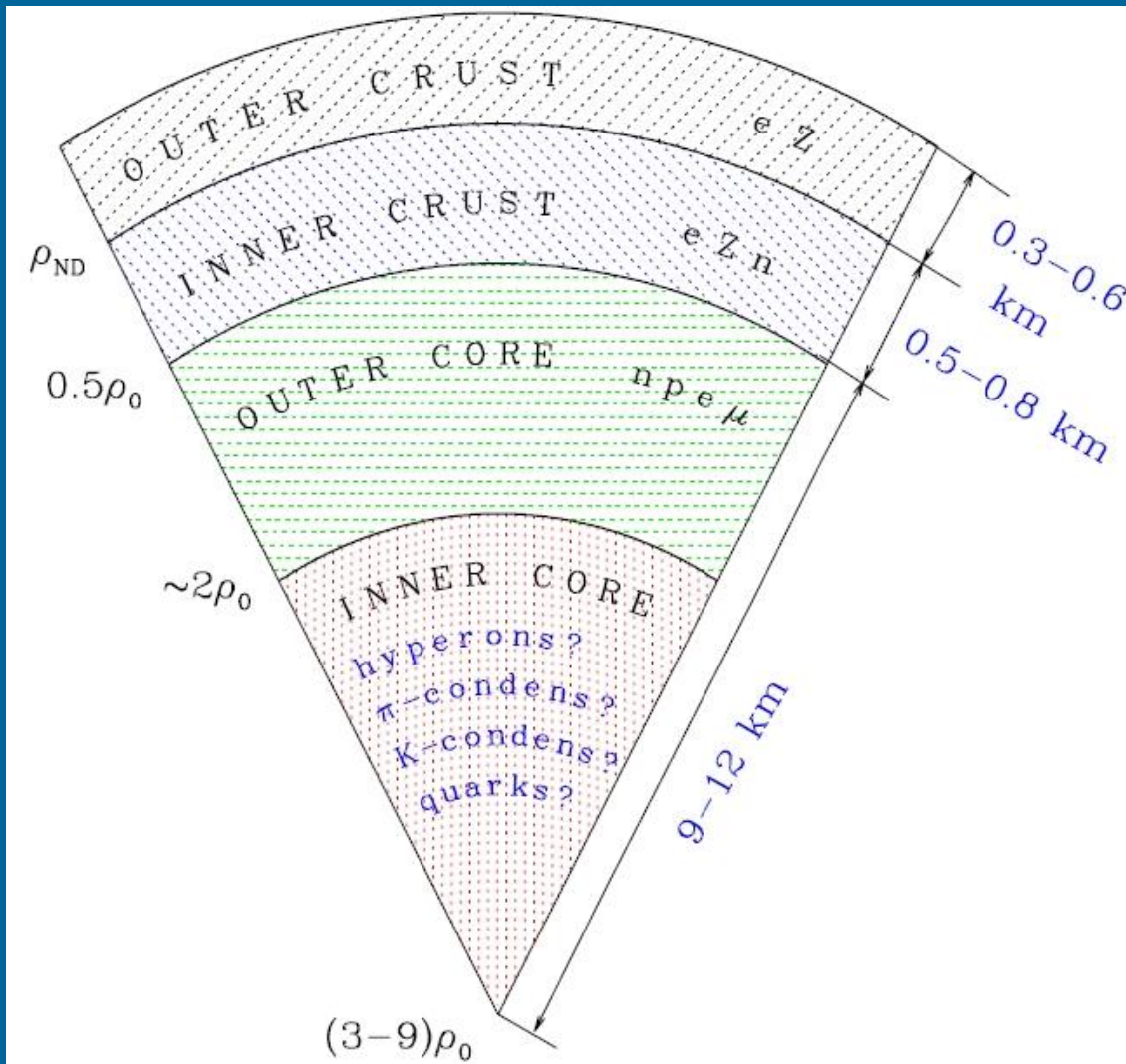
First papers on the thermal evolution appeared already in early 60s, i.e. before the discovery of radio pulsars.

[Yakovlev et al. (1999) Physics Uspekhi]

# Early evolution of a NS



# Structure and layers



Plus an atmosphere...

See Ch.6 in the book by Haensel, Potekhin, Yakovlev

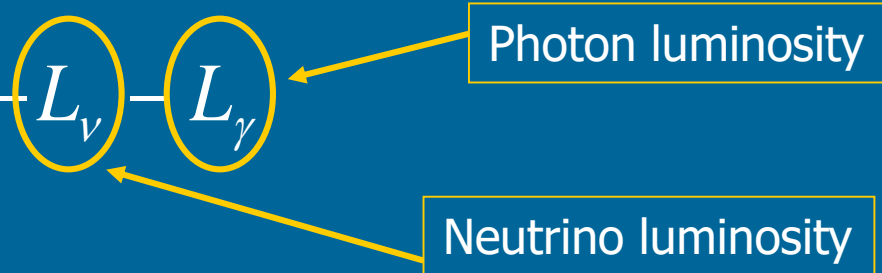
$$\rho_0 \sim 2.8 \cdot 10^{14} \text{ g cm}^{-3}$$

The total thermal energy of a nonsuperfluid neutron star is estimated as  $U_T \sim 10^{48} T_9^2 \text{ erg}$ .

The heat capacity of an  $npe$  neutron star core with strongly superfluid neutrons and protons is determined by the electrons, which are not superfluid, and it is  $\sim 20$  times lower than for a neutron star with a nonsuperfluid core.

# NS Cooling

- NSs are born very hot,  $T > 10^{10}$  K
- At early stages neutrino cooling dominates (exotic is possible – axions 1205.6940)
- The core is isothermal

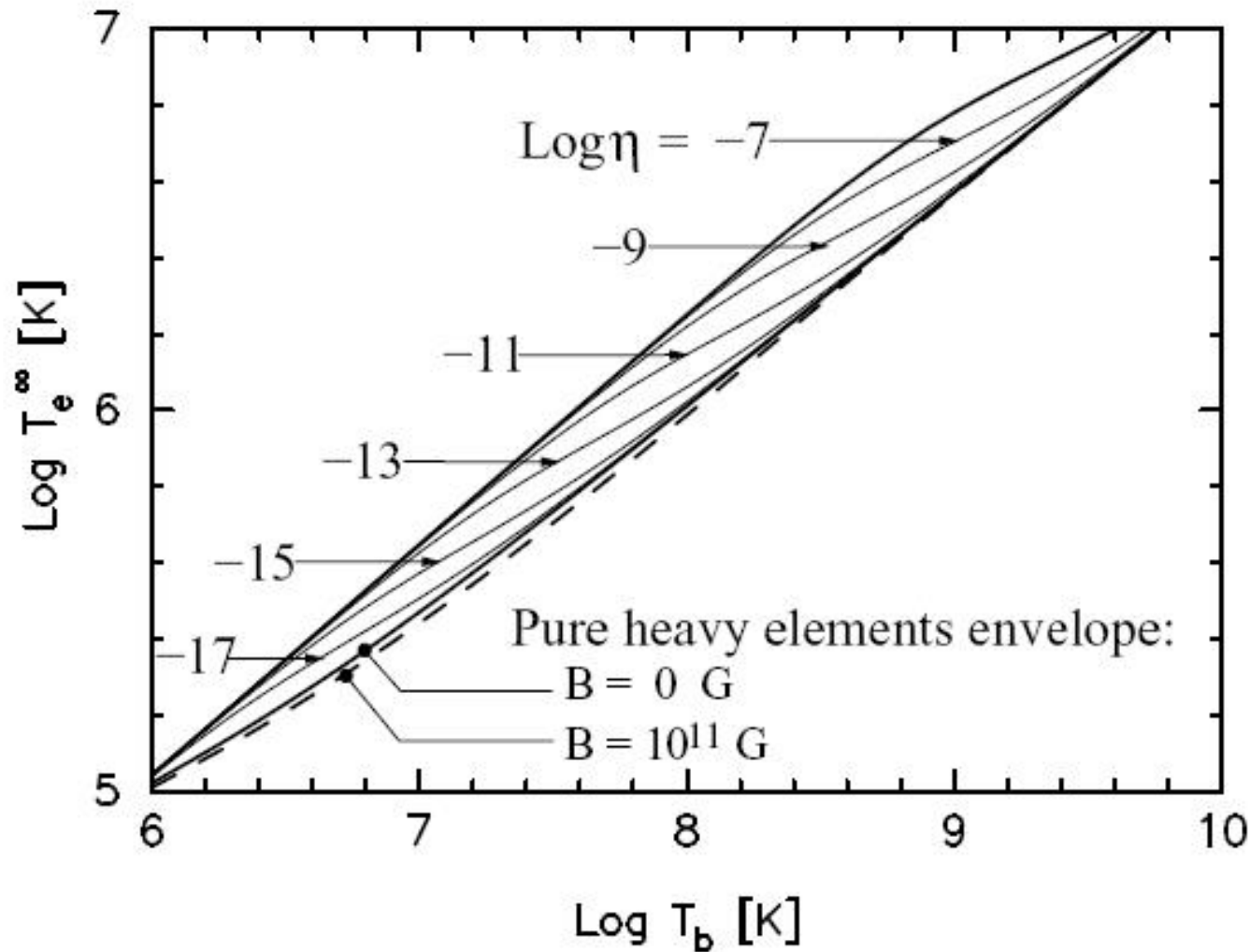
$$\frac{dE_{th}}{dt} = C_V \frac{dT}{dt} = -L_\nu - L_\gamma$$


Photon luminosity

Neutrino luminosity

$$L_\gamma = 4\pi R^2 \sigma T_s^4, \quad T_s \propto T^{1/2+\alpha} \quad (|\alpha| \ll 1)$$

# Core-crust temperature relation



Heat blanketing  
envelope.  
~100 meters  
density  $\sim 10^{10}$  gcm $^{-3}$

See a review about  
crust properties  
related to thermal  
evolution in  
1201.5602 and  
1507.06186



# Cooling depends on:

- 1. Rate of neutrino emission from NS interiors
  - 2. Heat capacity of internal parts of a star
  - 3. Superfluidity
  - 4. Thermal conductivity in the outer layers
  - 5. Possible heating
- } Depend on the EoS and composition

# Main neutrino processes

Model	Process	$Q_f, \text{ erg cm}^{-3} \text{ s}^{-1}$
Nucleon matter	$n \rightarrow pe\bar{\nu} \quad pe \rightarrow n\nu$	$10^{26} - 3 \times 10^{27}$
Pion condensate	$\tilde{N} \rightarrow \tilde{N}e\bar{\nu} \quad \tilde{N}e \rightarrow \tilde{N}\nu$	$10^{23} - 10^{26}$
Kaon condensate	$\tilde{B} \rightarrow \tilde{B}e\bar{\nu} \quad \tilde{B}e \rightarrow \tilde{B}\nu$	$10^{23} - 10^{24}$
Quark matter	$d \rightarrow ue\bar{\nu} \quad ue \rightarrow d\nu$	$10^{23} - 10^{24}$

Process	$Q_s, \text{ erg cm}^{-3} \text{ s}^{-1}$
Modified Urca $nN \rightarrow pNe\bar{\nu} \quad pNe \rightarrow nN\nu$	$10^{20} - 3 \times 10^{21}$
Bremsstrahlung $NN \rightarrow NN\nu\bar{\nu}$	$10^{19} - 10^{20}$

$$Q_{\text{slow}} = Q_s T_9^8, \quad Q_{\text{fast}} = Q_f T_9^6.$$

(Yakovlev & Pethick astro-ph/0402143)

## Fast Cooling (URCA cycle)

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

$$p + e^{-} \rightarrow n + \nu_e$$

## Slow Cooling (modified URCA cycle)

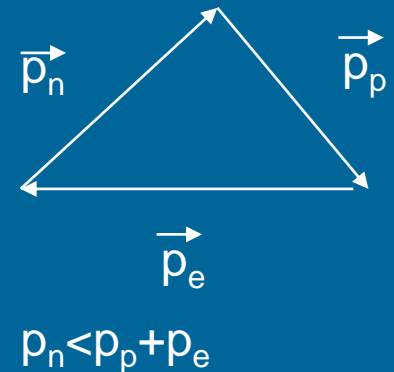
$$n + n \rightarrow n + p + e^{-} + \bar{\nu}_e$$

$$n + p + e^{-} \rightarrow n + n + \nu_e$$

$$p + n \rightarrow p + p + e^{-} + \bar{\nu}_e$$

$$p + p + e^{-} \rightarrow p + n + \nu_e$$

- Fast cooling possible only if  $n_p > n_n/8$
- Nucleon Cooper pairing is important
- Minimal cooling scenario (Page et al 2004):
  - no exotica
  - no fast processes
  - pairing included



[See the book Haensel, Potekhin, Yakovlev p. 265 (p.286 in the file)  
and Shapiro, Teukolsky for details: Ch. 2.3, 2.5, 11.]

# Equations

Neutrino emissivity

heating

$$\frac{e^{-\lambda-2\Phi}}{4\pi r^2} \frac{\partial}{\partial r} \left( e^{2\Phi} L_r \right) = -Q + Q_h - \frac{c_T}{e^\Phi} \frac{\partial T}{\partial t},$$

$$\frac{L_r}{4\pi \kappa T^2} = e^{-\lambda-\Phi} \frac{\partial}{\partial r} \left( T e^\Phi \right),$$

After thermal relaxation  
we have in the whole star:  
 $T_i(t) = T(r,t) e^{\Phi(r)}$

$$e^{-\lambda} = \sqrt{1 - 2Gm(r)/c^2 r},$$

At the surface we have:  $\Phi(R) = -\lambda(R)$

$$C(T_i) \frac{dT_i}{dt} = -L_\nu^\infty(T_i) + L_h^\infty - L_\gamma^\infty(T_s),$$

$$L_\nu^\infty(T_i) = \int dV Q(T) e^{2\Phi}, \text{ and } L_h^\infty = \int dV Q_h e^{2\Phi}, \quad C(T_i) = \int dV c_T(T),$$

$dV = 4\pi r^2 e^\lambda dr$  is the element of proper volume

$L_\nu^\infty$  is the total neutrino luminosity (for a distant observer)

$L_h^\infty$  is the total reheating power.

(Yakovlev & Pethick 2004)

Total stellar heat capacity

# Simplified model of a cooling NS

No superfluidity, no envelopes and magnetic fields, only hadrons.

**The most critical moment is the onset of direct URCA cooling.**

$$\rho_D = 7.851 \cdot 10^{14} \text{ g/cm}^3.$$

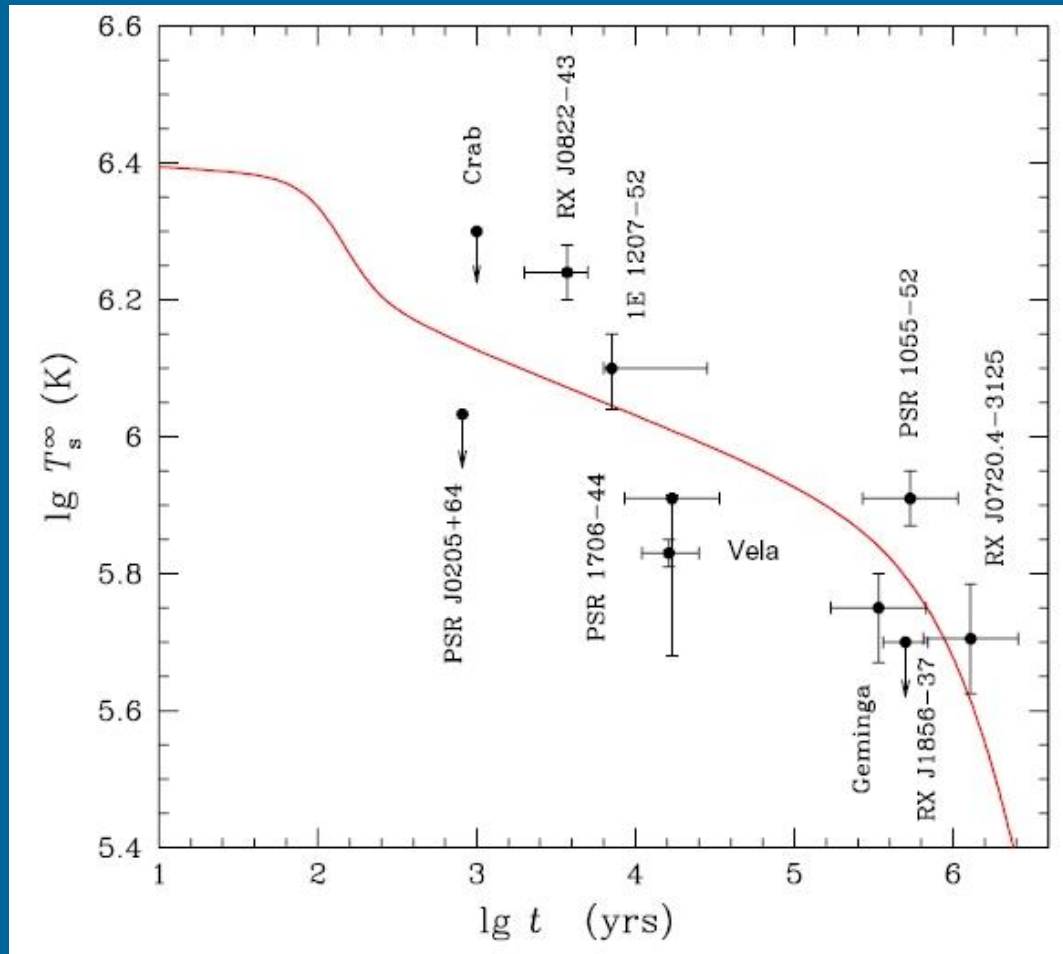
The critical mass  
depends on the EoS.  
For the examples below  
 $M_D = 1.358 M_{\text{solar}}$

$M$ ( $M_{\odot}$ )	$R$ (km)	$\rho_c$ ( $10^{14}$ $\text{g cm}^{-3}$ )	$M_{\text{crust}}$ ( $M_{\odot}$ )	$\Delta R_{\text{crust}}$ (km)	$\Delta M_D$ ( $M_{\odot}$ )	$R_D$ (km)
1.1	13.20	6.23	0.069	1.98	...	...
1.2	13.13	6.80	0.063	1.77	...	...
1.3	13.04	7.44	0.057	1.58	...	...
1.358 <sup>a</sup>	12.98	7.85	0.054	1.48	0.000	0.00
1.4	12.93	8.17	0.052	1.40	0.023	2.40
1.5	12.81	9.00	0.049	1.26	0.137	4.27
1.6	12.64	10.05	0.042	1.10	0.306	5.51
1.7	12.43	11.39	0.035	0.96	0.510	6.41
1.8	12.16	13.22	0.030	0.84	0.742	7.10
1.9	11.73	16.33	0.023	0.69	1.024	7.65
1.977 <sup>b</sup>	10.75	25.78	0.011	0.45	1.400	7.90

<sup>a</sup> Threshold configuration for the direct Urca process

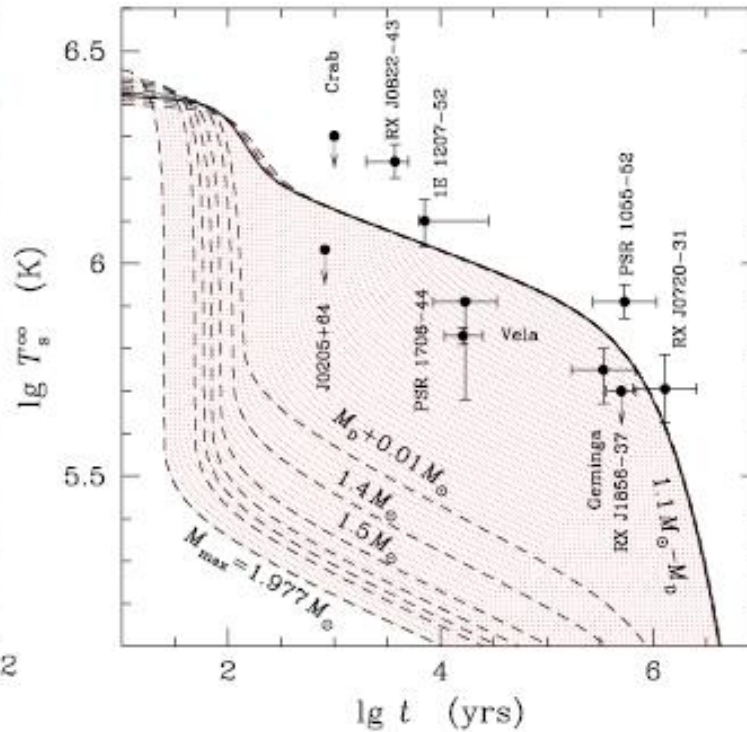
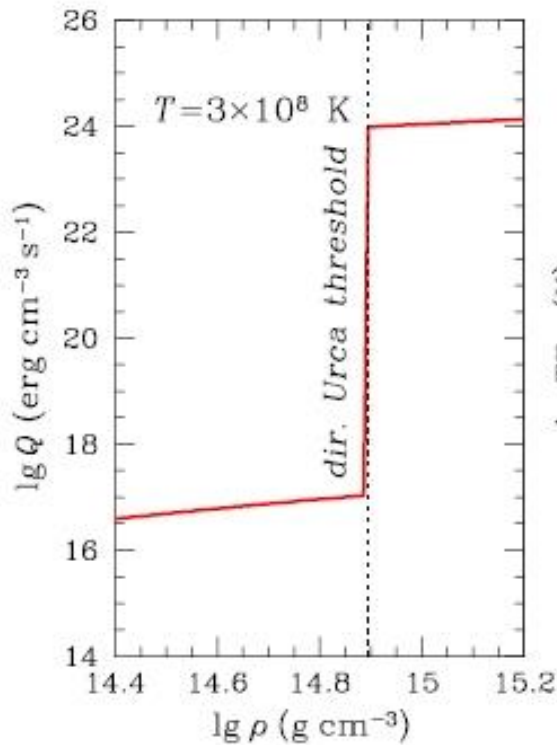
<sup>b</sup> Maximum-mass stable neutron star

# Simple cooling model for low-mass NSs.



Too hot .....  
Too cold ....

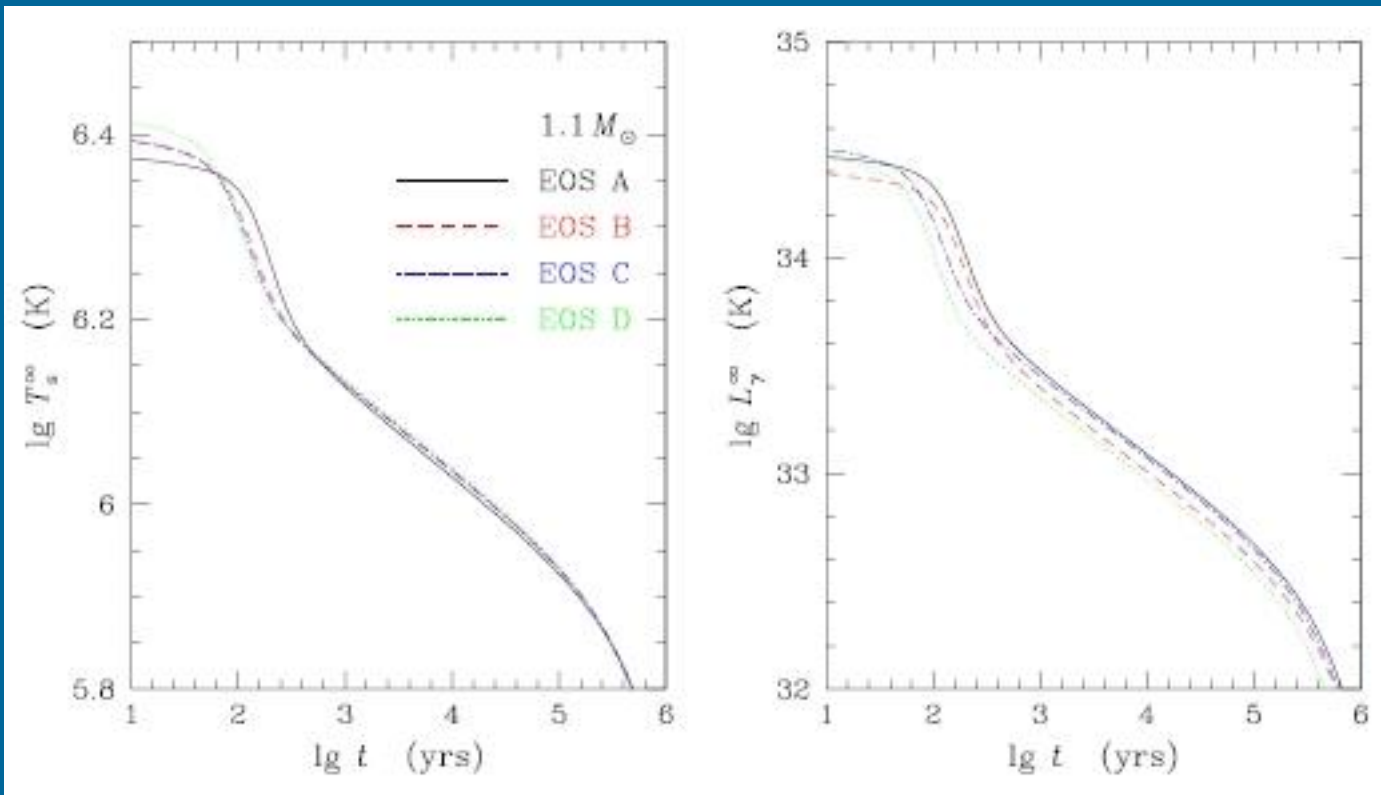
# Nonsuperfluid nucleon cores



Note “population aspects” of the right plot: too many NSs have to be explained by a very narrow range of mass.

For slow cooling at the neutrino cooling stage  $t_{\text{slow}} \sim 1 \text{ yr} / T_{10}^6$   
 For fast cooling  $t_{\text{fast}} \sim 1 \text{ min} / T_{10}^4$

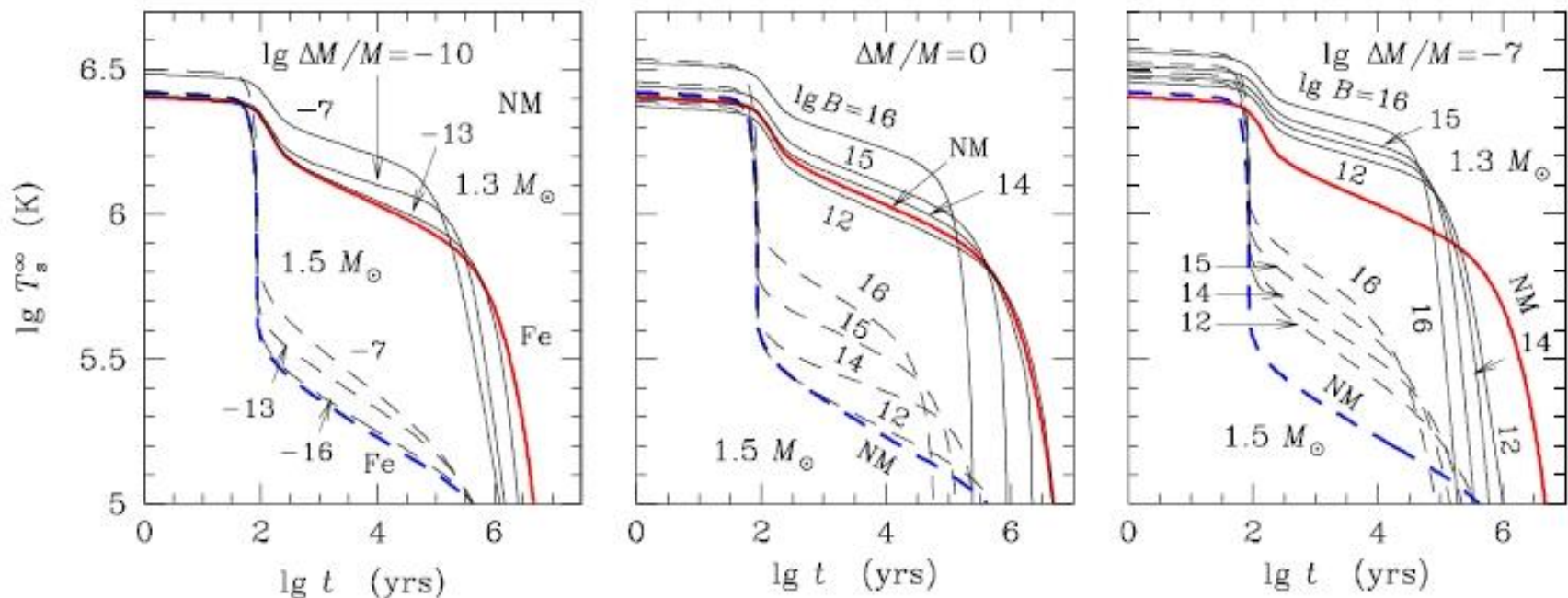
# Slow cooling for different EoS



For slow cooling there is nearly no dependence on the EoS.  
The same is true for cooling curves for maximum mass for each EoS.

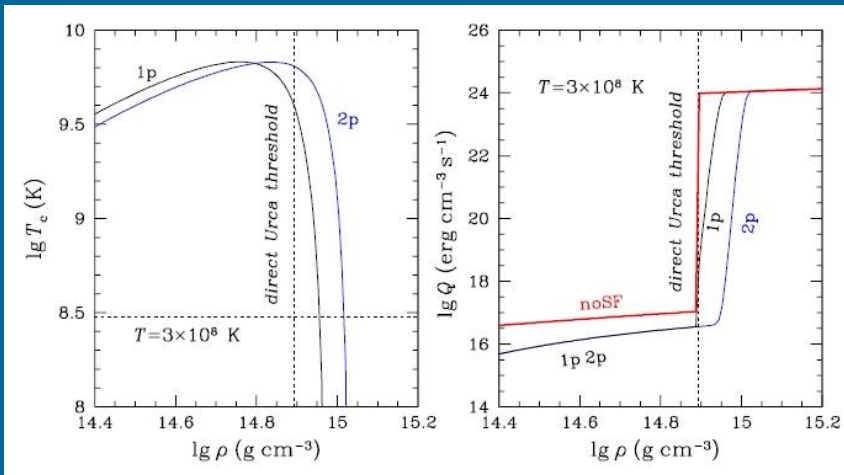


# Envelopes and magnetic field



Non-magnetic stars      No accreted envelopes,      Envelopes + Fields  
 Thick lines – no envelope      different magnetic fields.  
 Envelopes can be related to the fact that we see a subpopulation of hot NS  
 in CCOs with relatively long initial spin periods and low magnetic field, but  
 do not observed representatives of this population around us, i.e. in the Solar vicinity.  
 Solid line  $M=1.3 M_{\text{solar}}$ , Dashed lines  $M=1.5 M_{\text{solar}}$

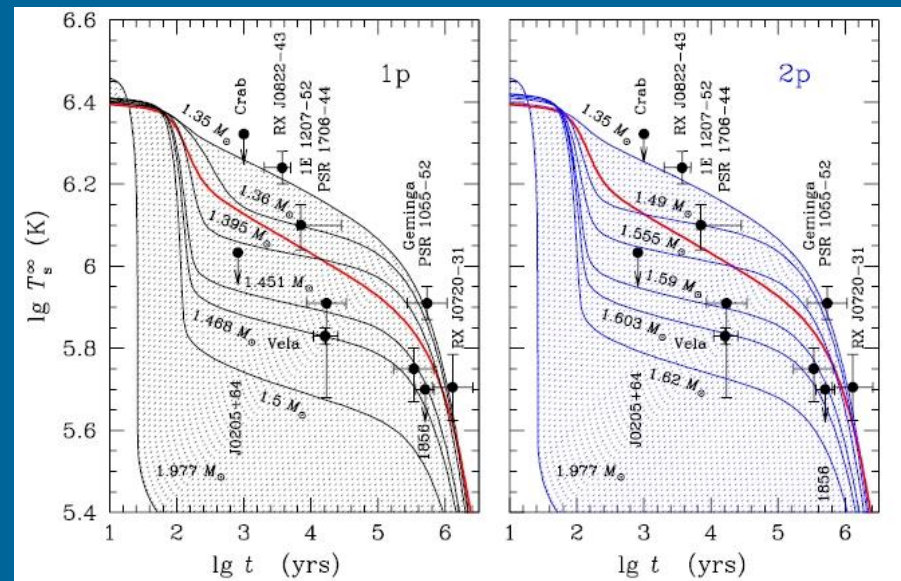
# Simplified model: no neutron superfluidity



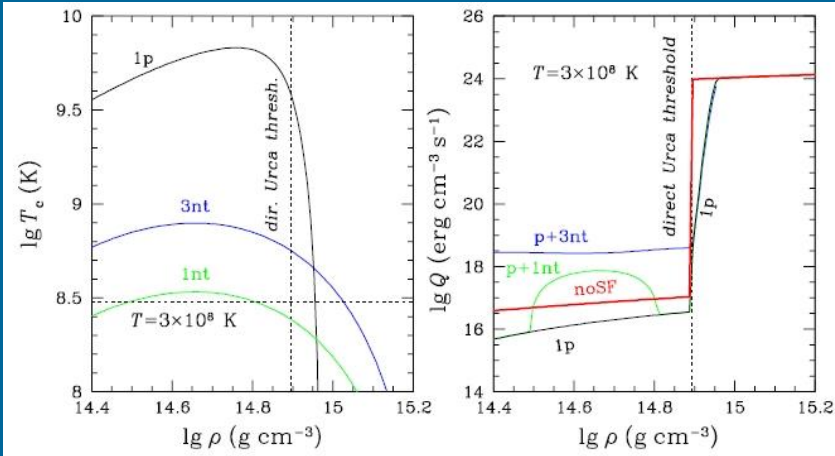
Superfluidity is an important ingredient of cooling models. It is important to consider different types of proton and neutron superfluidity.

There is no complete microphysical theory which can describe superfluidity in neutron stars.

If proton superfluidity is strong, but neutron superfluidity in the core is weak then it is possible to explain observations.

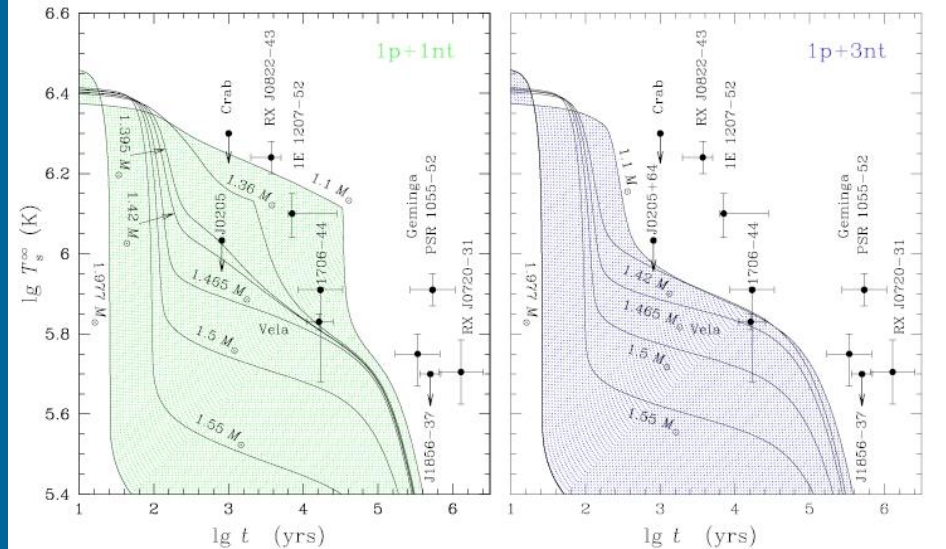


# Neutron superfluidity and observations

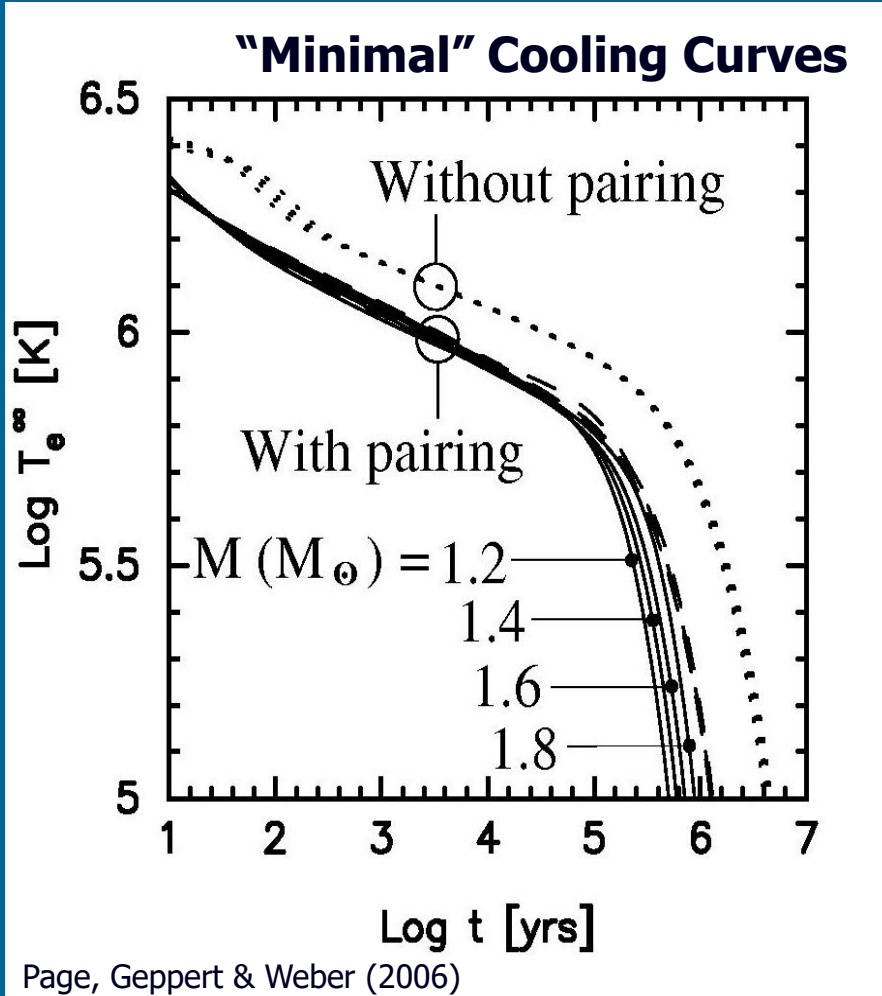


Mild neutron pairing in the core contradicts observations.

See a recent review about superfluidity and its relation to the thermal evolution of NSs in 1206.5011 and a very detailed review about superfluids in NSs in 1302.6626. A brief and more popular review in 1303.3282.



# Minimal cooling model

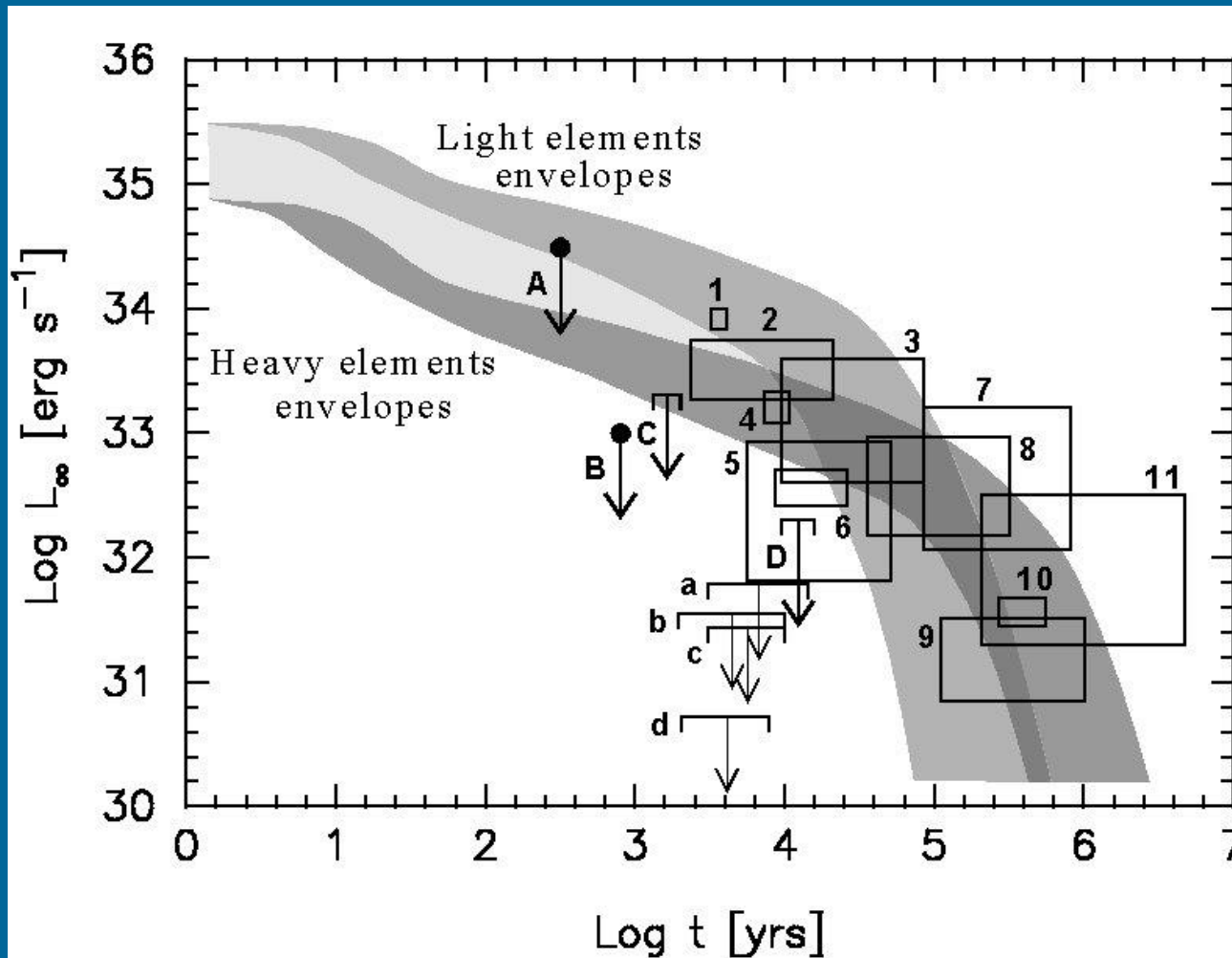


“minimal” means  
without additional cooling  
due to direct URCA  
and without additional heating

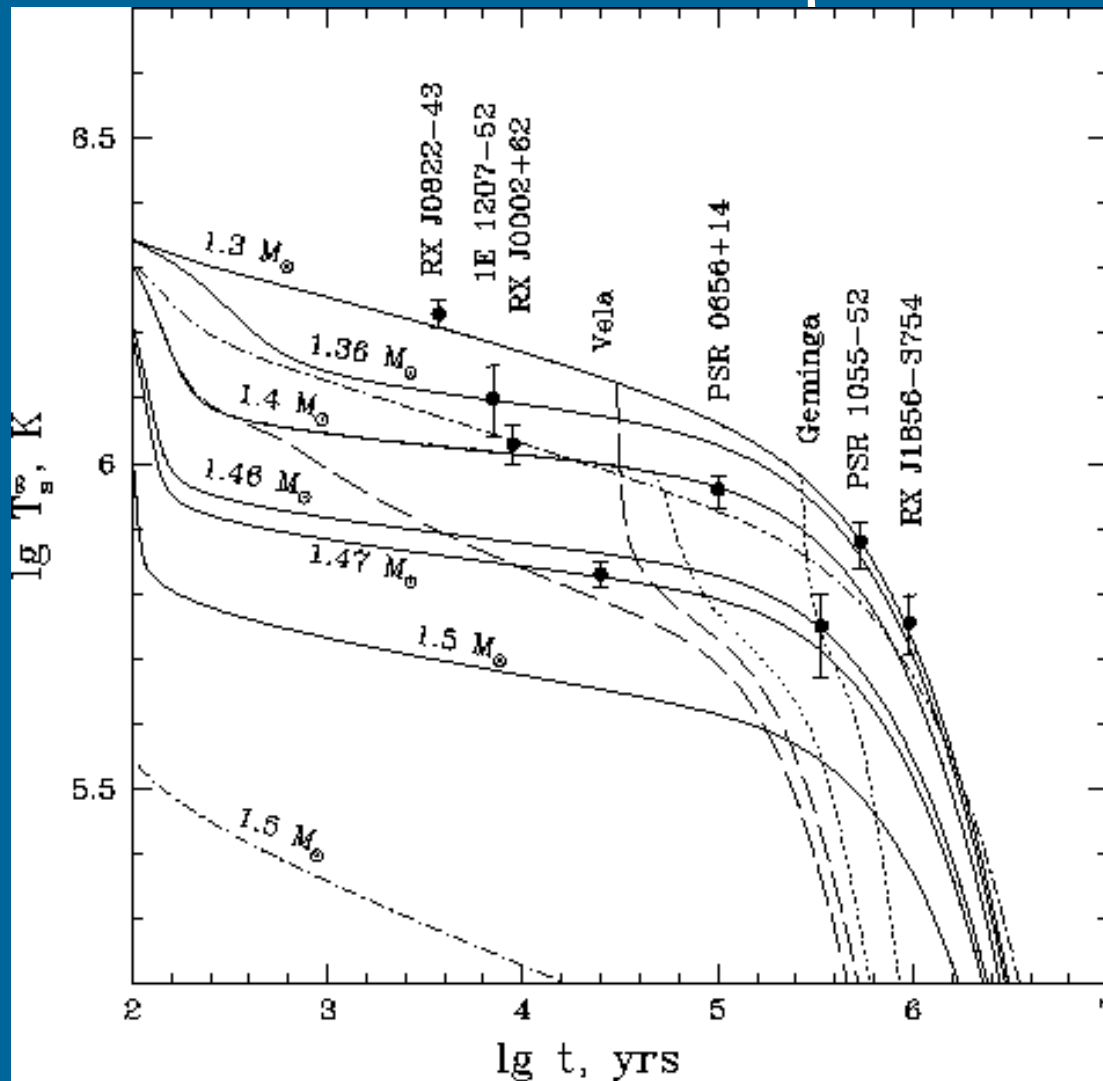
## Main ingredients of the minimal model

- EoS
- Superfluid properties
- Envelope composition
- NS mass

# Luminosity and age uncertainties



# Standard test: temperature vs. age



Kaminker et al. (2001)



# Data

NEUTRON STAR PROPERTIES WITH HYDROGEN ATMOSPHERES

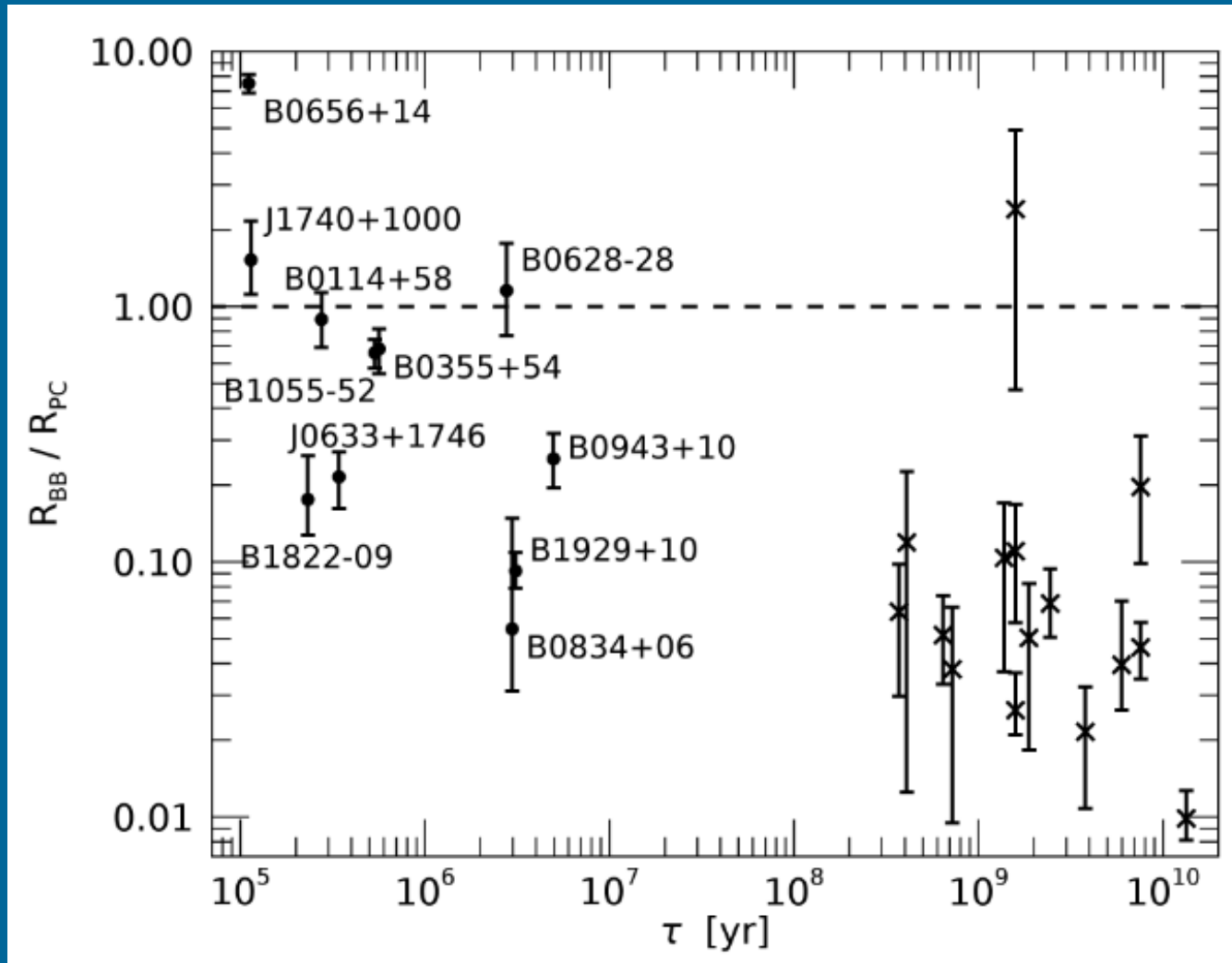
Star	$\log_{10} t_{sd}$ yr	$\log_{10} t_{kin}$ yr	$\log_{10} T_{\infty}$ K	$d$ kpc	$\log_{10} L_{\infty}$ erg/s
RX J0822-4247	3.90	$3.57^{+0.04}_{-0.04}$	$6.24^{+0.04}_{-0.04}$	1.9 – 2.5	33.85 – 34.00
1E 1207.4-5209	$5.53^{+0.44}_{-0.19}$	$3.85^{+0.48}_{-0.48}$	$6.21^{+0.07}_{-0.07}$	1.3 – 3.9	33.27 – 33.74
RX J0002+6246	–	$3.96^{+0.08}_{-0.08}$	$6.03^{+0.03}_{-0.03}$	2.5 – 3.5	33.08 – 33.33
PSR 0833-45 (Vela)	4.05	$4.26^{+0.17}_{-0.31}$	$5.83^{+0.02}_{-0.02}$	0.22 – 0.28	32.41 – 32.70
PSR 1706-44	4.24	–	$5.8^{+0.13}_{-0.13}$	1.4 – 2.3	31.81 – 32.93
PSR 0538+2817	4.47	–	$6.05^{+0.10}_{-0.10}$	1.2	32.6 – 33.6

NEUTRON STAR PROPERTIES WITH BLACKBODY ATMOSPHERES

Star	$\log_{10} t_{sd}$ yr	$\log_{10} t_{kin}$ yr	$\log_{10} T_{\infty}$ K	$R_{\infty}$ km	$d$ kpc	$\log_{10} L_{\infty}$ erg/s
RX J0822-4247	3.90	$3.57^{+0.04}_{-0.04}$	$6.65^{+0.04}_{-0.04}$	1 – 1.6	1.9 – 2.5	33.60 – 33.90
1E 1207.4-5209	$5.53^{+0.44}_{-0.19}$	$3.85^{+0.48}_{-0.48}$	$6.48^{+0.01}_{-0.01}$	1.0 – 3.7	1.3 – 3.9	32.70 – 33.88
RX J0002+6246	–	$3.96^{+0.08}_{-0.08}$	$6.15^{+0.11}_{-0.11}$	2.1 – 5.3	2.5 – 3.5	32.18 – 32.81
PSR 0833-45 (Vela)	4.05	$4.26^{+0.17}_{-0.31}$	$6.18^{+0.02}_{-0.02}$	1.7 – 2.5	0.22 – 0.28	32.04 – 32.32
PSR 1706-44	4.24	–	$6.22^{+0.04}_{-0.04}$	1.9 – 5.8	1.8 – 3.2	32.48 – 33.08
PSR 0656+14	5.04	–	$5.71^{+0.03}_{-0.04}$	7.0 – 8.5	0.26 – 0.32	32.18 – 32.97
PSR 0633+1748 (Geminga)	5.53	–	$5.75^{+0.04}_{-0.05}$	2.7 – 8.7	0.123 – 0.216	30.85 – 31.51
PSR 1055-52	5.43	–	$5.92^{+0.02}_{-0.02}$	6.5 – 19.5	0.5 – 1.5	32.07 – 33.19
RX J1856.5-3754	–	$5.70^{+0.05}_{-0.25}$	5.6 – 5.9	> 16	0.105 – 0.129	31.44 – 31.68
RX J0720.4-3125	$6.0 \pm 0.2$	–	5.55 – 5.95	5.0 – 15.0	0.1 – 0.3	31.3 – 32.5

(Page et al. astro-ph/0403657)

# Not to mix with polar caps heating!



$$R_{cap} = R_{NS} (R_{NS} / R_I)^{1/2}$$

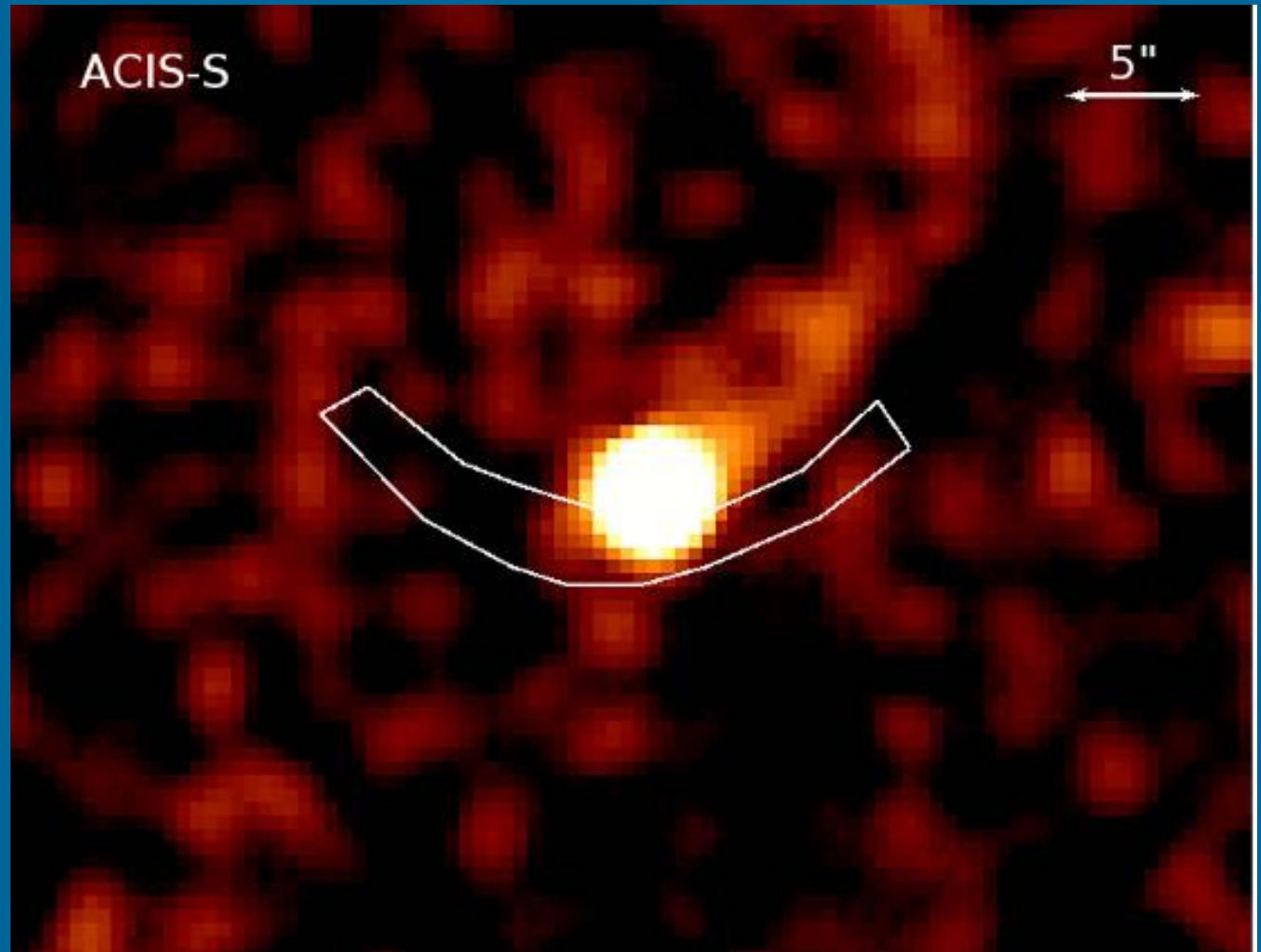


# A puzzling source

Millisecond Pulsar  
J2124-3358

Characteristic  
age 3.4 Gyr

$T \sim (0.5-2) \times 10^5 \text{ K}$



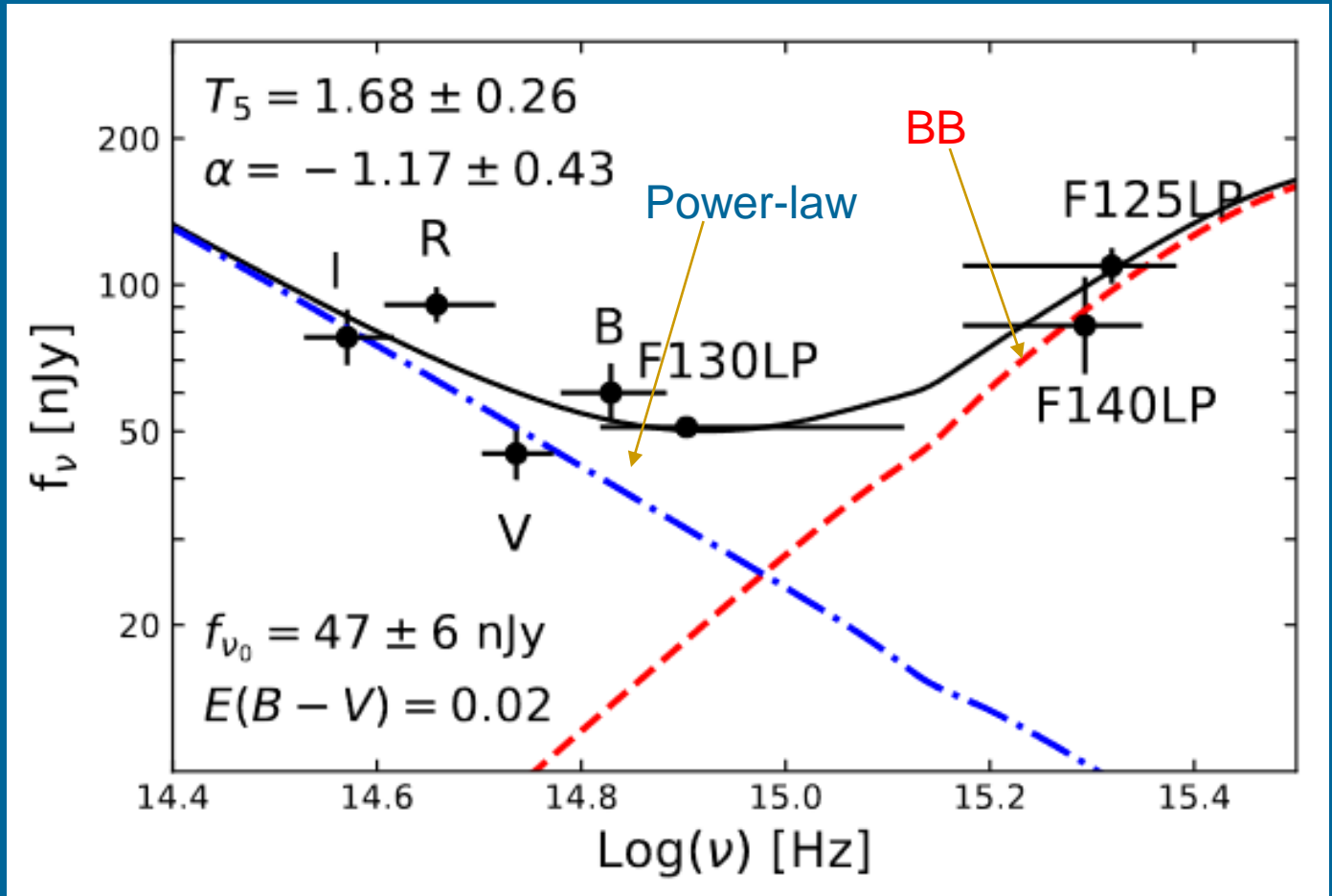
Rangelov et al. (2017)

# Another old, but hot

PSR B0950+08

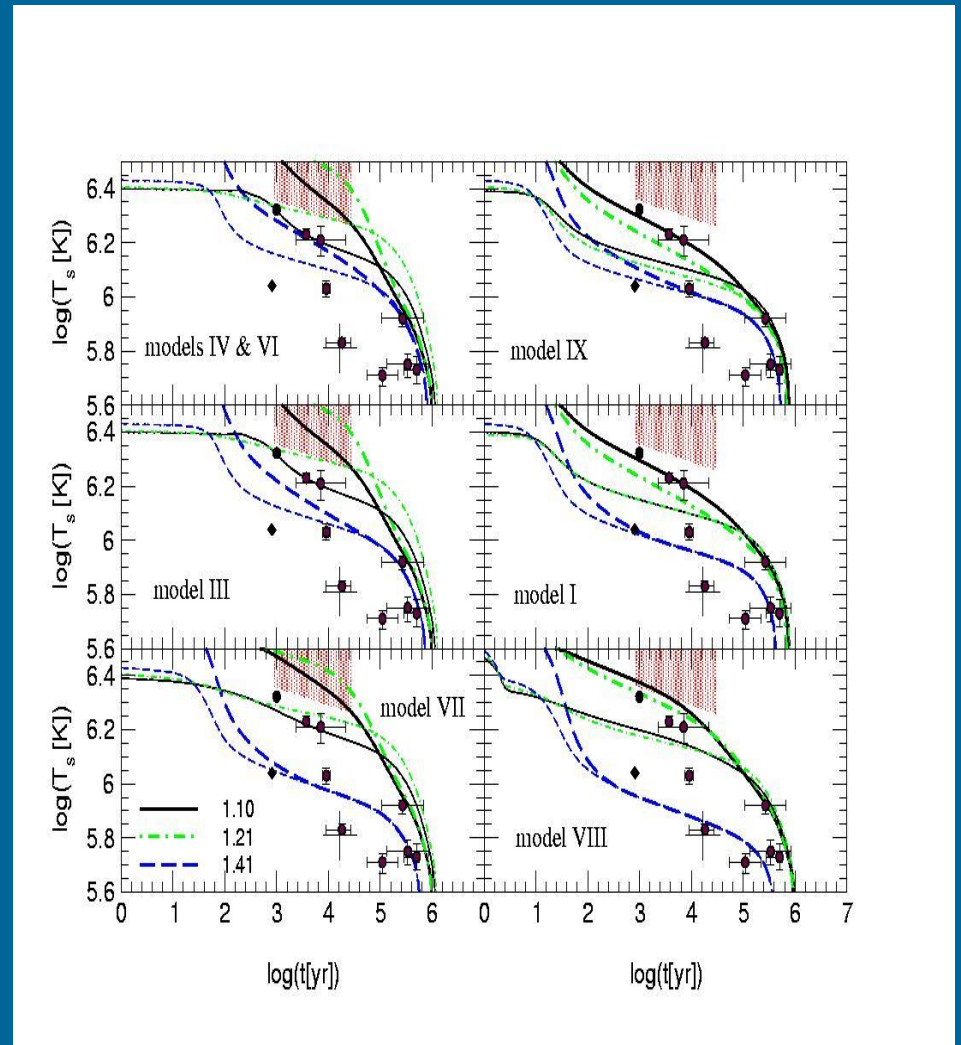
Characteristic  
age 17.5 Myr

$T \sim (1-3) \times 10^5 \text{ K}$



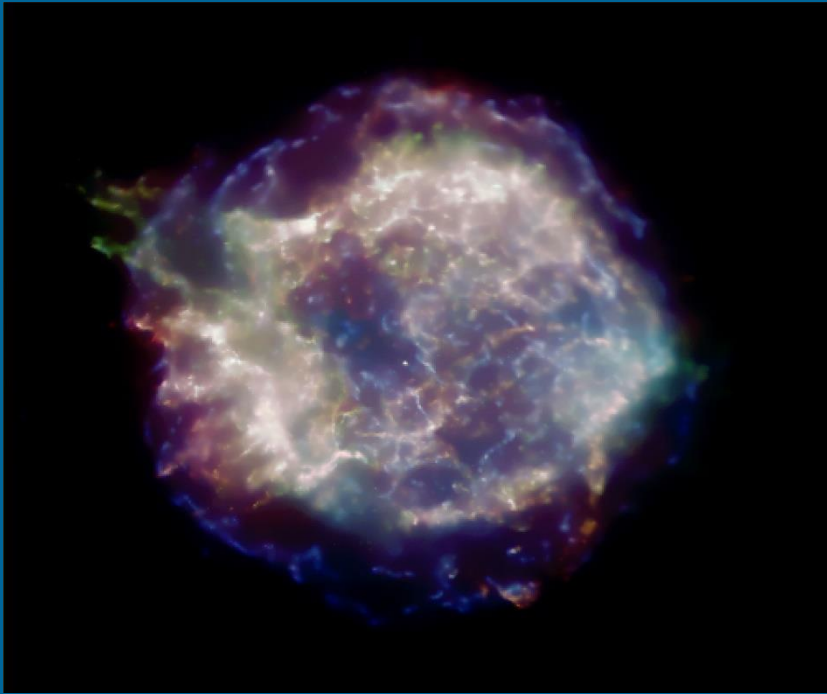
# Brightness constraint

Different tests and constraints are sensitive to different parameters, so, typically it is better to use several different tests



# CCOs

1. Found in SNRs
2. Have no radio or gamma-ray counterparts
3. No pulsar wind nebula (PWN)
4. Have soft thermal-like spectra



# Known objects

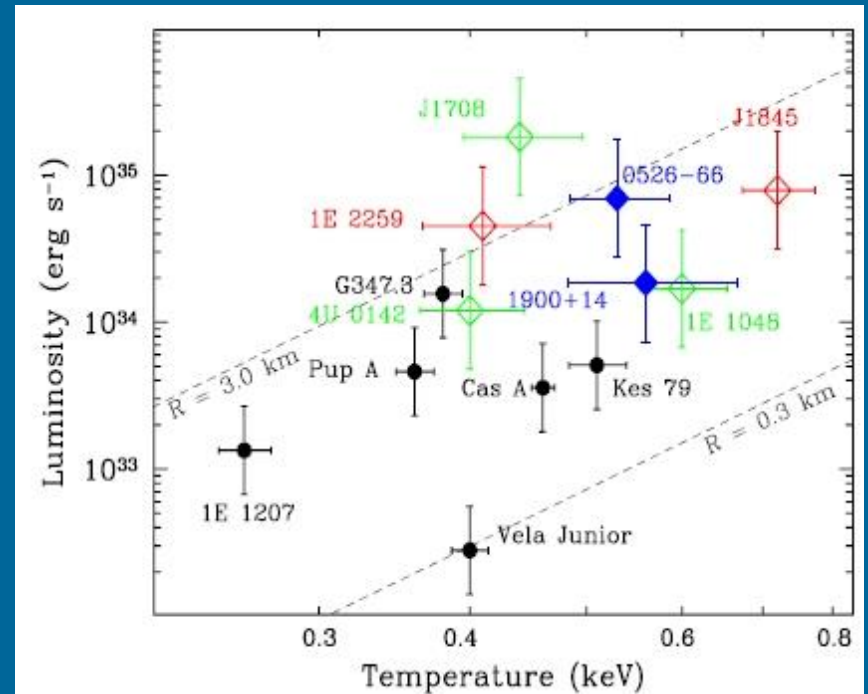
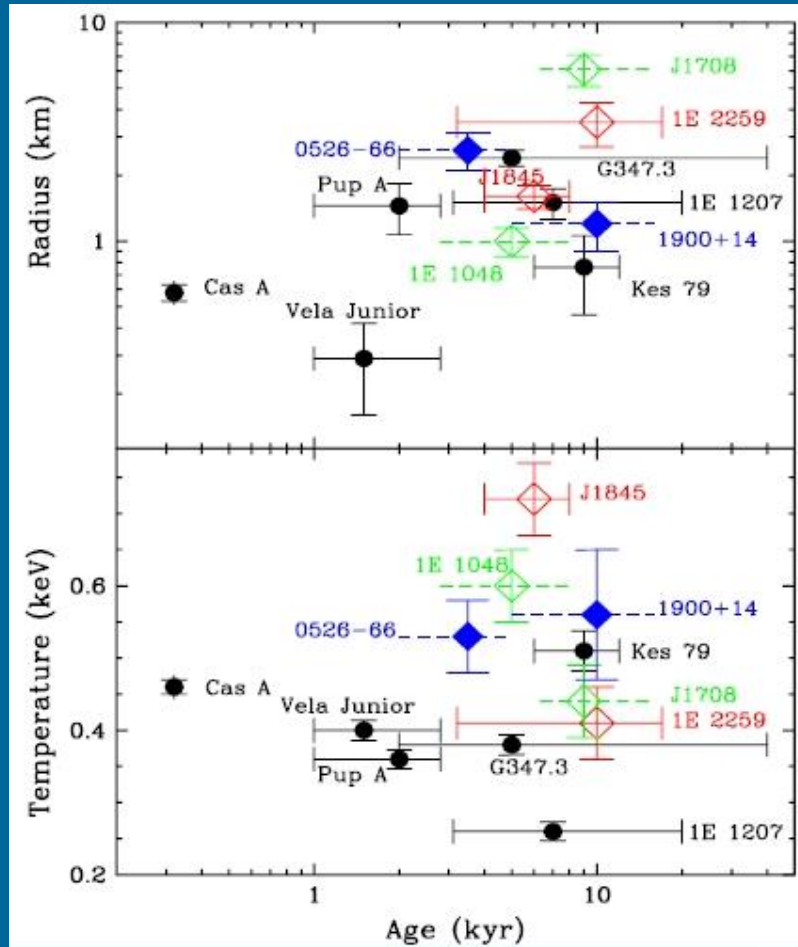
Object	SNR	Age kyr	$d$ kpc	$P$	$F_{x,-12}$
J232327.9+584843	Cas A	0.32	3.3–3.7	...	0.8
J085201.4–461753	G266.1–1.2	1–3	1–2	...	1.4
J161736.3–510225(x)	RCW 103	1–3	3–7	6.4hr	0.9–60
J082157.5–430017	Pup A	1–3	1.6–3.3	...	4.5
J121000.8–522628	G296.5+10.0	3–20	1.3–3.9	424ms	2.3
J185238.6+004020(n)	Kes 79	~9	~10	...	0.2
J171328.4–394955(n)	G347.3–0.5	~10	~6	...	2.8
J000256 +62465 (n,x)	G117.9+0.6[?]	?	~ 3[?]	...	0.1

New candidates  
appear continuously.

Object	$kT$ keV	$R$ km	$L_{\text{bol},33}$	$\Gamma$	$L_{\text{pl},33}$	$n_{\text{H},22}$	$F^{\text{bb}}/F^{\text{pl}}$
J2323+5848	0.43	0.6	1.6	4.2	13	1.8	1.1
	0.43	0.7	1.9	2.5	0.2	[1.2]	4.5
J0852–4617	0.40	0.3	0.3	unconstr	...	0.4	...
J0821–4300	0.40	1.0	3.3	unconstr	...	0.3	...
J1210–5226	0.22	2.0	1.2	3.6	1.2	0.13	3.0
J1852+0040	0.50	1.0	8.0	unconstr	...	1.5	...
J1713–3949	0.38	2.4	15	3.9	72	0.8	0.9

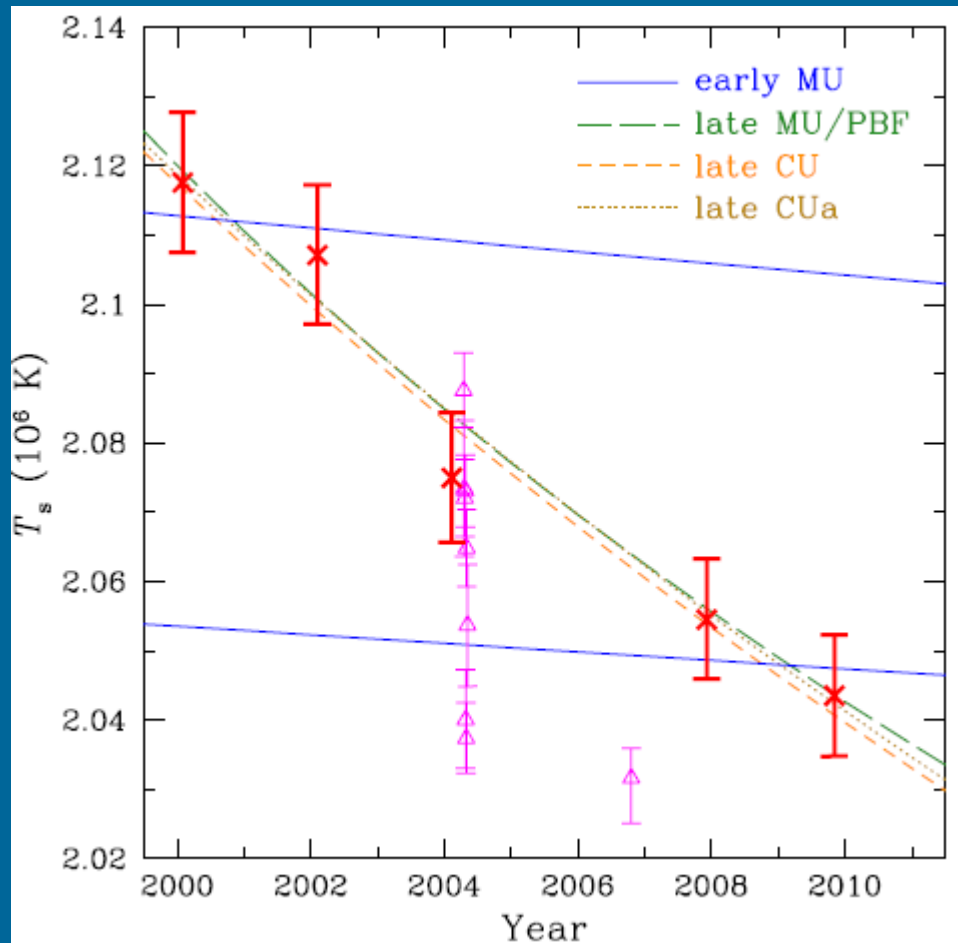
(Pavlov et al. astro-ph/0311526)

# Correlations



(Pavlov et al. astro-ph/0311526)

# Cas A peculiar cooling



330 years

~3.5 kpc

Carbon atmosphere

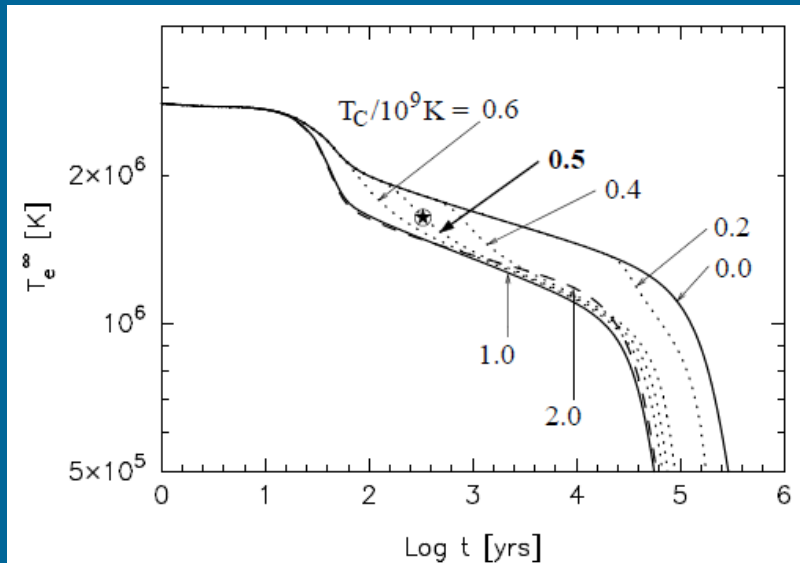
The youngest cooler known

Temperature steadily goes down  
by ~4% in 10 years:

2.12  $10^6$ K in 2000 – 2.04  $10^6$ K in 2009



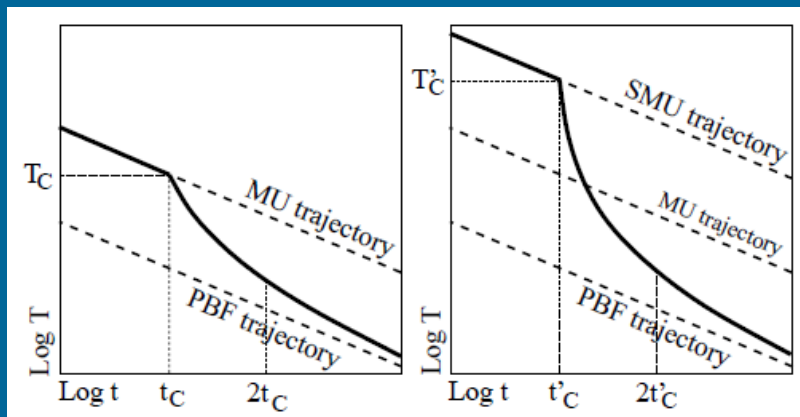
# Onset of neutron $^3\text{P}_2$ superfluidity in the core



The idea is that we see the result of the onset of neutron  $^3\text{P}_2$  superfluidity in the core.

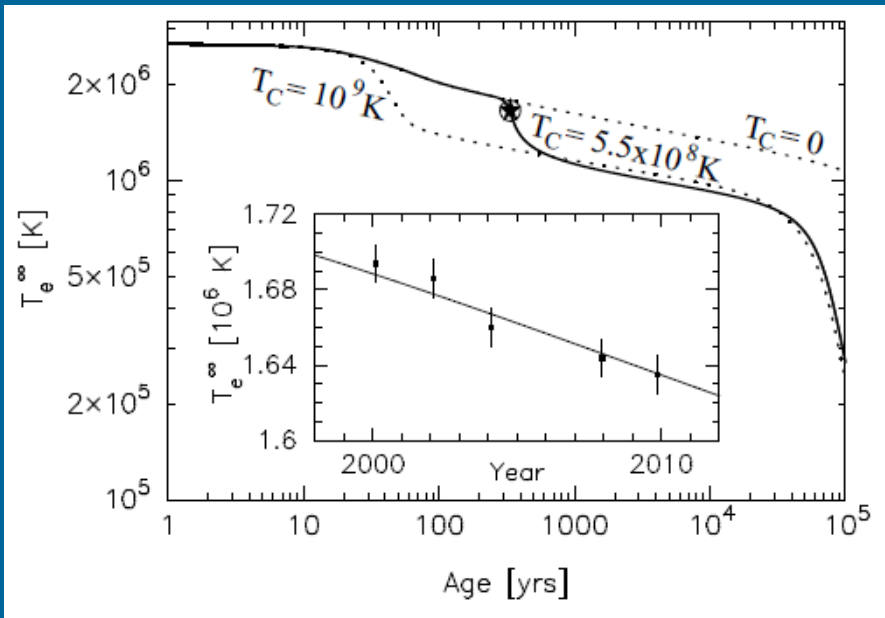
The NS just cooled down enough to have this type of neutron superfluidity in the core.

This gives an opportunity to estimate the critical temperature:  $0.5 \cdot 10^9 \text{ K}$





# The best fit model

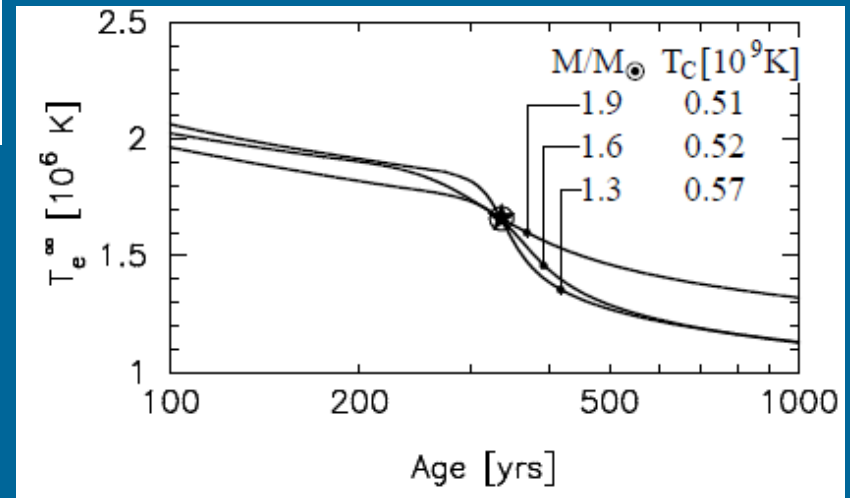


Cooling curves depend on masses, but the estimate of the critical temper. depends on  $M$  just slightly.

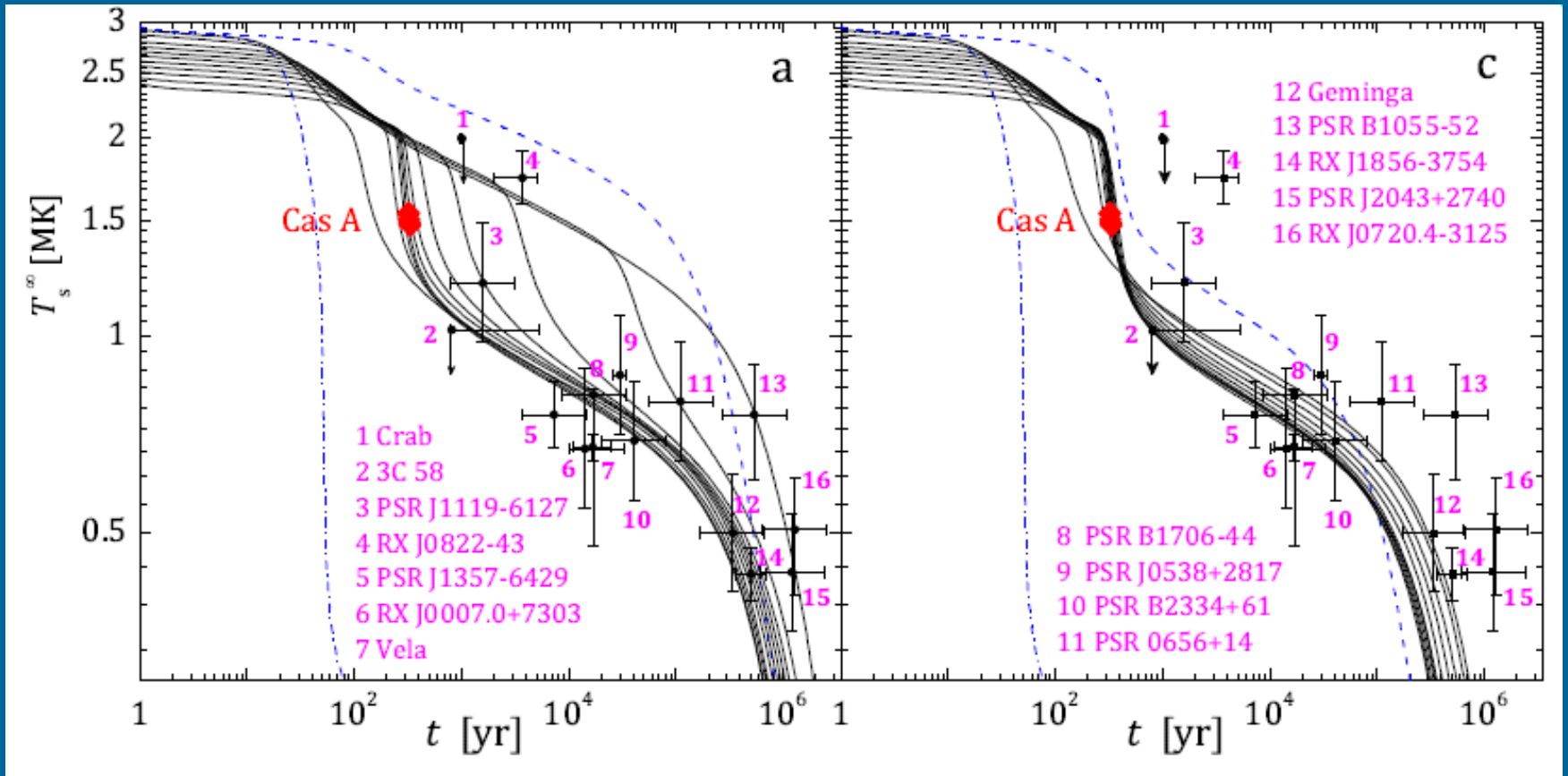
To explain a quick cooling it is necessary to assume suppression of cooling by proton  $^1S_0$  superfluidity in the core.

Rapid cooling will proceed for several tens of years more.

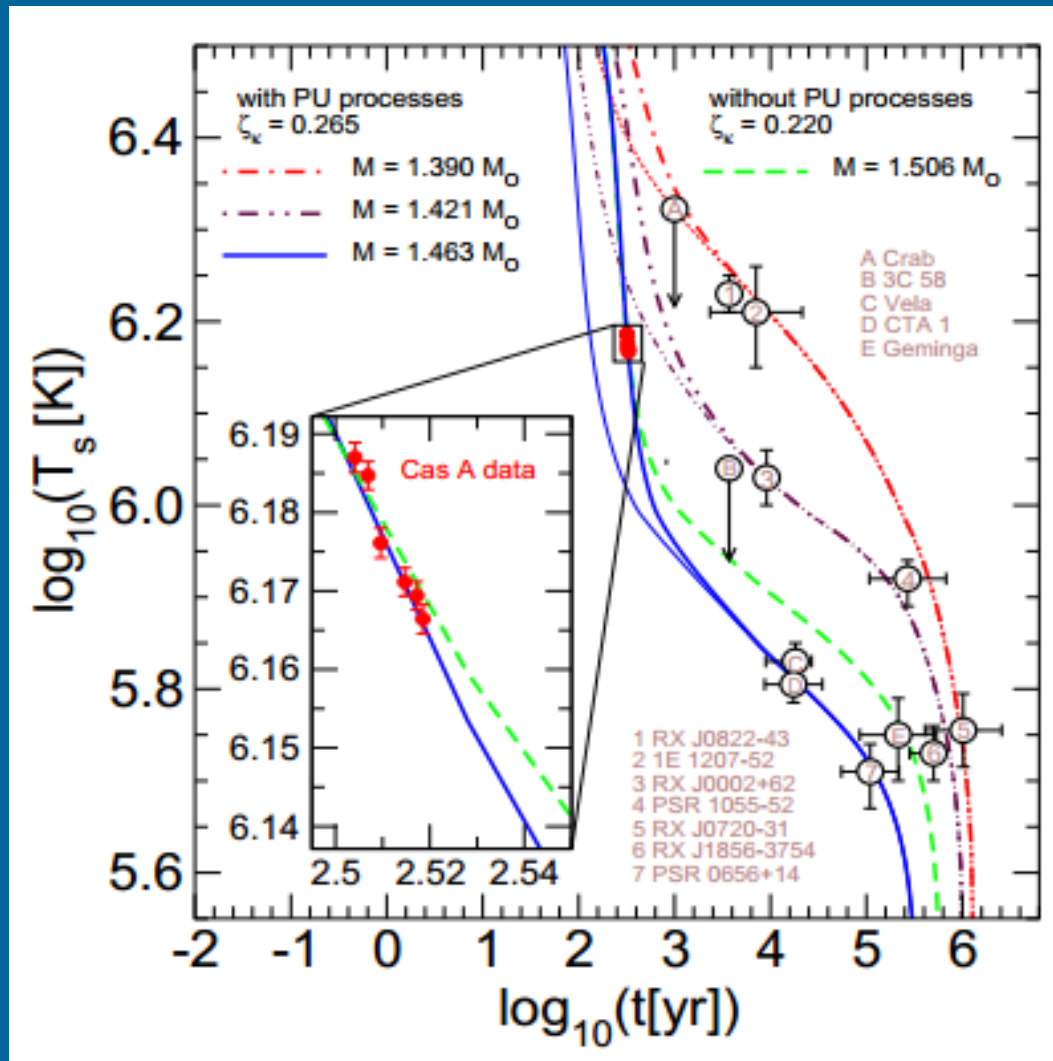
The plot is made for  $M=1.4M_\odot$



# Different superfluidity models

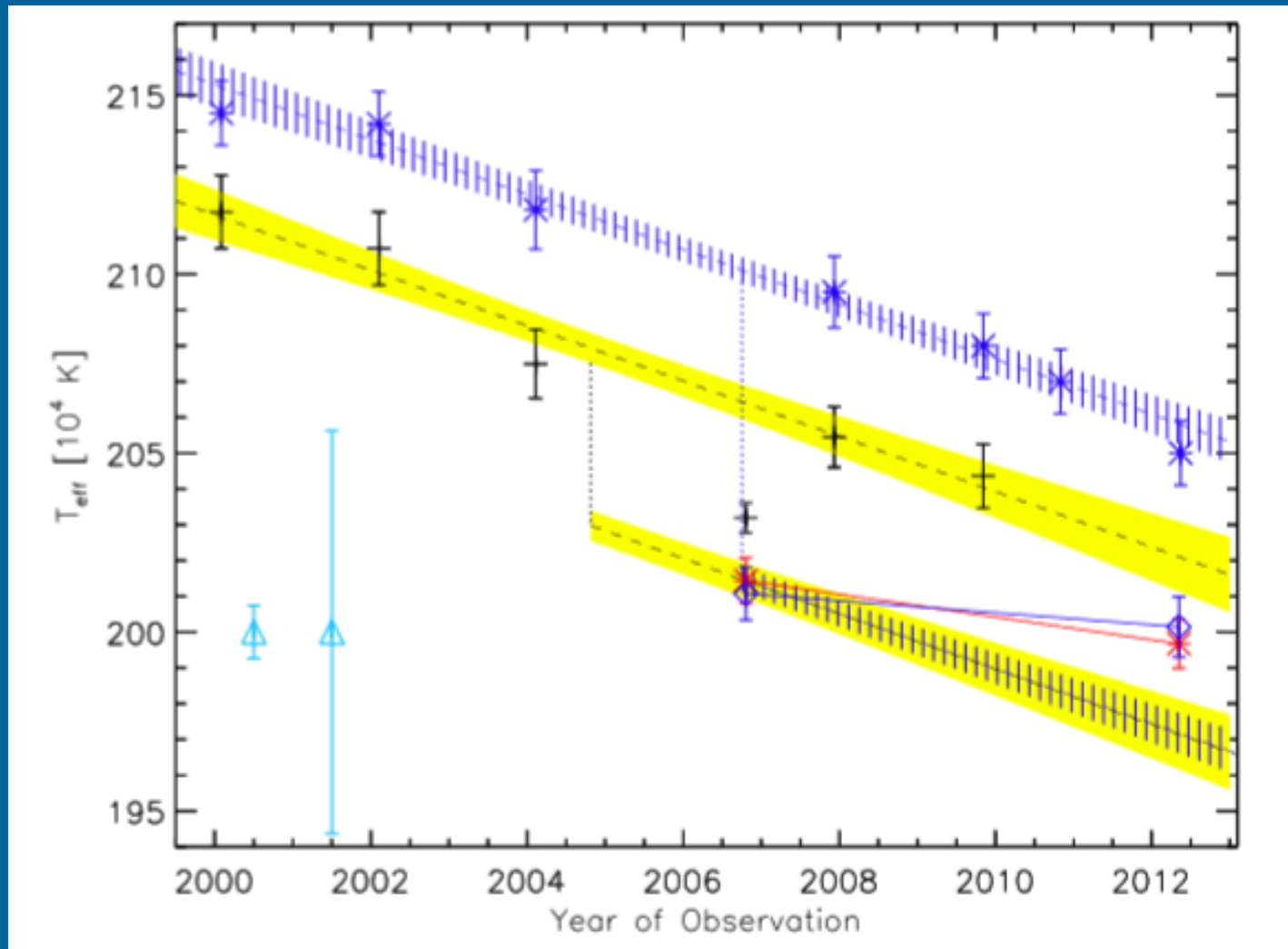


# Nuclear medium cooling

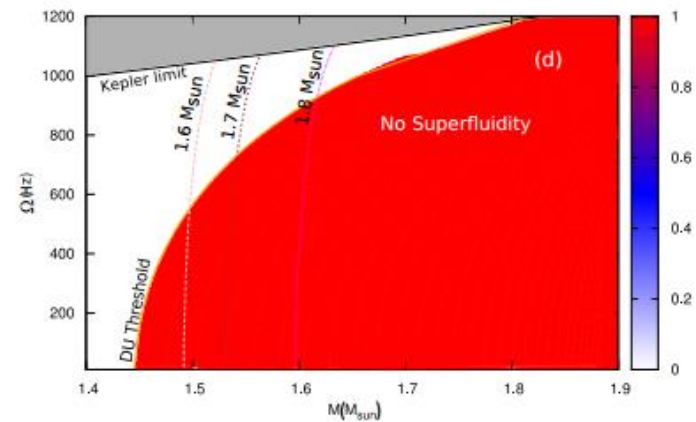
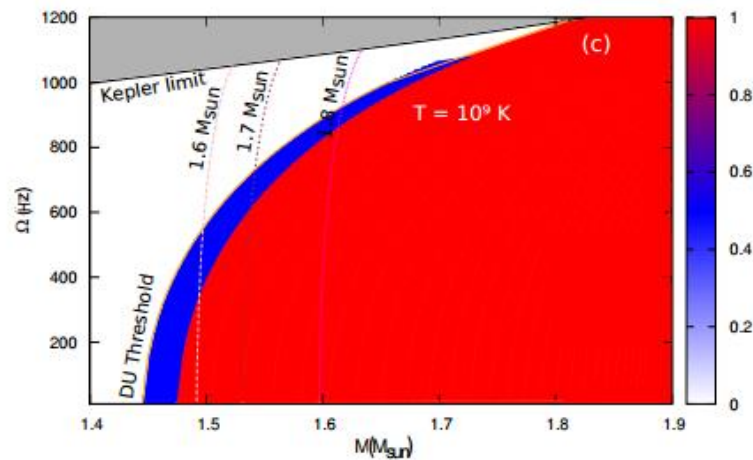
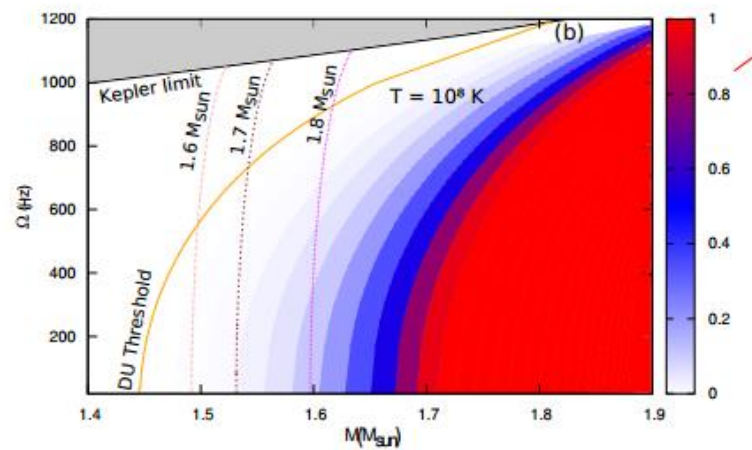
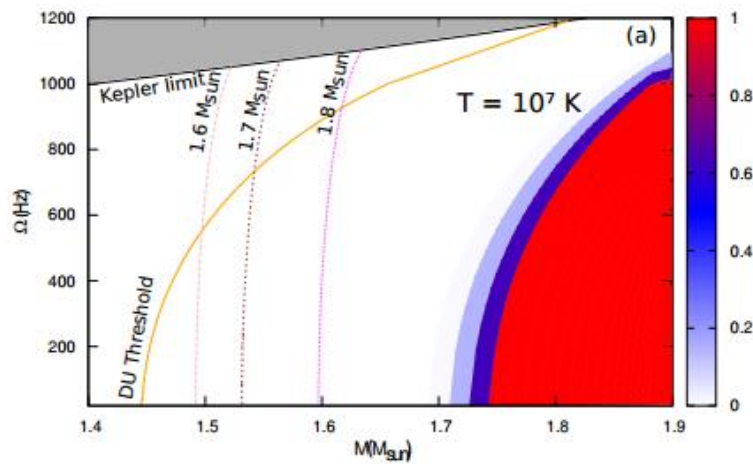


Crucial for the successful description of the observed data is a substantial reduction of the thermal conductivity, resulting from a suppression of both the electron and nucleon contributions to it by medium effects.

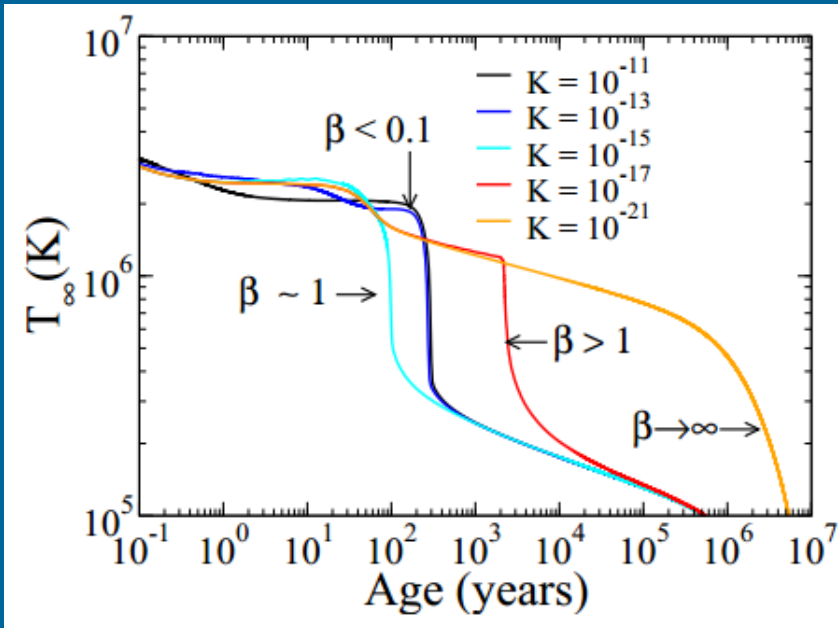
# New twist: no cooling!



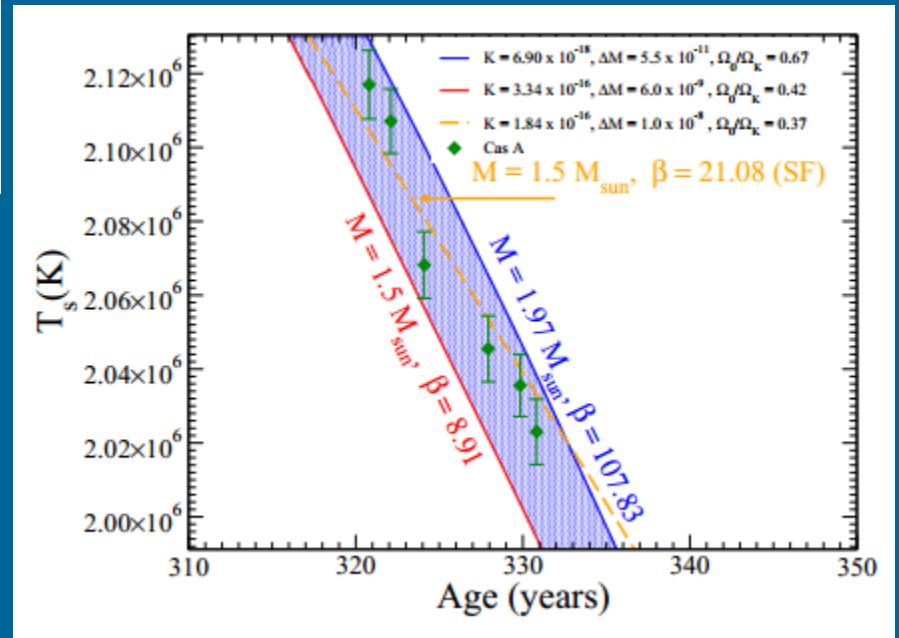
# Cooling and rotation



# Cas A case



$P_0 = 0.0025 - 0.00125$  sec  
 $B \sim 10^{11}$  G

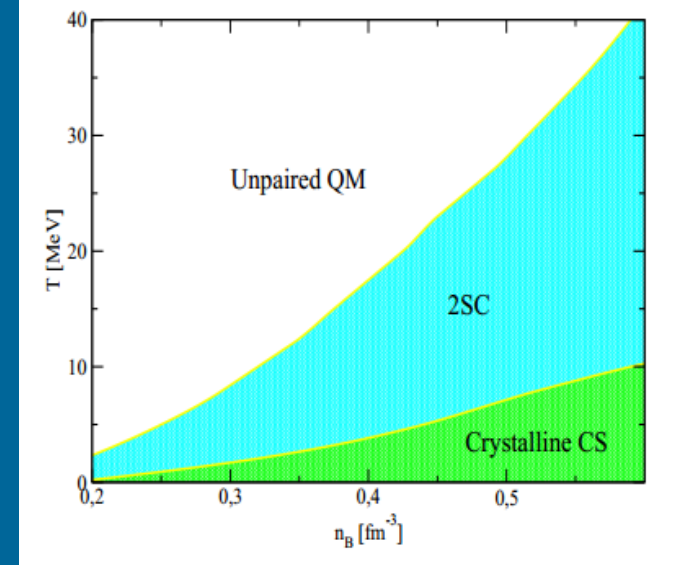
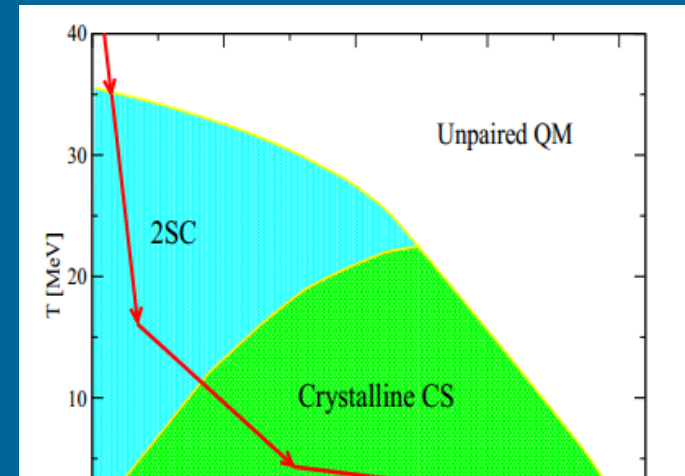
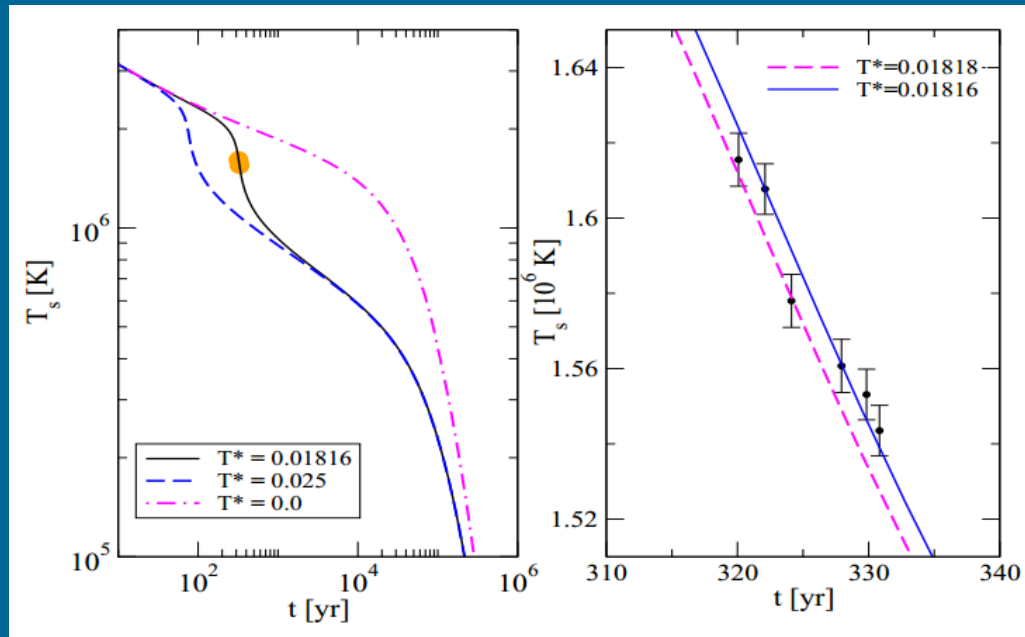


Other studies of the influence of effects of rotation see in 1201.2381

1103.3870

# Exotic phase transition

Rapid cooling of Cas A can be understood as a phase transition from the perfect 2SC phase to a crystalline/gapless color-superconducting state



# Cooling of X-ray transients

“Many neutron stars in close X-ray binaries are transient accretors (transients);

They exhibit X-ray bursts separated by long periods (months or even years) of quiescence.

It is believed that the quiescence corresponds to a lowlevel, or even halted, accretion onto the neutron star.

During high-state accretion episodes, the heat is deposited by nonequilibrium processes in the deep layers ( $10^{12}$  -  $10^{13}$  g cm<sup>-3</sup>) of the crust.

This deep crustal heating can maintain the temperature of the neutron star interior at a sufficiently high level to explain a persistent thermal X-ray radiation in quiescence (Brown *et al.*, 1998).”

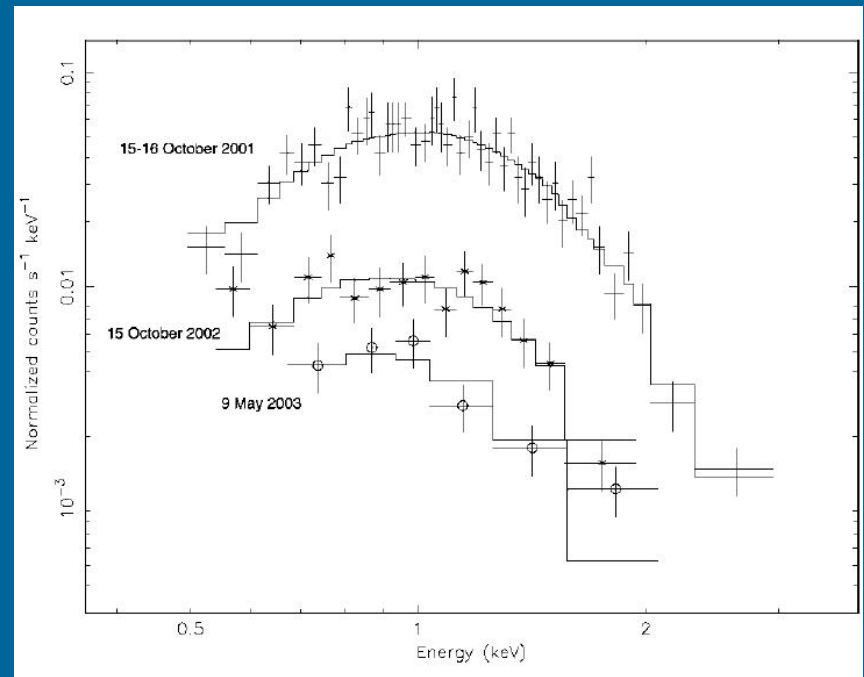
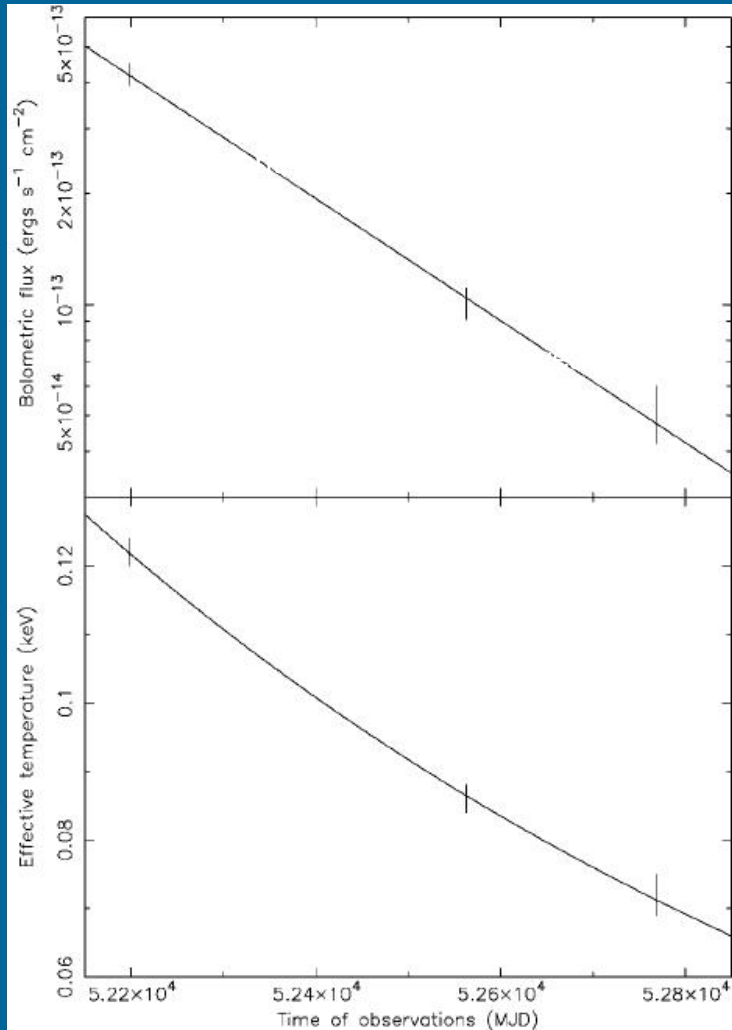
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(quotation from the book by Haensel, Potekhin, Yakovlev)

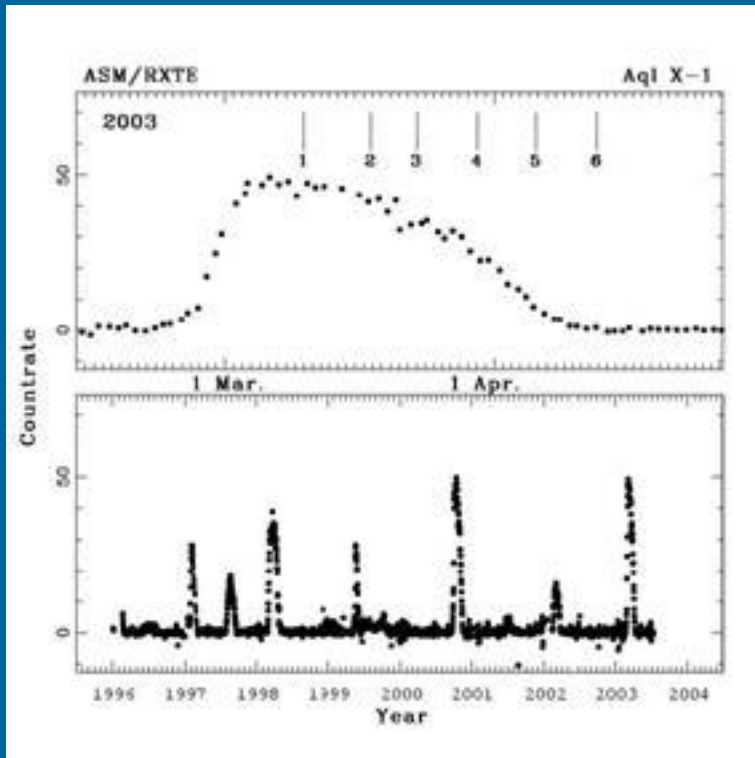


# Cooling in soft X-ray transients

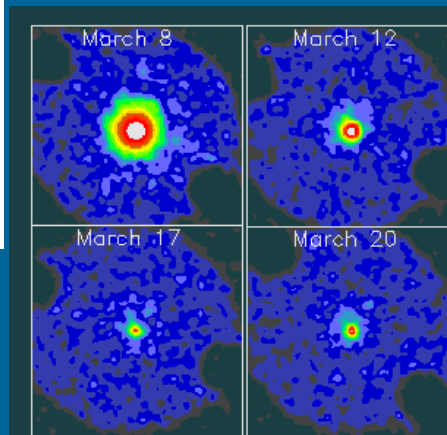
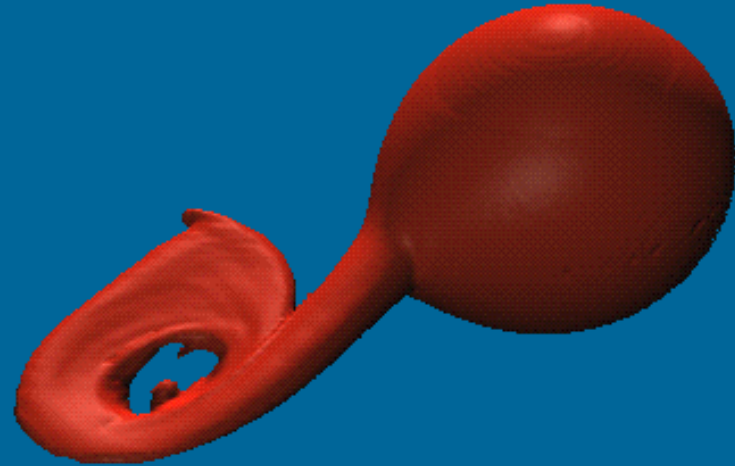
MXB 1659-29  
~2.5 years outburst



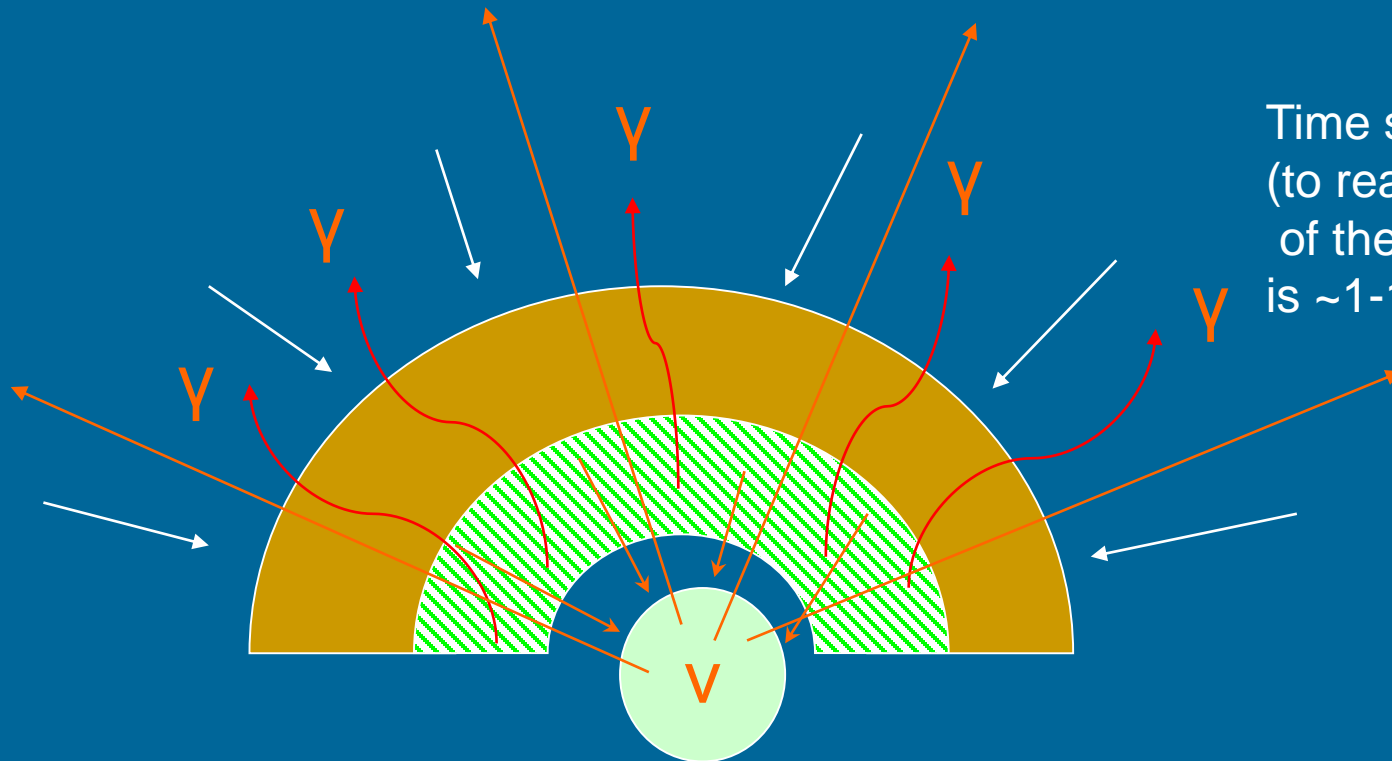
# Aql X-1 transient



A NS with a K star.  
The NS is the hottest  
among SXTs.



# Deep crustal heating and cooling



Time scale of cooling  
(to reach thermal equilibrium  
of the crust and the core)  
is  $\sim 1$ -100 years.

To reach the  
state “before”  
takes  $\sim 10^3$ - $10^4$  yrs

Accretion leads to deep crustal heating due to non-equilibrium nuclear reactions.  
After accretion is off:

- heat is transported inside and emitted by neutrinos
- heat is slowly transported out and emitted by photons

$$\rho \sim 10^{12} - 10^{13} \text{ g/cm}^3$$

See, for example, Haensel, Zdunik arxiv:0708.3996

New calculations appeared very recently 0811.1791 Gupta et al.

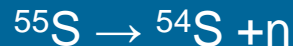
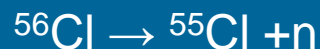
# Pycnonuclear reactions

Let us give an example from Haensel, Zdunik (1990)

We start with  $^{56}\text{Fe}$   
Density starts to increase



At  $^{56}\text{Ar}$ : neutron drip



Then from  $^{52}\text{S}$  we have a chain:



As  $Z$  becomes smaller  
the Coulomb barrier decreases.  
Separation between  
nuclei decreases, vibrations grow.



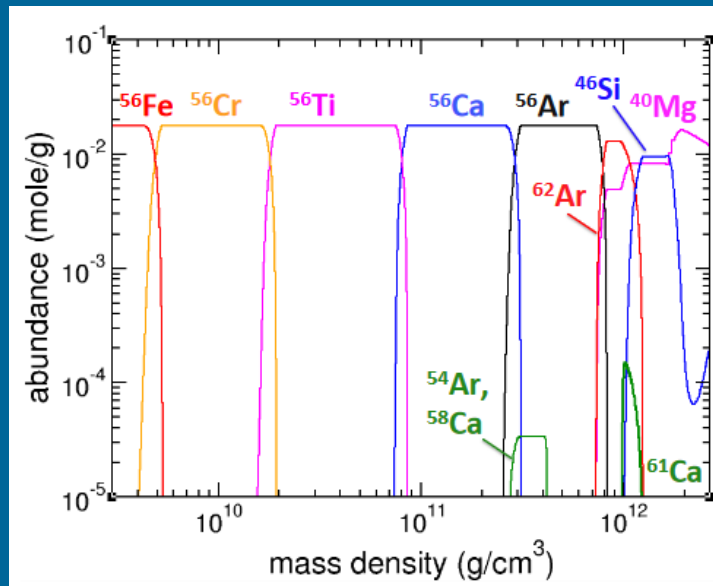
At  $Z=10$  (Ne) pycnonuclear reactions start.



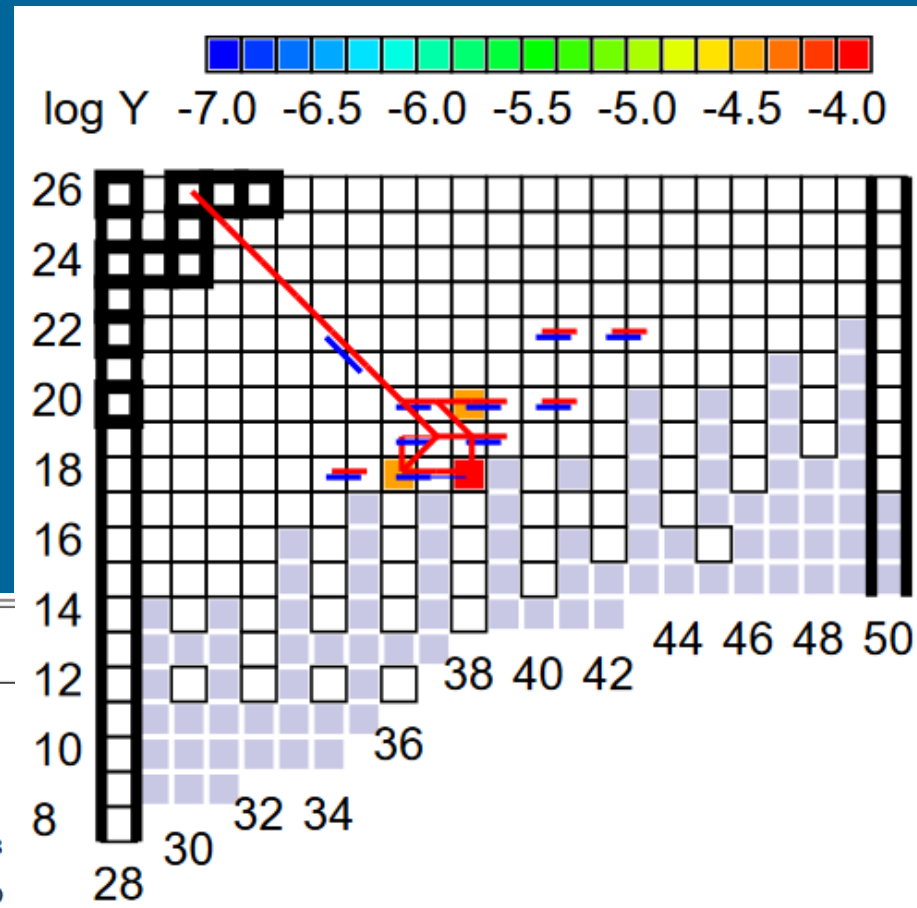
Then a heavy nuclei can react again:



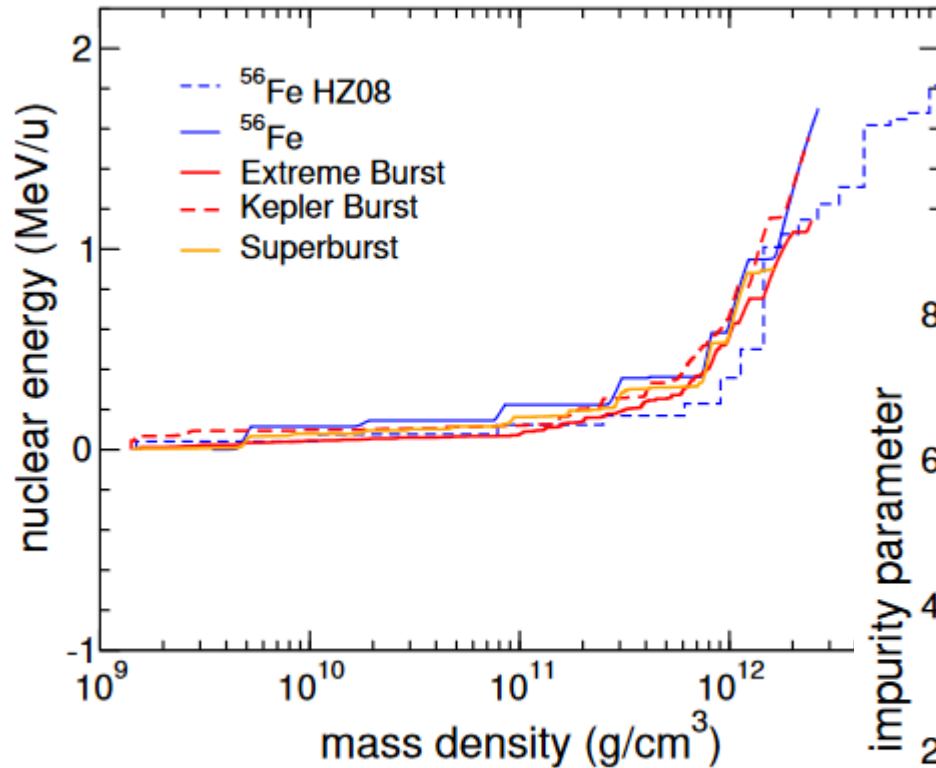
# Crust composition and reactions



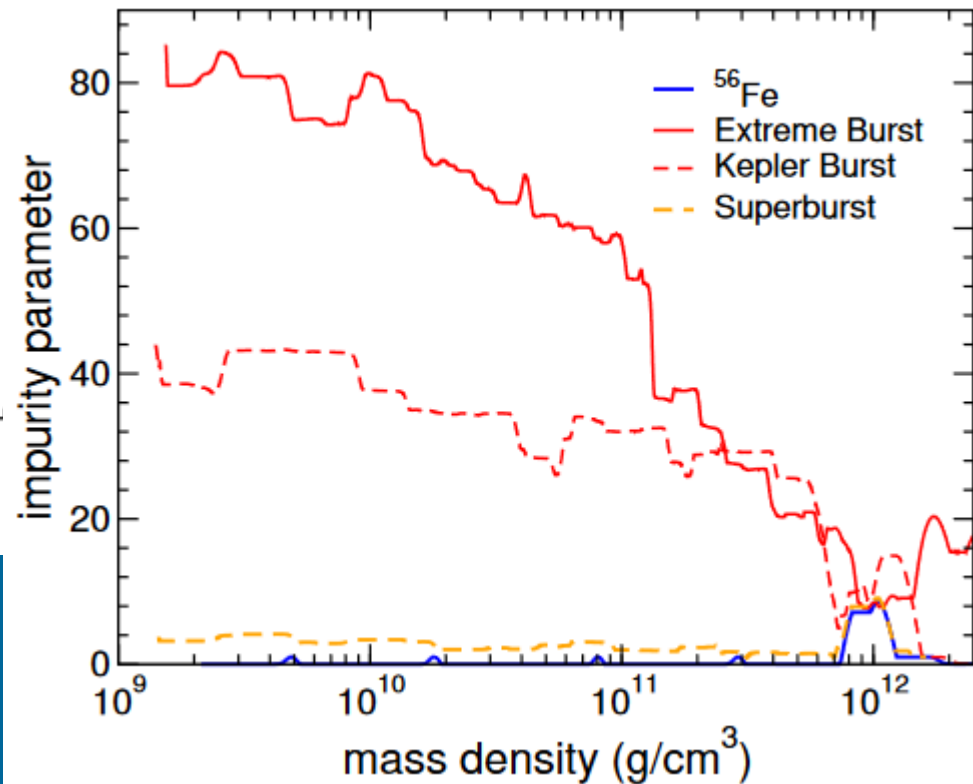
Transition	$P^a$	$\rho^b$	$\mu_e^c$	$X_n^d$
$^{56}\text{Fe} \rightarrow ^{56}\text{Cr}$	$3.4 \times 10^{27}$	$4.9 \times 10^9$	6.2	$<10^{-25}$
$^{56}\text{Cr} \rightarrow ^{56}\text{Ti}$	$1.7 \times 10^{28}$	$1.8 \times 10^{10}$	9.6	$<10^{-25}$
$^{56}\text{Ti} \rightarrow ^{56}\text{Ca}$	$1.1 \times 10^{29}$	$8.1 \times 10^{10}$	15.6	$<10^{-25}$
$^{56}\text{Ca} \rightarrow ^{56}\text{Ar}, ^{54}\text{Ar}, ^{58}\text{Ca}$	$5.5 \times 10^{29}$	$2.9 \times 10^{11}$	23.3	$1.2 \times 10^{-18}$
$^{56}\text{Ar}, ^{54}\text{Ar}, ^{58}\text{Ca} \rightarrow ^{56}\text{Ar}$	$8.3 \times 10^{29}$	$4.2 \times 10^{11}$	25.9	$7.2 \times 10^{-20}$
$^{56}\text{Ar} \rightarrow ^{40}\text{Mg}, ^{62}\text{Ar}$	$1.8 \times 10^{30}$	$7.8 \times 10^{11}$	31.6	$5.4 \times 10^{-8}$
$^{40}\text{Mg}, ^{62}\text{Ar} \rightarrow ^{40}\text{Mg}, ^{48}\text{Si}$	$2.3 \times 10^{30}$	$1.1 \times 10^{12}$	33.5	0.13
$^{40}\text{Mg}, ^{48}\text{Si} \rightarrow ^{40}\text{Mg}$	$4.2 \times 10^{30}$	$2.8 \times 10^{12}$	37.1	0.54



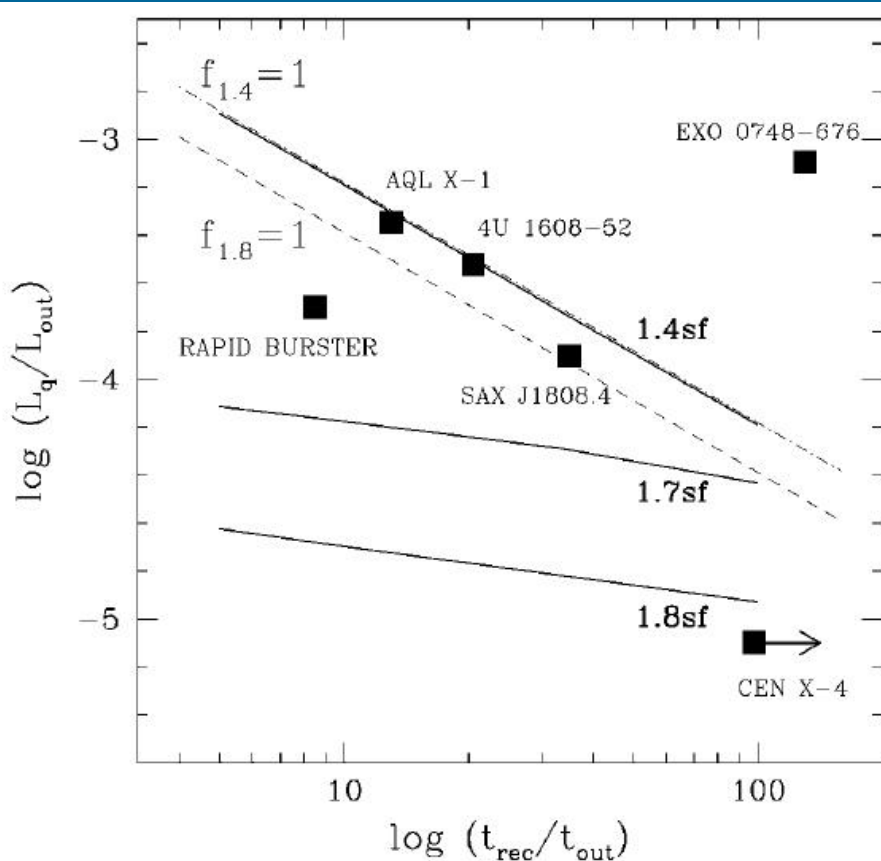
# Energy release vs. density and impurity



$$Q_{\text{imp}} = \sum_i Y_i (Z_i - \langle Z \rangle)^2 / \sum_i Y_i$$



# A simple model



$t_{rec}$  – time interval between outbursts

$t_{out}$  – duration of an outburst

$L_q$  – quiescent luminosity

$L_{out}$  – luminosity during an outburst

Dashed lines corresponds to the case when all energy is emitted from a surface by photons.

$$L_q \sim \frac{Q_{nuc}}{m_u} \langle \dot{M} \rangle \sim 6 \times 10^{32} \frac{\langle \dot{M} \rangle}{10^{-11} M_{\odot} \text{ yr}^{-1}} \text{ ergs s}^{-1}$$

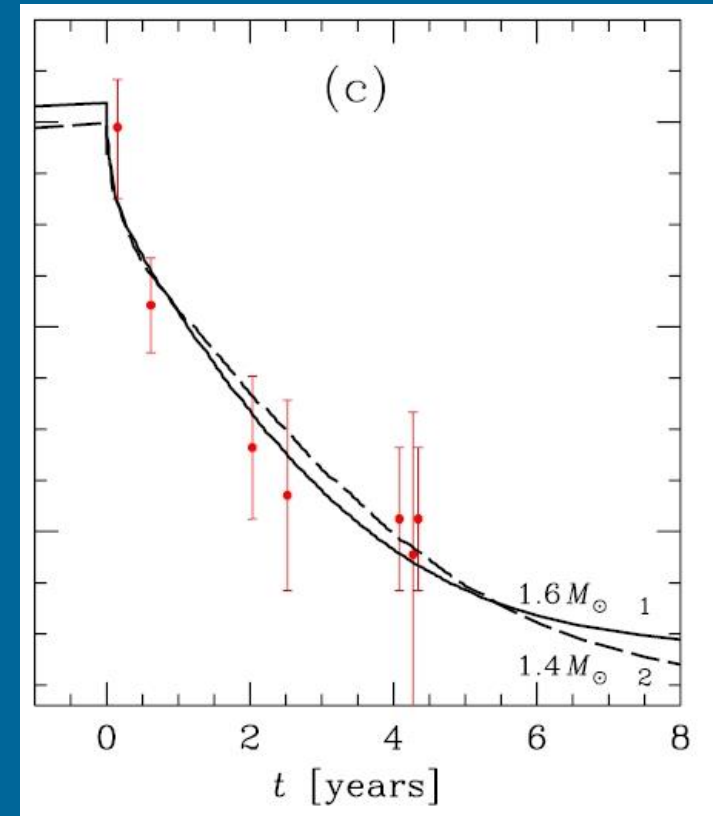
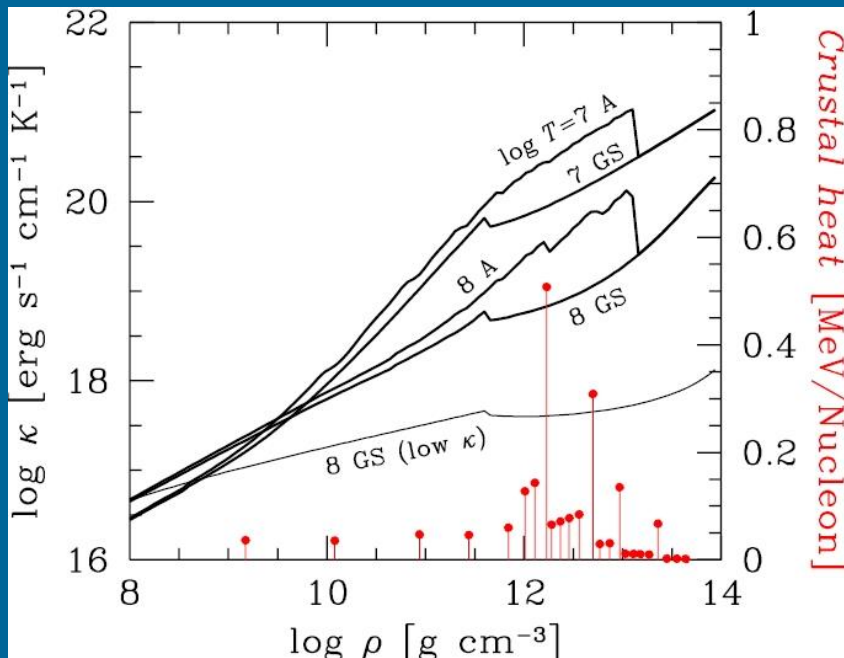


# Deep crustal heating

~1.9 Mev per accreted nucleon  
Crust is not in thermal equilibrium with the core.  
After accretion is off the crust cools down and  
finally reach equilibrium with the core.

KS 1731-260

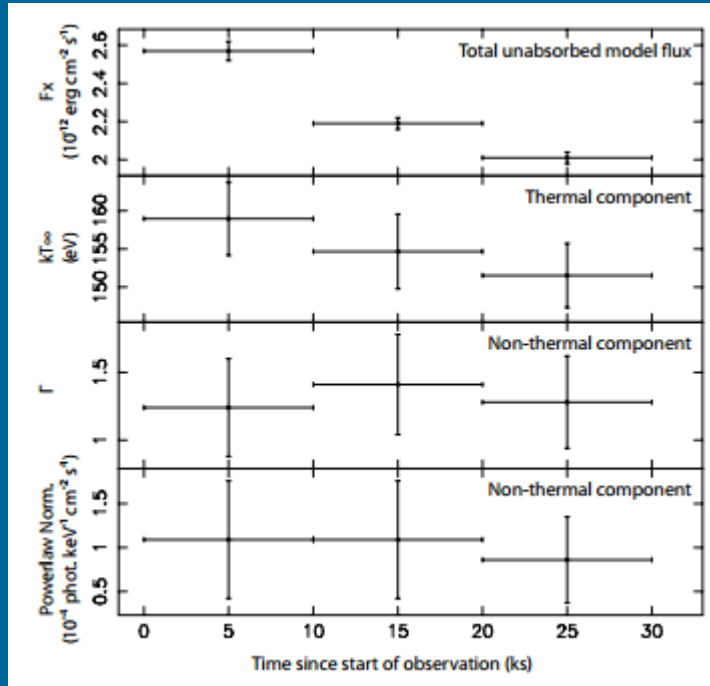
(see a recent model in 1202.3378)



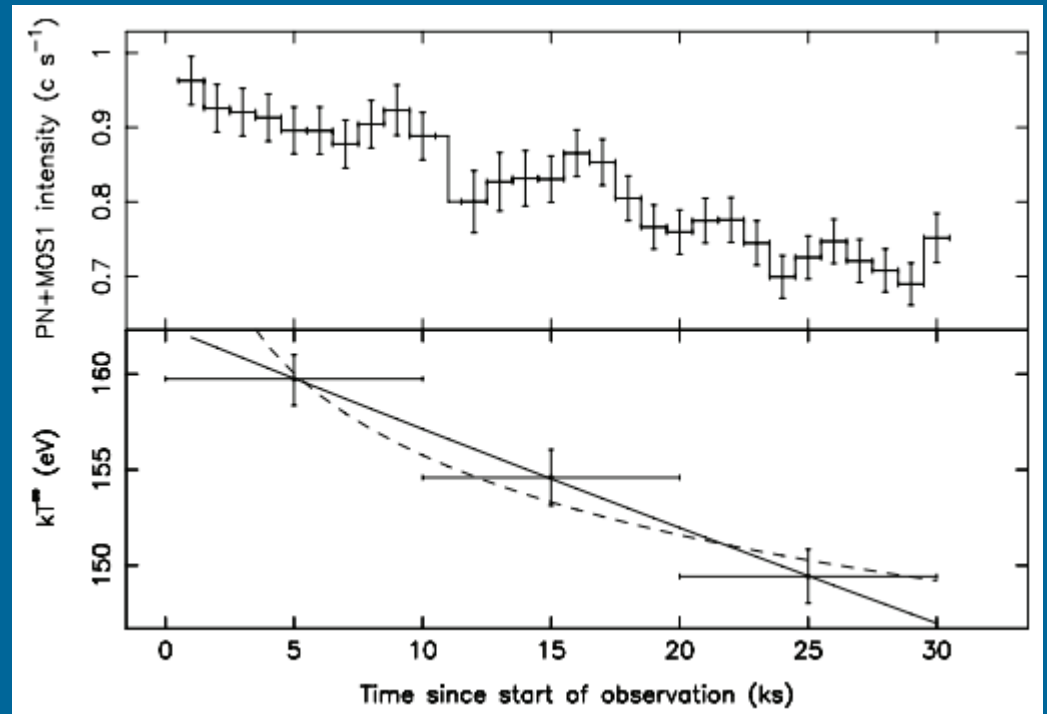
[Shternin et al. 2007]

See new results and discussion in 1702.08452

# Visible cooling of a NS in a binary

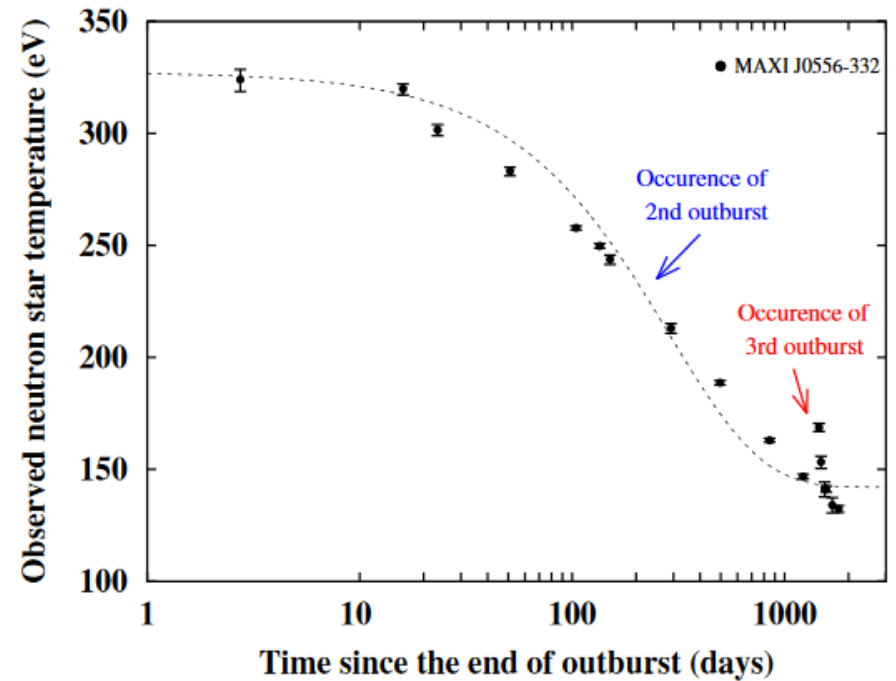
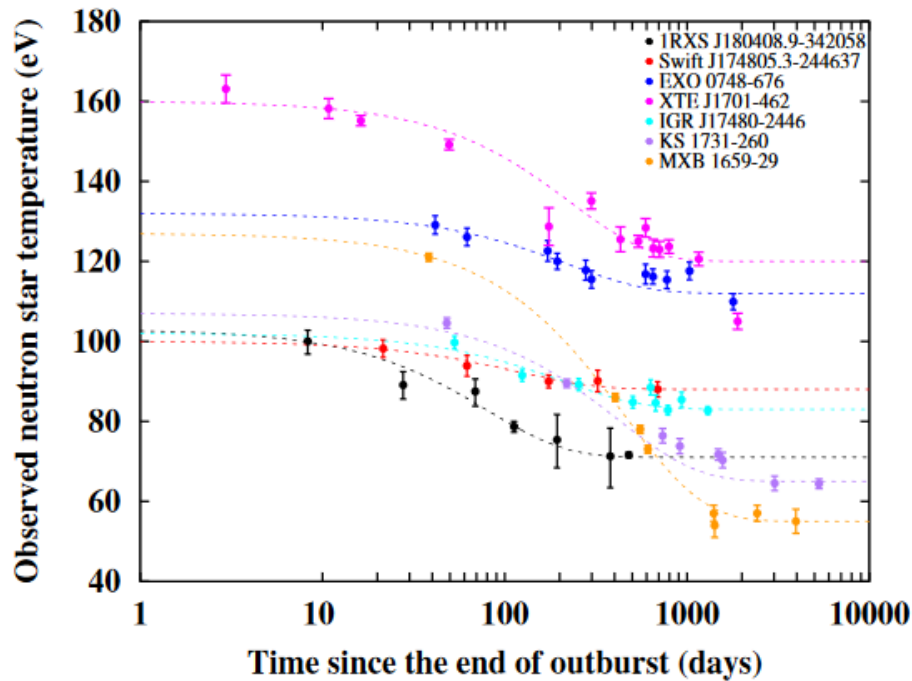


The authors interpret this as cooling of a layer located at a column density of  $y \simeq 5 \times 10^{12} \text{ g cm}^{-2}$  ( $\simeq 50 \text{ m}$  inside the neutron star), which is just below the ignition depth of superbursts.



XTE J1709-267

# Fitting cooling of known sources



Different systems allow to probe different regimes of cooling and different layers of the crust.

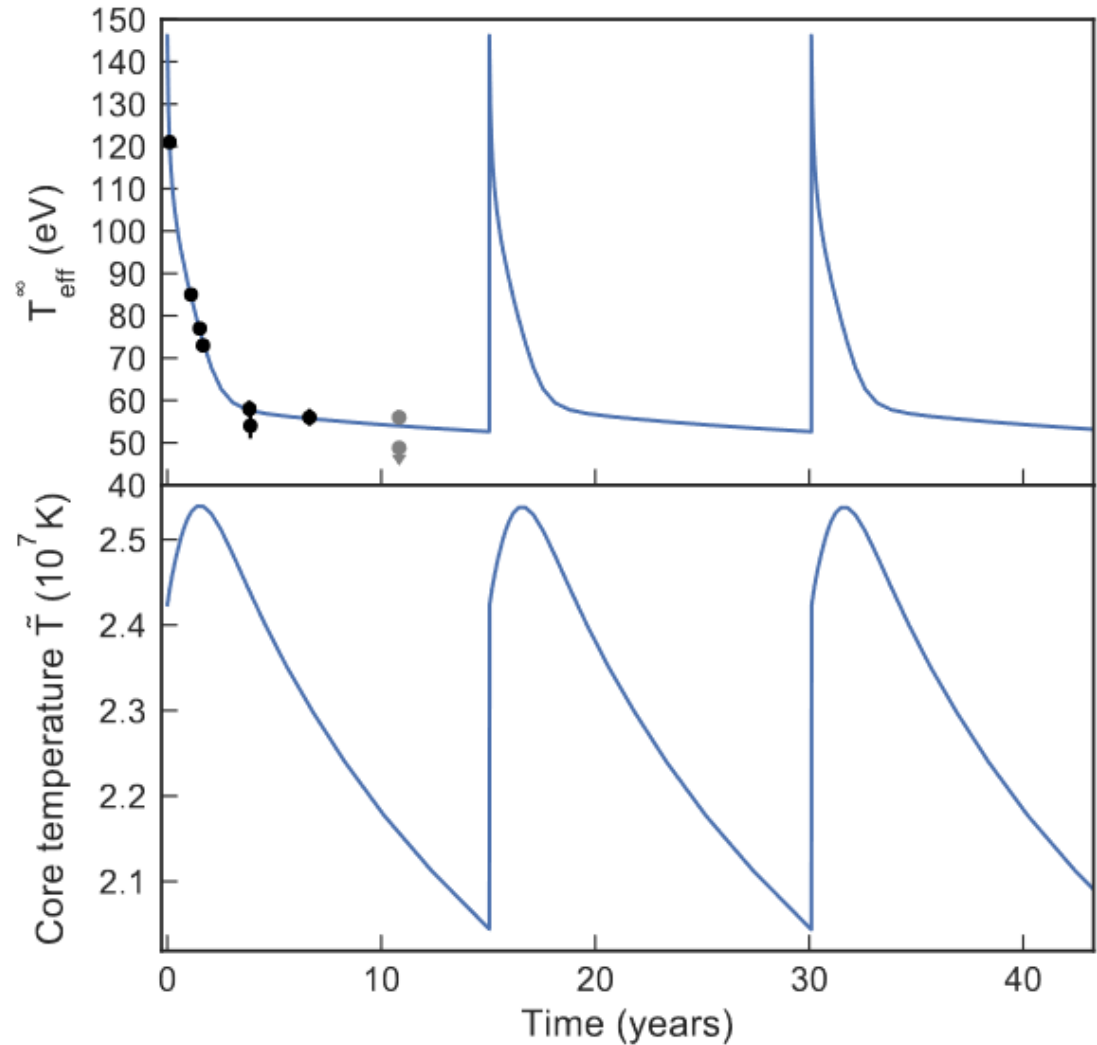
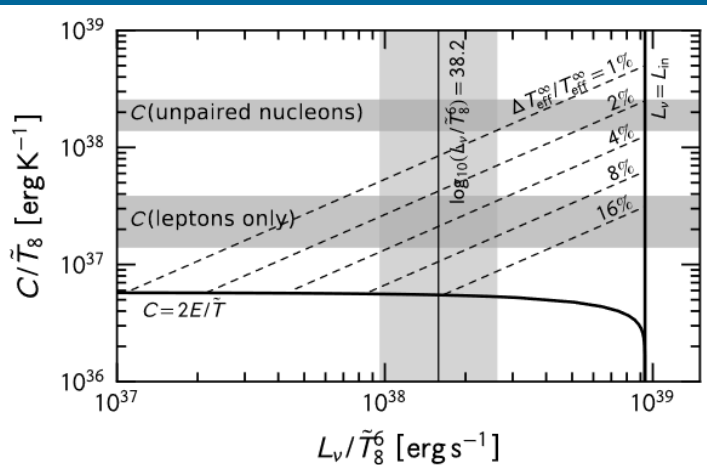
# Direct Urca in a cooling NS

MXB 1659-29

$$2.1 \times 10^{38} \text{ erg s}^{-1} \tilde{T}_8^6$$

$$C = 10^{37} \text{ erg K}^{-1} \tilde{T}_8$$

About 1% of the core volume available for direct URCA.



1801.00041

# Cooling and crustal properties

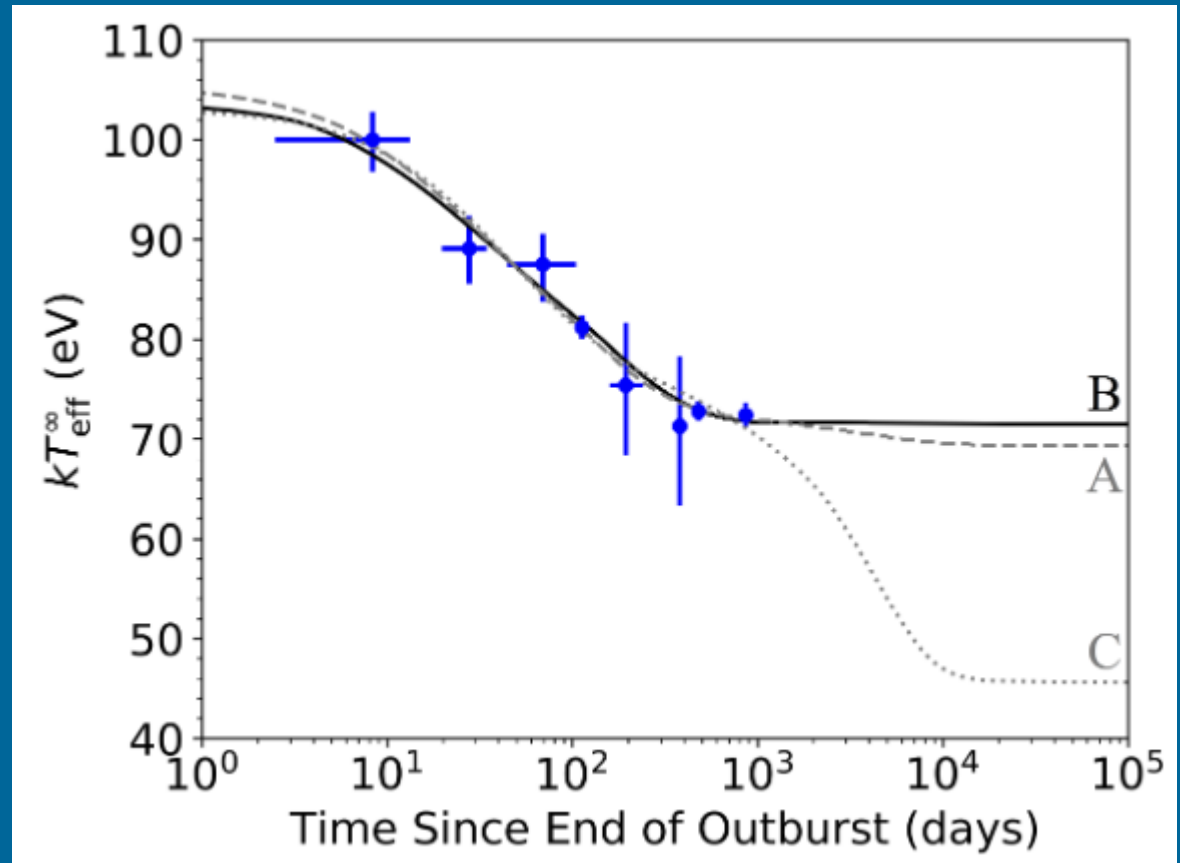
RXS J180408.9–342058  
LMXB

Rapid cooling  
down to thermal  
equilibrium between  
the core and the crust.

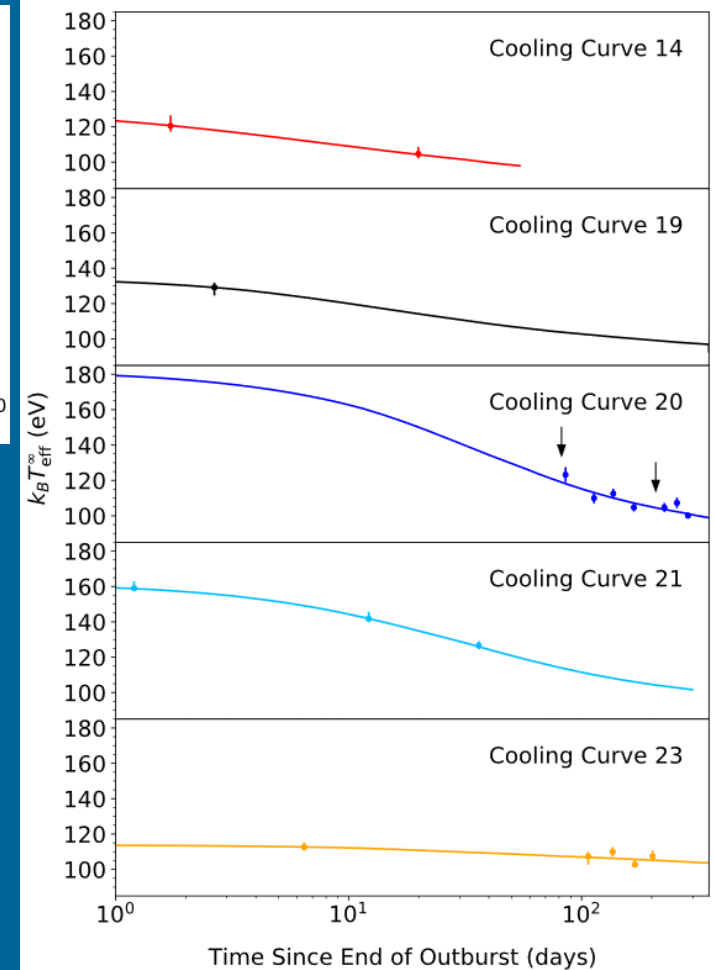
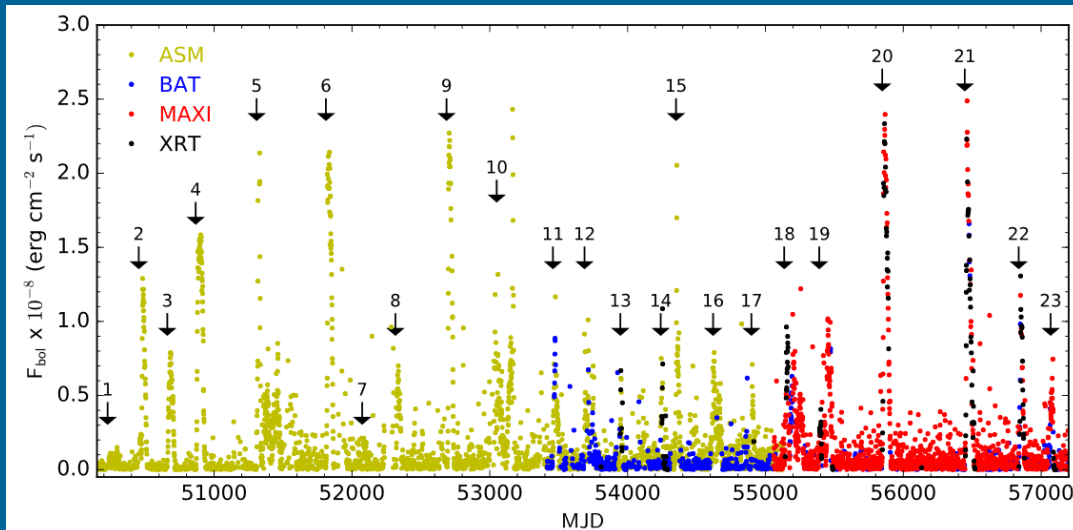
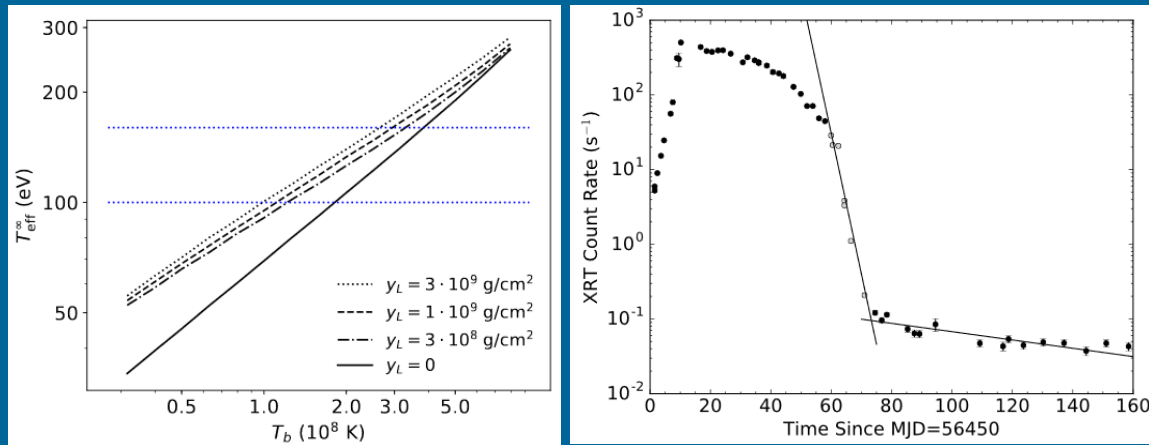
Deep crustal heating +  
shallow heat source.

The origin of the shallow  
heating is unknown.

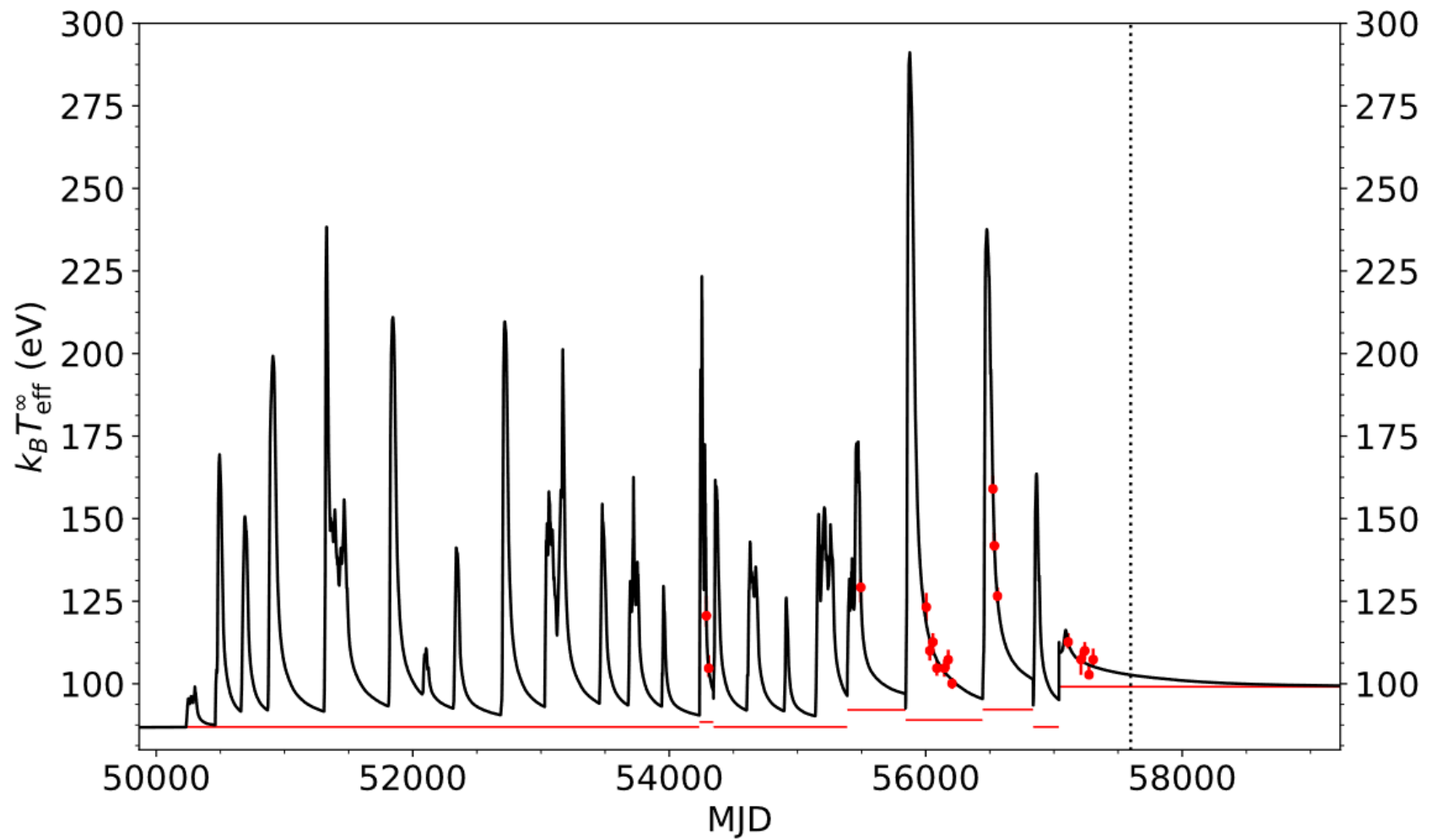
No DURCA.



# Aql X-1 modeling



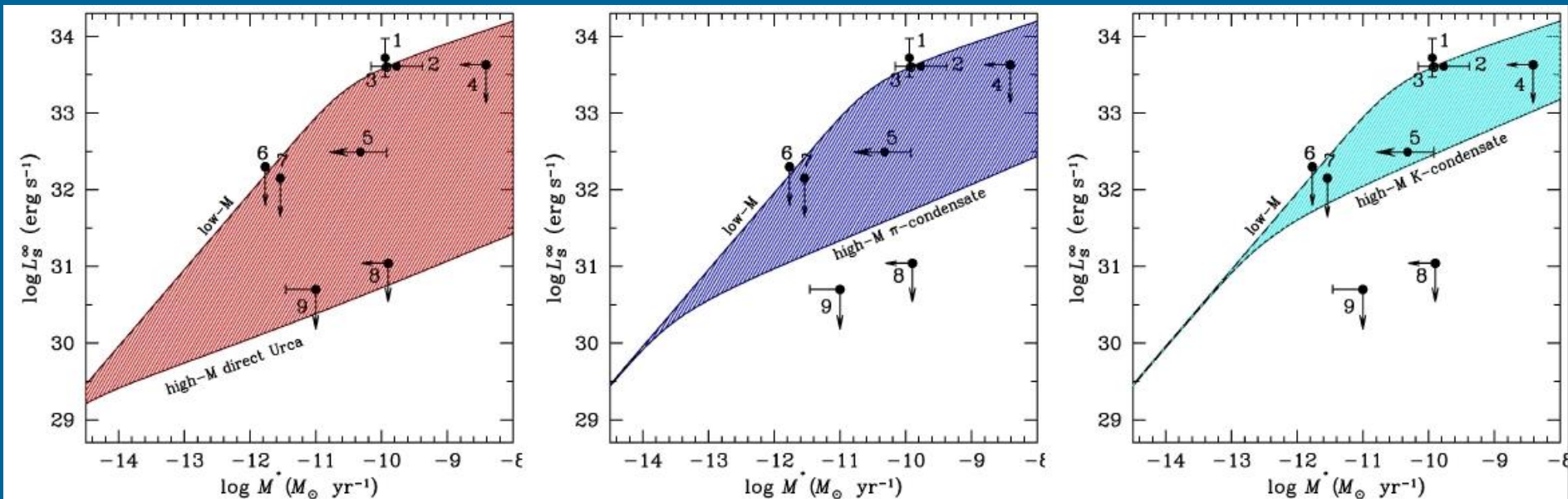
1802.06081



1802.06081



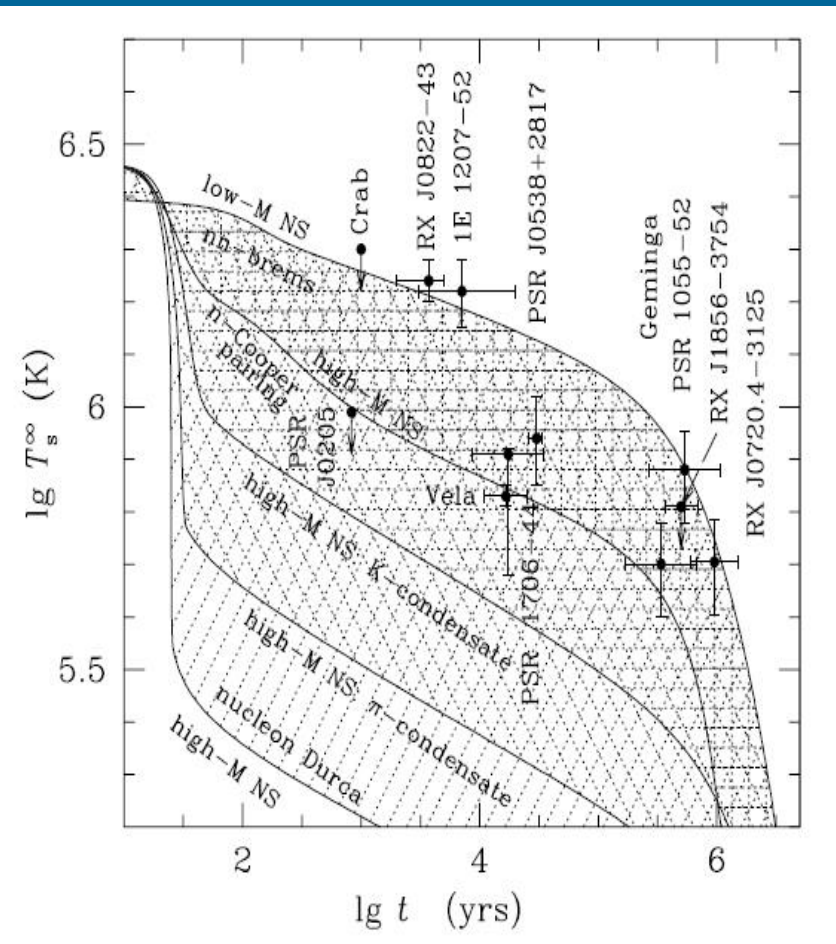
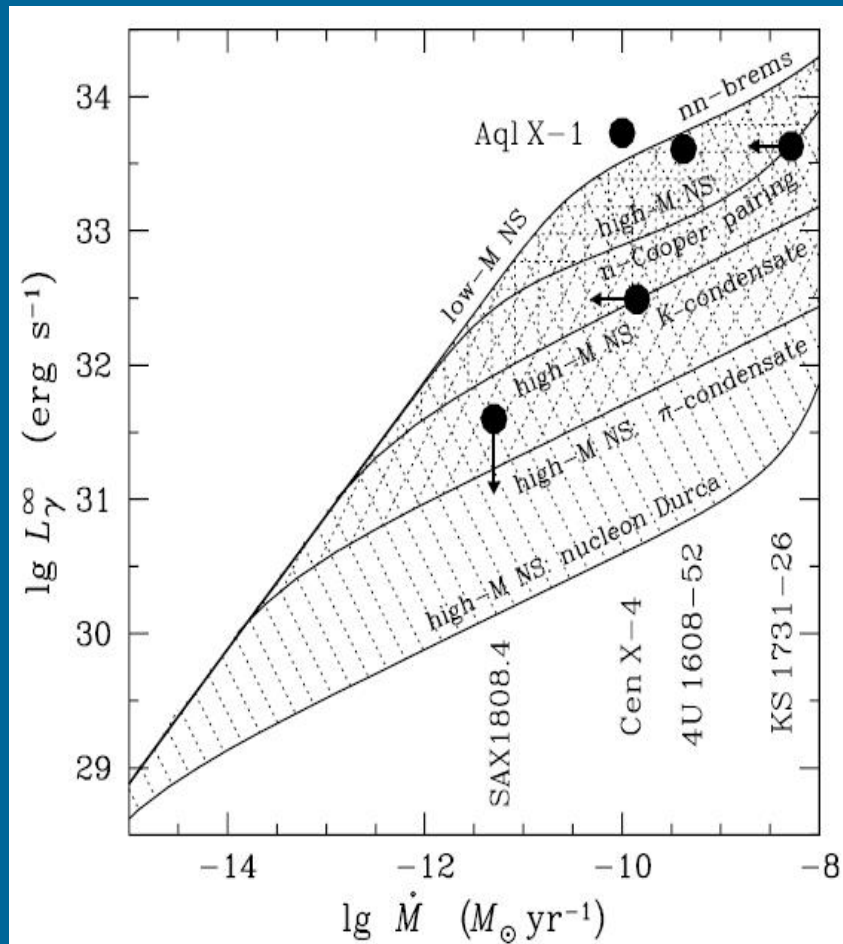
# Testing models with SXT



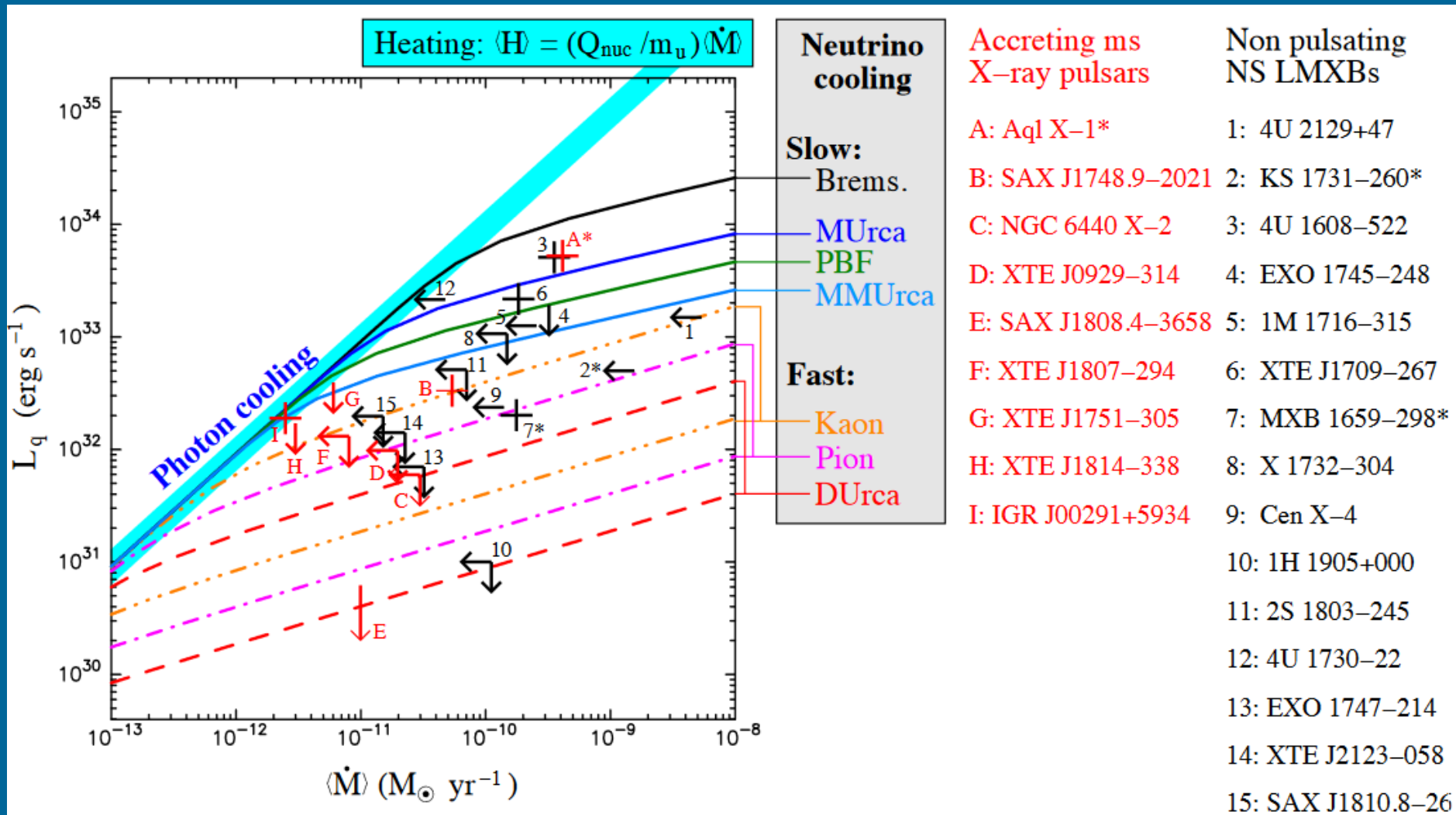
SXTs can be very important in confronting theoretical cooling models with data.

[from a presentation by Haensel, figures by Yakovlev and Levenfish]

# Theory vs. Observations: SXT and isolated cooling NSs



# Systems with deep crustal heating



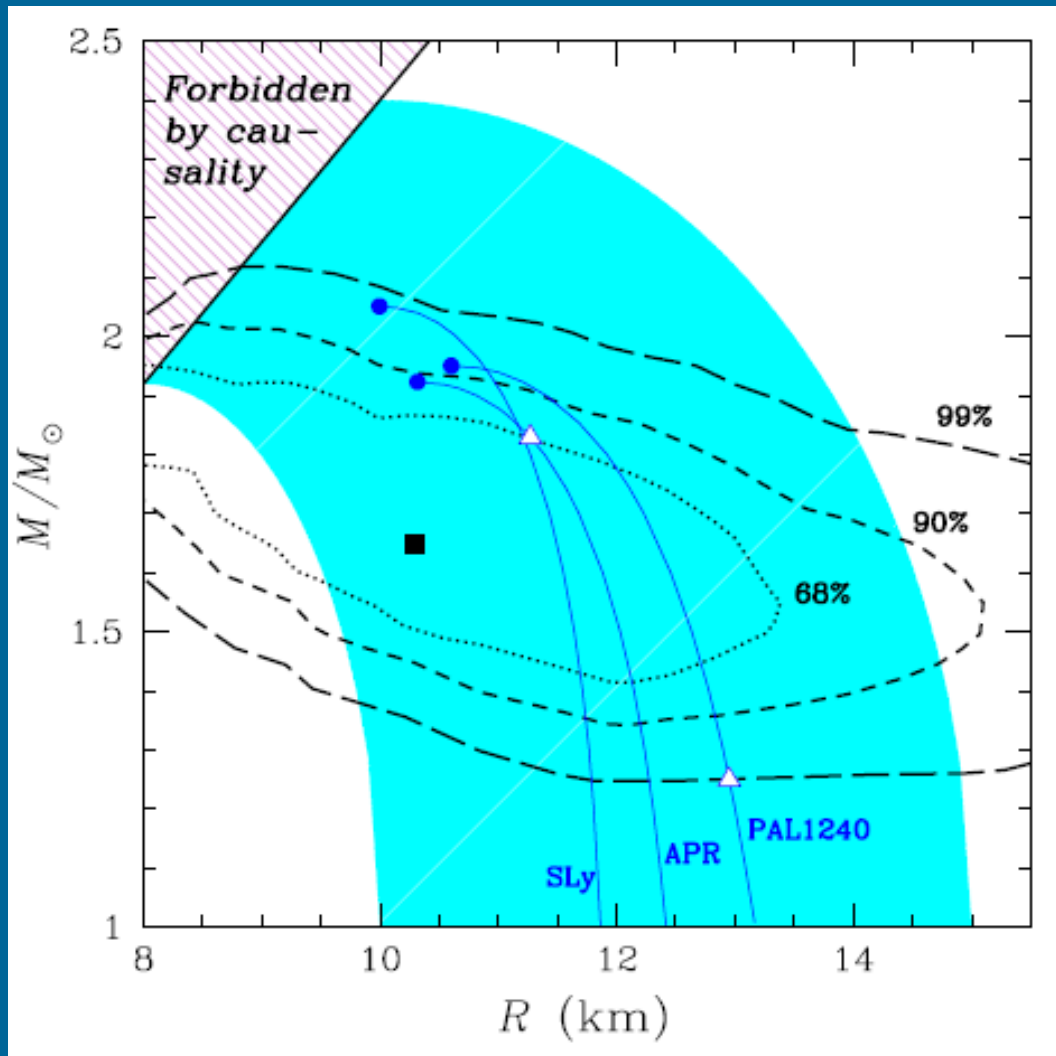
# Conclusions

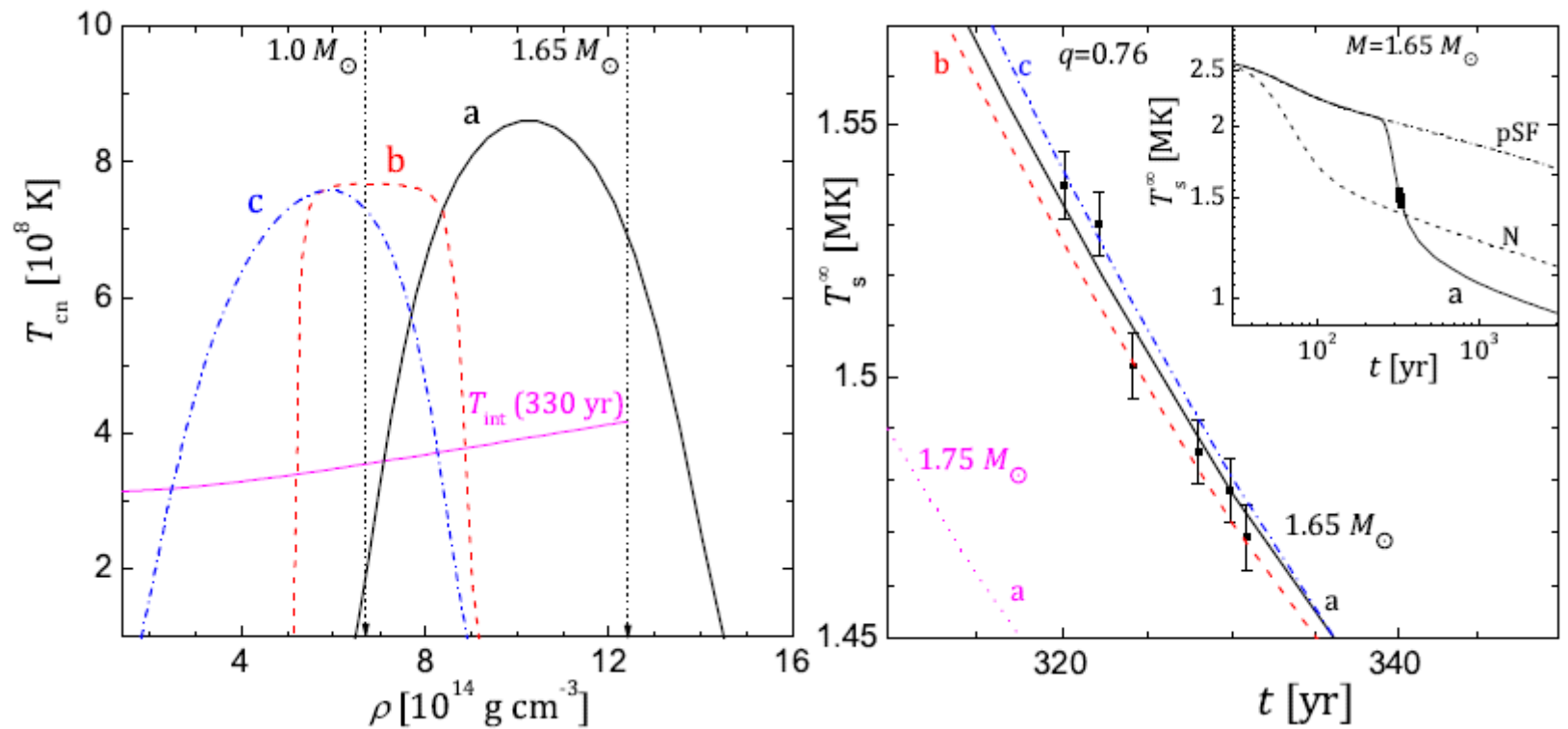
- NSs are born hot, and then cool down at first due to neutrino emission, and after – due to photon emission
- Observations of cooling provide important information about processes at high density at the NS interiors
- Two types of objects are studied:
  - isolated cooling NSs
  - NSs in soft X-ray transients

# Papers to read

- Or astro-ph/0403657  
Or astro-ph/0508056  
Or astro-ph/0402143 ←
- [arXiv:astro-ph/9906456](https://arxiv.org/abs/astro-ph/9906456) YΦH 1999
- 1709.07034 – about cooling of NSs in binaries

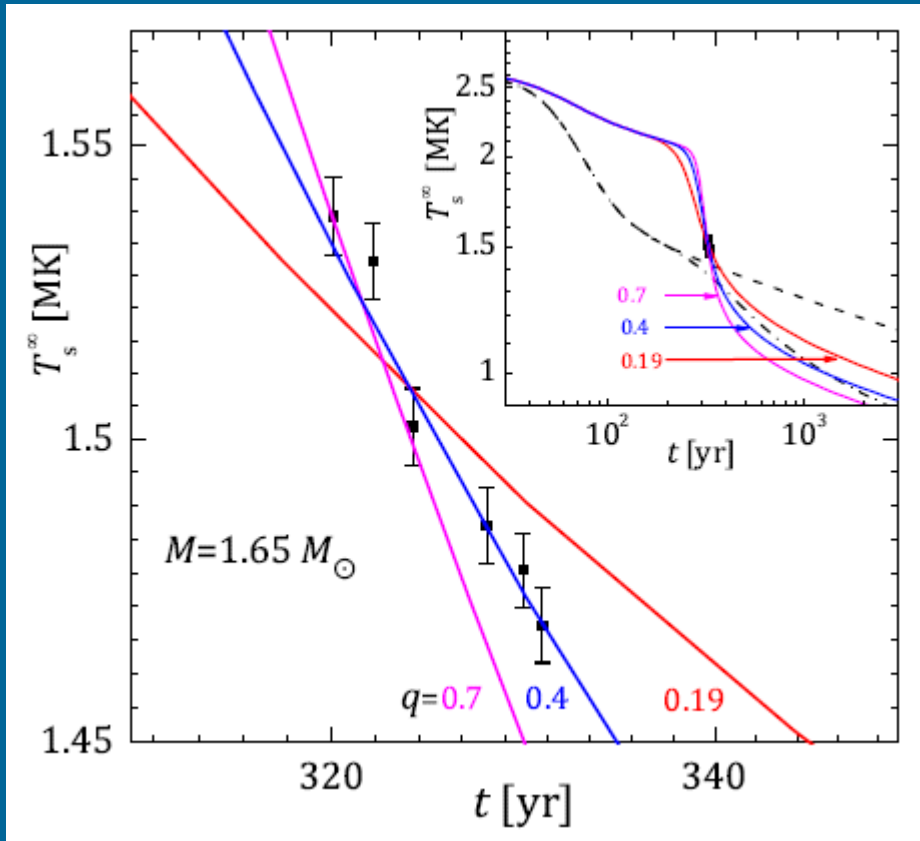
# M-R from spectral fit



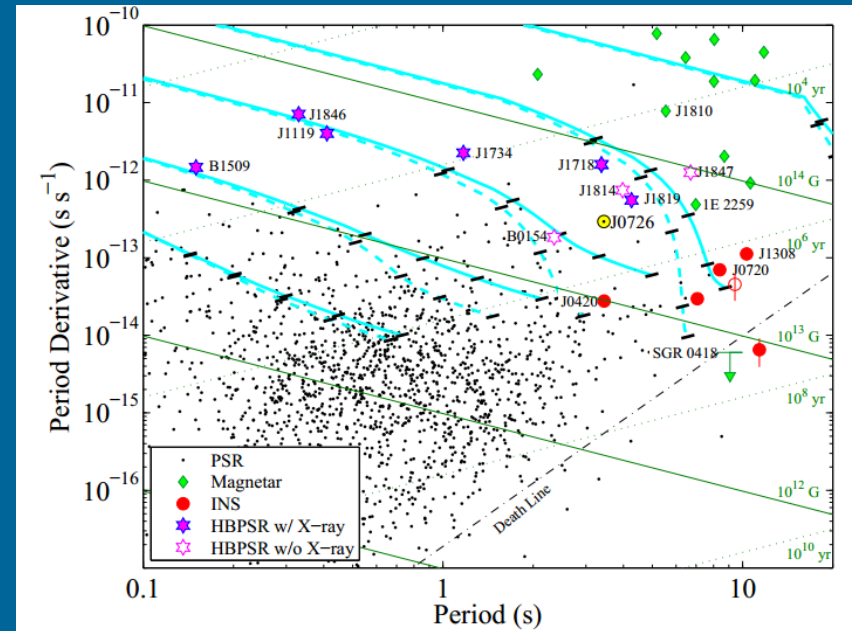
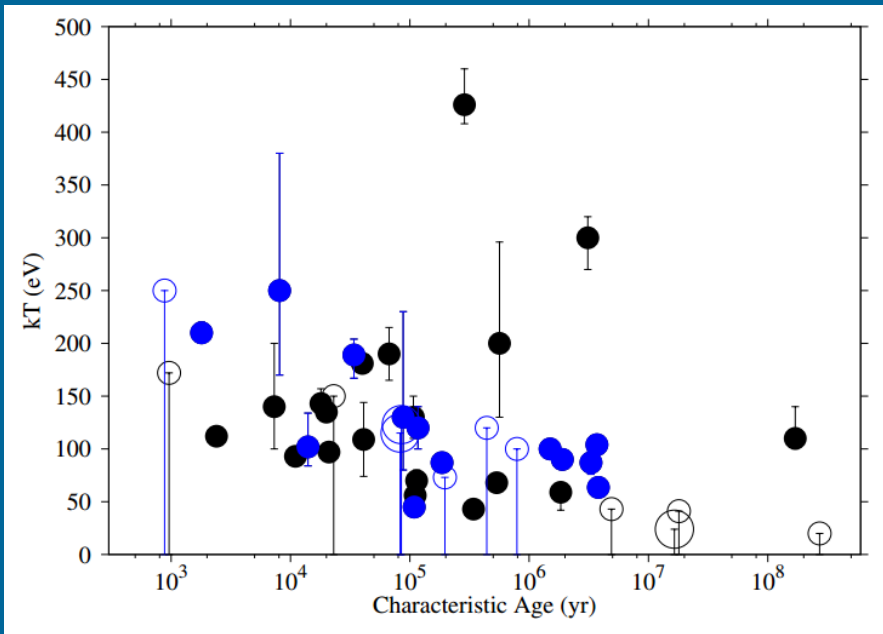




# Suppression in the axial-vector channel



# Cooling and grand unification for NSs



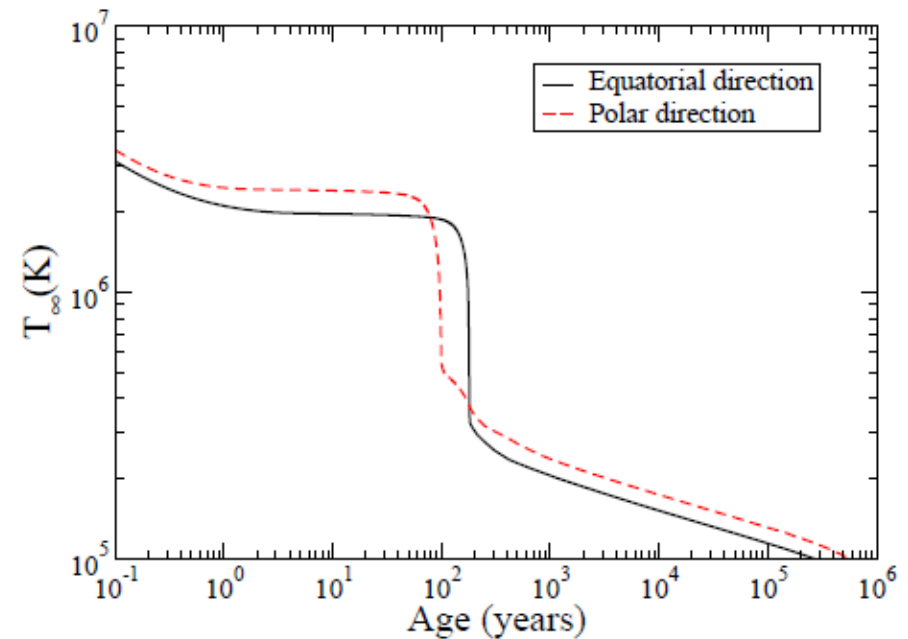
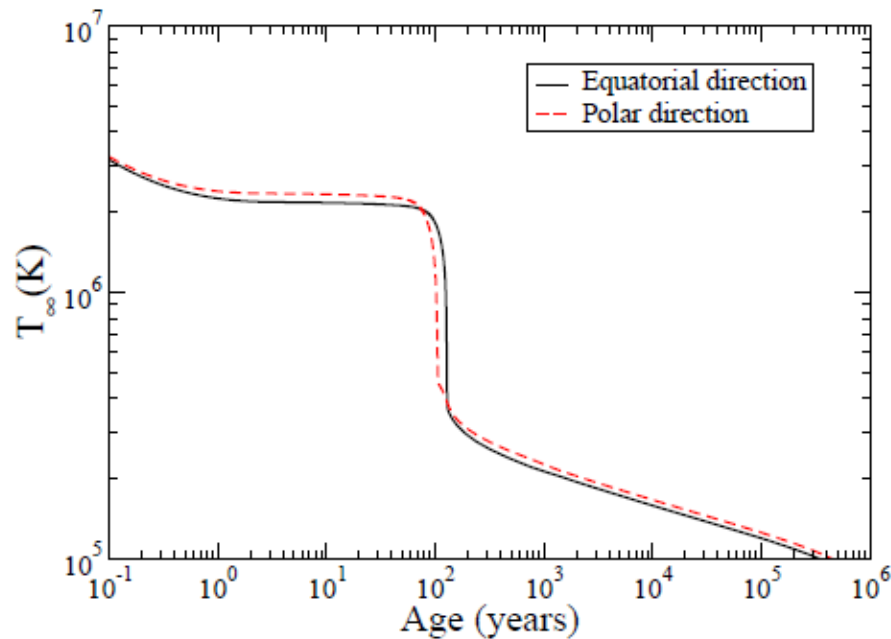
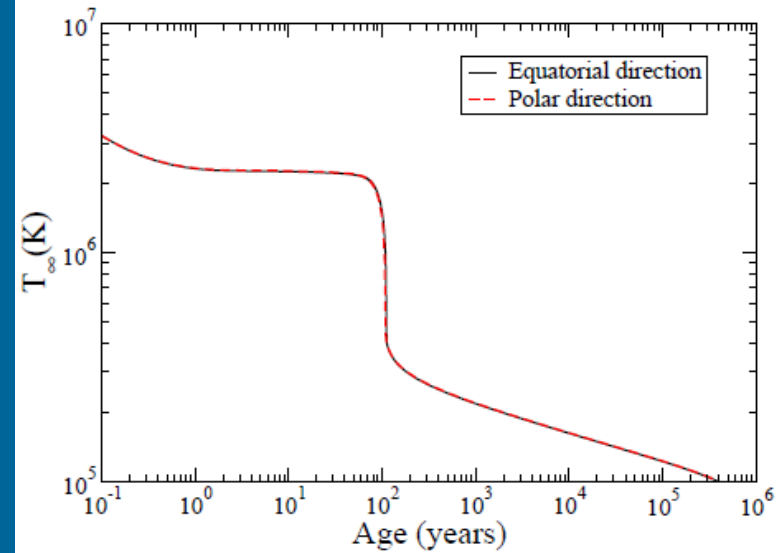
1301.2814

1111.2877

One study shows that highly magnetized NSs can be not hotter than NSs with standard magnetic fields.

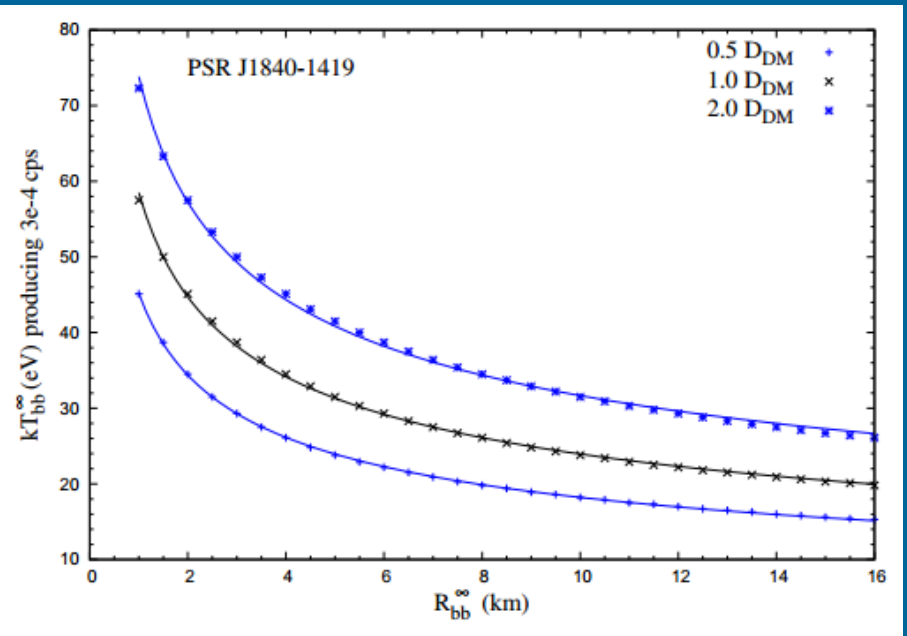
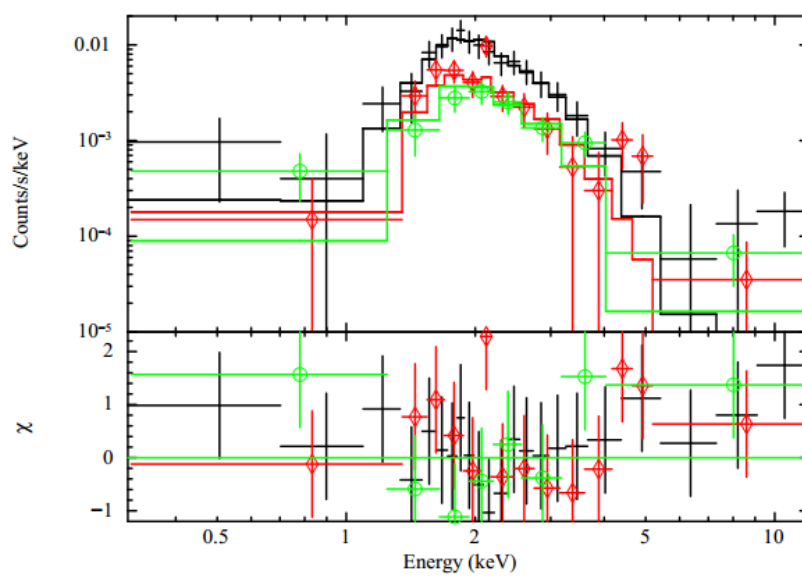
Another study demonstrates that some young PSRs with relatively large field are hot, similar to the M7.

# Влияние вращения



# Records

The hottest (in a binary, crustal heating)  
SAX J1750.8–2900.  $T \sim 150$  eV.  
1202.1531



The coldest. Isolated pulsar.  $T < 30$  eV  
PSR J18401419  
1301.2814