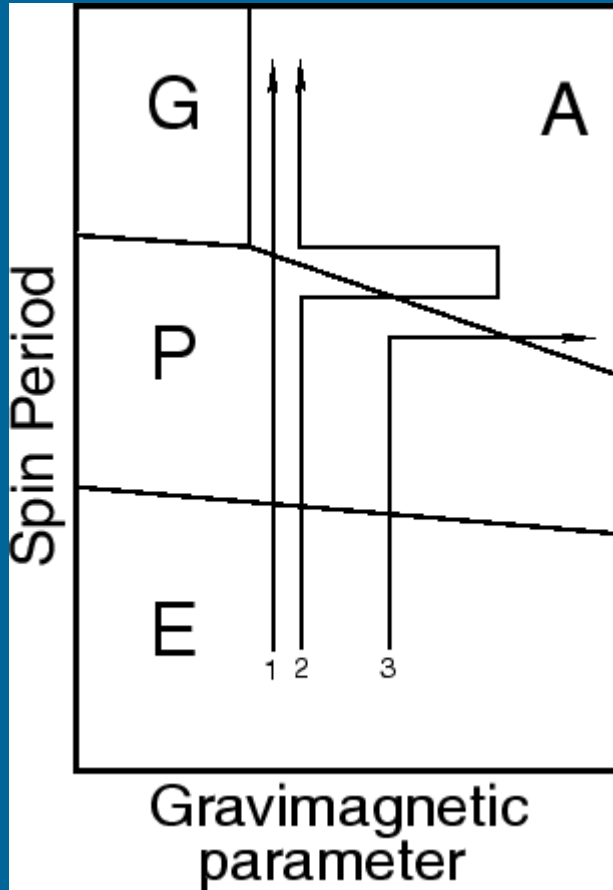
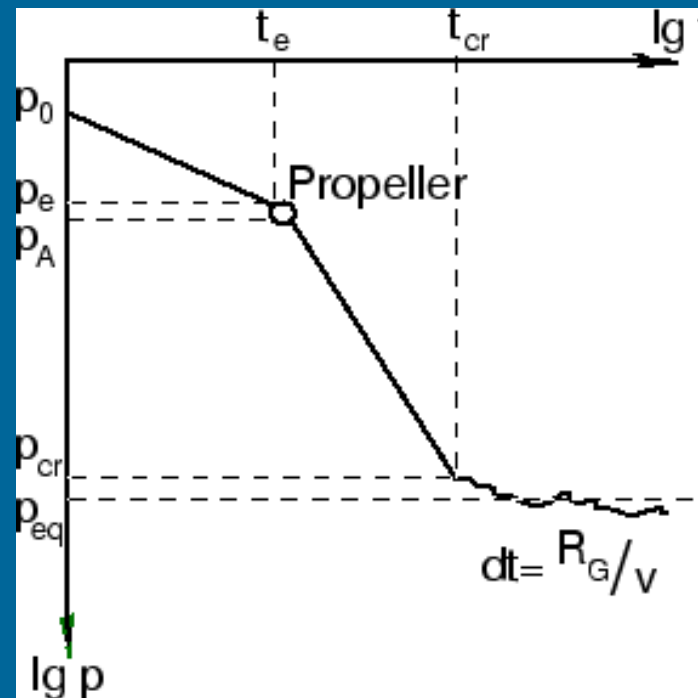

Thermal evolution of neutron stars

Evolution of neutron stars. I: rotation + magnetic field

Ejector → Propeller → Accretor → Georotator



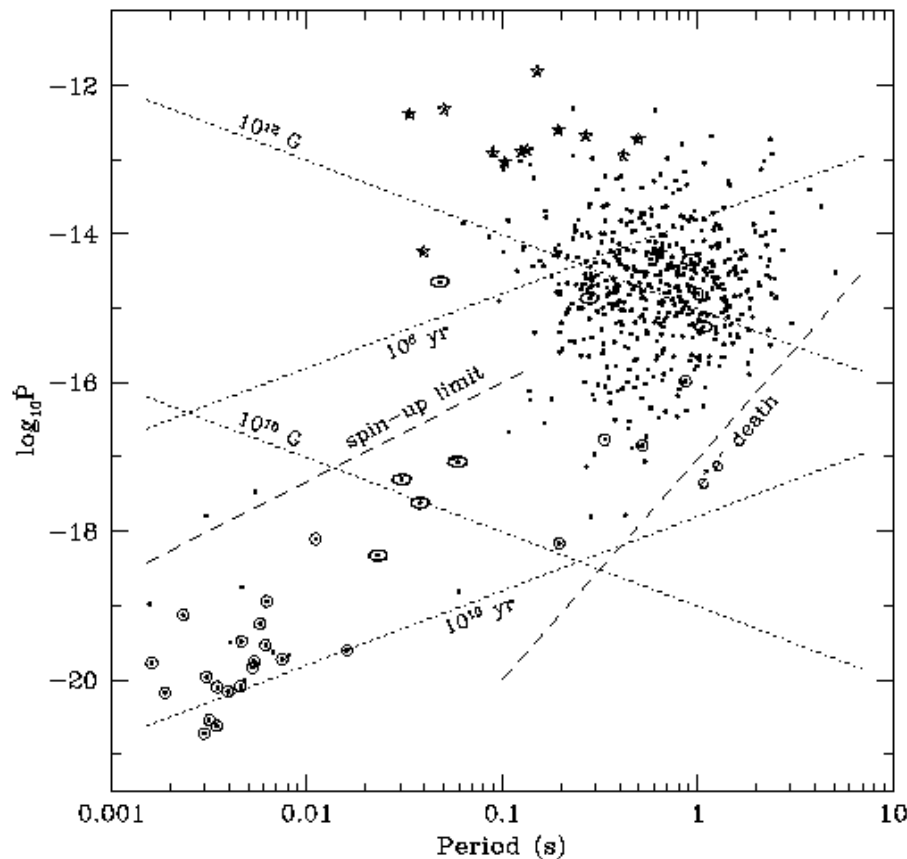
- 1 – spin down
- 2 – passage through a molecular cloud
- 3 – magnetic field decay



astro-ph/0101031

See the book by Lipunov (1987, 1992)

Magnetorotational evolution of radio pulsars



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

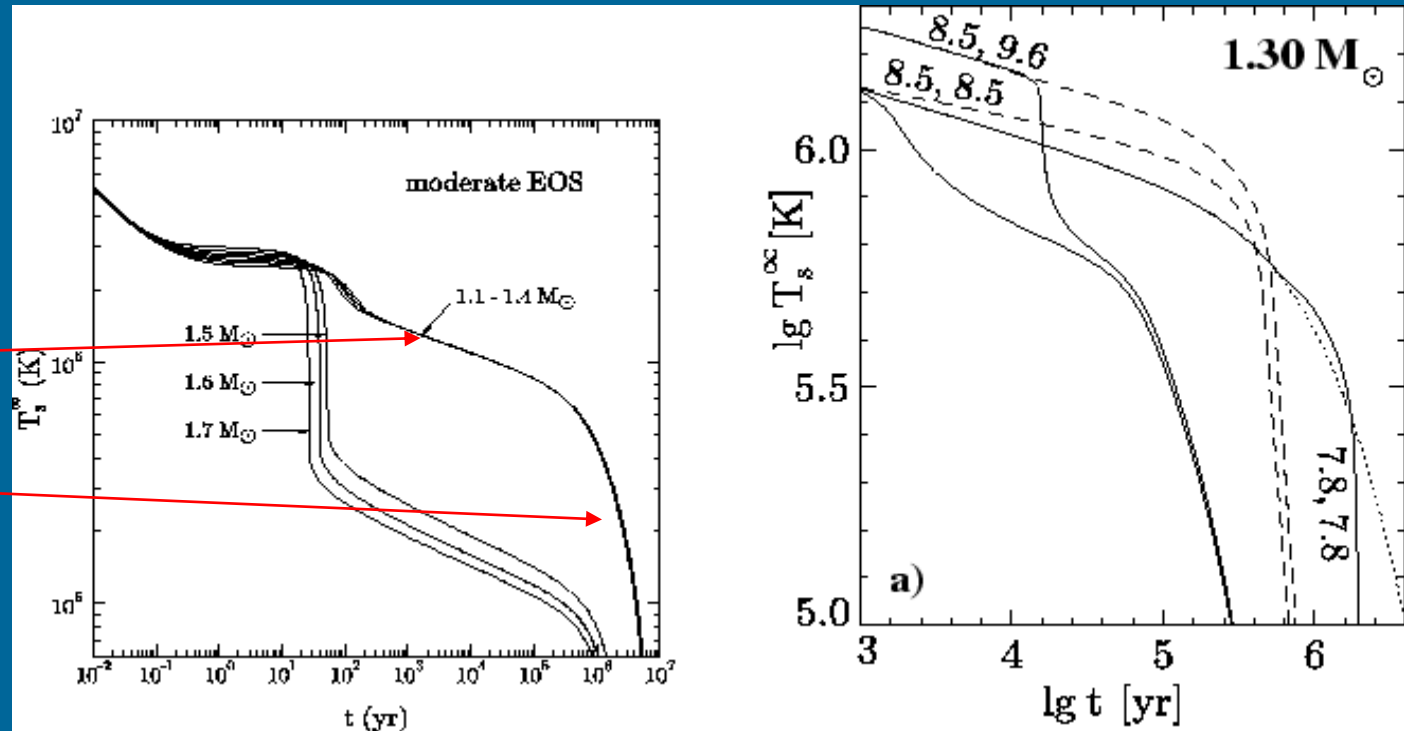
$$B \sim 3.2 \times 10^{19} (P dP/dt)^{1/2} \text{ G.}$$

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

Evolution of NSs. II.: temperature

Neutrino cooling stage

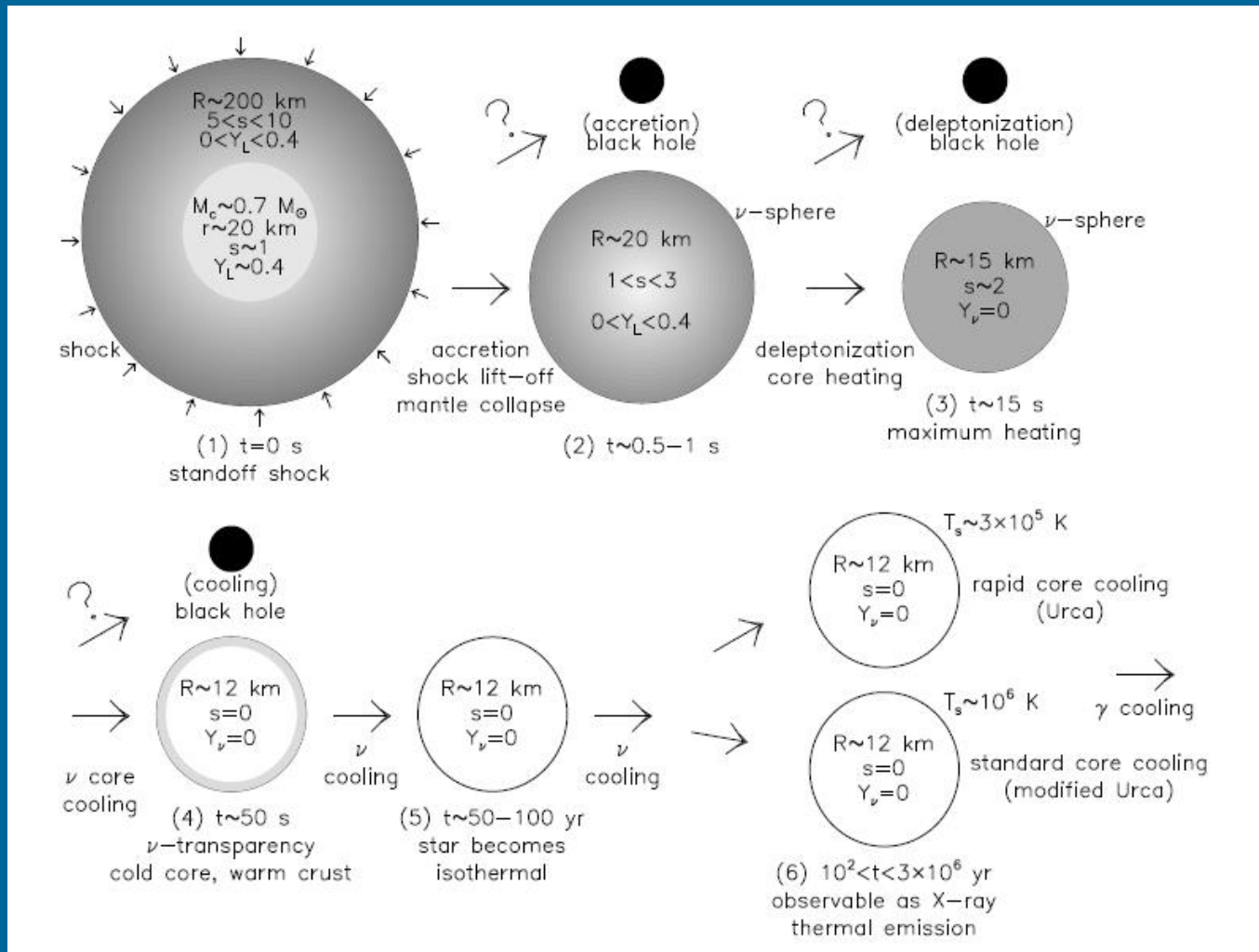
Photon cooling stage



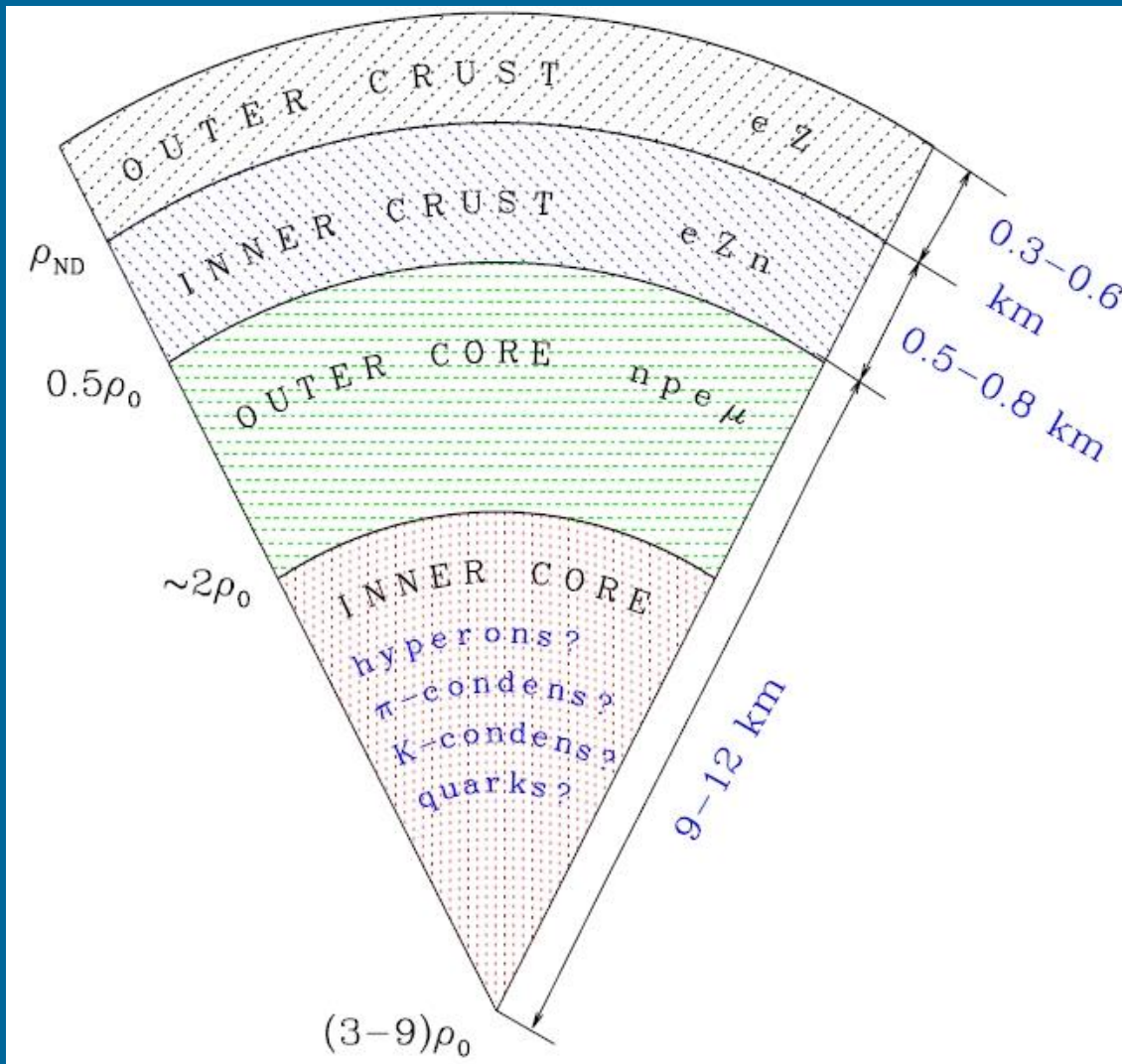
First papers on the thermal evolution appeared already in early 60s, i.e. before the discovery of radio pulsars.

[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 $U_T \sim 10^{48} T_9^2$ 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 ~ 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

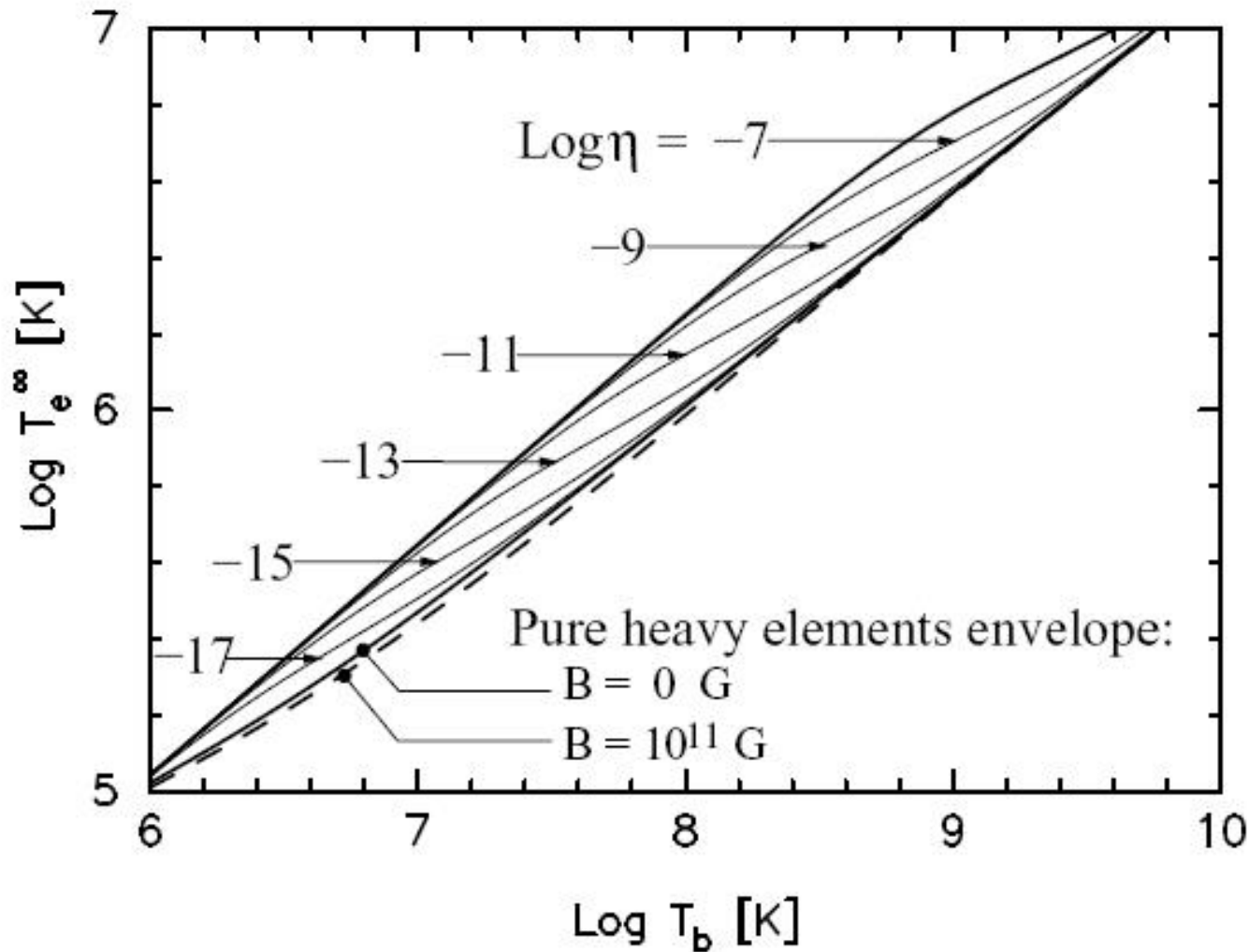
$$\frac{dE_{th}}{dt} = C_V \frac{dT}{dt} = -L_\nu - L_\gamma$$

Photon luminosity

Neutrino luminosity

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

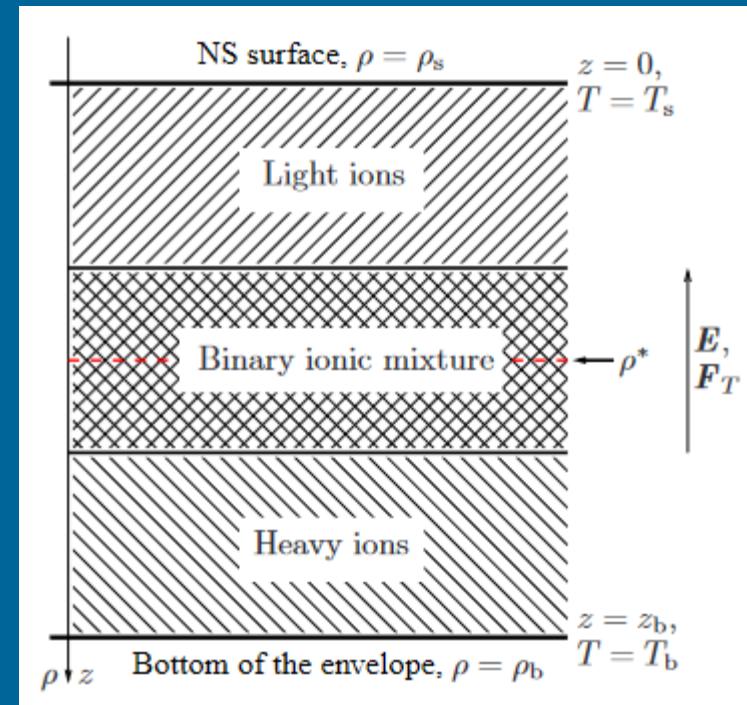
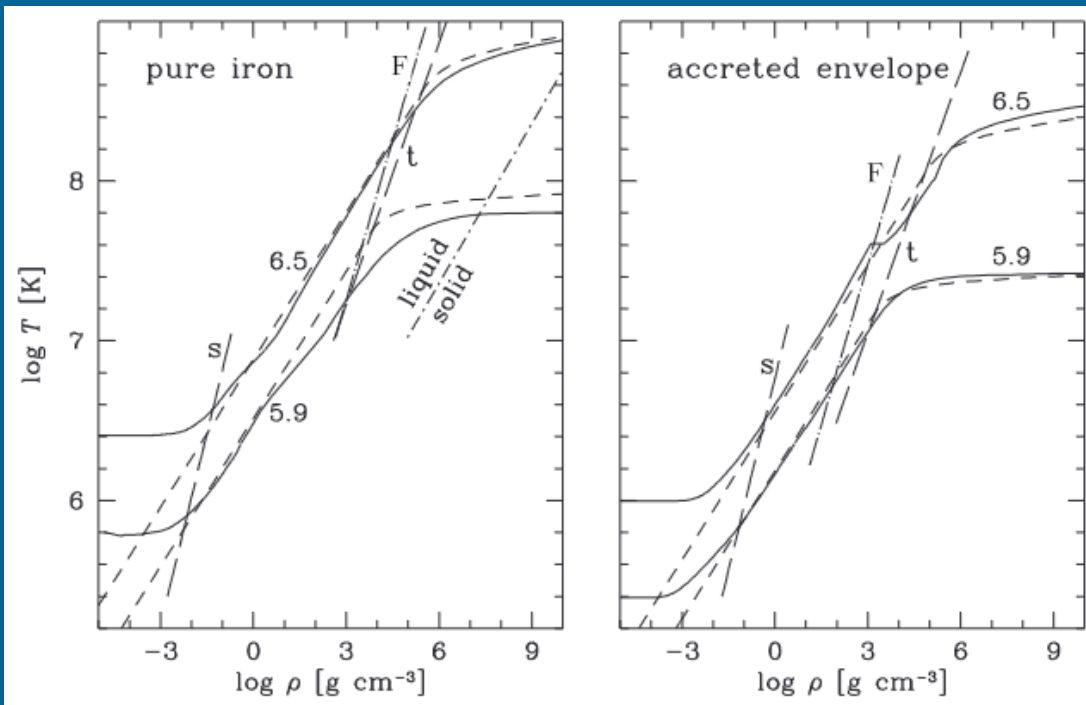
Core-crust temperature relation



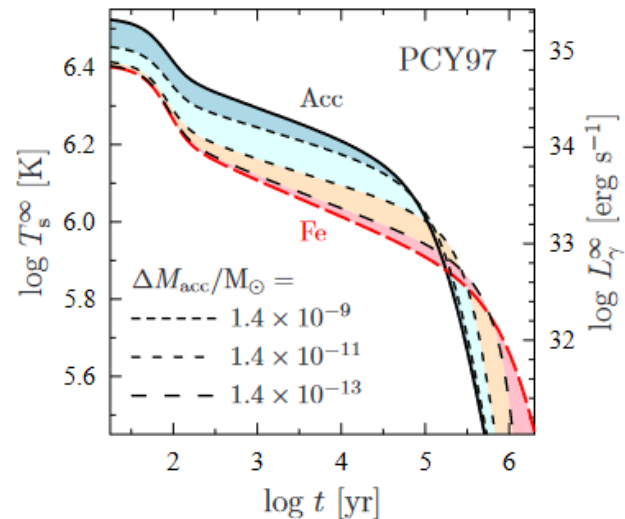
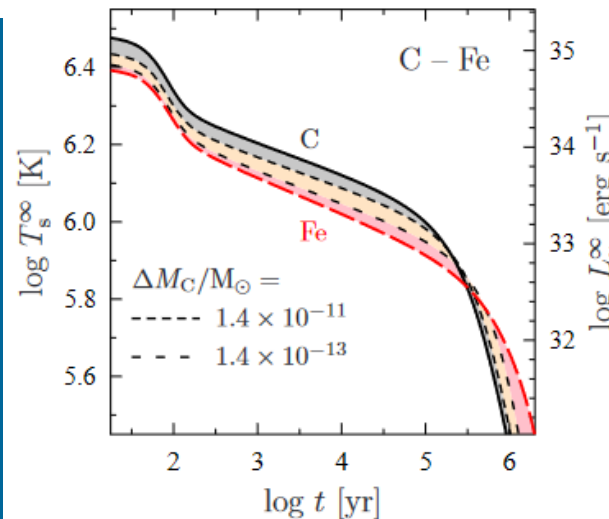
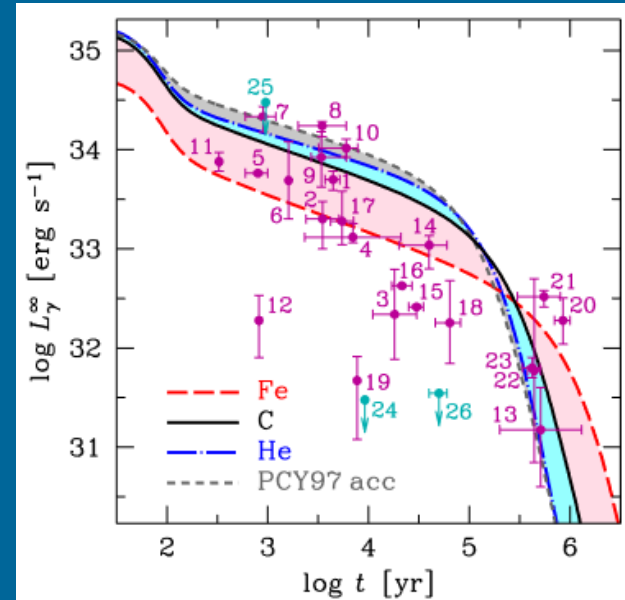
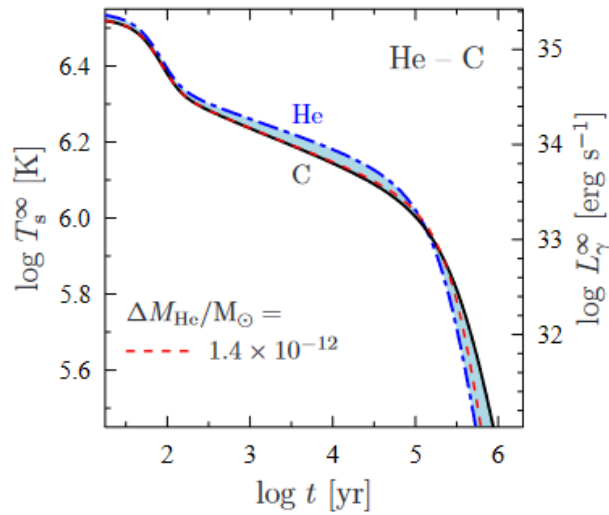
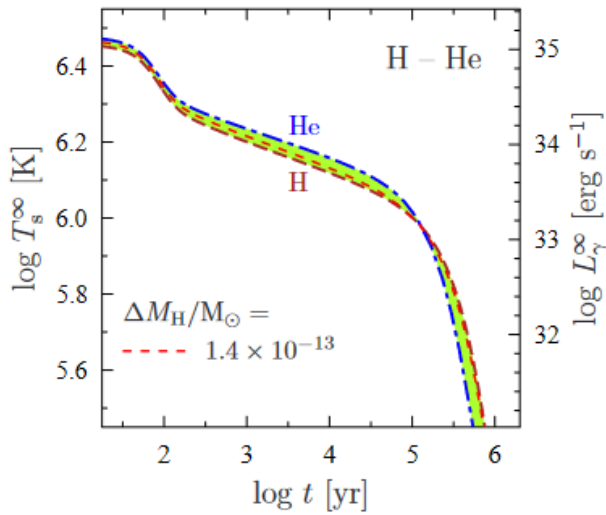
Heat blanketing envelope.
~100 meters
density $\sim 10^{10}$ gcm $^{-3}$

See a review about crust properties related to thermal evolution in 1201.5602, 1507.06186, and in a recent large review – 2103.12422

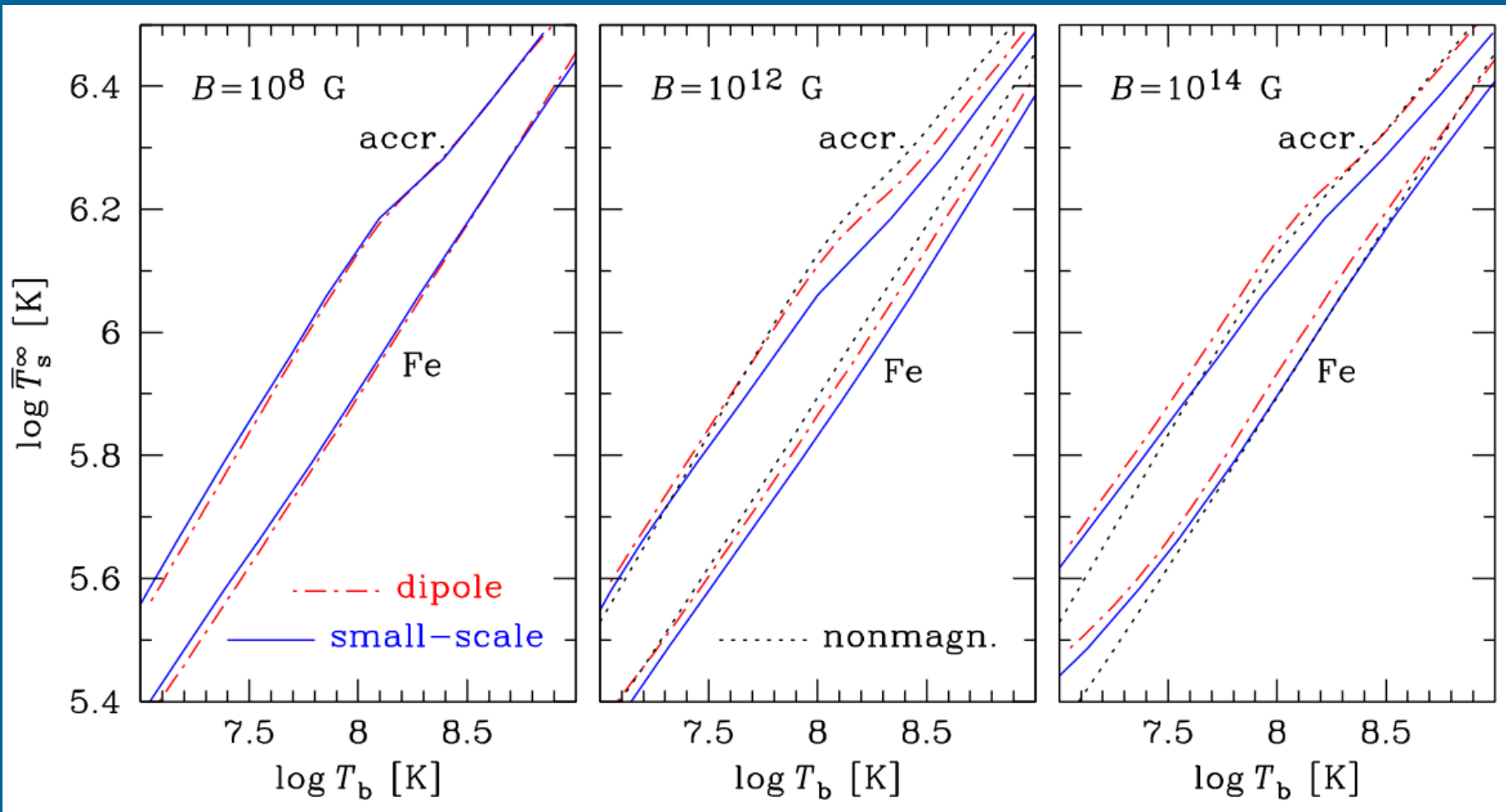
Temperature profile in an envelope



Composition dependence



Composition and field dependences



Envelope boundary: neutron drip density $4 \times 10^{11} \text{ g cm}^{-3}$

astro-ph/0508415

$$L = 4\pi R^2 \sigma \bar{T}_s^4$$

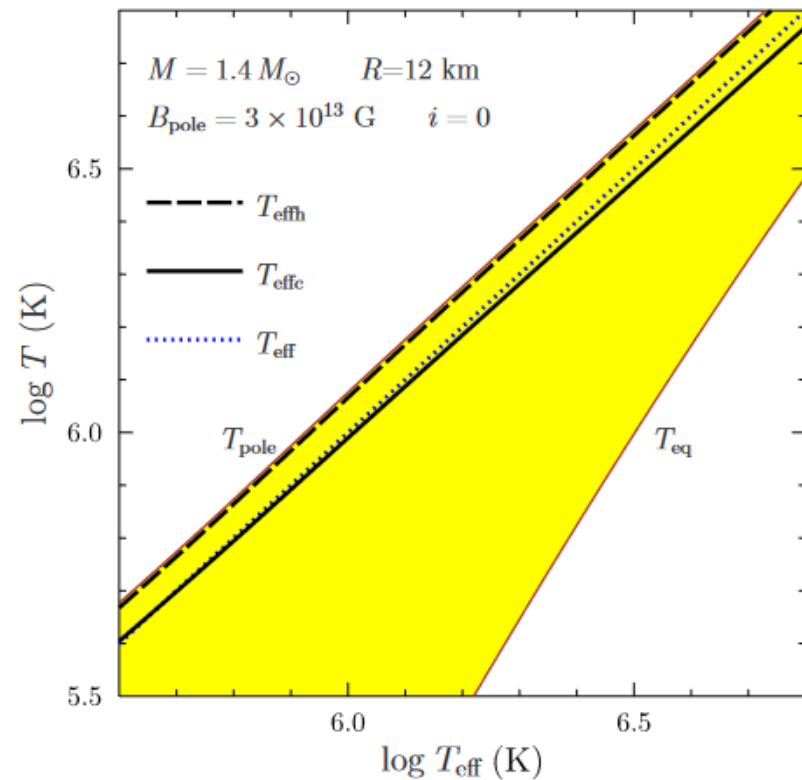
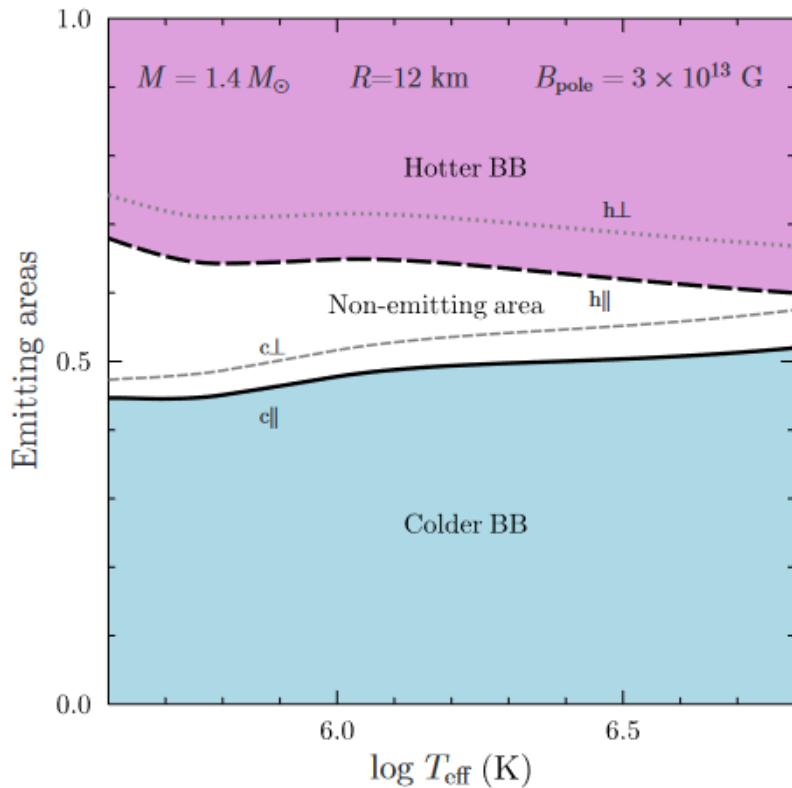
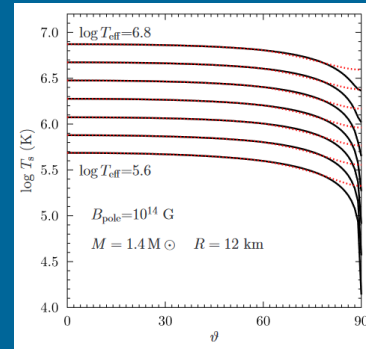
$$L^\infty = (1 - r_g/R)L$$

$$T_s^\infty = T_s \sqrt{1 - r_g/R}$$

Two BB approximation

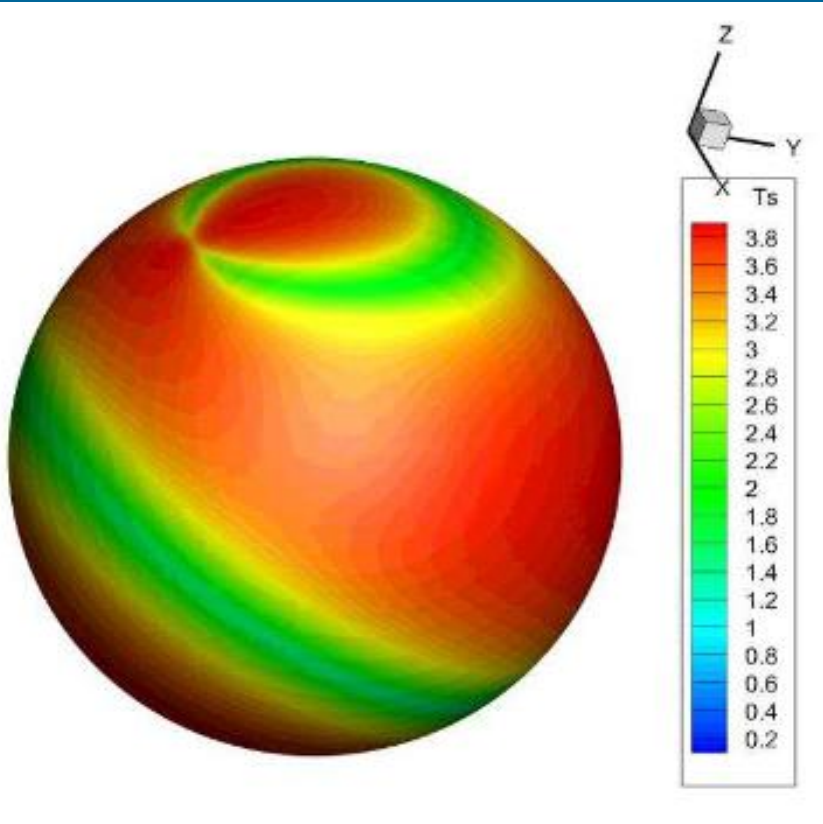
Temperature distribution is due to dipolar magnetic field ($B < 10^{14}$ G):
the pole is hotter than the equator.

2BB provides a good fit for such situation.

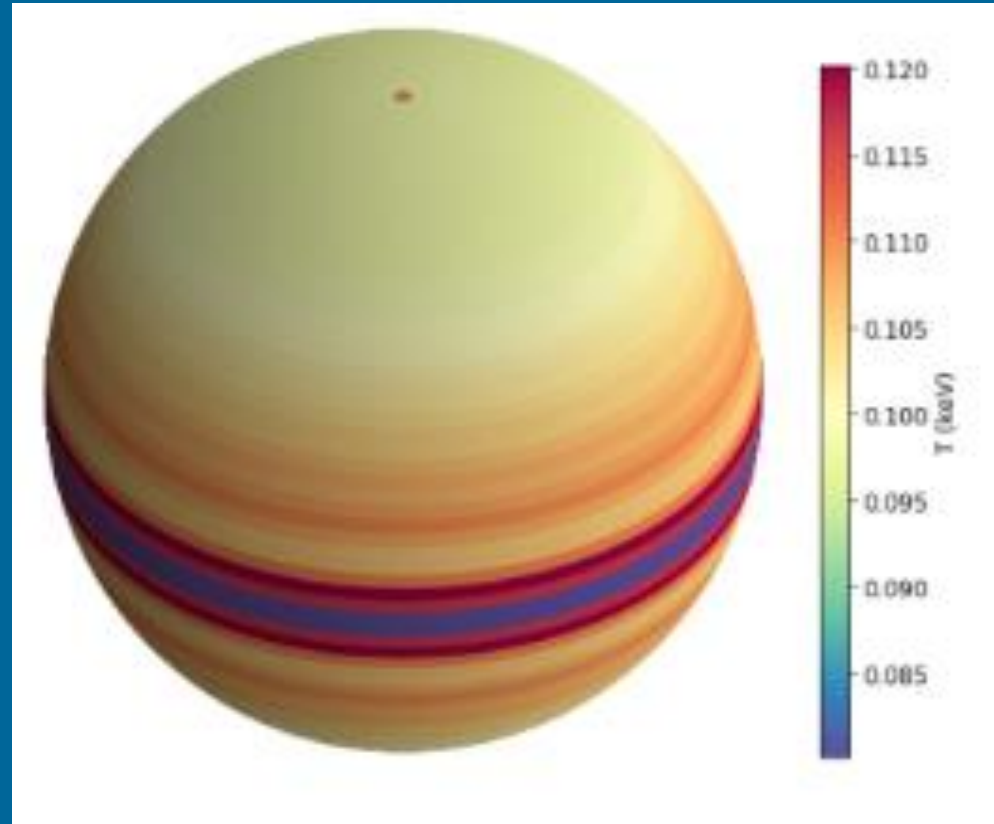


Field and surface temperature

Complicated field topology in the crust can result in complicated surface temperature distribution.



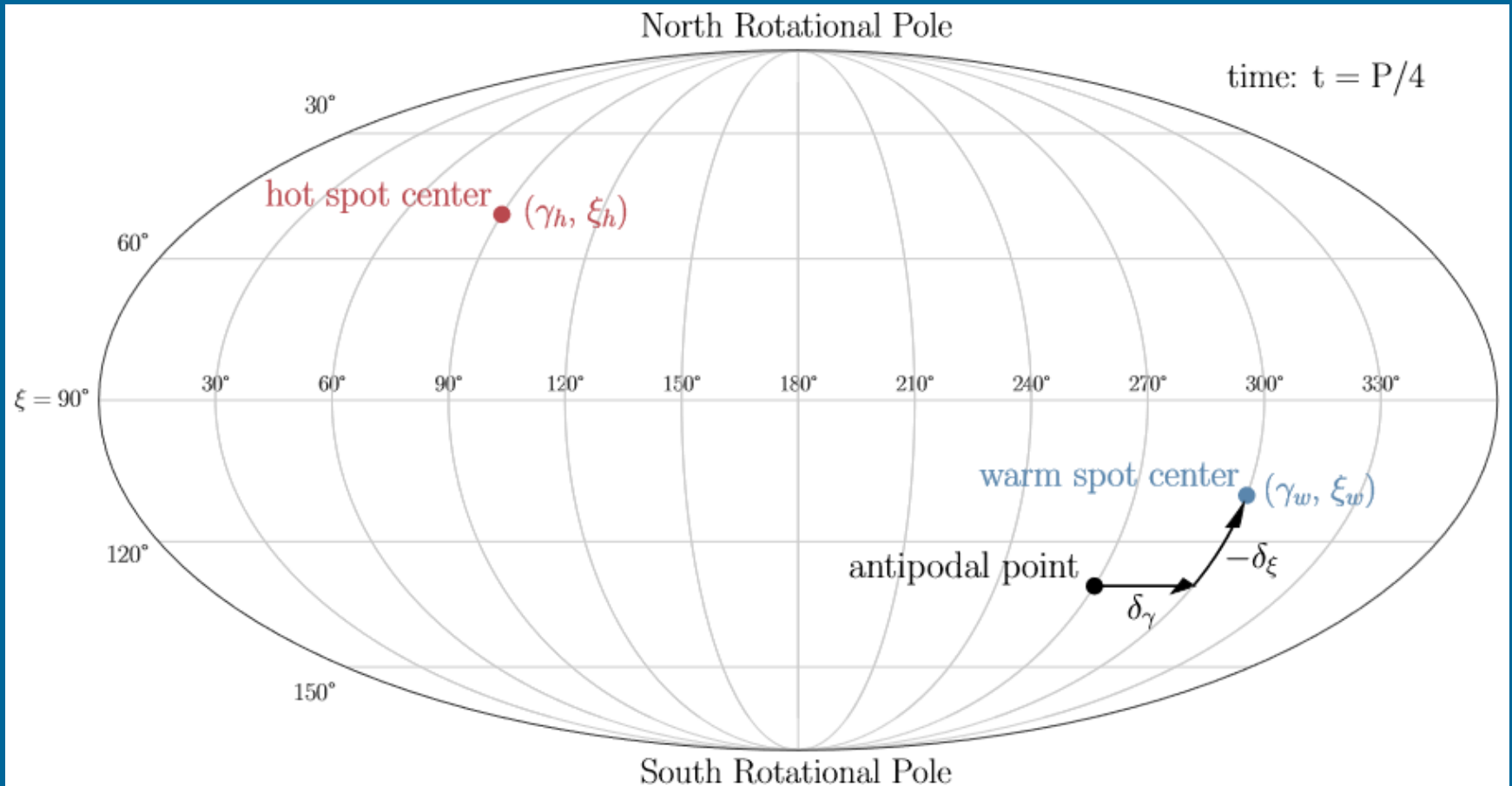
Dipole + quadrupole



Poloidal + toroidal

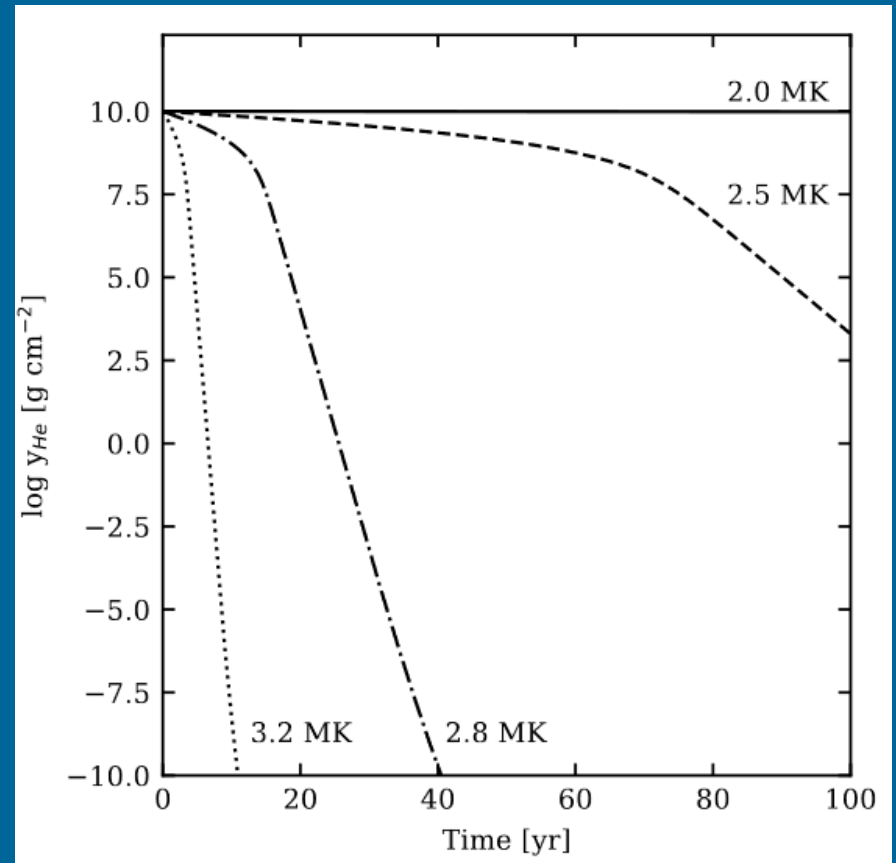
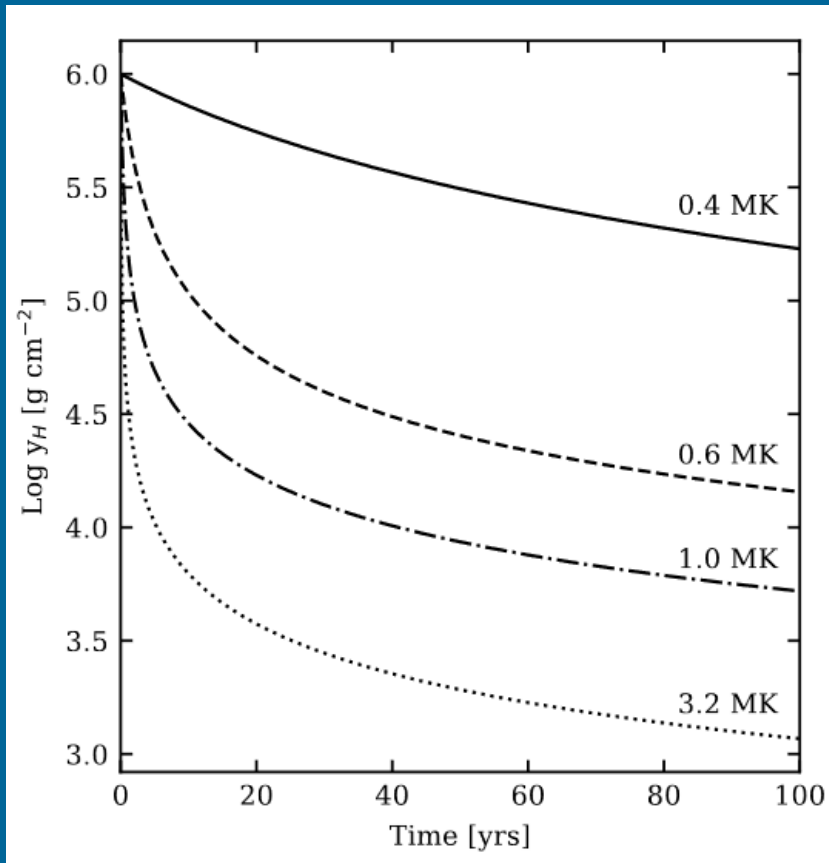
Temperature distribution for Puppis A

RX J0822-4300 has a double blackbody X-ray spectrum with temperatures of ≈ 0.4 keV and ≈ 0.2 keV.



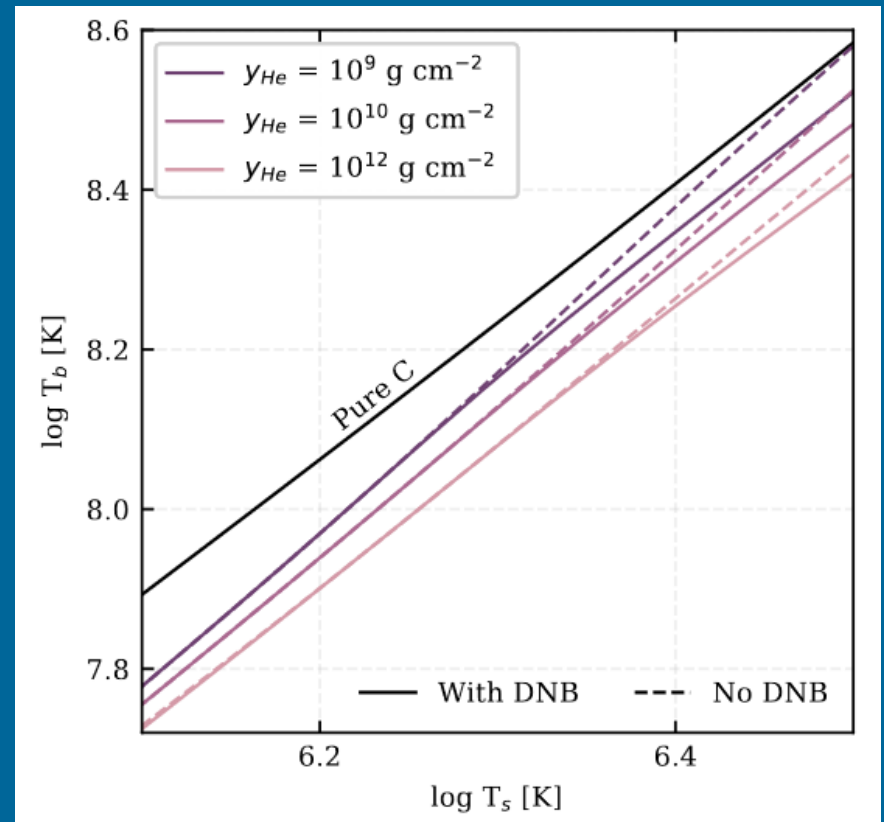
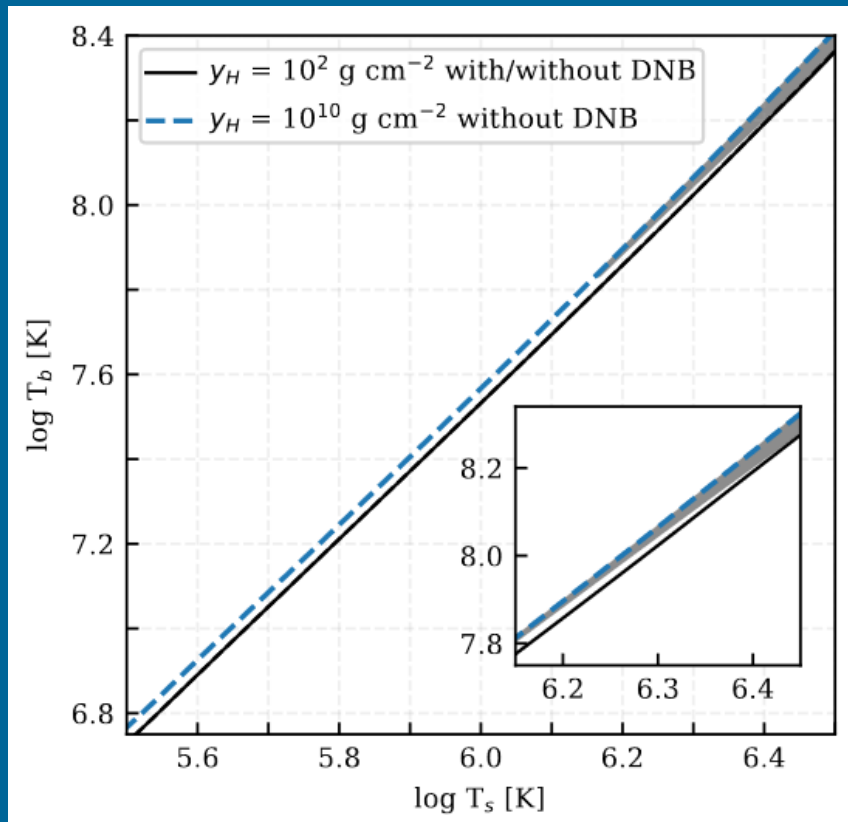
Diffusive nuclear burning

Time dependent envelope composition in early years.
Elements diffuse to depths where the density and temperature are sufficiently high to ignite nuclear burning.

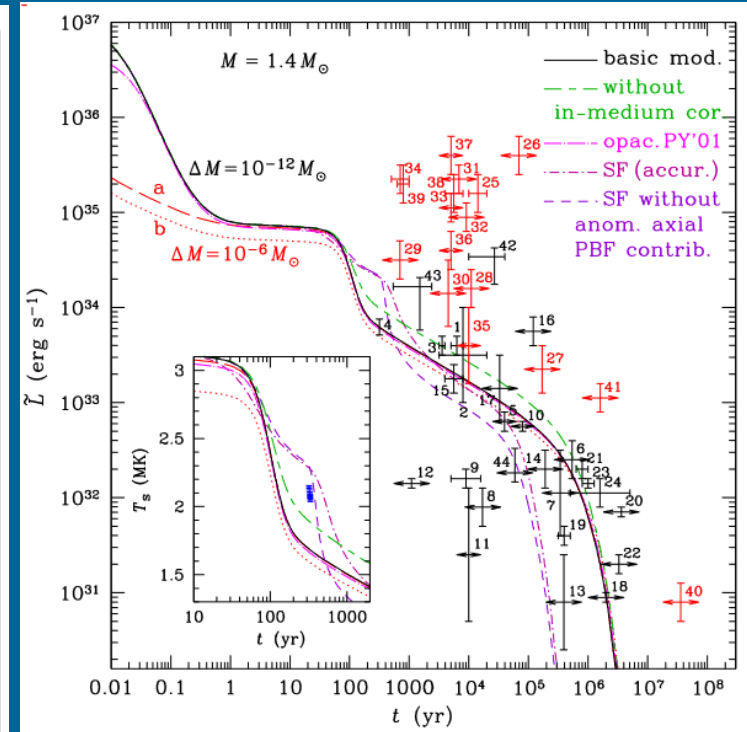
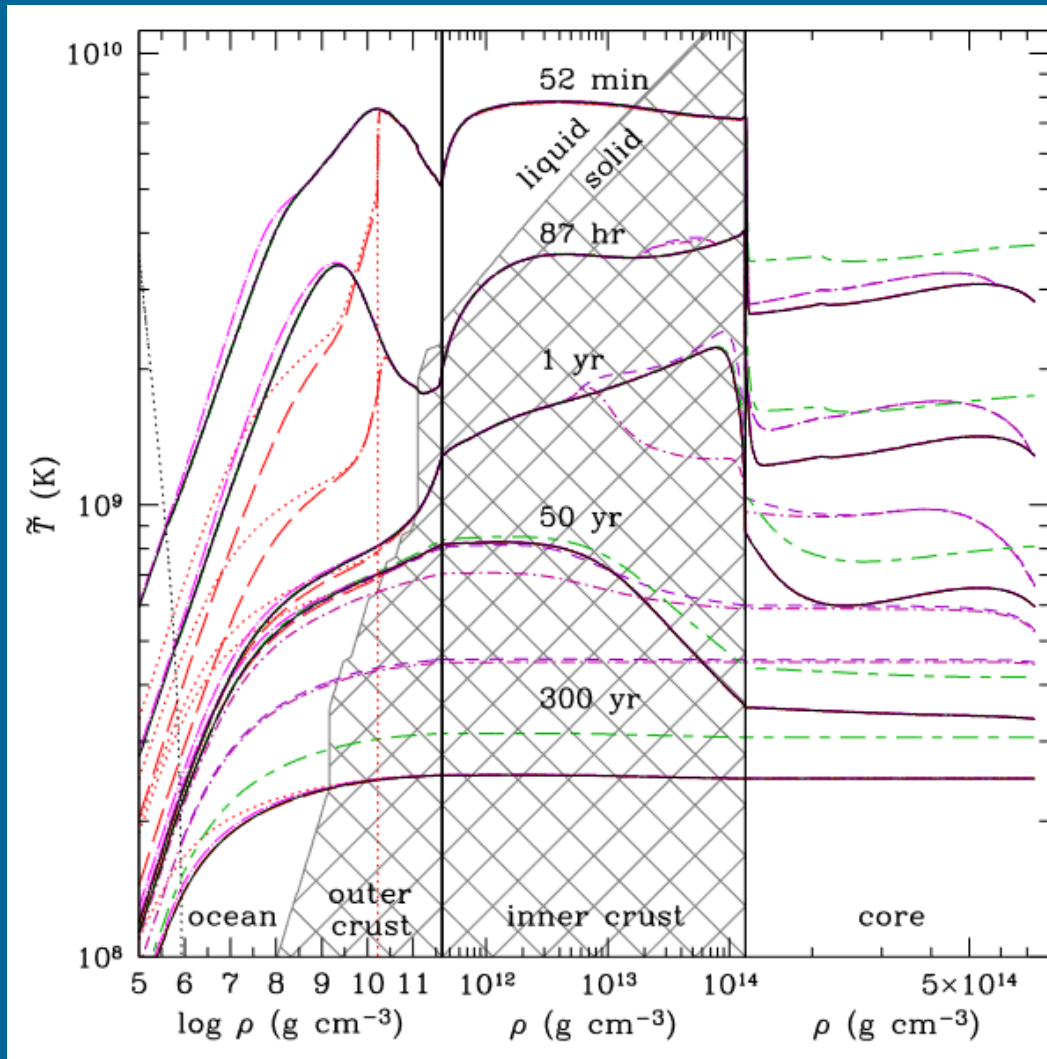


Cooling with DNB

Evolution of composition modifies cooling curves via T_s - T_b relation



Redshifted temperature evolution



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)

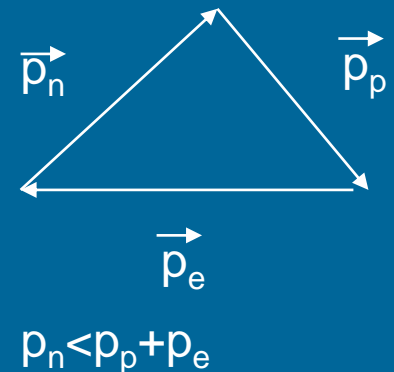
$$n + n \rightarrow n + p + e^- + \bar{\nu}_e$$

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

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

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

- 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

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

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_ν^∞ is the total neutrino luminosity (for a distant observer)

L_h^∞ is the total reheating power.

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.

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

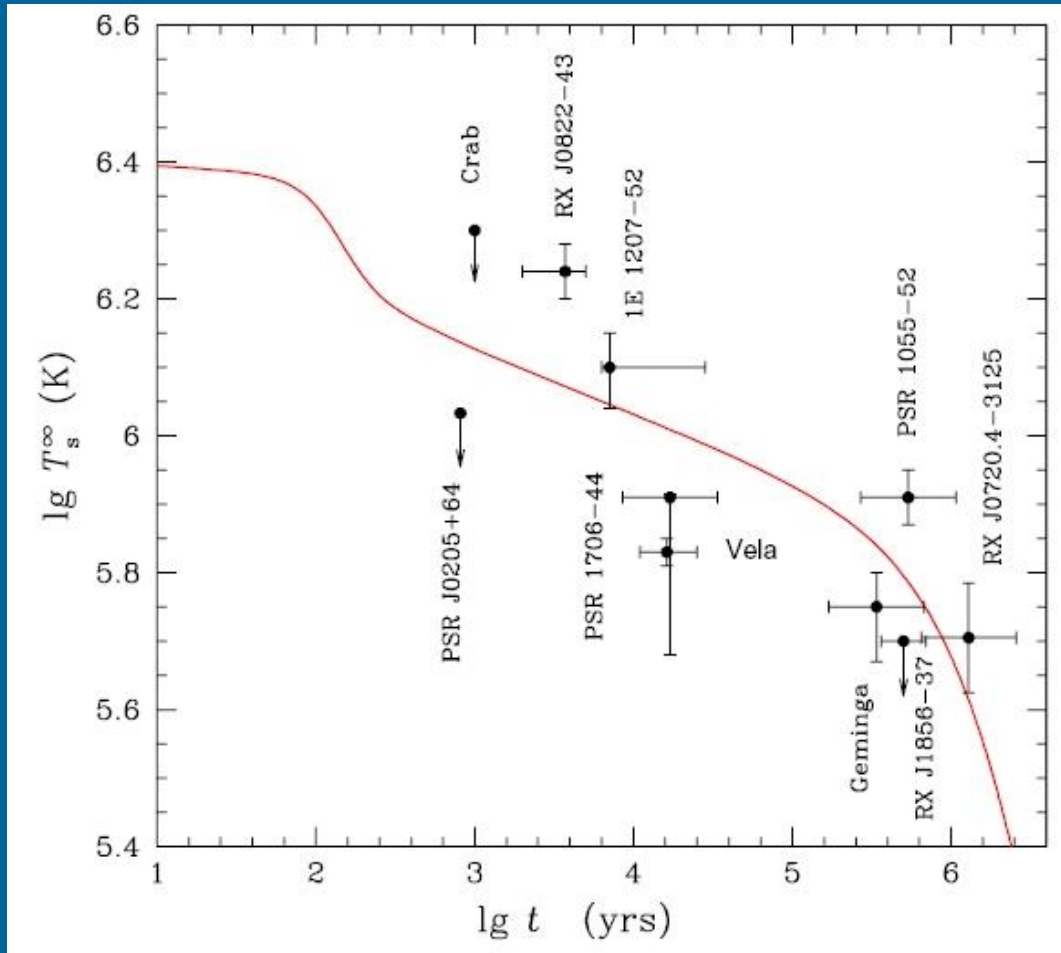
The critical mass depends on the EoS.
For the examples below $M_D = 1.358 M_{\text{solar}}$.

M (M_{\odot})	R (km)	ρ_c (10^{14} g cm^{-3})	M_{crust} (M_{\odot})	ΔR_{crust} (km)	ΔM_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 ^a	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 ^b	10.75	25.78	0.011	0.45	1.400	7.90

^a Threshold configuration for the direct Urca process

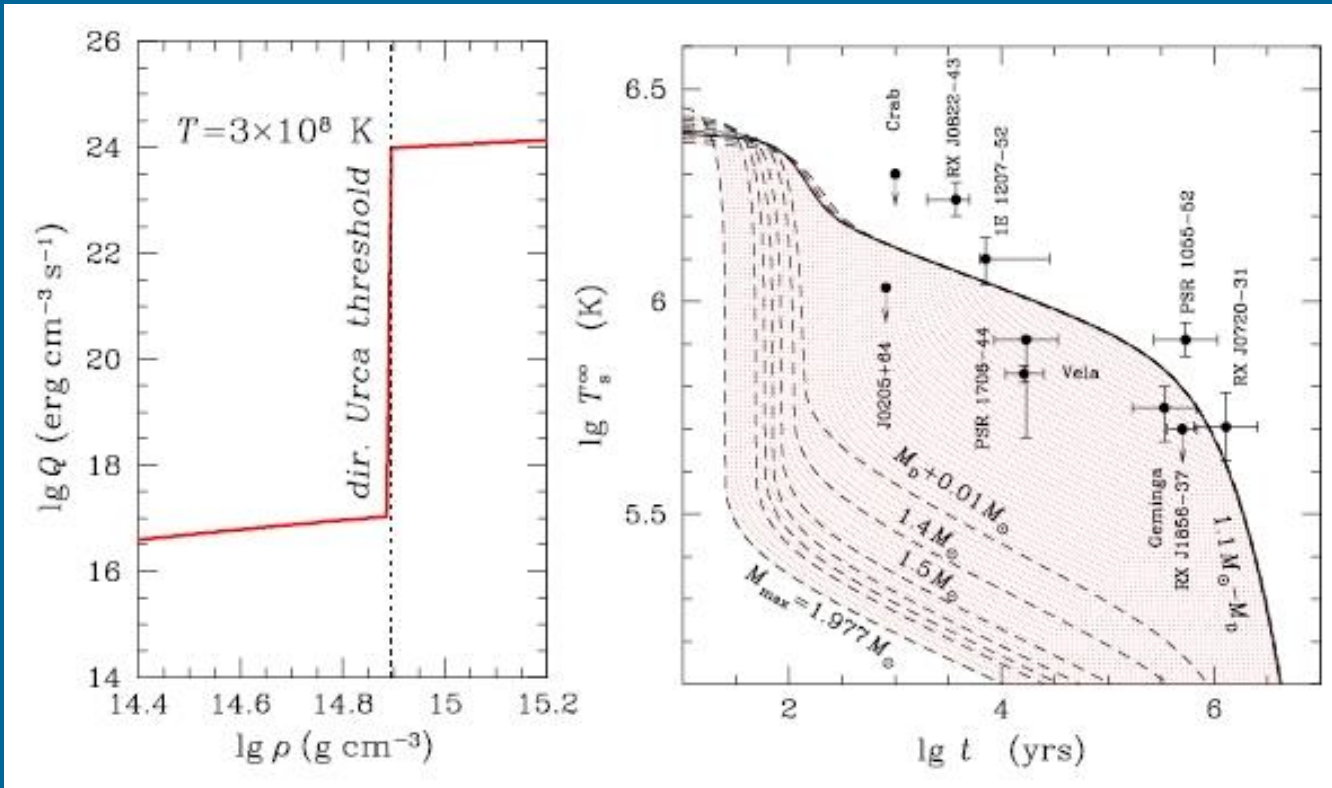
^b Maximum-mass stable neutron star

Simple cooling model for low-mass NSs.



Too hot
Too cold

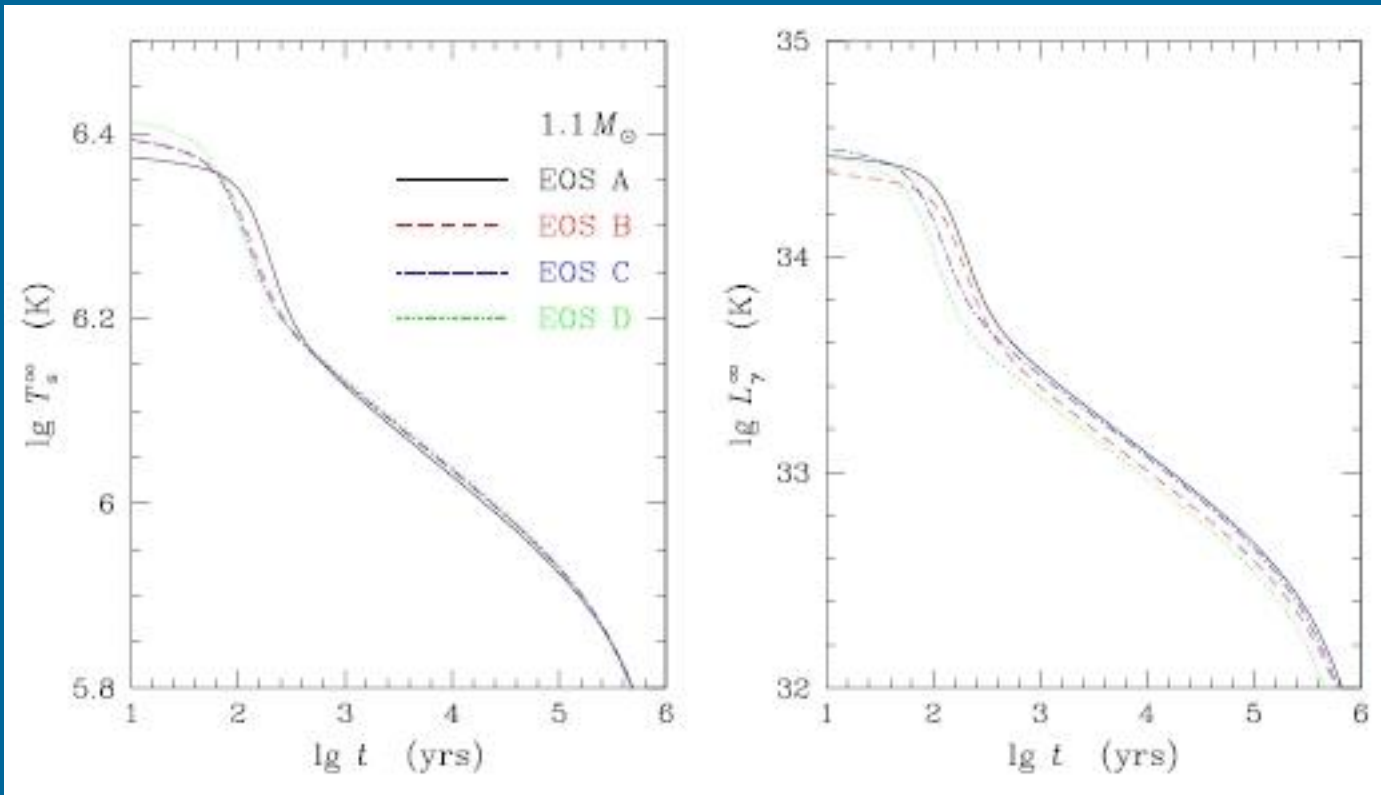
Nonsuperfluid nucleon cores



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

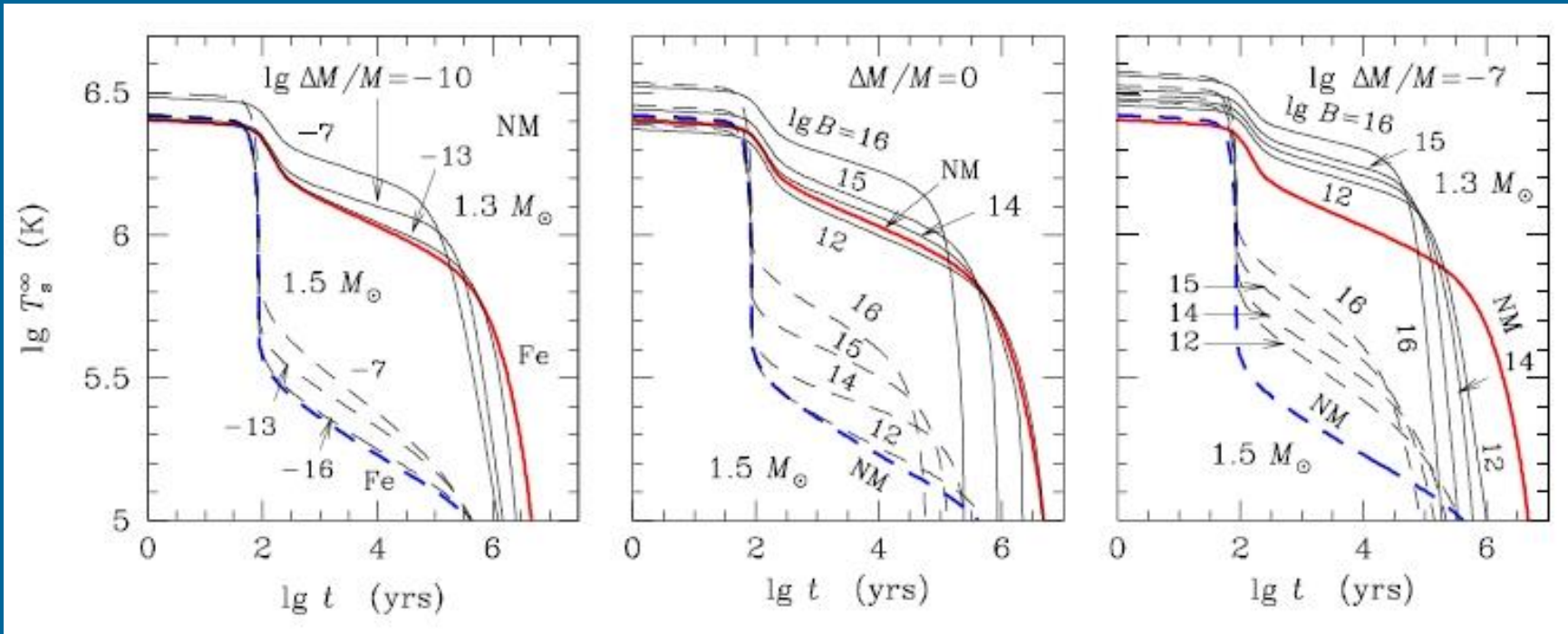
For slow cooling at the neutrino cooling stage $t_{\text{slow}} \sim 1 \text{ yr} / T_{i9}^6$
 For fast cooling $t_{\text{fast}} \sim 1 \text{ min} / T_{i9}^4$

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.

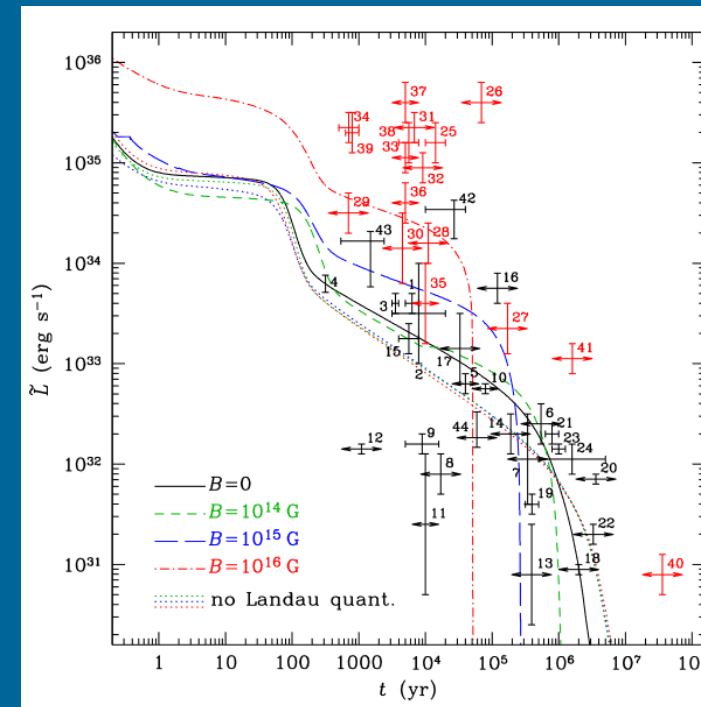
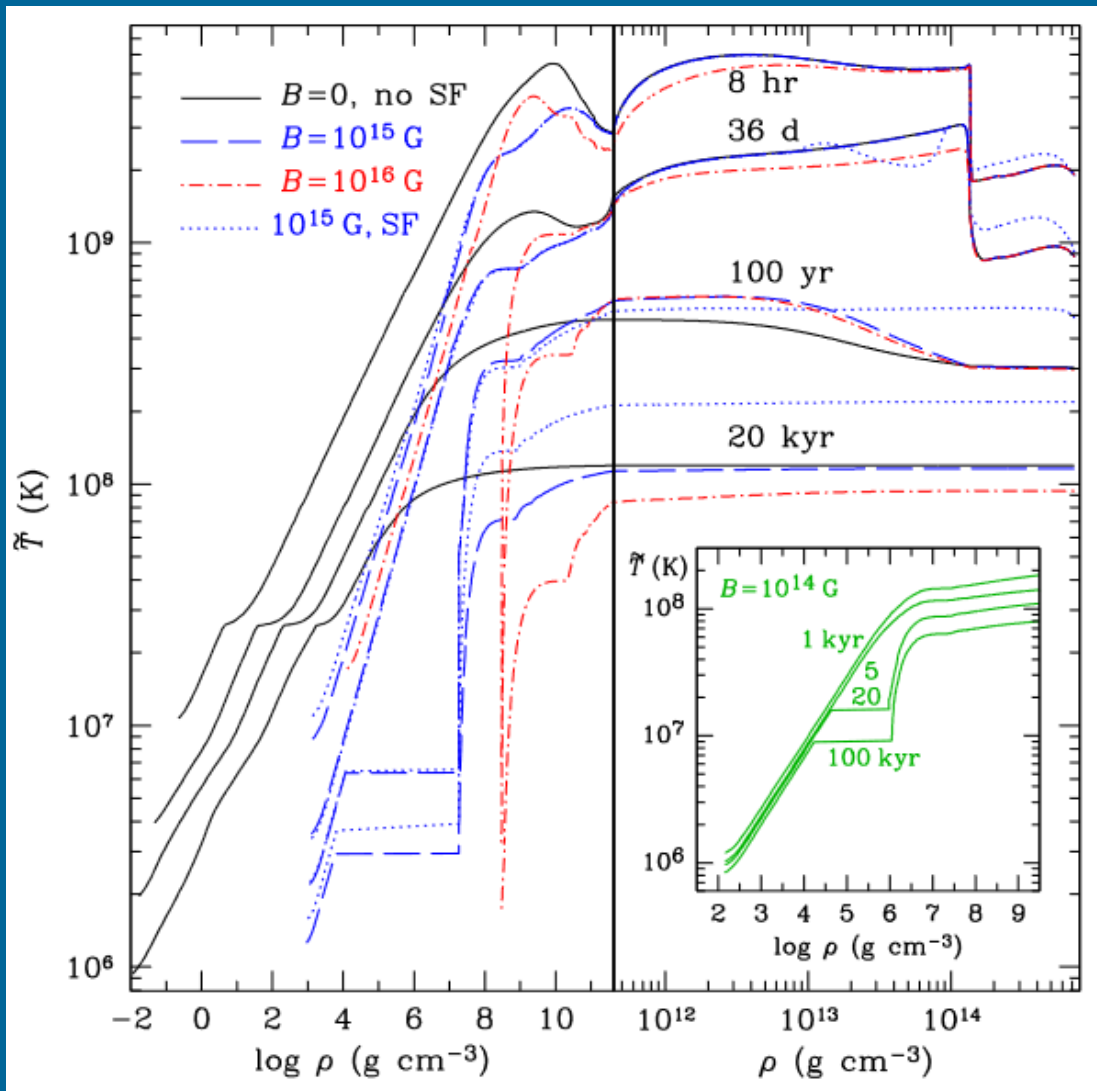
Envelopes and magnetic field



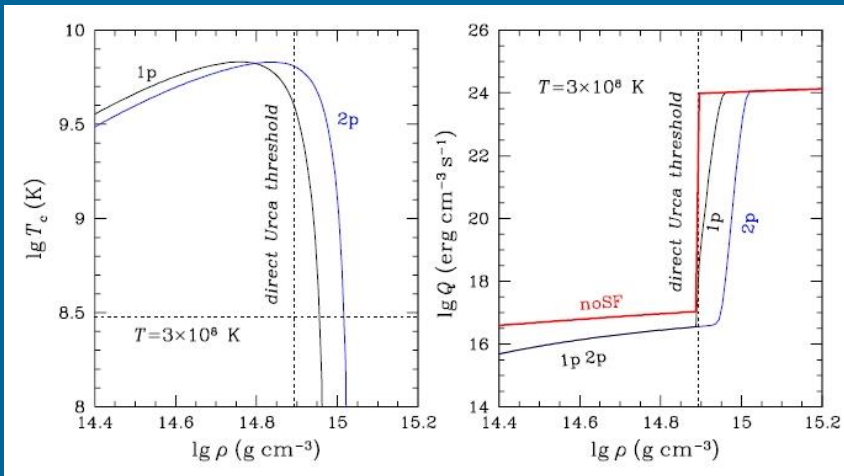
Non-magnetic stars No accreted envelopes, Envelopes + Fields
 Thick lines – no envelope different magnetic fields.
 Envelopes can be related to the fact that we see a subpopulation of hot NS
 in CCOs with relatively long initial spin periods and low magnetic field, but
 do not observed representatives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

(Yakovlev & Pethick 2004)

Magnetar cooling



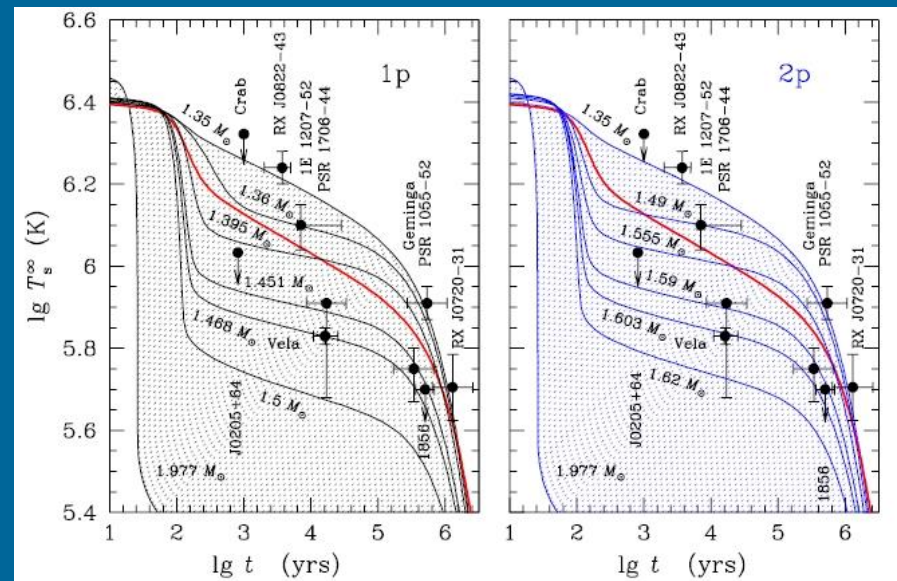
Simplified model: no neutron superfluidity



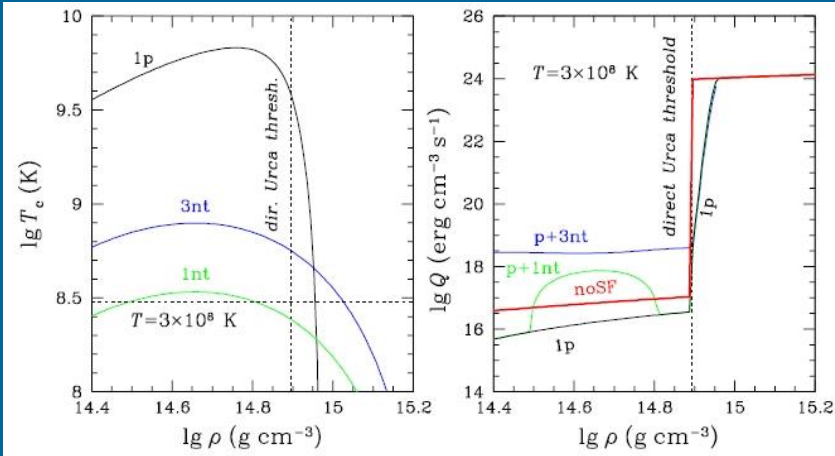
Superfluidity is an important ingredient of cooling models. It is important to consider different types of proton and neutron superfluidity.

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.

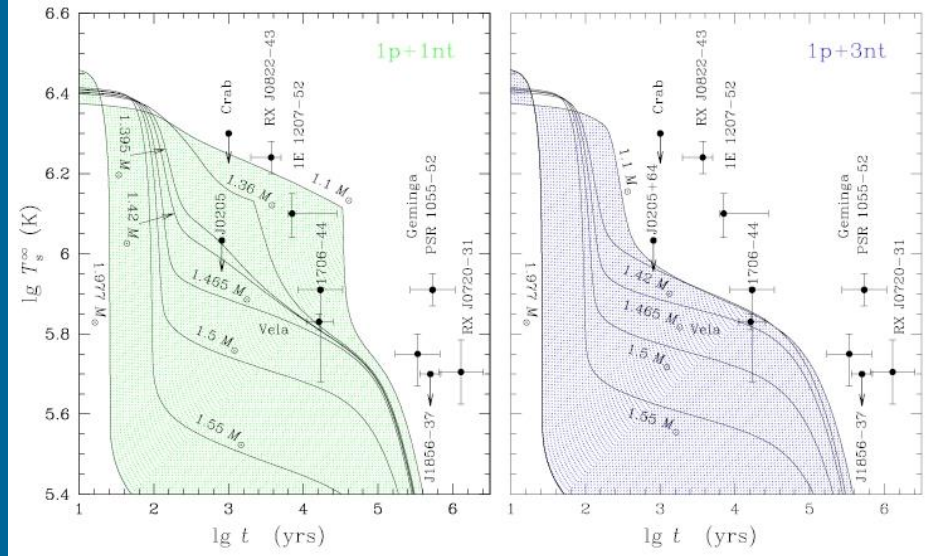


Neutron superfluidity and observations



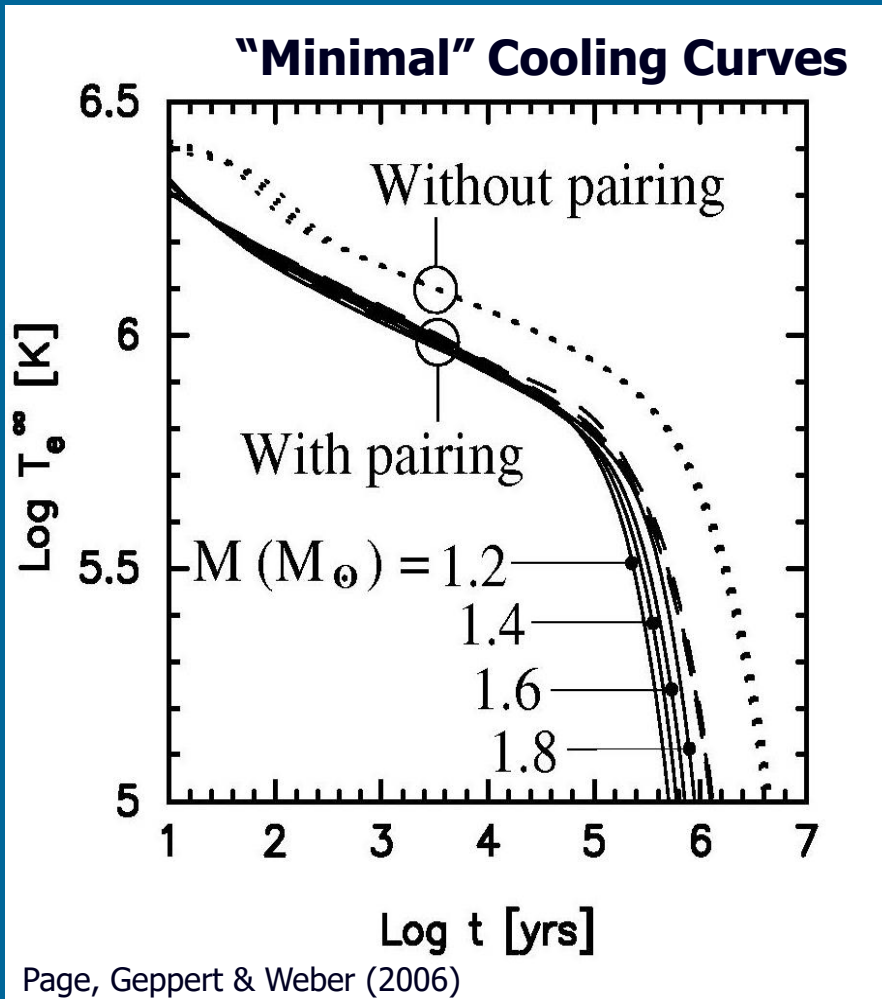
Mild neutron pairing in the core contradicts observations.

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.



(Yakovlev & Pethick 2004)

Minimal cooling model

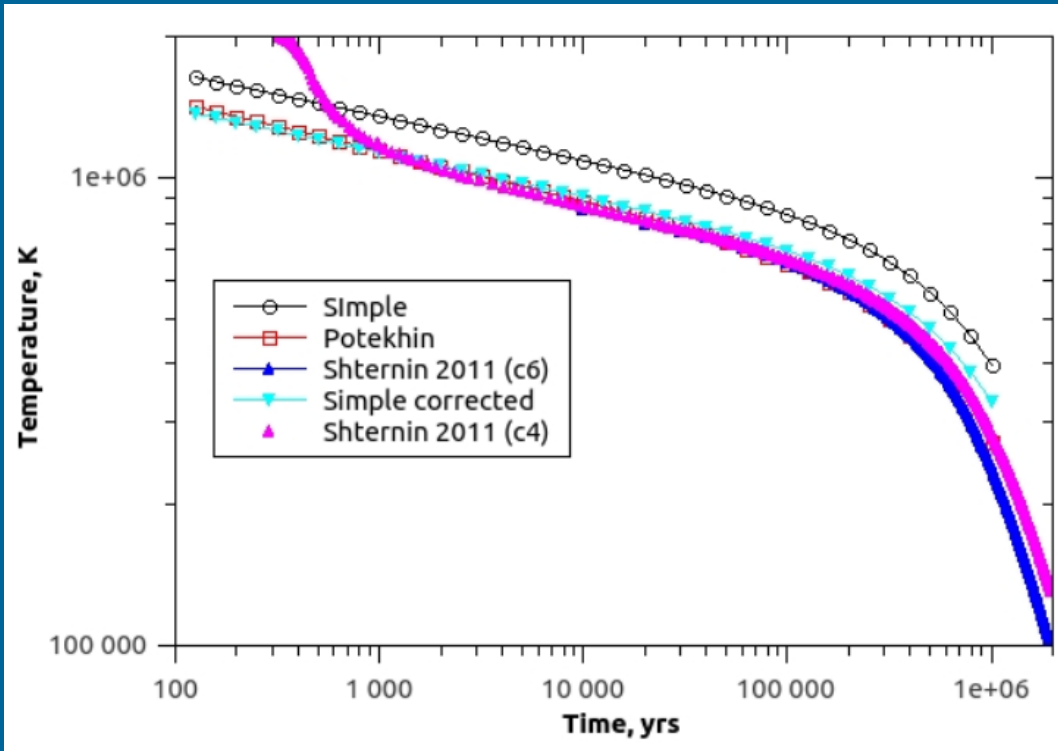


“minimal” means
without additional cooling
due to direct URCA
and without additional heating

Main ingredients of the minimal model

- EoS
- Superfluid properties
- Envelope composition
- NS mass

Analytical fits



$$T_{\text{surface}} \sim T_{\text{core}}^{1/2}$$

$$T_{\text{eff6}} = T_* \equiv (7 T_{\text{b9}} \sqrt{g_{14}})^{1/2}.$$

(iron envelope)

$$T_{\text{eff6,a}}^4 = g_{14} (18.1 T_{\text{b9}})^{2.42},$$

(accreted envelope)

astro-ph/9706148

astro-ph/0105261

$$T = b \left(\frac{t}{1\text{yr}} \right)^a \exp(-t/\tau_c).$$

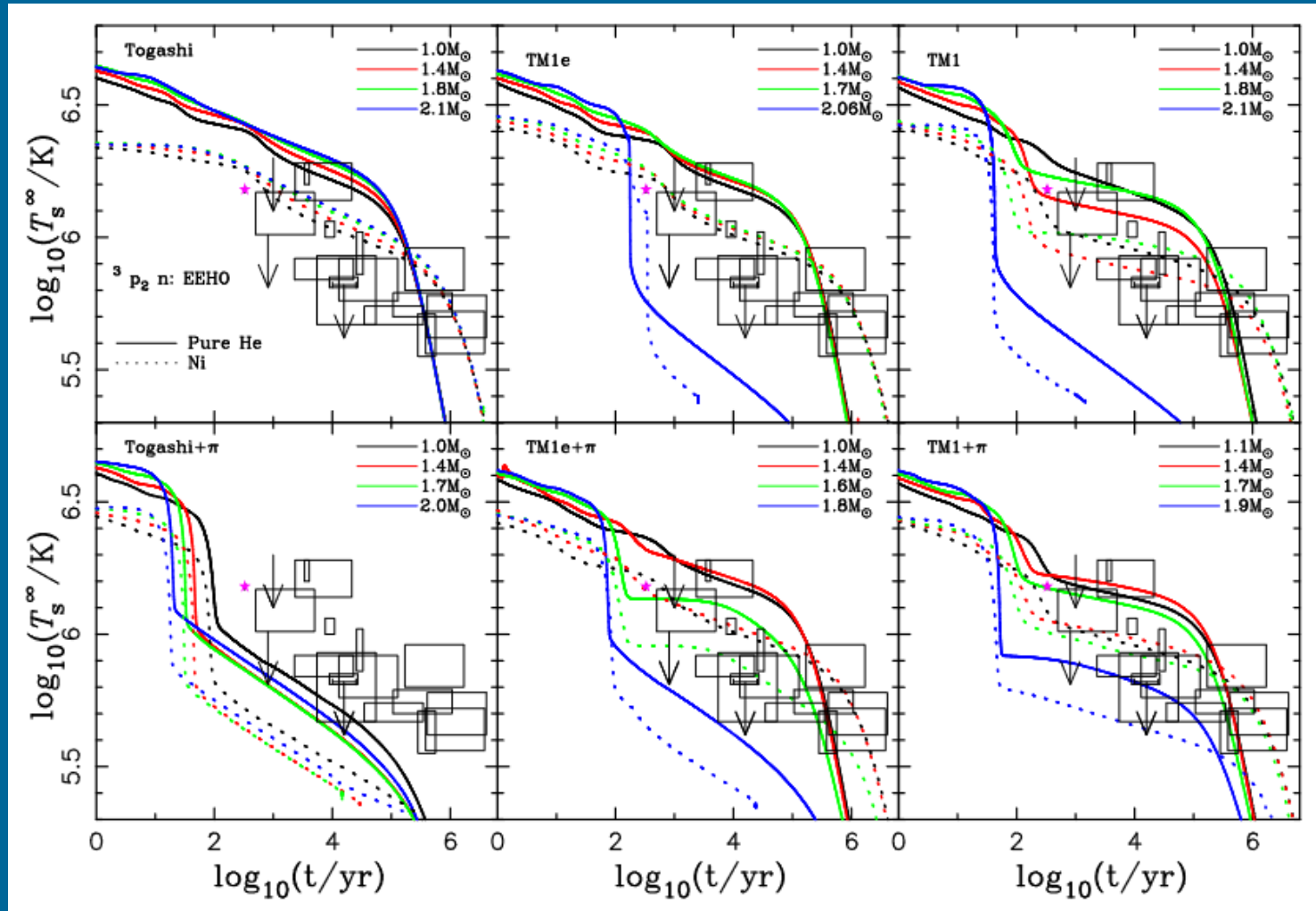
1709.10385

$$T_s^{(0)} \approx 10^6 g_{14}^{1/4} [(7\zeta)^{2.25} + (\zeta/3)^{1.25}]^{1/4} \text{ K}, \quad (27)$$

where $\zeta \equiv T_{\text{int},9} - 0.001 g_{14}^{1/4} \sqrt{7 T_{\text{int},9}}$, $T_{\text{int},9} \equiv T_{\text{int}}/(10^9 \text{ K})$ and $g_{14} \equiv g/10^{14} \text{ cm s}^{-2}$.

Non-standard cooling: role of pions

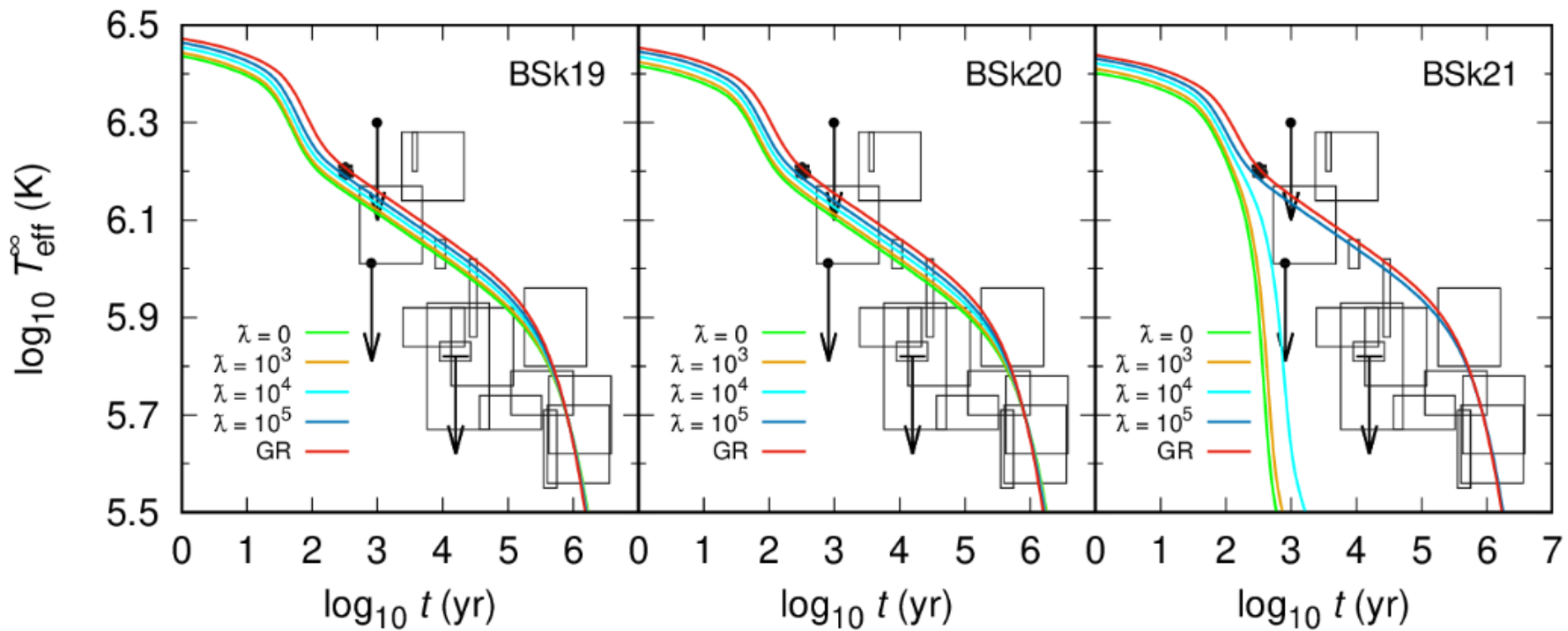
Upper panels:
no pions.



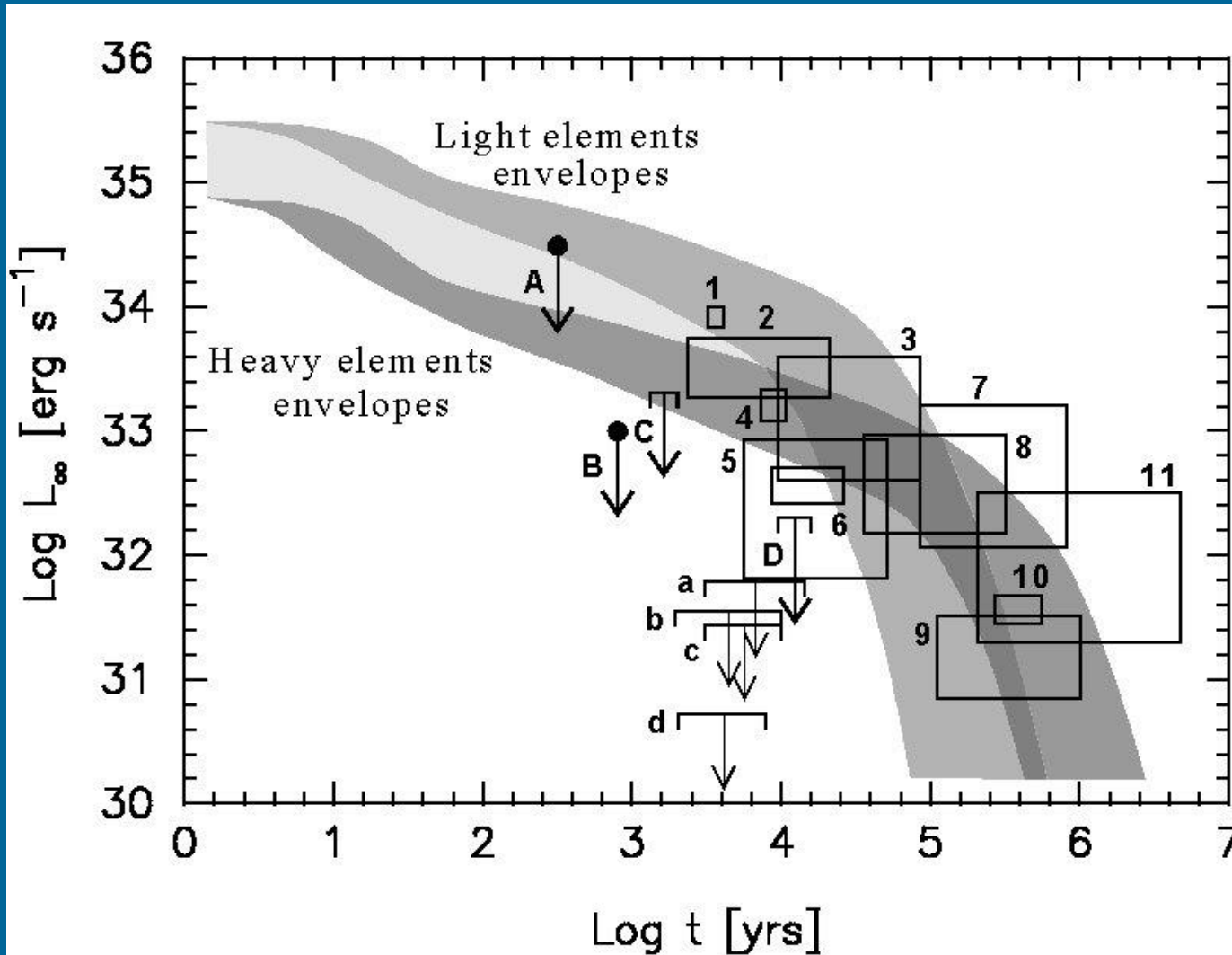
NS cooling in modified gravity theories

scalar-tensor theories

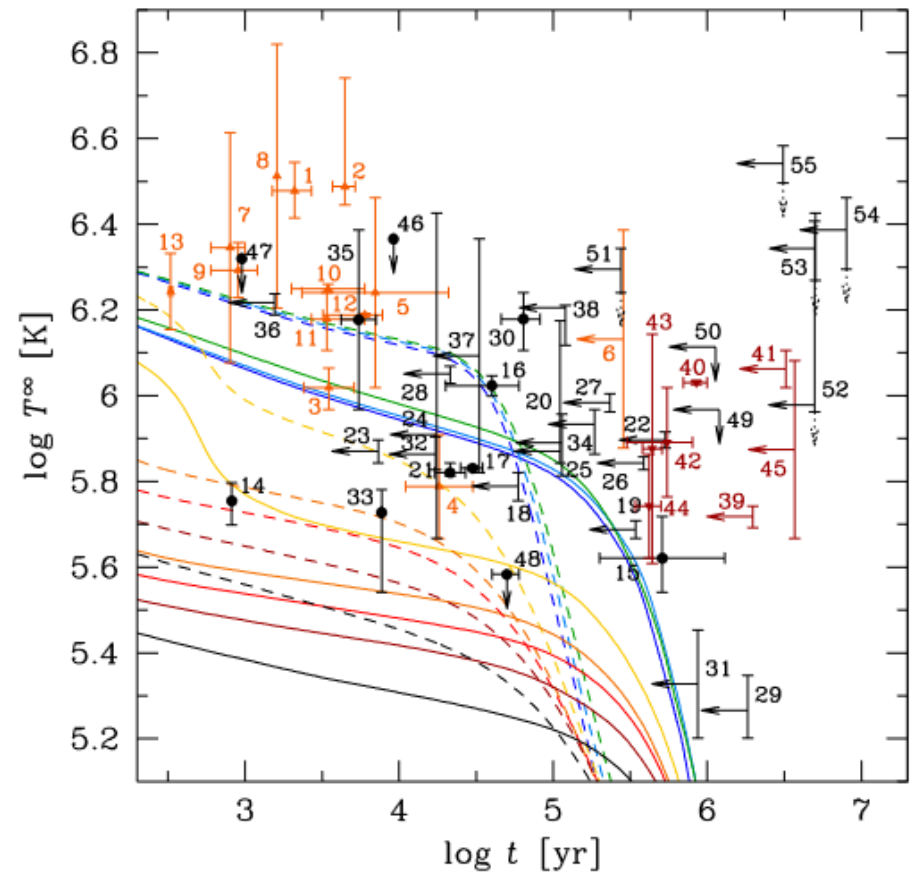
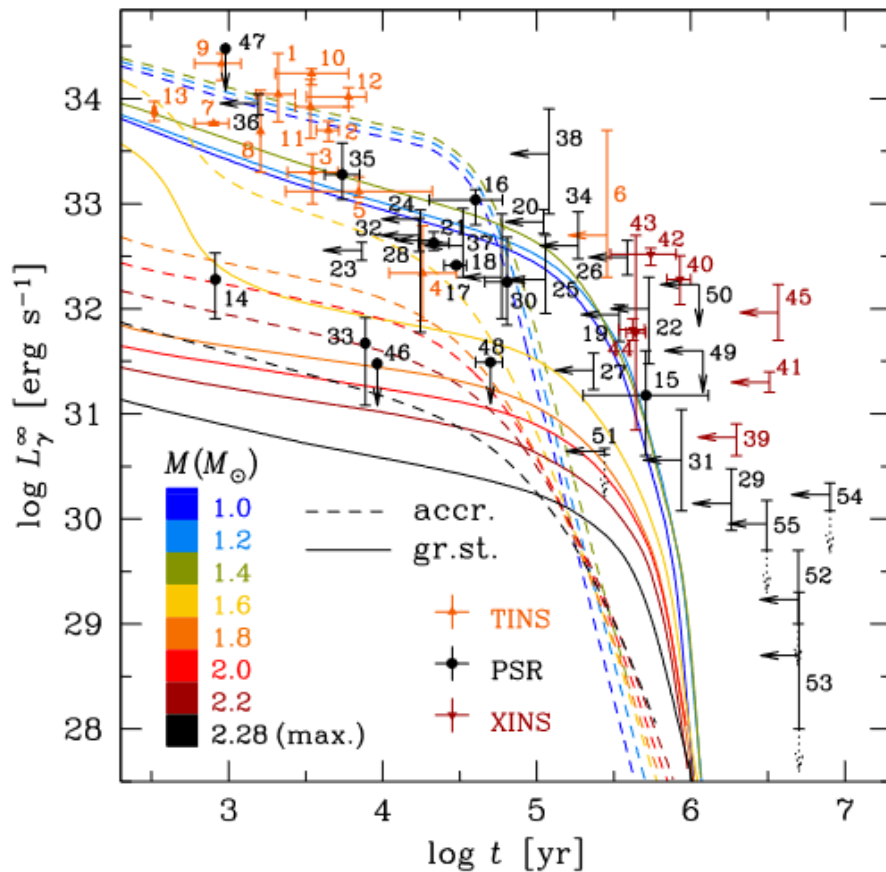
$M=1.4$ Msolar



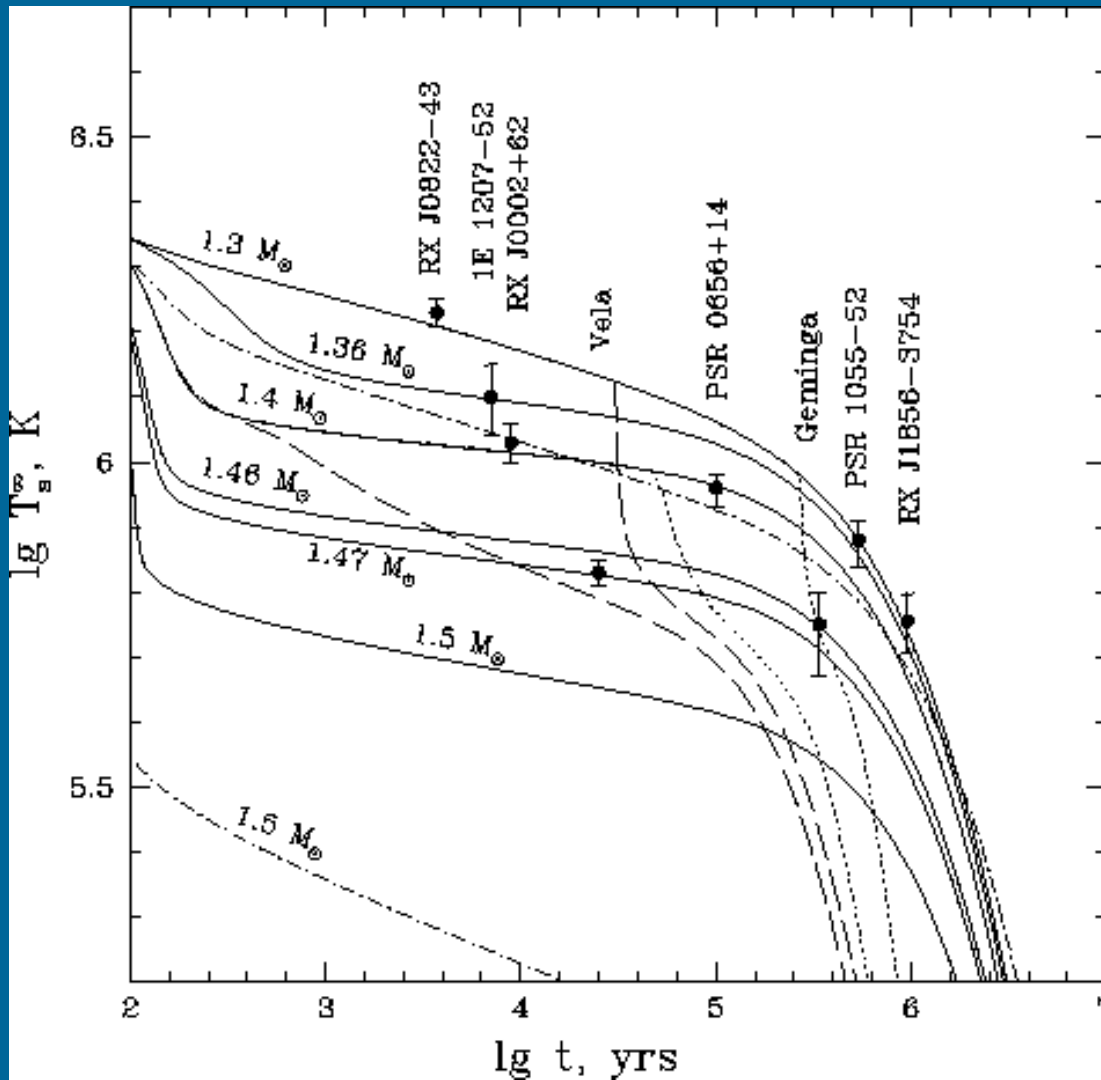
Luminosity and age uncertainties



Large set of data



Standard test: temperature vs. age



Kaminker et al. (2001)

Data

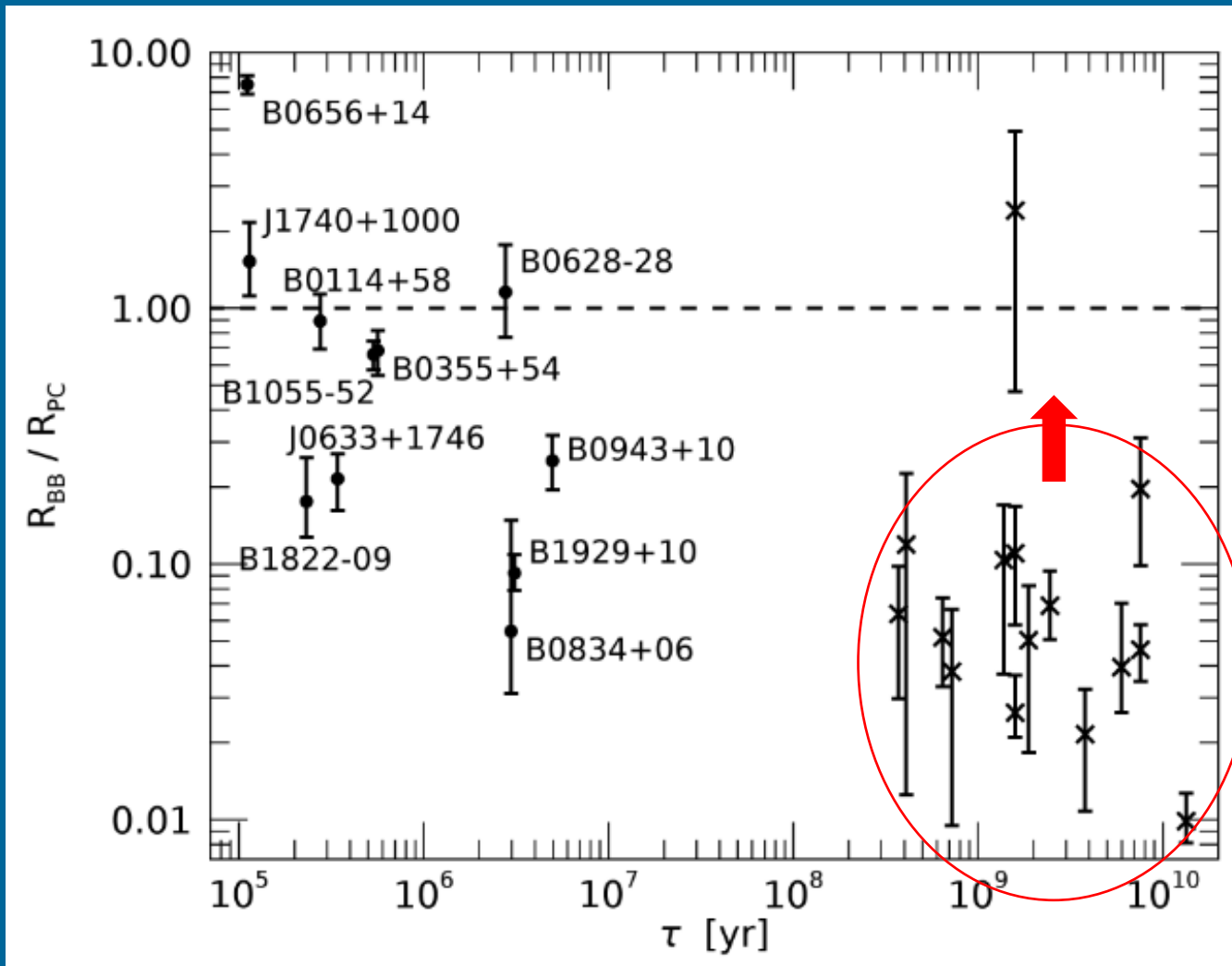
NEUTRON STAR PROPERTIES WITH HYDROGEN ATMOSPHERES

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_{∞} 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 ± 0.2	–	5.55 – 5.95	5.0 – 15.0	0.1 – 0.3	31.3 – 32.5

Not to mix with polar caps heating!



$$R_{\text{cap}} = R_{\text{NS}} (R_{\text{NS}} / R_{\text{I}})^{1/2}$$

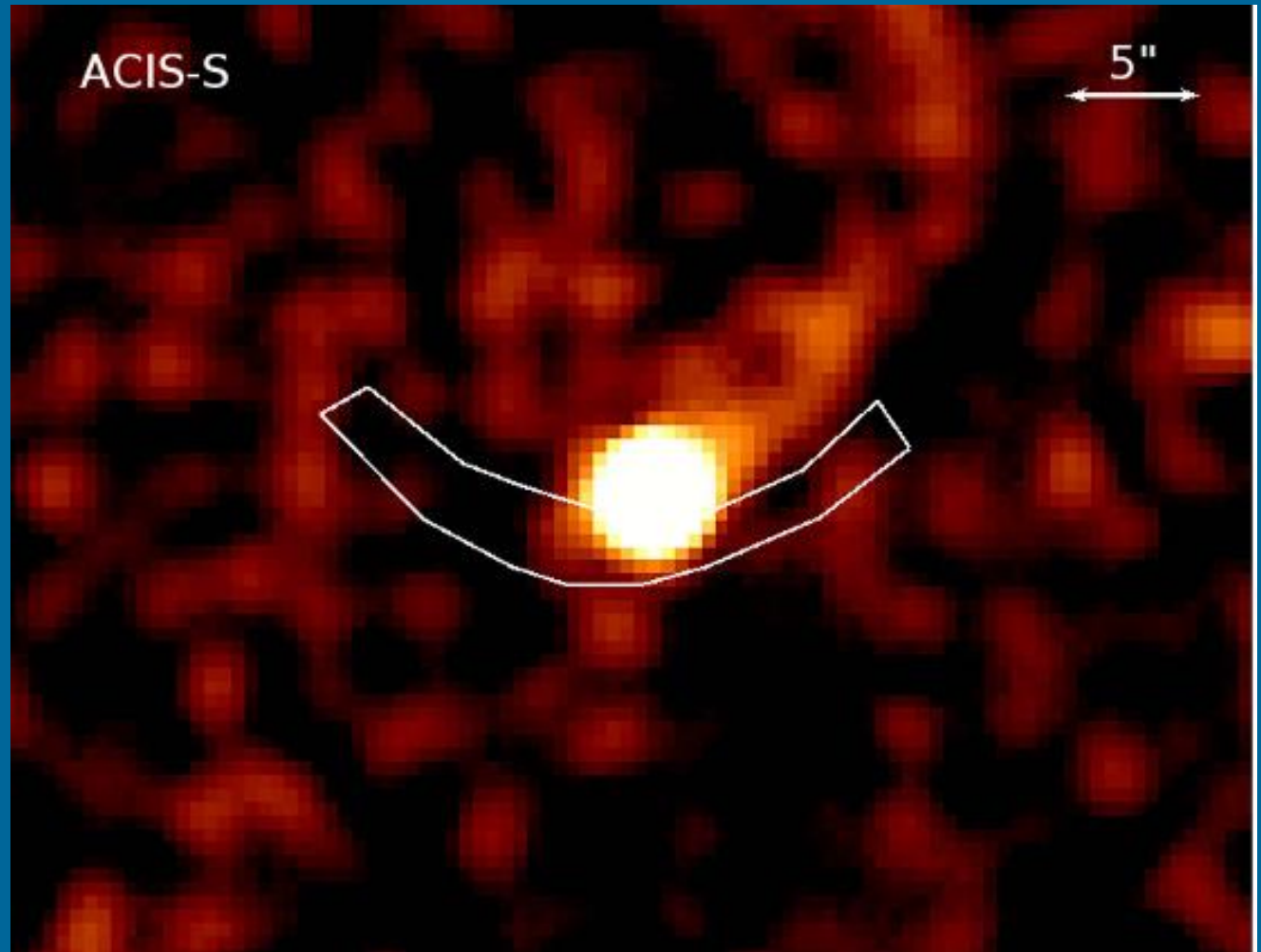
Might be shifted upwards due to account for hydrogen non-magnetic atmosphere

A puzzling source

Millisecond Pulsar
J2124-3358

Characteristic
age 3.4 Gyr

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



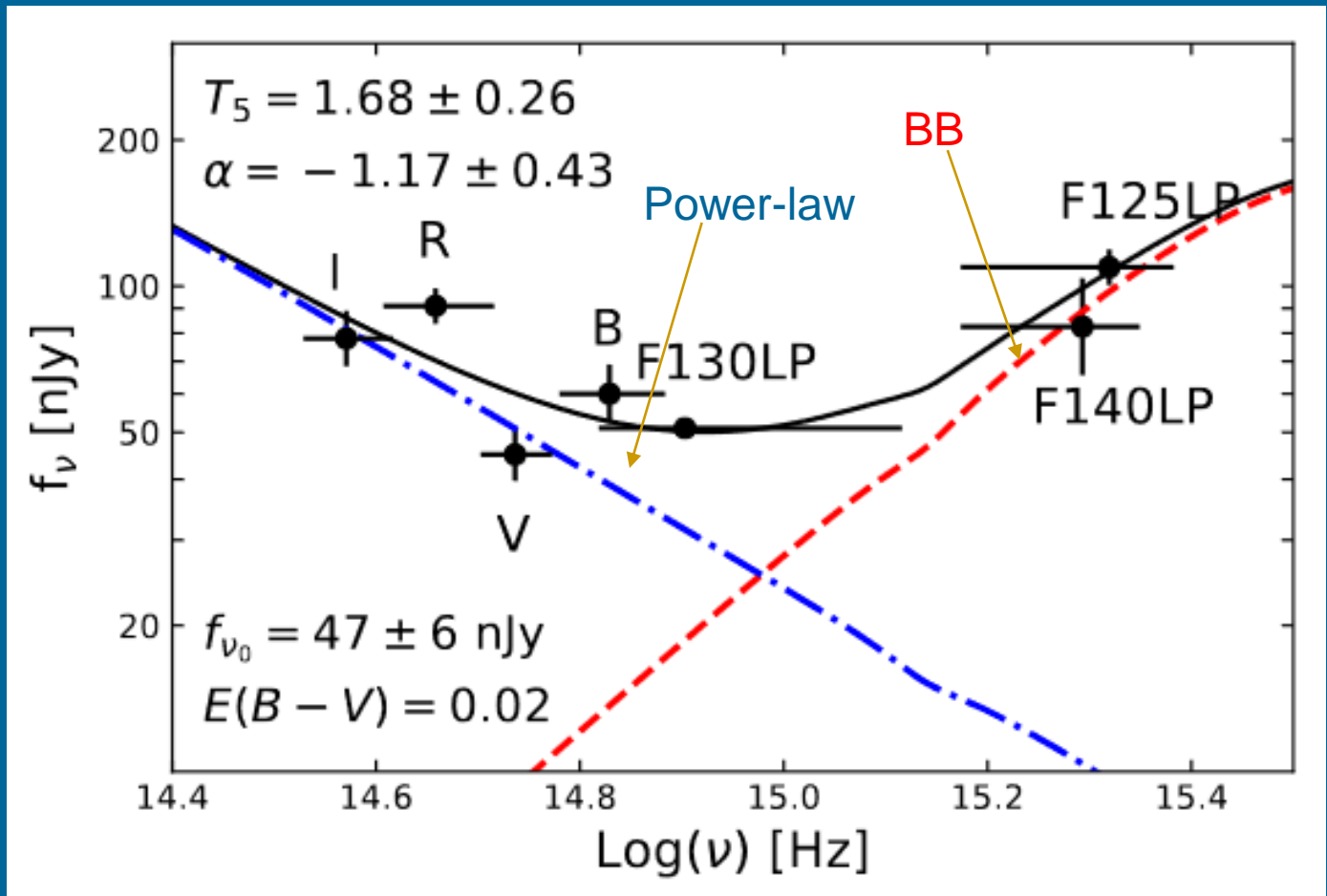
Rangelov et al. (2017)
1701.00002

Another old, but hot

PSR B0950+08

Characteristic
age 17.5 Myr

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



Rotochemical heating

Contraction due to spin down.
Thus, no beta-equilibrium.

$$C \frac{dT^\infty}{dt} = -L_\nu^\infty - L_\gamma^\infty + L_H^\infty,$$

$$L_H^\infty = \sum_{\ell=e,\mu} \sum_{N=n,p} \int dV \eta_\ell \cdot \Delta\Gamma_{M,N\ell} e^{2\Phi(r)}$$

$$\eta_\ell \equiv \mu_n - \mu_p - \mu_\ell$$

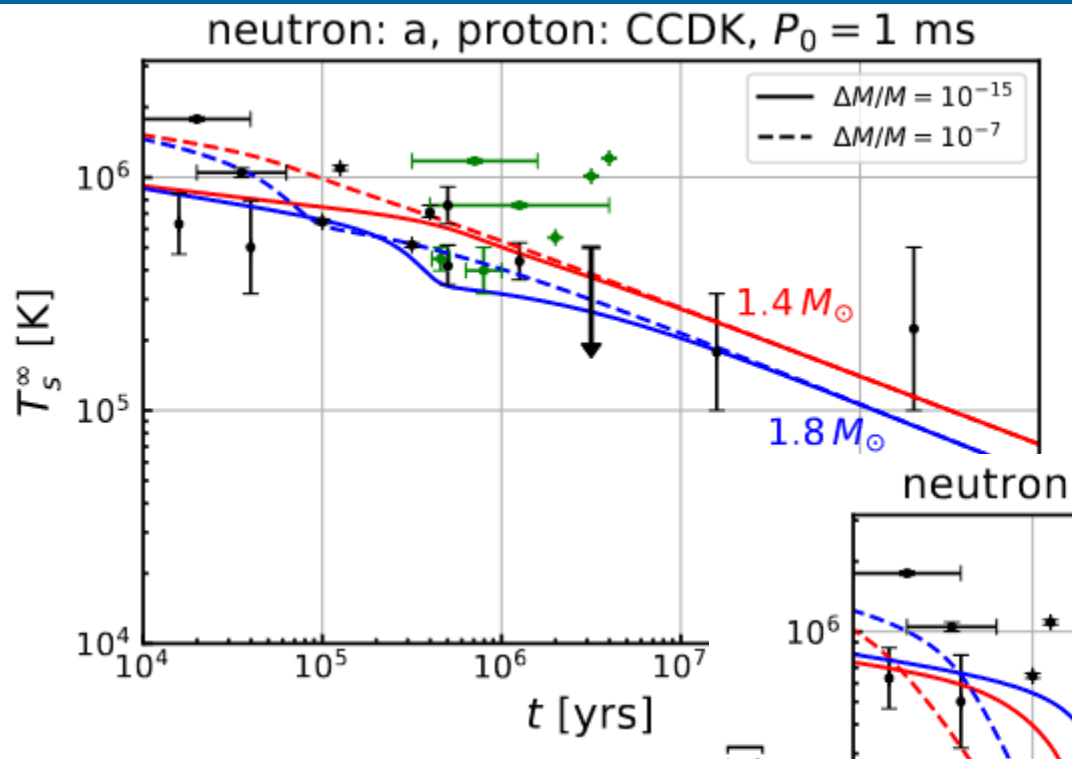
$$\ell = e, \mu.$$

$$\Delta\Gamma_{M,N\ell} = \int \left[\prod_{j=1}^4 \frac{d^3 p_j}{(2\pi)^3} \right] \frac{d^3 p_\ell}{(2\pi)^3} \frac{d^3 p_\nu}{(2\pi)^3} (2\pi)^4 \delta^4(P_f - P_i) \cdot \frac{1}{2} \sum_{\text{spin}} |\mathcal{M}_{M,N\ell}|^2 \\ \times [f_1 f_2 (1 - f_3)(1 - f_4)(1 - f_\ell) - (1 - f_1)(1 - f_2) f_3 f_4 f_\ell] .$$

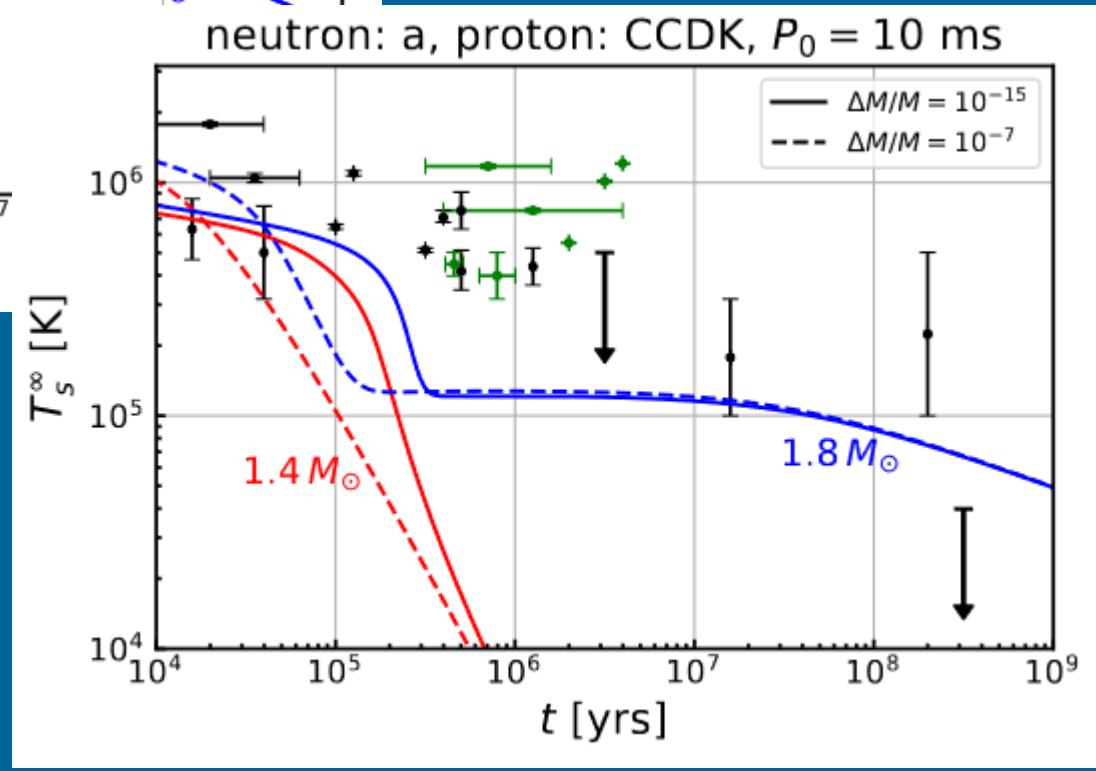
$$\frac{d\eta_e^\infty}{dt} = - \sum_{N=n,p} \int dV (Z_{npe} \Delta\Gamma_{M,Ne} + Z_{np} \Delta\Gamma_{M,N\mu}) e^{\Phi(r)} + 2W_{npe} \Omega \dot{\Omega},$$

$$\frac{d\eta_\mu^\infty}{dt} = - \sum_{N=n,p} \int dV (Z_{np} \Delta\Gamma_{M,Ne} + Z_{np\mu} \Delta\Gamma_{M,N\mu}) e^{\Phi(r)} + 2W_{np\mu} \Omega \dot{\Omega},$$

$$\eta_\ell^\infty \equiv \eta_\ell e^{\Phi(r)}$$



Strong dependence on the initial spin period.



Chemical heating

$$Q_{\text{heat}}^{\infty} = \sum_{l=e,\mu} \eta_l^{\infty} \Delta\Gamma_l e^{\nu/2},$$

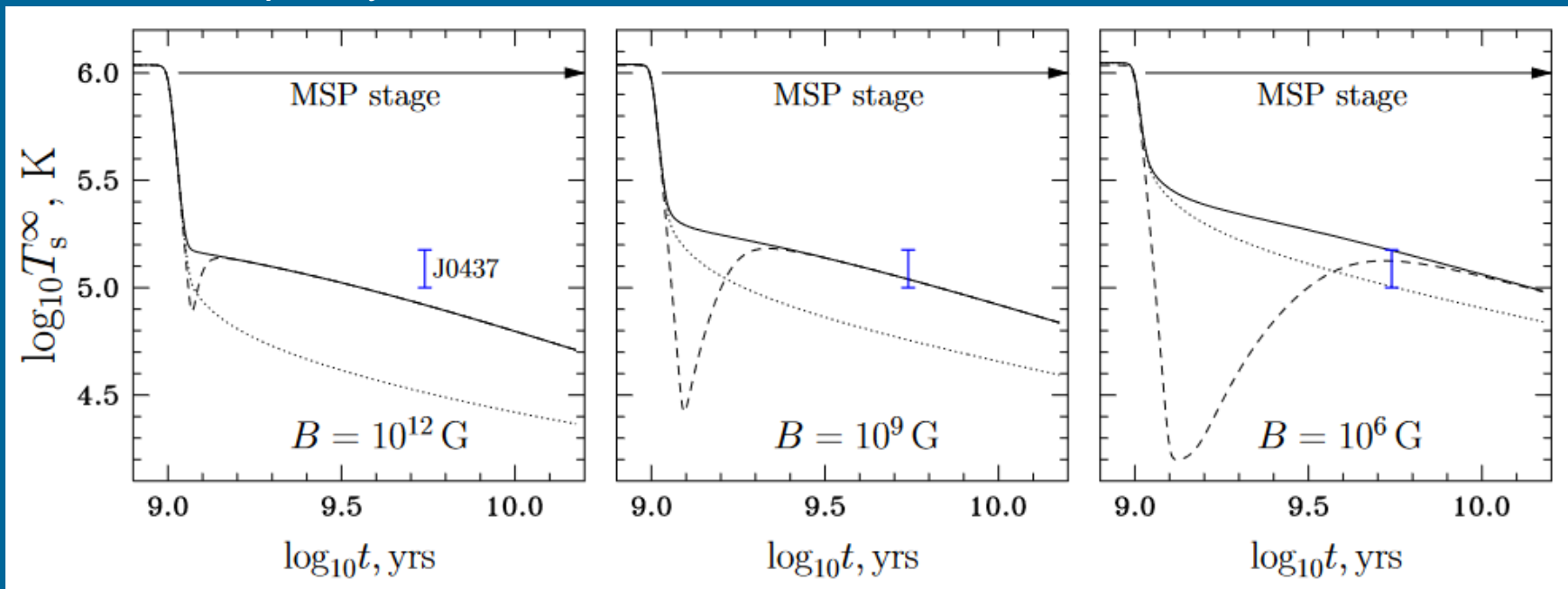
$$L_{\gamma}^{\infty} = 4\pi\sigma R^2 T_s^4 e^{\nu_s}$$

$$C\dot{T}^{\infty} = L_{\text{acc}}^{\infty} - L_{\gamma}^{\infty} + \int_V (Q_{\text{heat}}^{\infty} - Q_{\nu}^{\infty}) dV,$$

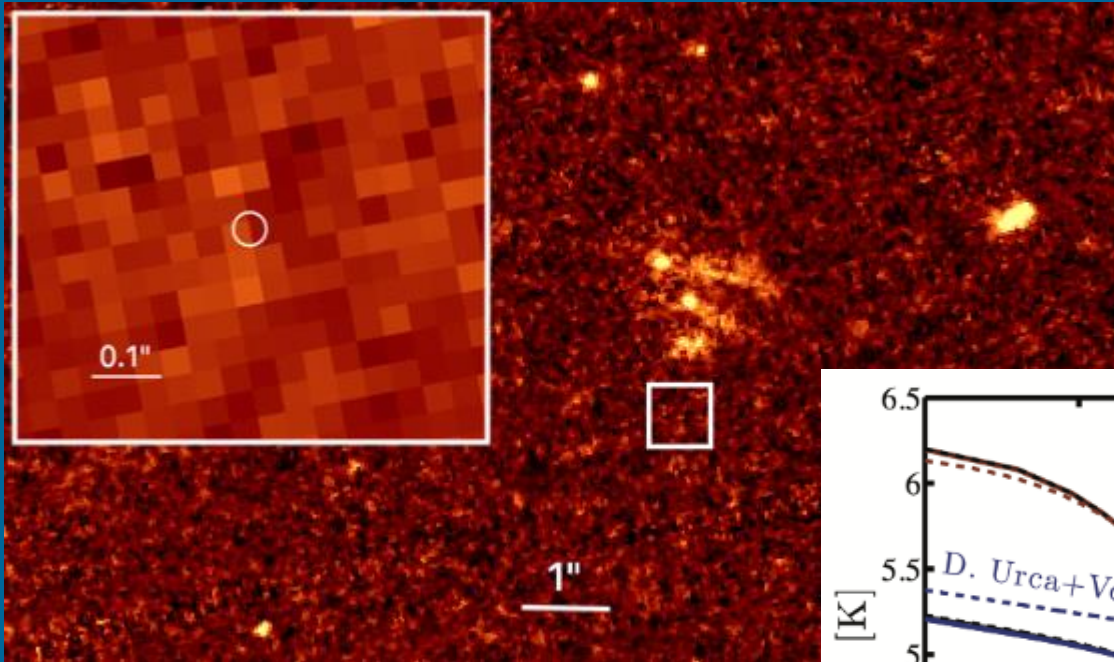
$$L_{\text{acc}}^{\infty} \approx \frac{\dot{M}}{m_u} q e^{\nu_s/2},$$

Magnetic field makes part of the stellar core non-superconducting and allows for unsuppressed nonequilibrium reactions there.

MUrca reactions are not suppressed inside the flux tubes (or normal domains), and are completely forbidden outside.



The coldest NS known



PSR J2144-3933

$P=8.5$ sec

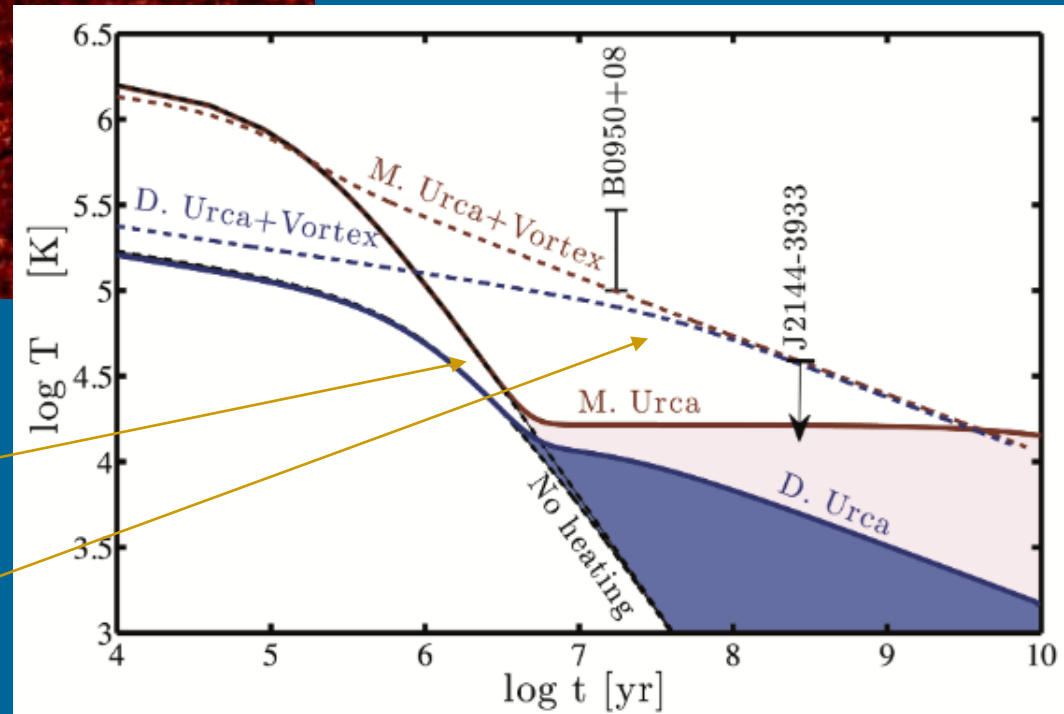
$B=2 \cdot 10^{12}$ G

$d=160-200$ pc

Limit: $T < 42000$ K

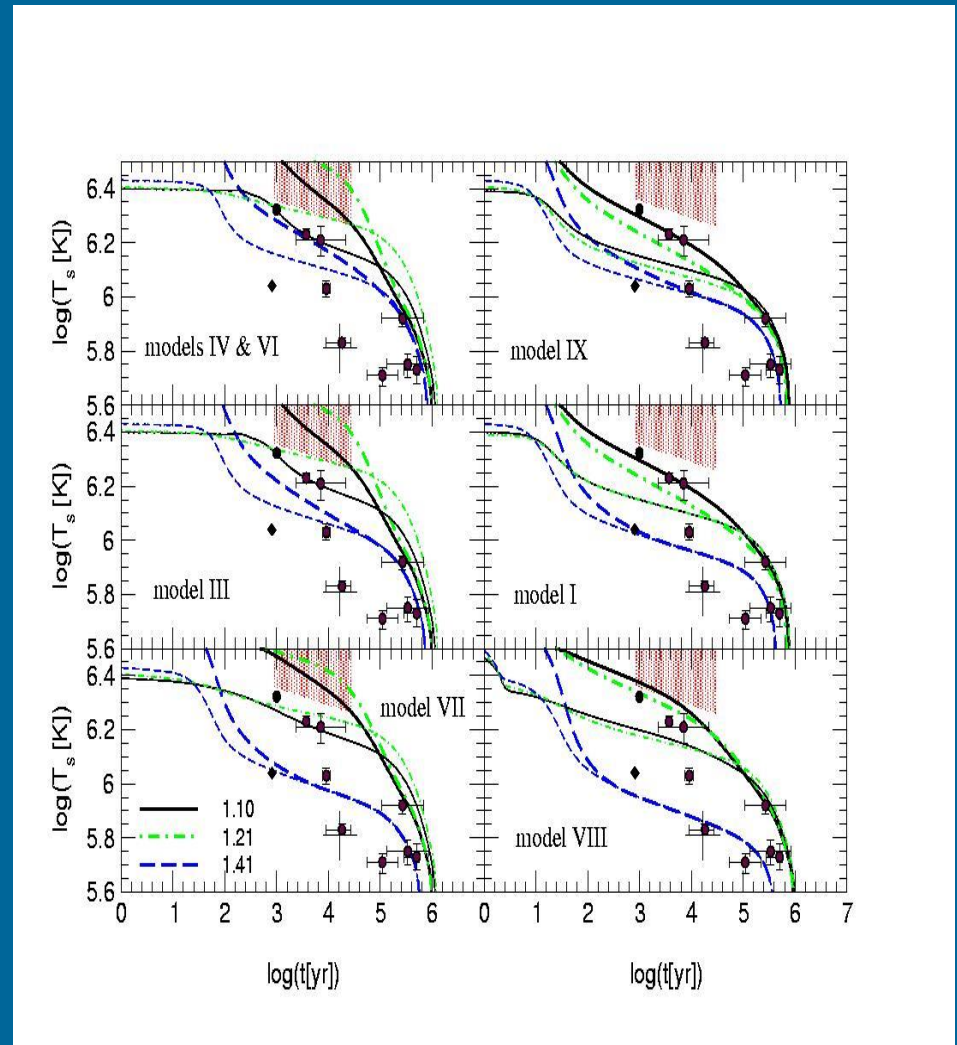
Rotochemical

Rotochemical+vortex friction



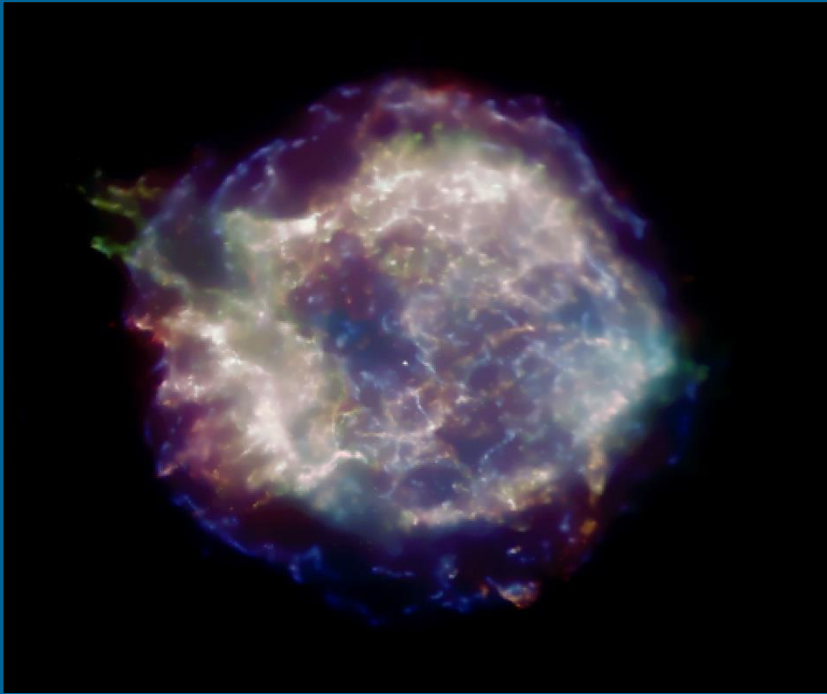
Brightness constraint

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



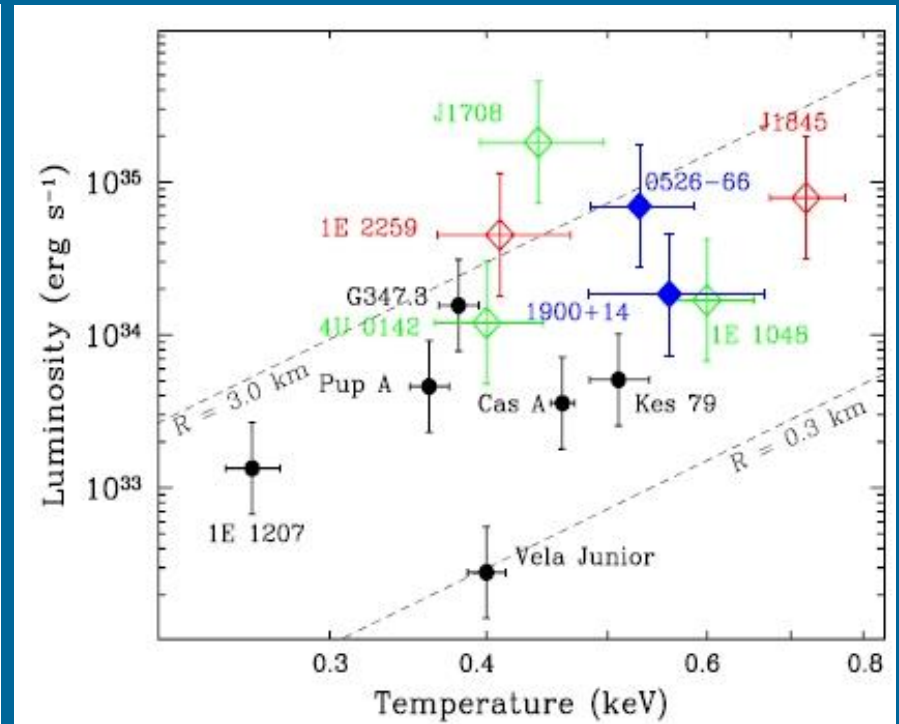
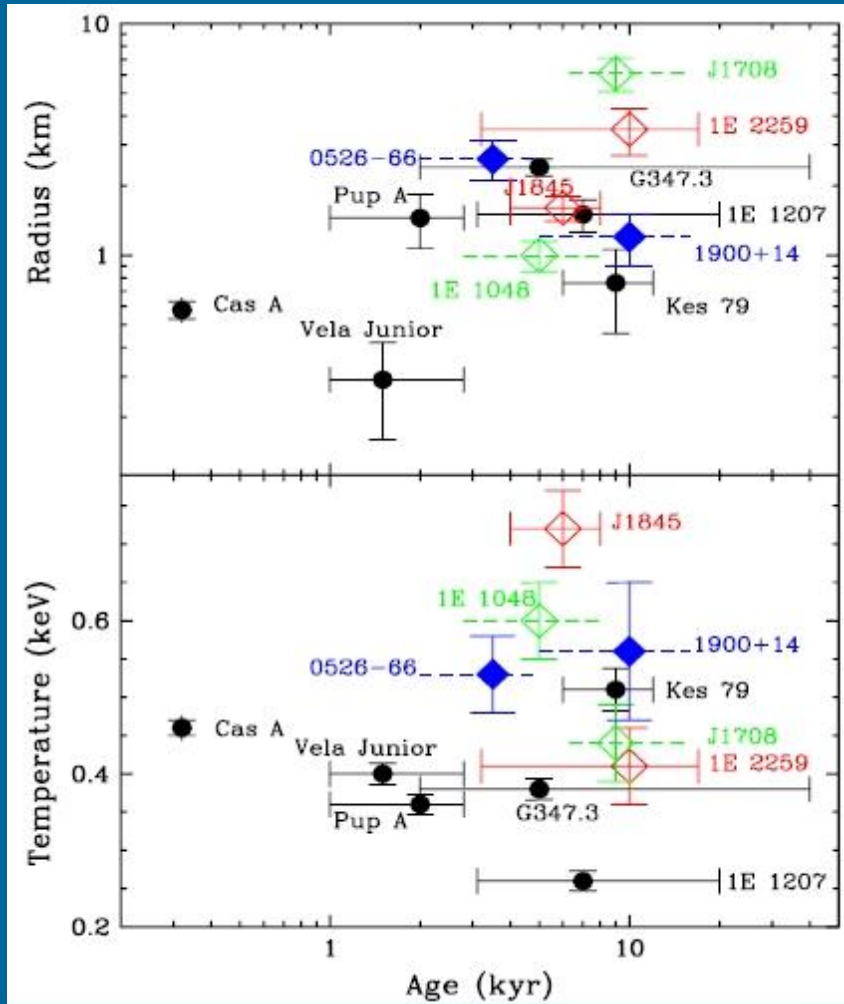
Known objects

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

Object	kT keV	R km	$L_{\text{bol},33}$	Γ	$L_{\text{pl},33}$	$n_{\text{H},22}$	$F^{\text{bb}}/F^{\text{pl}}$
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

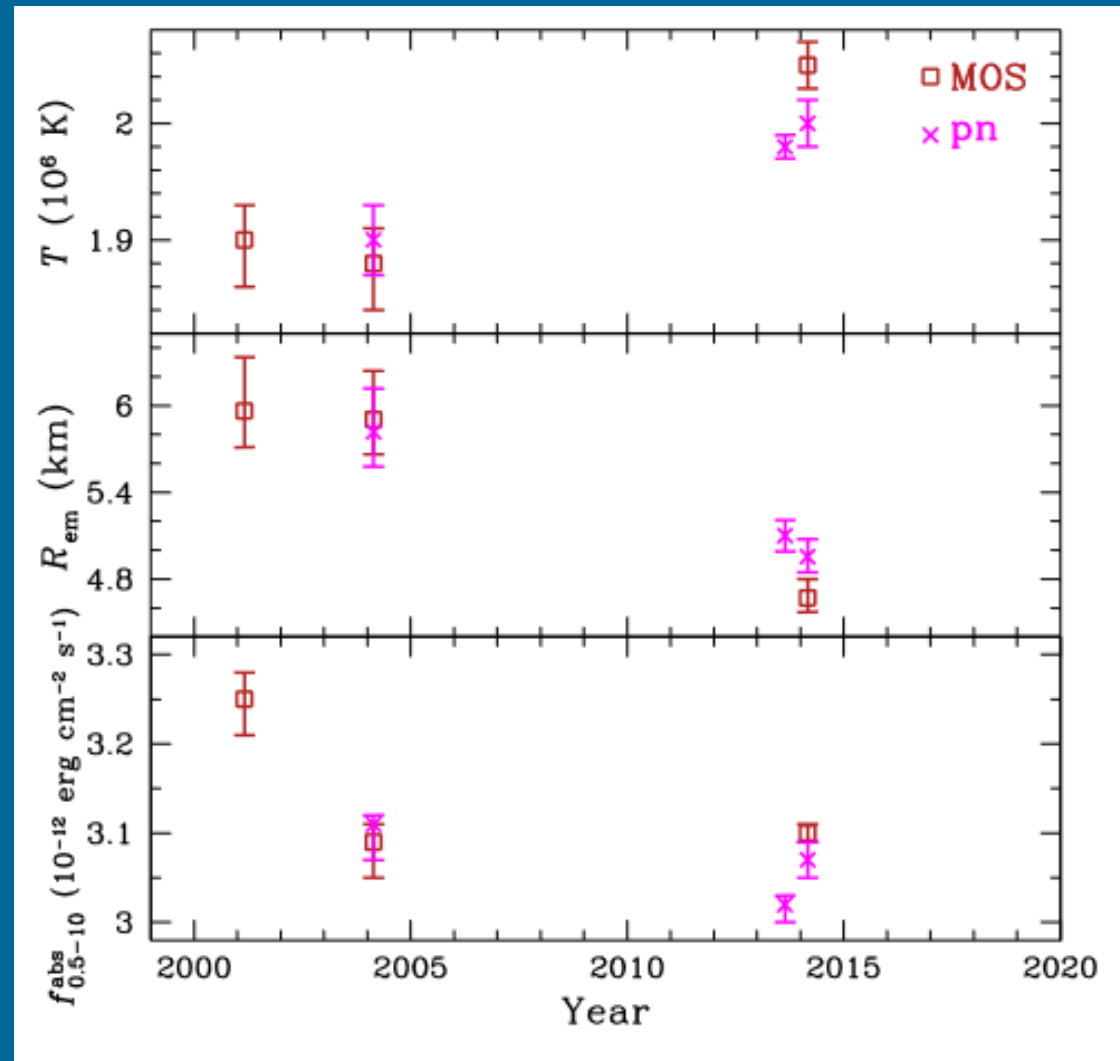


(Pavlov et al. astro-ph/0311526)

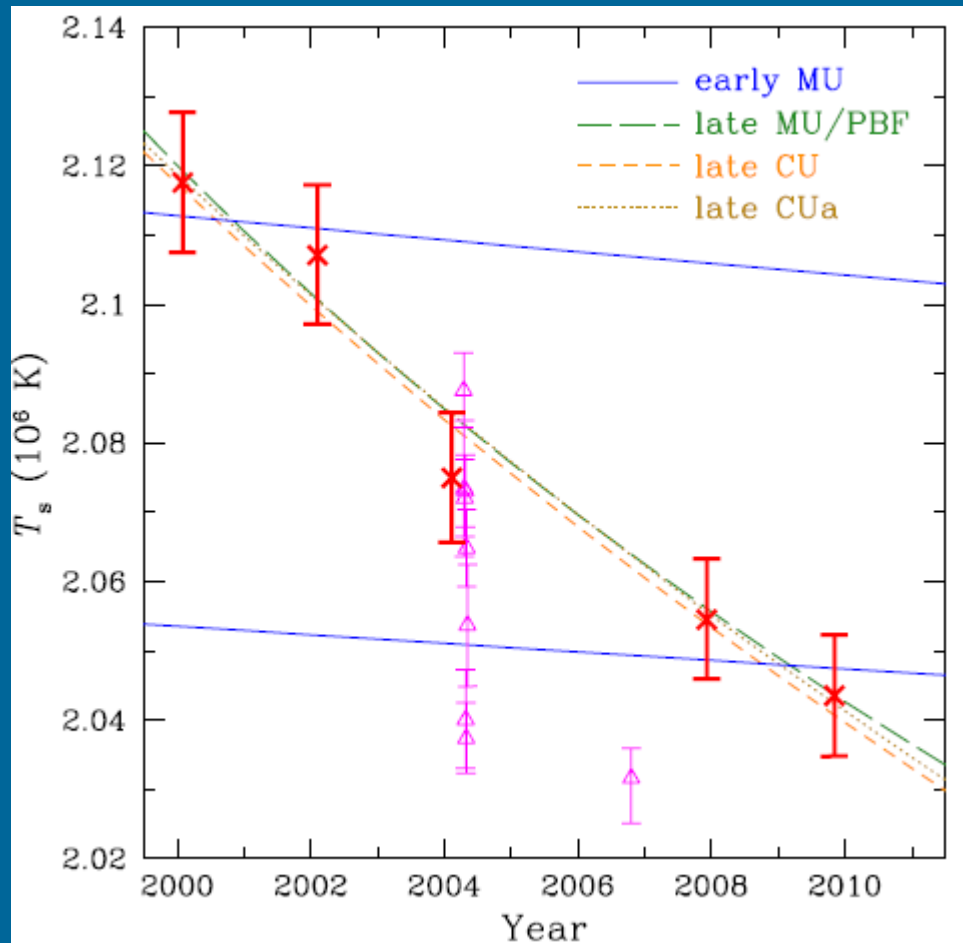
Increasing temperature?

1WGA J1713.4-3949

age 1500-2300 yrs



Cas A peculiar cooling



330 years

~3.5 kpc

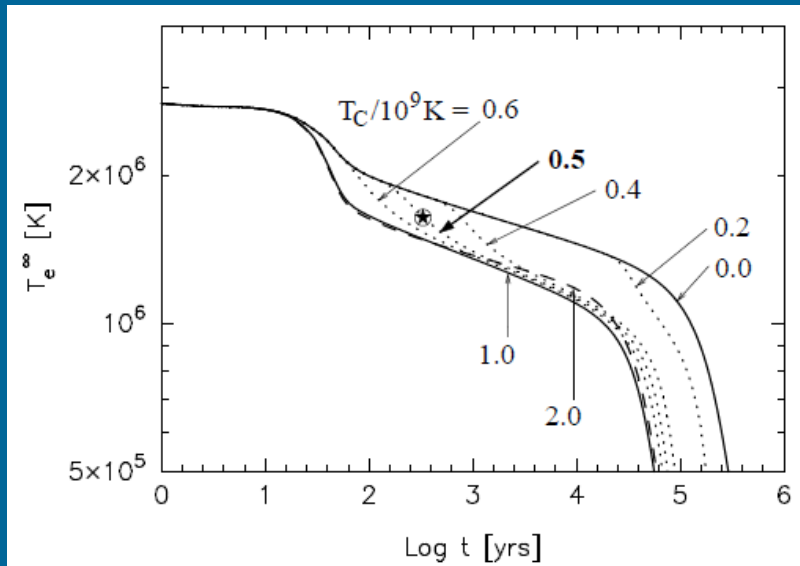
Carbon atmosphere

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

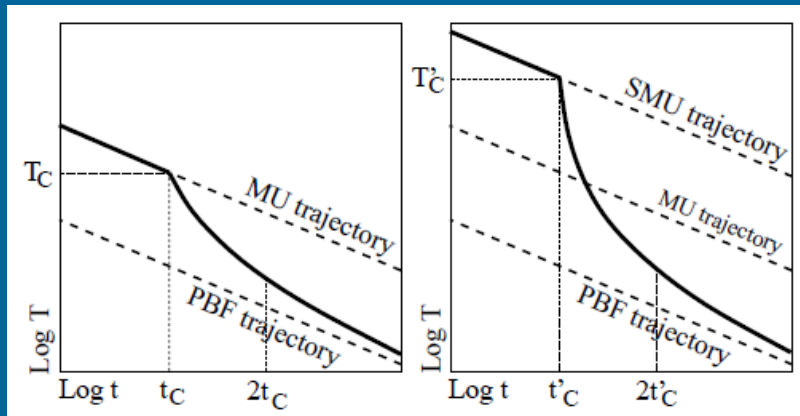
Onset of neutron 3P_2 superfluidity in the core



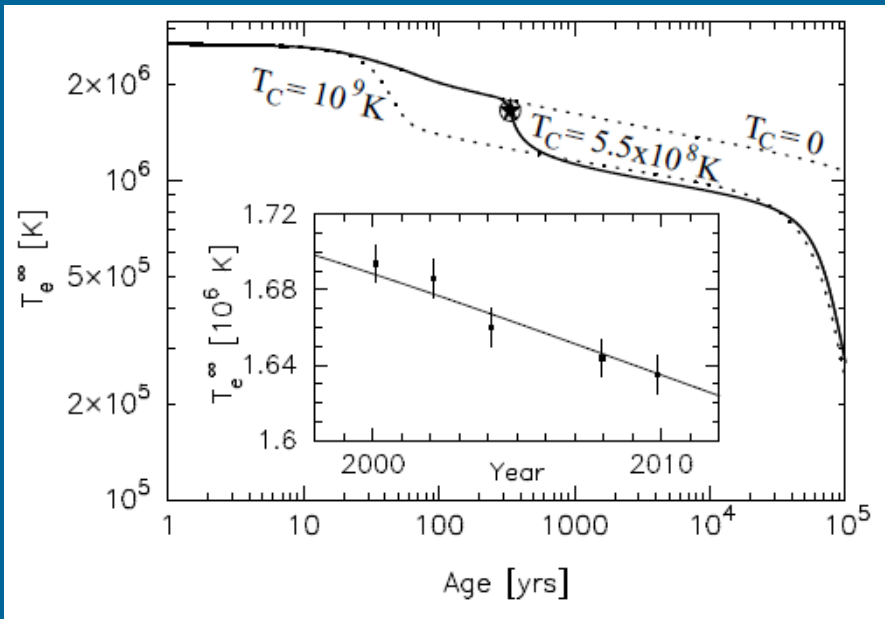
The idea is that we see the result of the onset of neutron 3P_2 superfluidity in the core.

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

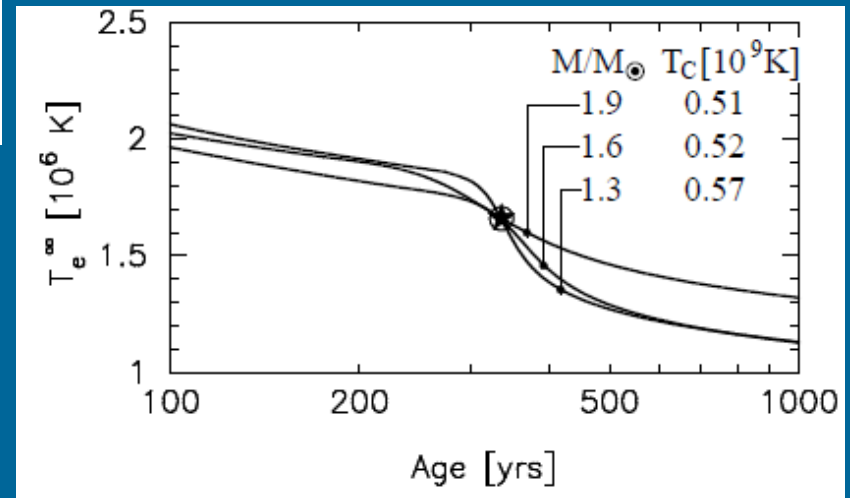


Cooling curves depend on masses, but the estimate of the critical temper. depends on M just slightly.

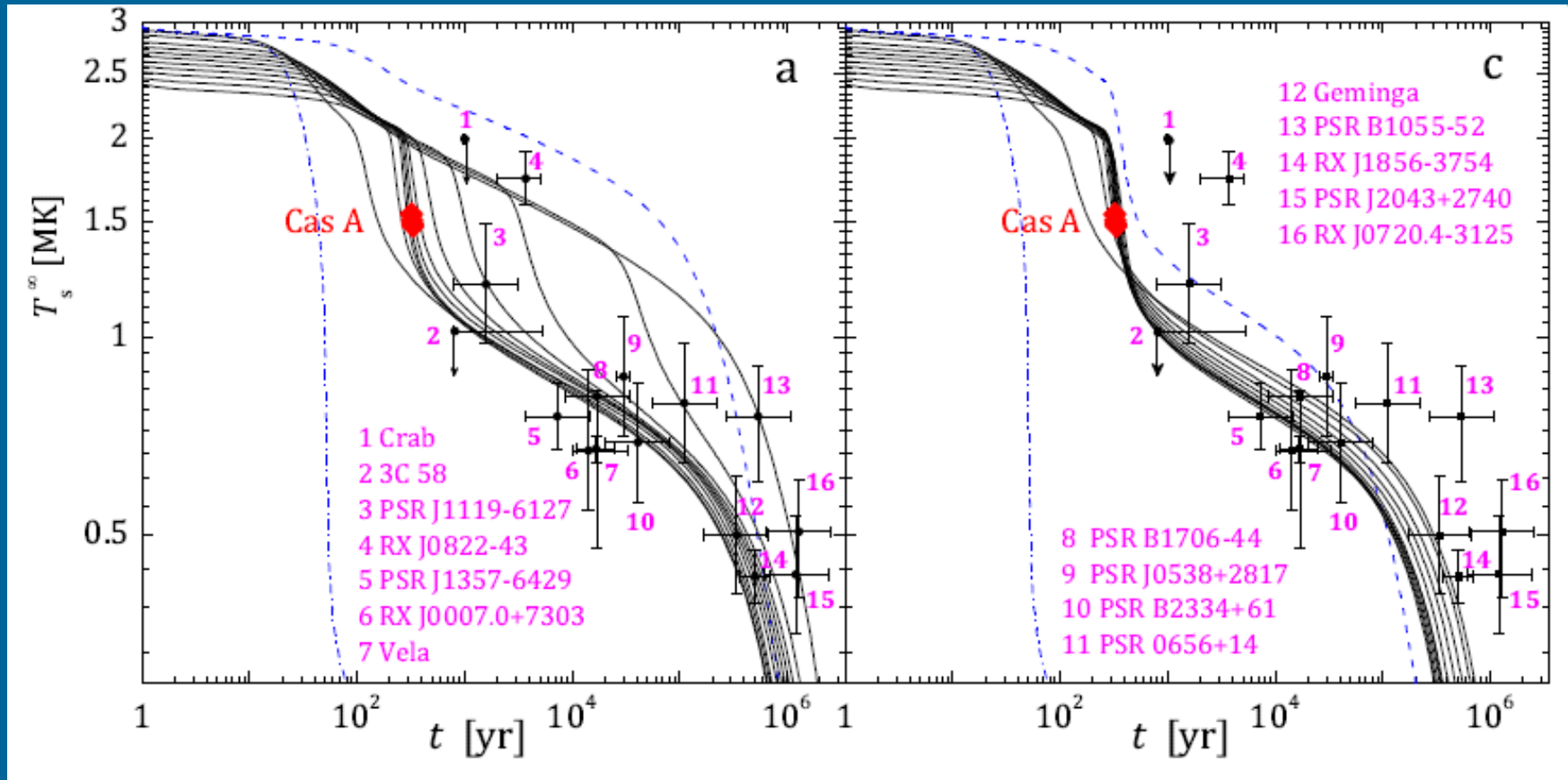
To explain a quick cooling it is necessary to assume suppression of cooling by proton 1S_0 superfluidity in the core.

Rapid cooling will proceed for several tens of years more.

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



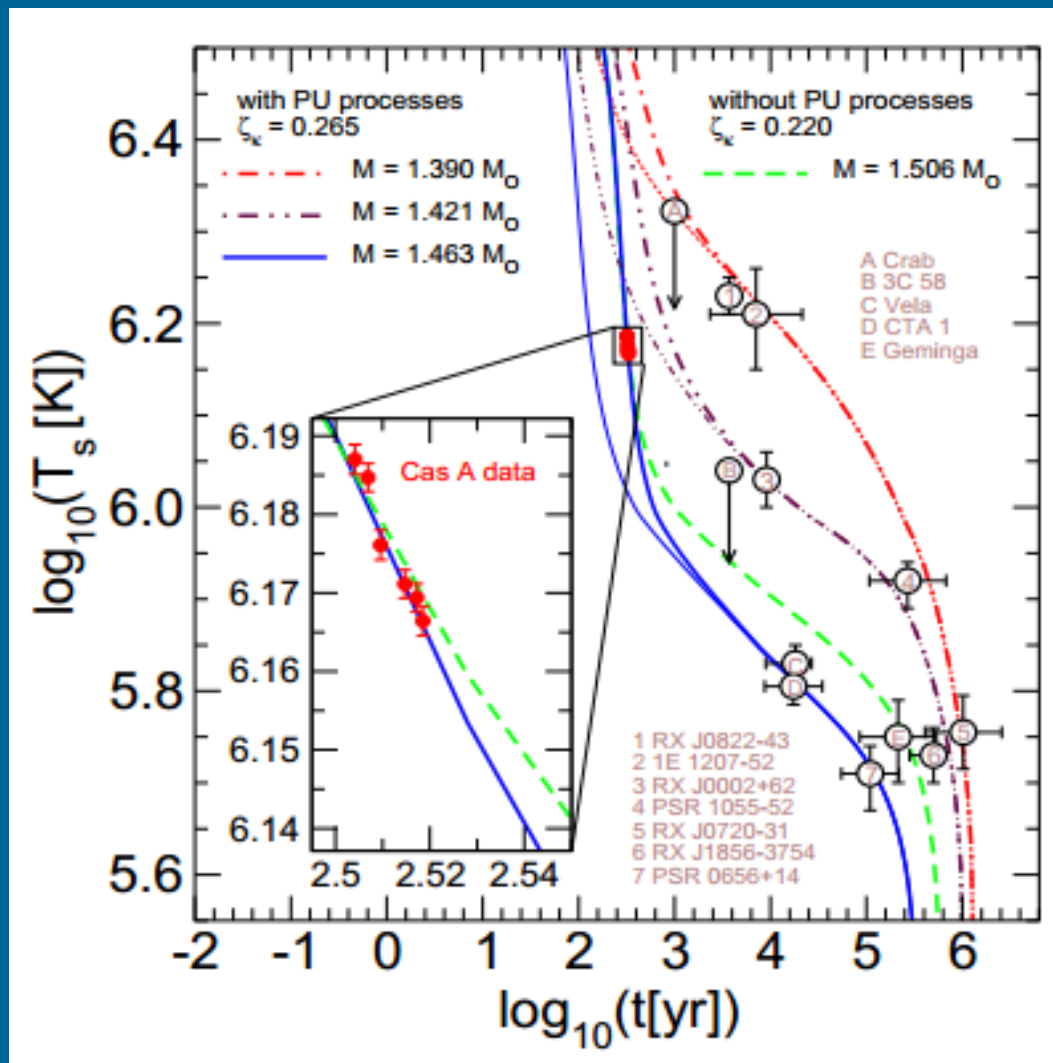
Different superfluidity models



1012.0045

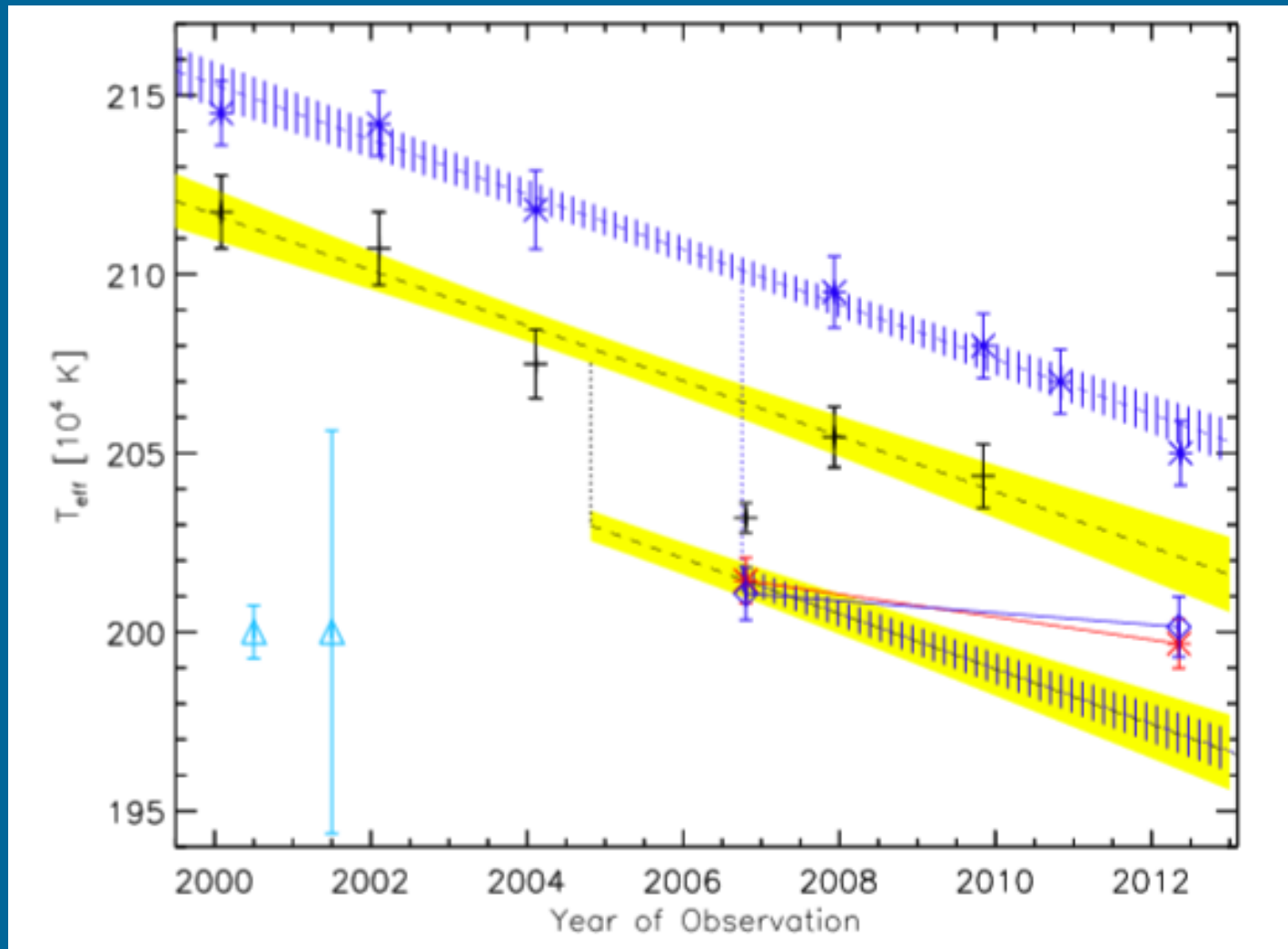
In 2106.05692 the authors obtained strong constraints on the critical temperature in NS interiors: $T_{\text{crit}}=(5-10)10^8$ K

Nuclear medium cooling



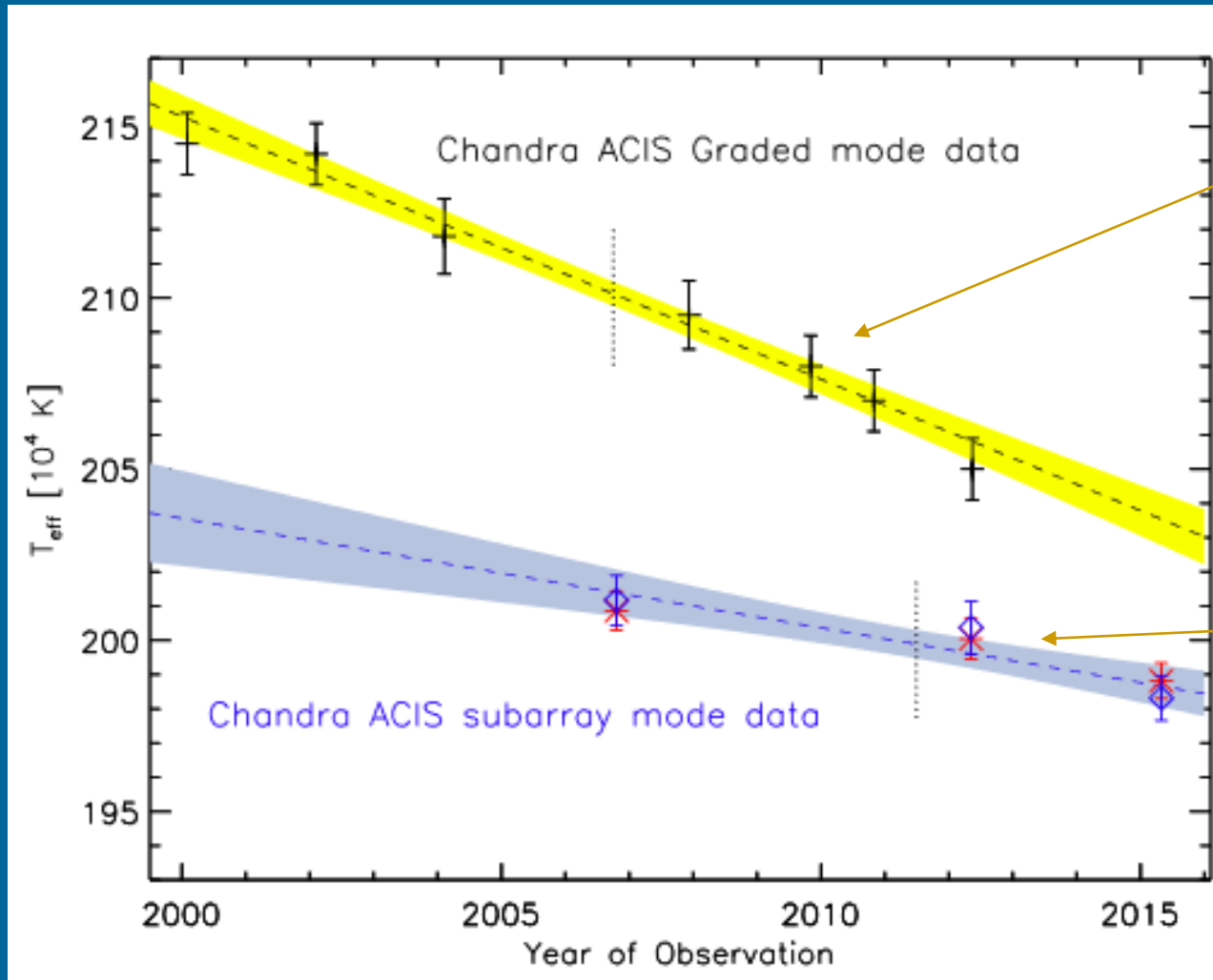
Crucial for the successful description of the observed data is a substantial reduction of the thermal conductivity, resulting from a suppression of both the electron and nucleon contributions to it by medium effects.

New twist: no cooling!



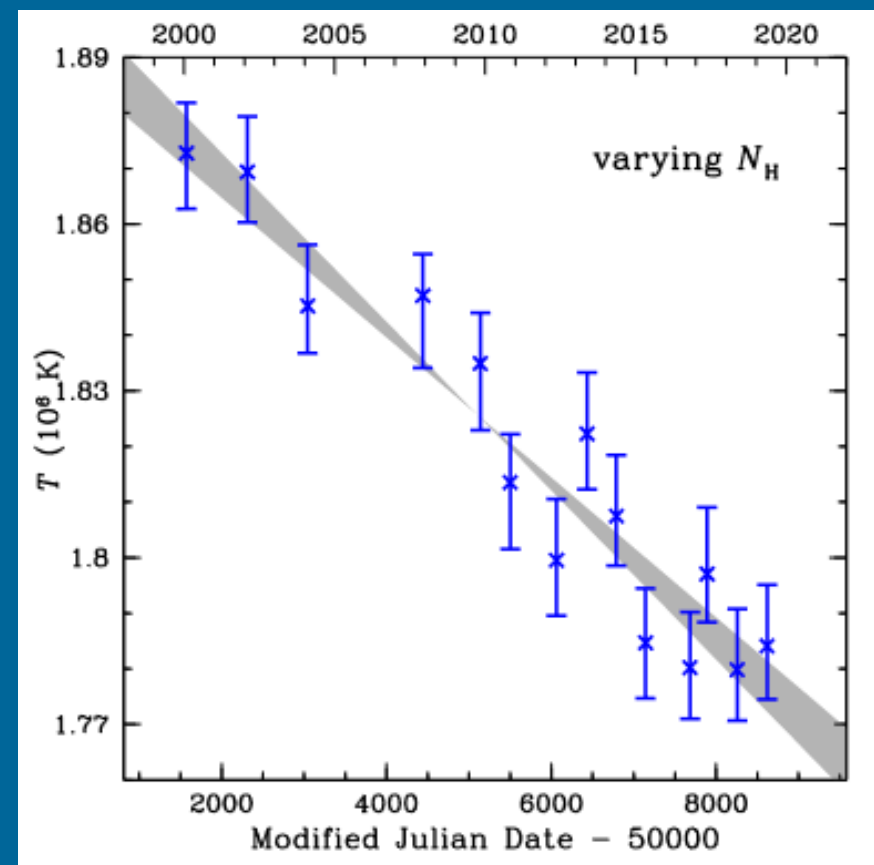
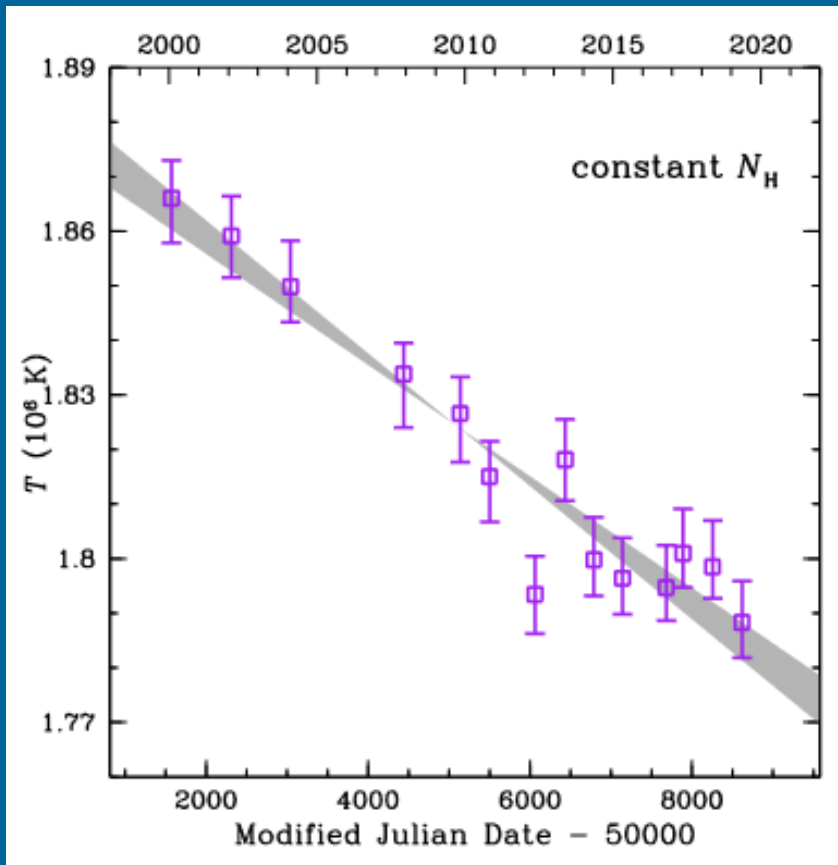
New data: still no cooling?

Elshamouty et al. 2013

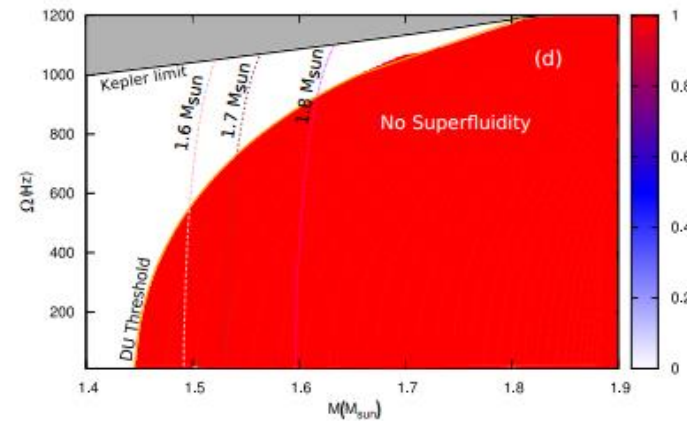
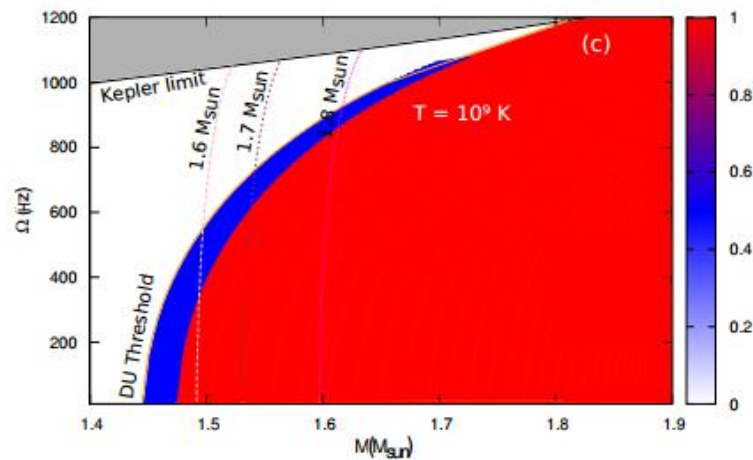
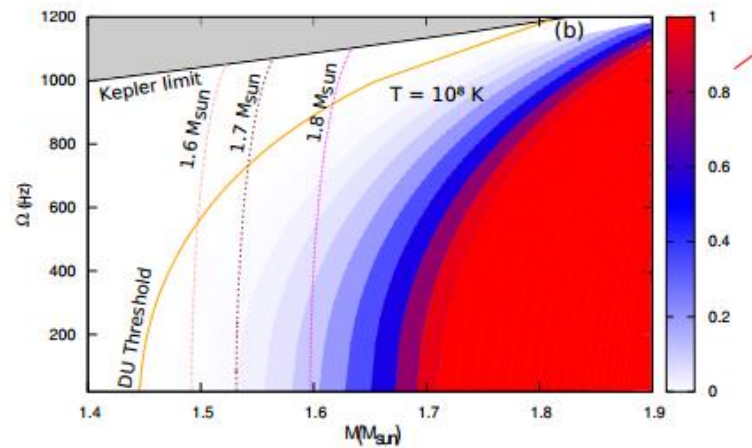
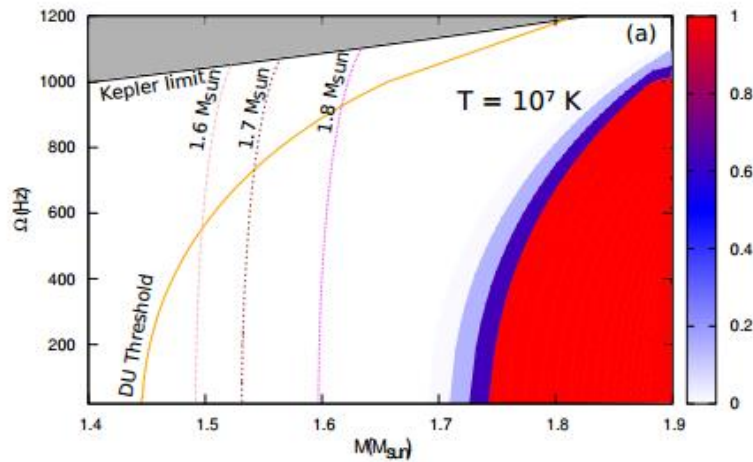


Posselt et al.

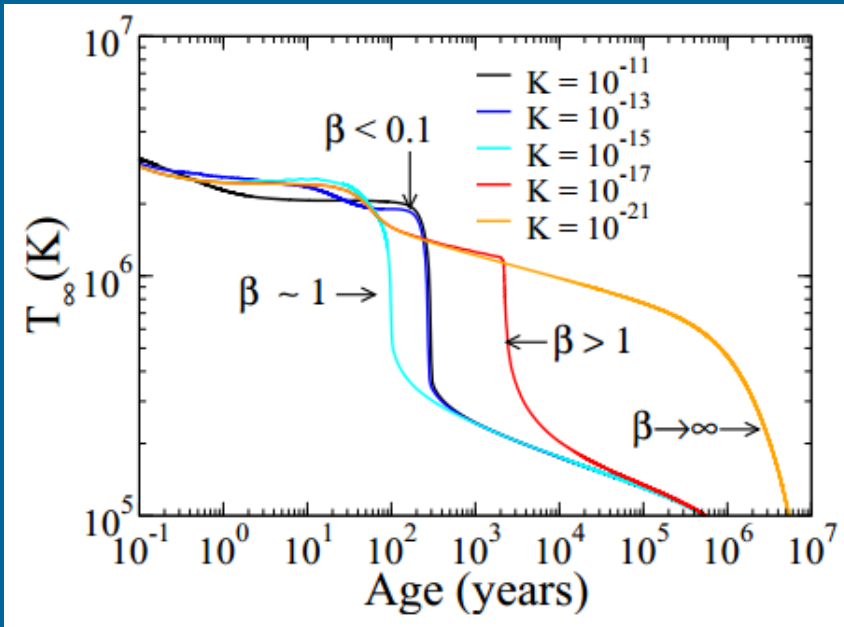
Most recent data demonstrates decay



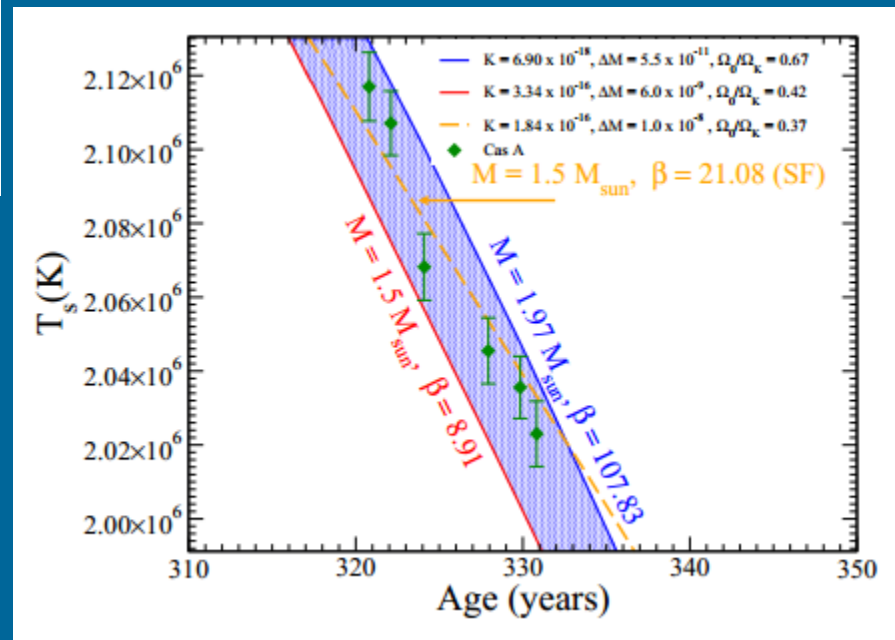
Cooling and rotation



Cas A case



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

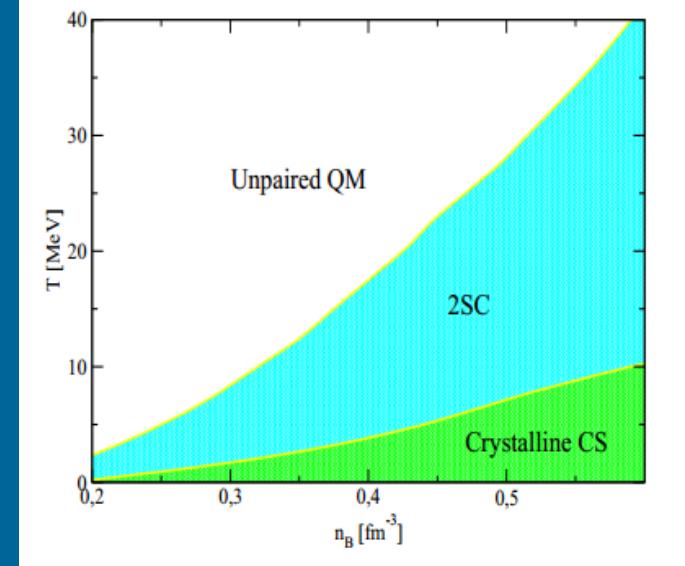
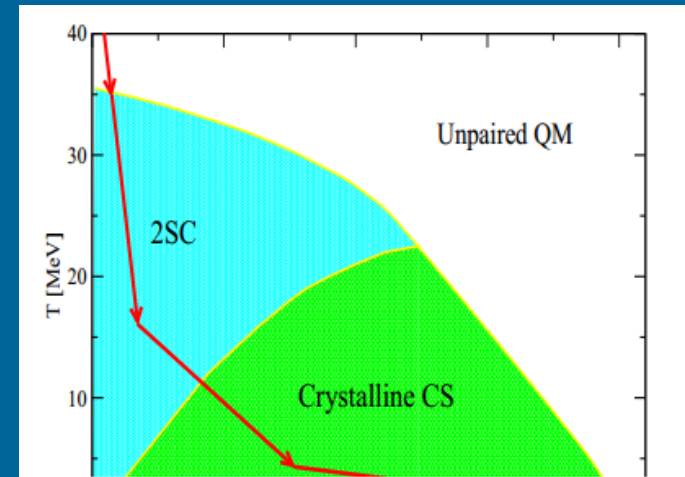
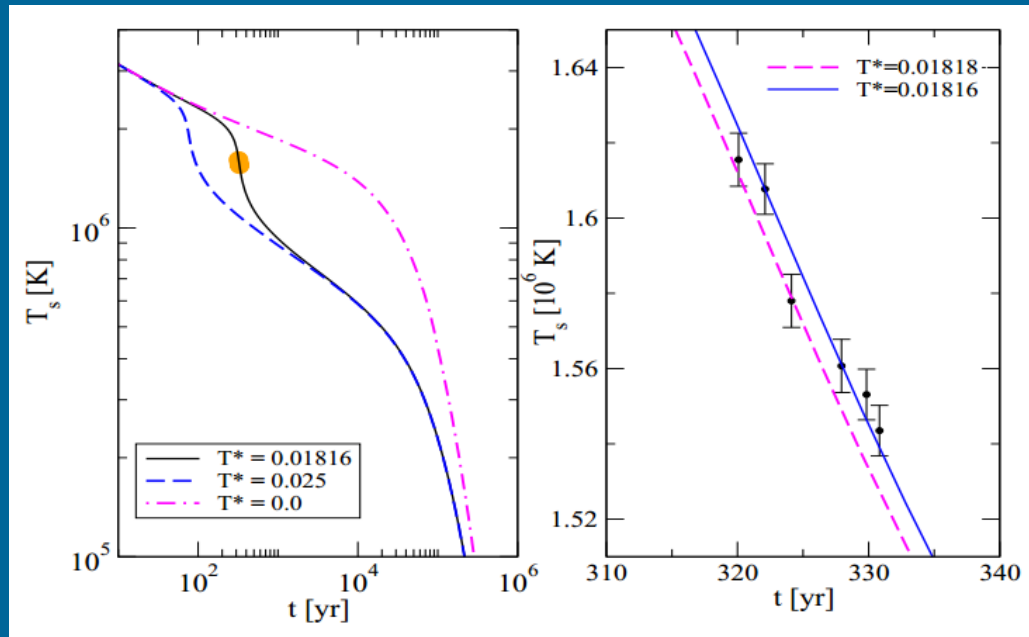


Other studies of the influence of effects of rotation see in 1201.2381

1103.3870

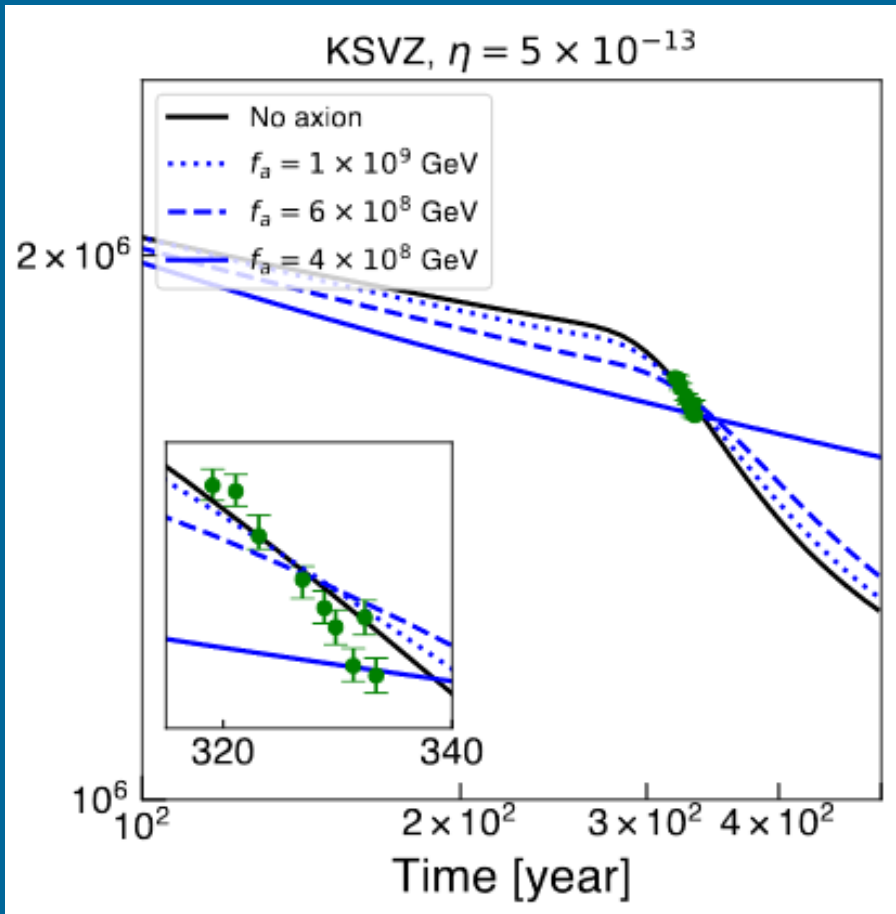
Exotic phase transition

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

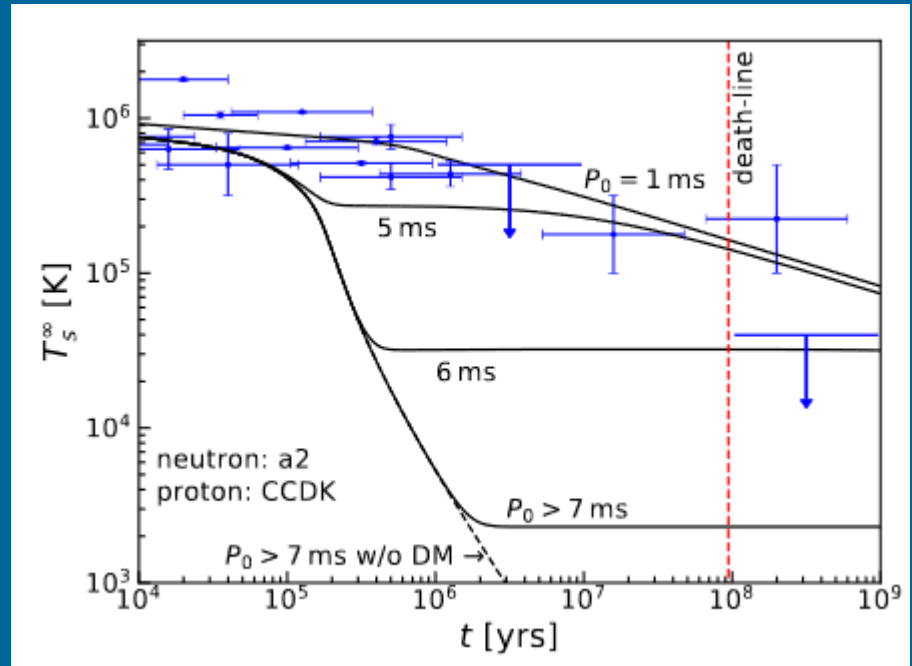


Physics behind Standard Model

Axions cooling and dark matter accumulation and annihilation



If dark matter is accumulated and there is annihilation, then the surface redshifted temperature does not fall down below 2200K.



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.

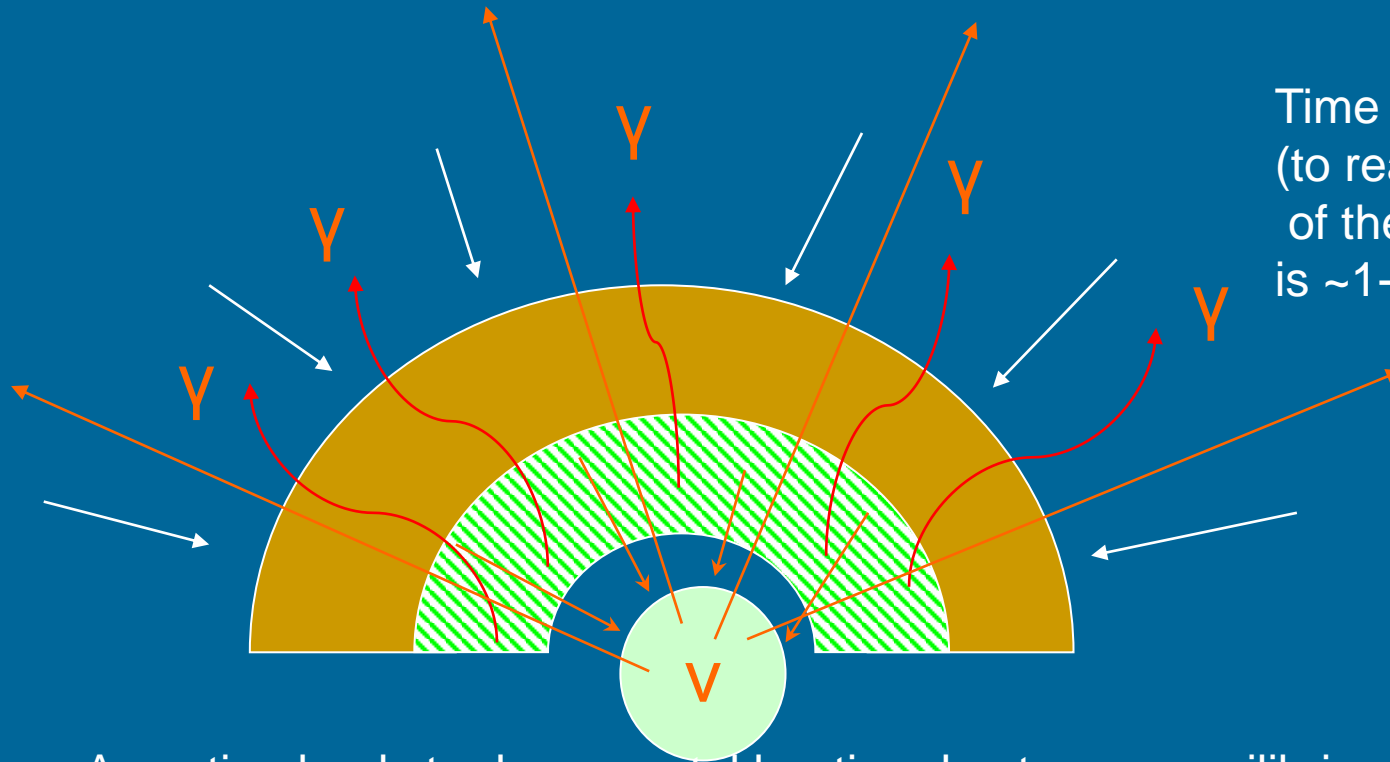
It is believed that the quiescence corresponds to a low level, or even halted, accretion onto the neutron star.

During high-state accretion episodes, the heat is deposited by nonequilibrium processes in the deep layers (10^{12} - 10^{13} g cm⁻³) 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).”

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

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

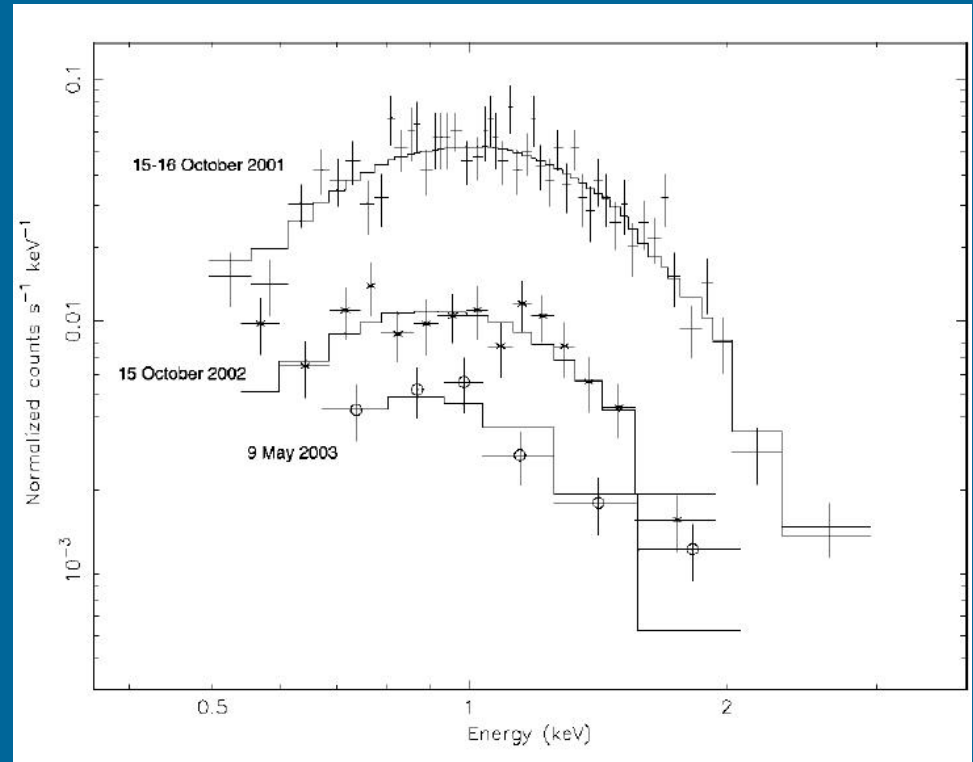
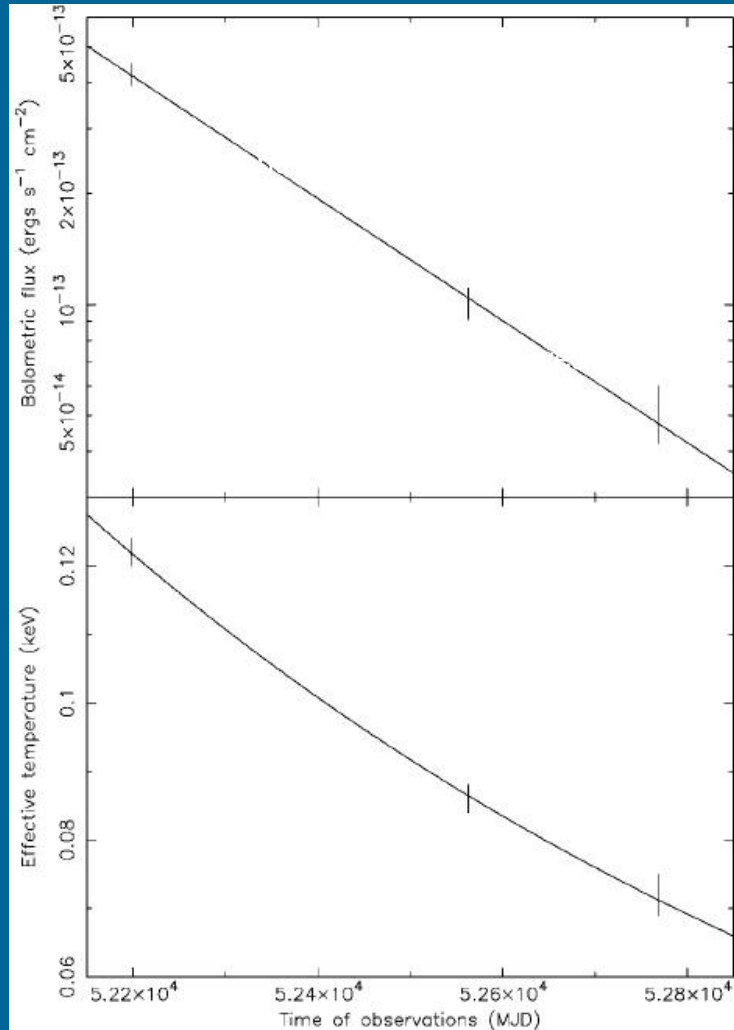
$$\rho \sim 10^{12}-10^{13} \text{ g/cm}^3$$

See, for example, Haensel, Zdunik arxiv:0708.3996

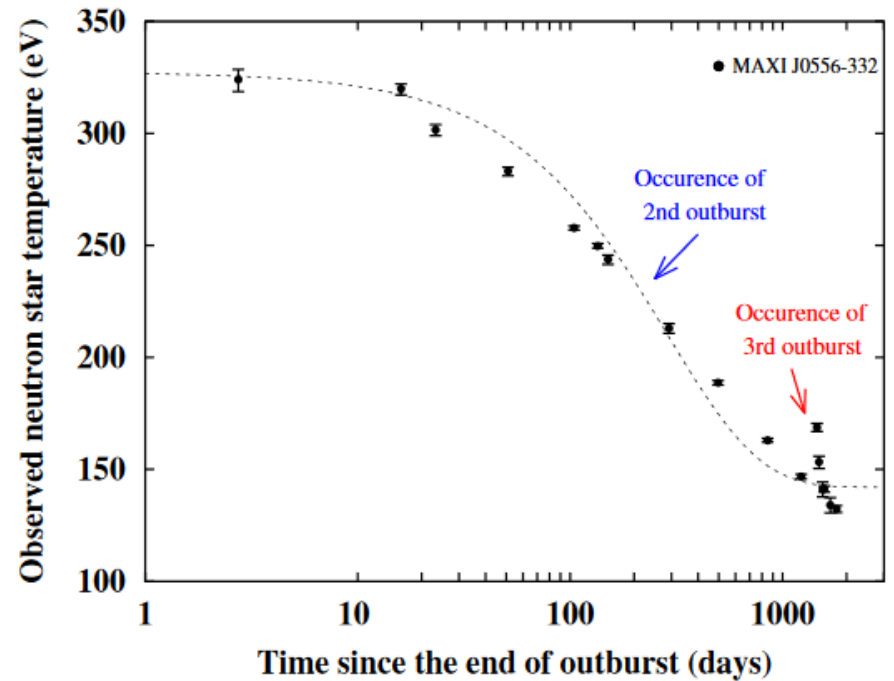
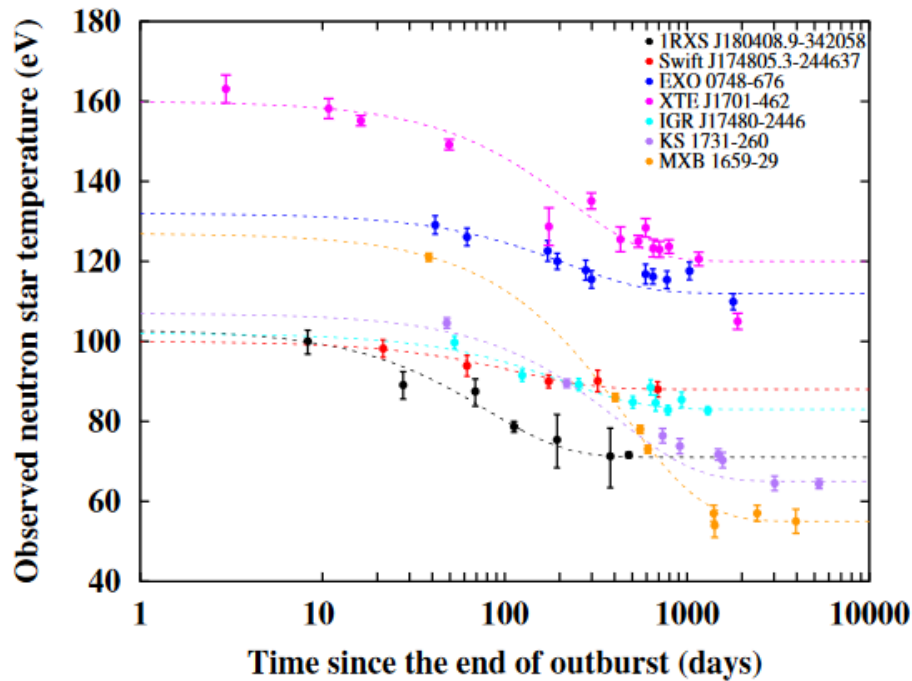
New calculations appeared very recently 0811.1791 Gupta et al.

Cooling in soft X-ray transients

MXB 1659-29
~2.5 years outburst



Fitting cooling of known sources



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

Pycnonuclear reactions

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

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



At ^{56}Ar : neutron drip



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



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



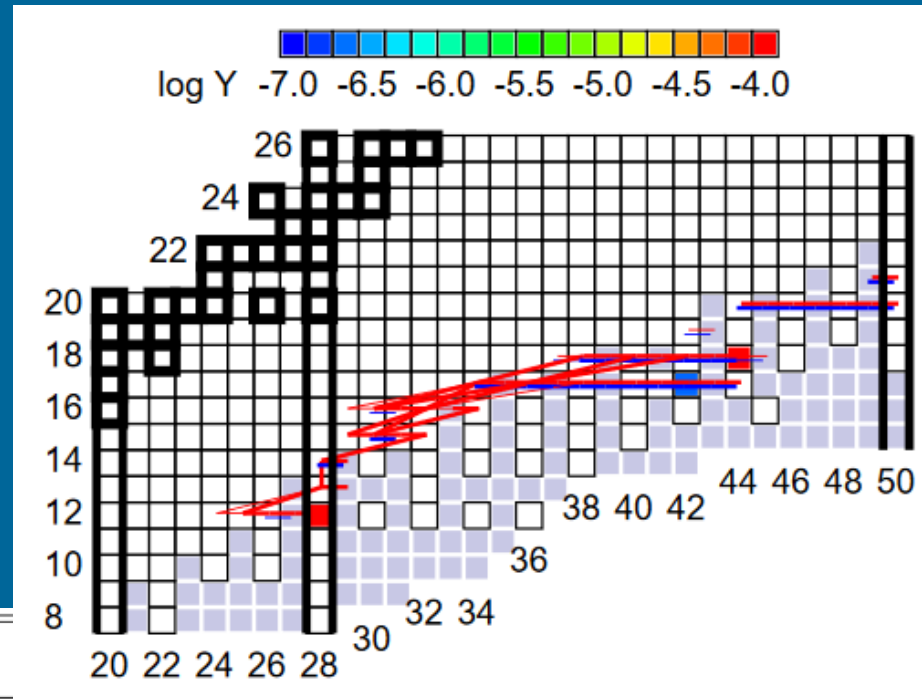
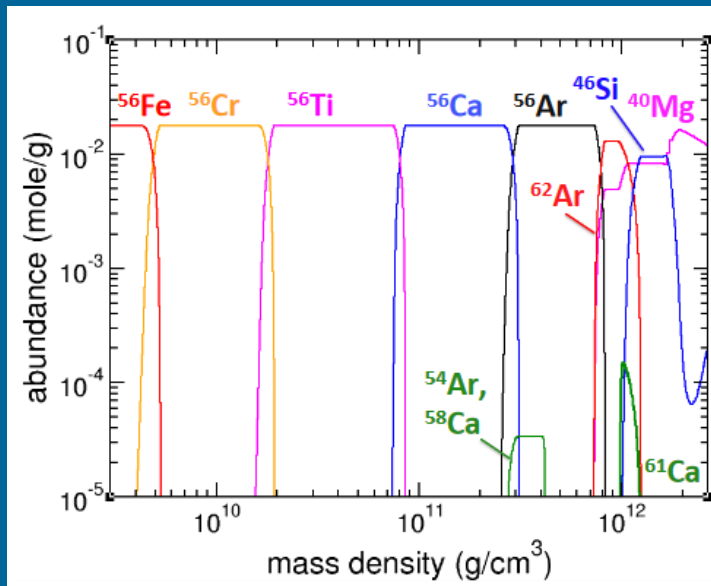
At Z=10 (Ne) pycnonuclear reactions start.



Then a heavy nuclei can react again:



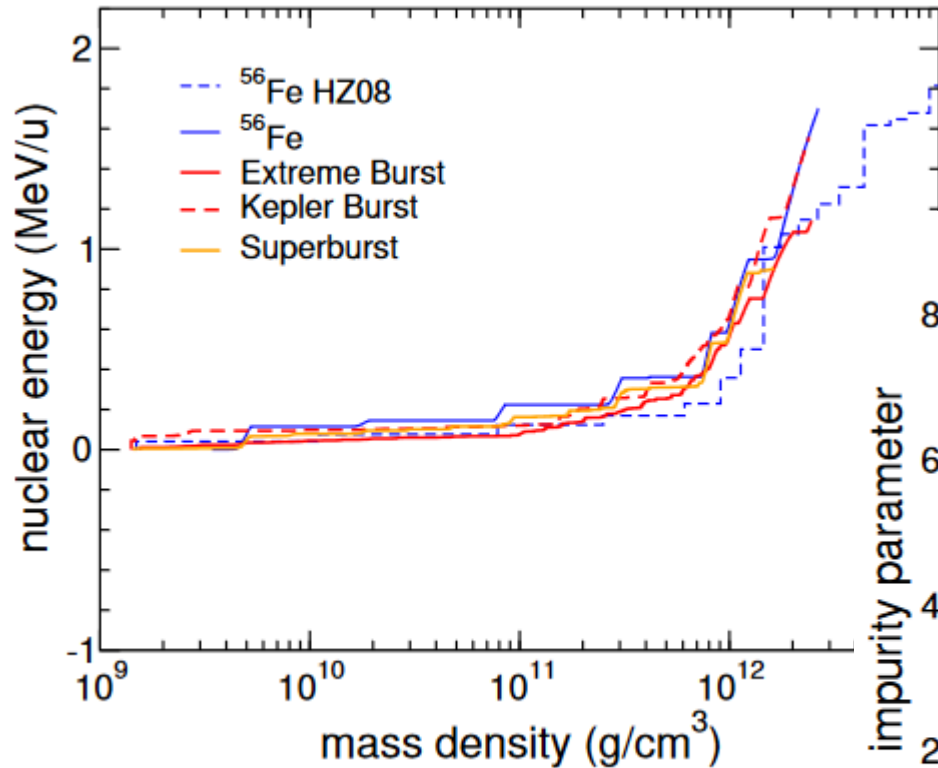
Crust composition and reactions



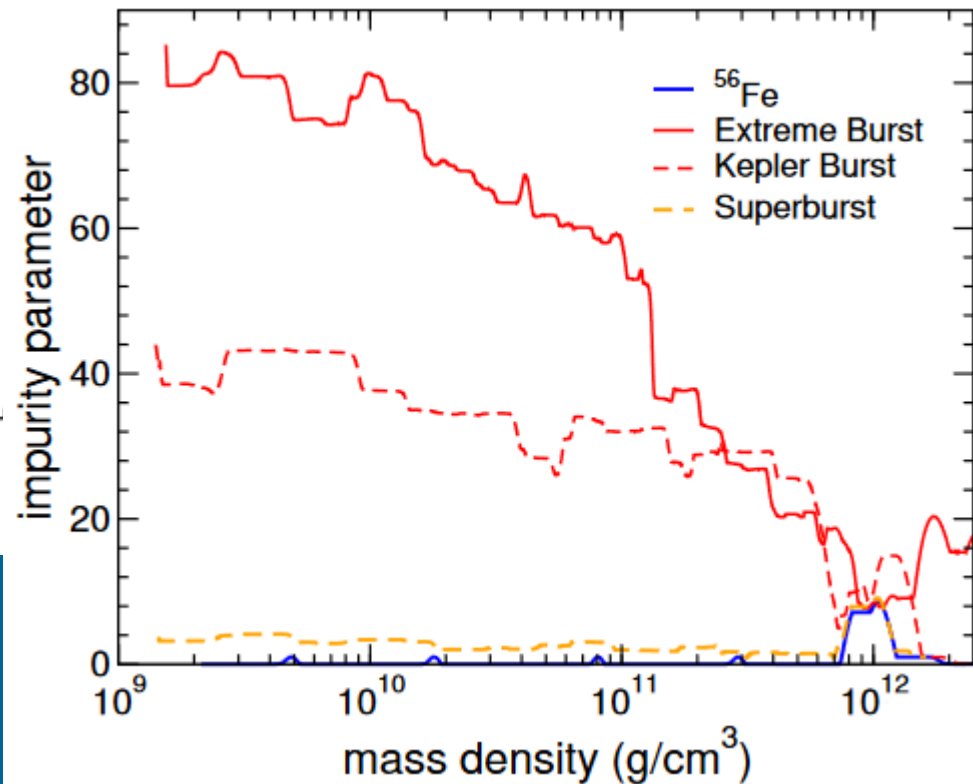
Transition	P^a	ρ^b	μ_e^c	X_n^d
$^{56}\text{Fe} \rightarrow ^{56}\text{Cr}$	3.4×10^{27}	4.9×10^9	6.2	$< 10^{-25}$
$^{56}\text{Cr} \rightarrow ^{56}\text{Ti}$	1.7×10^{28}	1.8×10^{10}	9.6	$< 10^{-25}$
$^{56}\text{Ti} \rightarrow ^{56}\text{Ca}$	1.1×10^{29}	8.1×10^{10}	15.6	$< 10^{-25}$
$^{56}\text{Ca} \rightarrow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

New calculations show that the model with one-to-one correspondence nuclei-density is an oversimplification, 2004.00997, 2004.04195

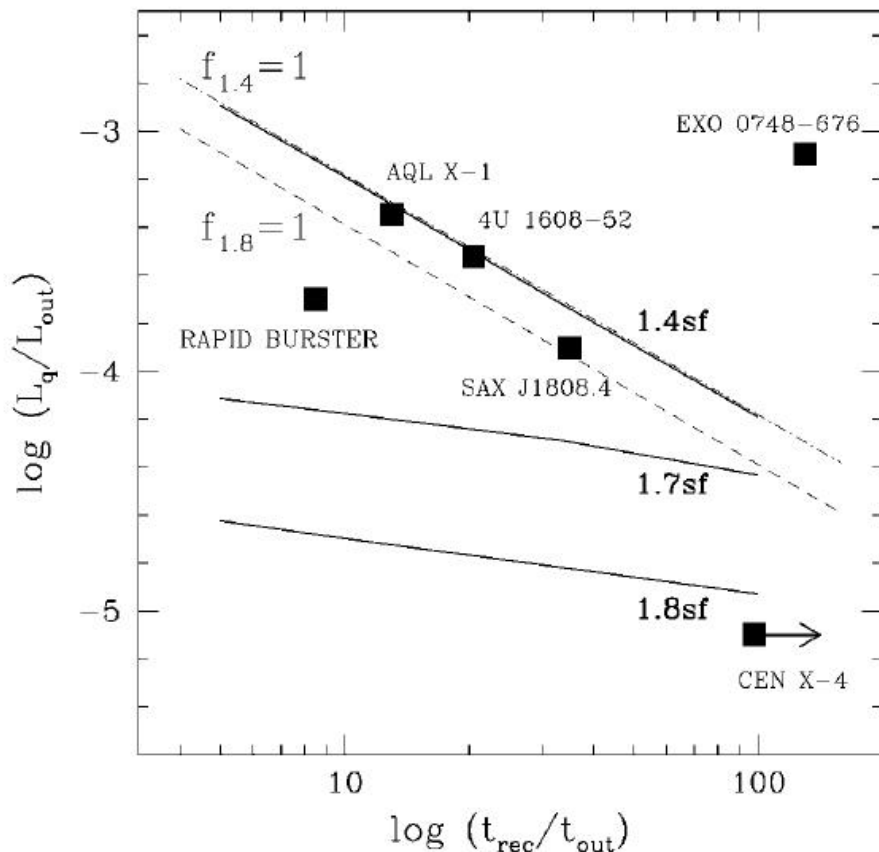
Energy release vs. density and impurity



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



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.

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

Average \dot{M} = $\dot{M} \cdot (t_{\text{out}} / (t_{\text{rec}} + t_{\text{out}}))$

$L_{\text{out}} \sim \dot{M} c^2$

$L_q/L_{\text{out}} = (Q/m_u) (\dot{M} t_{\text{out}}) / (t_{\text{rec}} \cdot L_{\text{out}})$, $t_{\text{rec}} \gg t_{\text{out}}$

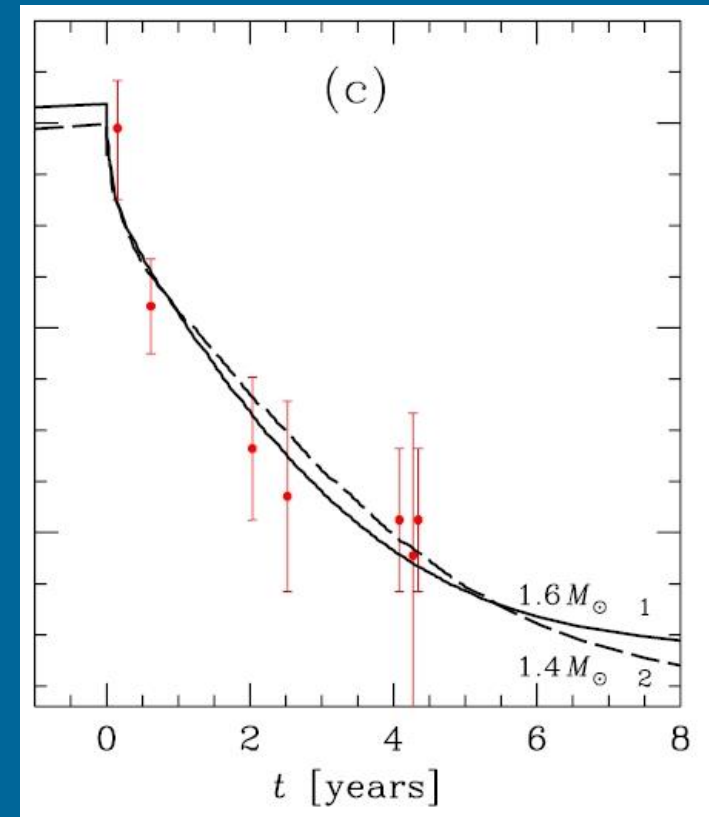
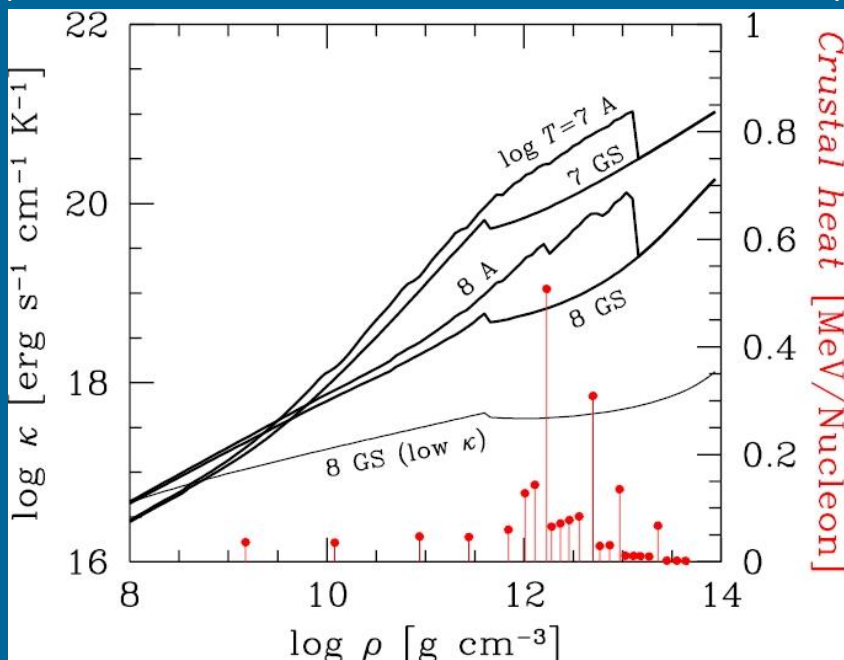
$$L_q/L_{\text{out}} = (Q/m_u) \cdot (1/10^{20}) \cdot (t_{\text{out}}/t_{\text{rec}})$$

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

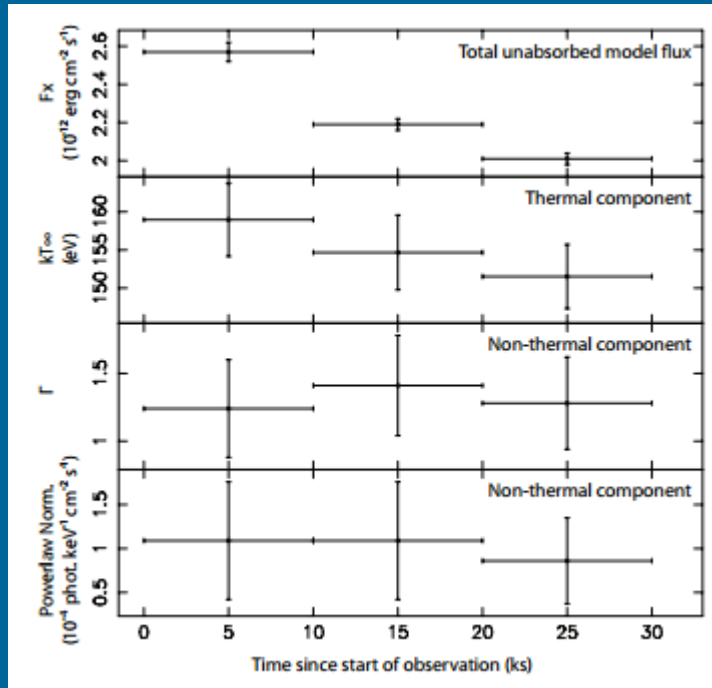
(see a more recent model in 1202.3378)



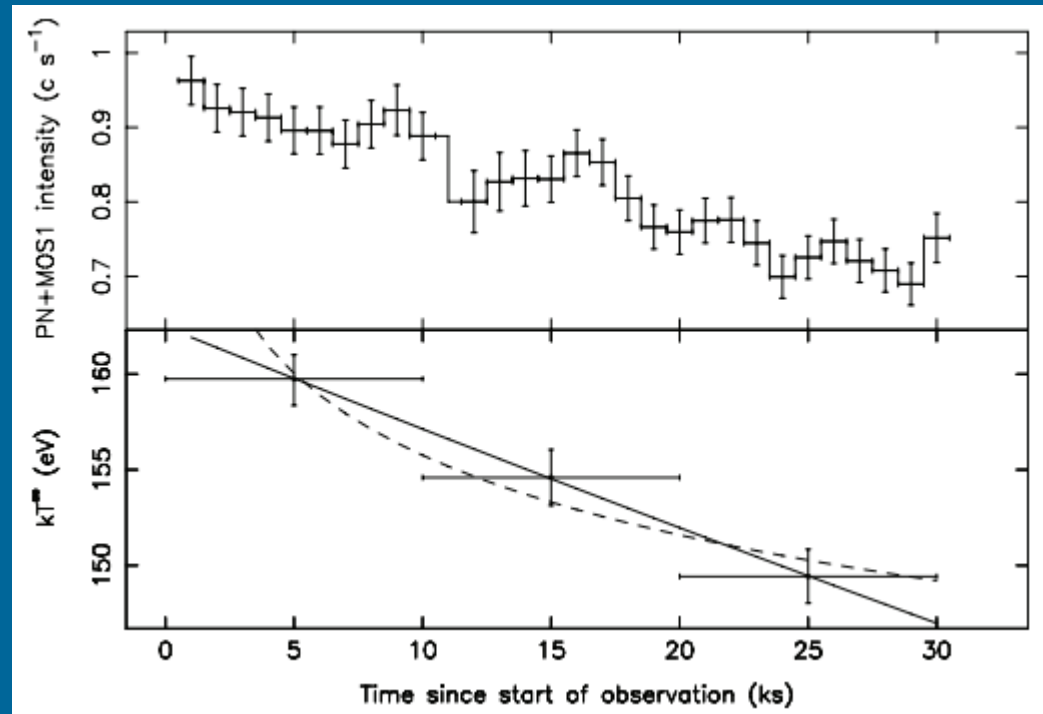
[Shternin et al. 2007]

See newer results and discussion in 1702.08452.
About energy release per nucleon see 2202.07486.

Visible cooling of a NS in a binary



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



XTE J1709-267

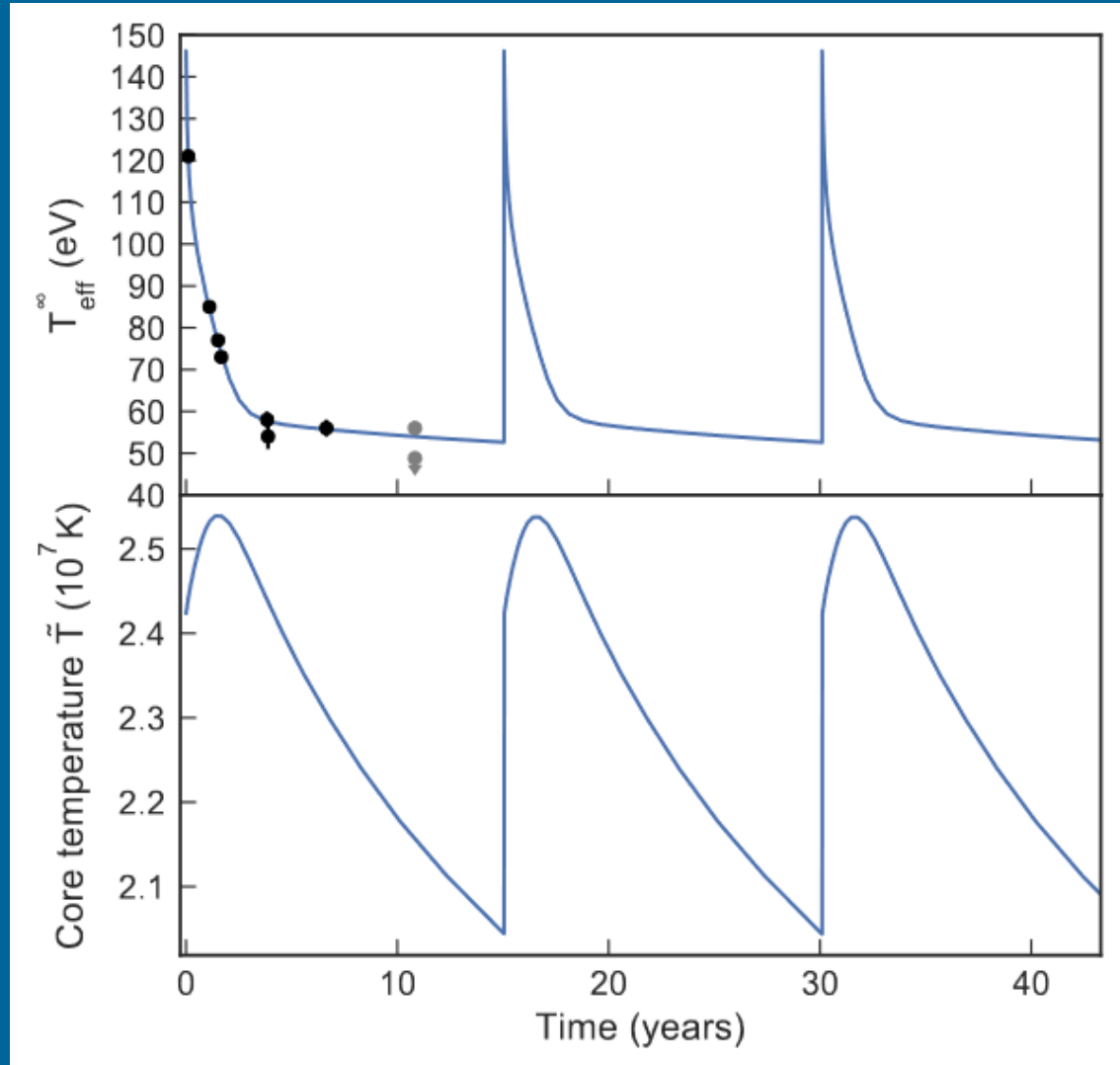
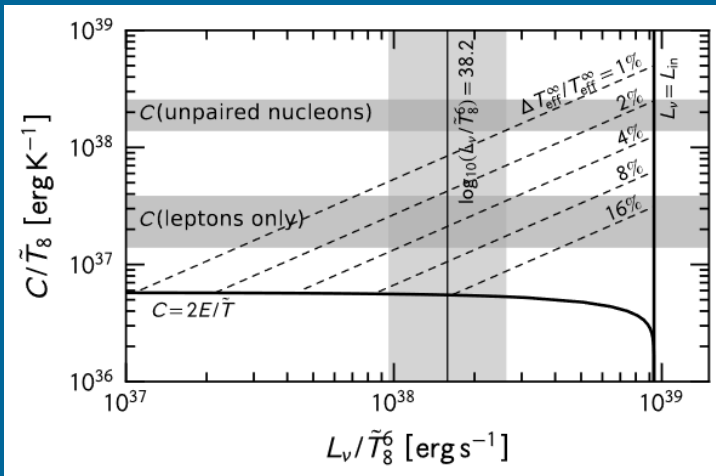
Direct Urca in a cooling NS

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.



Cooling and crustal properties

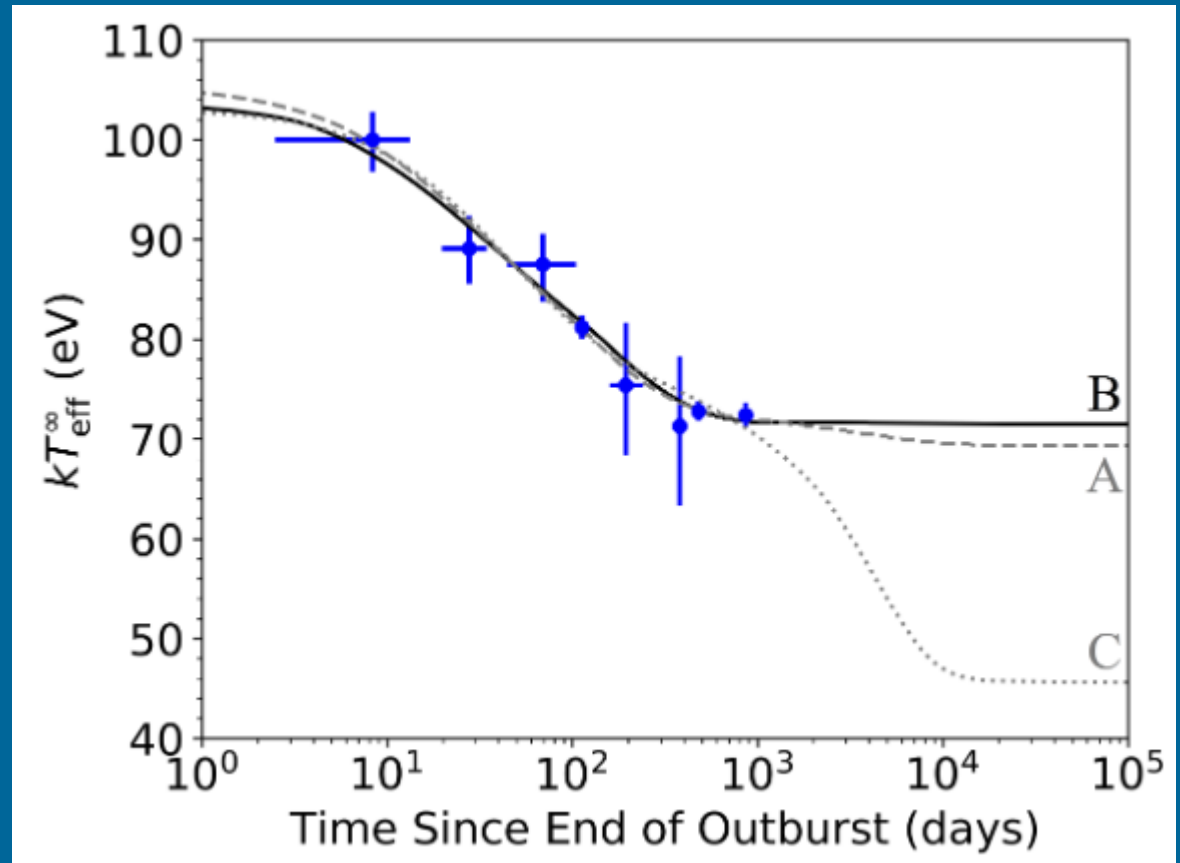
RXS J180408.9–342058
LMXB

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

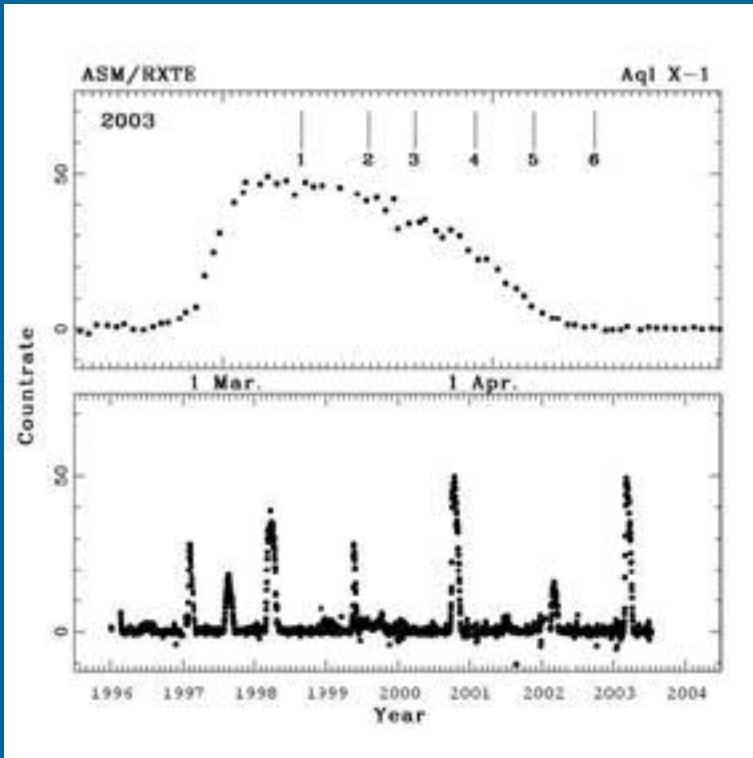
Deep crustal heating +
shallow heat source.

The origin of the shallow
heating is unknown.

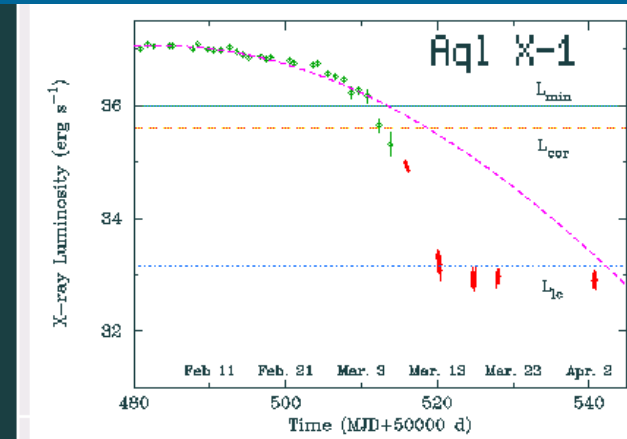
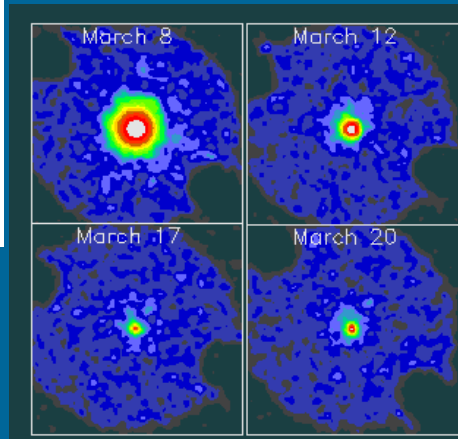
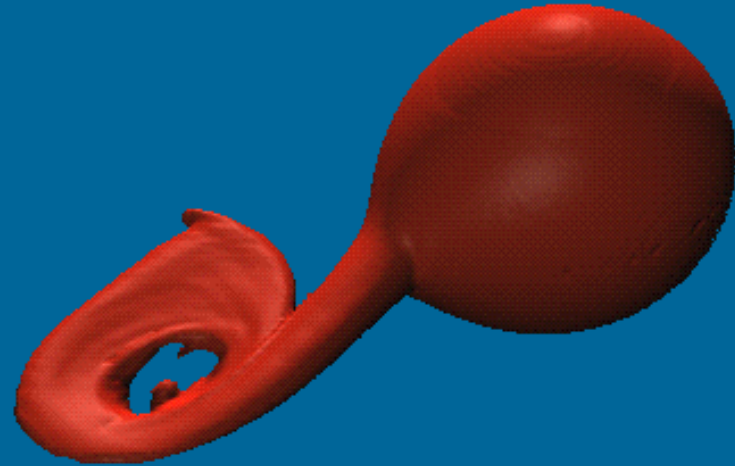
No DURCA.



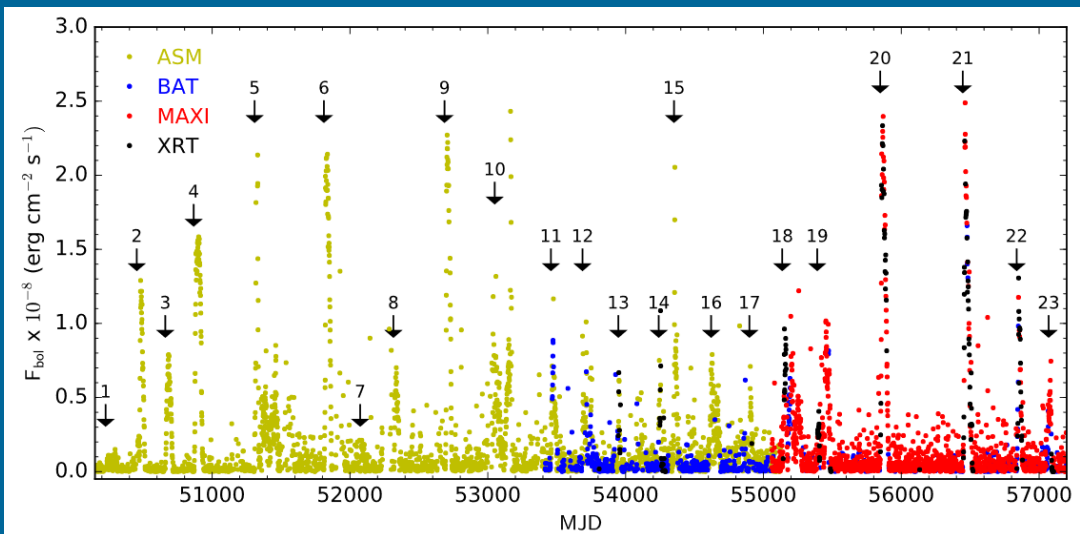
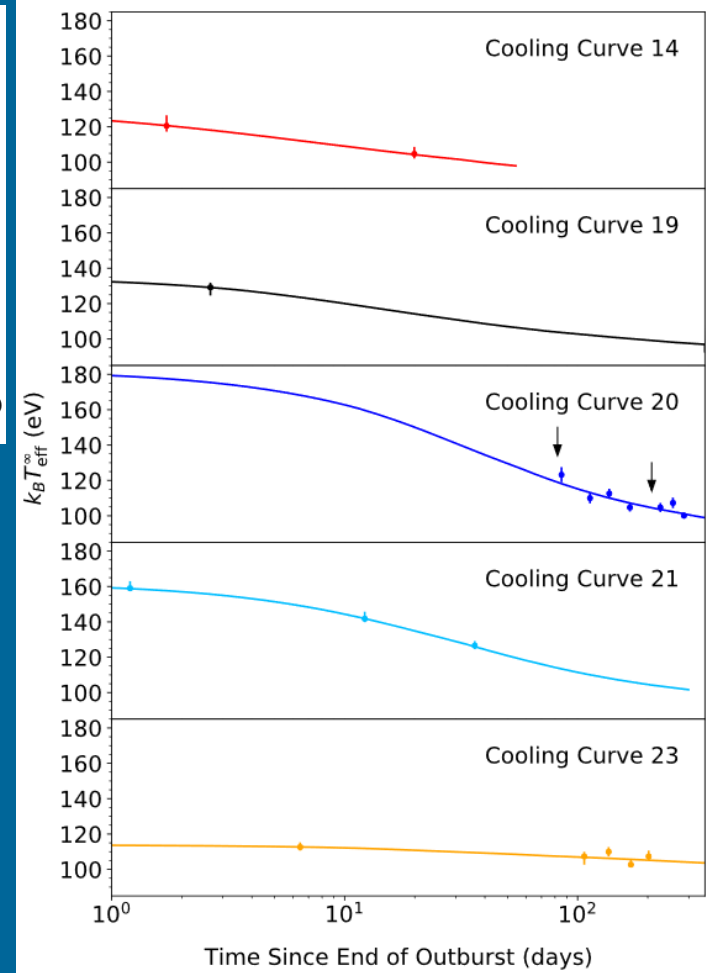
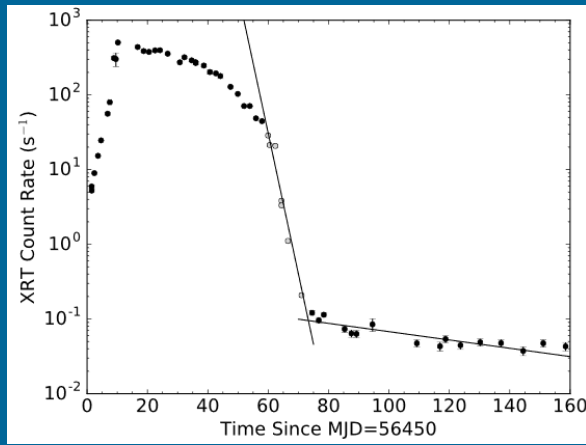
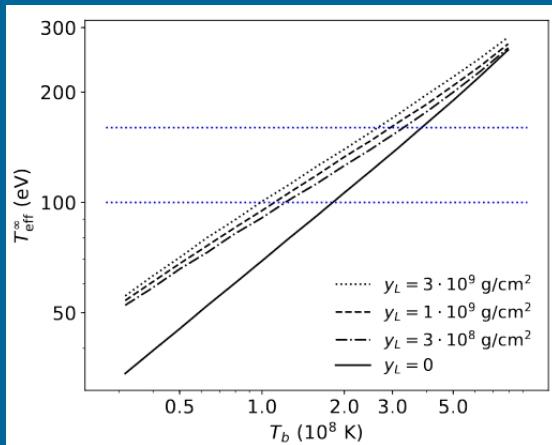
Aql X-1 transient



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

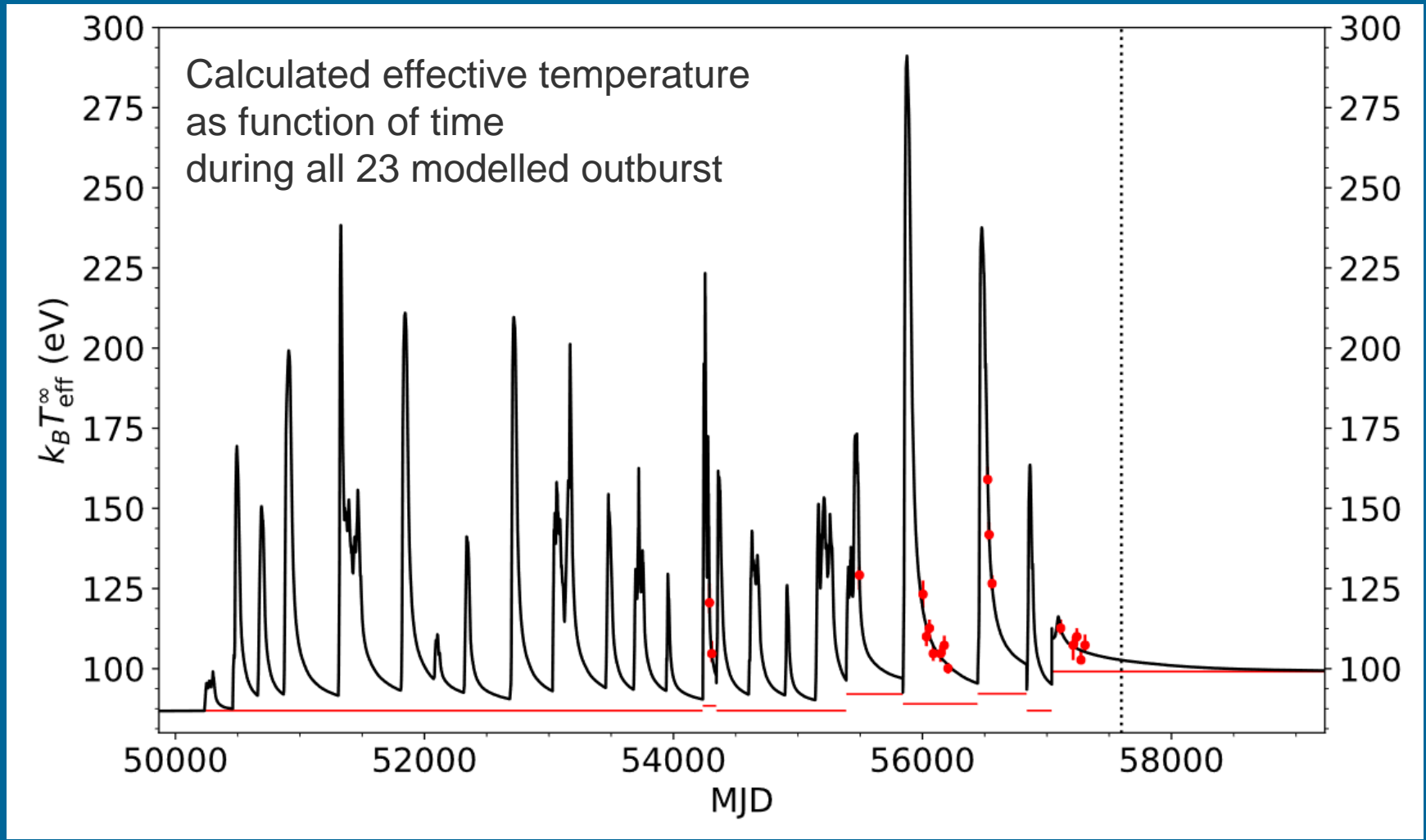


Aql X-1 modeling



1802.06081

Fitting multiple bursts and decays

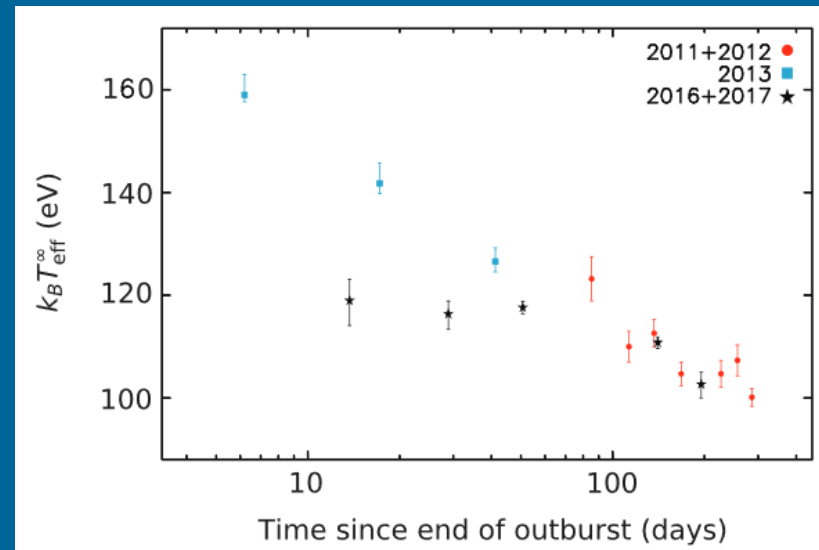


New questions from Aql X-1

Strong energy release is necessary not deep in the crust (intensive shallow heating).

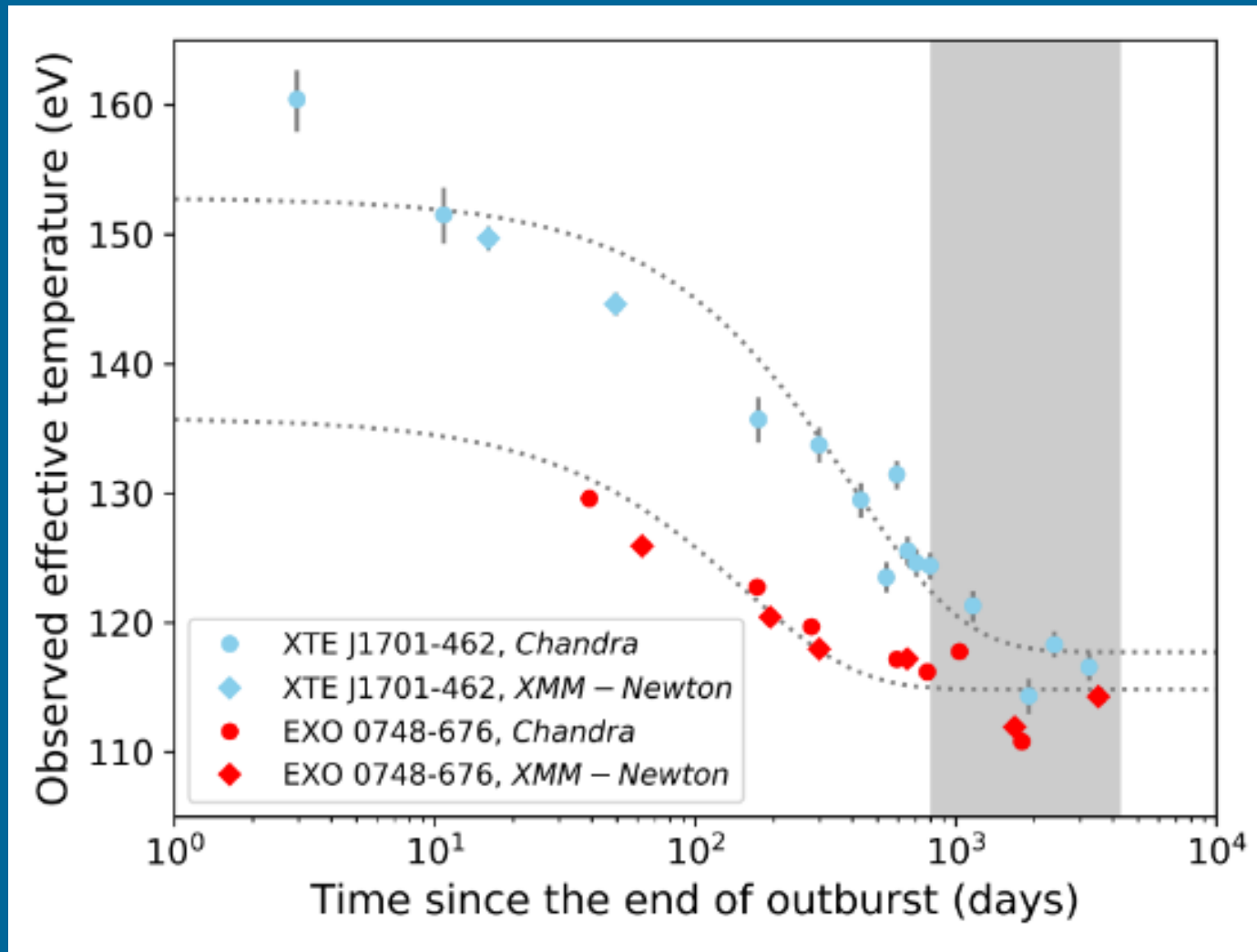
$$\sim 5 - 10 \text{ MeV nucleon}^{-1} \quad \sim 10^{10} \text{ g cm}^{-3}$$

In general, observations of different sources require different energy release and different depths, which are typically smaller than in the classical deep crustal heating ($10^{12} - 10^{13} \text{ g/cm}^3$).

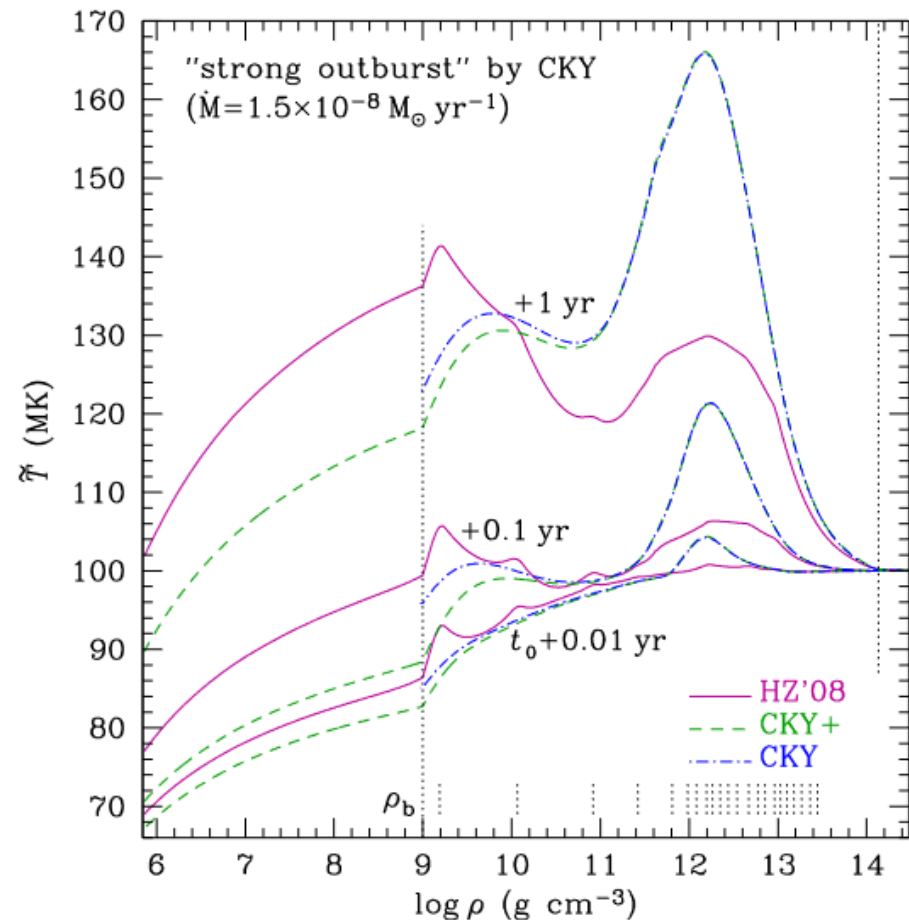
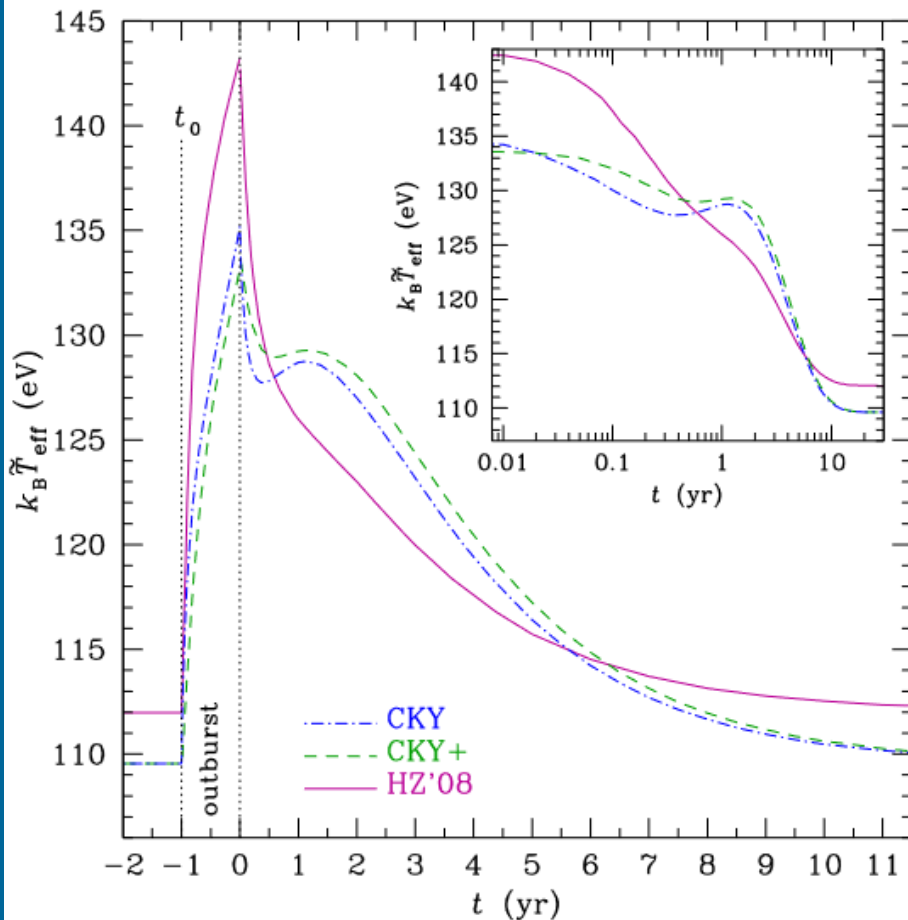


Outburst	$\log Y_C$	Q_{sh} (MeV nucleon $^{-1}$)	$\rho_{sh, \min}$ (g cm $^{-3}$)
2016	$6.6^{+0.9}_*$	9.2 ± 1.6	$2.8^{+0.1}_{-0.2} \times 10^{10}$
2016 - cold core	$10.5^{+0.3}_{-0.8}$	$5.3^{+5.4}_{-0.7}$	$3.4^{+1.2}_{-0.6} \times 10^{10}$
2013	$8.8^{+1.1}_{-1.5}$	$2.3^{+0.5}_{-0.3}$	$0.4^{+0.7}_* \times 10^9$
2011	$8.3^{+0.7}_{-0.9}$	$3.7^{+1.5}_{-0.9}$	$0.4^{+7.9}_* \times 10^9$

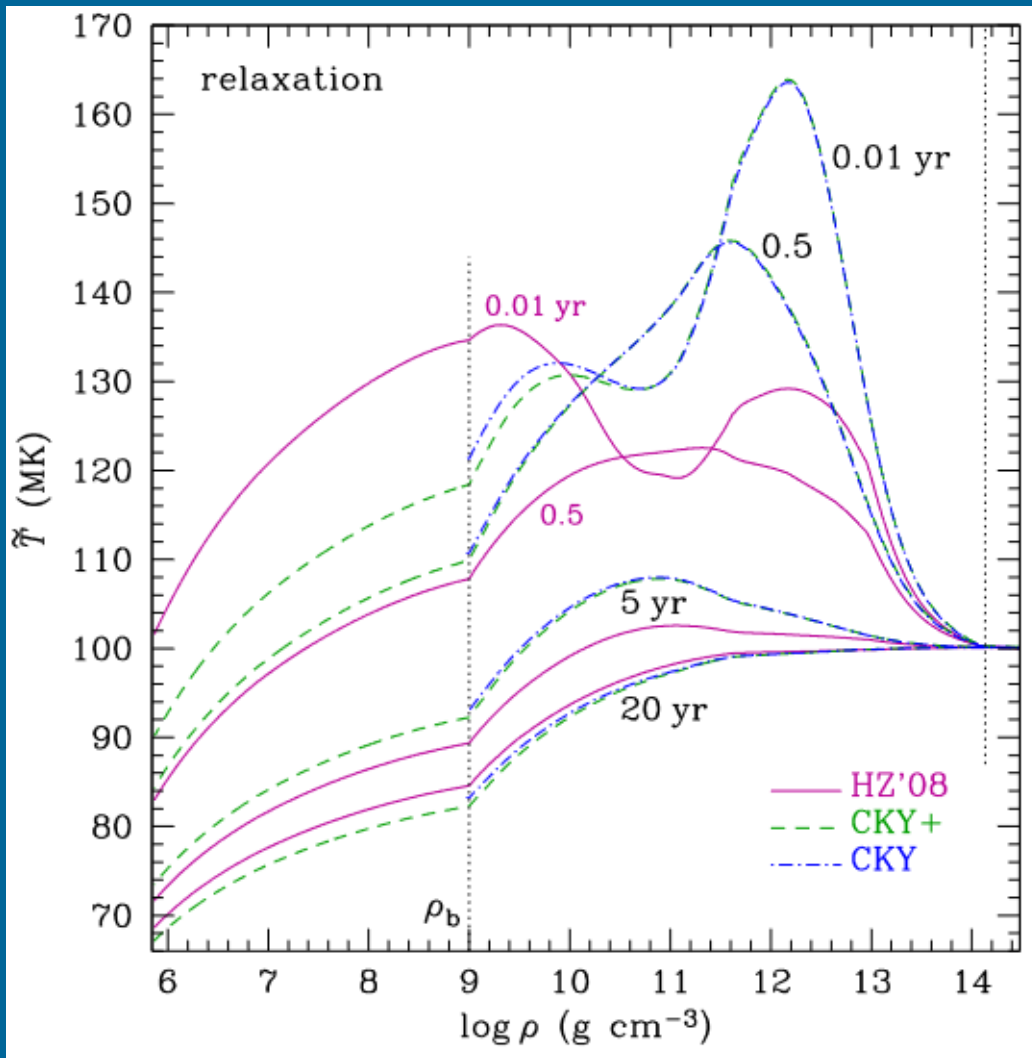
Unexpected temperature rise



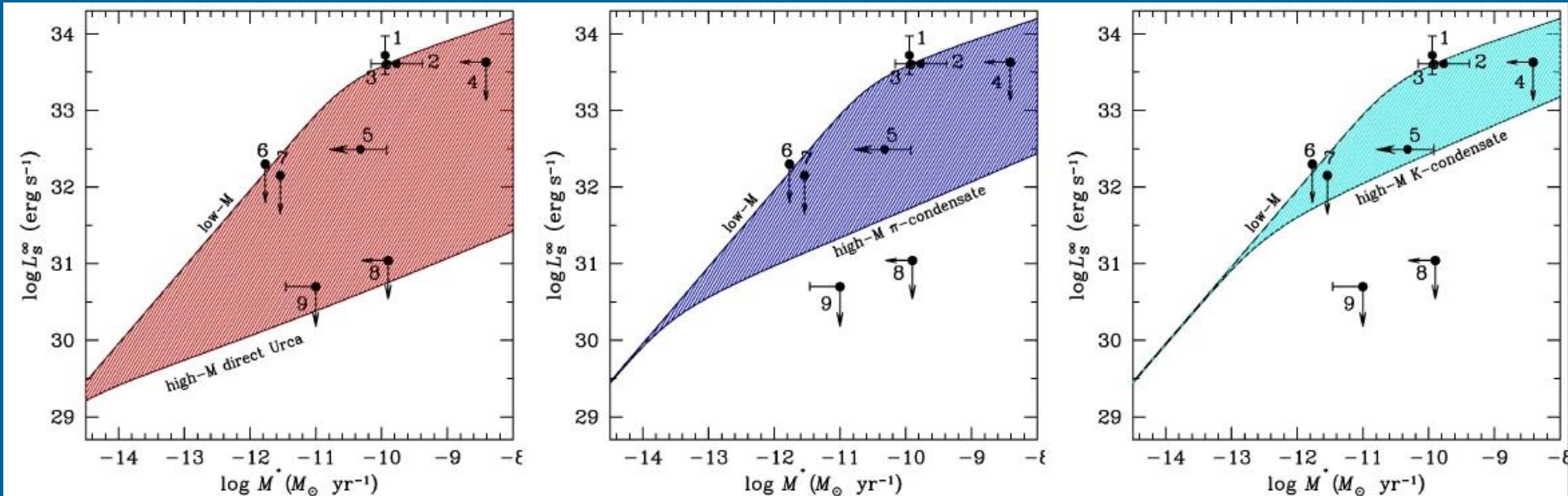
Detailed models



Quiescent state: temperature evolution



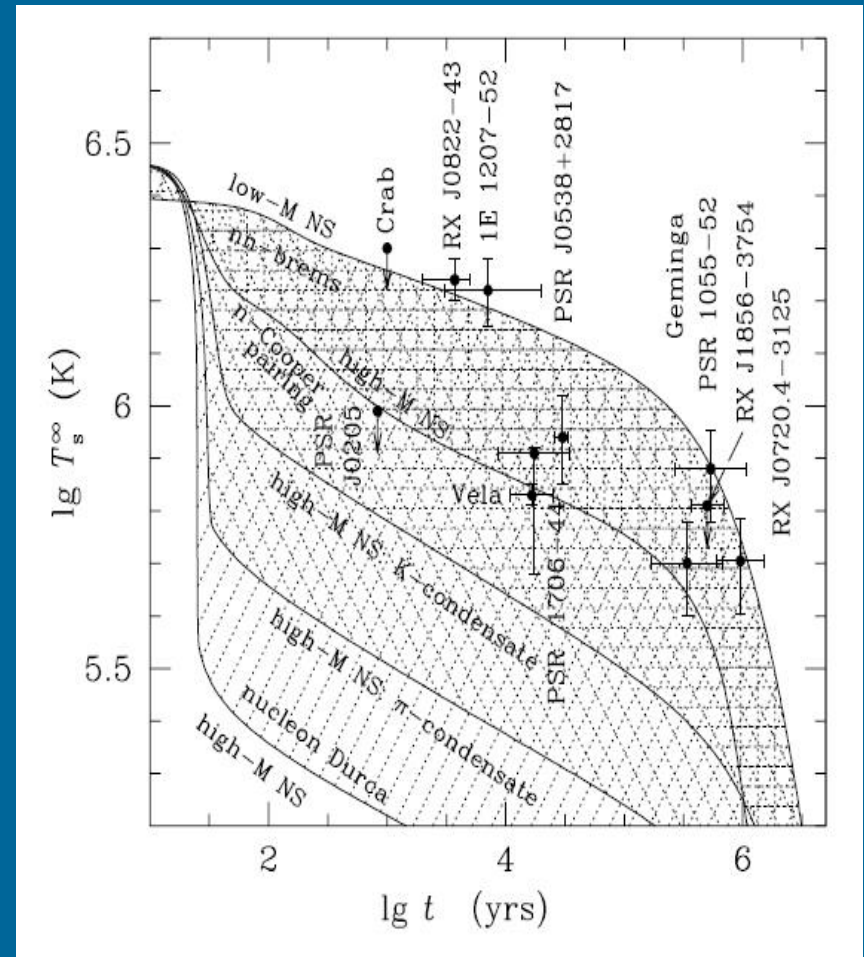
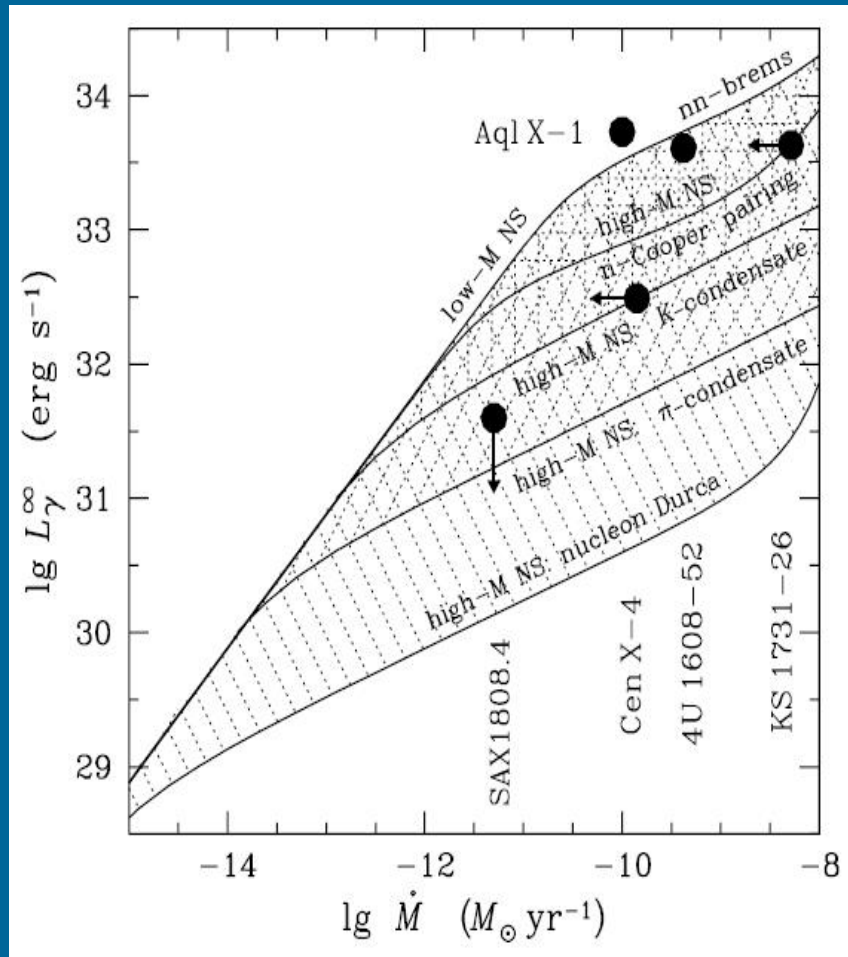
Testing models with SXT



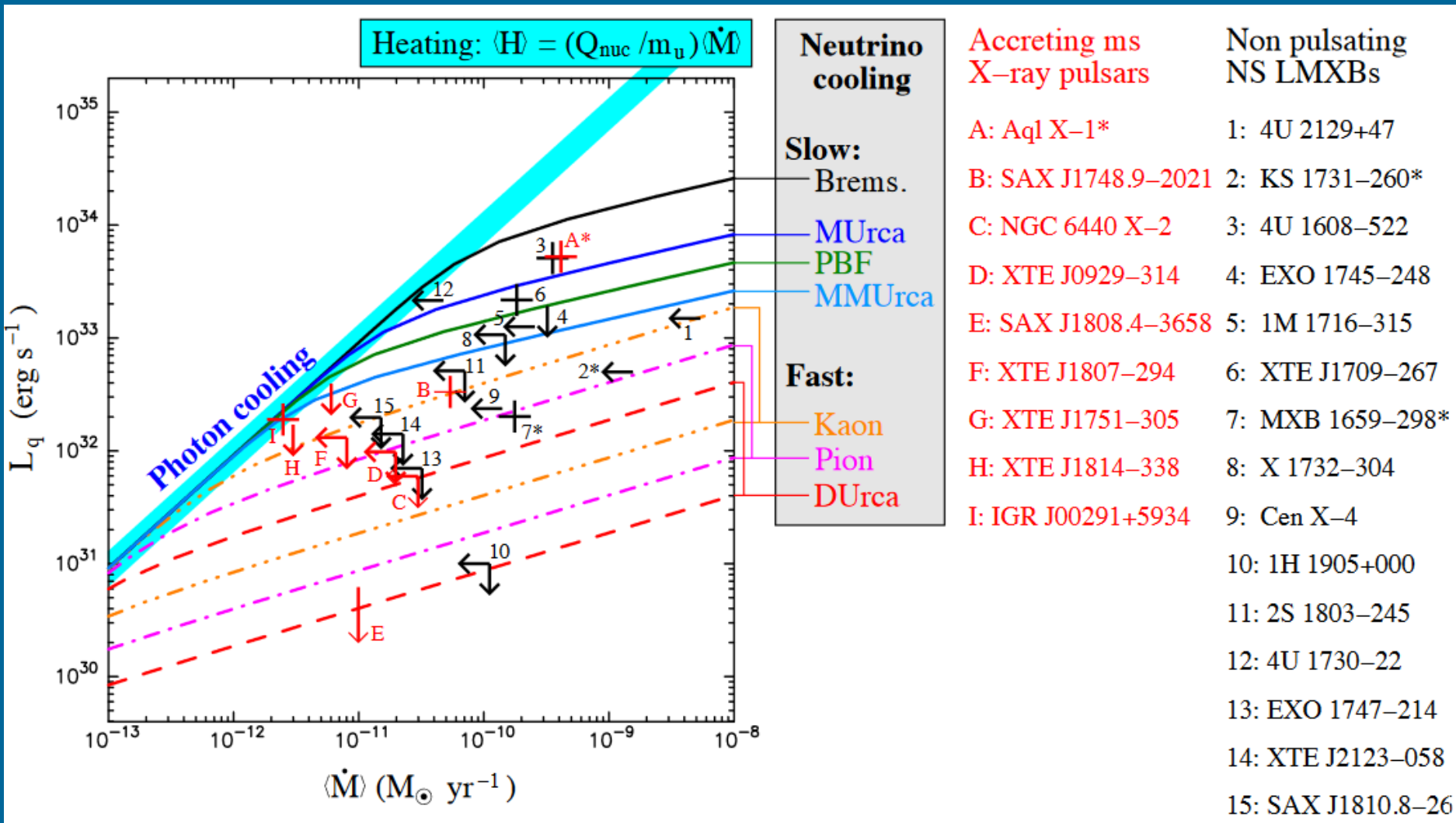
SXTs can be very important in confronting theoretical cooling models with data.

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

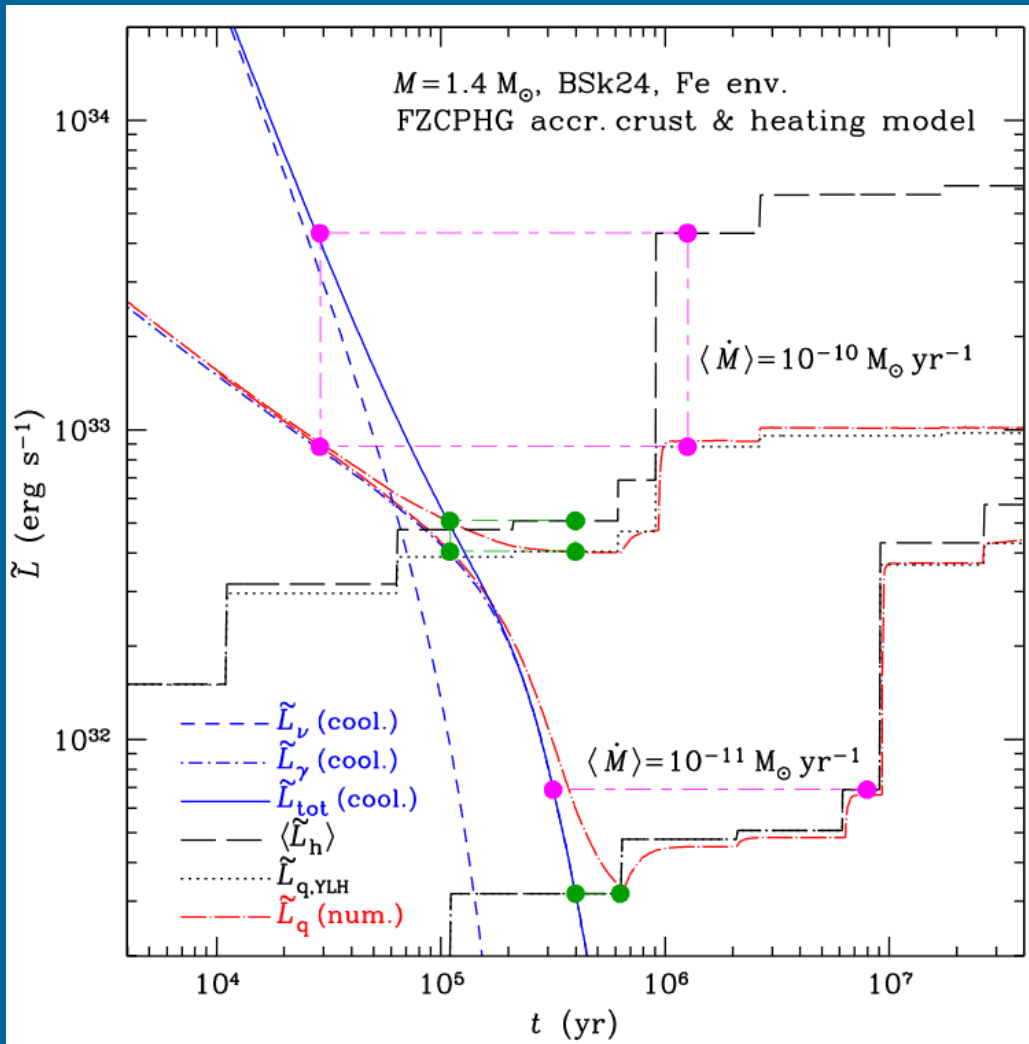
Theory vs. Observations: SXT and isolated cooling NSs



Systems with deep crustal heating



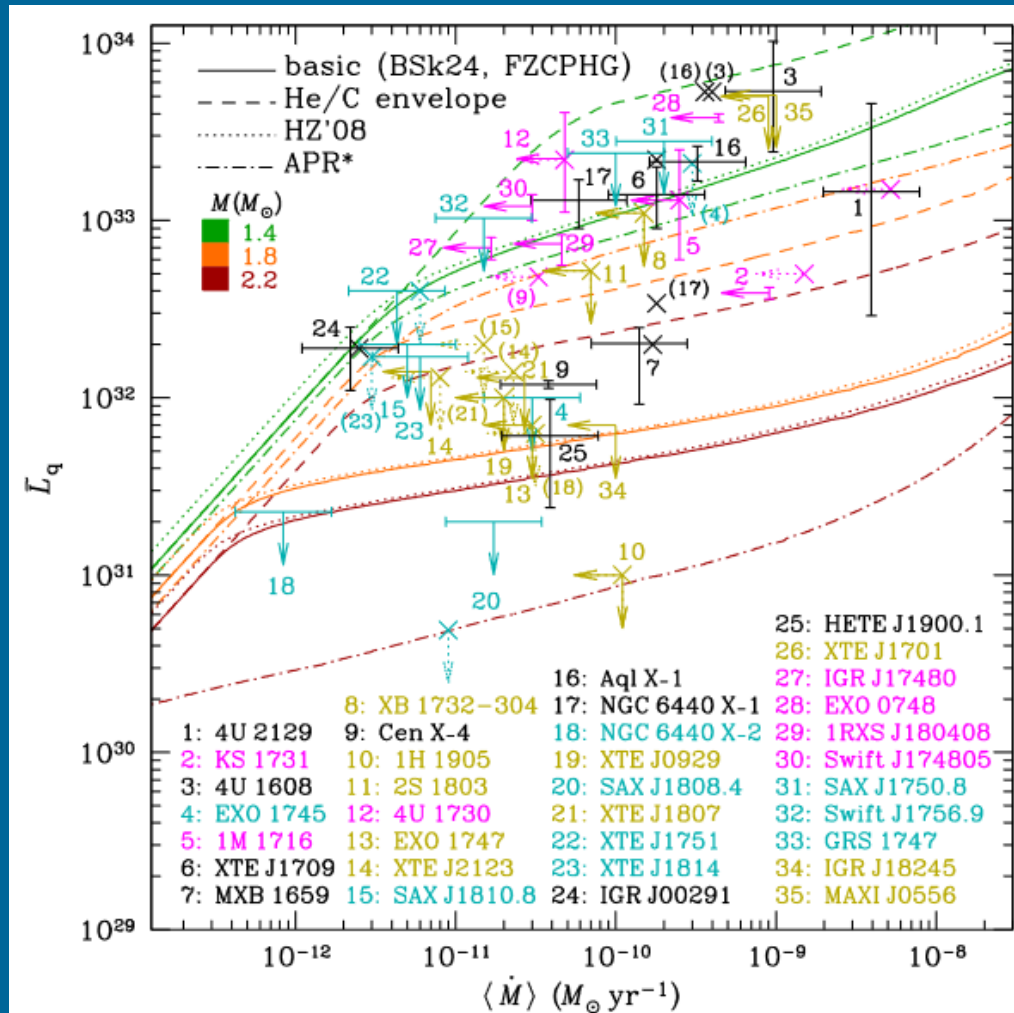
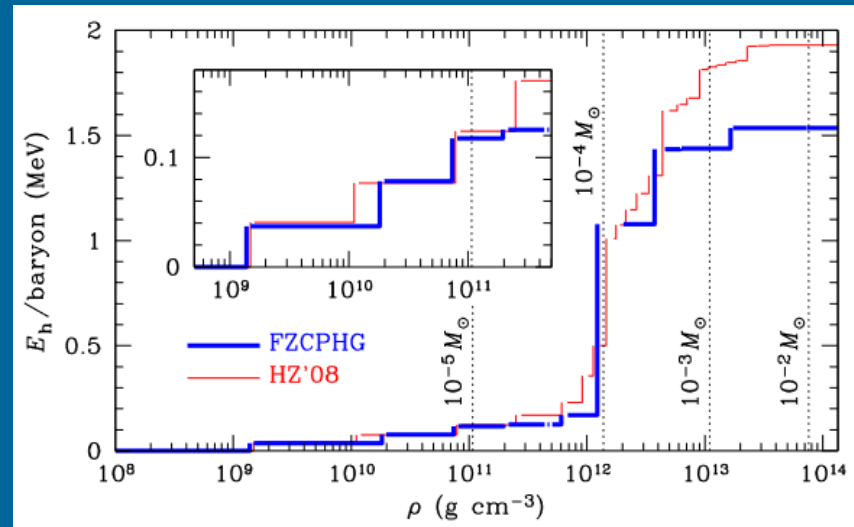
How to determine quiescent luminosity



Only reactions in the accreted crust are taken into account.

Quiescent luminosity (black dotted) is equal to the photon luminosity of the cooling curve (blue dot-dashed) at the moment when total cooling luminosity (blue solid) is equal to the heat energy release (black dashed).

Deep crustal heating



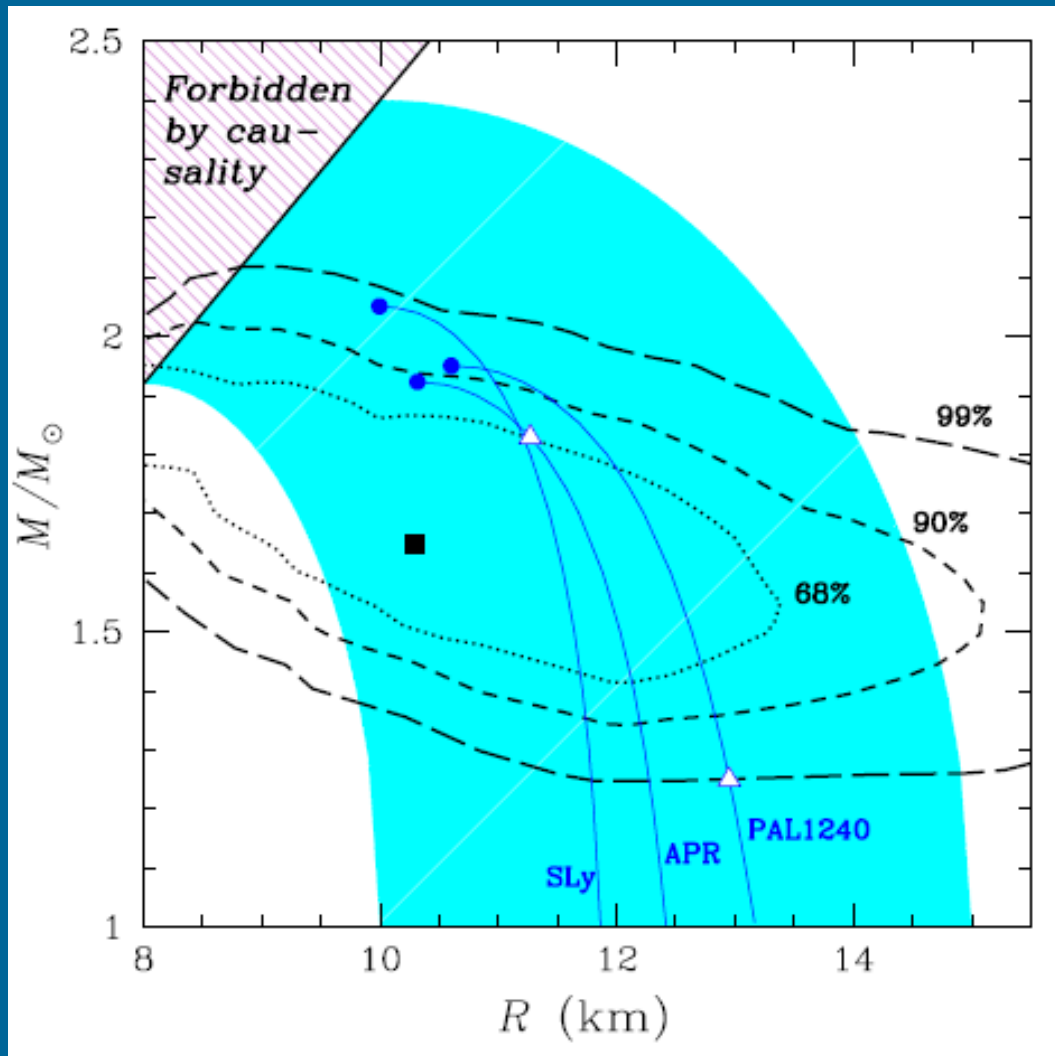
Conclusions

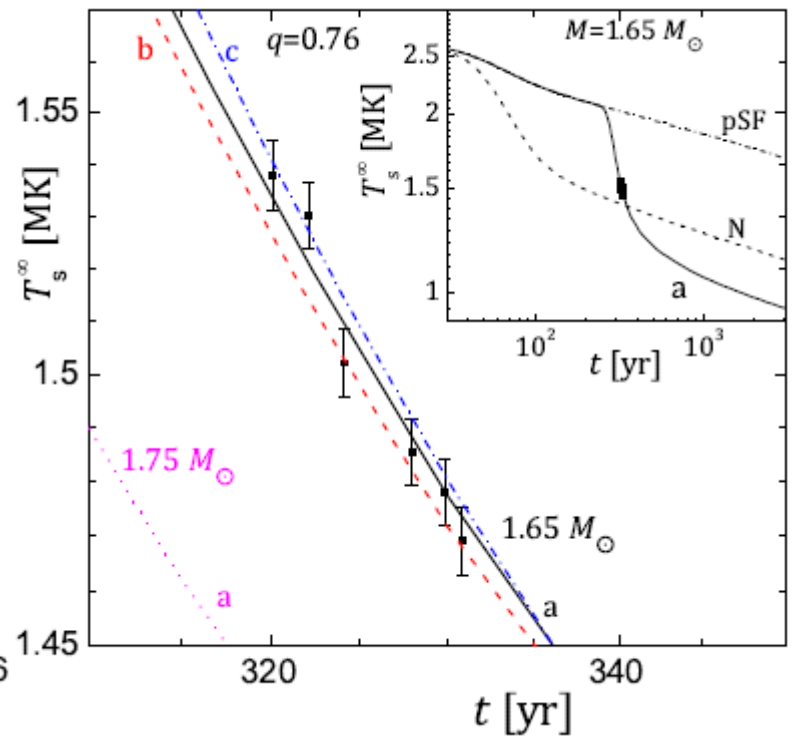
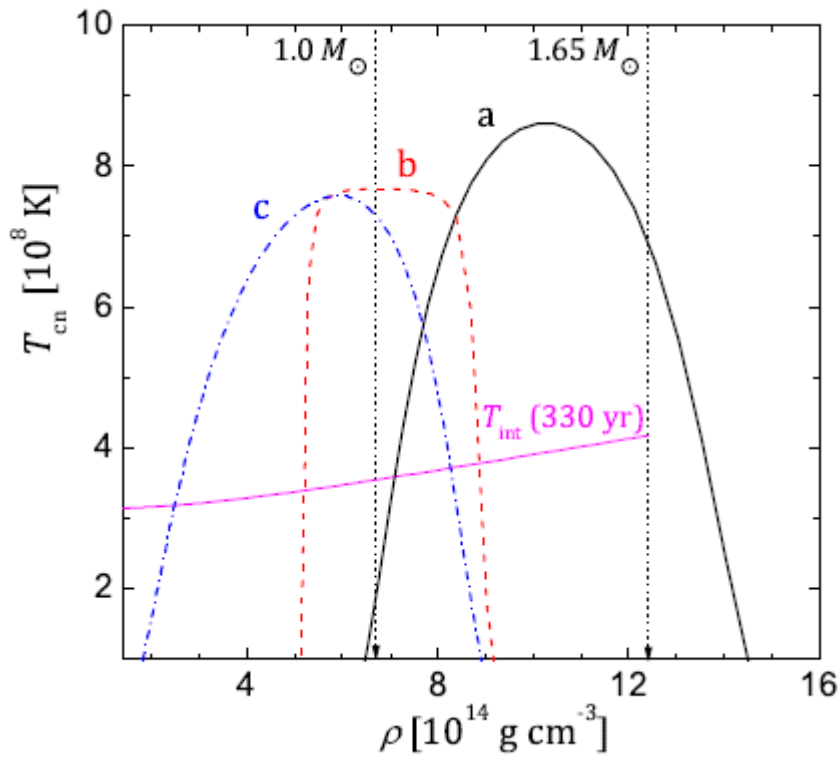
- NSs are born hot, and then cool down at first due to neutrino emission, and after – due to photon emission
- Observations of cooling provide important information about processes at high density at the NS interiors
- Two types of objects are studied:
 - isolated cooling NSs
 - NSs in soft X-ray transients

Papers to read

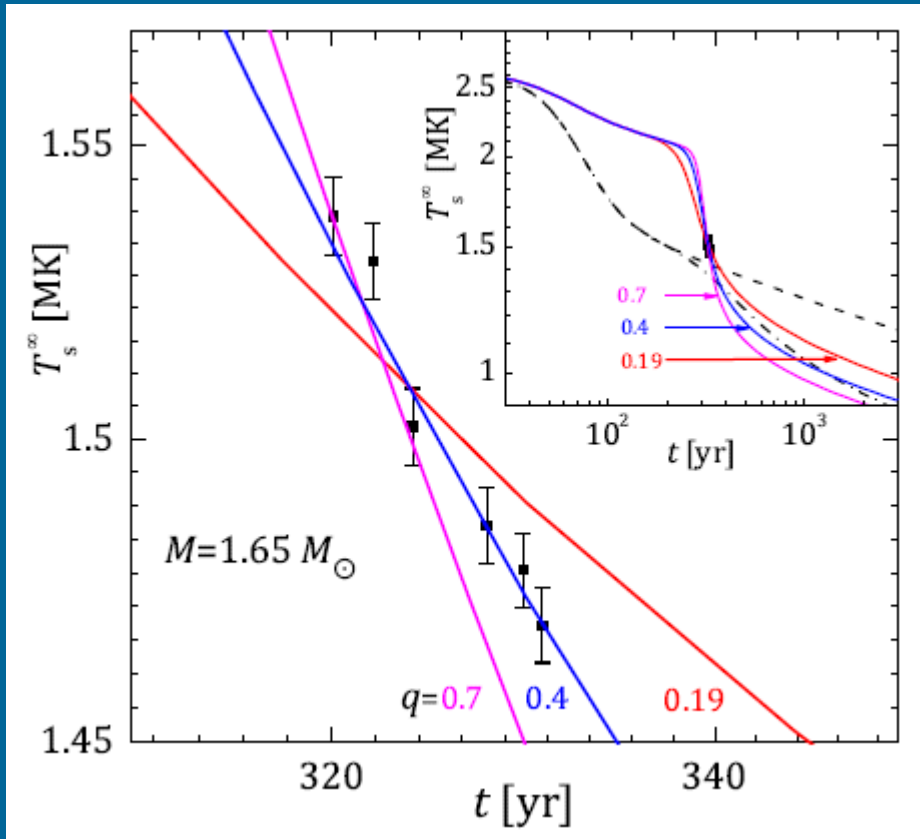
- Or astro-ph/0403657
Or astro-ph/0508056
Or astro-ph/0402143
Or 1507.06186
Or 2006.15004 ←
- [arXiv:astro-ph/9906456](https://arxiv.org/abs/astro-ph/9906456) УФН 1999
- 1709.07034 – about cooling of NSs in binaries
- Cooling of magnetars (and general basic of cooling and field evolution) 1911.03095
- Deep crustal heating 1907.08299 ←

M-R from spectral fit

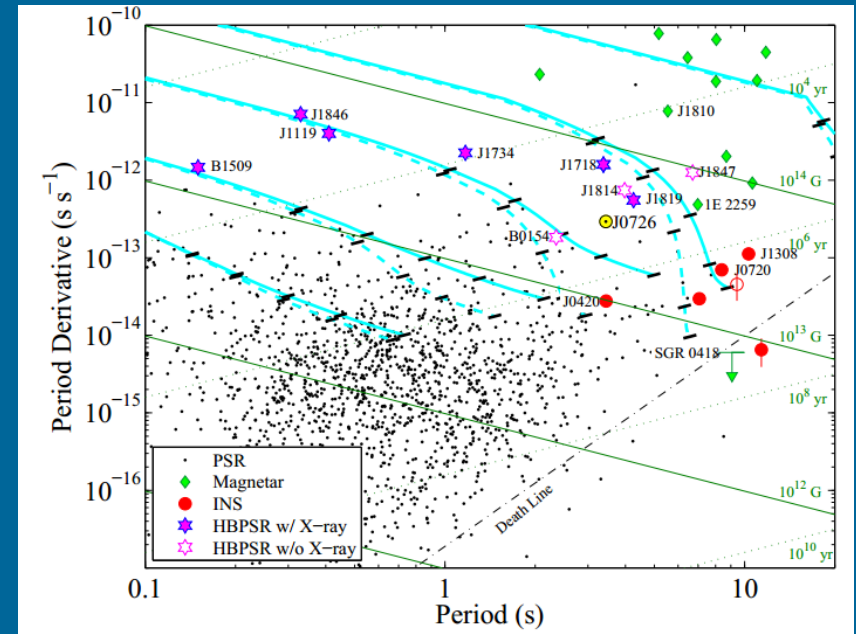
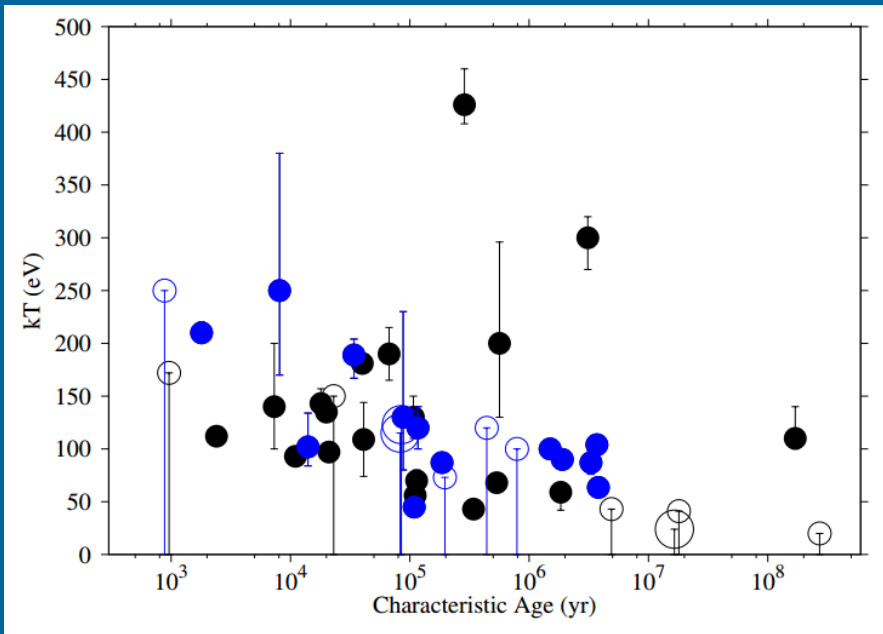




Suppression in the axial-vector channel



Cooling and grand unification for NSs



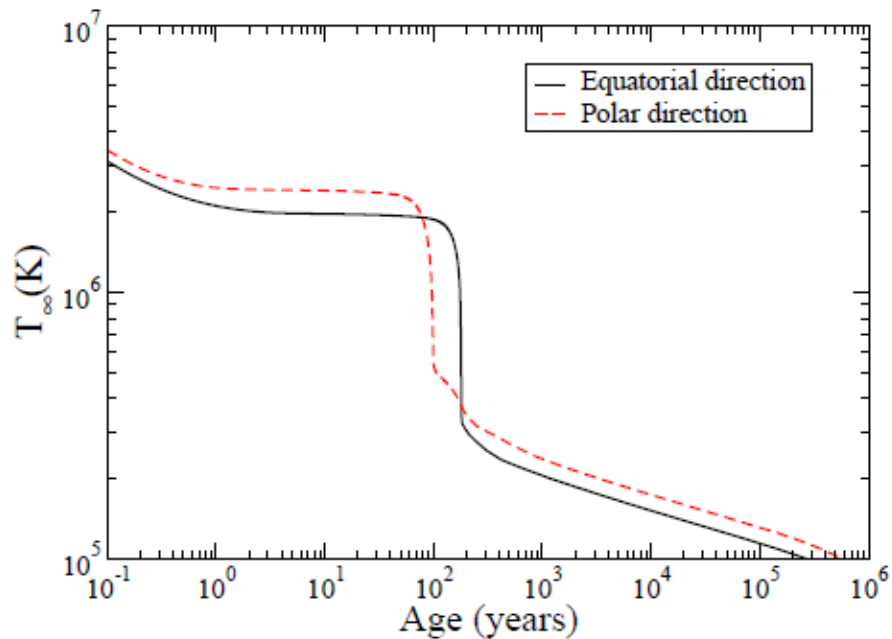
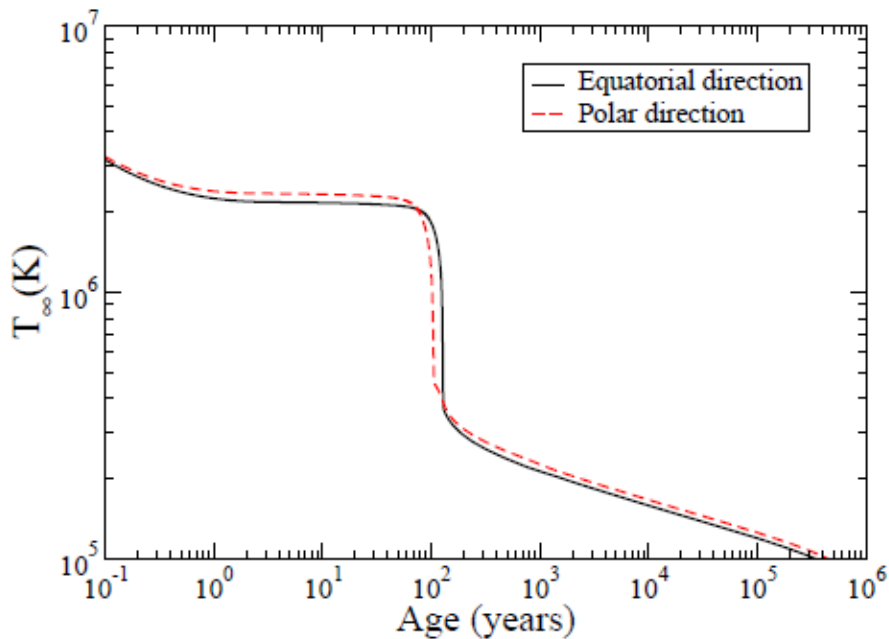
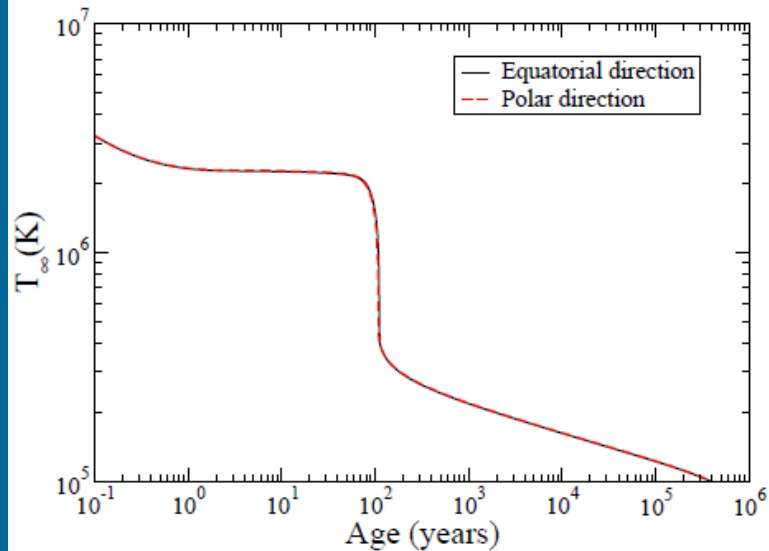
1301.2814

1111.2877

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

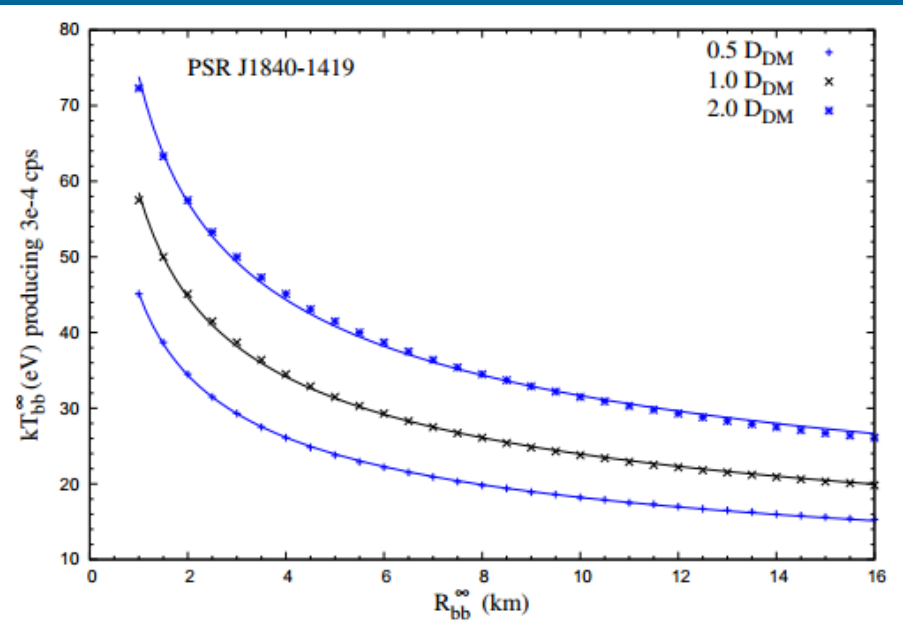
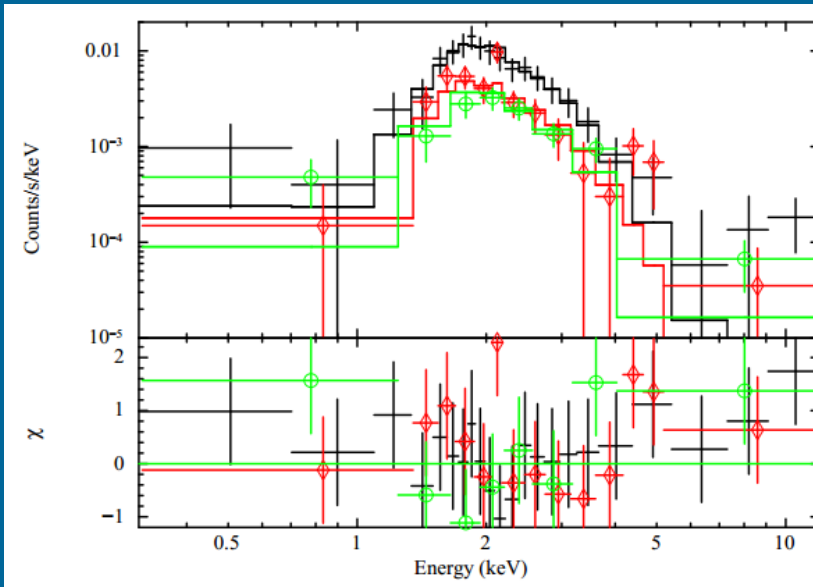
Another study demonstrates that some young PSRs with relatively large field are hot, similar to the M7.

Влияние вращения



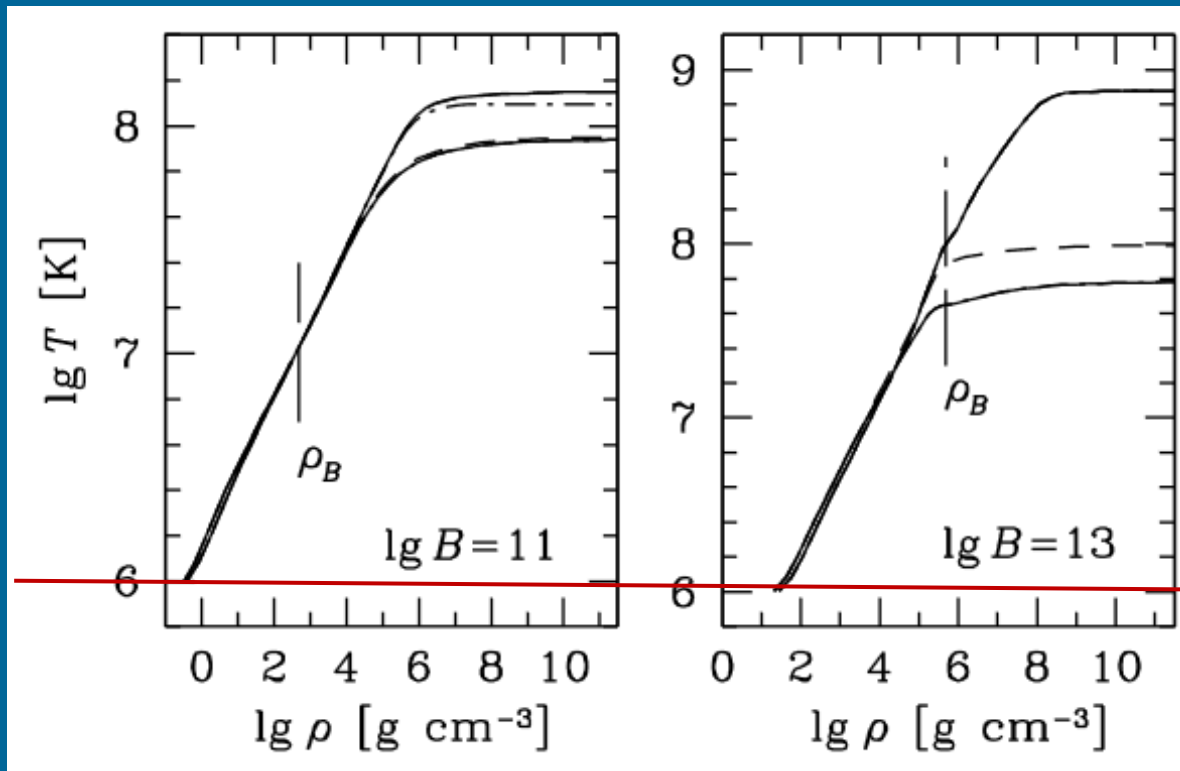
Records

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

Temperature profile in an envelope



Iron envelope.

Solid lines are new calculations for poles and equator (i.e., along and across magnetic field lines).

Surface temperature fixed at 10^6 K.

$$T_s^{(0)} \approx 10^6 g_{14}^{1/4} [(7\zeta)^{2.25} + (\zeta/3)^{1.25}]^{1/4} \text{ K}$$

$$\zeta \equiv T_{\text{int},9} - 0.001 g_{14}^{1/4} \sqrt{7 T_{\text{int},9}}$$