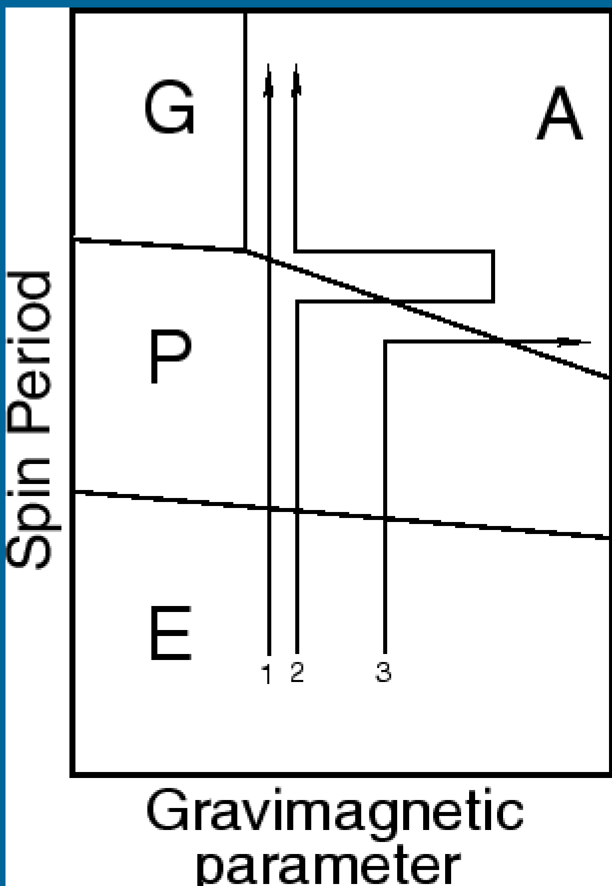
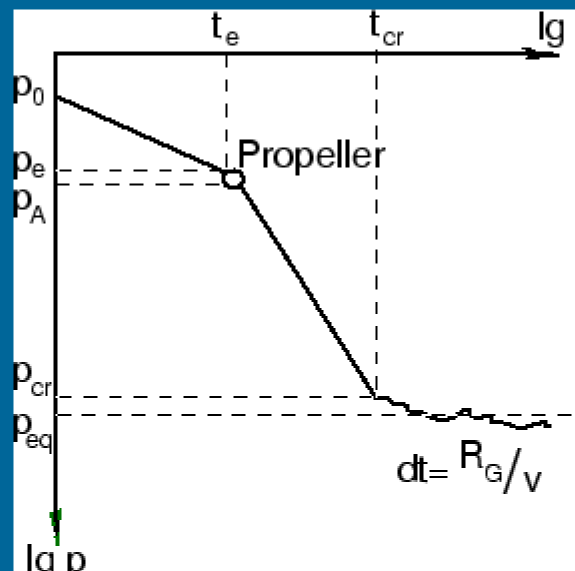
Thermal evolution of neutron stars

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

Ejector → Propeller → Accretor → Georotator



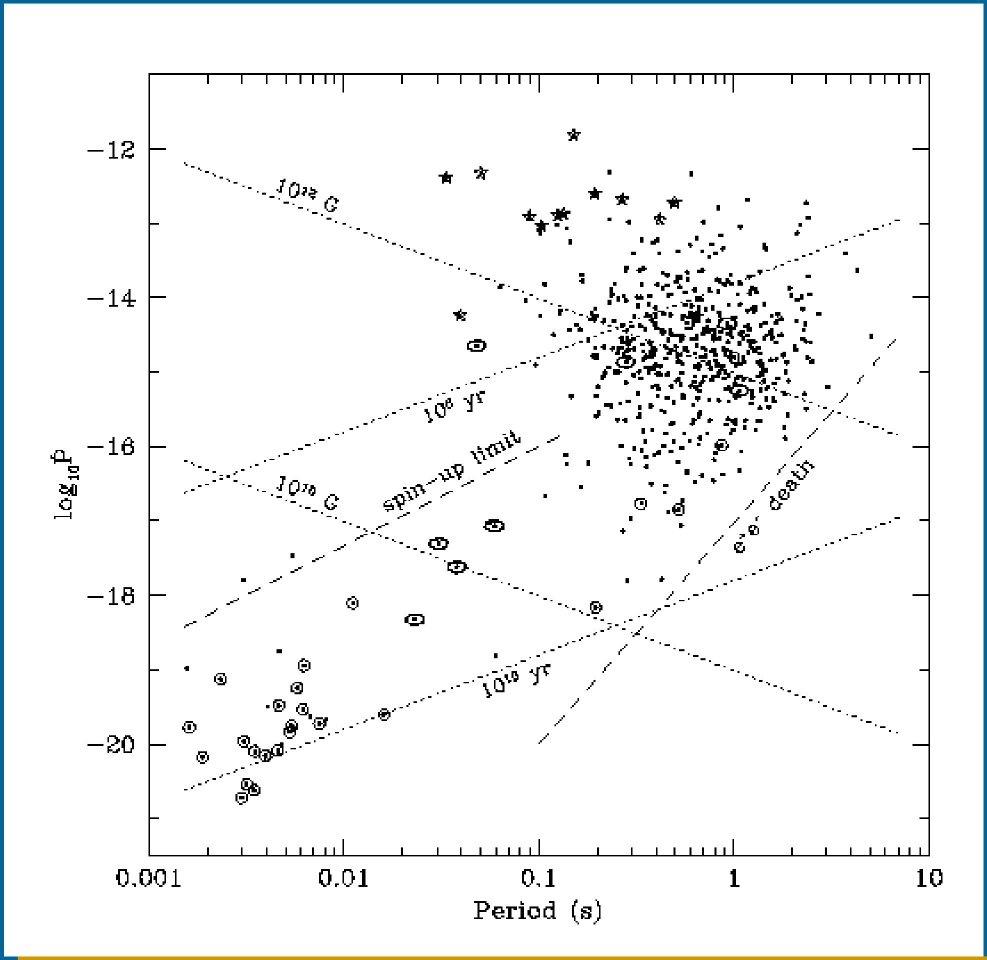
1 – spin down
2 – passage through a molecular cloud
3 – magnetic field decay



astro-ph/0101031

See the book by Lipunov (1987, 1992)

Magnetorotational evolution of radio pulsars



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

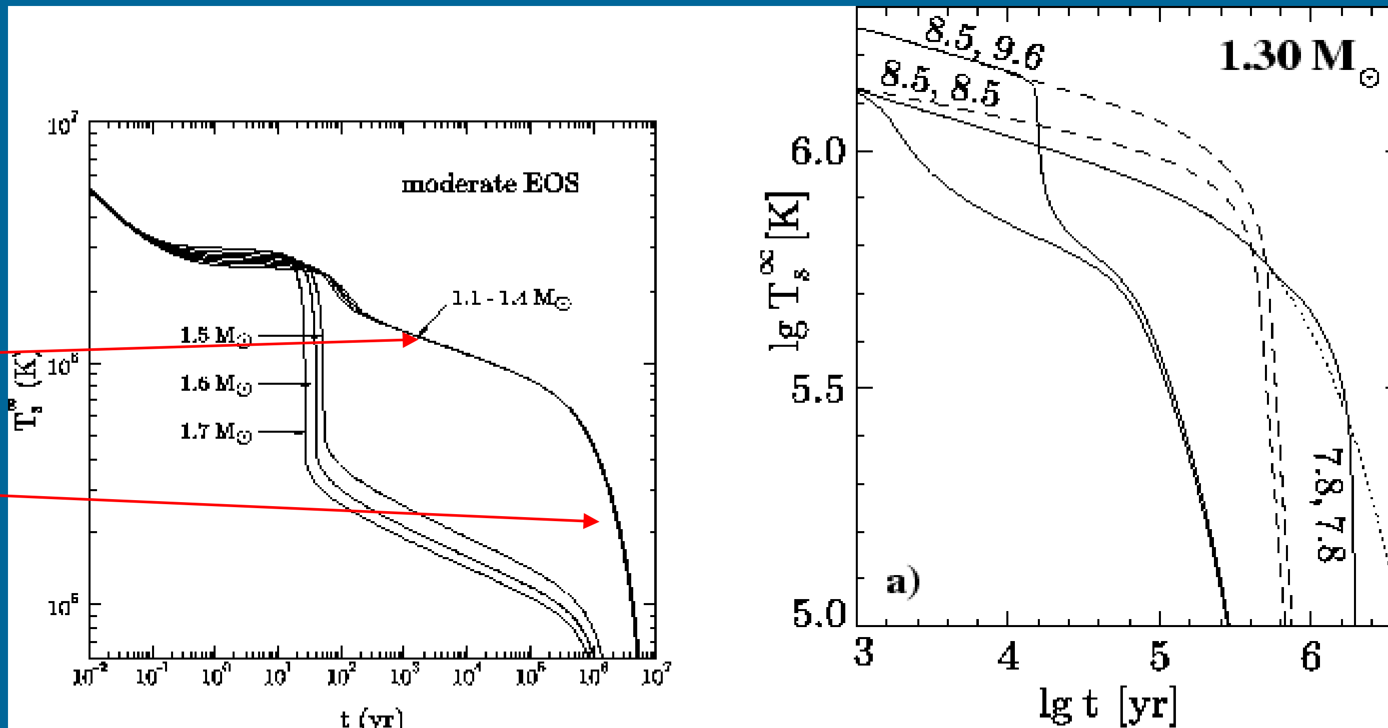
$$B \sim 3.2 \times 10^{19}\,(PdP/dt)^{1/2}\ \mathrm{G}.$$

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

Evolution of NSs. II.: temperature

Neutrino
cooling stage

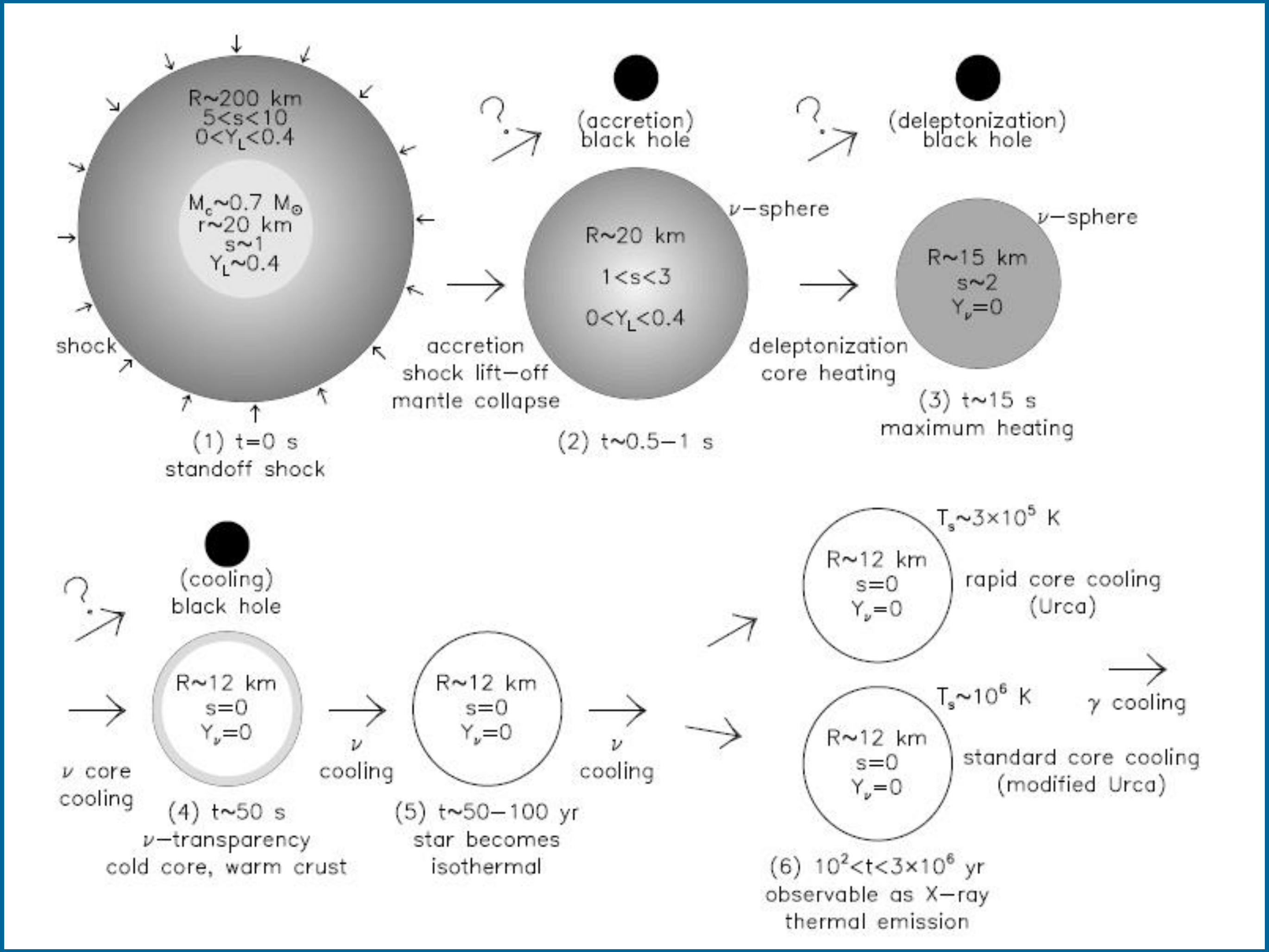
Photon
cooling stage



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

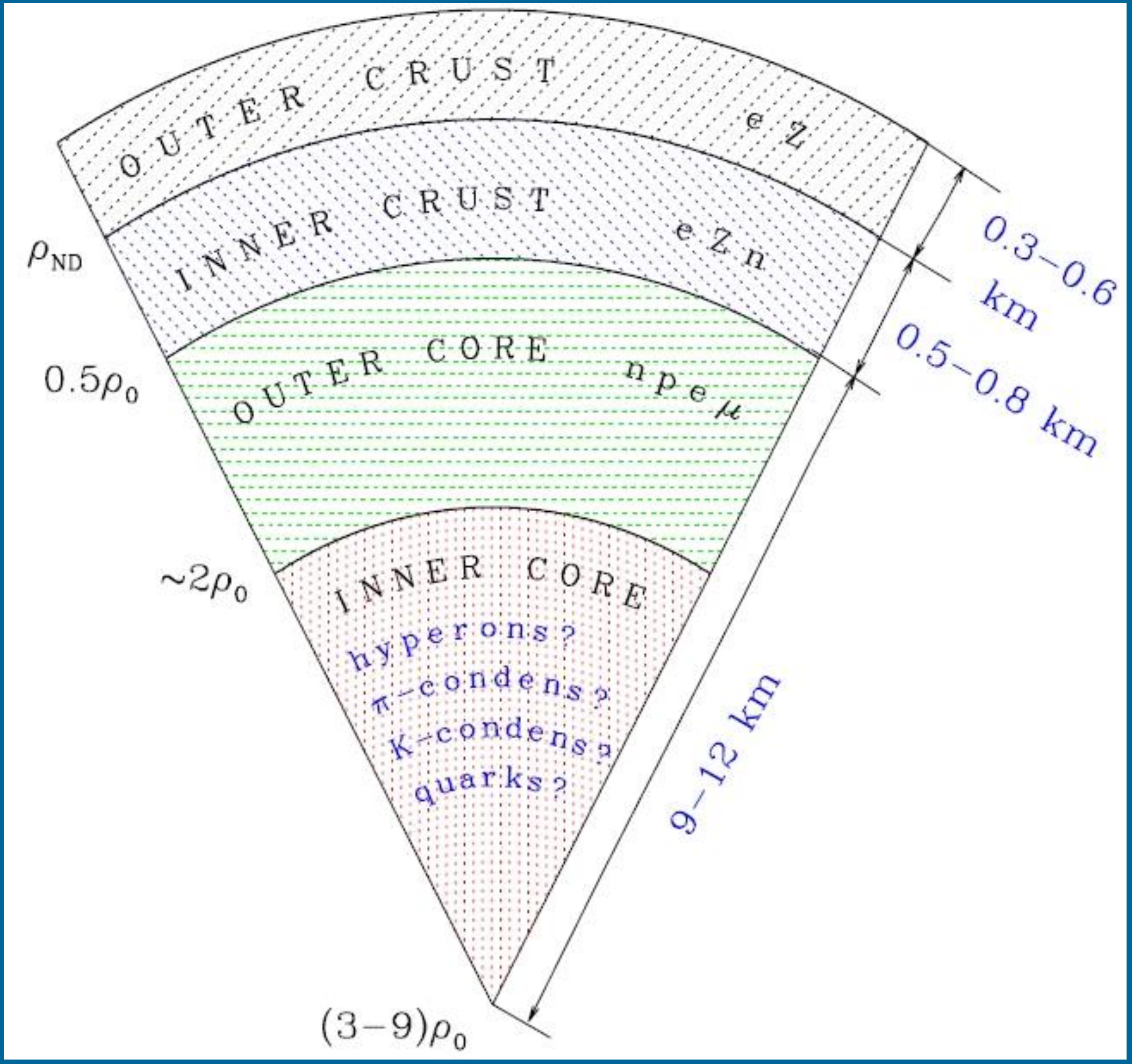
[Yakovlev et al. (1999) Physics Uspekhi]

Early evolution of a NS



(Prakash et al. astro-ph/0112136)

Structure and layers



Plus an atmosphere...

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

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

The total thermal energy of a nonsuperfluid neutron star is estimated as $U_T \sim 10^{48}\ T^2_9$ 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

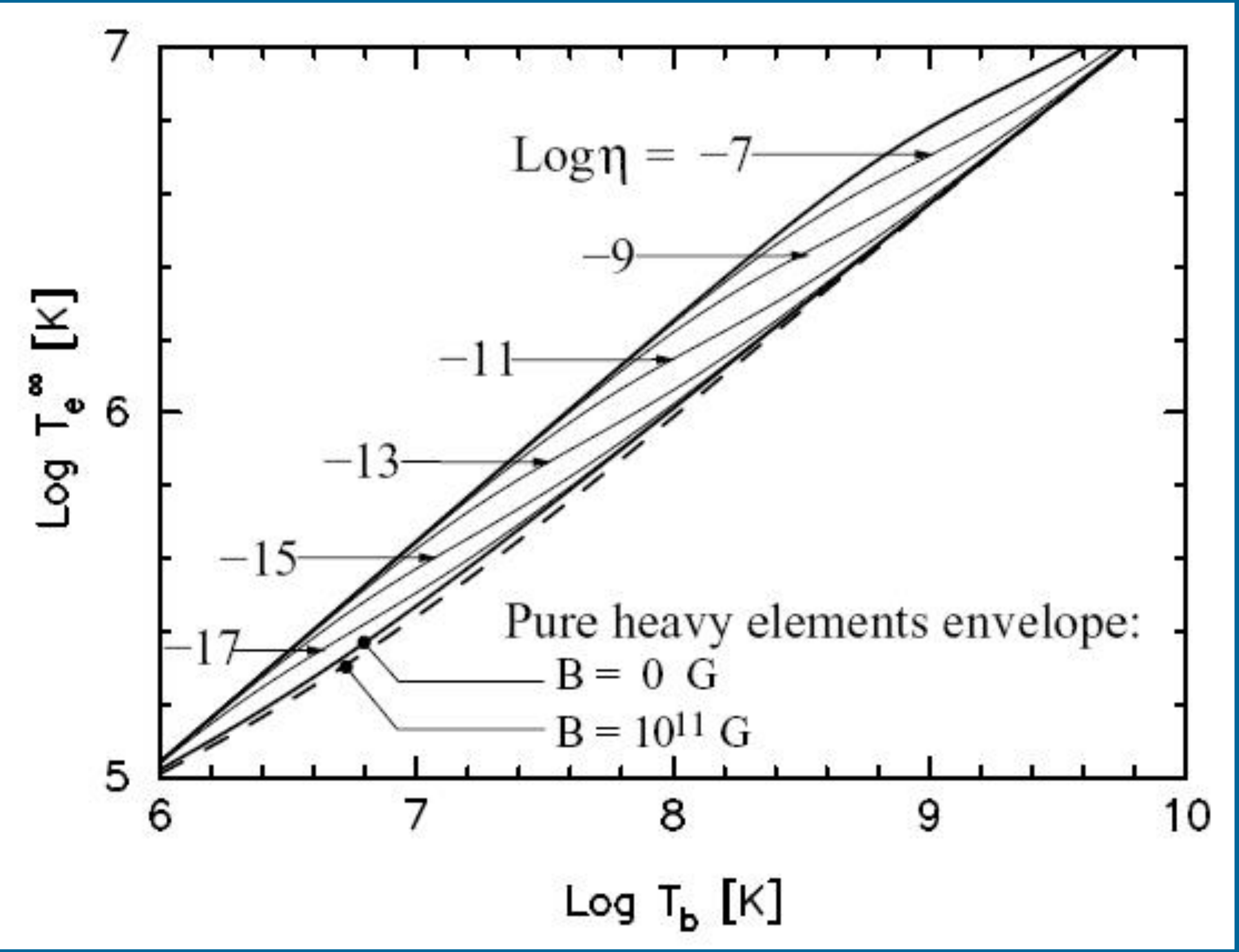
$$\frac{dE_{th}}{dt} = C_V \frac{dT}{dt} = -L_\nu - L_\gamma$$

Photon luminosity

Neutrino luminosity

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

Core-crust temperature relation



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

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

Page et al. astro-ph/0508056

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

(see Yakovlev & Pethick 2004)

Main neutrino processes

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

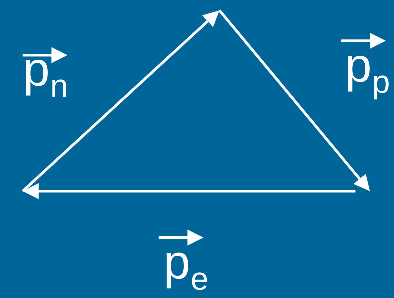
Process		$Q_{\rm s}$, erg cm^{-3} s^{-1}
Modified Urca	$nN \to pNe\bar{\nu} \quad pNe \to nN\nu$	$10^{20} - 3 \times 10^{21}$
Bremsstrahlung	$NN \to NN\nu\bar{\nu}$	$10^{19} - 10^{20}$

$$Q_{\rm slow} = Q_{\rm s} T_9^8, \qquad Q_{\rm fast} = Q_{\rm f} T_9^6$$

(Yakovlev & Pethick astro-ph/0402143)

Fast Cooling (URCA cycle)	Slow Cooling (modified URCA cycle)
$n \rightarrow p + e^- + \bar{\nu}_e$	$n + n \rightarrow n + p + e^- + \bar{\nu}_e$
$p + e^- \rightarrow n + \nu_e$	$n + p + e^- \rightarrow n + n + \nu_e$
	$p + n \rightarrow p + p + e^- + \bar{\nu}_e$
	$p + p + e^- \rightarrow p + n + \nu_e$

- 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



$p_n < p_p + p_e$

[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.

(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.

ρ_D= 7.851 10^{14} g/cm^3.

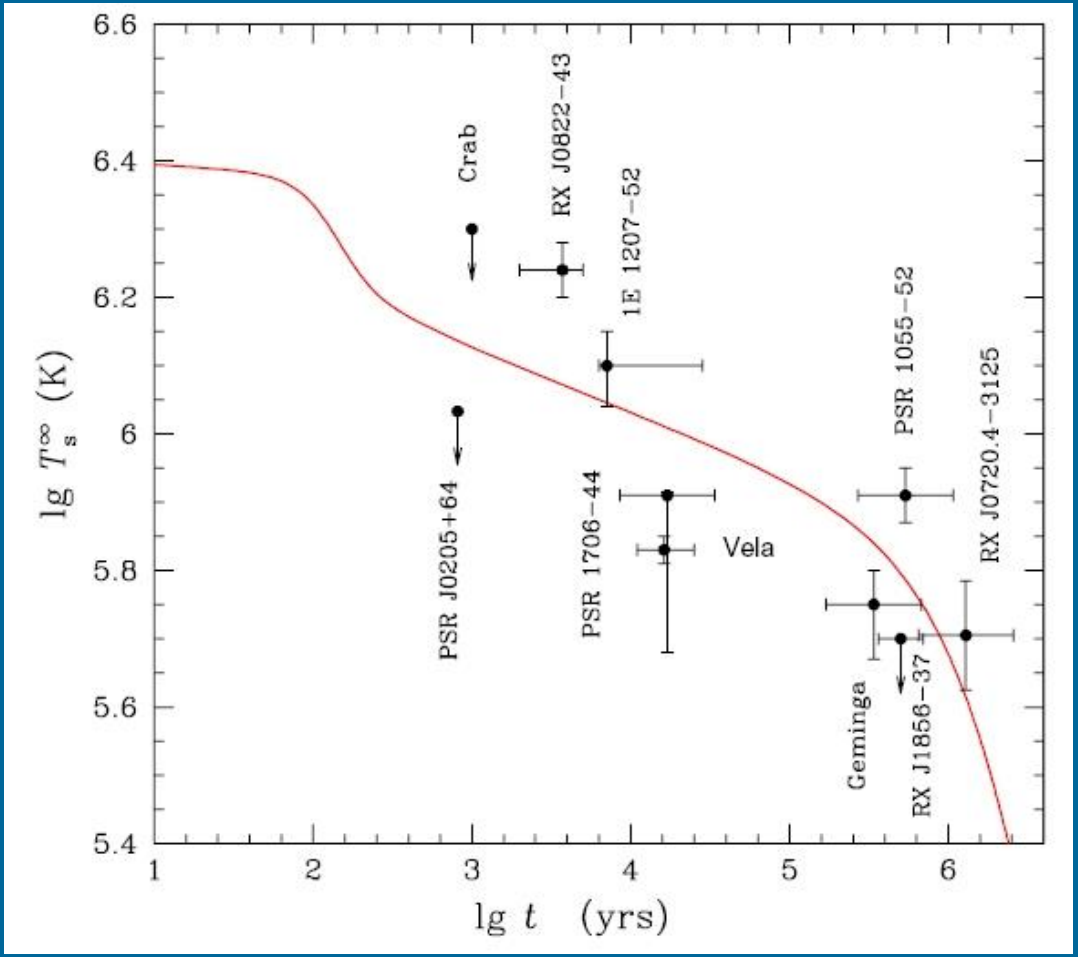
The critical mass depends on the EoS. For the examples below M_D=1.358 M_{solar}.

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

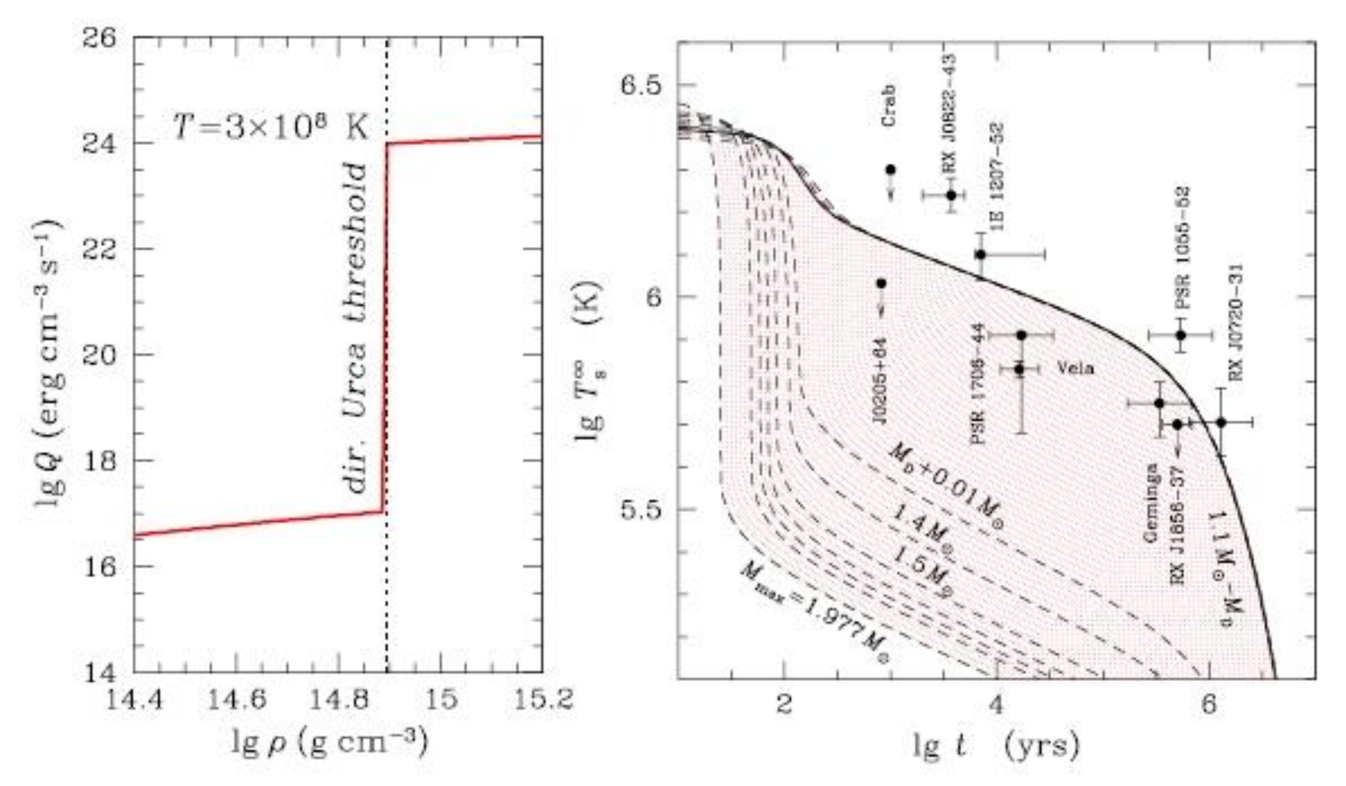
Simple cooling model for low-mass NSs.



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

(Yakovlev & Pethick 2004)

Nonsuperfluid nucleon cores



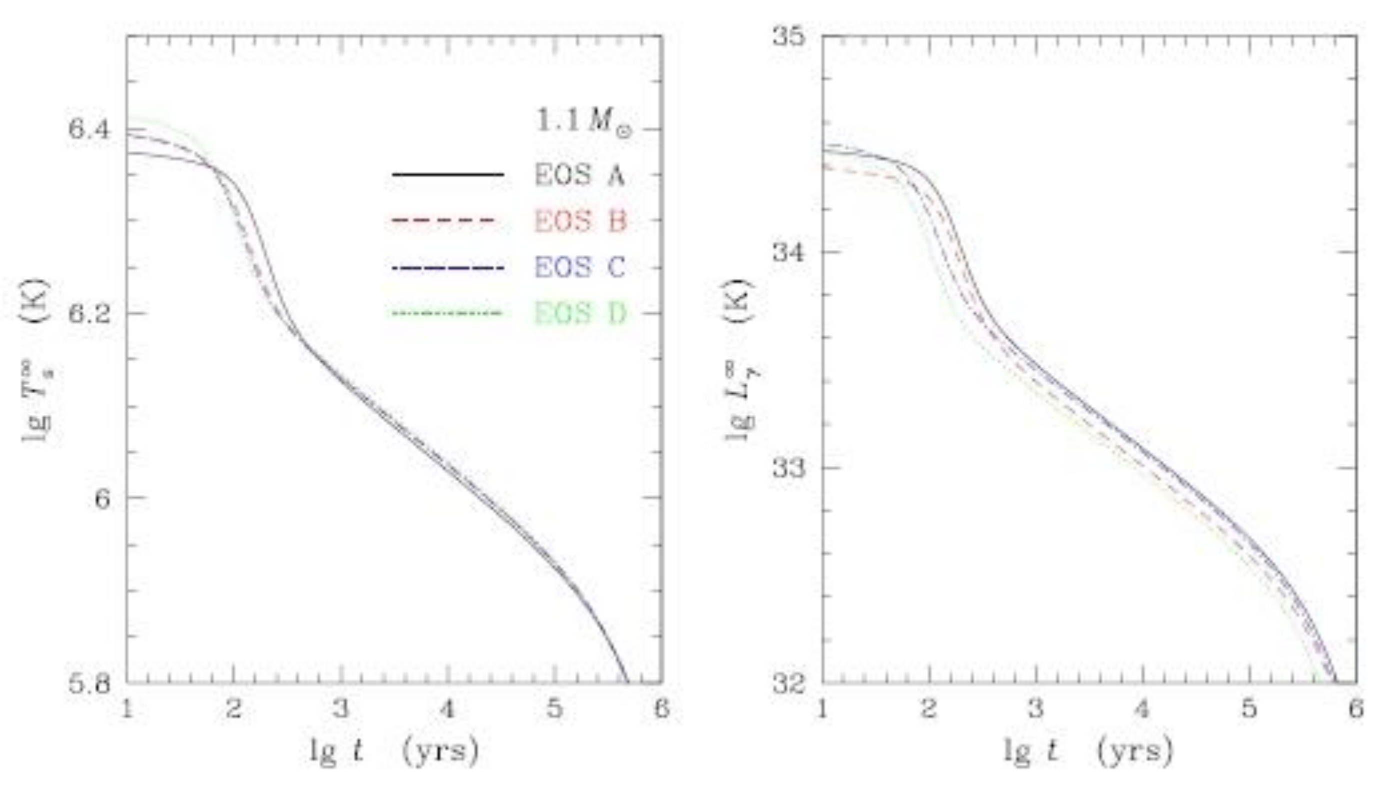
Note "population aspects" of the right plot: too many NSs have to be explained by a very narrow range of mass.

For slow cooling at the neutrino cooling stage t_{slow}~1 yr/T_{i9}^6

For fast cooling t_{fast}~ 1 min/T_{i9}^4

(Yakovlev & Pethick 2004)

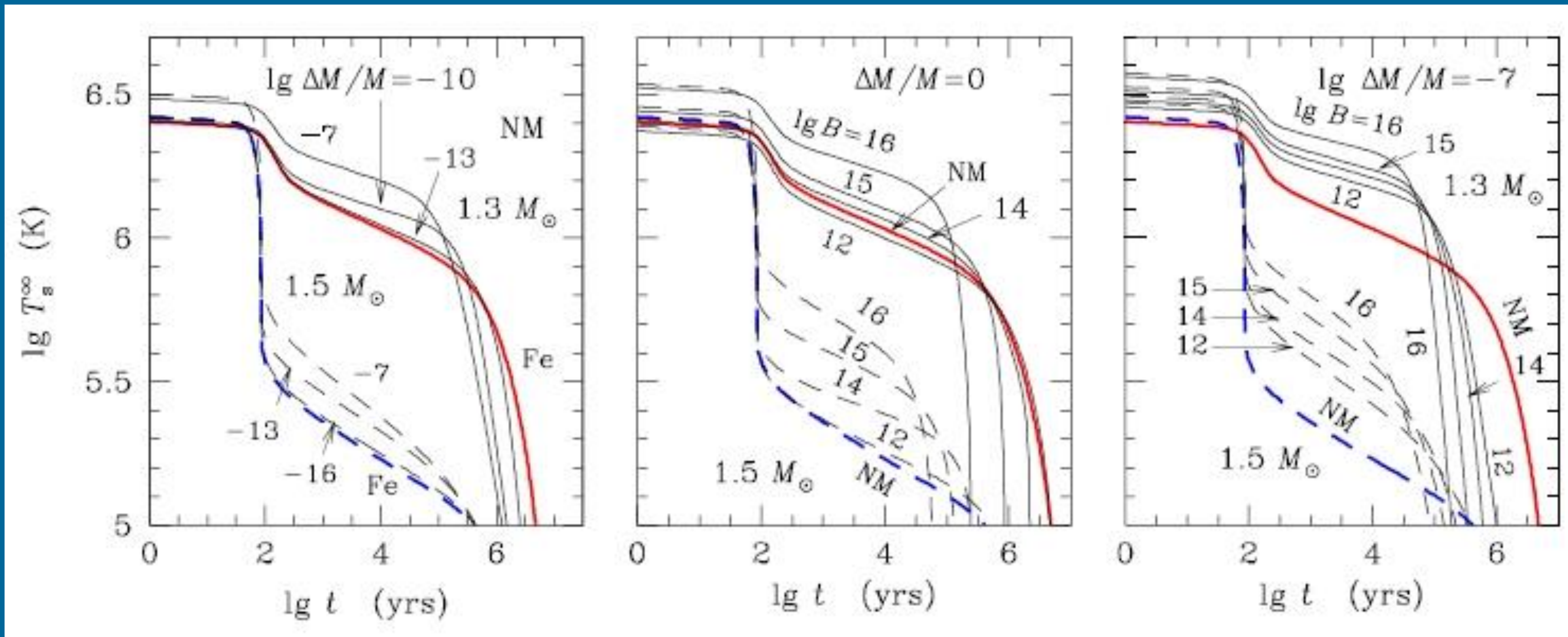
Slow cooling for different EoS



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

(Yakovlev & Pethick 2004)

Envelopes and magnetic field



Non-magnetic stars
Thick lines – no envelope

No accreted envelopes,
different magnetic fields.
Thick lines – non-magnetic

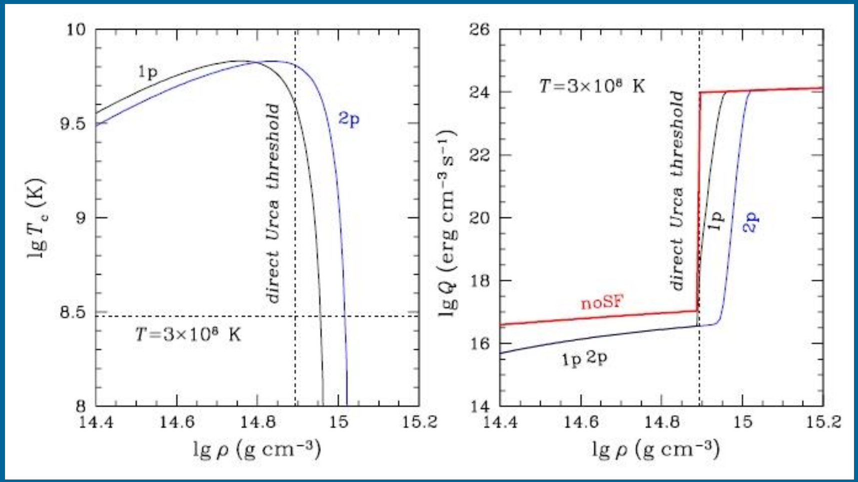
Envelopes + Fields

Solid line M=1.3 M_{solar}, Dashed lines M=1.5 M_{solar}

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.

(Yakovlev & Pethick 2004)

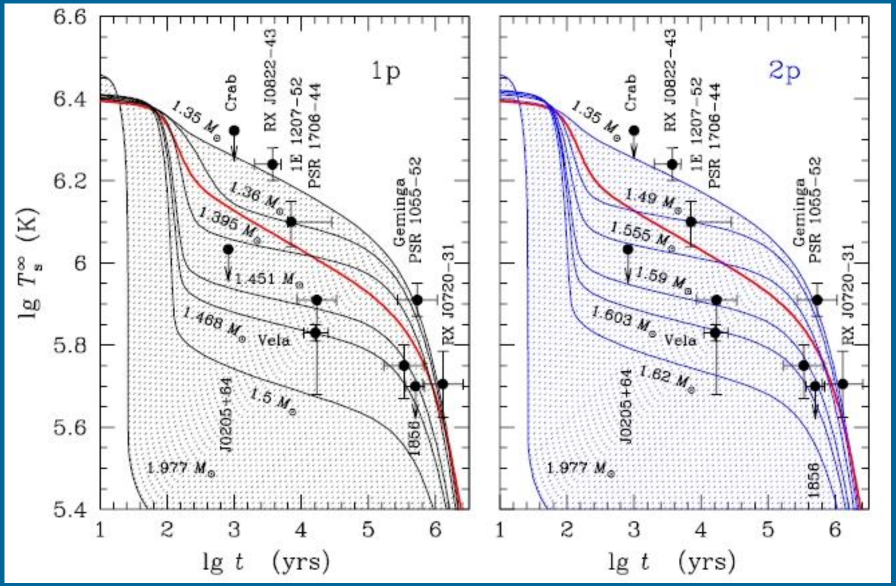
Simplified model: no neutron superfluidity



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

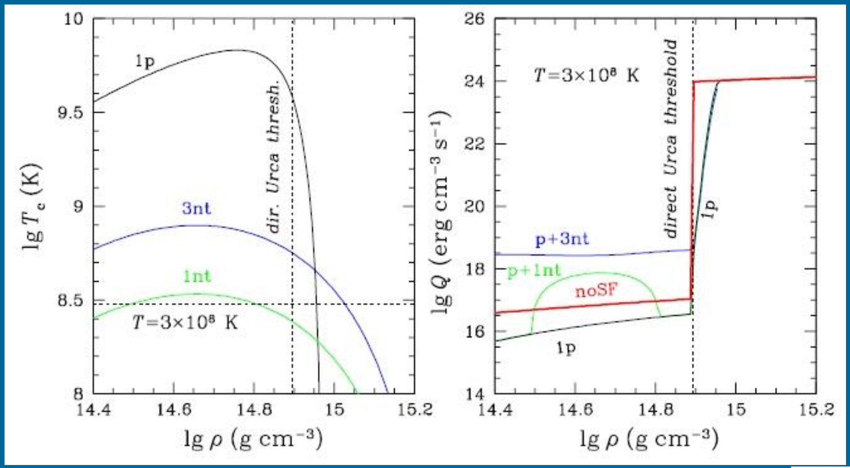
There is no complete microphysical theory which can describe superfluidity in neutron stars.

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



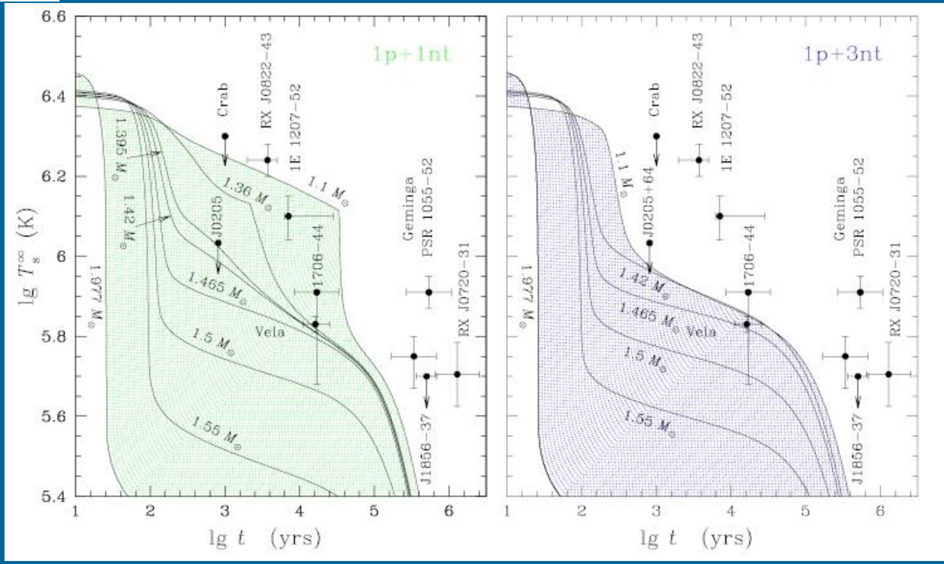
(Yakovlev & Pethick 2004)

Neutron superfluidity and observations



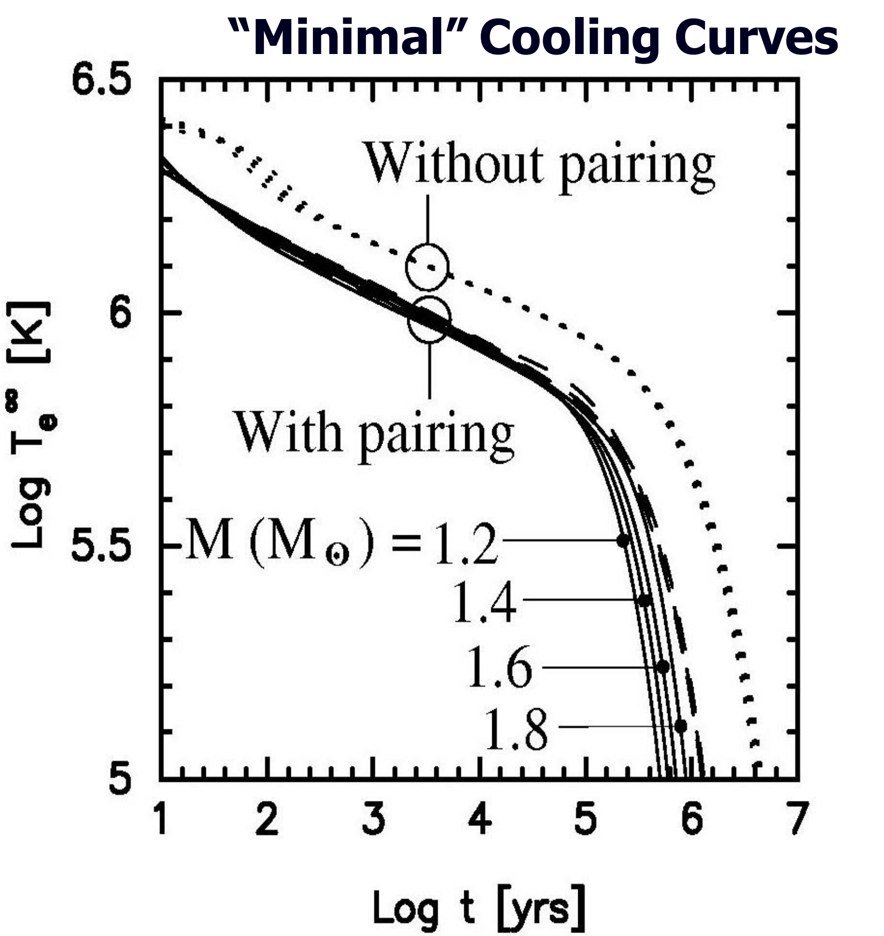
Mild neutron pairing in the core contradicts observations.

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



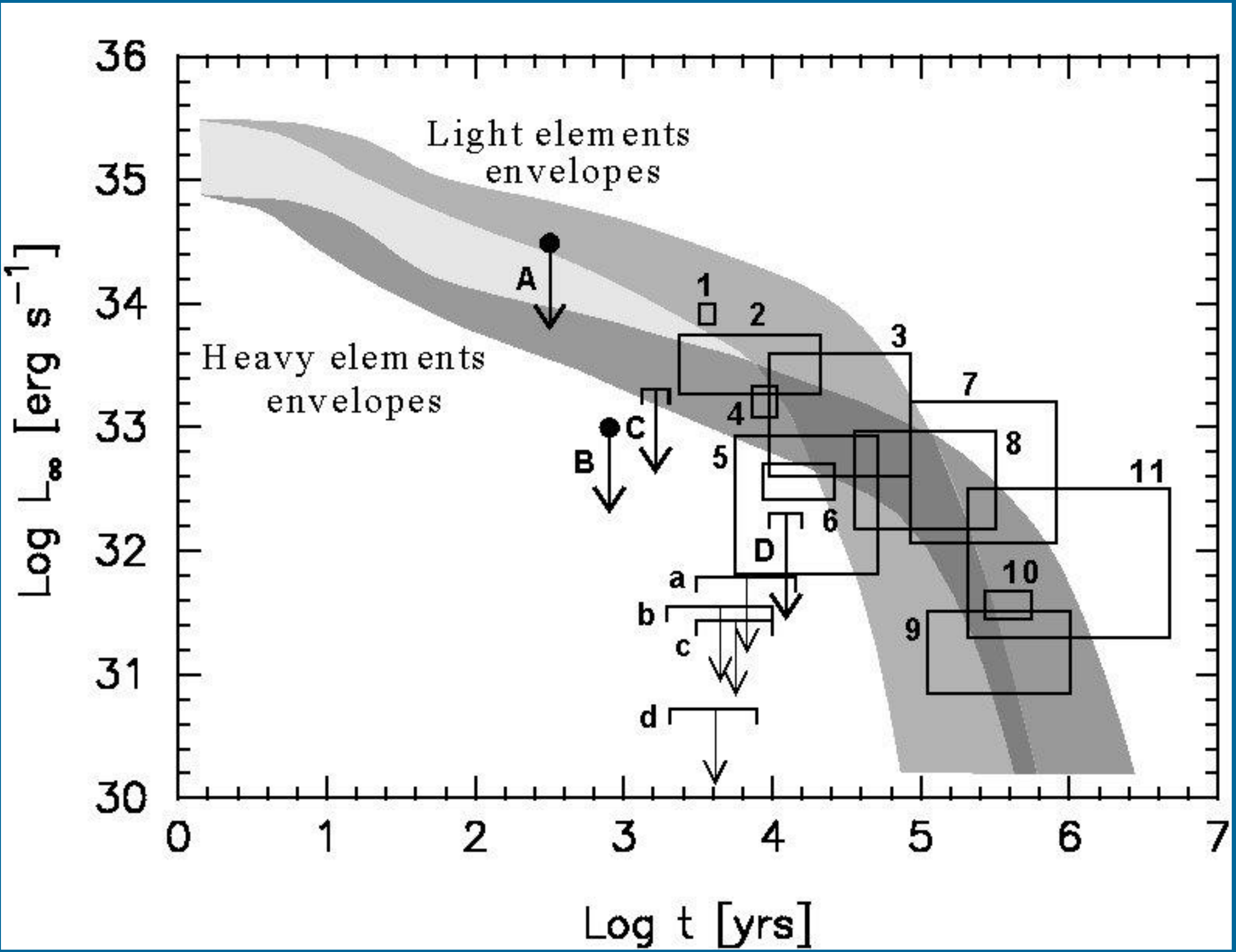
Page, Geppert & Weber (2006)

"minimal" means
without additional cooling
due to direct URCA
and without additional heating

Main ingredients of the minimal model

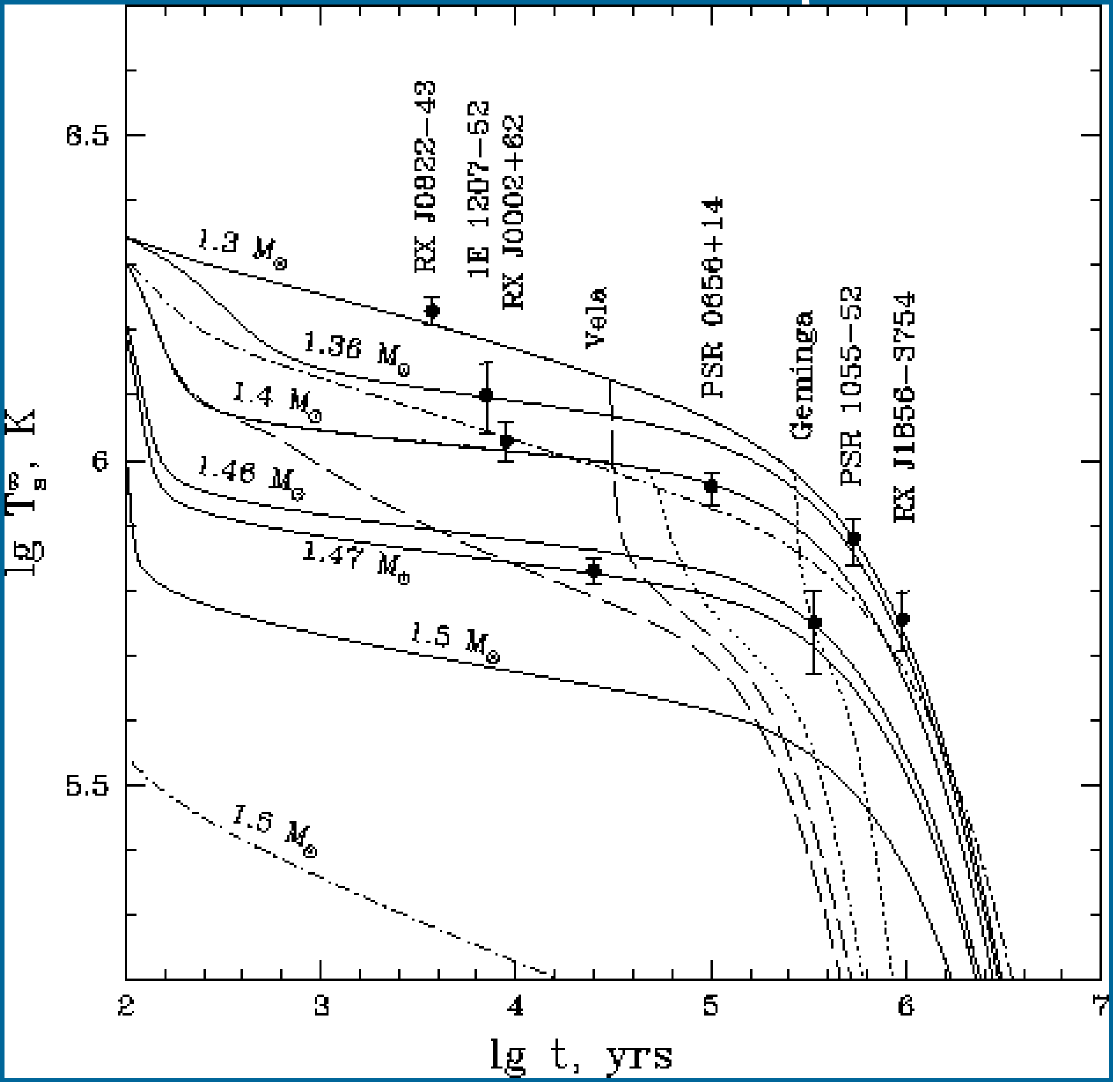
- EoS
- Superfluid properties
- Envelope composition
- NS mass

Luminosity and age uncertainties



Page, Geppert, Weber
astro-ph/0508056

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	$32.6 - 33.6$

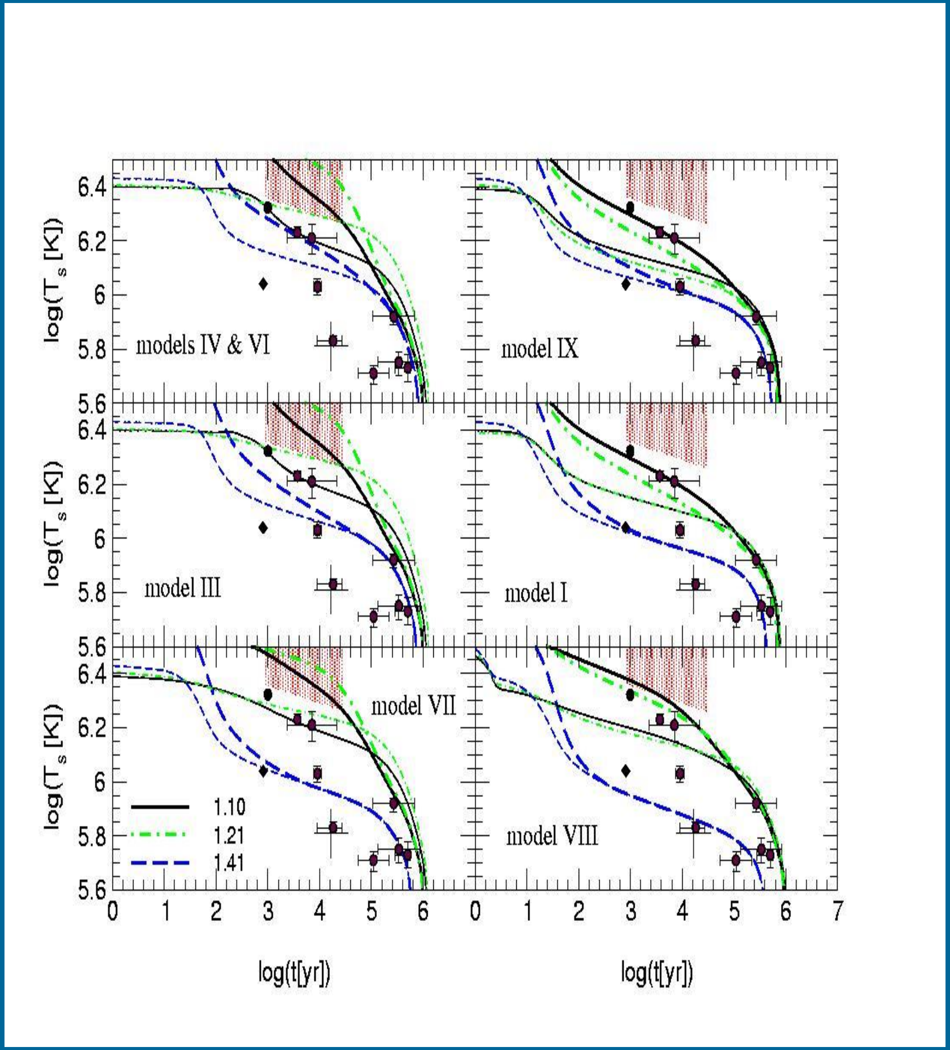
Neutron Star Properties with Blackbody Atmospheres

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	–	$5.55 - 5.95$	$5.0 - 15.0$	$0.1 - 0.3$	$31.3 - 32.5$

(Page et al. astro-ph/0403657)

Brightness constraint

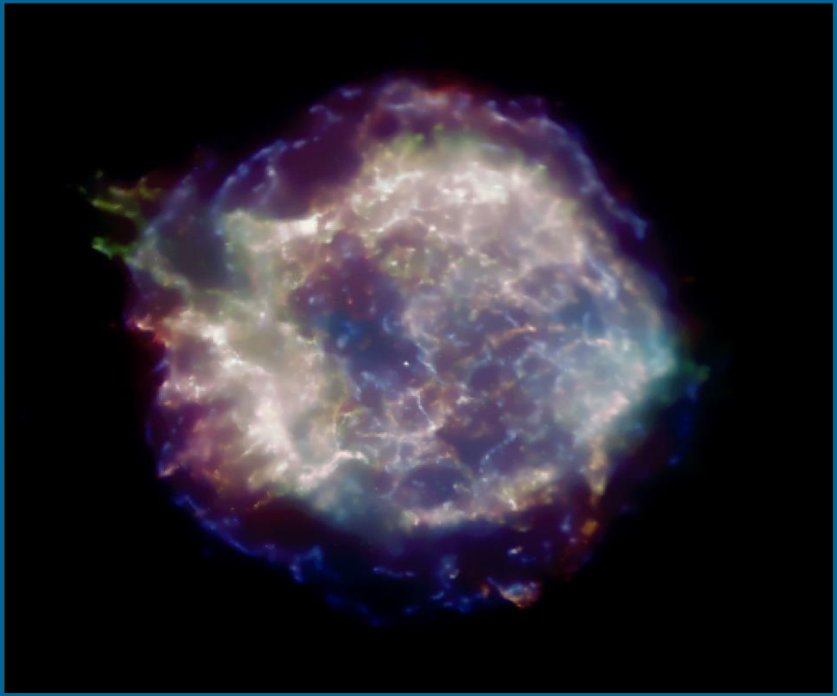
Different tests and constraints
are sensitive to different parameters,
so, typically it is better to use
several different tests



(H. Grigorian astro-ph/0507052)

CCOs

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



Known objects

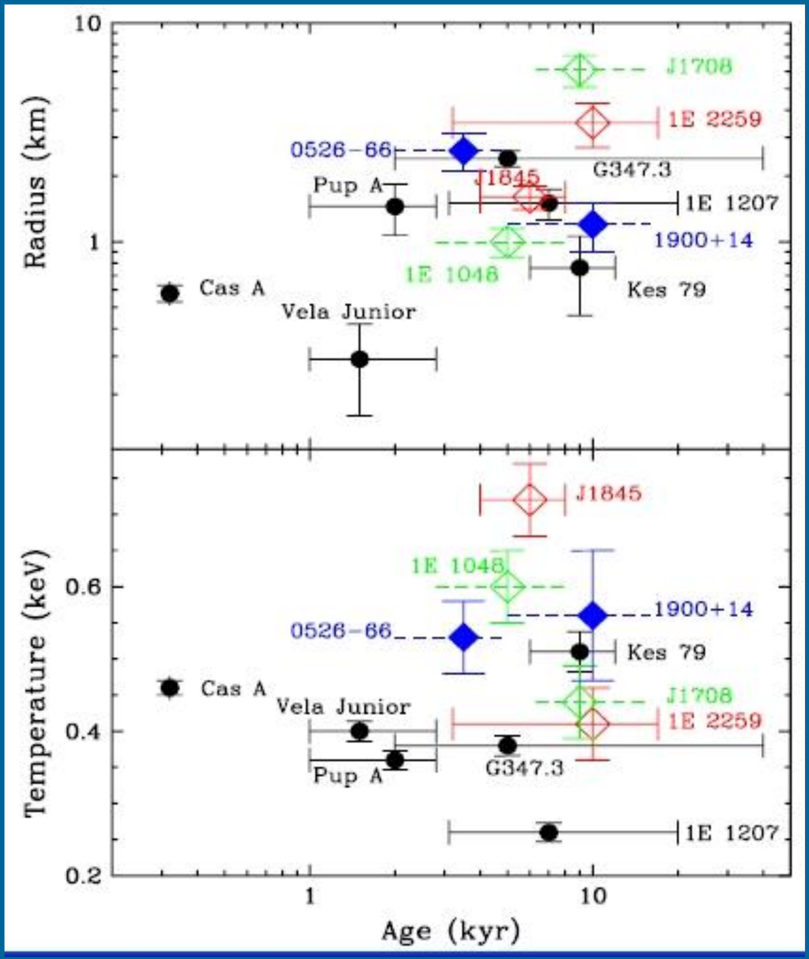
Object	SNR	Age kyr	d kpc	P	$F_{x,-12}$
J232327.9+584843	Cas A	0.32	3.3–3.7	...	0.8
J085201.4−461753	G266.1−1.2	1–3	1–2	...	1.4
J161736.3−510225(x)	RCW 103	1–3	3–7	6.4hr	0.9–60
J082157.5−430017	Pup A	1–3	1.6–3.3	...	4.5
J121000.8−522628	G296.5+10.0	3–20	1.3–3.9	424ms	2.3
J185238.6+004020(n)	Kes 79	∼9	∼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

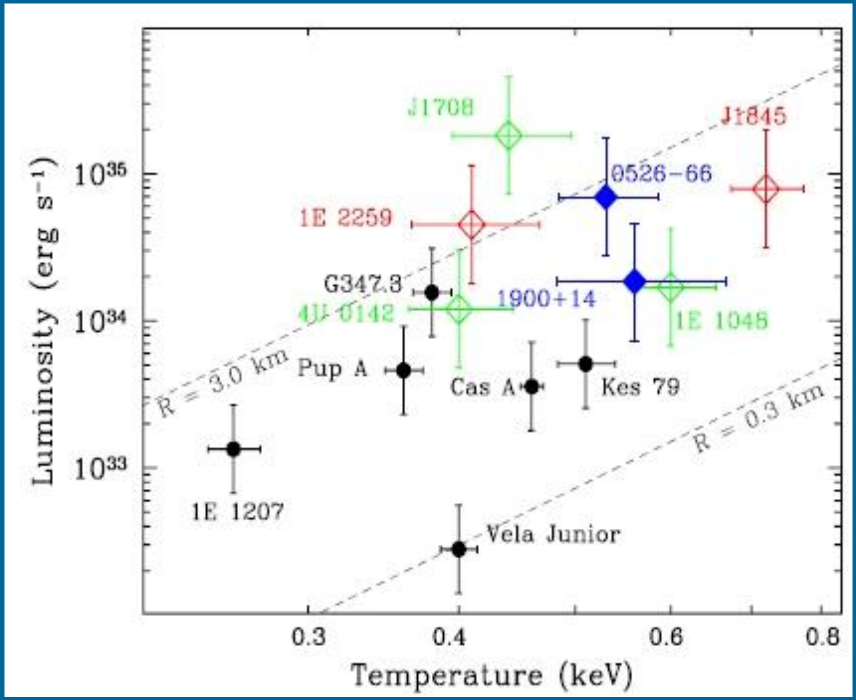
Object	kT keV	R km	$L_{bol,33}$	Γ	$L_{pl,33}$	$n_{H,22}$	F^{bb}/F^{pl}
J2323+5848	0.43	0.6	1.6	4.2	13	1.8	1.1
	0.43	0.7	1.9	2.5	0.2	[1.2]	4.5
J0852–4617	0.40	0.3	0.3	unconstr	...	0.4	...
J0821–4300	0.40	1.0	3.3	unconstr	...	0.3	...
J1210–5226	0.22	2.0	1.2	3.6	1.2	0.13	3.0
J1852+0040	0.50	1.0	8.0	unconstr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

New candidates appear continuously

(Pavlov et al. astro-ph/0311526)

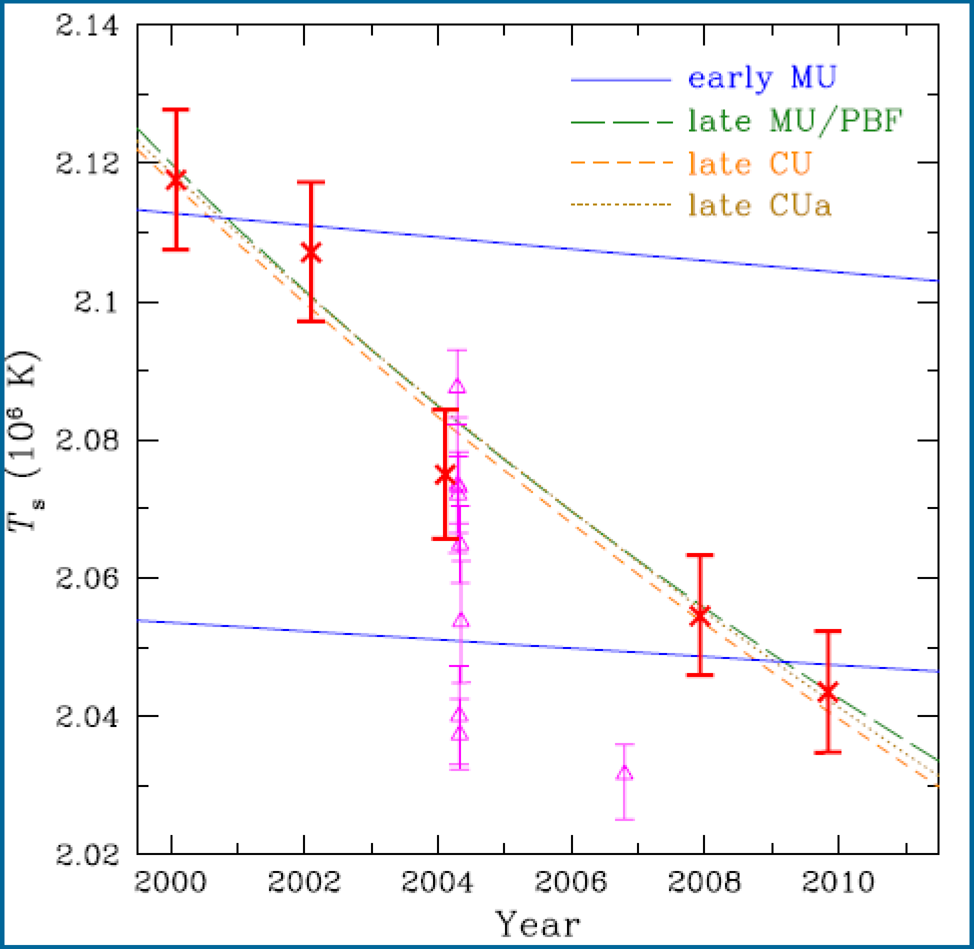
Correlations





(Pavlov et al. astro-ph/0311526)

Cas A peculiar cooling

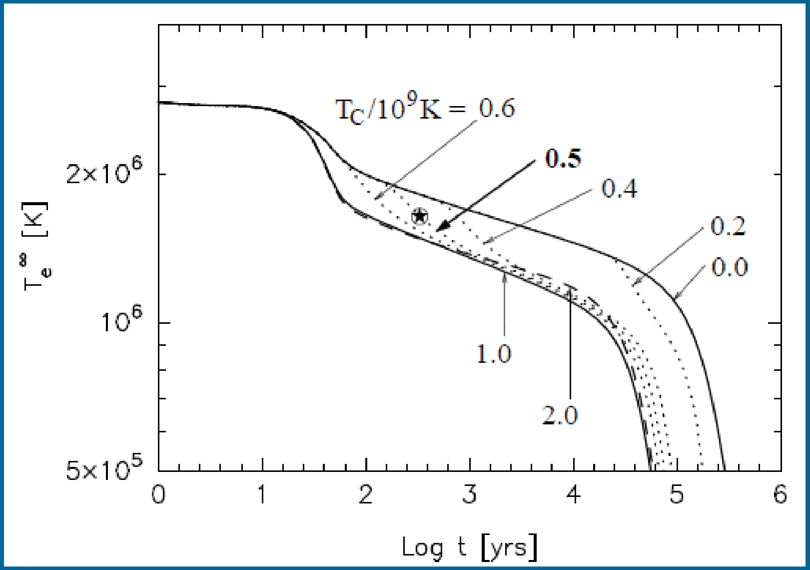


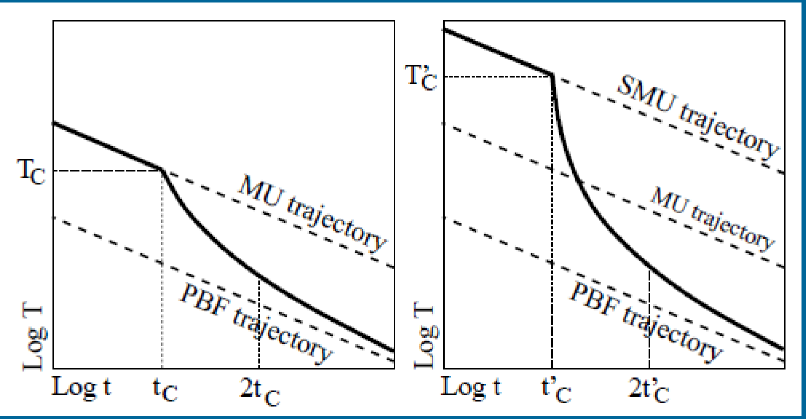
330 years
~3.5 kpc
Carbon atmosphere
The youngest cooler known

Temperature steadily goes down
by ~4% in 10 years:
2.12 10^6K in 2000 – 2.04 10^6K in 2009

1007.4719

Onset of neutron $^3P_2$ superfluidity in the core





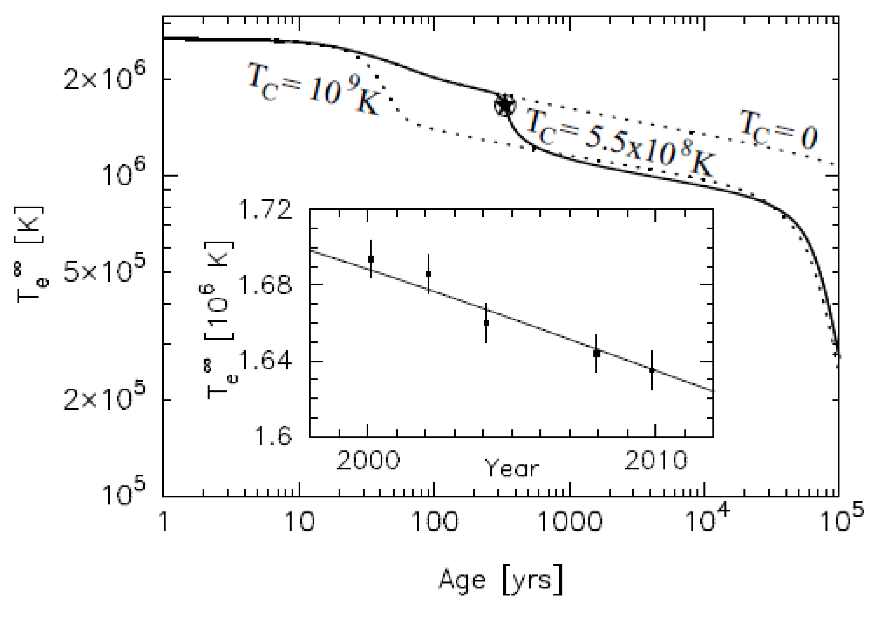
The idea is that we see the result of the onset of neutron $^3P_2$ superfluidity in the core.

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: $0.5\ 10^9$ K

1011.6142

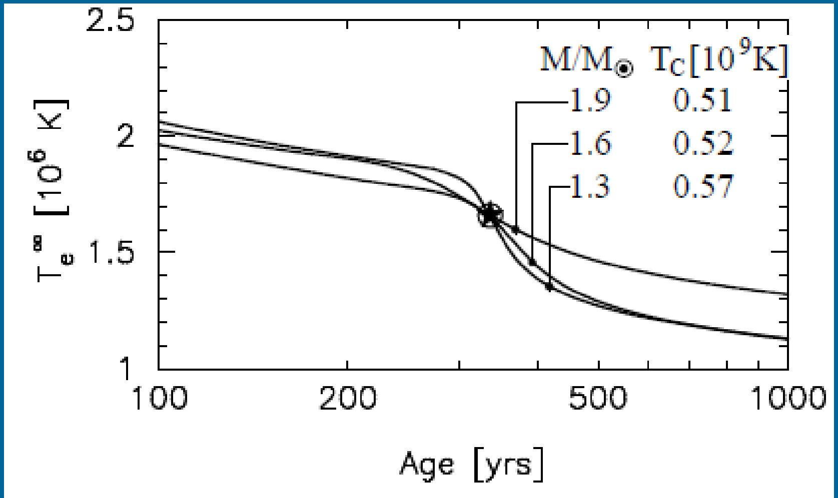
The best fit model



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.

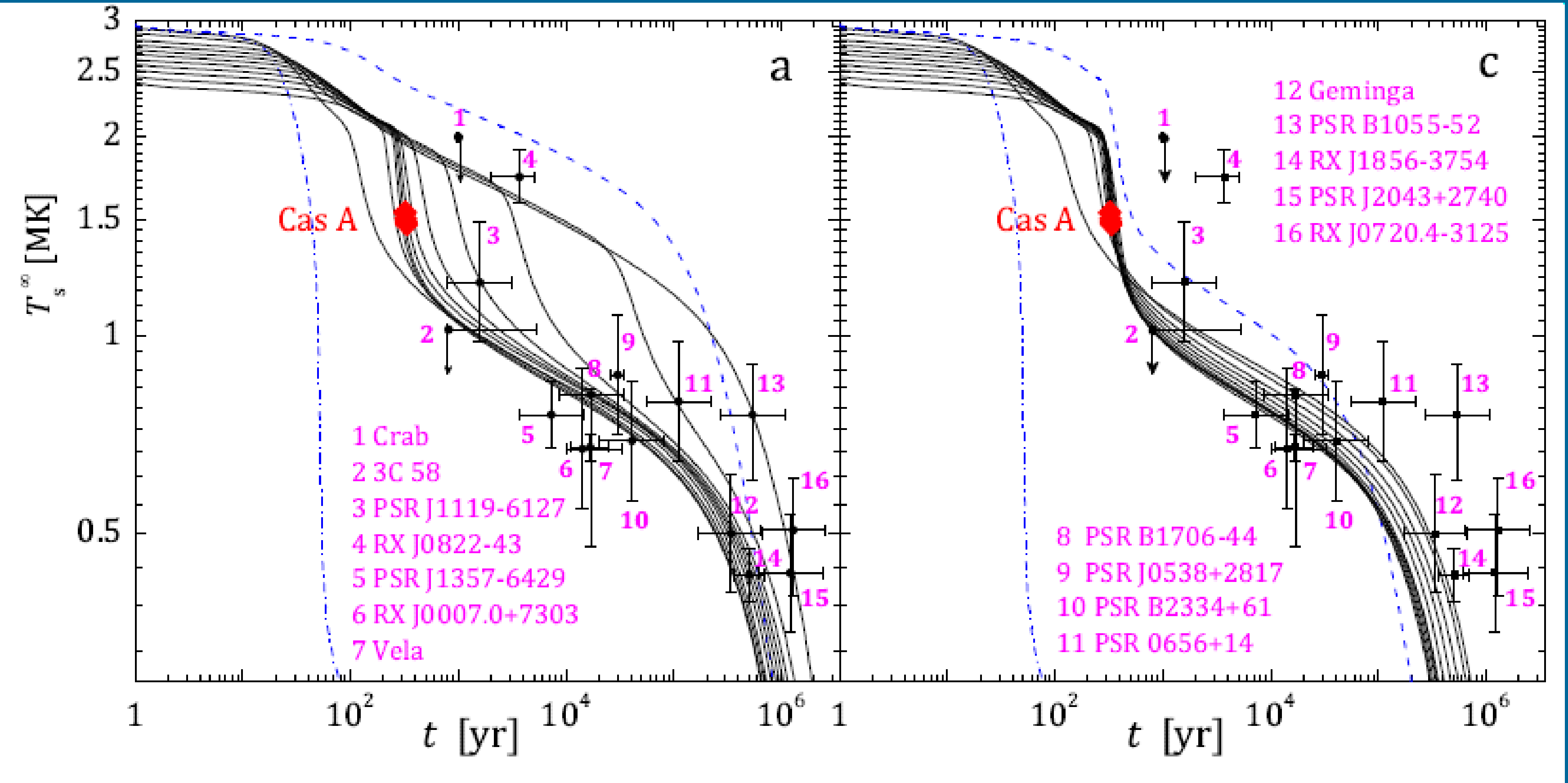
The plot is made for $M=1.4M_O$



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

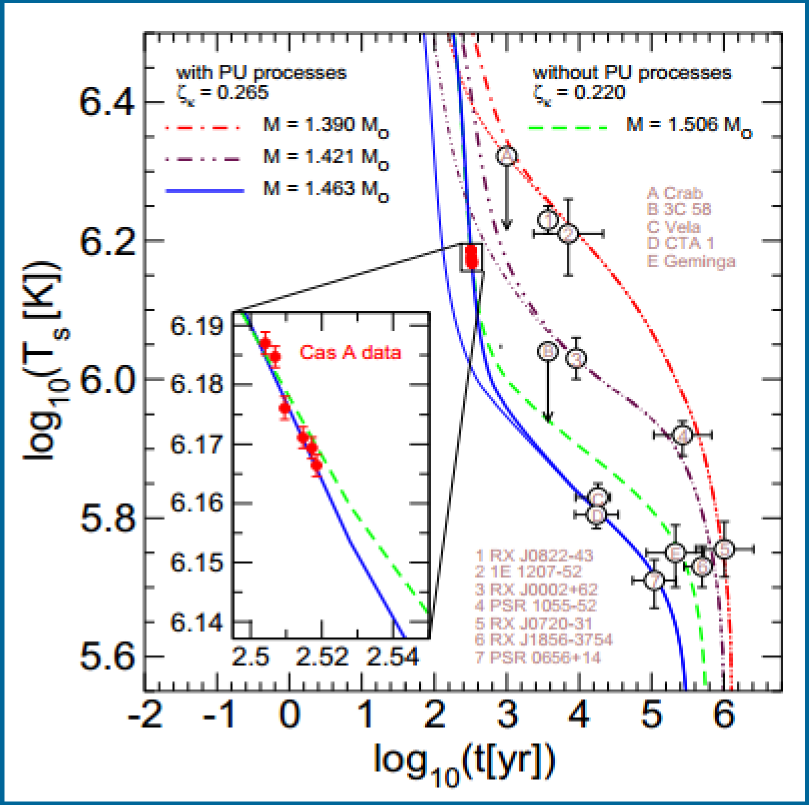
1011.6142, see many details in 1110.5116

Different superfluidity models



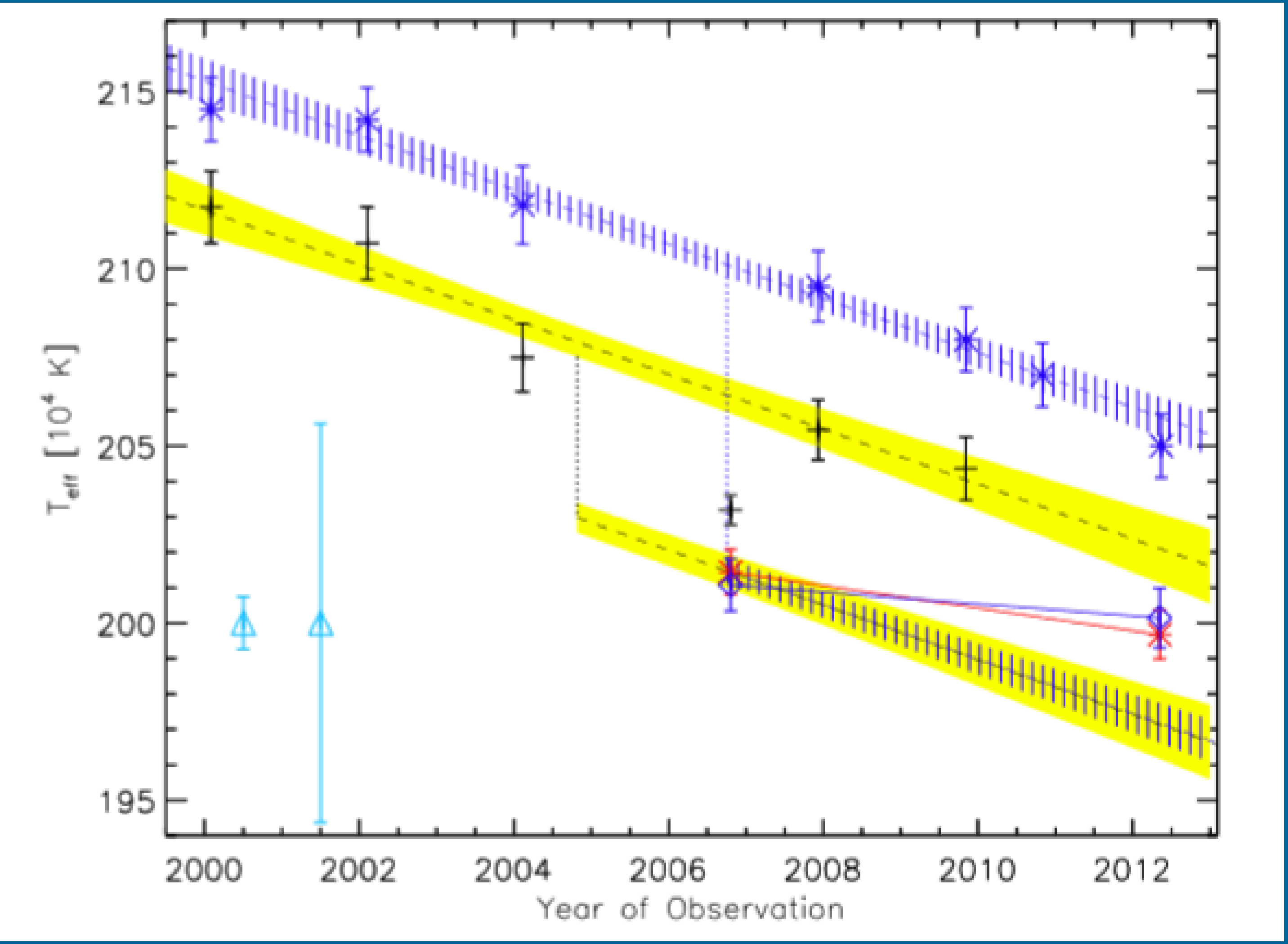
1012.0045

Nuclear medium cooling



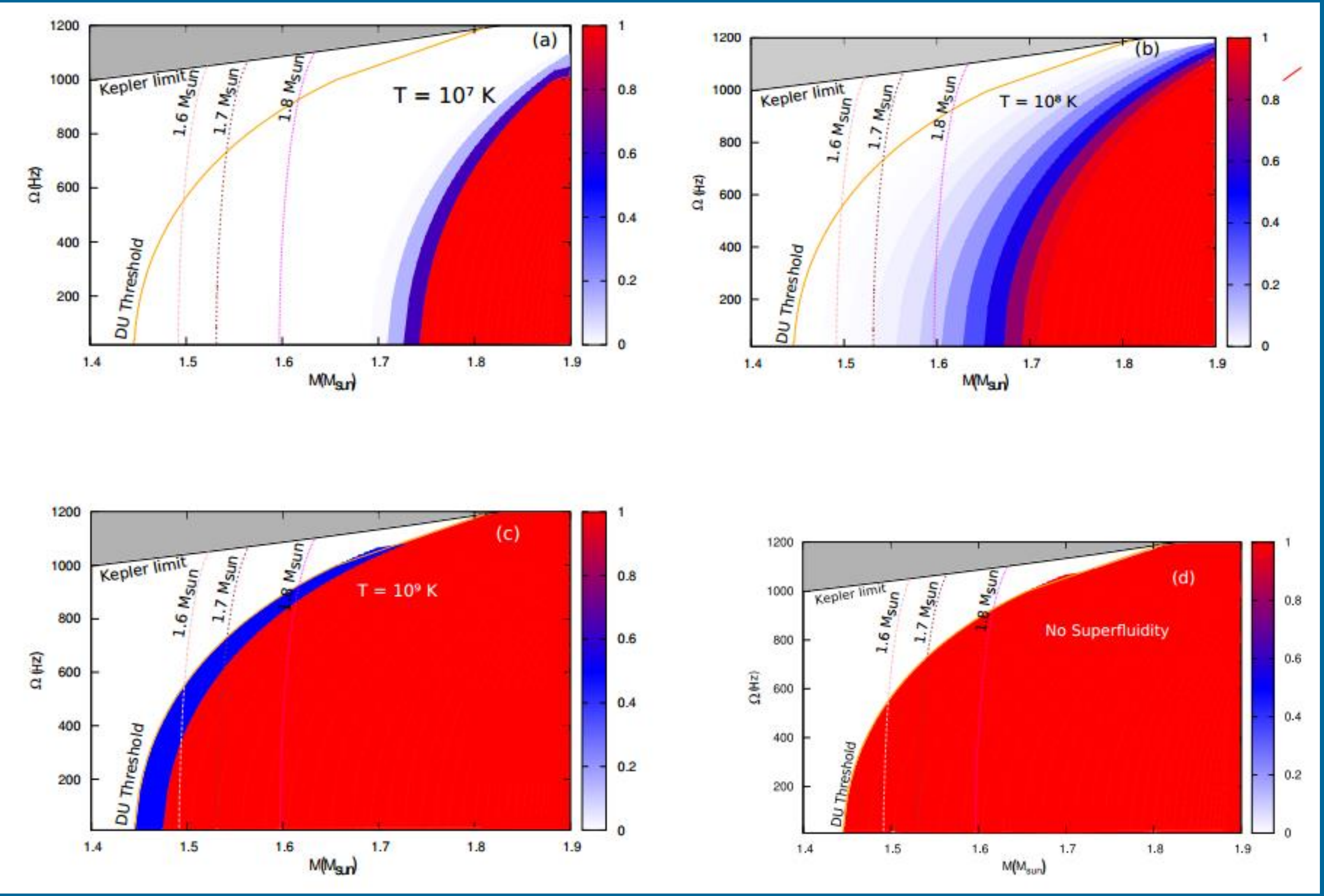
Crucial for the successful description of the observed data is a substantial reduction of the thermal conductivity, resulting from a suppression of both the electron and nucleon contributions to it by medium effects.

New twist: no cooling!



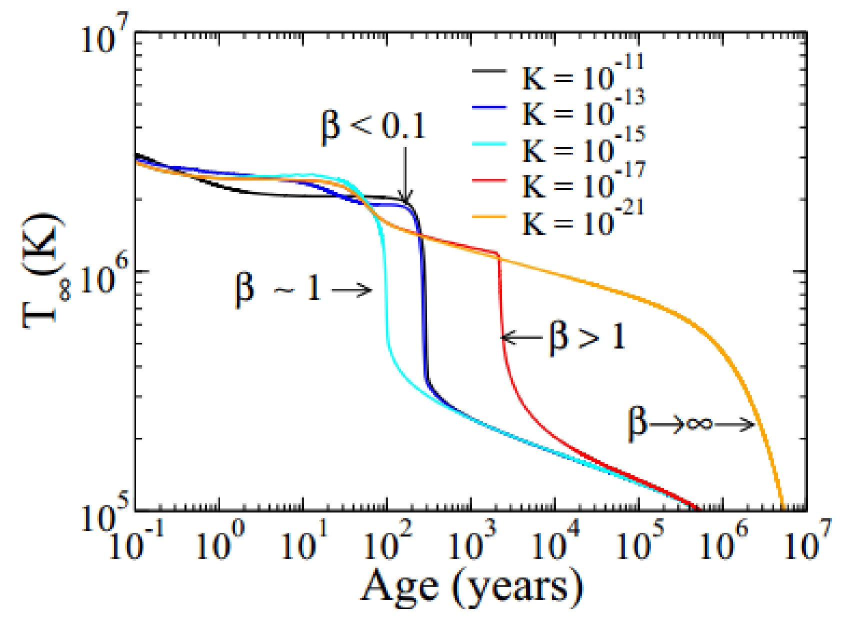
1311.0888

Cooling and rotation

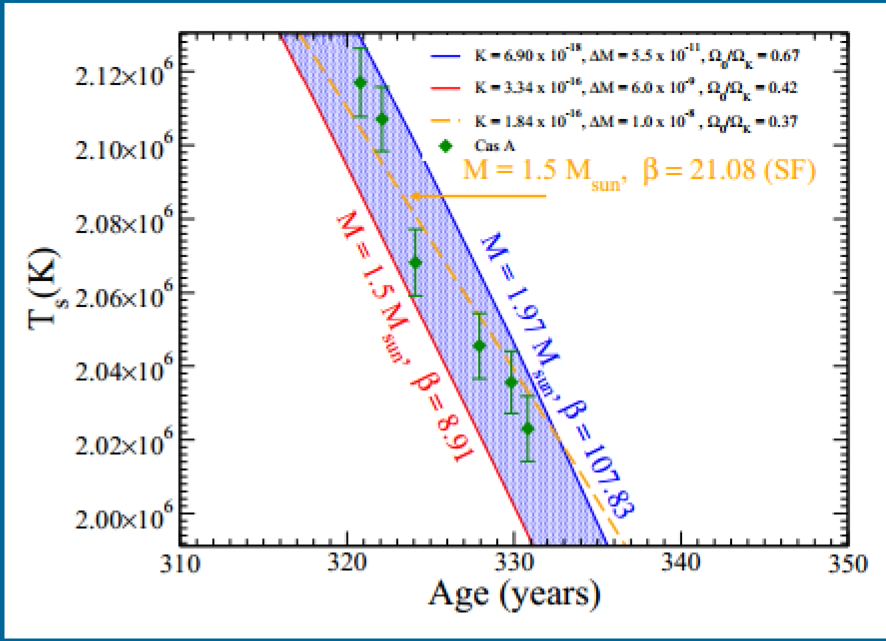


1103.3870

Cas A case



P_0=0.0025-0.00125 sec
B~10^{11} G

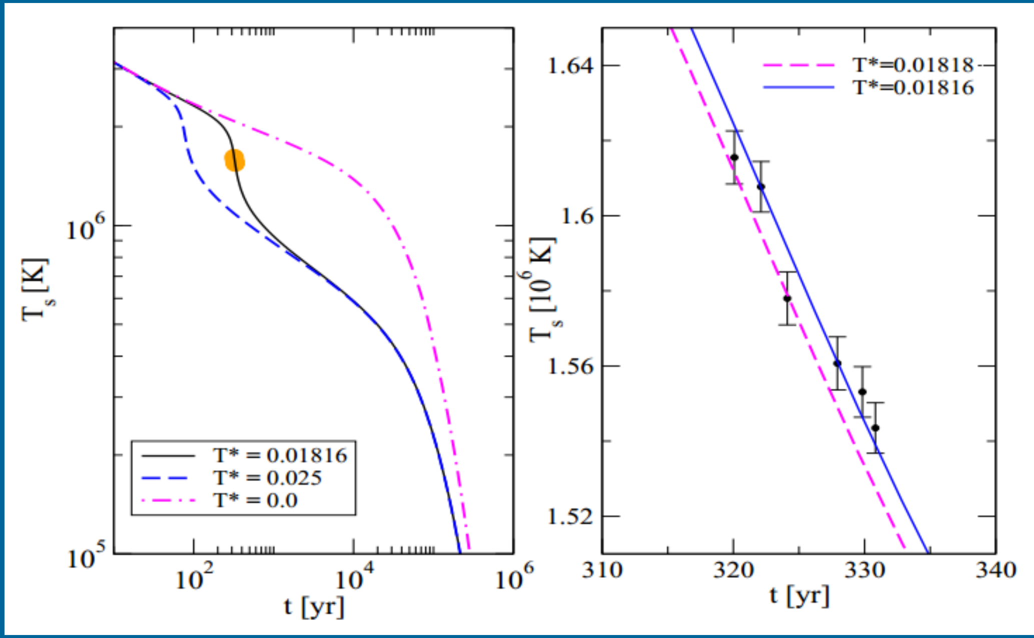


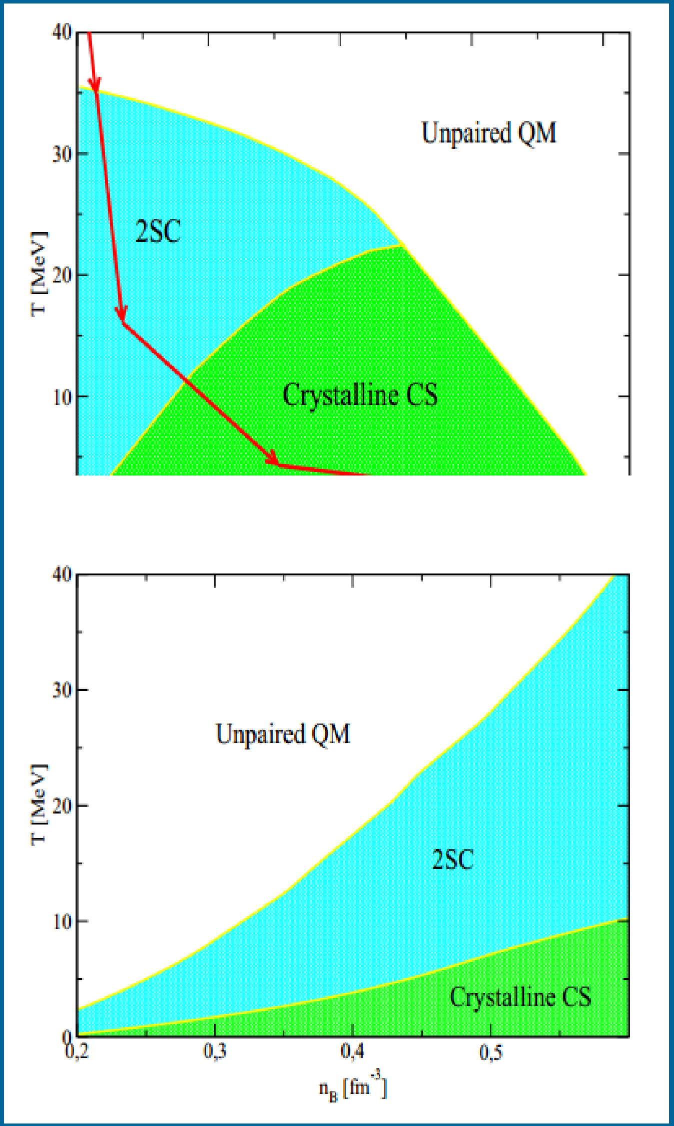
Other studies of the influence of effects of rotation see in 1201.2381

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





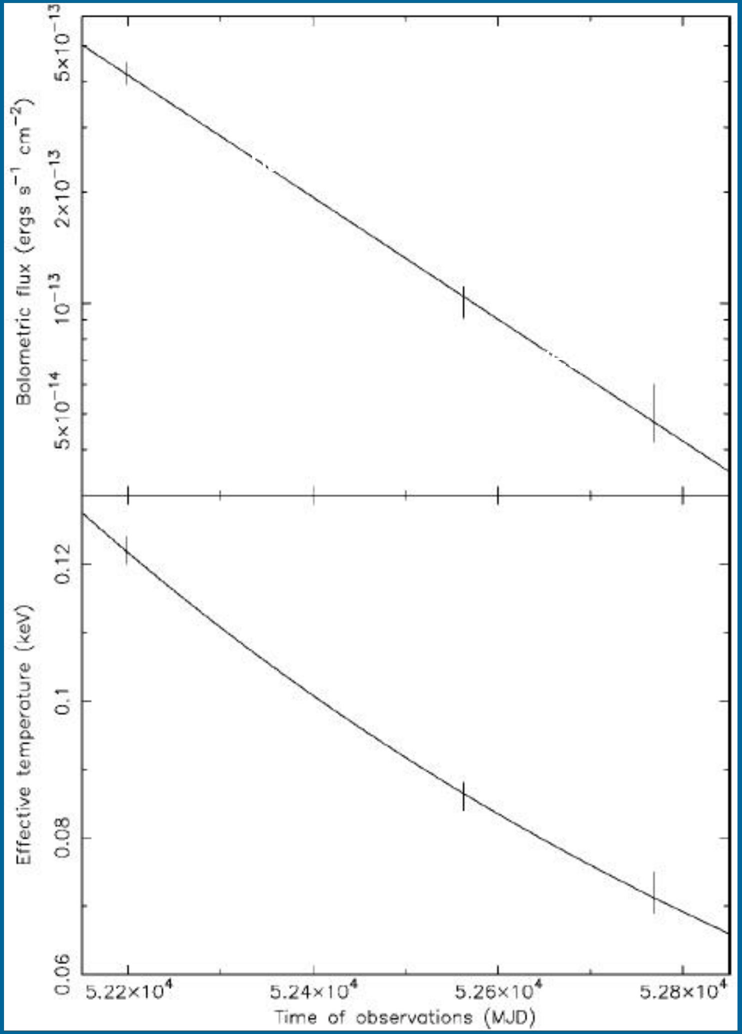
1301.2814

Cooling of X-ray transients

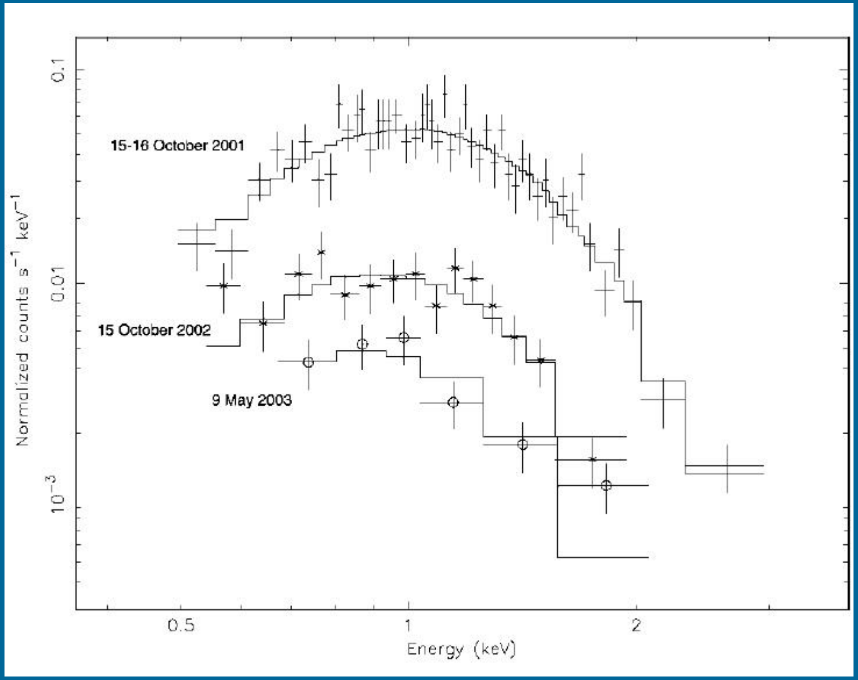
"Many neutron stars in close X-ray binaries are transient accretors (transients);
They exhibit X-ray bursts separated by long periods (months or even years) of quiescence.
It is believed that the quiescence corresponds to a lowlevel, or even halted, accretion onto the neutron star.
During high-state accretion episodes,
the heat is deposited by nonequilibrium processes in the deep layers (10^{12} -10^{13} g cm^{-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)

Cooling in soft X-ray transients

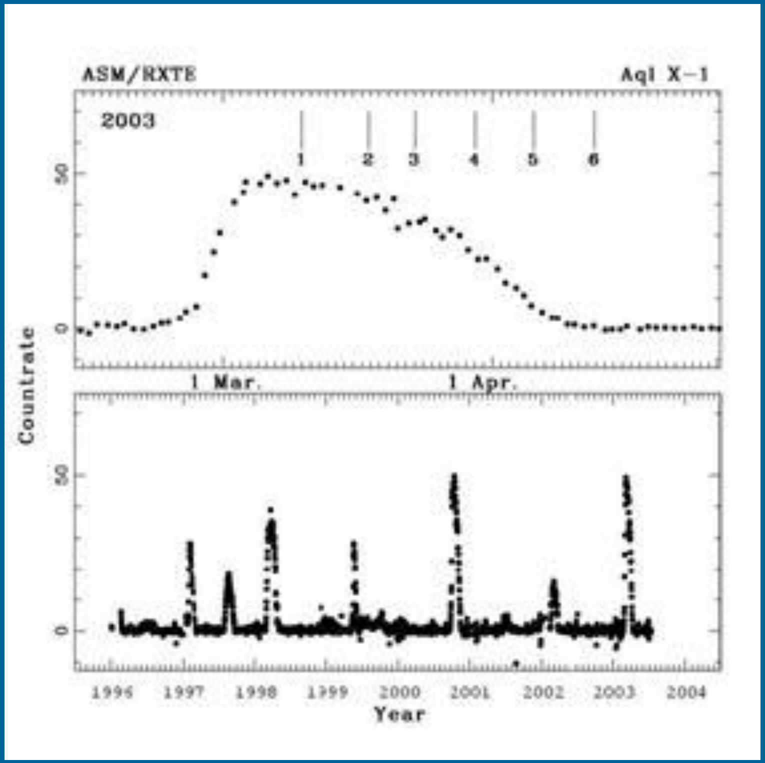


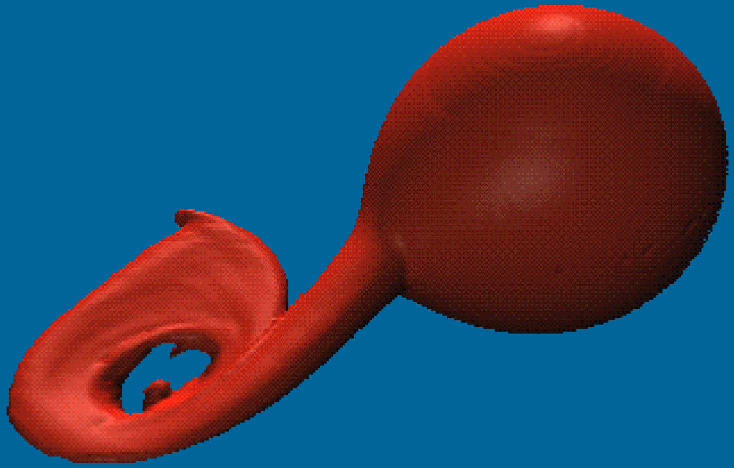
MXB 1659-29
~2.5 years outburst

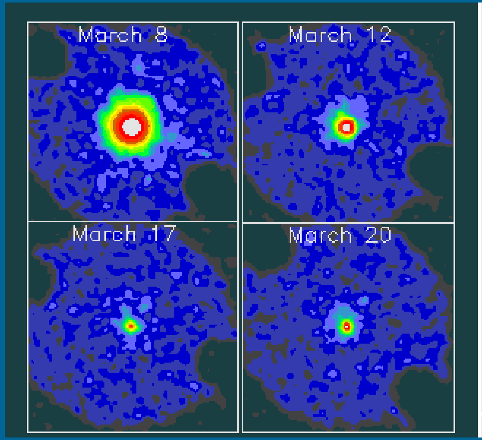


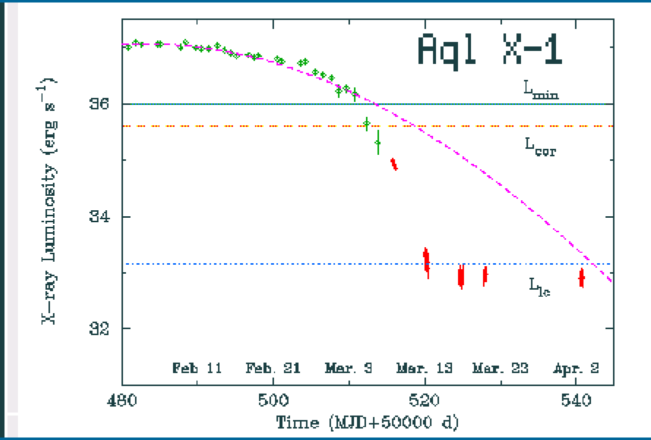
[Wijnands et al. 2004]

Aql X-1 transient



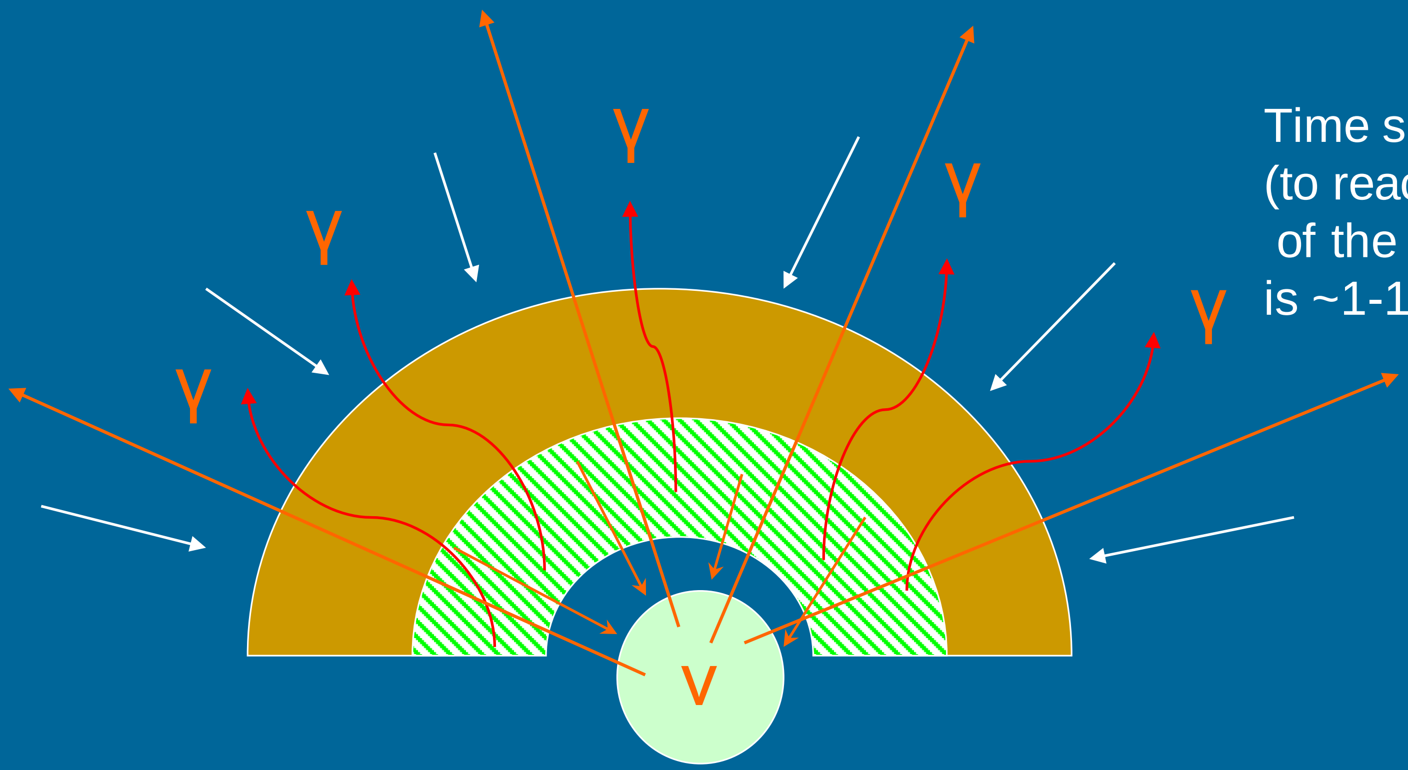






A NS with a K star.
The NS is the hottest among SXTs.

Deep crustal heating and cooling



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

To reach the
state “before”
takes ~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} 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}Fe
Density starts to increase

$^{56}Fe \rightarrow {}^{56}Cr$
$^{56}Fe + e^- \rightarrow {}^{56}Mn + \nu_e$
$^{56}Mn + e^- \rightarrow {}^{56}Cr + \nu_e$

At ^{56}Ar: neutron drip
$^{56}Ar + e^- \rightarrow {}^{56}Cl + \nu_e$
$^{56}Cl \rightarrow {}^{55}Cl + n$
$^{55}Cl + e^- \rightarrow {}^{55}S + \nu_e$
$^{55}S \rightarrow {}^{54}S + n$
$^{54}S \rightarrow {}^{52}S + 2n$

Then from ^{52}S we have a chain:
$^{52}S \rightarrow {}^{46}Si + 6n - 2e^- + 2\nu_e$

As Z becomes smaller
the Coulomb barrier decreases.
Separation between
nuclei decreases, vibrations grow.
$^{40}Mg \rightarrow {}^{34}Ne + 6n - 2e^- + 2\nu_e$

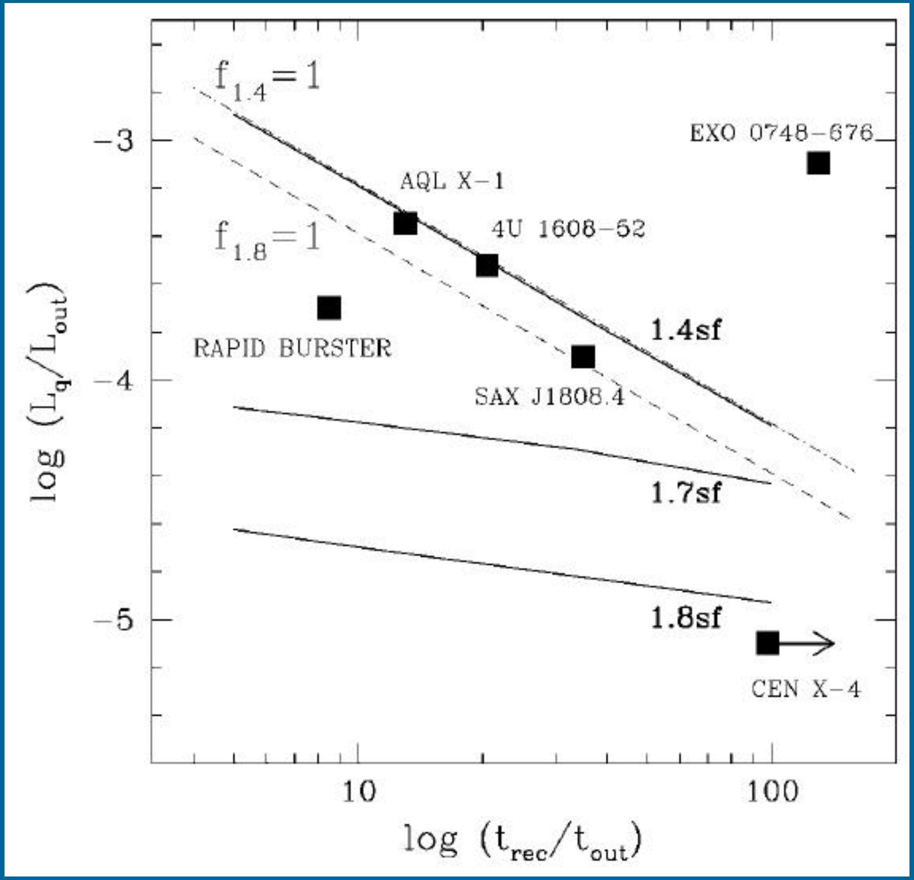
At Z=10 (Ne) pycnonuclear reactions start.

$^{34}Ne + {}^{34}Ne \rightarrow {}^{68}Ca$
$^{36}Ne + {}^{36}Ne \rightarrow {}^{72}Ca$

Then a heavy nuclei can react again:
$^{72}Ca \rightarrow {}^{66}Ar + 6n - 2e^- + 2\nu_e$

$^{48}Mg + {}^{48}Mg \rightarrow {}^{96}Cr$
$^{96}Cr \rightarrow {}^{88}Ti + 8n - 2e^- + 2\nu_e$

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.

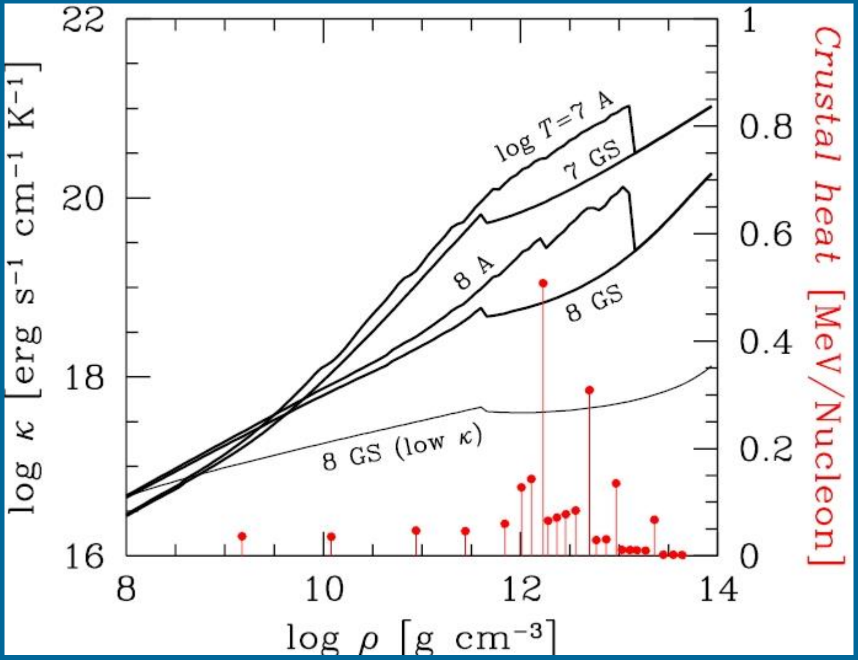
$$L_q \sim \frac{Q_{\rm nuc}}{m_u} \langle \dot{M} \rangle \sim 6 \times 10^{32} \frac{\langle \dot{M} \rangle}{10^{-11}\ M_\odot\ {\rm yr}^{-1}}\ {\rm ergs\ s^{-1}}$$

[Colpi et al. 2001]

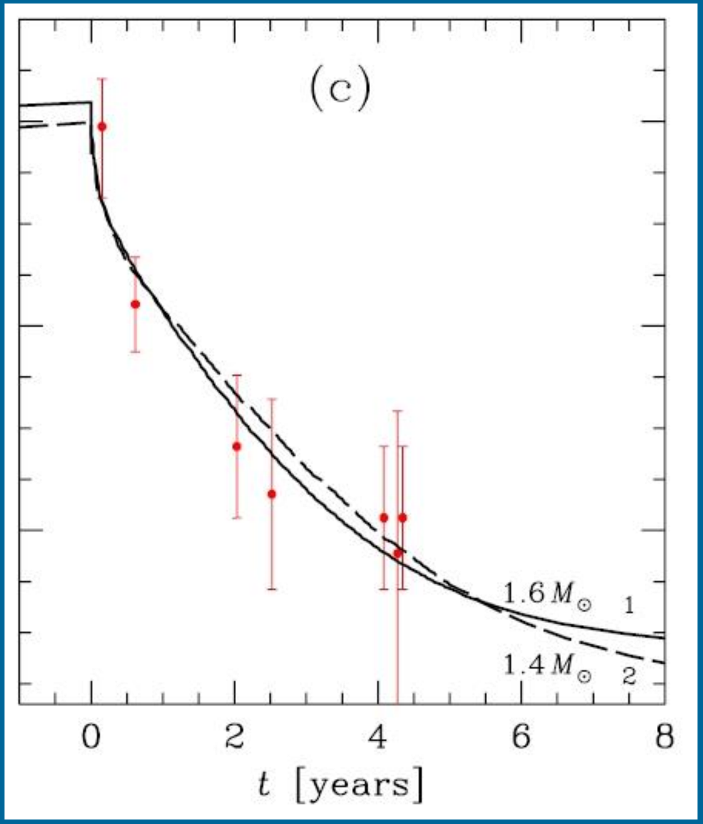
Deep crustal heating

~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.

(see a recent model in 1202.3378)



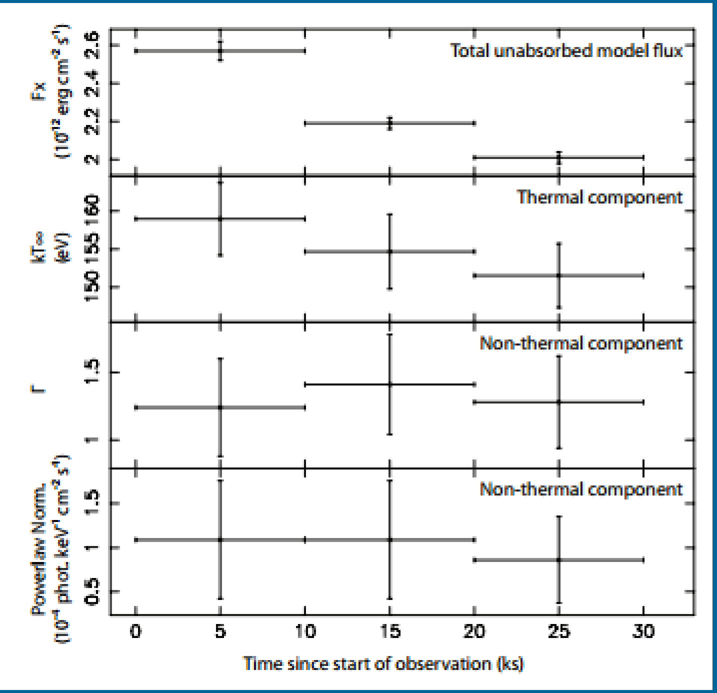
KS 1731-260



[Shternin et al. 2007]

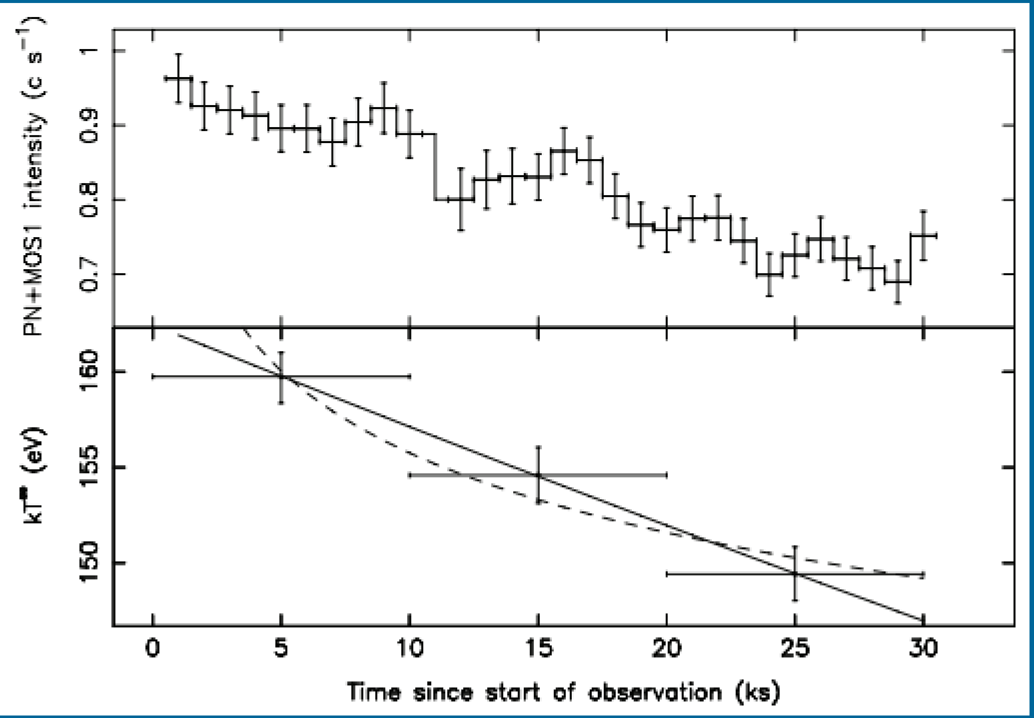
See new results and discussion in 1702.08452

Visible cooling of a NS in a binary

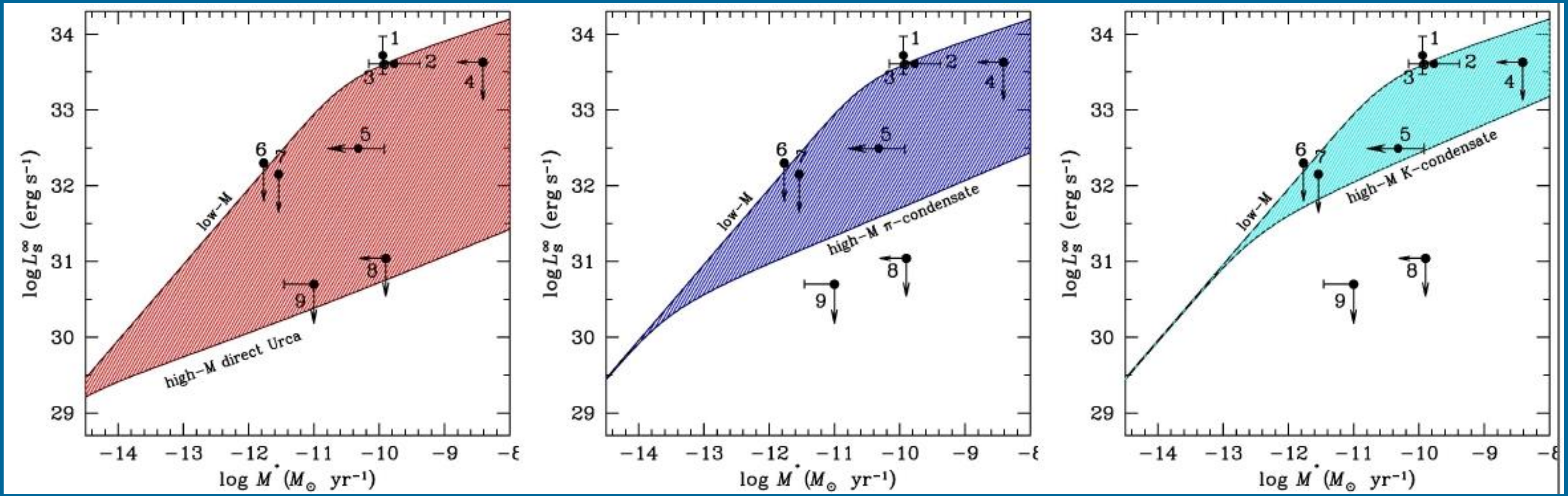


The authors interpret this as cooling of a layer located at a column density of $y \simeq 5\times10^{12}$ g cm^{-2} ($\simeq$50 m inside the neutron star), which is just below the ignition depth of superbursts.

XTE J1709–267



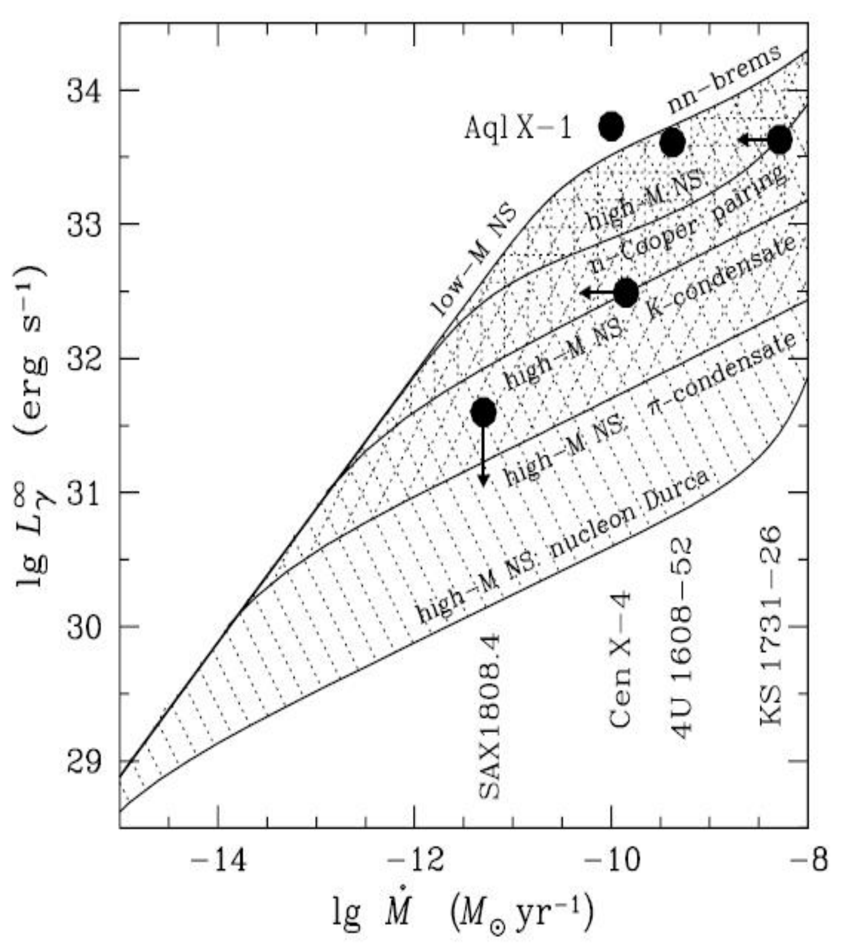
Testing models with SXT

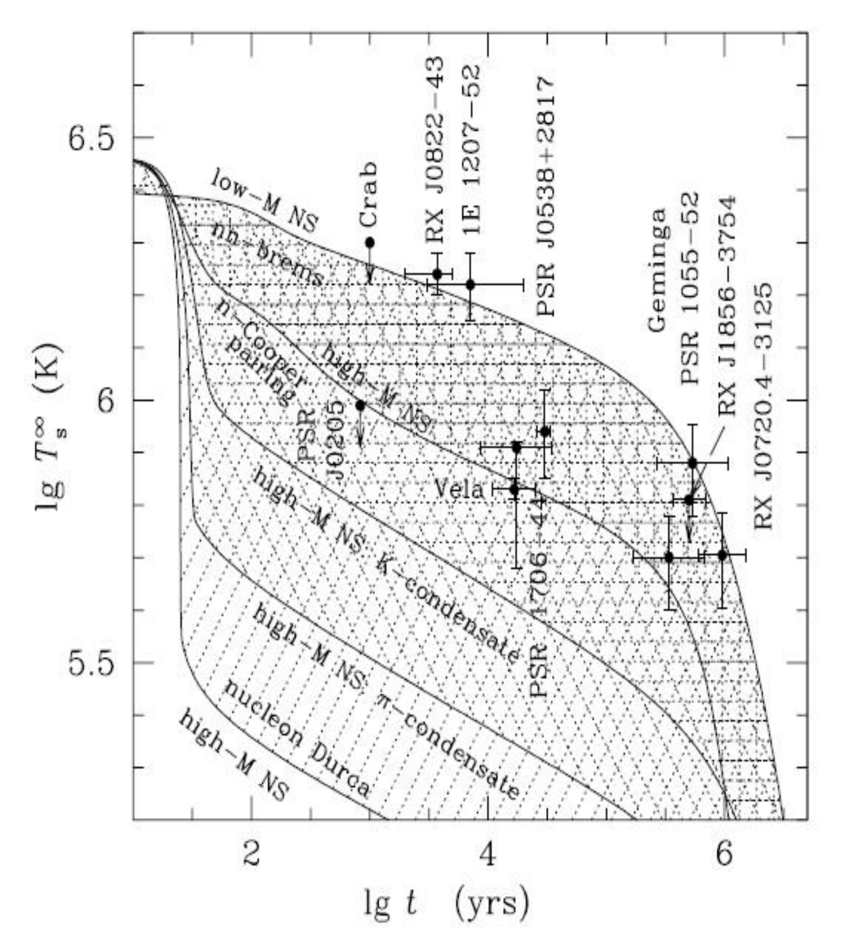


SXTs can be very important in confronting theoretical cooling models with data.

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

Theory vs. Observations: SXT and isolated cooling NSs





[Yakovlev et al. astro-ph/0501653]

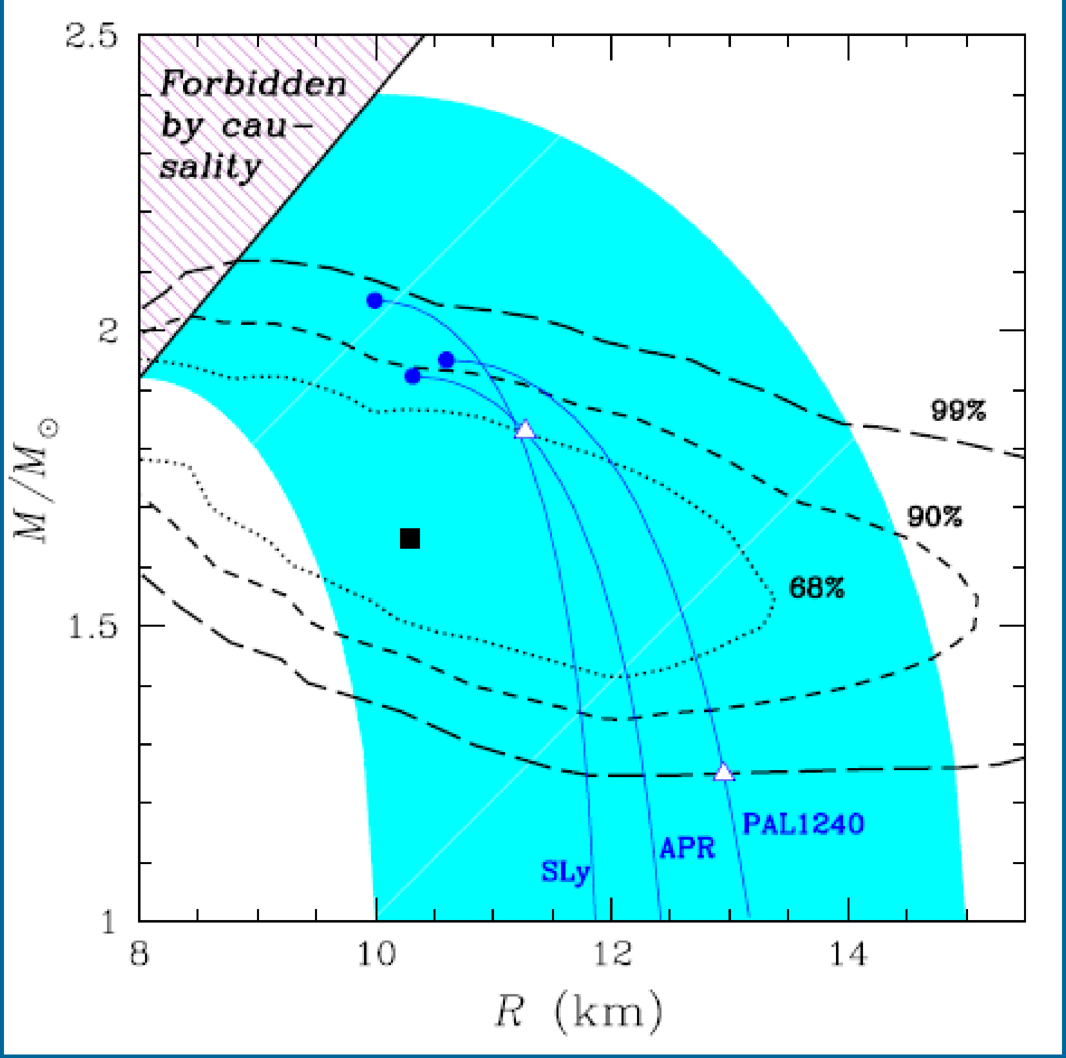
Conclusions

- 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

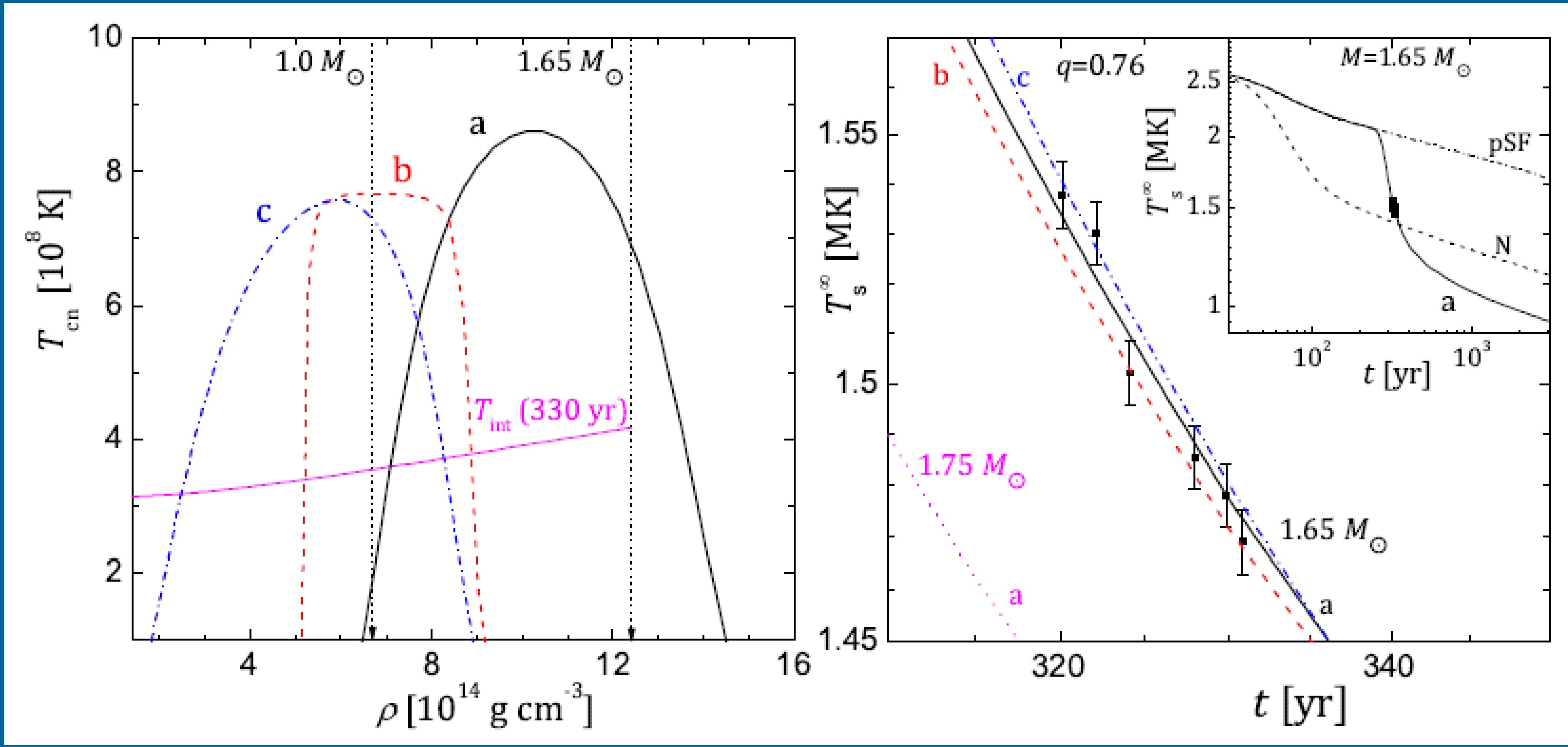
Papers to read

- Or astro-ph/0403657
  Or astro-ph/0508056
  Or astro-ph/0402143
- arXiv:astro-ph/9906456 УФН 1999

M-R from spectral fit



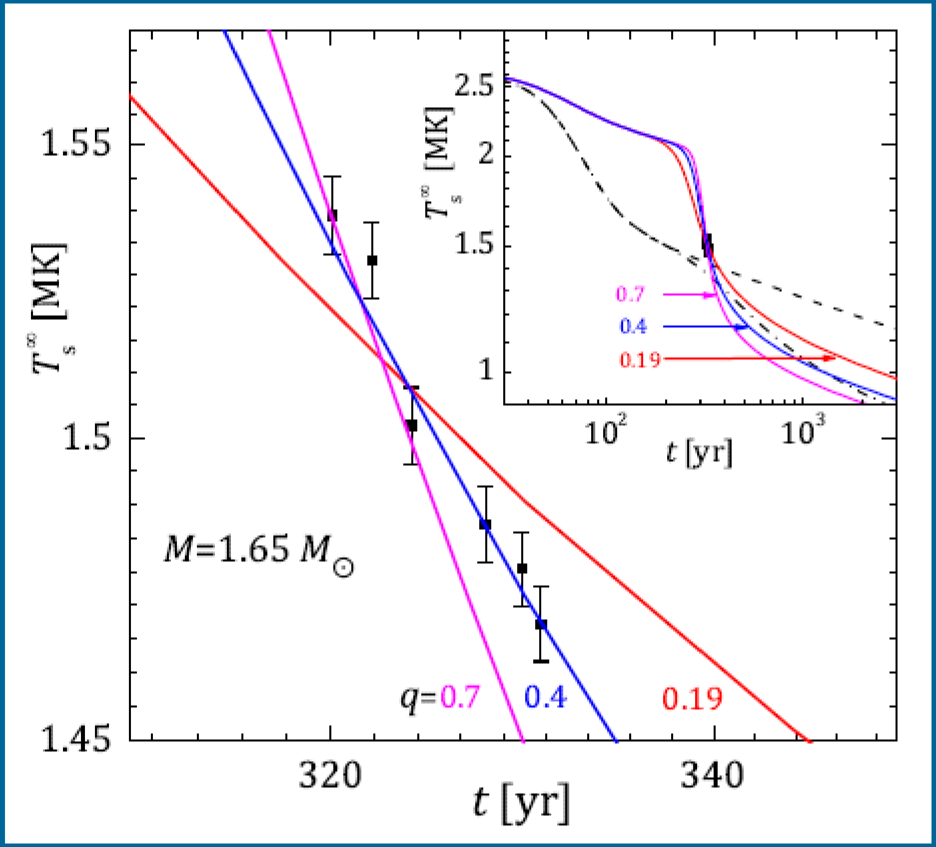
1010.1154



10
8
6
4
2
1.0 $M_\odot$
1.65 $M_\odot$
a
b
c
T_{int} (330 yr)
T_{cn} [10^8 K]
4
8
12
16
ρ [10^{14} g cm^{-3}]
b
c
q=0.76
1.55
1.5
1.45
T_s^∞ [MK]
1.75 $M_\odot$
a
1.65 $M_\odot$
a
320
340
t [yr]
M=1.65 $M_\odot$
2.5
2
1.5
1
pSF
N
a
10^2
10^3
t [yr]

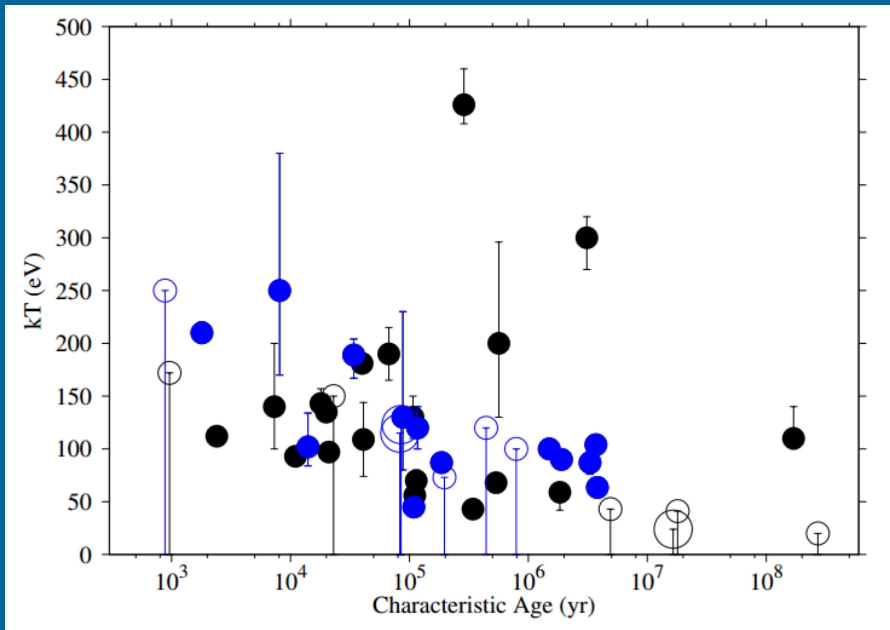
1012.0045

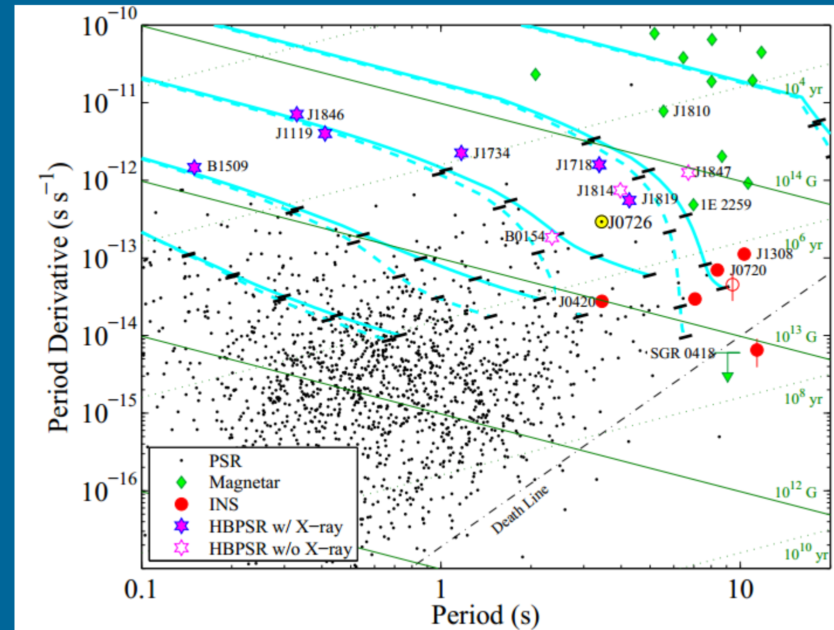
Suppression in the axial-vector channel



1012.0045

Cooling and grand unification for NSs



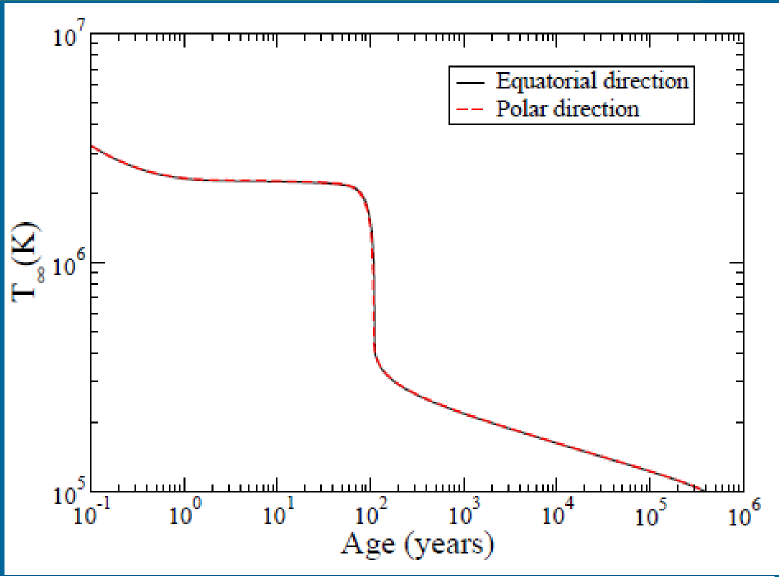


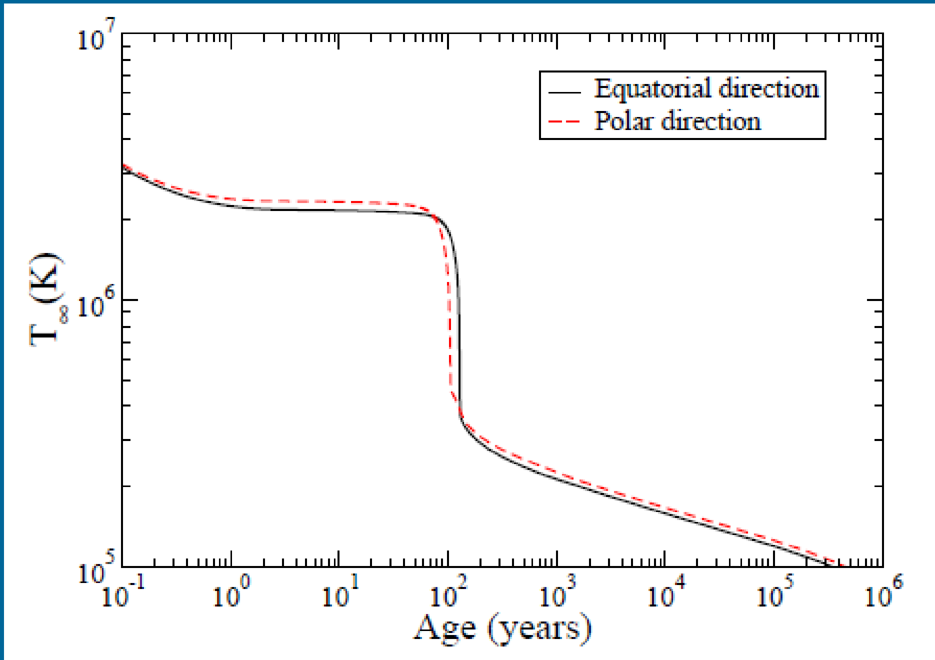
1301.2814

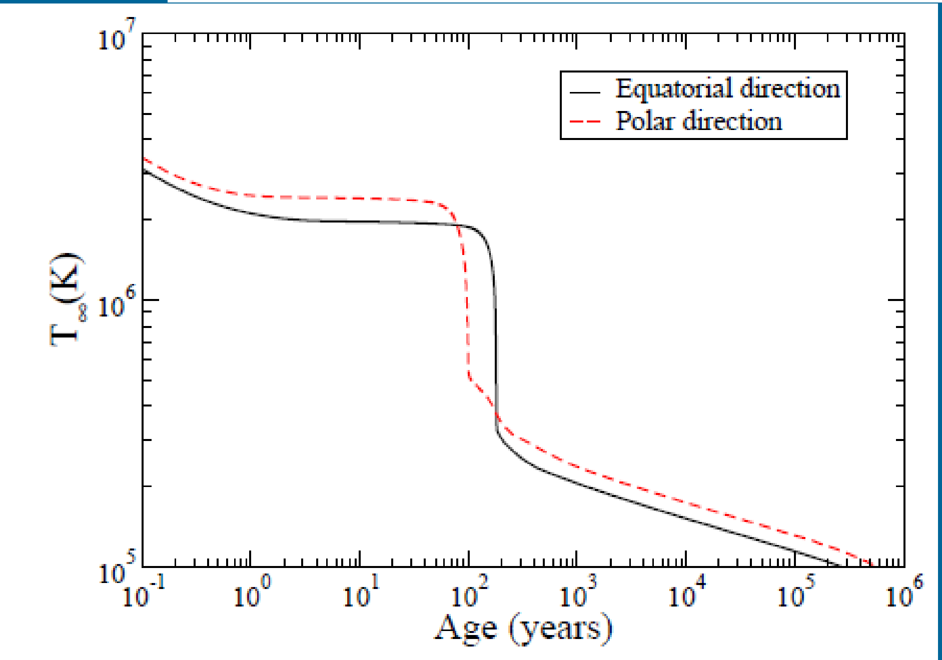
1111.2877

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

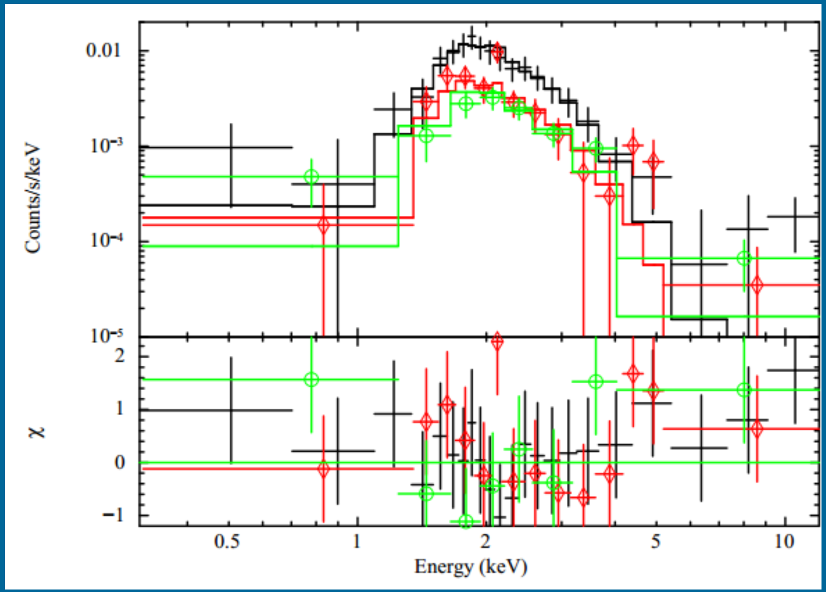




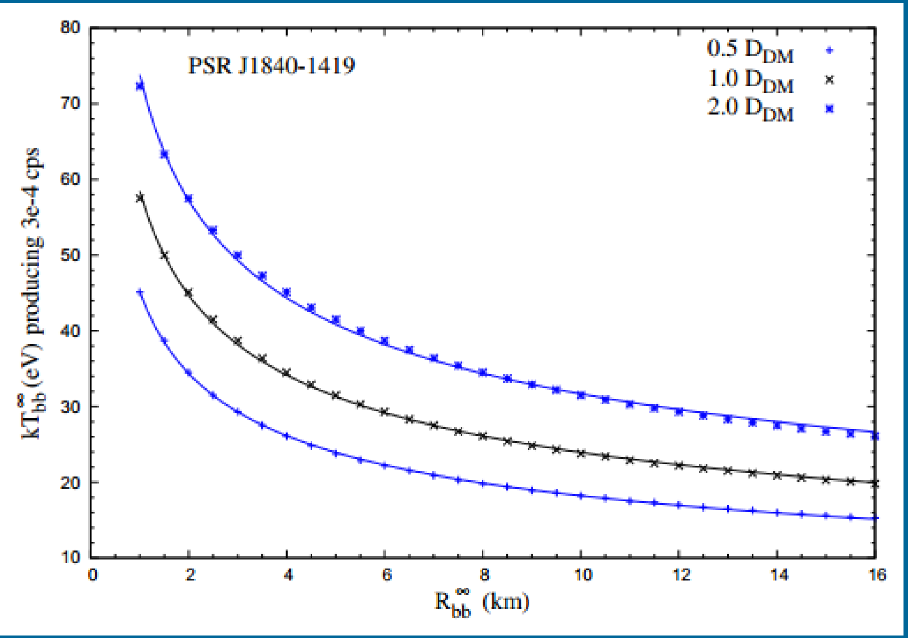


1307.7692

Records



The hottest (in a binary, crustal heating) SAX J1750.8−2900. T~150 eV.
1202.1531



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