Thermal Steady-States of Neutron Stars in Quiescent Soft X-ray Transients versus Deep Crustal Heating

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Brown, Bildsten, Rutledge '98 hypothesis:

Spectrum of quiescent emission from SXTs is well fitted by a NS atmosphere model and may be thus of thermal origin, being supported by deep crustal heating due to nuclear transformations in the accreted crust

In the outer NS crust:

ρ (g cm^{-3})	Process
1.49×10^{9}	$^{56}\mathrm{Fe} \rightarrow ^{56}\mathrm{Cr} - 2e^- + 2\nu_e$
1.11×10^{10}	$^{56}\mathrm{Cr} \rightarrow ^{56}\mathrm{Ti} - 2e^- + 2\nu_e$
7.85×10^{10}	$^{56}\mathrm{Ti} \rightarrow ^{56}\mathrm{Ca} - 2e^- + 2\nu_e$
2.50×10^{11}	$^{56}\mathrm{Ca} \rightarrow ^{56}\mathrm{Ar} - 2e^- + 2\nu_e$
6.11×10^{11}	$^{56}\mathrm{Ar} \rightarrow ^{52}\mathrm{S} + 4n - 2e^- + 2\nu_e$

In the inner NS crust:

ρ (g cm^{-3})	reactions
9.075×10^{11}	$^{52}\mathrm{S} \rightarrow ^{46}\mathrm{Si} + 6n - 2e^- + 2\nu_e$
1.131×10^{12}	$^{46}\mathrm{Si} \rightarrow ^{40}\mathrm{Mg} + 6n - 2e^- + 2\nu_e$
1.455×10^{12}	$^{40}\mathrm{Mg} \rightarrow ^{34}\mathrm{Ne} + 6n - 2e^- + 2\nu_e$
1.951×10^{12}	$^{34}\mathrm{Ne} + ^{34}\mathrm{Ne} \rightarrow ^{68}\mathrm{Ca}$
	$^{68}\mathrm{Ca} \rightarrow ^{62}\mathrm{Ar} + 6n - 2e^- + 2\nu_e$
2.134×10^{12}	$^{62}\mathrm{Ar} \rightarrow ^{56}\mathrm{S} + 6n - 2e^- + 2\nu_e$
2.634×10^{12}	$^{56}\mathrm{S} \rightarrow ^{50}\mathrm{Si} + 6n - 2e^- + 2\nu_e$
3.338×10^{12}	$^{50}\mathrm{Si} \rightarrow ^{44}\mathrm{Mg} + 6n - 2e^- + 2\nu_e$
4.379×10^{12}	$^{44}\mathrm{Mg} \rightarrow ^{36}\mathrm{Ne} + 8n - 2e^- + 2\nu_e$
	$^{36}\mathrm{Ne} + ^{36}\mathrm{Ne} \rightarrow ^{72}\mathrm{Ca}$
	$^{72}\mathrm{Ca} \rightarrow ^{66}\mathrm{Ar} + 6n - 2e^- + 2\nu_e$
5.839×10^{12}	$^{66}\mathrm{Ar} \rightarrow ^{60}\mathrm{S} + 6n - 2e^- + 2\nu_e$
7.041×10^{12}	$^{60}\mathrm{S} \rightarrow ^{54}\mathrm{Si} + 6n - 2e^- + 2\nu_e$
8.980×10^{12}	$^{54}\mathrm{Si} \rightarrow ^{48}\mathrm{Mg} + 6n - 2e^- + 2\nu_e$
1.127×10^{13}	$^{48}\mathrm{Mg} + ^{48}\mathrm{Mg} \rightarrow ^{96}\mathrm{Cr}$
1.137×10^{13}	$^{96}\mathrm{Cr} \rightarrow ^{88}\mathrm{Ti} + 8n - 2e^- + 2\nu_e$

Example of deep crustal heating model :

Haensel & Zdunik (1990)

Q_{dh} = 1.45 MeV/nucleon

Thermal states of :

- transiently accreting NSs &
- cooling isolated NSs

Test essentially the same physics :

- Composition and superfluidity of superdense NS cores
- Composition, conductivity and structure of NS crusts
- Light-elements accreted envelopes, etc …

Direct correspondense of the problems : Yakovlev, Levenfish, Haensel `03

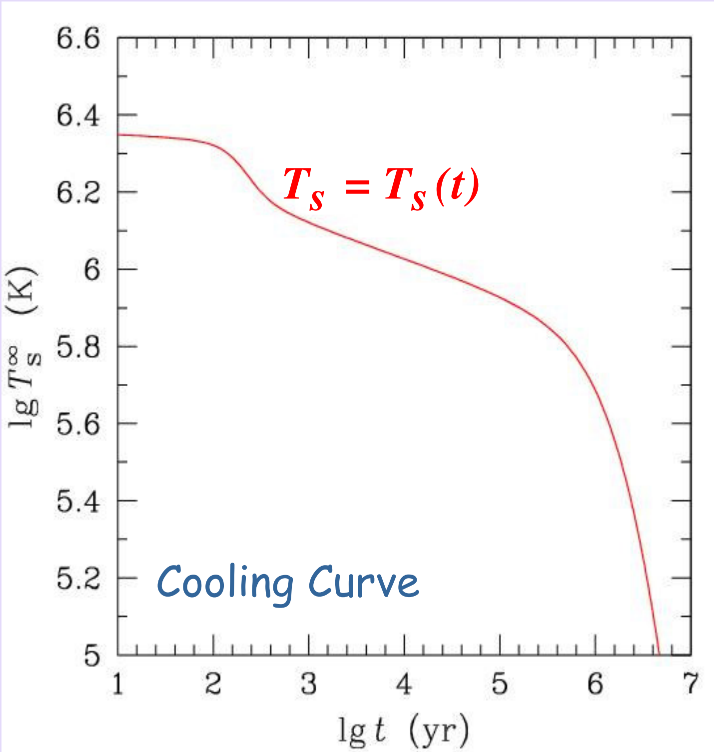
Thermal evolution :

$$C(T)\frac{dT}{dt} = - L_\nu(T) - L_\gamma(T_s) + L_{dh}(\dot{M})$$

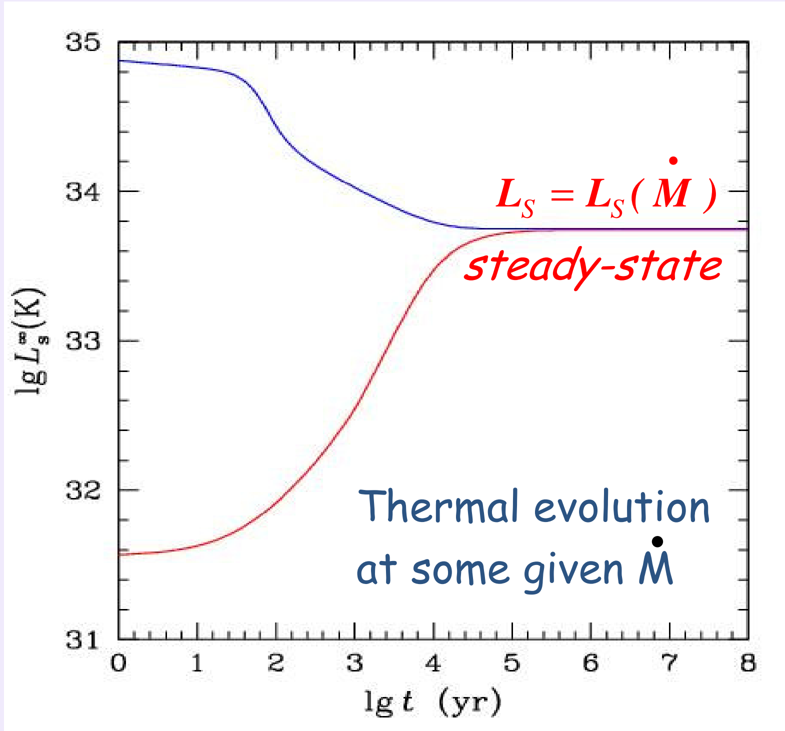
Thermal steady-state at given accretion rate :

$$L_{dh}(\dot{M}) = L_\nu(T) + L_\gamma(T_s)$$

Cooling Isolated NSs



Transiently accreting NSs in SXTs



Crustal heating is very sensitive to underlying nuclear physics :

? electron capture strengths (fix the heating from de-excitations of excited daughter nuclei)

? electron-capture thresholds

? neutron separation energies

? initial composition of ashes

? pycno-nuclear reactions

? ....

At the point,
there are many uncertainties ...

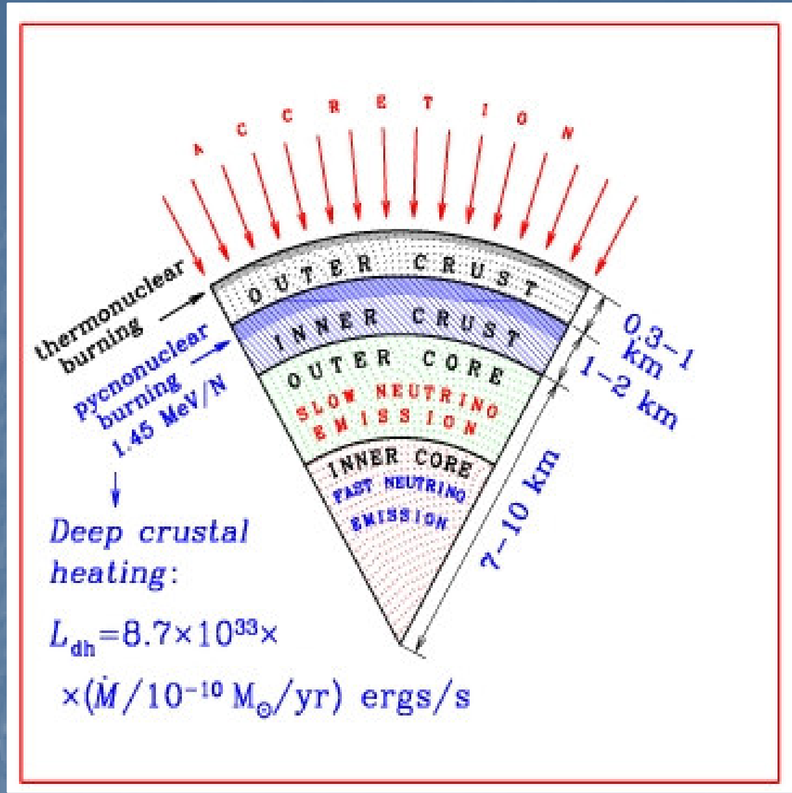
Wanted:

- reliable estimates of the structure of neutron-rich nuclei up to A=106
- nuclei masses
- reliable beta-decay rates
- reaction rates for the p- & He-induced reactions on neutron-deficient nuclei
- account for plasma screening effects
- dependence on mass accretion rate

- How sensitive are thermal states of SXTs to uncertainties of crustal heating theory?
- Can we put some constraints on deep crustal heating?

Crustal heating models:

Sato `79 .... 56 Fe
Haensel & Zdunik `90 ……………. 56 Fe
Haensel & Zdunik `03 ……………. 106 Pd
Gupta, Brown et al `06 ……….. ashes mixture



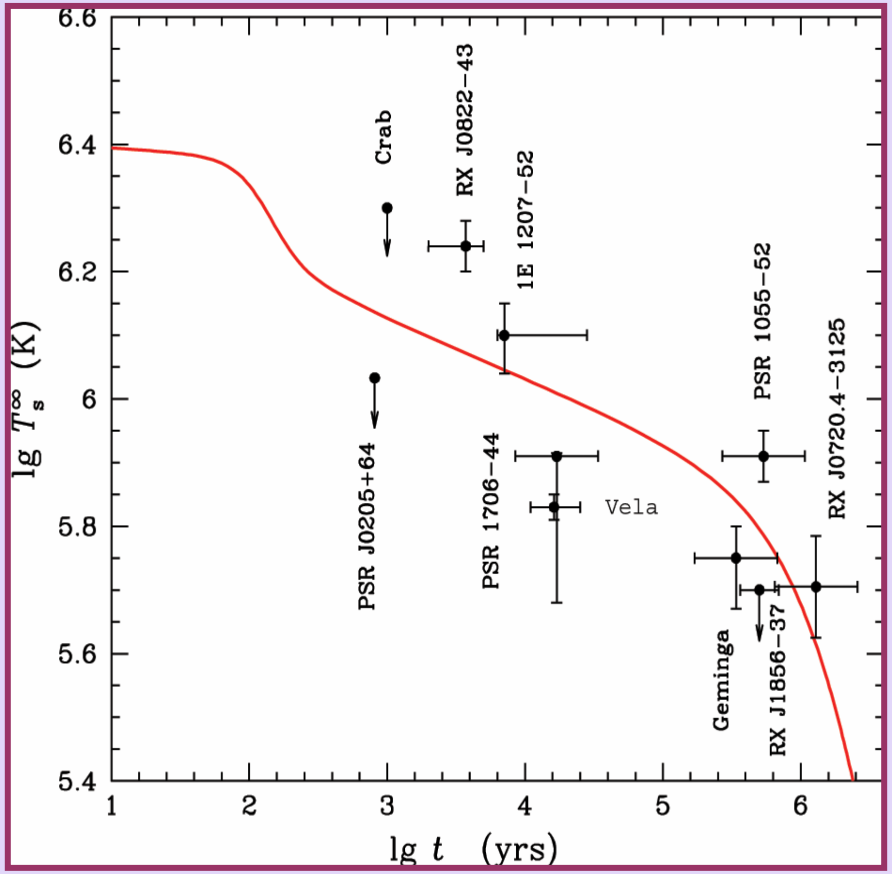
We probe deep crustal heating using a specific NS model :

- composed of nucleons (EoS by Prakash, Ainsworth, Lattimer 1988)
- direct Urca process is allowed in the inner core of NSs with M>1.35 Msun
- strong $^1S_0$ proton superfluidity in a core (model "1p" from Kaminker et al `01)
- no mild $^3P_2$ neutron superfluidity in a core (model "1nt" from Kaminker et al `01)

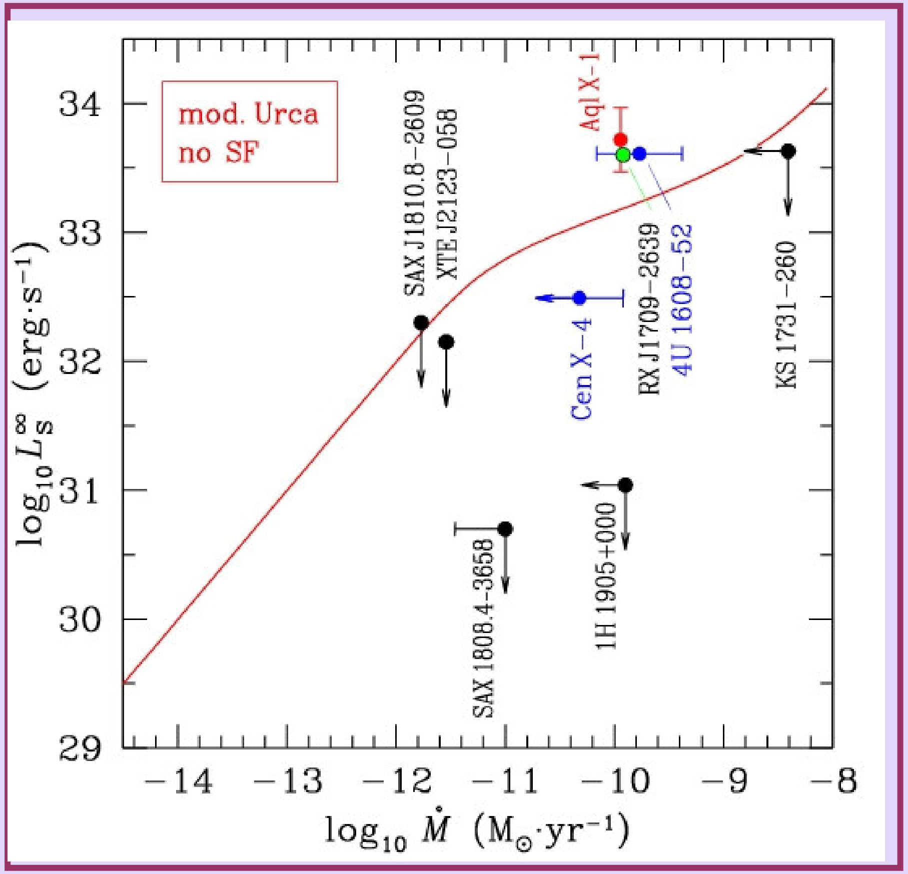
We allow for the enhanced neutrino processes because …

Standard cooling scenario (modified Urca, no SF) cannot explain thermal states of neither the Isolated NSs nor the SXTs in quiescence

INSs: Standard cooling curve



Accreting NSs: Standard heating curve

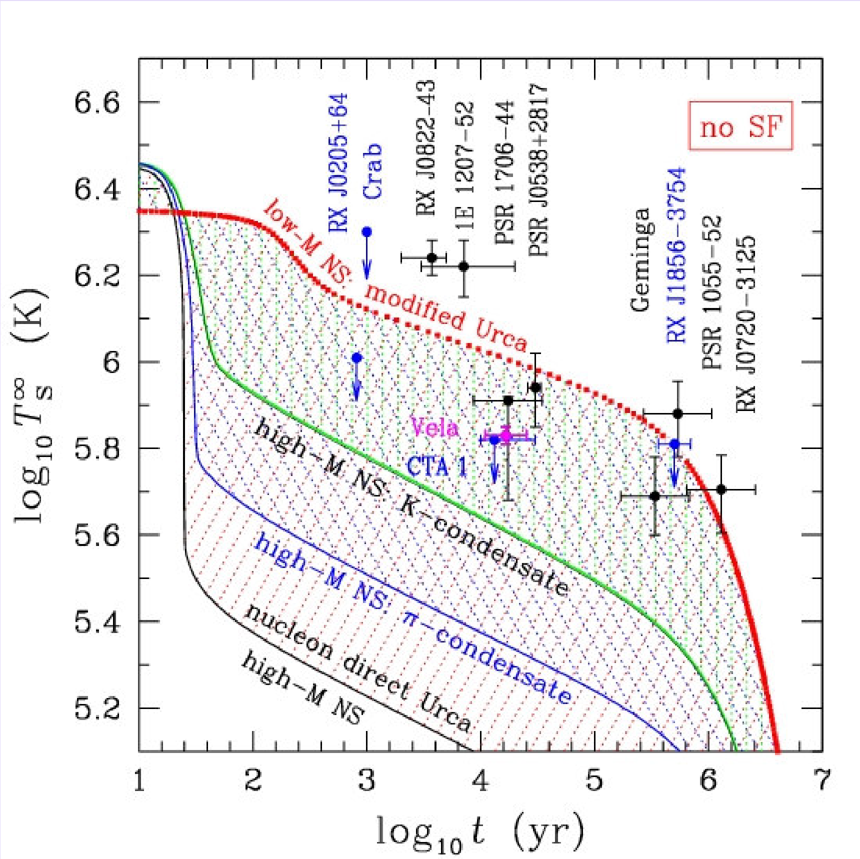


Data on two very cold SXTs: from Heinke et al 2007 & Jonker et al 2007

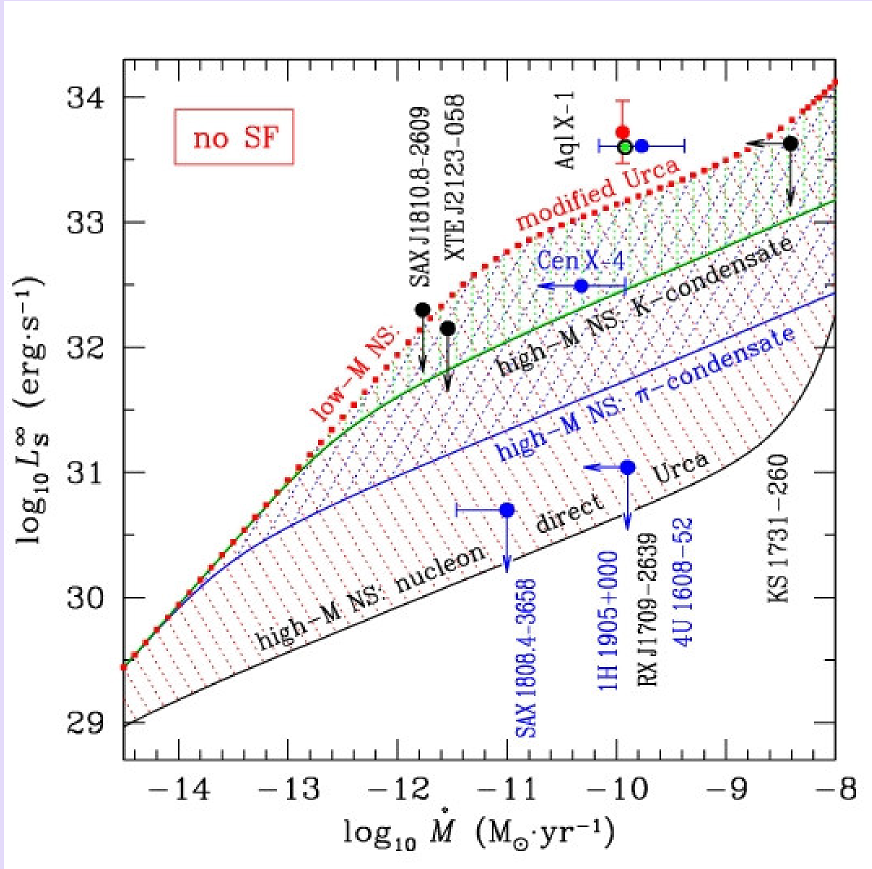
We assume a NS model composed of nucleons because ...

... exotic cooling scenarios cannot explain two very cold SXTs

Cooling of INSs



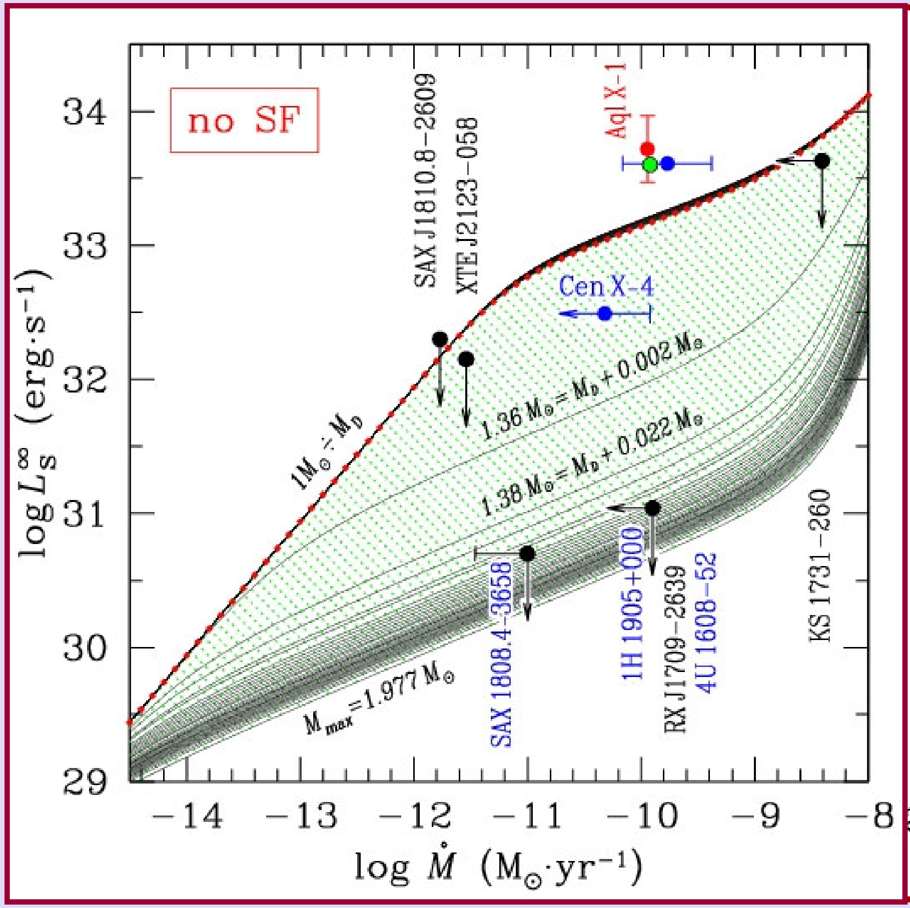
Steady-states of SXTs



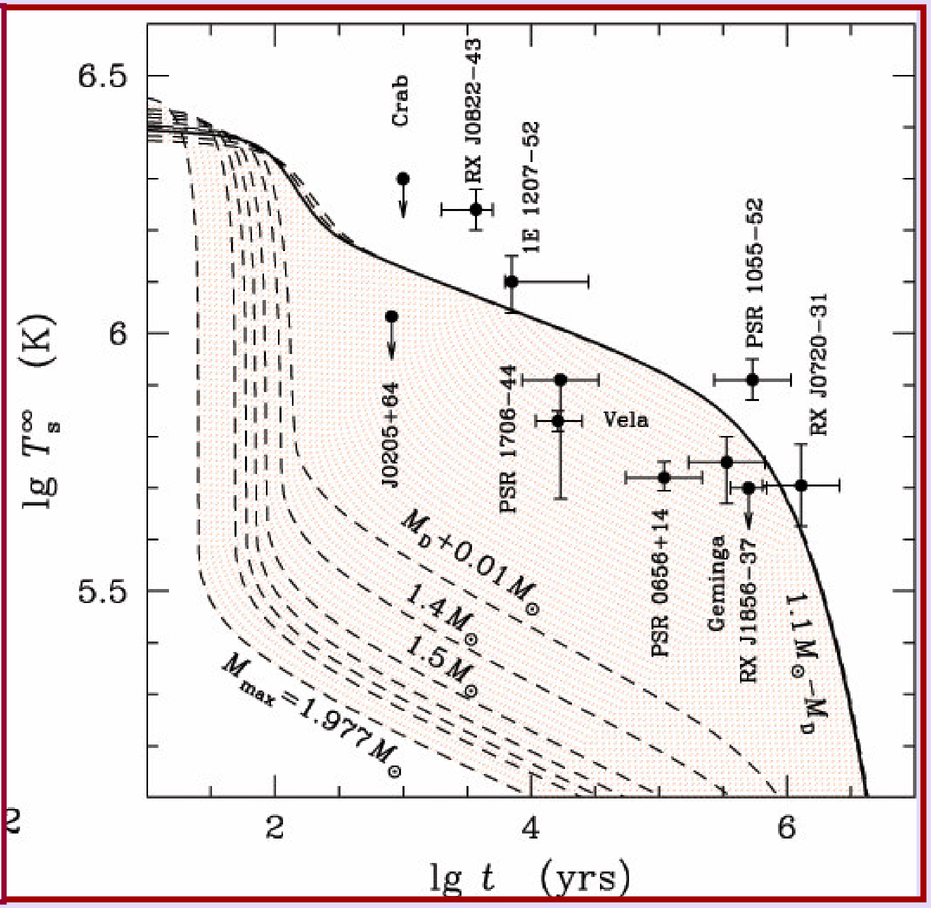
We allow for superfluidity because …

… mere admittance for enhanced mechanism of neutrino emission does not help to explain observations of the hot INSs and SXTs

Steady-states of SXTs



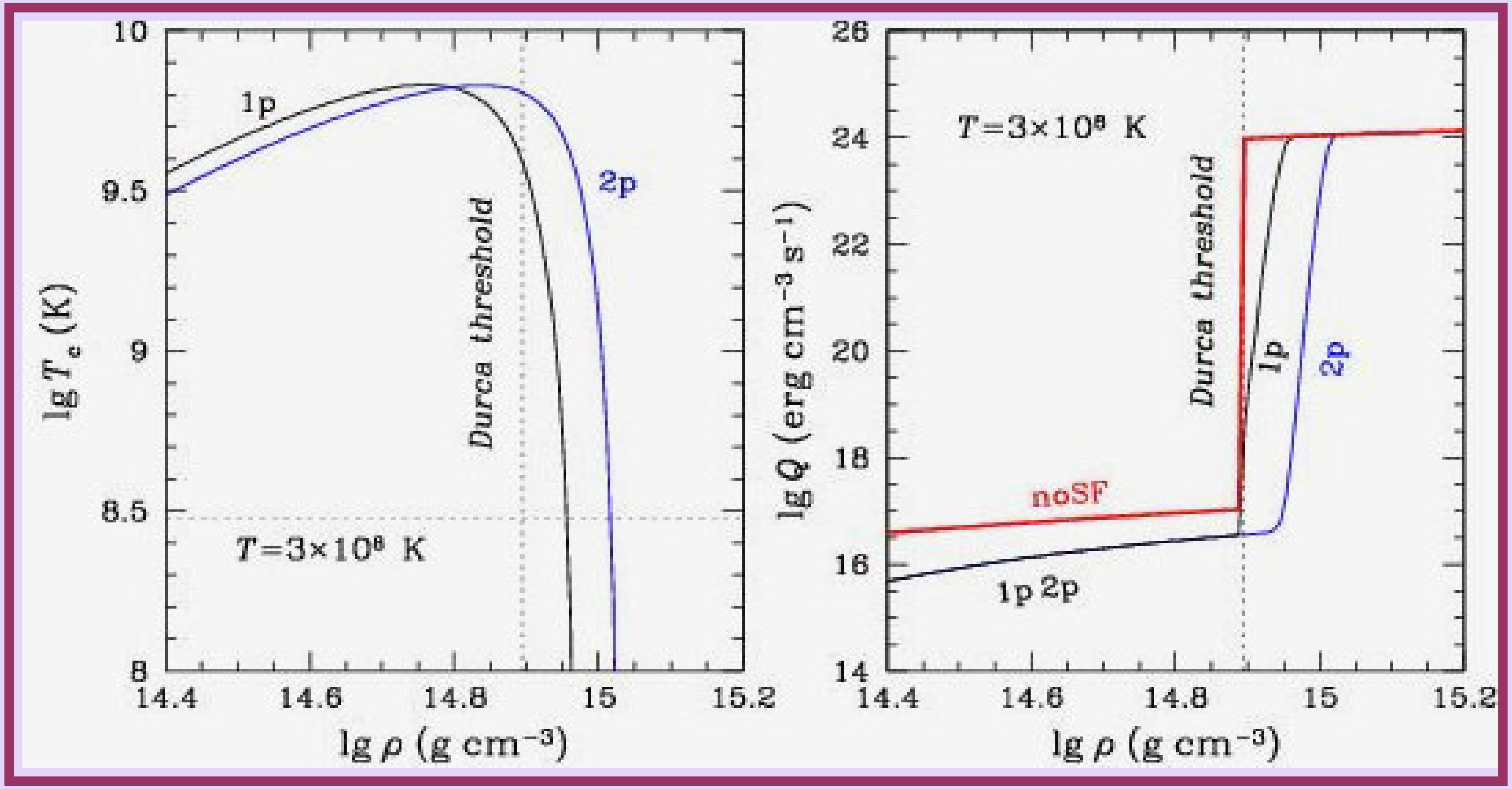
Cooling of INSs



Lattimer, Prakash, Pethick, Haensel 1991 : direct Urca processes
Page & Applegate 1992 : fast cooling scenario

We assume the strong proton superfluidity because it …

- ***suppresses the mod. Urca*** ⇒ ***slows down the cooling of the low-mass NSs;***
- ***smoothes the switching of the the direct Urca process*** ⇒ ***allows for existence of the medium-mass NSs;***

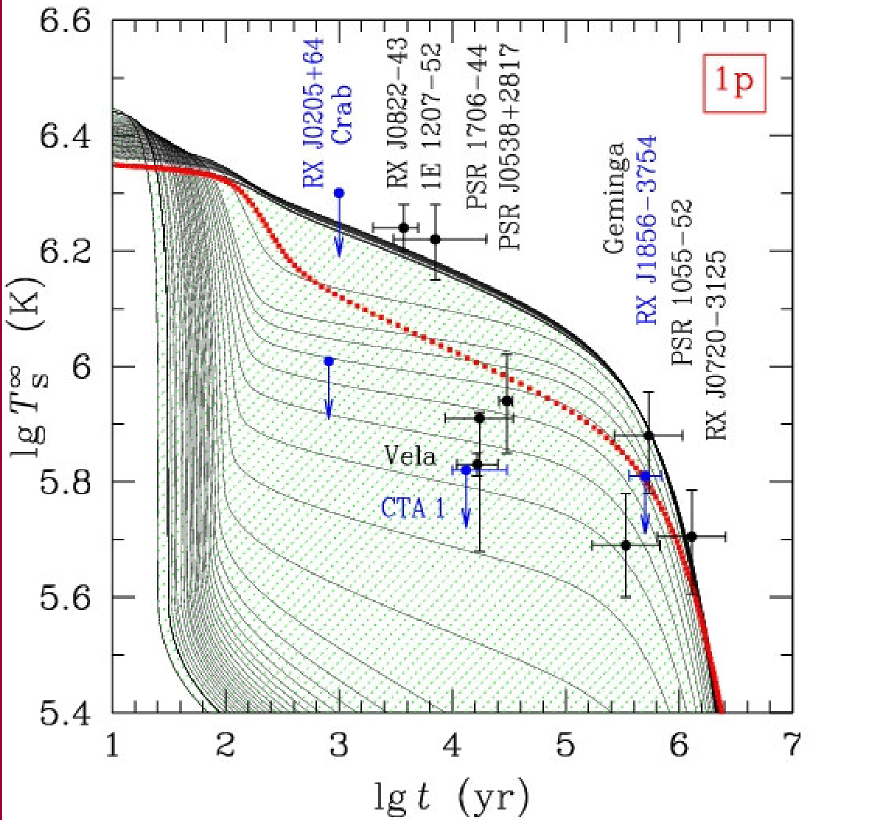


We assume the strong proton superfluidity because it …

- ***explains hot sources***
- ***smoothes the opening of the enhanced cooling***
- ***explains representative class of medium-mass NSs***

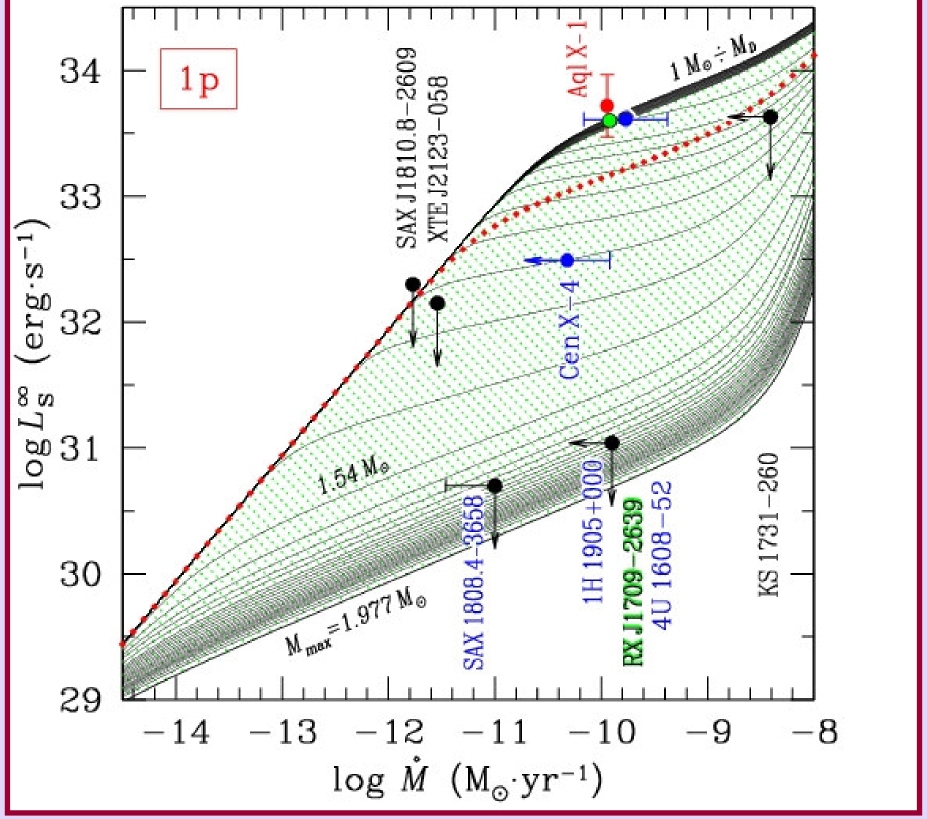
$$T_{cp} \geq 10^9\,\mathrm{K}$$

Thermal states of cooling isolated NSs



Kaminker, Yakovlev, Gnedin 2002

Steady-states of accreting NSs in SXTs



Levenfish, Haensel 2007

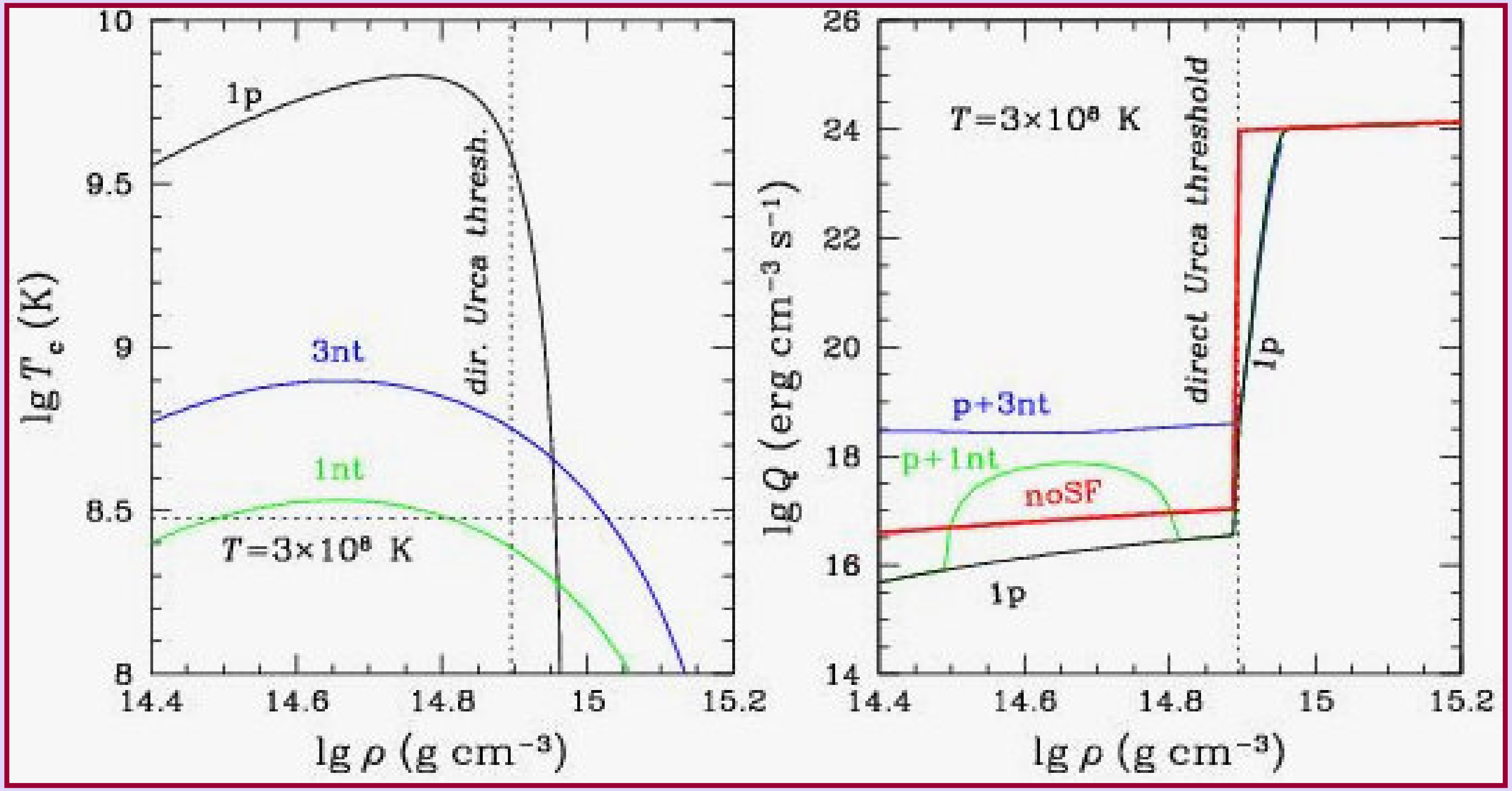
We don't allow for a mild neutron superfluidity in the outer NSs core because it…

- ***appears at the neutrino stage of NSs thermal evolution ;***
- ***boosts the neutrino emission due to the Cooper Pairing process.***
- ***reduces the NSs heat capacity almost in 4 times;***

Strongly accelerates the cooling of the low-mass NSs at the neutrino stage

Strongly accelerates the cooling at the photon stage

$$T_{cn} \notin (3\times 10^{8} \div 3\times 10^{9})\ \mathrm{K}$$

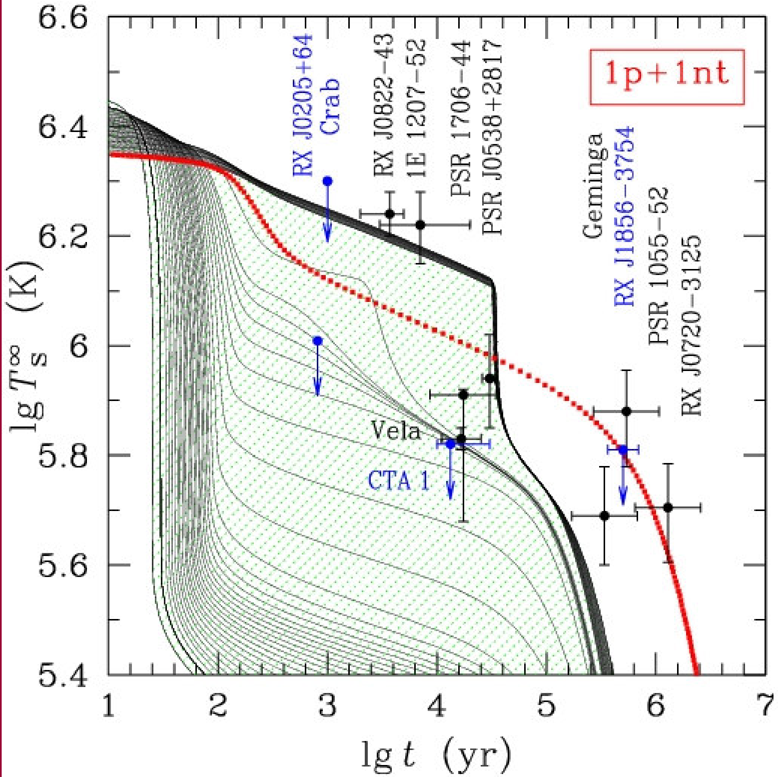


We don't allow for a mild neutron SF in the outer NS core because it …

- ***Contradicts observations of hot (low-mass) NSs***
- ***Can lead to dichotomy of thermal states of SXTs***

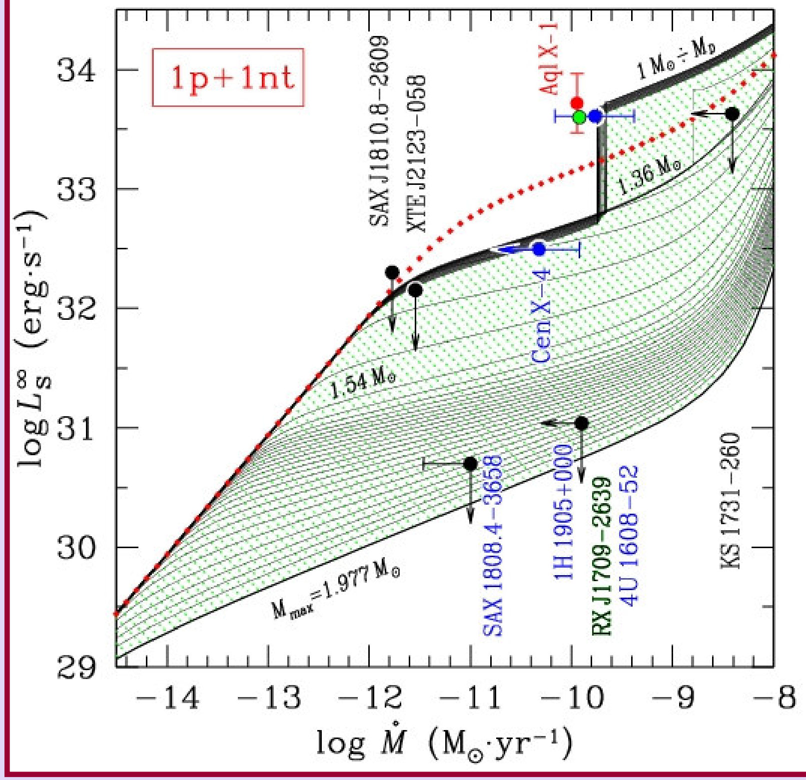
$$T_{cn} \notin (3\times10^8 \div 3\times10^9)\ \mathrm{K}$$

Thermal states of cooling ISNs



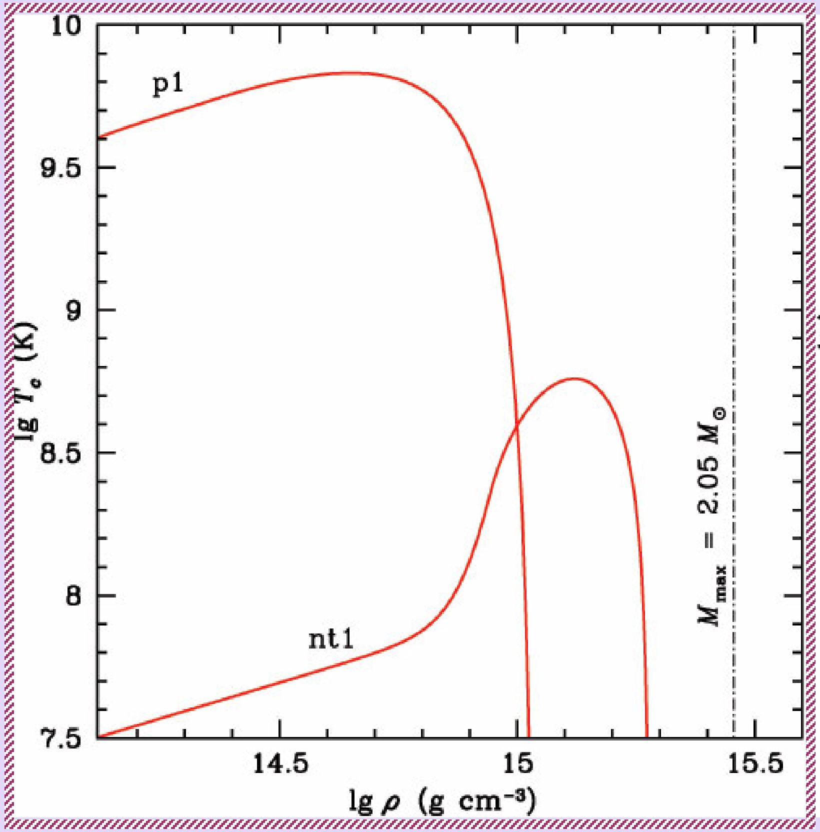
Yakovlev etal 2002

Steady-states of accreting NSs in SXTs



Levenfish, Haensel 2007

We don’t allow for a mild neutron SF in the inner NSs cores because…



Specific density profile:

weak neutron SF in the outer core,
mild neutron SF in the inner core

(such a SF does not affect
thermal states of low-mass NSs).

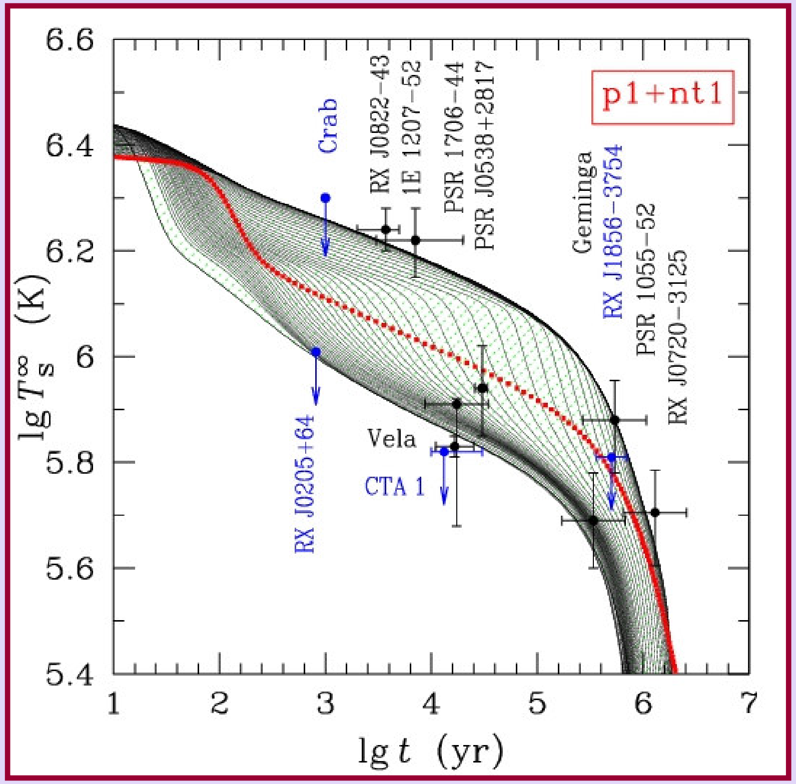
From: Gusakov et al 2004

We don't allow for a mild neutron SF in the inner NSs core because it …

- *Only marginally compatible with the data on INSs*
- *Contradicts the data on few SXTs in quiescence*

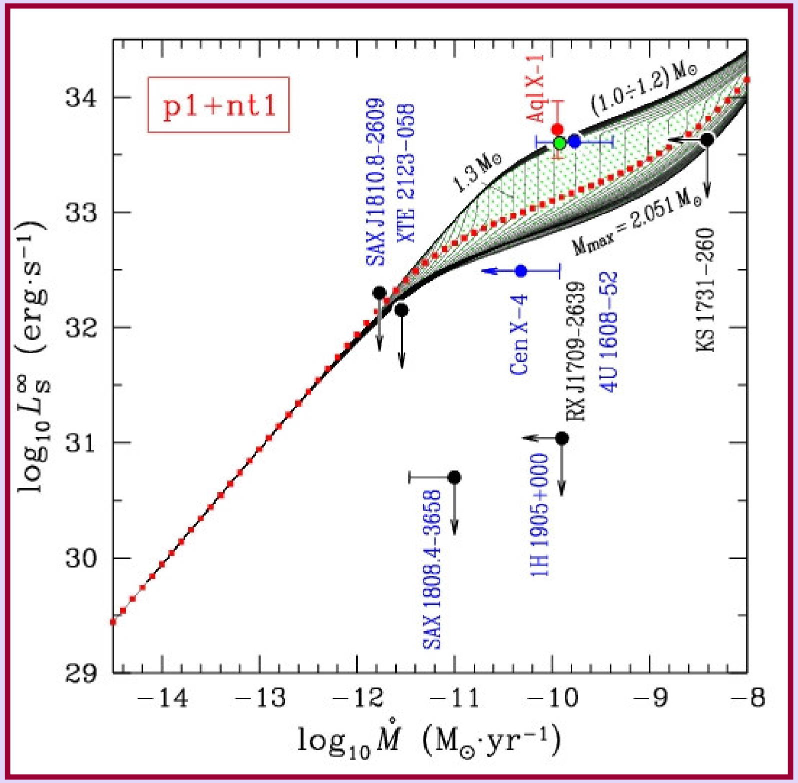
The enhanced cooling should be more powerful than the neutron Cooper pairing !!

Thermal states of the cooling INSs



Gusakov et al 2004 & Page et al 2004:
"Minimal cooling scenario" : fast cooling due to the neutron Cooper Pairing

Steady-states of the accreting NSs in SXTs

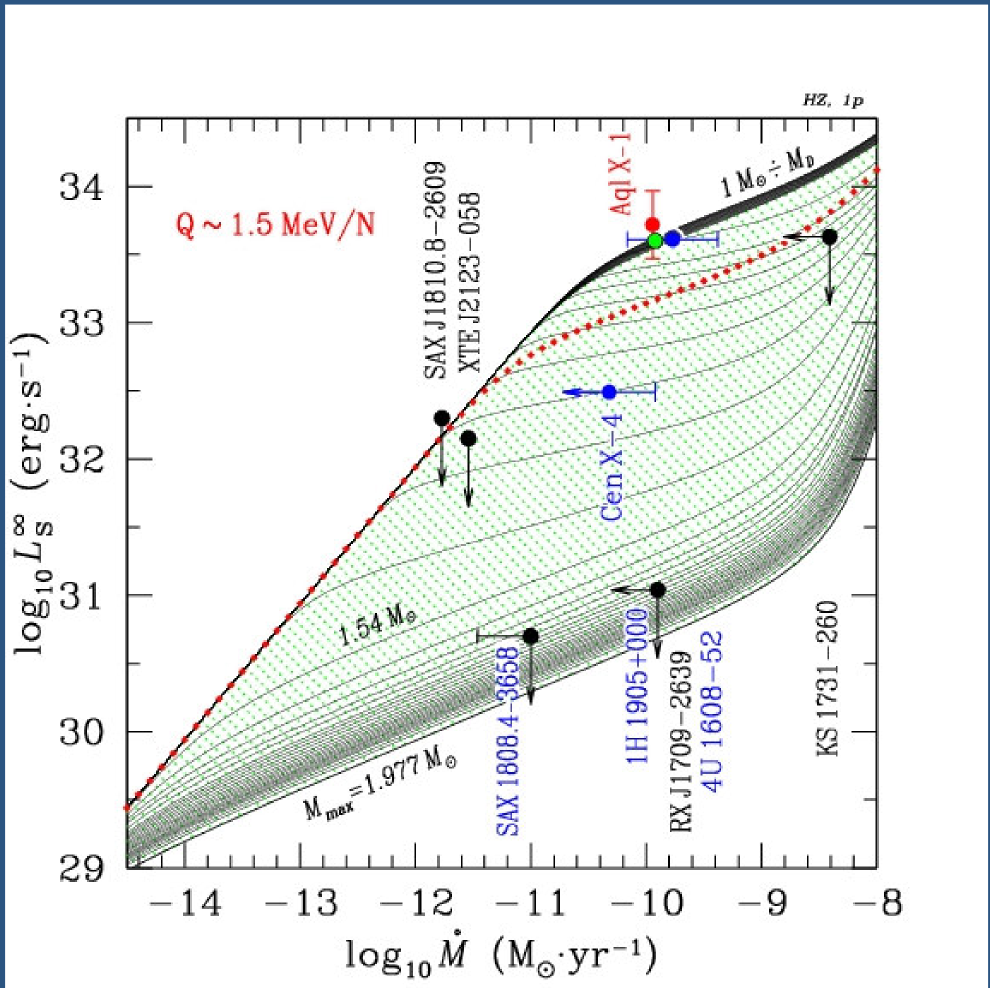


Levenfish, Haensel 2007:
EoS by Douchin, Haensel 2001 and SF models "p1" & "nt1" as in Gusakov et al 2001

SUMMARY

- *The data on INSs and SXTs test essentially the same physics of the internal structure of NSs and can be analyzed together*
- *These data can probe: the EOS and composition of a NS core, superfluidity of baryons, the level of neutrino emission, the models of accreted crusts, etc*
- *Interpretation of thermal emission from both INSs & SXTs require the presence of rather strong proton superfluidity with $T_{cp} > 10^9$ K in NS cores*
- *Both INSs and SXTs rule out the models of mild neutron superfluidity in the cores of low-mass NSs: $T_{cn} \sim 3\text{x}10^8 – 3\text{x}10^9$ K*
- *The data on SXTs seem to rule out the Cooper-pairing neutrino emission as an enhanced cooling agent*

Thermal states of SXTs vs deep crustal heating

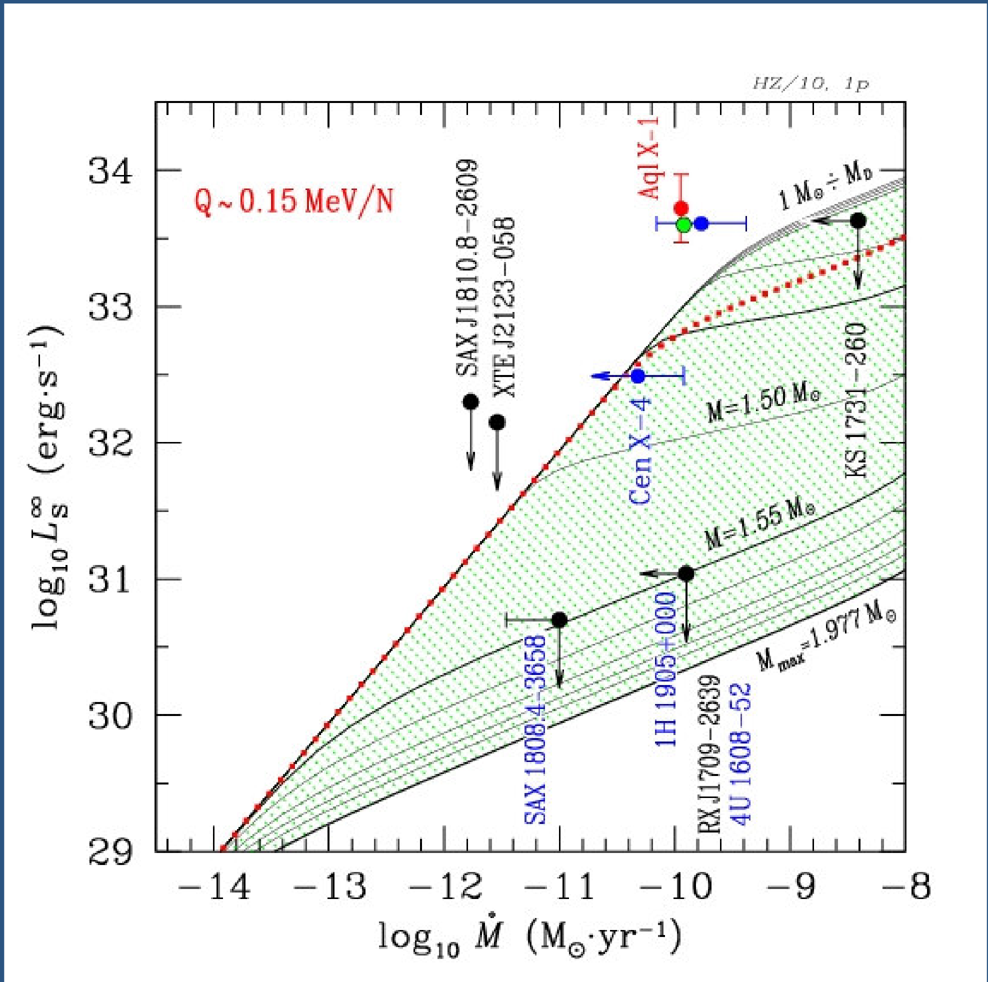


Deposited heat
Q ~ 1—2 MeV/nucleon:

- allows to explain all observed SXTs
- all SXTs are at the neutrino stage

(i.e. their thermal emission do depend on the state of matter in NS cores !)

Thermal states of SXTs vs deep crustal heating

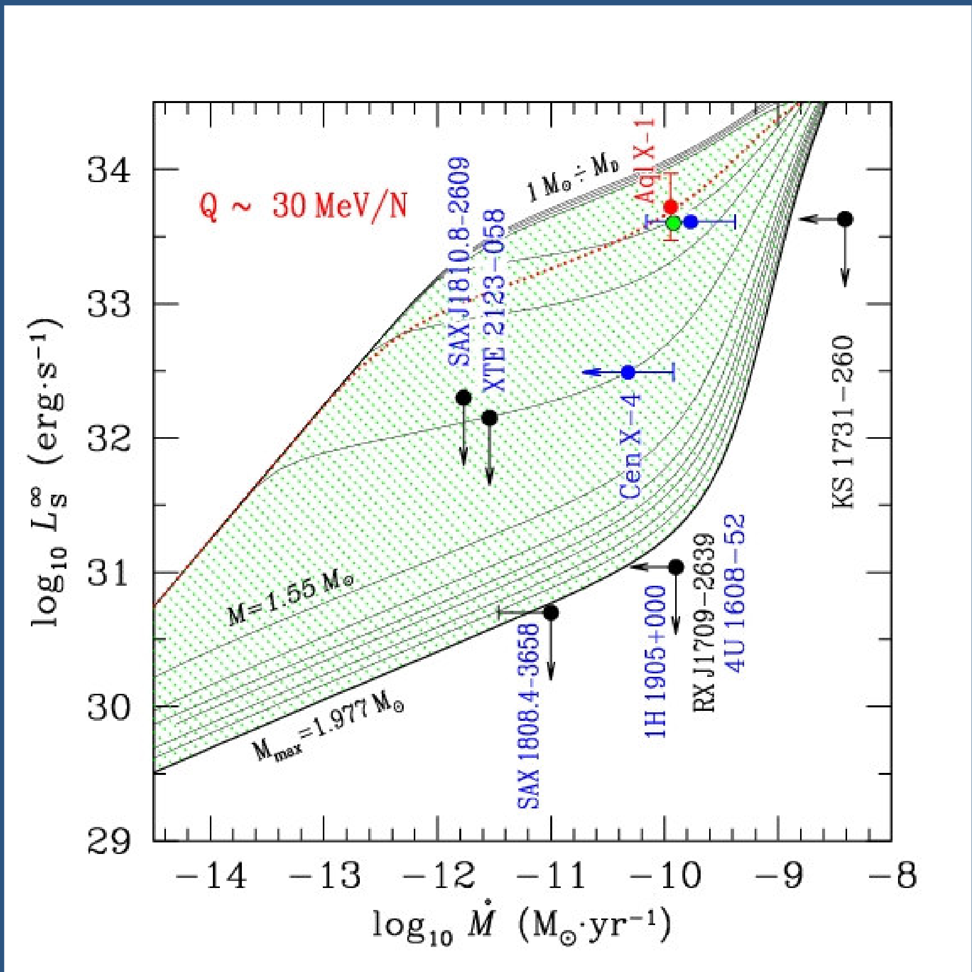


Deposited heat Q ~ hundred keV:

- cannot explain hot SXTs
- hot SXTs are mostly at the photon stage

(i.e. their thermal states don't depend on the state of matter in NS cores)

Thermal states of SXTs vs deep crustal heating



Deposited heat Q ~ dozens MeV:

- problem with KS 1726-260
- problem with two cold SXTs
- at least 3 SXTs may have nonsuperfluid interiors
- even at small accretion rate SXTs may be hot

Data on two very cold SXTs from Heinke et al 2007 & Jonker et al 2007

Model-dependent heat release of ~ dozens MeV/nucleon is suggested in the accreting strange stars with crust

It seems that ….

quiescent thermal emission of SXTs is most naturally explained within deep crustal heating hypothesis if …

the total heat deposited in the crust is ~ MeV/ nucleon !