Nucleon Superfluidity vs Thermal States of INSs & SXTs in quiescence

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- **Brown, Bildstein, Rutledge`98**

  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.

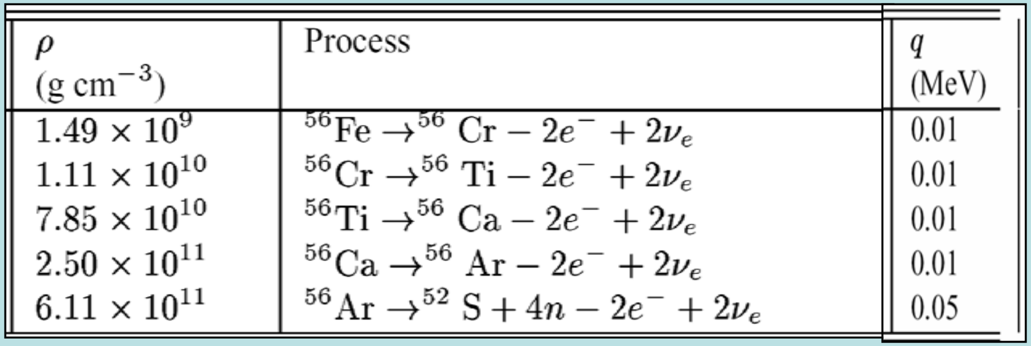
- **Yakovlev, Levenfish, Haensel `03**

  Direct correspondence of the problem of transienty accreting NSs to the problem of cooling isolated NSs.
  Quiescent SXTs test essentially the same physics as the ISNs:
  - ✓ composition and superfluidity of superdense matter,
  - ✓ crustal structure, composition and conductivity,
  - ✓ light-elements accreted envelope etc.

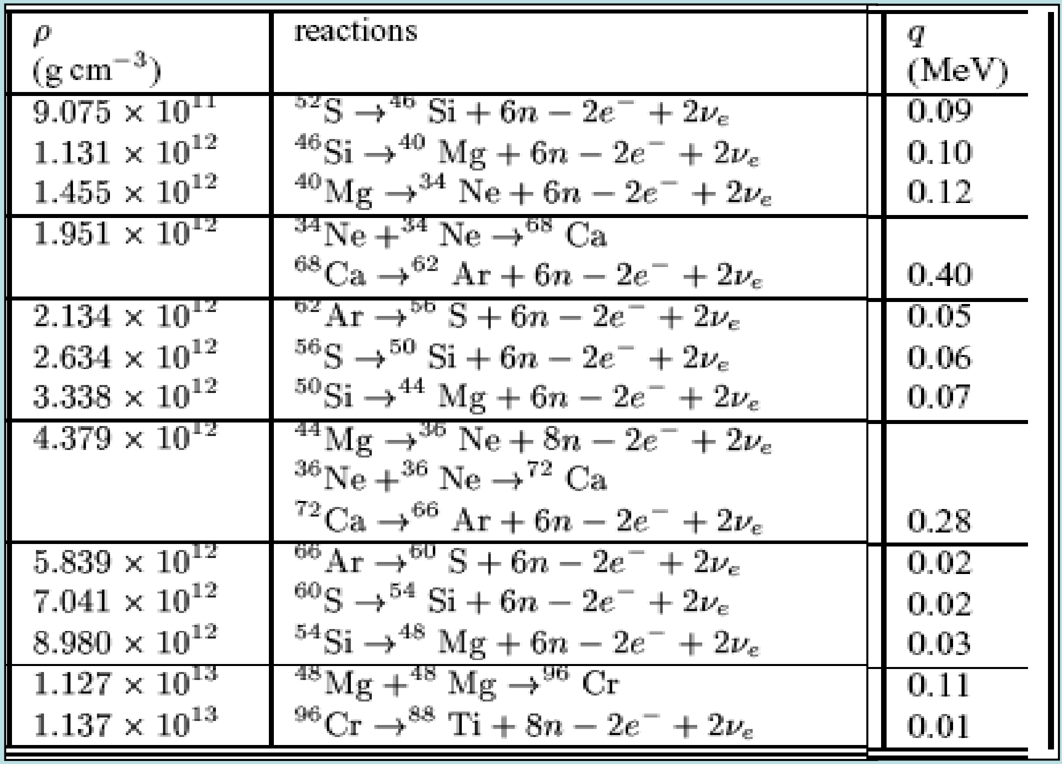
- **Ushomirsky & Rutledge`01, Colpi, Geppert, Page, Possenti `01, Brown, Bildsten, Chang `02, Rutledge etal `02, Yakovlev, Levenfish, Potekhin etal `04**

  Thermal states of transiently accreting NSs in SXTs vs observations of their quiescent thermal emission.

Deep crustal heating in transiently accreting NSs in SXTs

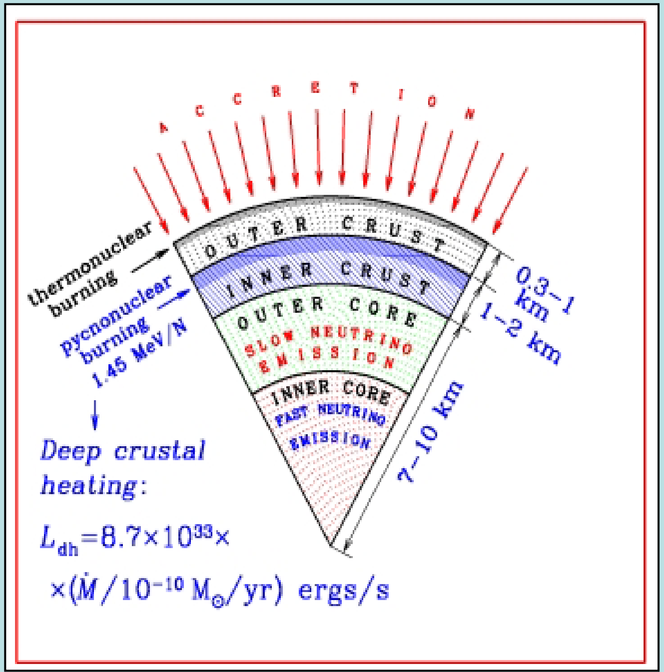


ρ (g cm^{-3})	Process	q (MeV)
1.49×10^9	$^{56}\mathrm{Fe} \to {}^{56}\mathrm{Cr} - 2e^- + 2\nu_e$	0.01
1.11×10^{10}	$^{56}\mathrm{Cr} \to {}^{56}\mathrm{Ti} - 2e^- + 2\nu_e$	0.01
7.85×10^{10}	$^{56}\mathrm{Ti} \to {}^{56}\mathrm{Ca} - 2e^- + 2\nu_e$	0.01
2.50×10^{11}	$^{56}\mathrm{Ca} \to {}^{56}\mathrm{Ar} - 2e^- + 2\nu_e$	0.01
6.11×10^{11}	$^{56}\mathrm{Ar} \to {}^{52}\mathrm{S} + 4n - 2e^- + 2\nu_e$	0.05



ρ (g cm^{-3})	reactions	q (MeV)
9.075×10^{11}	$^{52}\mathrm{S} \to {}^{46}\mathrm{Si} + 6n - 2e^- + 2\nu_e$	0.09
1.131×10^{12}	$^{46}\mathrm{Si} \to {}^{40}\mathrm{Mg} + 6n - 2e^- + 2\nu_e$	0.10
1.455×10^{12}	$^{40}\mathrm{Mg} \to {}^{34}\mathrm{Ne} + 6n - 2e^- + 2\nu_e$	0.12
1.951×10^{12}	$^{34}\mathrm{Ne} + {}^{34}\mathrm{Ne} \to {}^{68}\mathrm{Ca}$ $^{68}\mathrm{Ca} \to {}^{62}\mathrm{Ar} + 6n - 2e^- + 2\nu_e$	0.40
2.134×10^{12}	$^{62}\mathrm{Ar} \to {}^{56}\mathrm{S} + 6n - 2e^- + 2\nu_e$	0.05
2.634×10^{12}	$^{56}\mathrm{S} \to {}^{50}\mathrm{Si} + 6n - 2e^- + 2\nu_e$	0.06
3.338×10^{12}	$^{50}\mathrm{Si} \to {}^{44}\mathrm{Mg} + 6n - 2e^- + 2\nu_e$	0.07
4.379×10^{12}	$^{44}\mathrm{Mg} \to {}^{36}\mathrm{Ne} + 8n - 2e^- + 2\nu_e$ $^{36}\mathrm{Ne} + {}^{36}\mathrm{Ne} \to {}^{72}\mathrm{Ca}$ $^{72}\mathrm{Ca} \to {}^{66}\mathrm{Ar} + 6n - 2e^- + 2\nu_e$	0.28
5.839×10^{12}	$^{66}\mathrm{Ar} \to {}^{60}\mathrm{S} + 6n - 2e^- + 2\nu_e$	0.02
7.041×10^{12}	$^{60}\mathrm{S} \to {}^{54}\mathrm{Si} + 6n - 2e^- + 2\nu_e$	0.02
8.980×10^{12}	$^{54}\mathrm{Si} \to {}^{48}\mathrm{Mg} + 6n - 2e^- + 2\nu_e$	0.03
1.127×10^{13}	$^{48}\mathrm{Mg} + {}^{48}\mathrm{Mg} \to {}^{96}\mathrm{Cr}$	0.11
1.137×10^{13}	$^{96}\mathrm{Cr} \to {}^{88}\mathrm{Ti} + 8n - 2e^- + 2\nu_e$	0.01

Q_{dh} = 1.15 – 1.45 MeV / nucl



Deep crustal heating:

$L_{dh} = 8.7 \times 10^{33} \times (\dot{M}/10^{-10}\,M_\odot/\mathrm{yr})$ ergs/s

Haensel, Zdunik 1990, 2003

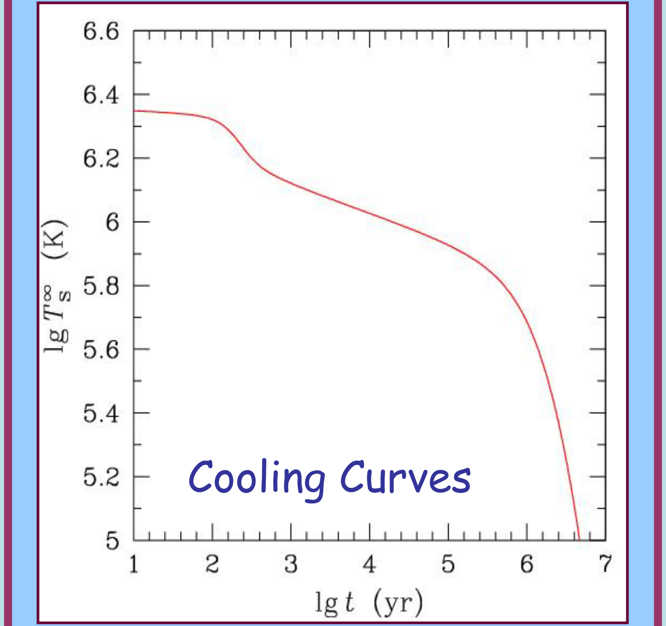
Two subsets of NSs

Cooling INSs

Thermal balance:

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

Cooling: $T_s = T_s(t)$

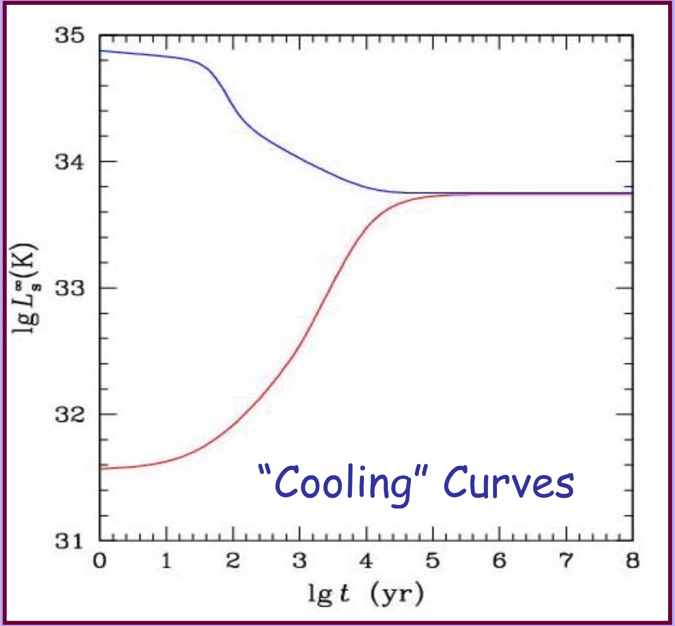


Transiently accreting NSs in SXTs

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

Heating (cooling) to steady-state: $\boldsymbol{L_\gamma = L_\gamma(t,\ \dot M)}$

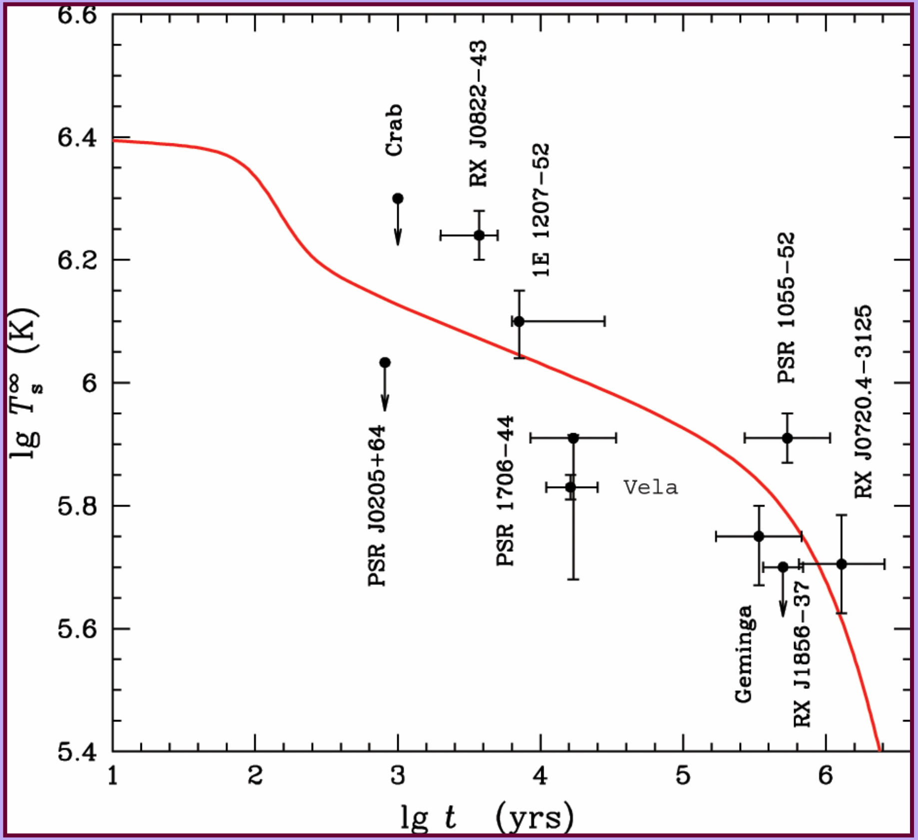
In steady-state: $L_{dh}(\dot M) = L_\nu(T) + L_\gamma(T_s)$



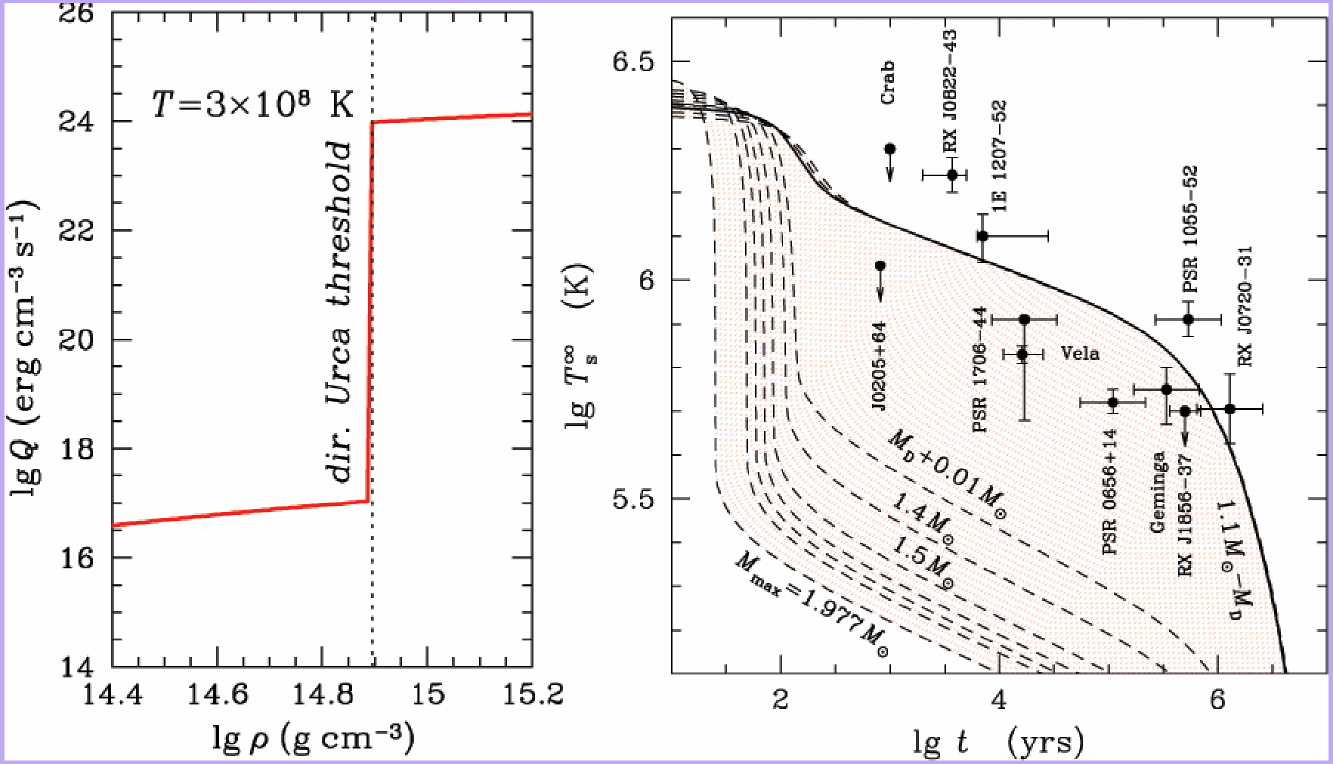
$$L_\gamma = L_\gamma(\dot M)$$

Heating Curves

Standard scenario (cooling dominated by Modified Urca in a nonsuperfluid NS core) cannot explain thermal states of neither the INSs nor the SXTs in quiescence



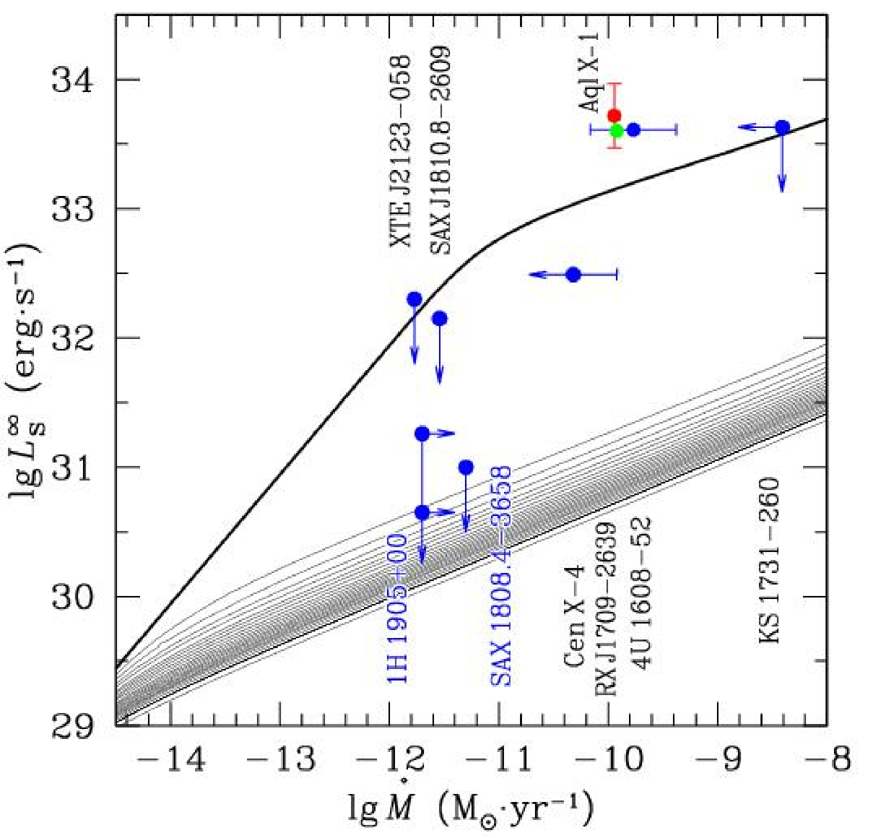
Mere admittance for enhanced mechanisms of neutrino emission in nonsuperfluid NS doesnot help to explain observations



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

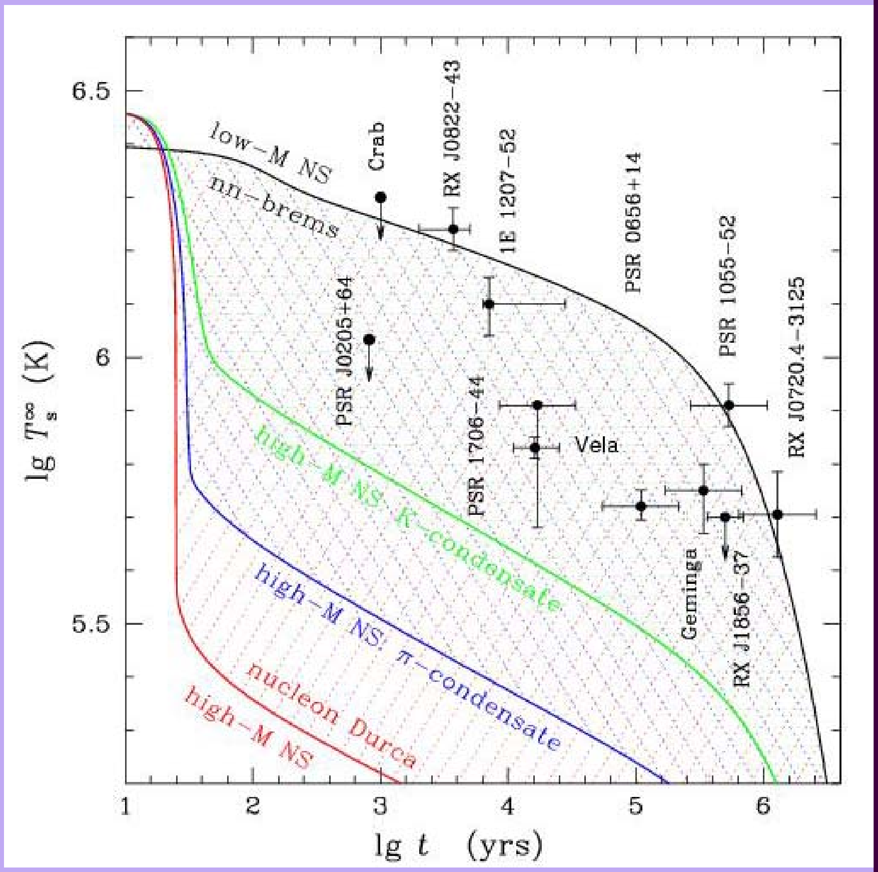
Scenario with enhanced cooling of nosuperfluid star cannot explain observations neither of the ISNs nor accreting NSs in SXTs

Steady-state of accreting NSs in SXTs

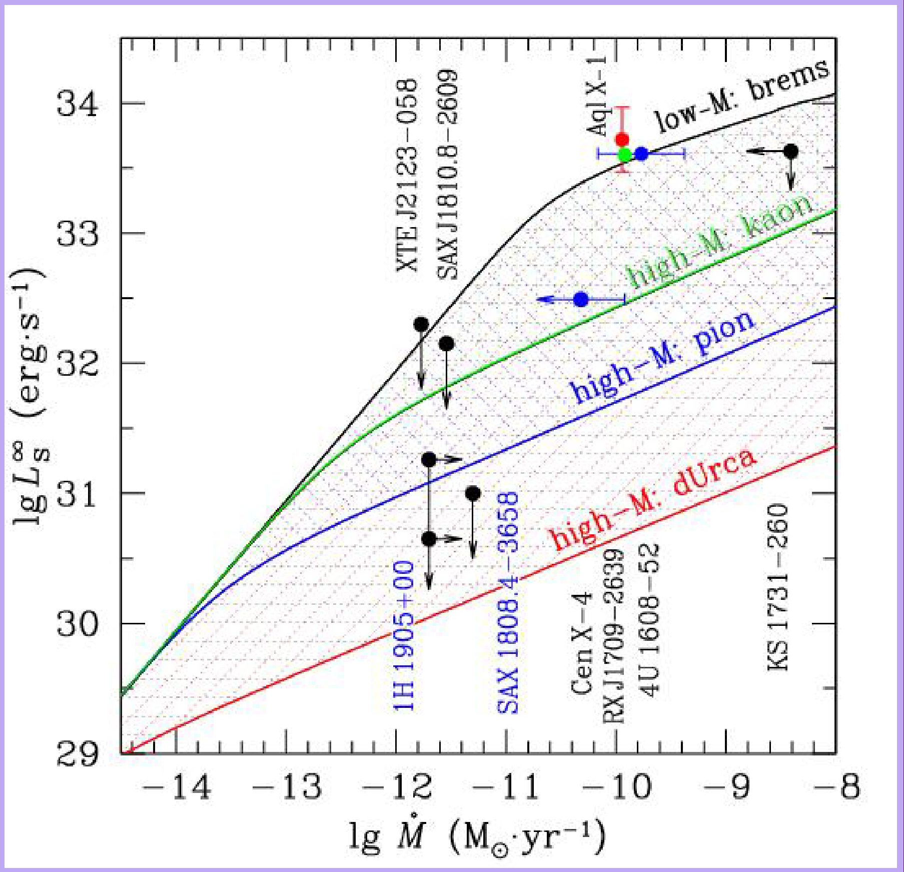


Composition of NSs cores: Nucleons? Hyperons?

Cooling of INSs



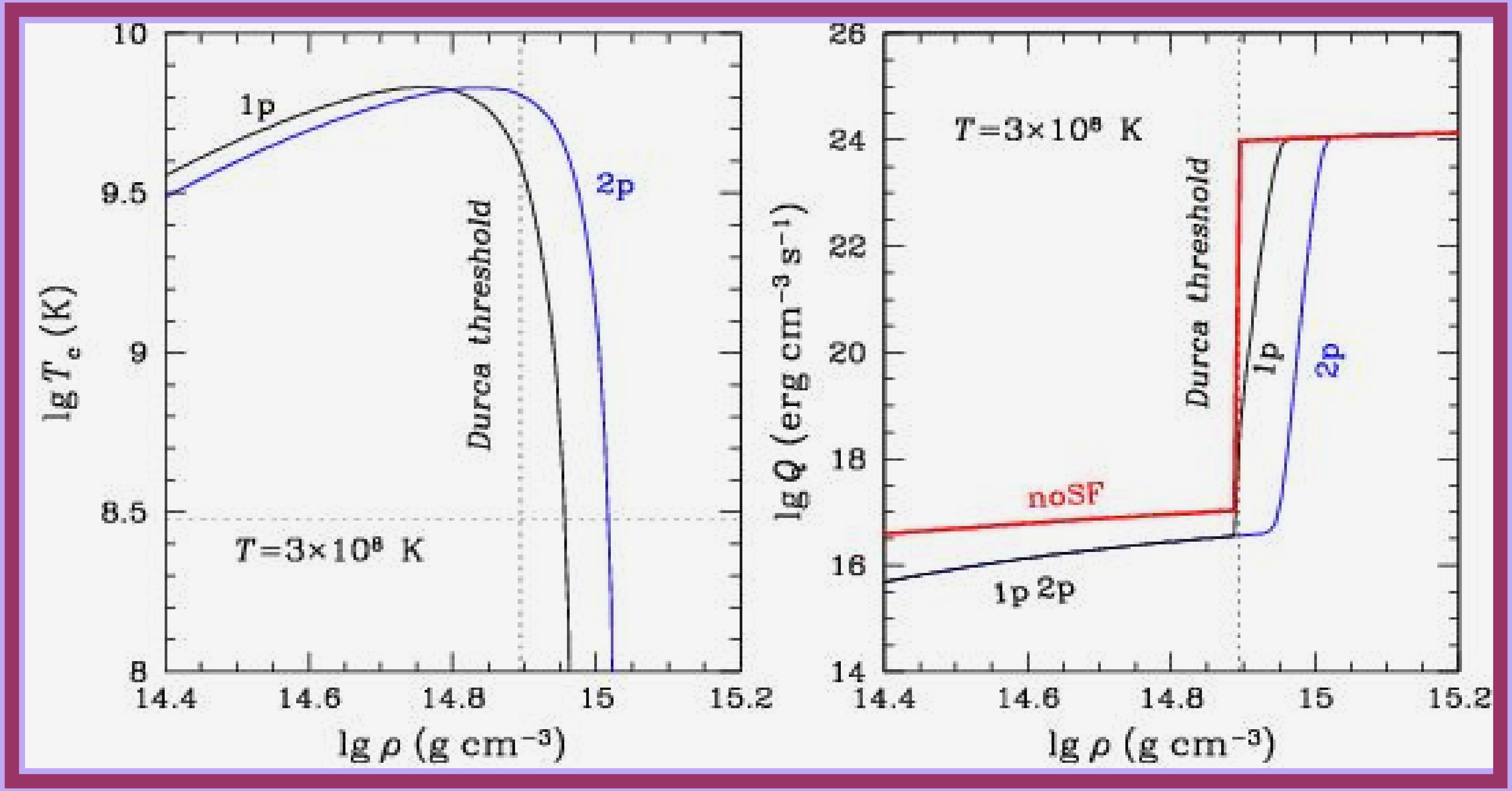
Steady-state of SXTs



Yakovlev etal 2004

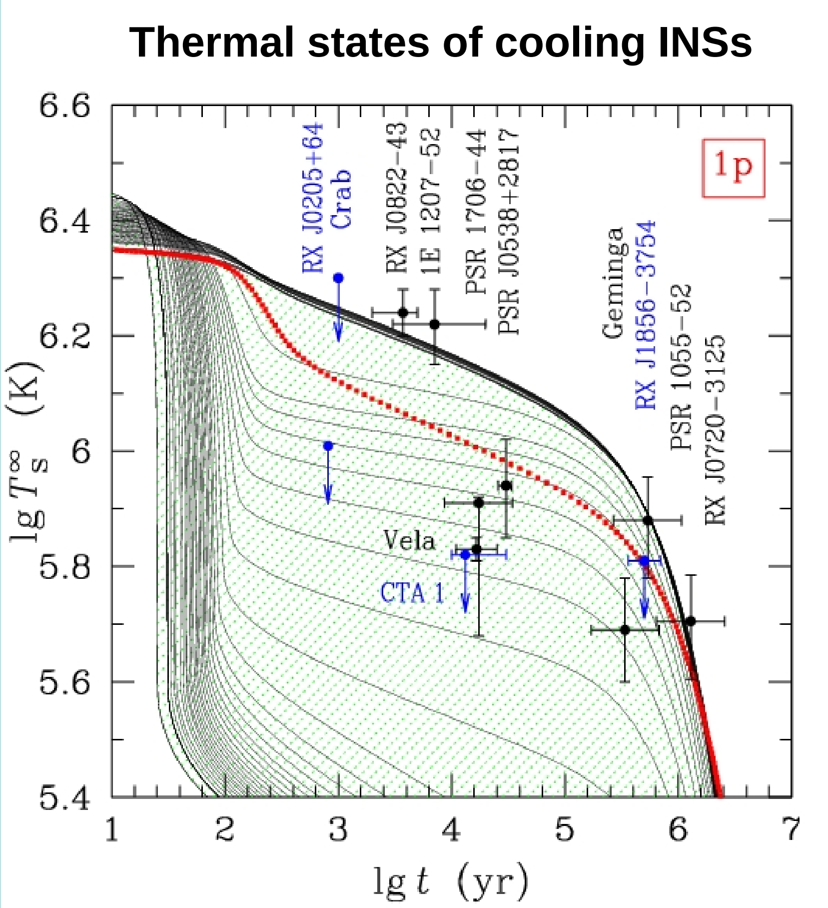
Srtong proton superfluidity :

- **suppresses the modified Urca :**
  slows down the cooling of the low-mass NSs
- **smoothes the switching of the direct Urca :**
  allows for existence of the representative class of the medium-mass NSs



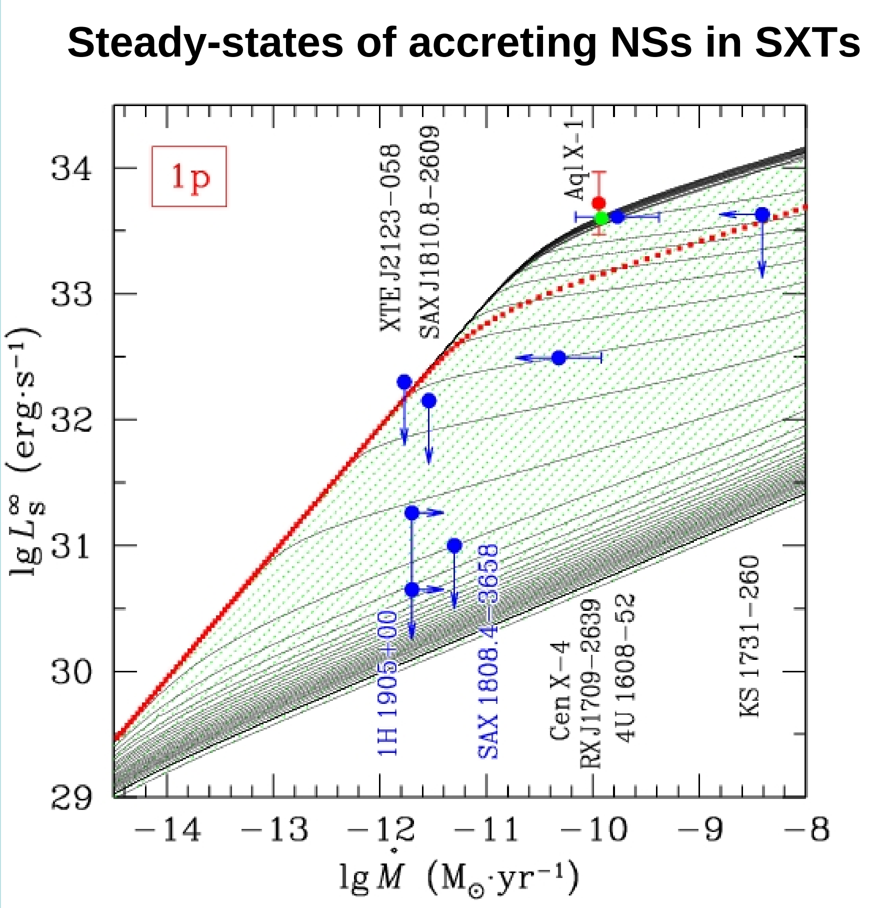
Strong proton superfluidity : : $T_{cp} \geq 10^9\,\mathrm{K}$

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



Thermal states of cooling INSs

Kaminker, Yakovlev, Gnedin 2002



Steady-states of accreting NSs in SXTs

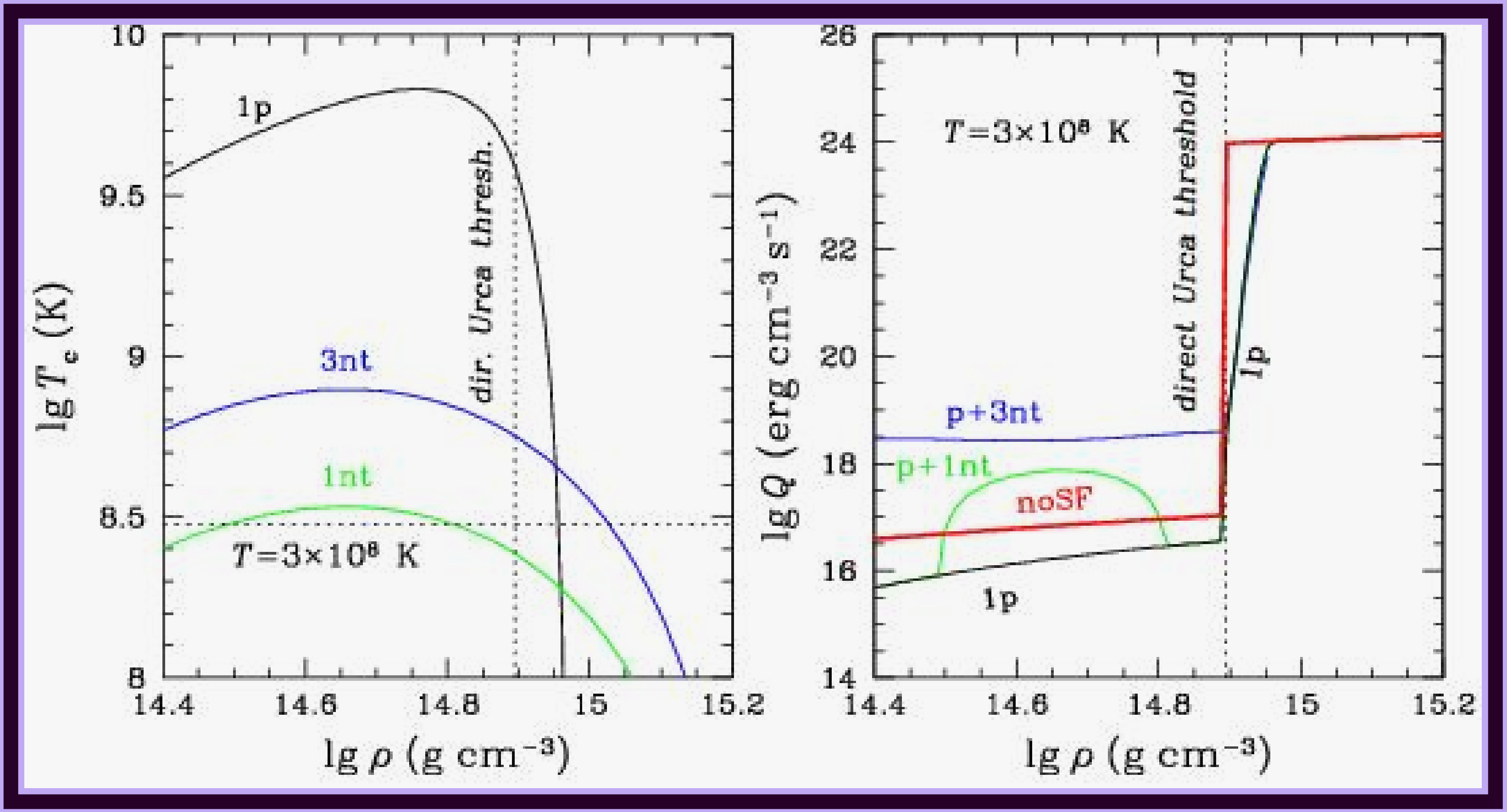
Levenfish Yakovlev,Haensel 2006

Mild neutron superfuidity:

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

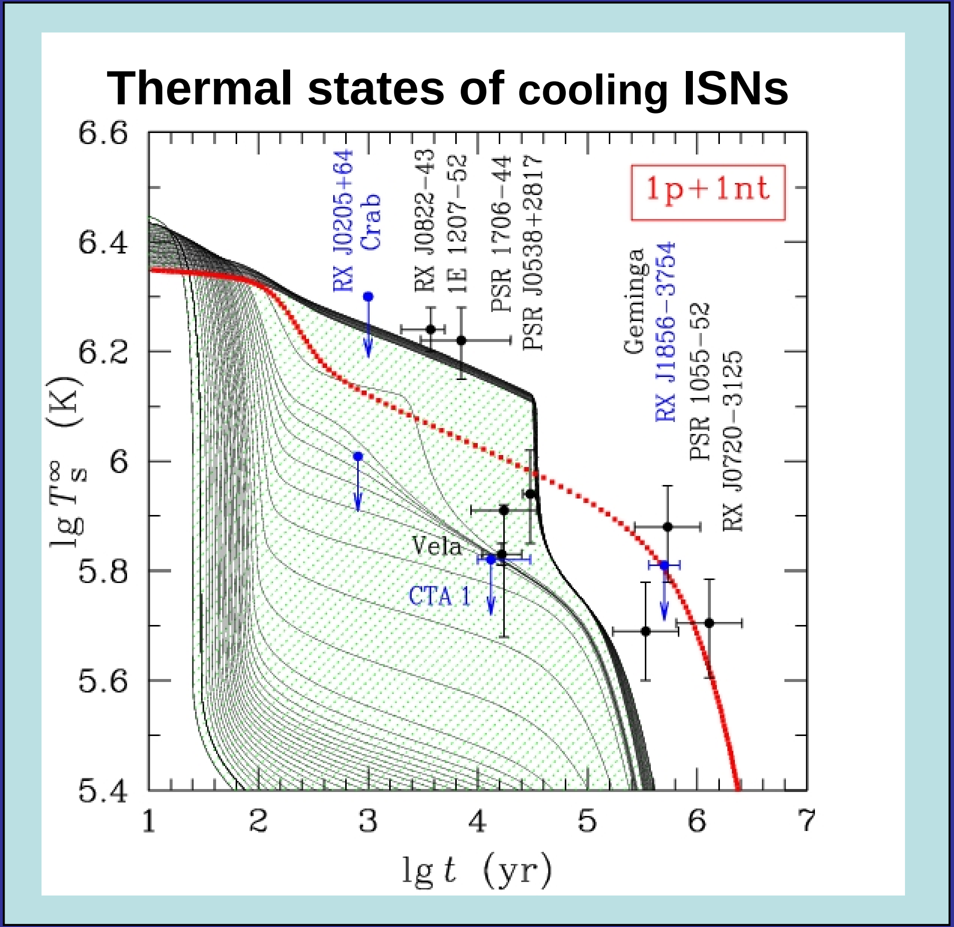
✓The neutron Cooper pairing process strongly accelerate the cooling of the low-mass NSs at the neutrino stage.

✓Reduction of the heat capacity strongly accelerates the cooling at the photon stage



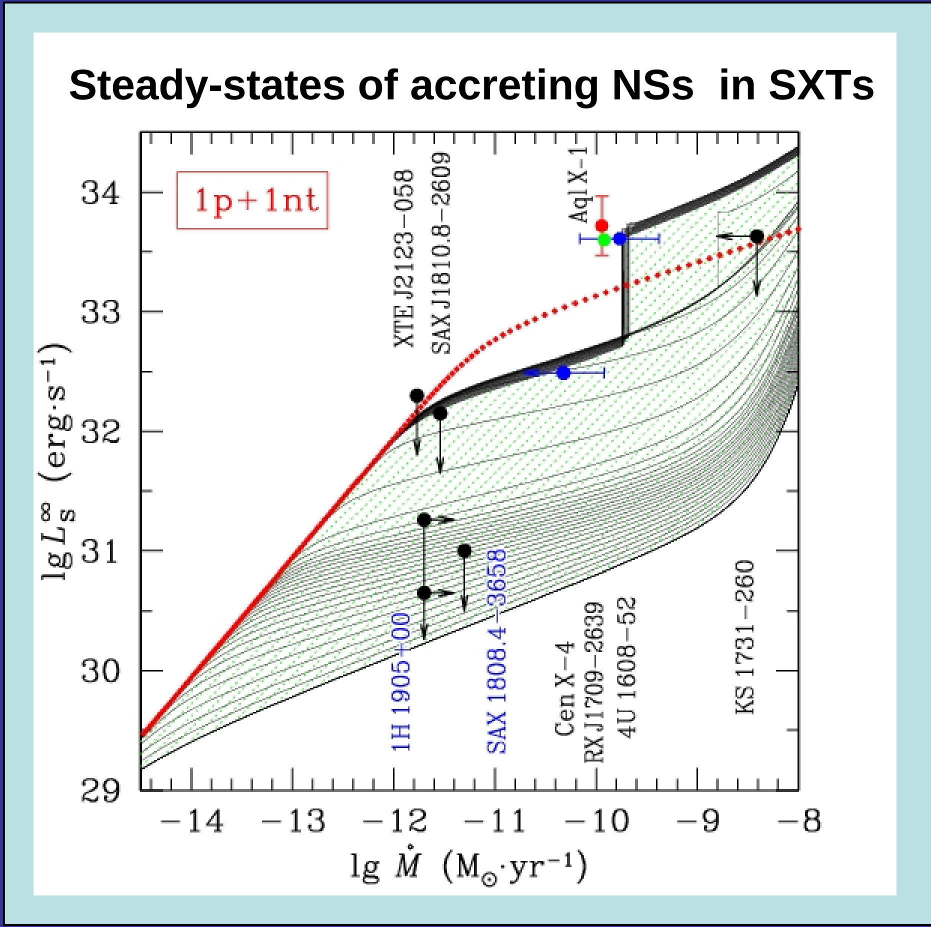
Mild neutron superfluidity : $T_{cn} = \left(2\times10^{8} \div 2\times10^{9}\right)K$

- Contradicts observations of hot sources
- Should be absent in low-mass NSs (in the outer NS cores)
- Can lead to dichotomy of thermal states of SXTs



Thermal states of cooling ISNs

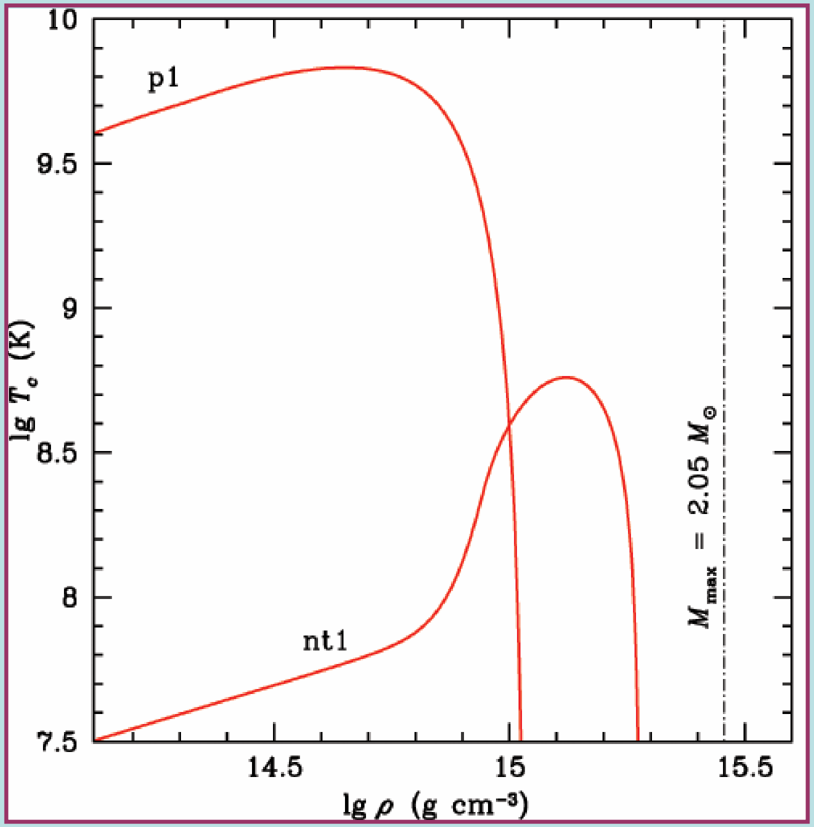
Yakovlev etal 2002



Steady-states of accreting NSs in SXTs

Levenfish,Yakovlev Haensel 2006

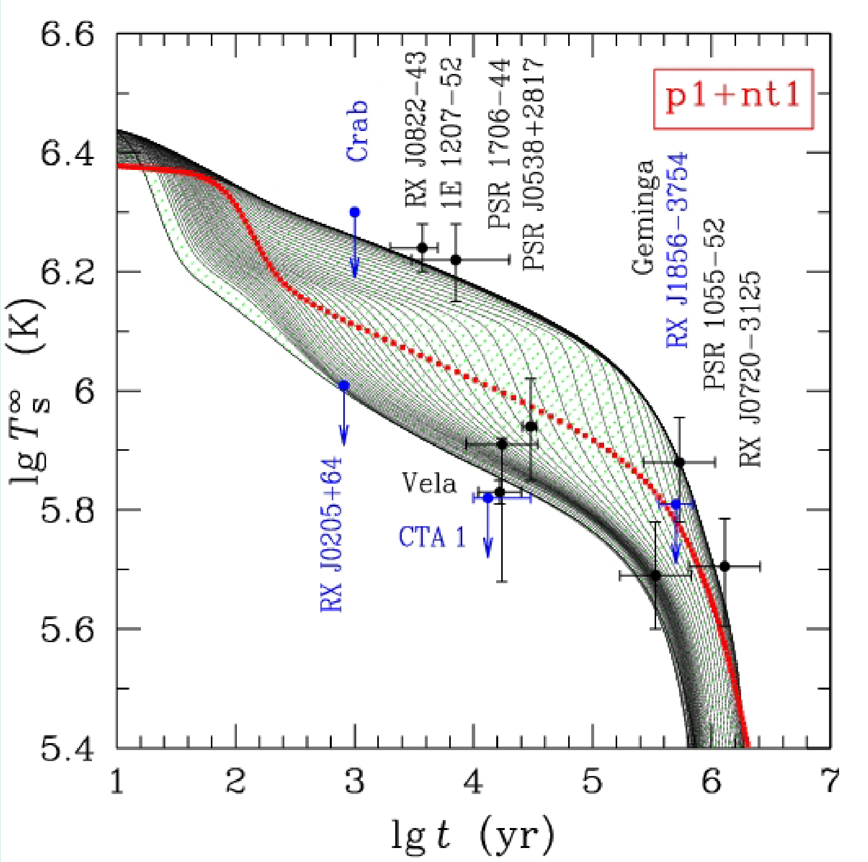
Mild neutron superfluidity in the inner NSs cores



Minimal cooling scenario (enhanced cooling due to neutron Cooper pairing):

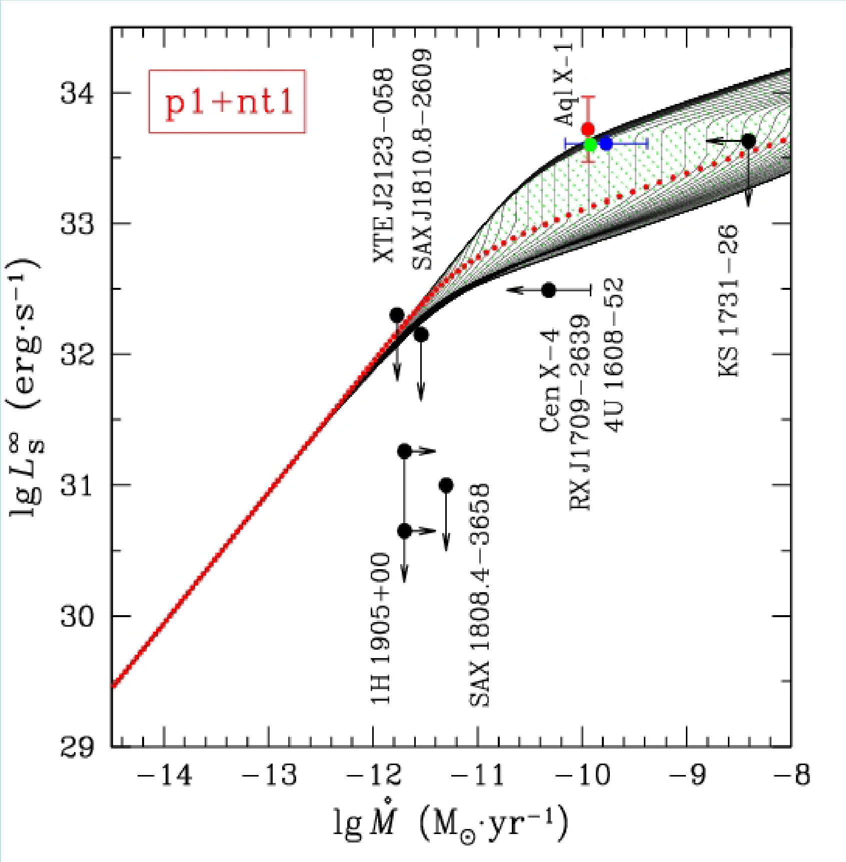
- Marginally compatible with the data on INSs
- Contradicts the data on SXTs in quiescence
- The enhanced cooling should be more powerful than the neutron Cooper pairing

Thermal states of cooling INSs



Gusakov etal 2004; Page etal 2004

Steady-state of SXTs



Levenfish, Yakovlev, Haensel 2006

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 crust

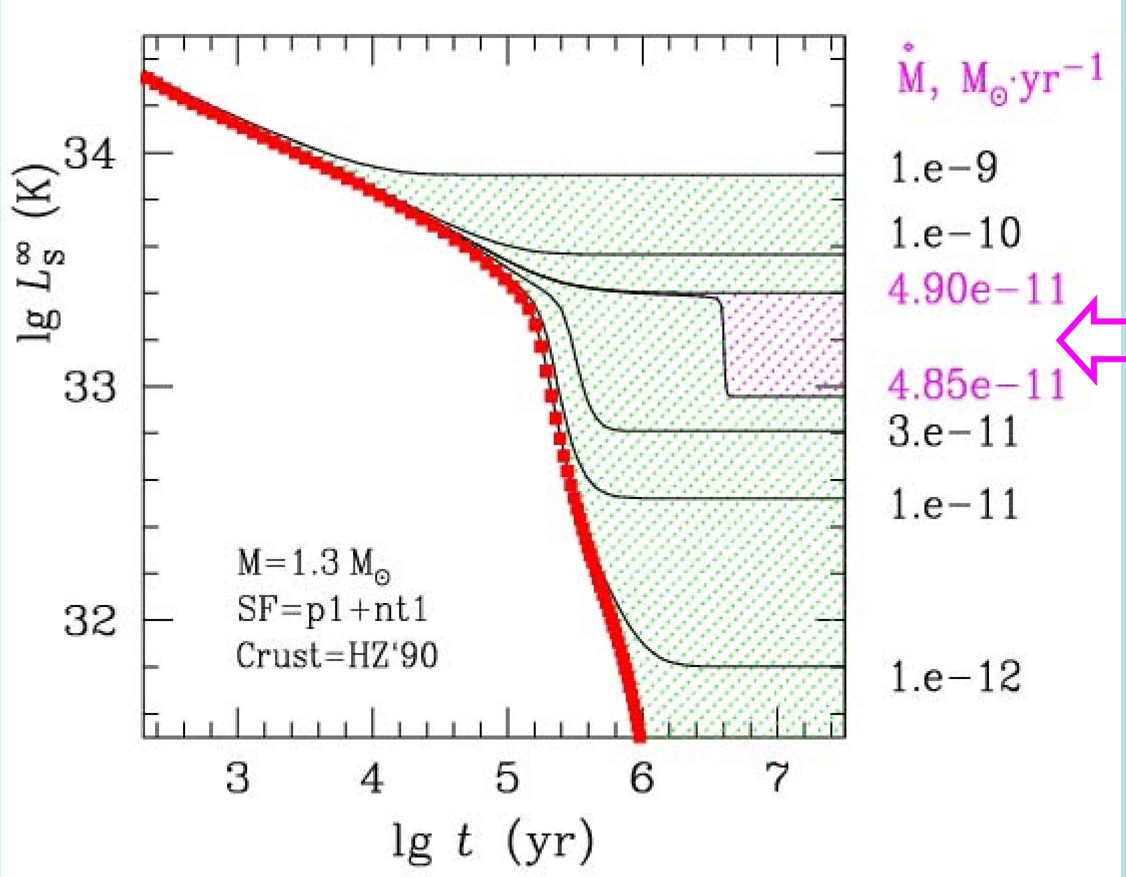
- Both INSs and SXTs require the presense of strong proton superfluidity

- Both INSs and SXTs rule out the models of mild neutron superfluidity in the cores of low-mass NSs

- The data on SXTs seem to rule out Cooper-pairing neutrino emission as an enhanced cooling agent

Dichotomy of thermal evolution of accreting NSs: Effect of the mild neutron superfluidity (mild Cooper pairing)

Steady-states of a SXT vs mass accretion rate $\dot{M}$

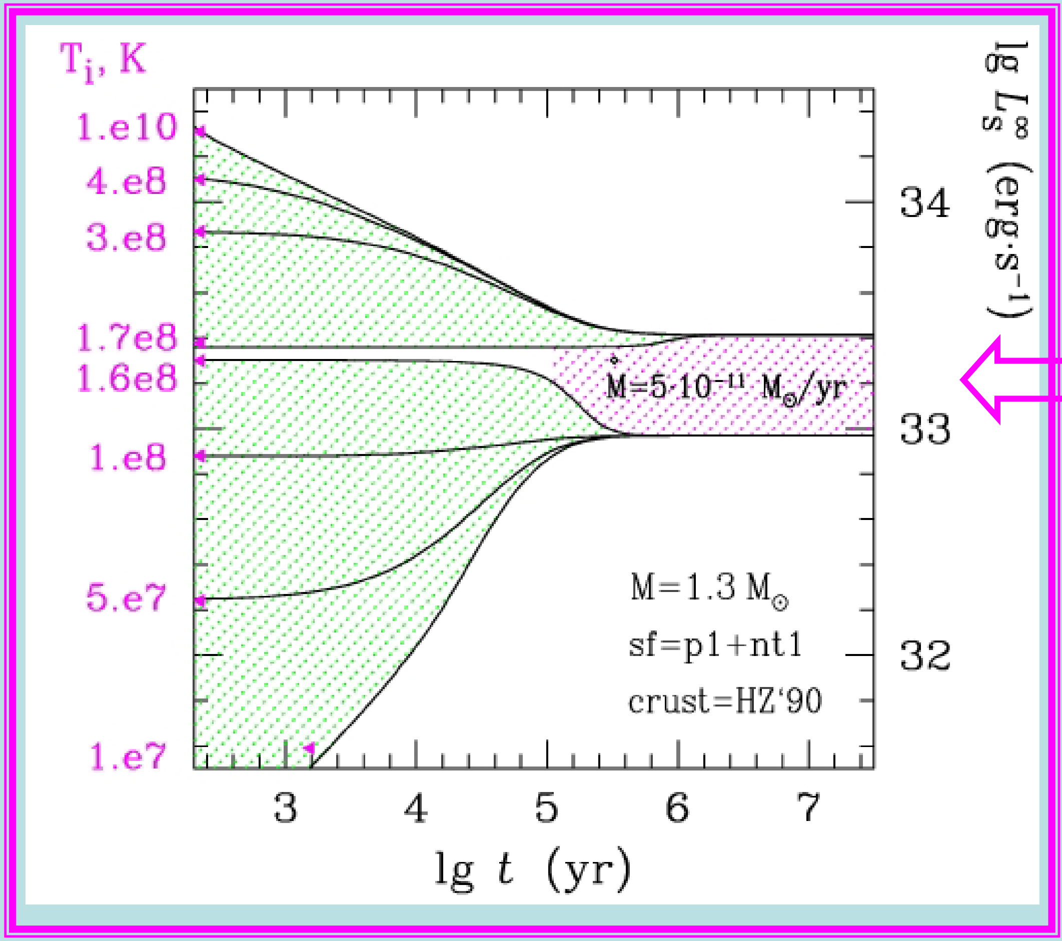


"BARRED" THERMAL STATES

Levenfish, Yakovlev, Haensel 2006

Dichotomy of thermal evolution of accreting NSs: Effect of the mild neutron superfluidity (mild Cooper pairing)

Steady-states of SXTs vs initial core temperature T



“BARRED” THERMAL STATES

Levenfish, Yakovlev, Haensel 2006

“Good questions” :

Observations:

- Average mass accretion rates
- Narrow observational constaints on themal emission in quiescence
- Nonthermal components of quiescent emission
- Variable thermal emission in quiescence

Theory:

- Deep crustal heating models
- Cooper pairing in the NSs crust

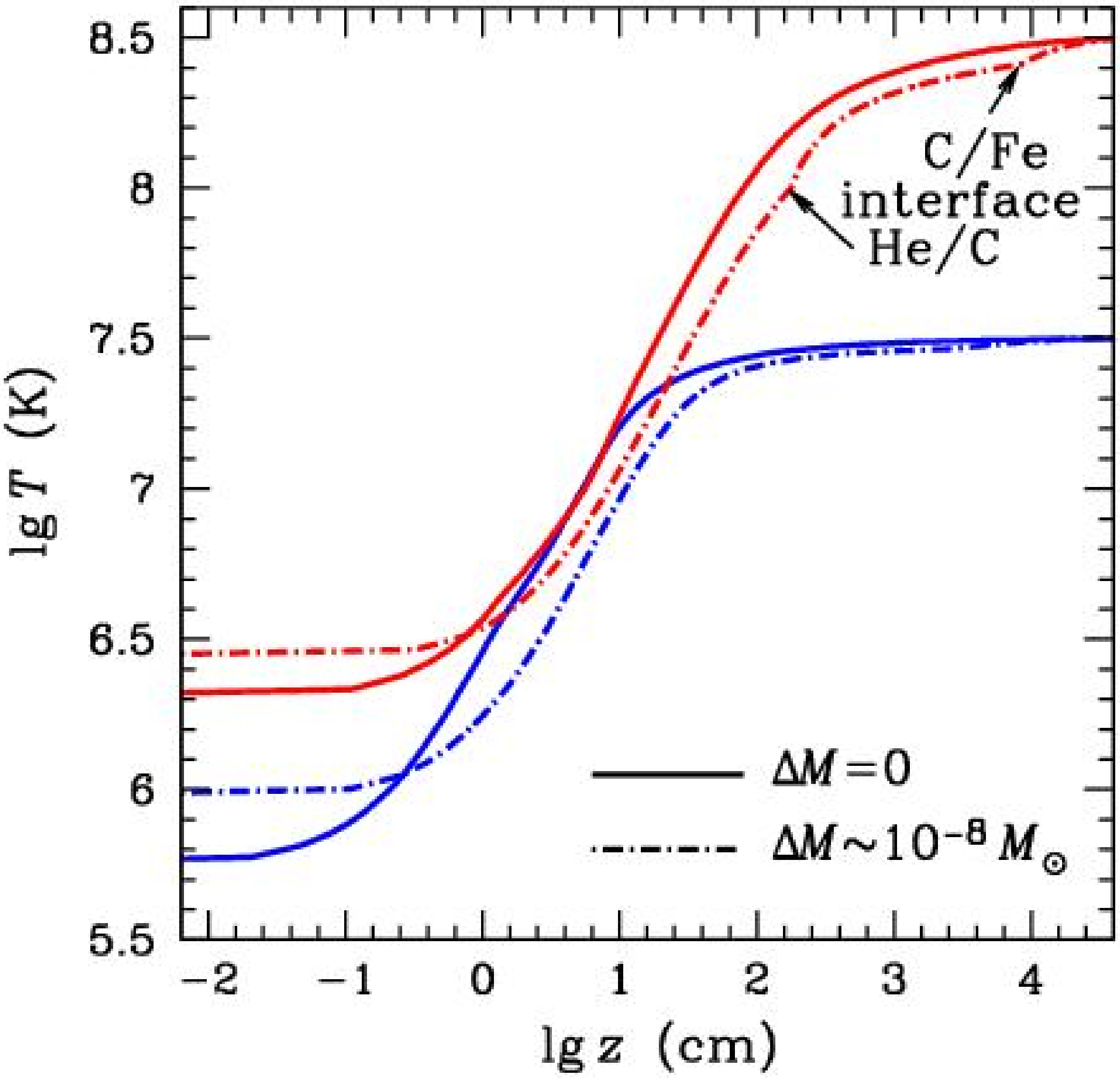
Everywhere in neutron star cores.

Most important in low-mass stars.

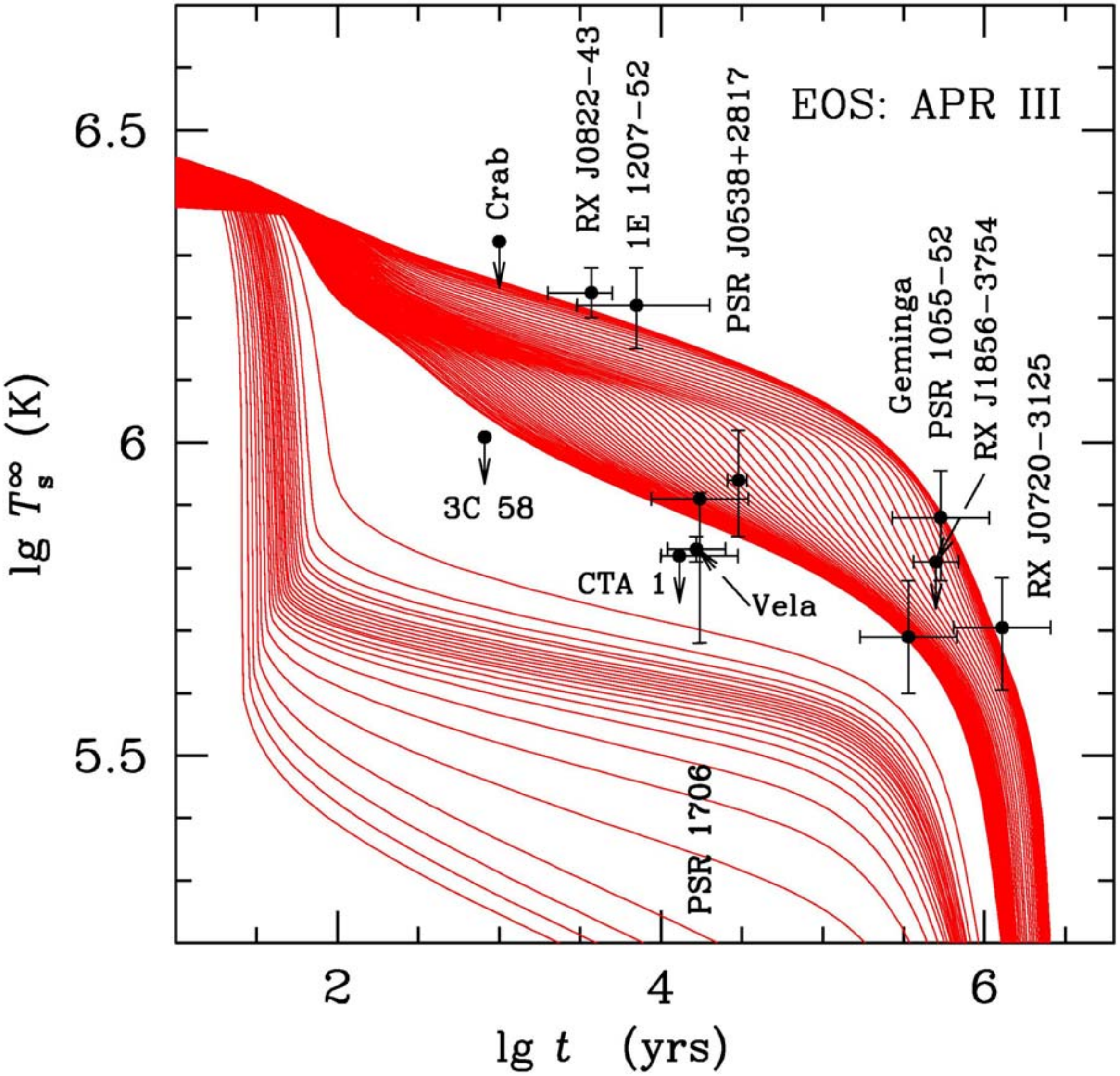
Modified Urca process	$n+N \rightarrow p+e+N+\bar{\nu}_e$ $p+e+N \rightarrow n+N+\nu_e$	$Q \sim 10^{20-22} T_9^8 \ \frac{erg}{cm^3\ s}$	$L_\nu \sim 10^{38-40} T_9^8 \ \frac{erg}{s}$
Brems-strahlung	$N+N \rightarrow N+N+\nu+\bar{\nu}$ $\Downarrow$ $\nu_e,\ \nu_\mu,\ \nu_\tau$	$Q \sim 10^{18-20} T_9^8 \ \frac{erg}{cm^3\ s}$	$L_\nu \sim 10^{36-38} T_9^8 \ \frac{erg}{s}$

Inner cores of massive neutron stars:

Nucleons, hyperons	$n \rightarrow p+e+\bar{\nu}_e$ $p+e \rightarrow n+\nu_e$	$Q \sim 3\times 10^{27} T_9^6 \ \frac{erg}{cm^3\ s}$	$L_\nu \sim 10^{46} T_9^6 \ \frac{erg}{s}$
Pion condensates	$\tilde{n} \rightarrow \tilde{p}+e+\bar{\nu}_e$ $\tilde{p}+e \rightarrow \tilde{n}+\nu_e$	$Q \sim 10^{24-26} T_9^6 \ \frac{erg}{cm^3\ s}$	$L_\nu \sim 10^{42-44} T_9^6 \ \frac{erg}{s}$
Kaon condensates	$\tilde{q} \rightarrow \tilde{q}+e+\bar{\nu}_e$ $\tilde{q}+e \rightarrow \tilde{q}+\nu_e$	$Q \sim 10^{23-24} T_9^6 \ \frac{erg}{cm^3\ s}$	$L_\nu \sim 10^{41-42} T_9^6 \ \frac{erg}{s}$
Quark matter	$d \rightarrow u+e+\bar{\nu}_e$ $u+e \rightarrow d+\nu_e$	$Q \sim 10^{23-24} T_9^6 \ \frac{erg}{cm^3\ s}$	$L_\nu \sim 10^{41-42} T_9^6 \ \frac{erg}{s}$



8.5
8
7.5
7
6.5
6
5.5
−2
−1
0
1
2
3
4
lg T (K)
lg z (cm)
C/Fe
interface
He/C
$\Delta M = 0$
$\Delta M \sim 10^{-8} M_\odot$



Gusakov, Kaminker, Yakovlev, Gnedin 2005