Gapless neutron superfluidity can explain the late time cooling of transiently accreting neutron stars

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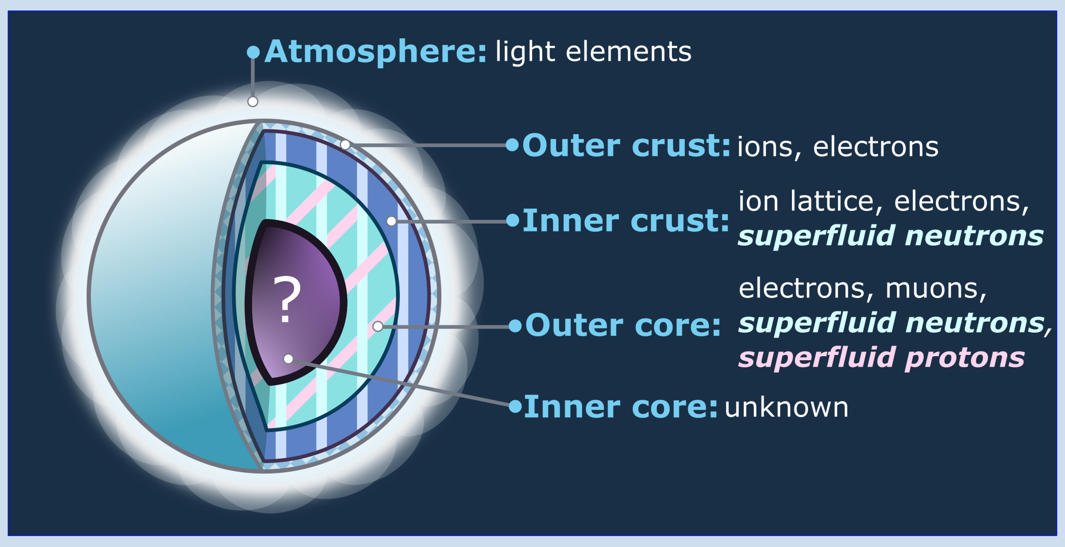
Abstract

Finite neutron superflow in the inner crust of neutron stars can lead to a new *gapless* superfluid phase, in which the neutron specific heat is significantly increased compared to the standard BCS superfluid phase. We investigated the impact of gapless superfluidity for the crust cooling of transiently accreting neutron stars and we obtained excellent fits to the observational data.

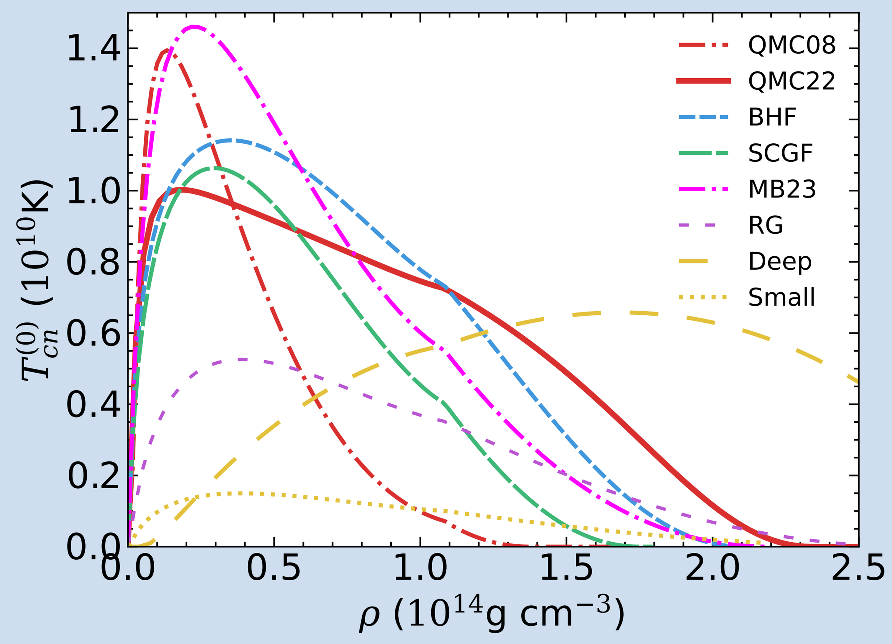
Introduction

Initially very hot, neutron stars cool down rapidly and as the temperature drops below $\sim 10^{10}$ K, free neutrons in the crust and the outer core are expected to become superfluid [1].



Picture adapted from K.C. Gendreau et al. (2012), SPIE, 8443, 13

The critical temperature $T_{cn}^{(0)}$ depends on the average mass density ρ:



Transiently accreting systems

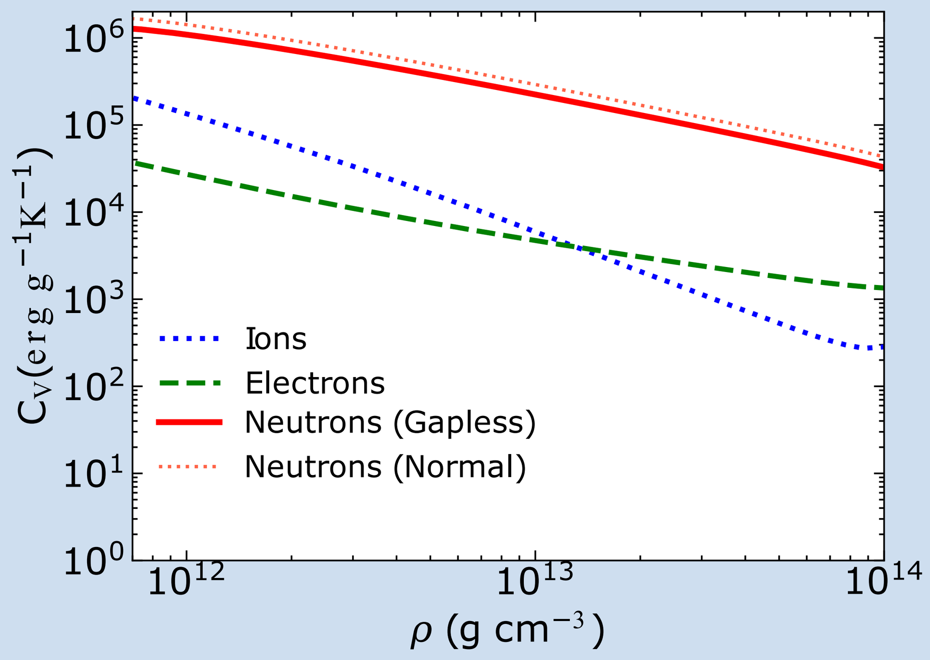
Neutron superfluidity has been recently challenged by observations of quasipersistent soft X-ray transients, in which long periods of accretion drive the crust out of thermal equilibrium with the core. The thermal relaxation during quiescence has been monitored in a dozen sources [2]. The most puzzling are:

- **KS 1731−260**: Observations in 2010 [3] suggested the source might still be cooling. $T_{cn}^{(0)}$ was extracted by fitting directly the cooling data [4] (see "Deep" and "Small").
- **MXB 1659−29**: An unexpected temperature drop in 2013 [5] suggested that neutrons are not superfluid at the crust bottom [6], as supported by quantum Monte Carlo calculations in 2008 (see "QMC08").

Both interpretations are at variance with recent microscopic calculations (see "QMC22", "SCGF" and "MB23").

Gapless superfluidity and neutron specific heat

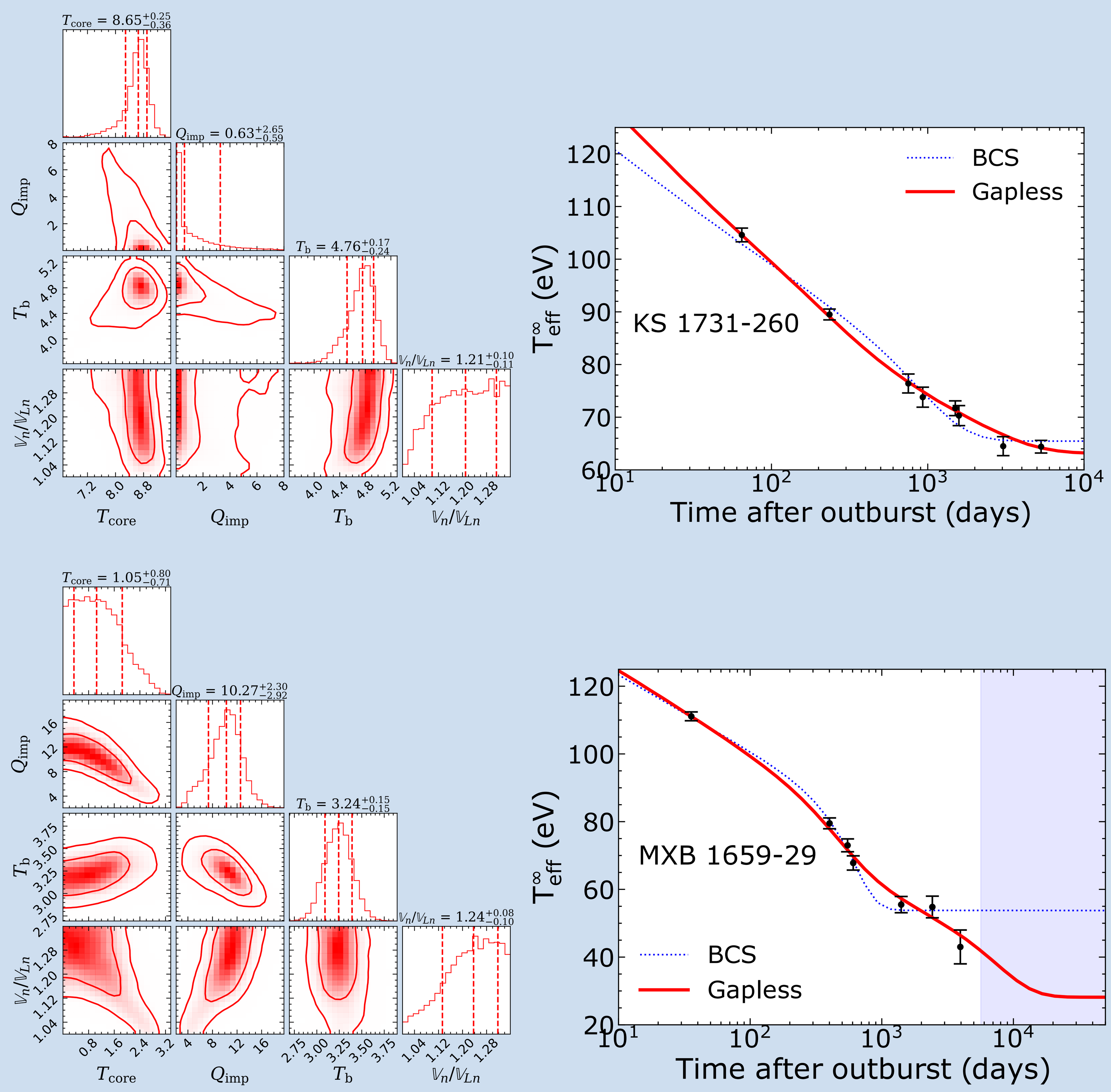
The thermal relaxation time during quiescence scales like $\tau_{\rm th} \propto C_V/\kappa$, where κ is the thermal conductivity of the crust (mainly due to electrons) and C_V is the specific heat (due to electrons, ions, and free neutrons).



- In the BCS phase assumed so far, the neutron contribution to C_V is negligibly small due to the existence of a pairing gap.
- However, the superfluid can become gapless in the presence of superflow [7], as evidenced by glitches [8]. In this case, neutrons give the main contribution to C_V thus delaying the thermal relaxation of the crust, as observed!

Cooling of MXB 1659-29 & KS 1731-260

We have revisited the cooling of transiently accreting neutron stars taking into account gapless superfluidity with realistic $T_{cn}^{(0)}$. Simulations were carried out based on the CRUSTCOOL code [9, 10]:



Conclusion

We have shown that gapless superfluidity can reconcile observations of quasipersistent soft X-ray transients with neutron-matter calculations. Our predictions could be tested by further observations.

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Acknowledgments

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