Neutron star cooling with microscopic equations of state

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Collaboration with F. Burgio and H.-J. Schulze.

J.-B Wei, G. F. Burgio, and H.-J.Schulze, MNRAS **484**,(2019)

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Outline

- Cooling Processes
- EOS
- Results
- Conclusion

Neutron star cooling

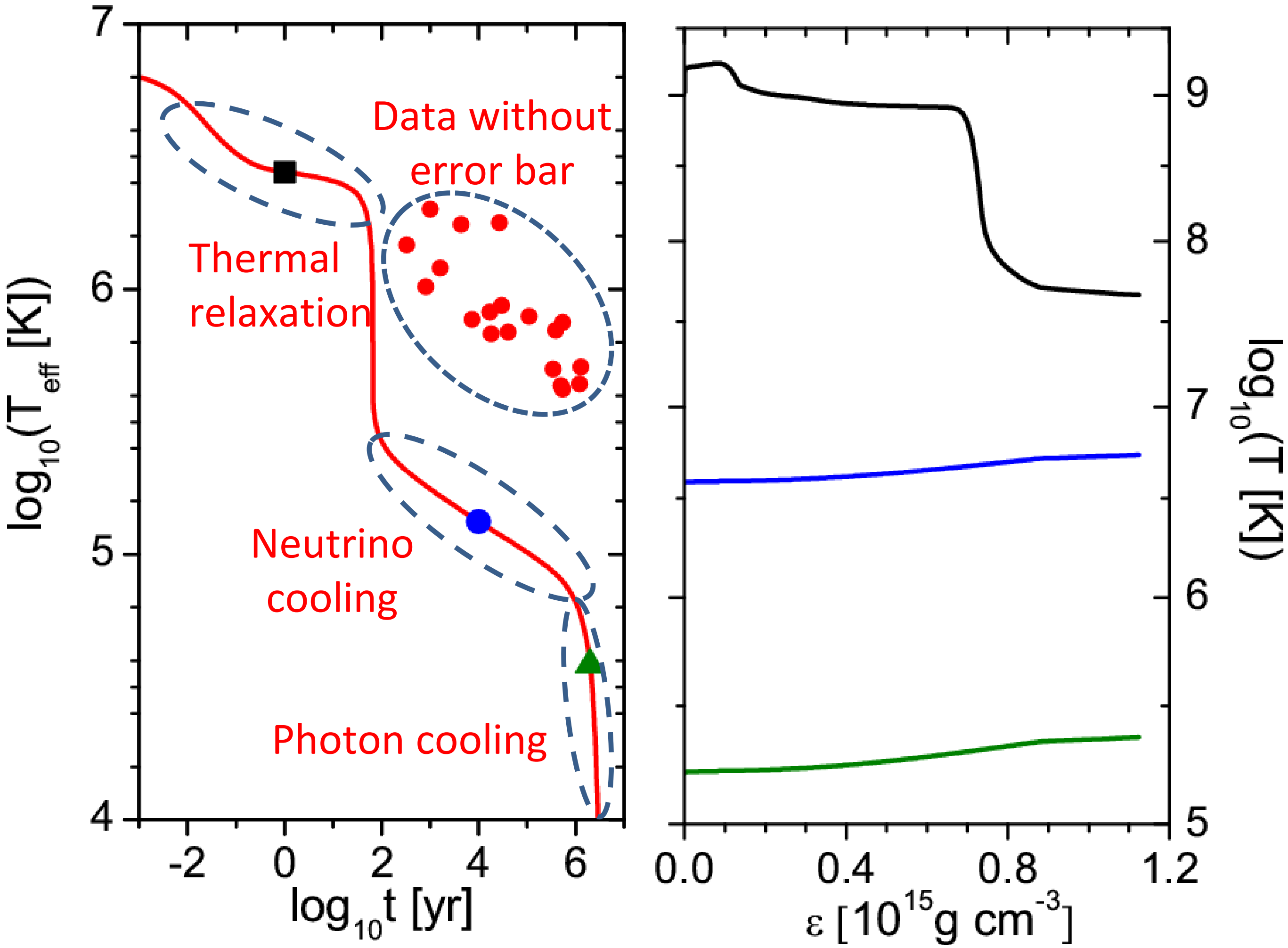
Cooling Processes

EOS

Results

Conclusion

- Standard cooling of a Neutron star



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Cooling equations

$$\begin{cases} \dfrac{d(Le^{2\Phi})}{dt} = \dfrac{4\pi r^2 e^{\Phi}}{\sqrt{1-2Gm/c^2 r}}\left(c_V \dfrac{dT}{dt} + e^{\Phi} Q_\nu\right) & \text{Energy balance} \\ \dfrac{d(Te^{\Phi})}{dr} = -\dfrac{1}{\lambda}\dfrac{Le^{\Phi}}{4\pi r^2\sqrt{1-2Gm/c^2 r}} & \text{Energy transport} \end{cases}$$

cv : specific heat capacity λ: thermal conductivity

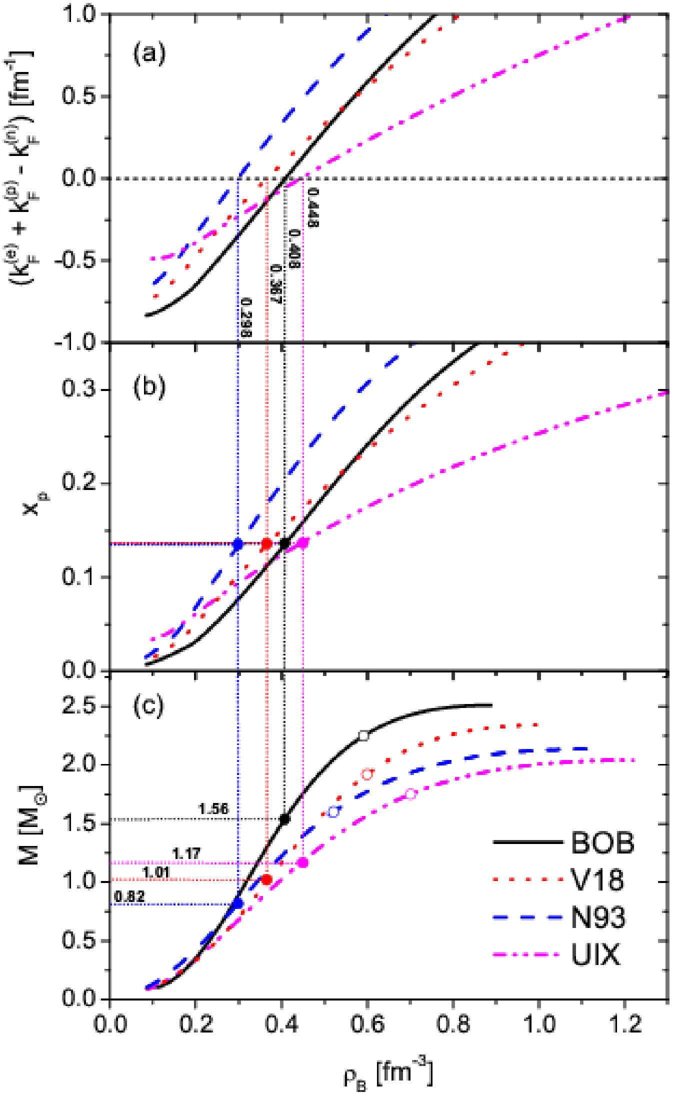
Qν: neutrino emission rate

Modified Urca cycle (neutron branch)	$n+n \to n+p+e^- + \bar{\nu}_e$ $n+p+e^- \to n+n+\nu_e$	$\sim 2\times 10^{21}\, R\, T_9^8$	Slow
Modified Urca cycle (proton branch)	$p+n \to p+p+e^- + \bar{\nu}_e$ $p+p+e^- \to p+n+\nu_e$	$\sim 10^{21}\, R\, T_9^8$	Slow
Bremsstrahlung	$n+n \to n+n+\nu+\bar{\nu}$ $n+p \to n+p+\nu+\bar{\nu}$ $p+p \to p+p+\nu+\bar{\nu}$	$\sim 10^{19}\, R\, T_9^8$	Slow
Direct Urca cycle	$n \to p+e^- + \bar{\nu}_e$ $p+e^- \to n+\nu_e$	$\sim 10^{27}\, R\, T_9^6$	Fast

D. Page, et al, Nuclear Physics A 777 (2006) 497–530

Direct Urca process

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



- **EOS:** within the Brueckner–Hartree–Fock (BHF) approach.
  - BOB: Bonn B + microscopic TBF
  - V18: Argonne V18 + microscopic TBF
  - N93: Nijmegen N93 +microscopic TBF
  - UIX : Argonne V18 + phenomenological TBF
- The Direct Urca starts early except EOS BOB.

EOS	x_{DU}	ρ_{DU}	M_{DU}	M_{max}
BOB	0.1357	0.41	1.56	2.51
V18	0.1348	0.37	1.01	2.34
N93	0.1331	0.3	0.82	2.13
UIX	0.1363	0.45	1.17	2.04

Cooling Curves (done with public code by Dany. Page)

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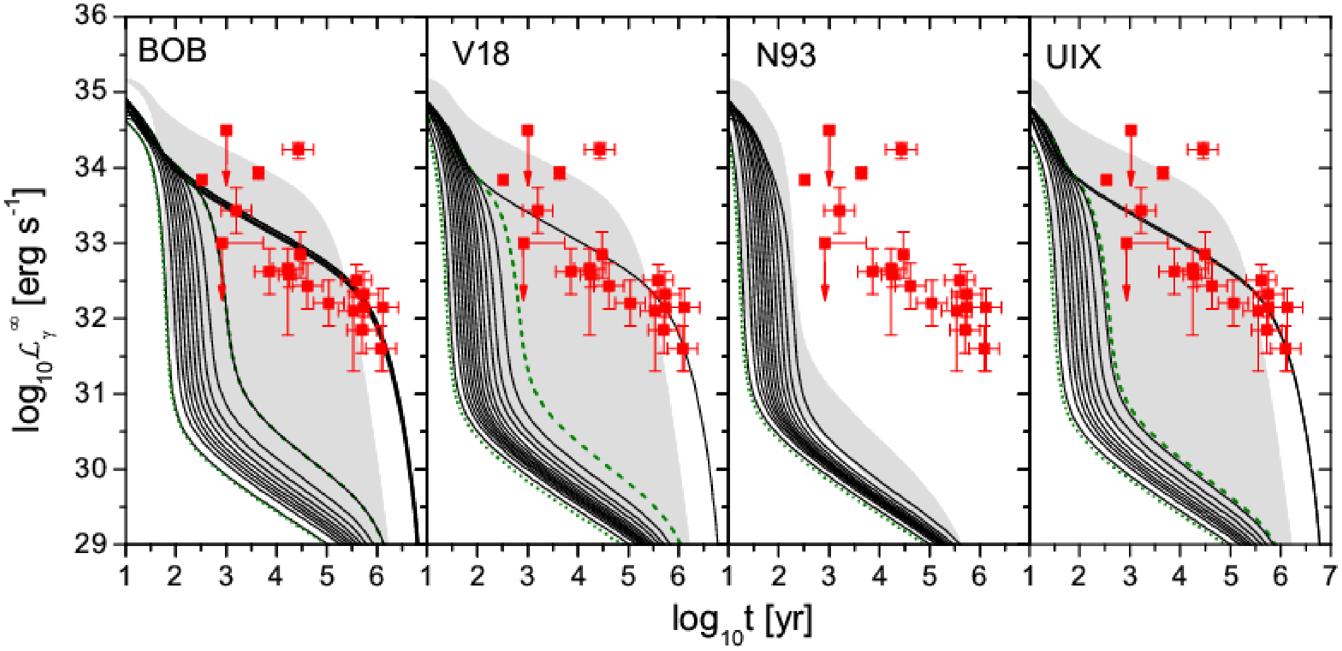
M =1.0, 1.1, …, Mmax



➢ No superfluidity:

1. If DU is active (xp ≳ 13%), it dominates all other processes
2. Too fast cooling of most NS

Superfluidity

Superfluidity

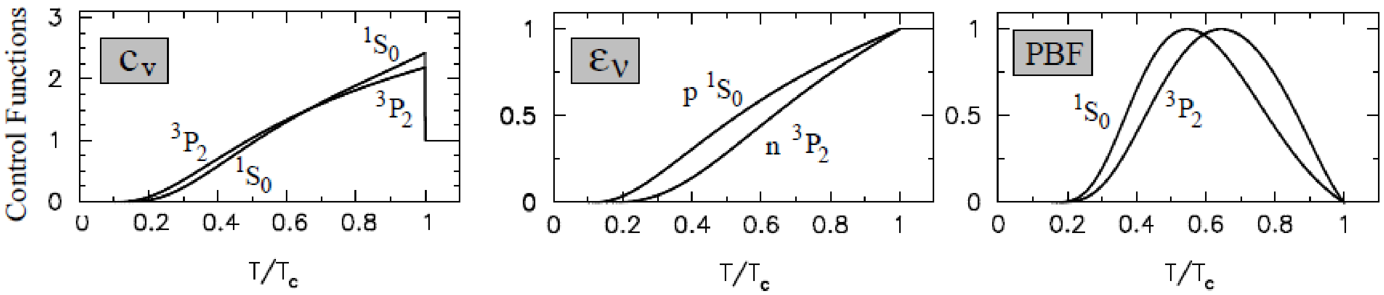
1. Damping of DU,MU,BNN reactions and specific heat.

$$c_V(T) \longrightarrow c_V^{\rm paired}(T) = R_c(T/T_c) \times c_V^{\rm normal}(T)\,,$$

$$\epsilon_\nu(T) \longrightarrow \epsilon_\nu^{\rm paired}(T) = R_\nu(T/T_c) \times \epsilon_\nu^{\rm normal}(T)\,,$$

2. A new cooling process: Pair Breaking and Formation:

$$Q_{PBF} \sim 10^{21}\ RT_9^7$$



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Superfluidity

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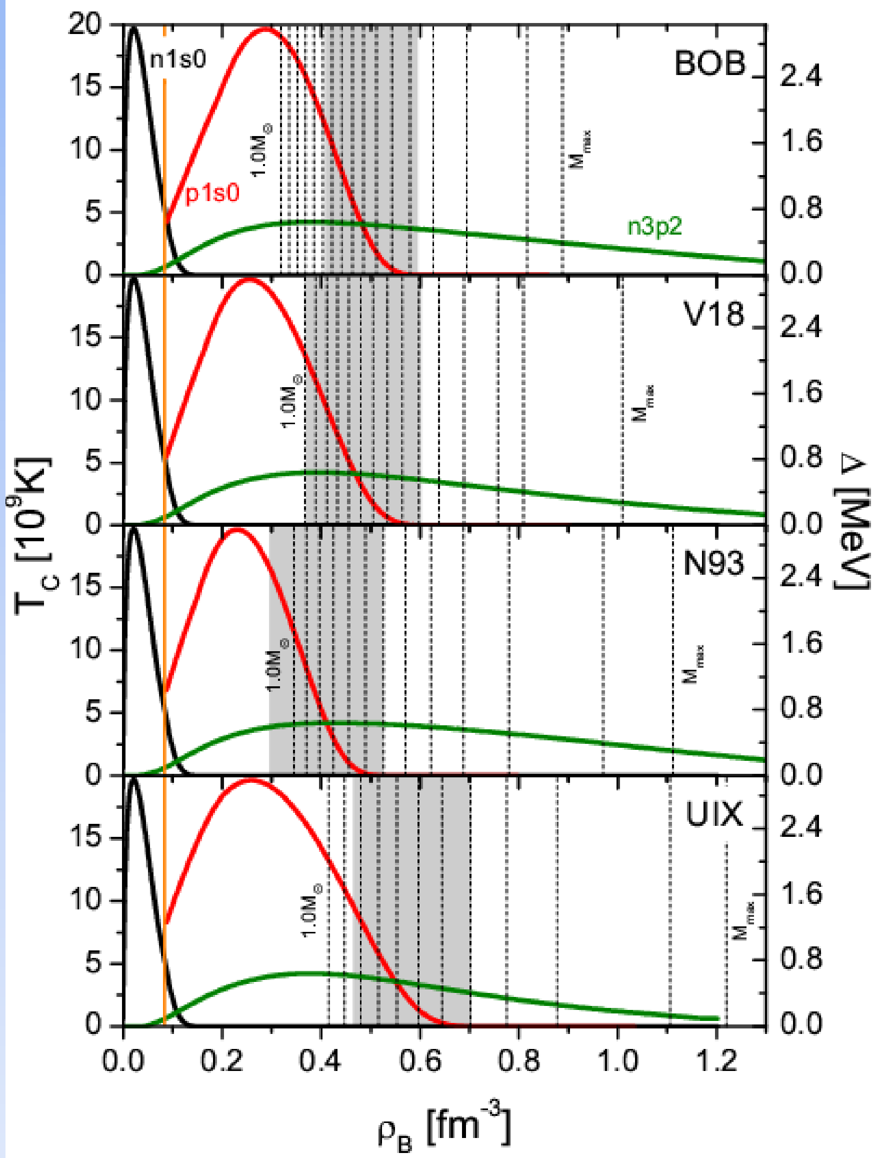


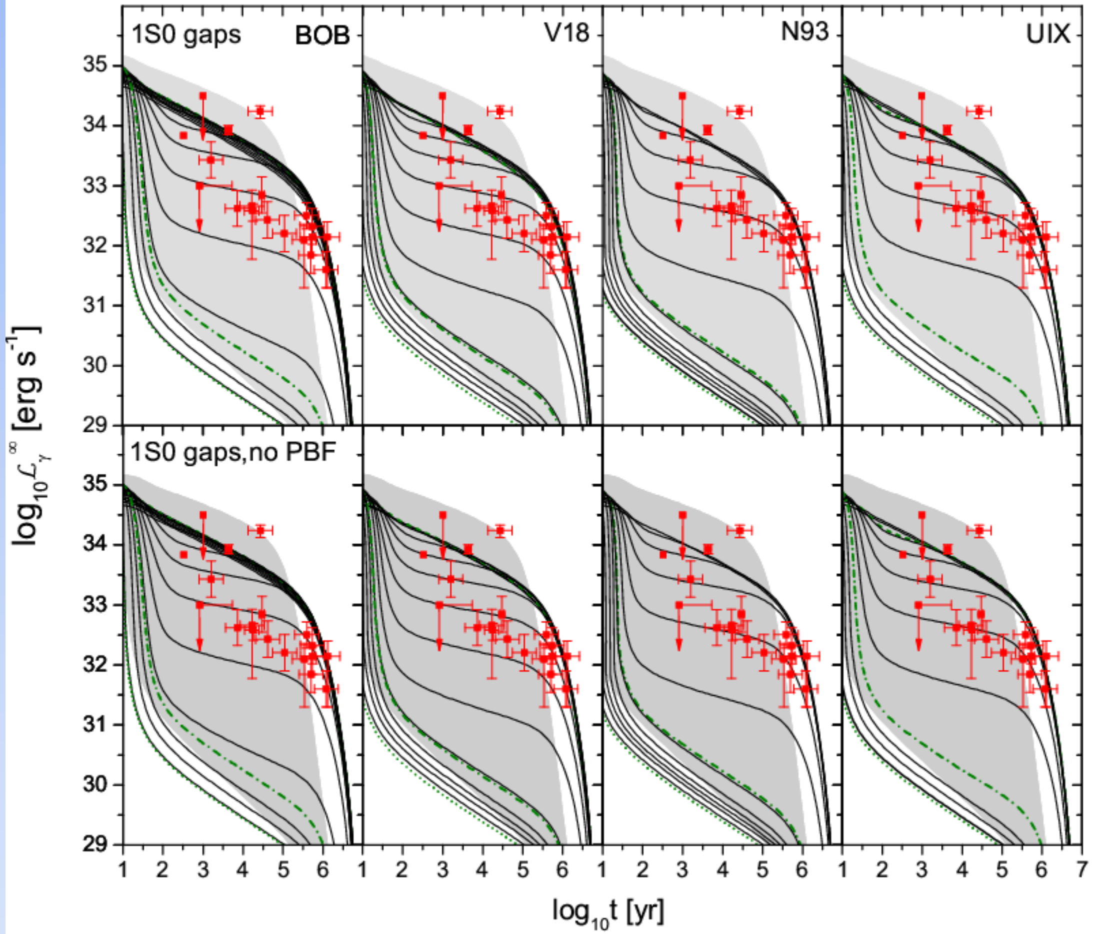
- **Gaps:** Zhou et al, Phys. Rev. C, 70, 048802
  Derived from BHF method with V18 N-N potential.

EOS	ρ_{DU}	ρ_{1S0}	M_{1S0}
BOB	0.41	0.59	2.23
V18	0.37	0.6	1.91
N93	0.3	0.52	1.59
UIX	0.45	0.7	1.7

Cooling Curves

M =1.0, 1.1, …, Mmax

Only 1S0 gap is considered.



- Yes pairing(1S0):

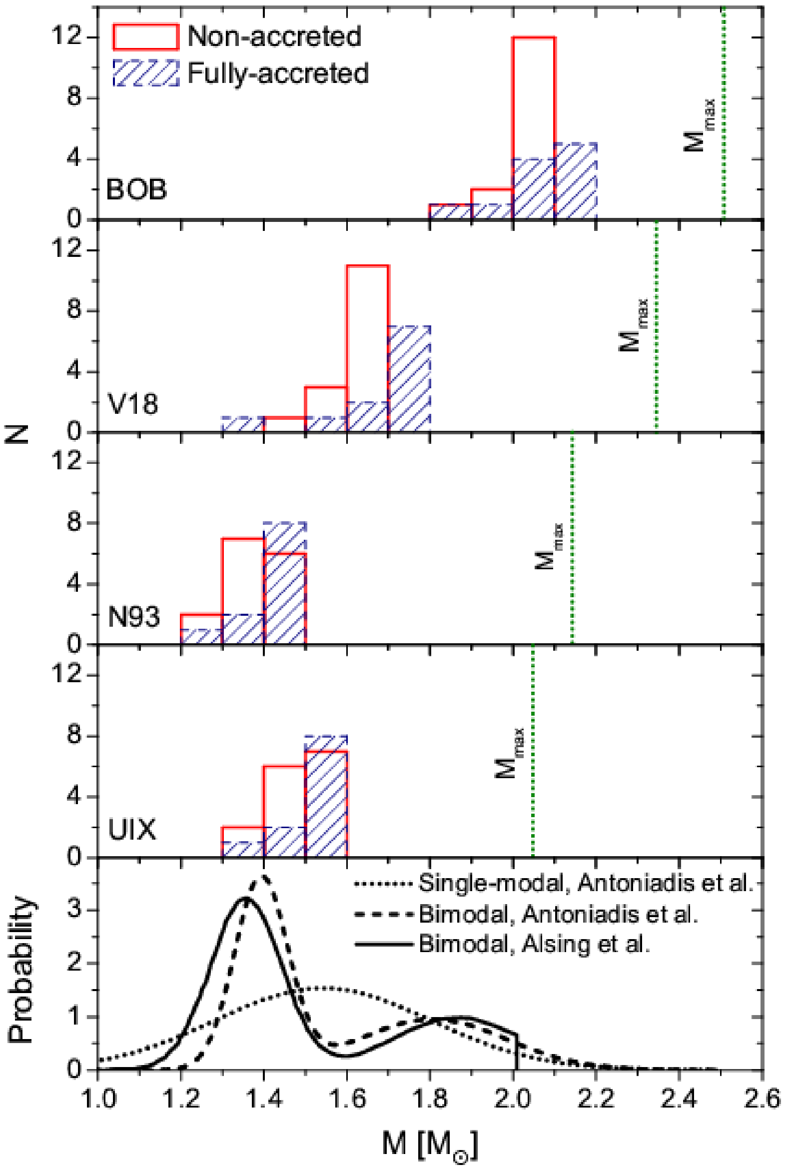
1. the BCS p1S0 gap alone is able to suppress sufficiently the DU cooling.

- No PBF

1. The effect of PBF is not obvious.

Combined with non and fully accreted cases, all data could be described for all microscopic EoSs.

Mass Distribution



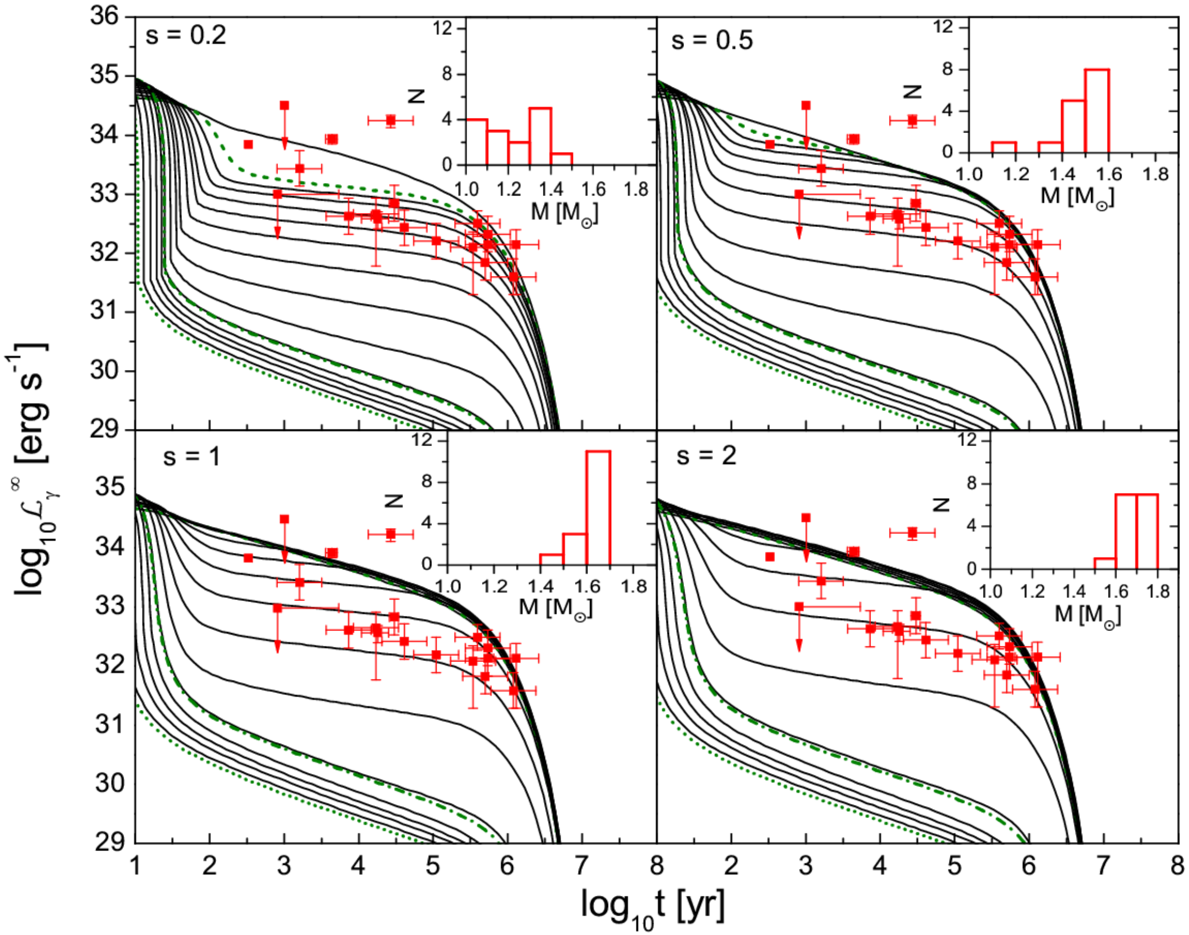
- ➢ The mass distribution of cooling data extracted from the cooling curves.

1. The error bar is disregard
2. Shows a small dependence on envolope model.

- ➢ BOB model is excluded if we assume the mass distribution is similar to overall mass distribution in the Universe.

Mass Distribution

- Dependence on the gap



Scaling factor s: 0.2, 0.5, 1, 2.

The deduced NS mass distributions (shown as insets) depend sensitively on the gap scaling factor.

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NS Cooling with microscopic EOS derived from BHF, and consistent 1S0 BCS gaps are considered.

- All EOSs feature strong DU cooling for a wide range of masses.
- The presence of superfluidity is required for realistic cooling scenarios. With the suppression due to the gaps , all current cooling data for isolated NSs can be achieved with any of the proposed EOSs.
- A naive and straightforward analysis of the deduced NS mass distribution would exclude only the stiffest EOS BOB.

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Thank you!