Cooling Of Neo-Neutron Stars

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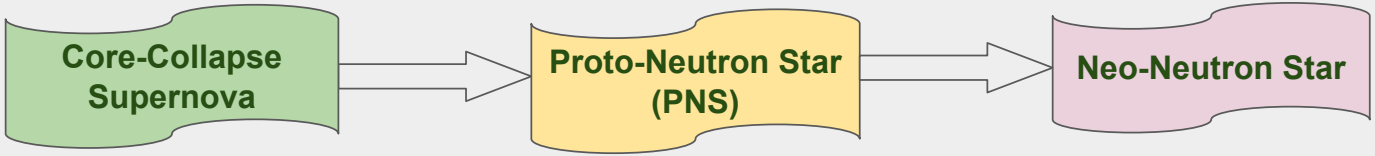
Thematic school GWsNS-2026: Gravitational Waves from Neutron Stars

What is a Neo-NS ?



- Age < 30-60s
- T ~ 10^{11} K
- Opaque to neutrinos
- Core of the star evolves towards zero temperature configuration

- Age ~ 30-60 secs to 1 day
- T ~10^{10} K
- The crust of the star forms

Thermal Evolution Equations :

$$\tilde{L} = -K\ (4\pi r^2)^2\ n\ e^{\phi}\frac{\partial \tilde{T}}{\partial a}$$

Circumferential Radius

Enclosed Baryon Number

$$C_V\ e^{\phi}\ \frac{\partial(\tilde{T}e^{-\phi})}{\partial t} = -(\tilde{Q}_L + \tilde{Q}_\nu + \tilde{Q}_V)$$

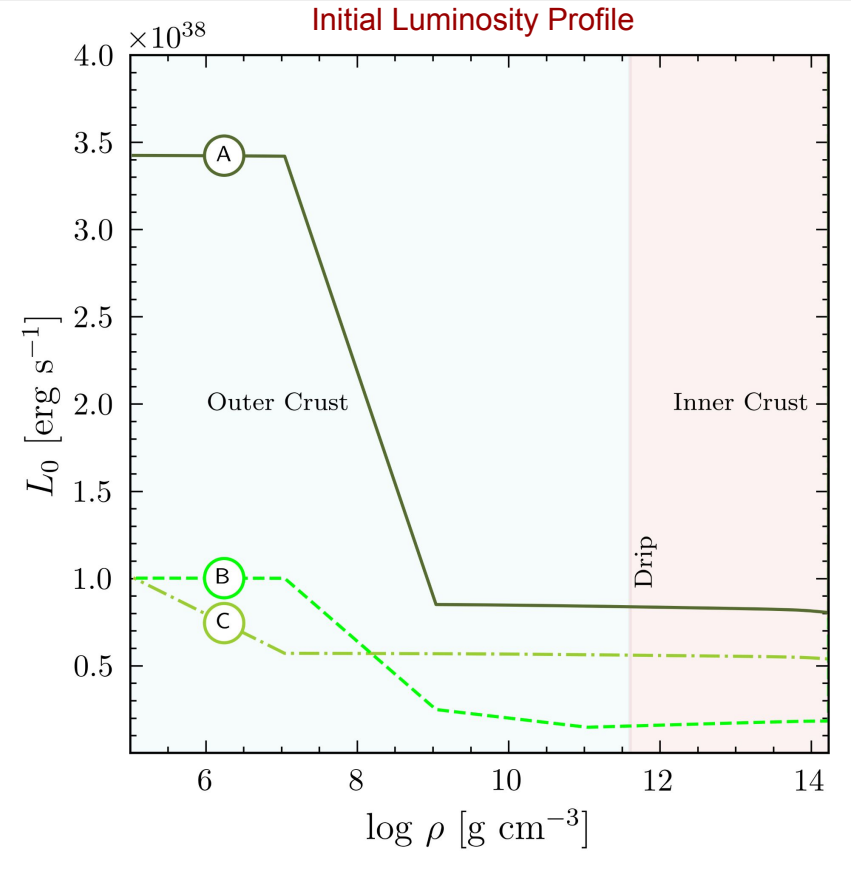
Contraction Energy

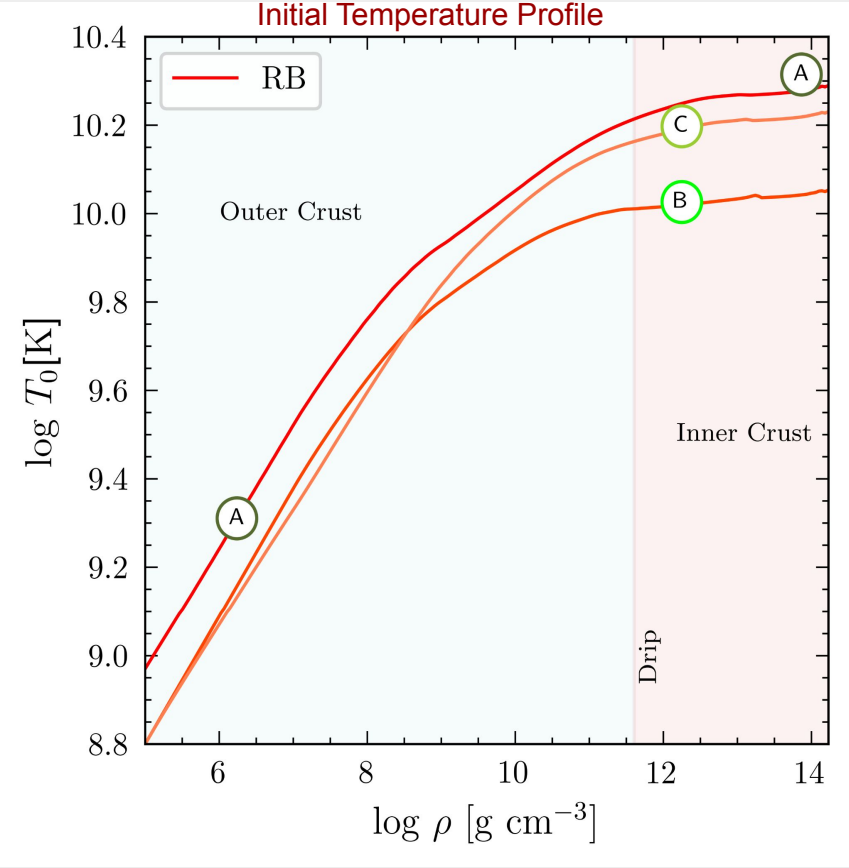
Heat Loss/Gain From Luminosity Gradient

Neutrino Energy Loss

SETUP:

Note: RB EoS refers to RB(BBSk1) EoS [**Beznogov & Raduta** Phys. Rev. C **110**, 035805; **Raduta & Beznogov** *A&A*, **701**, A143 (2025)]



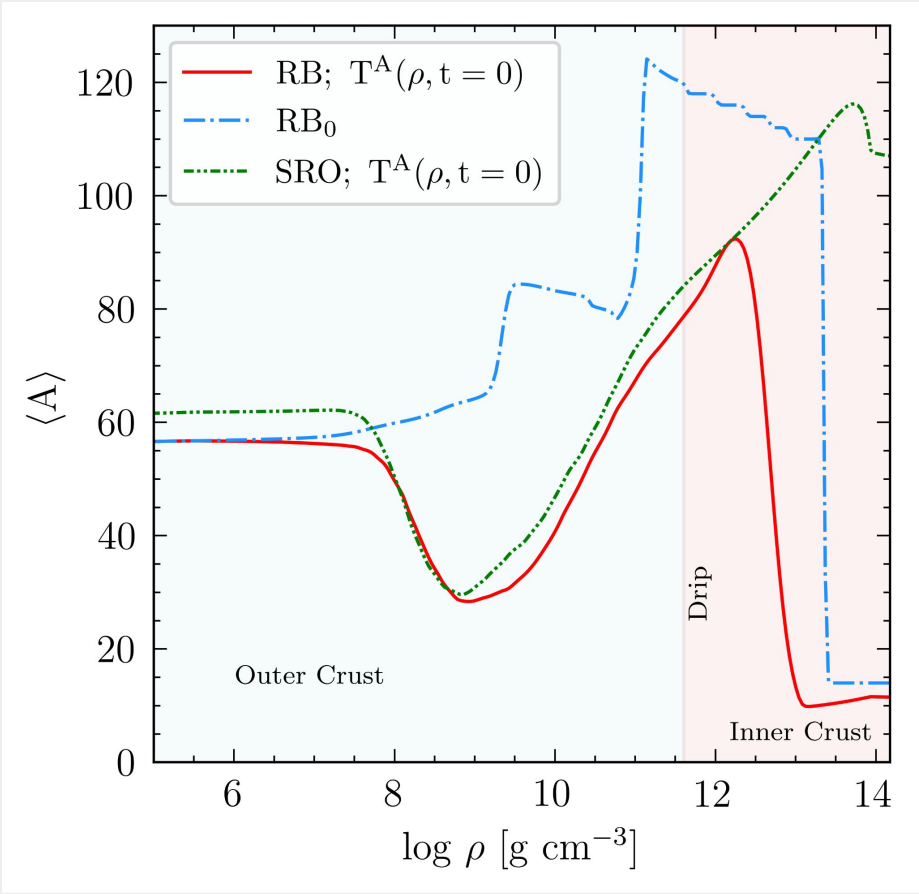


Note: All our results will correspond to a 1.4 solar mass NS unless mentioned explicitly

Temperature Dependent Composition

We analyze three sets of crustal EoSs :

- RB & SRO EoS with **temperature dependent** composition (average A).
- RB_0 **fixed composition at 0.1 MeV (1.16 ✕ 10^9 K)** from the lowest temperature of RB EoS table.
- The star with RB composition will eventually cool down to RB_0 at sufficiently low temperature

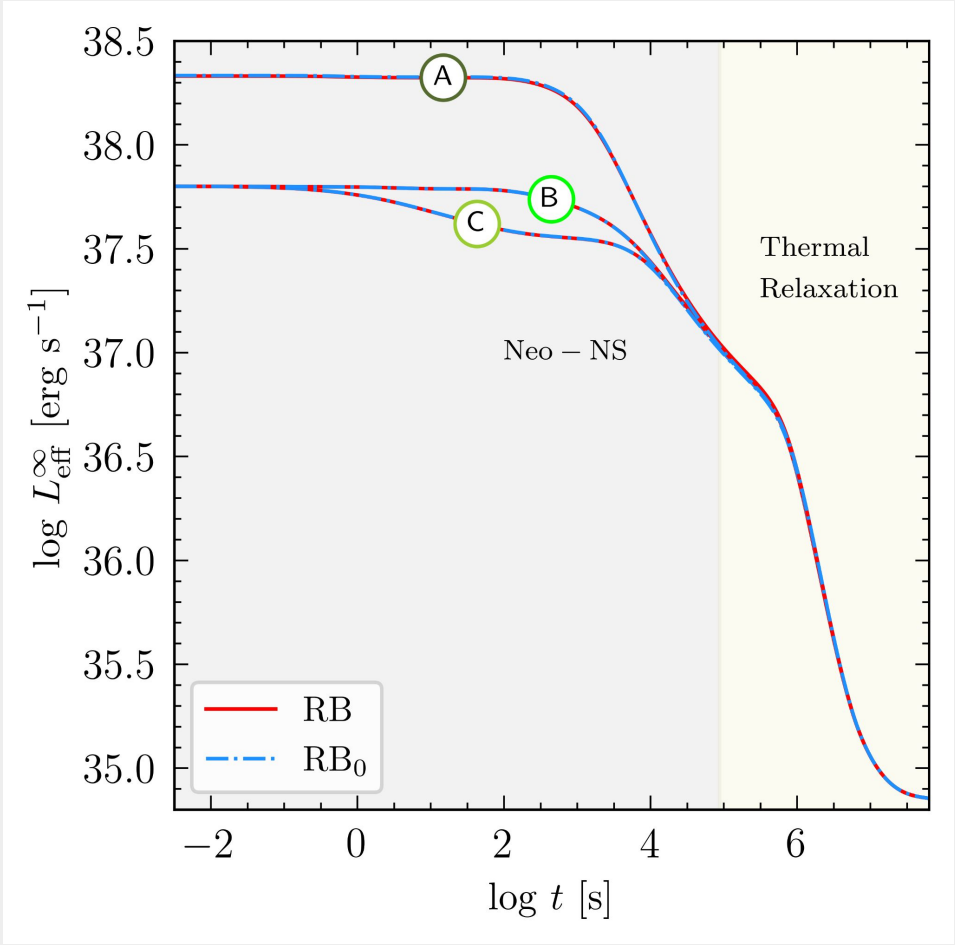


Note: SRO EoS refers to SRO(APR) SNA EoS [**Schneider et al.** Phys. Rev. C **100**, 025803 (2019)]

RESULTS:

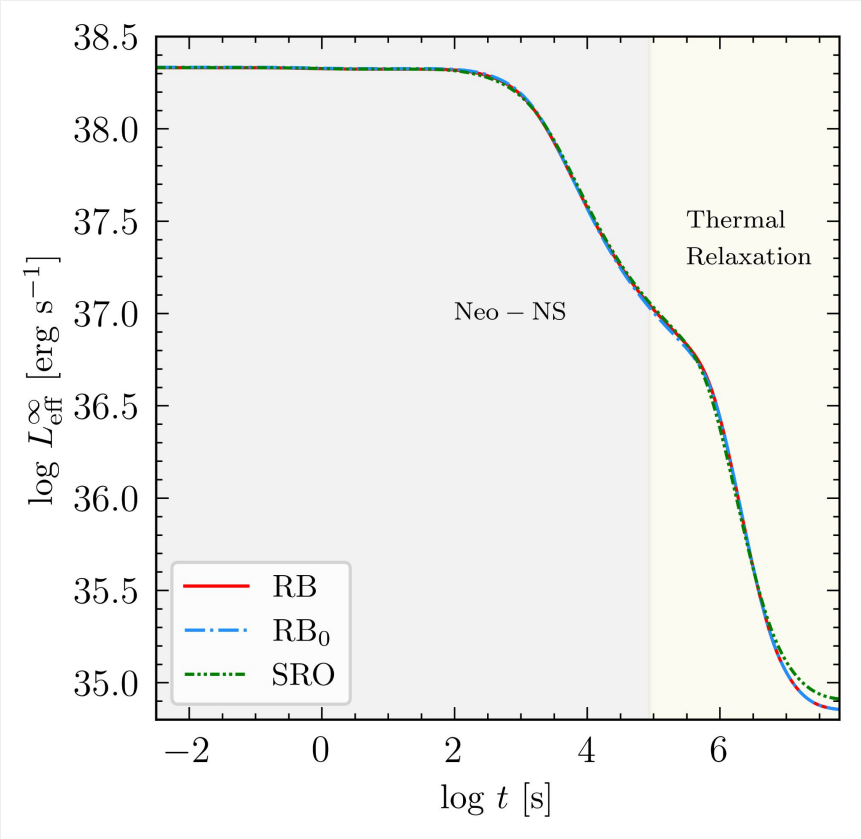
Cooling Curves

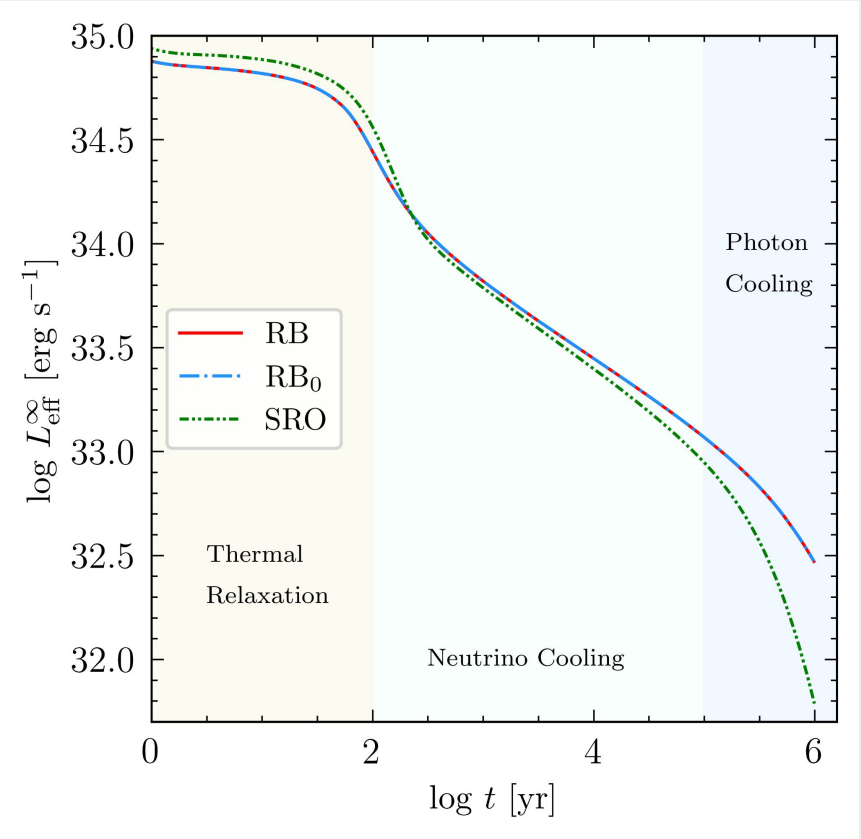
- The Cooling curves for profiles A, B and C are shown here.
- Irrespective of the initial luminosity profile the curves seem



RESULTS:

Comparisons of RB vs SRO

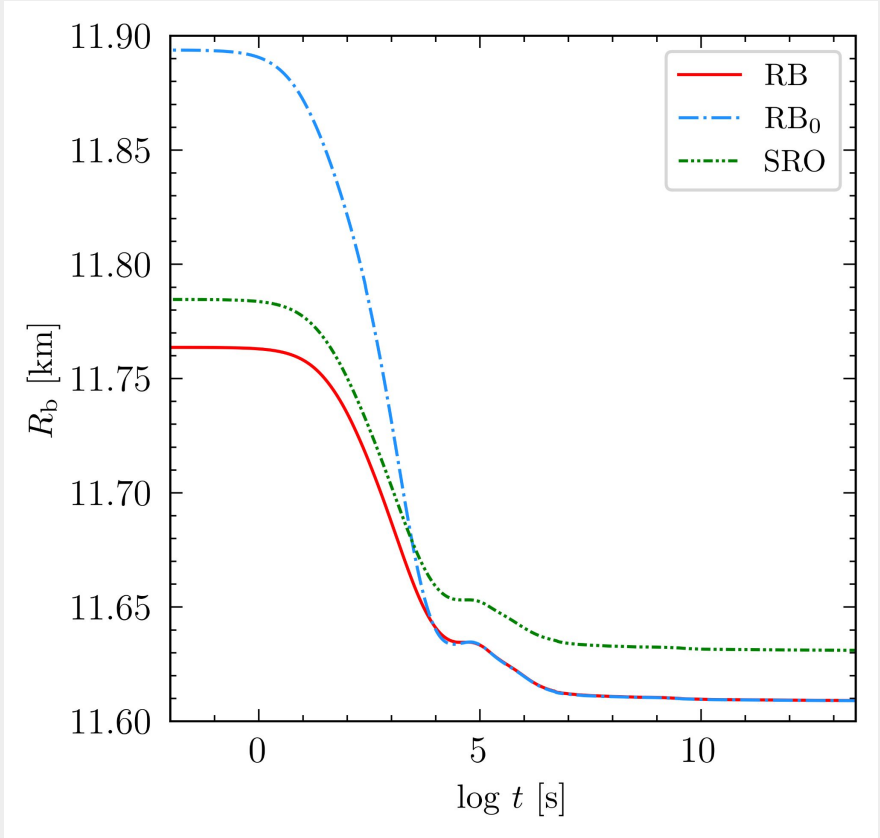




RESULTS:

Mechanical Structure

- The mechanical structure of the stars largely depends upon the composition of the crust.
- The stars with RB and RB_0 attain a final radius which is different to that of SRO.

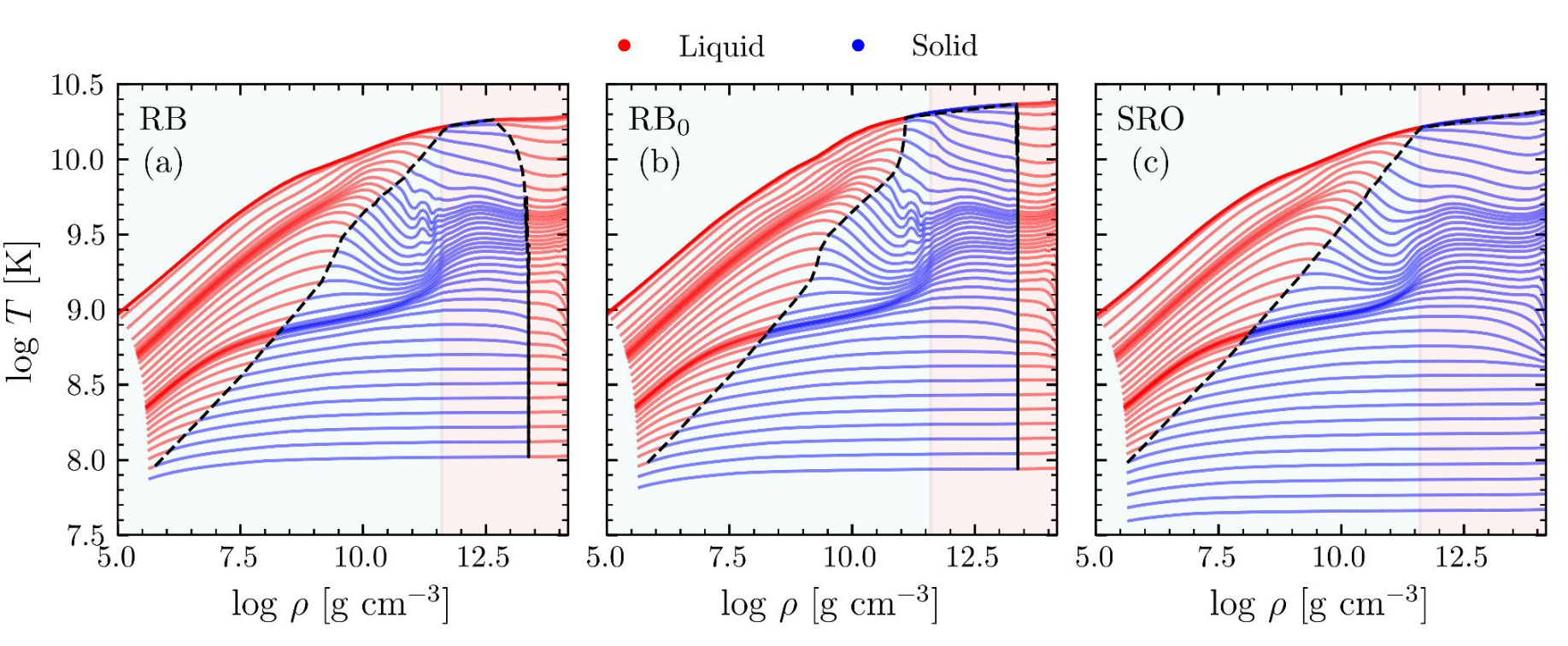


Summary & Conclusions

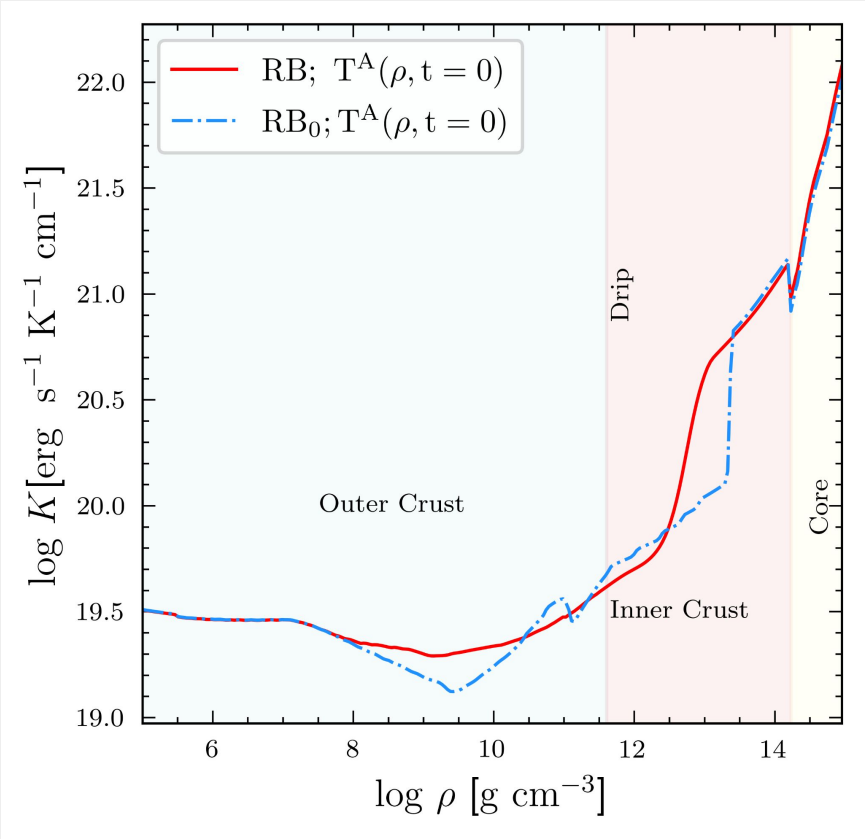
- In this work we study the effects of temperature dependent crust on the cooling curves.
- We study three different crustal compositions - two of them are temperature dependent and one temperature independent.
- For different initial luminosity profiles we study the effects of compositions on these cooling curves.
- The Cooling curves in the neo Neutron Star phase were found to be independent of the composition.
- The presence of lighter nuclei were found to affect the cooling mechanisms at the later stages
- The star was also found to expand a bit as it cooled down, which was a result of the chosen crustal EoS.

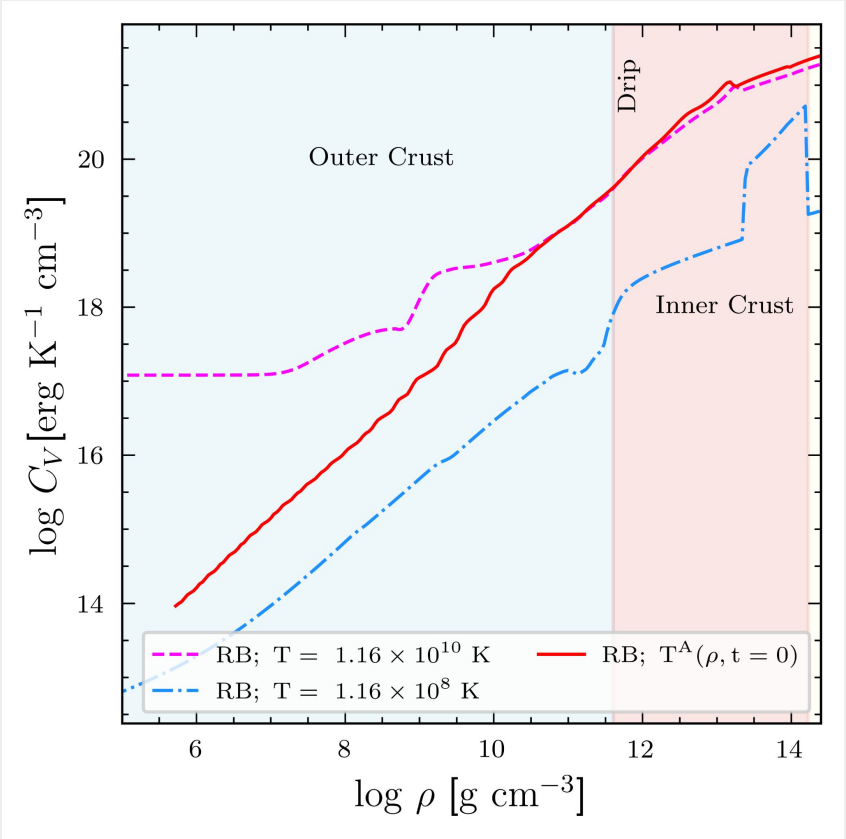
BACKUP SLIDES

RESULTS:


Liquid
Solid
RB
(a)
RB$_0$
(b)
SRO
(c)
log T [K]
log ρ [g cm^{-3}]
10.5
10.0
9.5
9.0
8.5
8.0
7.5
5.0
7.5
10.0
12.5

SETUP:

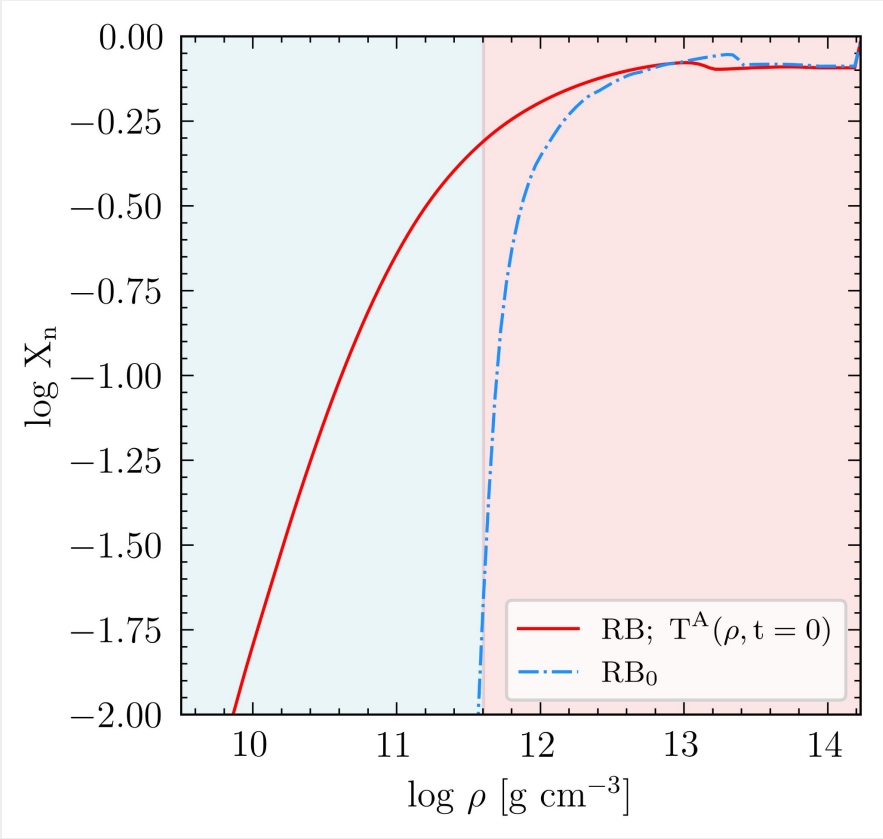

RB; $T^A(\rho, t = 0)$
$RB_0; T^A(\rho, t = 0)$
Outer Crust
Drip
Inner Crust
Core
log K[erg s^{-1} K^{-1} cm^{-1}]
log ρ [g cm^{-3}]
22.0
21.5
21.0
20.5
20.0
19.5
19.0
6
8
10
12
14


Outer Crust
Drip
Inner Crust
RB; T = 1.16×10^{10} K
RB; T = 1.16×10^{8} K
RB; $T^A(\rho, t = 0)$
log C_V[erg K^{-1} cm^{-3}]
log ρ [g cm^{-3}]
20
18
16
14
6
8
10
12
14

RESULTS:

Free Neutron Fraction

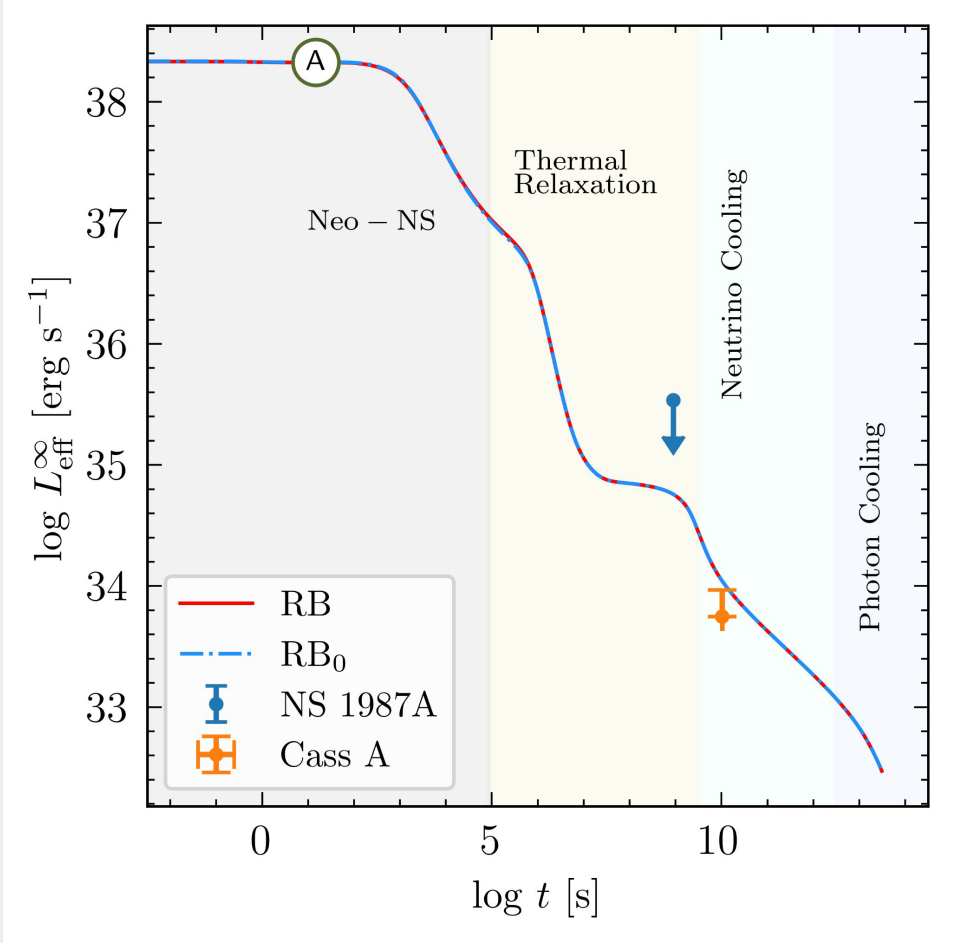
- The red curve evolves over time as the star cools down.
- The fraction of free neutrons changes with time.



RESULTS:

Cooling Curves

- The Cooling curves for initial Luminosity profile A is shown here.
- The Cooling curves show no dependence on the composition of the crust.



Superfluid Neutrons ??

- The presence of Superfluid neutrons were found to affect the internal temperature of the star.
- We do not see any change in the cooling curves at early stages as it has no impact on the surface temperature.