^{63}Fe-^{63}Mn: A Possible Strong Urca Pair and Its Potential Astrophysical Impact

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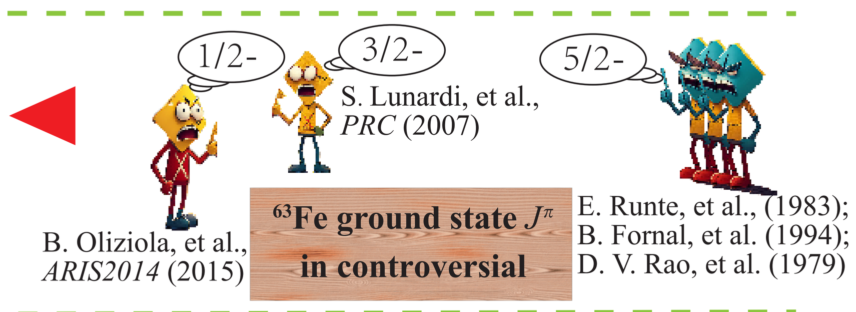
Introduction

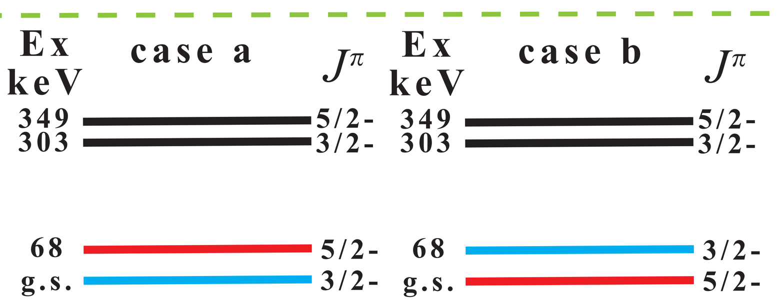
What is Urca Cooling?

Urca process, a cycle of electron captute and β^- decay , serves as an essential crust cooling mechanism in quiescent acctetion neutron stars, dominating neutrino cooling and balancing the heating at moderate temperatures. The Urca process in an accretion neutron star could alter our understanding of the observed cooling light curve, which provides insights into the outer layer structure of a neutron star.

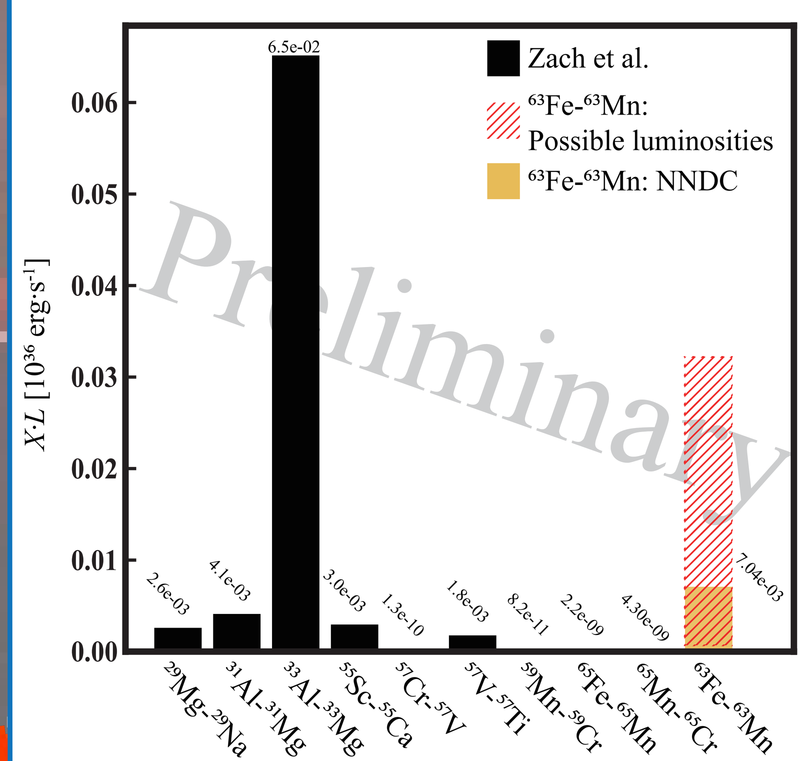
Why is ^{63}Fe-^{63}Mn?

- The ground state J^π value of ^{63}Fe remains controversial.
- A Large mass fraction in neutron star crust

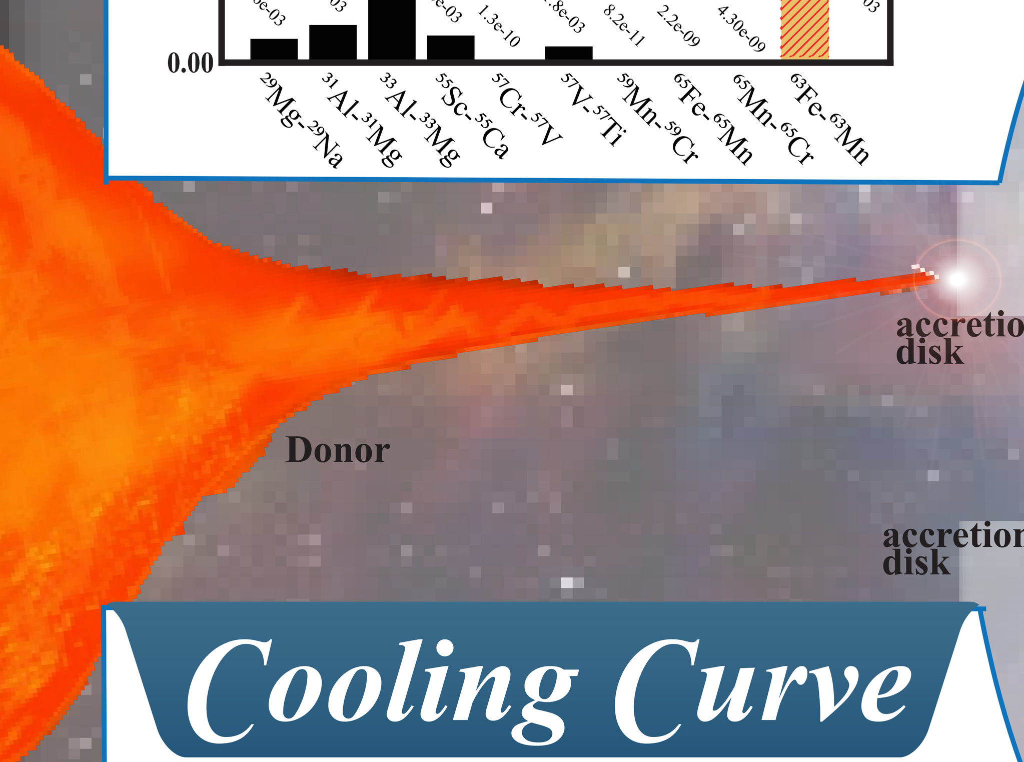


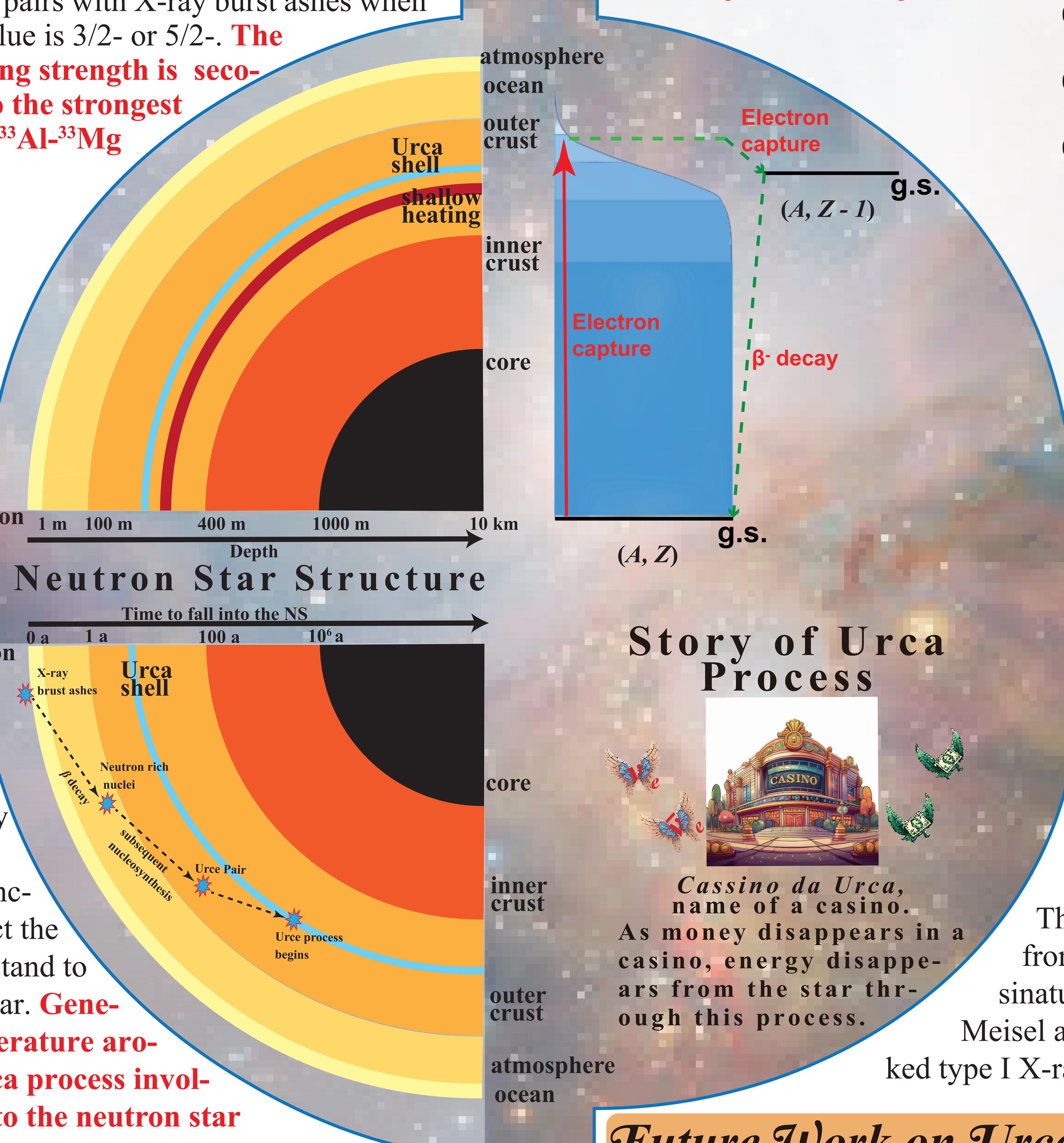


- Shell model calculation predicted the ^{63}Fe structure as shown in case a.
- Case b inverses the low lying state (red state) with the ground state and recalculate the cooling strength.



^{63}Fe-^{63}Mn could be among the strongest Urca pairs with X-ray burst ashes when J^π value is 3/2- or 5/2-. **The cooling strength is second to the strongest pair ^{33}Al-^{33}Mg only.**





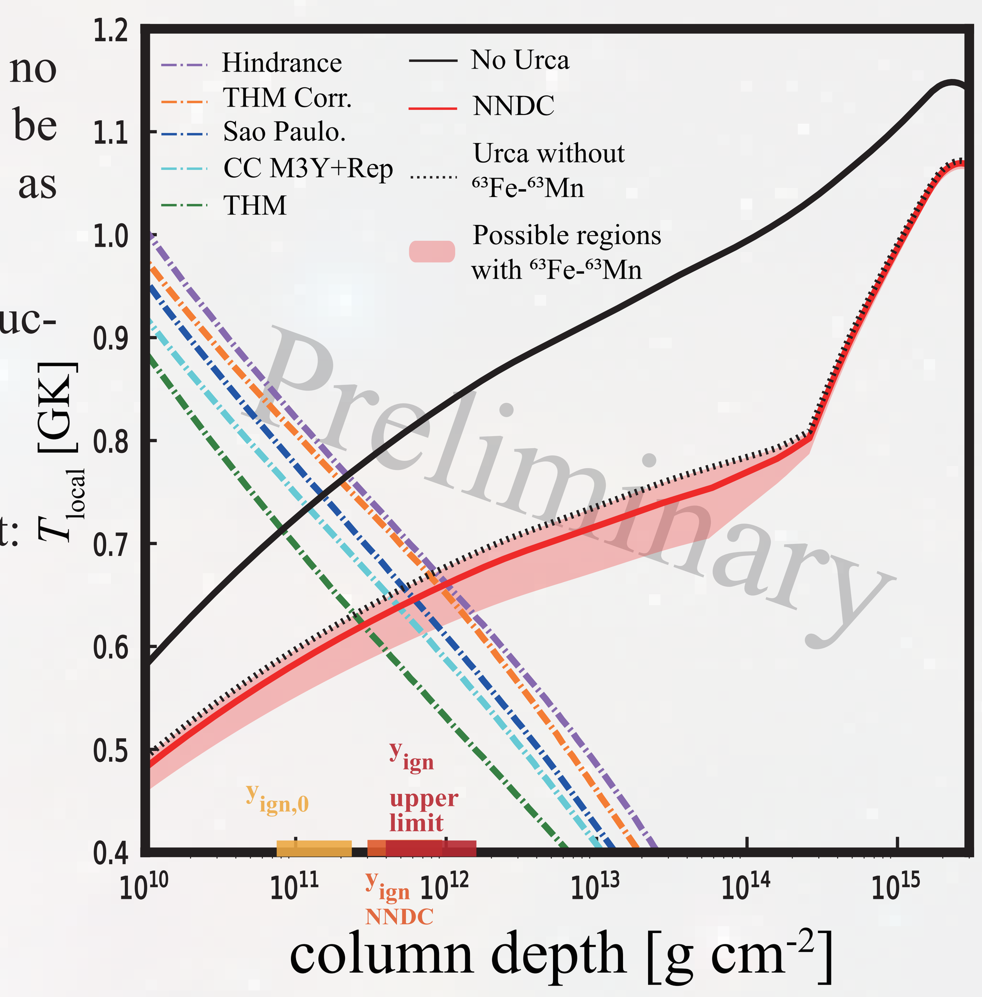
Cassino da Urca, name of a casino. As money disappears in a casino, energy disappears from the star through this process.

Superburst Ingnition

X-ray superbursts are thought to be energetic explosions ignitied by carbon fusion in the accreted neutron star ocean. The uncertainty in the carbon fusion reaction rate makes it difficult to determine the ignition depth of superbursts. In this work, we find that the impact of the Urca process on the ignition depth of superbursts can be comparable to the impact of the uncertainty in the carbon-carbon fusion reaction rate. **Urca process lowers the steady-state temperature and makes superbursts ignition deeper.**

A Deeper Superburst Ignition

- Superburst ignition depth in no Urca scenario is predicted to be 0.5-1.7 $\times 10^{11}$ g/cm², marking as $y_{ign,0}$.
- Ignition depth with nuclear structure from NNDC: $y_{ign} \sim$ 3.4-4.7 $y_{ign,0}$;
- Ignition depth with upper limit: $y_{ign} \sim$ 5.4-7.7 $y_{ign,0}$;



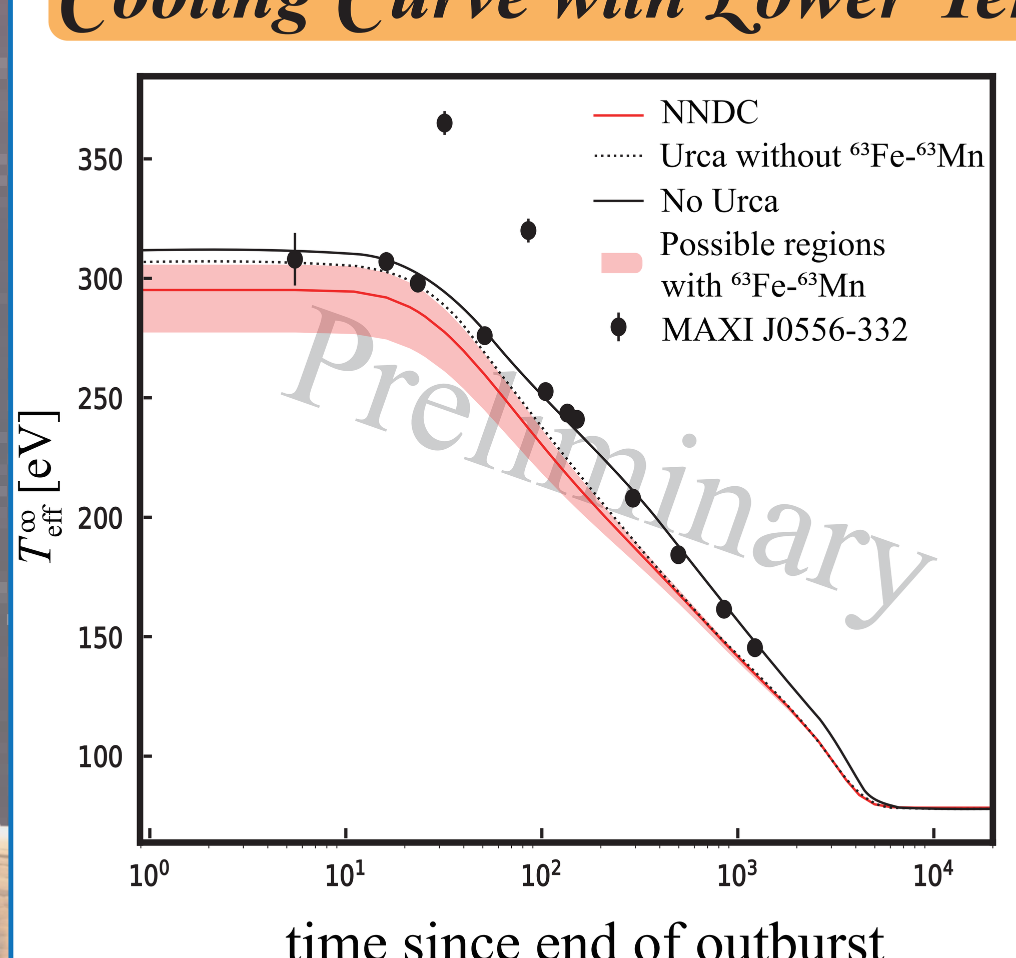
Neutron star parameters

- Neutron star mass: $M = 1.4\ M_\odot$
- Radius: $R = 10$ km
- Core temperature: $T_{core} = 10^7$ K
- Parameters are the same as those used in the pervious unstable carbon ignition study by Deibel et al.

Cooling Curve

The cooling light curve revals successively deeper layers with time and provides clues to the thermal and compositional profile as a function of depth. Urca process significantly affect the cooling light curve, which will help to understand to the inner structure of the a accretion neutrn star. **Generally, Urca process lowers the outlayer teperature around the Urca shell. Our study suggests Urca process involving ^{63}Fe–^{63}Mn extends the cooling region to the neutron star ocean.**

Cooling Curve with Lower Temperature



Neutron star parameters

- Neutron star mass: $M = 1.5\ M_\odot$
- Radius: $R = 11$ km
- Core temperature: $T_{core} = 10^8$ K
- Shallow heating : $Q_{shallow} = 6$ MeV
- Accretion rate: $\dot{M} = \dot{M}_{Edd} \equiv 2\times10^{-8}\ M_\odot\ yr^{-1}$
- Parameters are the same as those used in the early study on MAXI J0556-332

- Urca process generally lowers the cooling curve around hundreds days after the end of outburst.
- Cooling is enhanced by ^{63}Fe–^{63}Mn, espencially in the early outburst days. (co-process between ^{63}Fe–^{63}Mn pair and shallow heating?)
- MAXI J0556-332 lacked X-ray burst in the past due to lacking the cooling signature.

Discussion

Lacking X-ray Burst

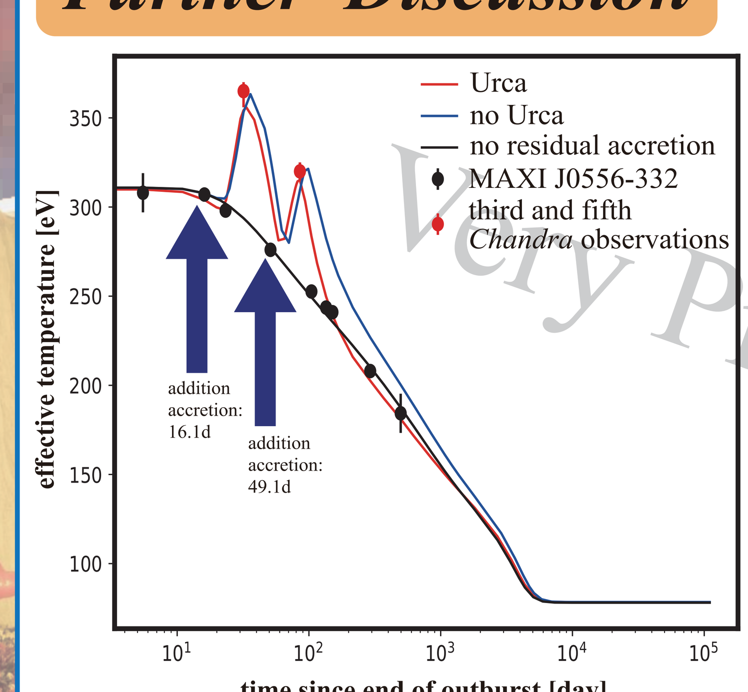
The cooing curve with Urca process deviates from the observation. The Lacking of cooling sinatures supports the conclusion made by Zach Meisel and Alex Deibel that MAXI J0556-332 lacked type I X-ray bursts and superbursts $\gtrsim$ 120 years ago.

Future Work on Urca

Observations: As the Urca cooling signature has not yet been observed, the discovery of more cooling transients with a hot crust like MAXI J0556-332 would provide additional tests for the presence of Urca cooling in the accreted crust.

Experiments: Future experiments, such as laser spectroscopy of ^{63}Fe or precise measurement of the β^- decay branching ratios of ^{63}Mn, could better determine the ground state J^π of ^{63}Fe and transition strength between the ground states of ^{63}Fe and ^{63}Mn , respectively. These determinations are essential for generating a precise cooling strength of the ^{63}Fe-^{63}Mn pair.

Further Discussion



Ignored observations: The third and fifth *Chandra* observations (red) are often ignored in early studies on MAXI J0556-332. Does including these anomalies better reproduce the observations?

TO BE DISCUSSDE • • •

Reference

[1] H. Schatz, S. Gupta, et al. Strong neutrino cooling by cycles of electron capture and decay in neutron star crusts, Nature 505, 7481 (2014).
[2] Z. Meisel and A. Deibel, Constraints on bygone nucleosynthesis of accreting neutron stars, The Astrophysical Journal 837, 73 (2017).
[3] J. Homan, J. K. Fridriksson, et al, A strongly heated neutron star in the transient z source maxi j0556–332, The Astrophysical Journal 795, 131 (2014).

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