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Light Hyperclusters in Warm Stellar Matter

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Abstract

Light nuclei can be found in core-collapse supernova matter and in binary star mergers. Their presence may impact the evolution of these systems. The presence of strange degrees of freedom such as hyperons and hyperclusters studied here may as well impact the composition of these systems at temperatures as high as $T \sim 50 - 100$ MeV achieved in both supernova and binary systems.

Introduction

Light nuclei and **hypernuclei** have been detected in several Heavy-Ion Collisions experiments (e.g. Alice, STAR, J-Parc). It is still not quite understood how these nuclei survive up to temperatures of the order $T = 150$ MeV, much larger than their binding energies.

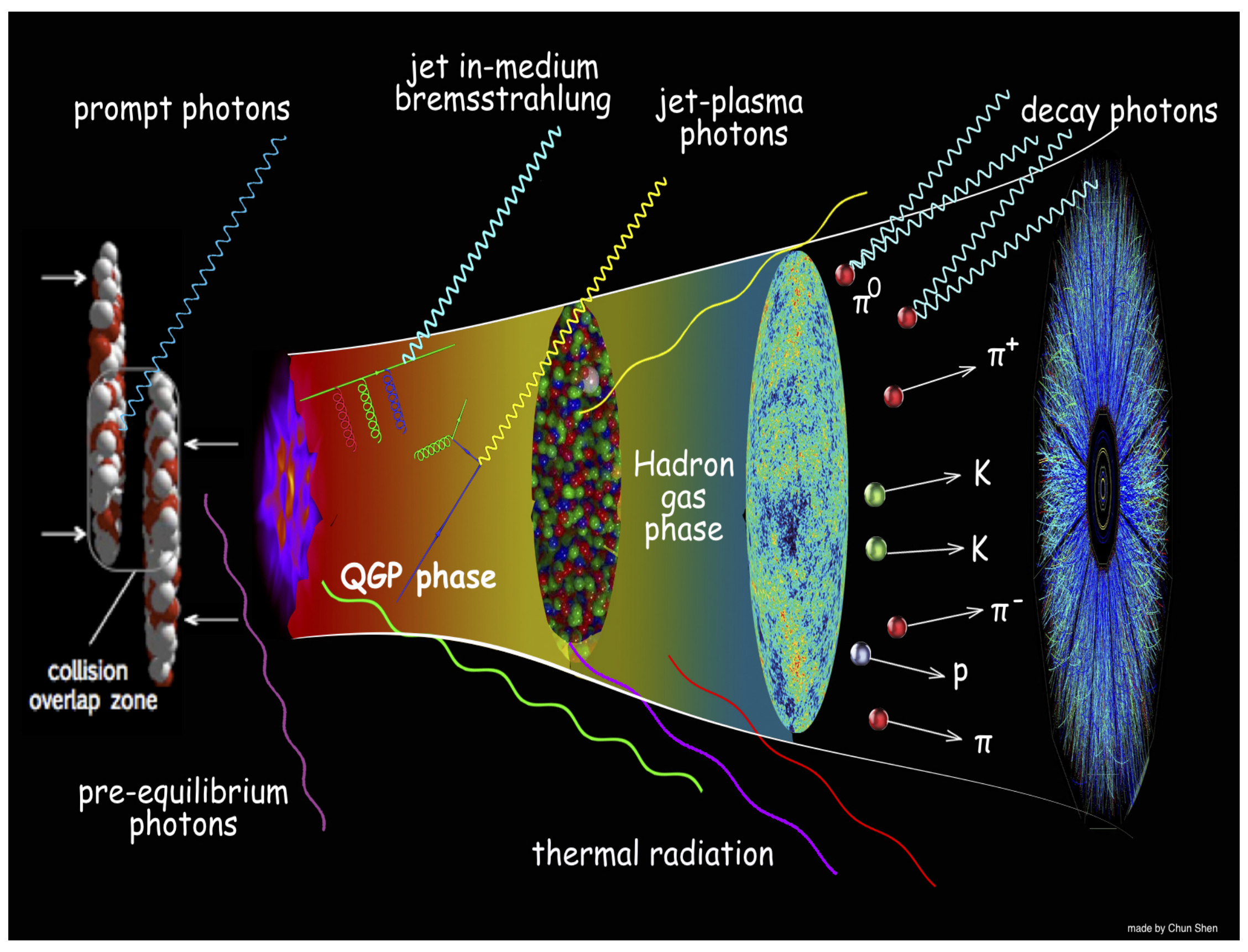

Figure 1: Heavy Ion Collision Scheme. **Credits:** Chun Shen & Ulrich Heinz

Light Nuclei can also be found in **Core-Collapse Supernova** matter and in **binary Neutron Star mergers**.

In **Core-Collapse Supernovae**, the presence of light clusters affects the rate of weak interactions during the collapse [1, 2].

In **binary neutron star mergers**, light clusters influences the dissolution of the remnant torus of accreted matter [3] and can have an impact in the dissipative processes that determine the post-merger evolution and mass ejection from the remnant [4, 5].

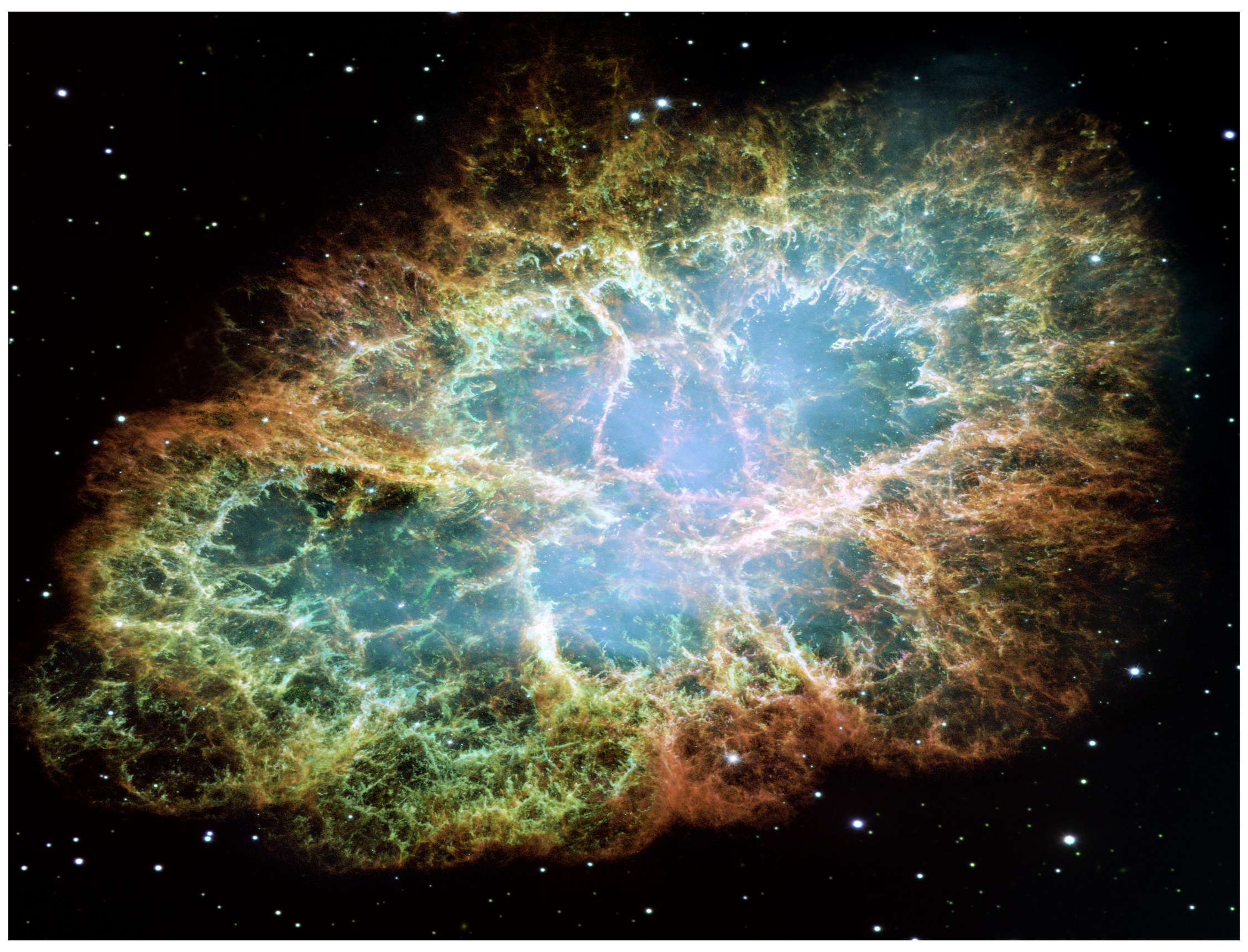

Figure 2: Core-Collapse Supernova. **Credits:** NASA, ESA, J. Hester, A. Loll (ASU)

The temperatures reached in these systems are as high as 50 to 100 MeV. To describe these events it is therefore necessary to cover a wide range of **temperatures** as well as **charge fractions** and **densities**.

It has also been shown that the inclusion of other particles such as **hyperons** reduces the free energy of the system [6, 7].

Therefore, in this work we considered the presence of light clusters as well as hyperons and hyperclusters and studied their abundances for several temperatures, charge fractions and densities.

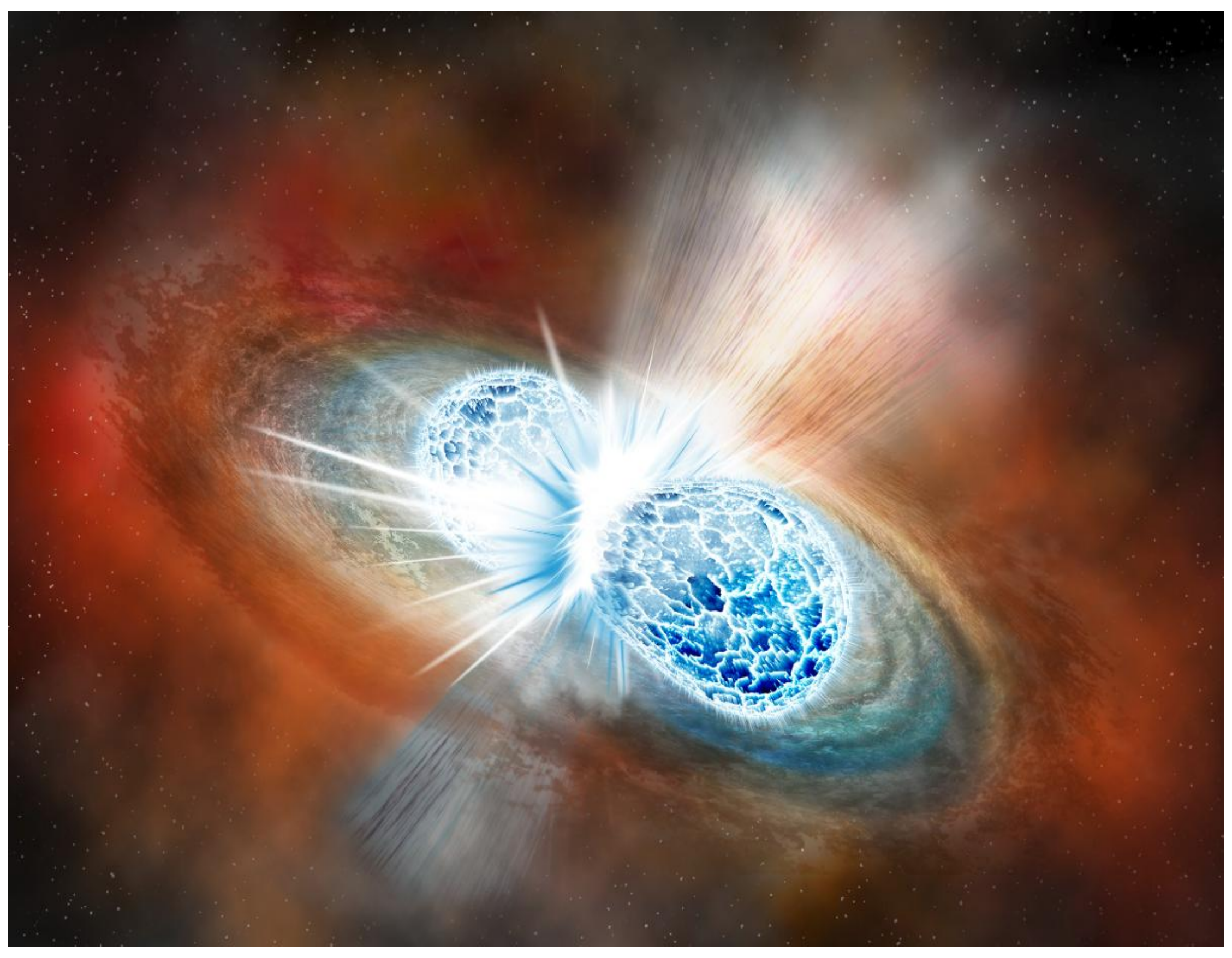

Figure 3: Binary Neutron Star Merger. **Credits:** NASA

Model and Results

We consider a gas of unbound **protons** and **neutrons** along with the following six **hyperons**: Λ, Σ^-, Σ^0, Σ^+, Ξ^-, Ξ^0 (baryonic octet).

Immersed in this gas, we also consider five **purely nucleonic light nuclei** (^{2}H, ^{3}H, ^{3}He, ^{4}He, ^{6}He) as well as three **hypernuclei** (${}^3_\Lambda$H, ${}^4_\Lambda$H, ${}^4_\Lambda$He) .

The Lagrangian density for such a system according to RMF theory is thus given by [7, 8, 9]:

$$\mathcal{L} = \sum_{\substack{b=baryonic\\ octet}} \mathcal{L}_b + \sum_{\substack{i=light\\ nuclei}} \mathcal{L}_i + \sum_{\substack{j=light\\ hypernuclei}} \mathcal{L}_j + \sum_{\substack{m=\sigma,\omega,\\ \phi,\rho}} \mathcal{L}_m$$

where we treat the light clusters and hyperclusters as **point-like particles**.

In Figure 4, we test the effect of including hyperons on the light clusters abundances and dissolution densities. We see that the presence of hyperons:

- Increases the cluster fractions above the maximum of the distribution, shifting the dissolution to larger densities;
- Starts to be non-neglegible for temperatures above $T \gtrsim 25 - 30$ MeV;
- Has a stronger effect for smaller charge fractions.

In Figure 5 we analyze the total light cluster and hypercluster fractions and compare them to the baryonic octet.

We can see that the abundances of hypernuclei are small compared to light nuclei which can be attributed to a weaker coupling of the Λ to the mesons.

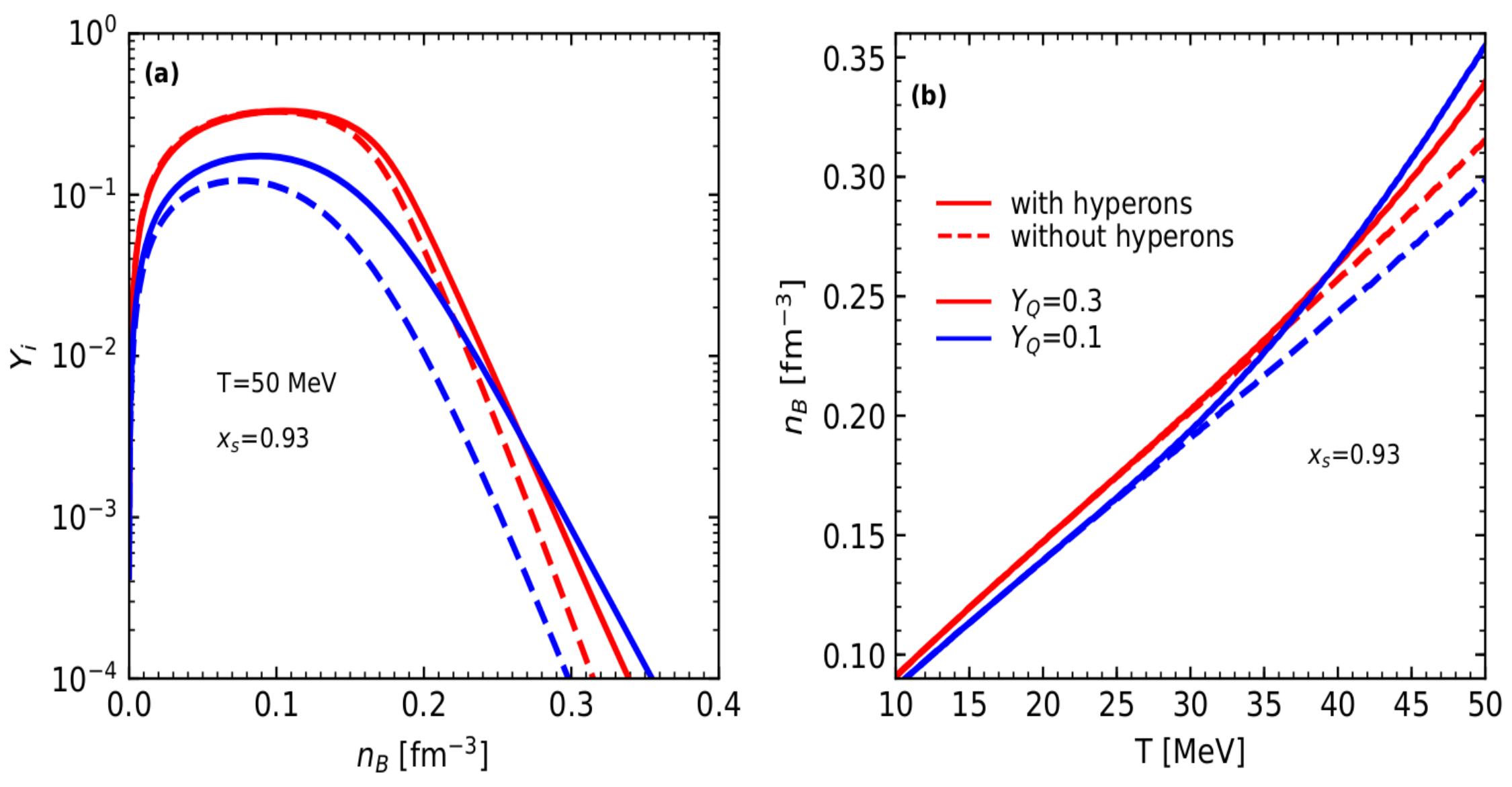

Figure 4: Total light cluster mass fraction for $T = 50$ MeV (left) and light cluster dissolution density considered at a cluster fraction equal to 10^{-4} as a function of the temperature (right) obtained for a charge fraction $Y_Q = 0.3$ (red) and 0.1 (blue) including (full line) or not including (dashed line) hyperons.

Nonetheless, we observed a competition between the hyperclusters and the heavier light clusters (^{4}He and ^{6}He).

We also found out that an hypercluster fraction above 10^{-4} is only obtained above $T \gtrsim 25$ MeV.

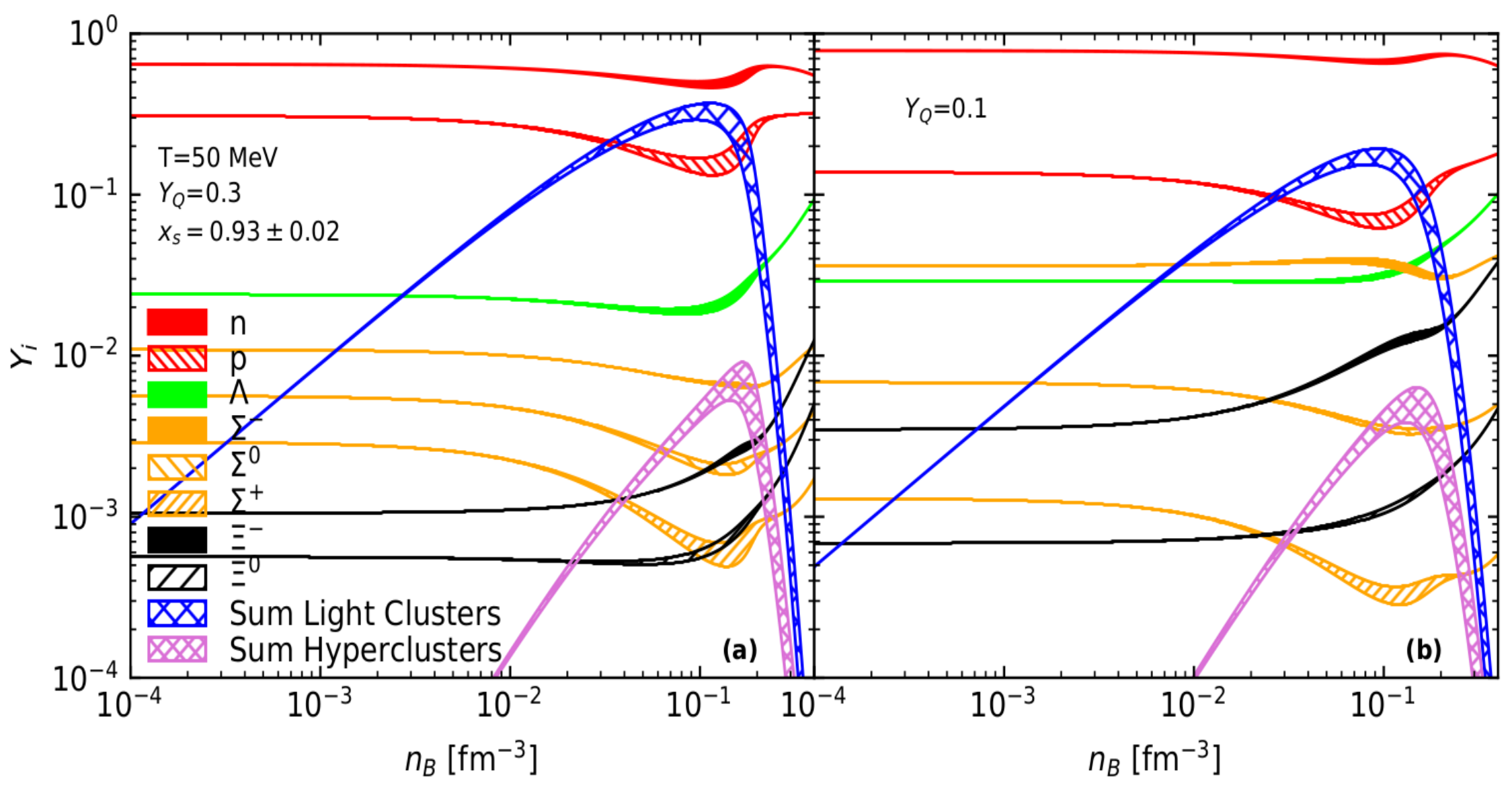

Figure 5: Unbound proton and neutron fractions (red lines), Λ (green), $\Sigma^{+,0,-}$ (orange) and $\Xi^{-,0}$ fractions (black), together with total light nuclei (blue band) and total light hypernuclei (pink band) mass fractions. The bands take into account the uncertainty on the x_S coupling fraction of the clusters to the σ-meson.

Conclusions

The inclusion of hyperons has a visible effect on the light clusters abundances and dissolution densities for high enough temperatures, which could have an impact in the reaction rates that determine the core-collapse supernova evolution or the binary merger.

On the other hand, given their small fractions, the hyperclusters do not have a large effect on the other particles abundances.

Acknowledgments

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