Nature of the first stars in the universe probed by metal-poor stars in the Milky Way

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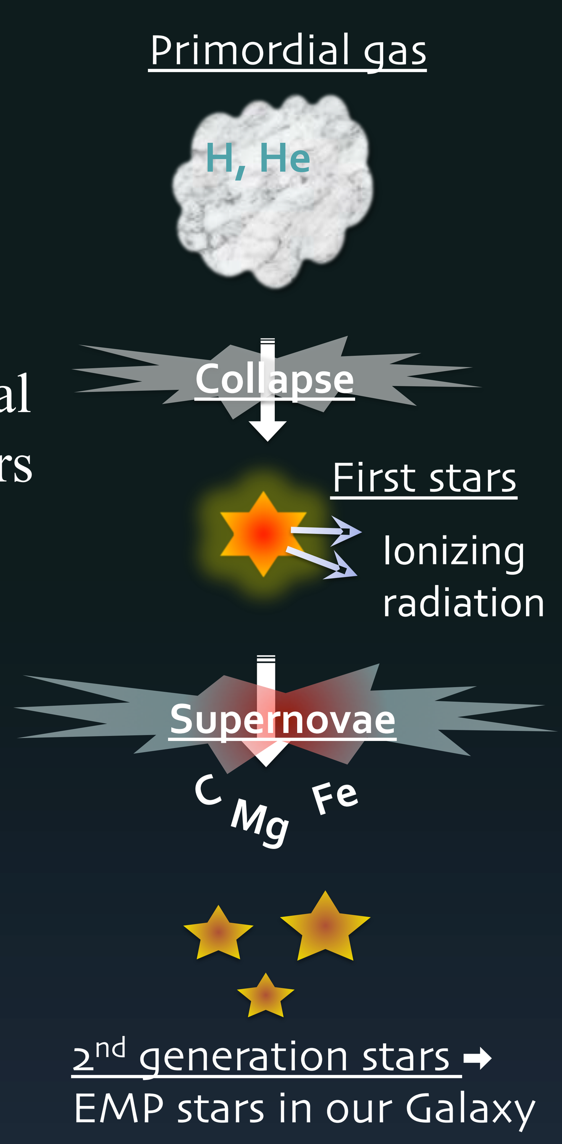
Abstract: Characterization of the first stars that form from the prestine gas in the universe is important to understand the history of cosmic reionization and the formation of seeds for the supermassive black holes at the centers of galaxies. In particular, the typical mass of the first stars determines ionizing photons for the cosmic reionization and feedback for the subsequent first galaxy formation. Extremely metal-poor (EMP) stars in the Milky Way Galaxy are likely second-generation stars formed out of gas enriched by nucleosynthetic products ejected by supernovae of the first stars and thus provide us with an important clue for the mass of the first stars. **We calculate supernova yields of the first stars that best reproduce elemental abundance patterns of the EMP stars to obtain possible insights into the typical mass of the first stars.** We found that the abundance patterns of the EMP stars are predominantly reproduced with the supernova/hypernova yields of the first stars with $M<40M_\odot$ leaving behind compact remnants (neutron stars or black holes) with masses up to a few tens of $M_\odot$.

I. Introduction

Revealing the nature of the very first generations of stars in the universe (first stars) is crucial to understand the cosmic reionization and the first metal enrichment that determine subsequent first galaxy formation. Since the first stars are formed out of primordial (i.e. metal-free) gas, their physical properties could be dramatically different from stars we see today. However, they are not, in general, directly observable and thus their basic properties, in particular masses, remain elusive. To obtain possible insights into the typical mass of the first stars, we use observations of the elemental abundances of so-called extremely metal-poor (EMP) stars in the stellar halo of our Milky Way Galaxy. Such stars are very old and have an iron abundance less than ~1/1000 of the solar composition and thus provide fossil records of nucleosynthesis products ejected via supernova explosions of the first stars.



II. Method

We calculate supernova yields of the first (e.i. metal-free) stars to be compared with elemental abundances of ~ 200 EMP stars, which provide significantly improved statistics than previous studies.

The yields of supernova (kinetic explosion energy $E_{51}=E/10^{51}$erg=1) and hypernova ($E_{51}\geq10$) are calculated for metal-free stars with main-sequence masses of M=13, 15, 25, 40 and $100M_\odot$ (e.g. Tominaga et al. 2007). Fig1 illustrates the abundance distribution after a supernova explosion of a $25M_\odot$ first star as a function of an enclosed mass (M_r). These elements are synthesized through either hydrostatic or explosive nucleosynthesis of the initially metal-free first star. Motivated by the fact that supernova explosions are non-spherical (e.g. Maeda et al.2008), we apply the mixing-fallback model (Umeda & Nomoto 2003; Tominaga et al. 2007) to the abundance distributions in order to take into account possible degree of asymmetry in the supernova/hypernova explosions. Sets of model parameters (mass, explosion energy, M_{mix}, and f_{ej}) that best reproduce the observed abundances of a metal-poor star are then searched by minimizing χ^2 between the data and the model. The procedure has been applied to the latest elemental abundance data of >200 EMP stars known so far.

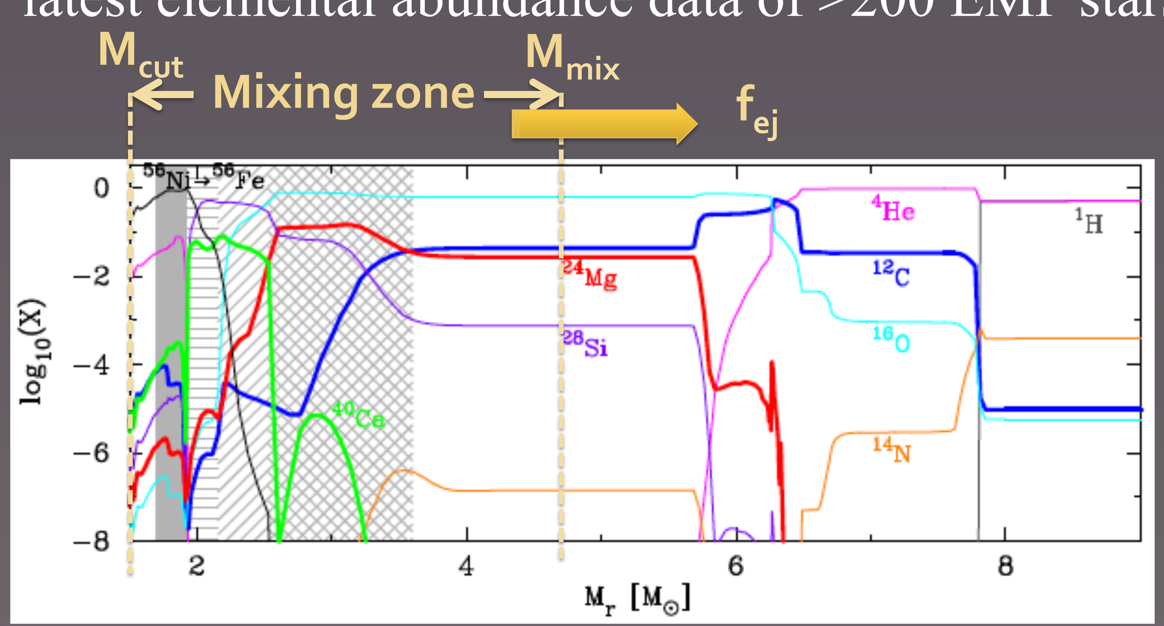


Fig 1: Abundance distribution as a function of enclosed mass (M_r) after a supernova of a first star with $M=25M_\odot$ and $E_{51}=1$. The mixing-fallback model assumes that the material in the mixing zone below M_{mix} is mixed and the fraction f_{ej} in this zone is finally ejected.

III. Result

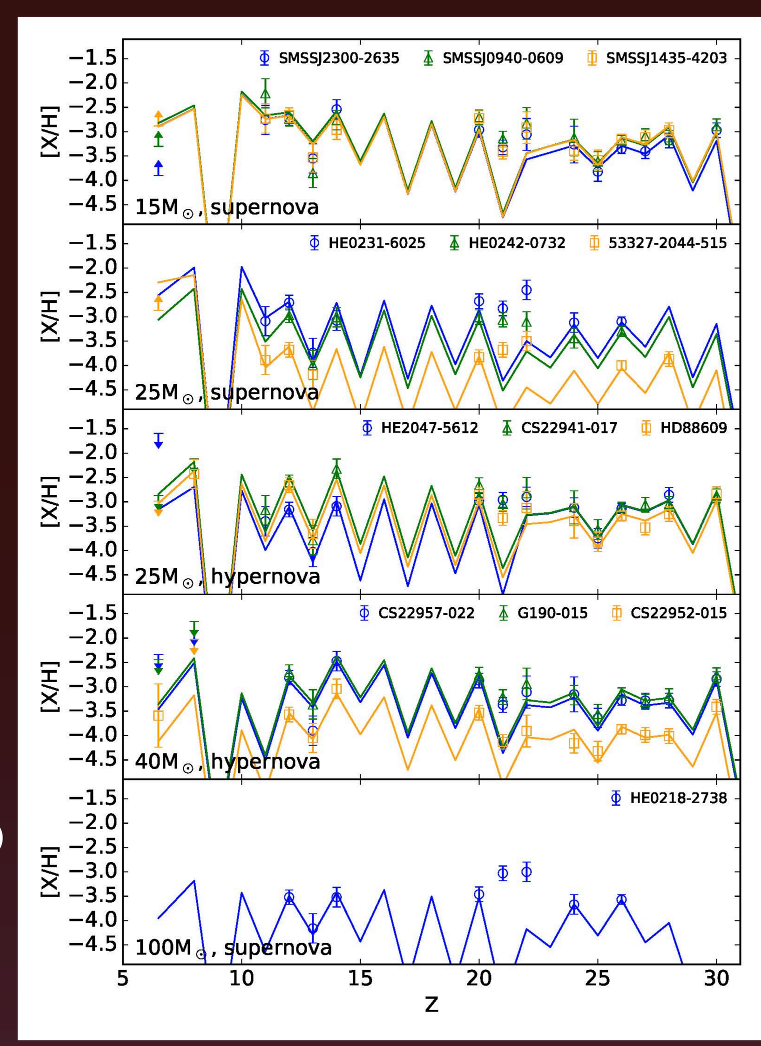


Fig 1. Example of the best-fit models (lines) to the elemental abundance patterns of EMP stars (circles with error bars). From top to bottom, the observed abundances are reproduced by supernovae/hypernova yield of 15, 25, 40 and $100M_\odot$. The characteristic abundance patterns according to the first star's masses can be seen; e.g. the abundance ratios between odd- and even-Z elements or the ratios between lighter and heavier elements. In particular abundance ratios of (C+N)/O and Na/Mg are found to be the most important in distinguishing the first star's masses.

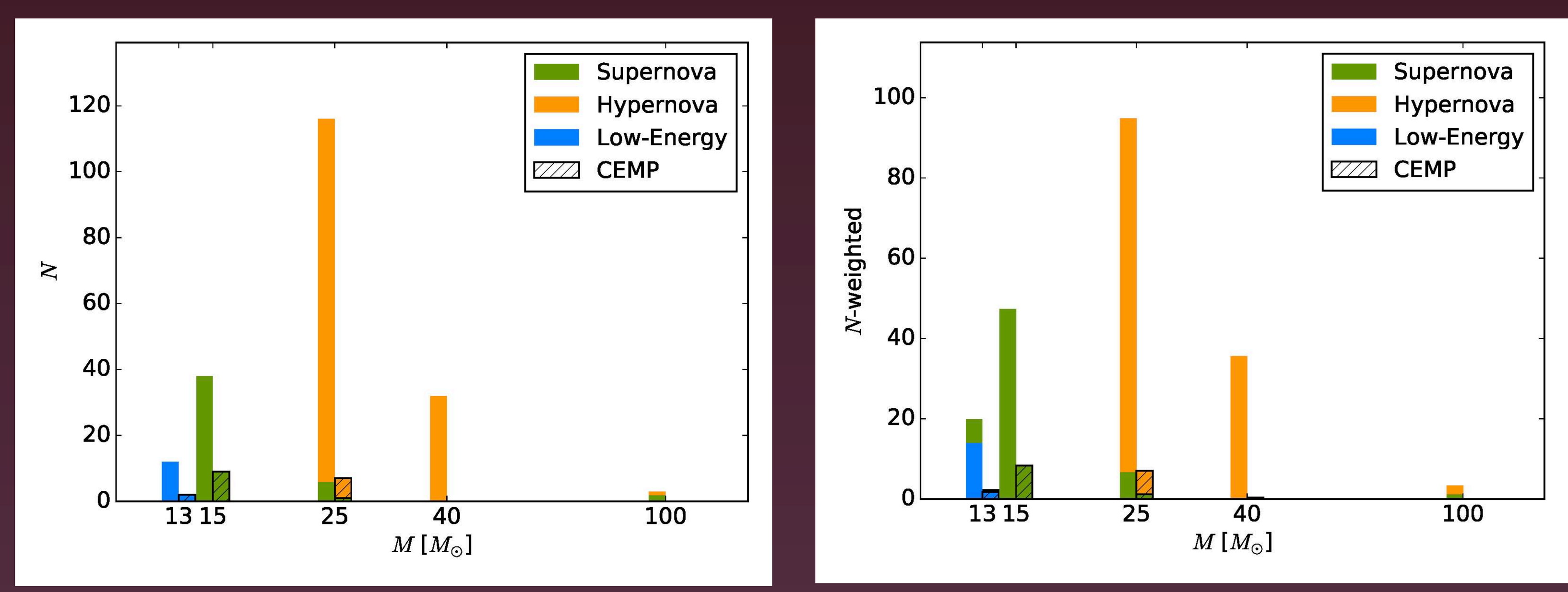


Fig 2: The histogram for the masses of the first stars obtained by our analyses. The left and right panels correspond to the best-fit results and the χ^2-weighted cases, respectively. As can be seen from the both panels, observed abundance patterns of the present sample of EMP stars are predominantly explained by the first stars with masses < $40M_\odot$.

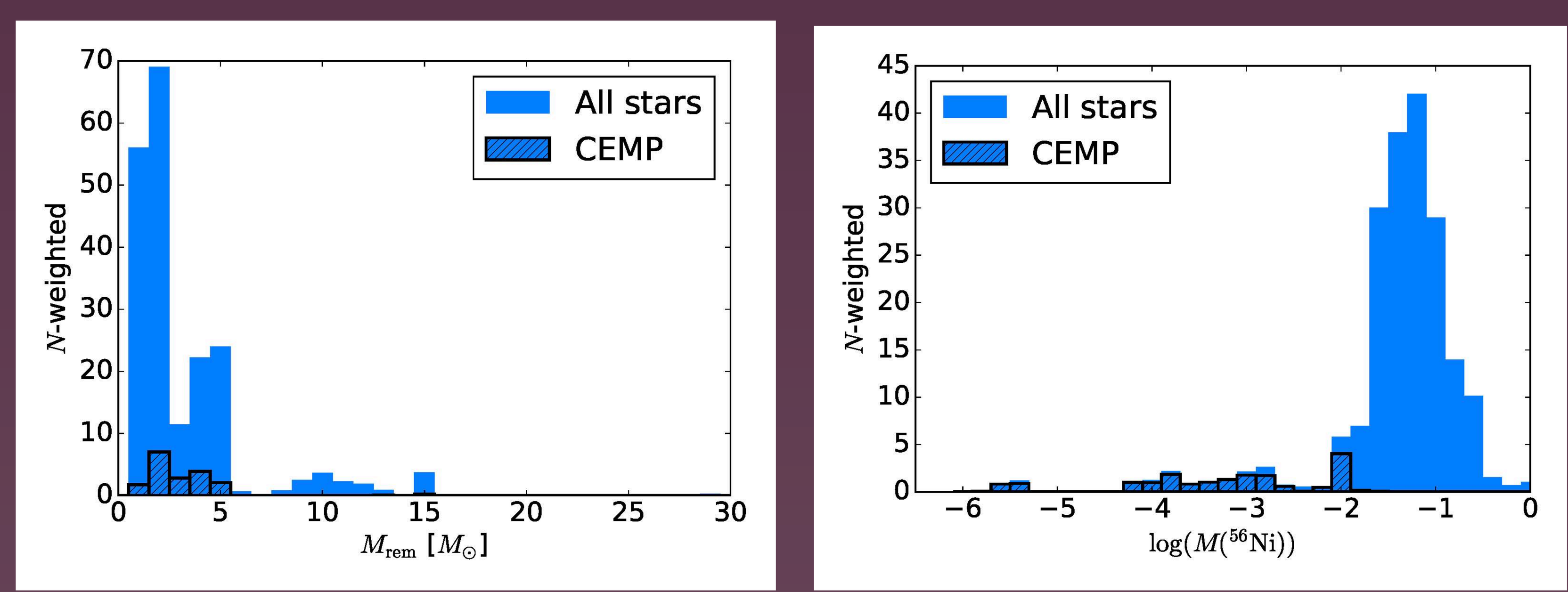


Fig 3: Distributions of masses of the compact remnant (left) and ejected ^{56}Ni (right) of the primordial supernovae/hypernovae. The remnant masses indicate that they are either a neutron-star or a black hole with masses in the range 1-15$M_\odot$. These primordial super-/hyper-novae typically eject 0.01-0.1$M_\odot$ of ^{56}Ni, while the progenitors of carbon enhanced metal-poor stars (hatched) eject <10^{-3} $M_\odot$ of ^{56}Ni. Since the radio-active decay of ^{56}Ni is one of the main sources of luminosity in supernovae, the small ^{56}Ni mass would result in a faint supernova.

IV. Summary and discussion

Numerical simulations for the formation of the first stars from the cosmological initial condition previously predicted that the first stars were predominantly extremely massive (> a few hundred $M_\odot$) as a result of the low efficiency for cooling of metal-free gas. On the other hand, recent simulations with more detailed physics, suggest that they could be as low mass as a few tens of $M_\odot$ or less since the proto-star of collapsing cloud can fragment into smaller pieces. **Our results based on the large sample of EMP stars support this picture, suggesting the presence of the first stars with initial masses < $40M_\odot$.**

Our results have an implication on physical process for the formation of the first stars. Also, predominance of the carbon-enhanced metal-poor stars among the Fe-poor stars may indicate **a significant fraction of the first stars end up with a black hole with up to a few ten's $M_\odot$ as the results of a supernova or hypernova that experience an extensive mixing and fallback.** Future spectroscopic surveys for metal-poor stars in the Milky Way would further reveal statistical properties of the first stars, which will help better understand the structure formation in the early universe.

References: Tominaga, N. et al. 2007, ApJ, 660, 516; Umeda & Nomoto 2003, Nature, 422, 871; Ishigaki, M. N. et al. 2014, ApJ, 792L, 32