Exploration of Supernovae Yields in the Formation of the Old, Metal-poor, Globular Cluster M15

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The metal-poor GC M15

The origin and evolution of Globular Clusters is poorly understood (Bastien & Lardo 2018; see Fig. 1). M15 is one of the oldest and most metal-poor ([Fe/H]=-2.3) globular clusters known (Harris 2010), however, it is unusual due to an observed spread in its heavy elements, e.g., Ba and Eu (Roederer et al. 2011). This implies that M15 experienced a contribution from a rare event that can synthesizes r-process elements, i.e., a kilonova event such as GW170817, the merger of two neutron stars (Berger et al. 2017). Using M15, we explore the star formation and early chemical evolution in the early Universe.

	(Near) ubiquity (Section 2)	Abundances (Section 5.1)	Li correlations (Section 5.1.2)	Variety/Stochasticity (Section 5.1.3)	Mg–Al (Section 5.1.5)	Discreteness (Section 5.2)	Mass budget (Section 5.4)	$f_{enriched}$ correlation with GC mass (Section 5.5)	He spread correlation with GC mass (Section 5.5)	YMCs (Section 5.6)	Age trend (Section 5.6.1)
AGB	X	X*	X*	X	✓*	X*	X*	X	X*	X	X
FRMS	X	X*	X	X	X	X	X*	X	X	X	X
VMS	X	X*	X	?	X*	X	✓*	✓*	✓*	✓	X
EDA	X	X*	X	X	X	X	X*	X	X	✓*	X
Reverse order	X	X*	X	?	?	X	✓*	X	X	X	X
eSF period	X	X*	X	X	X	X	X*	X	X	✓	X

Fig. 1 Compatibility between proposed GC formation models and observations (Fig. 6 from *Bastian & Lardo 2018*)

Fig. 2 Globular Cluster M15 (NGC 7078)

Some rejected SNe yields

Many pair-instability supernovae (PISNe) and core-collapse supernovae (CCSNe) models with varying progenitor metallicities make a wide range of nucleosynthesis predictions. Yet, the multiple and mutable parameters (explosion energies, reaction rates, convection and rotation models, neutrino processes, network range and core-to-mass relation) result in only a small fraction of those simulations in agreement with the observations of stars in M15. We have rejected the popular yields from two papers; *Woosley & Weaver (1995)* which overproduce most of the chemical abundances, and most of *Nomoto et al.'s (2013)* yields as their progenitors are too metal-rich. In Figs. 3 & 4, we highlight the best matches between theoretical predictions and observed chemical abundances of stars in M15.

Contributor Degeneracies

PISN 280$M_\odot$ *(Takahashi+2018)* + CCSN 15$M_\odot$ Z = 0.001 *(Nomoto+2013)*

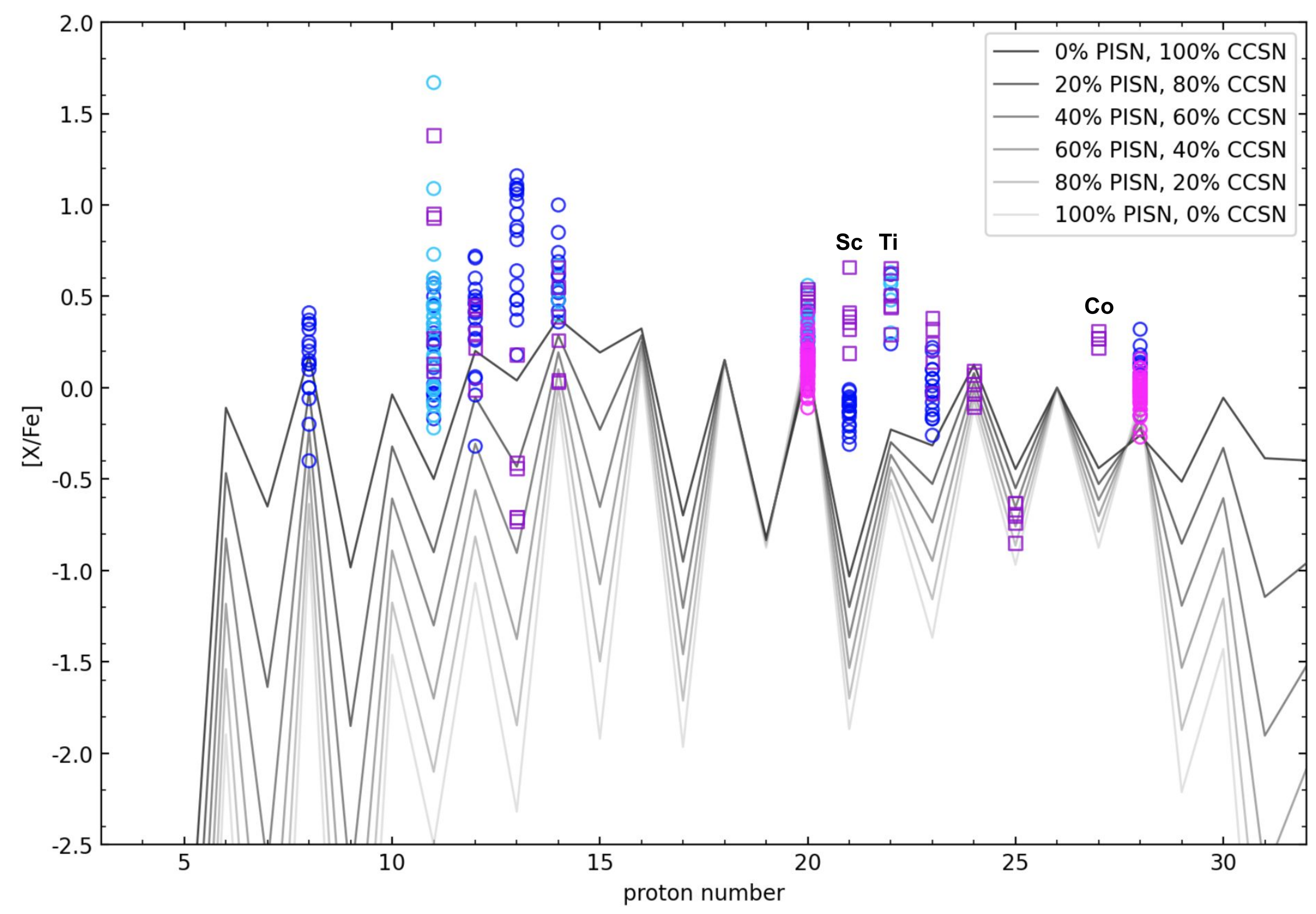

Fig. 3 Nucleosynthesis yields from the combined weighed contributions of a PISN and 15 $M_\odot$ CCSN. The blue, light blue, violet and magenta markers indicate chemical abundances of stars in M15 from *Sneden et al.1997*, *Sneden et al. 2000*, *Preston et al. 2006* and *Worley et al. 2013,* respectively. Circles indicate giants and squares indicate RHB stars

PISN 240$M_\odot$ *(Takahashi+2018)* + CCSN 19$M_\odot$ Z = 0.0001 *(Ebinger+2020)*

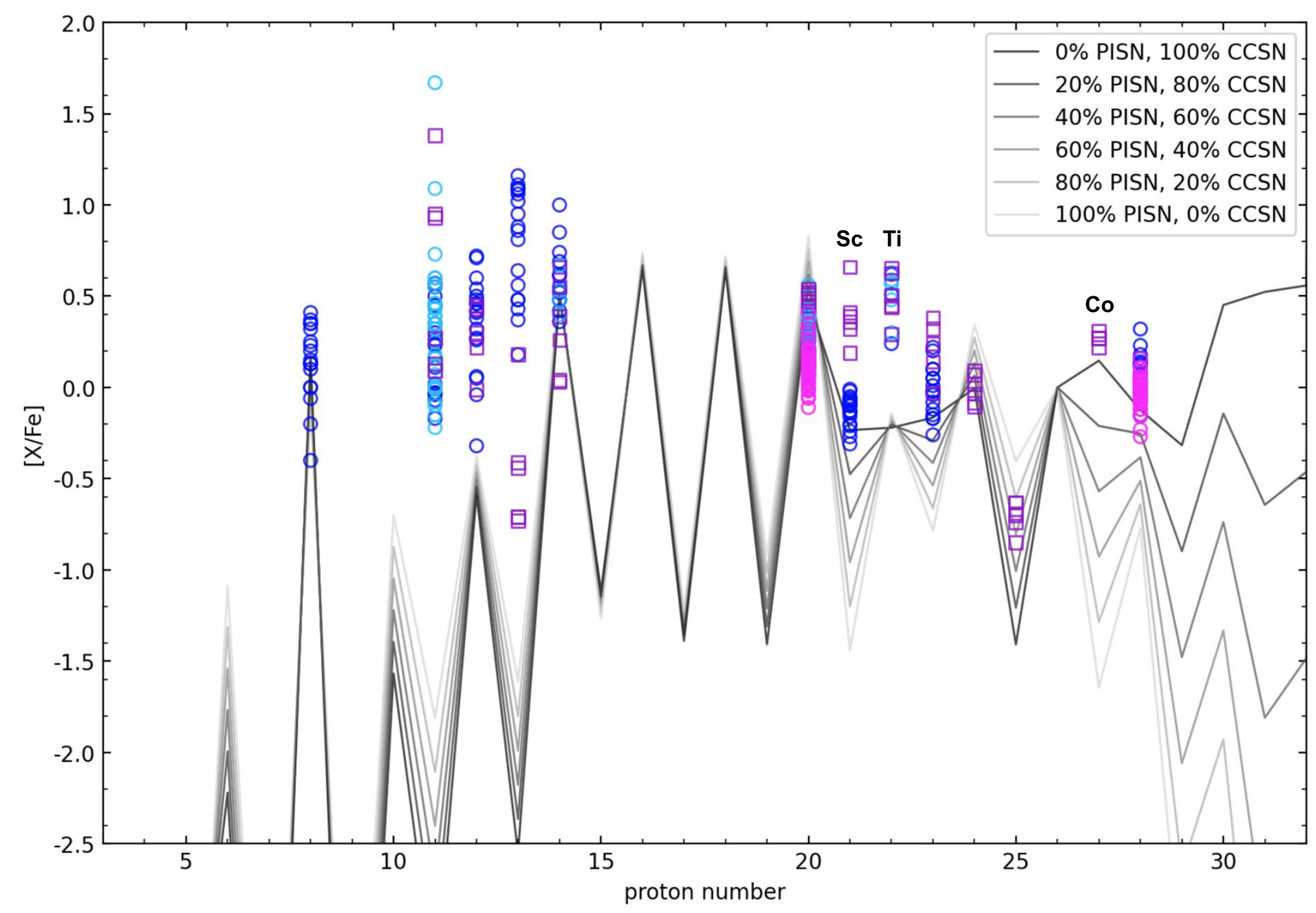

Fig. 4 Nucleosynthesis yields from the combined weighed contributions of a PISN and 19 $M_\odot$ CCSN. The markers are the same as in Fig. 3

- ★ **M15 appears to have been primarily enriched in CCSN rather than a single (or a few) higher mass PISN events.**
- ★ **We find the best fits to the M15 chemical abundances are when low mass CCSN progenitors (11 to 19$M_\odot$) are combined with only one (or a few) massive PISN events (with progenitor masses of 240 to 280$M_\odot$).**
- ★ **Scandium, Titanium, and Cobalt (proton numbers = 21, 22, and 27) are poorly reproduced in Fig. 3. However, they are better in Fig.4, showing that lower metallicity CCSN yields are necessary (Z = 0001, not Z = 001).**
- ★ **The predicted odd-even effect is not clearly seen; though Na and Al are complicated by 2nd generation effects.**

Metallicity dilution & EMP yields

CCSNe yields from Nomoto et al. (2013) are derived for metallicities (Z = 0.001, 0.004, 0.008 and 0.02), which are *higher* than those of the stars in M15. Nevertheless, we examine their Z = 0.001 ([Fe/H] ~ -1.5) to explore M15's chemical abundances, relative to the other fits. We do this proto-GCs could be diluted by gas inflows in cosmological simulations (Bustamante et al. 2018). However, we also explore the extremely metal-poor (EMP) predictions from Ebinger et al. (2020; Z = 0.0001, [Fe/H] ~ -2.5), and do find improvements for some elements. Future plans include exploring the degeneracies in combining these yields to constrain the early star formation and chemical evolution of the Universe that occurred to form ancient GCs like M15.

Eu and Ba abundances

Of special interest in M15 is the spread in Ba and Eu observed in its red giants (Roederer 2011), later recognized as a bimodal distribution (Worley et al. 2013). Most CCSNe models do not include yields of the heavy elements (proton number ≳ 34), but the new yields from *Ebinger et al.'s (2020)* do reach to Europium (proton number = 63) for CCSN with Z = 0.0001 ([Fe/H]~ -2.5). Their 24 $M_\odot$ yields can predict some of the observed heavy element abundances (Y, Sr, and Eu), but do not reproduce others (Ba, La and Zr). These models also overproduce many light elements. The discovery of r-process nucleosynthesis in the kilonova of the gravitational wave source GW170817 (*2017 Nobel Prize in Physics)* occurred after the discovery of the M15 heavy-element spread. It is very likely that the proto-M15 was enriched in a late neutron star binary merger, leading some stars with enhanced heavy elements (e.g., Drout et al. 2017).

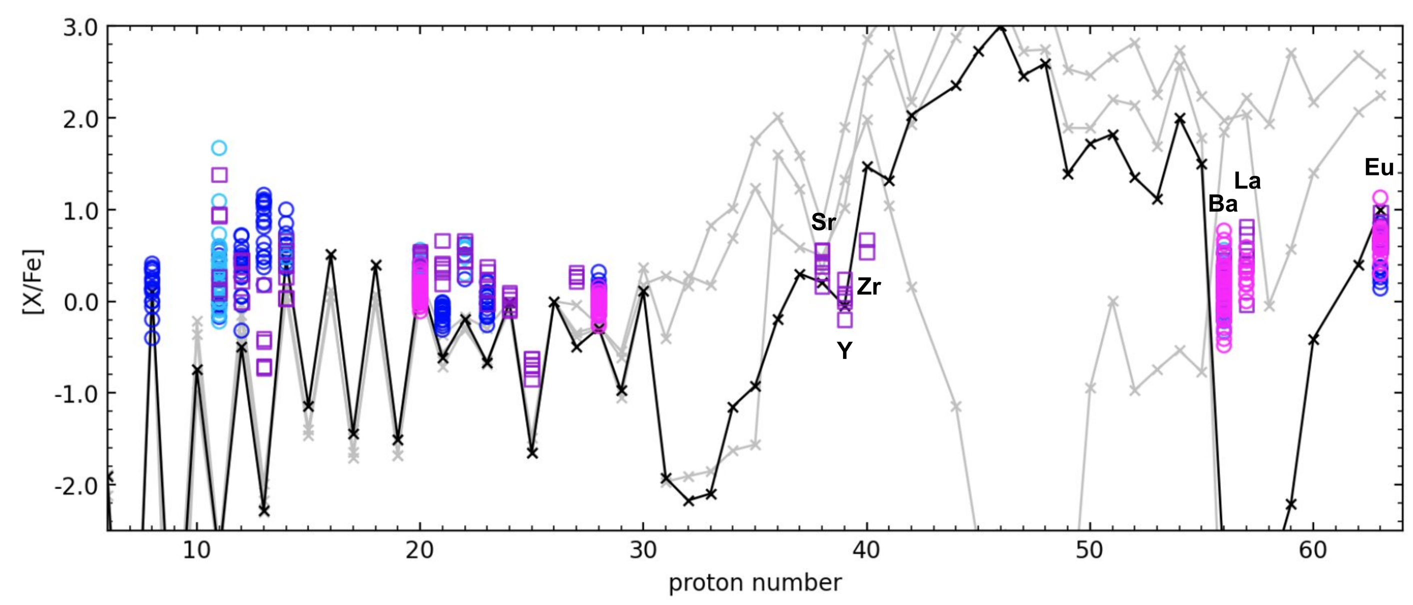

Fig. 5 Nucleosynthesis yields from *Ebinger et al. (2020)* 24 $M_\odot$ model (Z=0.0001, black line) and 25, 28 and 30$M_\odot$ (grey lines). Symbols as in Fig. 3

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