Tagging and Tracing Globular Cluster-Origin Stars from the Early Milky Way with Gaia

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Globular Clusters as Galactic Building Blocks

- Globular clusters (GCs) are groups of thousands of stars that form extremely efficiently, which has prompted questions of whether they may be critical to star formation in early galaxies.
- Stars with overabundances of nitrogen and aluminum and depletions in oxygen, among other elements, **can be uniquely tagged as having originated in a GC** even long after they escape their birth cluster [1, 2, 3, 4, etc.]
- Tracing field high-[N/O], GC-origin stars suggests that GCs were once a significant contributor to star formation in the proto-Milky Way and that that contribution dropped at the metallicity corresponding to spin-up, the formation of the Galactic disk [4].
- **The scarcity of known high-[N/O] stars poses a challenge for using them to understand the history of GCs in the Galaxy!**

Heteroscedastic Regression & *Gaia* BP/RP Spectra

- ***Gaia* BP/RP spectra** are low resolution (R~60) spectra and are available for about 220 million stars in *Gaia* DR3. They span approximately 330 nm to 1050 nm and are published as a set of 110 coefficients of a spectral basis function.
- We train a neural network to predict T_{eff}, $\log(g)$, [Fe/H], [N/O] and [Al/Fe] from the BP/RP coefficients.
  - A cross-matched dataset of BP/RP coefficients and APOGEE stellar parameters are used for training and validation.
- Our network performs **heteroscedastic regression**, taking into account non-uniform variance in the data, by using a **negative log-likelihood loss function**:

$$loss = \frac{(\mu_{pred} - y_{true})^2}{(\sigma_{pred})^2} + \log((\sigma_{pred})^2)$$

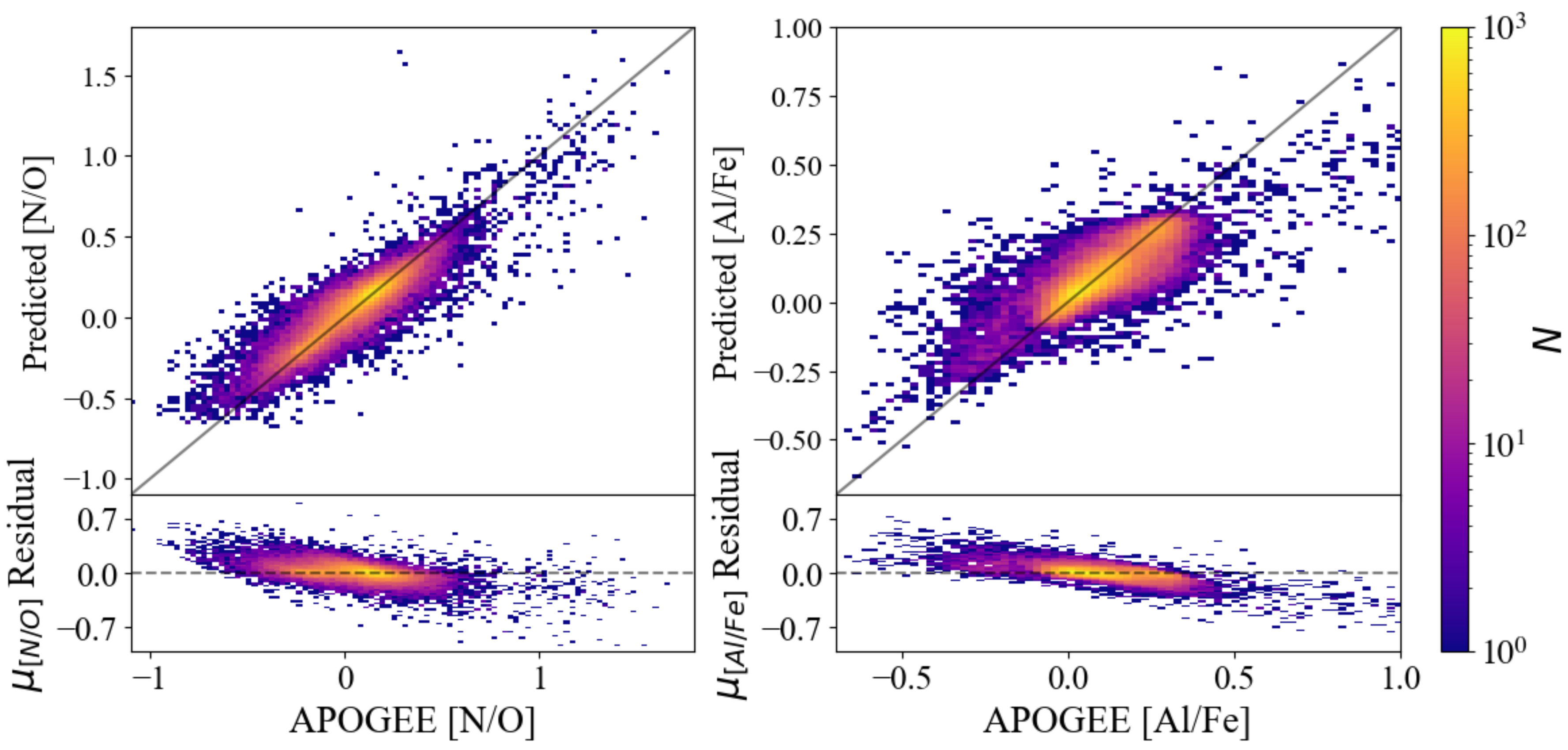


Figure 1: The validation performance of the network predictions for [N/O] (left) and [Al/Fe] (right). The large upper panel of each subplot depicts the prediction versus the true value from APOGEE with the 1:1 line marked in black. The narrow lower panel is the prediction residual with the horizontal black line marking a residual of zero.

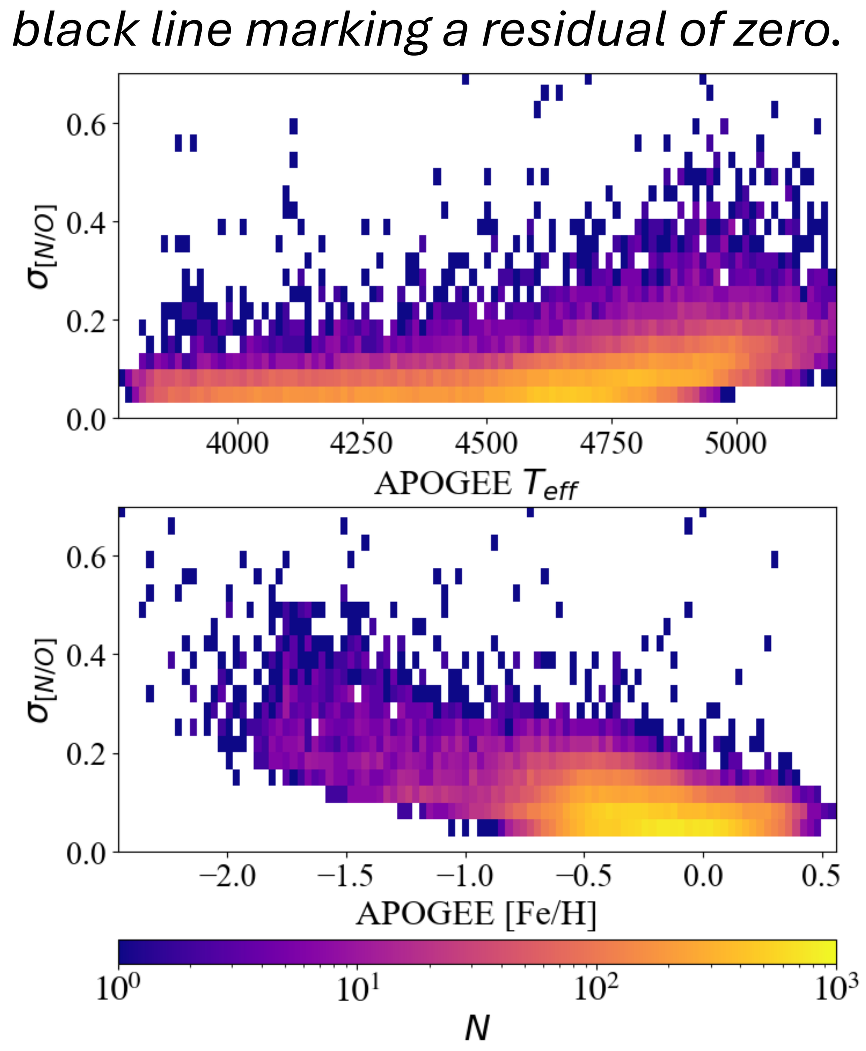


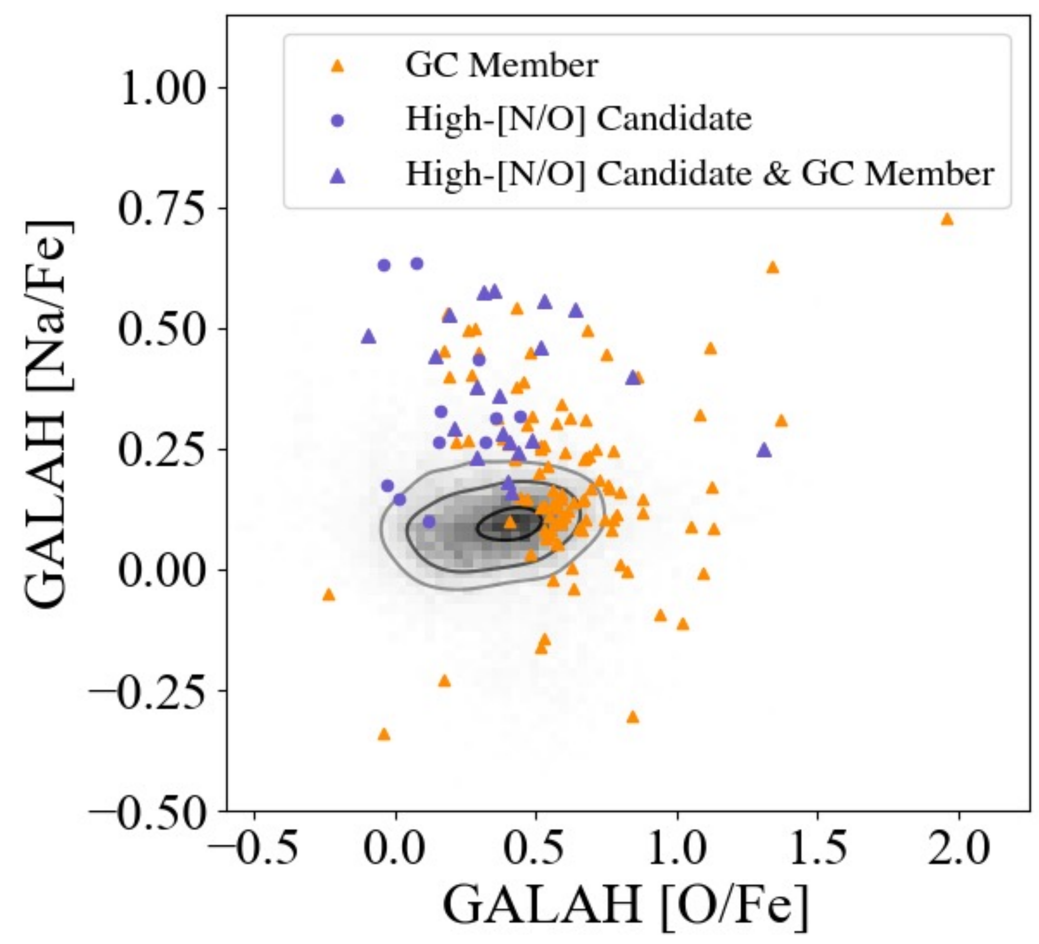
Figure 2: Network inferred [N/O] standard deviations ($\sigma_{[N/O]}$) versus APOGEE T_{eff} (top panel) and [Fe/H] (bottom panel).

References:
[1] Martell S. L., Grebel E. K., 2010, A&A, 519, A14
[2] Schiavon R. P., et al., 2017, MNRAS, 465, 501
[3] Horta D., et al., 2021, MNRAS, 500, 5462
[4] Belokurov V., Kravtsov A., 2023, MNRAS, 525, 4456
[5] Andrae R., Rix H.-W., Chandra V., 2023, ApJS, 267, 8
[6] Hawkins K., Jofré P., Masseron T., Gilmore G., 2015, MNRAS, 453, 758
[7] Belokurov V., Kravtsov A., 2022, MNRAS, 514, 689

Can we identify high-[N/O], GC-origin stars from BP/RP spectra?

- We use our predicted stellar parameters and abundances and their associated inferred variances to classify stars as high-[N/O] candidates.
  - We used the cutoff $\mu_{[N/O]} - 0.17\sigma_{[N/O]} > 0.65$, $\mu_{[Al/Fe]} - \sigma_{[Al/Fe]} > 0.$, $\mu_{T_{eff}} < 5000$, & $\mu_{[Fe/H]} > -2$
  - Our goal is to identify stars with true abundances [N/O] > 0.55 and [Al/Fe] > −0.1 (per [4]).
- Testing these cuts on the validation data yields a **~3.9% false positive rate!**

Figure 3: Our classification of high-[N/O] candidates in the GALAH [Na/Fe]-[O/Fe] plane. Our candidates are predominantly Na-enhanced and O-depleted and are much more common in GCs than in the field, both of which are consistent with expectations for true 2G GC-origin stars.



Newly-Identified GC-Origin Field Stars

- We apply our trained neural network to the BP/RP spectra of RGB stars identified by [5].
- Applying the same cuts described above and removing young, thin disk stars with $v_\phi < 160$ km/s**, we obtain 754 new high-[N/O], high-[Al/Fe] candidates in the Galactic field.**
  - By comparison, there are only 155 known stars in APOGEE with [N/O] > 0.55 and [Al/Fe] > −0.1 that pass similar cuts.
- Using our $\mu_{[Al/Fe]}$ values as a selector of in-situ and accreted stars [6], we find that **most of our high-[N/O] candidates are consistent with having formed in the MW**, in agreement with the results of [4].

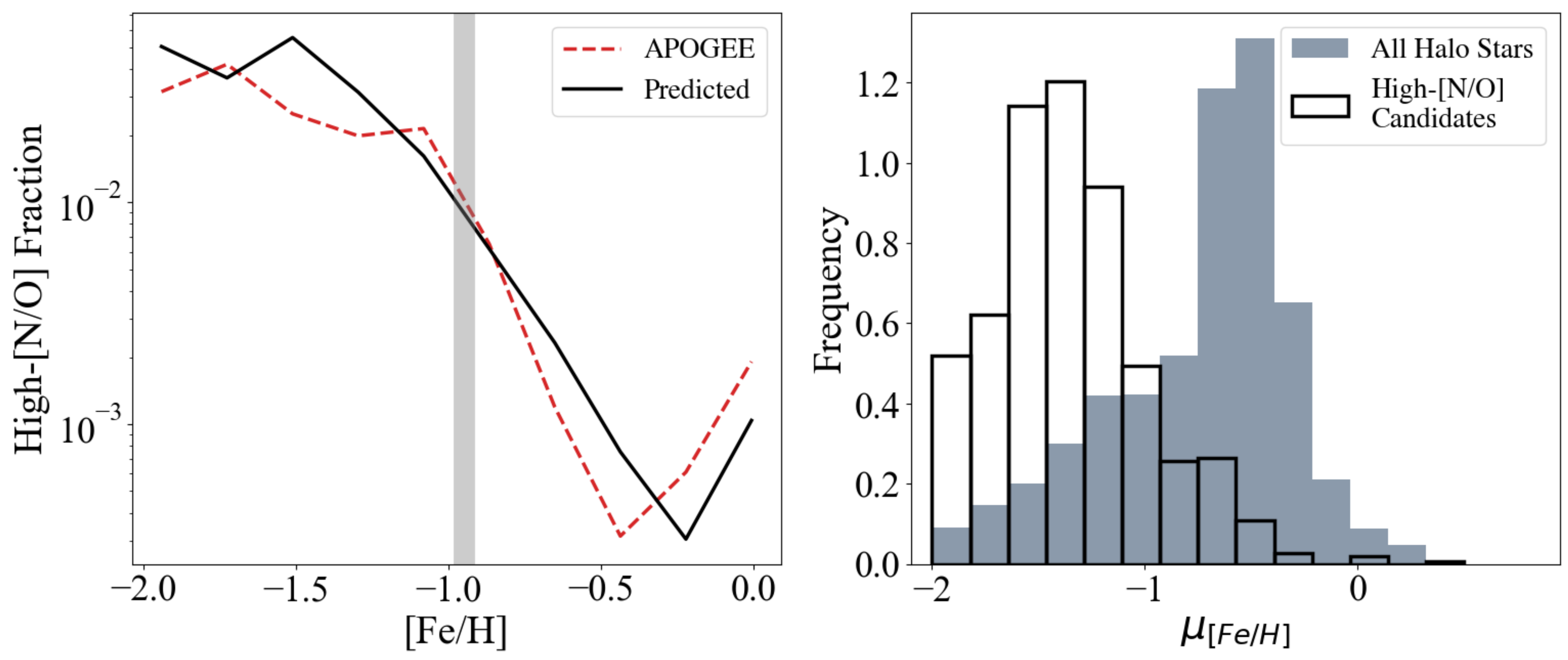


Figure 4: Left: The fraction of high-[N/O] field stars in the halo as a function of metallicity. The red dashed line shows the data from APOGEE using APOGEE [Fe/H], and the black line is constructed from our sample of candidates with $\mu_{[Fe/H]}$ as the metallicity. The high-[N/O] fraction from our candidates is multiplied by a factor of 3.44, consistent with our projected false positive rate from the validation data. Spin-up is marked by the vertical gray shading at $-1 \leq$ [Fe/H] ≤ -0.9 [7]. Right: The normalized metallicity distribution using $\mu_{[Fe/H]}$ of all giants in our sample (purple) and the candidate high-[N/O] stars (black outline).