Infrared colours and inferred masses of metal-poor giant stars in the *Kepler* field

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ABSTRACT

Intrinsically luminous giant stars in the Milky Way are the only potential volume-complete tracers of the distant disk, bulge, and halo. The chemical abundances of metal-poor giants also reflect the compositions of the earliest star-forming regions, providing the initial conditions for the chemical evolution of the Galaxy. However, the intrinsic rarity of metal-poor giants combined with the difficulty of efficiently identifying them with broad-band optical photometry has made it difficult to exploit them for studies of the Milky Way. One long-standing problem is that photometric selections for giant and/or metal-poor stars frequently include a large fraction of metal-rich dwarf contaminants. We re-derive a giant star photometric selection using existing public *g*-band and narrow-band DDO51 photometry obtained in the *Kepler* field. Our selection is simple and yields a contamination rate of main-sequence stars of $\lesssim 1\%$ and a completeness of about 80\% for giant stars with $T_{\text{eff}} \lesssim 5250\, \text{K}$—subject to the selection function of the spectroscopic surveys used to estimate these rates, and the magnitude range considered ($11 \lesssim g \lesssim 15$). While the DDO51 filter is known to be sensitive to stellar surface gravity, we further show that the mid-infrared colours of DDO51-selected giants are strongly correlated with spectroscopic metallicity. This extends the infrared metal-poor selection developed by Schlaufman & Casey, demonstrating that the principal contaminants in their selection can be efficiently removed by the photometric separation of dwarfs and giants. This implies that any similarly efficient dwarf/giant discriminant (e.g., *Gaia* parallaxes) can be used in conjunction with *WISE* colours to select samples of giant stars with high completeness and low contamination. We employ our photometric selection to identify three metal-poor giant candidates in the *Kepler* field with global asteroseismic parameters and find that masses inferred for these three stars using standard asteroseismic scaling relations are systematically over-estimated by 20–175\%. Taken at face value, this small sample size implies that standard asteroseismic scaling relations over-predict stellar masses for metal-poor giant stars.

Key words: stars: abundances, fundamental parameters; photometry: infrared; asteroseismology: masses, scaling relations

1 INTRODUCTION

Red giant stars are effective tracers of the disk, bulge, and halo of the Milky Way. They are especially important for penetrating the most extincted regions of the bulge (e.g., Geisler 1984; Rich 1990; Rich et al. 2007; Casey & Schlaufman 2015). In short, they allow for a thorough and relatively unbiased examination of all major components of the Milky Way and its satellite systems. Given their importance for tracing the structure and evolution of the Milky Way, an efficient photometric selection for giant stars has been long-standing goal of Galactic astronomers.

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sification of the narrow-band Washington (Canterna 1976) 

DDO$_{51}$ filter demonstrated that the $g$–DDO$_{51}$ colour was significantly different for FGK-type dwarfs and giants. The colour separation is the result of strong stellar absorption features that appear in the spectra of FGK-type stars near the central wavelength of the DDO$_{51}$ filter. Specifically, the Mg I triplet near 517 nm is one of the strongest spectral features in late-type stars, with dwarfs showing extended wings induced by pressure broadening. In addition to the Mg I triplet lines contributing log $g$ sensitivity to the DDO$_{51}$ filter, several bands of the MgH $A^2\Pi - X^2\Sigma$ structure are present in this narrow wavelength range. Despite a small secondary dependence on metallicity (Paltoglou & Bell 1994; Majewski et al. 2000), these features are much weaker in giants than dwarfs at the same effective temperature. Although the $g$-band filter is broader than the narrow DDO$_{51}$ filter by more than 100 nm, both responses curves peak near the same central wavelength. For these reasons, the $g$–DDO$_{51}$ colour provides outstanding photometric sensitivity in surface gravity in late-type stars. For comparison, metal-rich main-sequence stars overlap with very metal-poor giant stars in the $c_1,0-(b-y)_0$ plane of Strömgren photometry, and giant/dwarf separation using Strömgren photometry is extremely sensitive to reddening (Arnadóttir et al. 2010). Thus, the $g$–DDO$_{51}$ colour is among the most promising for distinguishing giant stars, particularly metal-poor giant stars, from main-sequence stars.

While the DDO$_{51}$ filter is known for its ability to distinguish dwarfs from giants, it has not seen extensive use in large-scale studies of Milky Way (though see Majewski et al. 2000; Morrison et al. 2001; Helmi et al. 2003; Munoz et al. 2003; Saha et al. 2010; Janesh et al. 2016; Slater et al. 2016; Blanton et al. 2017). Most galactic studies seeking to assemble a clean (i.e., relatively uncontaminated) sample of giant stars have focused on later-type M stars. In constructing the standard $JHKLM$ system, Bessell & Brett (1988) showed that dwarfs and giants bifurcated in infrared colours at spectral types later than M. This feature allows for a clean sample of either cool M dwarfs or giants to be easily constructed without the need for narrow-band photometry. Given that M giants are more luminous than FGK type stars, many studies have produced inferences about Milky Way structure through uncontaminated samples of M giants (e.g., see Sheffield et al. 2014; Koposov et al. 2015; Li et al. 2016).

While it is tempting to assert that M giants selected from public infrared photometry are sufficient tracers of the Milky Way, it is well understood that M giants preferentially trace metal-rich stellar populations. For this reason, most of the structure in the Milky Way’s metal-poor halo will not appear in even the cleanest M-giant sample. This can result in biased inferences, leaving the largest component of the Milky Way (by volume) less than fully understood.

This Article is organised in the following manner. In Section 2 we use public photometry and spectral data available in the Kepler field to re-derive a giant photometric selection with high completeness and negligible contamination. We show that the stars in the resulting photometrically-selected giant sample have spectroscopic metallicities that are strongly correlated with infrared colours. Confident in our photometric selection, we then use photometrically-selected metal-poor giant stars with publicly available asteroseismic parameters $\Delta \nu$ and $\nu_{\text{max}}$ to show that masses inferred using scaling relations are systematically over-estimated for metal-poor stars. This observation suggests that a modification to the asteroseismic scaling relations is warranted in the metal-poor regime. In Section 3 we discuss how these results extend existing work on searches for metal-poor stars using mid-infrared photometry and the implications for asteroseismic scaling relations. Our conclusions follow in Section 4.

2 DATA & ANALYSIS

2.1 Photometric Selection

We constructed our photometric selection using the extensive public photometric and spectroscopic data available in the Kepler field. We first cross matched the Kepler Input Catalogue (hereafter KIC, Brown et al. 2011) against LAMOST Data Release (DR) 3 (Luo et al. 2015) using a 1” search radius. This match revealed 53,090 sources. We cross matched the resulting sample against the ALLWISE catalogue (Wright et al. 2010) using the IRS web service and an increased search radius of 2” to account for the larger point spread function in ALLWISE. This revealed 48,999 unique sources. We corrected bright WISE photometry using the prescription of Patel et al. 2014, and we discarded stars based on a number of quality criteria. First, we required that all stars have reported magnitudes in $g$, $i$, DDO$_{51}$, W1 and W2. We further removed stars where there was uncertainty in the WISE photometry: $\sigma(W1) > 0.025$ mag, or $\sigma(W2) > 0.022$ mag, or if the $\chi^2$ value in the W1 or W2 profile fitting exceeded 2. We made no quality cuts based on spectroscopy (e.g., using any information from LAMOST).

The distilled sample contains 25,668 stars.

We use $g$–DDO$_{51}$ colour to separate dwarf and giant stars, as shown in Figure 1. In the first panel we show the effective temperature $T_{\text{eff}}$ and surface gravity log $g$ for all LAMOST stars in our sample, where we have separated main-sequence and giant stars with log $g >$ max{6.1 − 2.4(T$_{\text{eff}}$/6000)}, 4.1. The $g-i$ and $g$–DDO$_{51}$ colours of the main-sequence and giant star samples are shown in the second and third panels of Figure 1 where it is clear that the lack of spectral absorption in the giant stars separates them very neatly from the dwarfs in the $(g-i, g$–DDO$_{51})$ colour space, as shown in previous studies.

We note that the separation we find in $g$–DDO$_{51}$ appears qualitatively better than existing studies using this selection, presumably because these stars are relatively bright and the DDO$_{51}$ imaging obtained for the KIC is of high quality. Using the $g-i$ colour, it is clear that the dwarf/giant separation is maintained for effective temperatures as low as ~4000 K. The separation for cooler stars is less distinct for $g-r$, $J$, $H$, and $K_s$, but comparable for $g-z$. For stars below ~4000 K, $V-K$ and $J-H$ can be effectively used to separate dwarfs from giants (Bessell & Brett 1988). On the hotter end, however, we caution that log $g$ sensitivity is largely lost for stars with $T_{\text{eff}} > 5250$ K. Giant stars in this temperature regime overlap with main-sequence stars (of all metallicities) and cannot be efficiently selected using only $g$, $i$, and DDO$_{51}$ magnitudes without introducing considerable contamination by main-sequence stars. For this reason, we
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Figure 1. a. Spectroscopically-derived stellar parameters for stars in the LAMOST/KIC/ALLWISE sample, with the line we adopted to separate main-sequence stars from giant stars. b. The \(g - i\) and \(g - \text{DDO}_{51}\) colours of (spectroscopically-selected) main-sequence stars in this LAMOST/KIC/ALLWISE sample. The criteria box we adopt to photometrically select giant stars is shown in panel (b) and (c). In (b) we also show main-sequence stars in APOGEE sample to demonstrate how redder main-sequence stars (which are not present in LAMOST) appear in this colour plane. c. \(g - i\) and \(g - \text{DDO}_{51}\) colours of spectroscopically-selected giant stars in LAMOST/KIC/ALLWISE, coloured (and ordered on the plot) by their effective temperature. Stars with \([\text{Fe/H}] < -1.5\) are drawn with black edges, showing a mild metallicity dependence in the \(g - \text{DDO}_{51}\) colour. Most giants fall within the photometric selection, although the completeness drops for stars \(T_{\text{eff}} \gtrsim 5250\) K as they overlap with main-sequence star colours in this plane.

We can expect that any effective dwarf/giant selection using the \(g - \text{DDO}_{51}\) colour will be biased against hotter stars near the base of the red giant branch.

The photometric selection we adopt for giant stars in this work is,

\[
g - \text{DDO}_{51} > \max\{0.46 - 0.2(g - i), -0.10 + 0.2(g - i)\},
\]

and

\[
g - \text{DDO}_{51} < \min\{0.15 + 0.2(g - i), +0.96 - 0.2(g - i)\}.
\]

Using this selection we classify 8,947 stars as likely giants from the LAMOST/KIC/ALLWISE catalogue (of the 25,668 that met our photometric quality cuts). Of these, 8,891 (99.4\%) are spectroscopically-confirmed giant stars, giving a contamination rate of main-sequence stars of 0.6\%. The completeness fraction is 71\%. While the photometric selection could be adjusted to improve completeness, here we have chosen simple criteria to maintain a low contamination fraction. Note that the completeness fraction is temperature-dependent, and drops quickly for higher effective temperatures near \(T_{\text{eff}} \gtrsim 5250\) K, as main-sequence stars and hotter giant stars share similar \(g - i\) and \(g - \text{DDO}_{51}\) colours. The completeness fraction for LAMOST giant stars with \(T_{\text{eff}} < 5250\) K is 76\%. We stress, however, that the contamination and completeness fraction is subject to the LAMOST selection function (e.g., magnitude range, biases towards or against spectral types), and by the quality constraints that we have enforced on the ALLWISE photometry.

We repeated the steps above using the APOGEE DR14 Abolfathi et al. (2017) to investigate the impact on completeness and contamination. We find 20,124 matches between APOGEE and the KIC, and 19,952 unique sources that also have ALLWISE photometry. After applying the same quality cuts described above, our distilled APOGEE/KIC/ALLWISE sample contained 13,555 stars. Most of these stars are giants, a reflection of the APOGEE selection bias towards giant stars.

Despite this strong bias in favour of observing giant stars, we find that the estimated completeness and contamination fraction arising from our photometric selection do not change considerably. The completeness fraction is about 80\% – whether or not we restrict the sample to \(T_{\text{eff}} > 5250\) K – and the contamination fraction is 0.6\%. Since APOGEE is biased towards giant stars, this completeness fraction may be representative of an upper limit of what could be expected from our colour selection, unless we were to adjust it for the sake of increasing contamination. Nevertheless, although these estimated rates are sample-dependent, it is clear that the DDO_{51} filter can be used to identify giant stars with very little contamination whilst maintaining a reasonably high completeness fraction. From the APOGEE and LAMOST samples investigated, both showed comparable completeness and contamination rates: the photometric selection for giant stars recovered about 75\% of the true number of giants (as determined by spectroscopy), and the contamination of main-sequence stars is \(\lesssim 1\%\).

Using the APOGEE sample, in Figure 2 we plot WISE W1 – W2 colour as a function of \(J - K_s\), showing the same bifurcation in dwarf and giant stars noted by Bessell & Brett (1988) for purely near-infrared colours. From Figure 2 it can also be seen that all metal-poor giant stars have a WISE W1 – W2 colour of \(\gtrsim -0.05\), with a negligible temperature dependence. The most metal-poor stars can be retained by keeping giant stars with the reddest WISE W1 – W2 colour. However, the vast majority of giants in our sample are sufficiently warm that a purely near-infrared selection of metal-poor giant stars would suffer heavy contamination by main-sequence stars. Coupled with our \(g - \text{DDO}_{51}\) photometric selection to cleanly distinguish main-sequence stars from giant stars, we can now illustrate how this sample permits the easy identification of metal-poor giant stars using only photometry.

Continuing with the APOGEE sample, in Figure 3 we...
Based on the ant stars ([Fe/H] < −1.5) are marked with black edges, showing that all metal-poor giant stars in this sample have −0.05 < W1 − W2 < 0.05 (indicated by the coloured region). A photometric selection using only W1−W2 colour would be severely contaminated by main-sequence stars (shown in grey).

Figure 2. J − Ks colours (Skrutskie et al. 2006) against W1 − W2 colours for the APOGEE/KIC/ALLWISE sample. Spectroscopically-confirmed giant stars are coloured by their effective temperature $T_{\text{eff}}$ (Abolfathi et al. 2017), and all other points are shown in gray. Metal-poor giant stars ([Fe/H] < −1.5) are marked with black edges, showing that all metal-poor giant stars in this sample have −0.05 < W1 − W2 < 0.05 (indicated by the coloured region). A photometric selection using only W1−W2 colour would be severely contaminated by main-sequence stars (shown in grey).

Figure 3. Metallicity of the APOGEE/KIC/ALLWISE photometrically-selected giant sample ($N = 7,432$) as a function of W1 − W2 colour. Points are coloured by their APOGEE effective temperature. Another 487 (6%) photometrically-selected giant stars are not shown because they do not have metallicities in APOGEE, likely due to analysis issues (see text). We also show the fraction of metal-poor stars per colour bin for our photometrically-selected sample of giants. Above W1 − W2 > −0.05, the fraction of stars with [Fe/H] < −1.5 exceeds 25%. Thus, our photometric selection has increased the yield of metal-poor giant stars recovered by a factor of ~250 over a randomly selected sample.

2.2 Weighing the Giants

We have presented an efficient and effective photometric selection to identify giant metal-poor stars. Given the paucity of known metal-poor stars in the Kepler field and the routine use of asteroseismic scaling relations to estimate stellar masses and radii, this provides us with a unique opportunity to critically examine the existing scaling relations. While the number of metal-poor giant stars with publicly-available asteroseismic fundamental parameters ($\nu_{\text{max}}, \Delta \nu$) is very small, there is theoretical and observational evidence to suggest that the current scaling relations warrant a metallicity-dependent term in order to reconcile systematically over-estimated masses inferred from metal-poor stars (e.g., White et al. 2011, Mosser et al. 2013, Epstein et al. 2014, Gaulme et al. 2016, Guggenberger et al. 2016, Sharma et al. 2016, Huber et al. 2017). Here we cross match our catalog of photometrically-selected metal-poor stars with publicly available asteroseismic fundamental parameters to infer their masses and radii, and explore whether any correction is necessary to the existing scaling relations.

We cross matched the KIC and ALLWISE and se-
lected likely metal-poor giant stars based on \( g\text{--}\text{DDO}_{51} \) and \( W_1\text{--}W_2 \) colours, while maintaining the photometric quality cuts described earlier. We cross matched the resulting sample against the Hekker et al. (2011) catalog, which includes a thorough comparison of six different asteroseismic pipelines. Our search revealed four new highly likely metal-poor giant stars with measured \( \Delta \nu \) and \( \nu_{\text{max}} \) from multiple pipelines: \( \text{KIC} \)’s 6304081 (all 6 pipelines), 6231193 (6), 7729396 (3), and a fourth which will appear in a subsequent paper (Schlaufman et al. 2018, in preparation). The pipeline measurements are typically in agreement within a few percent for all three stars (see Table 1).

We assume \( T_{\text{eff,}\odot} = 5777 \) K for the Sun, and adopt \( \Delta \nu_\odot = 135.0 \pm 0.1 \) \( \mu \)Hz and \( \nu_{\text{max,}\odot} = 3140 \pm 30 \) \( \mu \)Hz as per Epstein et al. (2014). If we employ the photometric temperatures from the KIC and take the mean \( \nu_{\text{max}} \) and \( \Delta \nu \) values from Table 1 the asteroseismic scaling relations imply respective solar masses of 1.01, 2.19, 1.04, and solar radii of 10.7, 10.6, 20.5 for our metal-poor giant star candidates. The estimated uncertainties on these masses is of order 10\% (e.g., Chaplin & Miglio 2013). The indicated masses are relatively high for metal-poor stars. Metal-poor stars are generally thought to be ancient, which demands that they would live relatively short lifetimes and not remain observable today. Given the good agreement in global oscillation parameters reported from multiple pipelines, the choice of mean oscillation parameters or those from any individual pipeline has little impact on the inferred masses and radii. For example, the scatter in oscillation parameters for KIC 6231193 translates to a scatter in inferred mass of just \( \sigma(M) = 0.03 M_\odot \). We also note the effective temperatures estimated by the KIC catalog agree excellently with the distribution of temperatures found for confirmed metal-poor giant stars in the Schlaufman & Casey (2014) catalog. The photometric temperatures would have to be systematically overestimated by \( \sim 2,500 \) K to bring all inferred masses within 0.8 \( M_\odot \).

3 DISCUSSION

We have leveraged existing public photometry and spectroscopy in the Kepler field to verify that the \( \text{DDO}_{51} \) filter is successful in separating FGK dwarf and giant stars. While late-type (M0.0 and later) giant stars are difficult to separate from dwarf stars given the \( g\text{--}\text{DDO}_{51} \) colour, infrared photometric selections already exist that allow for a clean selection of M-type giant stars (Bessell & Brett 1988). Our photometric selection for giants is extremely simple (i.e., we did not choose to optimise parameters to maximise yields), and we estimate the contamination in our giant sample to be \( \sim 1\% \), subject to the selection function of the APOGEE and LAMOST samples used. The completeness fraction is estimated to be about 75\%, with a bias against giant stars with \( T_{\text{eff}} \gtrsim 5150 \) K.

The dwarf/giant separation power of \( \text{DDO}_{51} \) is well established, and there is no doubt it was the primary reason that the KIC was successful in identifying dwarf stars (Verner et al. 2011). Here we have shown that the giant stars in the resulting sample have spectroscopic metallicities that are strongly correlated with \( W_1\text{--}W_2 \) infrared colour. This correlation is not present in dwarf stars at a level that permits metal-poor stars to be easily identified. Indeed, Figure 2 demonstrates that dwarf stars of all metallicities display...
infrared colours that are indistinguishable from metal-poor giant stars. For this reason, a dwarf/giant discriminant is required to reveal the correlated signature between stellar metallicity and infrared colour.

An examination of theoretical stellar spectra reveals the explanation for this strong correlation between metallicity and W1 – W2 colour. Using the PHOENIX spectral library [Husser et al. 2013], Kennedy & Wyatt (2012) and Schlaufman & Casey (2014) showed that the dependence of metallicity on W1 – W2 relies on the presence of strong CO absorption at \( \approx 4.5 \mu m \) (i.e., in the middle of W2). This bandhead is strong, and only begins to disappear at [Fe/H] \( \lesssim -2 \) for a giant star with \( T_{\text{eff}} \approx 4800 \) K. There are no strong stellar absorption features in wavelengths covering the W1 band, therefore making W1 – W2 a sensitive proxy for stellar metallicity.

Schlaufman & Casey (2014) first utilised W1 – W2 colour to efficiently identify bright metal-poor stars from existing public data. Their selection is as efficient as existing studies seeking metal-poor stars, while the candidates they identify are several magnitudes brighter. This property minimises the requisite telescope time for spectroscopic confirmation and subsequent detailed chemical abundance analysis. A number of photometric cuts are employed by Schlaufman & Casey (2014) in addition to the W1 – W2 colour. Some cuts accounted for expected temperature dependencies, while others were included because they empirically improved the yield of metal-poor giant stars.

Young, relatively metal-rich dwarf stars are the primary contaminant that result from the original Schlaufman & Casey (2014) photometric selection. Our analysis of public photometry and spectroscopy in the Kepler field has revealed the reason for this contamination and further verified the potential in using infrared colours to select metal-poor giant stars. When coupled with a simple dwarf/giant photometric selection, our analysis shows that the W1 – W2 infrared sensitivity alone is sufficient to effectively select metal-poor stars. It would appear the additional empirical photometric cuts employed by Schlaufman & Casey (2014) primarily served to minimise the dwarf contamination, thereby improving the overall yield of metal-poor giant stars.

Infrared photometric selections are advantageous because they are minimally affected by strong absolute or differential extinction. While we have shown the metallicity sensitivity in giants is principally correlated with the mid-infrared W1 – W2 colour, the central wavelengths of \( g \) and DDO\(_{11}\) nearly overlap at 510 nm. Due to the their bluer wavelengths, one might expect the \( g \) and DDO\(_{11}\) filters to be considerably impacted by extinction. However, because the \( g \) and DDO\(_{11}\) filters have central wavelengths that are very similar, both filters are affected by dust in a similar way. For this reason, the \( g – \)DDO\(_{11}\) colour has a very small dependence on extinction. Therefore, a photometric selection of metal-poor stars that makes use of \( g – \)DDO\(_{11}\) and W1 – W2 will be minimally impacted by dust. This is particularly relevant for metal-poor star searches in the inner Galaxy, where absolute and differential extinction is strongest. This is important, as theoretical models of galaxy formation predict that the oldest stars in the Milky Way should be metal-poor stars found in the bulge (e.g., Tumlinson 2010).

We have employed our photometric selection to identify likely metal-poor giant star candidates with publicly available global oscillation parameters. There is excellent agreement between reported parameters from different pipelines for our candidates. Standard asteroseismic scaling relations imply masses exceeding 1 \( M_\odot \), up to 2.19 \( M_\odot \) for the most extreme case. For metal-poor giant stars – which are presumably old halo stars – the expected masses are \(~0.8 \) \( M_\odot \). Higher masses are inconsistent with the requisite ancient age of the halo stars. Although our sample size is small (\( N = 3 \)), this discrepancy implies that the standard scaling relations would have to be over-predicting the masses of metal-poor stars by 25% to \(~175\% \) in order to be consistent with the observations. Although there are theoretical modifications to standard scaling relations that attempt to correct for some of this discrepancy (e.g., White et al. 2011), the impact is of the order 5%. Therefore, our metal-poor giant star candidates suggest that either a stronger metallicity-dependent correction is necessary to resolve this discrepancy, or that metal-poor stars have much higher masses than expected from stellar evolution.

### Table 1. Global oscillation parameters measured from six different pipelines for photometrically-selected metal-poor giant star candidates. Pipeline acronyms are as per [Hekker et al.](2011).

<table>
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<th>A2Z</th>
<th>SYD</th>
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4 CONCLUSIONS

We have derived a simple photometric selection for FGK-type giants based on public \( g, i, \) and DDO\(_{11}\) photometry in the Kepler field. Given a single two-colour cut, we find giant completeness rates of \(~75\% \), with \( \lesssim 1\% \) contamination of dwarfs, subject to the selection functions of LAMOST and APOGEE, and the magnitude ranges considered. We distill a sample of photometrically-selected giant stars and show a strong correlation between spectroscopic metallicity and mid-infrared W1 – W2 colour. This relationship is not present in dwarfs, so metal-poor candidate stars selected solely from mid-infrared W1 – W2 excess will be contaminated by dwarf stars across all metallicities.

Our work extends that of Schlaufman & Casey (2014), who first showed that metal-poor stars could be successfully...
identified through infrared colours (see also Kennedy & Wyatt [2012]). Here we have shown that the additional cuts used in Schlaufman & Casey (2014) to empirically improve the yield of metal-poor giant stars primarily act to minimise the number of dwarf stars in the sample, rather than principally discriminating on metallicity.

Our photometric cuts are well-founded theoretically. The log g sensitivity in g−DDO51 arises from pressuresensitive spectral features that are strong in dwarfs but weak or non-existent in giants of the same temperature. Similarly, the dependence of W1 − W2 colour on metallicity relies on negligible spectral features in W1, but strong molecular CO absorption present in giant stars at ≈ 4.5 µ (i.e., in W2). Here we have demonstrated that coupling these two simple photometric selections provides enormous potential in robustly identifying metal-poor stars, even in heavily extinguished regions (e.g., the bulge). For these reasons, we argue that a photometric selection that employs g−DDO51 and W1 − W2 colours to identify metal-poor star candidates in the inner Galaxy may be the most promising way to discover any remaining low-mass Population III in the Galaxy.

We have identified metal-poor giant star candidates in the Kepler field that have publicly available global oscillation parameters from asteroseismic pipelines. There is good agreement between different asteroseismic pipelines for these stars. However, the masses inferred from standard scaling relations are higher than expectations for ancient metal-poor stars. These results imply that either asteroseismic scaling relations over predict masses for metal-poor giant stars, or that the metal-poor giant stars examined here are younger than expected.

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