The SkyMapper Search for Extremely Metal-Poor Stars in the Galactic Halo

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on behalf of:

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- The *SkyMapper* photometric survey of the southern sky has the *discovery of extremely metal-poor (EMP) stars* as one of its *main science aims*.

This is accomplished by the inclusion of an intermediate-band '*v*' filter that encompasses the H+K lines of Ca II (3933, 3968Å) to generate a photometric index that is sensitive to metallicity.

- During the commissioning of the telescope, a 'commissioning survey' for EMP stars was carried out. Despite generally poor image quality, this survey led to the *the discovery of the* ***most iron-poor star known****: SMSS J031300.36-670839.3 which has [Fe/H] < -6.5 (3D, NLTE - see Nordlander et al 2016).*

- The commissioning survey also led to the discovery and analysis of a further 41 new EMP stars with [Fe/H] < -3 (Jacobson et al 2015).

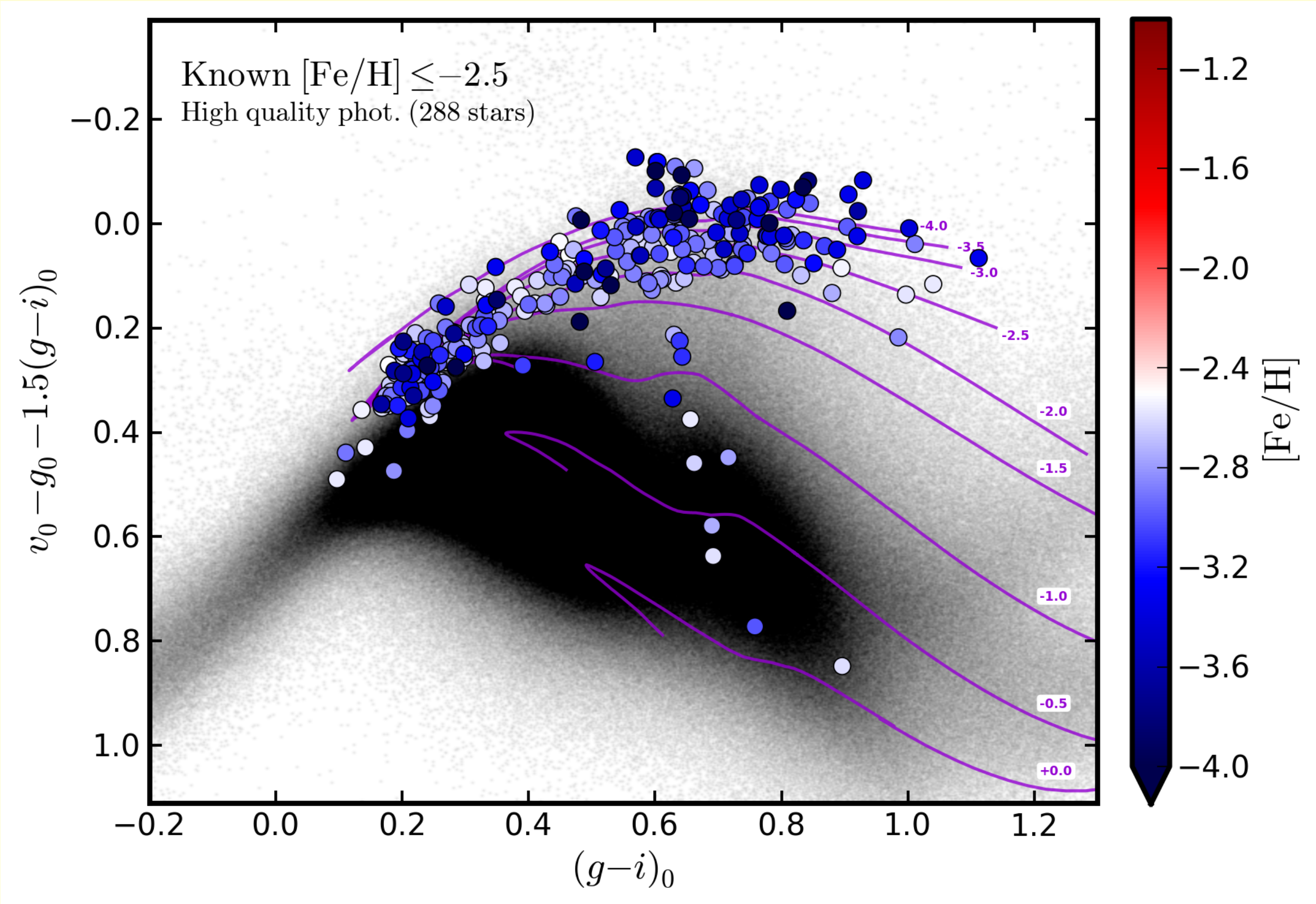
• The 'commissioning survey' ended when the telescope became fully operational and since March 2015 the *SkyMapper* Southern Sky Survey has been on-going.

• The *SkyMapper* survey program has been dominated initially by the acquisition of relatively short exposure images that will ultimately provide the photometric calibration for the full survey.

• *The limiting magnitudes of the short exposure data (v ~ 17.3, g ~ 17.7, i ~ 17.7 AB mags) are perfect for searching for EMP stars bright enough to follow-up with high dispersion spectroscopy on 8-10m class telescopes.*

We are currently using the SkyMapper DR1 photometry to search for EMP candidates in the Galactic Halo.

SkyMapper DR1 photometry metallicity sensitive 2-colour diagram



Shown in purple are a set of Dartmouth isochrones for age 12.5 Gyr and metallicities between solar and -4.0. The lower part of the main sequence is NOT plotted – i.e., biased to giants, subgiants and turnoff stars. A metallicity index offset +0.05 has been applied to the isochrones.

The isochrones and the location of known metal-poor stars are (mostly) consistent.

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• Given that metallicity sensitive diagram seems to show the expected sensitivity, how should we go about selecting candidates for low resolution spectroscopy?

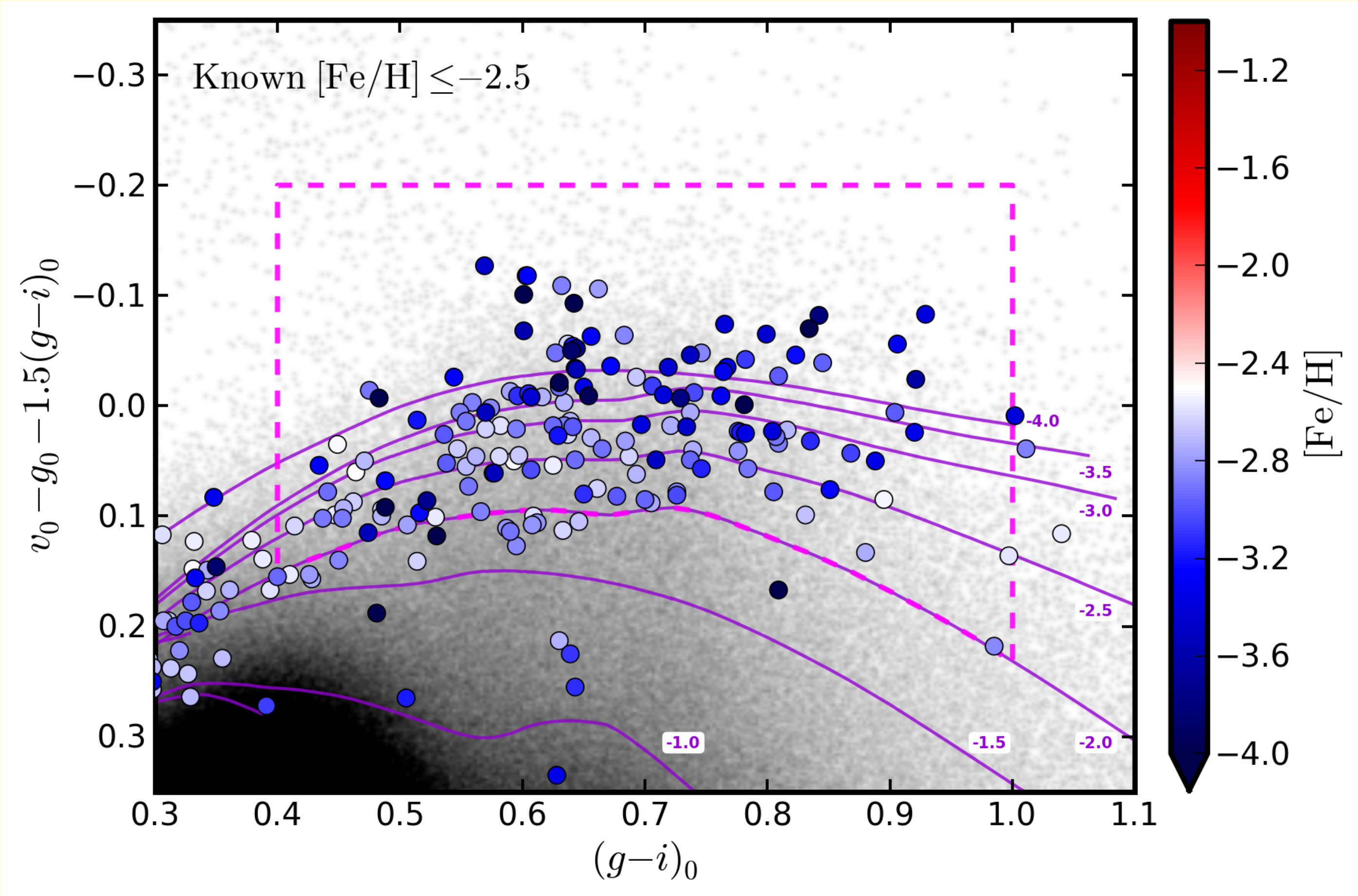
• The previous plot suggests we should concentrate on giants because for the hotter stars the isochrones are relatively close together (i.e., metallicity sensitivity is reduced) and the known metal-poor stars are not as well separated from the large number of solar-type dwarfs. So we have chosen:

- $0.4 \leq (g\text{-}i)_0 \leq 1.0$
- $-0.20 \leq m\_index \leq \sim 0.11$

The upper *m_index* value allows for errors in the *m_index* (which are potentially as large as 0.085 mag) while the lower cutoff is actually the location of the -2.0 isochrone.

This selection yields about ~29,500 candidates for $g < 16$ and 10,850 candidates for $g < 15$. (!!)

SkyMapper DR1 photometry metallicity sensitive 2-colour diagram



The value of the lower cutoff is quite crucial as *the number of candidates goes up very steeply as it's increased.* On the other hand it would a pity to miss any "prime" candidates because their *m_index* errors scattered the star downwards.

- We have then taken the candidate list and proceeded to observe stars from the list with the ANU 2.3m telescope and the WiFeS spectrograph (B3000 setup – λ coverage ~3500-6000 Å).

- The reduced 2.3m spectra are flux calibrated and the best fitting model from a grid of MARCS model atmosphere fluxes determined using the "fitter" code developed by Simon Murphy (described in Norris et al 2013). *The spectrophotometric model fits provide estimates of T_{eff}, log g and [Fe/H] for each observed spectrum.*

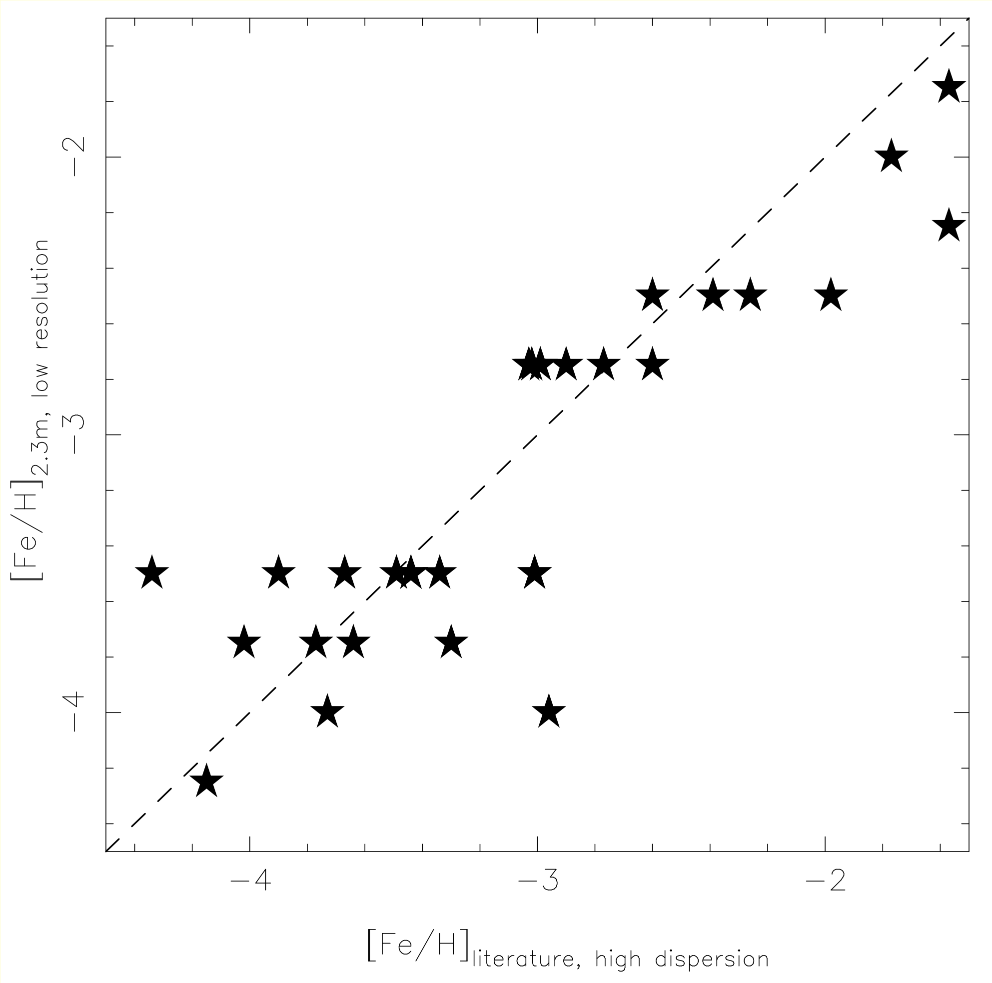
- *Here we report the outcome the 2.3m observing runs from Feb 2016 until early Oct 2017, during which spectra have been obtained for over 2000 EMP candidates.*

<u>Note:</u> because the 2.3m observing started before the DR1 release, there are some EMP-candidates that are not in DR1. However, the on-going observations now use just the DR1 photometry defined sample.

- We have also finally understood the reason(s) for the previous non-trivial contamination in the reduced 2.3m spectra from non-EMP stars that nominally lay in the selection window.
- In the most recent 2.3m runs we find that:
  - at most a few percent of targets have [Fe/H] > -2.0
  - ~40% of the targets have [Fe/H] ≤ -2.75

As a result our survey is among the most efficient known for identifying candidate EMP-stars. For example, it is comparable with that for the northern hemisphere based PRISTINE survey (Starkenburg et al 2017), which uses similar photometric selection techniques, but with a narrower filter, compared to the SkyMapper v-filter, centred on Ca II H+K.

- One obvious question is how good are the ‘fitter’ [Fe/H] values?



Plot shows a well defined relation between the ‘fitter’ [Fe/H] values (quantizied at the 0.25 dex level) and high dispersion spectroscopic values of [Fe/H] from the literature for 30 stars.

Selecting stars with ‘fitter’ abundances at and below -3 is unlikely to significantly bias the actual metallicity distribution of the stars.

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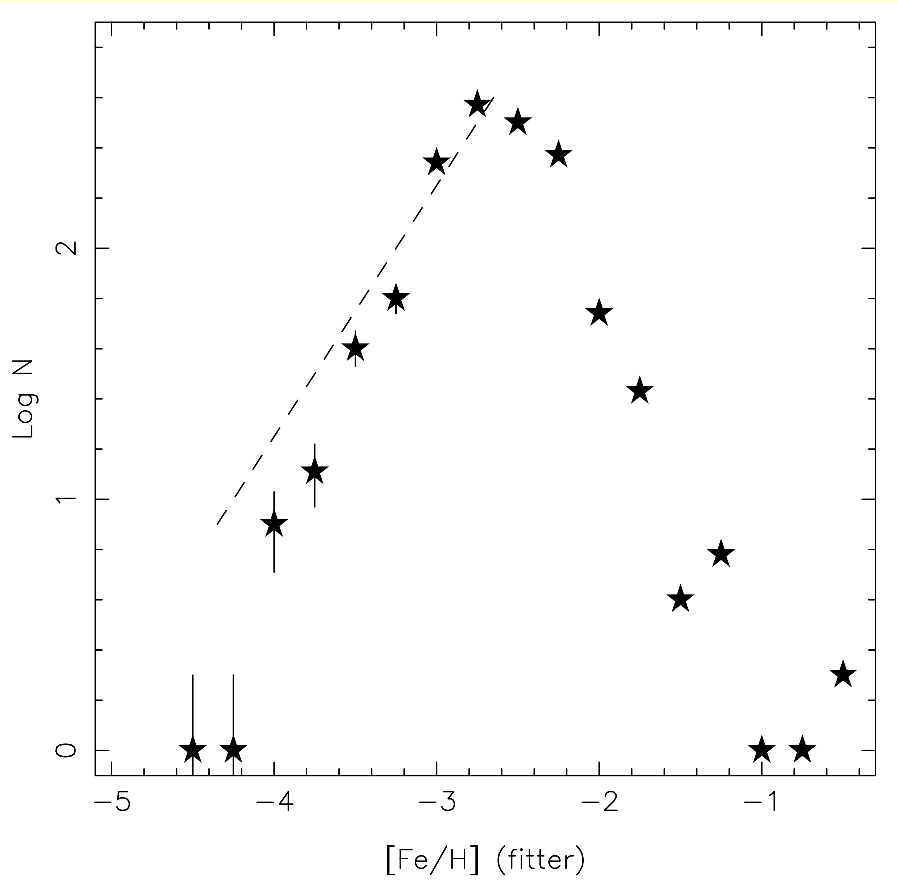
- *Metallicity Distribution Function*



The MDF for the 1362 candidates observed at the 2.3m that lie in the selection window confirms that the process is basically working:

- the turnover in the metallicities is at [Fe/H] = -2.75, which is where we'd like it. The *efficiency is excellent* (~25% at or below -3, 52% at or below -2.75) and the *contamination is minimal* (~4% above -2).
- The apparent cutoff in the MDF at ~ -4.0 is not new (e.g. Yong et al 2013) and illustrates how rare stars below -4 really are.

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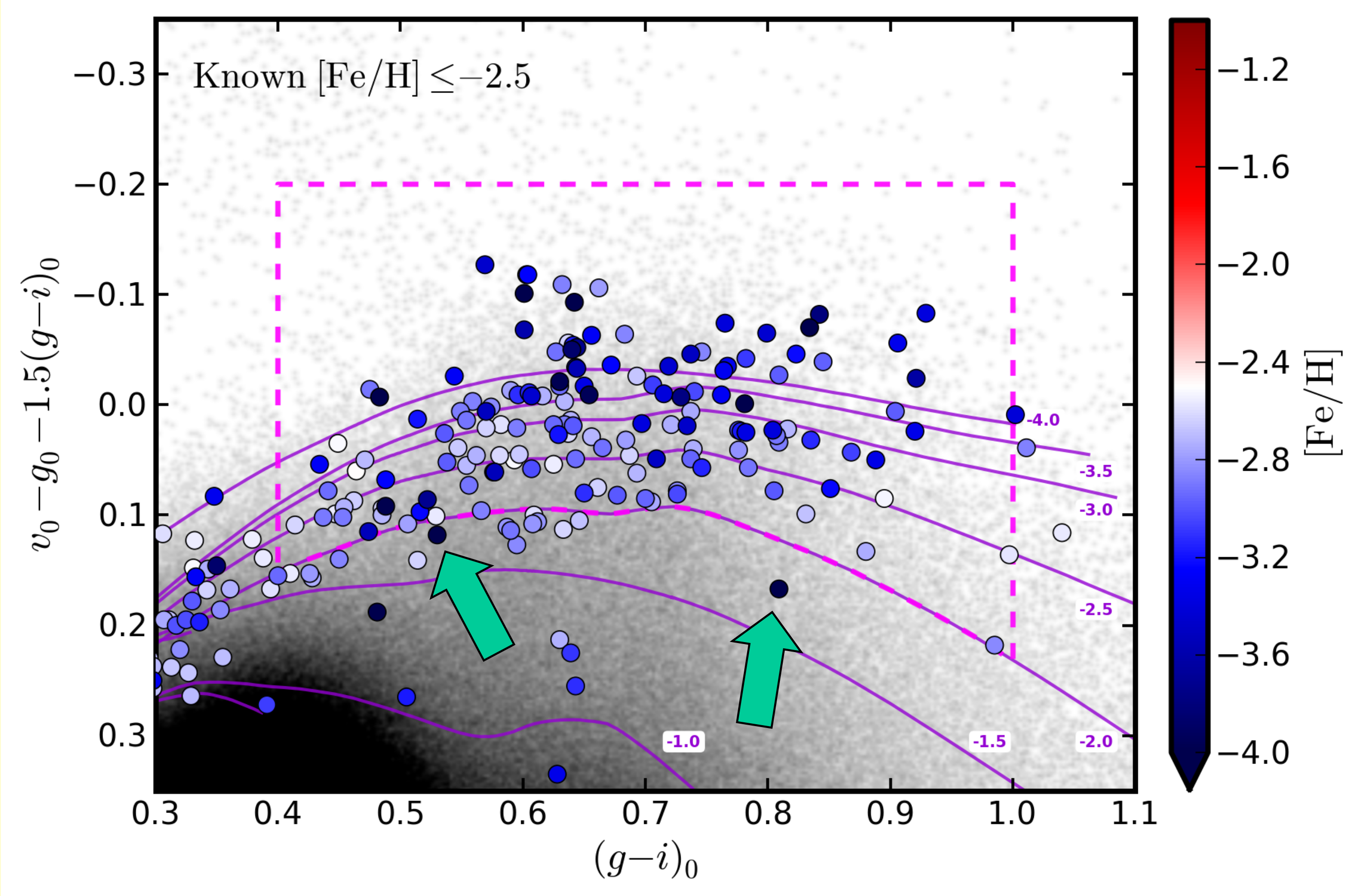
Issues:



Marked stars are HE2139-5432 (left) and HE1310-0536 (right) which have ([Fe/H], [C/Fe]) values of (-4.02,+2.59) and (-4.15,+2.36), respectively.

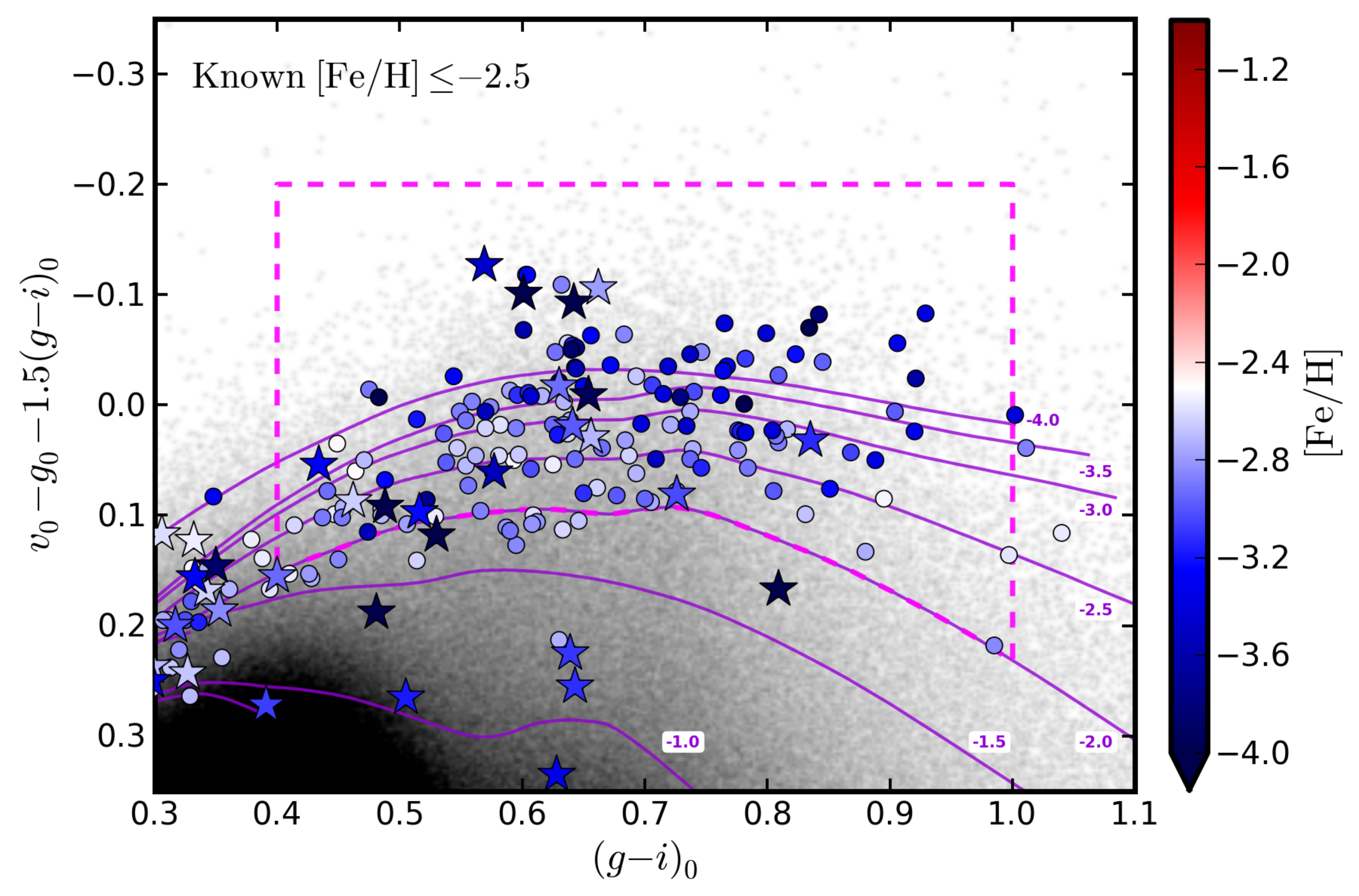
Issues:

Clearly we would NOT select these very carbon-enhanced EMP stars with the current selection window. *They lie 'low' in the metallicity index plot because the additional CH-feature absorption in the v filter band pass causes them to mimic a more metal-rich object.*

The effect of this potential bias remains to be fully quantified, and it is likely we'll need to use additional photometric colours to isolate stars of this type. The bias will likely be a function of [Fe/H], [C/Fe] and temperature (colour).

We note that the bias may only apply to very strong carbon enhancements ([C/Fe] > +2 at [Fe/H] = -4 ?) because the Jacobson et al 2015 sample did not obviously lack CEMP stars, although it did not contain any stars with [C/Fe] > 1.4. Also, the extremely iron-poor star SMSSJ0330-67 was found and it is very C-rich ([C/Fe] > +4).

Issues:



Star symbols are objects with [C/Fe] > +0.7; some are substantially more C-rich.

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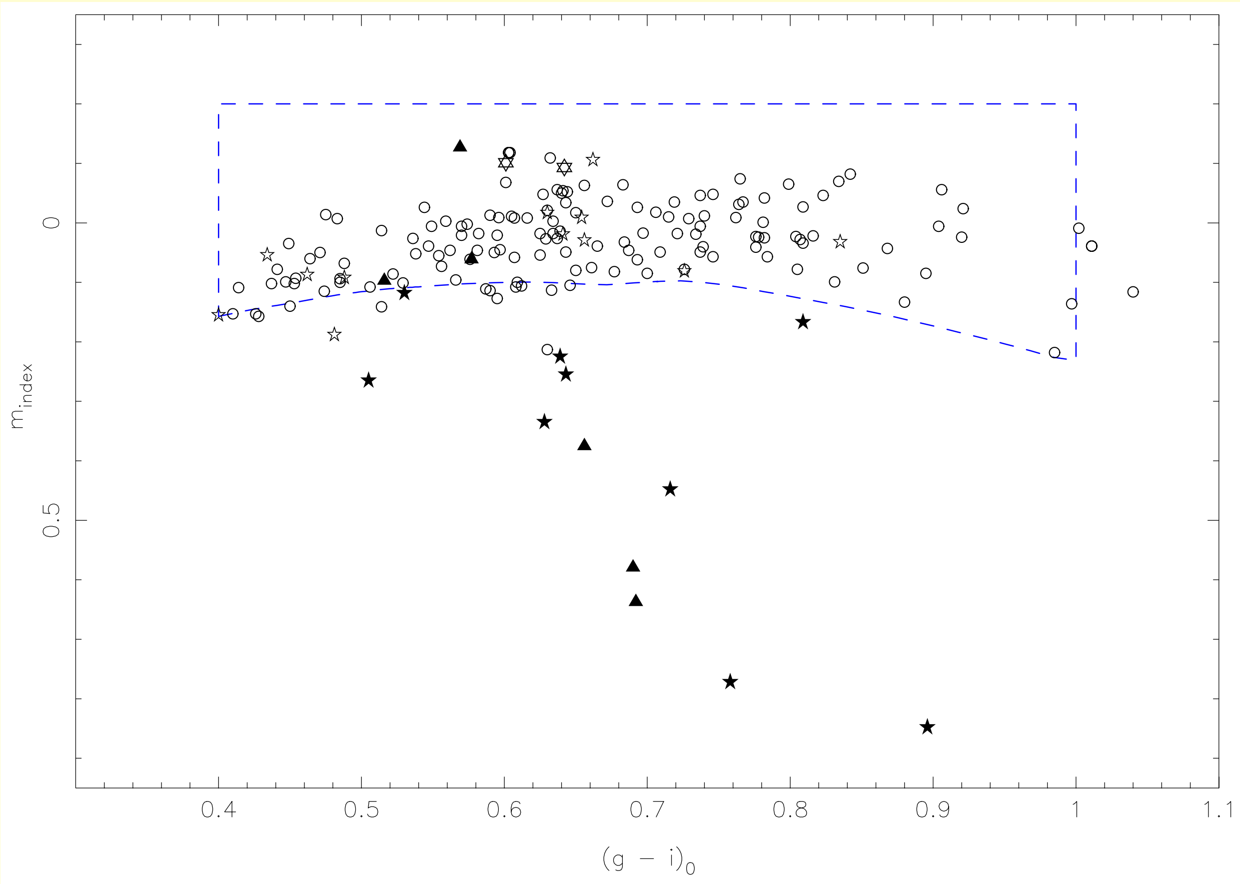
We can use the sample of known stars with [Fe/H] < -2.5 and a measured [C/Fe] to investigate the 'bias' in more detail. There are 172 stars in this sample.



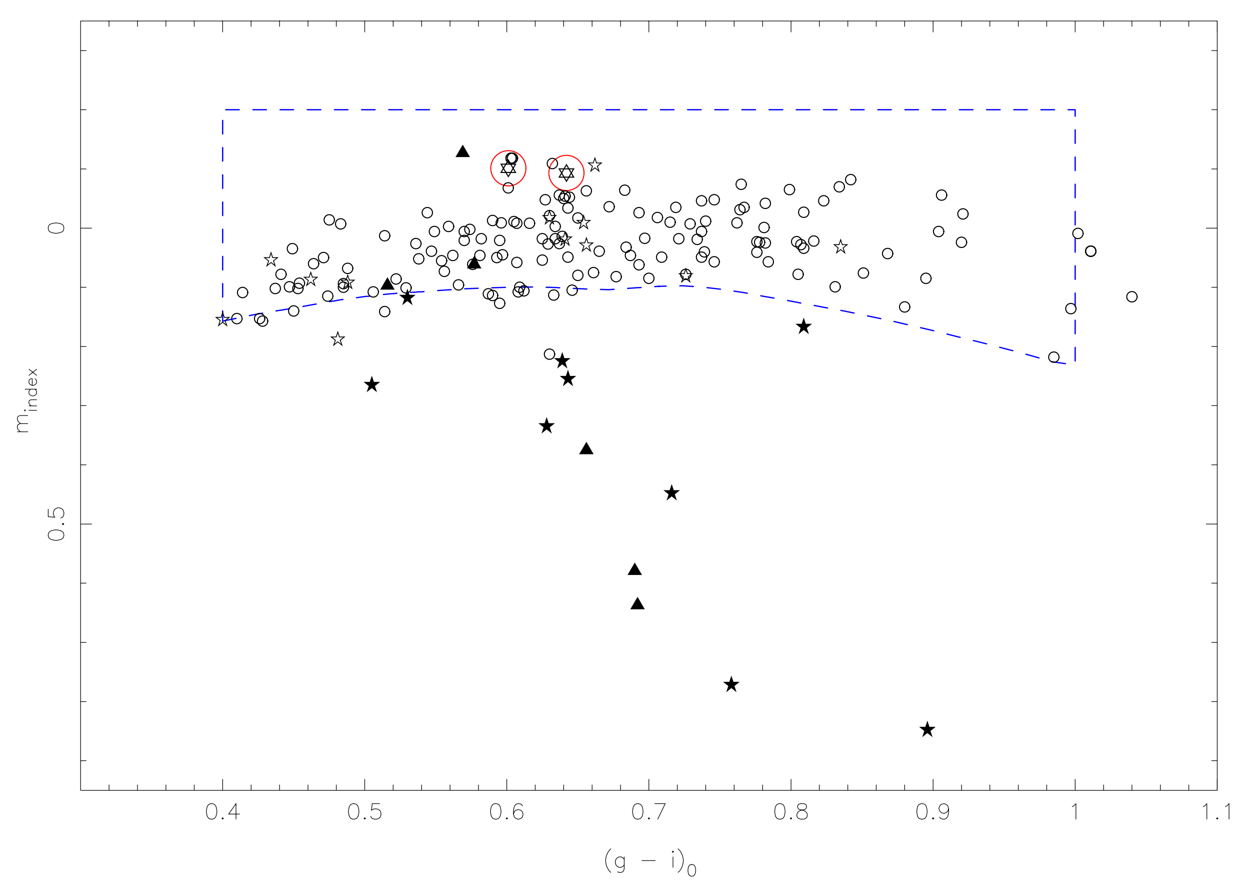
Filled 5-pt stars have [C/Fe] ≥ +2 (9 stars)

Filled triangles have 1.2 ≤ [C/Fe] < 2.0 (6)

Open 5-pt stars have 0.7 ≤ [C/Fe] < 1.2 (12)

Open circles have [C/Fe] < 0.7 (143)

The good news is that the survey is likely basically 100% complete for [C/Fe] < +0.7 and [Fe/H] < -2.5.



<u>Red circled stars are SMSS0313-67 and HE0107-5240</u> which have ([Fe/H, [C/Fe]) of (< -6.5, > +4) and (-5.4 and +3.7), respectively. Clearly we would not miss similar stars, so *survey likely 'complete' for [Fe/H] < -5 regardless of [C/Fe]*.

(not that we have found any new ones yet)

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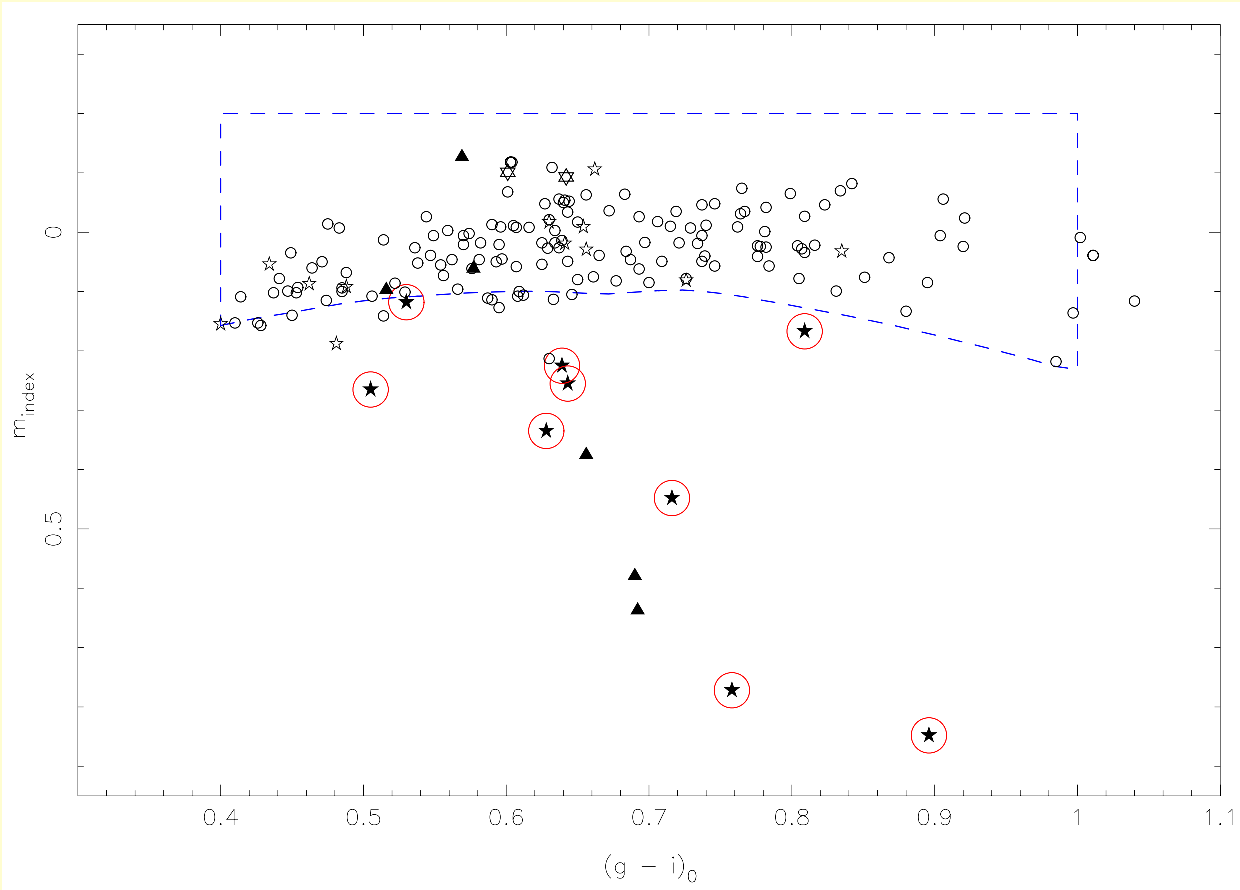

<u>Red circled stars all have [C/Fe] > +2.</u> The two nearest the boundary have [Fe/H] ~ -4.1, the next four have [Fe/H] ~ -3.2, the other three have [Fe/H] > -3. *Conclusion: survey is likely 100% <u>incomplete</u> for [Fe/H] > ~ -4.3 and [C/Fe] > +2.*

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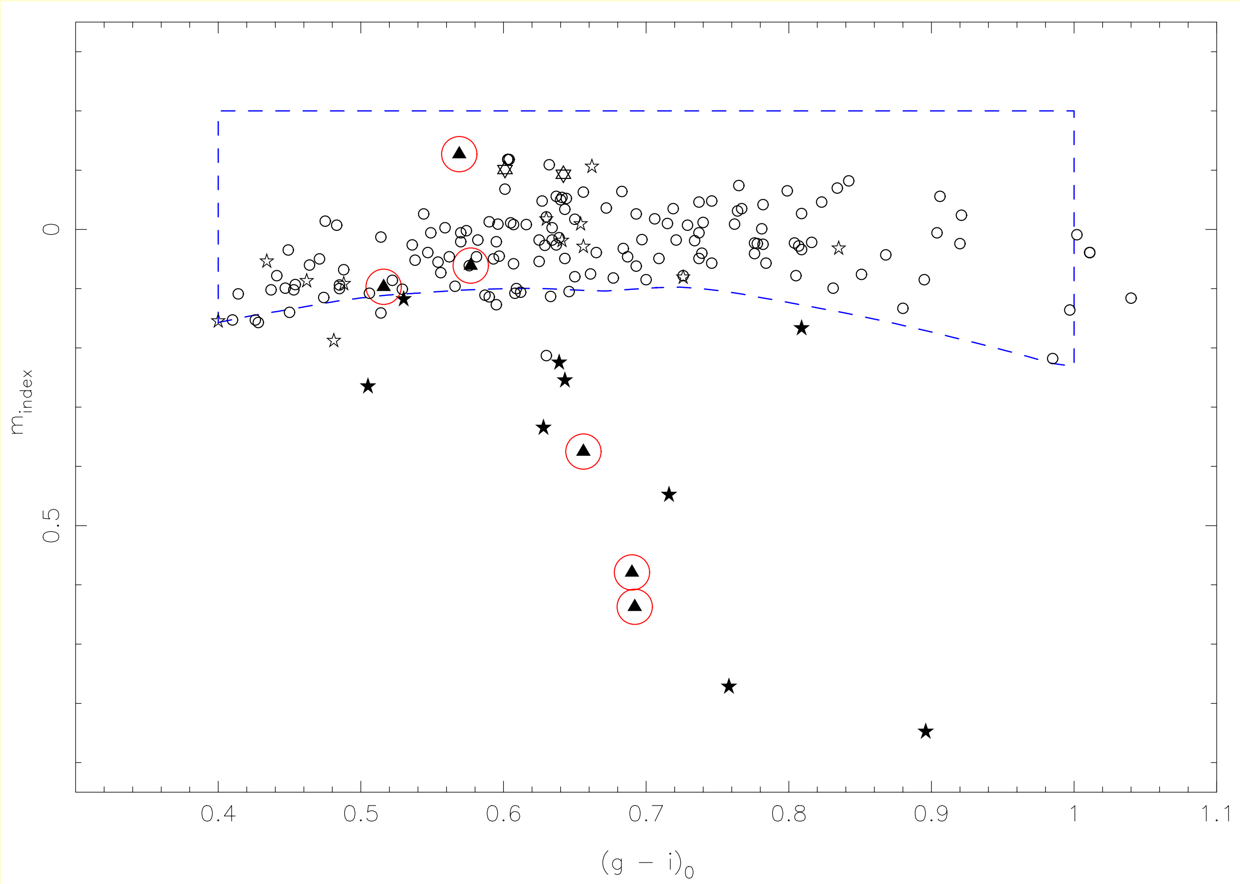

<u>Red circled stars all have [C/Fe] between 1.2 and 2.0.</u> The three inside the selection window have [Fe/H] ~ -3.5, the others have [Fe/H] ~ -2.6,

Conclusion: survey is likely close to 100% <u>complete</u> for [Fe/H] < ~ -3.5 and [C/Fe] between 1.2 and 2.0.

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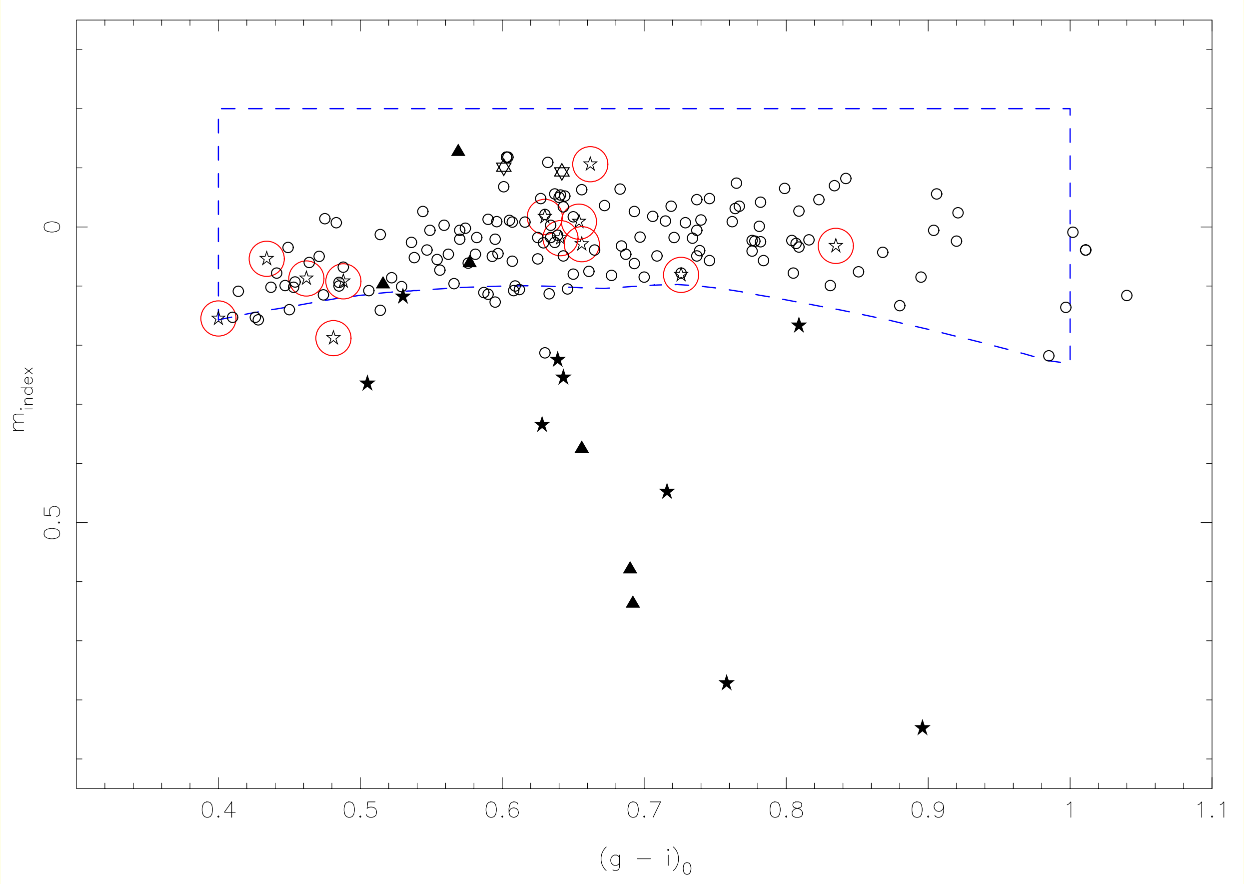
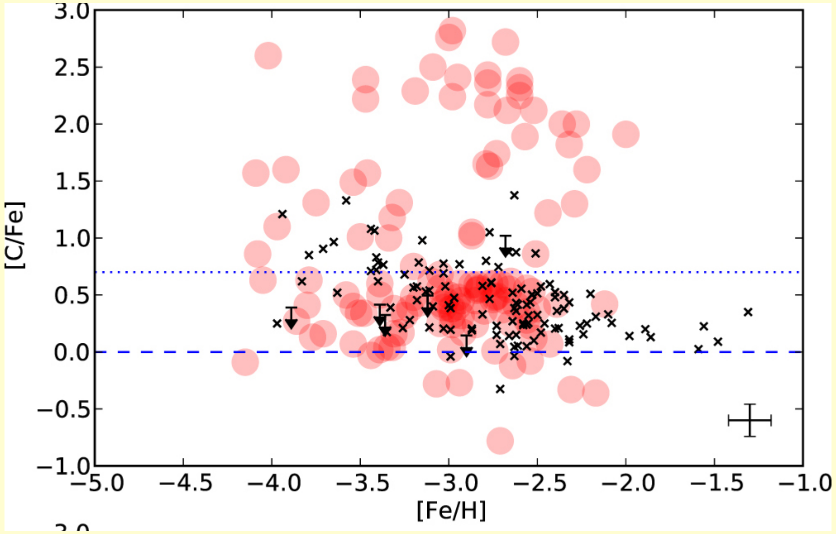


Red circled stars all have [C/Fe] between 0.7 and 1.2. [Fe/H] values range from -4.1 to -2.7. *Conclusion: survey is likely ~100% complete for [Fe/H] < ~ -2.7 and [C/Fe] between 0.7 and 1.2*.

• In summary, the SkyMapper EMP survey seems to be basically unbiased for all metallicities of interest if [C/Fe] < ~ +1.2, and for all ultra metal-poor stars regardless of [C/Fe].

• But it is clearly biased against stars more metal-rich than ~ -4.3 that have large carbon enhancements. An additional selection process will be needed to find these stars.

• This is all consistent with the results from Jacobson et al (2015):



Plus-symbols are from the commissioning survey follow-up: note the lack of stars with [C/Fe] > ~ +1.2 compared to the Yong et al (2013) sample (red circles).

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Conclusions

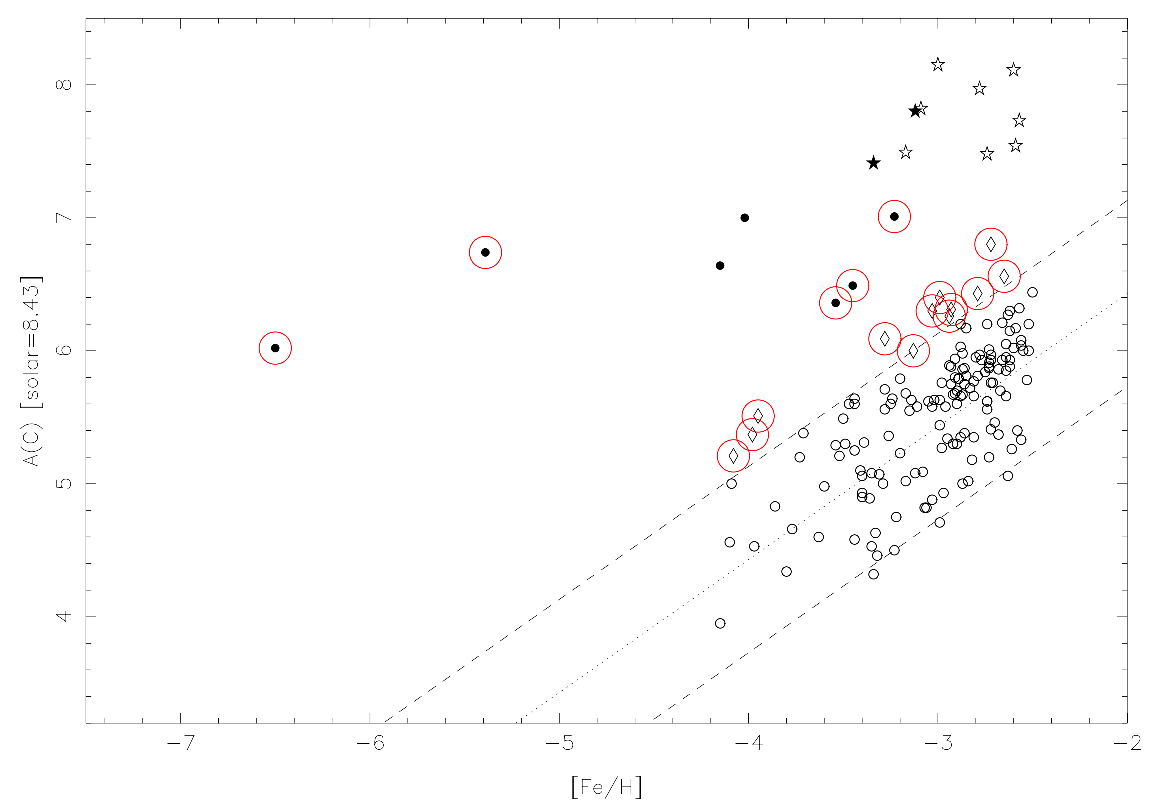
- Overall a useful set of candidate EMP stars can be reliably selected from the SkyMapper DR1 dataset.
- 2.3m spectroscopic follow-up has produced a number of candidates for follow-up at high dispersion with Magellan.
- EMP stars are nevertheless rare and we will need to continue to pursue the 2.3m program in order to increase the number of candidates at the lowest metallicities. Ultimately a sample 4-5x larger (~5000 stars) may well be required to find a significant number (~dozen?) of stars below -4.5 with the current selection process.
- *While we will continue with the 2.3m program we are expecting substantial numbers of our targets to be included in the observing programs of the Taipan and FunnelWeb surveys that will commence early next year.*

Thanks to all the people at SSO and at Mt Stromlo who keep the SkyMapper Survey running, in the sense of the telescope and its systems, the processing of the imaging, and the distribution of the data products.

Without you the EMP-stars project would not happen!

SkyMapper operations are supported in part by a LIEF Grant from the ARC. SkyMapper Data products can be accessed through the SkyMapper node of the All Sky Virtual Observatory (ASVO). The SkyMapper ASVO node is hosted by the National Computational Infrastructure (NCI). Development and support the SkyMapper node of the ASVO has been funded in part by Astronomy Australia Limited and the Australian Government through the Commonwealth's Education Investment Fund and National Collaborative Research Infrastructure Strategy, particularly the National eResearch Collaboration Tools and Resources (NeCTAR) and the Australian National Data Service Projects.

Bonus Slide (generated as a result of questions after the talk).



Lines are for [C/Fe] = +0.7, 0.0, -0.7

The figure shows the known abundance stars in the A(C) – [Fe/H] plane. Red circled symbols, and all the points lying below the upper dashed-line ([C/Fe] = +0.7), are in the SkyMapper selection box. But clearly the Group I stars (A(C) > ~7.3, [2 CEMP-no, 8 CEMP-s]) are all missed, and the two Group III stars at [Fe/H] ~ -4.1 are also not selected. However, all Group II stars selected.

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