Group meeting

Probing the inner Galactic Halo with blue horizontal branch stars: Gaia DR3 based catalogue with atmospheric and stellar parameters

R. Culpan, M. Dorsch, S. Geier, I. Pelisoli, U. Heber, B. Kubátová, and M. Cabezas

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Reporter：Tao Wang

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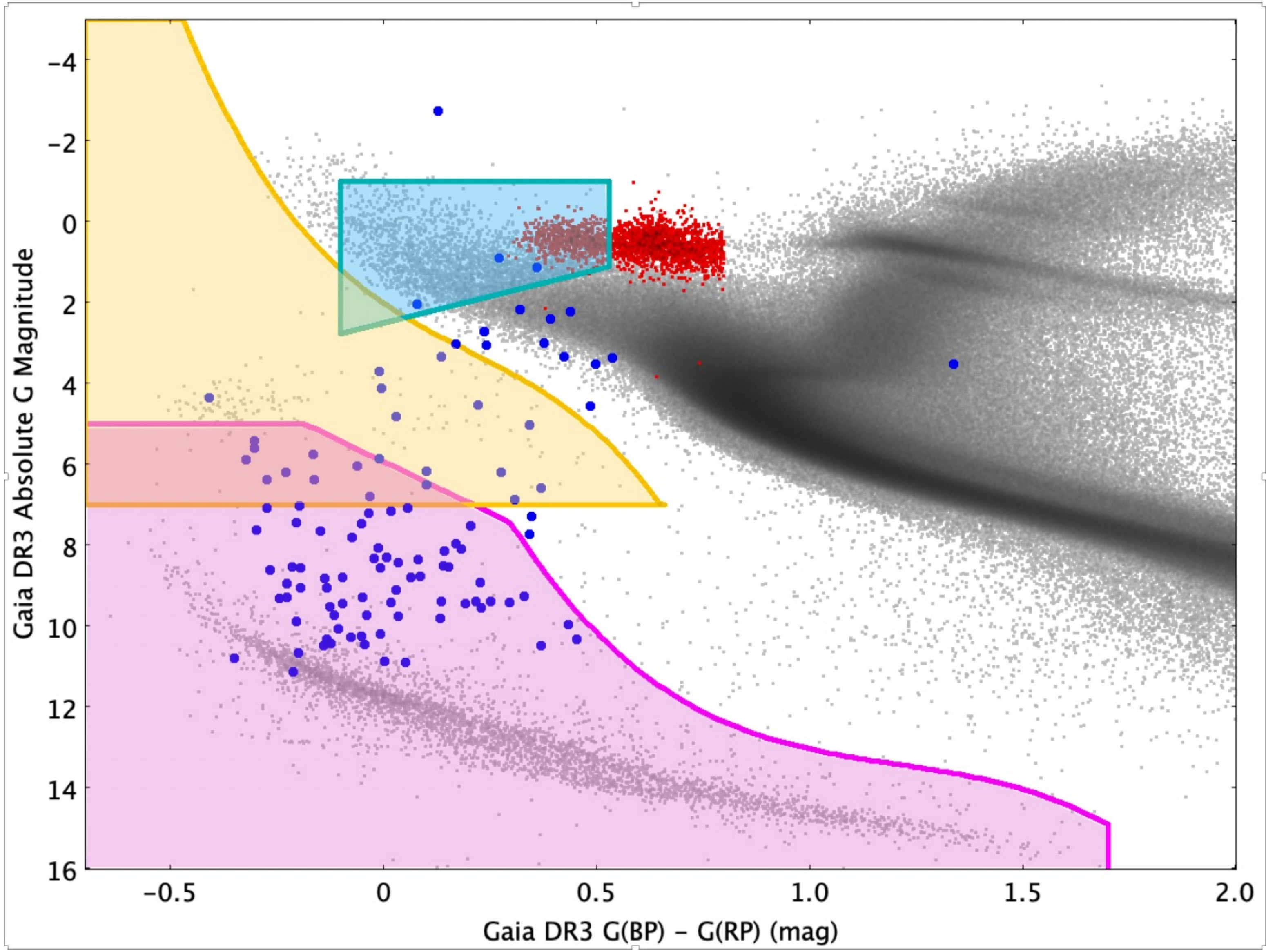
1. Introduction

- The term horizontal branch (HB) was coined to describe a horizontal structure observed in the colour magnitude diagram (CMD) in globular clusters.
- The horizontal branch extends from the red clump at the red end through the instability strip where RR-Lyrae are found to the extreme horizontal-branch (EHB) at the blue end (*Catelan 2009*).
- HB stars are what remains of low-metallicity $\sim 0.8 M_{\odot}$ to $\sim 2.3\ M_{\odot}$ main-sequence stars that have evolved past the helium flash at the end of the red-giant phase.
- The extent of the HB varies from cluster to cluster which led to the distinction of red HB stars red wards of the instability strip and blue HB stars blue wards. As such these are early type stars that are already billions of years old when they move to the BHB.

- Observationally, the photometry of cooler, A-type, BHB stars places them in the same colour-magnitude space as main-sequence A- and B-type stars.
- The cooler A-type BHB fall on the bluer side of the instability strip where RR-Lyrae are found (*Montenegro et al. 2019*).
- The hotter B-type BHB stars fall on the redder side of the EHB stars, also called hot subdwarf stars (*Heber 2009*).



- turquoise shading: BHB CMD selection region from *Culpan et al. (2021)*
- red dots: a selection of RR-Lyrae from Gaia DR3 *Clementini et al. (2022)*
- yellow shading: hot-subdwarfs CMD selection region from *Culpan et al. (2022)*
- pink shading: white dwarfs CMD selection region from *Gentile Fusillo et al. (2021)*
- blue circles: ELM white dwarfs from Pelisoli & Vos (2019)

This work they present a new release of the *Gaia* DR3 based catalogue of halo BHB stars that is more complete than the original *Gaia* Early Data Release 3 (EDR3) based version (*Culpan et al. 2021*) in crowded regions, particularly close to the Galactic Plane, and at the bluer end of the HB where late B-type BHB stars are expected.

The catalogue of Galactic Halo BHB candidate stars with stellar parameters derived from their spectral energy distributions (SEDs) is a subset of the newly released *Gaia* DR3 based catalogue.

The SEDs have been generated using photometric data from multiple large-scale surveys.

They have used the SED results to modify the *Gaia* DR3 selection criteria to populate the catalogue.

They were further combined with newly acquired spectra to estimate the level of contamination in the catalogue.

2. Spectral energy distribution analysis of BHB candidates

- They used all of the 16,794 BHB star candidates with parallax errors < 20% found by ***Culpan et al. (2021)*** as the starting point for the SED analysis.
- Photometric data from 66 surveys, had no error flags set and thus conformed to all the quality criteria for the survey from which they came.

Survey	Data count	Citation
The DENIS Database	42502	DENIS Consortium (2005)
Dark Energy Camera Plane Survey (DECaPS) DR1	8762	Schlafly et al. (2018)
DECam Local Volume Exploration Survey (DELVE) DR2	29080	Drlica-Wagner et al. (2022)
Dark Energy Survey (DES) DR2	6201	Abbott et al. (2021)
Far Ultraviolet Spectroscopic Explorer (FUSE)	39	Dixon et al. (2009)
Gaia Data Release 3 BP/RP low-resolution spectral data	329732	De Angeli et al. (2023)
Hubble Source Catalog (V1 and V2)	16	Whitmore et al. (2016)
Tycho-2 Catalogue	2509	Høg et al. (2000)
Hipparcos Catalogue	38	van Leeuwen (2007)
Yale/San Juan Southern Proper Motion (SPM) Catalog 4	35970	Girard et al. (2011)
Gaia EDR3	92827	Riello et al. (2021)
Homogeneous Means in the UBV System	104	Mermilliod (2006)
The Geneva Photometry Catalogue	47	Rufener (1999)
uvby-beta Catalogue	233	Hauck & Merlilliod (1998)
Stellar Photometry in Johnson's 11-color system	1	Ducati (2002)
2 Micron All-Sky Survey - Catalog of Point Sources	90454	Skrutskie et al. (2006)
Beijing-Arizona-Taiwan-Connecticut (BATC) Large Field Multi-Color Sky Survey	186	Xu & Zahaoji (2005)
IRSF Magellanic Clouds Point Source Catalog	135	Kato et al. (2008)
Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE)	102	Spitzer Science Center (200
Spitzer Survey of the Large Magellanic Cloud	250	Meixner et al. (2006)
UKIDSS-DR6 Galactic Plane Survey	282	UKIDSS Consortium (2012
UKIDSS-DR9 LAS, GCS and DXS Surveys	6421	Lawrence et al. (2013)
AllWISE Data Release	58617	Cutri et al. (2013)
Revised catalog of GALEX UV sources	29991	Bianchi et al. (2017)
AAVSO Photometric All Sky Survey (APASS) DR9	114422	Henden et al. (2015)
Swift/UVOT Serendipitous Source Catalog	799	Yershov (2014)
KiDS-ESO-DR3 multi-band source catalog	194	de Jong et al. (2015)
Pan-STARRS release 1 (PS1) Survey	70115	Chambers et al. (2016)
VLT Survey Telescope ATLAS	7680	Shanks et al. (2015)
XMM-OM Serendipitous Source Survey Catalogue	608	Page et al. (2012)
The Dark Energy Survey (DES): Data Release 1	5387	Abbott et al. (2018)
The band-merged unWISE Catalog	60584	Schlafly et al. (2019)
CatWISE2020 catalog	59057	Marocco et al. (2021)
Catalogue of stellar UV fluxes	12	Thompson et al. (1978)
UBVRIJKLMNH Photoelectric Catalogue	11	Morel & Magnenat (1978)
Spectroscopically Identified Hot Subdwarf Stars	23	Kilkenny et al. (1988)
UBV(RI)cHalpha photometry in omega Cen	588	Bellini et al. (2009)
South Galactic cap MCT blue objects	1	Lamontagne et al. (2000)
Magellanic Clouds Photometric Survey: The LMC	182	Zaritsky et al. (2004)
UBVRI Standard Stars	1	Landolt (2007)
Omega Centauri Spitzer photometry	491	Boyer et al. (2008)
Extended Kepler-INT Survey	1522	Greiss et al. (2012)
JK photometry of 12 galactic globular clusters	6	Cohen et al. (2015)
OGLE LMC BVI photometry	12	Udalski et al. (2000)
UBVI photometry in NGC 6752	9	Kravtsov et al. (2016)
UBV photometry of metal-weak candidates	15	Norris, et al. (1999)
The ZTF catalog of periodic variable stars	152	Chen et al. (2020)
Spitzer Kepler Survey (SpiKeS) catalog	200	Werner et al. (2021)
Edinburgh-Cape Blue Object Survey. Zone 1	30	Kilkenny et al. (1997)
Edinburgh-Cape Blue Object Survey. III.	42	O'Donoghue et al. (2013)
Edinburgh-Cape Blue Object survey. IV	28	Kilkenny et al. (2015)
Edinburgh-Cape Blue Object survey. V	15	Kilkenny et al. (2016)
UBVRI photometry in 48 globular clusters	1917	Stetson et al. (2019)
Javalambre Photometric Local Universe Survey Data Release DR3	16533	von Marttens et al. (2024)
Pan-STARRS Data Release 2	67667	Flewelling (2018)
Survey of the Magellanic Stellar History (SMASH) DR2	2182	Nidever et al. (2017)
Southern Photometric Local Universe (S-PLUS) Survey DR3	12934	Mendes de Oliveira (2019)
SkyMapper Southern Survey: DR2	124543	Onken et al. (2019)
SDSS Photometric Catalogue, Release 12	30601	Alam et al. (2015)
IGAPS. merged IPHAS and UVEX of northern Galactic plane	1562	Monguió, et al. (2020)
Visible and Infrared Survey Telescope for Astronomy DR6	41589	McMahon et al. (2021)
Final Merged Log of International Ultraviolet Explorer Observations	1636	NASA (1985)
VISTA Deep Extragalactic Observations (VIDEO) Survey DR5	33	Jarvis (2013)
VISTA Kilo-degree Infrared Galaxy Public Survey (VIKING) DR4	1384	Edge et al. (2013)
VISTA Magellanic Survey (VMC) catalog DR4	98	Cioni et al. (2011)
VISTA Variable in the Via Lactea Survey (VVV) DR4	1539	Minniti et al. (2023)

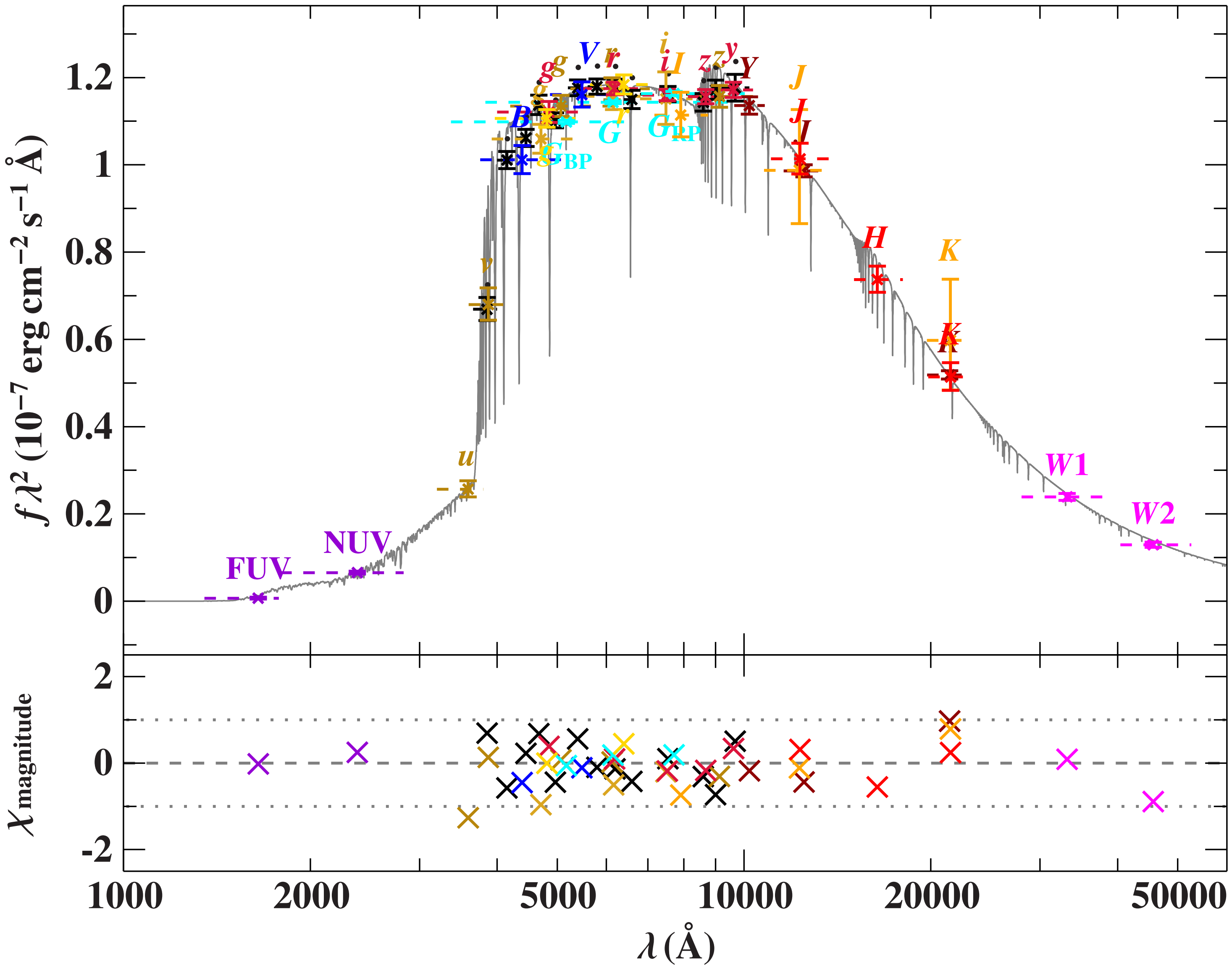
Grids of synthetic SEDs were calculated with an amended version of the *ATLAS12*

Free parameters in this $\chi 2$ fit were the:

1. star's effective temperature (*Teff*)
2. surface gravity (*log g*)
3. angular diameter (Θ)
4. colour excess caused by interstellar extinction.

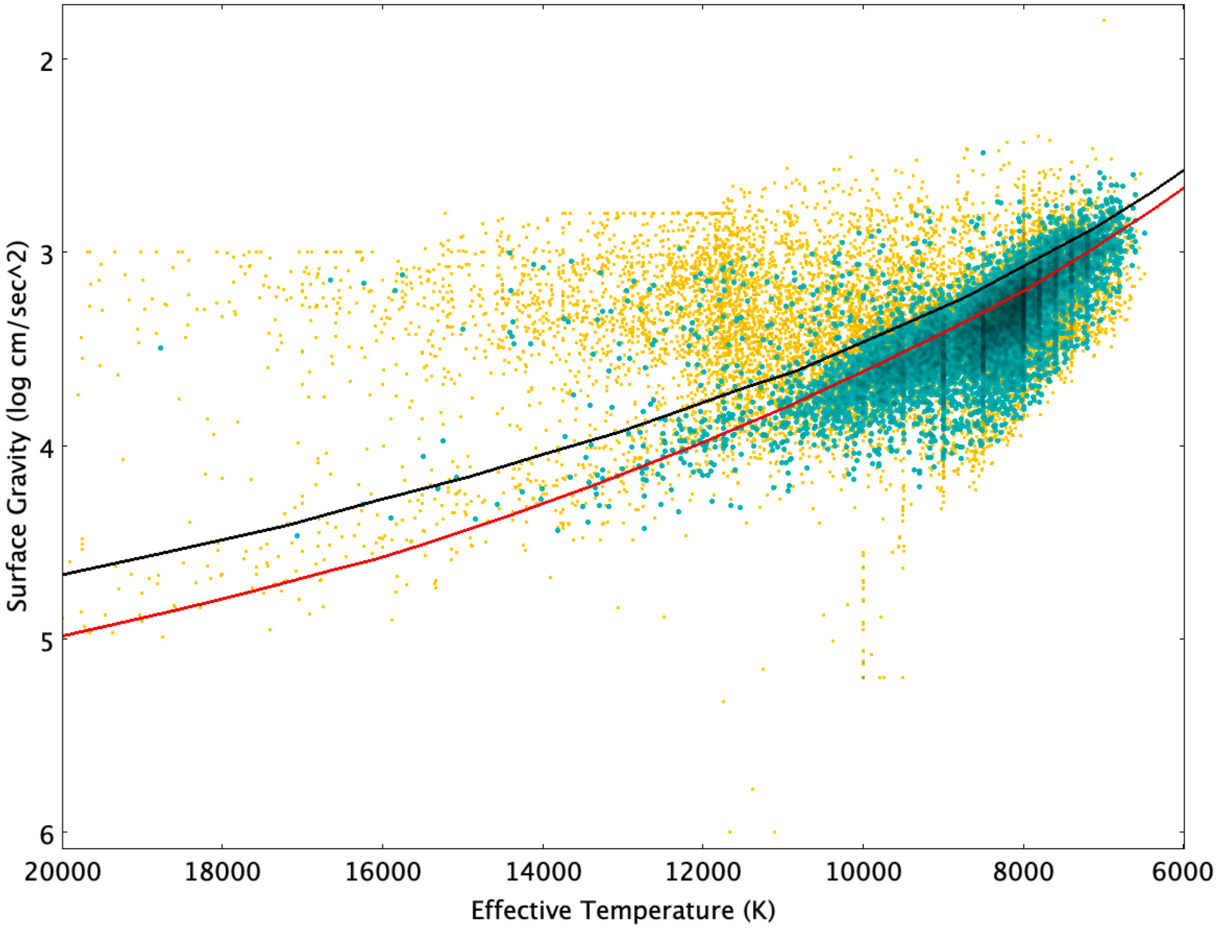
The extinction law: Fitzpatrick et al. (2019)
Metallicity: [Fe/H] = −1.7, a standard value for cool BHB stars in the Galactic field (Behr 2003).
Distance: Gaia DR3 parallax
Stellar radius: $R = \Theta/(2\pi)$

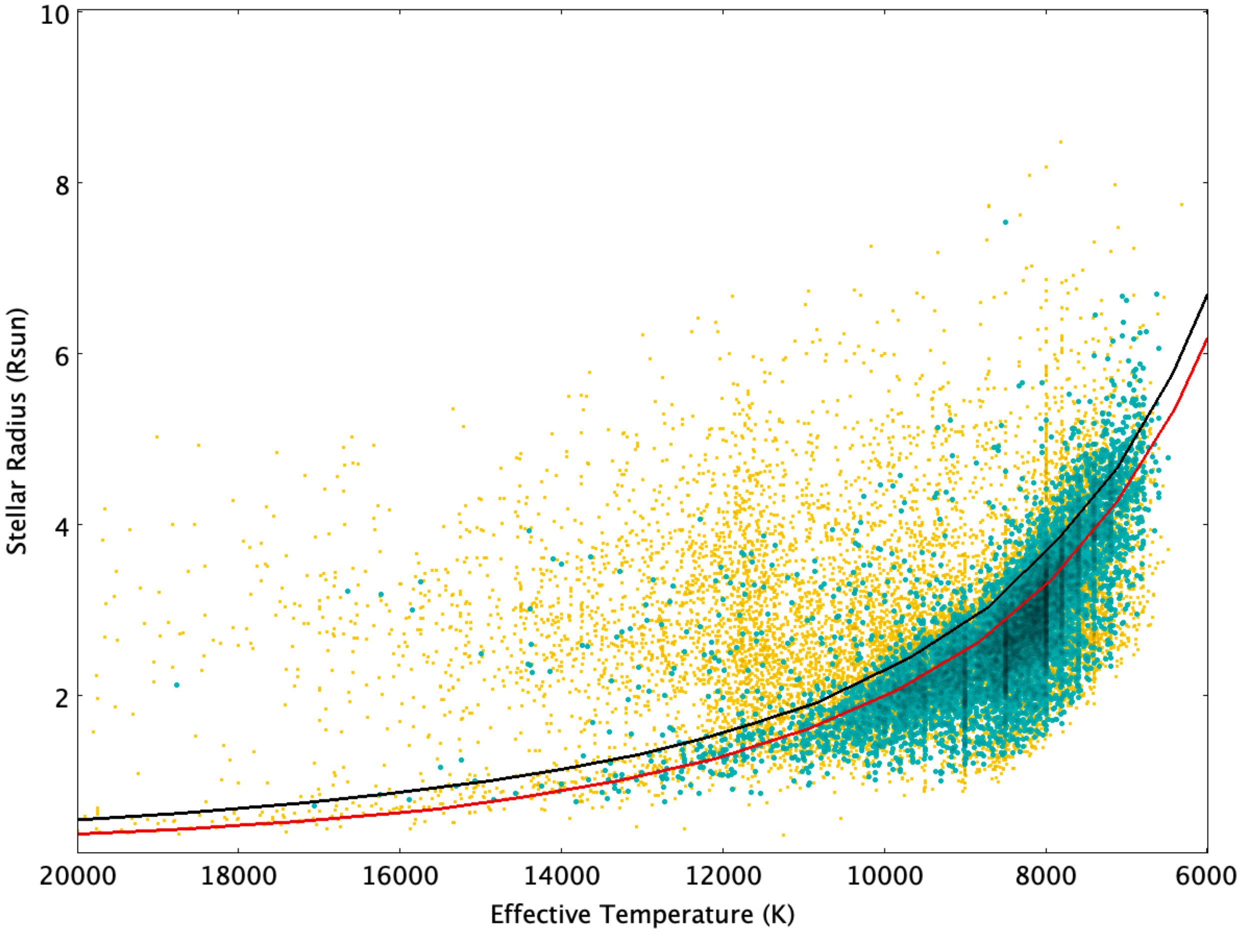
An example of the results of a spectral energy distribution generated for the BHB candidate star *Gaia* DR3 6305433829332391168 with the photometric data labelled.



They found that the SEDs for stars where photometric data were available over the full range of wavelengths (from ultra-violet to infra-red) gave the most reliable results on the *T*eff versus *log g* and the *Teff* versus *R* plots with the BHB candidates plotting close to the BaSTI **ZAHB** (zero-age horizontal-branch) and the **TAHB** (terminal-age horizontal-branch) lines.

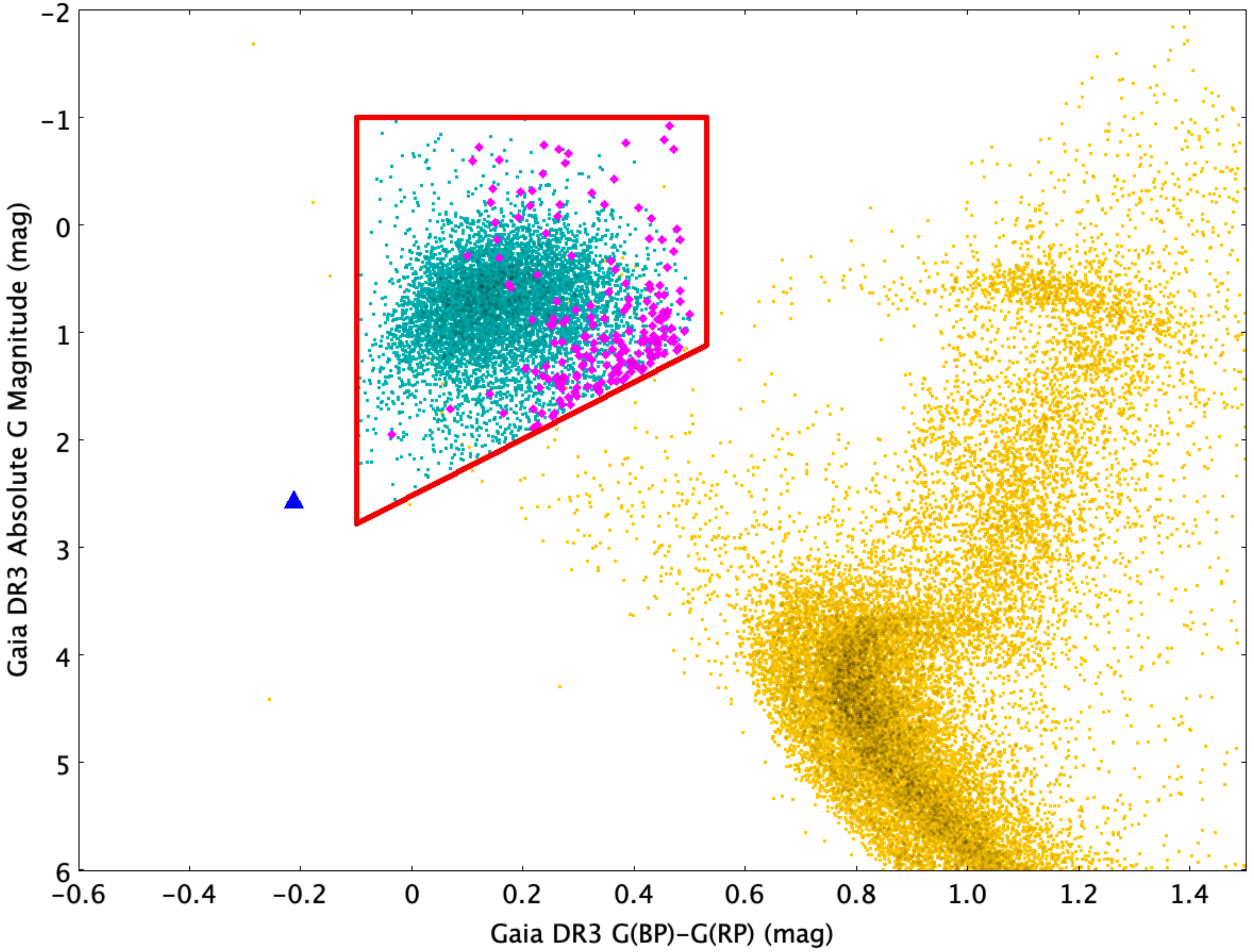
- All SED results are shown as yellow circles, the SED results for objects with full wavelength range (**less than 2000 Å to over 8000 Å**) photometric data available are shown as turquoise triangles.
- The Red line is the **BaSTI ZAHB** line. The black line is the **BaSTI TAHB**.





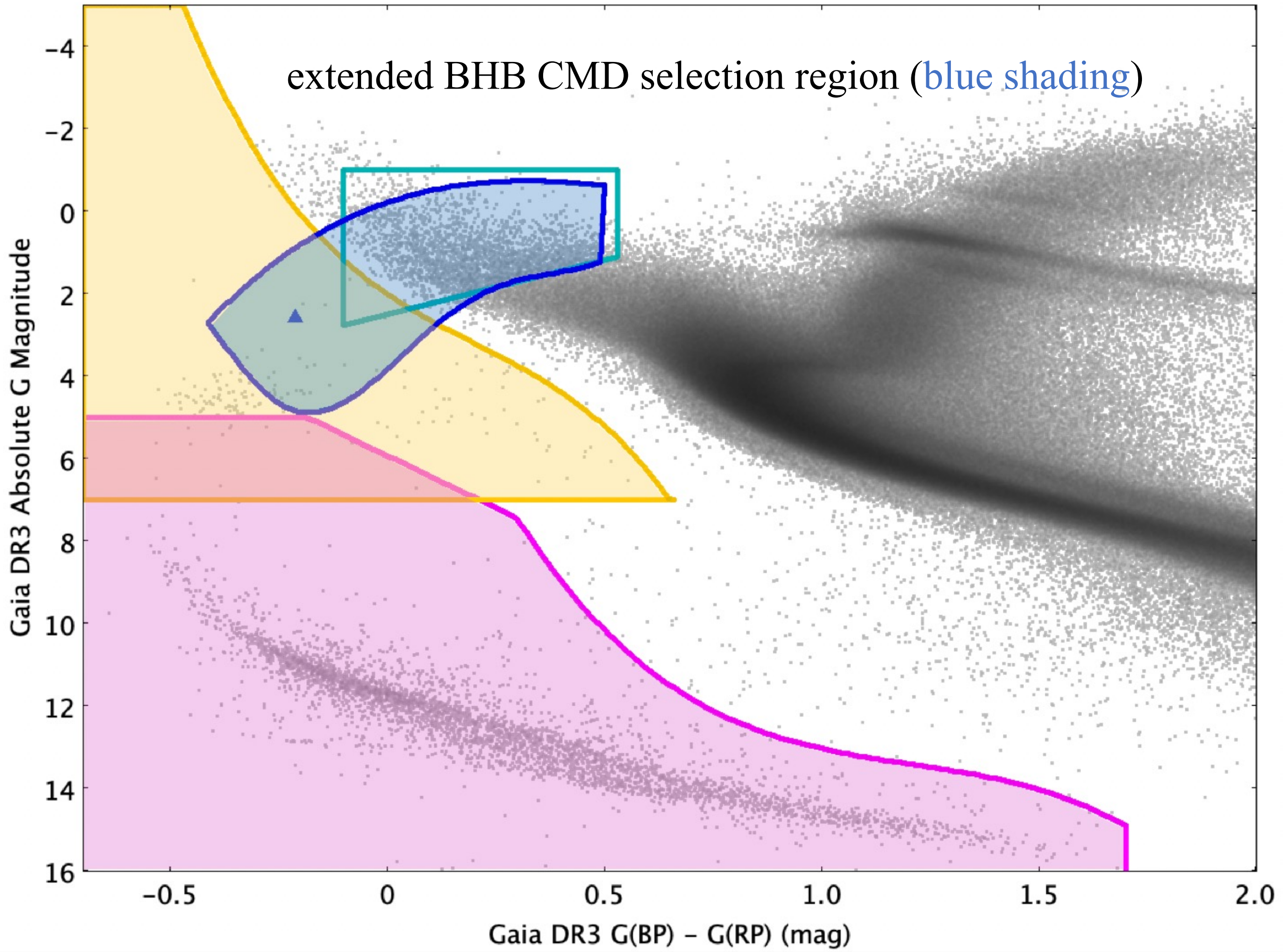
- They found that the interstellar reddening that was calculated for the SED generation was a critical issue.
- When they included the objects that had reddening values greater than 0.2 mag in the candidate selection thy found a greatly increased scatter in the CMD plots

- yellow dots: The Gaia DR3 CMD showing a sample of stars with tangential velocities greater than 145 km/s
- cyan dots: *Culpan et al. (2021)* objects with full range SEDs
- magenta squares: *Culpan et al. (2021)* objects with full range SEDs and modelled reddening greater than 0.2 mag
- blue triangle: The known BHB *Feige 86* possessing ***Teff*** around 15,000K (Németh 2017) which lies outside the Gaia DR3 CMD BHB region from Culpan et al. (2021).



3. Revising the BHB star candidate catalogue from Gaia DR3 using the SED results

In order to raise the upper limit on the ***Teff*** they extended the *Gaia* DR3 CMD search criteria towards the cluster of hot subdwarfs found in *Culpan et al. (2022)*. The resulting overlap means that **643** of the BHB candidates found are also hot subdwarf candidates as found in *Culpan et al. (2022)*.



3.1. Determination of the Gaia DR3 data quality filtering criteria

They applied the photometry quality criterion from *Riello et al. (2021)* that calculates the **astrometric_excess_noise_corrected** = ***C****

The *Culpan et al. (2022)* criterion requires that the BHB candidate's *G* flux must make up at least 70% of the *G* flux detected within a 5 arcsec radius around that candidate.

1. Gaia DR3 CMD selection (see Appendix C): 30,228 objects
`parallax` > 0 `parallax_over_error` > 5 $-0.4 < (G_{\mathrm{BP}} - G_{\mathrm{RP}}) < 0.5$ $G_{\mathrm{abs}} < 138.07(G_{\mathrm{BP}} - G_{\mathrm{RP}})^6 - 153.85(G_{\mathrm{BP}} - G_{\mathrm{RP}})^5 - 40.727(G_{\mathrm{BP}} - G_{\mathrm{RP}})^4 + 73.368(G_{\mathrm{BP}} - G_{\mathrm{RP}})^3$ $-7.4054(G_{\mathrm{BP}} - G_{\mathrm{RP}})^2) - 9.5575G_{\mathrm{BP}} - G_{\mathrm{RP}} + 3.8459$ $G_{\mathrm{abs}} > -3.2382(G_{\mathrm{BP}} - G_{\mathrm{RP}})^3 + 7.1259(G_{\mathrm{BP}} - G_{\mathrm{RP}})^2 - 3.583(G_{\mathrm{BP}} - G_{\mathrm{RP}}) - 0.2$ $v_t >= 145km/s$
2. Photometric quality selection criteria: 30,088 objects
$\lvert C^* \rvert < 5.\sigma_{c^*}$
3. Blended object rejection criterion: 23,619 objects
BHB candidate flux fraction from 5 arcsec radius > 0.7
4. RR-Lyrae removal criterion: 22,335 objects
Objects listed as RR-Lyrae in Simbad   Objects considered RR-Lyra candidates in Gaia DR3   `excess_flux_error` > 6.0
5. BHB candidates with wide wavelength range photometric data: 10,604 objects
from 2000 Å to 8000 Å
6. SEDs calculated without error flags: 10,222 objects
At least 5 photometry measurements used for the fit   Maximum 20% uncertainty in radius   Maximum 0.3dex uncertainty in log(L)

3.2. Sources of catalogue contamination

Two types of contaminant:

1. The stars that should not plot in the same *Gaia* DR3 colour magnitude space as BHB stars but do so because of erroneous *Gaia* DR3 measurements. (The main contaminants of this type are hot subdwarfs, pre-ELM white dwarfs, and RR-Lyrae stars.)
2. The stars that are not BHB stars but correctly plot in the same region in *Gaia* DR3 colour magnitude space. This category includes young A-type and B- type main-sequence stars and blue stragglers.

a) They cross-matched the BHB candidate stars with the **SIMBAD** database and the *Gaia* DR3 variability RR-Lyrae catalogue: 1,004 known RR-Lyrae from the **SIMBAD** database and 1,136 in the *Gaia* catalogue.
b) Then they calculated the excess flux error as defined in Gentile Fusillo et al. (2021) and Culpan et al. (2022) for all BHB candidates.
c) Removal of a further 189 candidate variable stars that are not found among those that are known in **SIMBAD** or in the Gaia DR3 variability RR-Lyrae catalogue.

The application of the data quality filters as described above to the *Gaia* DR3 data set resulted in **22,335** BHB candidates.

4. Catalogue contamination estimation

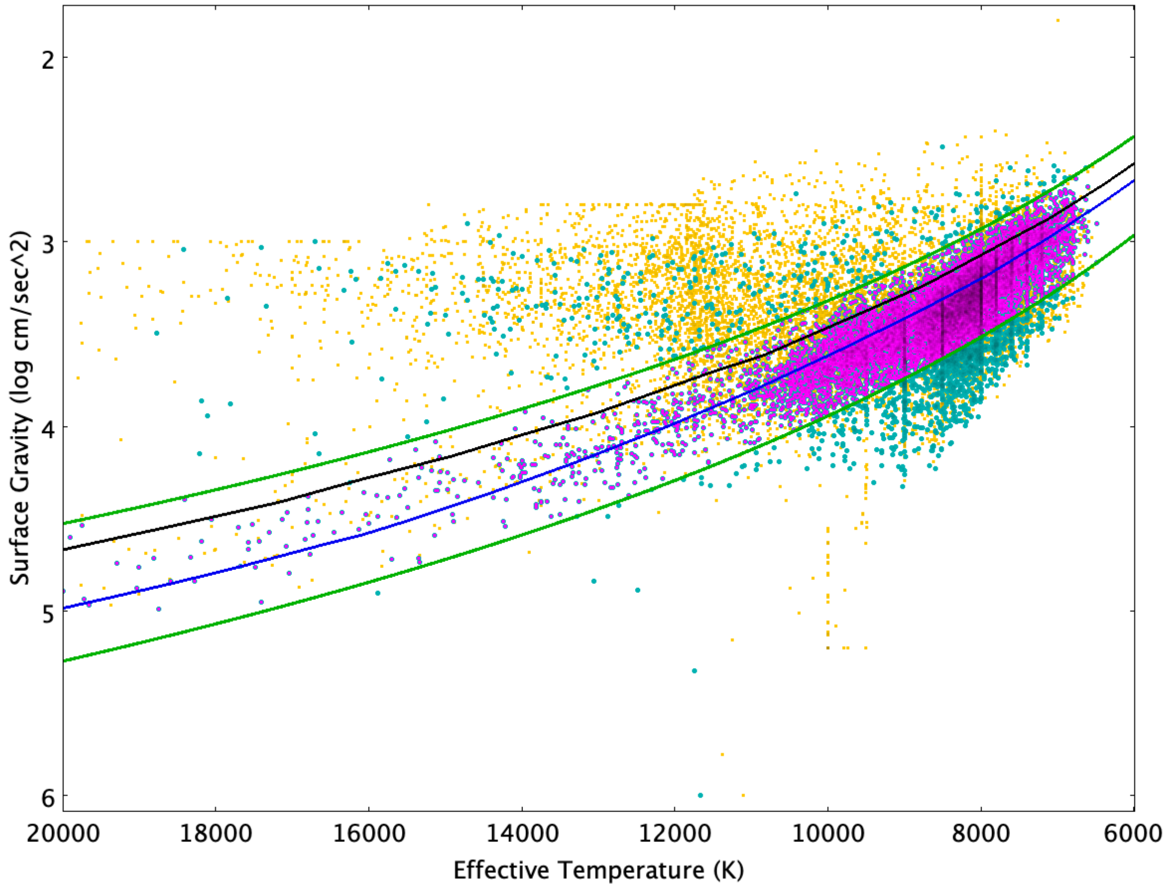
In order to estimate the levels of contamination in the *Gaia* DR3 catalogue of BHB stars they used two independent methods that both were not dependent on *Gaia* DR3 data:

1. The SED method.
2. The analysis of spectra acquired specifically for this project using the Astronomical Institute of the Czech Academy of Sciences' Perek 2m telescope located at Ondrejov in the Czech Republic.

4.1. Contamination estimation using SED results

- Full range photometric data were used in generating the SED for 10,604 of the 22,335 (53%) BHB candidates found.
- They found that 9,172 of the 10,604 objects with full photometric range data plotted within the horizontal branch region.
- These cut-off lines are based on the **ZAHB** and **TAHB** isochrones from **BaSTI** models given in *Pietrinferni et al. (2004),* but somewhat widened to include the coherent cloud of BHBs.

This gave an estimated contamination level of 14%.



4.2. Contamination estimation from spectral analysis

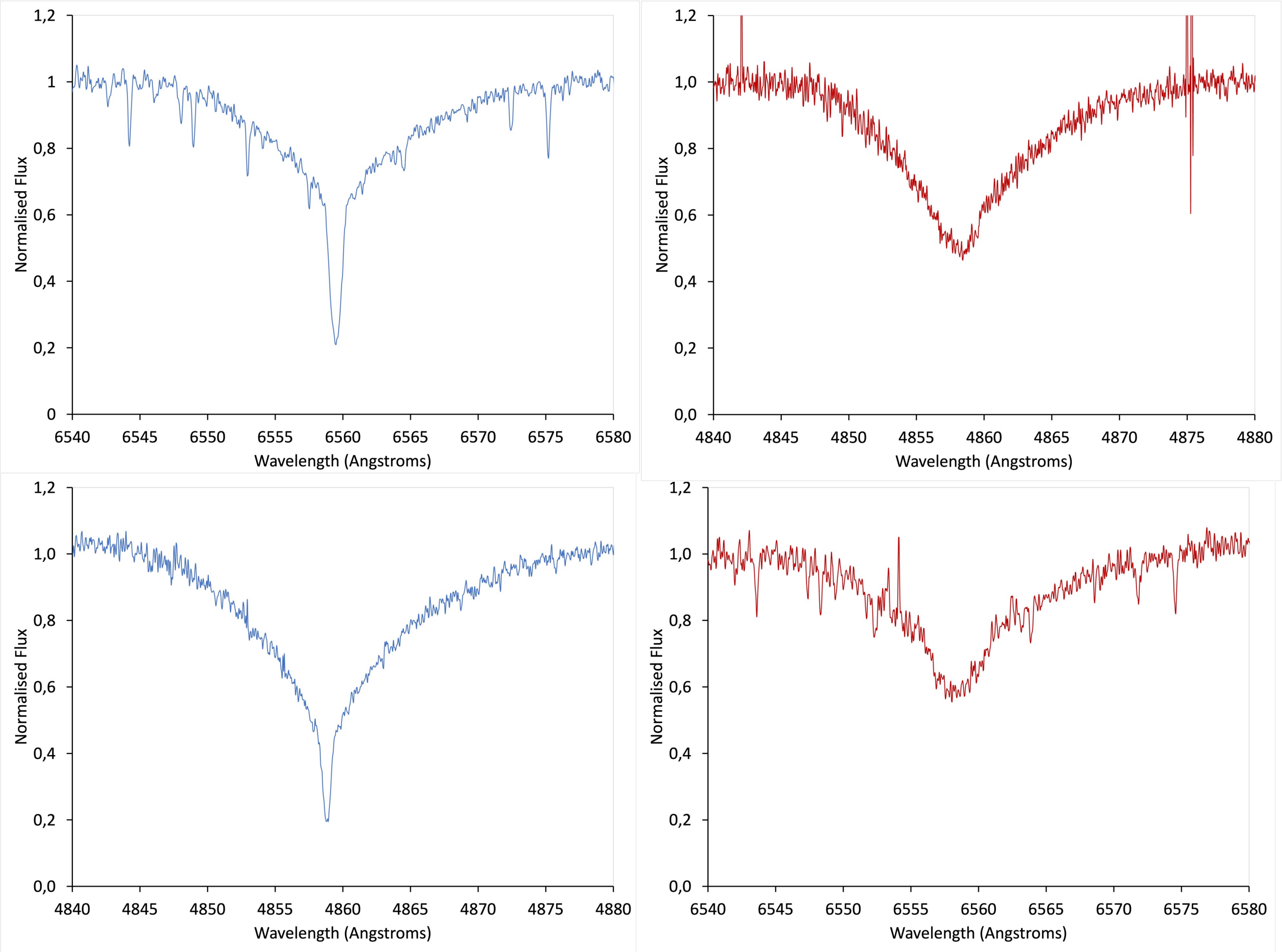
Spectra were acquired for BHB candidates with a *Gaia* DR3 apparent *G* magnitude of brighter than 11.0 mag at the Ondrejov Observatory in the Czech Republic over a 18 month period.

The spectra were acquired using the Perek 2m telescope through an Echelle spectrograph with a resolving power of R = 51,600 around $H\alpha$.

Over an 18 month period they acquired spectra for 69 BHB candidates of which 6 were found to be main-sequence stars giving a 9 ± 3 % contamination level, similar to that found with the SED analyses albeit with a far smaller sample.

$H\alpha$

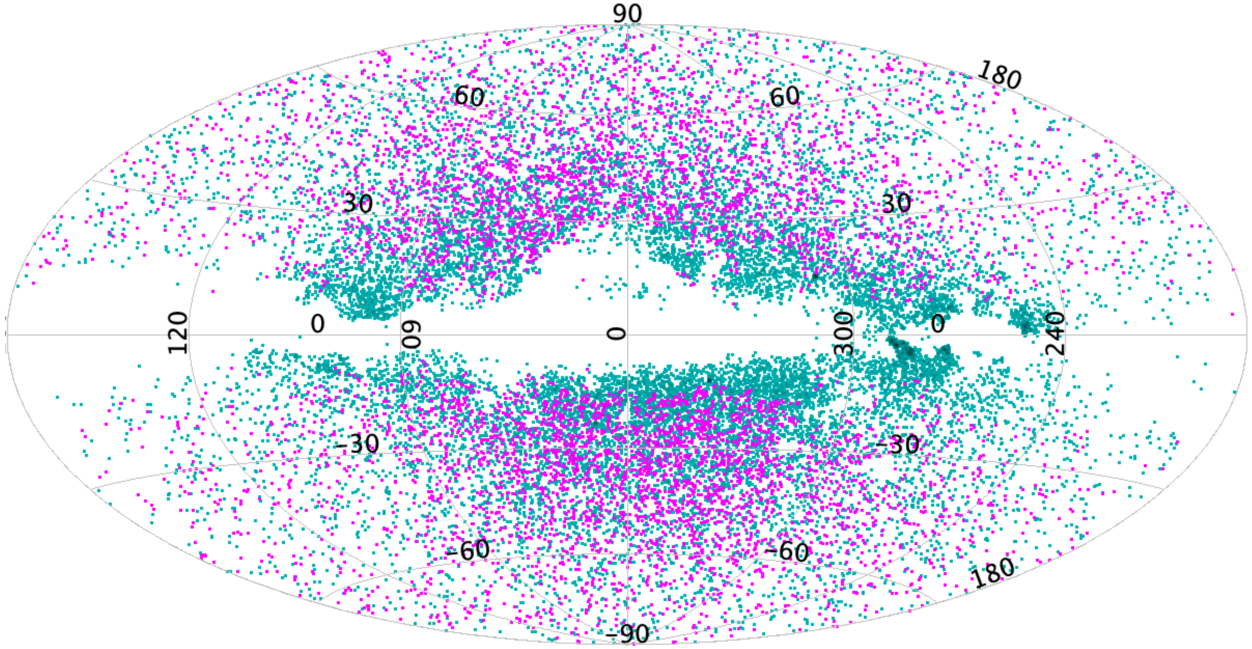
BHB stars



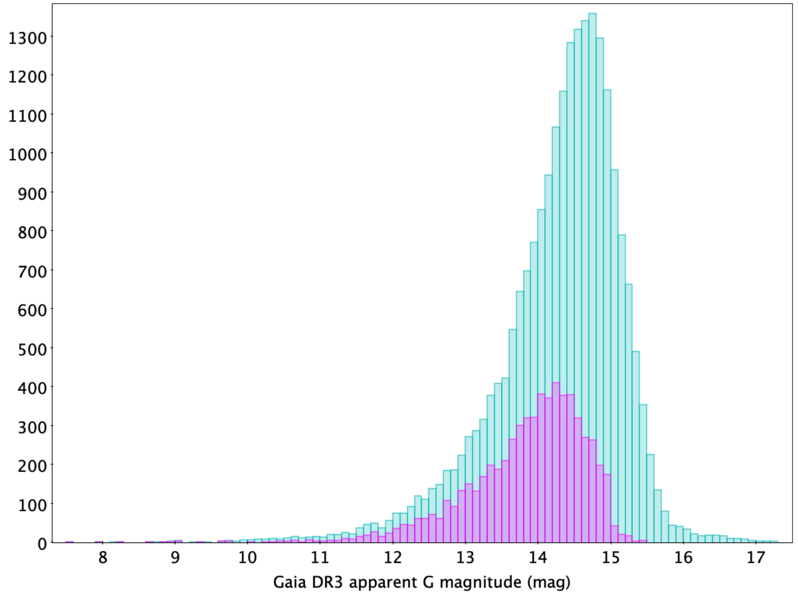
main-sequence stars

$H\beta$

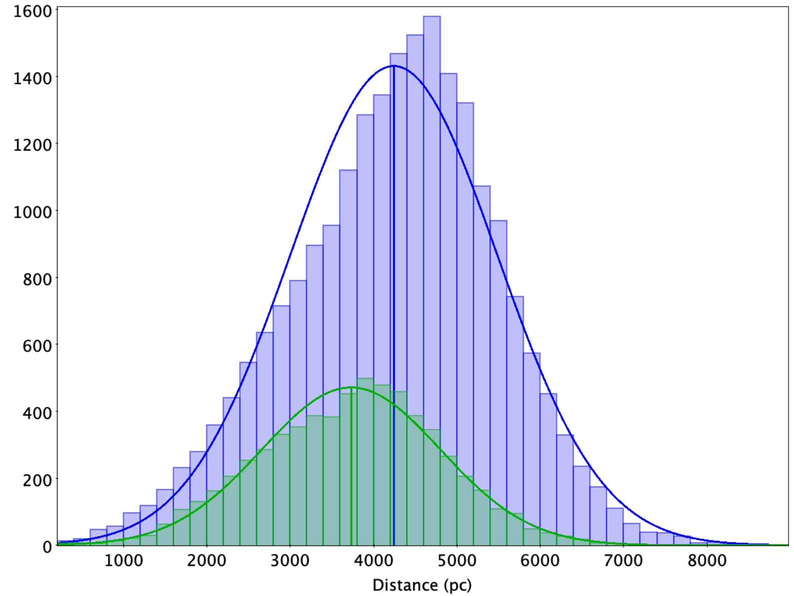
5. Sky Coverage, magnitude, and distance



7.6 mag to 15.5 mag



235 pc to 7,435 pc



6. Summary and Conclusions

- They have used photometric data from 66 large scale surveys to generate synthetic SEDs and associated stellar parameters for a large number of BHB candidates where no spectra are available.

- The *Gaia* DR3 catalogue of BHB star candidates is an update to the parallax selected catalogue presented in *Culpan et al. (2021)*.

- A further iteration was made using these newly defined *Gaia* DR3 CMD selection criteria and **22,335** BHB candidates were found. Of these candidates **10,222 (46%)** had photometric data available that supported the generation of stellar- and atmospheric parameters from SEDs. The stellar- and atmospheric parameters generated indicate that **9,172 (41%)** of these objects lie in the parameter space expected for BHBs.

- This increase of **32%** in the number of BHB candidate stars compared to *Culpan et al.(2021)* but with in the same volume and apparent magnitude range, represents another step in generating a more complete full-sky catalogue of BHB stars in the inner Galactic Halo.

Thanks for your attention!