J-PLUS: Estimating the Galactic halo density profile using Blue Horizontal Branch stars selected from multifilter data

A. Domínguez-Fernández (adominguez@cefca.es), C. López-Sanjuan, H. Vázquez Ramió, and J-PLUS Team
Centro de Estudios de Física del Cosmos de Aragón (CEFCA, Teruel, Spain)

The Galactic Halo and BHB stars

The information of the assembly history of our Galaxy is stored in the halo (see Fig. 1), either in the form of coherent structures in space and velocity of its constituent stars, or as chemical imprints in those stars.

Blue horizontal branch (BHB) stars are intrinsically luminous (Mg 0.6 mag, Deason et al. 2011[1]), evolved (population II) stars (see Fig. 1). The first characteristic means that they can be observed at large distances (several 100's of kpc), which in conjunction with a low dispersion of their intrinsic luminosities, made them fairly distance indicators (a.k.a standard candles) with an accuracy 5%. In addition, they trace old stellar populations, being therefore ideal to study of the Milky Way halo. However, they are relatively sparse, so wide-field surveys are needed to construct large samples. Moreover, field BHB-star samples traditionally have suffered from relatively high levels of contamination (e.g., Deason et al. 2011[1], Vickers et al. 2012[2]), what has hindered their use.

Among the main questions about the Galactic halo and its connection to the merger history still to be addressed is the shape of its radial density profile, which has been studied using star counts for decades but no consensus model has emerged even using the same stellar tracer (e.g., Fukushima et al. 2019[3]).

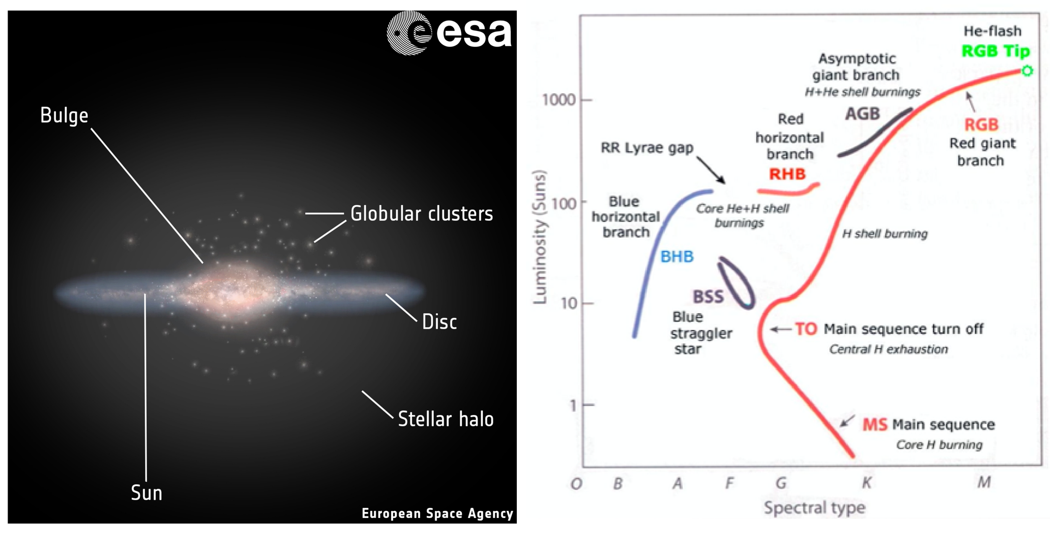

Figure 1: Left: Schematic view of the principal stellar components of the Galaxy. Credit: Adapted from an original by ESA. Right: HR diagram (luminosities vs spectral type) showing the main evolutionary steps of the stars up to the AGB. Although BHB stars are intrinsically more luminous than BSS stars, when studying the halo their apparent magnitudes get mixed with field BSS due to their different distances. Credit: Murdin et al. 2001[4].

J-PLUS photometry as a tool

The Javalambre Photometric Local Universe Survey (J-PLUS, Cenarro et al. 2019[5]) is an optical survey conducted with an 83-cm telescope (JAST80, see left panel of Fig. 2) from the Observatorio Astrofísico de Javalambre (OAJ; Teruel, Spain) that provides images in 12 bands (7 medium-to-narrow + 5 broad, see right panel of Fig. 2). Its panoramic camera (T80Cam) has an array of 9.2 x 9.2 kpix CCDs that covers a 2 sq. deg FoV with a plate scale of 0.55''/pixel. The second data release (DR2) of J-PLUS comprehends 2,200 sq. deg (δ>-5 deg, |b| > 10 deg).

The first goal of our work is to disentangle BHB stars from their contaminants using photometric proxies of surface gravity, taking advantage not only of the information provided but the narrow-band filters that target key stellar features but also of the wavelength coverage of all the bands. The second goal is to use these BHB stars to study the density profile of the Galactic halo.

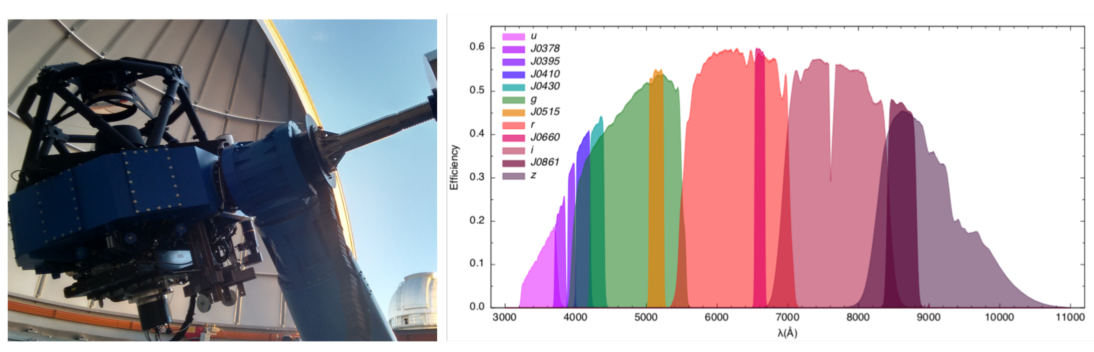

Figure 2: Left: Image of the JAST80, and its panoramic camera, T80Cam. Credit: J-PLUS web page. Right: The 12 filters that comprehends the J-PLUS filter system. Credit: Cenarro et al. 2019[5].

References

1. Deason, A. J., Belokurov, V. & Evans, N. W. The Milky Way stellar halo out to 40 kpc: squashed, broken but smooth. **416,** 2903–2915. arXiv: 1104.3220 [astro-ph.GA] (Oct. 2011).
2. Vickers, J. J., Grebel, E. K. & Huxor, A. P. Identifying Blue Horizontal Branch Stars Using the z Filter. **143,** 86. arXiv: 1201.4571 [astro-ph.GA] (Apr. 2012).
3. Fukushima, T. *et al.* The stellar halo of the Milky Way traced by blue horizontal-branch stars in the Subaru Hyper Suprime-Cam Survey. **71,** 72. arXiv: 1904.04966 [astro-ph.GA] (Aug. 2019).
4. Murdin, P. *Encyclopedia of astronomy and astrophysics* (2001).
5. Cenarro, A. J. *et al.* J-PLUS: The Javalambre Photometric Local Universe Survey. **622,** A176. arXiv: 1804 . 02667 [astro-ph.GA] (Feb. 2019).
6. Wan, Z. *et al.* Galactic cartography with SkyMapper - I. Population substructure and the stellar number density of the inner halo. **480,** 1218–1228. arXiv: 1807.03664 [astro-ph.GA] (Oct. 2018).
7. Starkenburg, E. *et al.* The Pristine survey - VII. A cleaner view of the Galactic outer halo using blue horizontal branch stars. **490,** 5757–5769. arXiv: 1910.07547 [astro-ph.GA] (Dec. 2019).
8. Xue, X. X. *et al.* The Milky Way's Circular Velocity Curve to 60 kpc and an Estimate of the Dark Matter Halo Mass from the Kinematics of ~2400 SDSS Blue Horizontal-Branch Stars. **684,** 1143–1158. arXiv: 0801.1232 [astro-ph] (Sept. 2008).
9. Lenz, D. D., Newberg, J., Rosner, R., Richards, G. T. & Stoughton, C. Photometric Separation of Stellar Properties Using SDSS Filters. **119,** 121–140 (Dec. 1998).
10. Bland-Hawthorn, J. & Gerhard, O. The Galaxy in Context: Structural, Kinematic, and Integrated Properties. **54,** 529–596. arXiv: 1602.07702 [astro-ph.GA] (Sept. 2016).
11. Bell, E. F. *et al.* The Accretion Origin of the Milky Way's Stellar Halo. **680,** 295–311. arXiv: 0706.0004 [astro-ph] (June 2008).
12. López-Sanjuan, C. *et al.* J-PLUS: Spectral evolution of white dwarfs by PDF analysis. **658,** A79. arXiv: 2110 . 14421 [astro-ph.SR] (Feb. 2022).
13. Xue, X.-X. *et al.* Quantifying Kinematic Substructure in the Milky Way's Stellar Halo. **738,** 79. arXiv: 1011 . 1925 [astro-ph.GA] (Sept. 2011).

Blue Colors as Surface Gravity Indicators

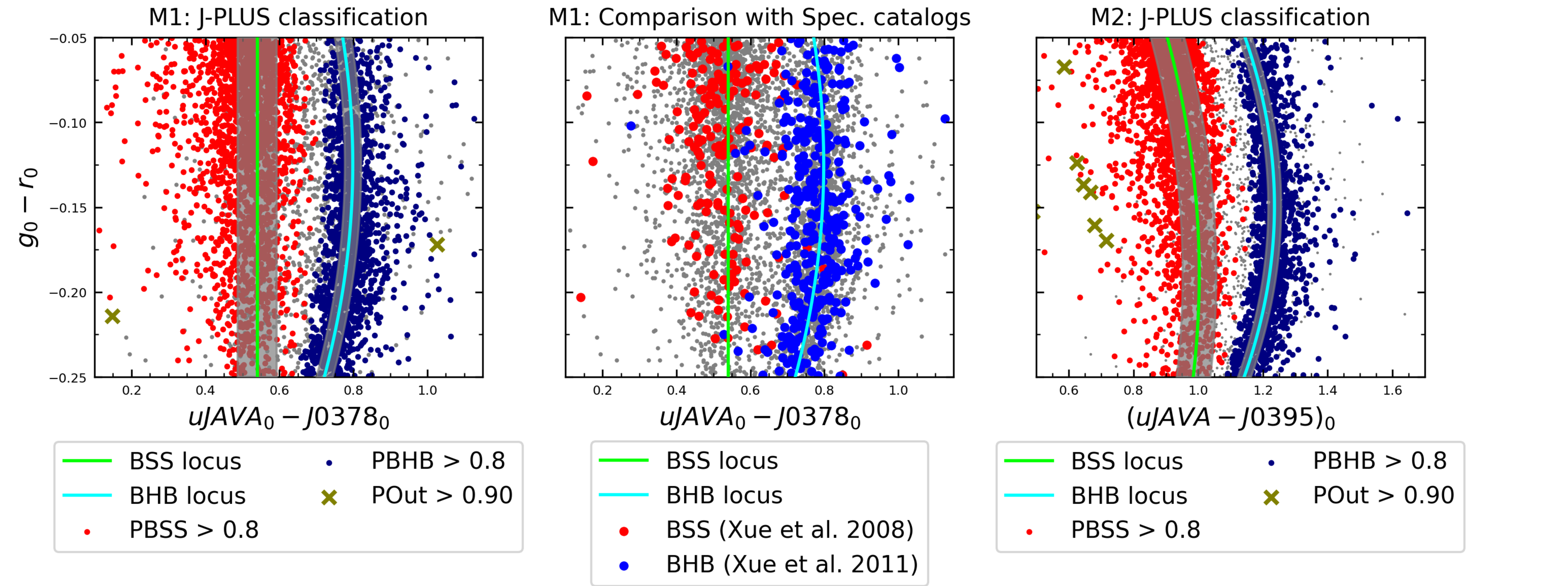

Figure 3: Left: Classification with the method that uses the uJAVA-J0378 color (M1). Middle: Spectroscopic confirmed sources on the same color-color diagram as previous panel. Right: Classification with the method that employs uJAVA-J0395 color. Caveat: a tiny fraction of the sample is beyond the boundaries of the plots shown here (<0.4% (12 sources) in the case of M1 and <0.2%(5 sources) in the M2 case. The whole sample has 5,600 sources).

In this work, we have developed three methods to disentangle BHB stars from their contaminants (primarily, blue straggler stars or BSS) based on their different location in color-color (cc) spaces. Blue colors (using bands with central wavelengths bluewards of 4,000 Å) have shown to be particularly efficient for this task (Wan et al. 2018[6]; Starkerburg et al. 2019[7]) as they probe the region of the Balmer jump, which is sensitive to surface-gravity for A-type stars.

J-PLUS has two narrow-band filters in that region: J0378 and J0395. By constructing color-color diagrams using uJAVA-m vs g-r, where m is one of those narrow-band filters (see Fig. 3), the median distance between the locations of BHB and BSS stars (>0.2 mag) is more than two times that reported using SDSS broad-bands (<0.1 mag, Deason et al. 2011[1]), while the intrinsic dispersion of the BHB stars is a factor of two lower, and that of BSS only increase by a 1.2 factor. By comparing with the spectroscopic catalog of Xue et al. 2008[8], the selections using these colors have mean probabilities of PBHB=0.8, and PBSS=0.9, for 11.7<g<18.5 mag, with a median completeness of 95%. Notice that the shape of the locus of a population is not the same in the two methods. The shape of the loci has been chosen as those that provide the lower Bayesian information criterion (BIC).

Combining multiple colors: SED fitting

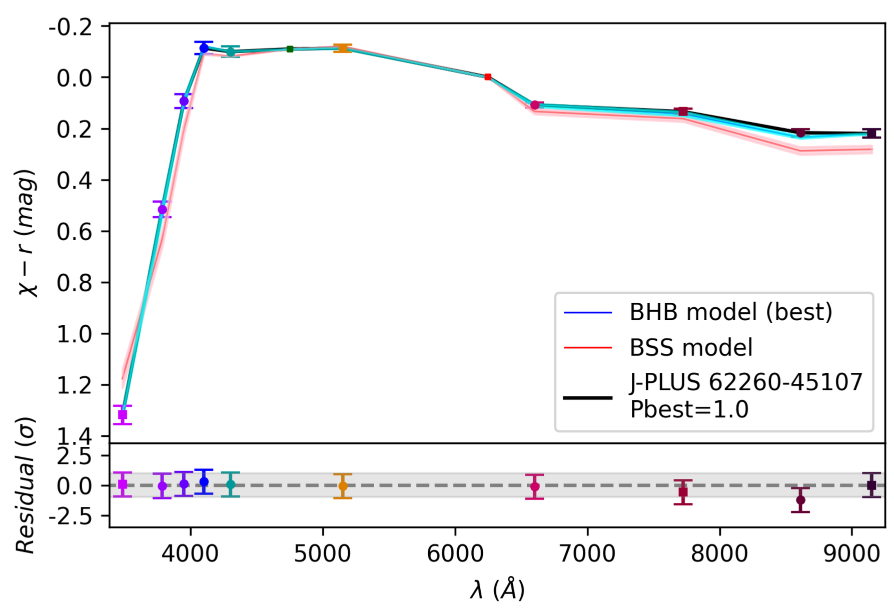

Figure 4: Upper panel: SED of a confirmed BHB star (black line, and colored markers in the upper figure) along with the SED models for BHB (cyan) and BSS (red) for its (g-r) color. Lower panel: Residuals for the best fitting model (scaled to the uncertainties).

Surface gravity information is also known to be packed at the region of the Paschen lines (Lenz et al. 1998[9]; Vickers et al. 2012[2]). To combine all possible information from the near-UV (~ 3,485 Å) to the near-IR (~9,114 Å) wavelength range, we have developed spectral energy distribution (SED) models for BHB, and BSS stars (see Fig. 4) based on their locations in 10 cc diagrams. Then, by combining the information in all the cc, we have assigned probabilities of being BHB, BSS, and Outlier. Relying on the spectroscopic classification from Xue et al. 2008[8], the mean probabilities are PBHB=0.9, and PBSS=0.9 (with a median completeness of 95%).

Density Profile

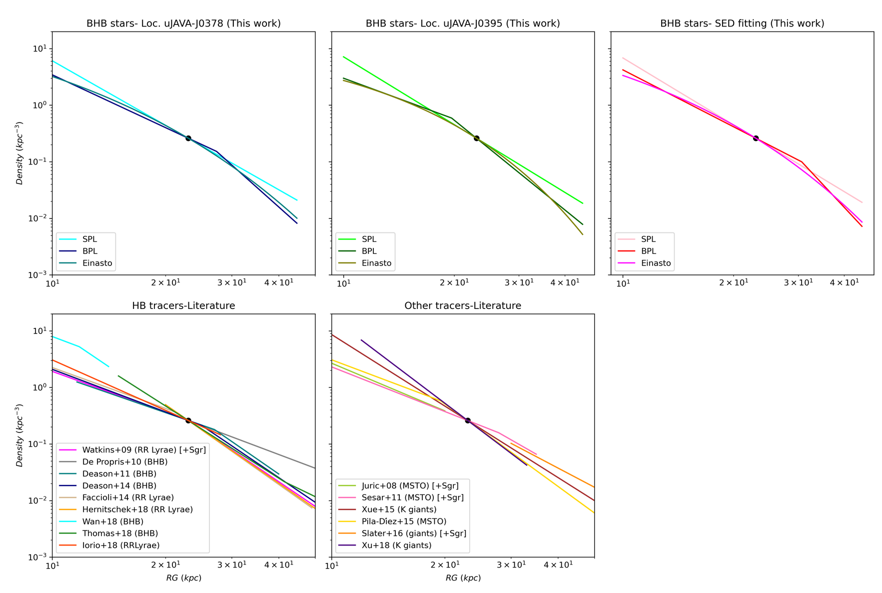

Figure 5: Upper panels: Density profiles obtained using our 3 selections of BHB stars based on J-PLUS data. For each selection, we display the SPL, BPL and Einasto profile resulting from the fitting of the observational data. Lower panels: A brief summary of the recent results from the literature on the density profile of the halo: using HB (left), and other (center) tracers.

We have studied the radial density profile of the Galactic halo between 10 and 35 kpc with our 3 different selections of BHB stars, finding that it is well described by a broken power law as well as an Einasto profile using spherical models (q=1). By allowing oblate models (fixed q=0.65, Bland-Hawthorn & Gerhard 2016[10]), the same conclusion holds. We have excised the most larger, known overdensities using the masks proposed by Bell et al. 2008[11] (Virgo, and some parts of Sgr), and Starkenburg et al. 2019[7] (the rest of Sgr stream).

Validating the different classifications

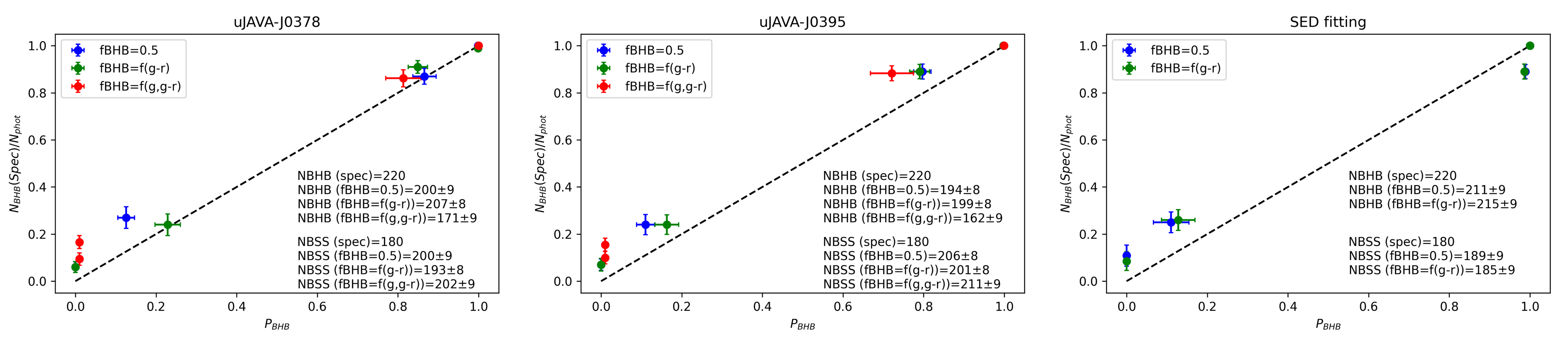

Figure 6: Validation test for the probabilities of being BHB stars obtained for the different classification methods used in this work (different panels). In each panel, the different color dots and errorbars represent different probabilities obtained using different priors. See the text below for further details.

We have tried different priors for each classification in order to get the most reliable probabilities as possible (in other words, the best agreement with the spectroscopic sample). For the methods that use only one cc diagram, three types of priors have been adopted: fBHB=0.5 (non-informative), fBHB=f(g-r), and fBHB=f(g,g-r). For the SED fitting method, we have only considered the first two types. The validation test in the figures (see López-Sanjuan et al. 2022a[12]) shows the correspondence between the median probability for being a BHB star in a range compared to the fraction of confirmed BHB stars in that range. Note that we only employ stars with spectroscopic label in the tests. Then, if the probabilities are realible, we expect that they follow the 1:1 relation shown as a black dashed line. As an extra test (also borrowed from López-Sanjuan et al. 2022a[12]), we show inside the figures (see inserted text), the different total numbers of each population computed by summing the probabilities using the different priors.

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