Detection of multiple stellar systems from modern-precision single-epoch photometry

Gregor Traven

University of Ljubljana

Science and technology roadmap for µas studies of the Milky Way

Lund, July 2023

Importance of multiple stars

Moe & Di Stefano 2017

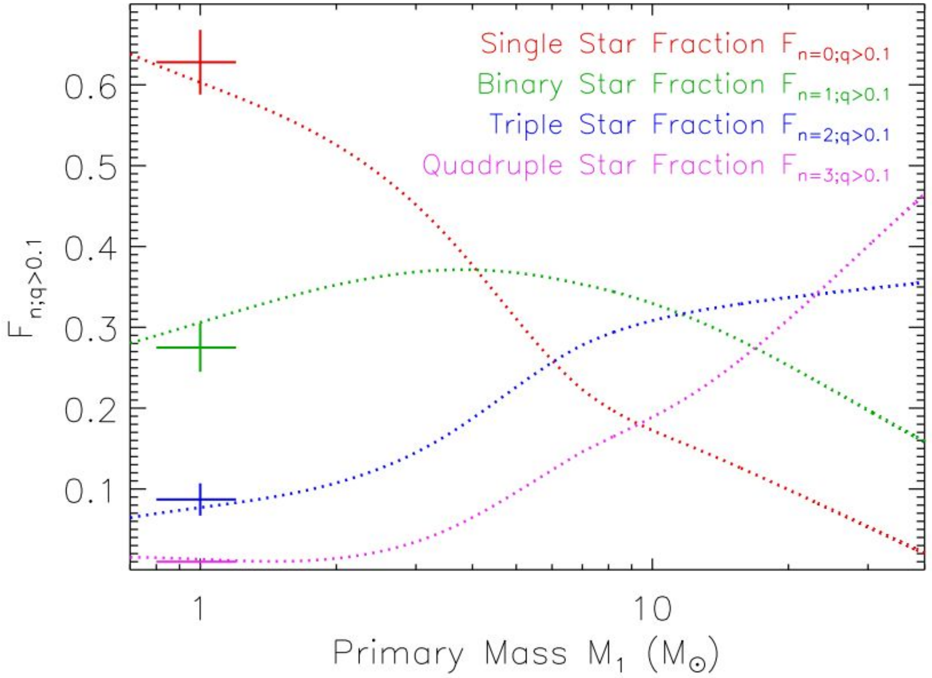
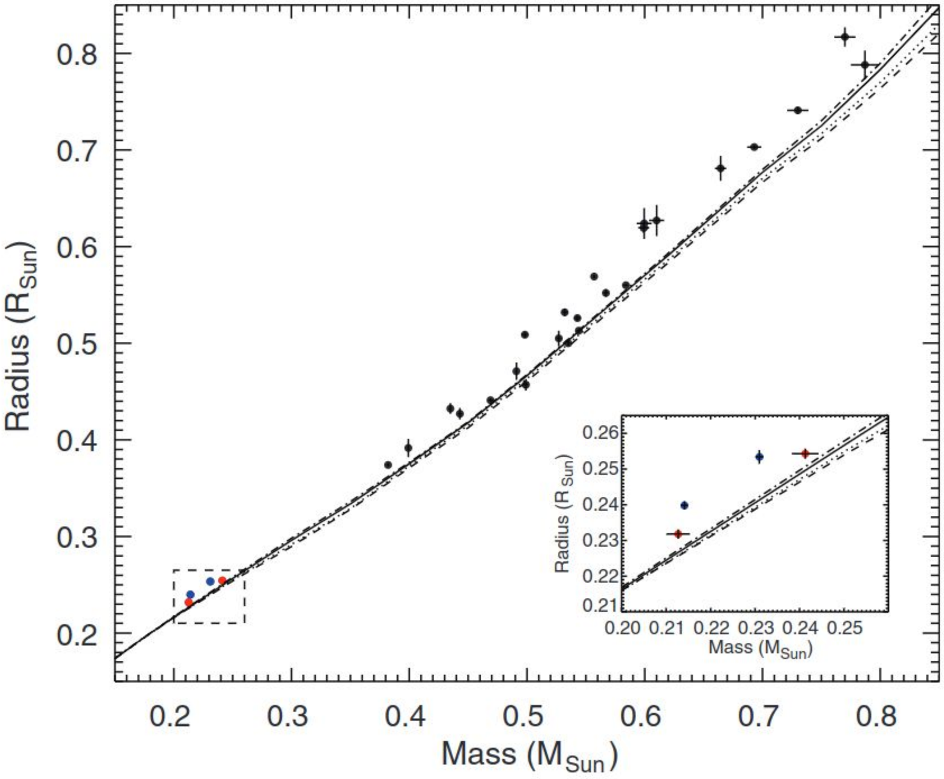


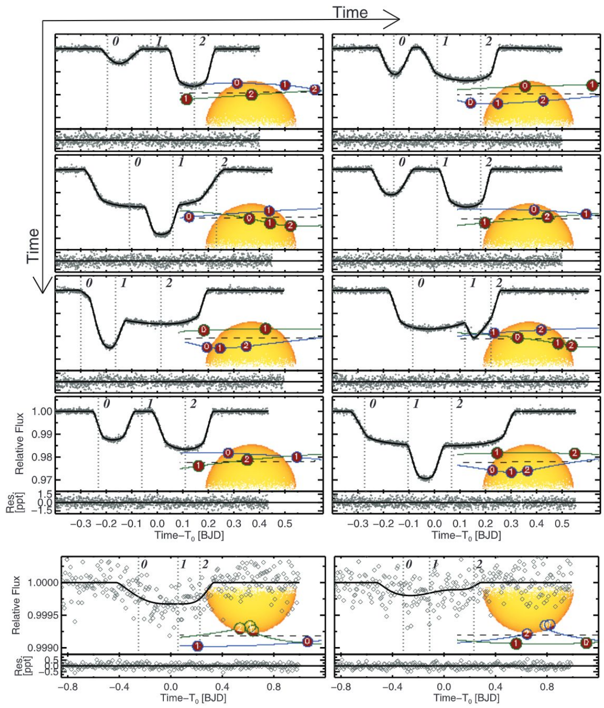
Figure 39. Multiplicity fractions as a function of primary mass (dotted lines), including the single-star fraction $\mathcal{F}_{n=0;q>0.1}$ (red), binary-star fraction $\mathcal{F}_{n=1;q>0.1}$ (green), triple-star fraction $\mathcal{F}_{n=2;q>0.1}$ (blue), and quadruple-star fraction $\mathcal{F}_{n=3;q>0.1}$ (magenta). Given a primary mass M_1, our model *assumes* that the multiplicity fractions follow a Poisson distribution across the interval n = [0, 3] in a manner that reproduces the measured multiplicity frequency $f_{\mathrm{mult};q>0.1} = \sum_{n=1}^{3} n\,\mathcal{F}_{n;q>0.1}$. For solar-type stars, this model matches the measured values (solid) within their uncertainties. Regardless of the uncertainties in the multiplicity fractions, $\lesssim$10% of O-type stars are single while $\gtrsim$55% are born in triples and/or quadruples.

KOI-126: A Triply Eclipsing Hierarchical Triple (Carter+ 2011)

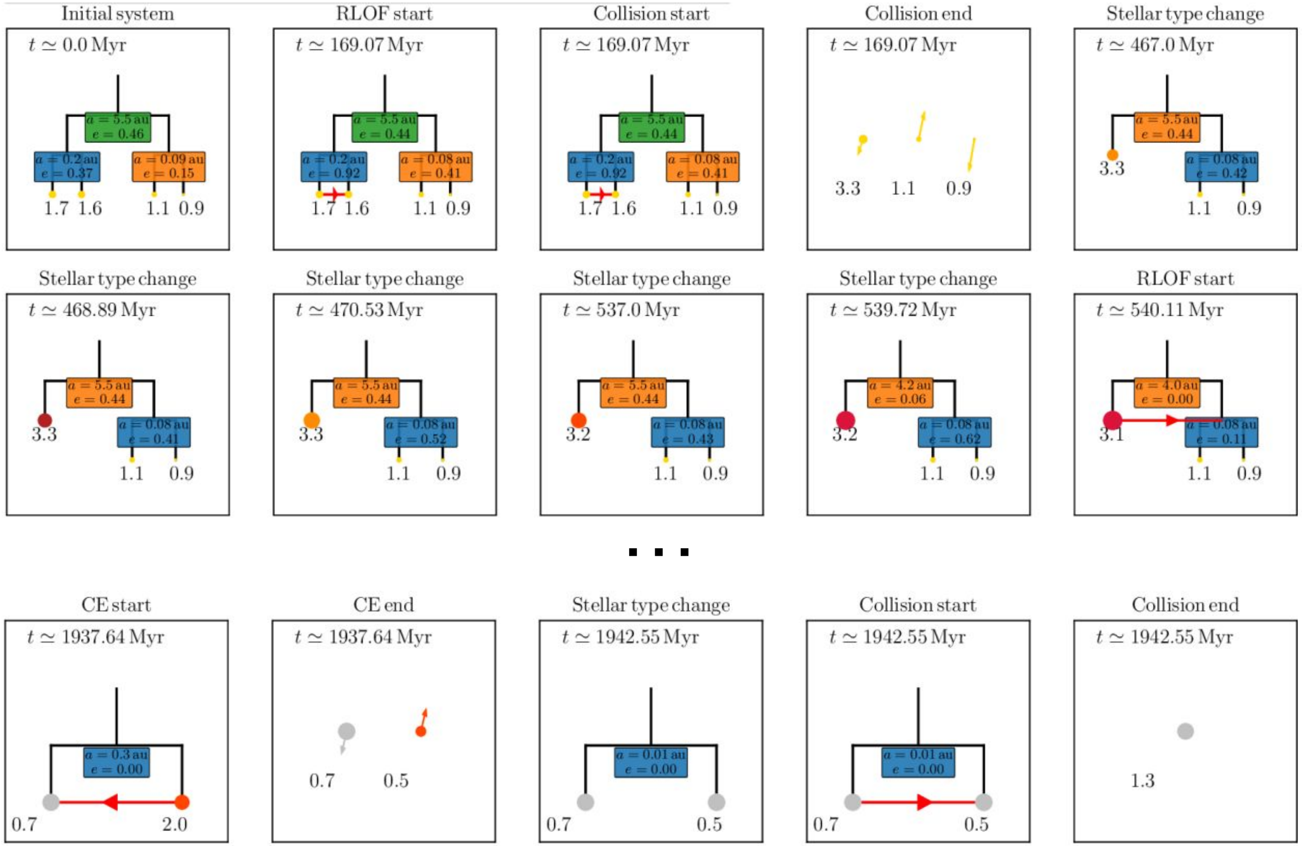
Fig. 2. Masses and radii of known low-mass stars with dynamically estimated masses and radii measured to better than 3% fractional accuracy (*22*, *28*). The black curves correspond to the theoretical stellar isochrones by Baraffe *et al.* (*23*). The dashed, dotted, solid, and dash-dotted curves correspond to 1 Gy, 2 Gy, 4 Gy, and 5 Gy solar metallicity isochrones, respectively. The blue points correspond to CM Draconis A, B, and the red points correspond to KOI-126 B, C. The inset panel corresponds to the region in the larger plot enclosed by the dashed rectangle.

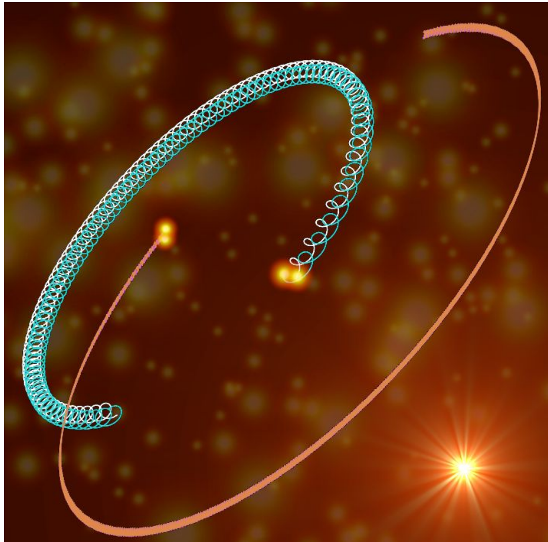


Potential to determine masses and radii to 0.1 %

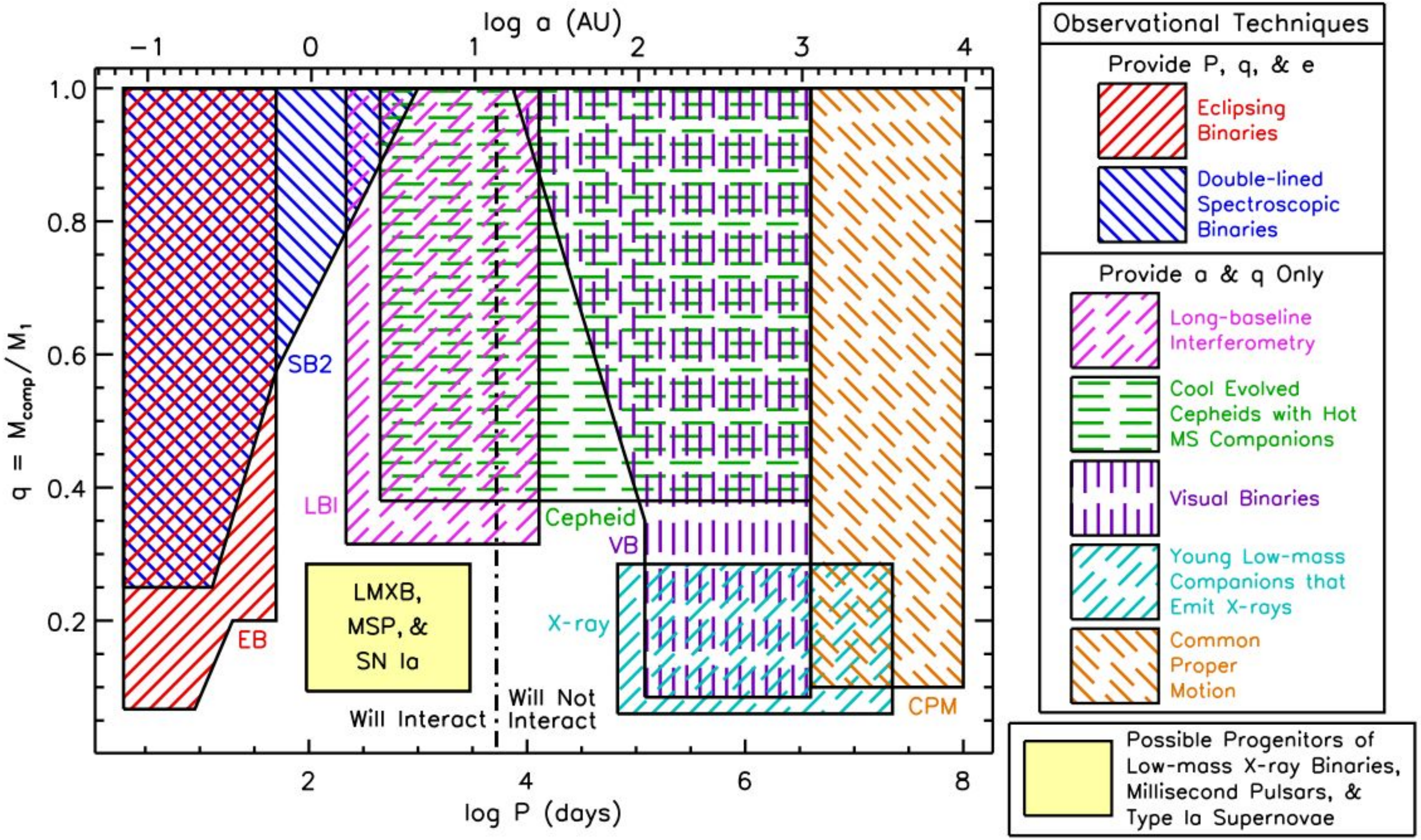


A spectroscopic quadruple as a possible progenitor of sub-Chandrasekhar type Ia supernovae (Merle+ 2022)





Present-day detection (characterisation) techniques



Moe and Di Stefano
2017

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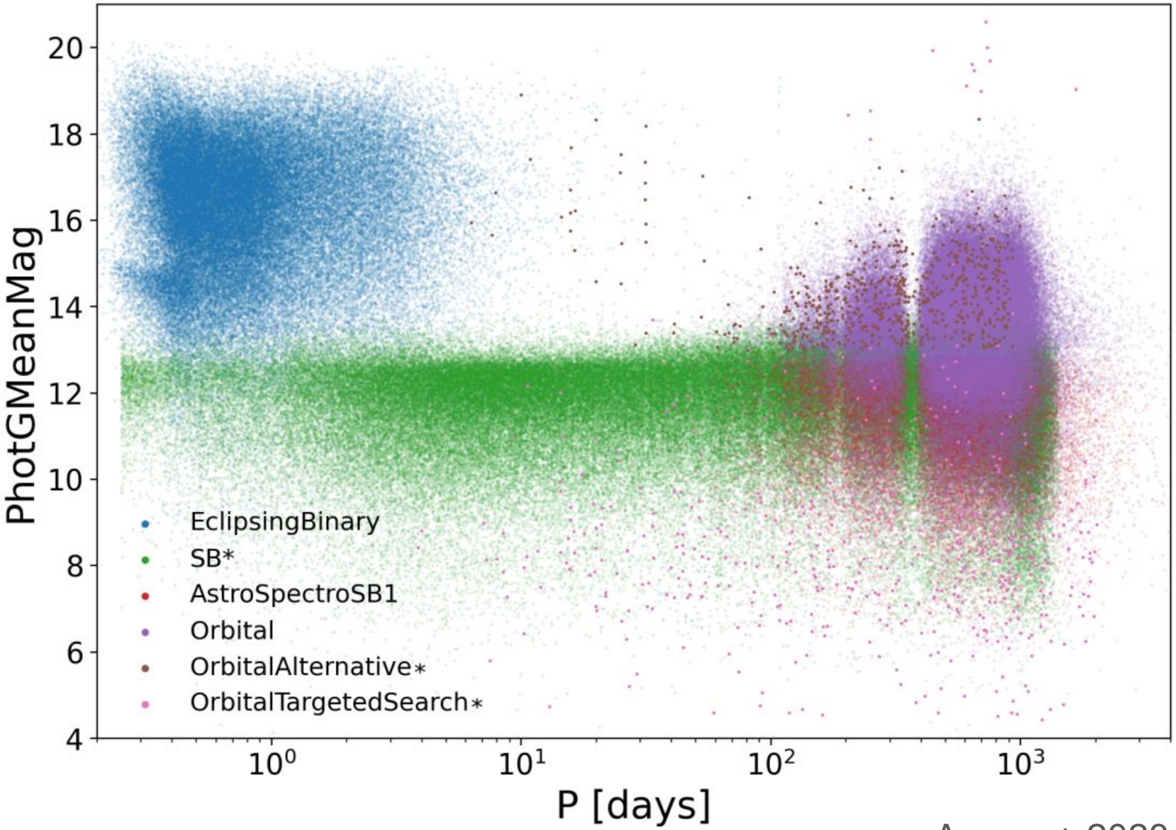


Arenou+ 2023

Light-curve signal $\propto R_*/a$
(inclination limit)

Astrometric signal $\propto a/D_*$
(orbit coverage limit)

Velocity signal $\propto \sqrt{M/a}$
(orbital period limit)

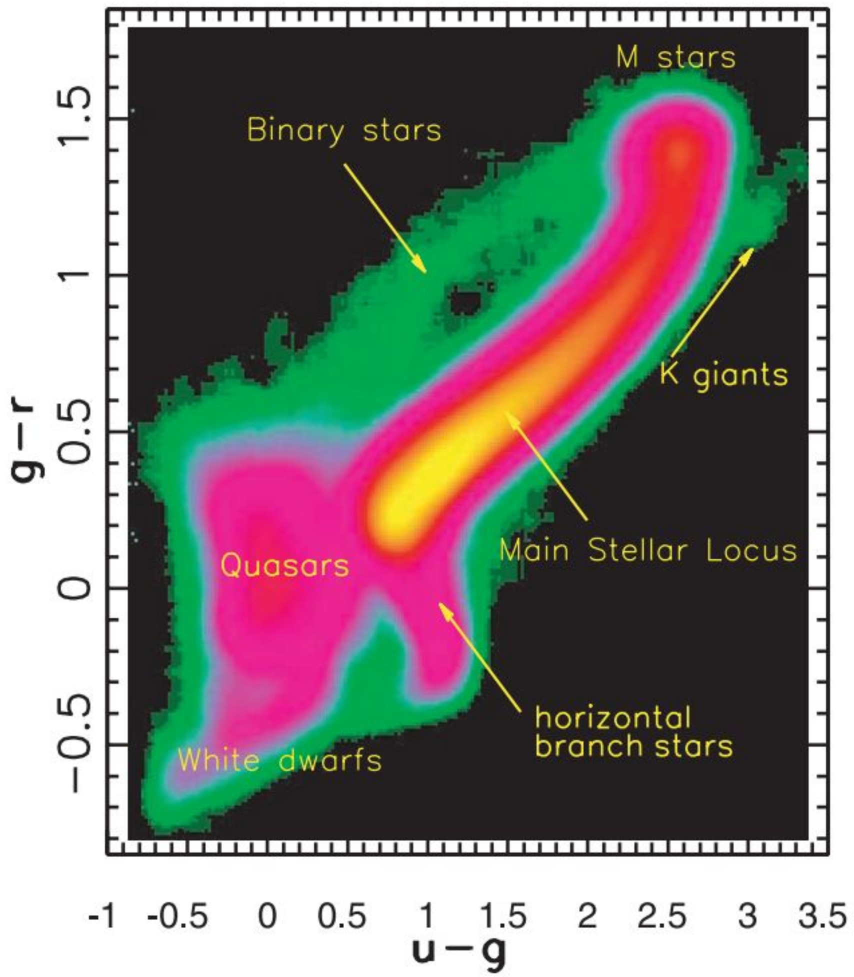
A complementary approach to detection

Distinguish multiple stars from all other single stars based on SED shape alone

Work in photometric colour space

A Second Stellar Color Locus: a Bridge from White Dwarfs to M stars
(Smolčić+ 2004)

FIG. 1.—Number density, displayed on a logarithmic scale, of ~1.99 million stars with $u < 20.5$ from SDSS Data Release 1 in the $g-r$ vs. $u-g$ color-color diagram (increasing from green to red to yellow). The most prominent features are the main stellar locus and the clump of low-redshift ($z < 2.3$) quasars, as marked. Other notable features include the locus of white dwarfs, horizontal branch stars (also including blue stragglers and RR Lyrae stars), and solar-metallicity K giants. The fainter feature colored green (*above and to the left of the main locus*) is the locus of ~1,000 binary stars. The properties of this locus are consistent with a distribution of M dwarf–white dwarf pairs with varying luminosity ratios. The root-mean scatter of stars about this locus is only ~0.1 mag.



Color-Induced Displacement

(Pourbaix+ 2004)

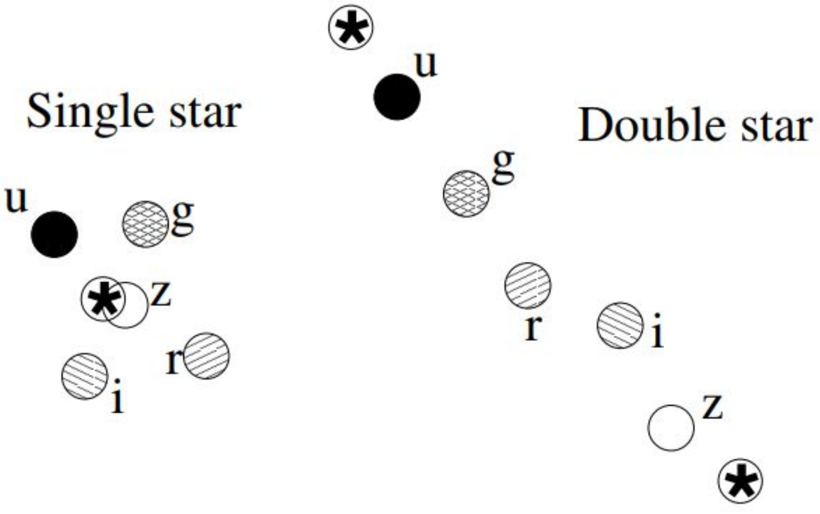


Fig. 1. Schematic position of the photocenter in the different SDSS bands. For double stars, the positions are aligned with the two stars and their order follows the central wavelength of the filter. Measurement error prevents the positions from being perfectly superposed/aligned for a single/double star. The true position of the star(s) is represented as a five-branch "star".

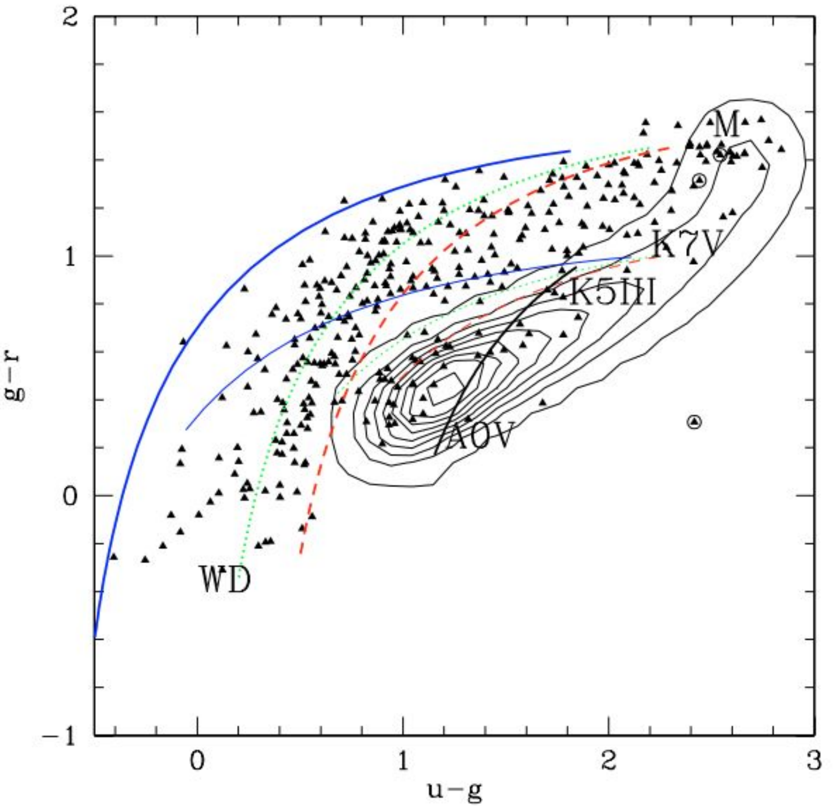
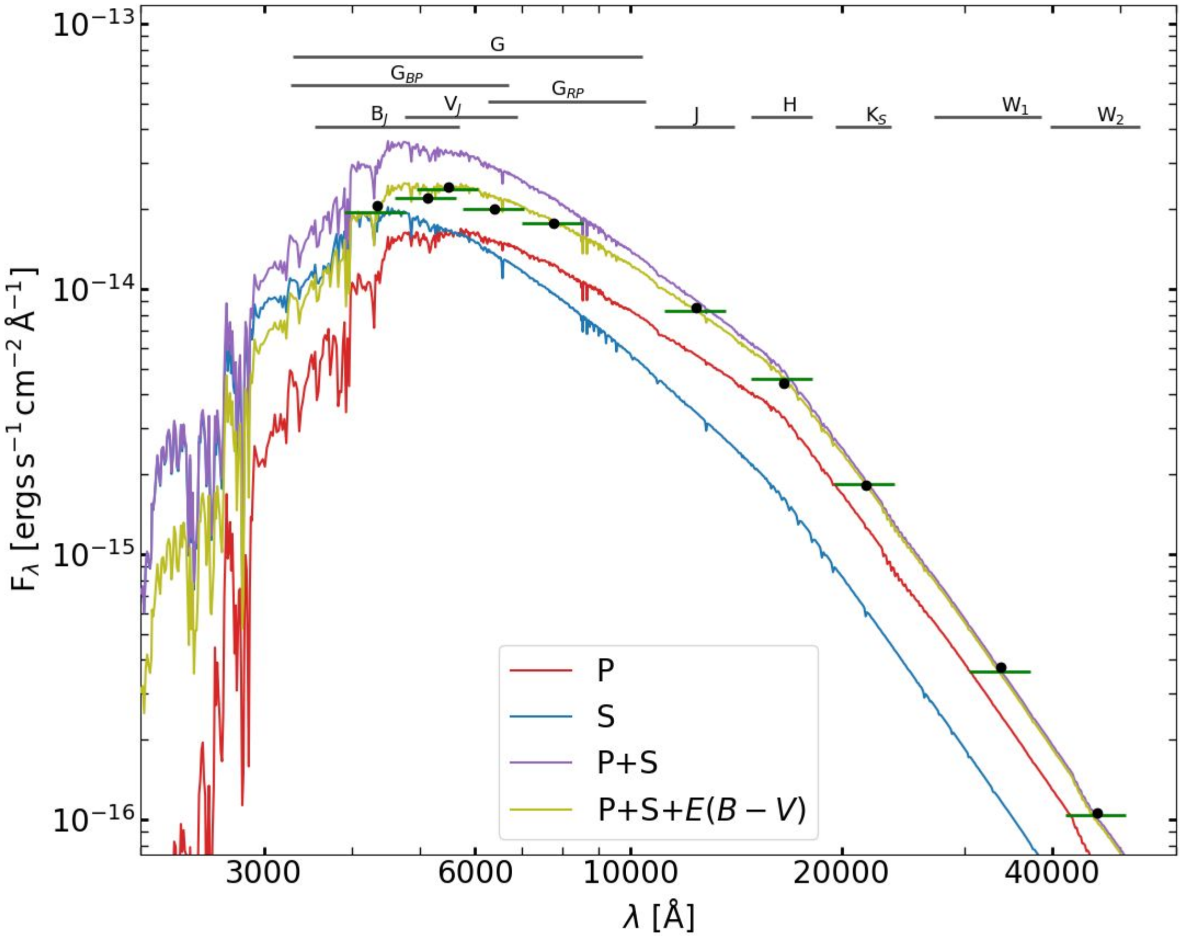


Fig. 4. Color−color diagram of the putative binaries (triangles) superposed over the original parent population of 284 503 stars (contours). The thick/thin lines represent systems with a M dwarf/K7V component. The short thick line close to the center corresponds to A0V+K5III systems. Triangles with a circle around have weird colors that could be the cause of the displacement.

Showcase binary system 2MASS J11051973-3905282



Traven et al. 2020
SB2 analysis:

Gmag = 12.73

Teff 1 = 5026 K
Teff 2 = 6163 K

[Fe/H] = -0.31
E(B−V) = 0.11

R 1 = 3.5 Rsun
R 2 = 2.1 Rsun

delta RV = 77.5 km/s

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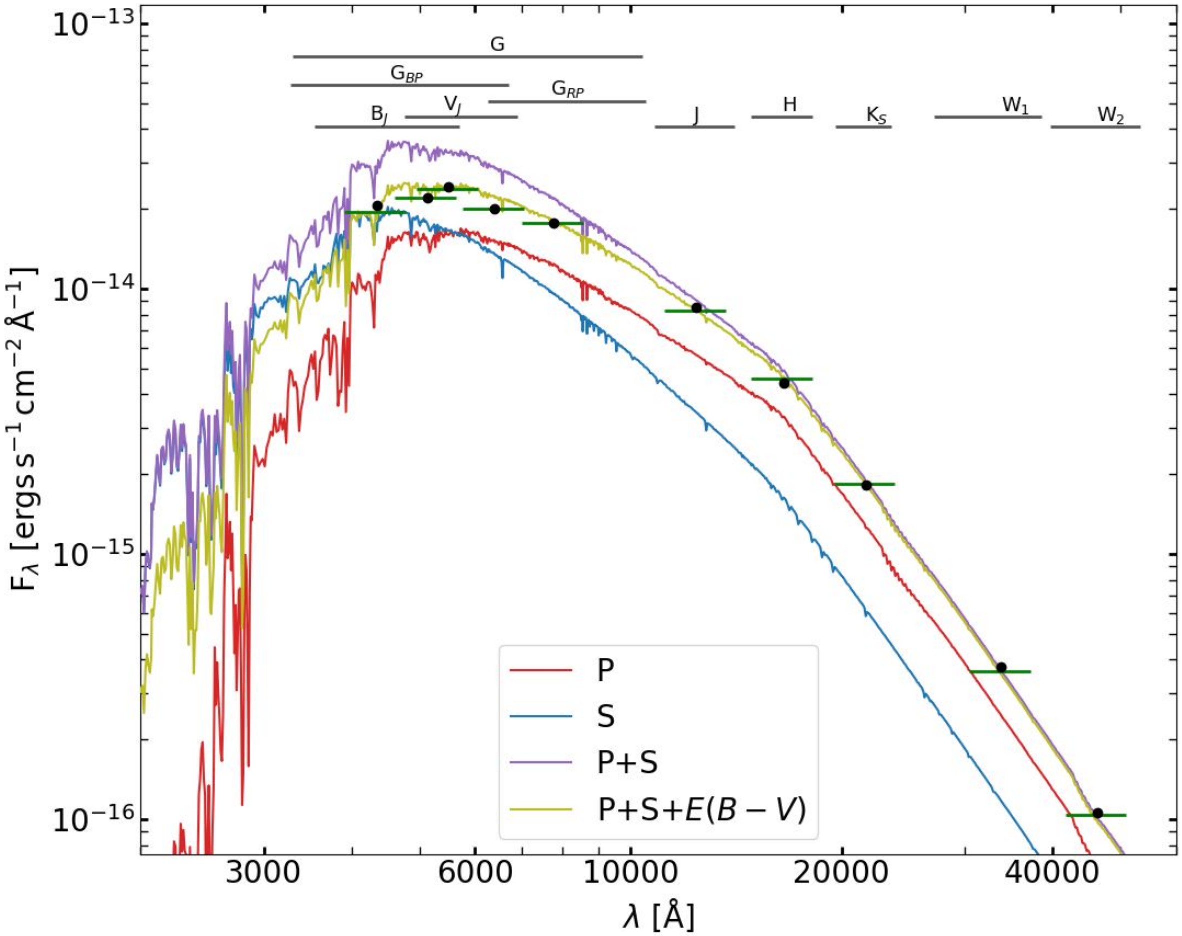
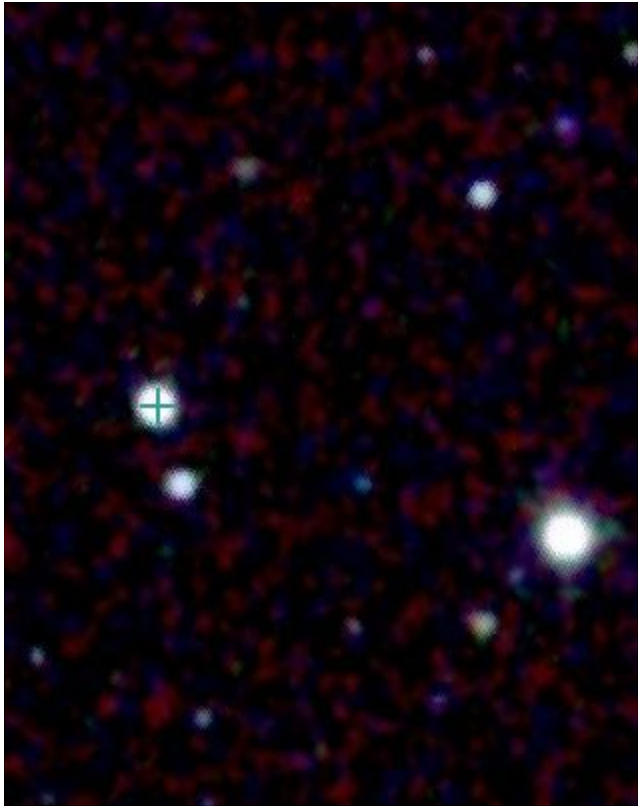
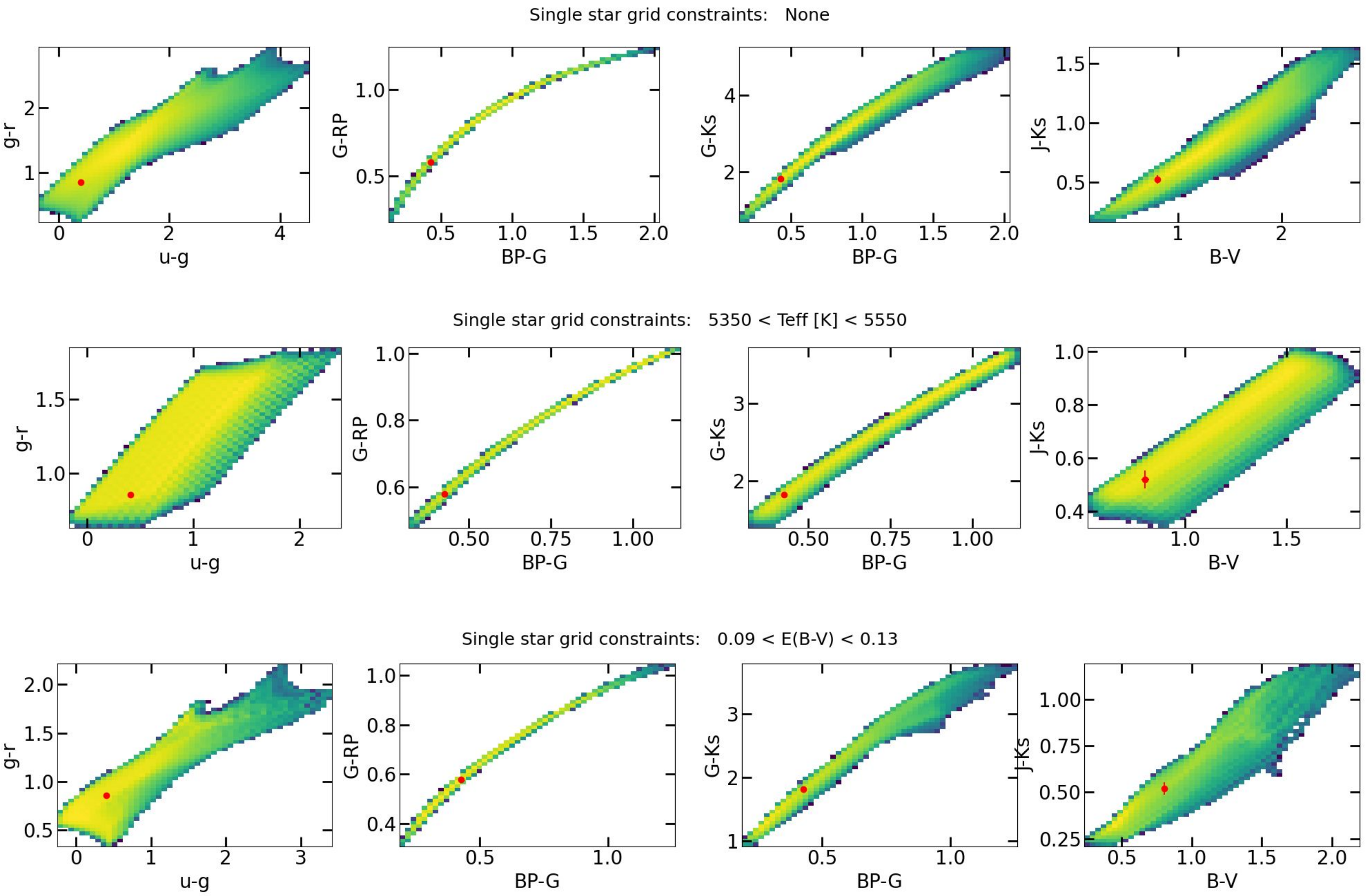




Compare binary vs single star synthetic colours

- Gaia (G, BP, RP), APASS (B, V), 2MASS (J, H, K), WISE (W1, W2) synthetic photometry (pysynphot with Castelli&Kurucz spectra + pyphot package)
- Parameters range for single stars (possibly non-physical combinations):
  - Teff: [3700, 6700] K with **10 K** step
  - logg: [0, 5.5] dex with **0.5 dex** step
  - Fe/H: [-2.5, 0.5] dex with **0.25 dex** step
  - E(B-V): [0, 1.0] with **0.005 mag** step
- Create 45 colour indices from all available magnitudes, e.g.: B-V, BP-J, G-W1

Showcase binary system 2MASS J05553880-7441202



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Measure of similarity between SEDs

Reduced Manhattan Distance - RMD

$$\text{RMD} = \frac{\text{Manhattan distance in colour space}}{\text{N colours}}$$

The photometric precision has to be better than this

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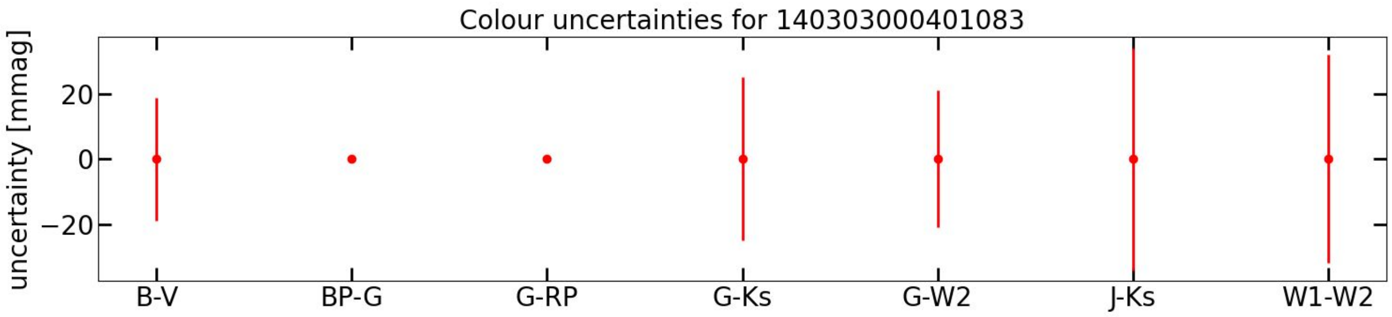

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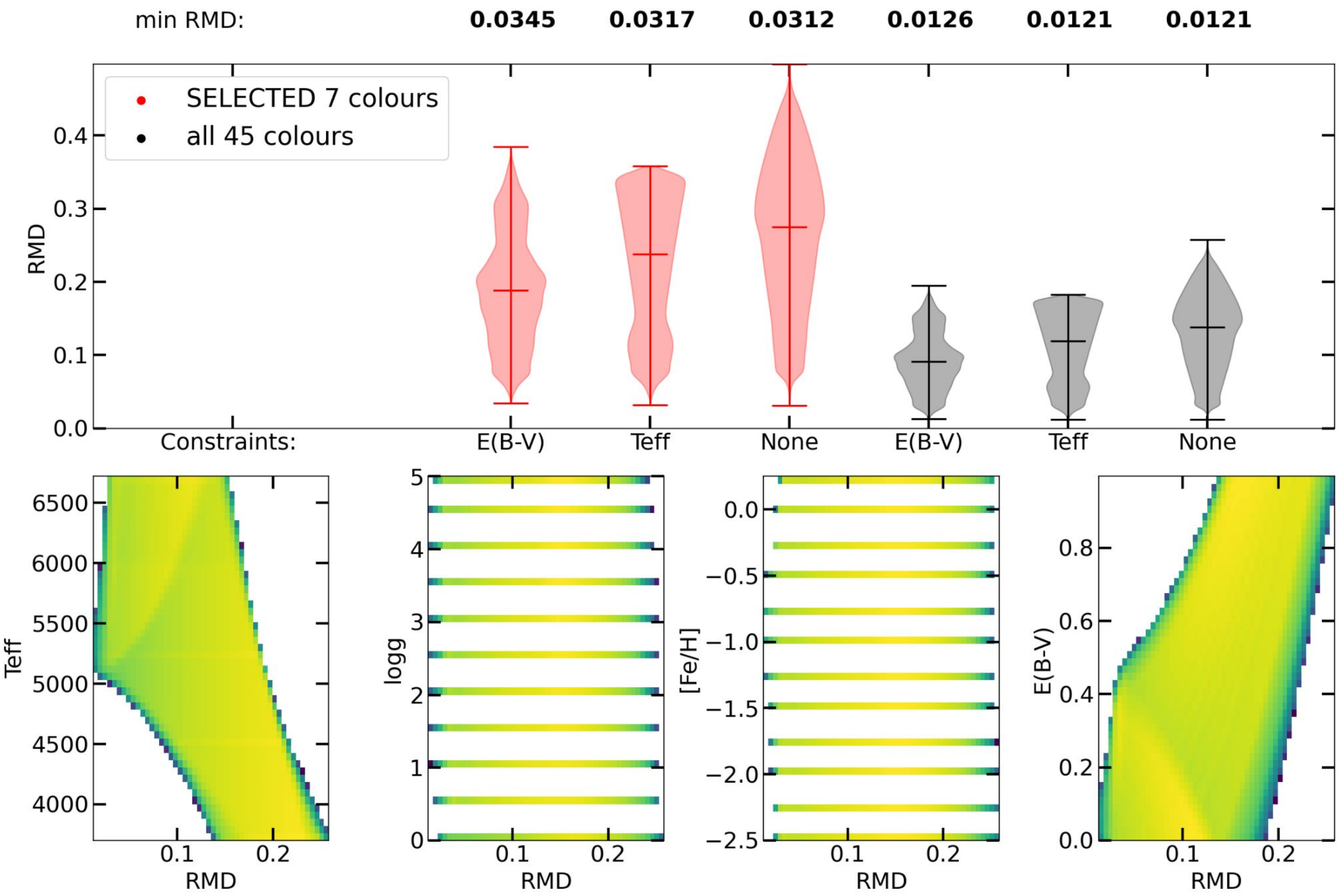
Case study: binary system 2MASS J05553880-7441202



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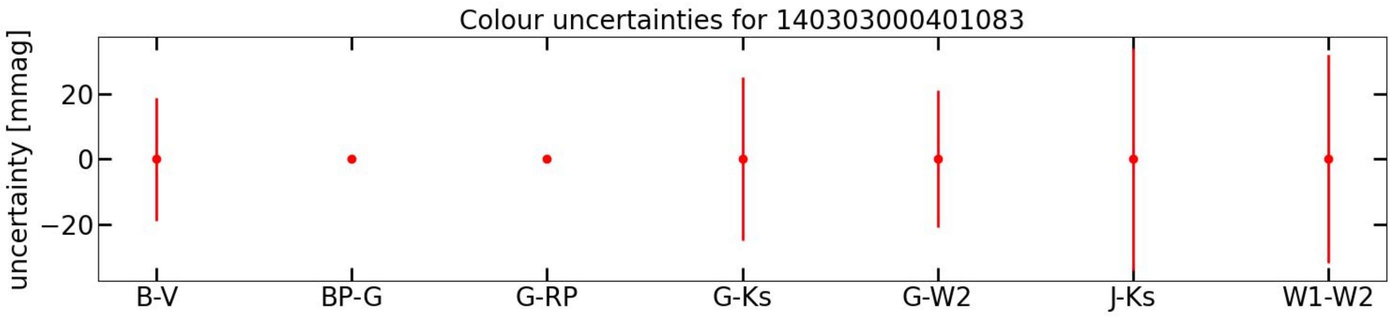

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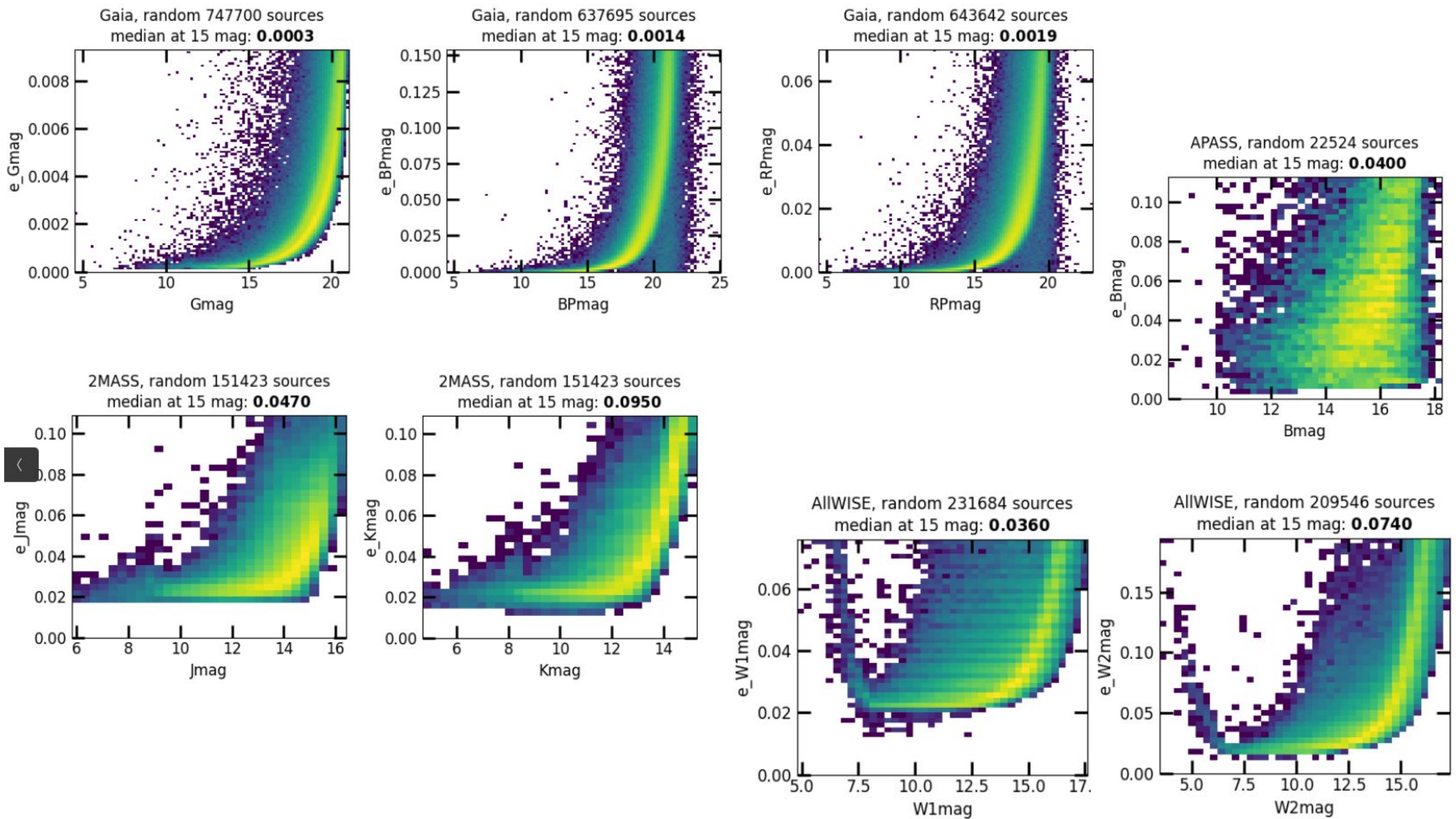
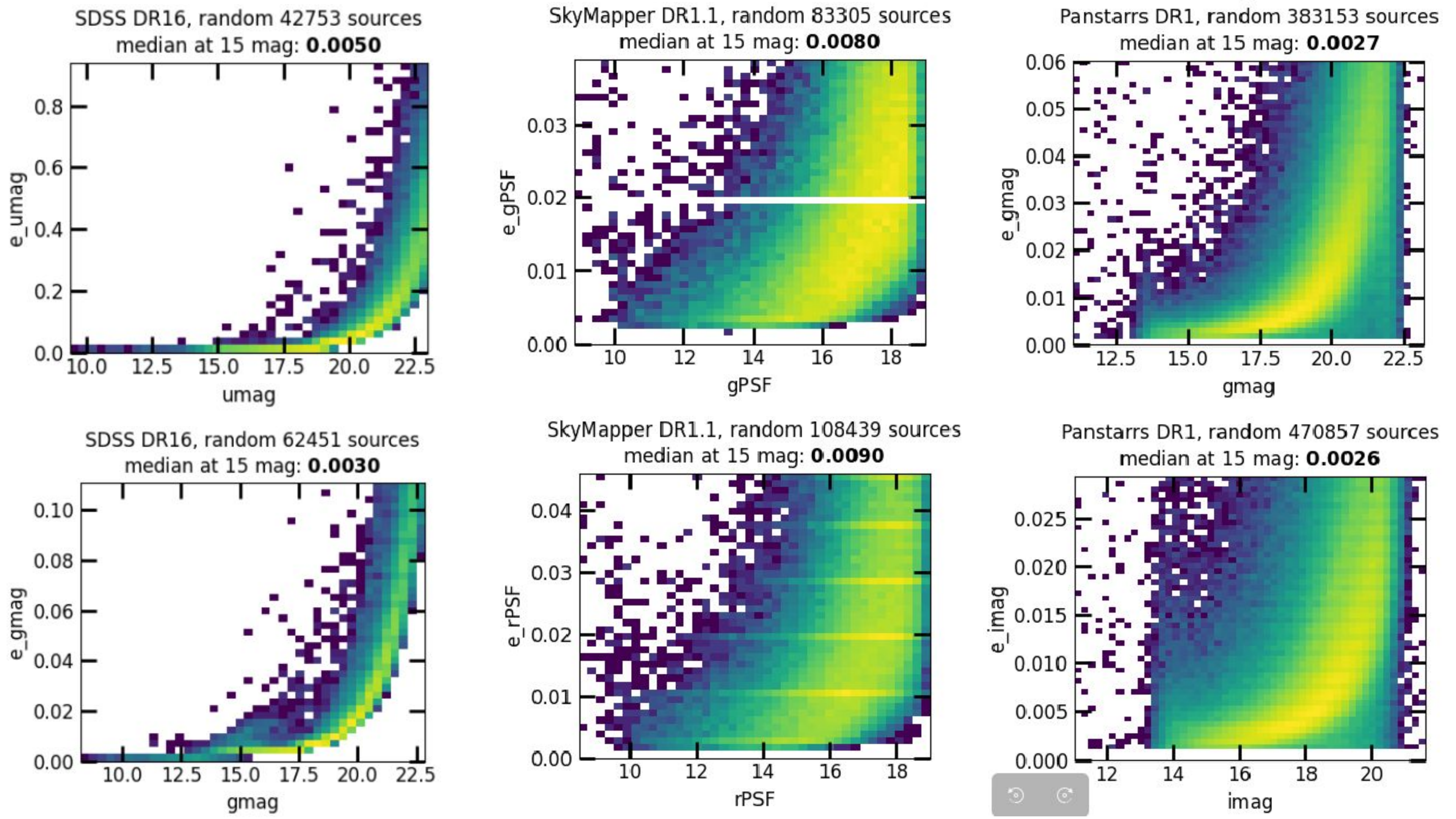

Gaia, random 747700 sources
median at 15 mag: **0.0003**
e_Gmag
Gmag
Gaia, random 637695 sources
median at 15 mag: **0.0014**
e_BPmag
BPmag
Gaia, random 643642 sources
median at 15 mag: **0.0019**
e_RPmag
RPmag
APASS, random 22524 sources
median at 15 mag: **0.0400**
e_Bmag
Bmag
2MASS, random 151423 sources
median at 15 mag: **0.0470**
e_Jmag
Jmag
2MASS, random 151423 sources
median at 15 mag: **0.0950**
e_Kmag
Kmag
AllWISE, random 231684 sources
median at 15 mag: **0.0360**
e_W1mag
W1mag
AllWISE, random 209546 sources
median at 15 mag: **0.0740**
e_W2mag
W2mag



SDSS DR16, random 42753 sources
median at 15 mag: 0.0050
e_umag
umag
SkyMapper DR1.1, random 83305 sources
median at 15 mag: 0.0080
e_gPSF
gPSF
Panstarrs DR1, random 383153 sources
median at 15 mag: 0.0027
e_gmag
gmag
SDSS DR16, random 62451 sources
median at 15 mag: 0.0030
e_gmag
gmag
SkyMapper DR1.1, random 108439 sources
median at 15 mag: 0.0090
e_rPSF
rPSF
Panstarrs DR1, random 470857 sources
median at 15 mag: 0.0026
e_imag
imag

Proposed detection approach summary

- Efficiency does not depend on orbital configuration (e.g. period, inclination, eccentricity, phase) of multiple stellar systems
- We need mmag precision or better, offered already by selected photometric surveys
- Limited by luminosity ratio - it doesn’t work for equal mass or low mass ratio systems, giant/dwarf systems
- A very low-cost approach

Plan for further investigation

- Explore the feasibility of detection across the parameter space with current (and future, e.g. GaiaNIR) observational capabilities

- Select/define best suited photometric filters

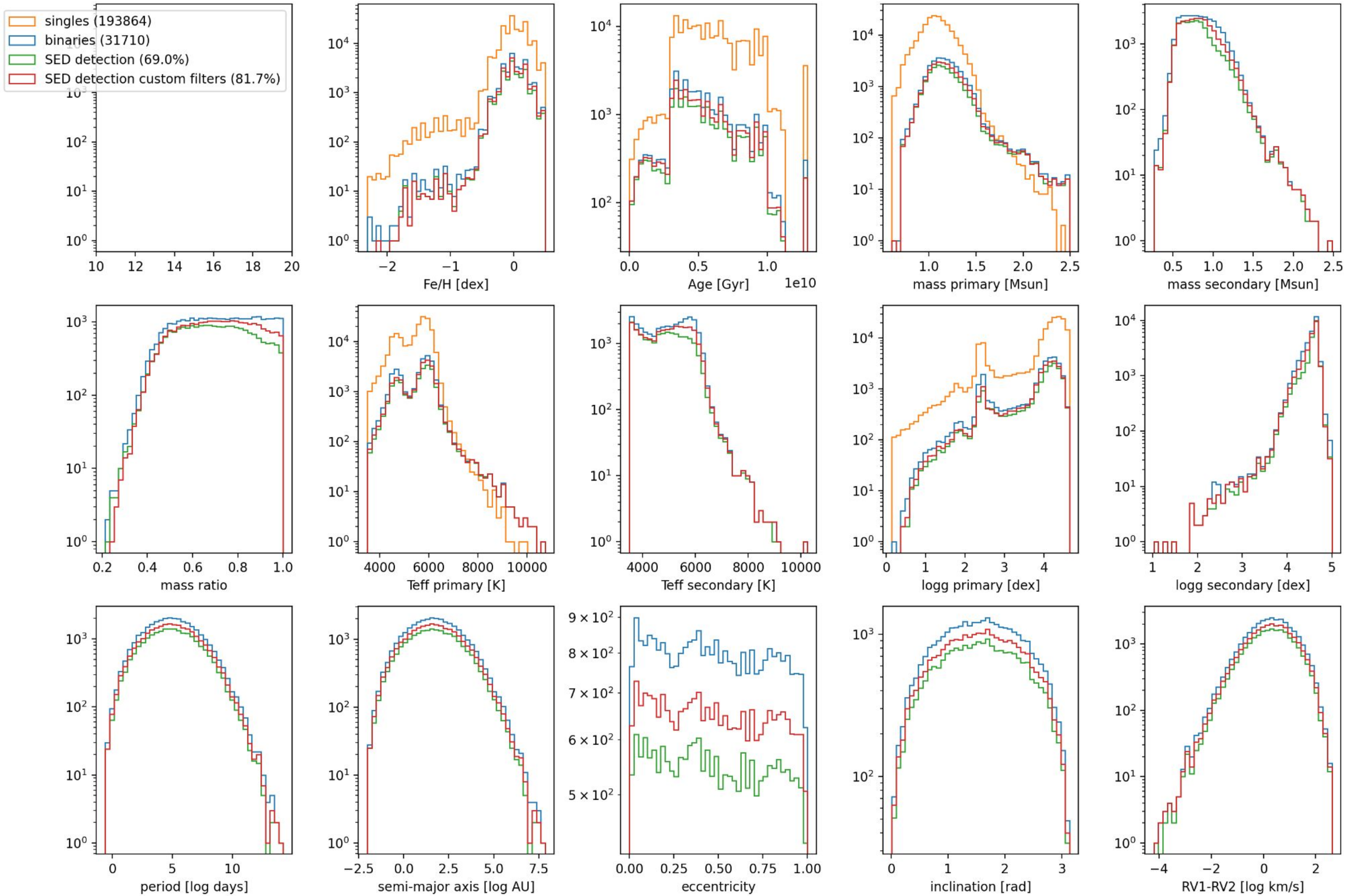
- Create an (ML) algorithm for assigning multiplicity probabilities, taking into account individual observational uncertainties and external information (e.g. extinction)

Current observed multiple stars for exploration / training

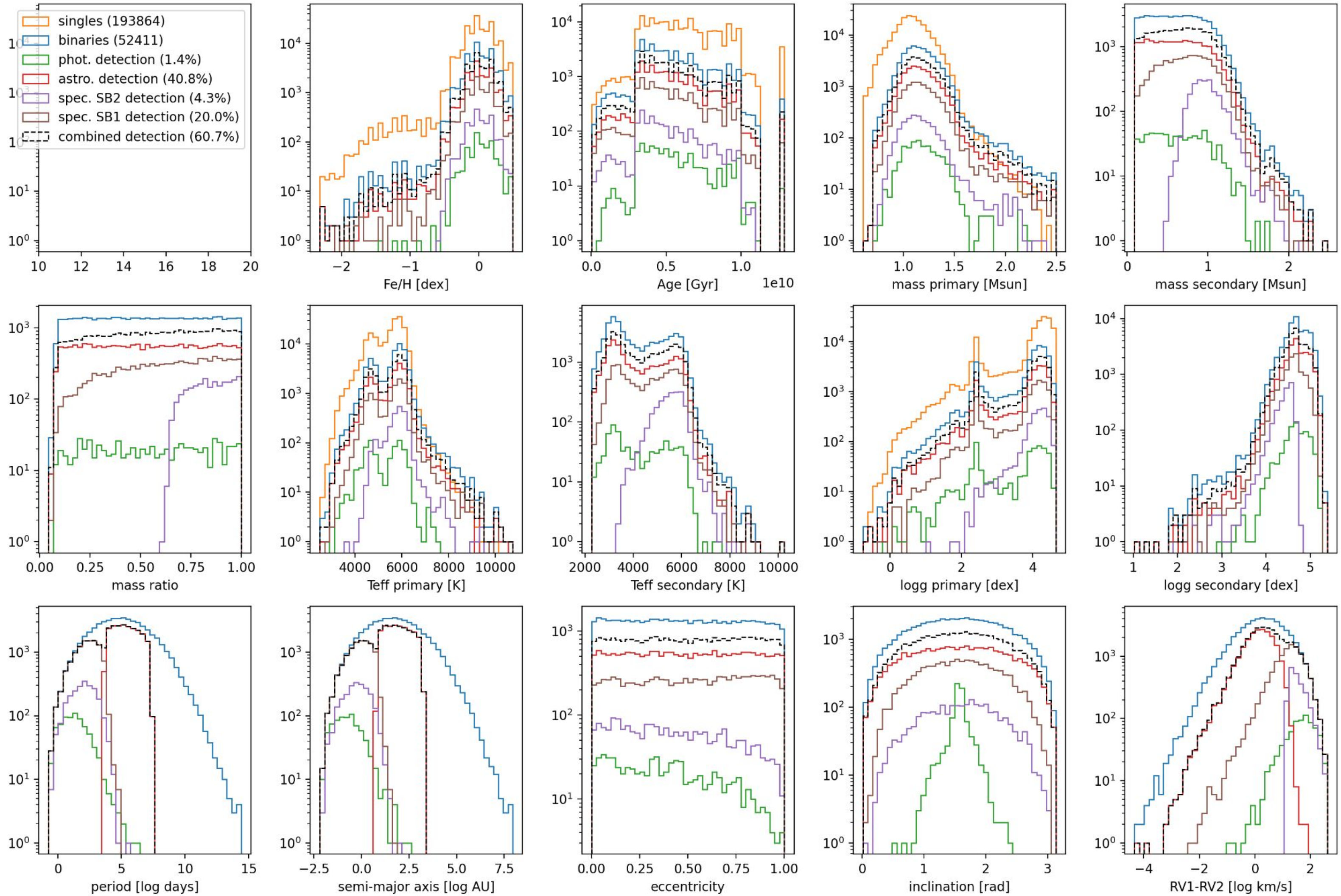
- **Gaia** astrometric, eclipsing, spectroscopic binaries (**~2 million**)
- GALAH binaries (~13k), triples (~40), quadruples (~2)
- Apogee binaries (~20k), triples (~200)
- LAMOST binaries (~3k), triples (~130)
- GaiaESO binaries (~400), triples (~10), quadruples (~2)
- RAVE + Gaia (~30k)
- SB9 binaries (~4k)
- TESS binaries (~15k)
- Kepler binaries (~3k)
- OGLE binaries (~400k)
- …
- BUT WHICH STARS ARE SINGLE ?

Caveats / Open questions

- Detection yes, how about characterisation (temperature, luminosity) ?
- Is detection enough for studies of e.g. binary star fraction vs metallicity or mass ?
- How well this method works for higher multiples ?
- How to account for possible systematics between synthetic/observed photometric domain ?
- How well do we know the extinction law ?
- How to account for chance alignments ?
- Spurious signal due to peculiar stars ?
- Can we define more optimal filters for detection keeping in mind general science goals of photometry (what kind of cutoffs/filters would we like for the GaiaNIR) ?
- How can Gaia XP spectra help to constrain the SED or provide additional information e.g. metallicity ?



singles (193864)
binaries (31710)
SED detection (69.0%)
SED detection custom filters (81.7%)
Fe/H [dex]
Age [Gyr]
1e10
mass primary [Msun]
mass secondary [Msun]
mass ratio
Teff primary [K]
Teff secondary [K]
logg primary [dex]
logg secondary [dex]
period [log days]
semi-major axis [log AU]
eccentricity
inclination [rad]
RV1-RV2 [log km/s]



singles (193864)
binaries (52411)
phot. detection (1.4%)
astro. detection (40.8%)
spec. SB2 detection (4.3%)
spec. SB1 detection (20.0%)
combined detection (60.7%)
Fe/H [dex]
Age [Gyr]
1e10
mass primary [Msun]
mass secondary [Msun]
mass ratio
Teff primary [K]
Teff secondary [K]
logg primary [dex]
logg secondary [dex]
period [log days]
semi-major axis [log AU]
eccentricity
inclination [rad]
RV1-RV2 [log km/s]

Robust detection of CID double stars in SDSS
(Pourbaix+ 2016)

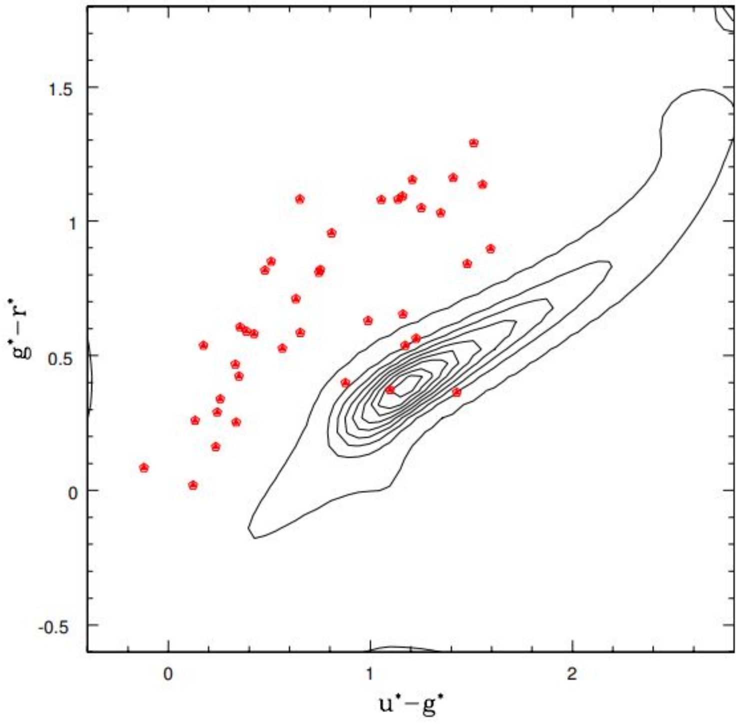


Fig. 2. Position of the confirmed CID candidates in the dereddened colour–colour diagram together with the stellar locus.

Fig. 3. Image of 96981424 (SDSS J011123.90+000935.1) exhibits a colour gradient whose orientation seems to be orthogonal to the CID.

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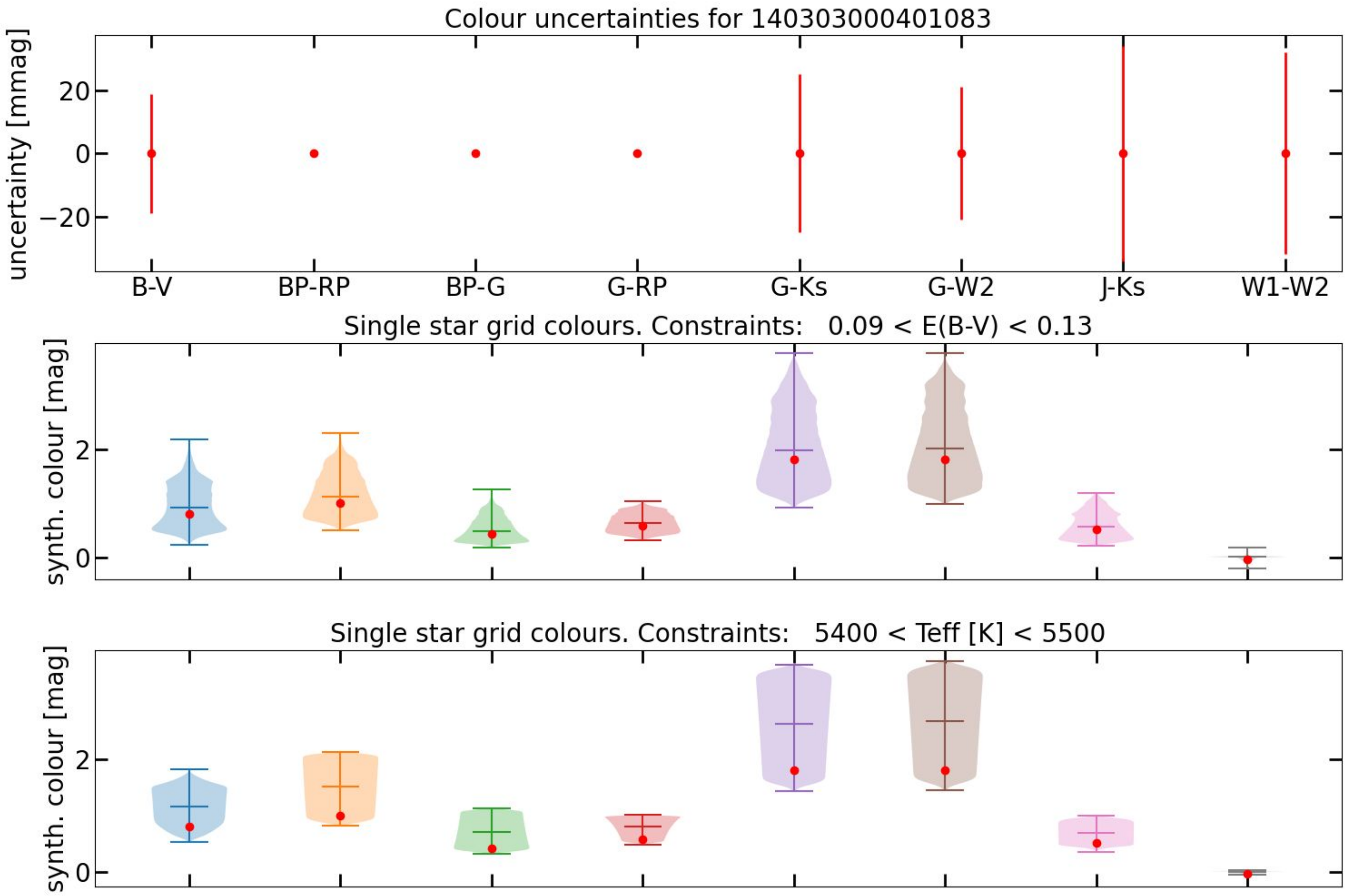

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