The binary fraction in star clusters (within 1 kpc)

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Stellar variability, stellar multiplicity: periodicity in time & motion - June 6-8th, Sofia, Bulgaria

Are most Milky Way stars single or binary?

Binary Formation

- Low Likelihood that some binaries might be created by gravitational capture between two single stars.
- Binaries in young stars supports the theory that binaries develop during star formation. Fragmentation of the molecular cloud during the formation of protostars is possible explanation for the formation of a binary or multiple star system.
- It seems to be impossible to dynamically produce binaries in anywhere near the numbers observed, and so most binaries must have formed as binaries (Goodman & Hut 1993).
- Multiplicity properties appear to be mostly set at the PMS phase.
- Subsequent evolution is modest at best, as expected from dynamical evolution models.
- Observations suggest that a significant fraction of stars (perhaps most) *in the field* are in binary or multiple systems (e.g. Duquennoy & Mayor 1991; Fischer & Marcy 1992; Lada 2006; Eggleton & Tokovinin 2008).

In open clusters: The binary fraction, can evolve over time due to various factors such as dynamical interactions and stellar evolution.

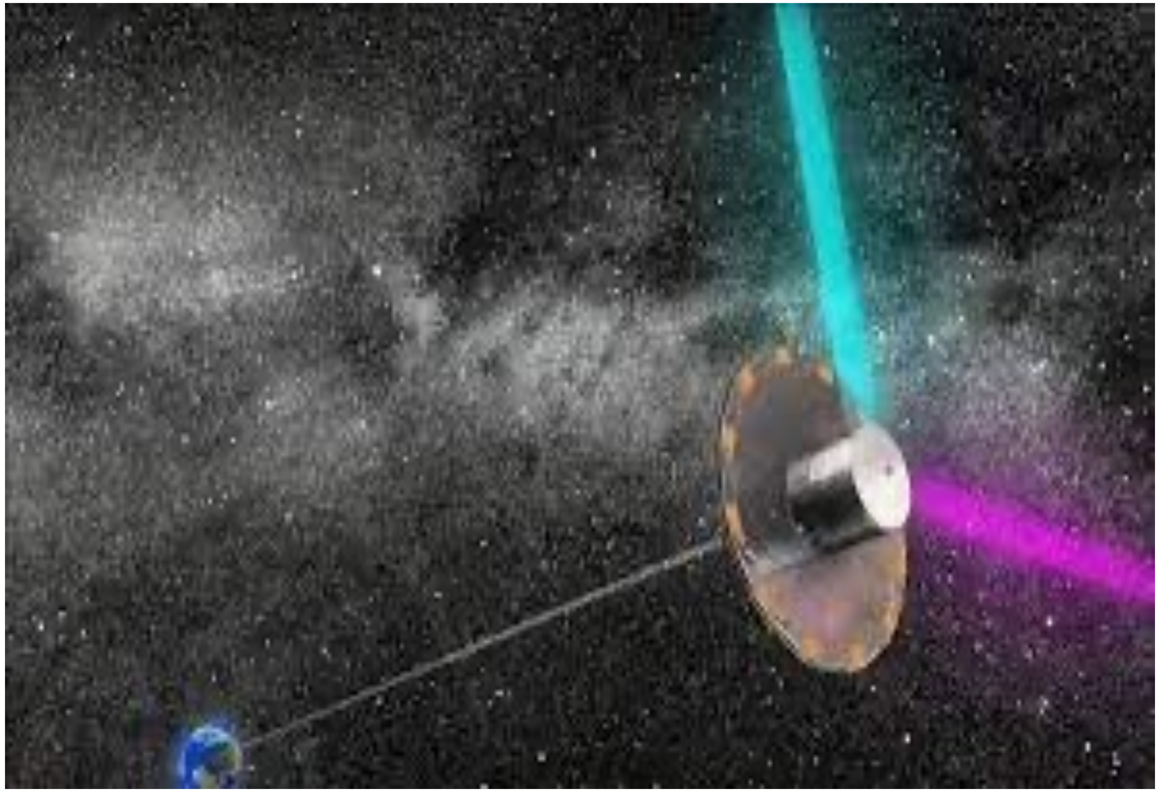
- Formation: The initial binary fraction of an open cluster is therefore set during its formation.
- Dynamical interactions: Binary systems can be disrupted through gravitational interactions with other stars, or two binary systems can merge to form a higher-order binary system. The strength of these interactions depends on the density and velocity dispersion of stars in the cluster.
- Stellar evolution: As stars evolve, their binary properties can change. For example, a binary system can become wider, or it can become tighter if one star loses mass to its companion. The frequency and outcome of such changes depend on the initial properties of the binary system, such as the masses and separation of the stars.
- Escaping the cluster: Binary systems can also be ejected from the cluster due to gravitational interactions with other stars. This can either increase or decrease the binary fraction, depending on whether the ejected systems were single or binary stars.

A complex process!

GAIA: 6D revolution

RA, Dec, parallax, RV, pmra, pmdec

Two identical, three-mirror anastigmatic (TMA) telescopes, with apertures of 1.45 m × 0.50 m pointing in directions separated by the basic angle ($\Gamma = 106^\circ.5$)
Accuracy of 24 microarcsec= 42 kpc, 0.06arcsec pixels



Galactic Archealogy!!! Imagine!!!

Modus Operandi

- Our sample is 376 clusters within 1 kpc from Cantat-Gaudin(2020)
- We use ASteCA to find the binary fraction
- study its evolution in time in relation to their galactocentric distance, size (core and limiting radii), location in the galaxy (l,b) and mass-functions.
- We use isochrones to find the binary fraction

ASteCA (Automated Stellar Cluster Analysis)

A suit of tools designed to fully automatize the standard tests applied on stellar clusters to determine their basic parameters.

The set of functions included in the code make use of positional and photometric data to obtain precise and objective values for a given cluster's center coordinates, radius, luminosity function and integrated color magnitude, as well as characterizing through a statistical estimator its probability of being a true physical cluster rather than a random overdensity of field stars.

It incorporates a Bayesian field star decontamination algorithm capable of assigning membership probabilities using photometric data alone.

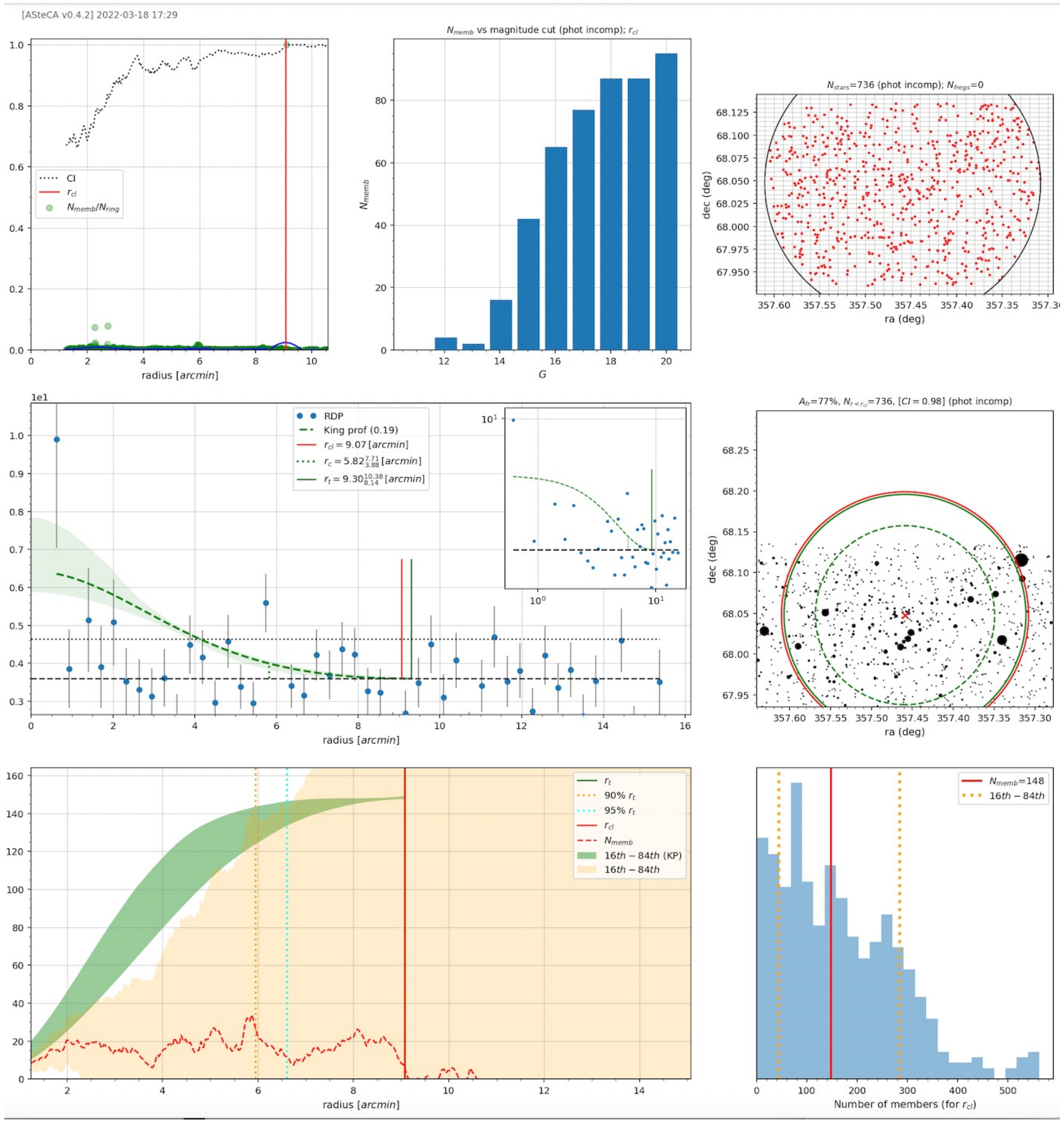
An isochrone fitting process based on the generation of synthetic clusters from theoretical isochrones and selection of the best fit through a genetic algorithm is also present, which allows ASteCA to provide accurate estimates for a cluster's metallicity, age, extinction and distance values along with its uncertainties.

ASteCA (NGC 7762)

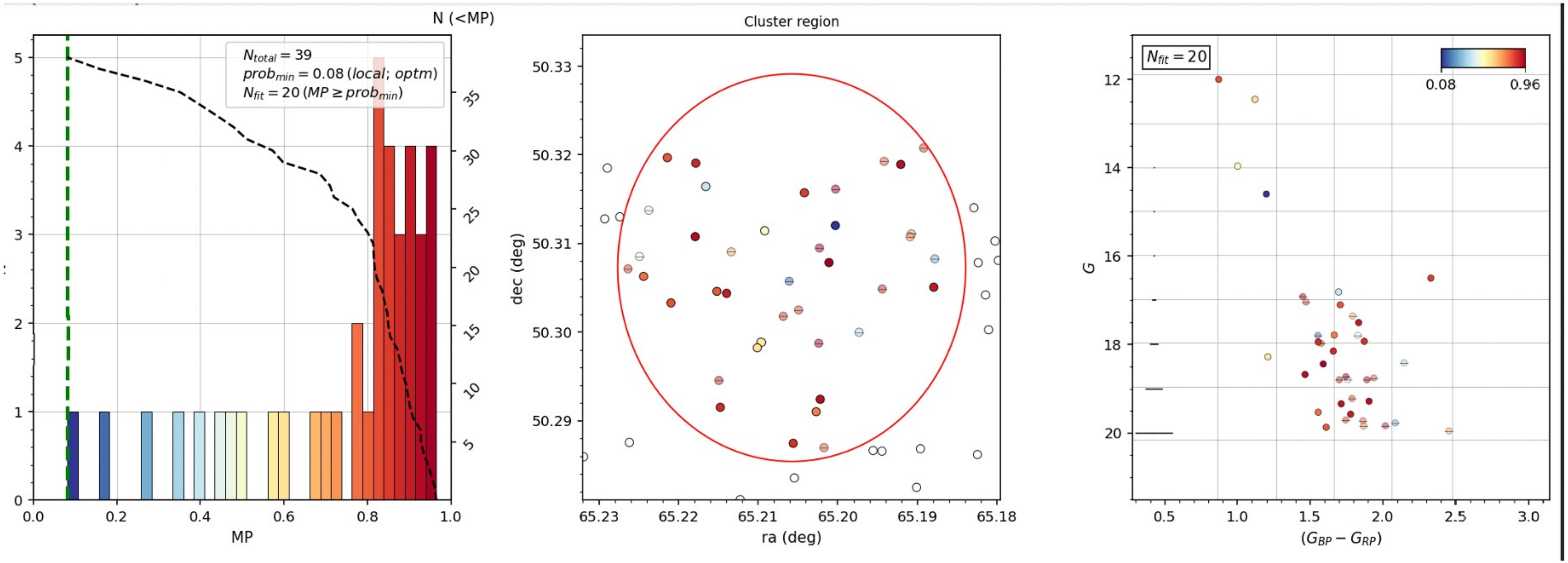
A&A 576, A6 (2015)

ASteCA: Automated Stellar Cluster Analysis

G. I. Perren[1,3], R. A. Vázquez[1,3] and A. E. Piatti[2,3]

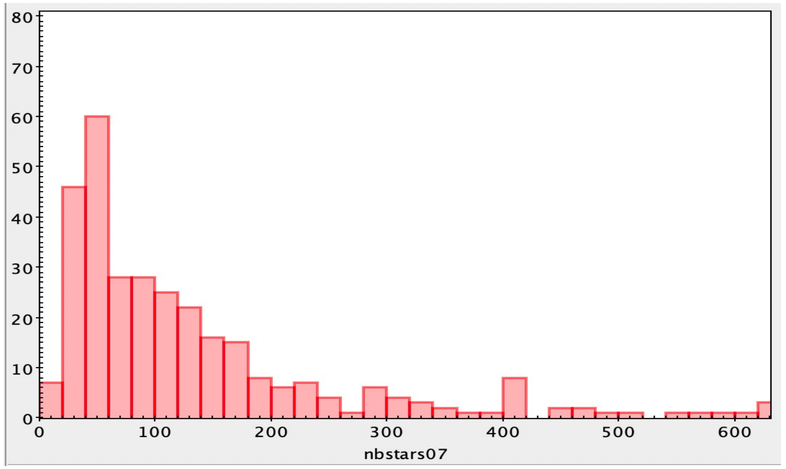


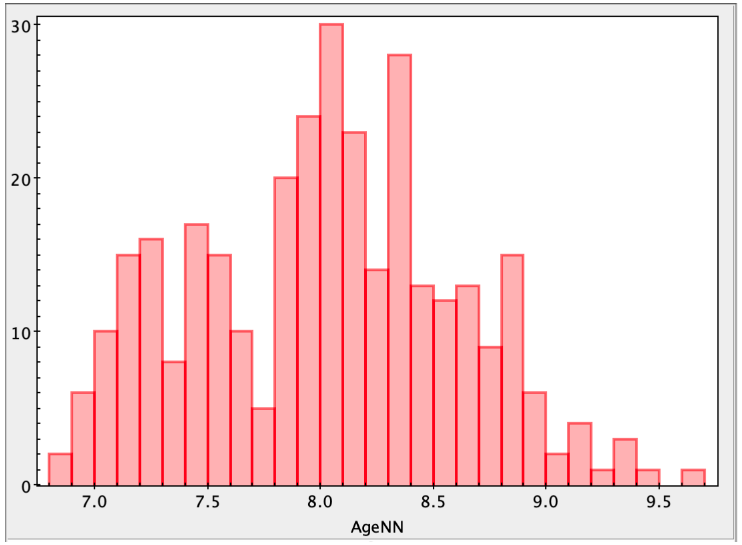
NGC 1542

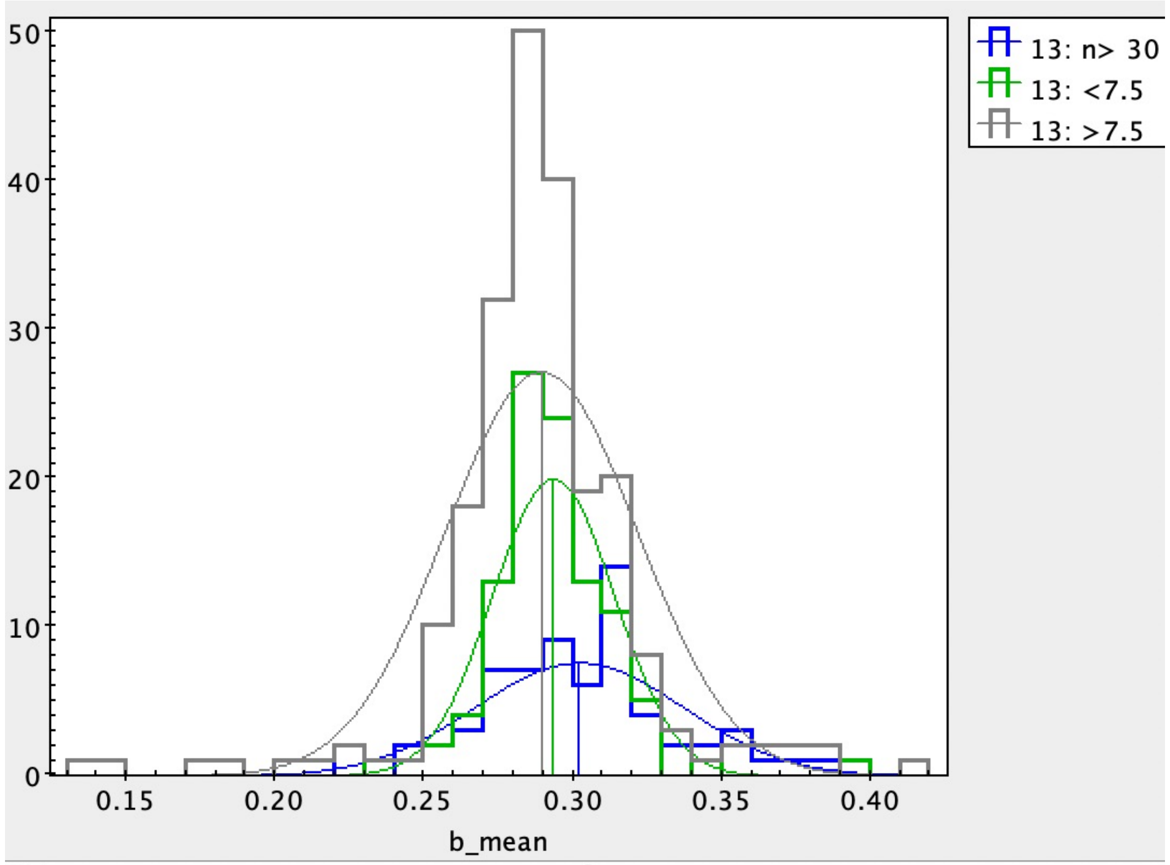


N (<MP)
$N_{total} = 39$
$prob_{min} = 0.08$ (local; optm)
$N_{fit} = 20$ ($MP \geq prob_{min}$)
MP
Cluster region
dec (deg)
ra (deg)
$N_{fit} = 20$
0.08
0.96
G
$(G_{BP} - G_{RP})$

Our Sample

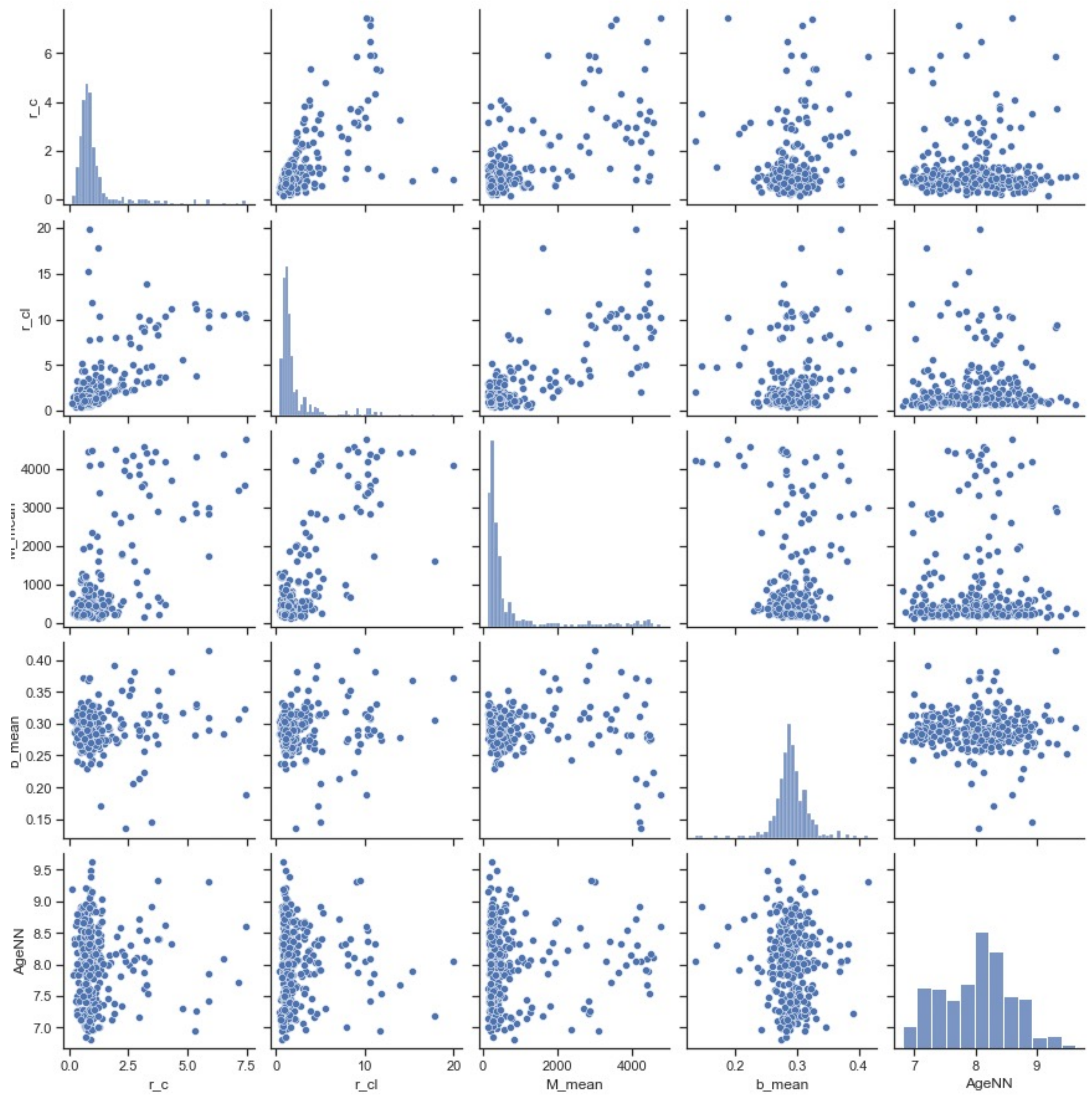






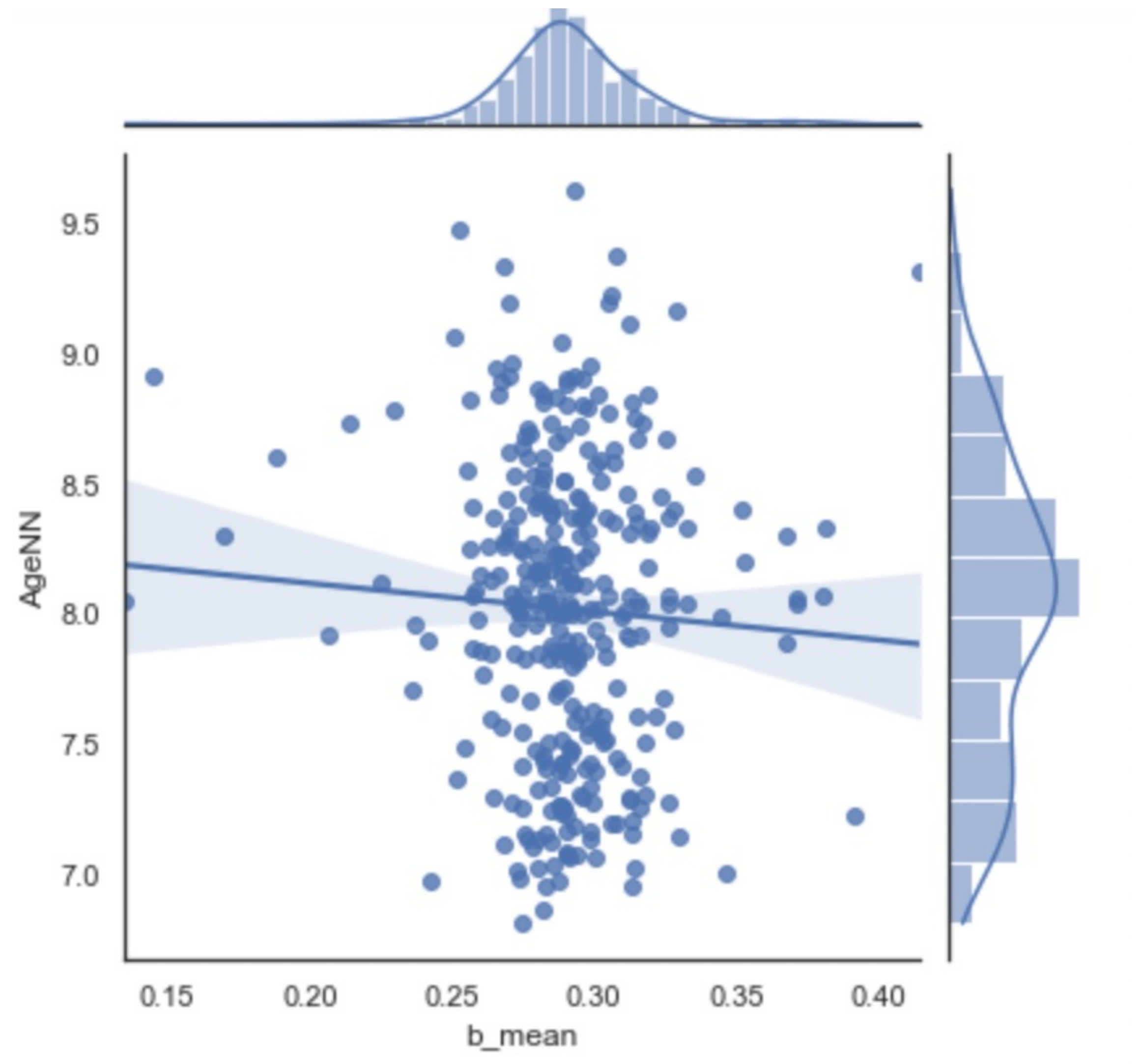
All	373	
n> 30	67	0.3 \pm 0.03
<7.5	103	0.29\pm 0.02
>7.5	220	0.29 \pm 0.03

Pair Plots

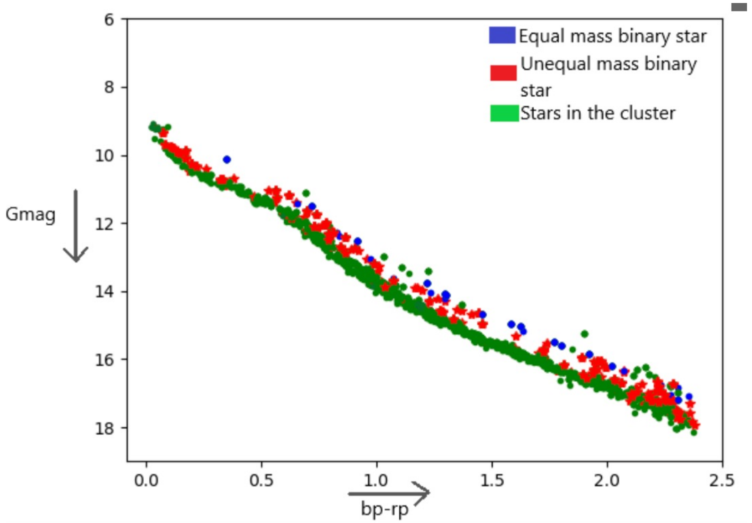


Evolution of binary fraction

- We find that the binary fraction seems to be almost constant 0.29 ± 0.03 for all clusters within 1000 pc of the Sun, irrespective of size, age and mass.



Binary Fraction with Isochrones
(0.15-0.3)



Cluster Name	fraction of Equal mass Binary Stars	fraction of Unequal mass Binary Stars	Total Binary Star Fraction
Preasepe	0.02	0.11	0.13
Pleiades	0.03	0.15	0.18
NGC2682	0.02	0.2	0.22
NGC2360	0.06	0.24	0.30
NGC2447	0.06	0.27	0.33
NGC2516	0.04	0.14	0.18
BGC6475	0.03	0.2	0.23
NGC3532	0.05	0.20	0.25
NGC1039	0.06	0.18	0.24
NGC2422	0.05	0.25	0.30

$$I < 2I_1$$

$$I = 2I_1$$

$$m_1 > m > m_1 - .75$$

$$m = -2.5log(I_1) - .75$$

What do simulations say?

NBODY4 code and include a full mass spectrum of stars, stellar evolution, binary evolution, and the tidal field of the Galaxy

Hurley et al (2007)

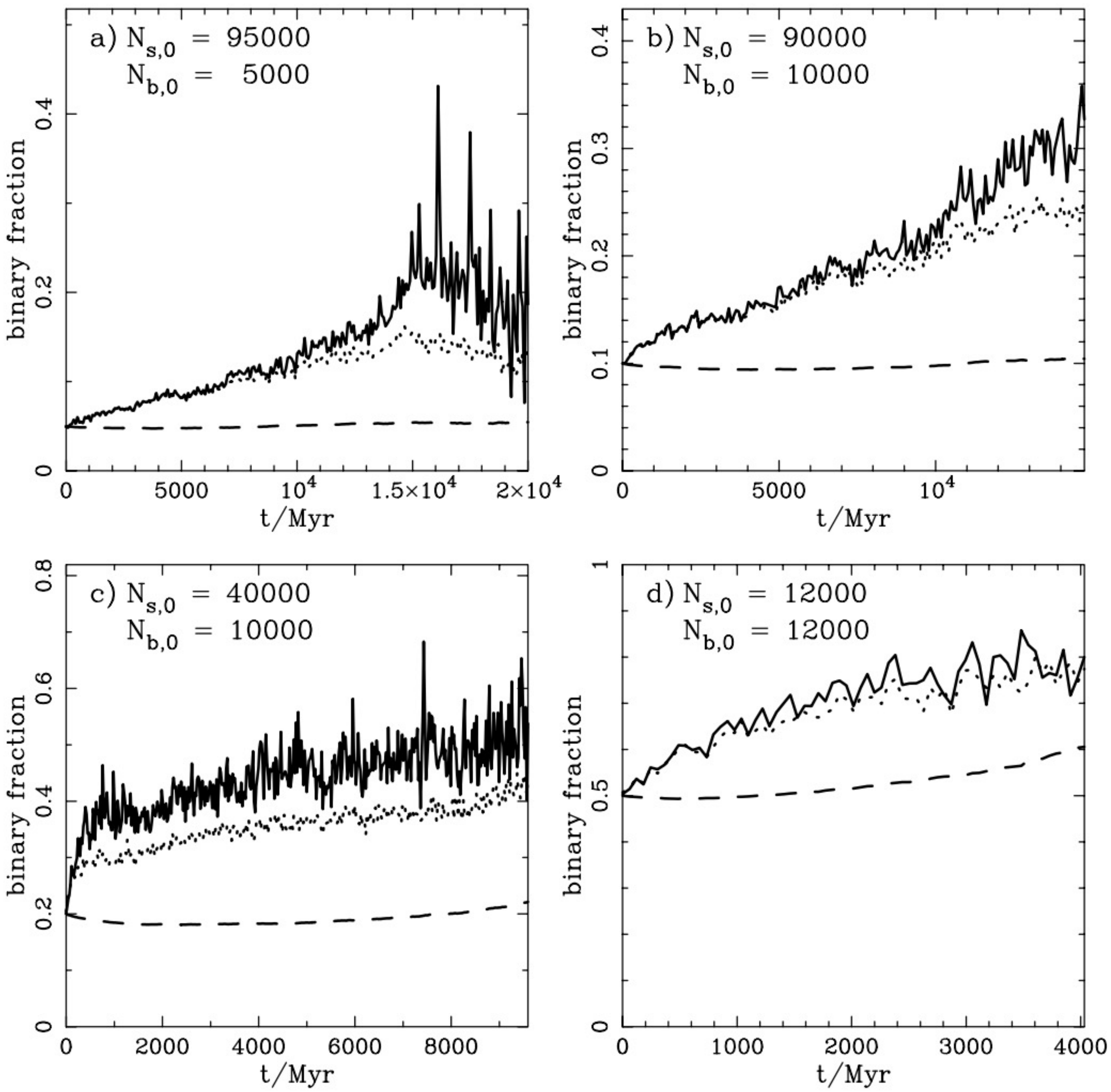
TABLE 1

Details of the Four N-Body Simulations Used in This Work

$N_{s,0}$ (1)	$N_{b,0}$ (2)	$\psi(a)$ (3)	a_{max} (4)	$f_{b,0}$ (5)	n_c (6)	$t_{1/2}$ (7)	Label (8)
95,000.............	5000	EFT30	100	0.05	10^2–10^4	8920	K100-5
90,000.............	10000	EFT30	100	0.10	100–500	8850	K100-10
40,000.............	10000	EFT30	50	0.20	10^3	5560	K50-20
12,000.............	12000	log a	50	0.50	100–350	2060	K24-50

Evolution of the binary fraction in the core (solid lines), within the 10% Lagrangian radius (dotted lines), and for the entire cluster (dashed lines).
Results are shown for the (a) K100-5, (b) K100-10, (c) K50-20, and (d) K24-50 simulations

Hurley et al (2007)



What do simulations say?

- Binary Convection: The binary population in the core of a cluster is continually replenished by stars from outside the core, many of which were previously in the core
- The binary content of an evolved star cluster is dominated by exchange binaries provided that the stellar density is relatively high.
- The overall binary fraction of a cluster does not vary appreciably from the primordial value as a cluster evolves.
- Binary destruction being balanced by a greater rate of escape of single stars compared to binaries. The primordial binary frequency of a cluster is well preserved outside of the cluster half-mass radius.
- Observations of the current binary fraction is a good indicator of the primordial binary fraction. The core binary fraction provides an upper limit.

Hurley et al 2007

Wide Binaries in star clusters

Members of open clusters represent young (typically 50 Myr to 1 Gyr) and uniform populations that will eventually dissipate in the galactic field. These clusters are dynamically old, in the sense that their age is much larger than their crossing time, and wide binaries have long been disrupted (e.g., Kroupa 1995, Parker et al. 2009)

If these systems are indeed easily disrupted by interactions, we should expect more of them when we look at younger populations, such as those in open clusters.

Using Gaia data, Niall Deacon and Adam Kraus studied double stars within Pleiades, Beehive and Alpha Persei clusters.

Mon. Not. R. Astron. Soc. 000, 1–?? (2015) Printed 15 June 2020 (MN LATEX style file v2.2)

Wide binaries are rare in open clusters

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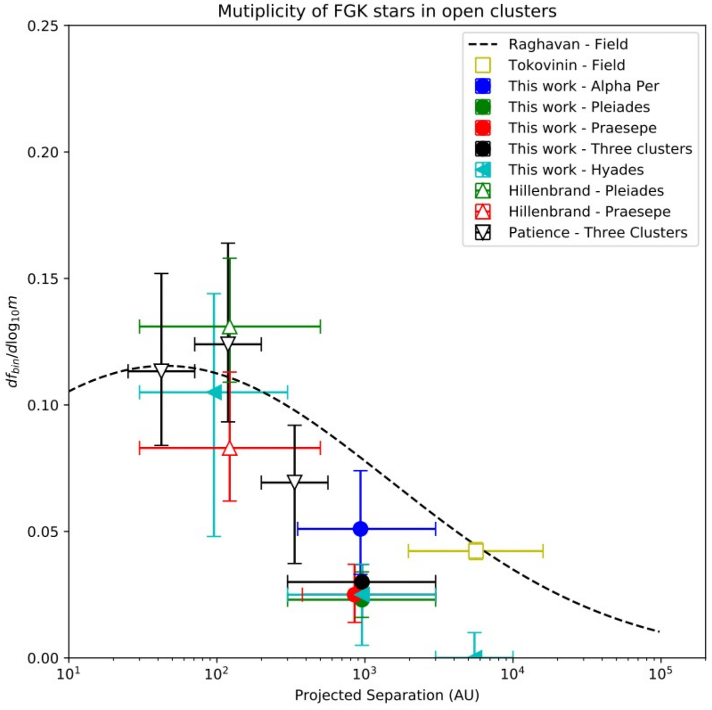
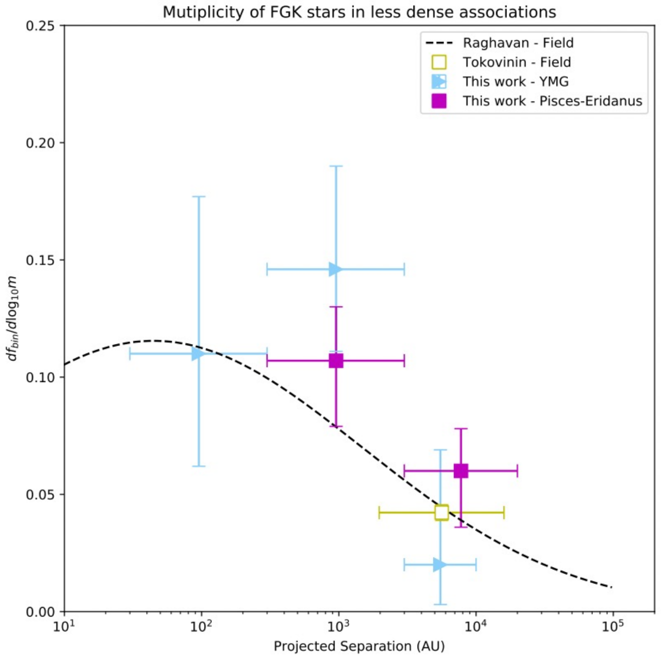
Alpha Per, the Pleiades and Praesepe





A deficit of wide (300–3000 AU) binaries in open clusters
Wide binaries are more likely form and/or survive in low density formation environments than more dense star clusters.

Left: It appears that while closer binaries in Alpha Per, the Pleiades, Praesepe and the Hyades are in agreement with the field population, there is a deficit of wider binaries. Right: Conversely the less dense Young Moving Groups and Pisces-Eridanus stream show wide binary fractions at or above the field values.

What about the field?

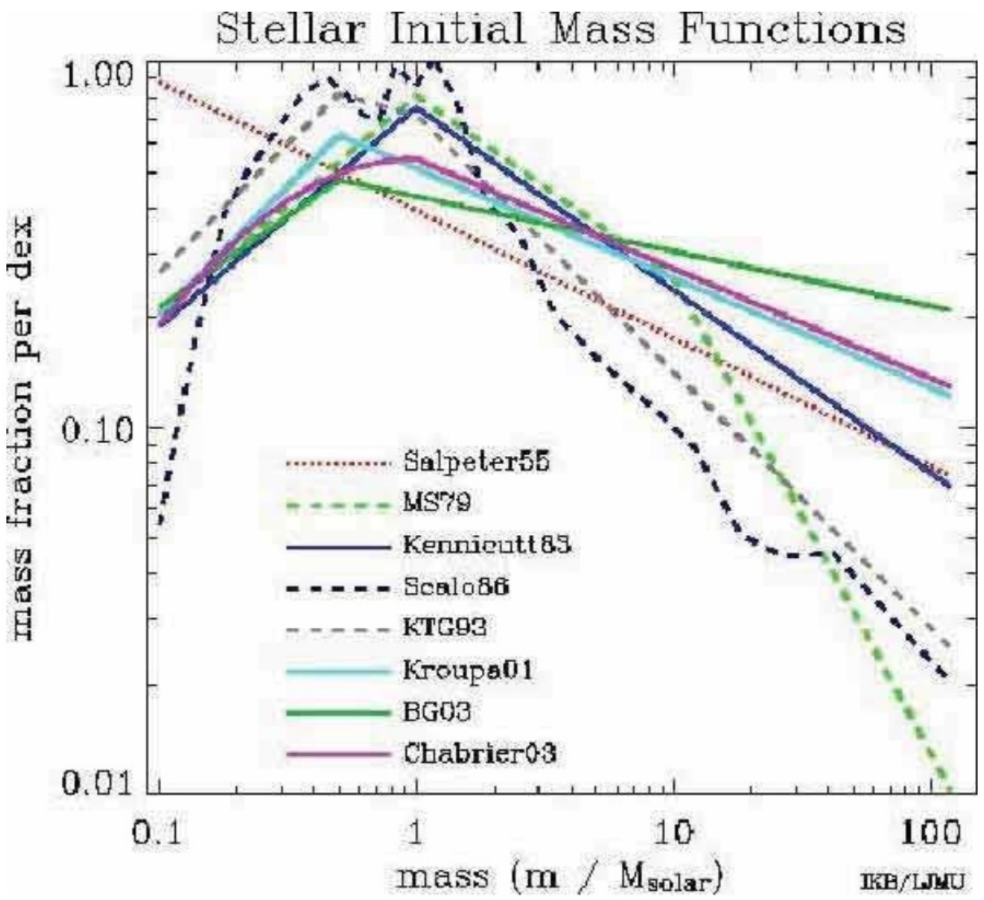
The field is the sum of star formation in high- and low-mass clusters and isolated star formation (ISF).

Initial Mass Function

Distribution of mass at birth

- Imprint of Star Formation process
- Evolution of the star is determined by mass (and chemical composition)
- Roughly 3/4 of all stars formed are M stars

INITIAL MASS FUNCTION



A comparison of popular stellar initial mass functions (Ivan Baldry).

Peak broadly between 0.1 - 0.5 M⊙, indicating that most stars formed in the Galactic disk are M stars

3/4 of all stars formed are M stars

- Among very massive stars, known as O- and B-type stars, 80 percent of the systems are thought to be multiple, but these very bright stars are exceedingly rare.

  SSF for M stars appears to be at least 70%. increases from about 43% for G stars to ~ 85% for brown dwarfs, M stars ~74% Delfosse et al. (2004)

  Slightly more than half of all the fainter, sun-like stars are multiples.

  However, only about 25 percent of red dwarf stars have companions.

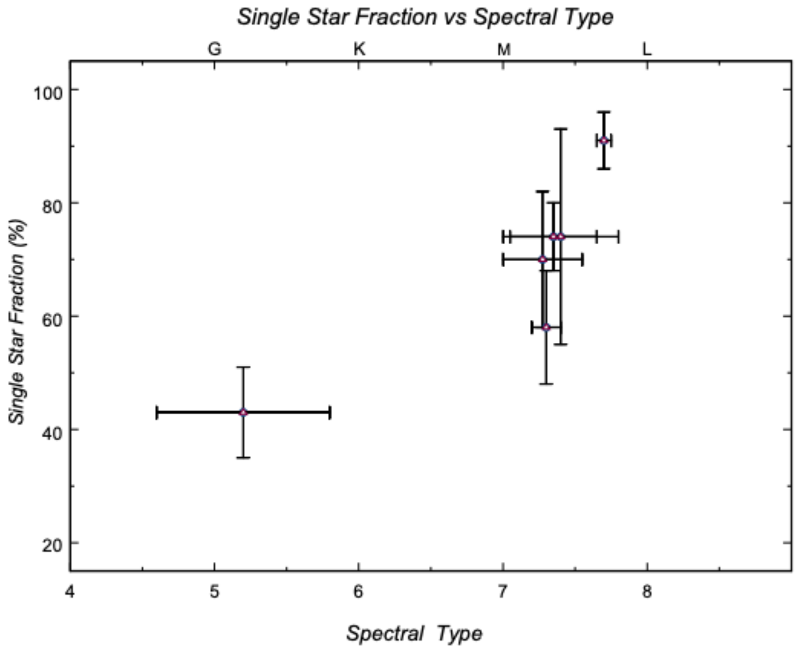


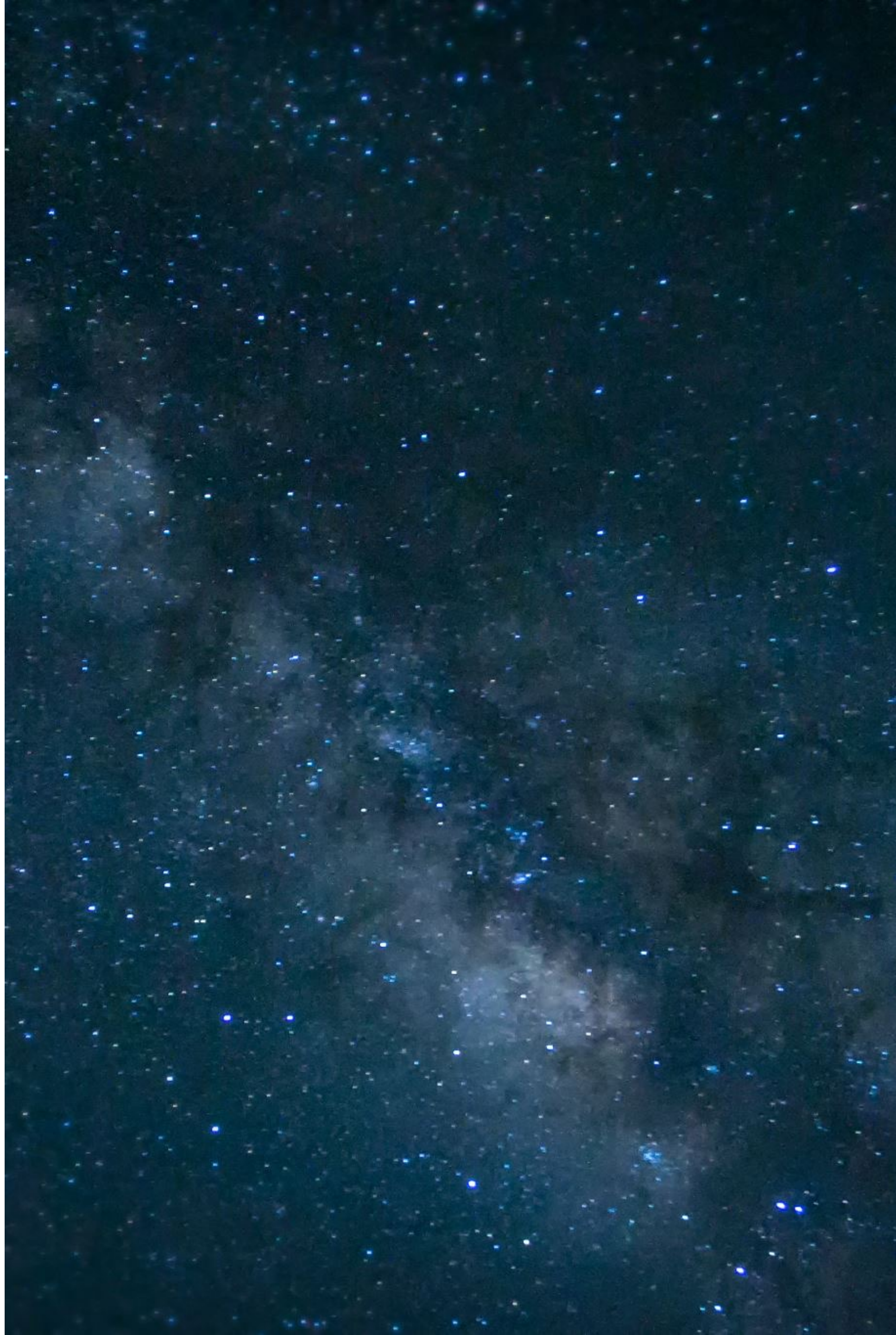
FIG. 1.— The single star fraction vs spectral type. The single star fraction increases significantly with spectral type reaching values of ~ 75% for M stars, the most populous stars in the IMF and the field. Vertical error bars represent statistical uncertainties in the SSF. The horizontal error bars indicate the approximate extent in spectral type covered by the individual surveys and do not represent an uncertainty in this coordinate. Data taken from Duquennoy & Mayor (1991), Reid & Gizis (1997), Fischer & Marcy (1992), Delfosse et al. (2004), Leinert et al. 1997, and Siegler et al. (2005).

Duchêne, Gaspard ;Kraus, Adam *Annu. Rev. Astron. Astrophys. 2013 51*

We now know…

- As Lada (2006) pointed out ~ 90% of stars are M dwarfs and the Mdwarf binary fraction is ~ 30% with M-dwarf secondaries. So for every 100 M-dwarf systems, 30 are primaries, 70 are single, and there are 30 secondaries => of every 130 M dwarfs, 60 are in multiple systems. Lada concludes that upwards of two-thirds of all star systems in the galaxy are single, red dwarf stars.
- low-mass stars rarely occur in multiple systems!!
- So binary fraction in the field is ~ 33%

Lada 2006



Conclusions:

(Within 1 kpc)

Most stellar systems formed in the Galaxy are likely single and not binary as has been often asserted.

In the current epoch two-thirds of all main sequence stellar systems in the Galactic disk are composed of single stars.

Binary Fraction in clusters ~ 0.3!!!

Hasan, in prep

RUWE

Renormalized Unit Weight Error

RUWE is a robust metric for testing for unresolved multiplicity of Gaia sources.
It is highly sensitive to deviations to photocenter motion from center-of-mass motion, even (or especially) below RUWE = 1.4, the often-used cutoff for reliable Gaia astrometry.
RUWE ≳2 is not strongly correlated with binarity. The amount of perturbation also establishes a lower limit for the angular separation of the pair; Gaia is likely most sensitive to separations – 10 – between 0.18″ and 1.2″.
For RUWE ≲ 1.4, the angular semi-major axis of the photocenter wobble can be estimated but should be interpreted with caution for any singular system.
RUWE excess can be caused by other perturbations such as marginally resolved systems or chance alignments and variability

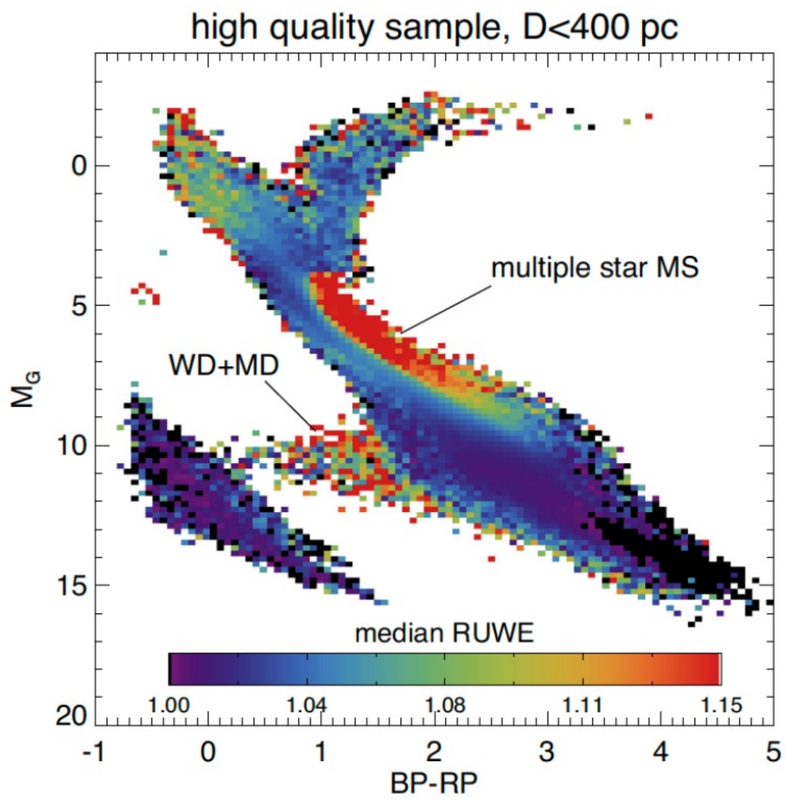


Fig. 3.— Figure 1 of Belokurov et al. 2020 showing an HRD for 4M Gaia DR2 objects from their selection criteria (see Sec 2.1) color coded by RUWE. Two distinct regions of elevated RUWE are evident, corresponding to main sequence (MS) multiples and white dwarf - M dwarf binaries (WD+MD). The supports the claim that RUWE can be used to probe multiplicity.

Pearce, 2022

Badry at al 2001

from *Gaia* eDR3 an extensive catalogue of spatially resolved binary stars within ≈1 kpc of the Sun, with projected separations ranging from a few au to 1 pc.