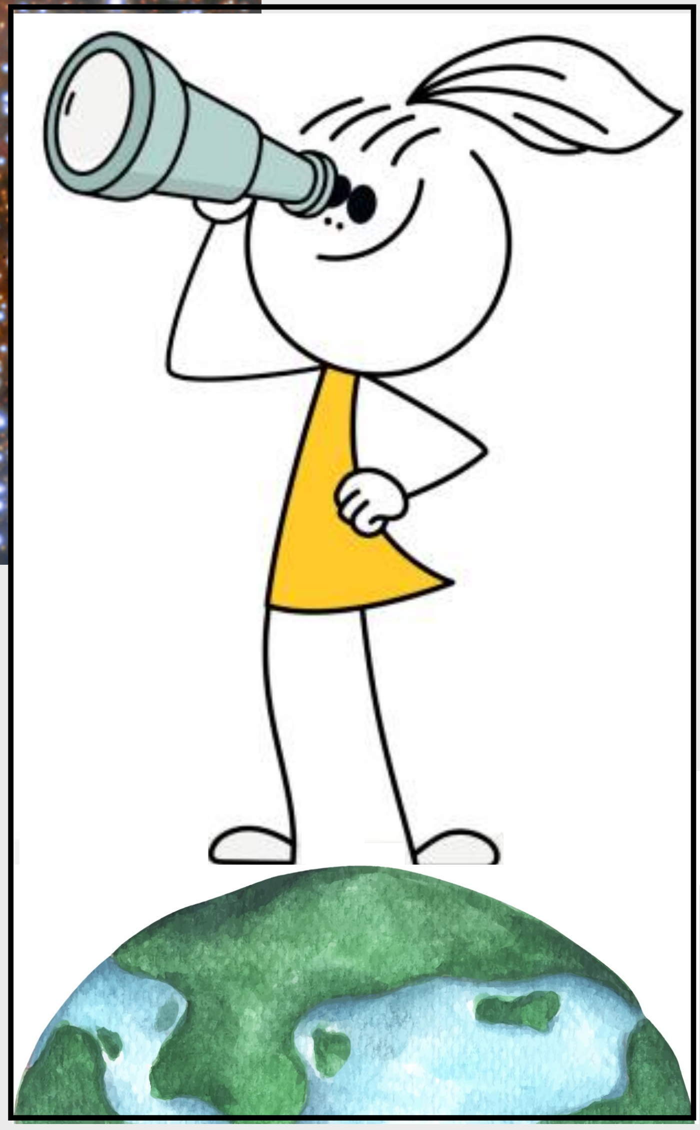
NASA/ESA/HUBBLE ST @ M. Hakan Ozsarac. – NGC1850

NASA/ESA/HUBBLE ST @ Maximilian Häberle – ω Centauri



Binaries in massive clusters with MUSE: Omega Cen and NGC 1850

Sara Saracino (JMU - Liverpool)

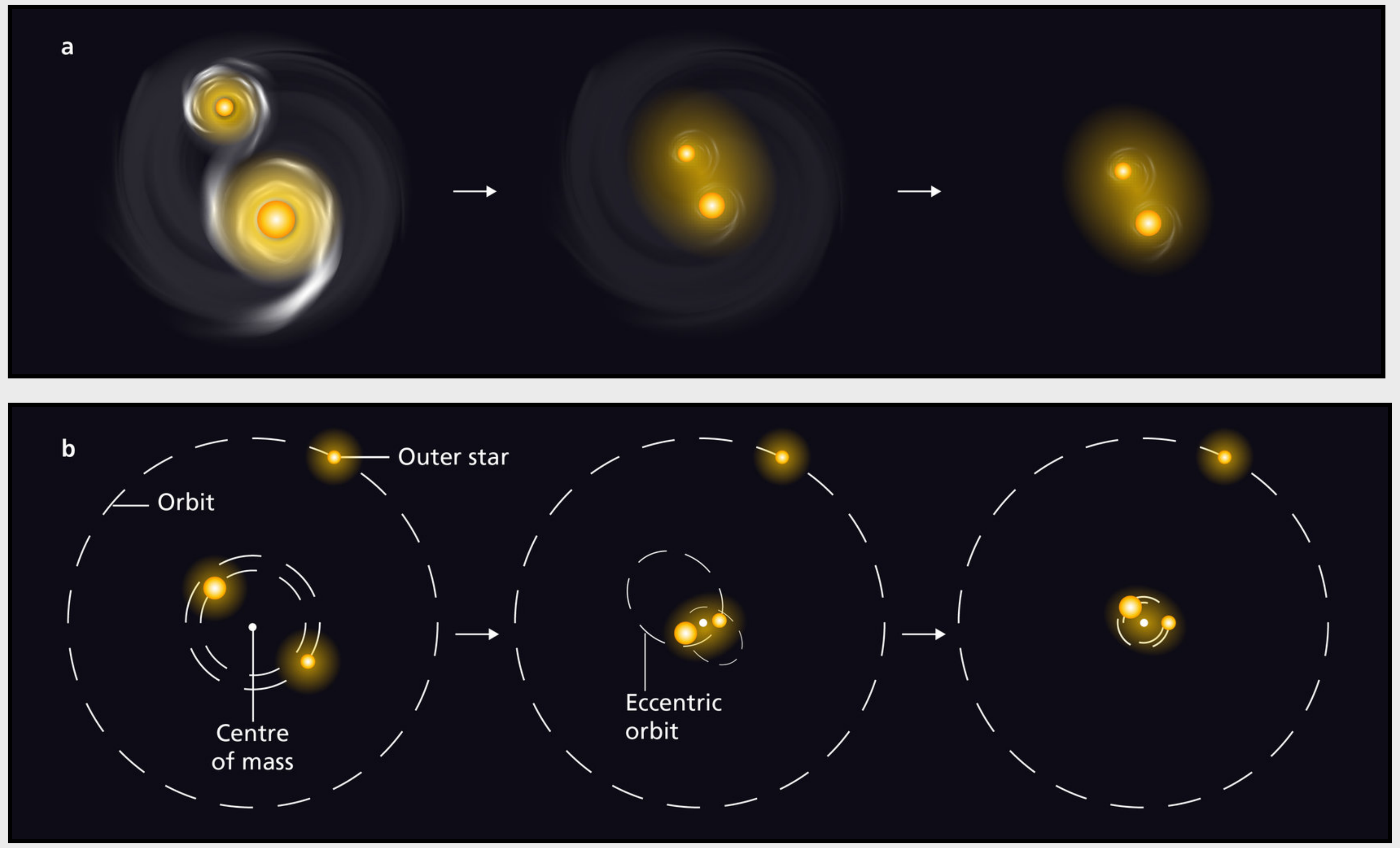
in collaboration with S. Kamann, F. Wragg & the MUSE GC Team

20 August 2024, Warsaw, MODEST-24 conference

LIVERPOOL JOHN MOORES UNIVERSITY

The interplay of binaries and star clusters

- Trigger the formation of (new) close binary systems;
  - via fly-by, dynamical interactions, three-body exchanges.



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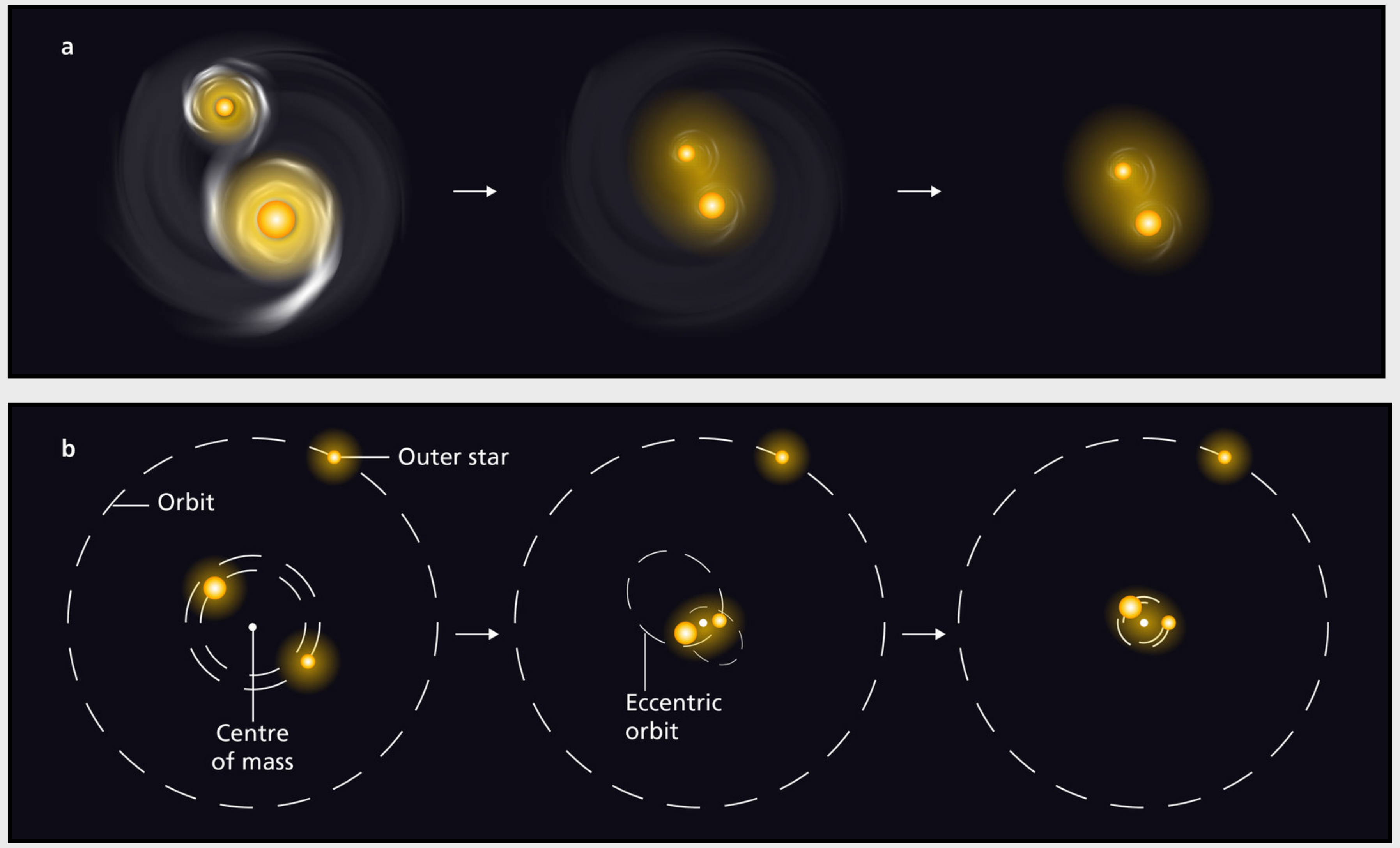
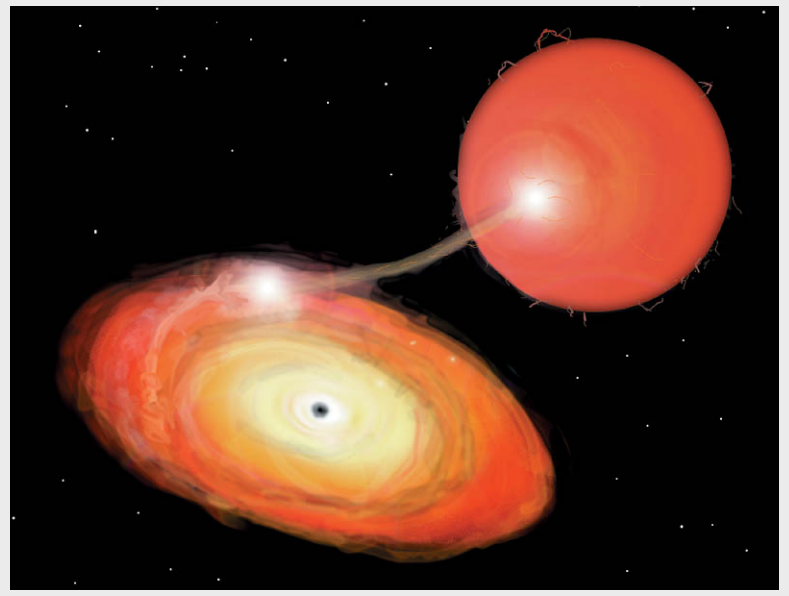


- Trigger the formation of (new) close binary systems;
  - via fly-by, dynamical interactions, three-body exchanges.

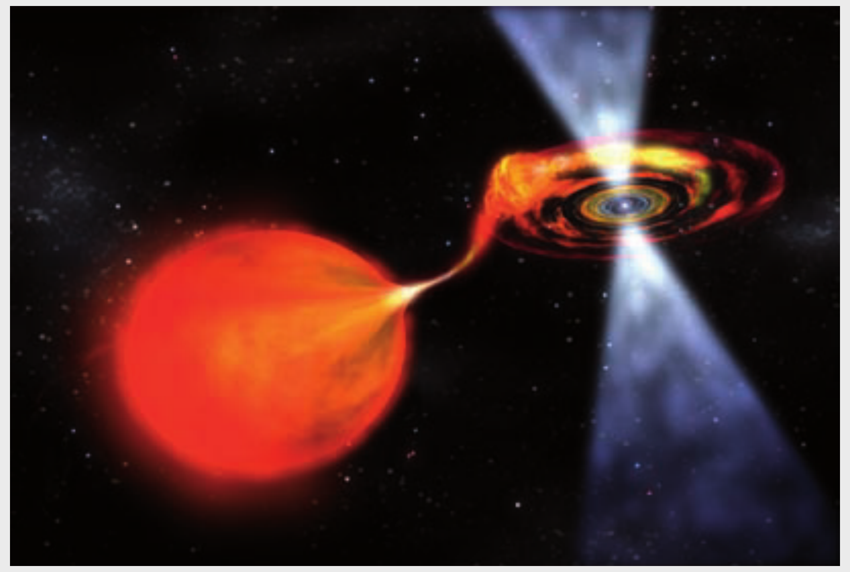
- Lead to exotic binary interaction products;

  [Bailyn1992, Paresce+1992, Ferraro+1999, Pols+1991, Zorec&Briot1997, Bodensteiner+2020]

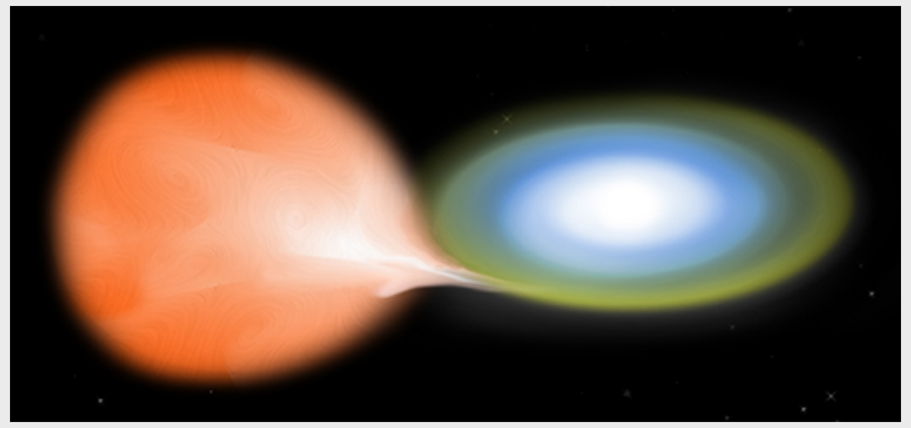
Low Mass X-ray binaries
(hosting black holes)



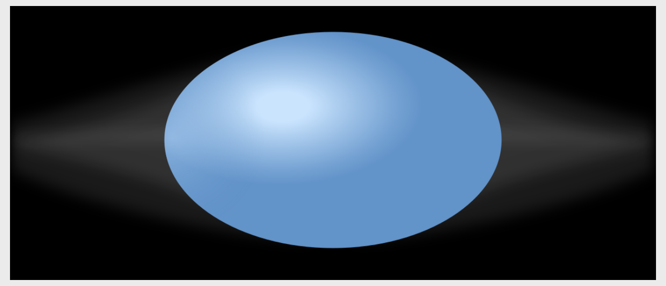
Millisecond Pulsars
(hosting neutron stars)



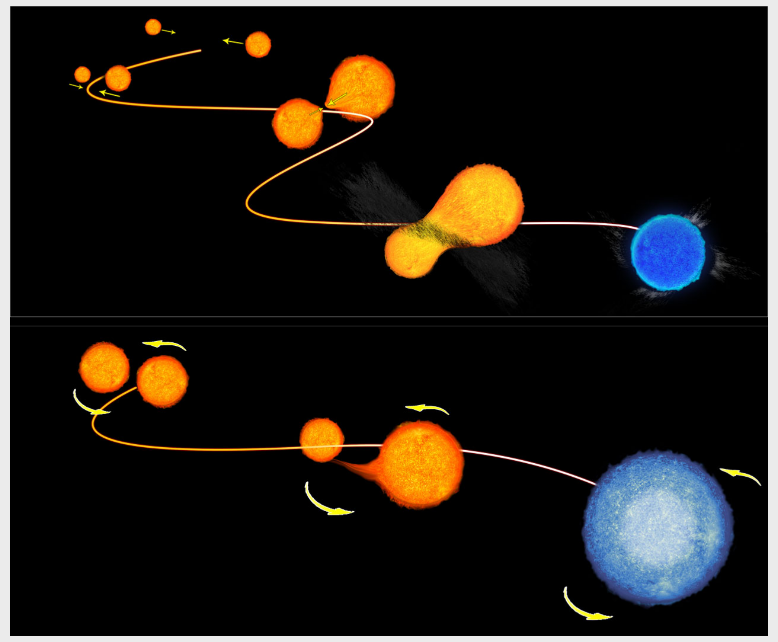
Cataclysmic Variables
(hosting white dwarfs)



Be and shell stars



Blue Straggler Stars



The interplay of binaries and star clusters

- Trigger the formation of (new) close binary systems;
  - via fly-by, dynamical interactions, three-body exchanges.

- Lead to exotic bi

  [Bailyn1992, Paresce+1992

We need to constrain the orbital properties of binaries in clusters to understand which phenomena they are responsible for.

Low Mass X-ray binaries (hosting black holes)

Millisecond Pulsars (hosting neutron stars)

Cataclysmic Variables (hosting white dwarfs)

Be and shell stars

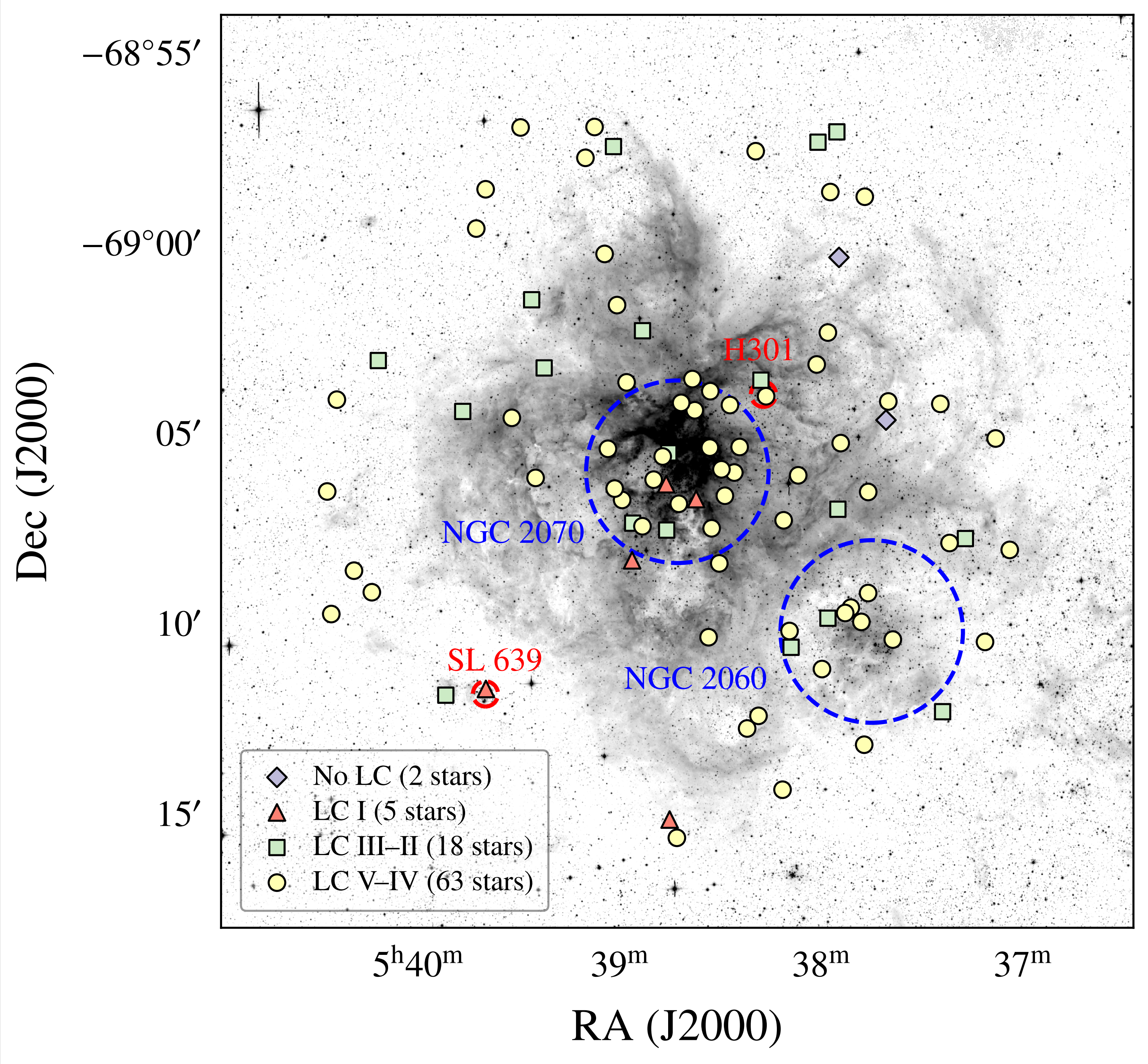
Blue Straggler Stars

Where do we stand?

See Dreizler's talk tomorrow!

VERY YOUNG CLUSTERS

30 Doradus, few Myrs

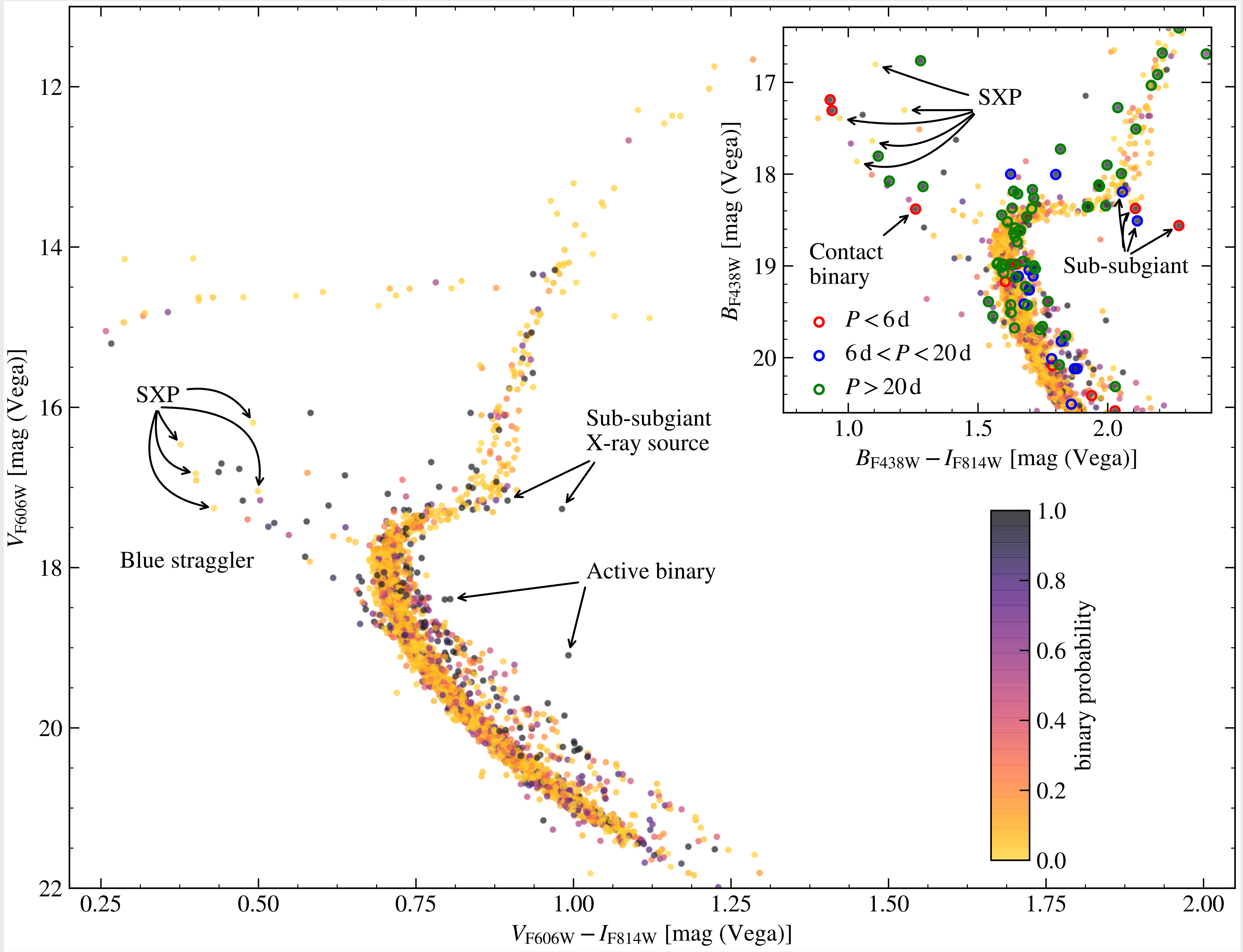


Villasenor+2021, Almeida+2017

.. see also Ritchie+2022 for Westerlund 1

OLD, EVOLVED CLUSTERS

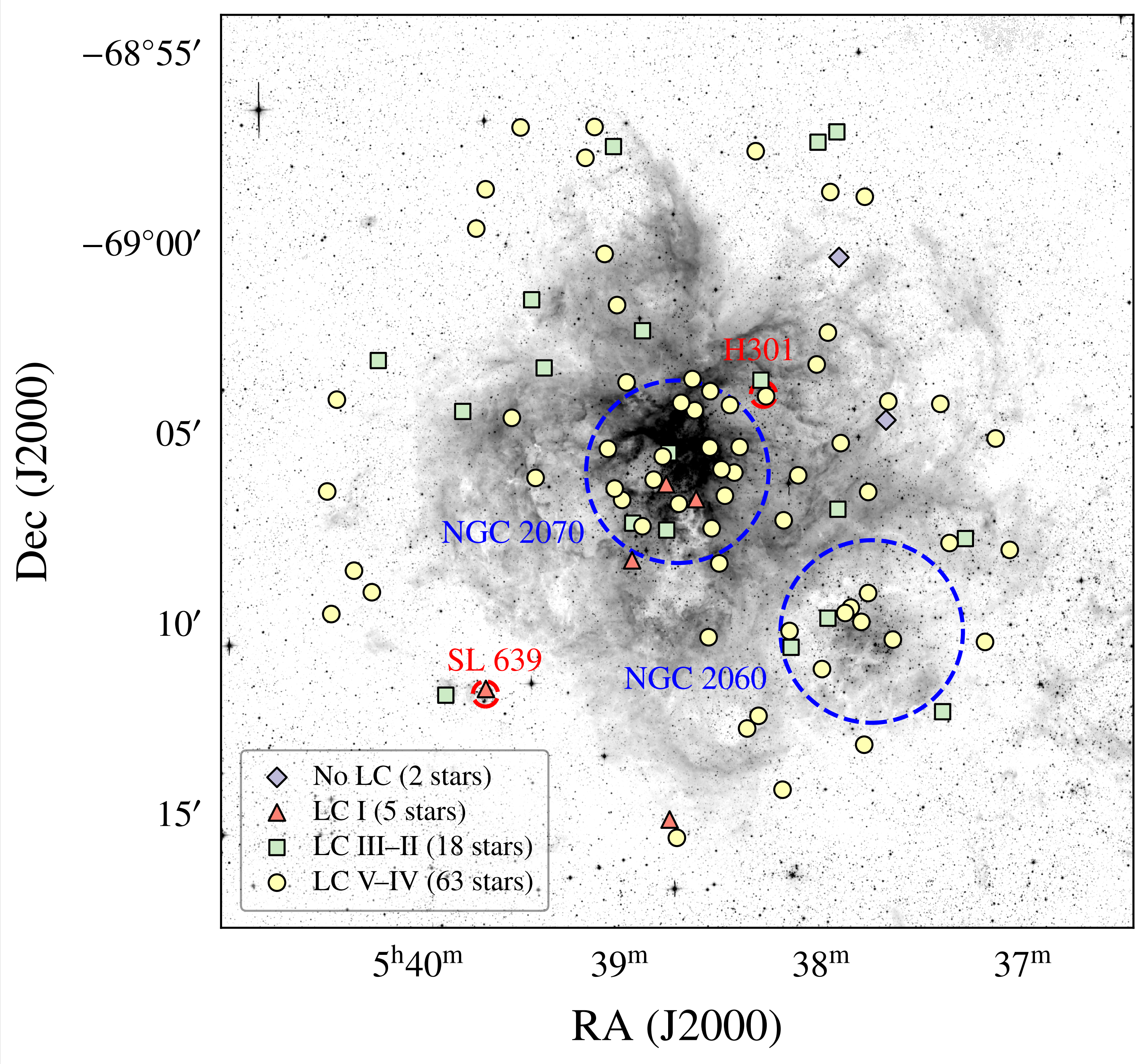
NGC3201, ~12 Gyr



Giesers+2019

Where do we stand?

VERY YOUNG CLUSTERS
30 Doradus, few Myrs



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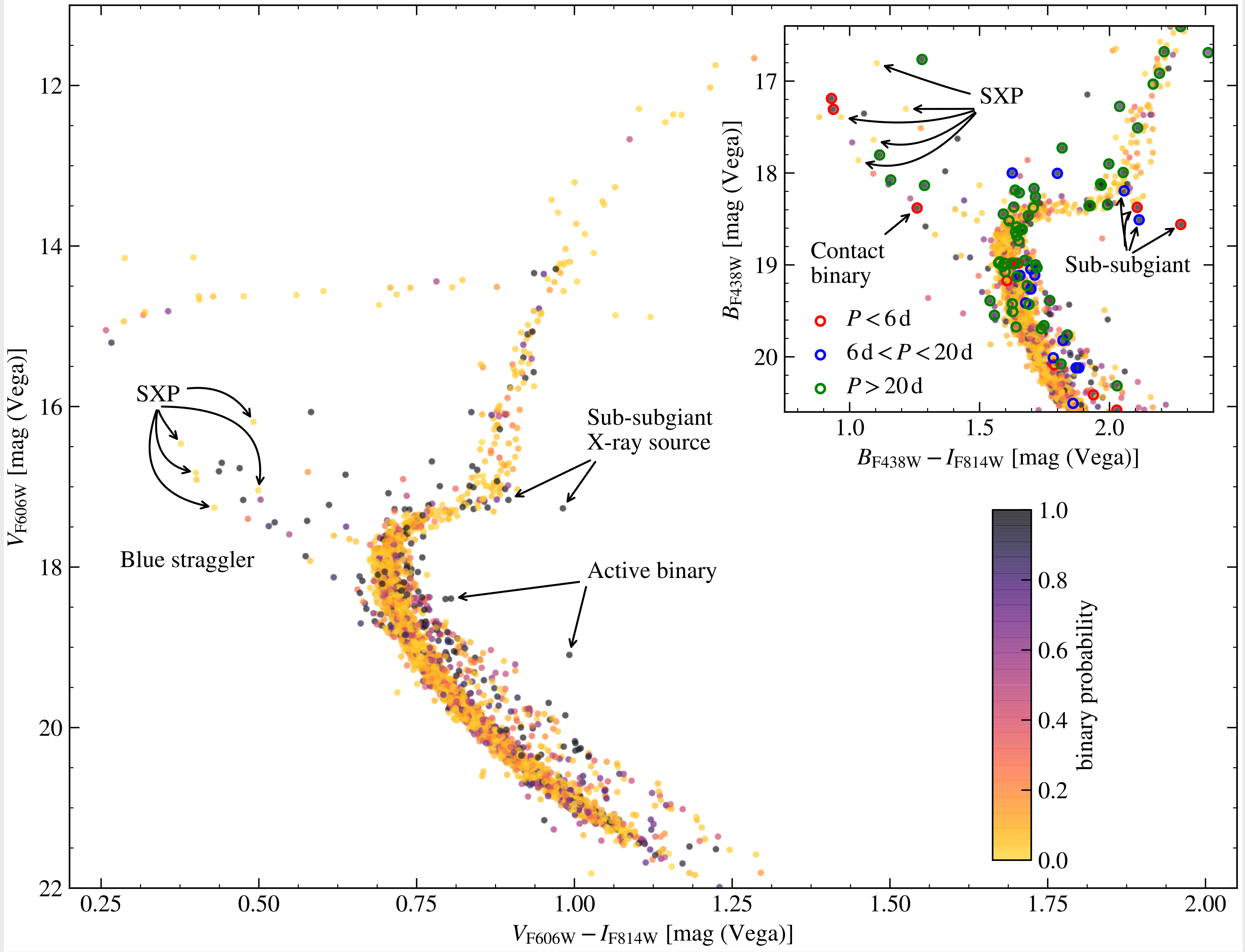


Giesers+2019

Little or no info are available on intermediate-age clusters.
How do we bridge the gap between very young clusters (with massive stars ~10 $M_{\odot}$) and old, evolved clusters (with only low-mass stars ~1 $M_{\odot}$)?

The project: "Systematic study" of the binary content and interaction products of massive clusters through cosmic time

Main open questions we aim to answer at the end of the survey:

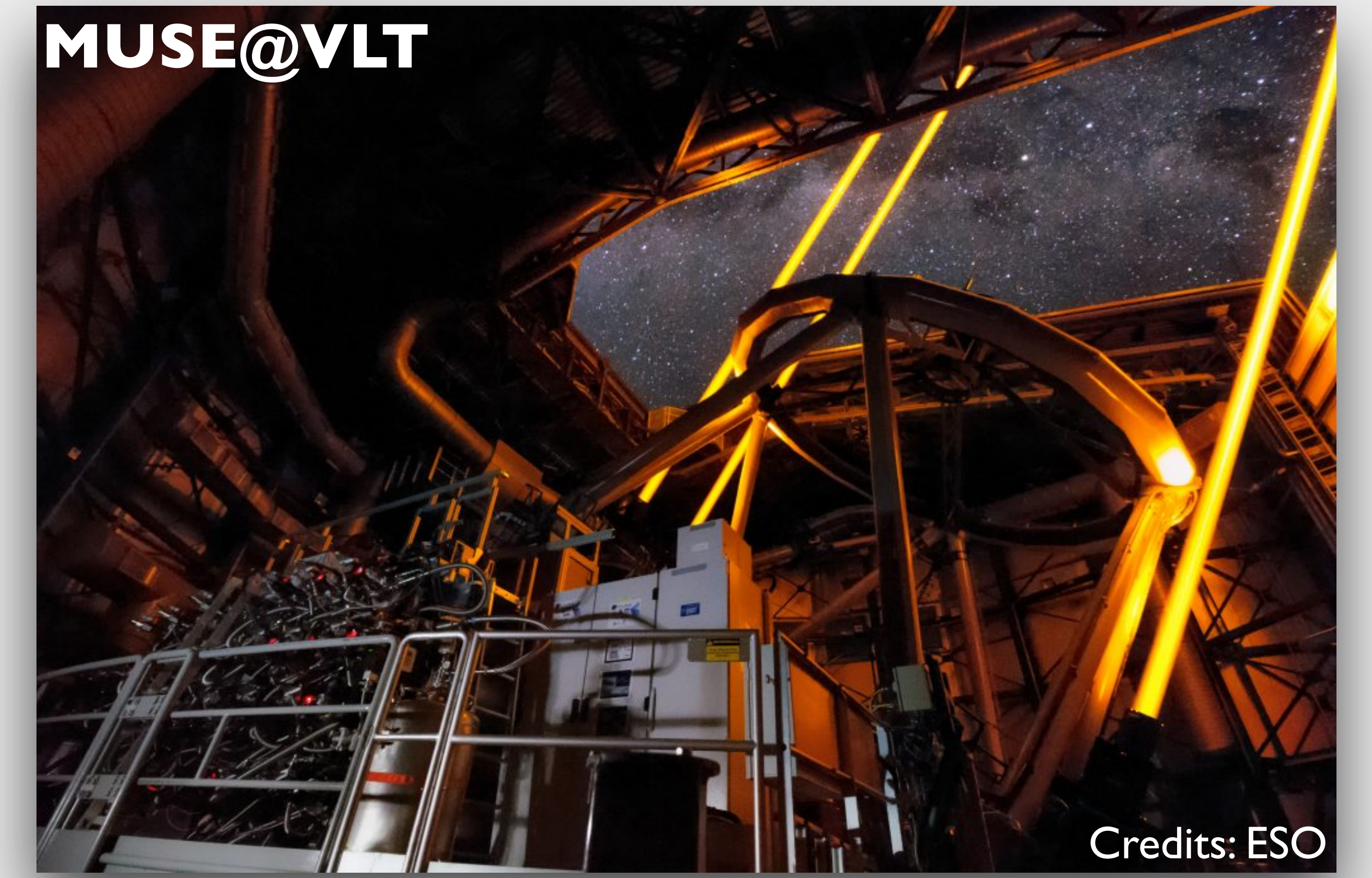
- ***How strongly does a cluster binary population evolve with time?***
  in terms of binary fraction, orbital parameter distributions, or pairing fractions.

- ***What is the frequency of interactions/mergers between binary components?***

- ***How many stellar exotica (e.g. NS/BHs) can we find in clusters?***

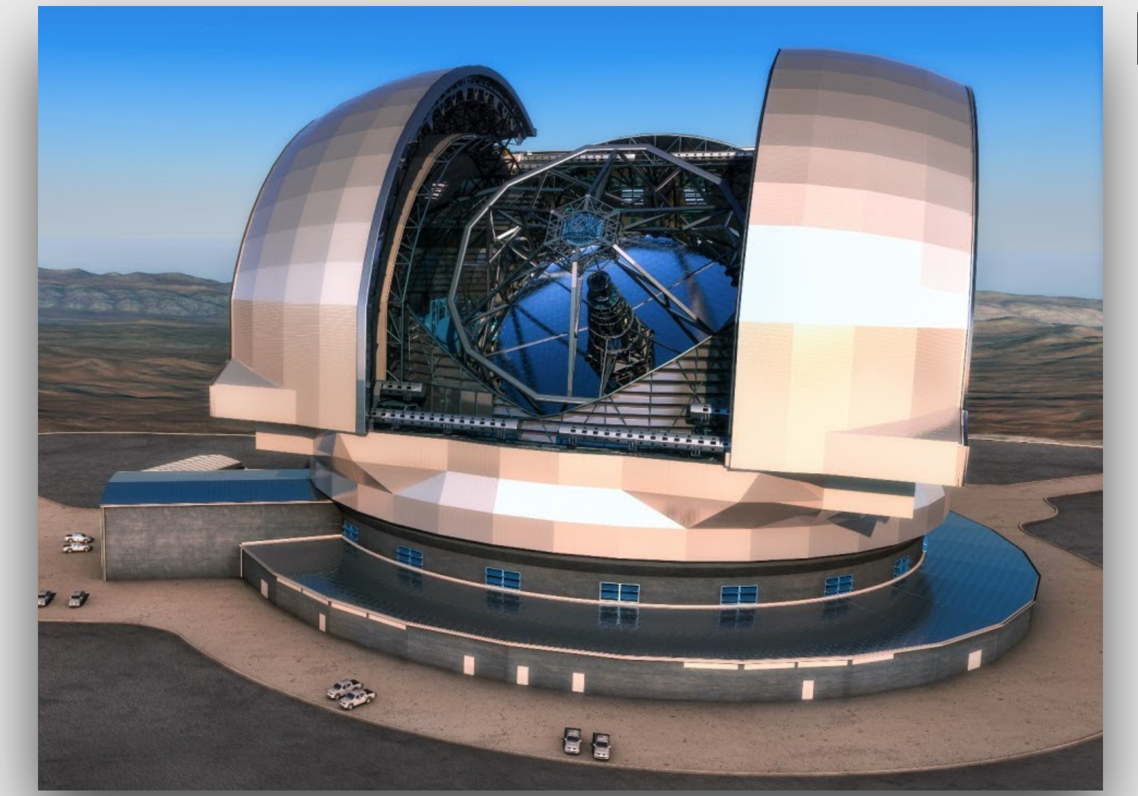
Detecting binaries spectroscopically:

1 **IFU spectrograph**



THE BEST in terms of resolution and field of view!

Looking at the future..



HARMONI@ELT

Credits: ESO

Credits: ESO/S. Kamann

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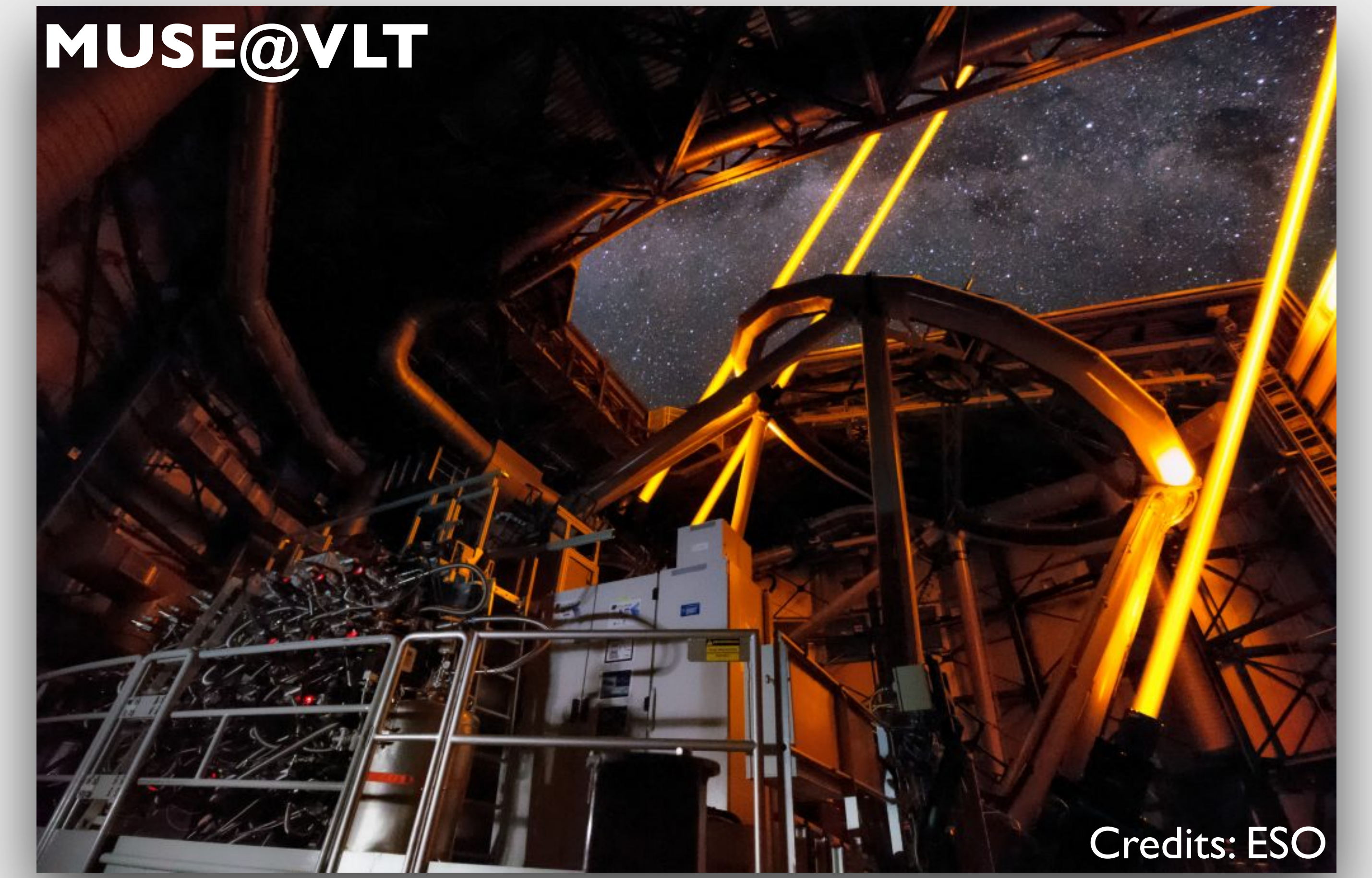

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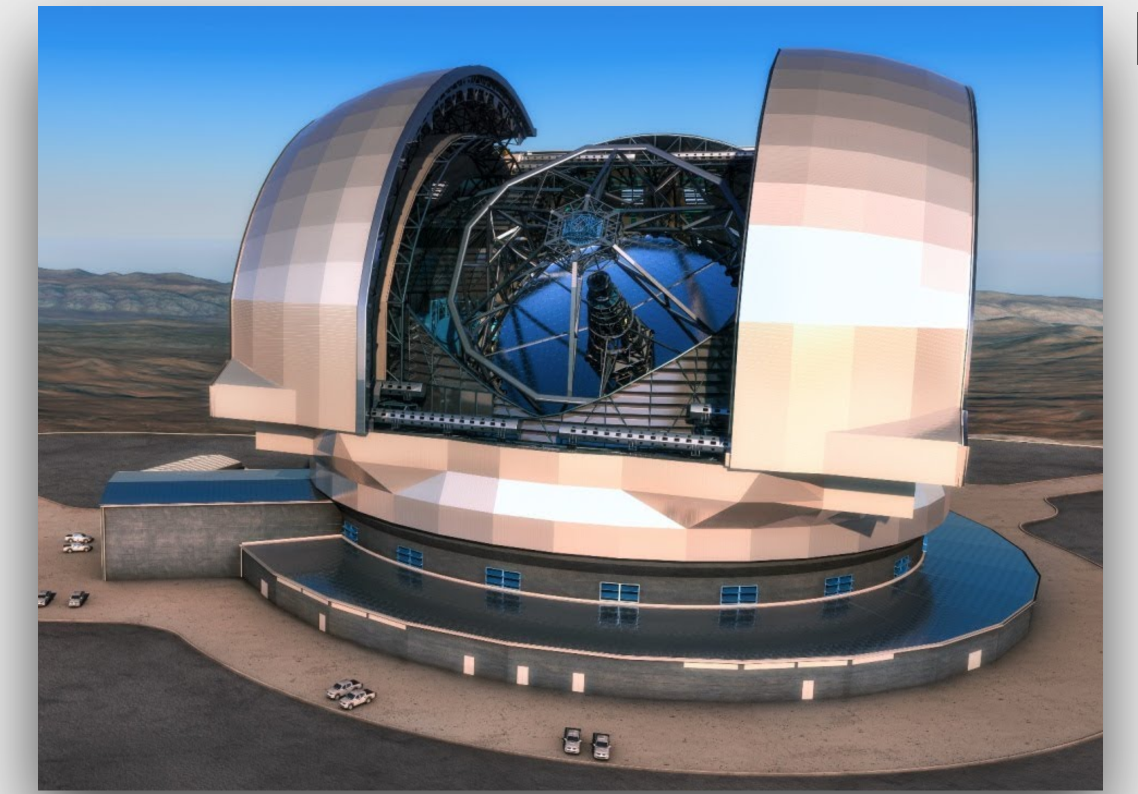
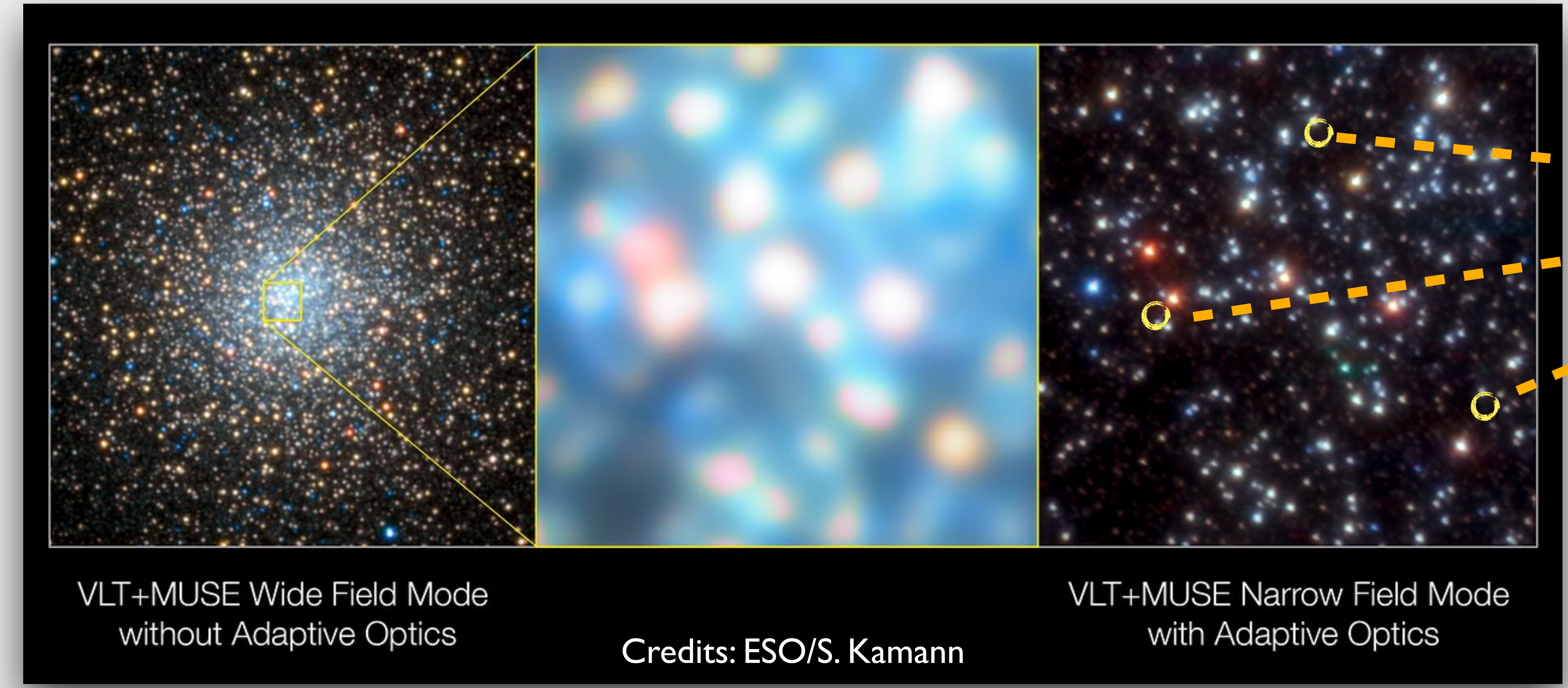


HARMONI@ELT

Credits: ESO

2 The reduction software **PAMPELMUSE** (Kamann et al. 2013)

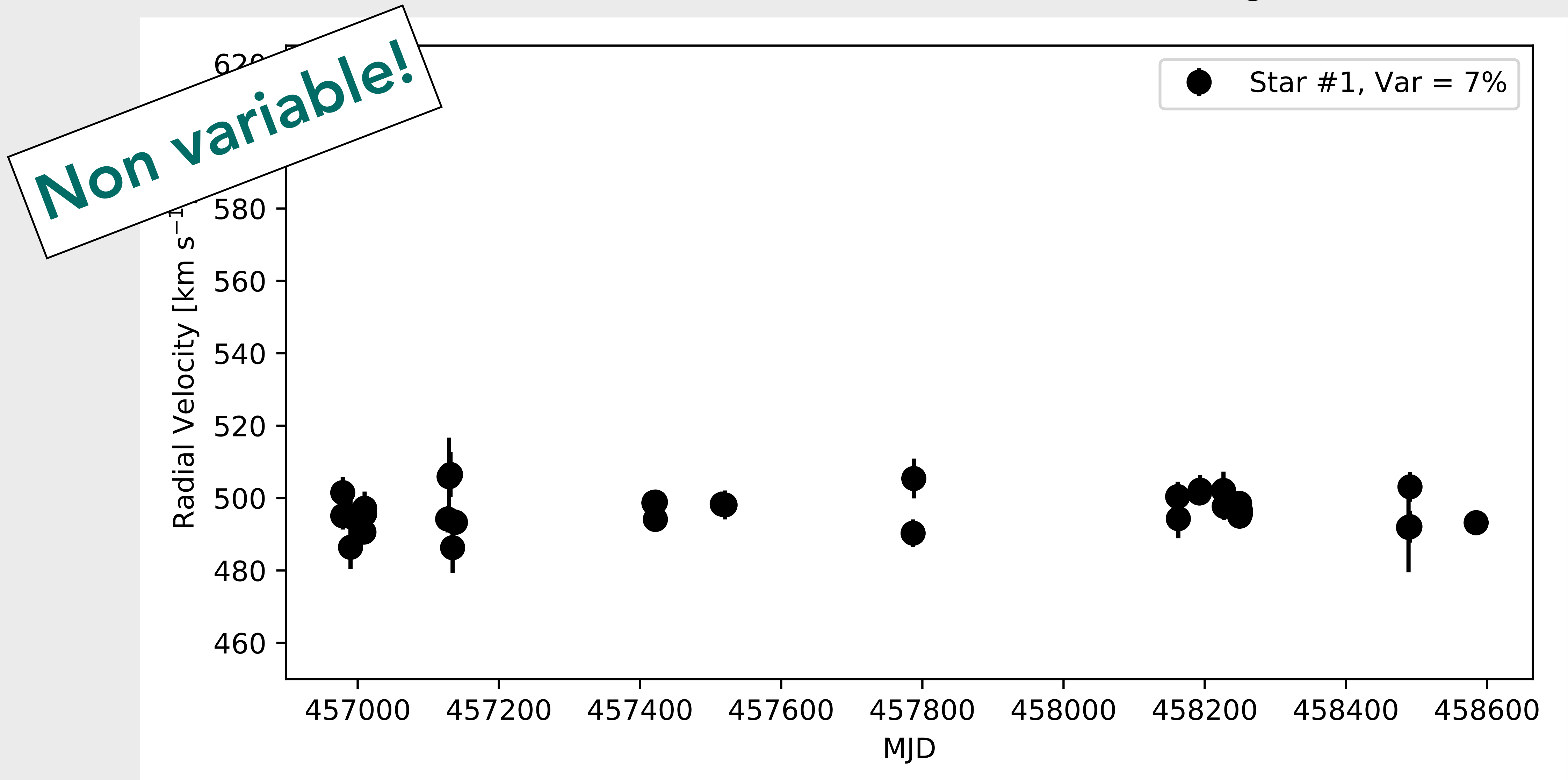


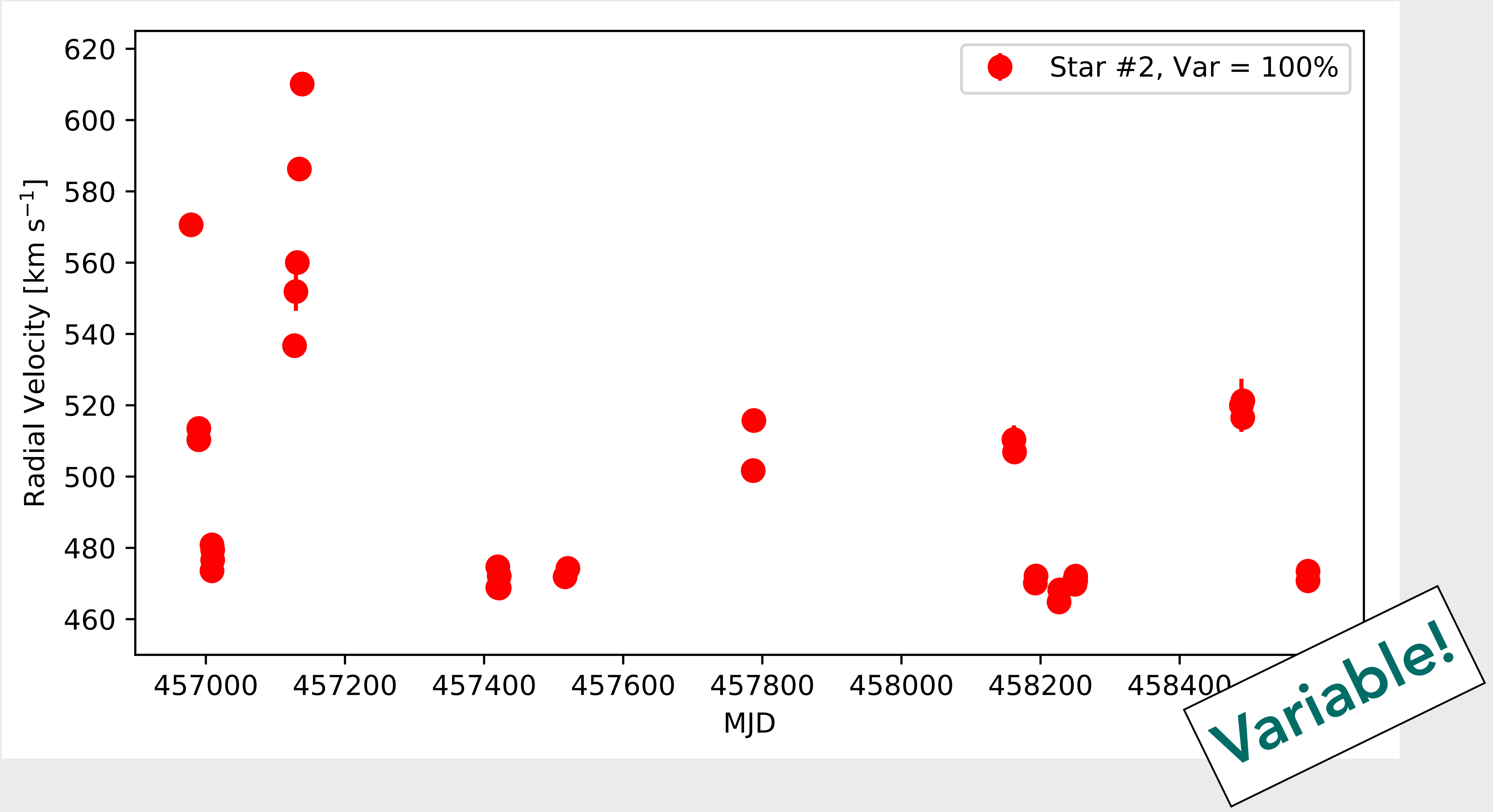
You get a high S/N spectrum
for every single star in the FOV

Inner regions of stellar clusters:
<u>Thousands of stars in one shot!</u>

Detecting binaries spectroscopically:

③ **Time series radial velocities** to distinguish between single and binary stars





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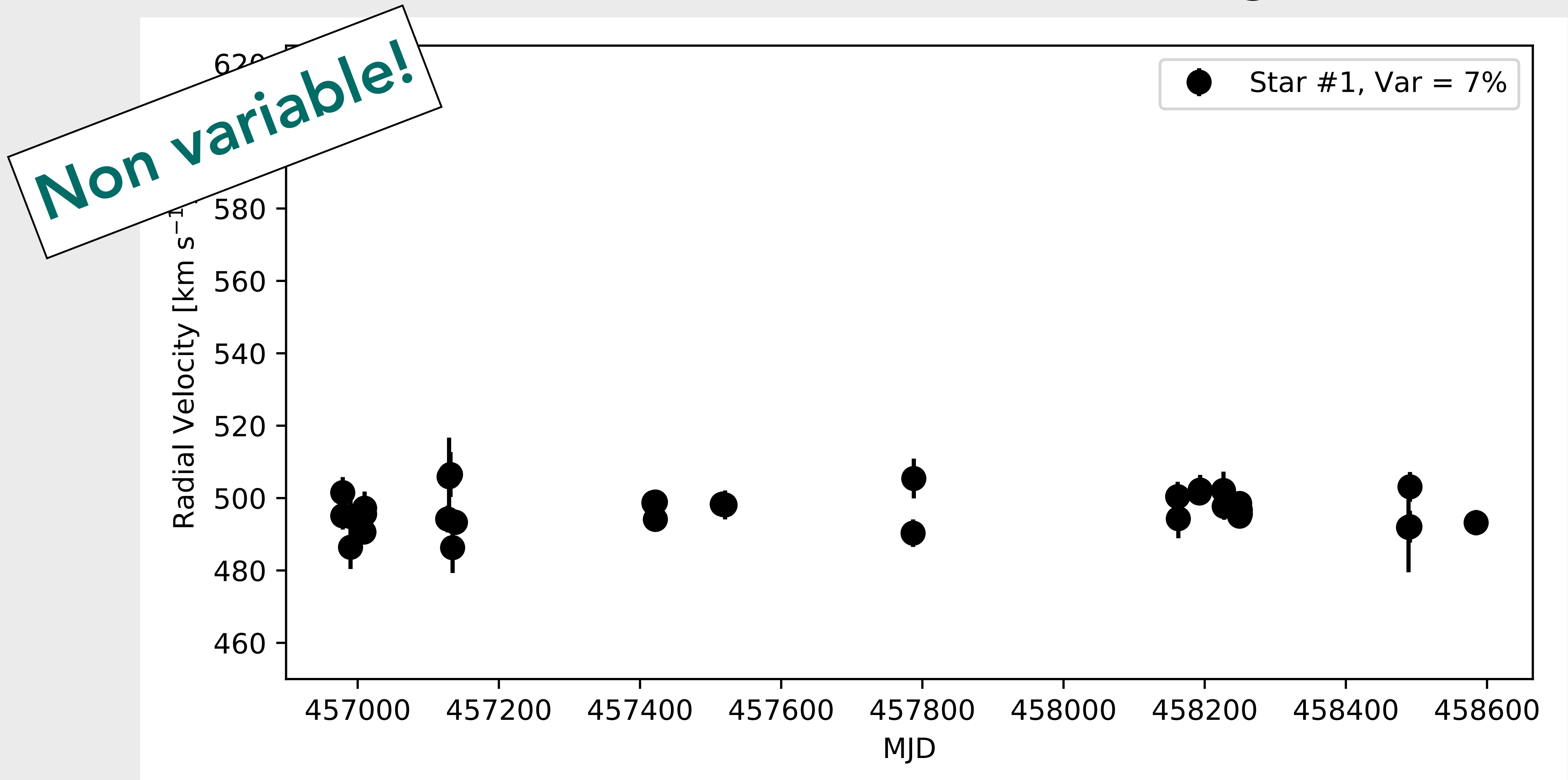
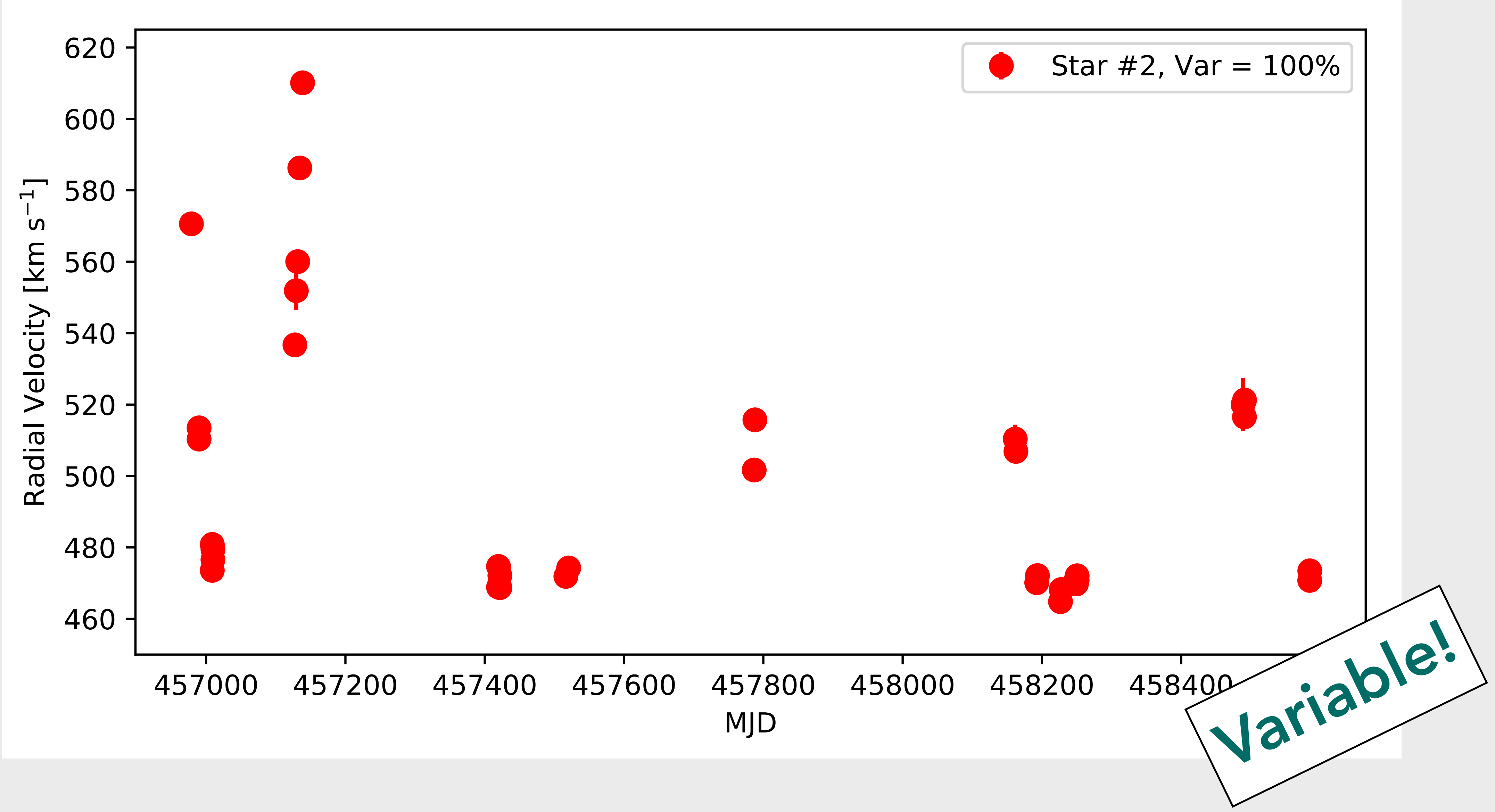
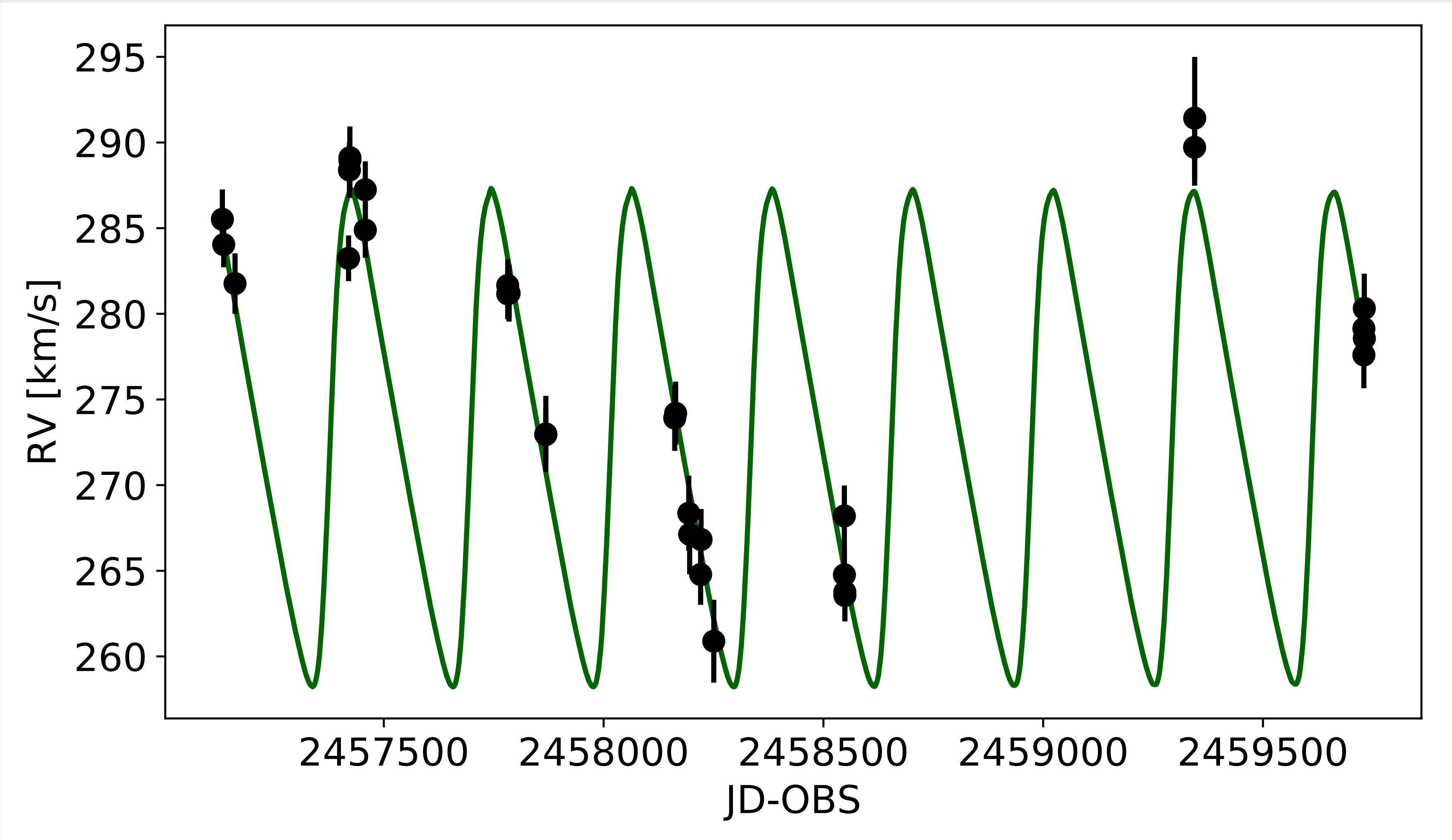
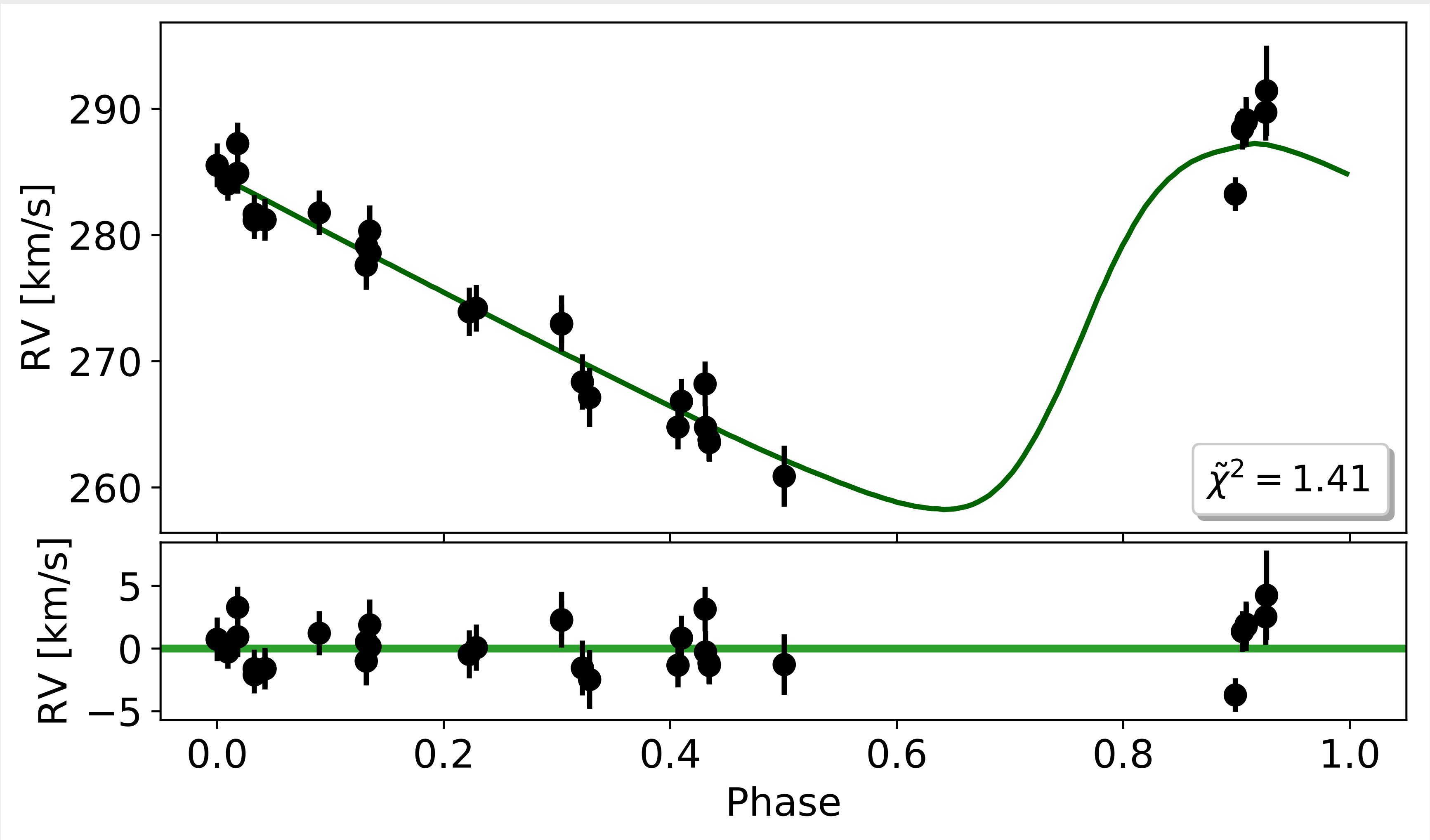




4 **Software for modelling RV curves** e.g. THE JOKER, Ultranest





to get orbital parameters and identify massive companions (e.g. **NS/BH candidates**)!

From the MUSE Survey of massive star clusters:

NGC 1850

Identity Card:

- In the Large Magellanic Cloud;
- Young (~100 Myr-old);
- Massive (~0.52 x 10^5 M⊙, Song+2021).

OBSERVATIONS:

- **UV/Optical/NIR photometry** from HST

- **Multi-epoch Spectroscopy** from VLT/MUSE
  16 epochs covering more than 2 years

FINAL SAMPLE: 2 500 stars

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FINAL SAMPLE: 2 500 stars

ω Centauri

Identity Card:

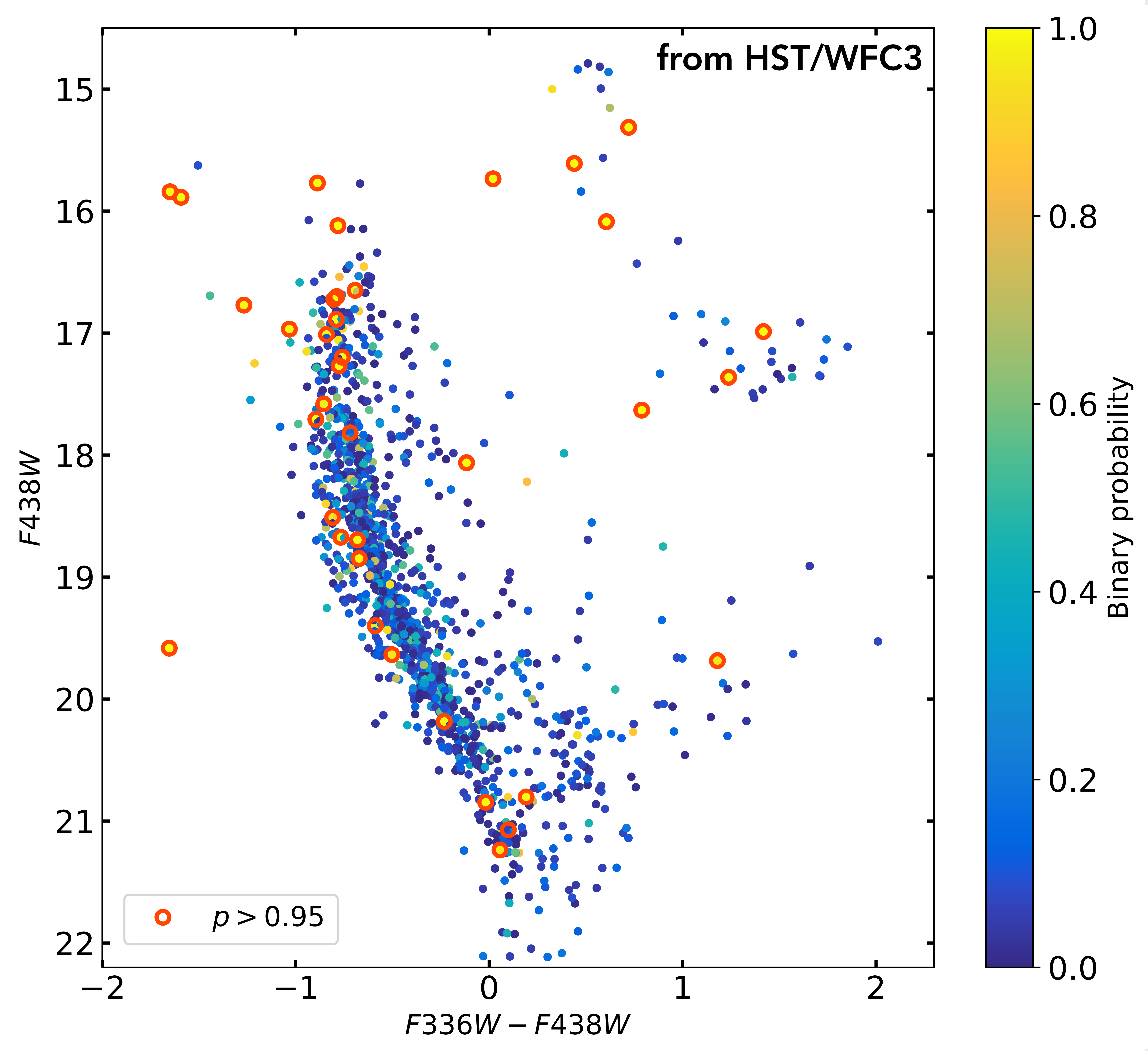
- the most massive (> $10^6 M_\odot$) Galactic stellar system;
  (Meylan 1987; White & Shawl 1987)
- complex stellar system with metallicity spread > 1dex;
  (Johnson+2020)
- 15 stellar populations, with different element abundance;
  (Bellini+2017)

OBSERVATIONS:

- **UV/Optical/NIR photometry** from HST
- **Multi-epoch Spectroscopy** from VLT/MUSE
  17 epochs covering 8 years (2015 - 2022)

FINAL SAMPLE: 29 000 stars

NGC 1850: detecting binaries

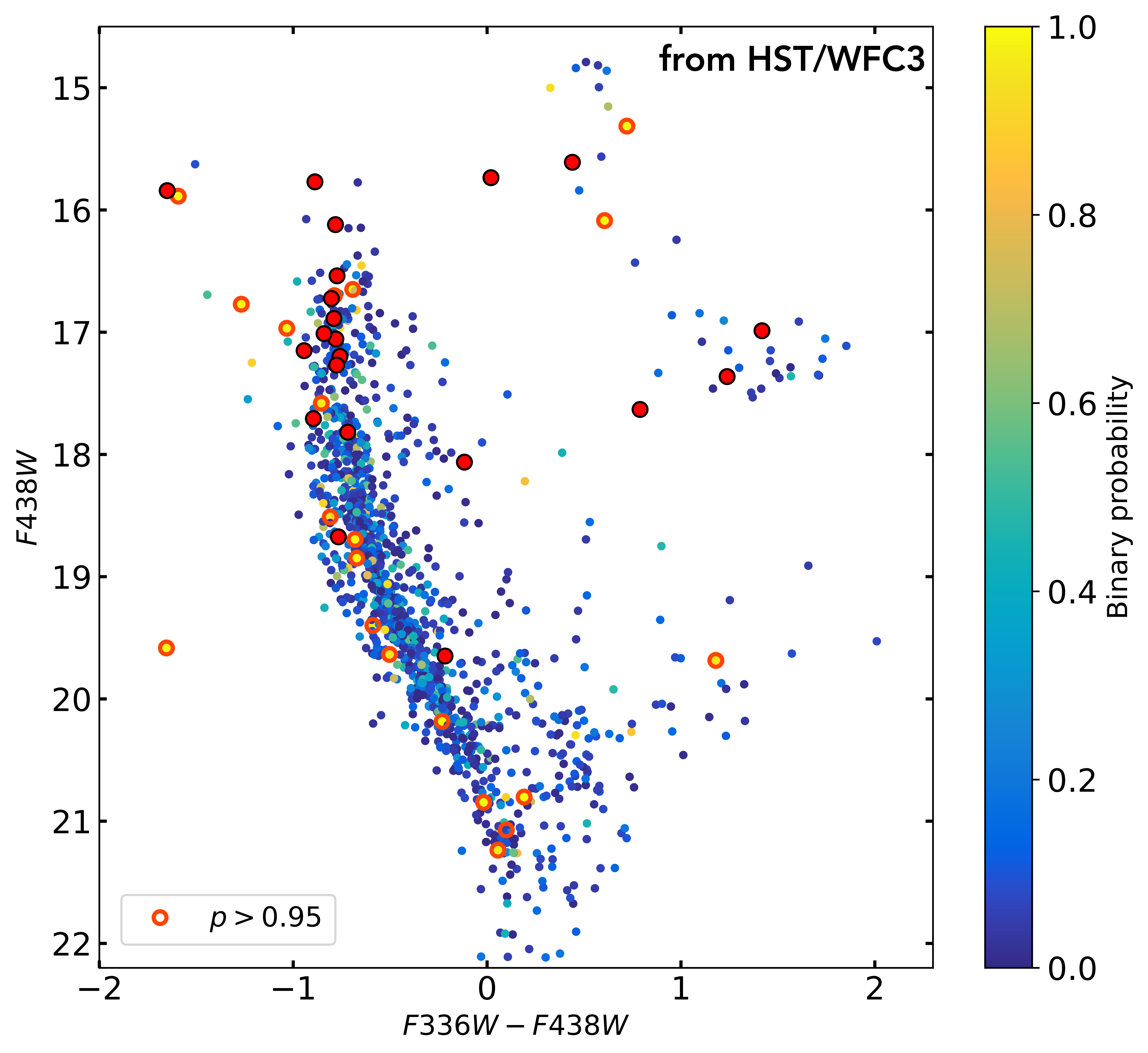


ORANGE OPEN POINTS:

Obvious BINARY SYSTEMS
[> 95 % probability]

Saracino+2023b

NGC 1850: detecting binaries



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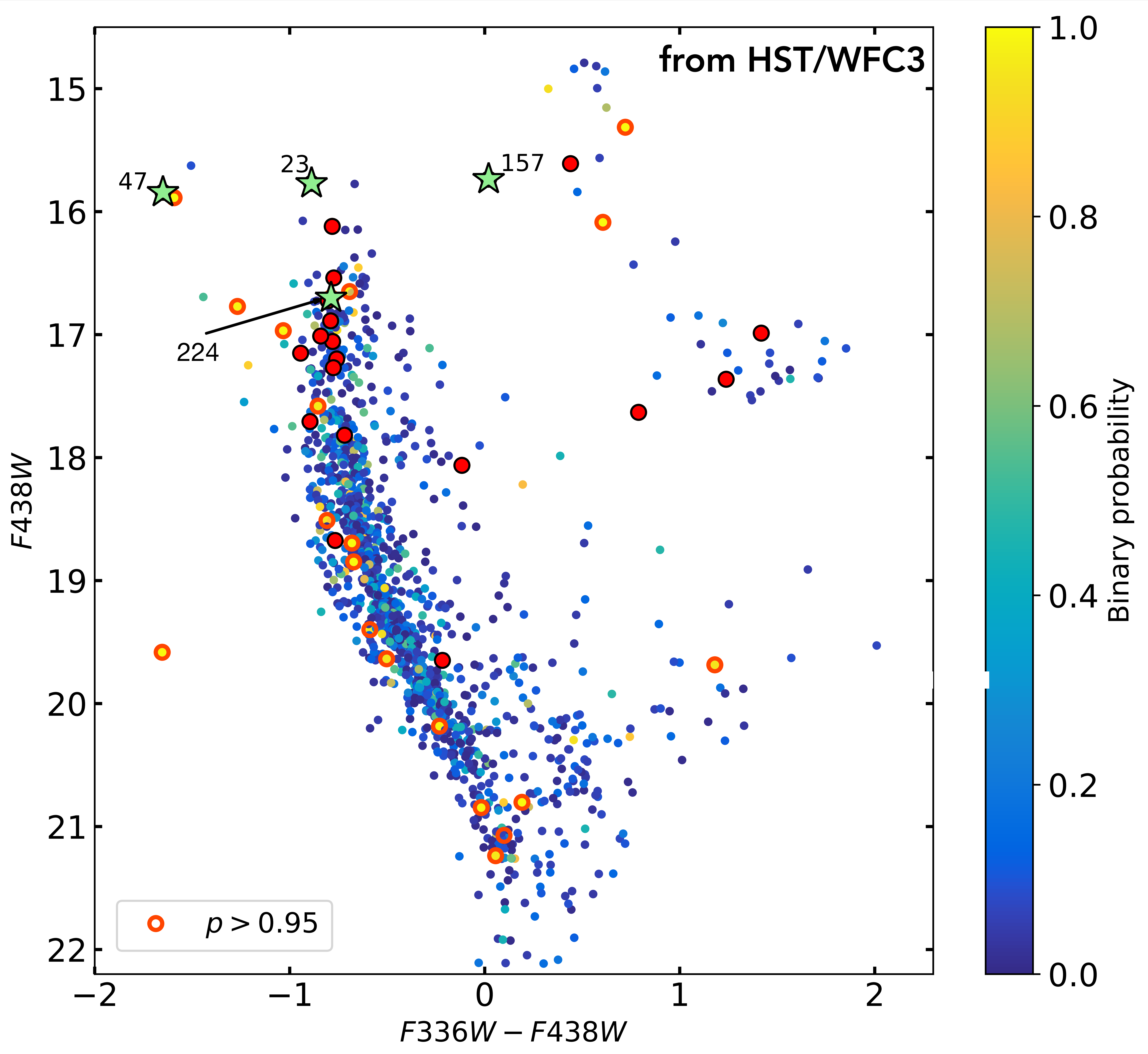
RED FILLED POINTS:

Binary systems with
constrained orbital properties

Saracino+2023b

NGC 1850: detecting binaries



ORANGE OPEN POINTS:

Obvious BINARY SYSTEMS
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RED FILLED POINTS:

Binary systems with
constrained orbital properties

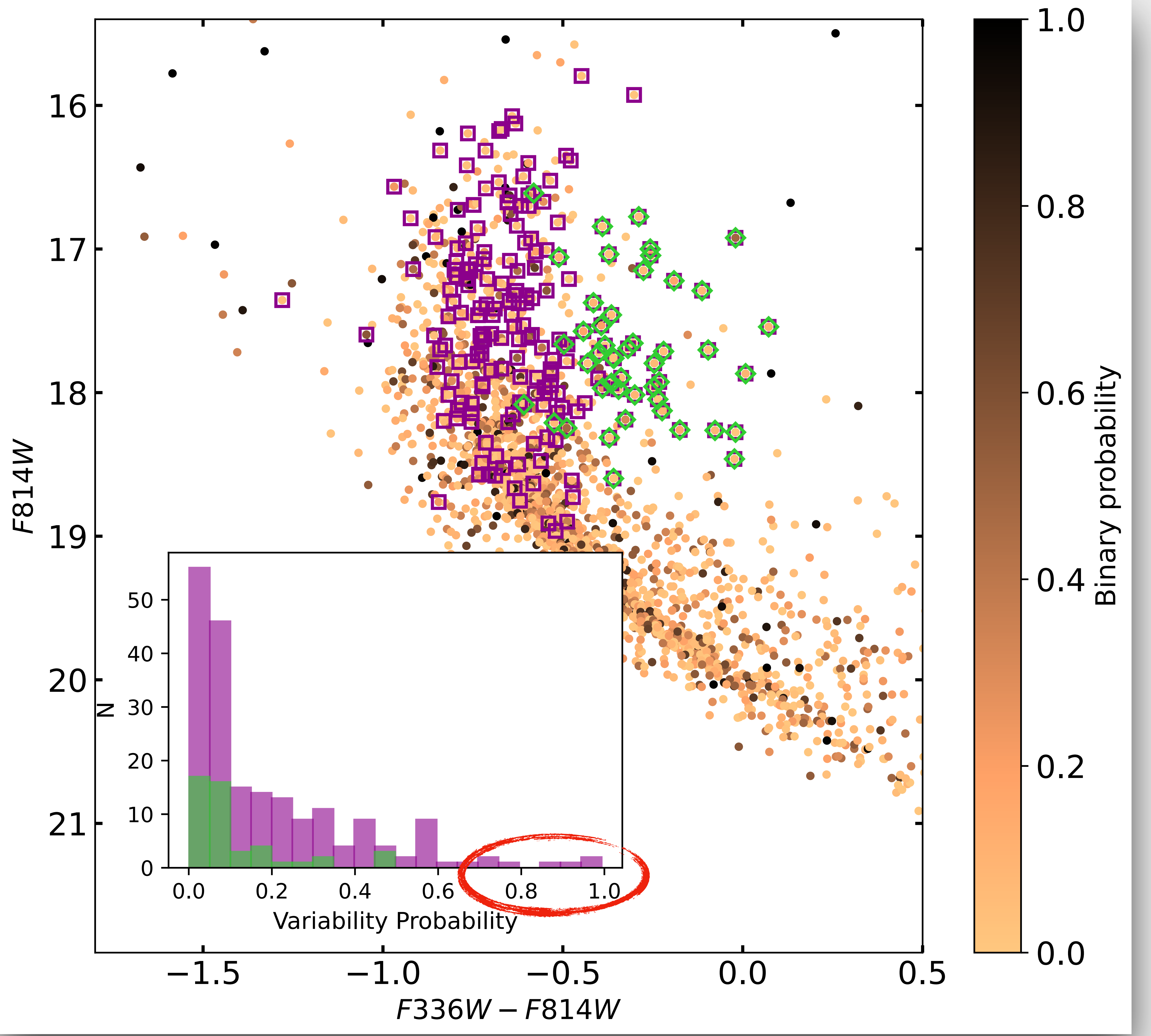
GREEN STAR SYMBOLS:

Binary systems with
constrained orbital properties &
massive companions

Saracino+2023b

NGC 1850: Binary Fraction

- Binary fraction: (24 ± 5) % for 2.5 $M_\odot$<M<5 $M_\odot$ stars.
  Little/no obvious binaries among Be and shell stars, consistent with other studies (e.g. NGC 330, Bodensteiner+2021)



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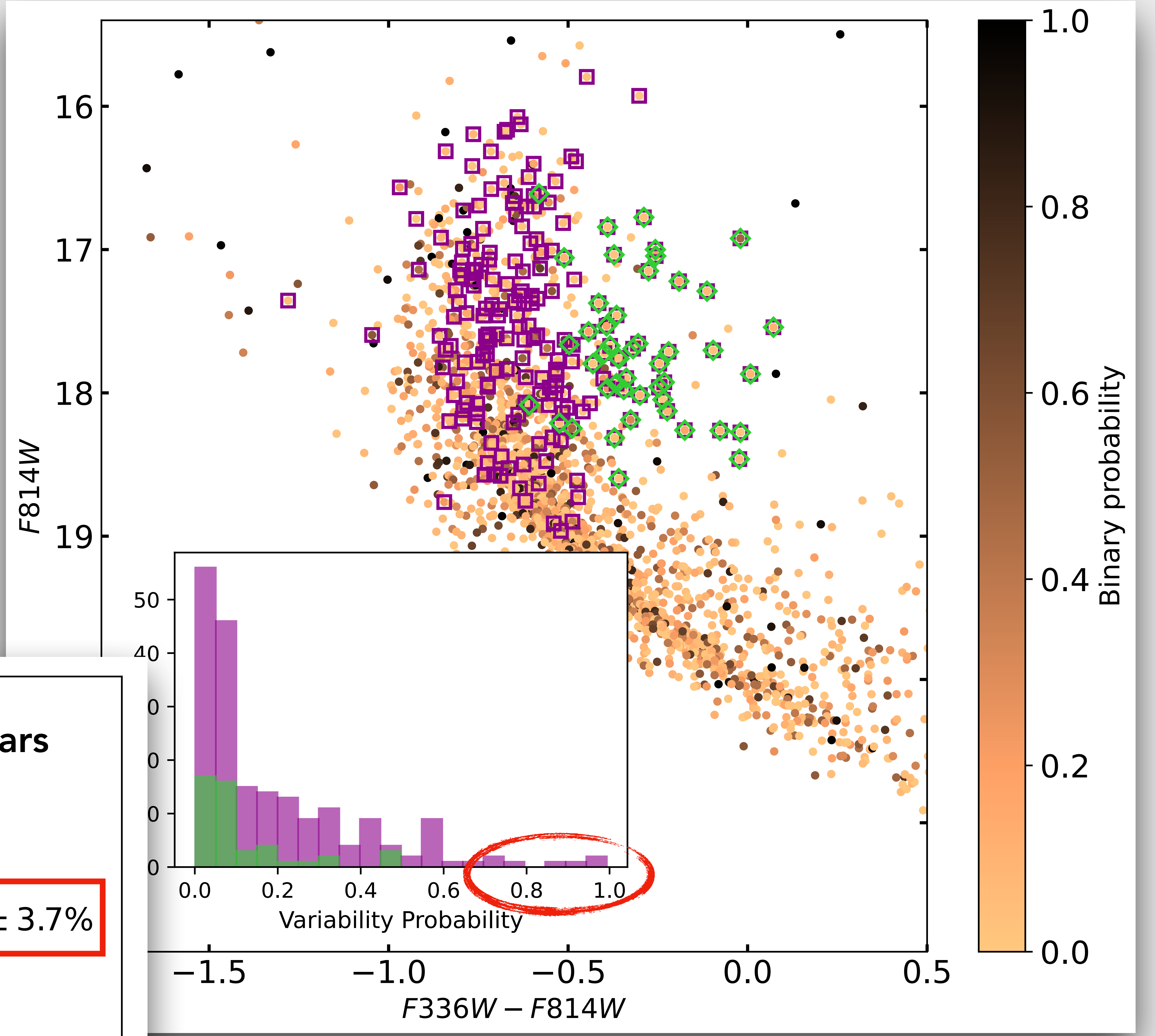
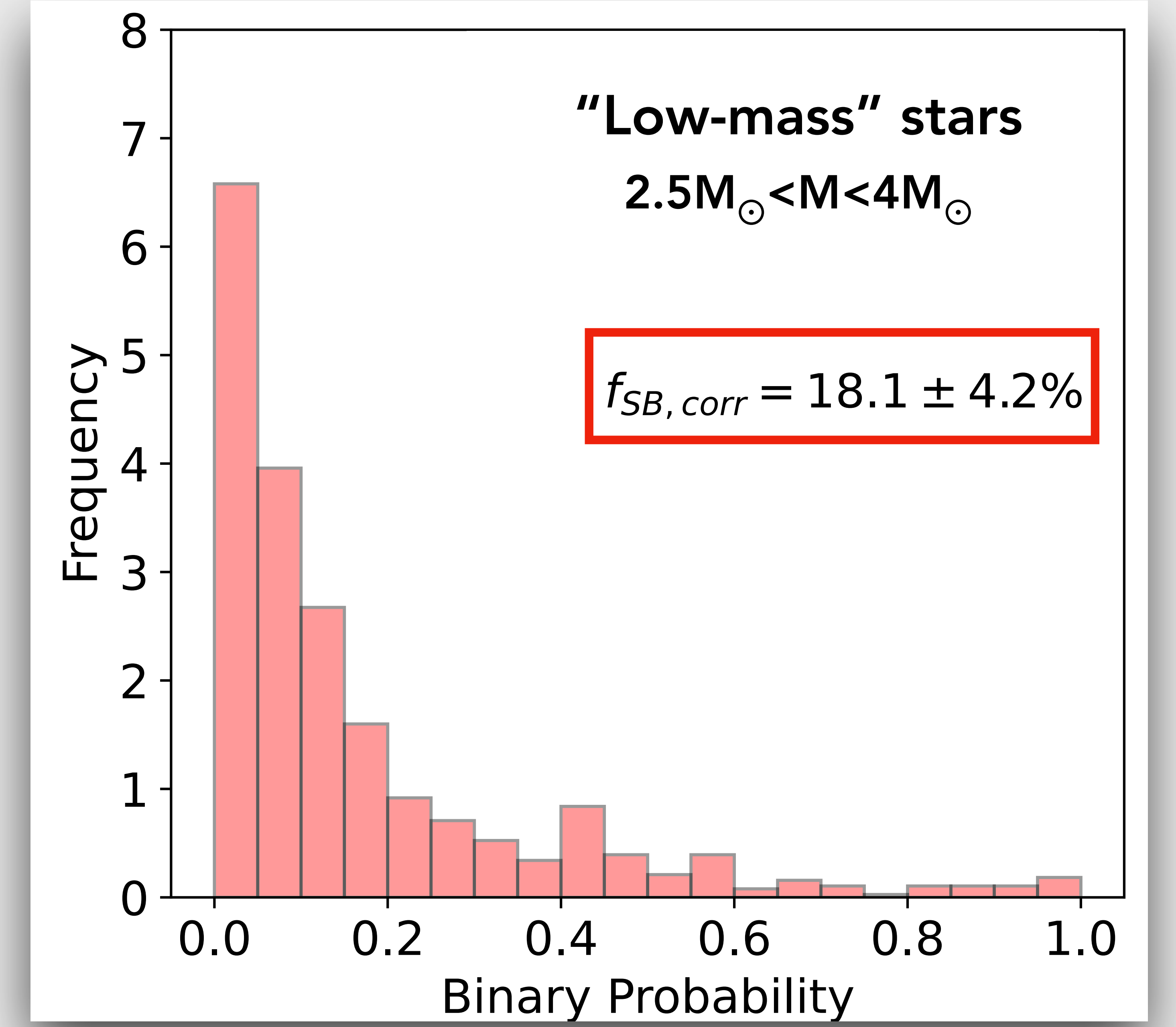
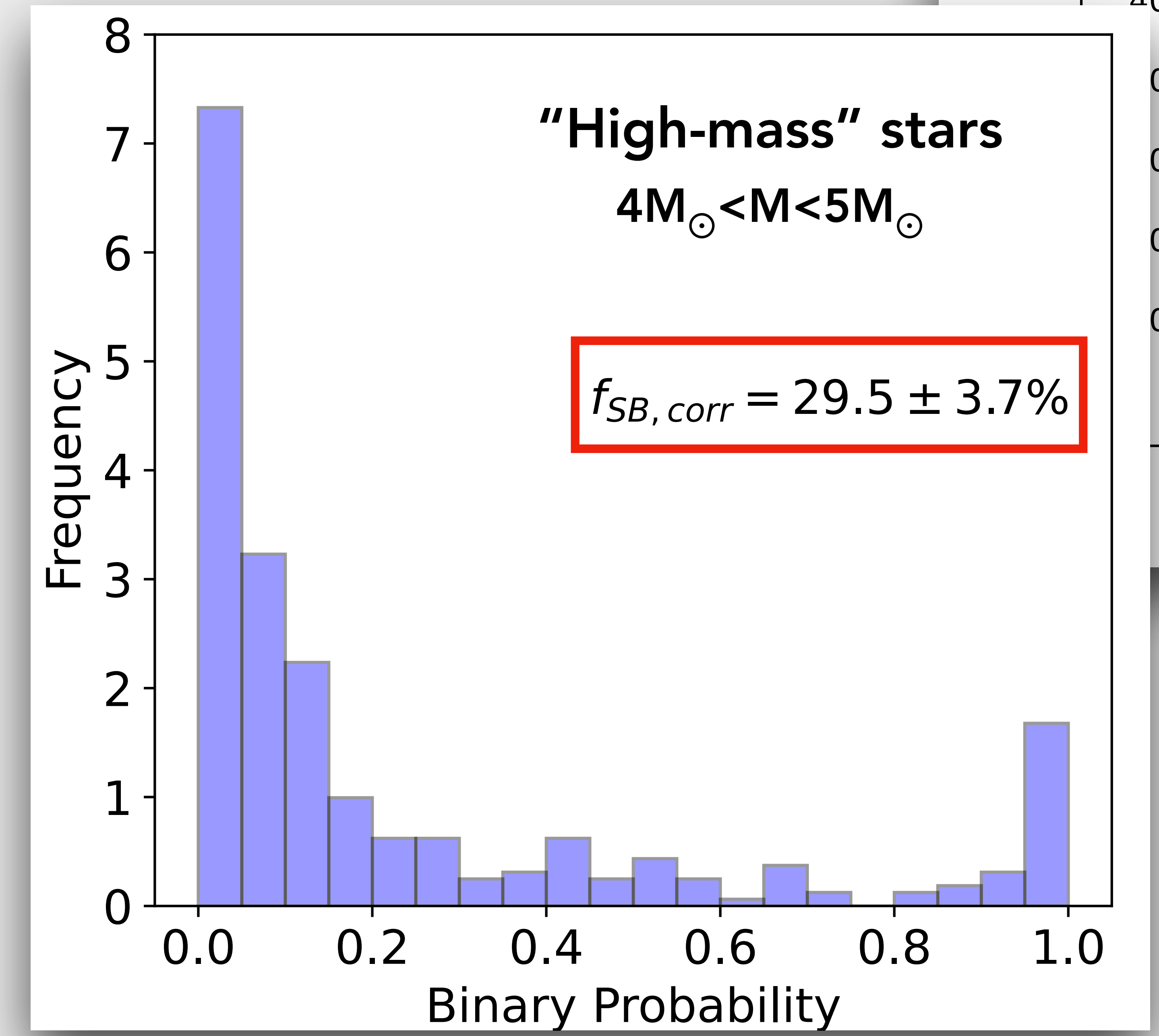
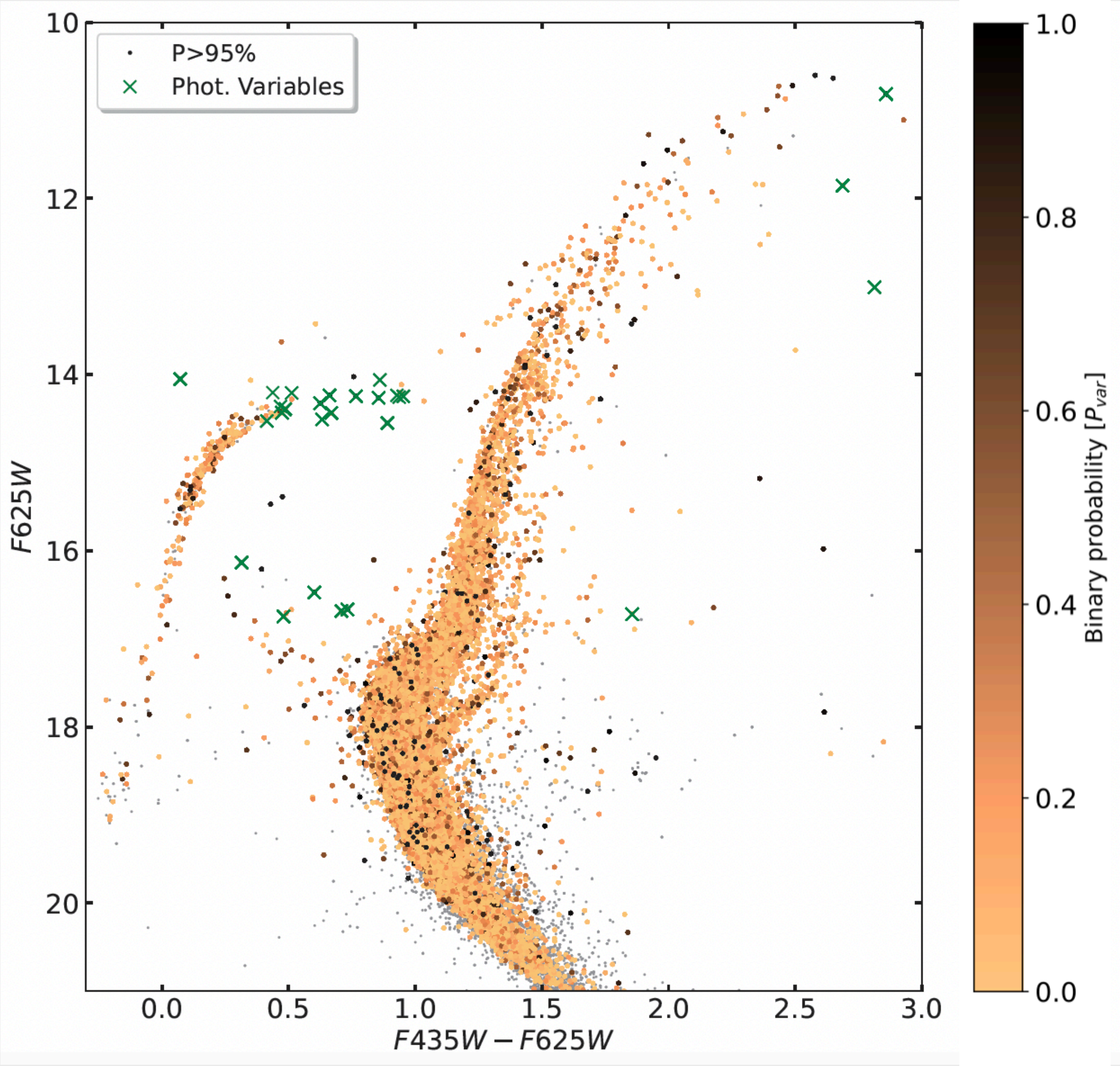
- Observed trends in mass (magnitude) for cluster stars.







ω **Cen**: detecting binaries



DARK POINTS:
Obvious BINARY SYSTEMS
[> 95 % probability]

LIGHT POINTS:
Single Stars

GREEN CROSSES:
Photometric variables
from literature catalogs.
(RR Lyrae, SX Phe, LPV etc.)

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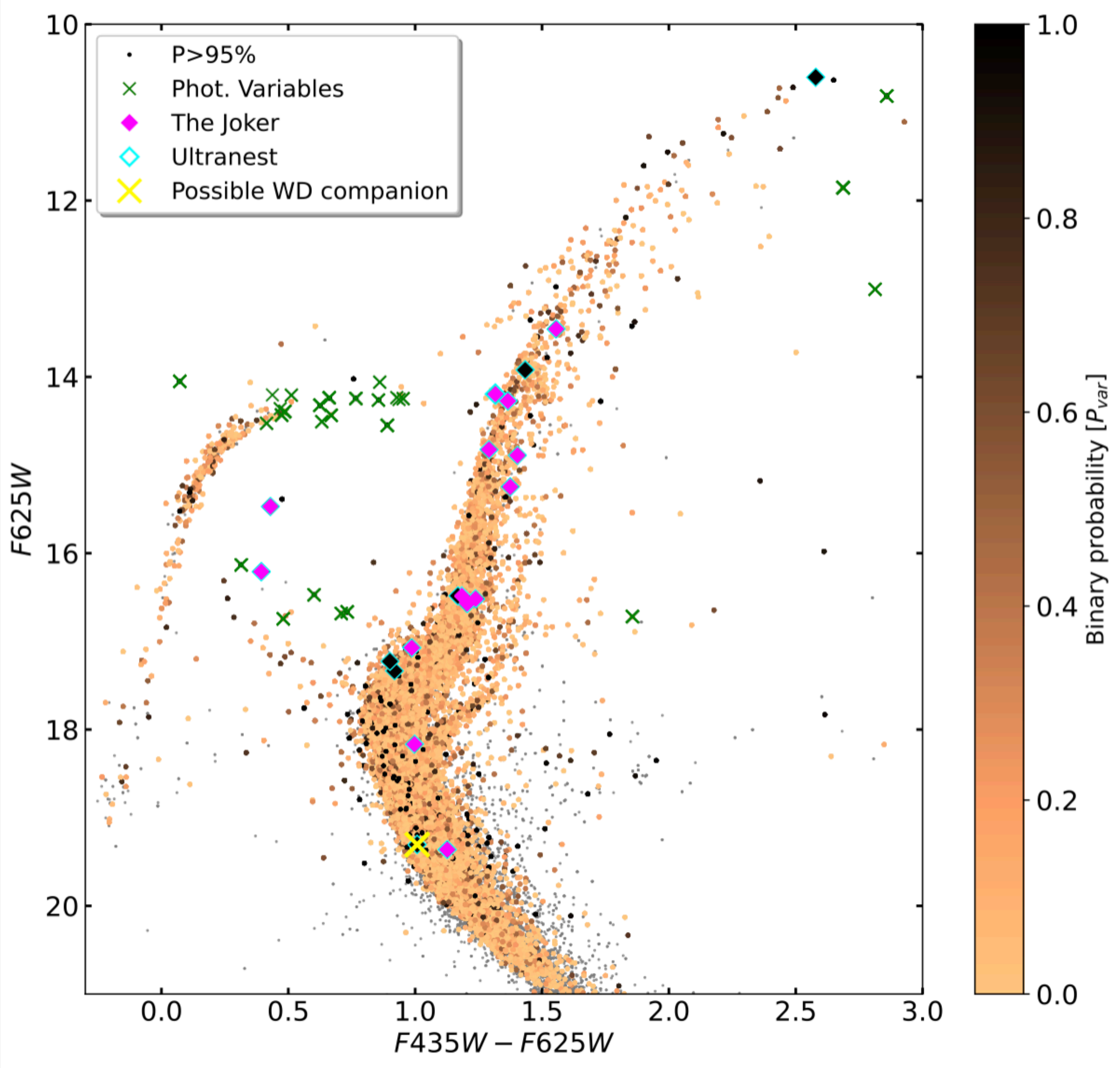

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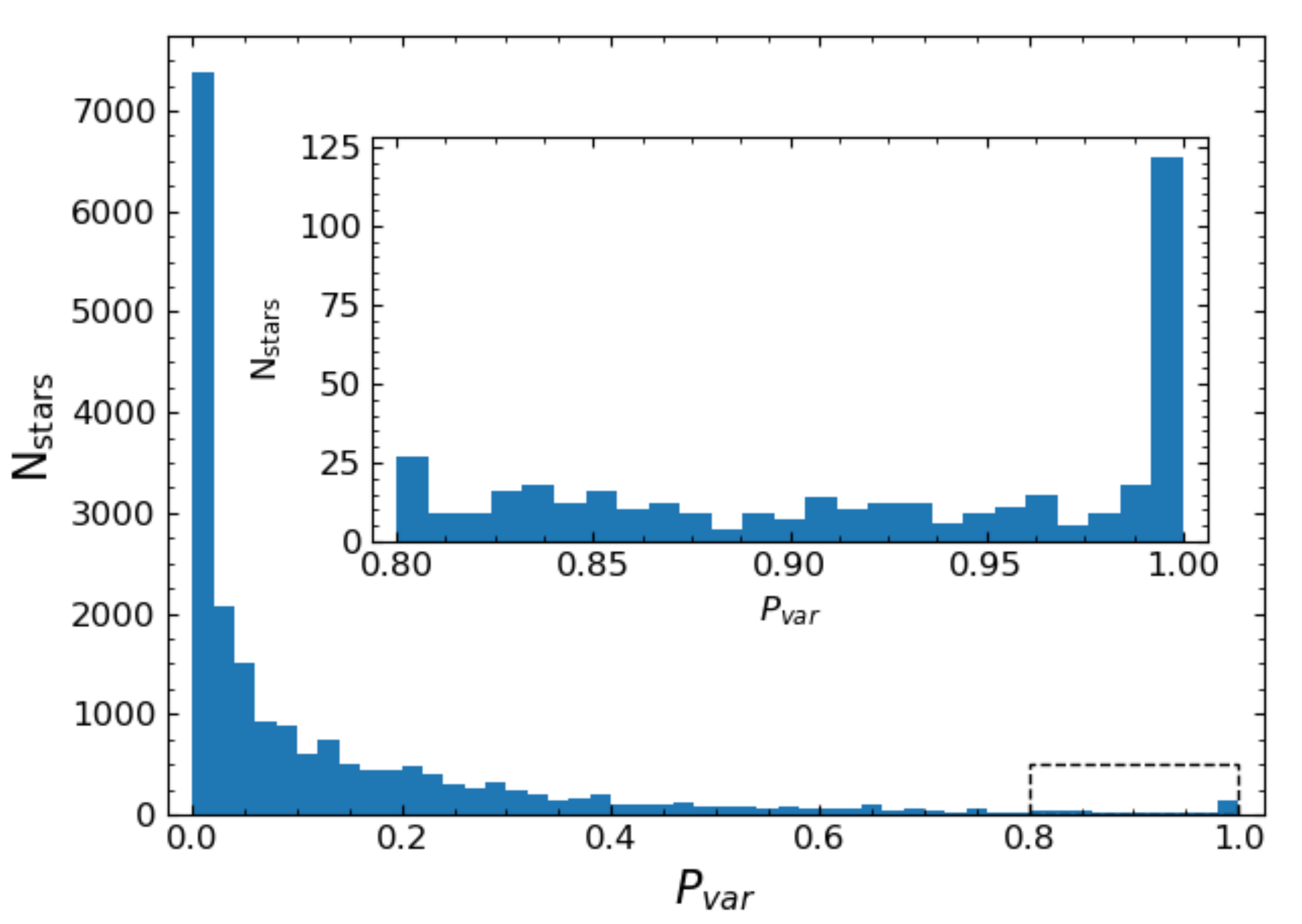
MAGENTA, CYAN SQUARES:
Binary systems with
constrained orbital properties

ω **Cen**: Binary Fraction



222 binaries ($P_{var} > 0.8$)

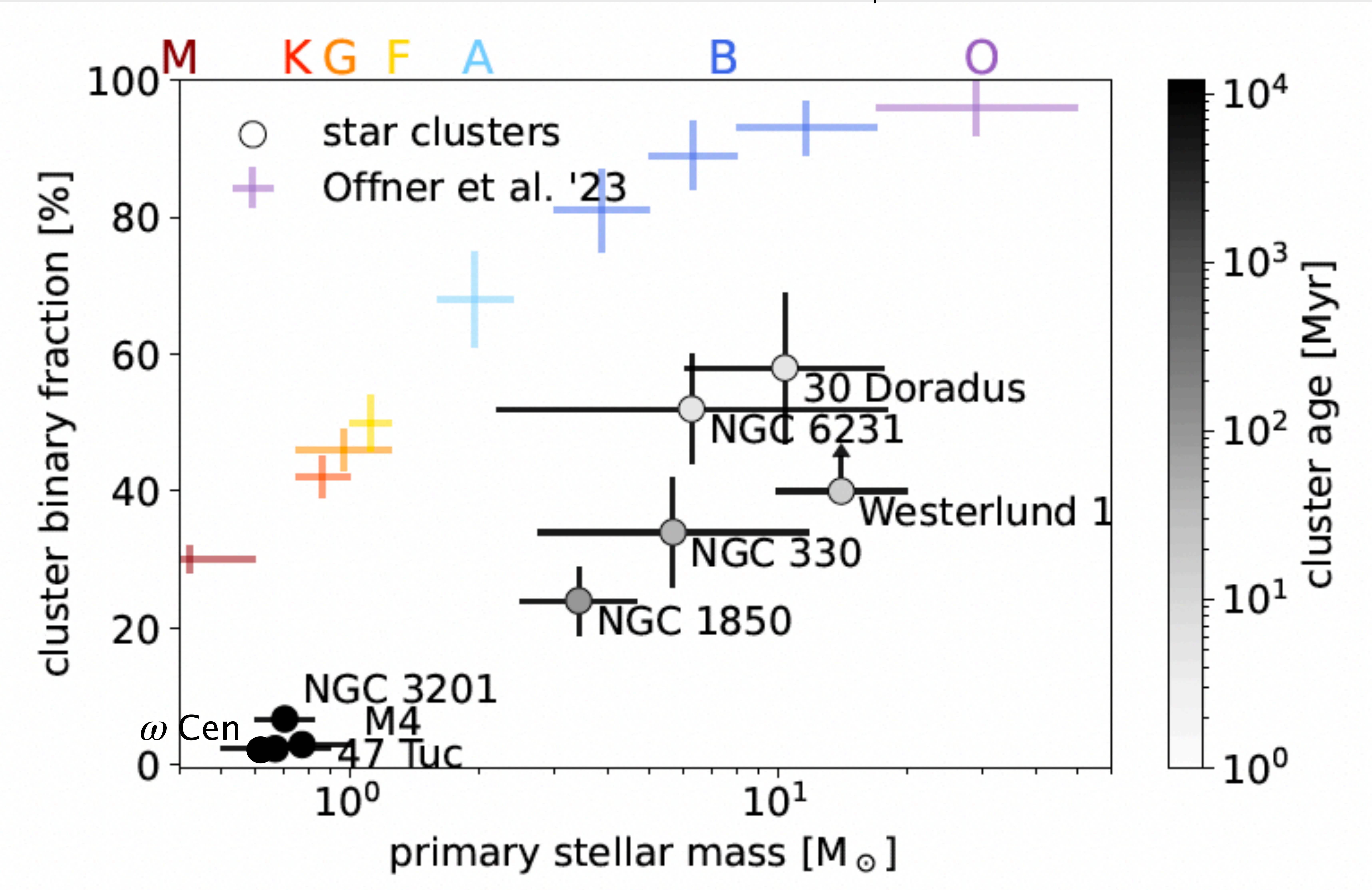
Low binary fraction (~2%), consistent with previous studies. (Bellini et al. 2017, Elson et al. 1995)

Stellar Type (a)	N_{stars}(b)	$N_{binaries}$ (c)	Discovery Fraction (d)	Sample Completeness (e)	Binary Fraction (f)
Global fraction	19059	275	1.4% ± 0.1%	0.7 ± 0.1	2.1% ± 0.4%
MS	14871	183	1.2% ± 0.1%	0.6 ± 0.1	2.0% ± 0.5%
TO	7897	84	1.1% ± 0.1%	0.6 ± 0.1	1.6% ± 0.4%
SGB	2396	23	1.0% ± 0.3%	0.8 ± 0.1	1.2% ± 0.4%
RGB	1811	41	2.3% ± 0.4%	0.9 ± 0.1	2.4% ± 0.4%
HB	232	6	2.6% ± 1.3%	0.8 ± 0.1	3.0% ± 1.5%
AGB	33	0	0%	-	-
BSS	44	6	13.6% ± 5.1%	0.6 ± 0.1*	21.9% ± 9.5%

Wragg+2024, subm.

Literature comparison:

Adapted from Muller-Horn+2024, subm.

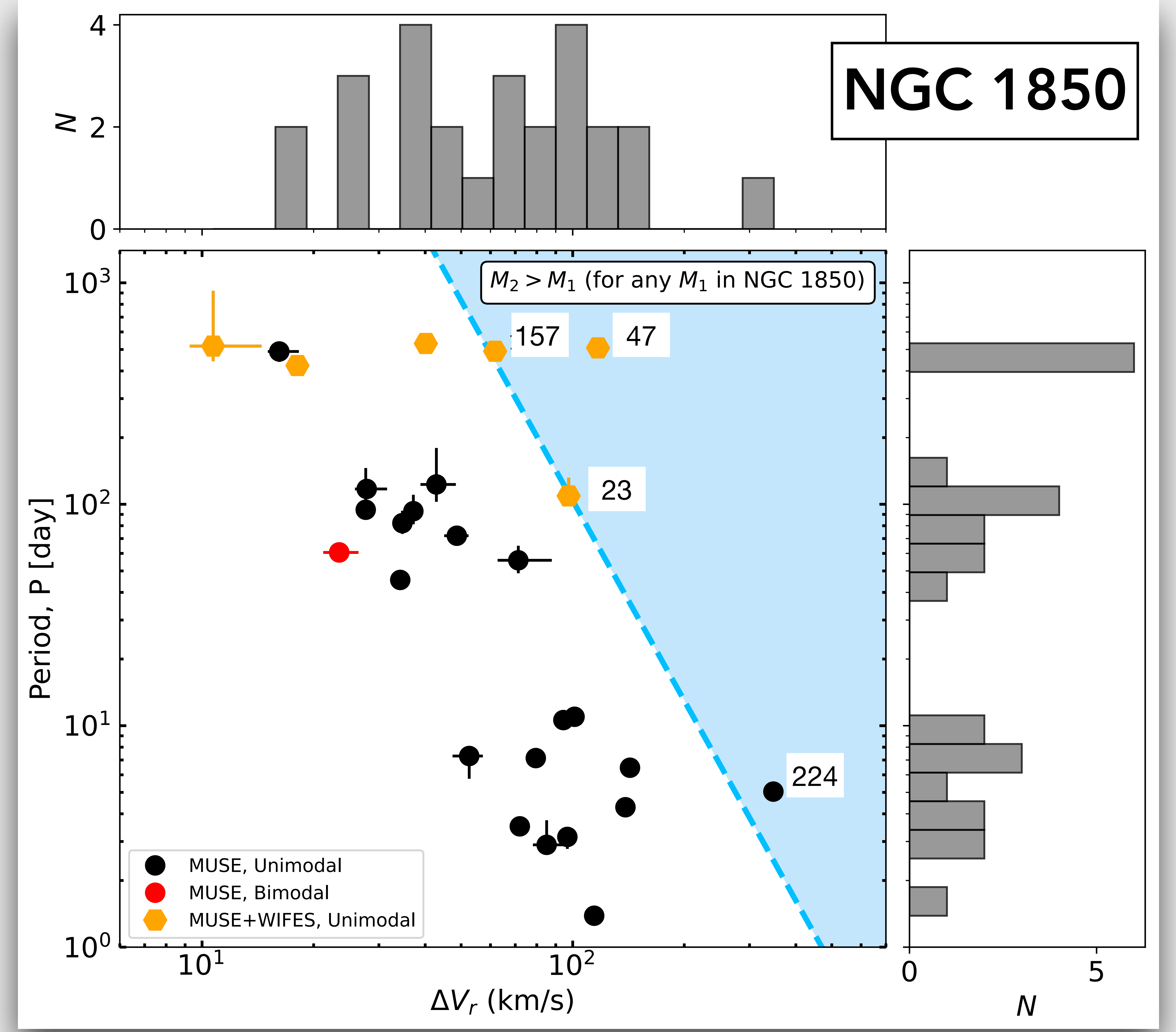


Both stellar evolution and dynamical interactions at play.

Data from:

Sana+2013, Dunstall+2015, Banyard+2022, Ritchie+2022, Bodensteiner+2021, Giesers+2019, Saracino+2023b, Wragg+2024,subm, Muller-Horn+2024,subm

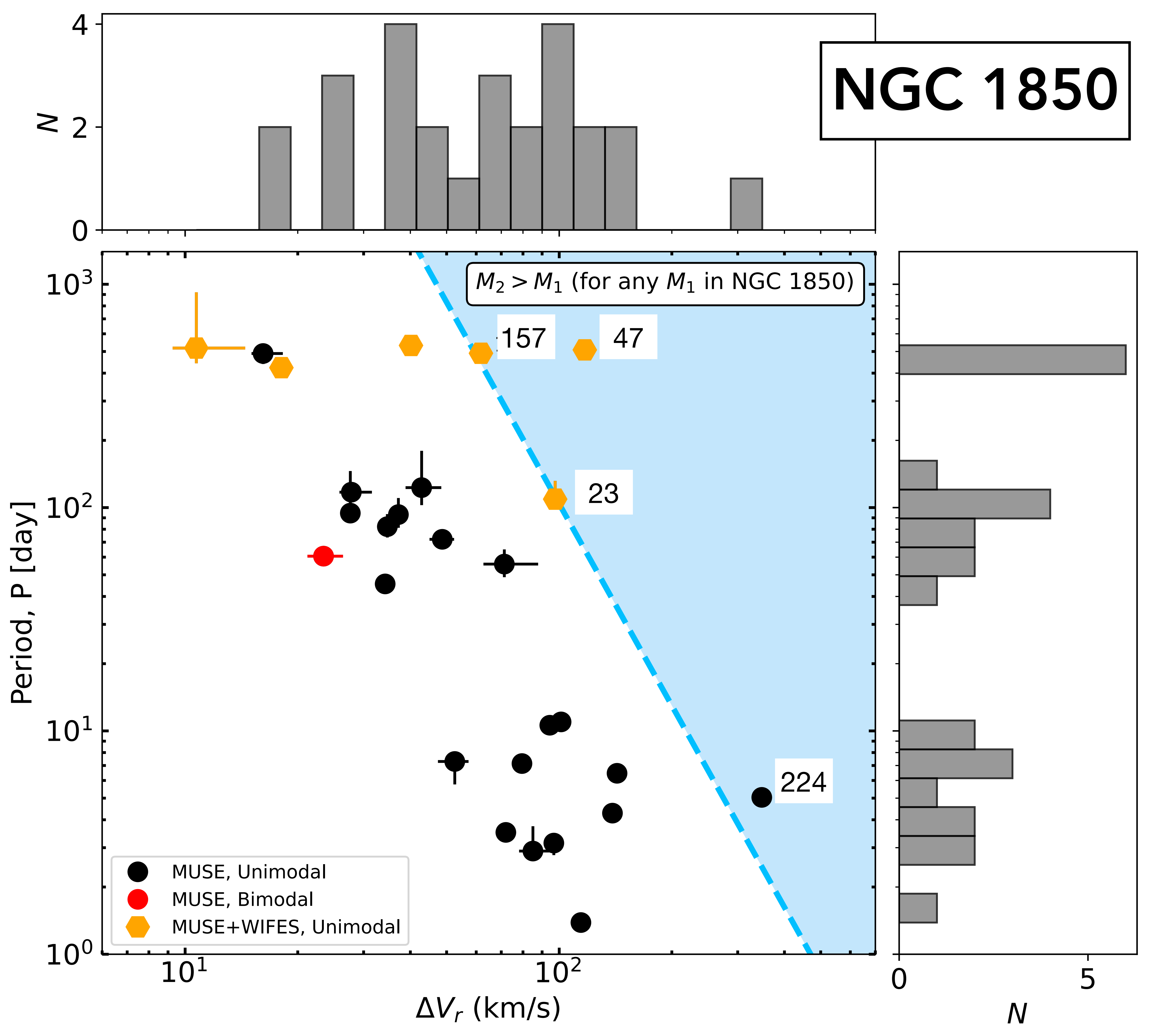
Observed binary properties

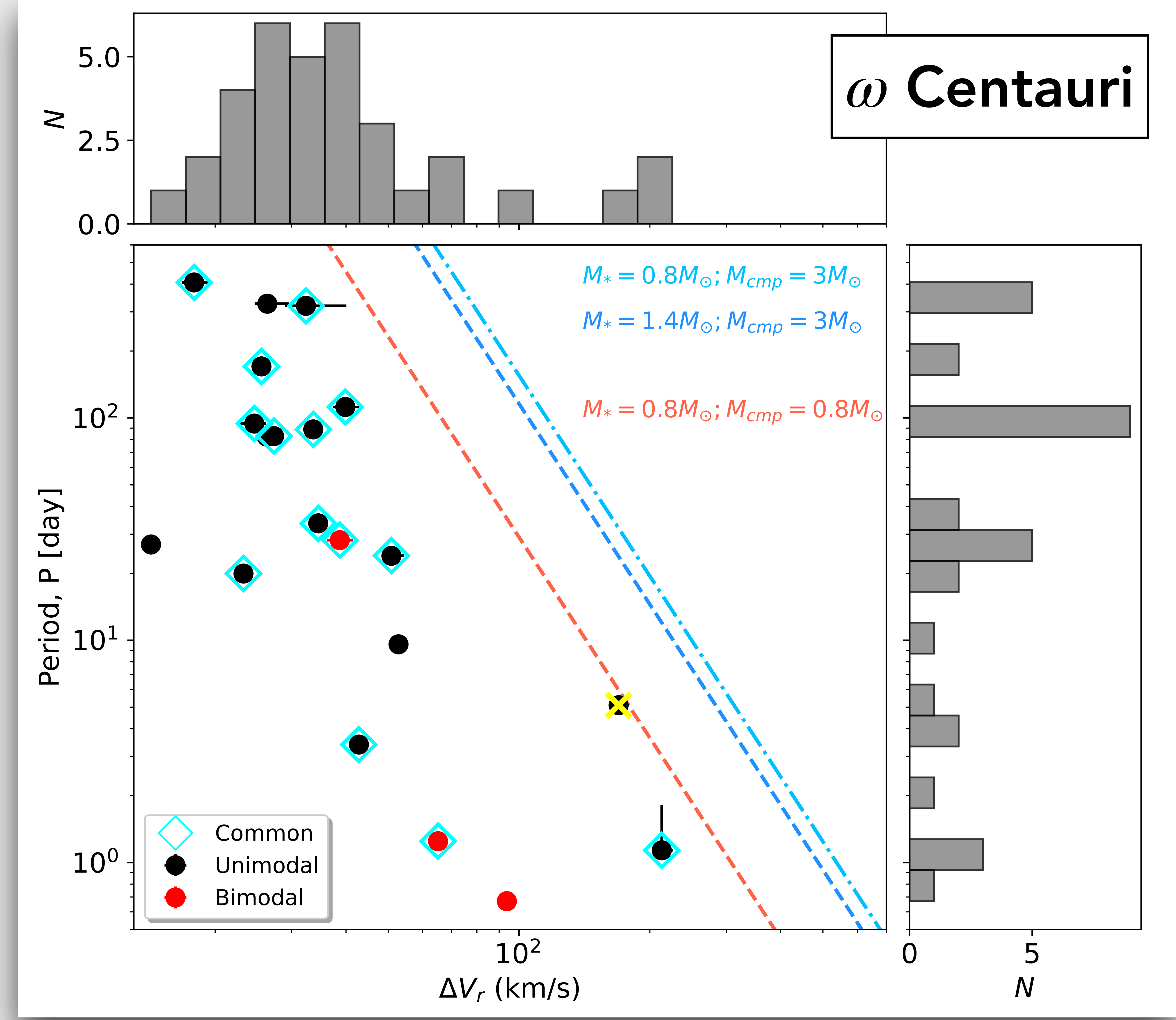


27 well-constrained binaries (17% of the total)

- 4 binaries with high binary mass function.

Observed binary properties





27 well-constrained binaries (17% of the total)

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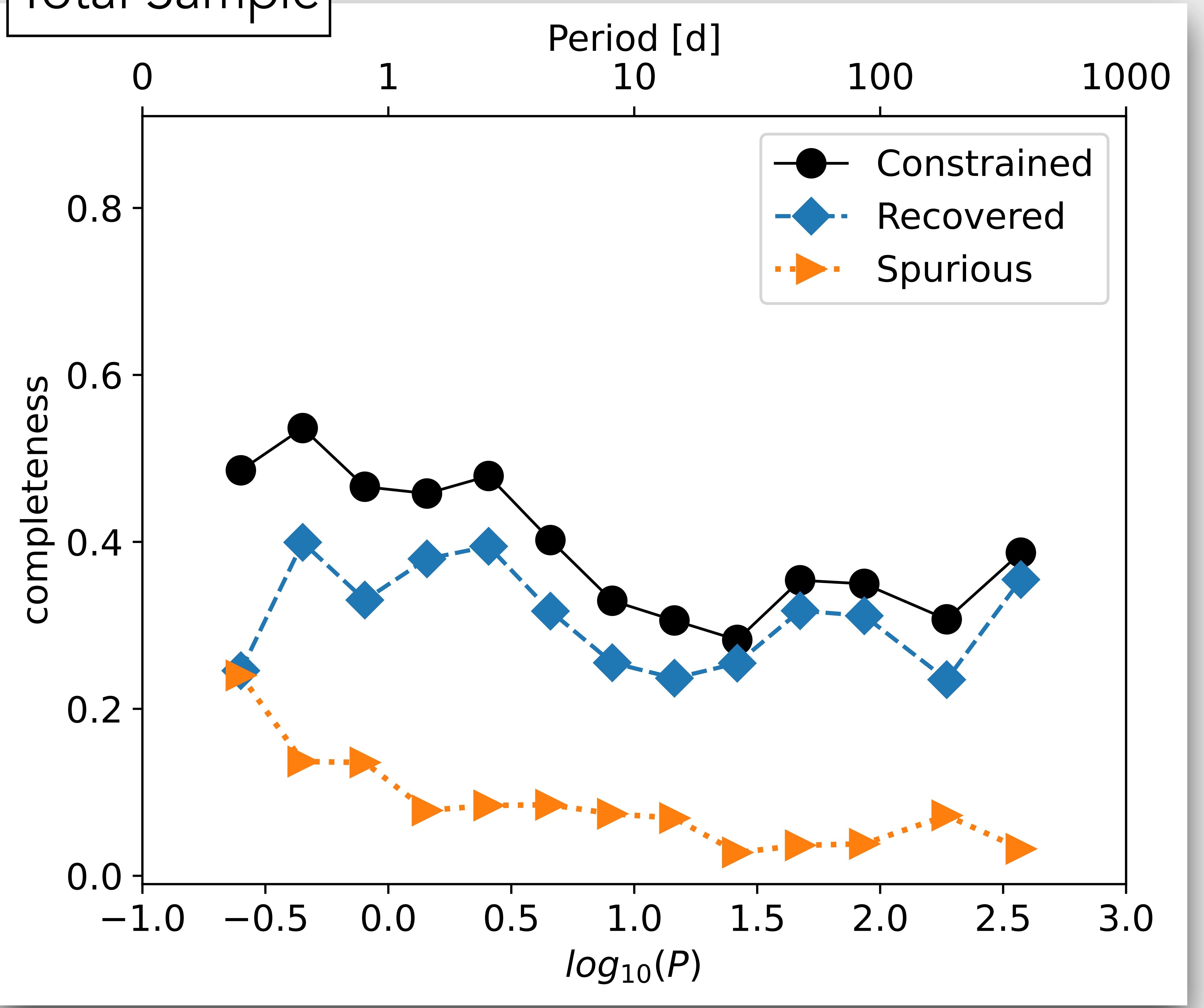
20 well-constrained binaries (9% of the total)

- No BH or NS candidates. A WD candidate.

ω **Cen**: completeness & purity of the sample

Total Sample



Completeness
[0.1 d < P < 500 d]: 42.5 % MS - MS binaries

- The observed abundance of binaries with P>10 d is likely a real feature, as the completeness decreases as a function of P.

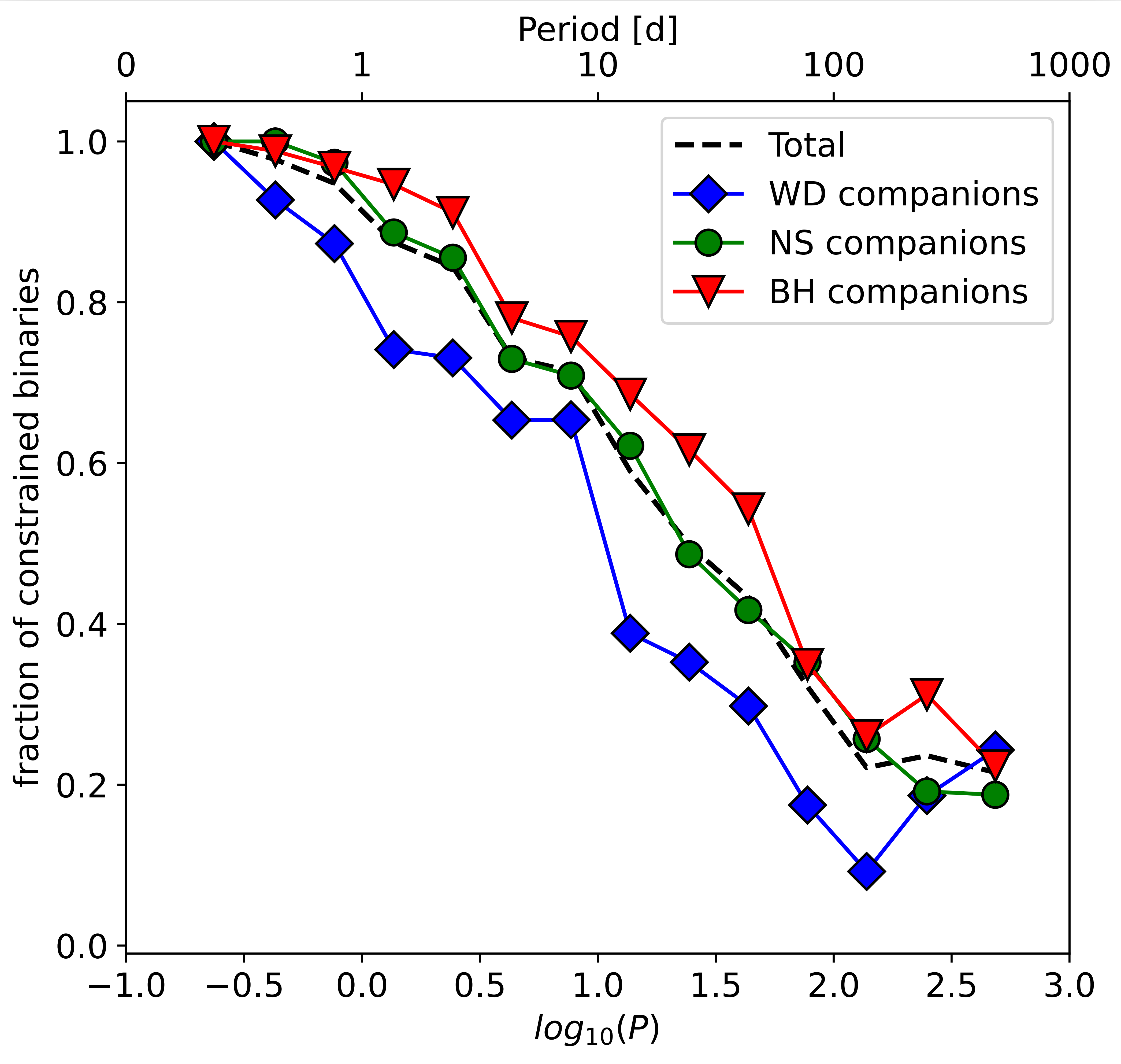
- Increase of spurious solutions for binary systems with P<1 d.

ω **Cen**: completeness & purity of the sample

A purity of almost 100% for evolved stars.

- 75% of the constrained binaries in ω Cen have an evolved primary -

ω **Cen**: mock data with dark remnants



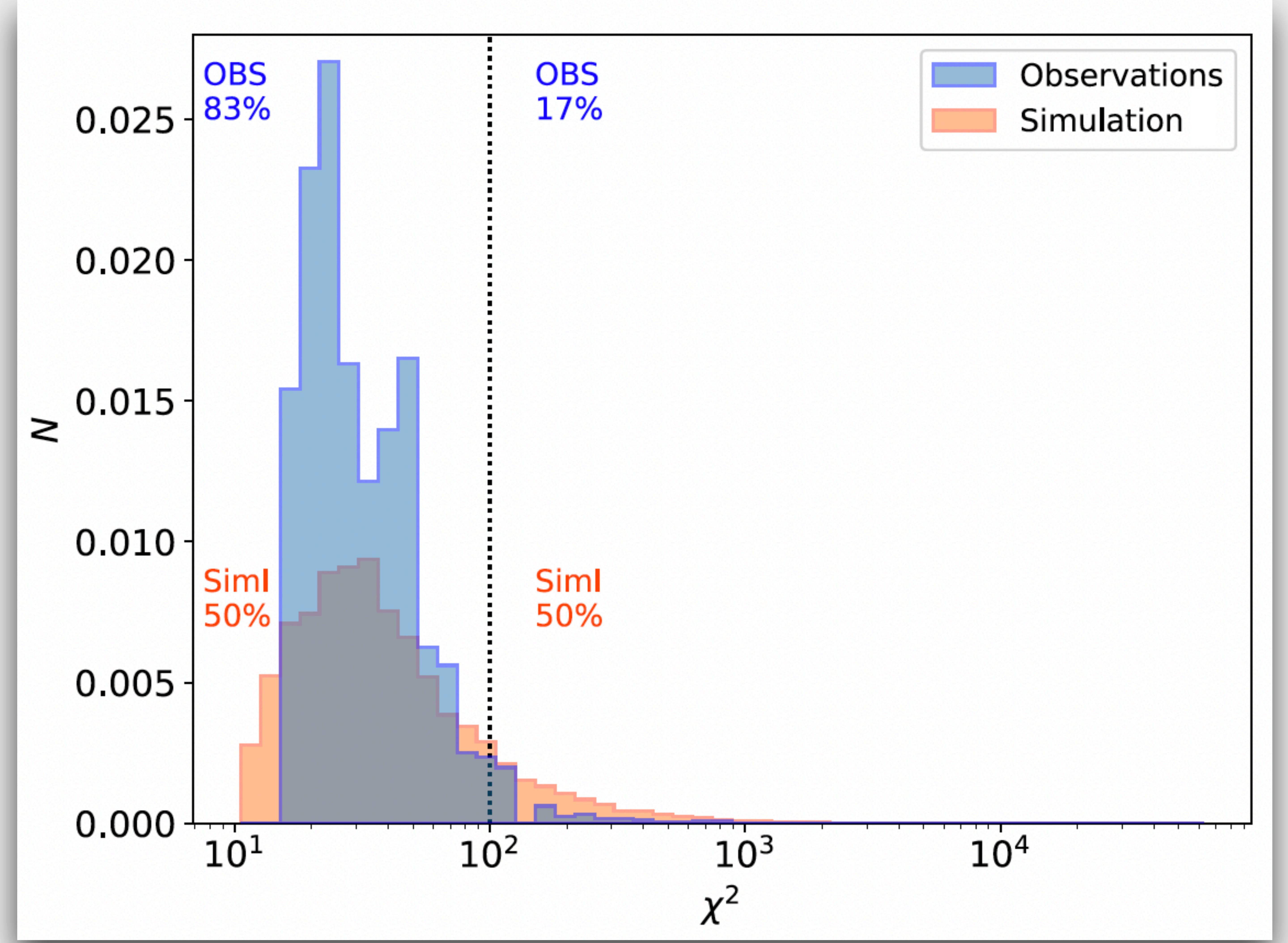
Completeness [0.1 d < P < 500 d]:	51% star - WD binaries 61% star - NS binaries 66% star - BH binaries

- Stars orbiting dark remnants (especially NSs and BHs) are intrinsically rare;

and/or

- Dark remnants are in binaries with periods longer than expected from cluster dynamics.

ω **Cen**: simulation vs observations



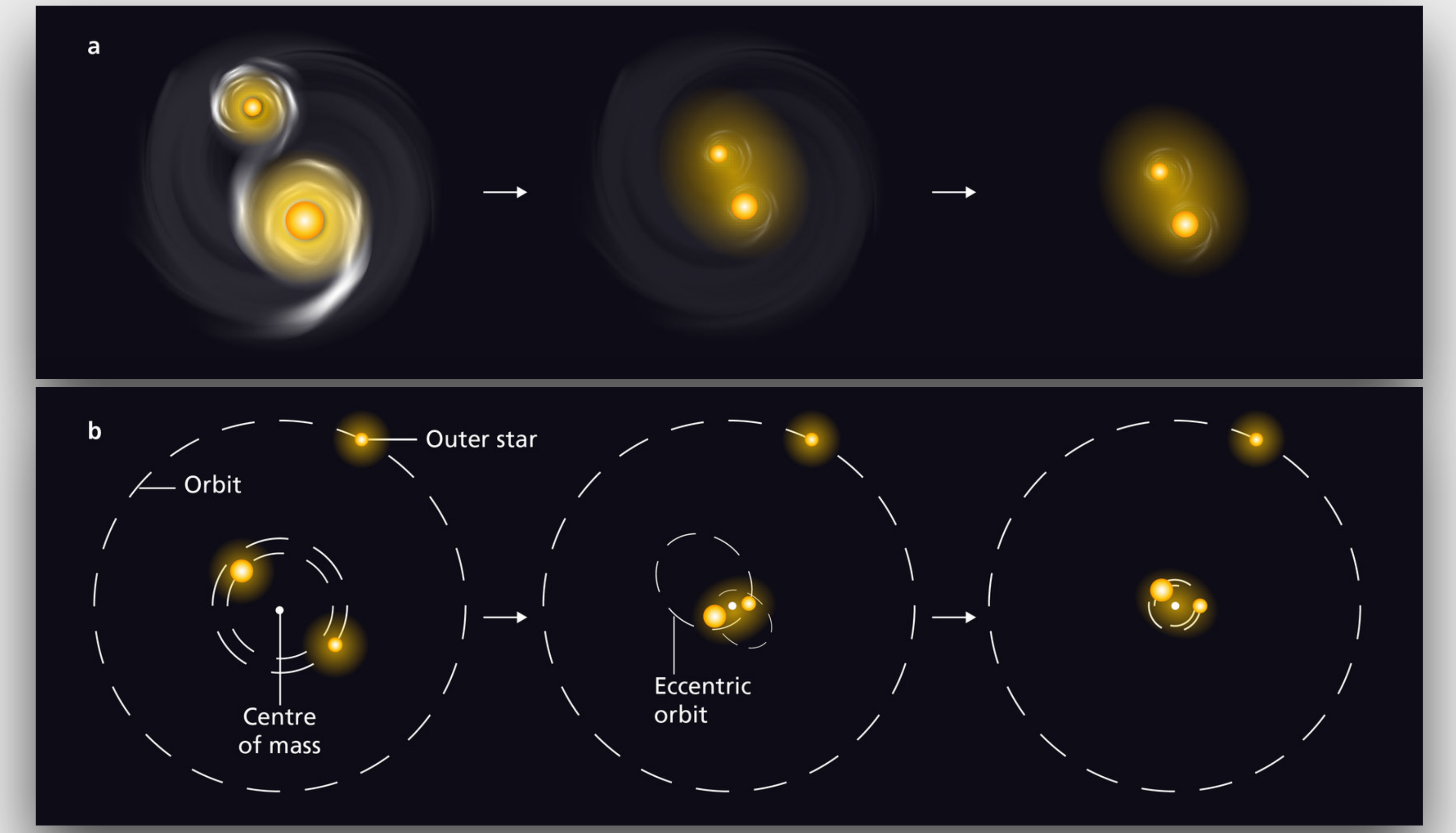
The intrinsic period distribution of binaries in ω Cen looks different from what predicted by current theoretical simulations (i.e. CMC) after over 10 Gyrs of simulated evolution.

Is it because of the initial binary properties, the treatment of binary evolution or the lack of a simulation tailored to ω Cen?

Not clear, but worth investigating..

Conclusions & Future Work:

1. Binaries are of key importance in massive star clusters, however very little is known about their orbital properties.



Credits: MPIA

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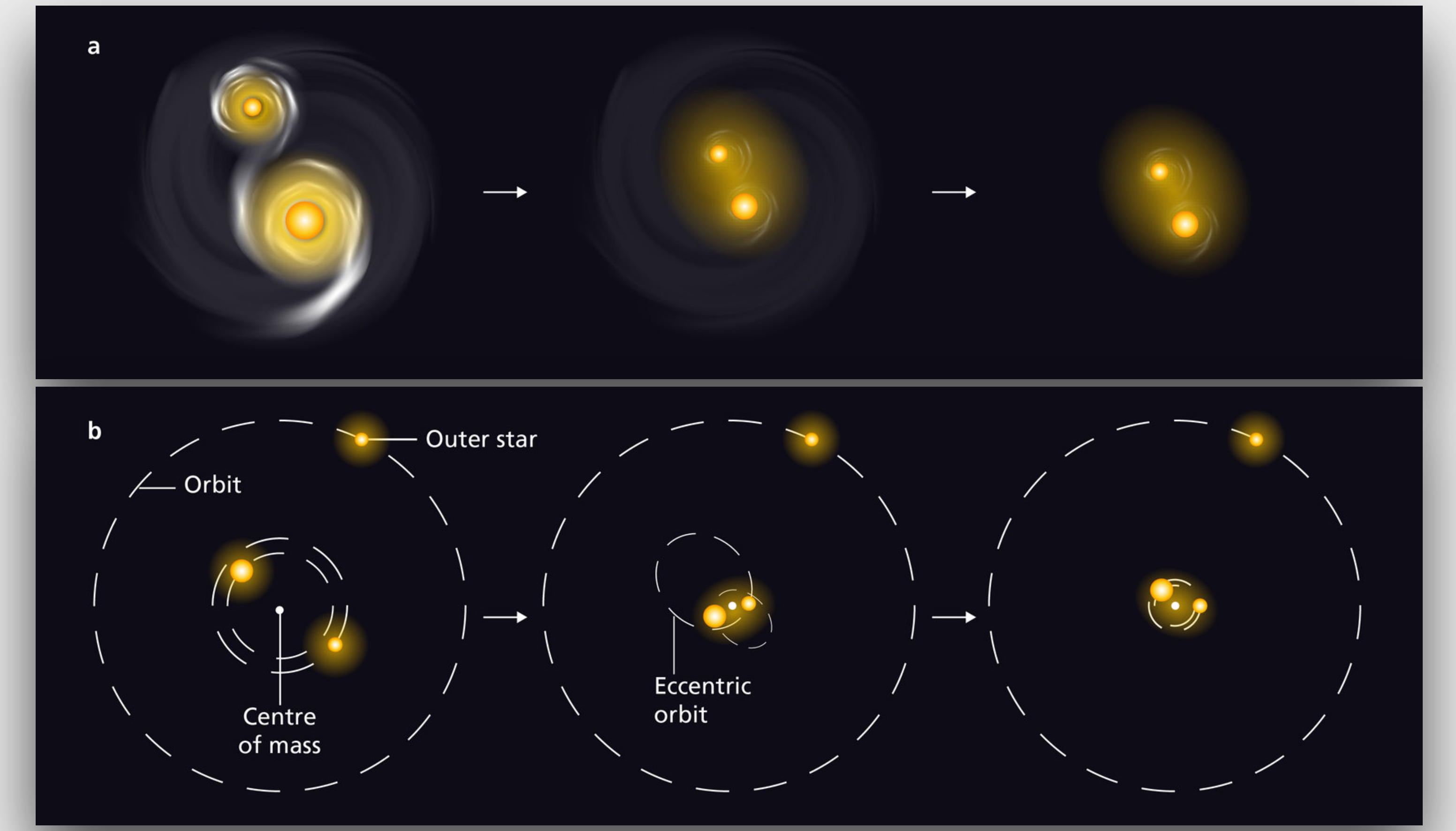
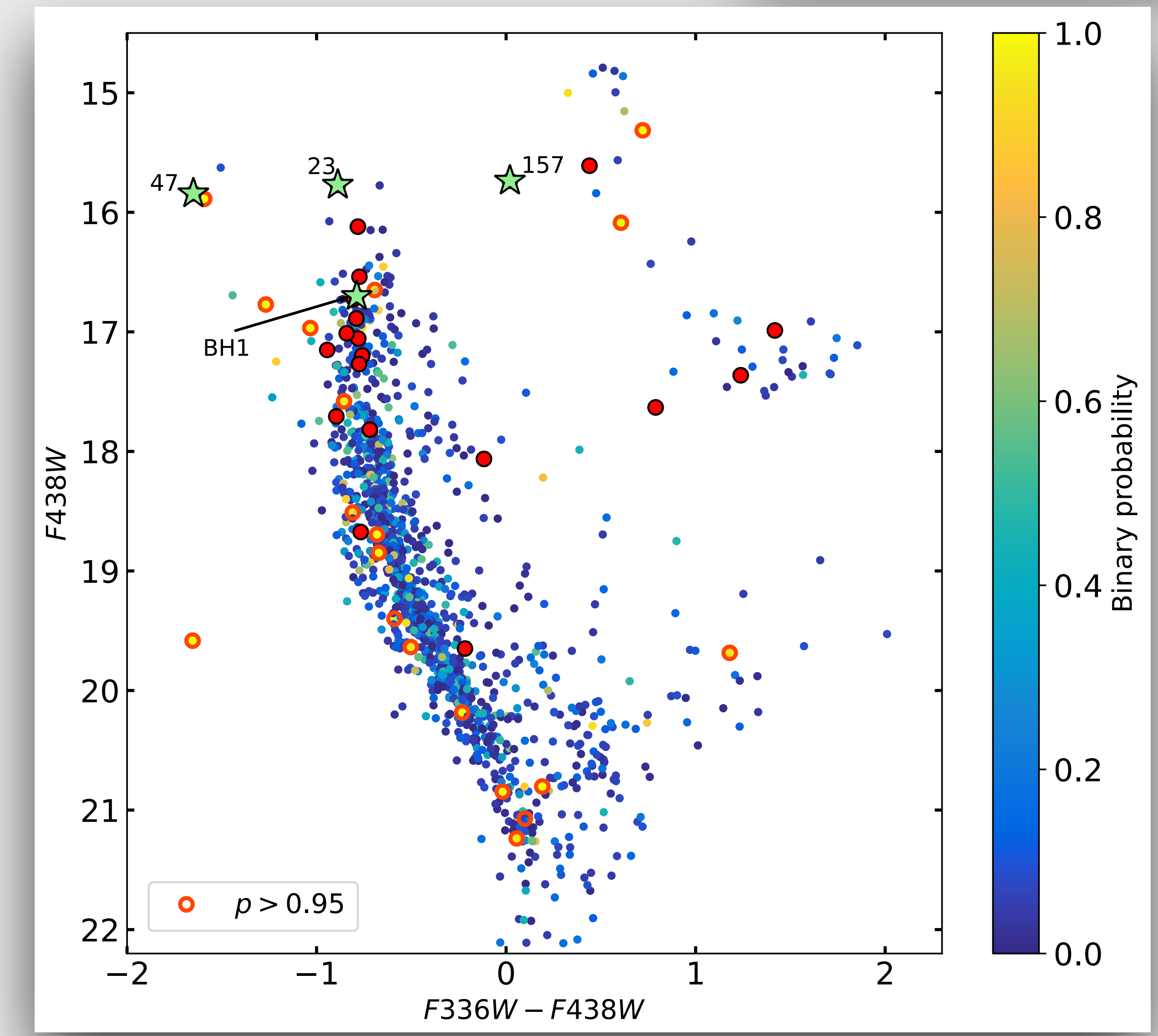


Credits: MPIA

2. A "systematic" study of binaries in clusters of various ages helps understanding:
   1) how the binary content evolves over time;
   2) the expected number of binary interaction products.



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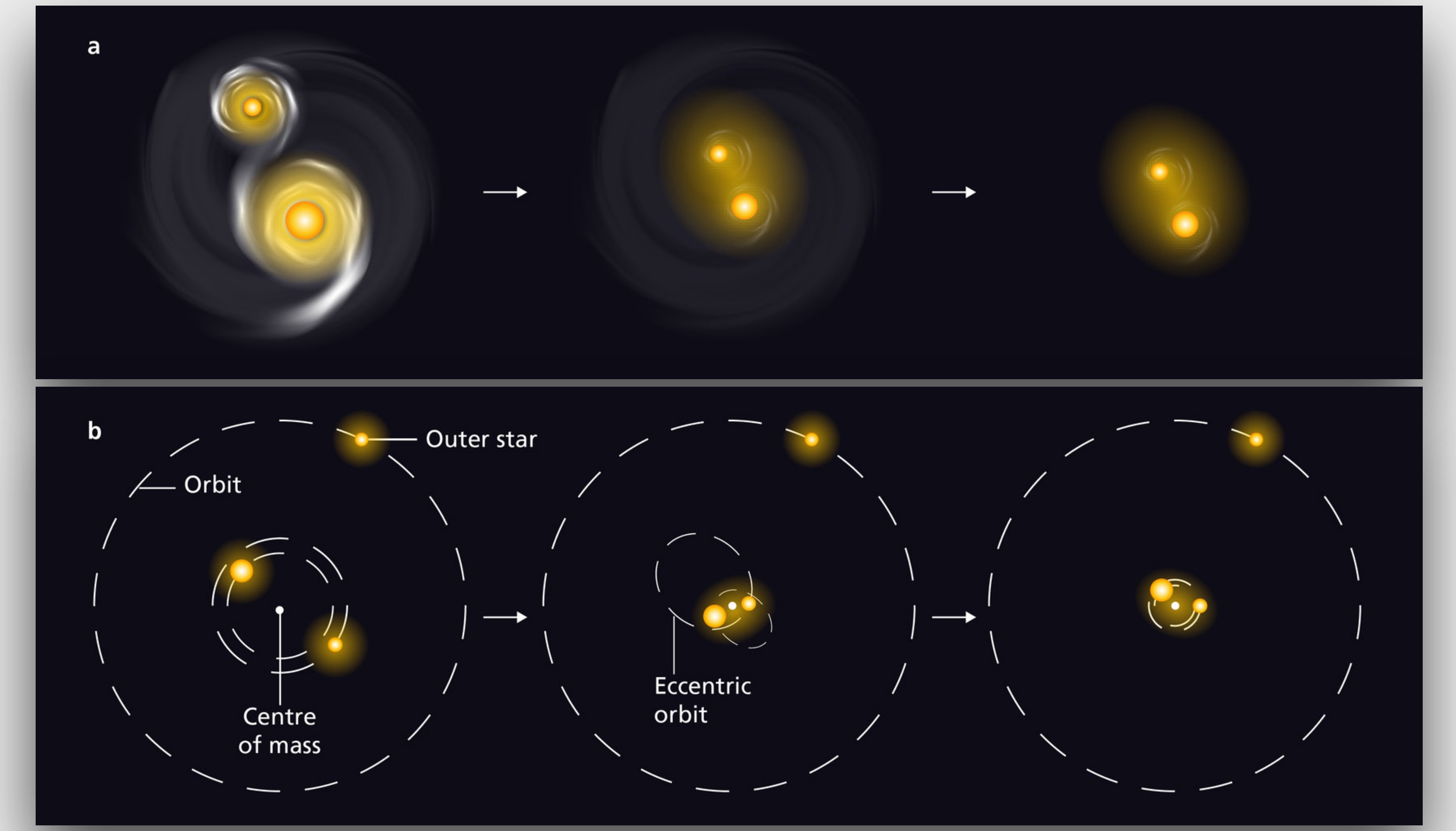

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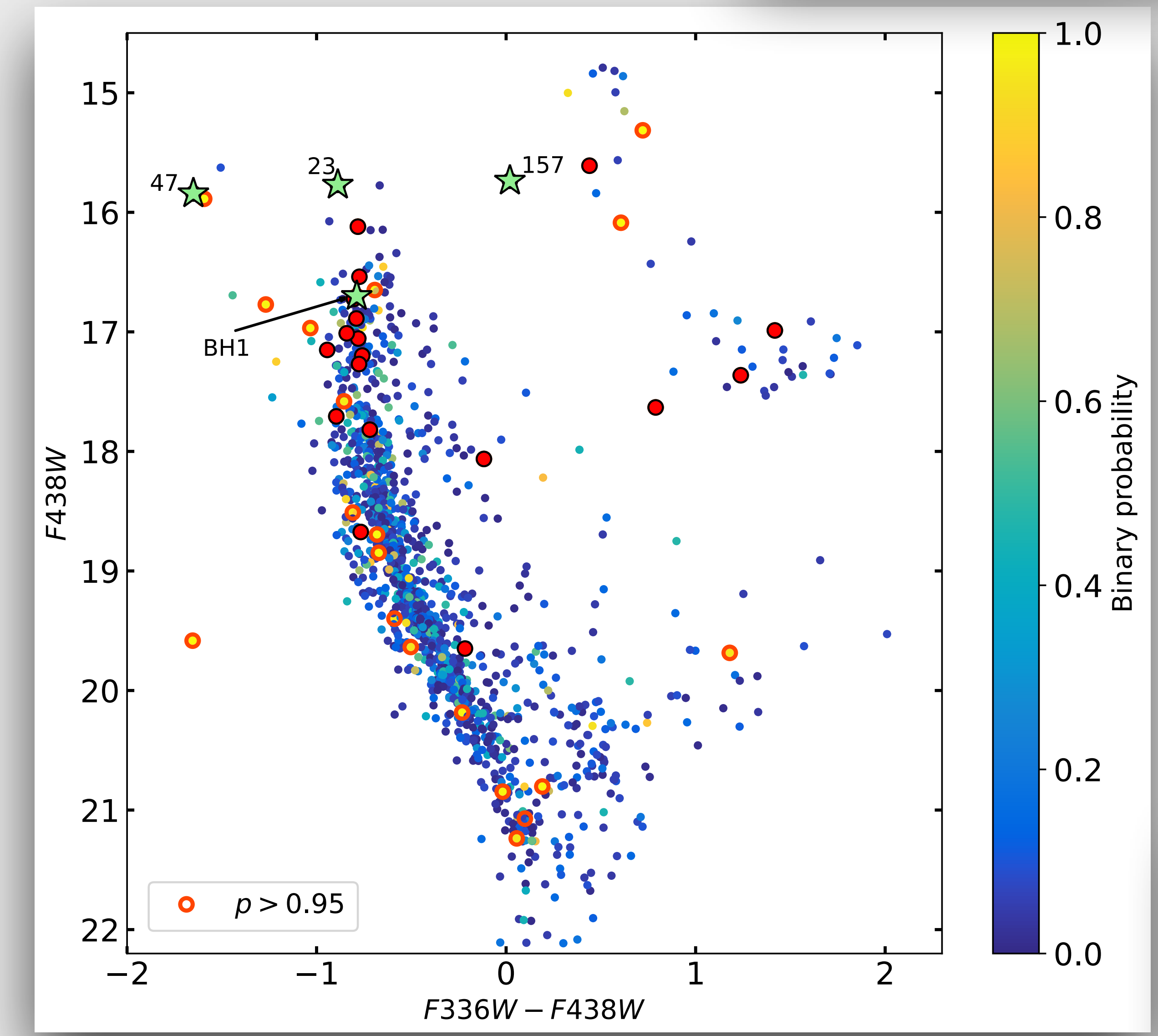

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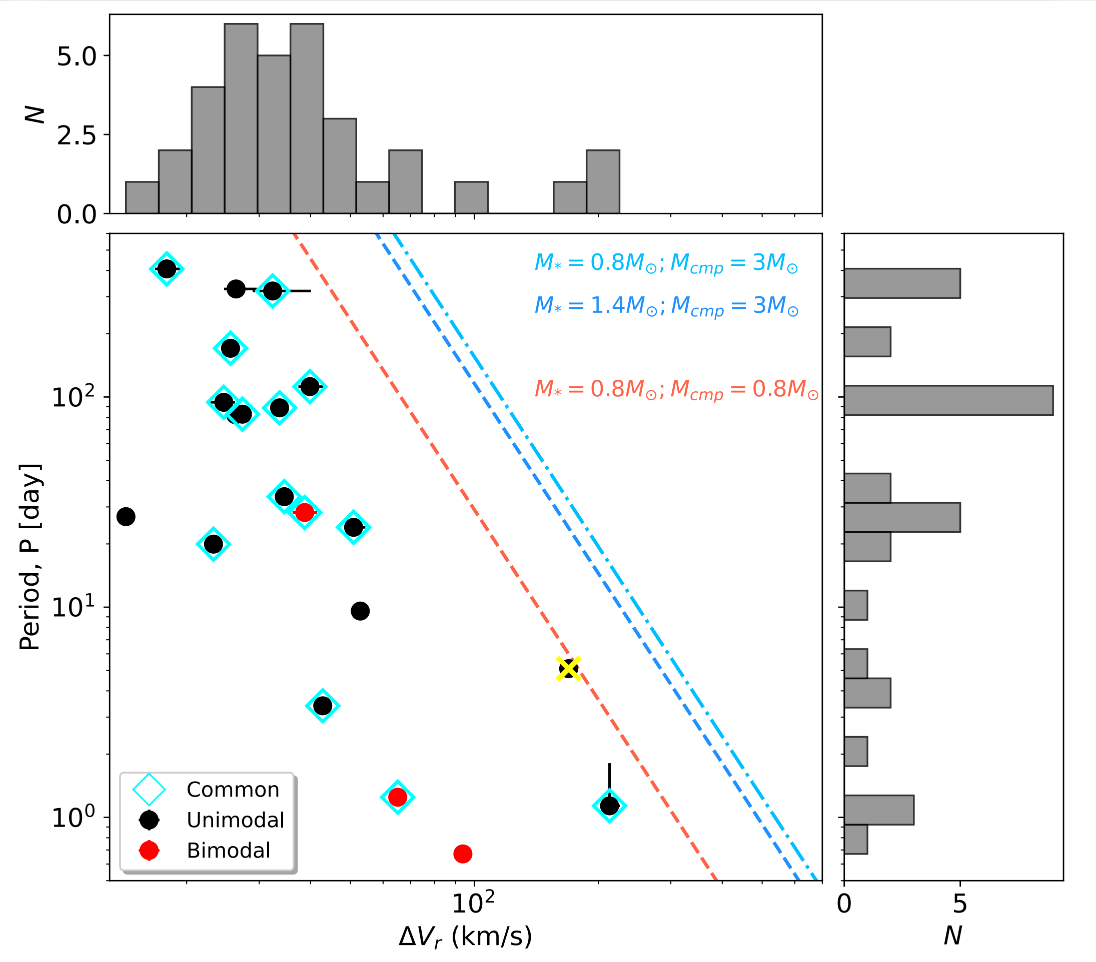
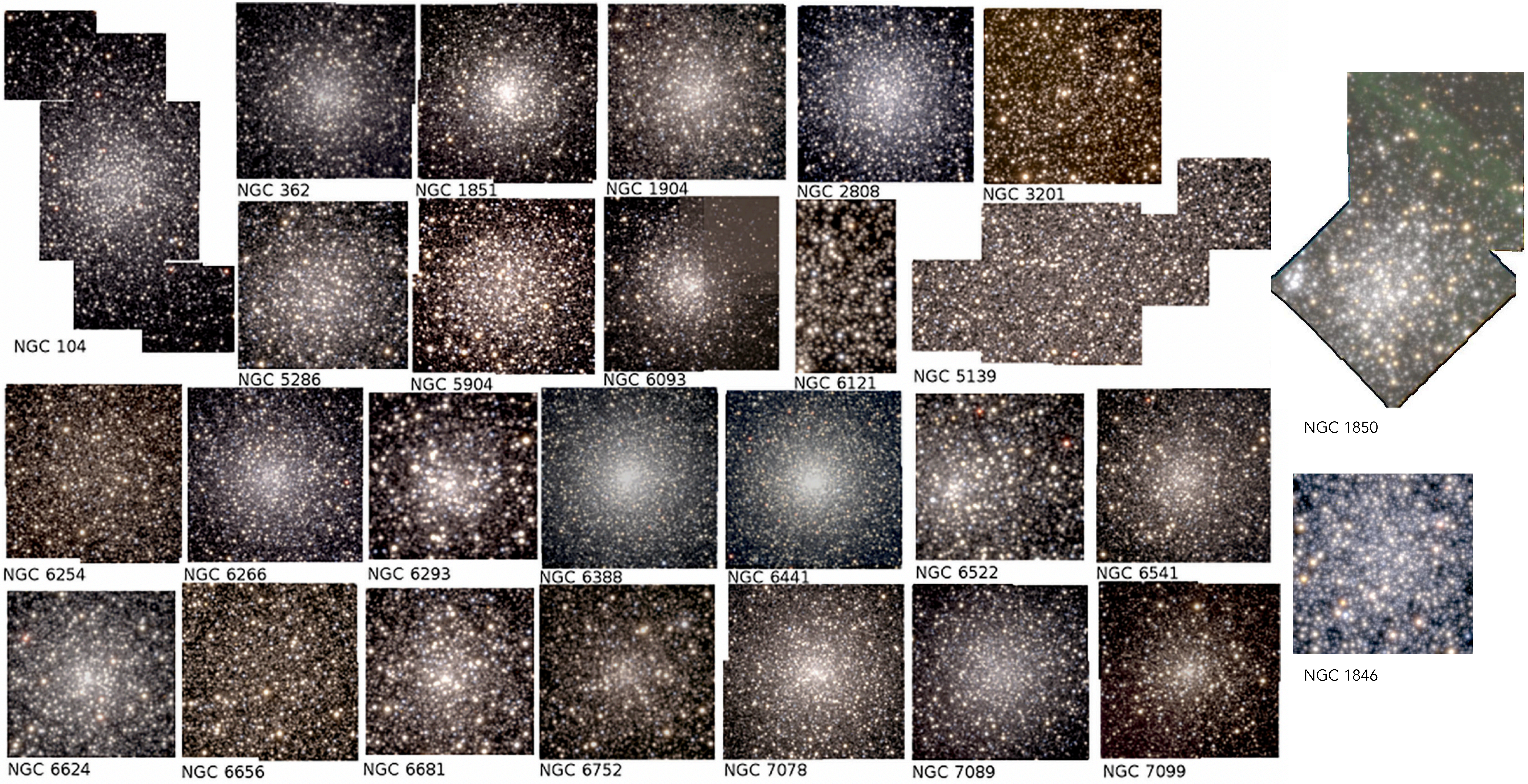


3. The investigation of NGC 1850 and ω Centauri consolidates the path for studying stellar and binary evolution in clusters but a detailed comparison with simulations is needed.

An ideal dataset of **massive star clusters** to play with..

Spectroscopy (VLT/MUSE) + UV/Optical Photometry (HST)

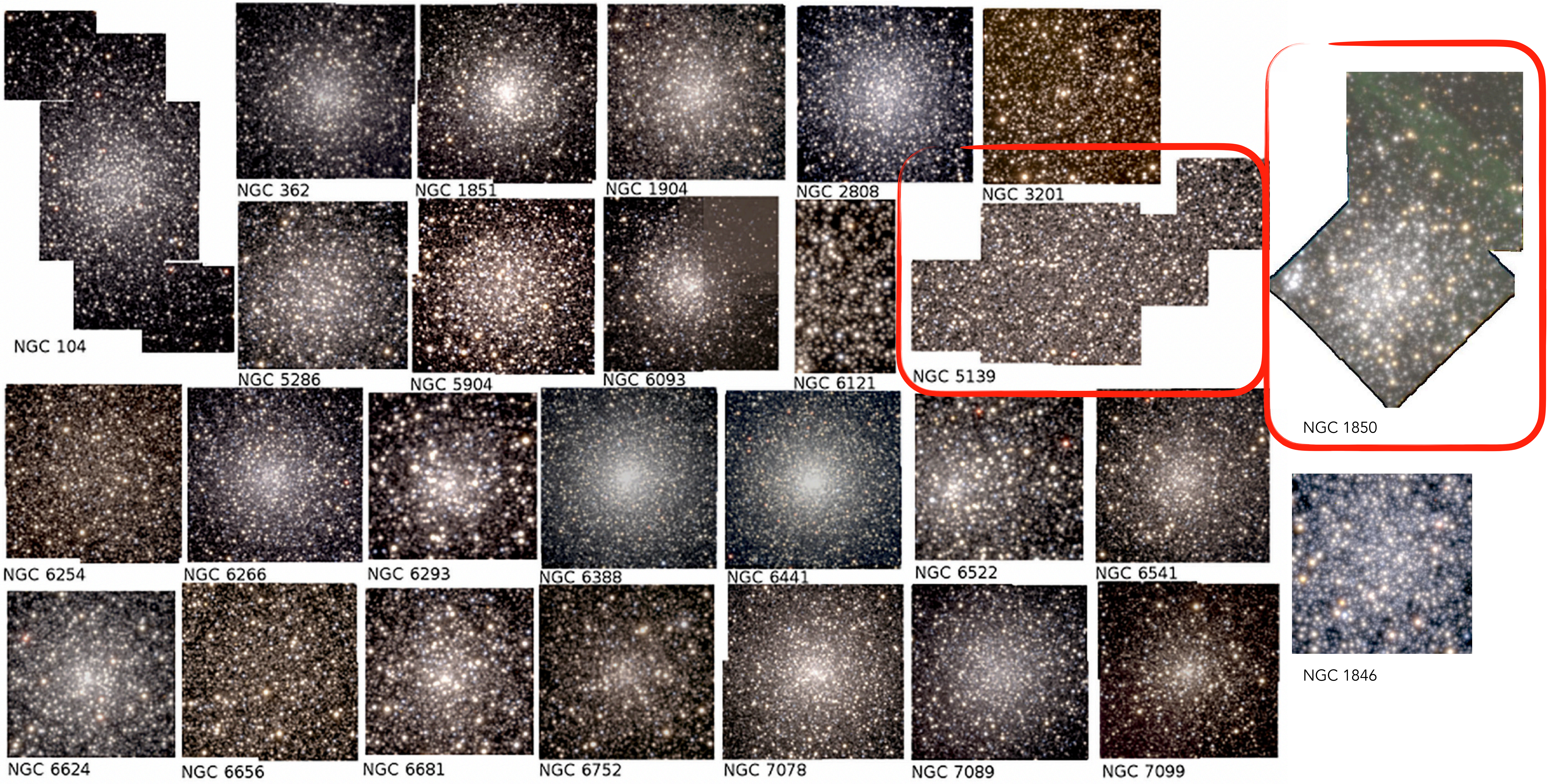


A collection of **young** (< 1 Gyr), **intermediate** (2-6 Gyr) and **old** (~12/13 Gyr) clusters in both the Milky Way and the Magellanic Clouds.

Kamann+2018; Saracino+2022; Kamann, SS +2023; etc.

An ideal dataset of **massive star clusters** to play with..

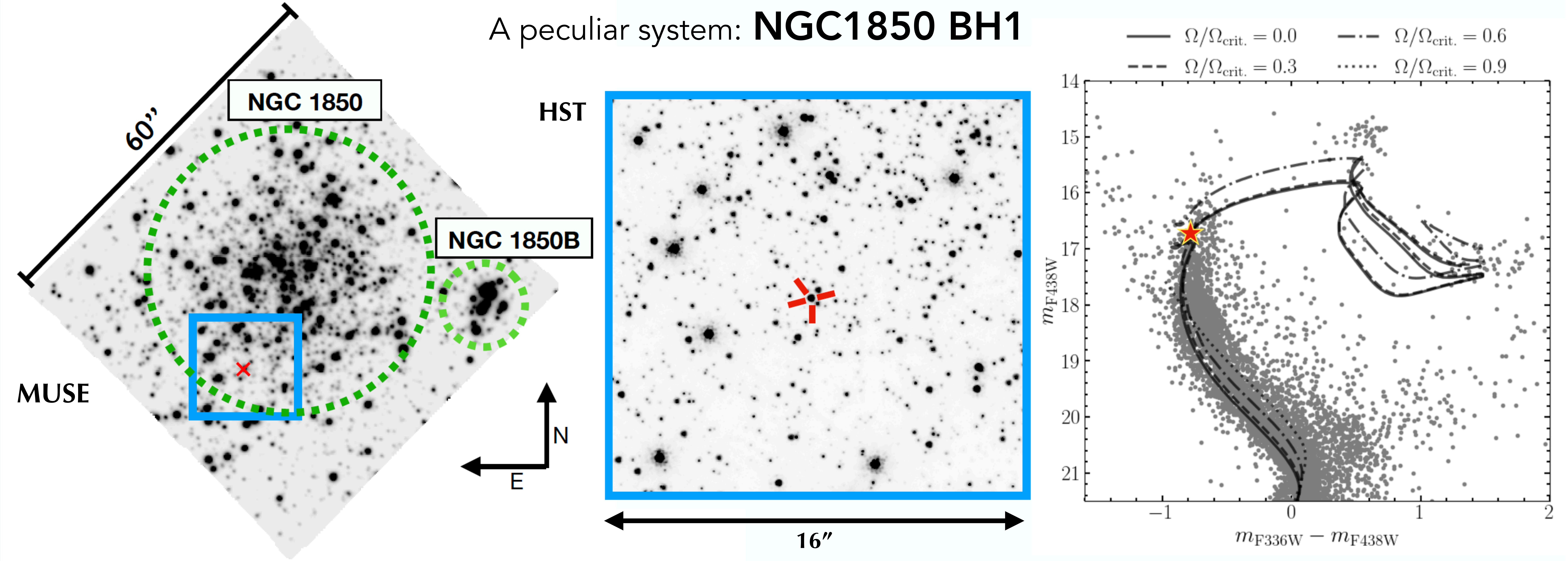
Spectroscopy (VLT/MUSE) + UV/Optical Photometry (HST)



A collection of **young** (< 1 Gyr), **intermediate** (2-6 Gyr) and **old** (~12/13 Gyr) clusters in both the Milky Way and the Magellanic Clouds.

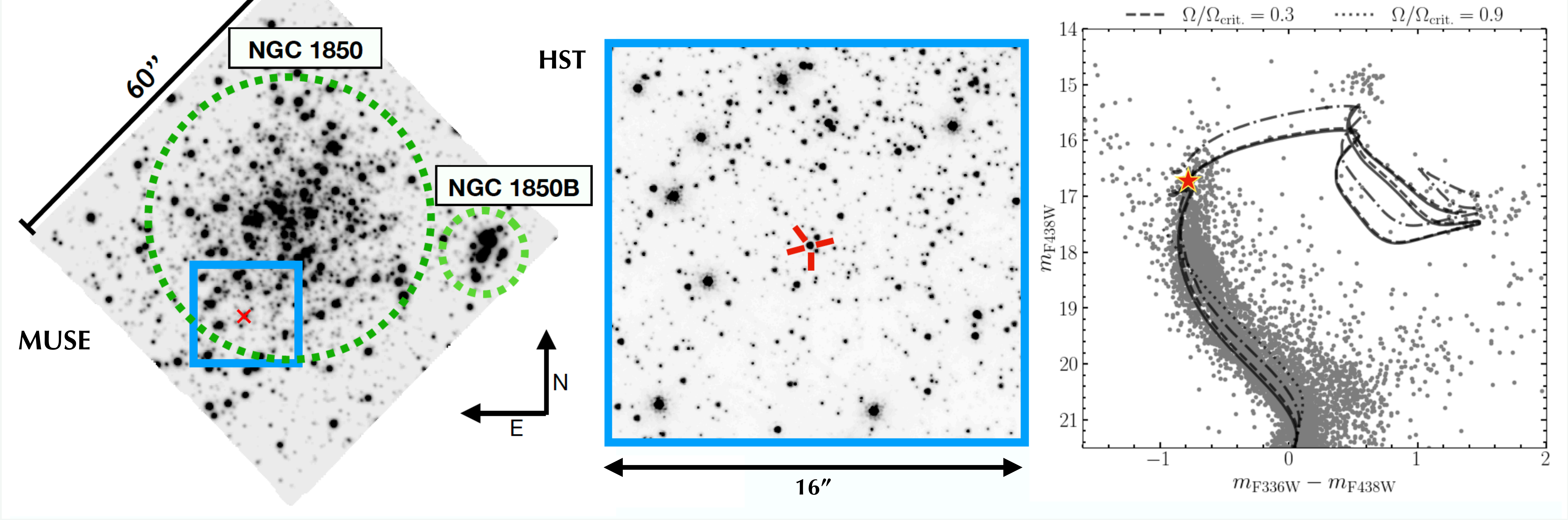
Kamann+2018; Saracino+2022; Kamann, SS +2023; etc.

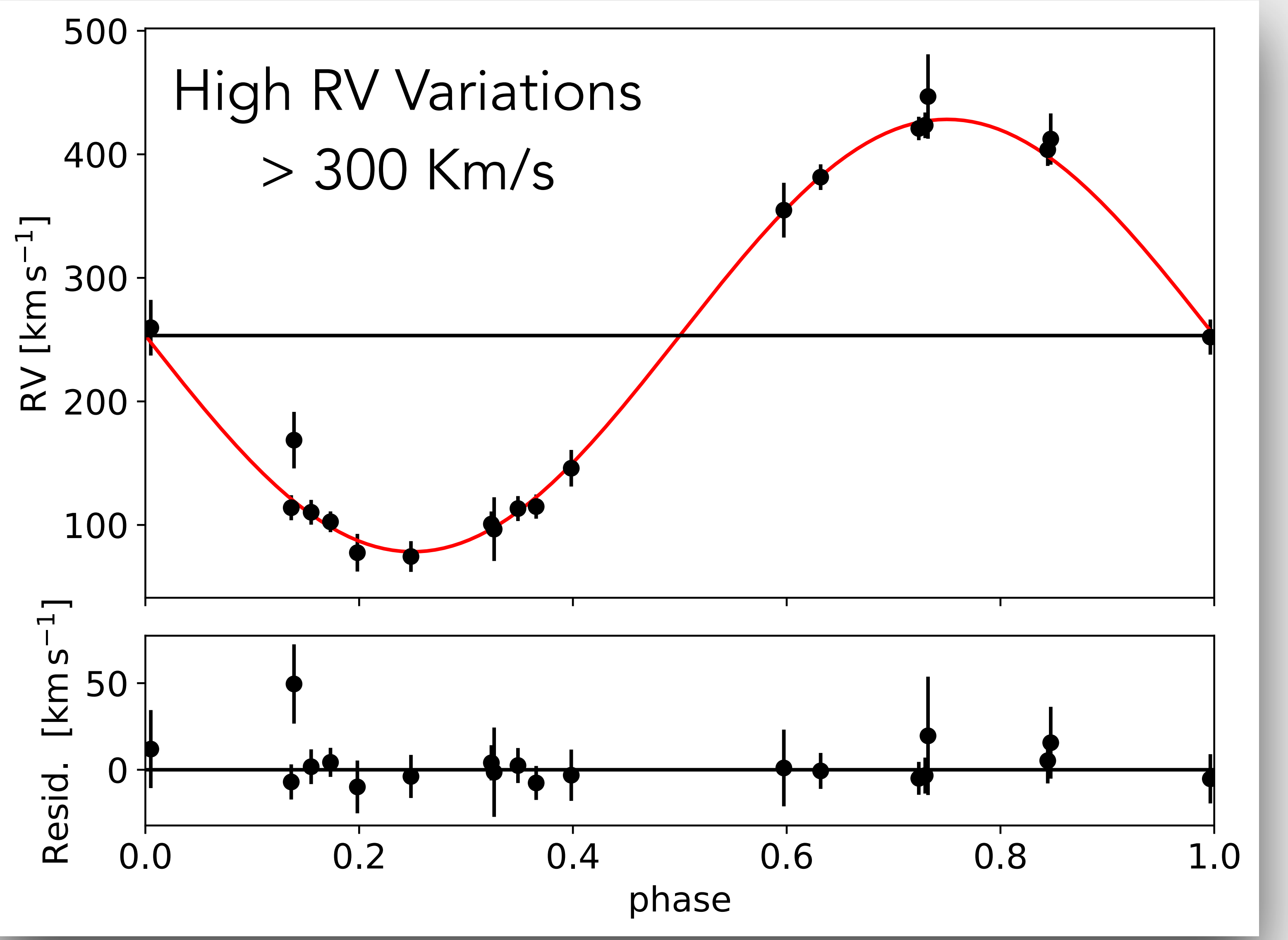
A peculiar system: **NGC1850 BH1**



Saracino+2022; +2023a; El Badry & Burdge+2022; Stevance+2022

A peculiar system: **NGC1850 BH1**





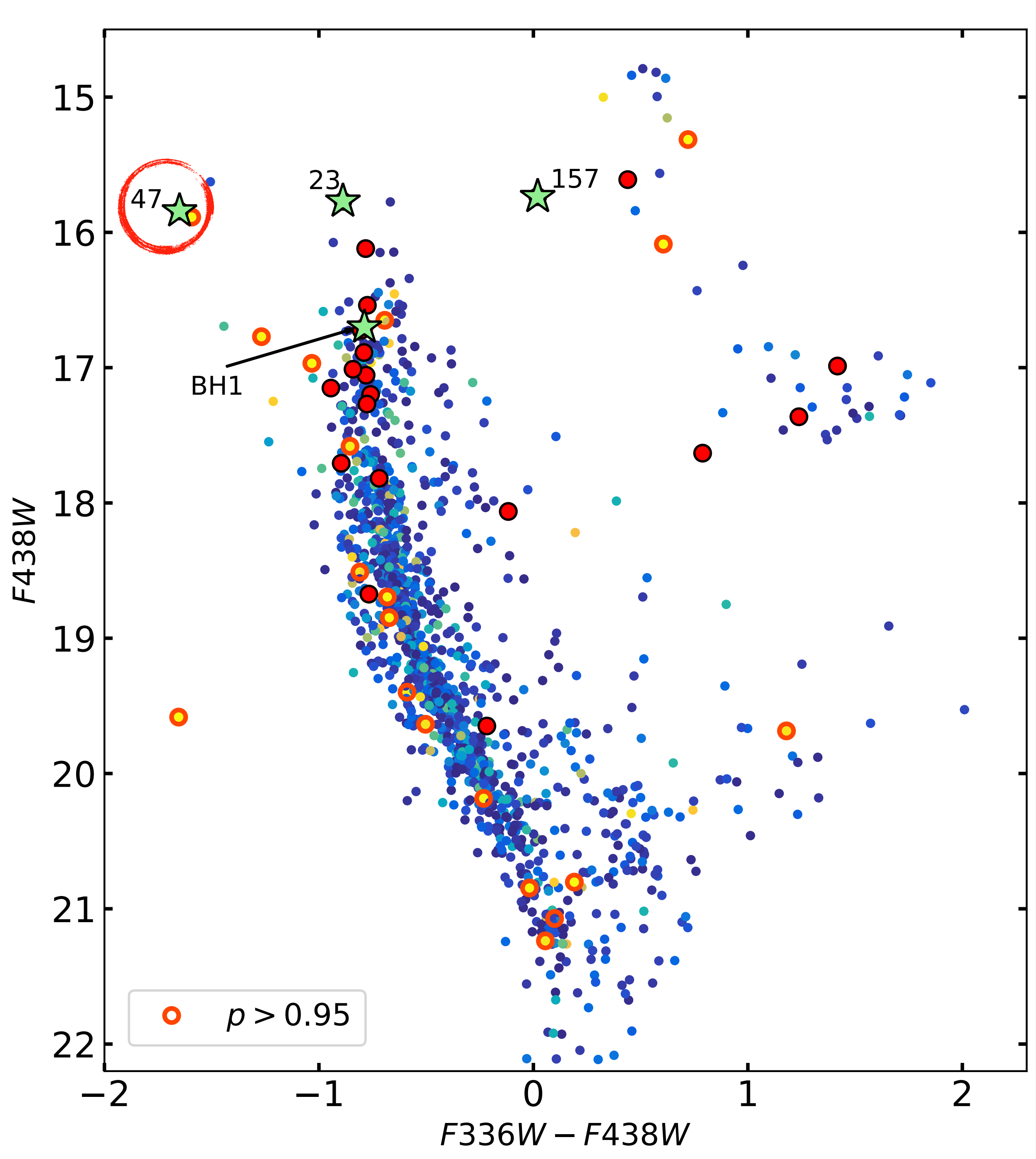
PROPERTIES:

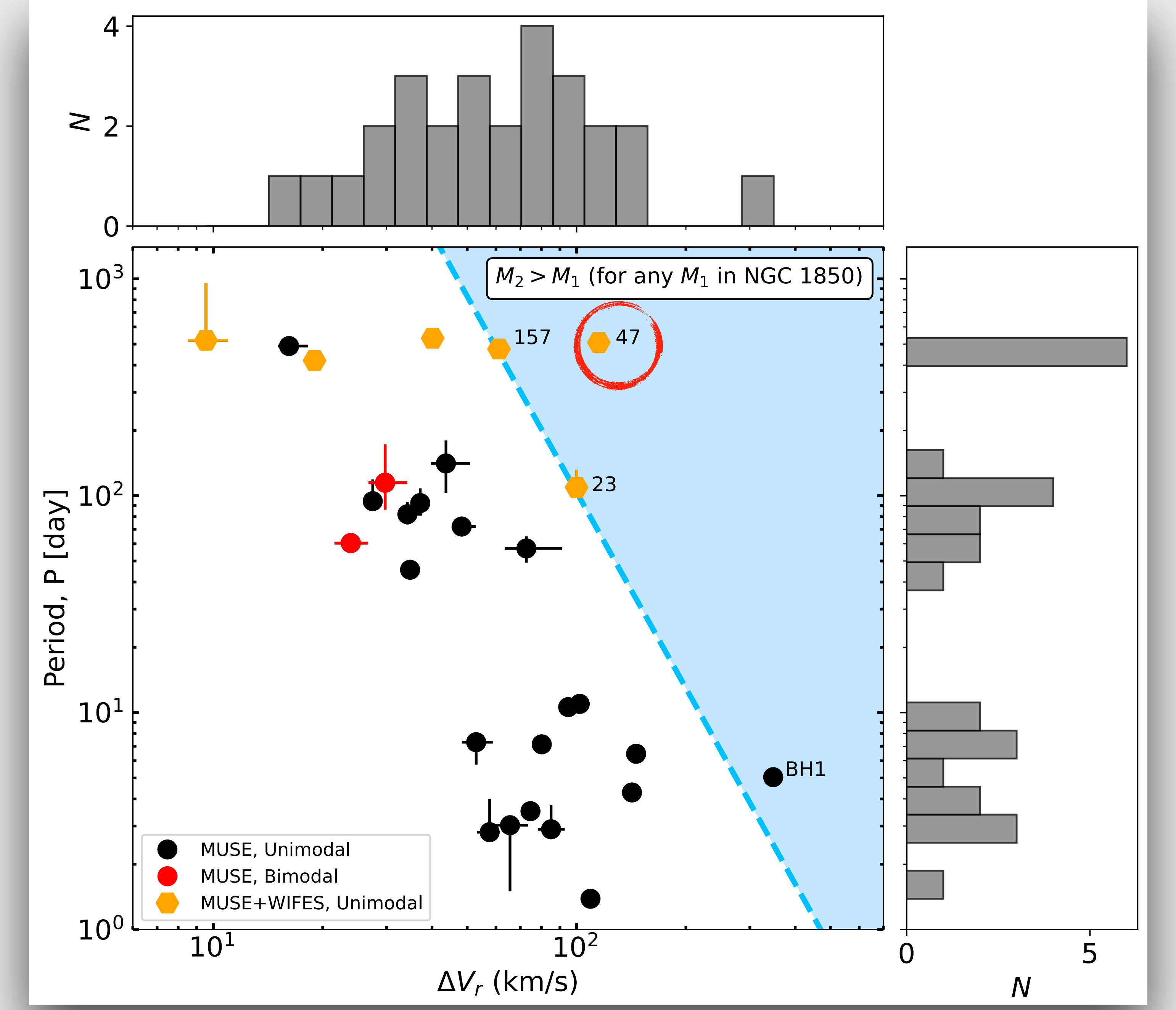
- P = 5.04 d, almost circular orbit;
- ellipsoidal variable, no eclipses;
- Mass function f(M) = 2.83 M⊙;

- M2: Low-mass stripped star (1-2 M⊙);
- M1 is more massive than 4.7 M⊙.

Saracino+2022; +2023a; El Badry & Burdge+2022; Stevance+2022

Star #47:
another
peculiar binary

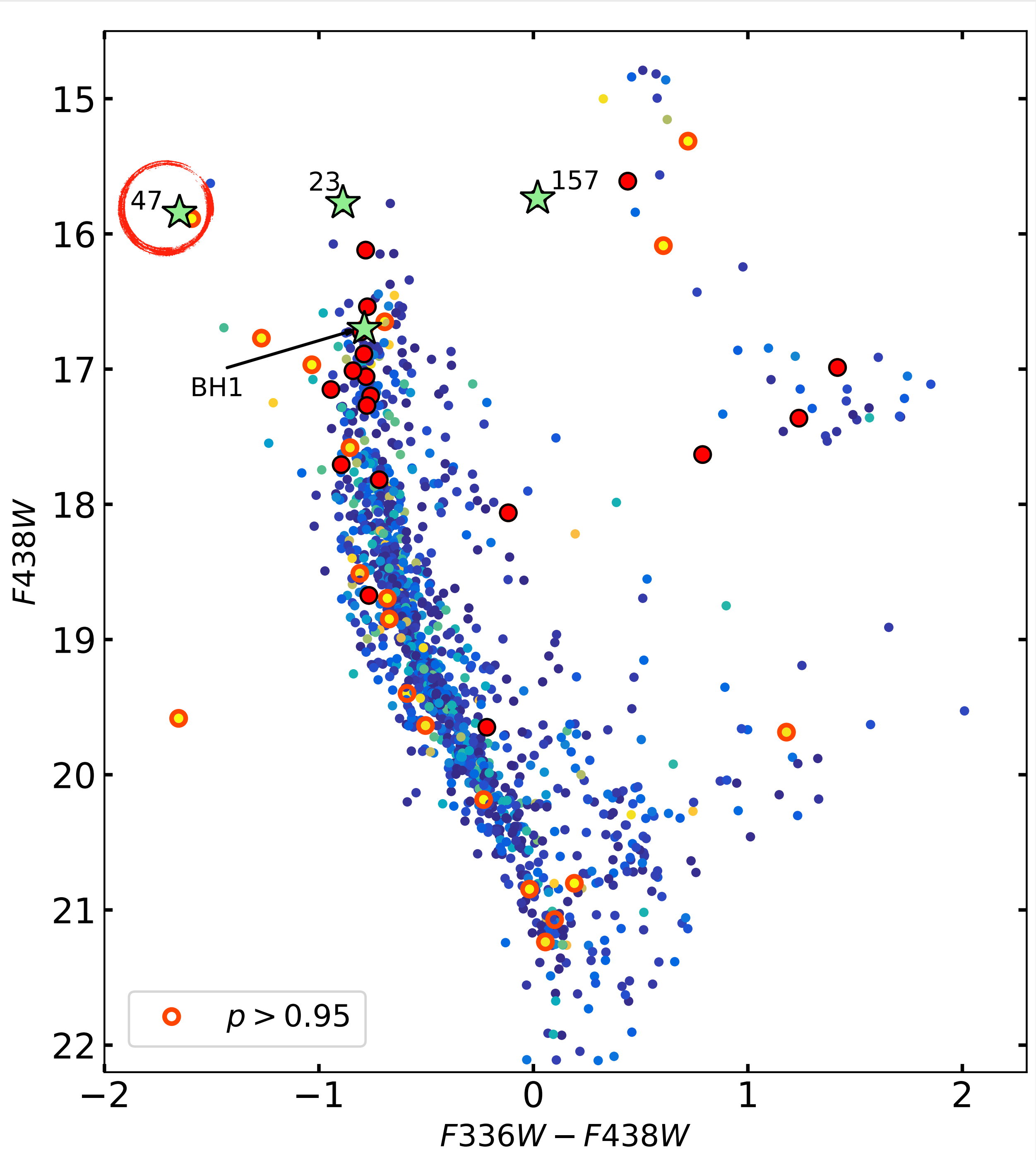


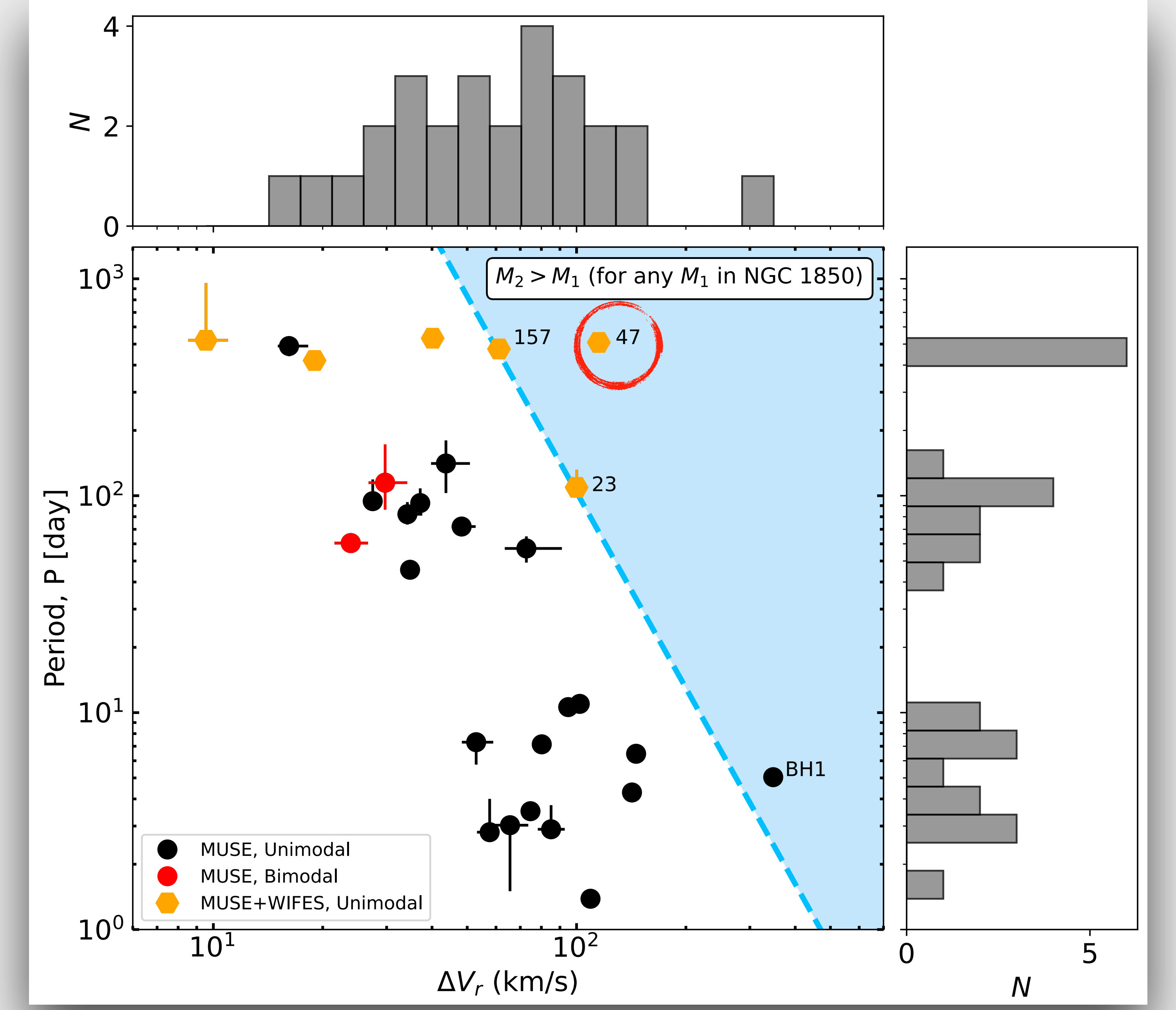


- Located in the blue straggler region
- NGC 1850 member, within its half-light radius

Saracino+2023b

Star #47: another peculiar binary

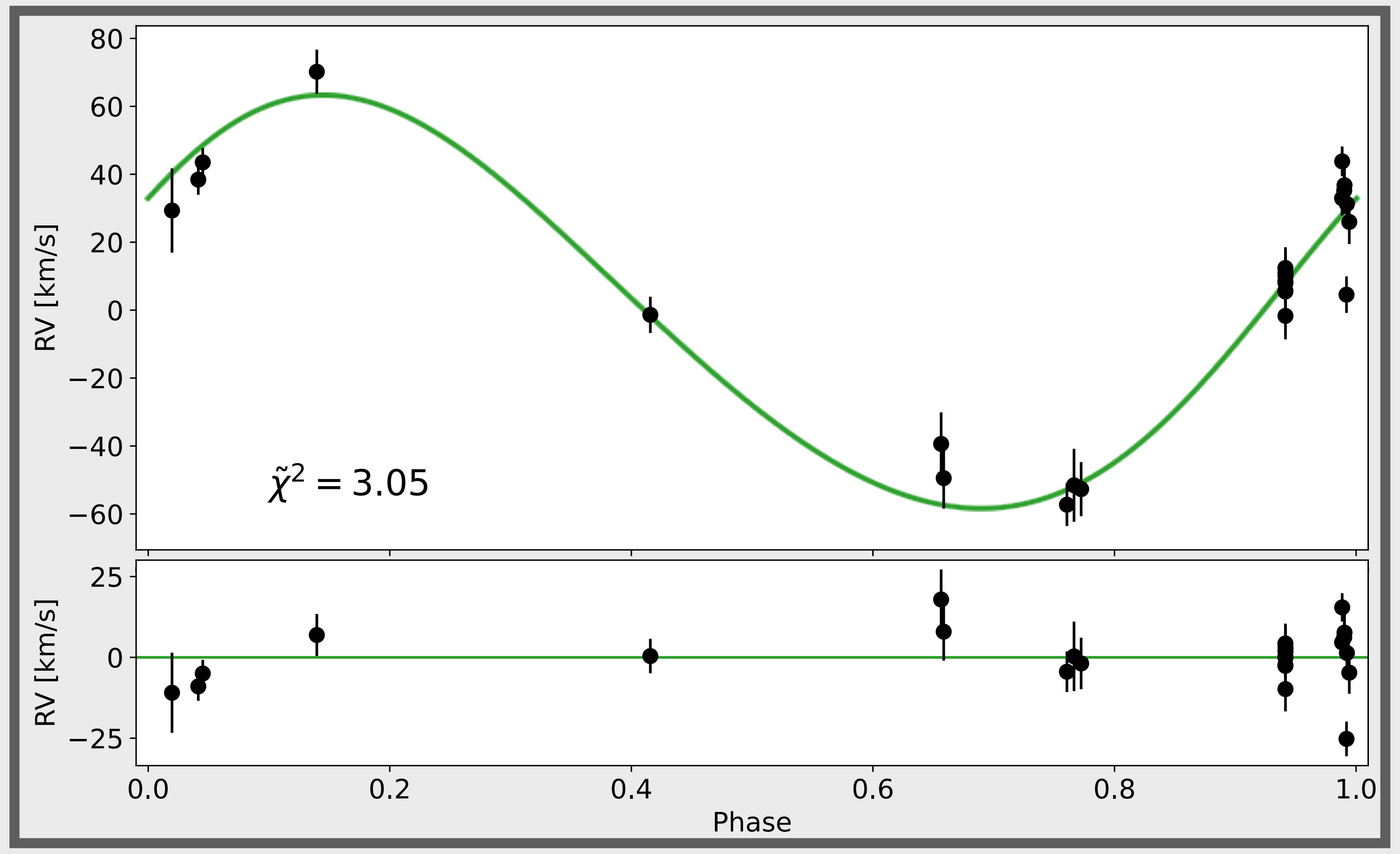




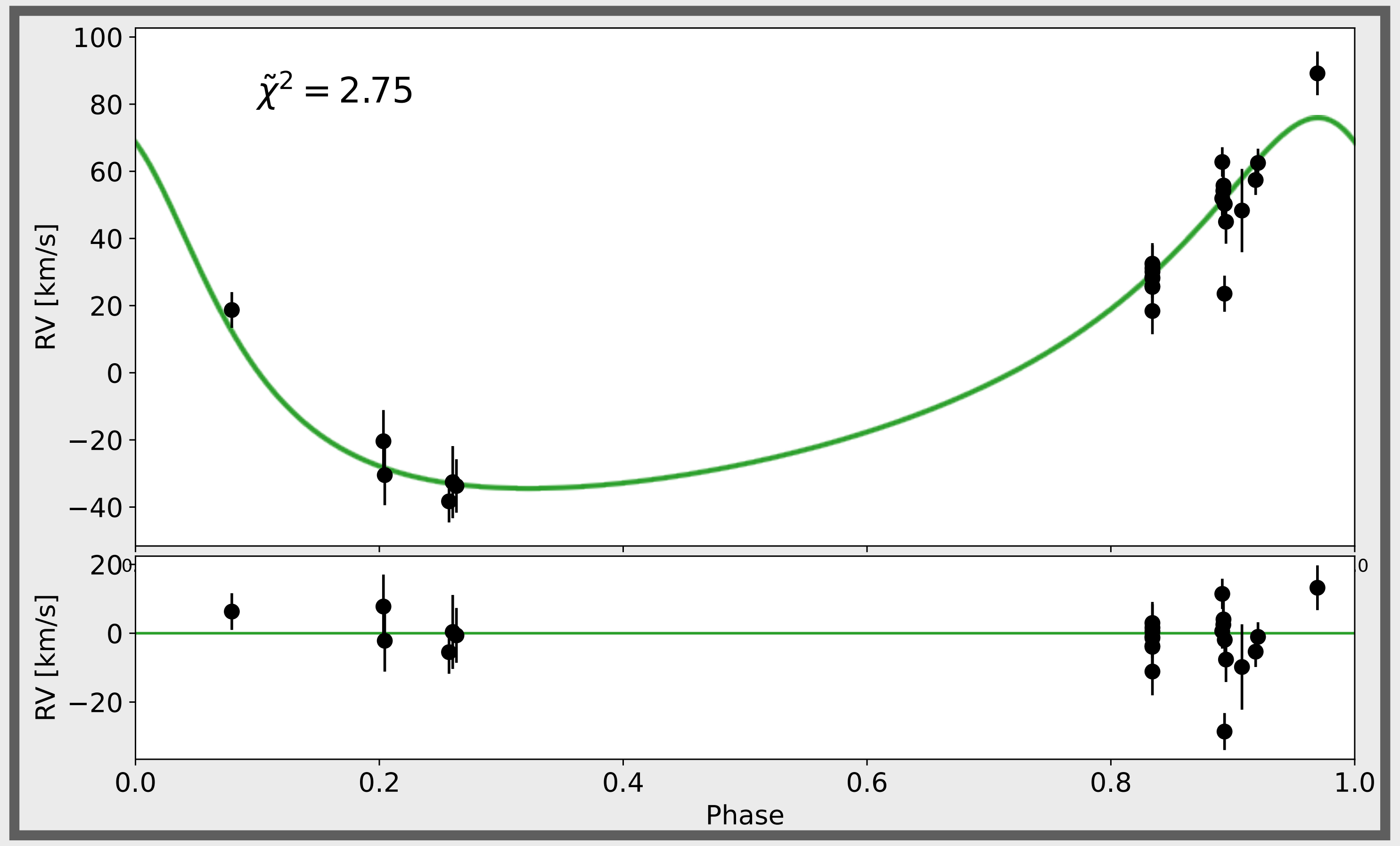
- Located in the blue straggler region
- NGC 1850 member, within its half-light radius

Saracino+2023b

Long-period binary, with two possible orbital solutions:



P ~ 505 d
e ~ 0.05
f(M) ~ **10.5** $M_\odot$



P ~ 980 d
e ~ 0.5
f(M) ~ **14.5** $M_\odot$

Given f(M), if the visible star has no mass (M2=0), the unseen object has M > 10 $M_\odot$.