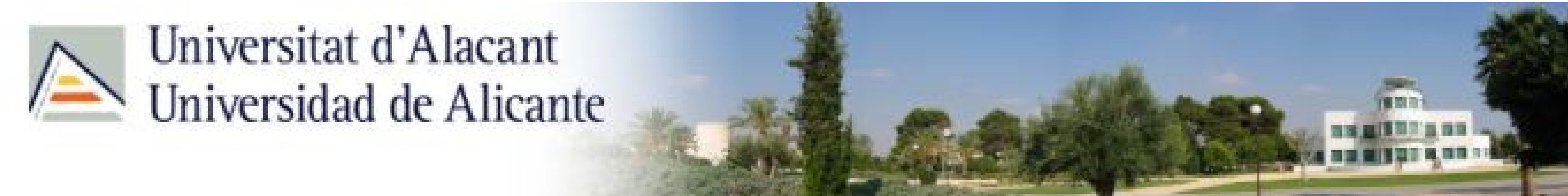
Young clusters in the *Gaia* era

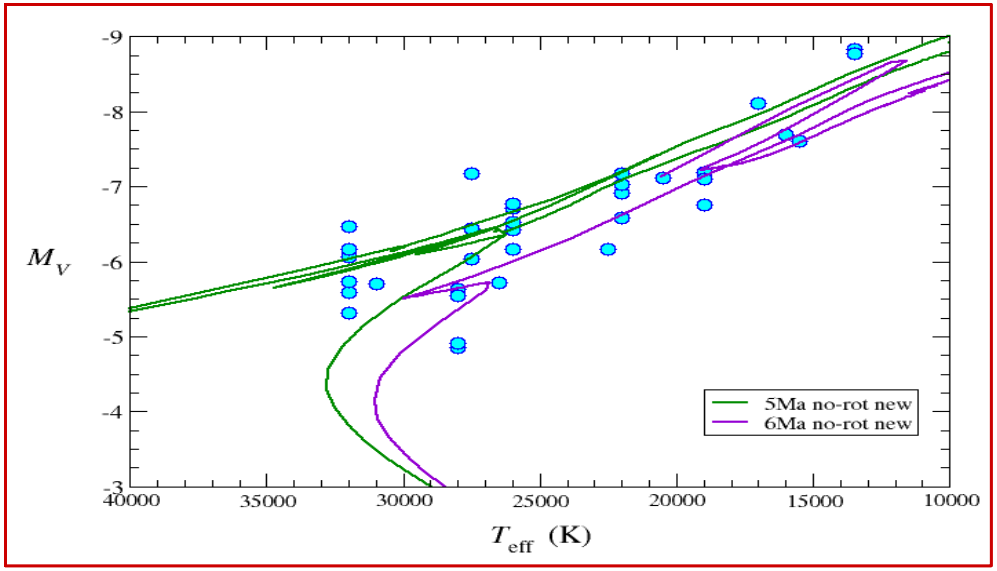
Ignacio Negueruela

Barcelona, February 2020



Westerlund 1 is the most massive young open cluster so far known in the Milky Way.

- At least 150 evolved massive ($M > 30\ \mathrm{M}_\odot$) stars observed imply $M \approx 10^5 \mathrm{M}_\odot$ (**Clark+ 2005**)



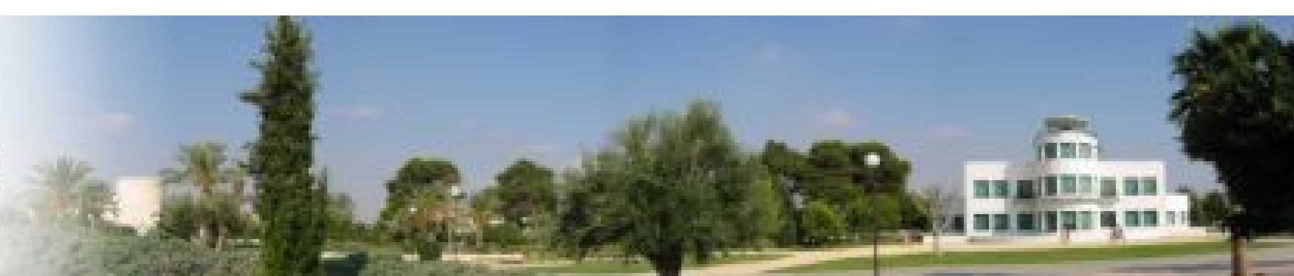
Negueruela+ 2010

- Age $\gtrsim 5$ Ma
- $d \sim 6$ kpc
- $A_V \approx 12$

- Javier Alonso-Santiago (INAF-Catania)
- Berto Castro (AIP Potsdam)
- J. Simon Clark (OU)
- Ricardo Dorda (IAC)
- Carlos González-Fernández (Cambridge)
- Marcus Lohr (OU)
- Amparo Marco (Alicante)
- Hugo Tabernero (IA Porto)

Barcelona, February 2020

Universitat d'Alacant
Universidad de Alicante



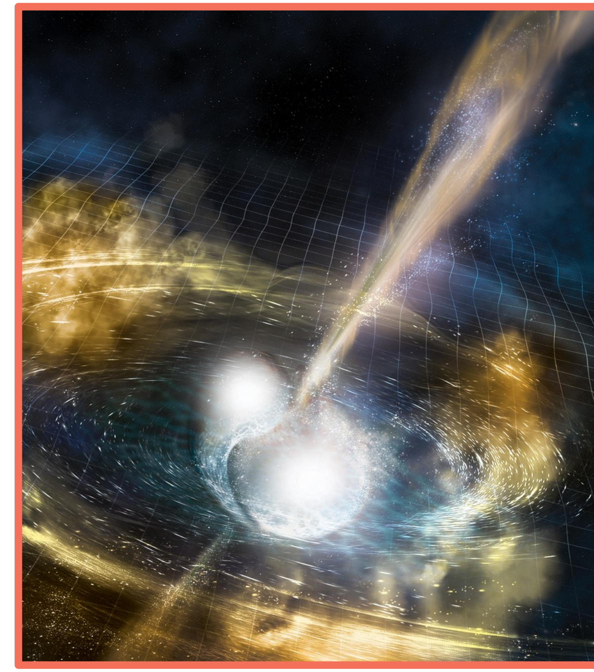
Outline

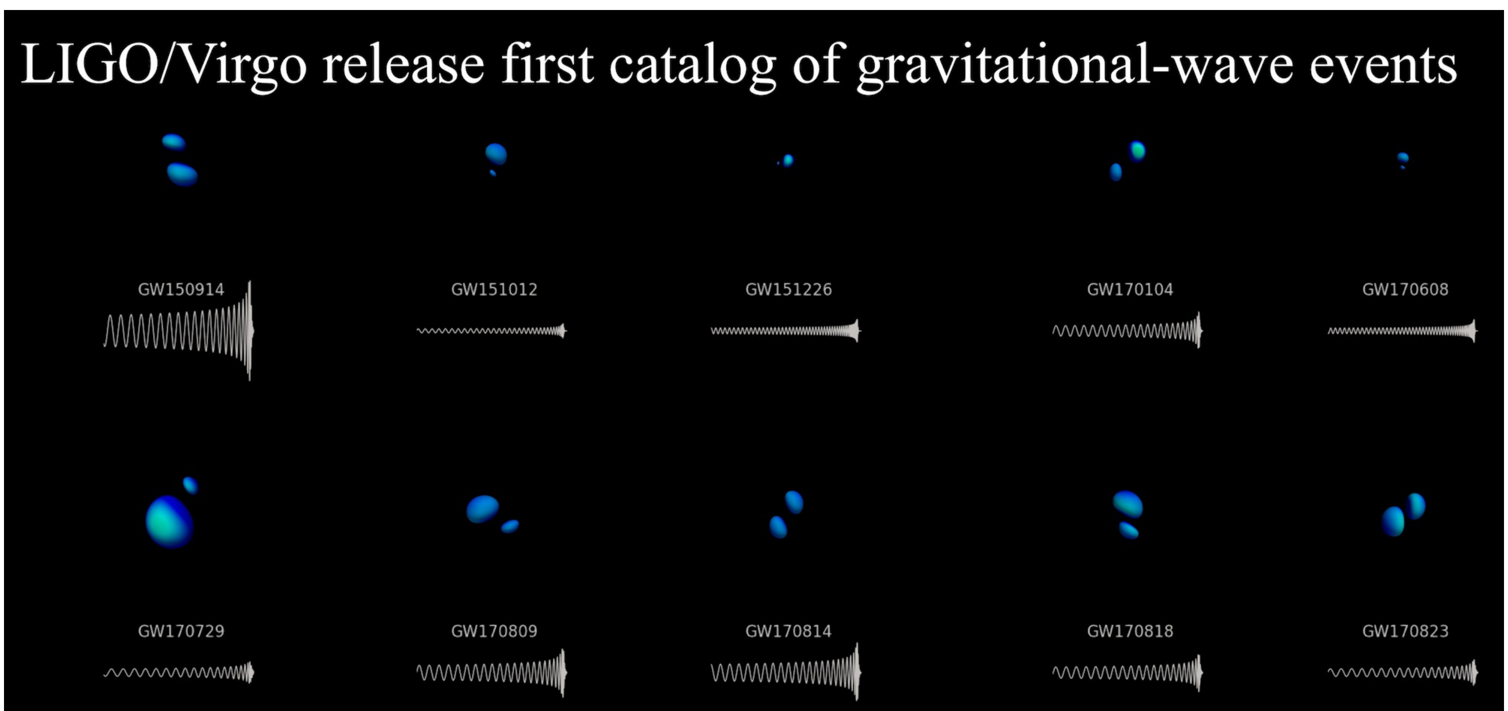
- Age of discovery
- Stellar evolution with *Gaia* : evidence for binary evolution
- Stellar evolution with *Gaia* : constraints on Cepheid evolution

An age of discovery

Gravitational waves @ LIGO, Virgo

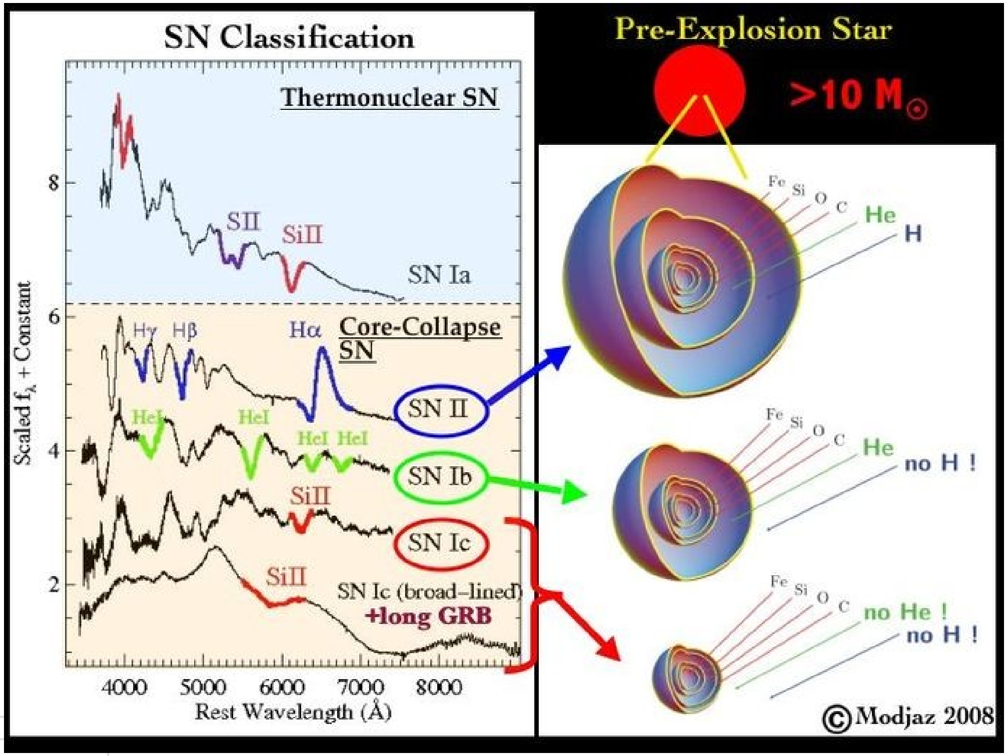
- GW150914 36 $M_\odot$ + 29 $M_\odot$
- GW170817 NS + NS? Hypernova
  S190425z, S190901ap
- S190814bv, S190910d (BH + NS)
- GW170729 50.6 $M_\odot$ + 34.3 $M_\odot$
- 45+ candidates in current run

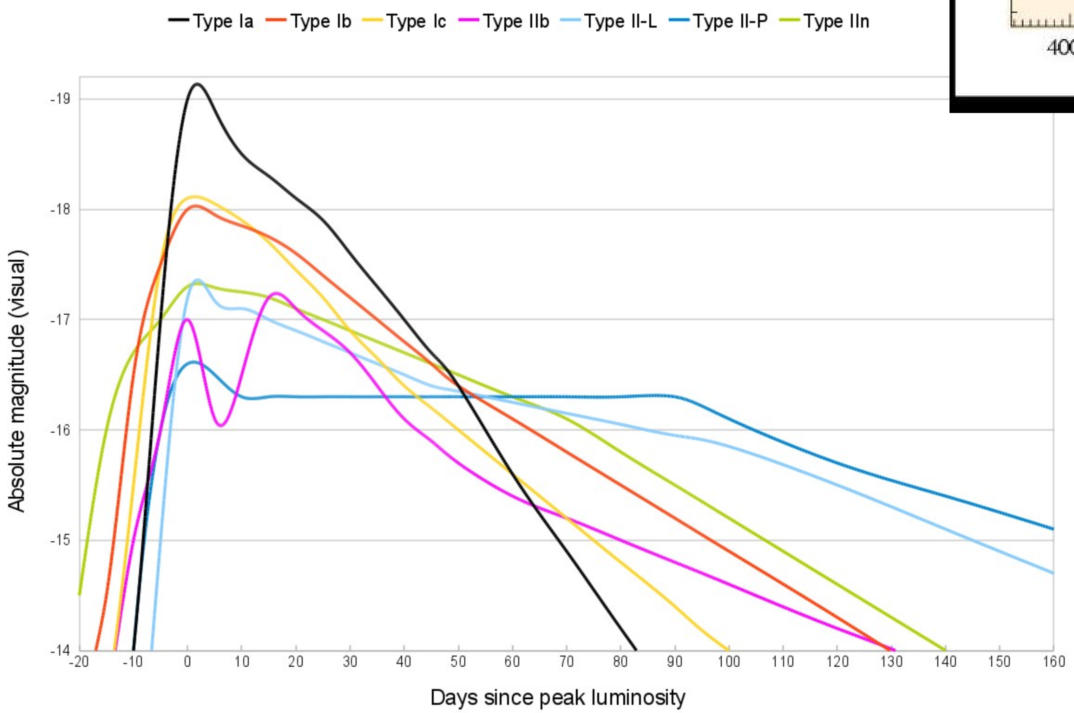


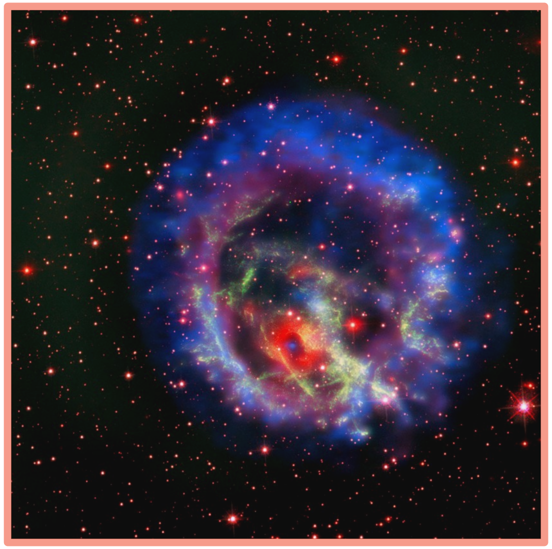


Age of discovery

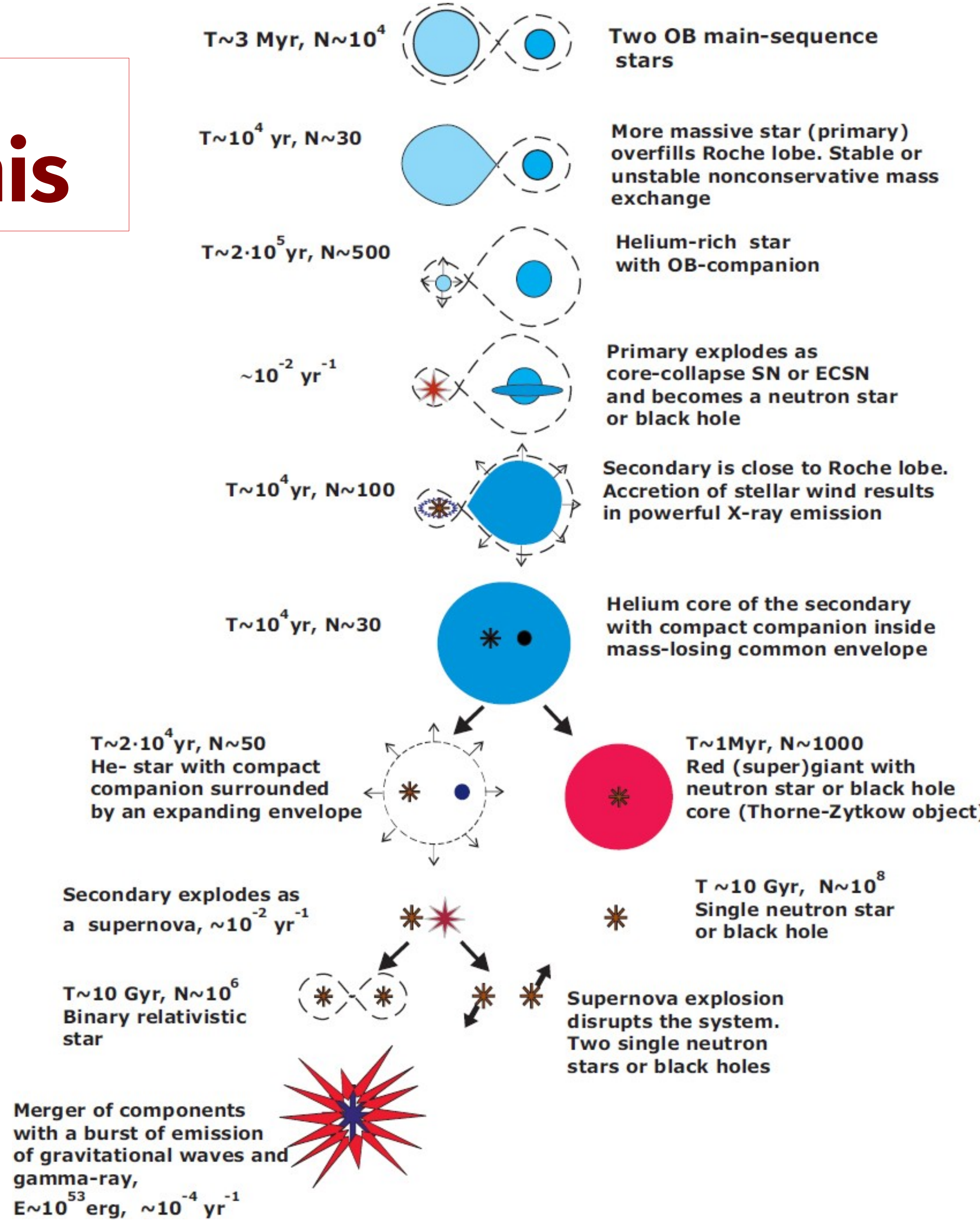
- Searches for supernovae in the local Universe:
  - Images (surveys + archival)
  - Spectra
  - ASASSN, Lick, PTF – ZTF, PESSTO, ePESSTO
- Searches for their progenitors







We understand this



Postnov & Yungelson (2014; LRR 17,3)

Do we?

- Population synthesis models have serious trouble accommodating so many NS + NS detections.

- The observed rate of BH + BH mergers can only be achieved by choosing rather extreme parameters
  Mapelli & Giaccobo 2018 (MNRAS 479, 4391)

- Fine tuning needed to explain NS + NS and BH + BH events may not be compatible
  Chruslinska+ 2018 (MNRAS 474, 2937)

- Only known Be + BH system hardly compatible with models
  Grudzinska+ 2015 (MNRAS 452, 2773)

- All the BHs we know have masses between 5 and 15 $M_\odot$, while merging BHs have masses around 30 $M_\odot$ or higher (bias?).

Is reality too complex?

- **Uncertainties in the evolution of massive stars**

Mass loss, broadened main sequence, eruptions, internal physics, transport of processed material to the surface, the role of binarity, etc.

- **Uncertainties in interaction processes in binaries**

Mass and angular moment transfer, rejuvenation processes, common envelope, etc.

- **Uncertainties in initial parameters**

Initial mass function, initial binary fraction, dependence on metallicity, mass ratio distribution, initial orbital parameters, etc.

Laboratories for massive star evolution: High-mass stars in their native environment

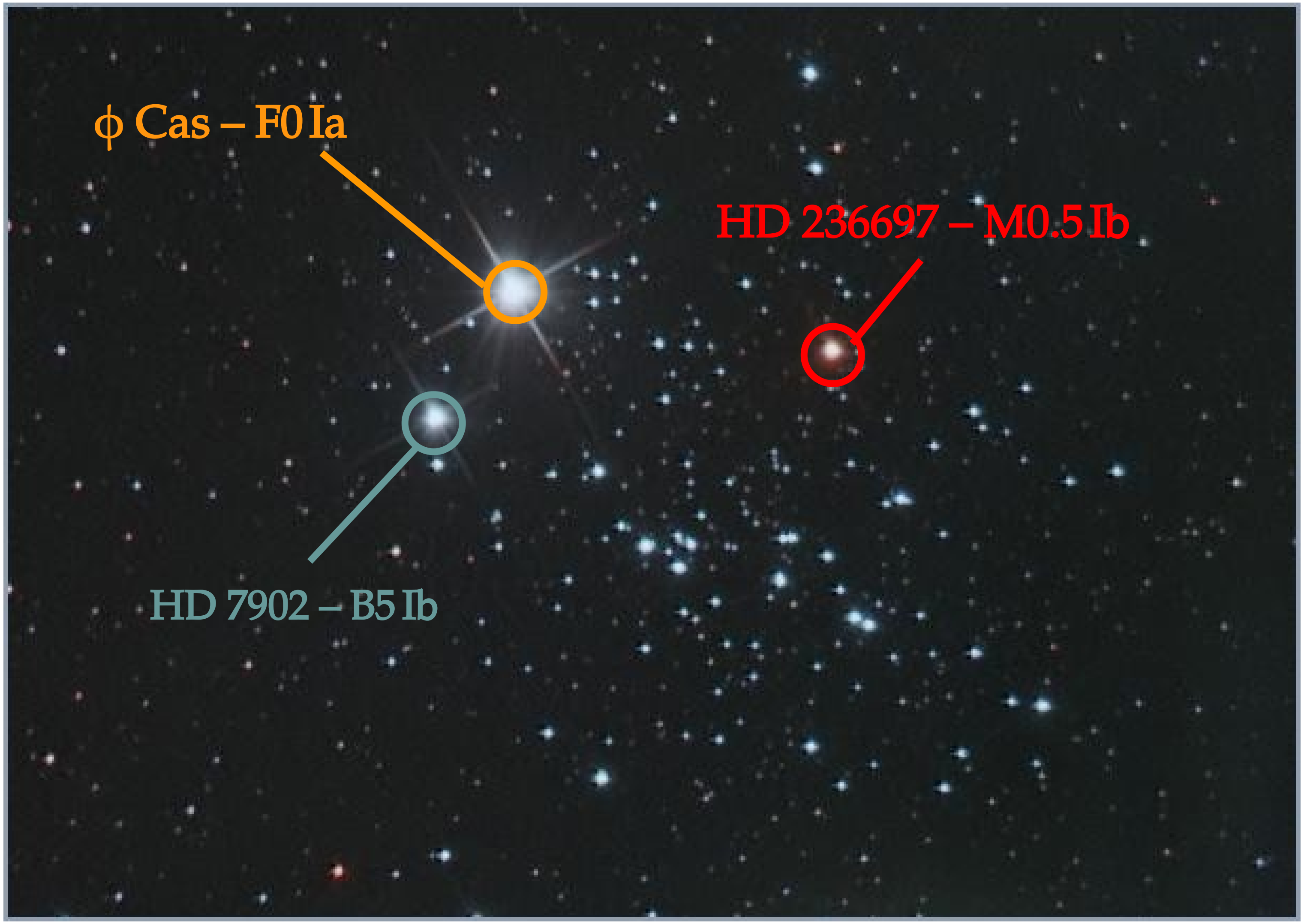
- High-mass stars are born in clusters
- Clusters give us astrophysical context (distance, age, extinction, ...)
- Astrophysical laboratories for:
    - Star formation
    - Stellar evolution

NGC 457

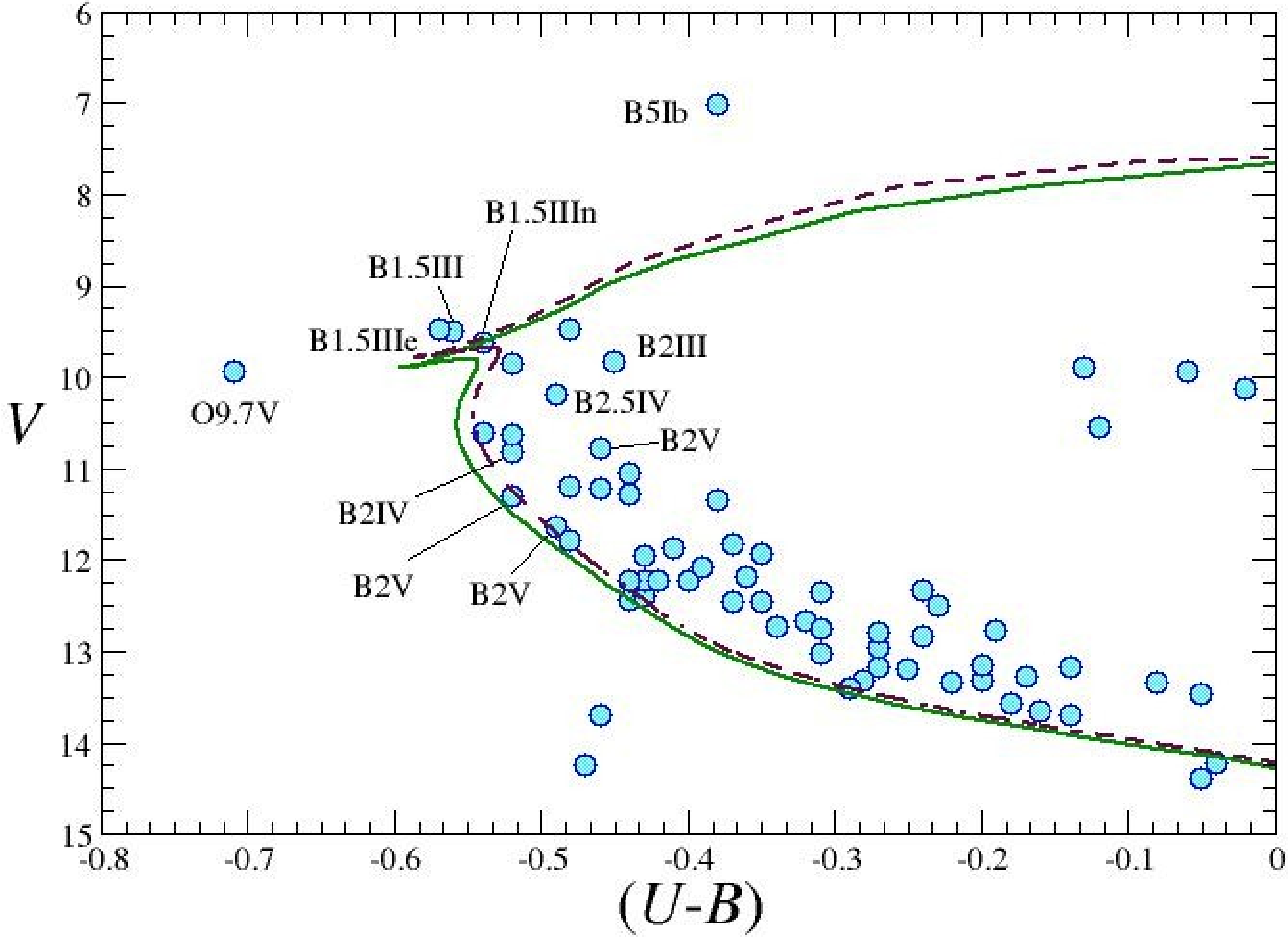
Typical cluster in the Perseus arm

NGC 457

Typical cluster in the Perseus arm



NGC 457

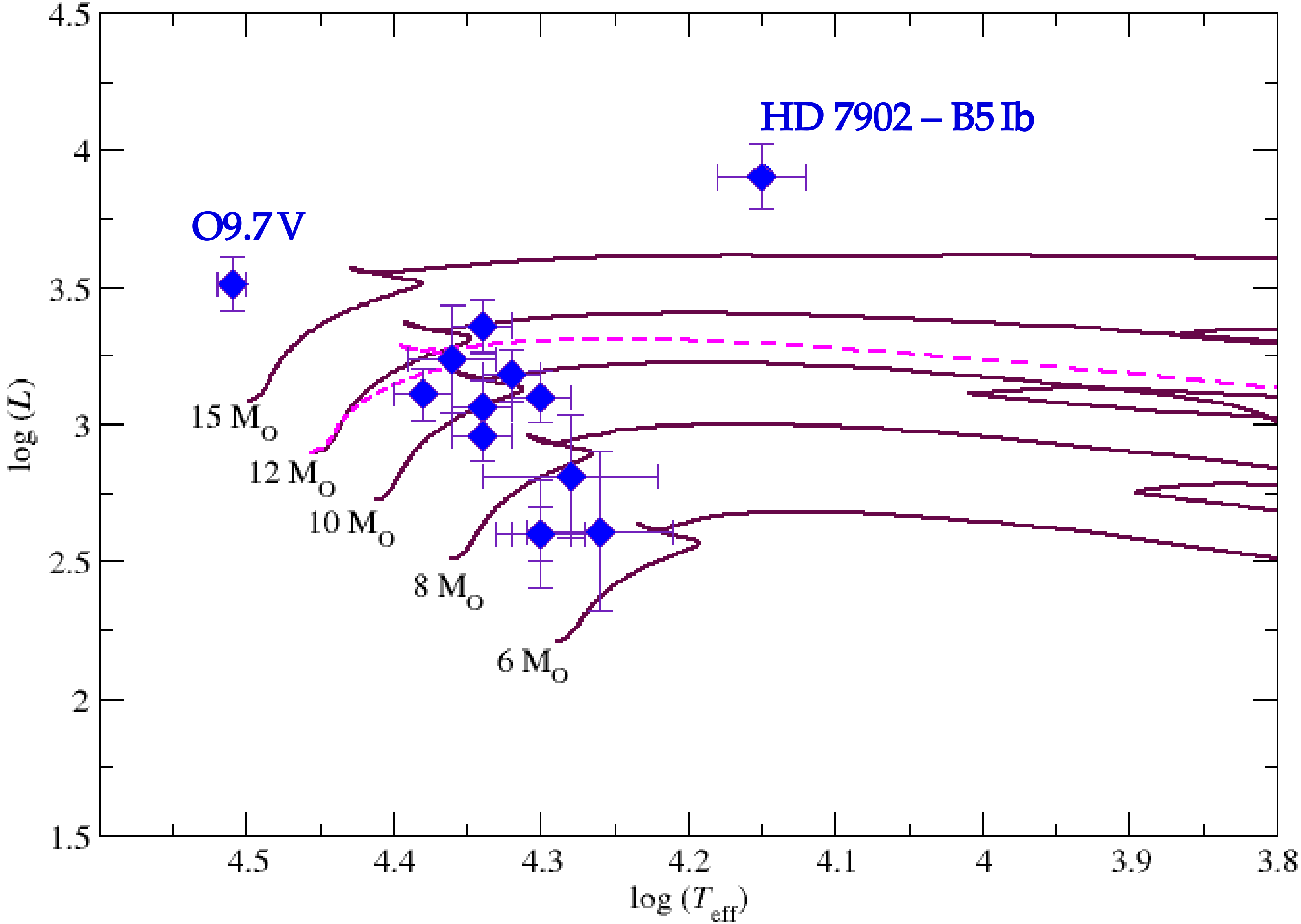


Tracks by **Georgy+ (2013)**

16 Ma with $\Omega_{ini} = 0$

20 Ma with $\Omega_{ini}/\Omega_{cri} = 0.3$

NGC 457

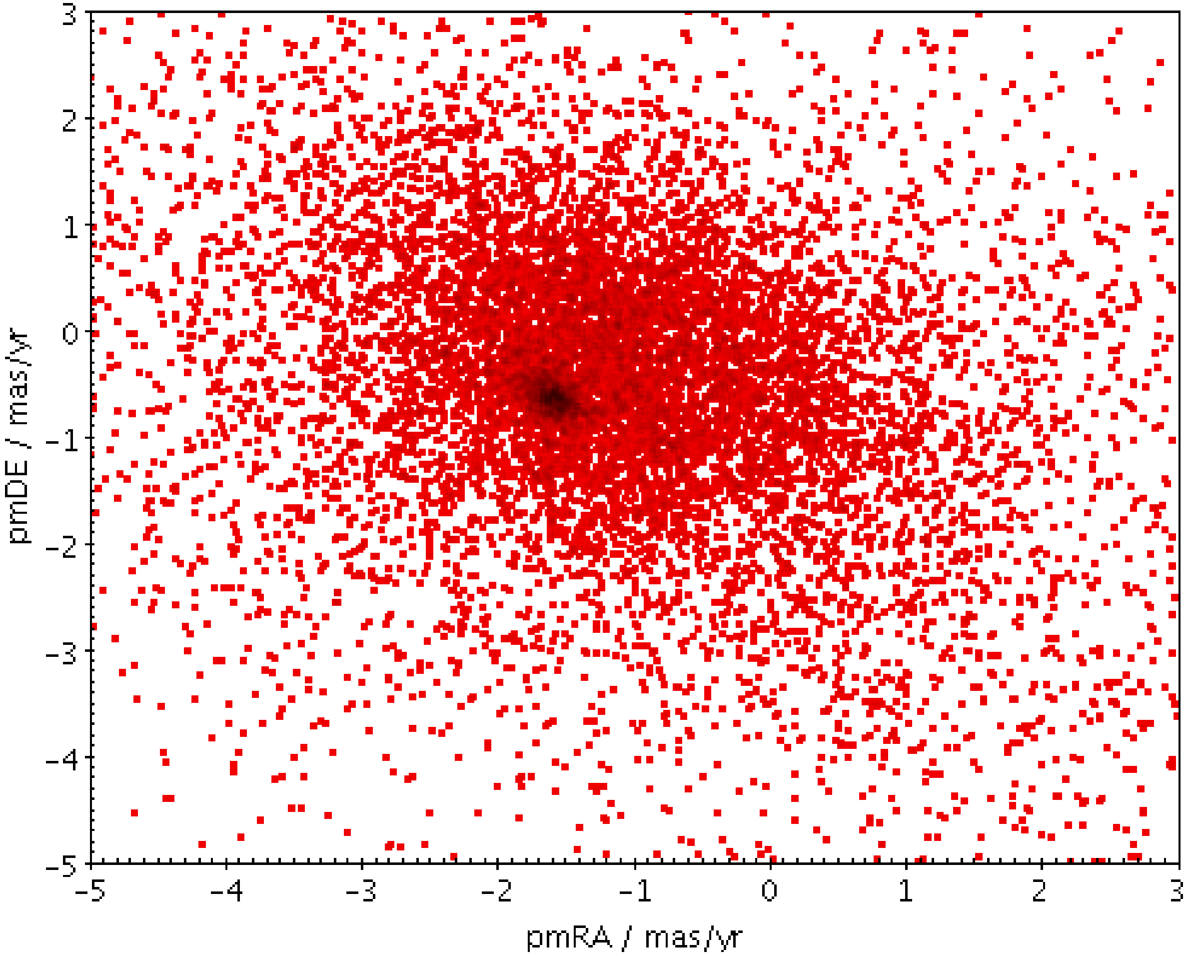


Automated FASTWIND analysis, as in Castro+ 2012

Tracks by Ekström+ 2012

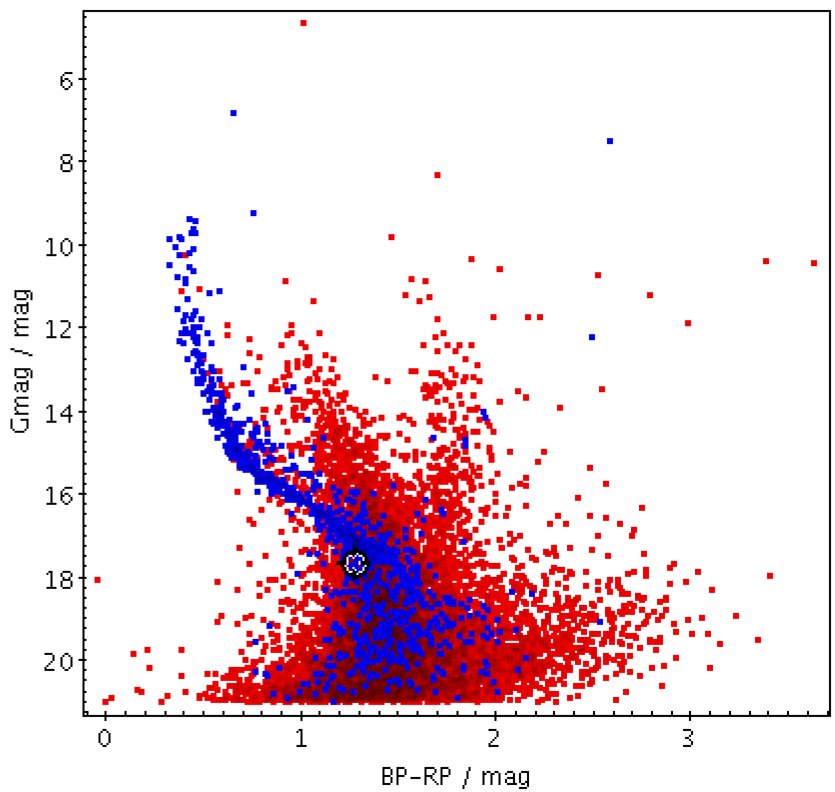
NGC 457

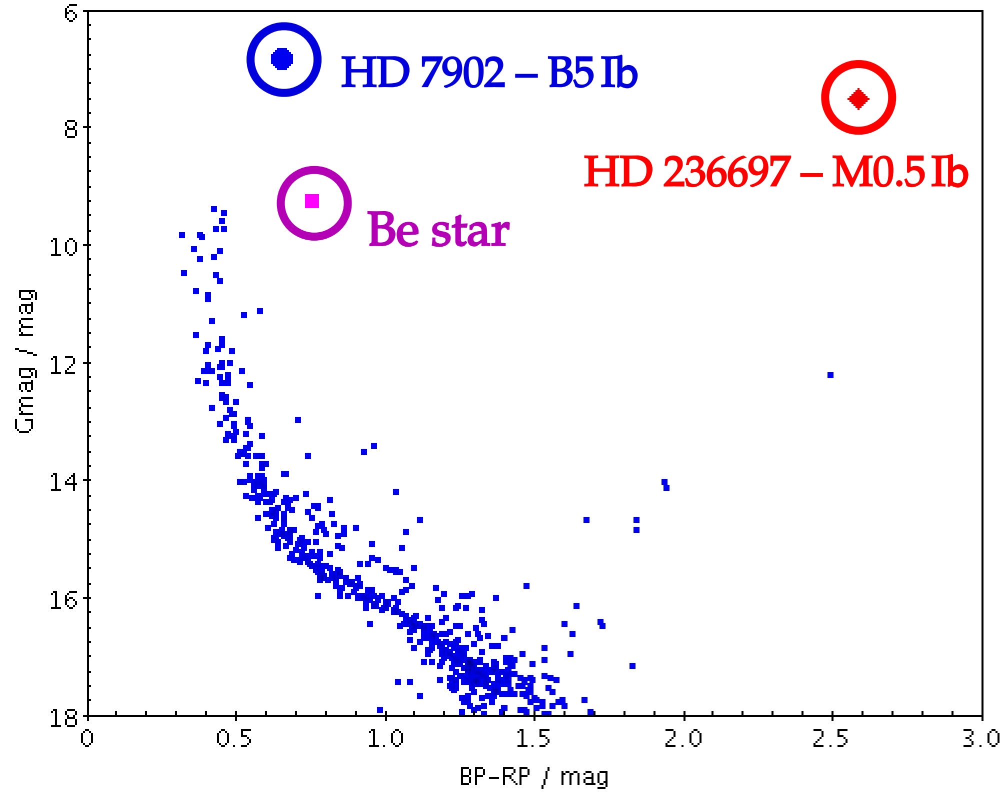
Gaia DR2 proper motion plane for a wide field (~20') around NGC 457.



NGC 457

Gaia DR2 photometric CMD for a wide field (~20') around NGC 457.





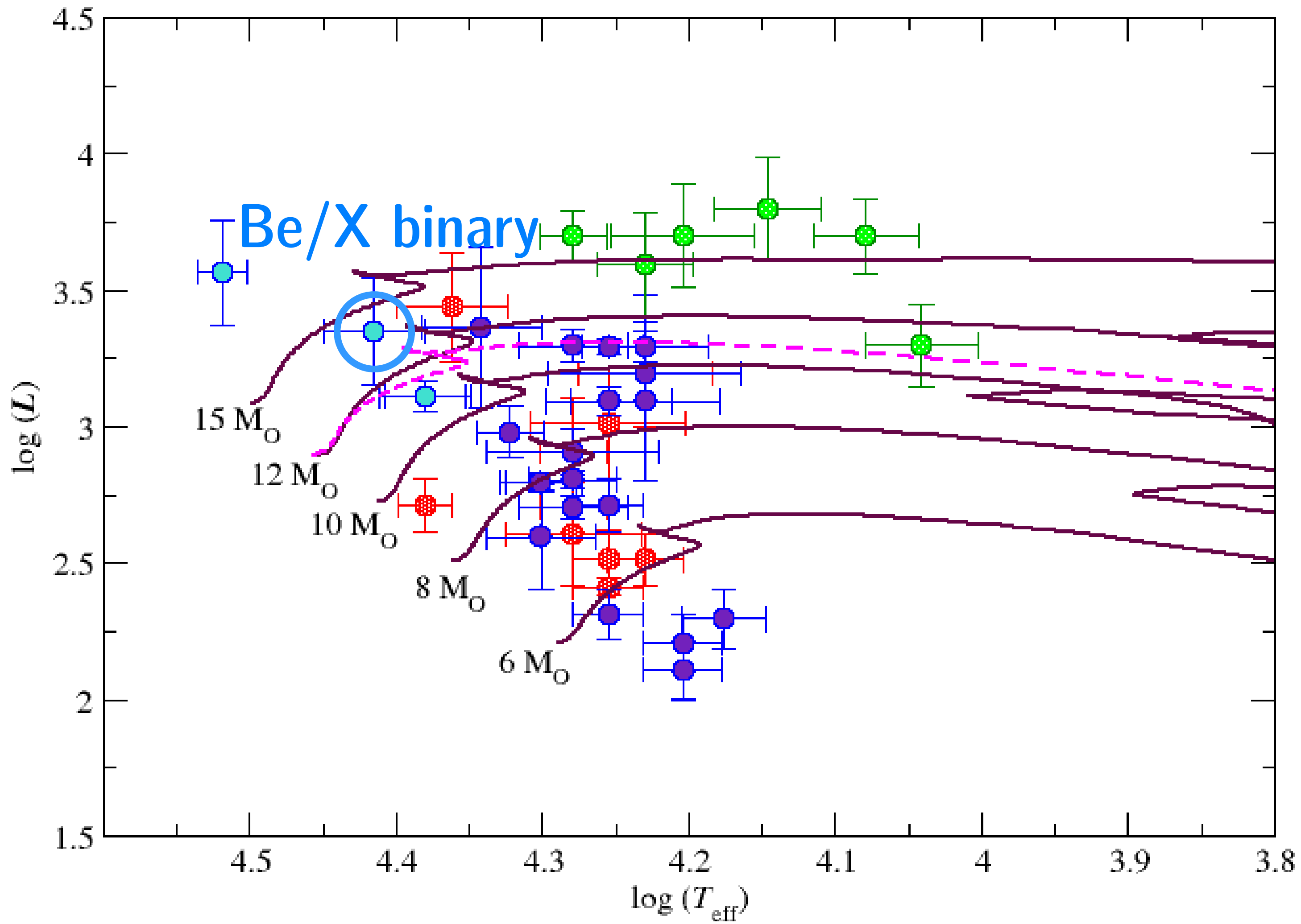
NGC 663

- Persistent low-luminosity Be/X-ray binary (**Reig+ 1997**).
- Little X-ray variability.

- B0.5 IV

NGC 663

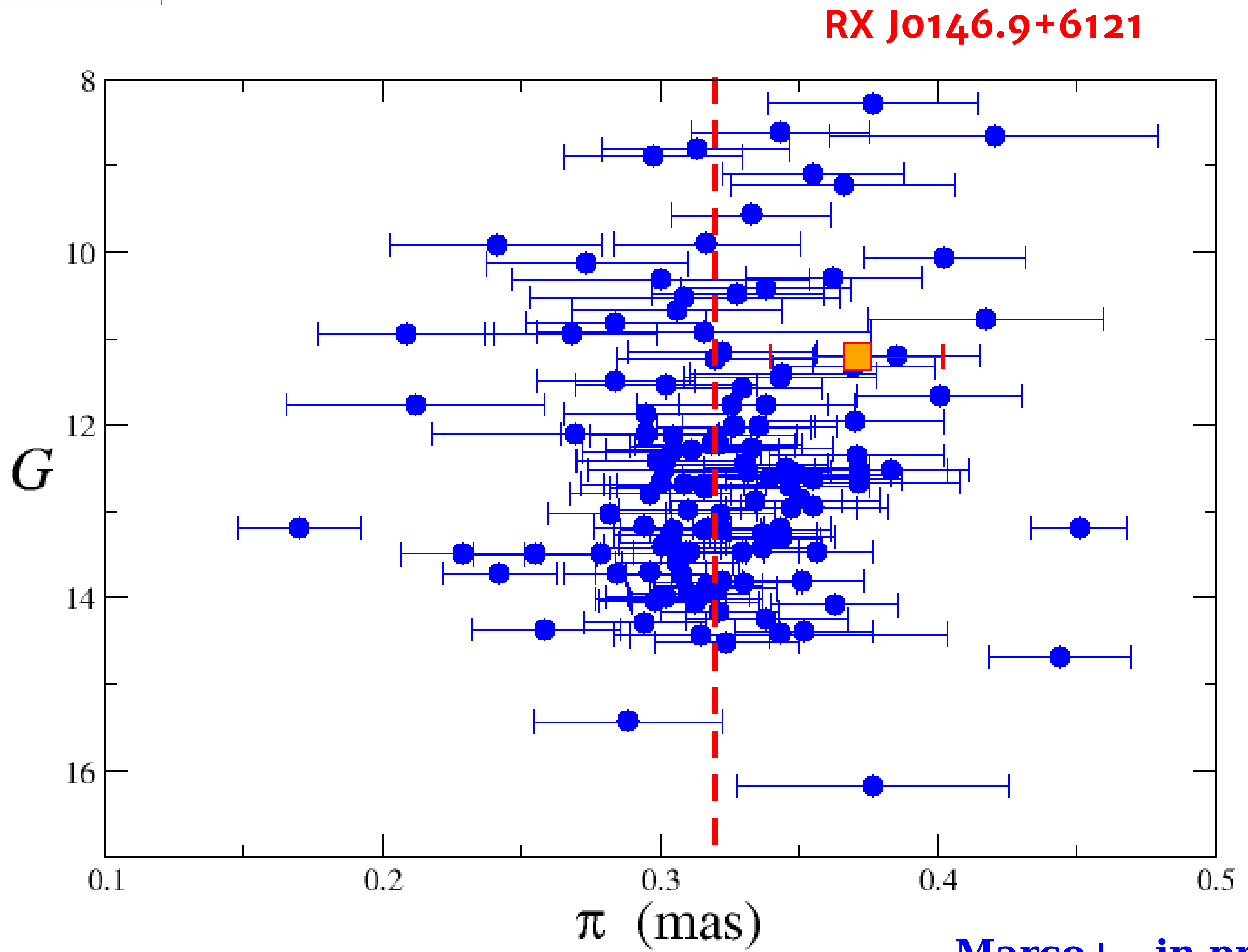
- Be stars
- Spectroscopic blue stragglers
- Blue supergiants
- Other



Automated FASTWIND analysis, as in **Castro et al. (2012)**

Tracks by **Ekström+ (2012)**

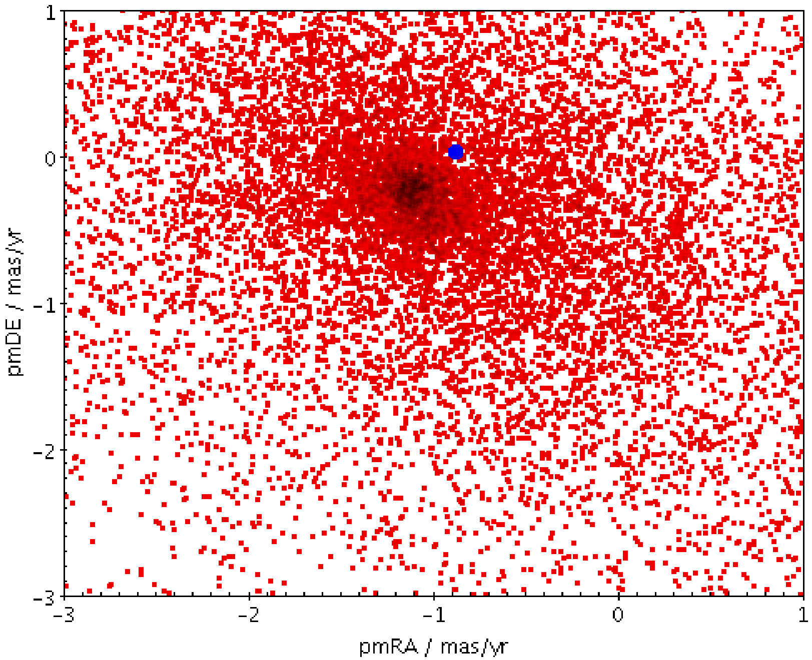
NGC 663



Marco+ , in prep.

NGC 663

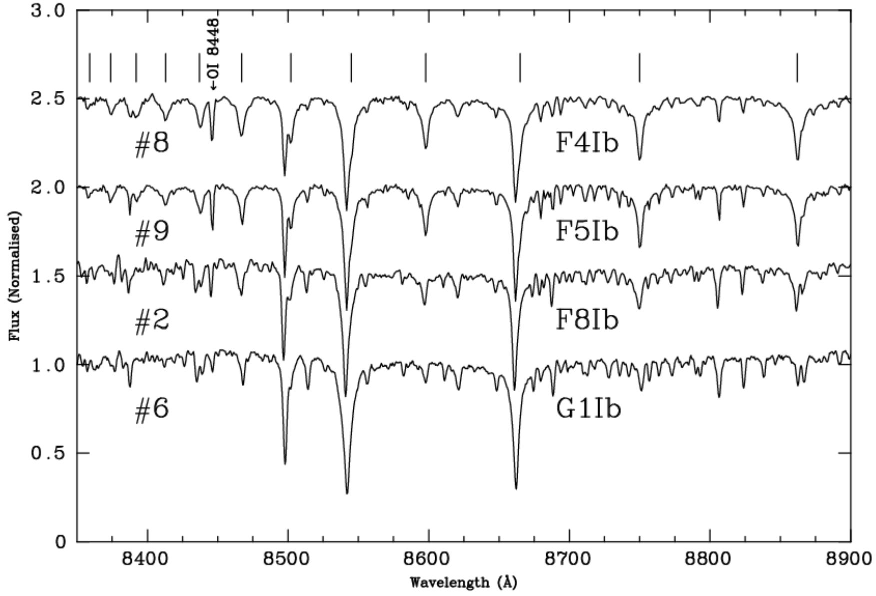
RX J0146.9+6121



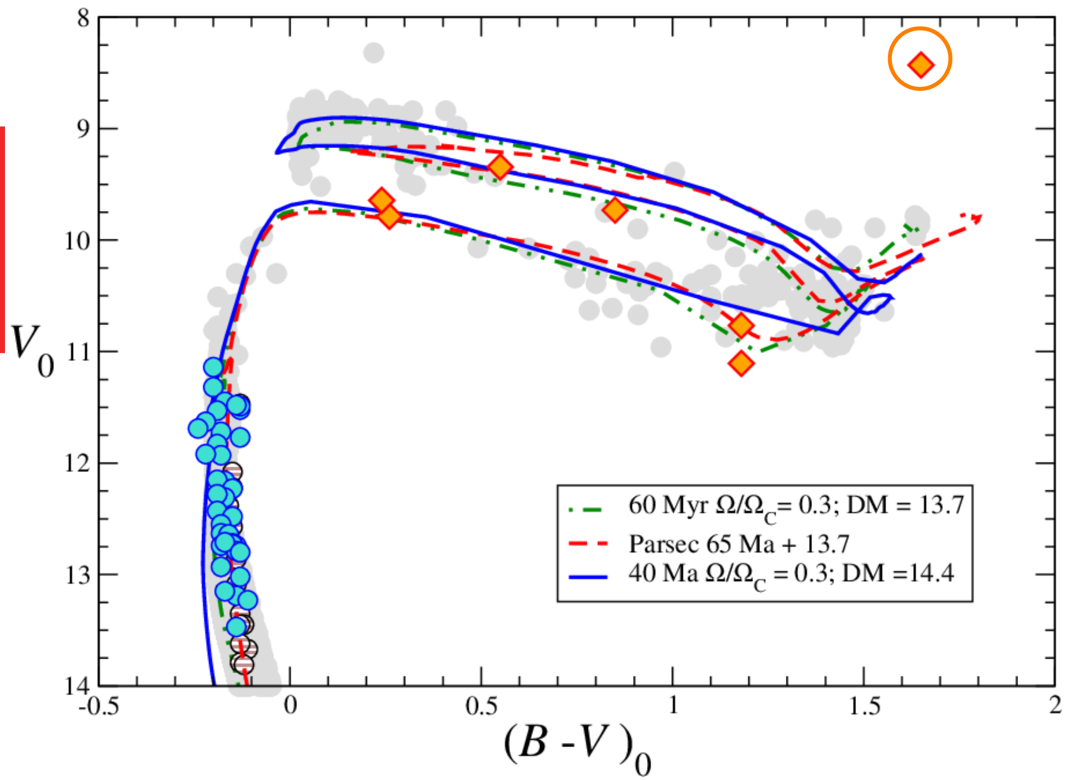
This object cannot have experienced a significant supernova kick.

Marco+ , in prep.

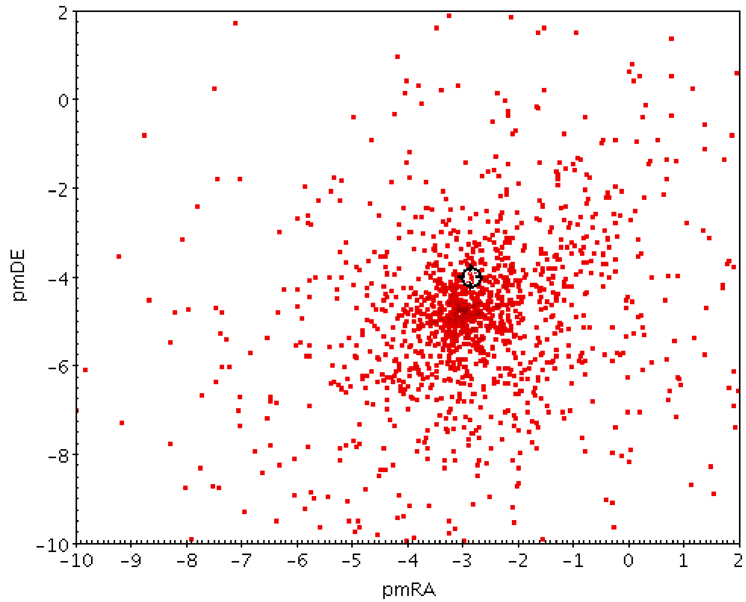
Be 51



Negueruela+ (2018)



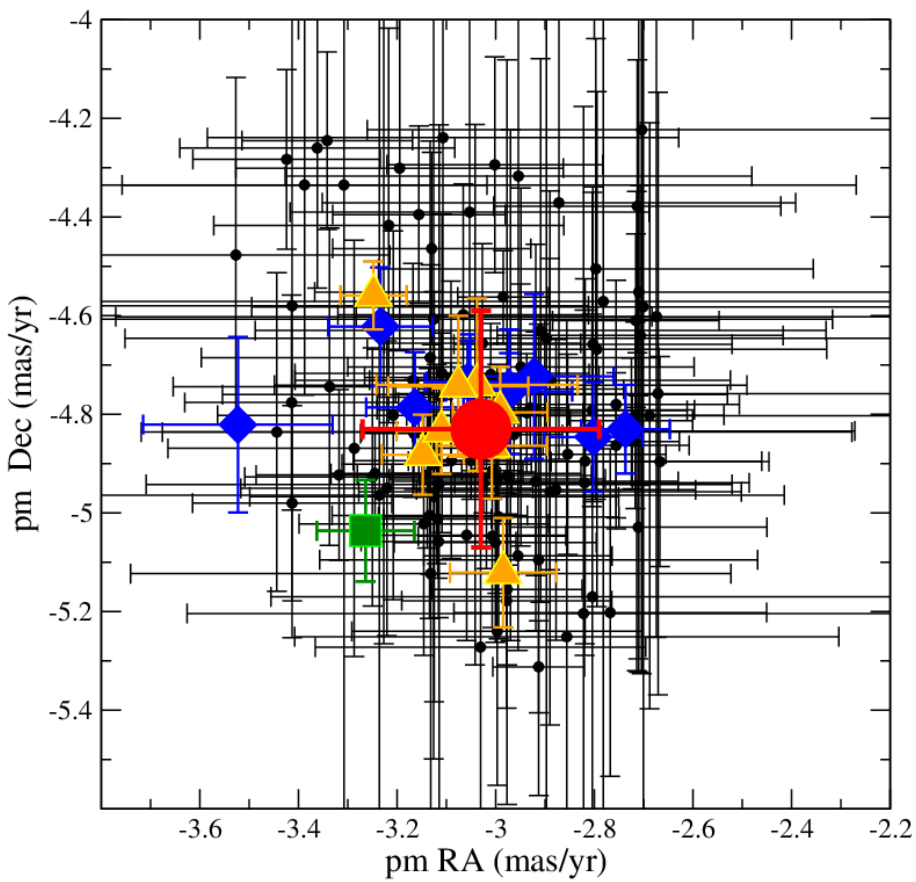
Be 51

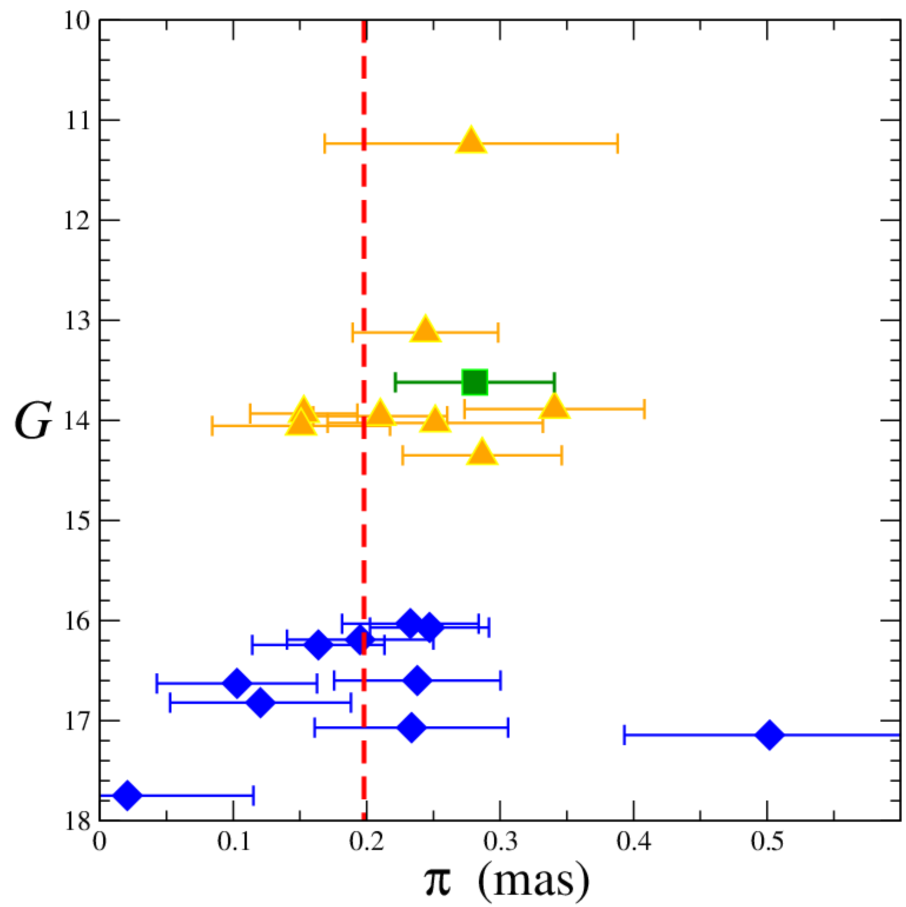


Lohr+ (2018)

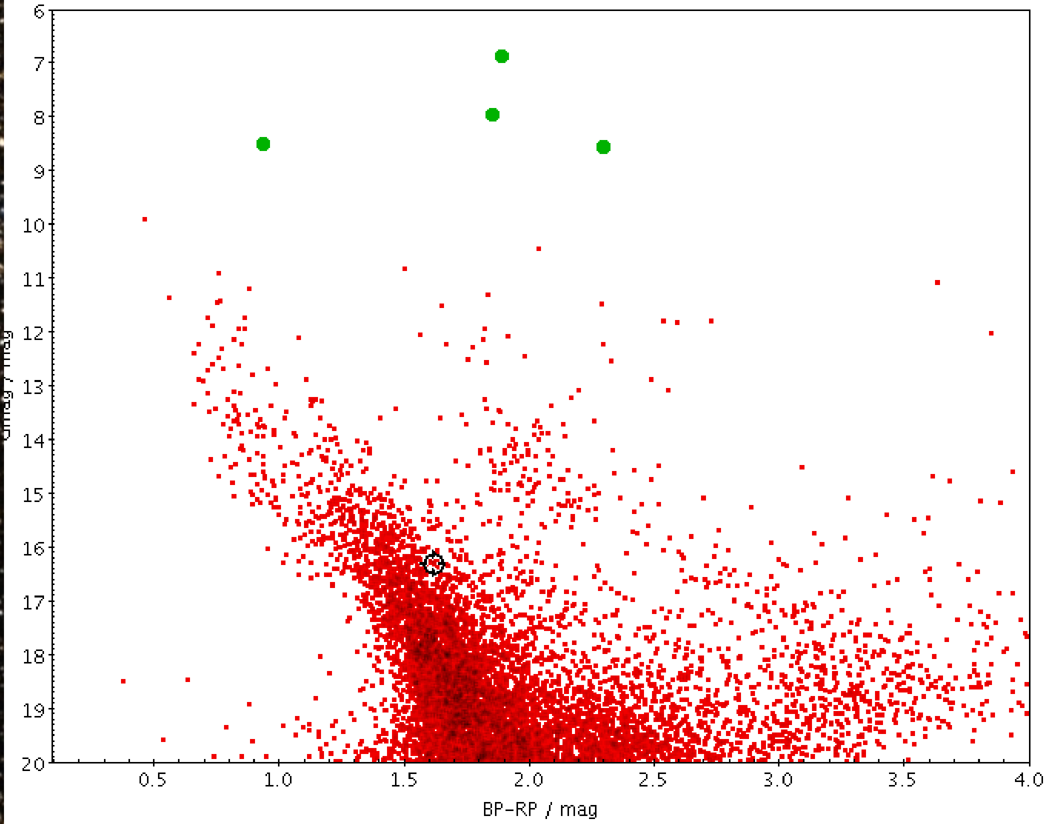
Two new Cepheids in clusters

$$M_* = 6 - 7\,M_\odot$$



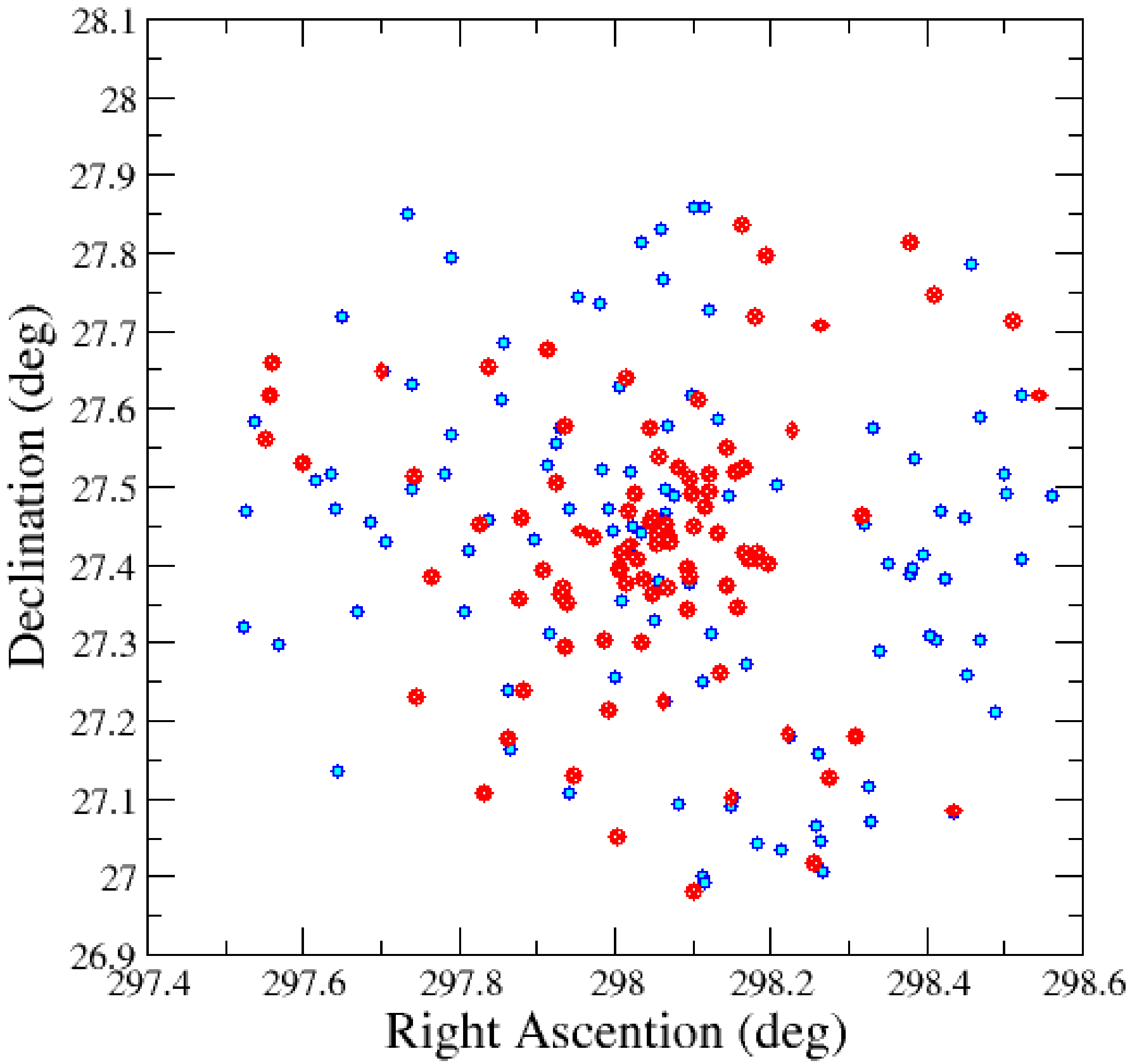



CDS/P/DSS2/color
1'
Powered by Aladin
18.95' x 20.75'
N
E


6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
BP-RP / mag

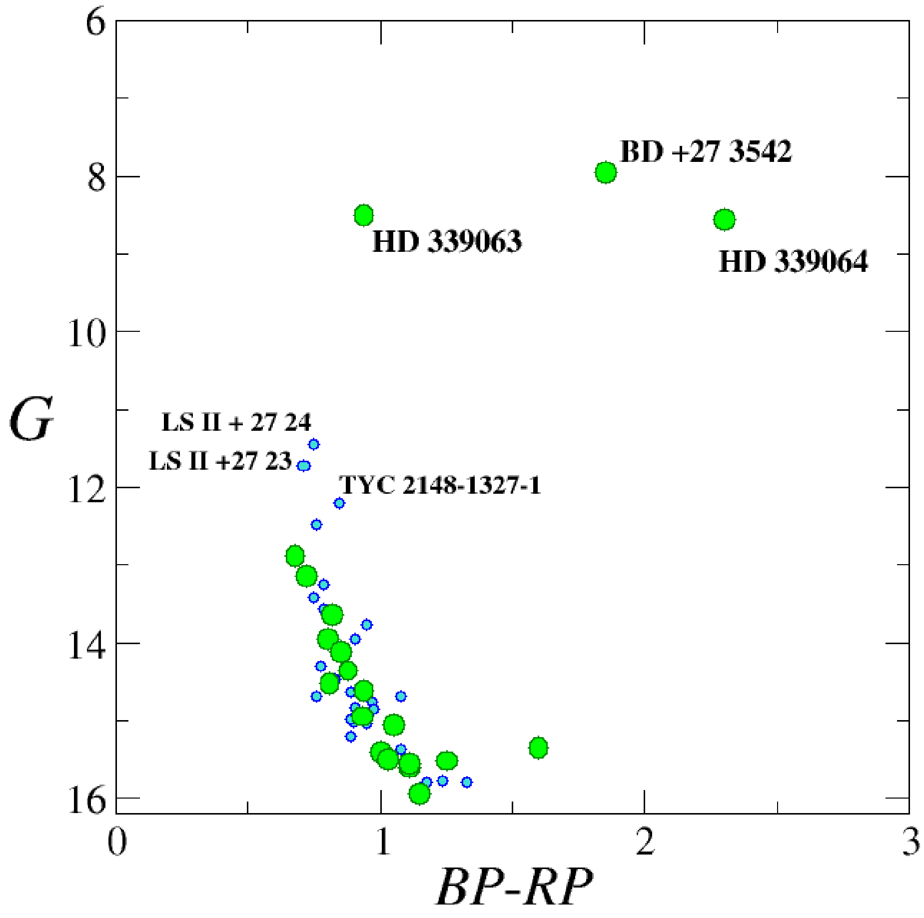
Alicante 13

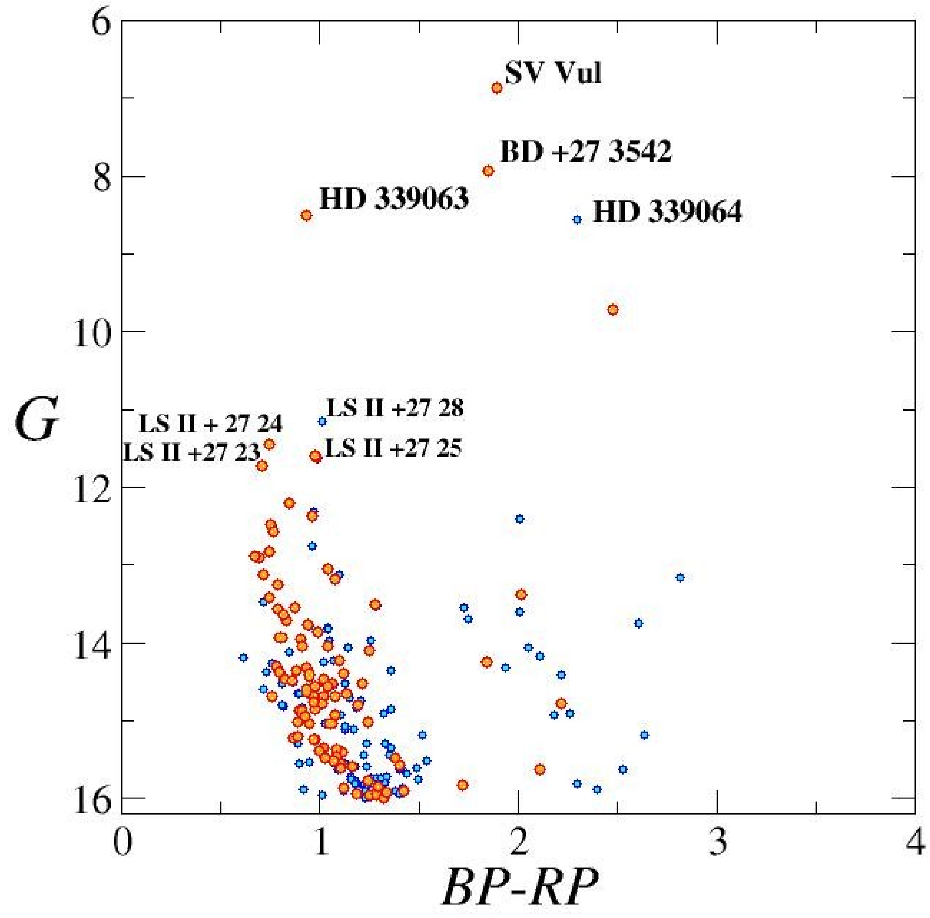
- Clusterix (**Balaguer-Nuñez+**)
- ASteCA (**Perren**)



Negueruela+20, MNRAS, in press

Alicante 13

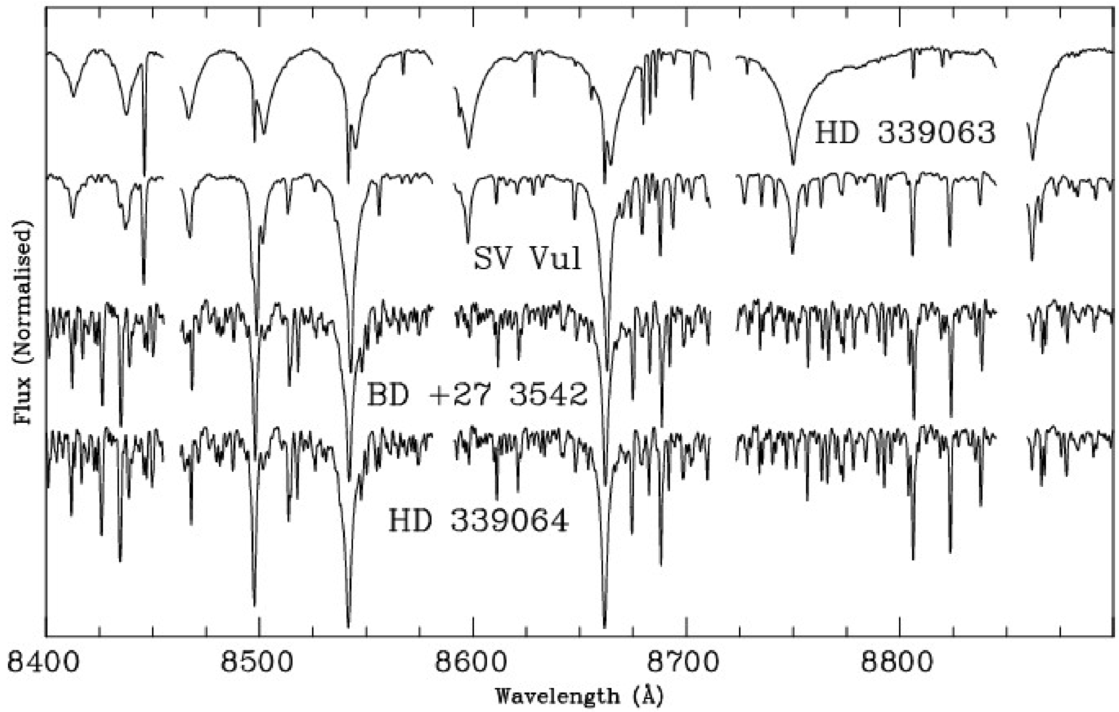


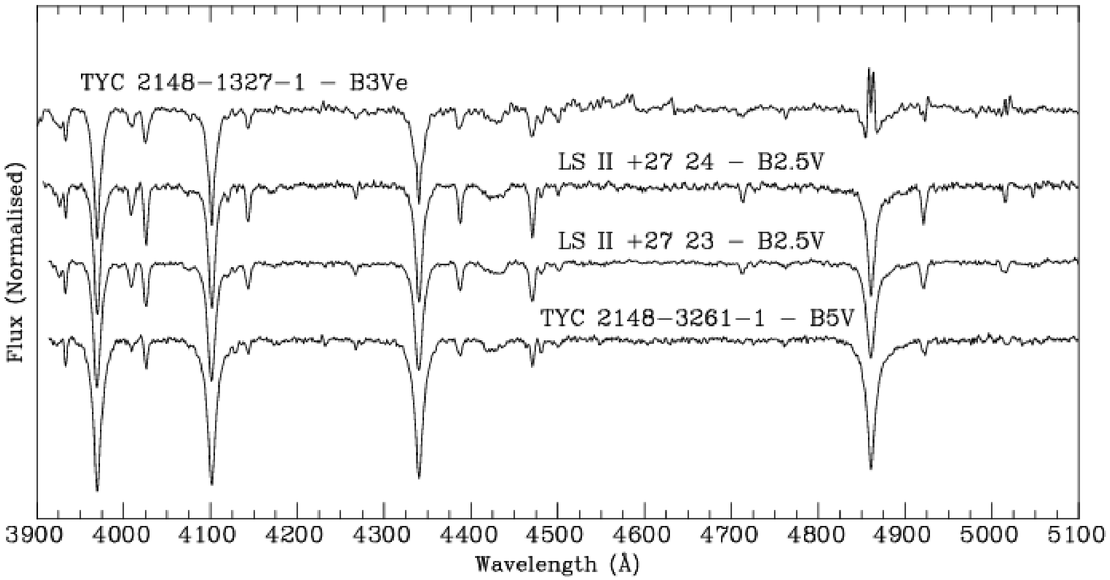


Negueruela+20, MNRAS, in press

Alicante 13

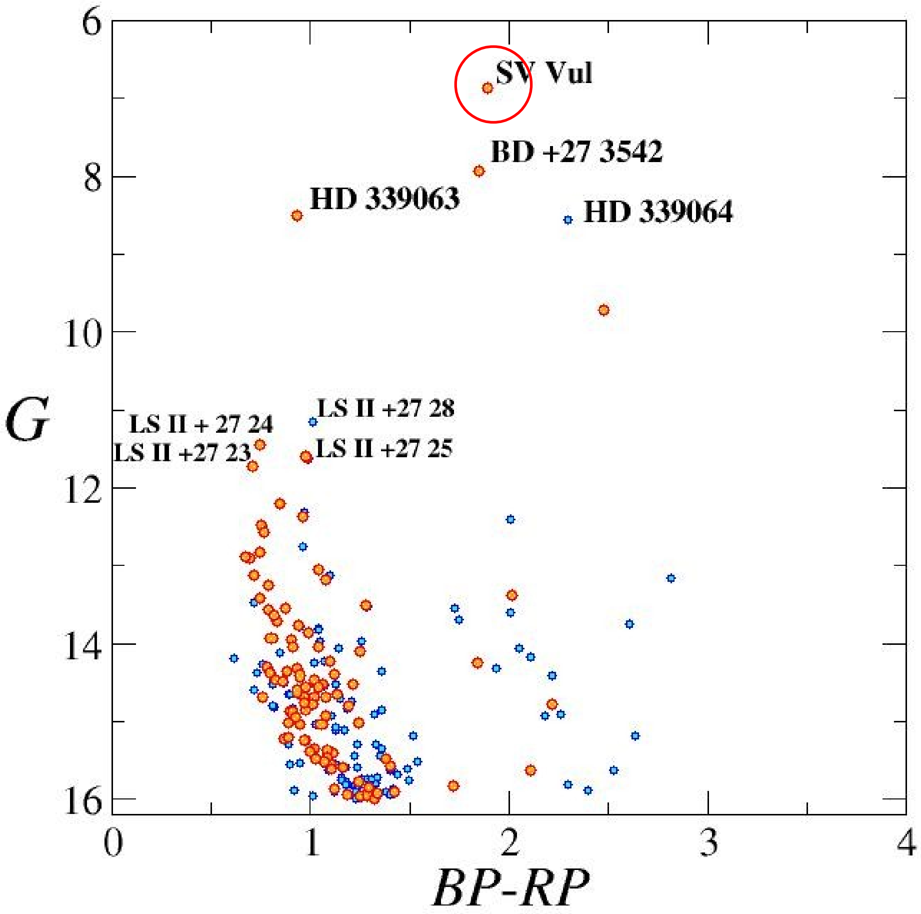
Alicante 13 = UBC 130





Negueruela+20, MNRAS, in press

Alicante 13



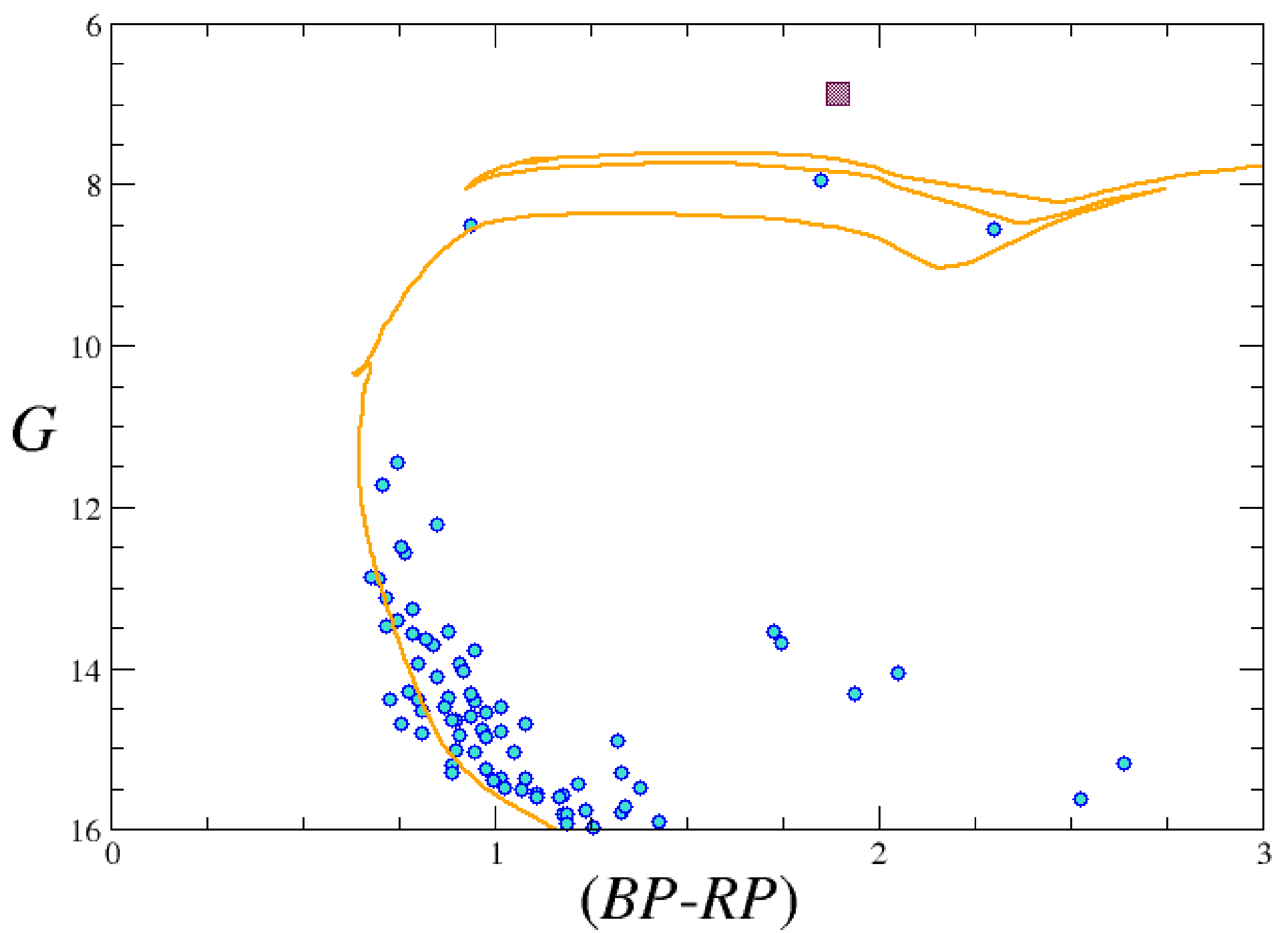
Negueruela+20, MNRAS, in press

Table 7. Adopted absolute magnitudes of the 59 calibrators in 7 photometric bands (from B to K_s) and for two Wesenheit indices, W_{vi} and W_{bi}.

Star	log *P*	M_B	M_V	M_{Rc}	M_{Ic}	M_{Wvi}	M_{Wbi}	M_J	M_H	M_{Ks}
RT Aur	0.571489	–2.31	–2.84		–3.40	–4.28	–4.35	–3.94	–4.15	–4.24
QZ Nor	0.578244	–1.83	–2.47	–2.85	–3.15	–4.21	–4.29	–3.67	–3.91	–4.01
SU Cyg	0.584952	–2.61	–3.08	–3.38	–3.63	–4.47	–4.50	–4.08	–4.28	–4.36
Y Lac	0.635863	–2.79	–3.31	–3.65	–3.90	–4.81	–4.86	–4.33	–4.58	–4.66
T Vul	0.646934	–2.48	–3.06	–3.41	–3.66	–4.58	–4.68	–4.12	–4.36	–4.45
FF Aql	0.650397	–2.46	–3.02	–3.35	–3.64	–4.60	–4.65	–4.09	–4.29	–4.37
T Vel	0.666501	–2.28	–2.93	–3.32	–3.64	–4.74	–4.81	–4.13	–4.41	–4.51
VZ Cyg	0.687034	–2.62	–3.23	–3.62	–3.88	–4.90	–4.98	–4.36	–4.60	–4.70
V350 Sgr	0.712165	–2.74	–3.34	–3.73	–4.02	–5.06	–5.13	–4.51	–4.78	–4.85
BG Lac	0.726883	–2.56	–3.22	–3.62	–3.91	–4.99	–5.08	–4.36	–4.64	–4.73
δ Cep	0.729678	–2.88	–3.47	–3.87	–4.11	–5.11	–5.18	–4.55	–4.82	–4.91
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
WZ Car	1.361977	–3.83	–4.61	–5.09	–5.43	–6.70	–6.81	–6.08	–6.42	–6.54
SW Vel	1.370016	–4.07	–4.88	–5.37	–5.73	–7.05	–7.17	–6.34	–6.68	–6.80
T Mon	1.431915	–4.18	–5.17	–5.68	–6.08	–7.51	–7.73	–6.75	–7.14	–7.27
RY Vel	1.449158	–4.32	–5.14	–5.65	–5.99	–7.32	–7.44	–6.62	–6.92	–7.04
AQ Pup	1.478624	–4.56	–5.39	–5.93	–6.28	–7.67	–7.78	–6.85	–7.20	–7.31
KN Cen	1.531857	–4.79	–5.59	–6.14	–6.43	–7.74	–7.86	–7.15	–7.53	–7.67
ℓ Car	1.550816	–4.11	–5.22		–6.21	–7.74	–8.03	–6.91	–7.33	–7.46
U Car	1.588970	–4.51	–5.43	–5.94	–6.32	–7.71	–7.89	–6.97	–7.32	–7.45
RS Pup	1.617420	–4.78	–5.76	–6.32	–6.72	–8.22	–8.40	–7.37	–7.74	–7.87
SV Vul	1.652569	–4.97	–5.97	–6.53	–6.90	–8.35	–8.58	–7.52	–7.86	–7.96

Alicante 13

- Cluster supergiants may have $\gtrsim 9\,\mathrm{M}_\odot$
- SV Vul is compatible with evolution of a fast rotator of $\approx 10\,\mathrm{M}_\odot$
- Geneva models (**Anderson+ 14**) predict a highest mass of $10\,\mathrm{M}_\odot$ for Cepheids coming from fast rotators
- The highest luminosity for a Cepheid is $\log(L/L_\odot) = 4.3$
- SV Vul has $\log(L/L_\odot) = 4.2 \pm 0.2$



Negueruela+20, MNRAS, in press

What’s coming?

- **DR3 will bring much more accurate proper motions, which will allow us to look into internal dynamics (cluster formation history).**
- **DR3 will bring lightcurves for all sources, allowing us to identify most of the close binaries.**
- **DR3 or 4 will bring solutions for visual binaries, allowing us to probe the range of separations that likely result in BH + BH systems.**
- **DR3 distances to clusters will be good enough to tie down ages – will probably require more sophisticated stellar models.**
- **DR4 will provide accurate distances to individual stars, allowing us to use the whole Galactic population to probe physical variables.**
- **WEAVE/SCIP will provide us with accurate stellar parameters for tens of thousands of massive stars.**

YOUNG CLUSTERS IN THE *GAIA* ERA

Ignacio Negueruela

Barcelona, February 2020

Universitat d'Alacant
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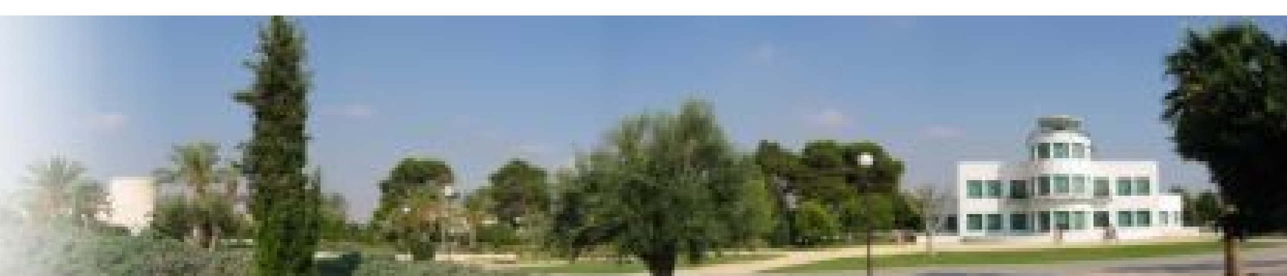
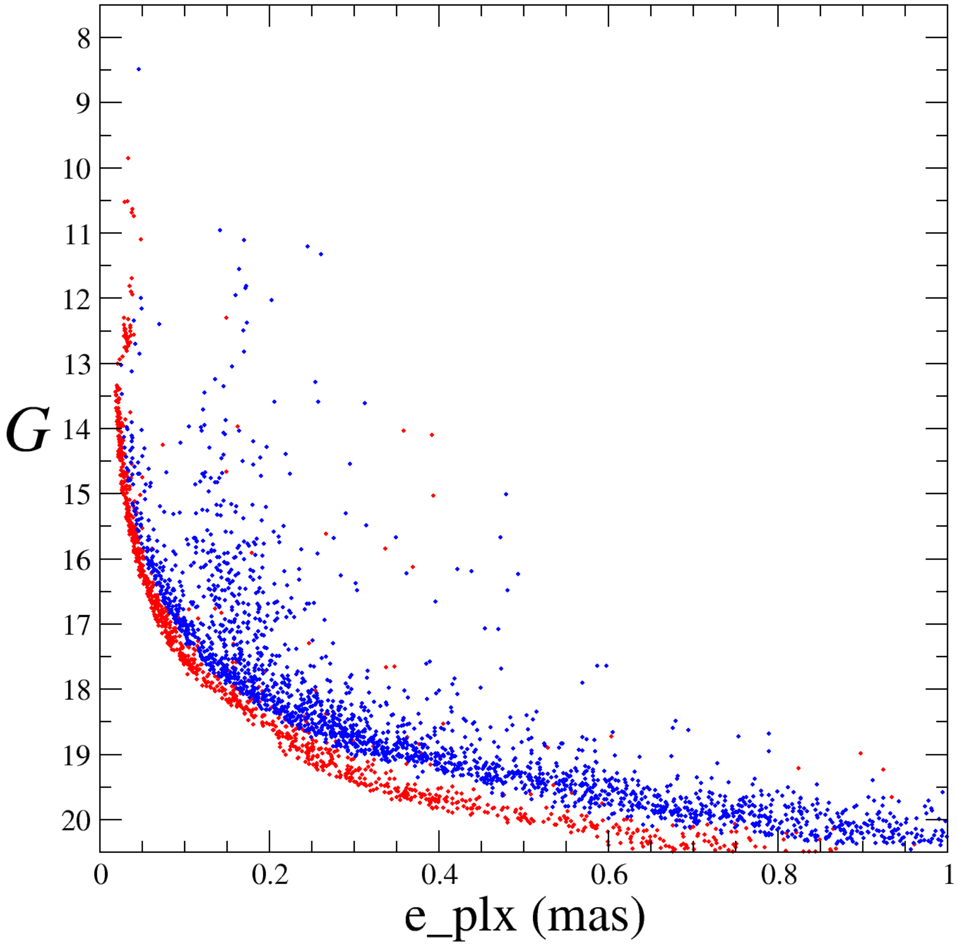
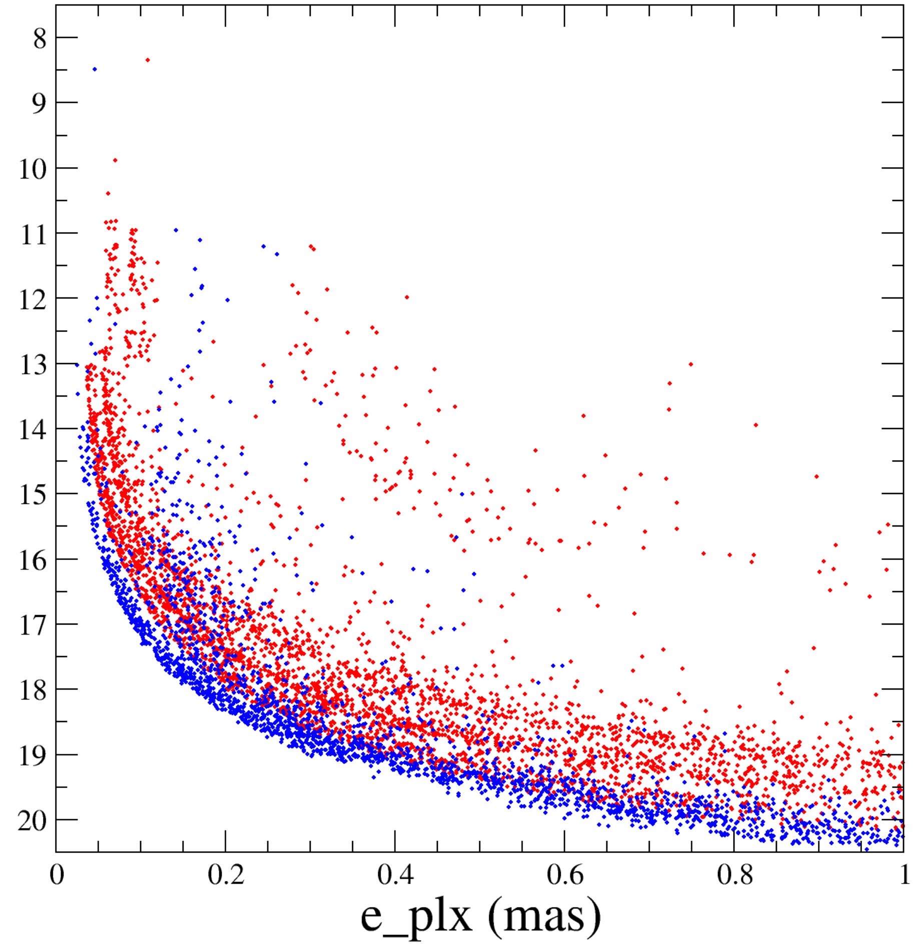


Wd 1 in Gaia

Clark+ 2019, A&A 623, A83

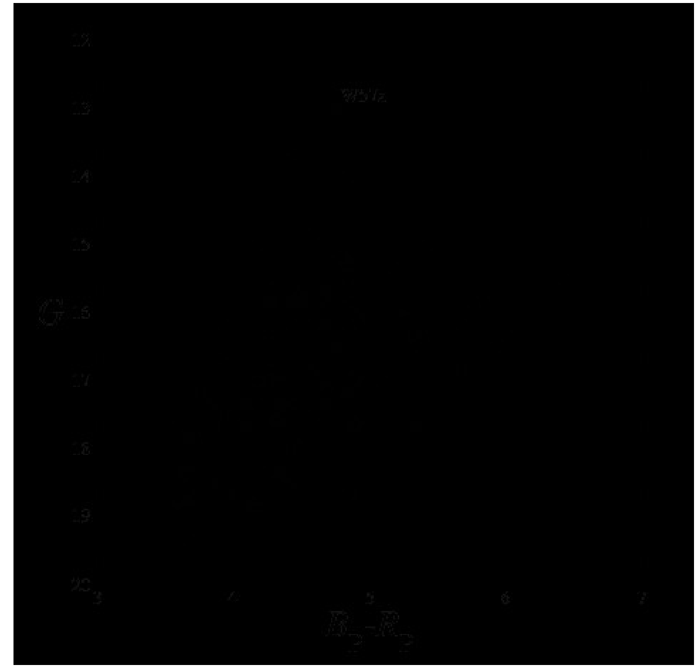


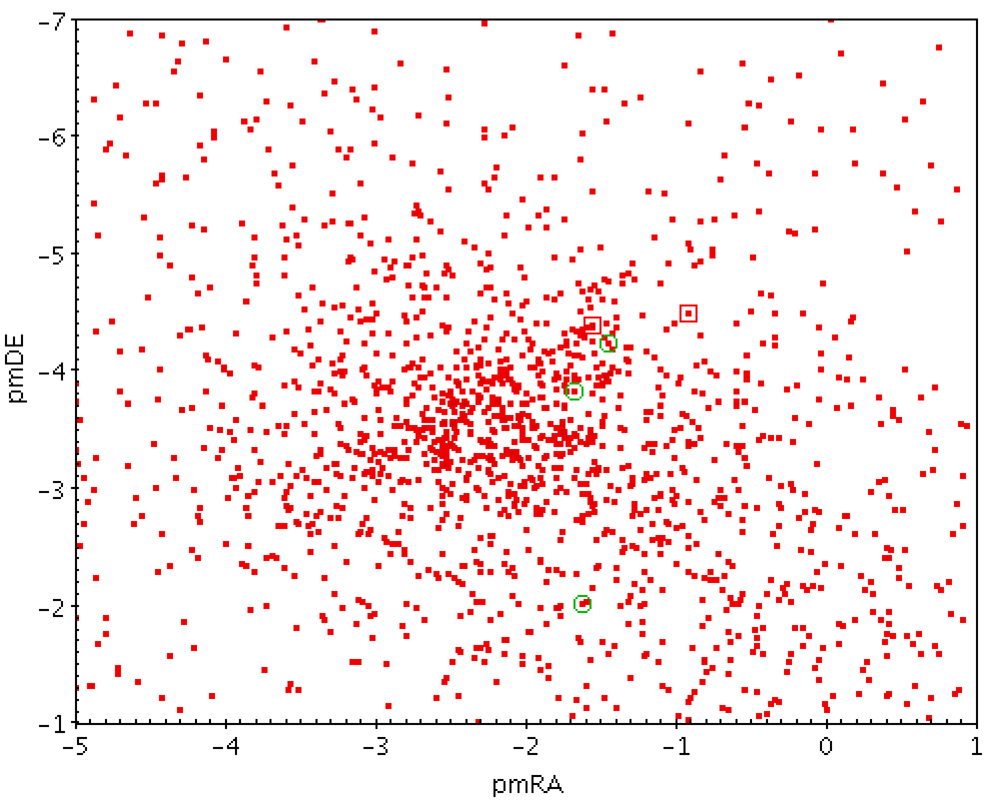
Gaia data for 3.5’ around Wd 1
compared to 3.5’ around NGC 7789
3500 (65%) 1300 (92%)

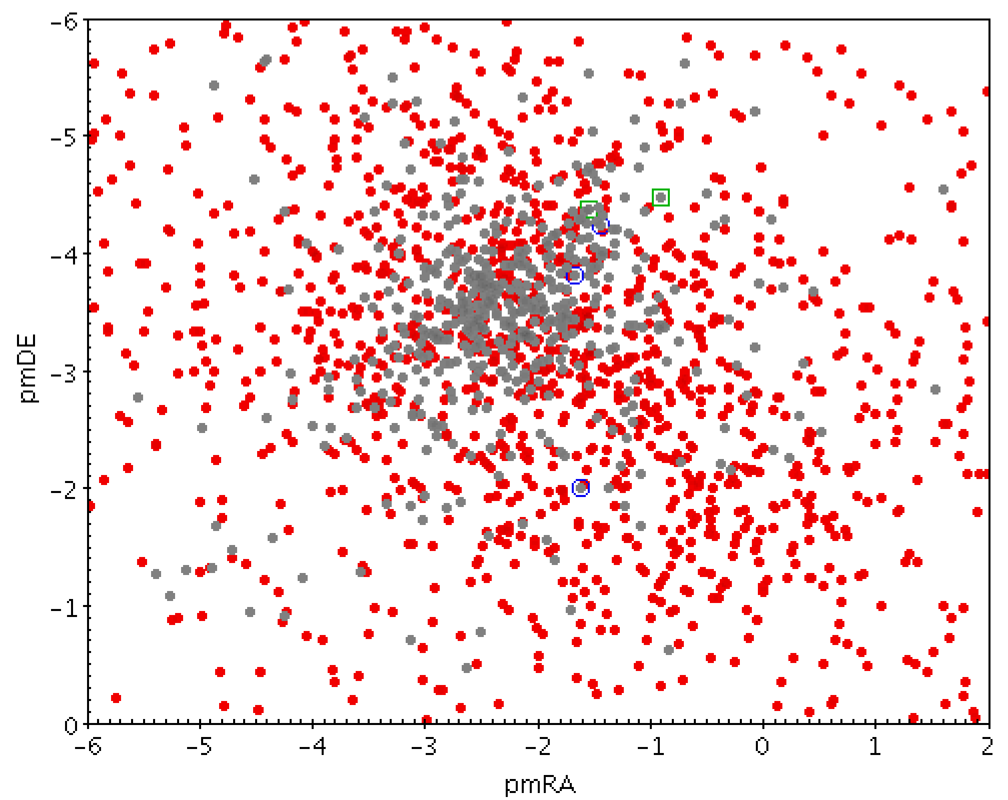


Gaia data for 3.5’ around Wd 1
compared to 3.5’ around M11
3500 (65%) 6800 (60%)

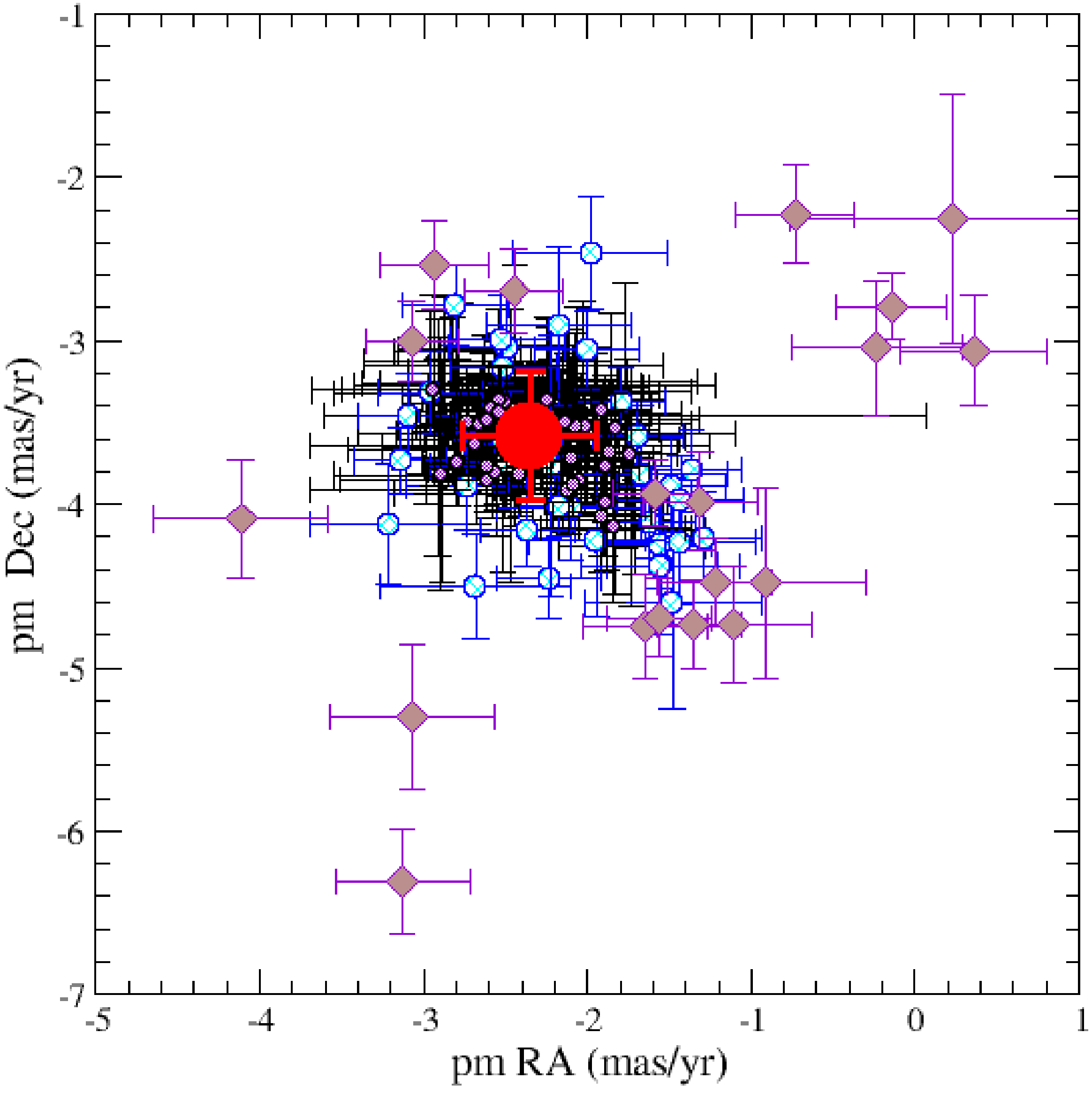
Wd 1 in Gaia







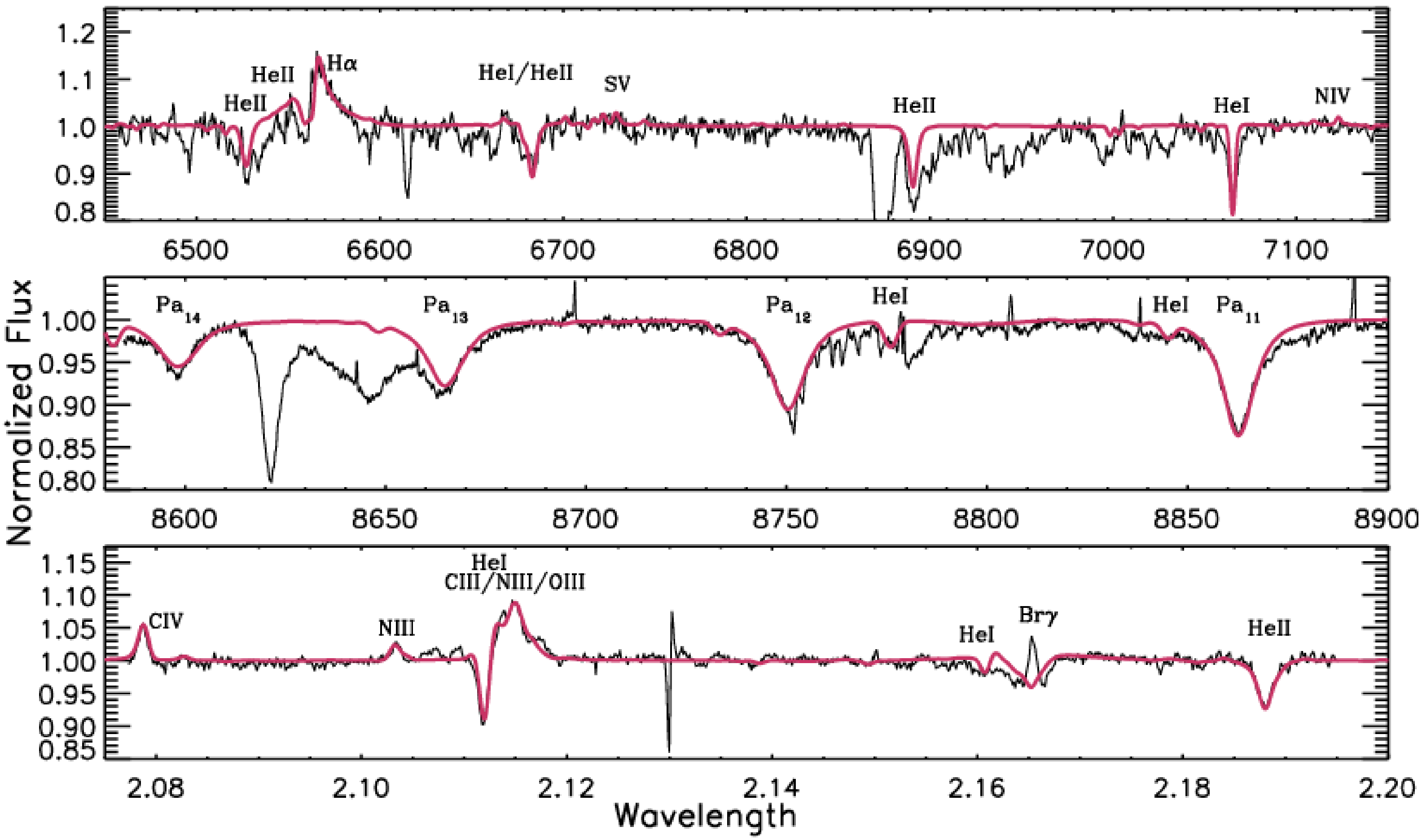
Wd 1 in Gaia



Clark+ 2019, A&A 623, A83

Very massive blue straggler

Clark+ 2019, A&A 623, A83



- Wd1-27 is an astrometric member.
  O7 Ia, probably $M_\star \approx 50\text{-}60\,\mathrm{M}_\odot \Rightarrow$ **merger product**
- Wd1-30a is another member that seems to be in the process of forming an O5 Iaf