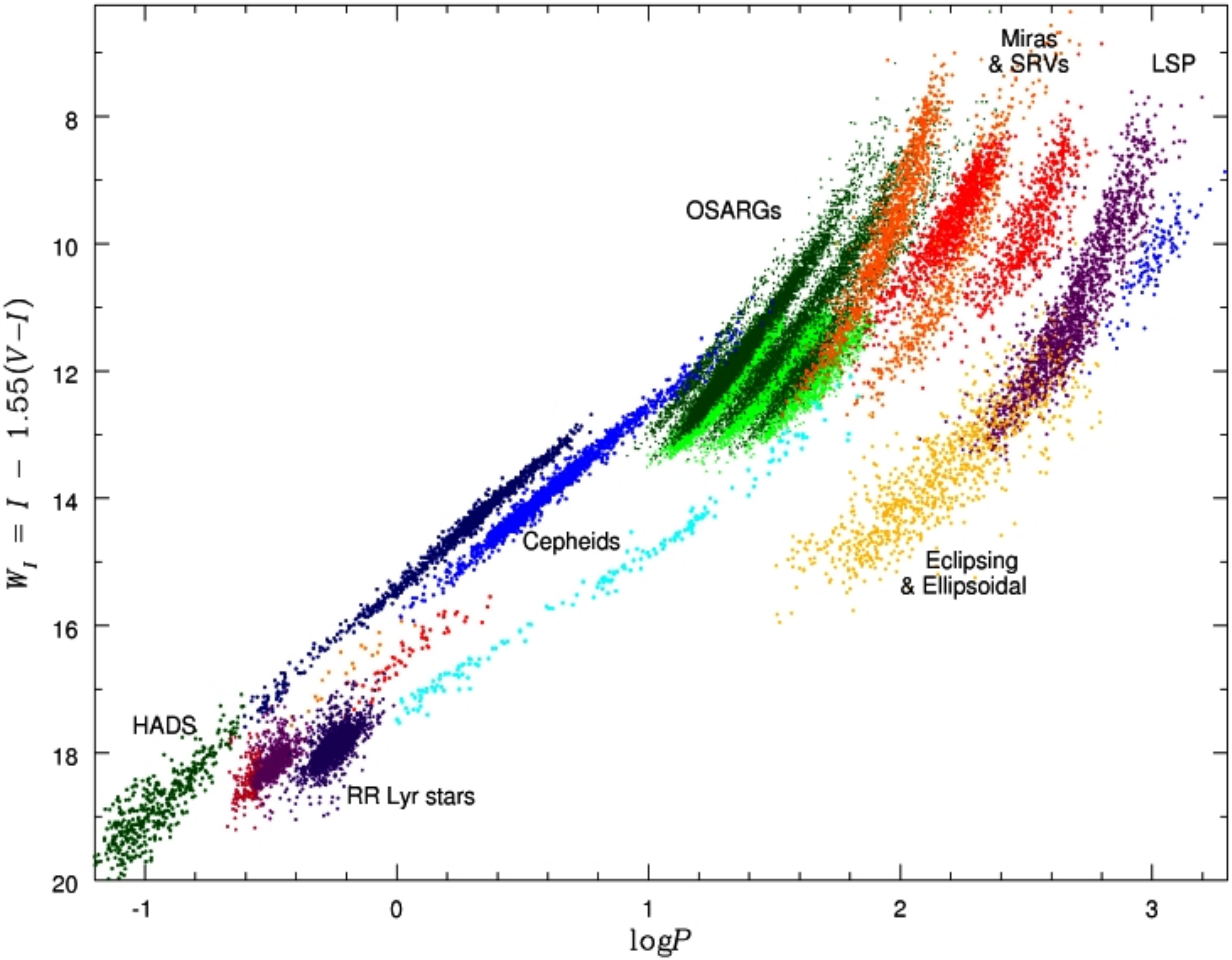
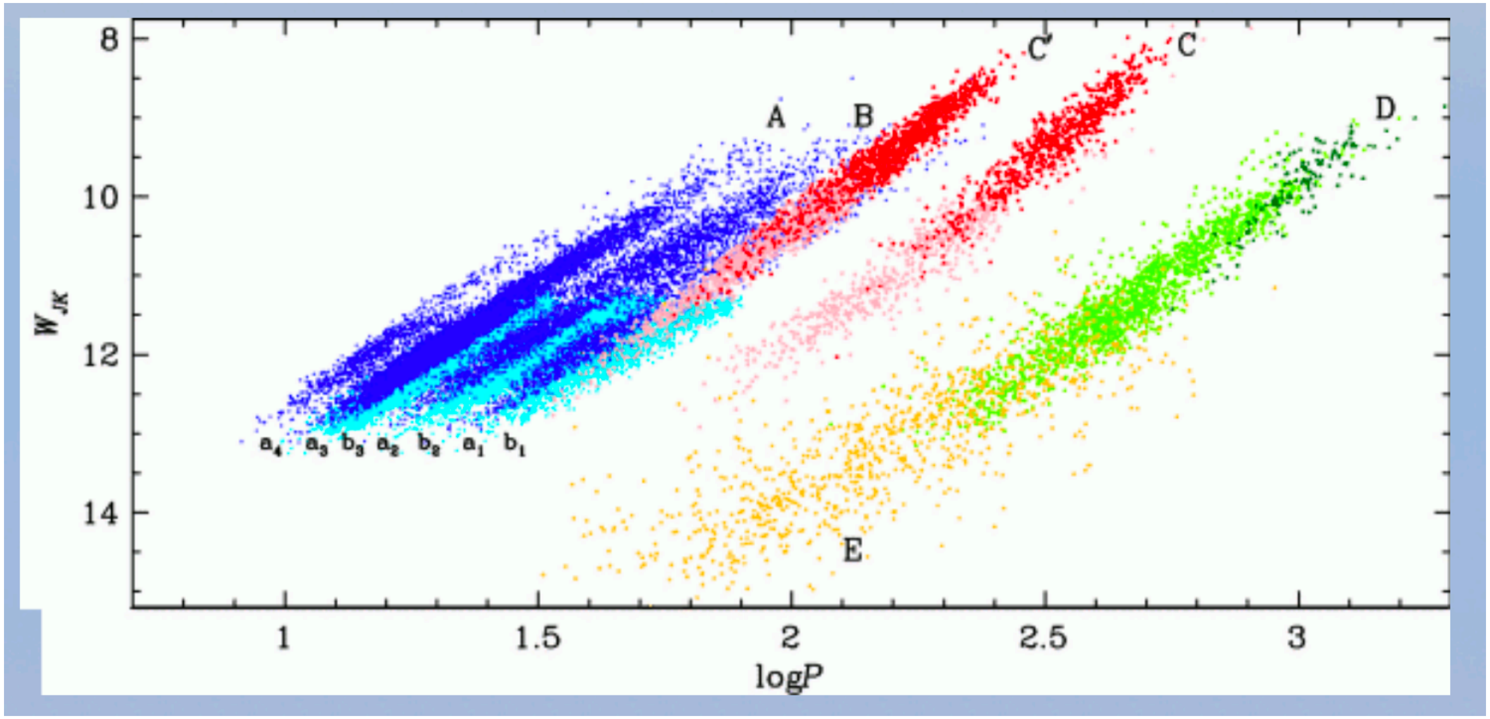
Extragalactic Distance Scale lect. IX
Pulsating stars – cont.

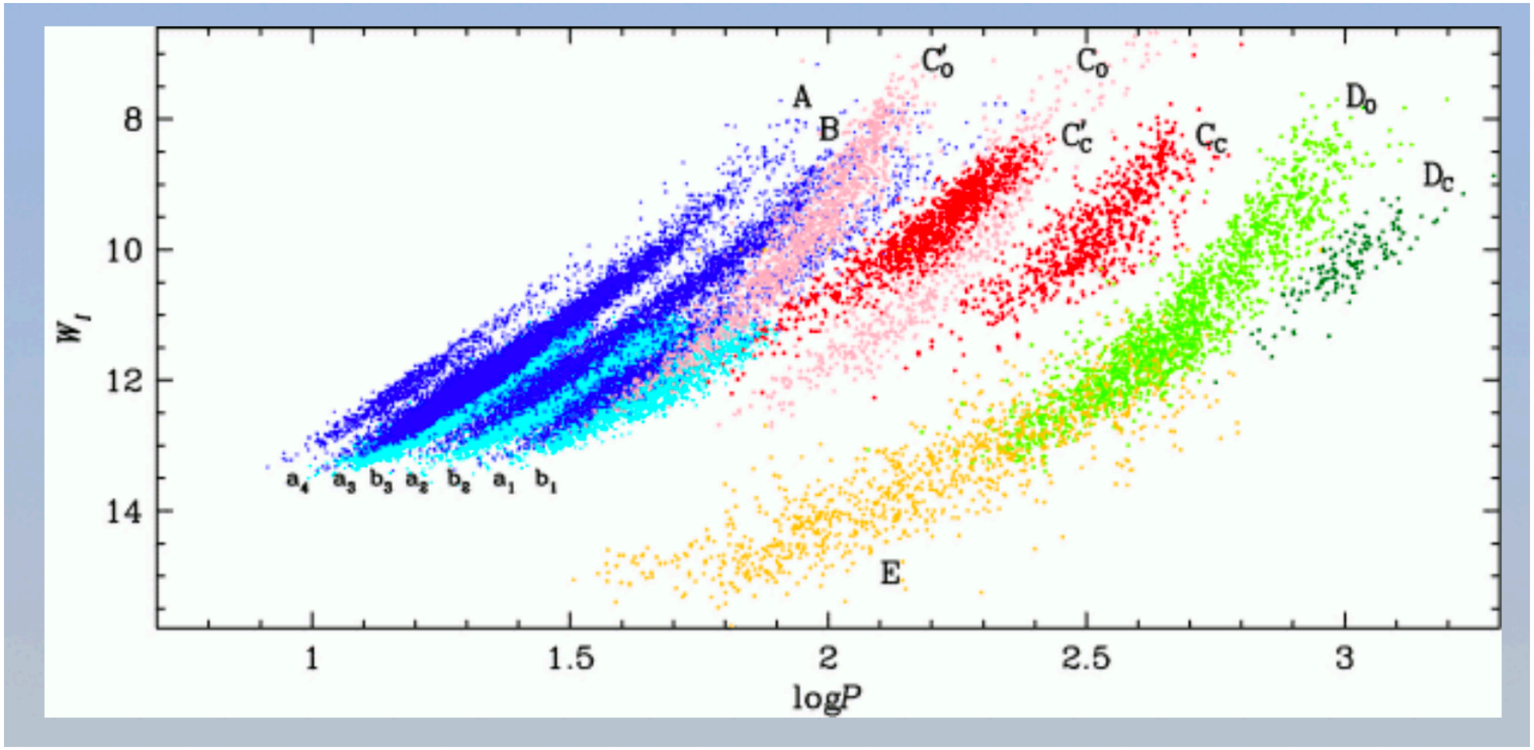
Lectures on /work/chuck/pci/wyklady (Paweł Ciecieląg)
https://www.camk.edu.pl/pl/archiwum/2019/08/14/cosmic-distance-scale/

Pulsating Stars



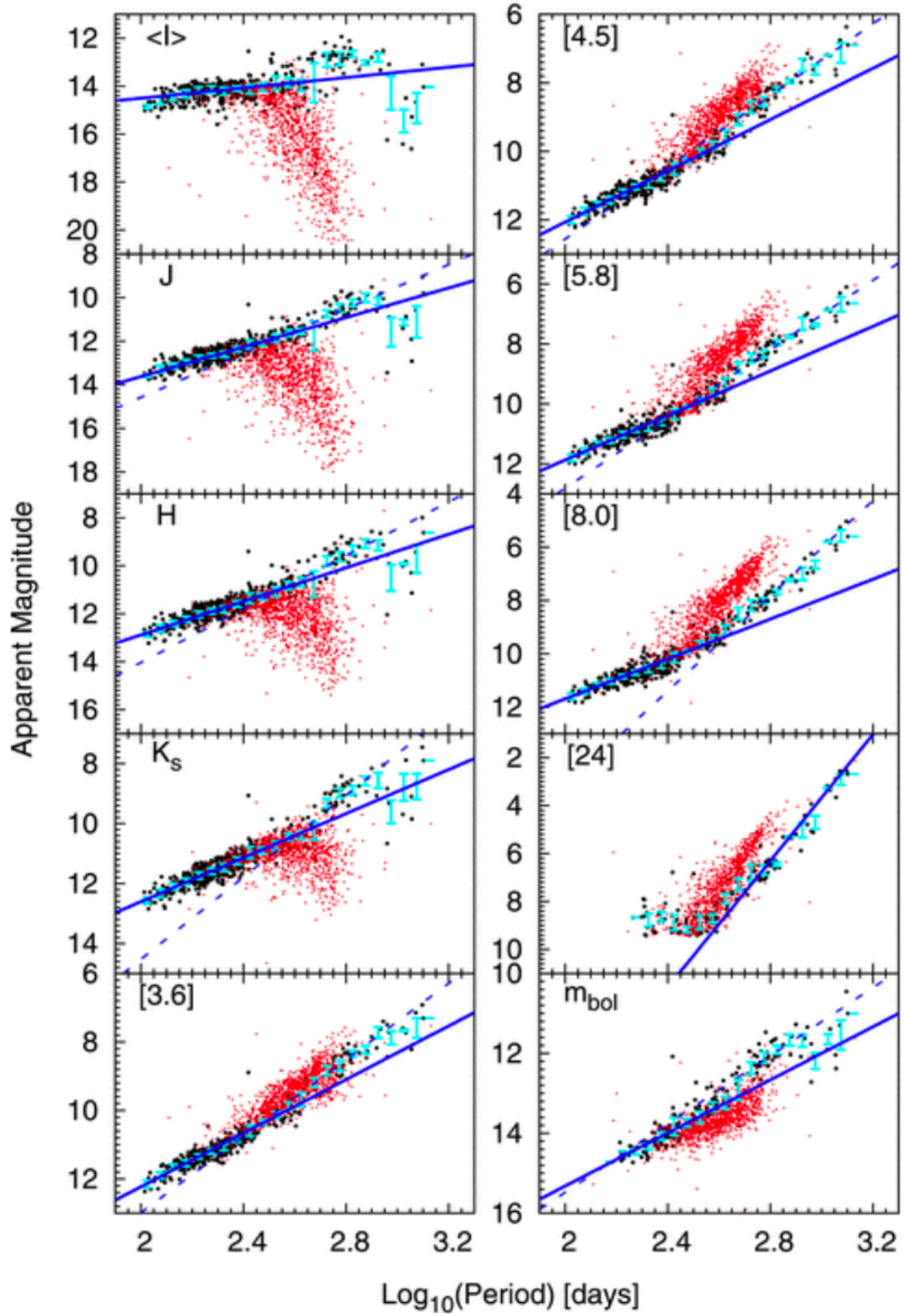


W_{JK}
8
10
12
14
1
1.5
2
2.5
3
logP
A
B
C'
C
D
E
a_4 a_3 b_3 a_2 b_2 a_1 b_1



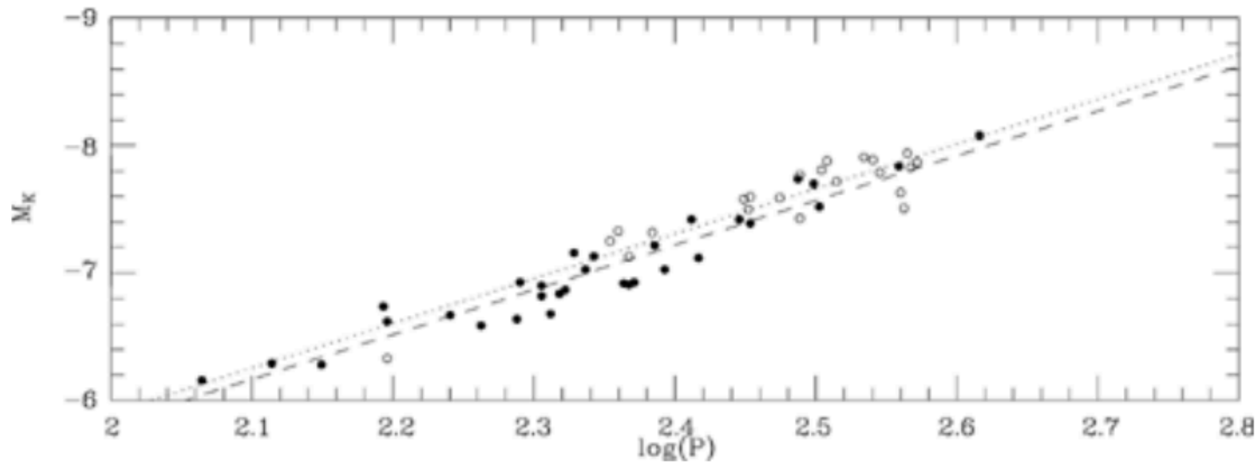
W_I
8
10
12
14
1
1.5
2
2.5
3
logP
A
B
C'_O
C_O
C'_C
C_C
D_O
D_C
E
a_4 a_3 b_3 a_2 b_2 a_1 b_1

Miras



Apparent Magnitude
Log10(Period) [days]
<I>
J
H
Ks
[3.6]
[4.5]
[5.8]
[8.0]
[24]
mbol

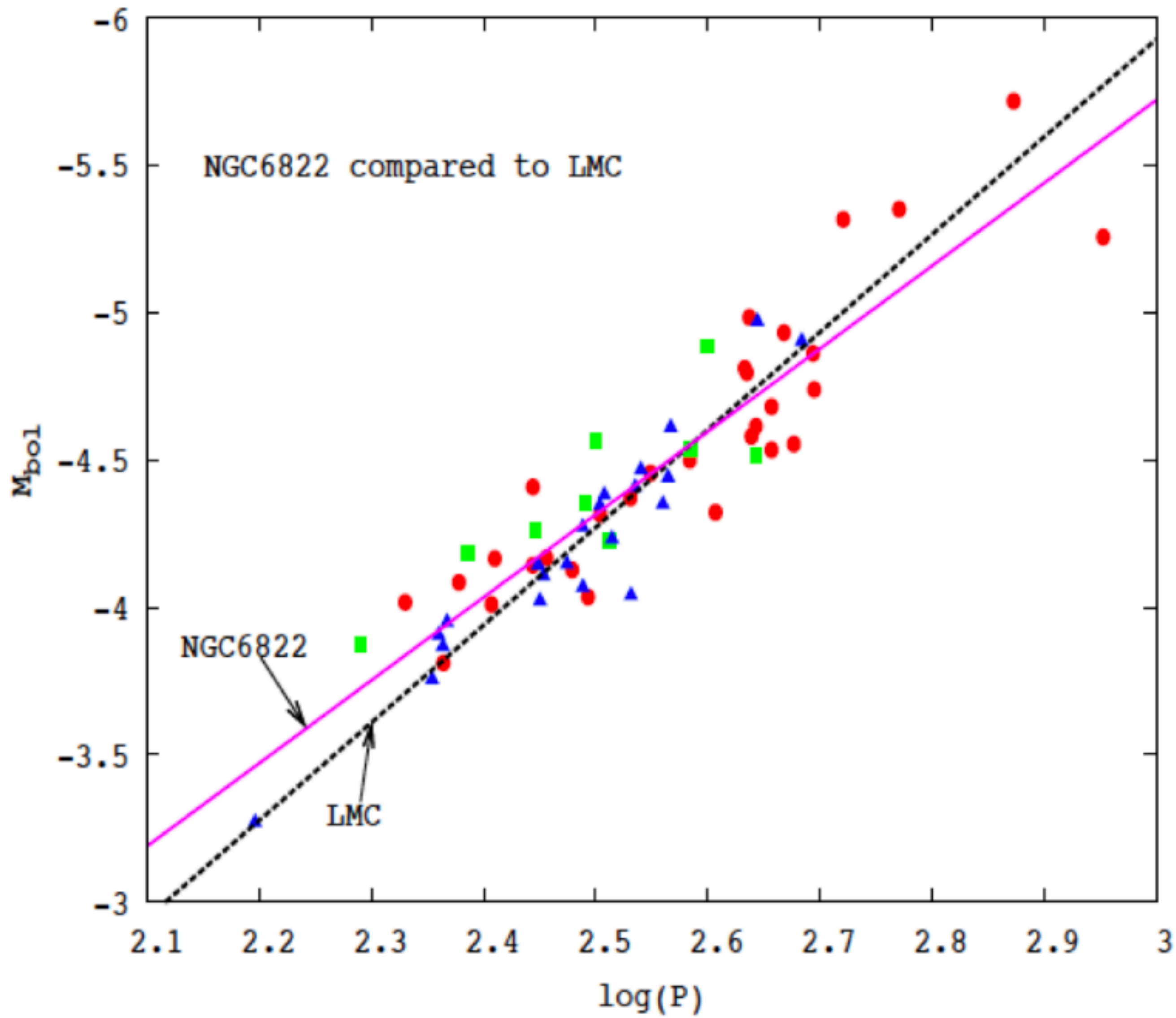
Miras



Scatter (statistical error) 10 times larger than Cepheids (note on Fitting M, logP and M, log(P-1))

Table 2 PL(K) relation Zero-Point (δ)

No.	δ	σ_δ	stars included
168	–7.27	0.14	Hipparcos π, $\Delta H_P > 1.5$ mag; excluding SP-red stars
42	–7.32	0.10	Hipparcos π, Miras + non-Miras with $\Delta H_P > 1.5$ mag; high weight π only
5	–7.08	0.17	VLBI π for OH-Miras
11	–7.34	0.13	Globular cluster Miras (cluster distances from Hipparcos subdwarfs)
29	–7.04	0.11	Miras in Galactic Bulge $(m - M)_0 = 14.44$ mag
	–7.18	0.11	Miras near the GC (Matsunaga et al. 2009)
31	–7.15	0.06	LMC O-rich Miras
16	–7.18	0.37	Hipparcos π, $\Delta H_P > 1.0$, hi weight C stars
22	–7.24	0.07	LMC C-rich Miras



NGC6822 compared to LMC
NGC6822
LMC
M_{bol}
log(P)
-6
-5.5
-5
-4.5
-4
-3.5
-3
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3

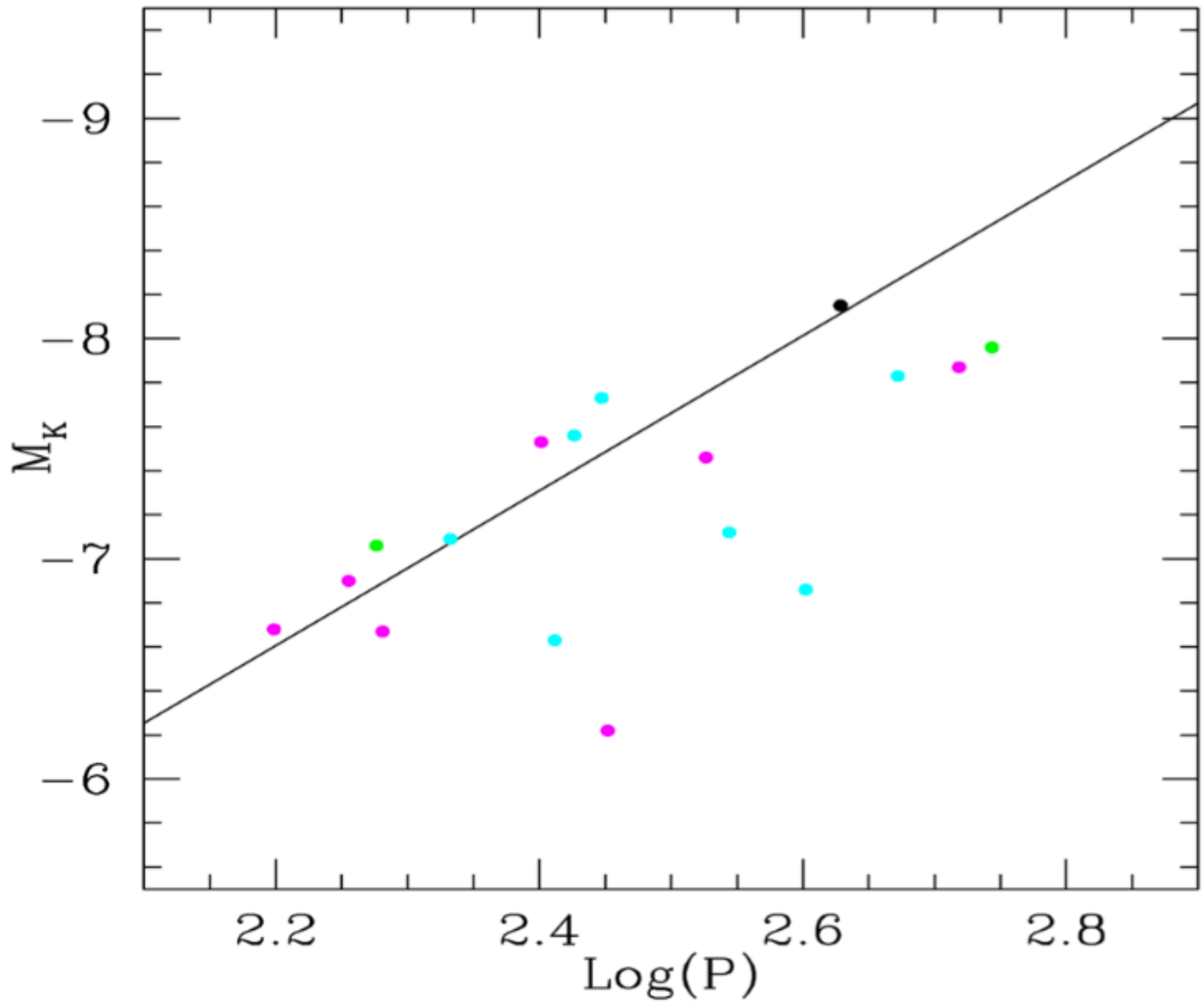
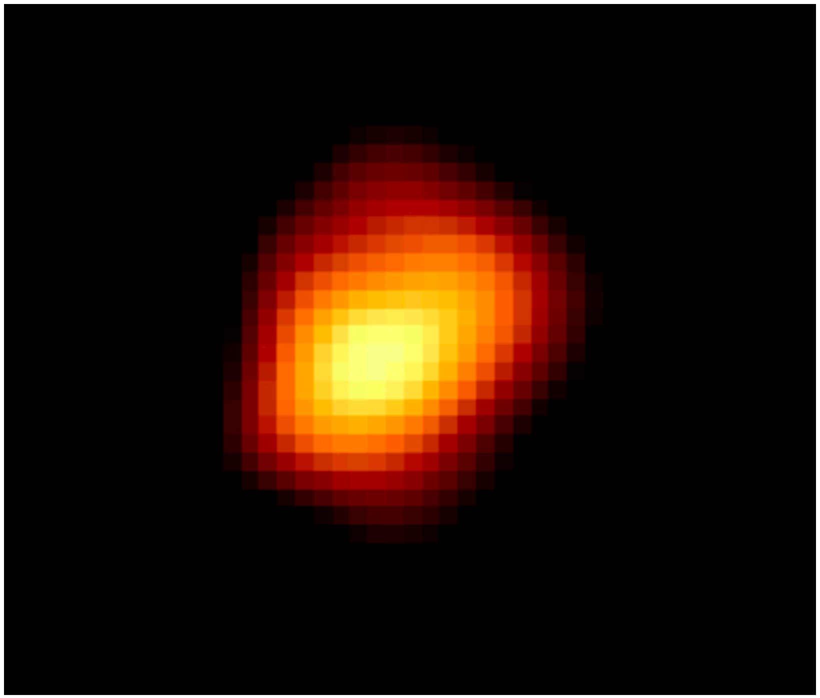


Fig. 6 PL(K) relation for Local Group Dwarfs: Fornax (7), Leo I (7), Sculptor (2) and Phoenix (1)

Miras



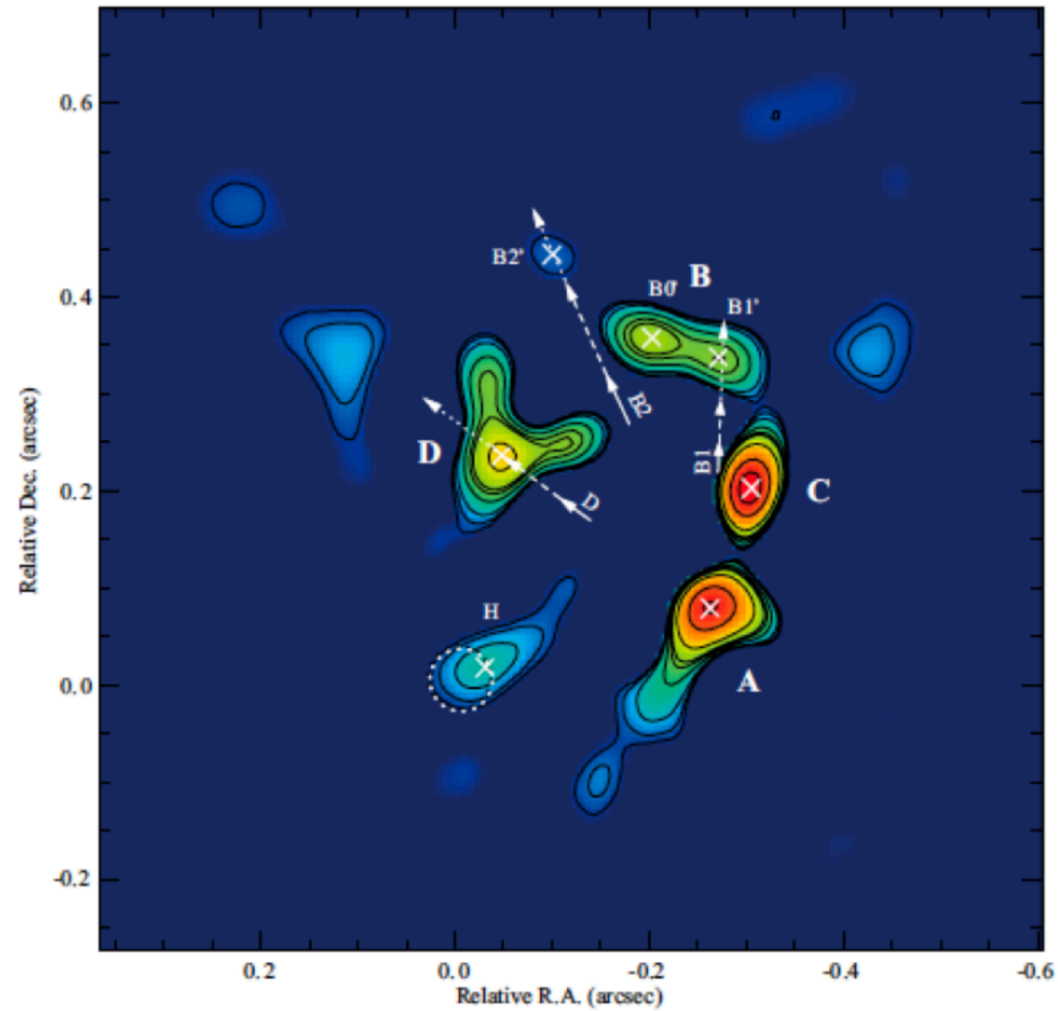
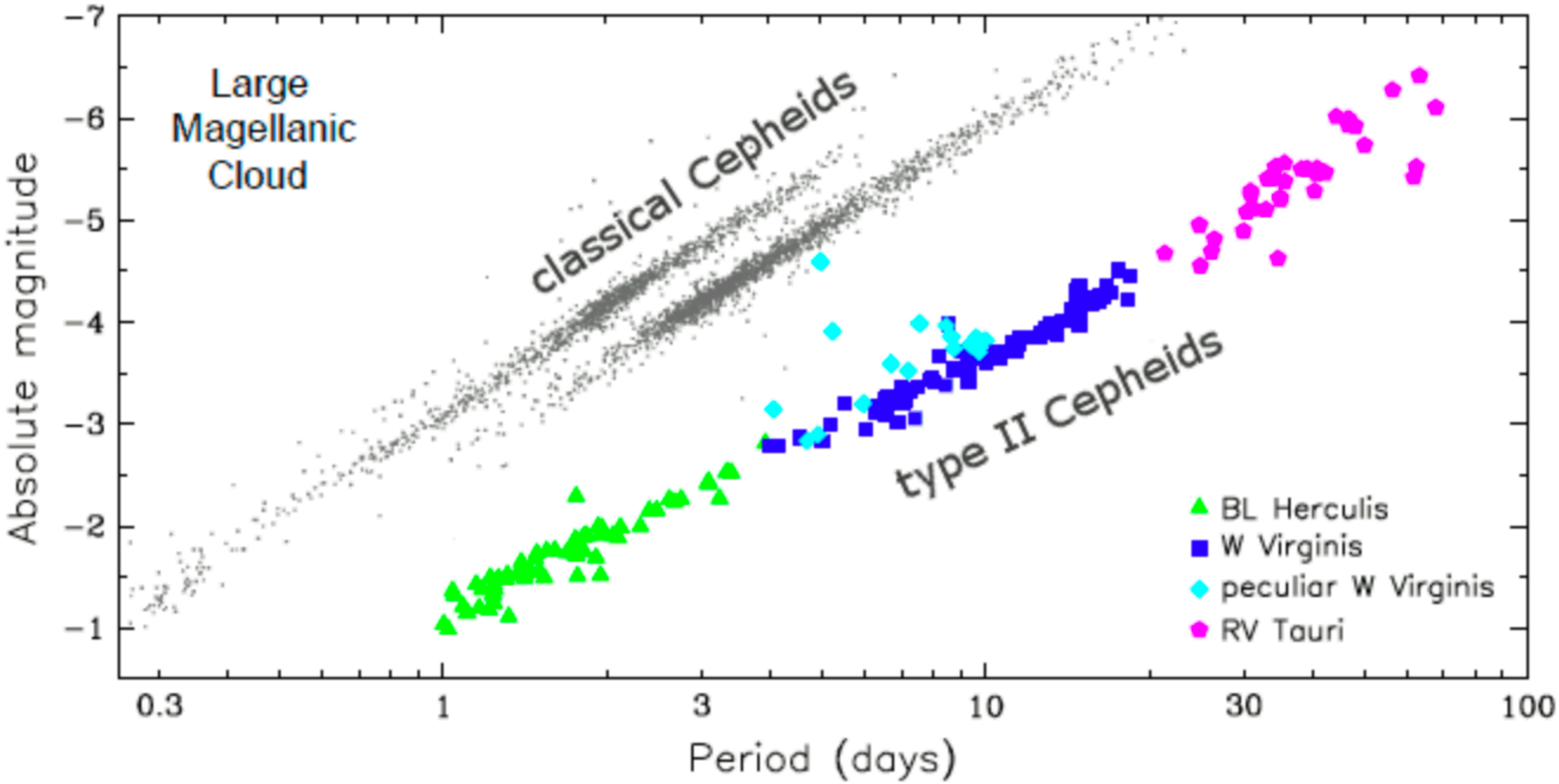


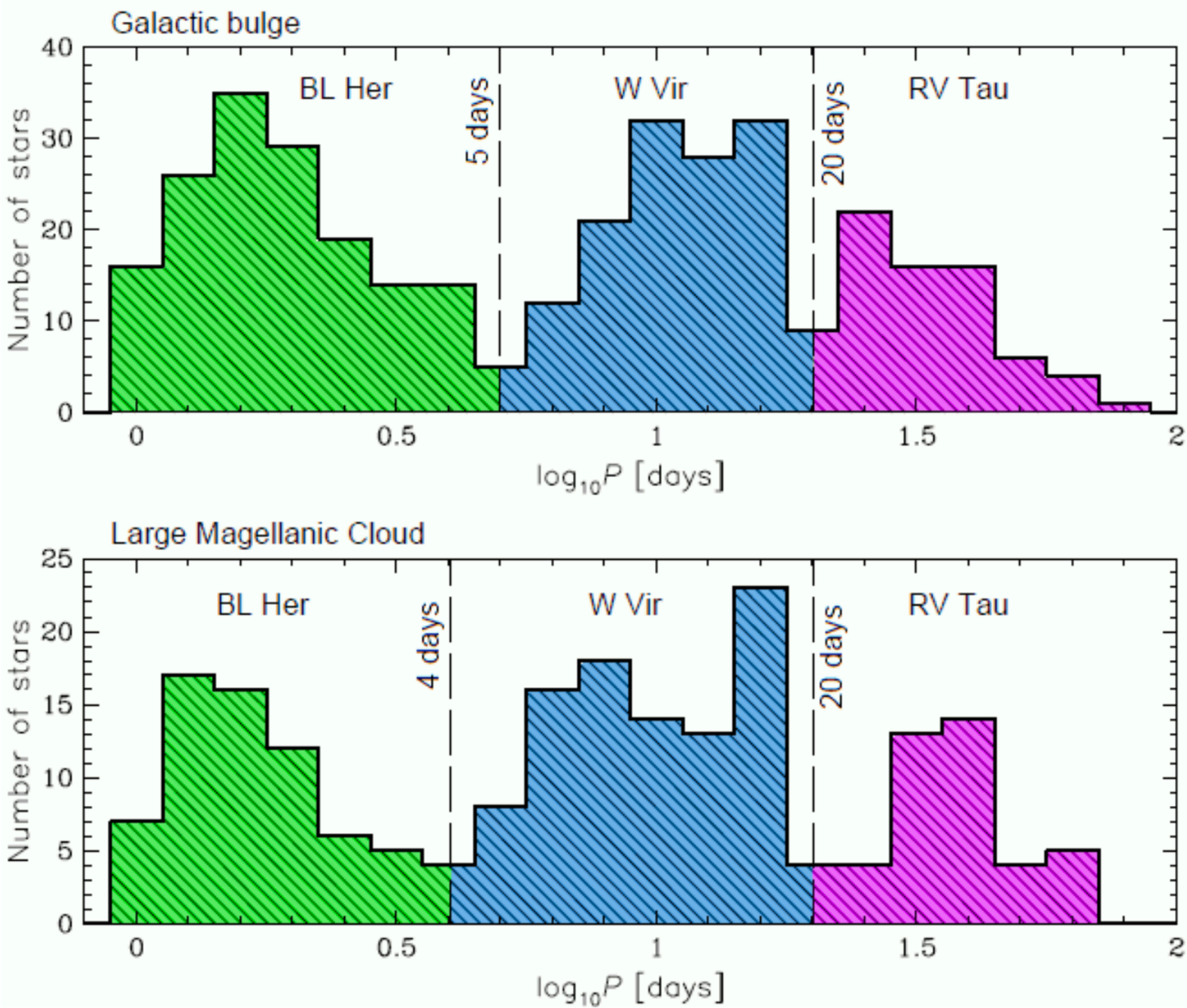
Fig. 9 *H* image of the C-rich Mira CW Leo showing only the high spatial frequencies, from Leão et al. (2006)

Anyway people try to use Miras for H0 determination e.g. Riess et al. 2019

Type II Cepheids

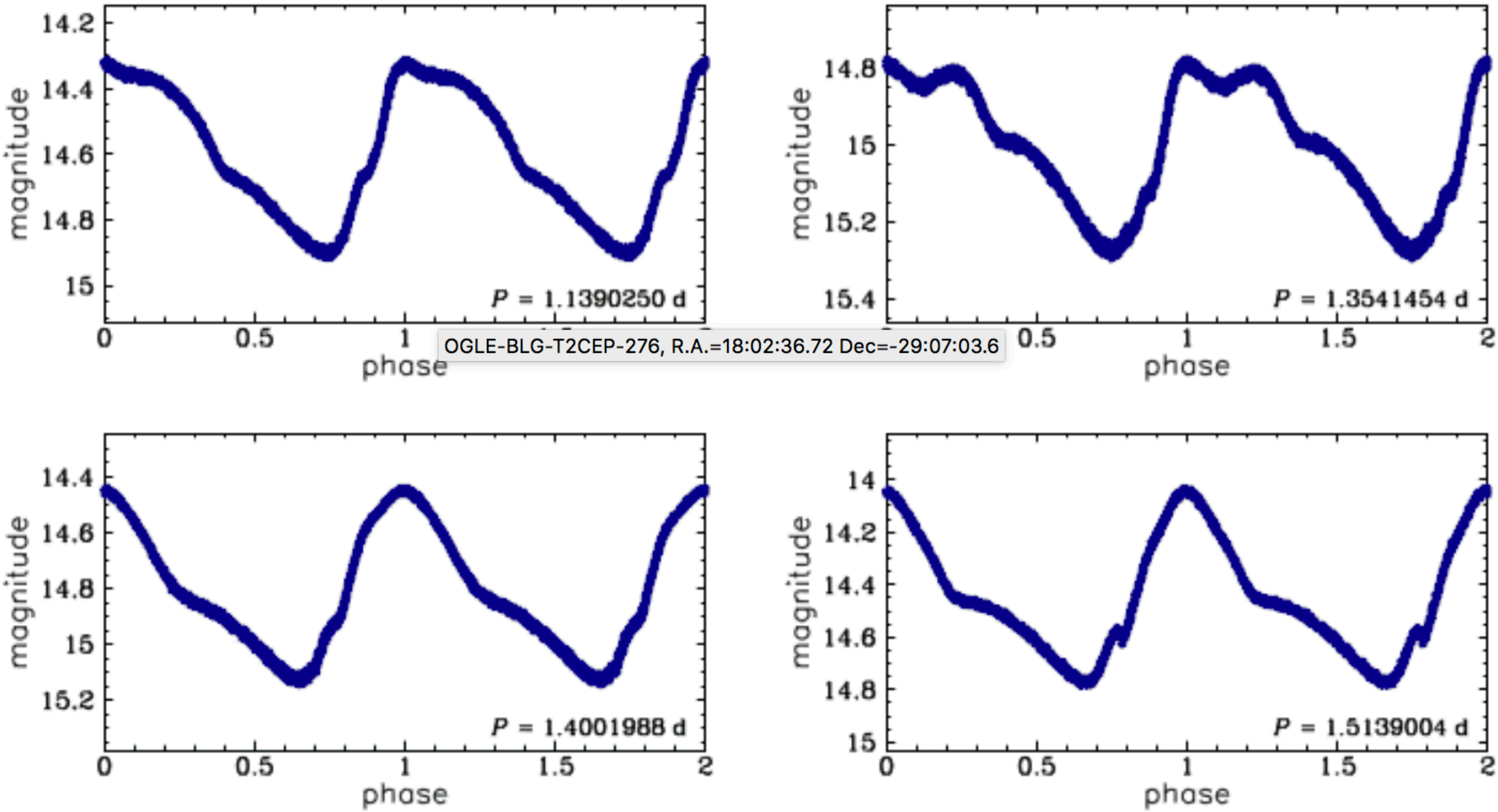


Type II Cepheids consist of three subclasses - **BL Herculis**, **W Virginis** and **RV Tauri stars** - each one in a different stage of stellar evolution. The shortest-period BL Herculis stars cross the pulsation instability strip in the HR diagram evolving from the horizontal branch toward the asymptotic giant branch. W Virginis stars cross the instability strip as a result of the helium-shell-flash episodes which occur during the asymptotic giant branch stage. The brightest type II Cepheids are the RV Tauri stars, which cross the instability strip evolving away from the asymptotic giant branch toward the white dwarf domain.



Galactic bulge
BL Her
5 days
W Vir
20 days
RV Tau
Number of stars
$\log_{10} P$ [days]
Large Magellanic Cloud
BL Her
4 days
W Vir
20 days
RV Tau
Number of stars
$\log_{10} P$ [days]

BL Her

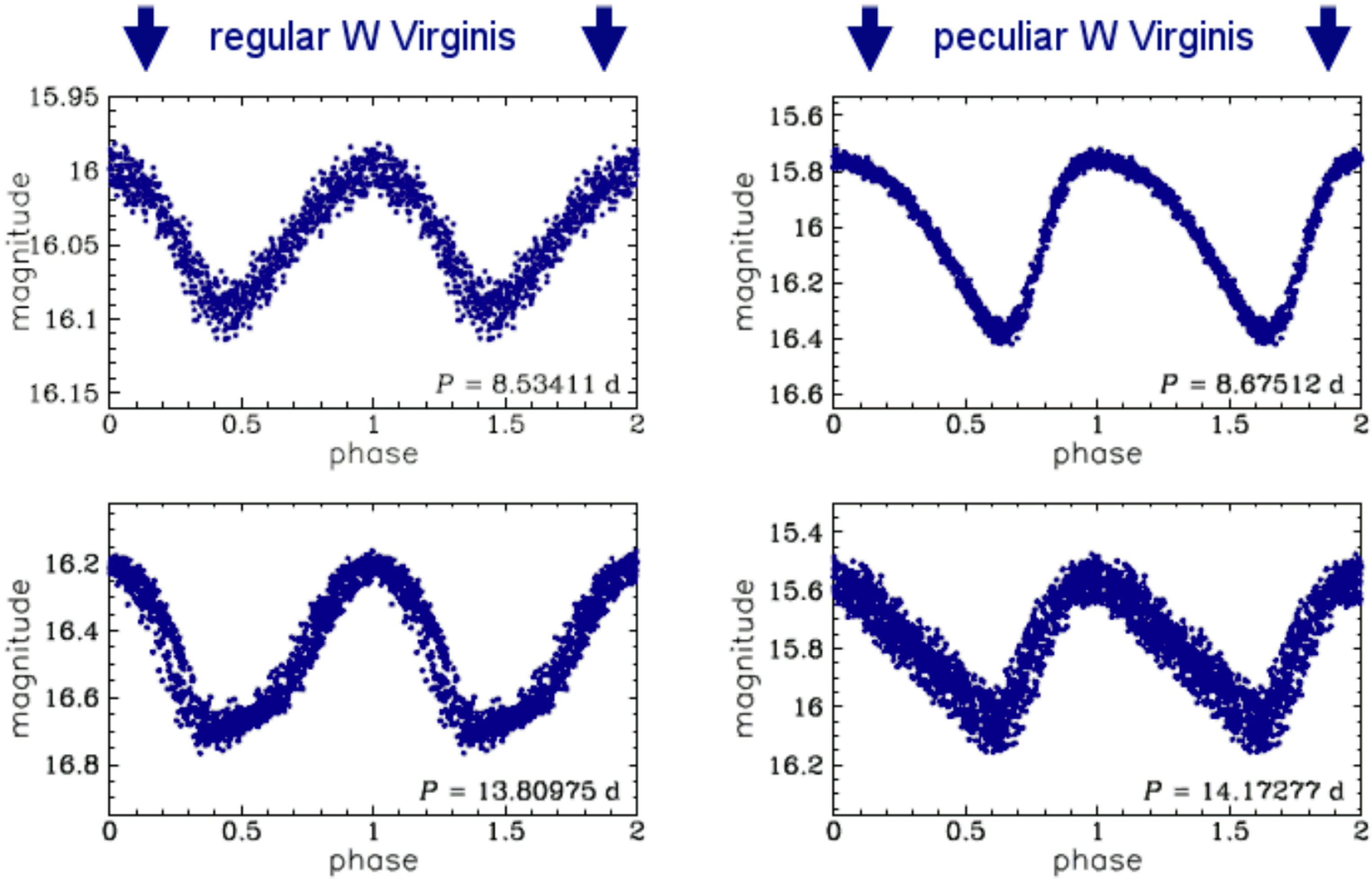


OGLE-BLG-T2CEP-276, R.A.=18:02:36.72 Dec=-29:07:03.6
magnitude
phase
P = 1.1390250 d
P = 1.3541454 d
P = 1.4001988 d
P = 1.5139004 d

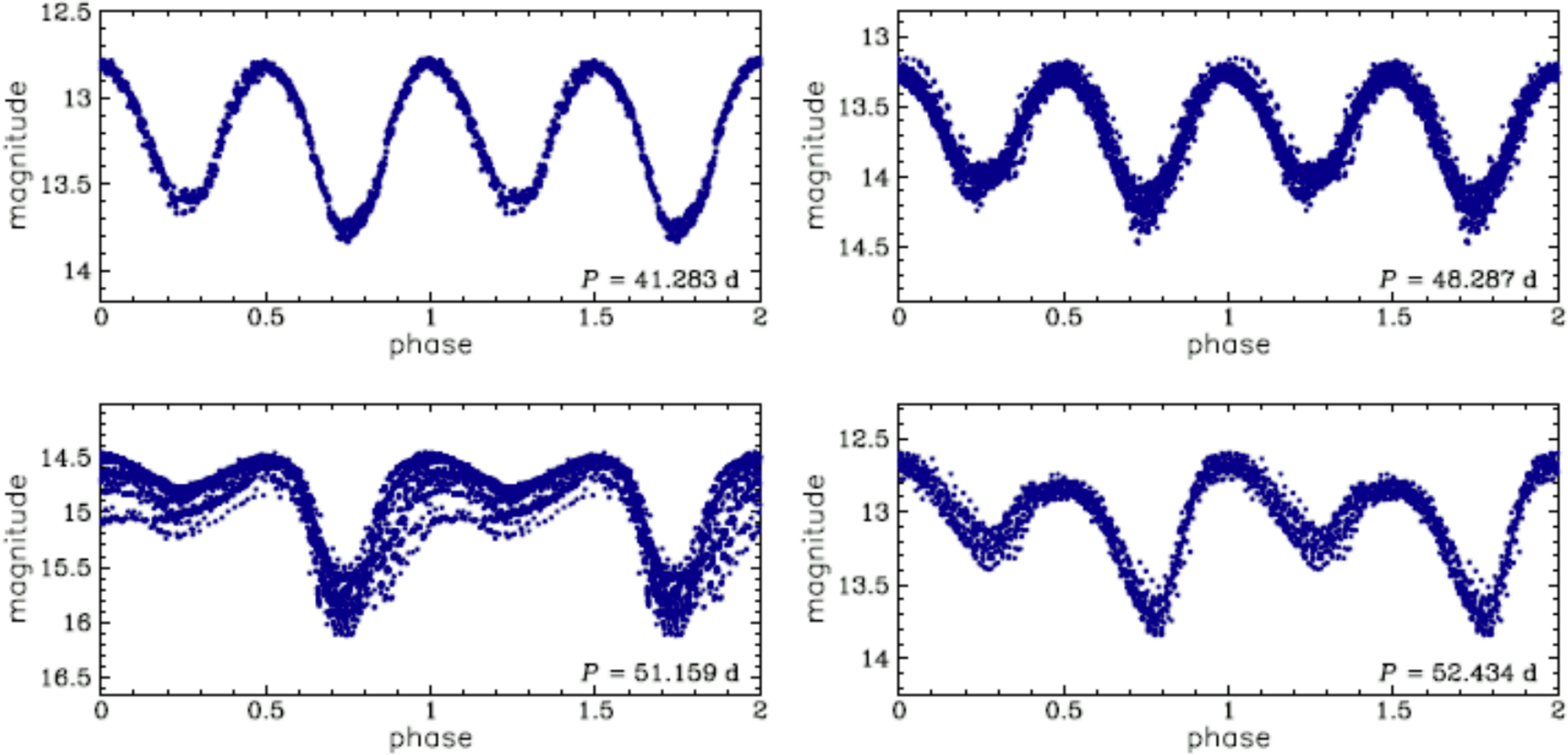
W Virginis

Peculiar W Virginis stars

In the Large and Small Magellanic Clouds we isolated a subclass of type II Cepheids stars, which we called peculiar W Virginis stars (**Soszyński et al. 2008**, **2010**). These stars are on average bluer and brighter than regular W Virginis stars, so peculiar W Virginis stars do not follow the period-luminosity relation of regular type II Cepheids. Besides, both subclasses of W Virginis stars are characterized by a different light curve morphology. Compare two pairs of regular and peculiar W Virginis stars with similar periods:



RV Tauri



Type II Cepheids

Well defined groups quite easy to identify

2 mag fainther than classical Cepheids and less frequent

Only BL Her and W Vir useful for distance determination

Caution with peculiar W Vir

Metallicity effect not so well studied so far

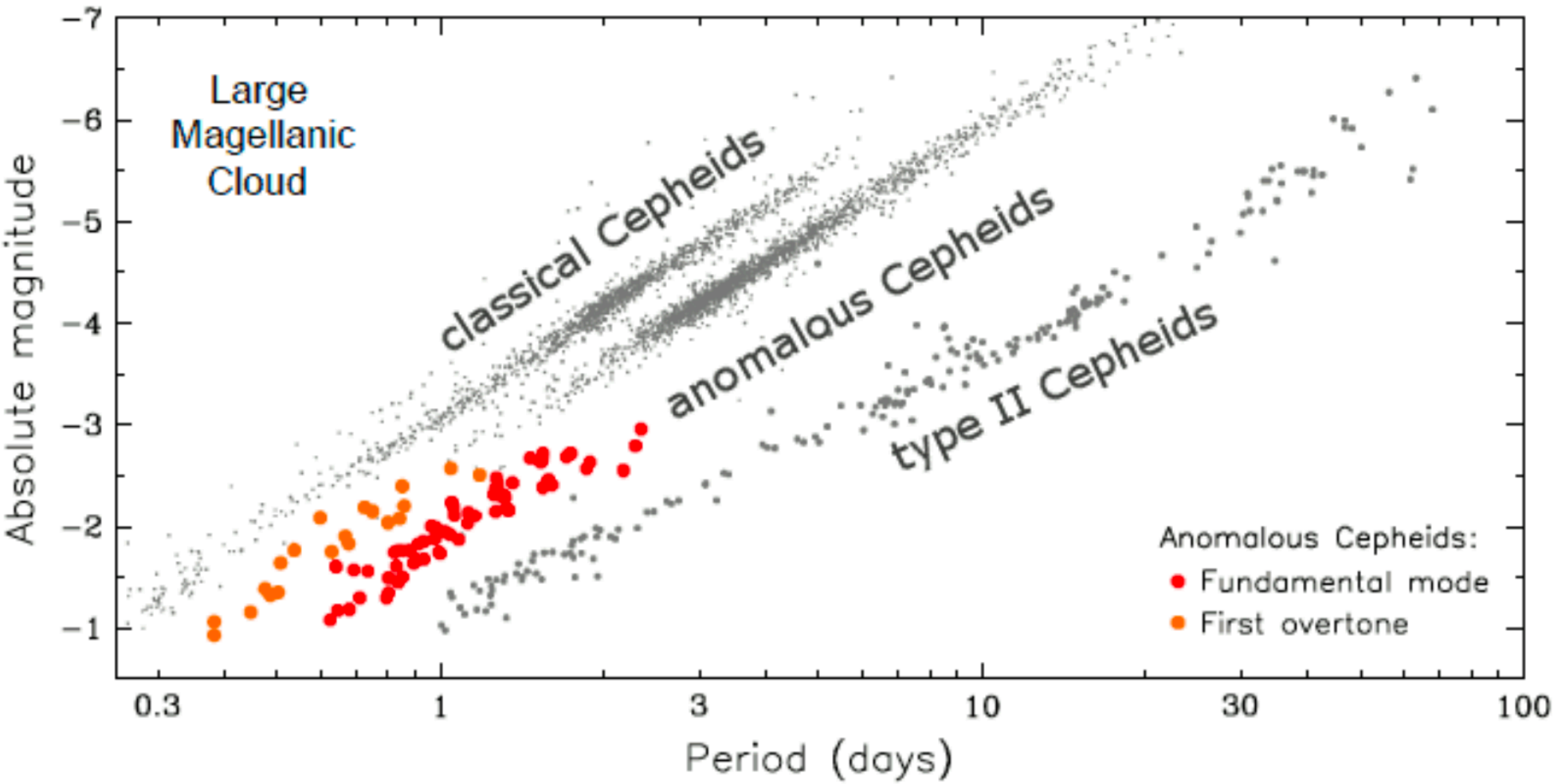
Zero point (just two had reasonable Hipparcos parallaxes and one of them is peculiar ...)

BW / p-factors very scarse studies (e.g. Pilecki et al. 2017)

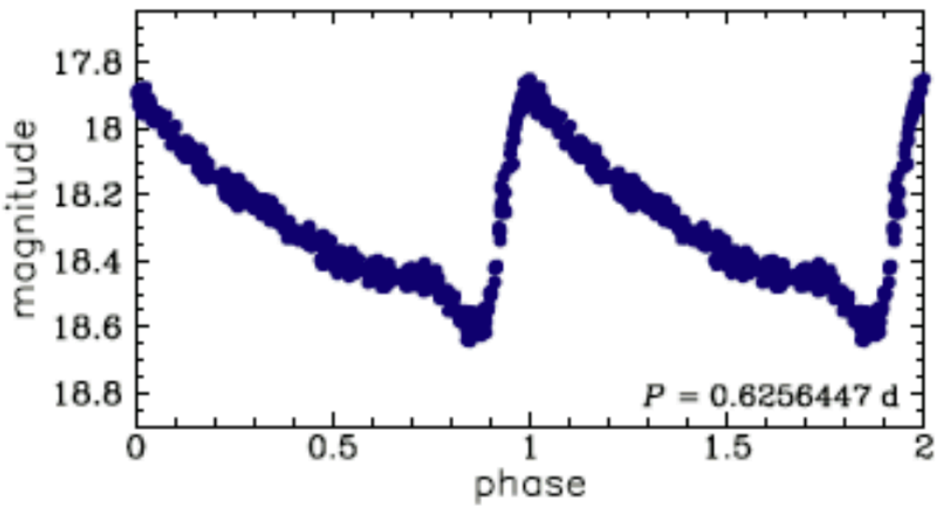
Very inetresting for determining distances to dwarf spheroidal galaxies / globular clusters were we do not observe classical Cepheids

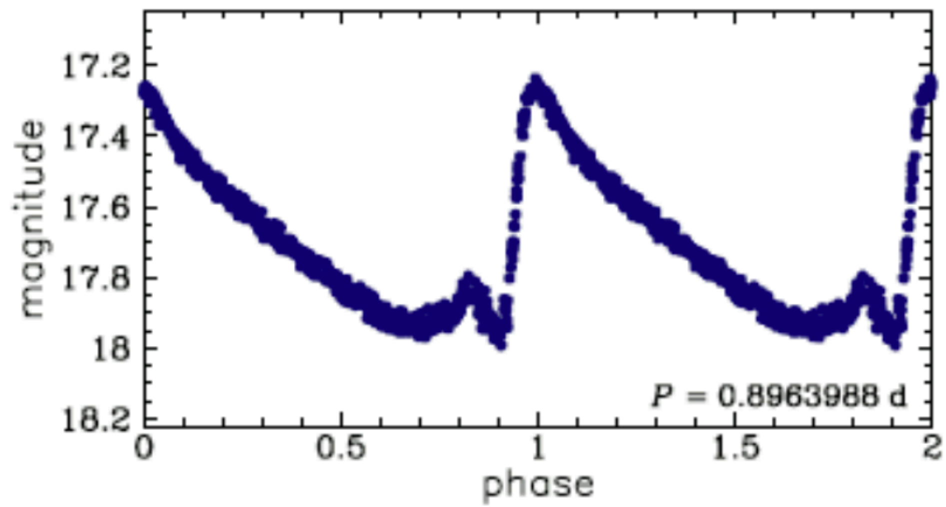
Independent technique (other population, so population effects should be different)

Anomalous Cepheids

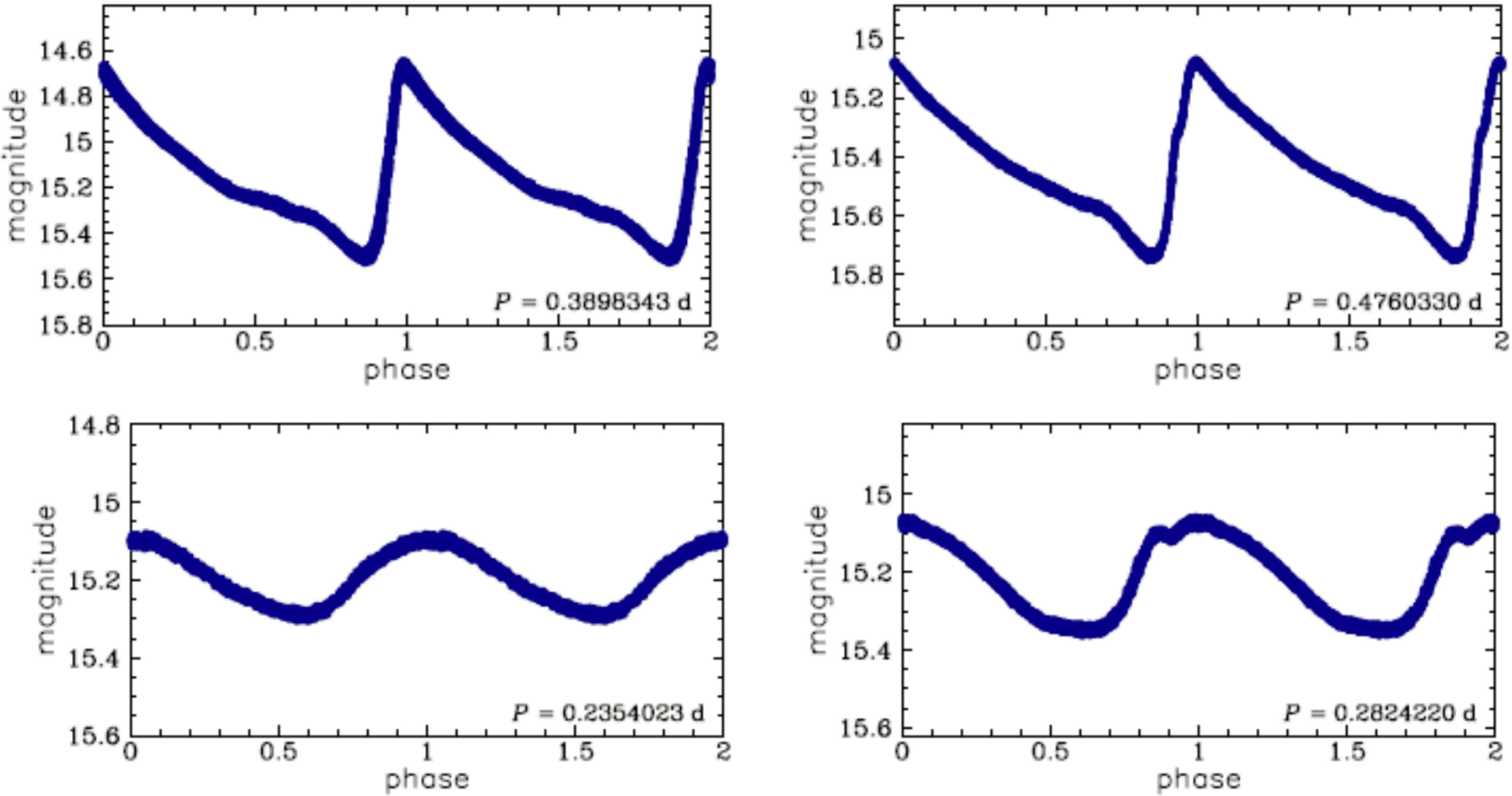


Anomalous Cepheids pulsating in the fundamental mode have periods from a few hours to over 2 days. They have asymmetric light curves with a rapid rise to maximum and a slow decline. Many of the fundamental-mode pulsators exhibit a small bump just before the rise to maximum light. The light curves of anomalous Cepheids are very similar to the light curves of **classical Cepheids** (for periods above 1 day) and **RR Lyrae stars** (below 1 day), and the distinction between these types of pulsating stars is very difficult, if not impossible, when objects are at different distances and there is no information about their absolute magnitudes. Below we present OGLE-IV *I*-band light curves of four anomalous Cepheids from the Large Magellanic Cloud. Move the mouse pointer over the image to see the designation and J2000 equatorial coordinates of a given star.



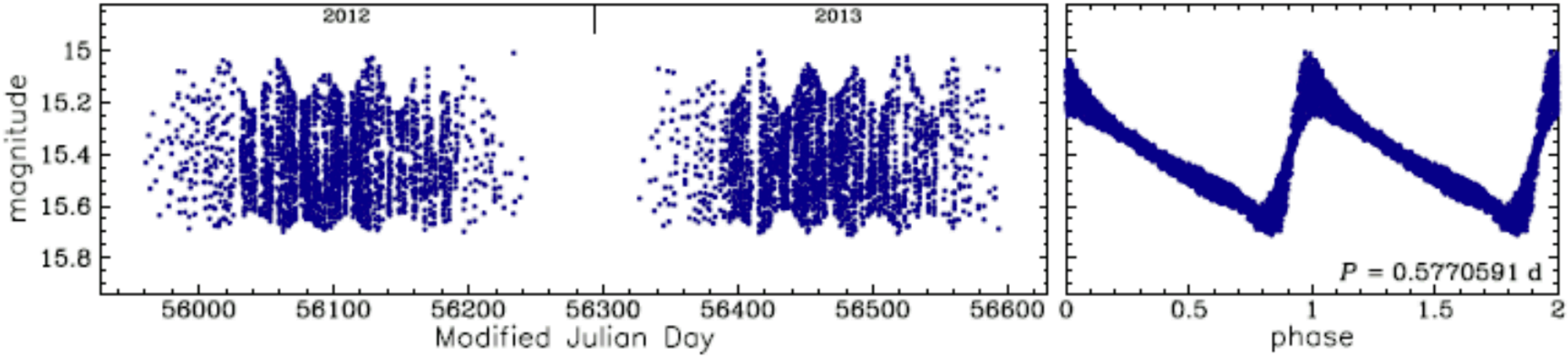


RR Lyrae



magnitude
phase
P = 0.3898343 d
P = 0.4760330 d
P = 0.2354023 d
P = 0.2824220 d

The RR Lyrae variables above show stable or nearly stable light curves. However, a significant number of RRab stars (up to 50% according to **Jurcsik et al. 2009**) exhibit long-term modulations of the amplitudes and phases of their light curves. This phenomenon was discovered by Sergey Blazhko in 1907 and the origin of this effect remains a mystery to the present day. The Blazhko modulation of light curves may be strictly periodic (with periods ranging from days to years), multi-periodic, or irregular. Below we show four RRab stars with conspicuous Blazhko effects. To display the amplitude changes, left panels present unfolded light curves collected over two years - 2012 and 2013. Right panels show the same light curves folded with the pulsation periods.

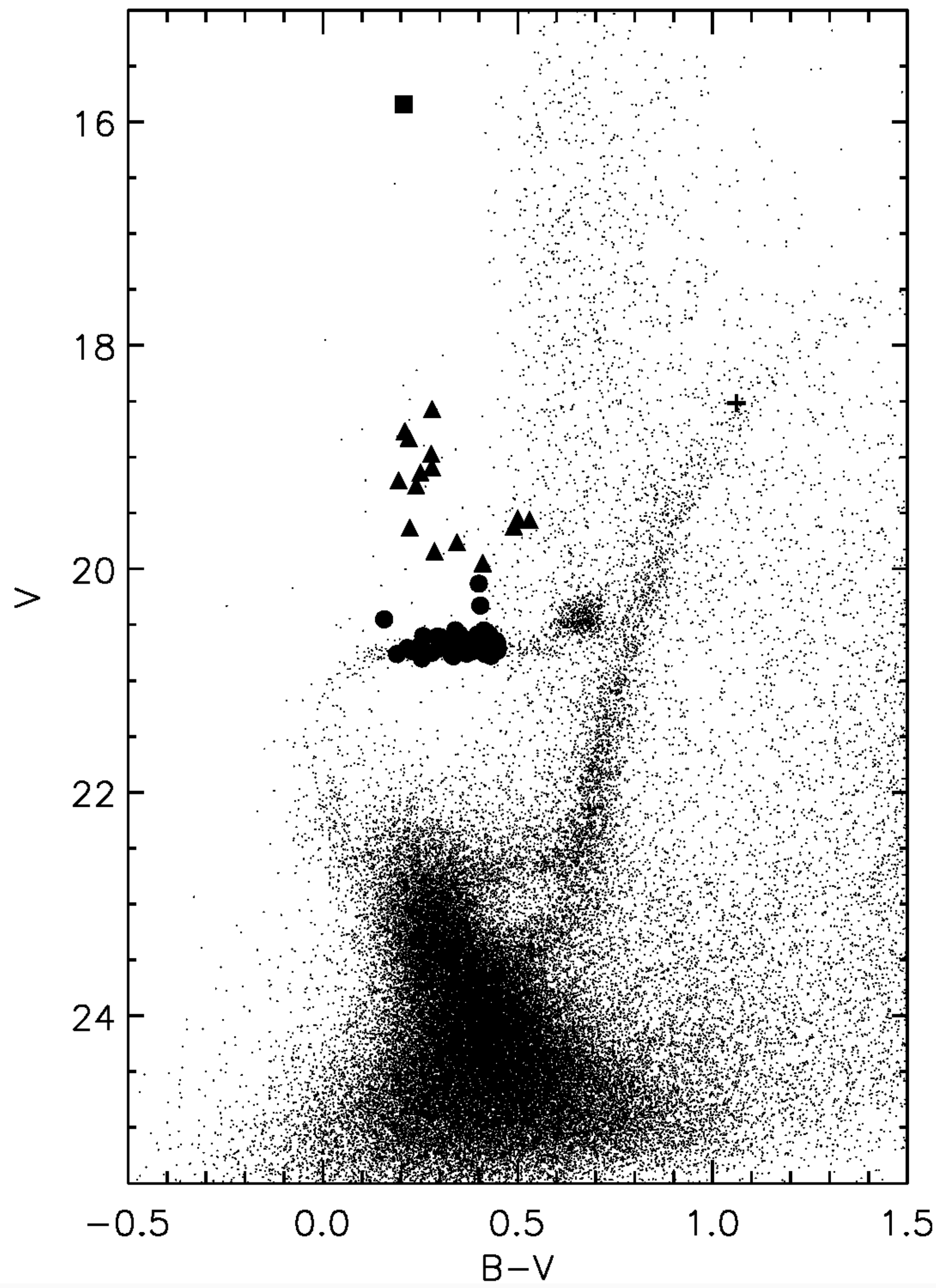


RR Lyrae

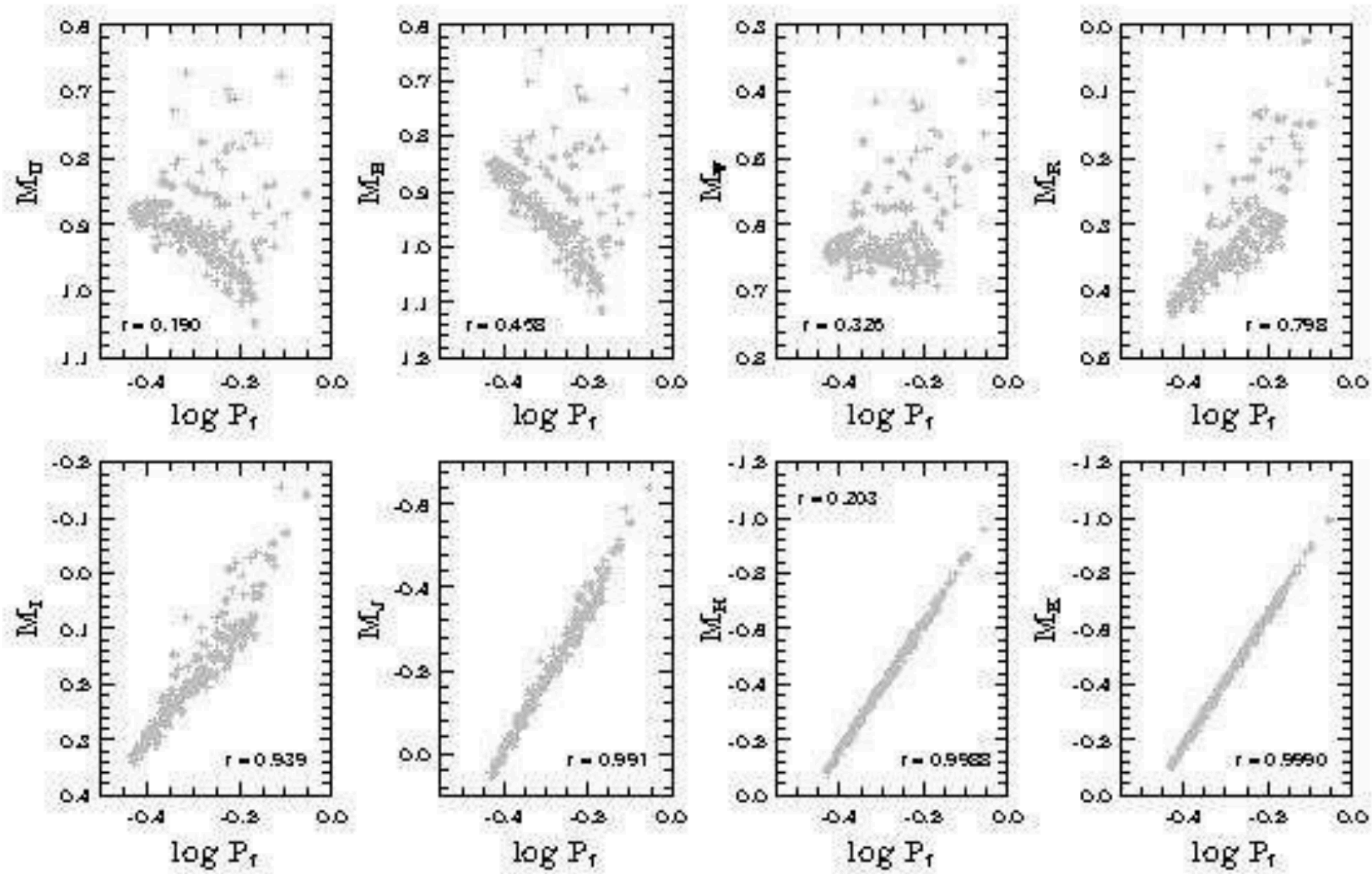
Ancient population

Frequent in GCs and all galaxies

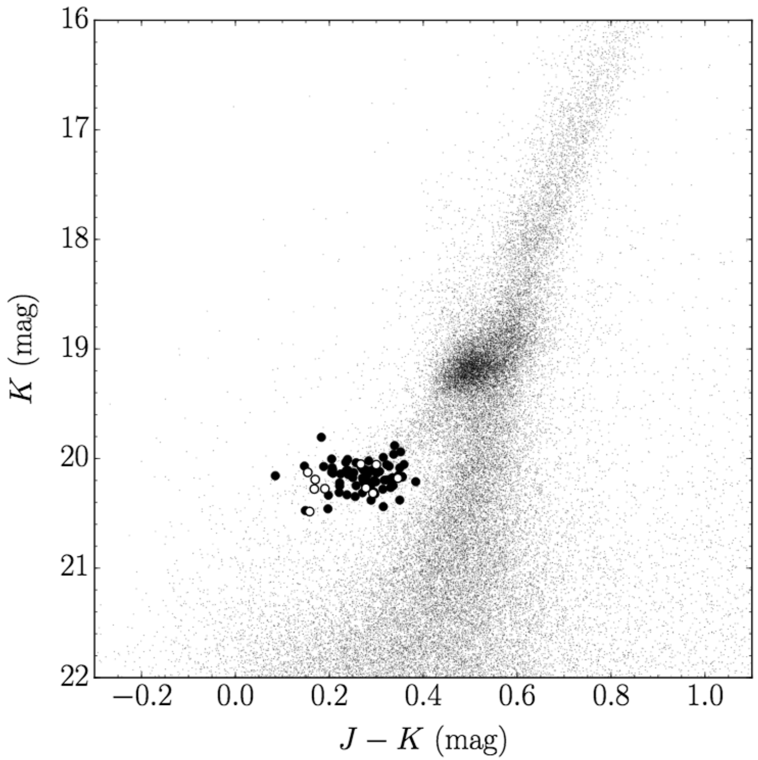
Easy to identify

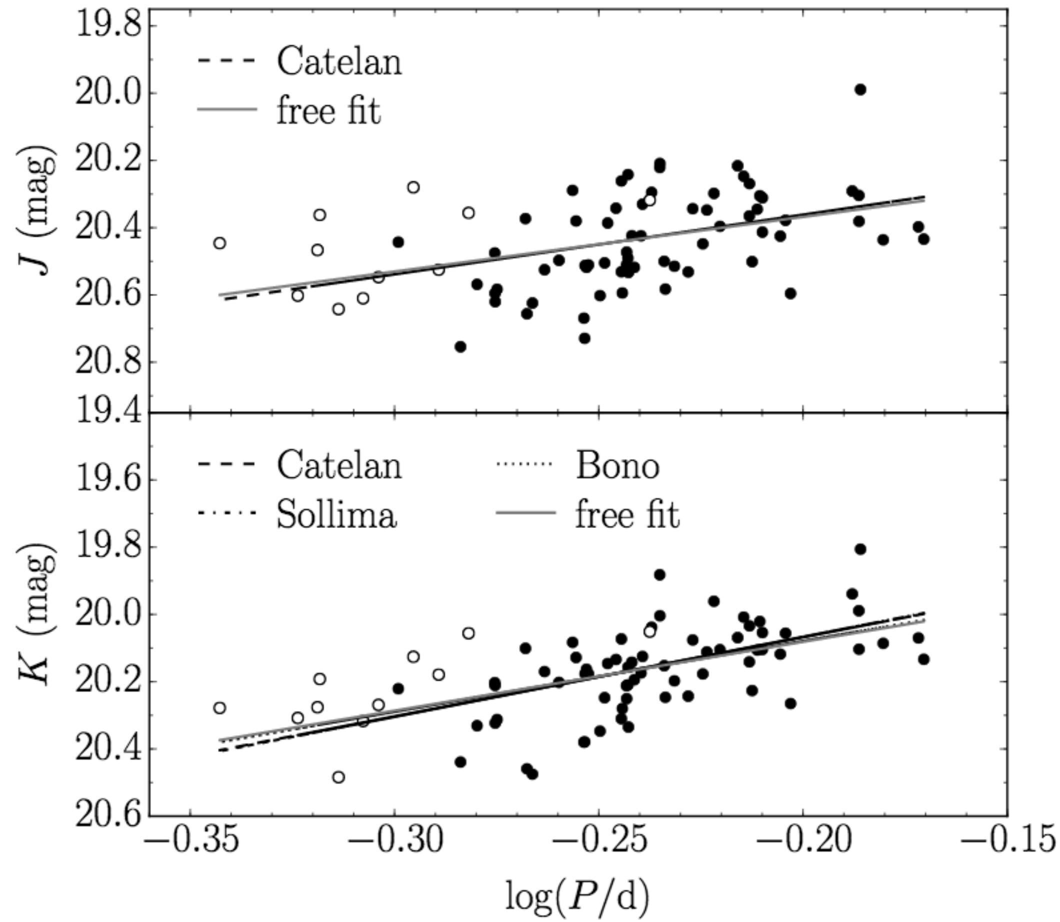


RR Lyrae PL relations



An example: distance to Fornax galaxy
Karczmarek et al. 2017





$$M_J = -1.773 \log P + 0.190 \log Z - 0.141$$
(Catelan et al. 2004)

$$M_K = -2.353 \log P + 0.175 \log Z - 0.1597$$
(Catelan et al. 2004)

$$M_K = -2.101 \log P + 0.231\,[\mathrm{Fe/H}] - 0.77$$
(Bono et al. 2003)

$$M_K = -2.138 \log P + 0.08\,[\mathrm{Fe/H}] - 1.07$$
(Sollima et al. 2008)

Table 5. True distance moduli derived from different calibrations.

Filter	K	K	K	J
Calibration	Sollima	Bono	Catelan	Catelan
$(m-M)_0$	20.787	20.834	20.820	20.837
Statistical error	0.013	0.013	0.013	0.015
Systematic error	0.116	0.084	0.076	0.083

RR Lyrae resume

Robust tool for 5% distance determination

Soon better once the ZP is well calibrated

Metallicity estimation (quite difficult given faint magnitudes)

Usually proxy from RGB morphology.

Problem with mass

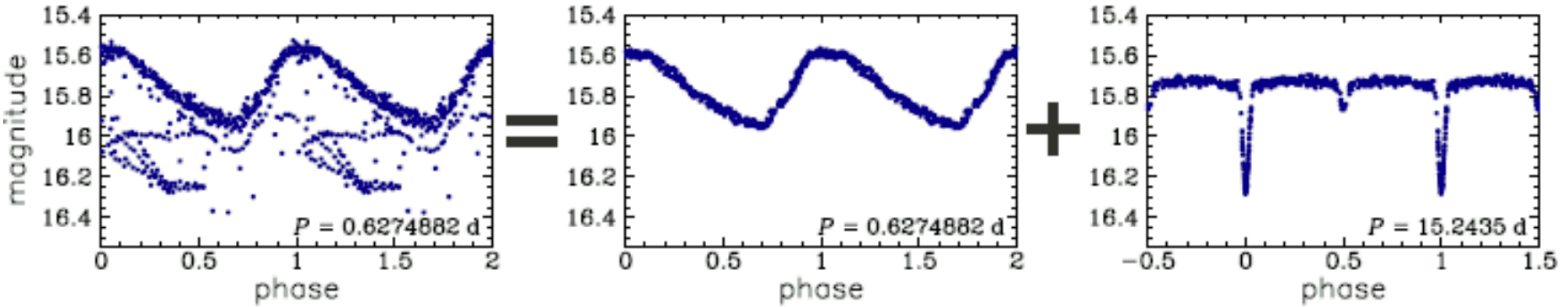
Theoretical models differ by some 30 %

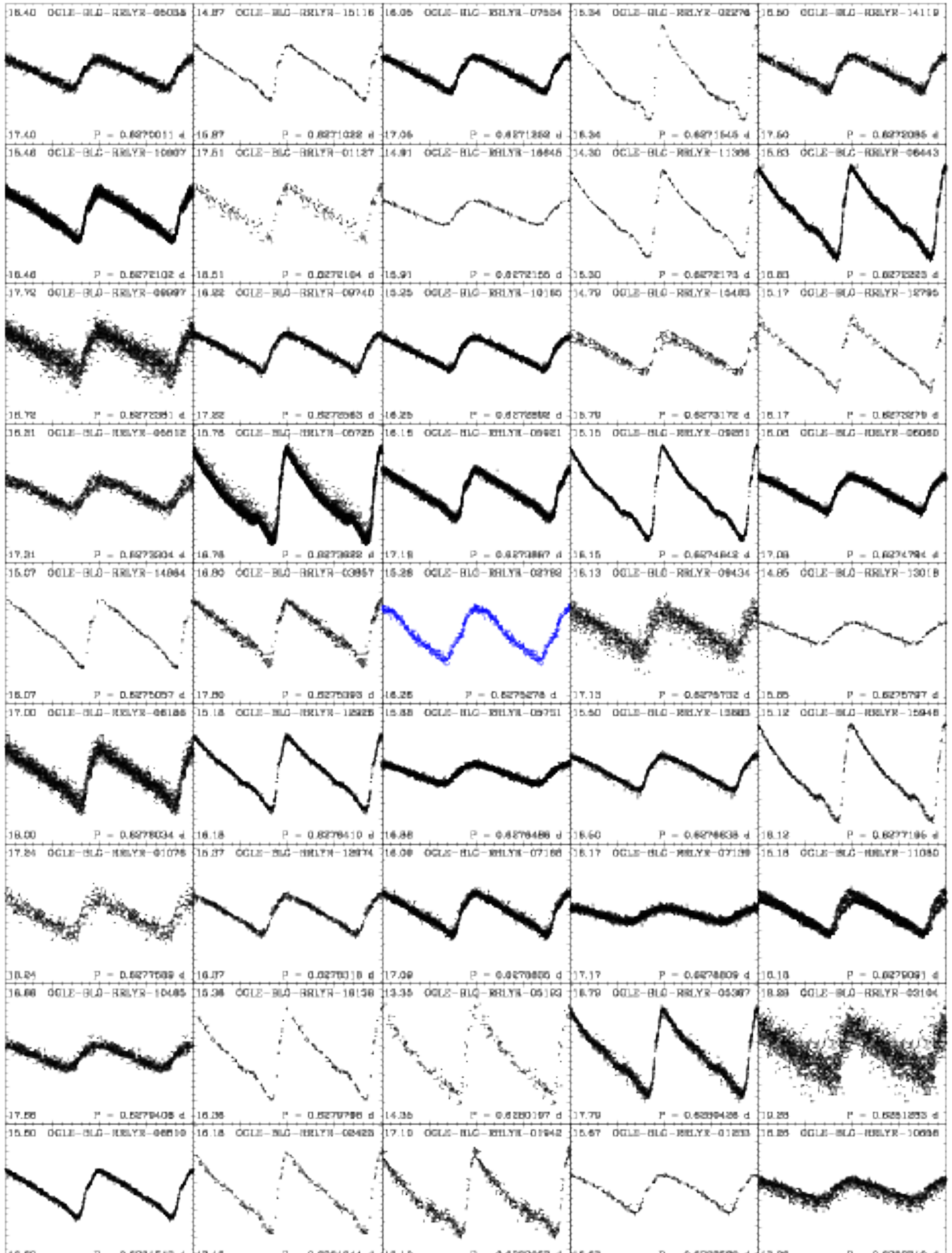
No RR Lyrae in eclipsing binary known so

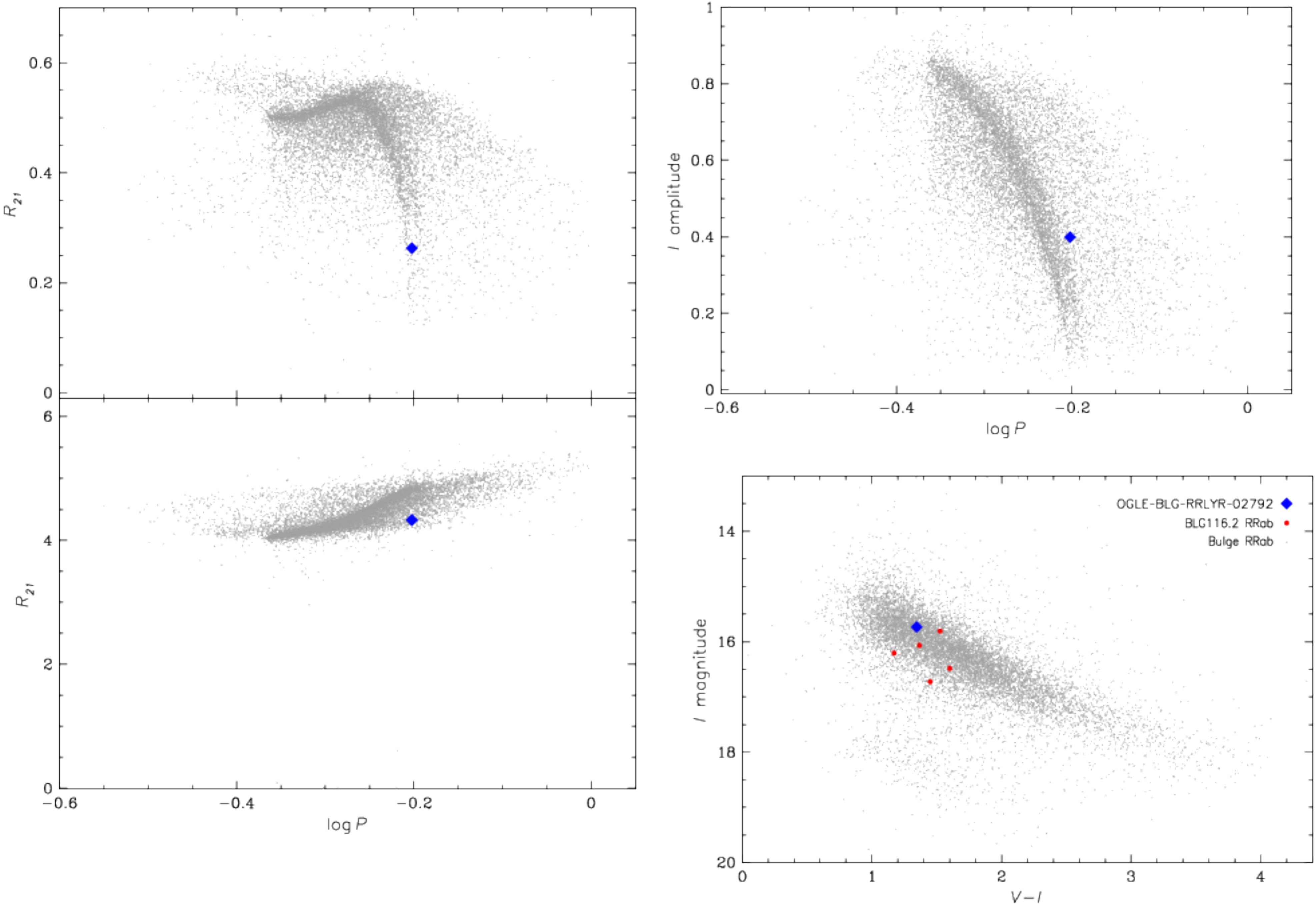
We do not have empirical determinations of physical parameters of RR Lyrae stars.

Eclipsing RR Lyrae !

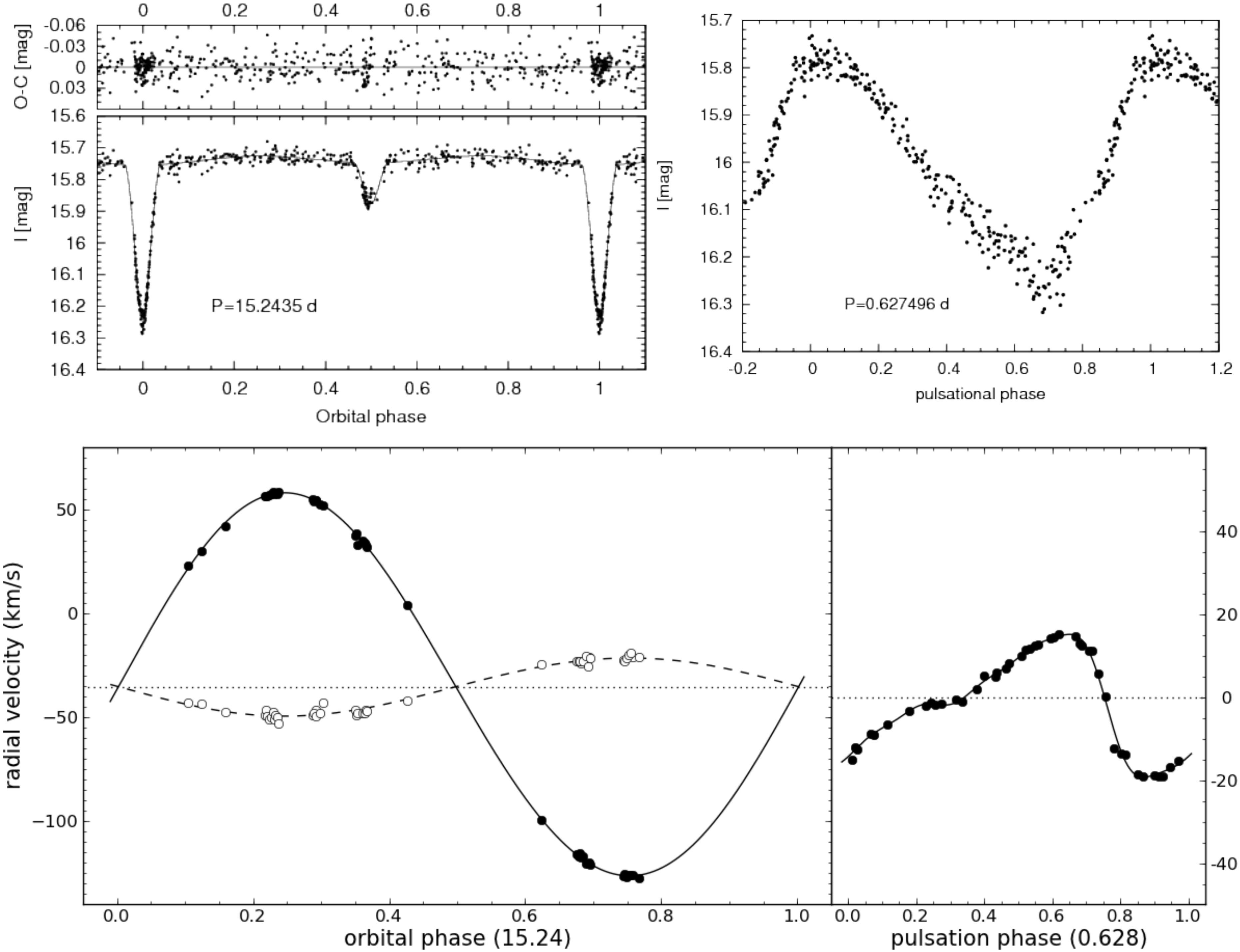
Soszyński et al. Acta Astronomica vol. 61 p. 1-23





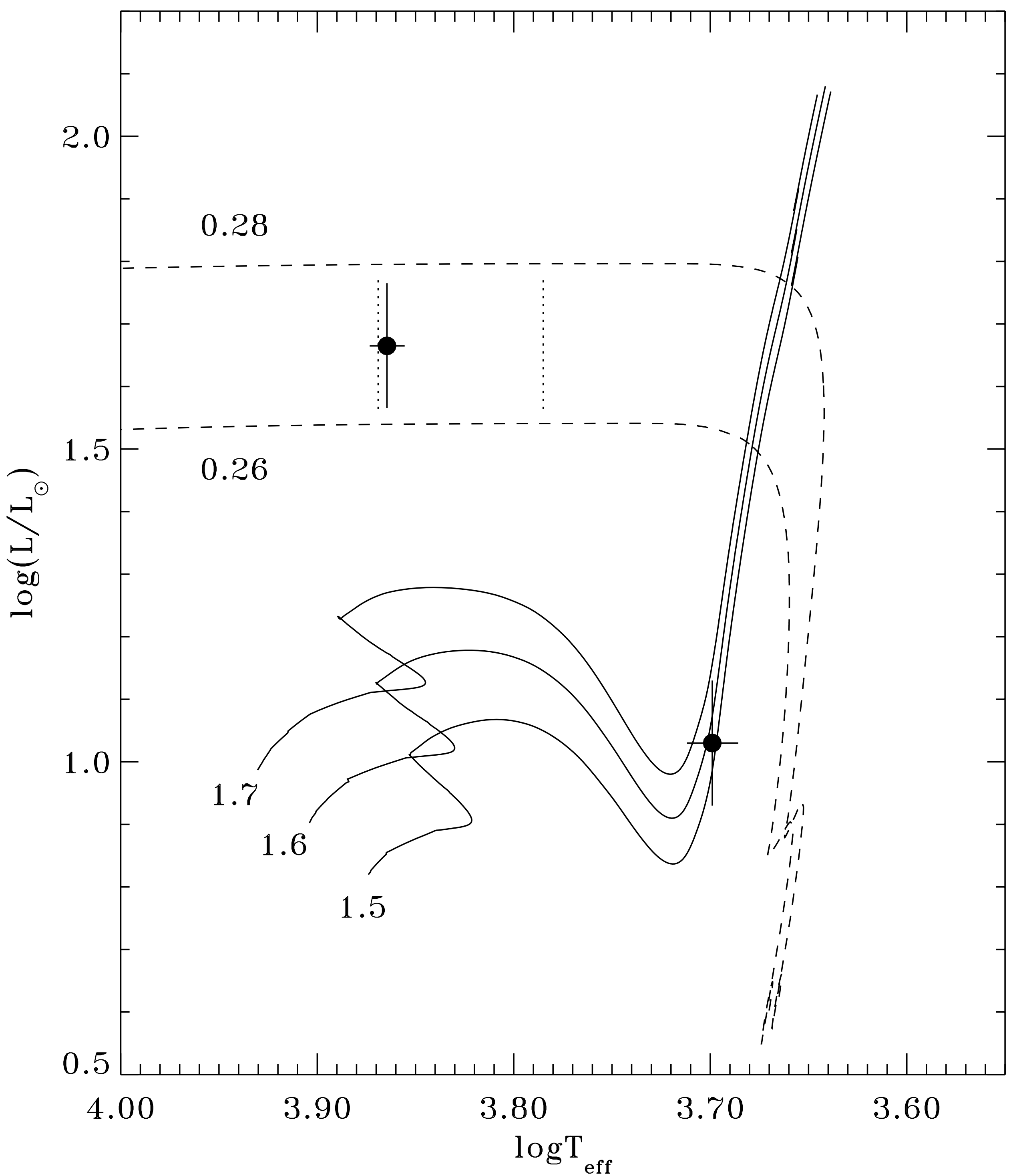


R_{21}
0.6
0.4
0.2
0
6
4
2
0
R_{21}
−0.6
−0.4
−0.2
0
log P
I amplitude
1
0.8
0.6
0.4
0.2
0
−0.6
−0.4
−0.2
0
log P
OGLE-BLG-RRLYR-02792
BLG116.2 RRab
Bulge RRab
I magnitude
14
16
18
20
0
1
2
3
4
$V-I$

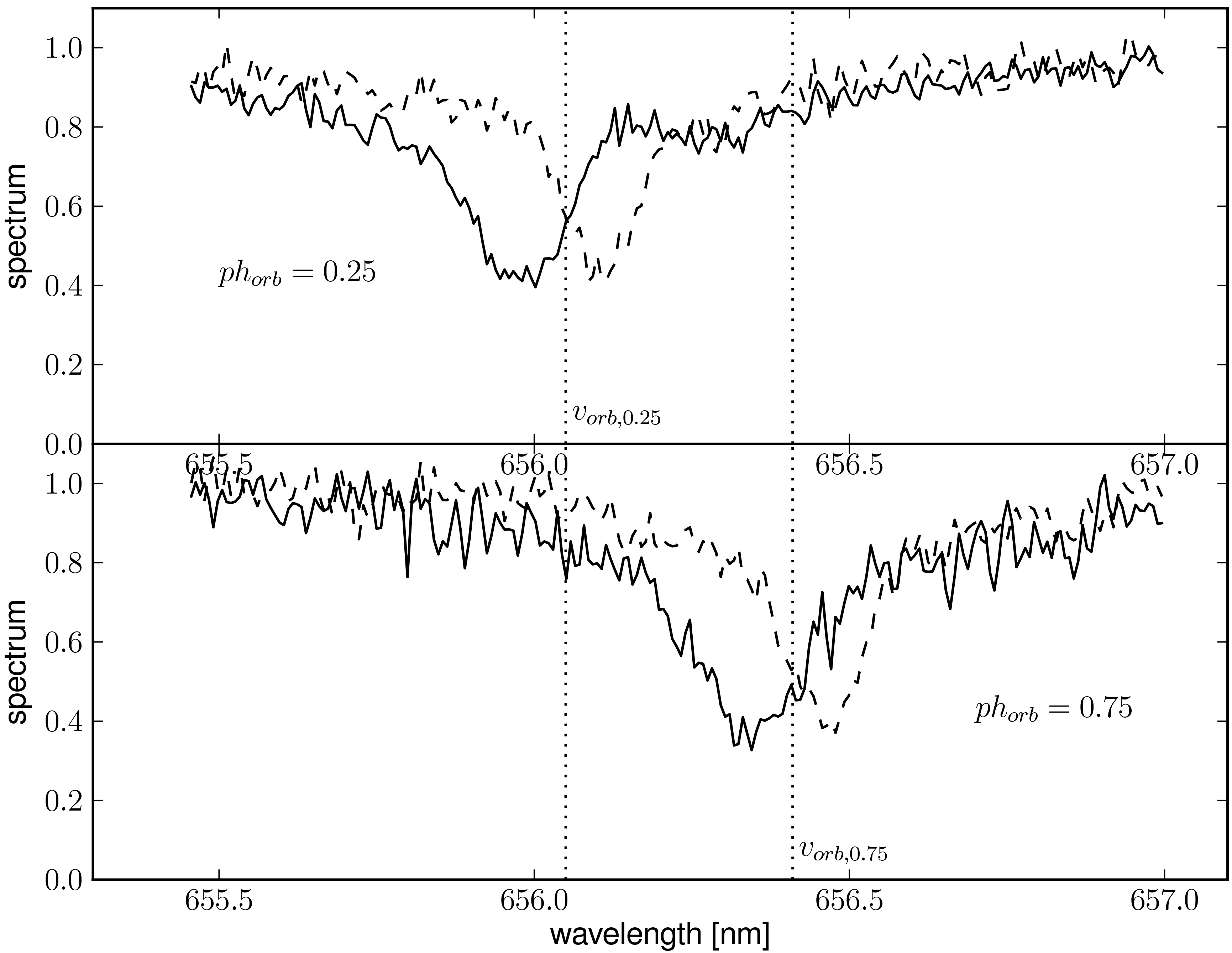


O-C [mag]
I [mag]
P=15.2435 d
Orbital phase
P=0.627496 d
pulsational phase
radial velocity (km/s)
orbital phase (15.24)
pulsation phase (0.628)

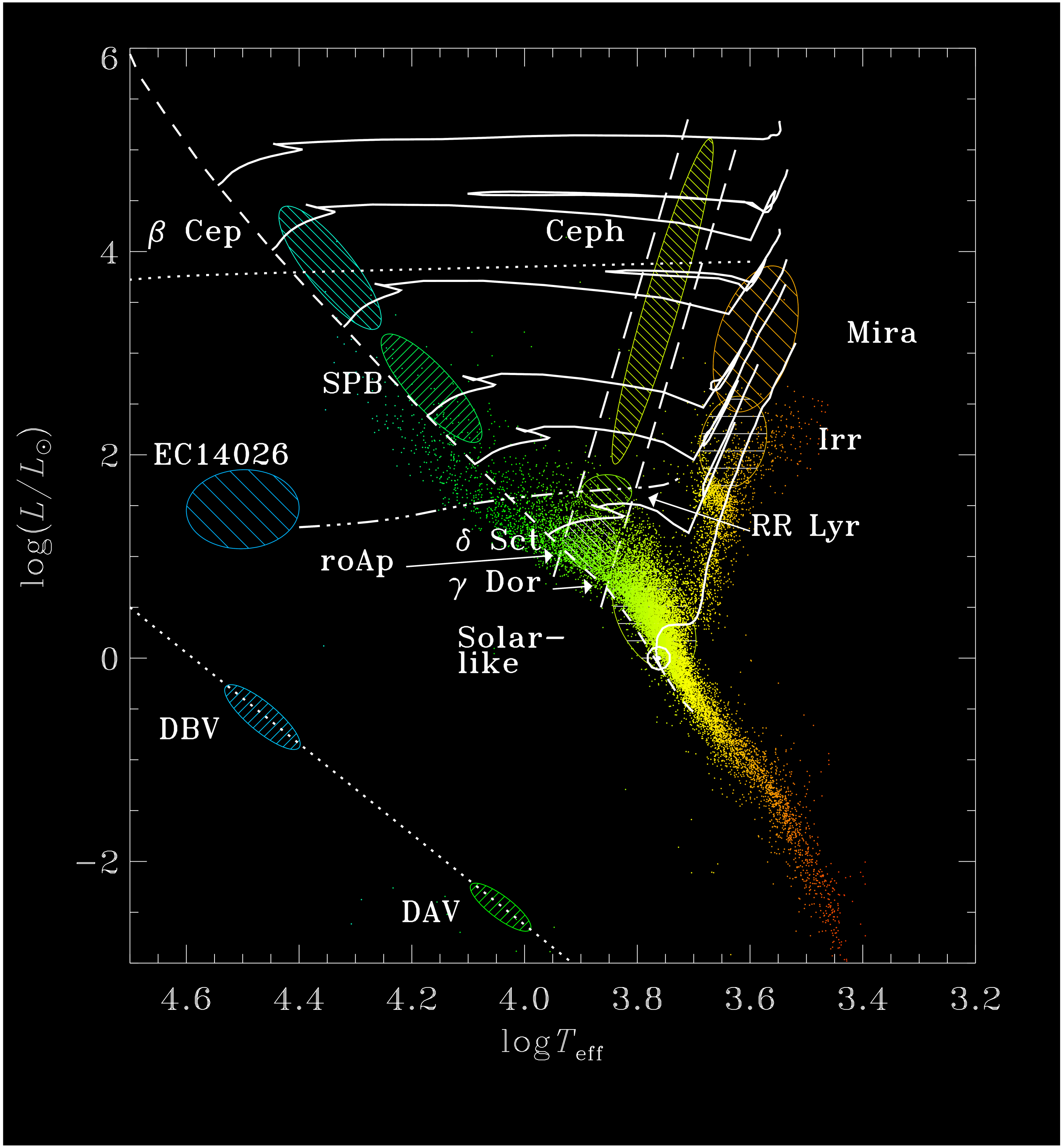
Astrophysical parameters of the OGLE-BLG-RRLYR-02792 system		
Parameter	**Primary (pulsating)**	**Secondary**
$M/M_\odot$ = mass	0.261 ± 0.015	1.67 ± 0.06
$R/R_\odot$ = *radius*	4.24 ± 0.24	4.27 ± 0.31
T = *effective temperature*	7320 ± 160 K	5000 ± 150 K (assumed)
e = eccentricity	0.0072 ± 0.0029	
ω=periastron passage	277 ± 16 deg	
γ = systemic velocity	-34.7 ± 0.2 km/s	
P_{ORB} P_{PUL} = *periods*	15.24340 ± 0.00021 days 0.627496 ± 0.000008 days	
dP_{PUL}/dt = *period change*	$- 8.4 \times 10^{-6}$ days/year	
i = inclination	83.4 ± 0.3 deg	
$a/R_\odot$ = orbit size	32.20 ± 0.32	
q = *mass ratio*	6.42 ± 0.20	



0.28
0.26
1.7
1.6
1.5
2.0
1.5
1.0
0.5
4.00
3.90
3.80
3.70
3.60
$\log(L/L_\odot)$
$\log T_{eff}$



spectrum
$ph_{orb} = 0.25$
$v_{orb,0.25}$
spectrum
$ph_{orb} = 0.75$
$v_{orb,0.75}$
wavelength [nm]
0.0
0.2
0.4
0.6
0.8
1.0
655.5
656.0
656.5
657.0



6
4
2
0
−2
4.6
4.4
4.2
4.0
3.8
3.6
3.4
3.2
log(L/L⊙)
log Teff
β Cep
Ceph
Mira
SPB
Irr
EC14026
RR Lyr
δ Sct
roAp
γ Dor
Solar-
like
DBV
DAV

New Class of variable stars
(Binary Evolution Pulsator - BEP)

=> 0.8 % contamination in RR Lyrae catalogs

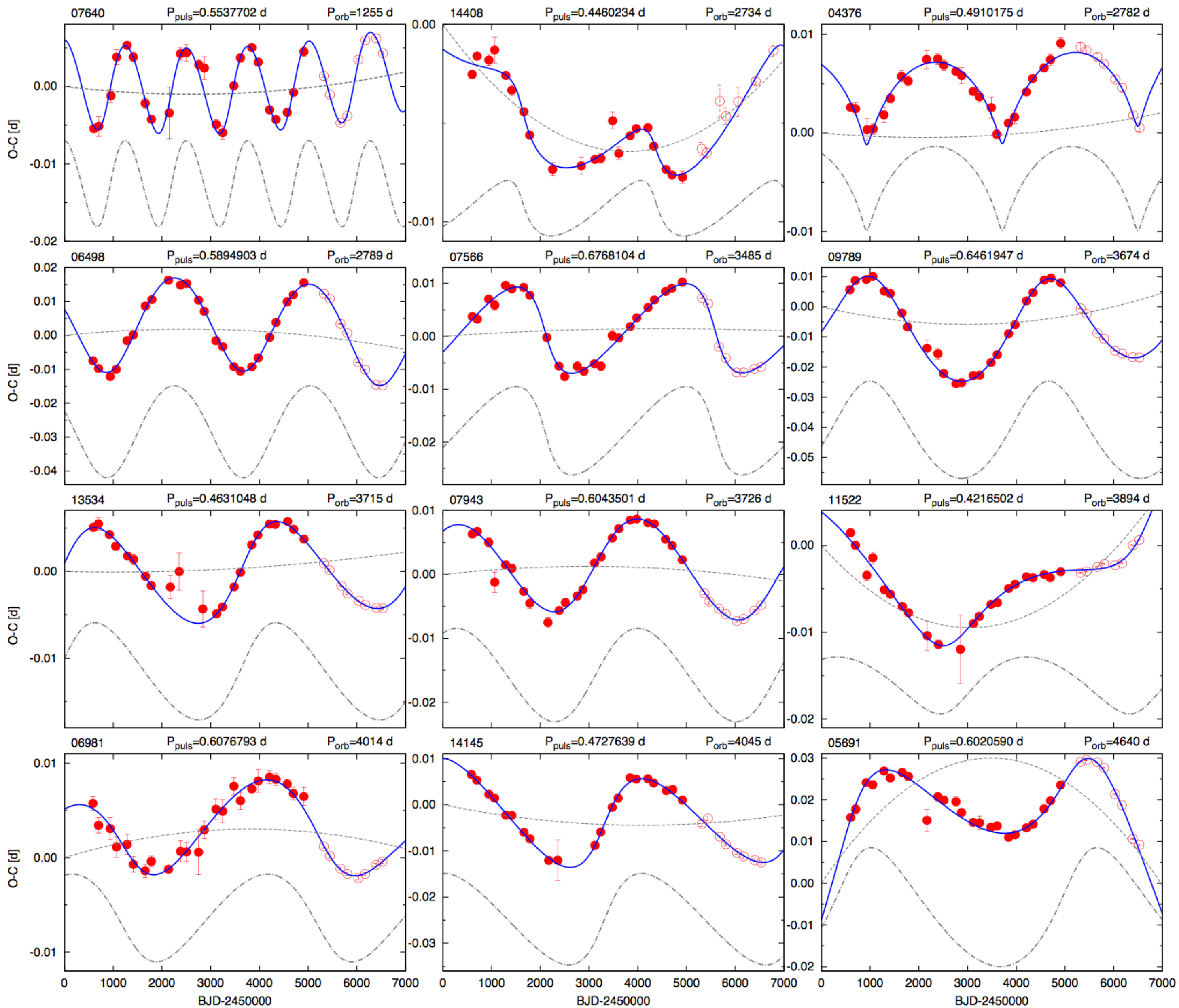
=> New evolutionary channel discovered

=> Study of pulsating properties (Smolec et al. 2012)

=> Around 5% contamination for Cepheids

=> Most probably peculiar W Virginis are also BEPs

- Good candidates for RR Lyrae in eclipsing binaries
- OGLE data (Hajdu et al. 2015)



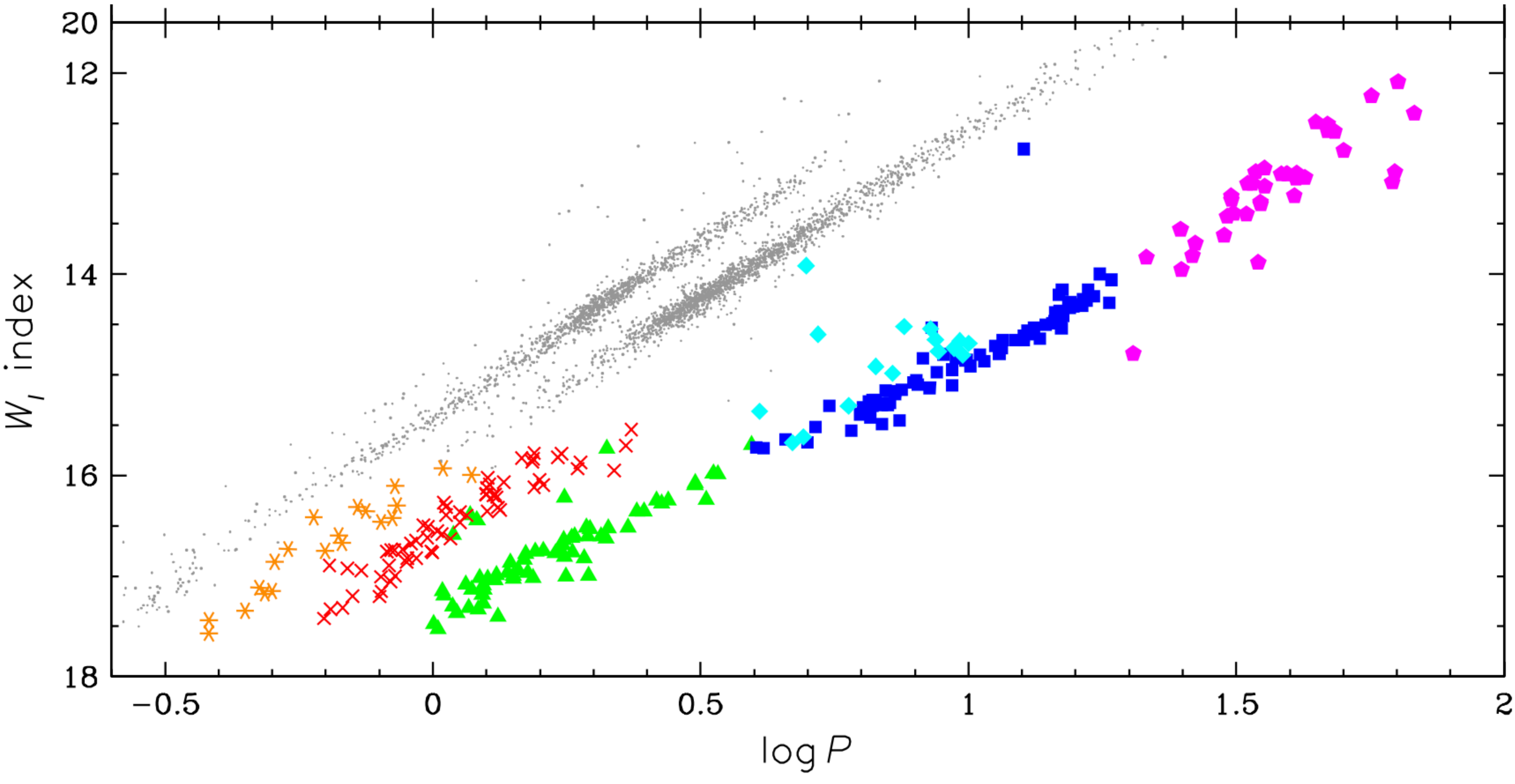
Binarity

Unique possibility to measure geometrical distances

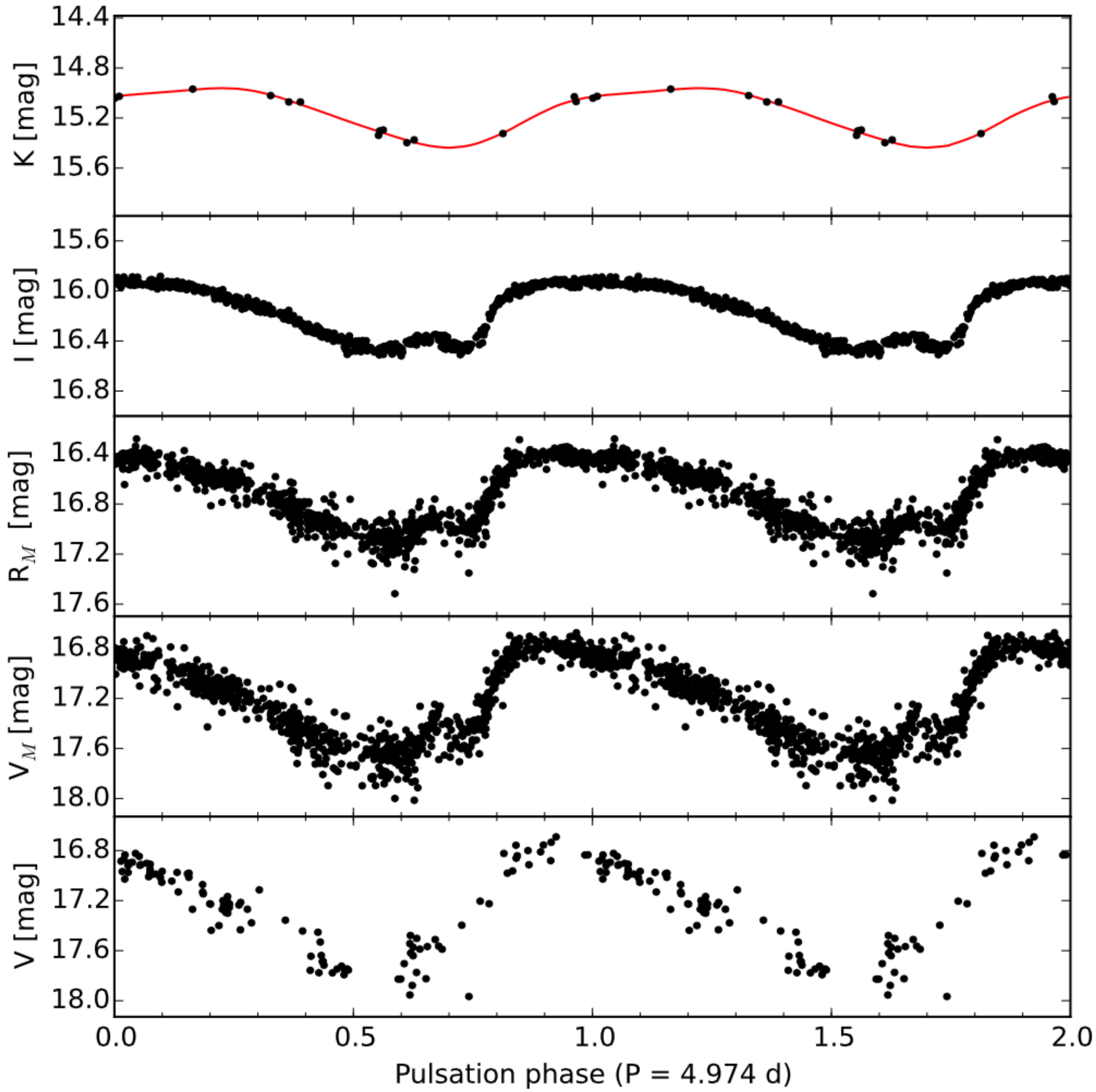
Unresolved blends (bias in distance determination)

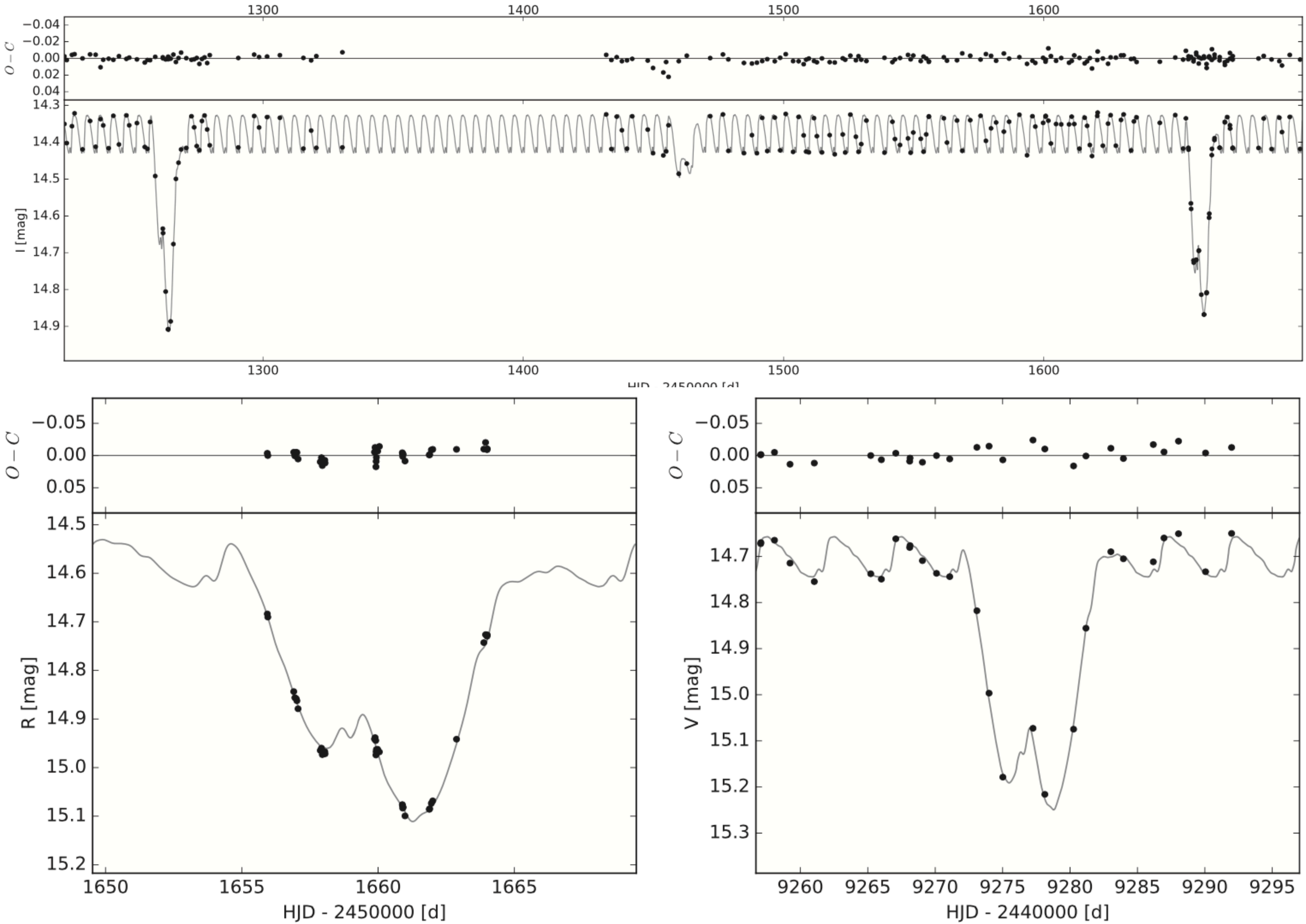
BEPs − peculiar stars mimicking classical pulsators

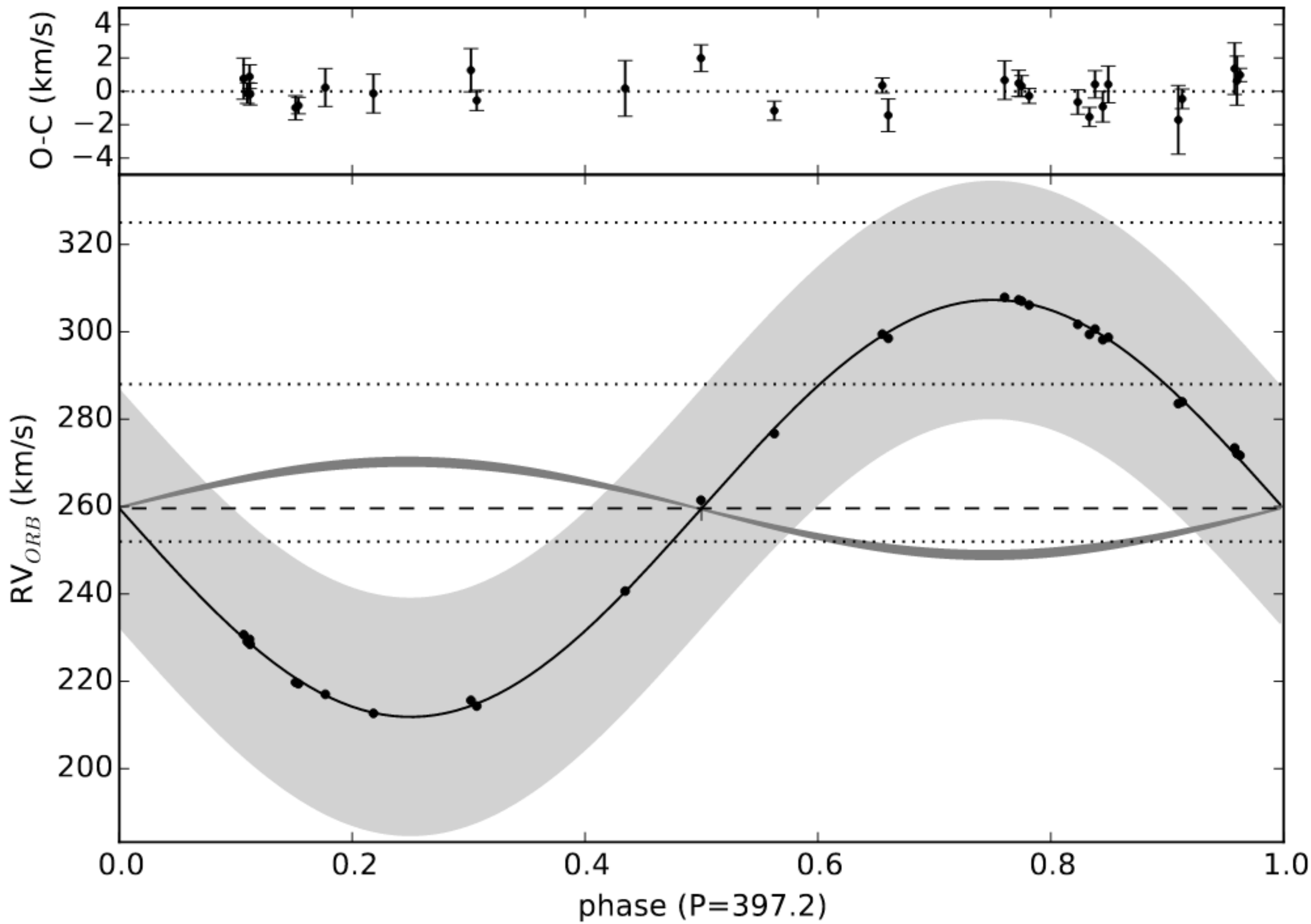
Type II Cepheids



Piculiar W Vir OGLE-LMC-T2CEP-098
(Pilecki et al. 2017)




1300
1400
1500
1600
−0.04
−0.02
0.00
0.02
0.04
$O-C$
14.3
14.4
14.5
14.6
14.7
14.8
14.9
I [mag]
1300
1400
1500
1600
−0.05
0.00
0.05
$O-C$
14.5
14.6
14.7
14.8
14.9
15.0
15.1
15.2
R [mag]
1650
1655
1660
1665
HJD - 2450000 [d]
−0.05
0.00
0.05
$O-C$
14.7
14.8
14.9
15.0
15.1
15.2
15.3
V [mag]
9260
9265
9270
9275
9280
9285
9290
9295
HJD - 2440000 [d]


O-C (km/s)
4
2
0
−2
−4
RV$_{ORB}$ (km/s)
320
300
280
260
240
220
200
0.0
0.2
0.4
0.6
0.8
1.0
phase (P=397.2)

Pulsating stars conclusions

Classical Cepheids are by far the best for calibrating SN Ia

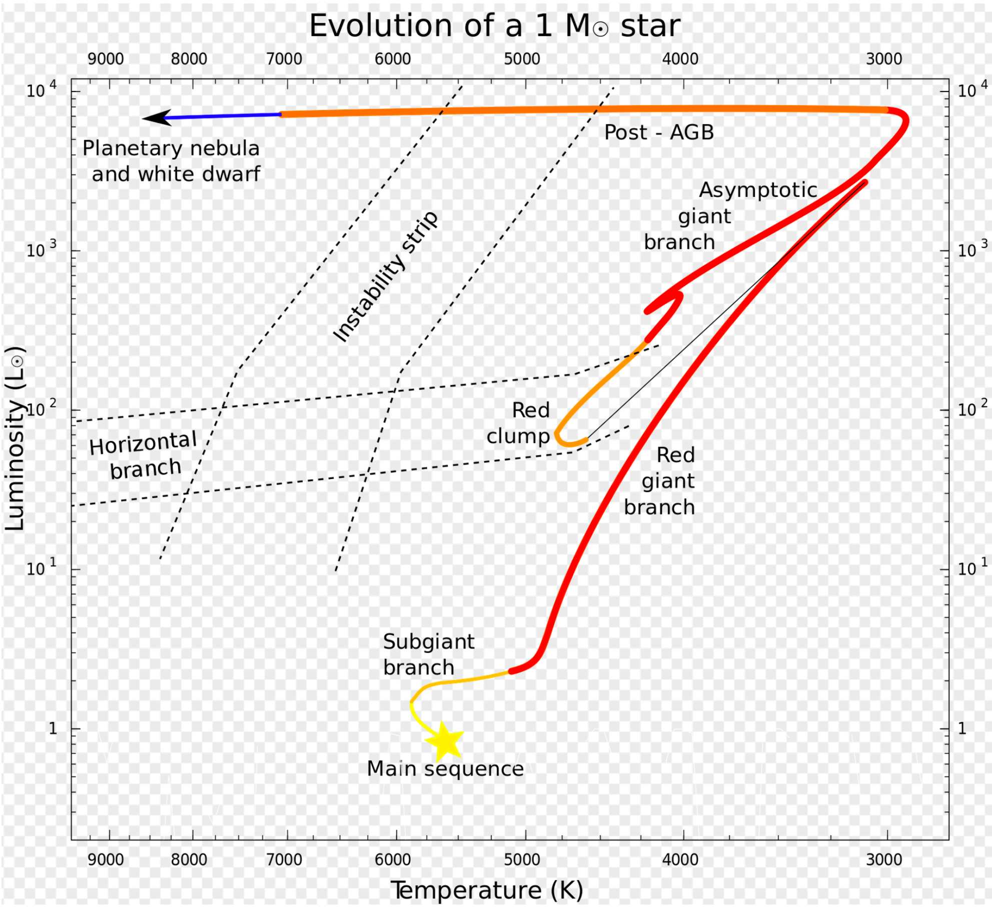
Best studied and calibrated

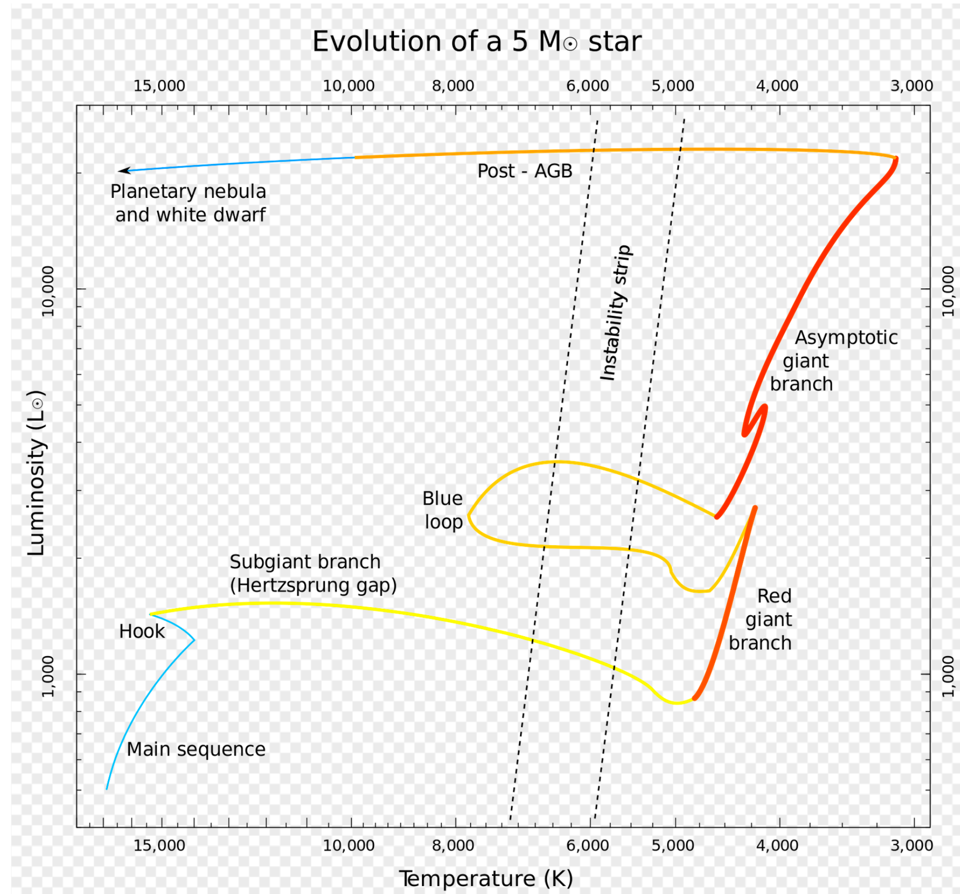
Other stars very usefull to test pupulation effects

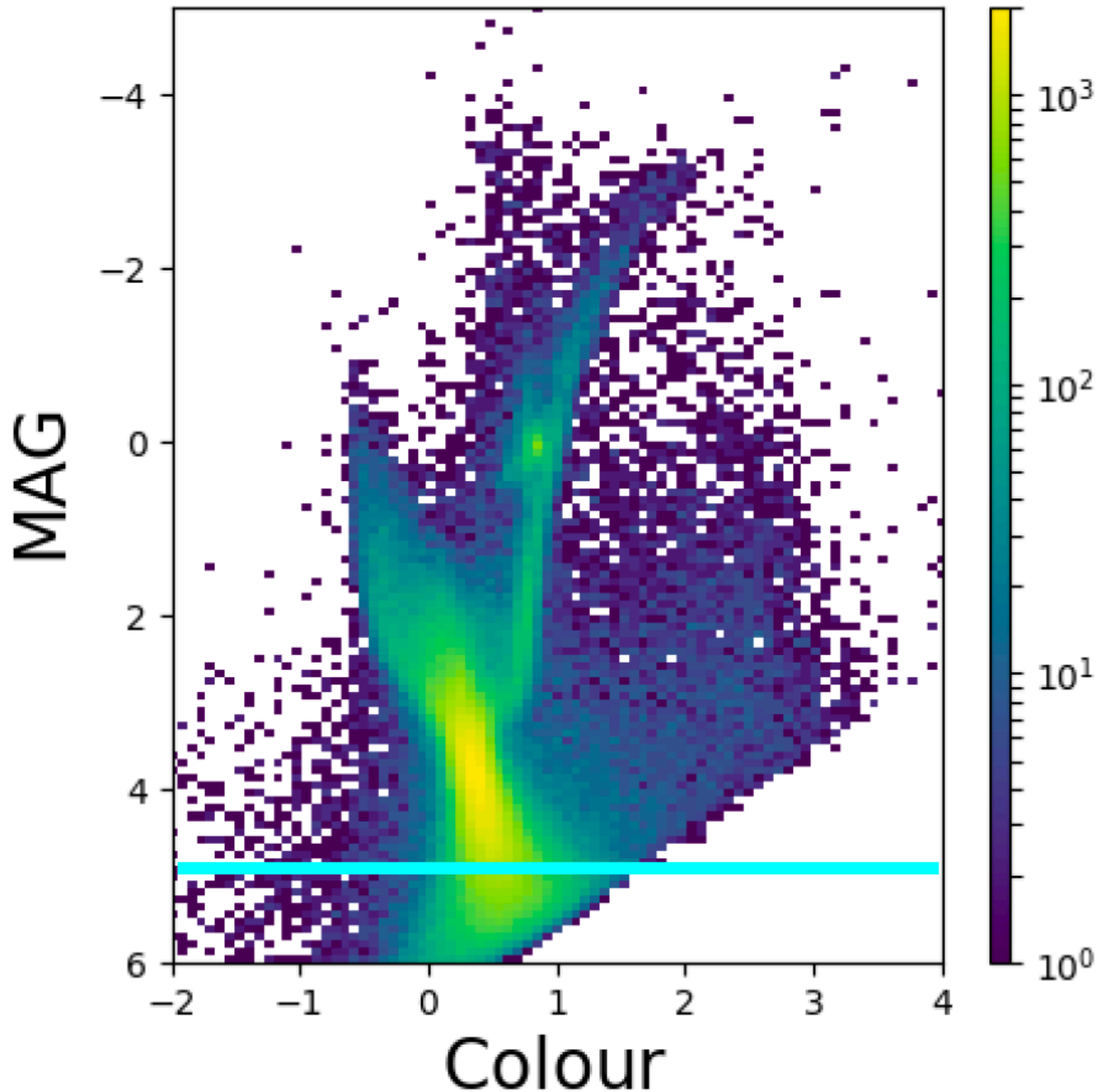
(in general we can conclude calibration of the cosmic distance scale once we get consistent picture from all methods)

In some environments we do not have classical Cepheids

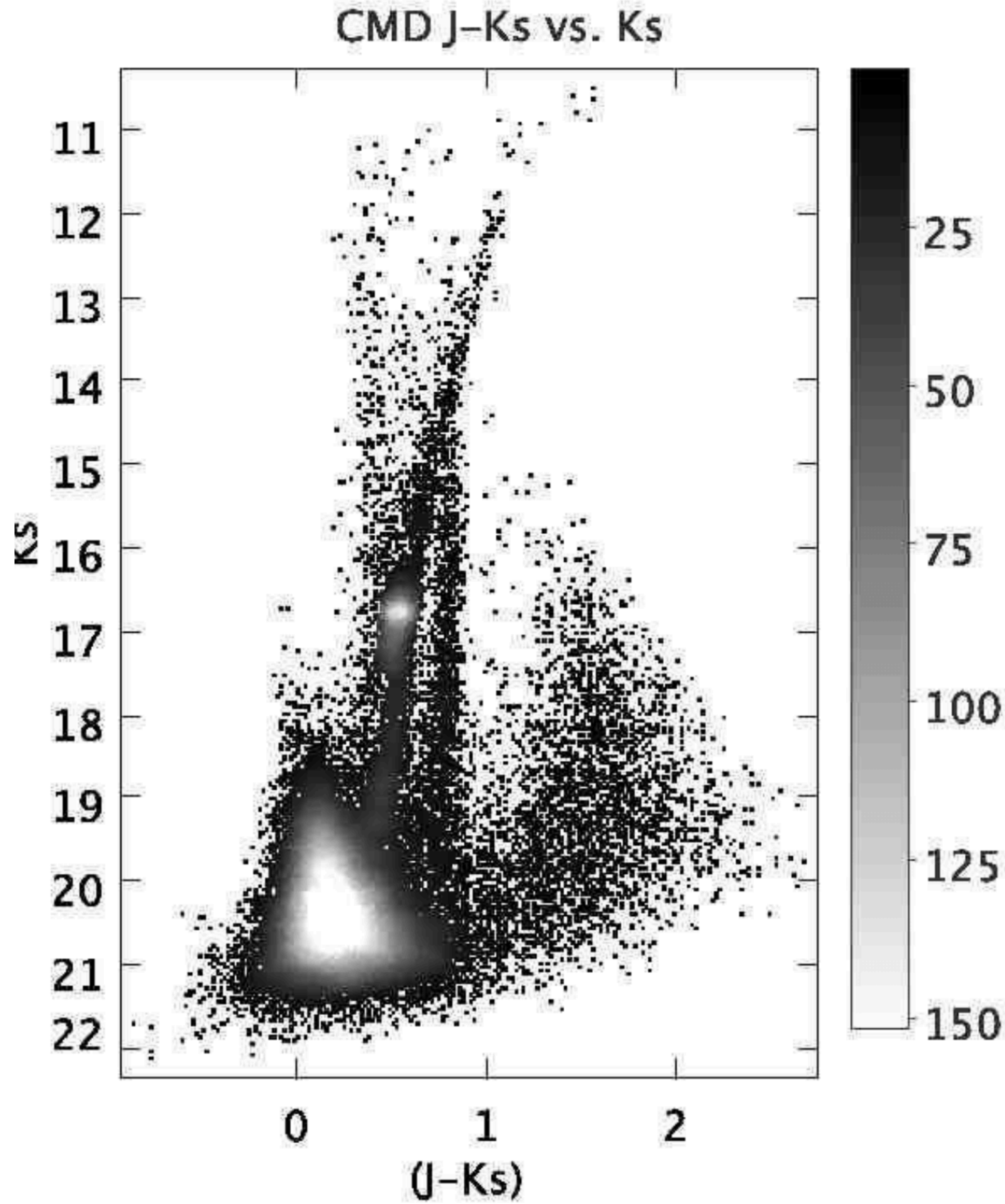
Structures on the CMD



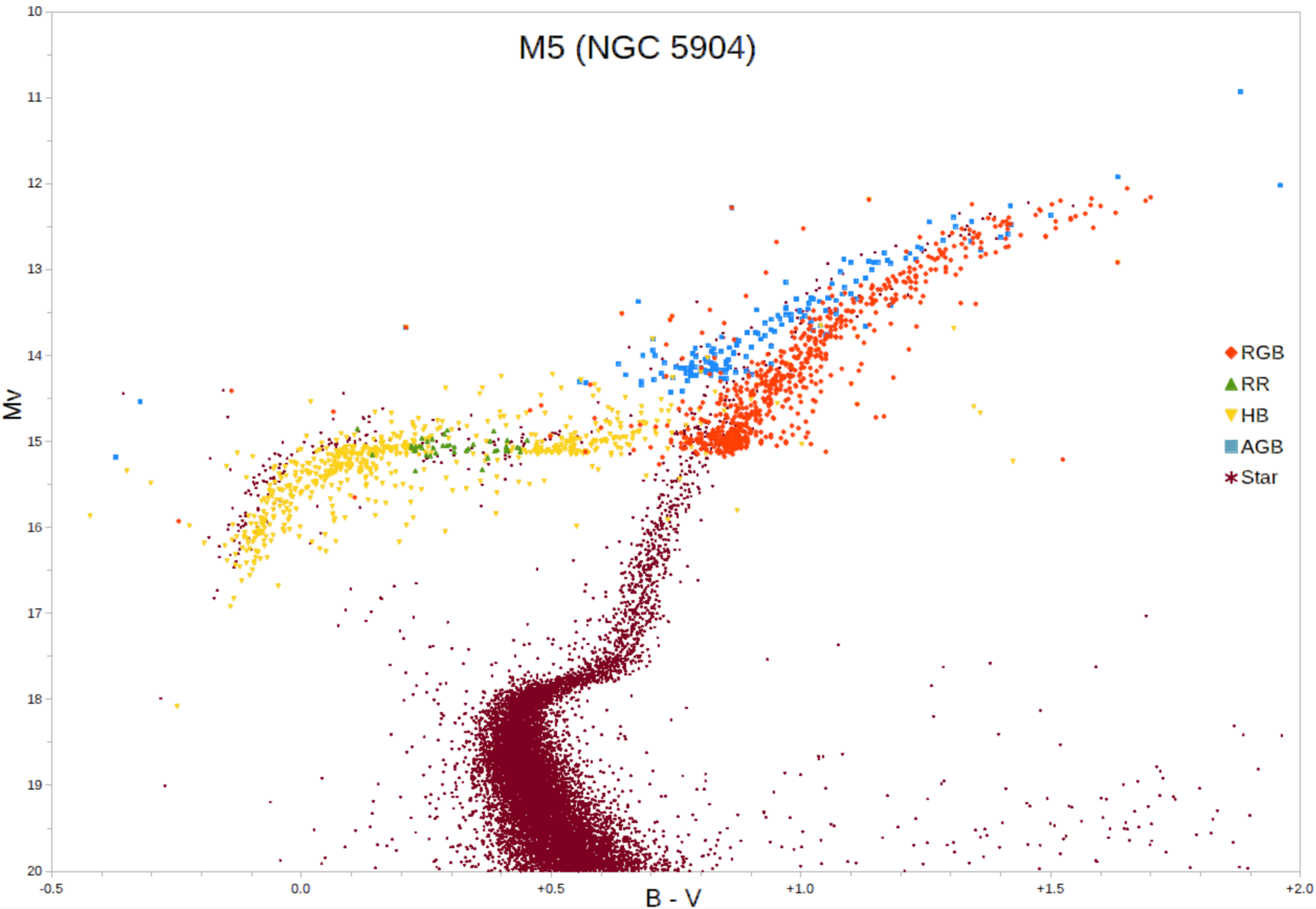




MAG
Colour
−4
−2
0
2
4
6
−2
−1
0
1
2
3
4
10^3
10^2
10^1
10^0

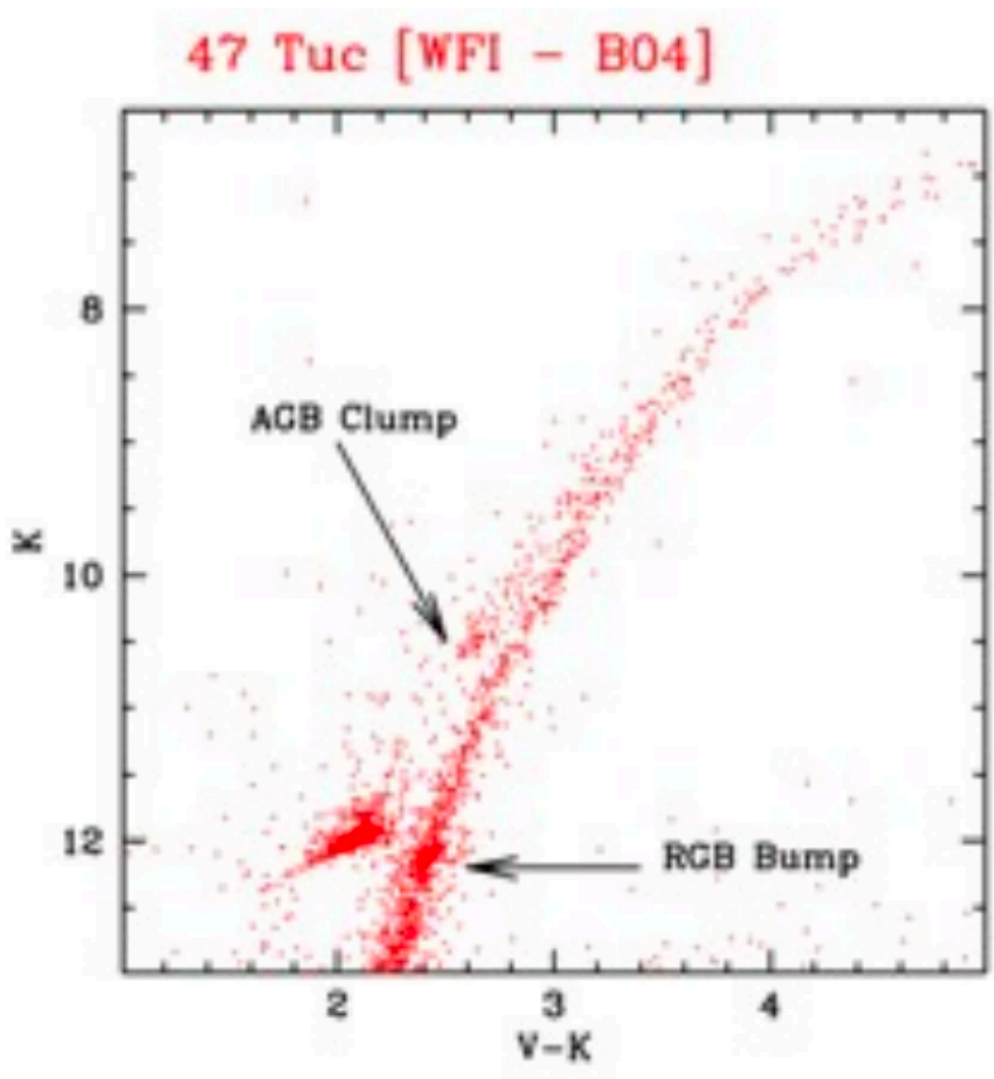


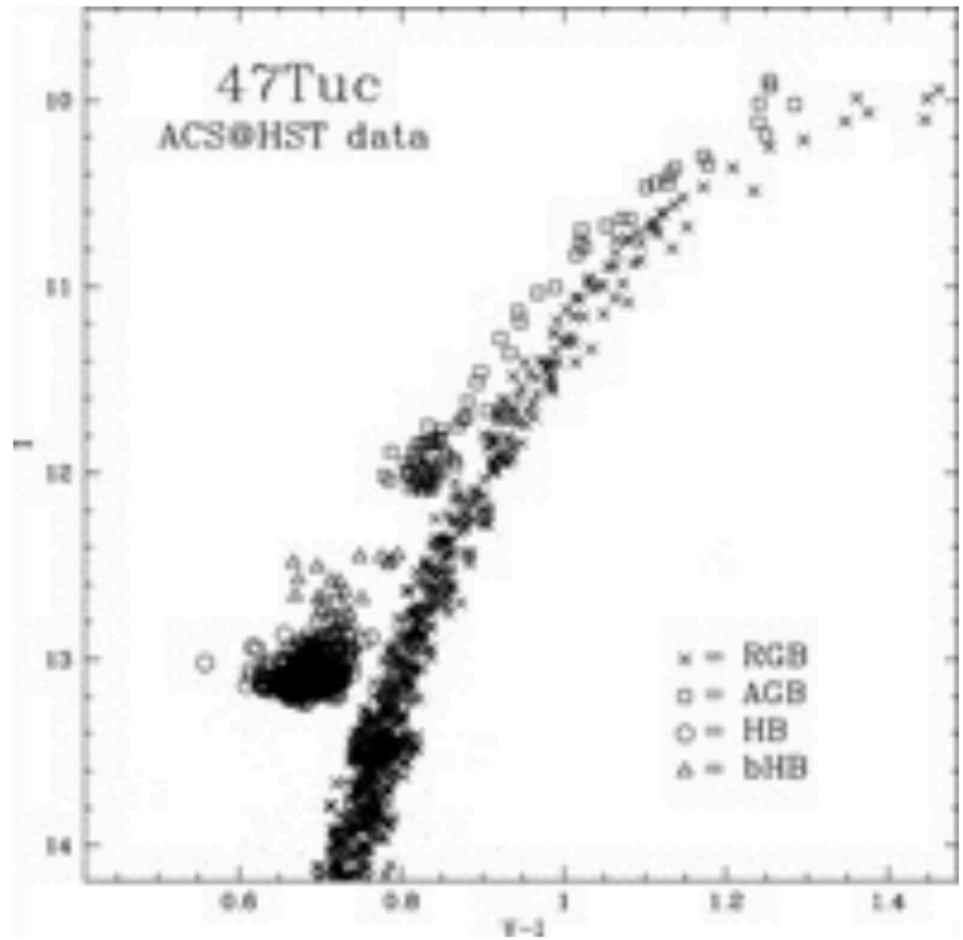
CMD J-Ks vs. Ks
Ks
11
12
13
14
15
16
17
18
19
20
21
22
0
1
2
(J-Ks)
25
50
75
100
125
150



M5 (NGC 5904)
Mv
B - V
10
11
12
13
14
15
16
17
18
19
20
-0.5
0.0
+0.5
+1.0
+1.5
+2.0
RGB
RR
HB
AGB
Star

Structures on the CMD





Red clump stars

form very compact feature in CMD

are very numerous

about 1000 RC stars have very accurate (< 10 %) paralaxes measured by Hipparcos.

population effects ?

RC population effects in I band

=> Analysis of Hipparcos sample ($-0.5 < [Fe/H] < 0.1$) showed that the dependence on metallicity is of 0.14 +- 0.04 mag/dex (Udalski 2000).

⇒ Studies of RC stars in clusters in MC yielded no dependence on age in the range from 2 to 9 Gyrs (Udalski 1998)

⇒ Strong dependence on both age and metallicity (Girardi and Salaris 2001) was found from models.

⇒ LMC distances m-M = 18.06 mag (Udalski et al. 1998), m-M = 18.24 Udalski et al. 2000, 18.50 Girardi and Salaris 2000

RC in K band

=> Negligible dependence on reddening !

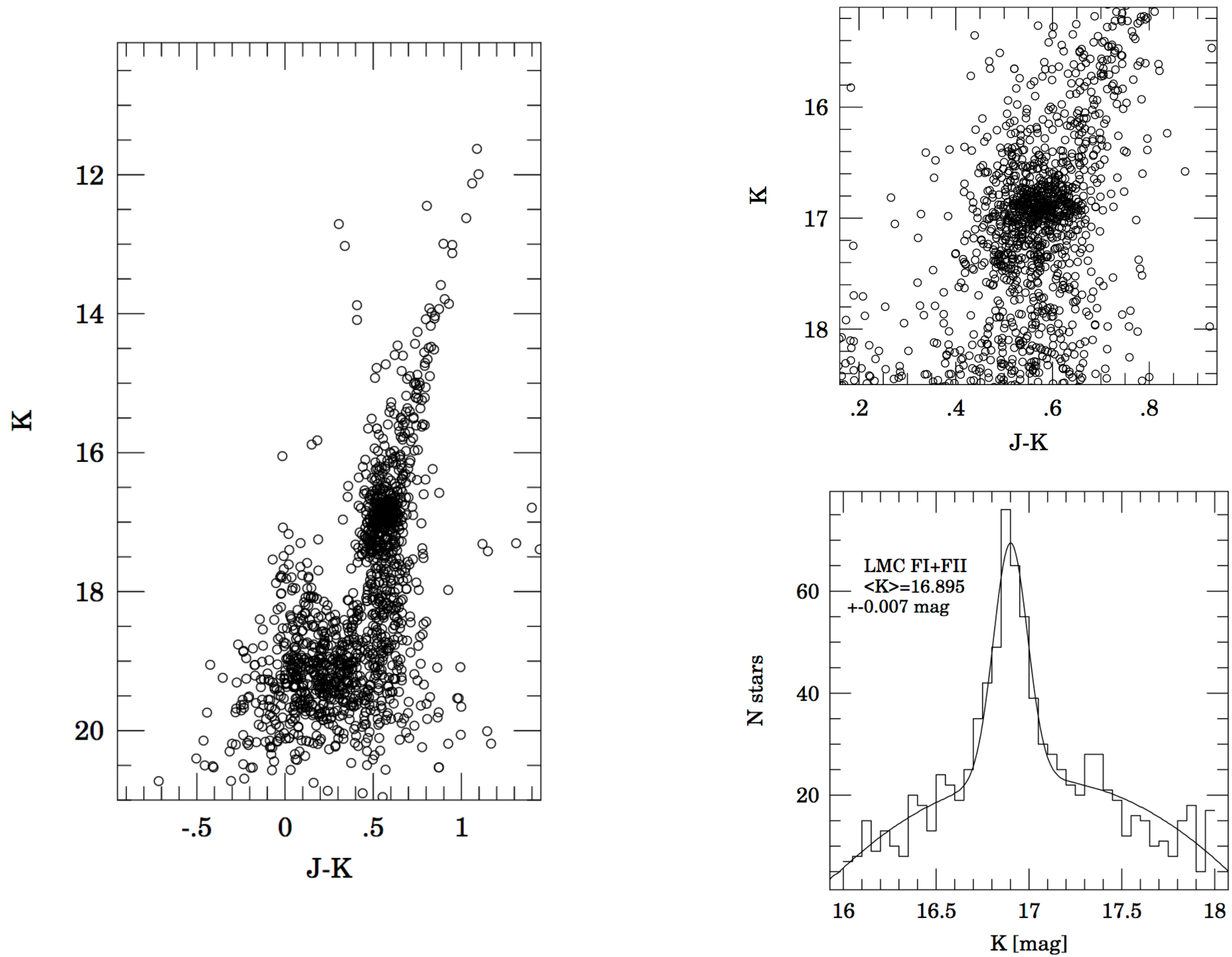
⇒ Calibration based on archival photometry from 1960s (Alves 2000).

⇒ The photometry of the faintest stars from the sample was checked to be on the Koornneef system (Alves 2000).

⇒ No dependence on metallicity for the stars from the Hipparcos sample (Alves 2000).

⇒ No dependence on age in the range from 2 to 9 Gyrs Grocholsky and Sarajedini (2002), Girardi and Salaris 2001

RC in the LMC



K
12
14
16
18
20
-.5
0
.5
1
J-K
K
16
17
18
.2
.4
.6
.8
J-K
LMC FI+FII
<K>=16.895
+-0.007 mag
N stars
20
40
60
16
16.5
17
17.5
18
K [mag]

LMC distance RC in the K band
calibration: Alves 2000

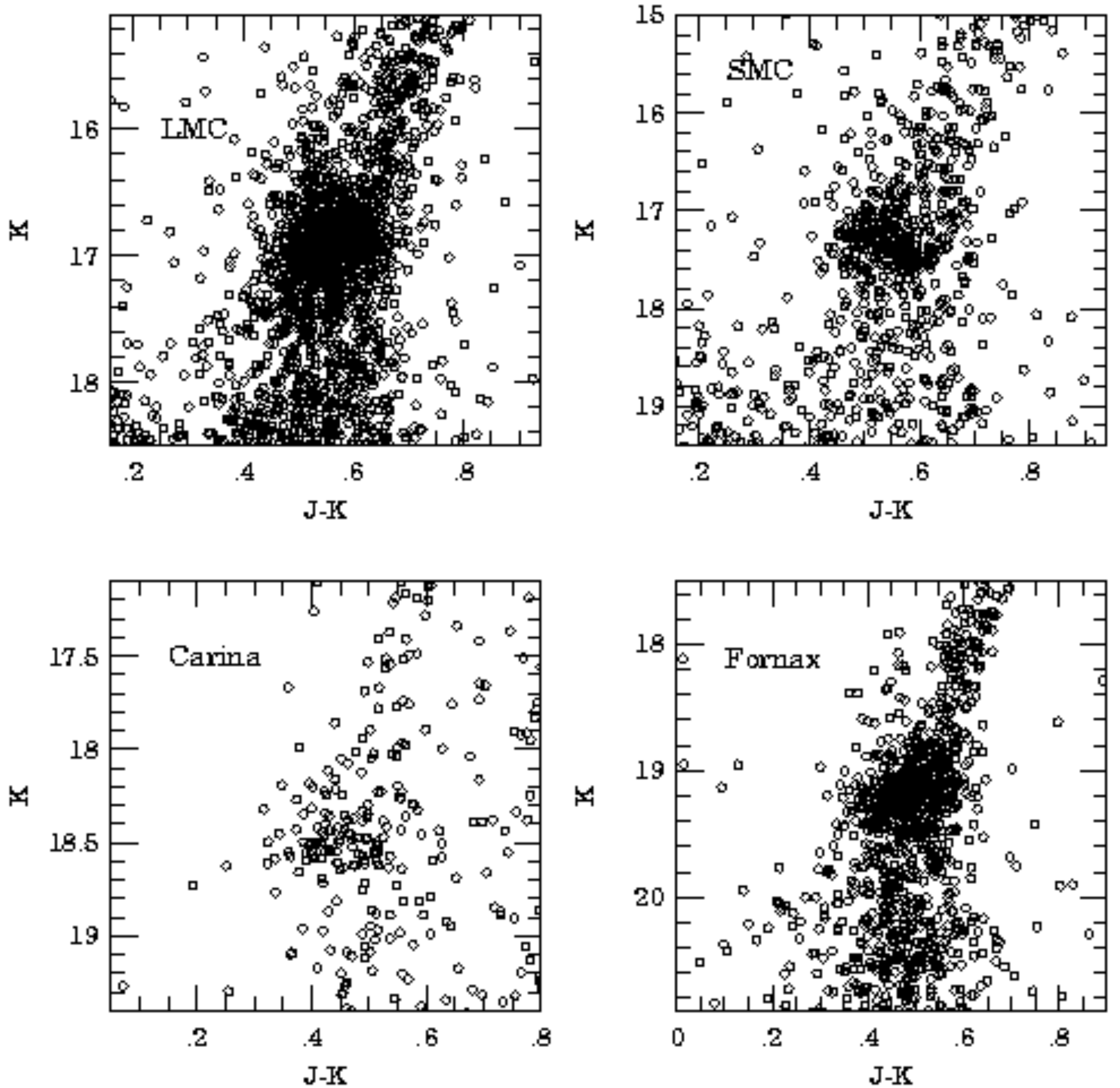
2002:
Alves et al.; Pietrzynski and Gieren; Sarajedini

all m-M close to 18.50 mag

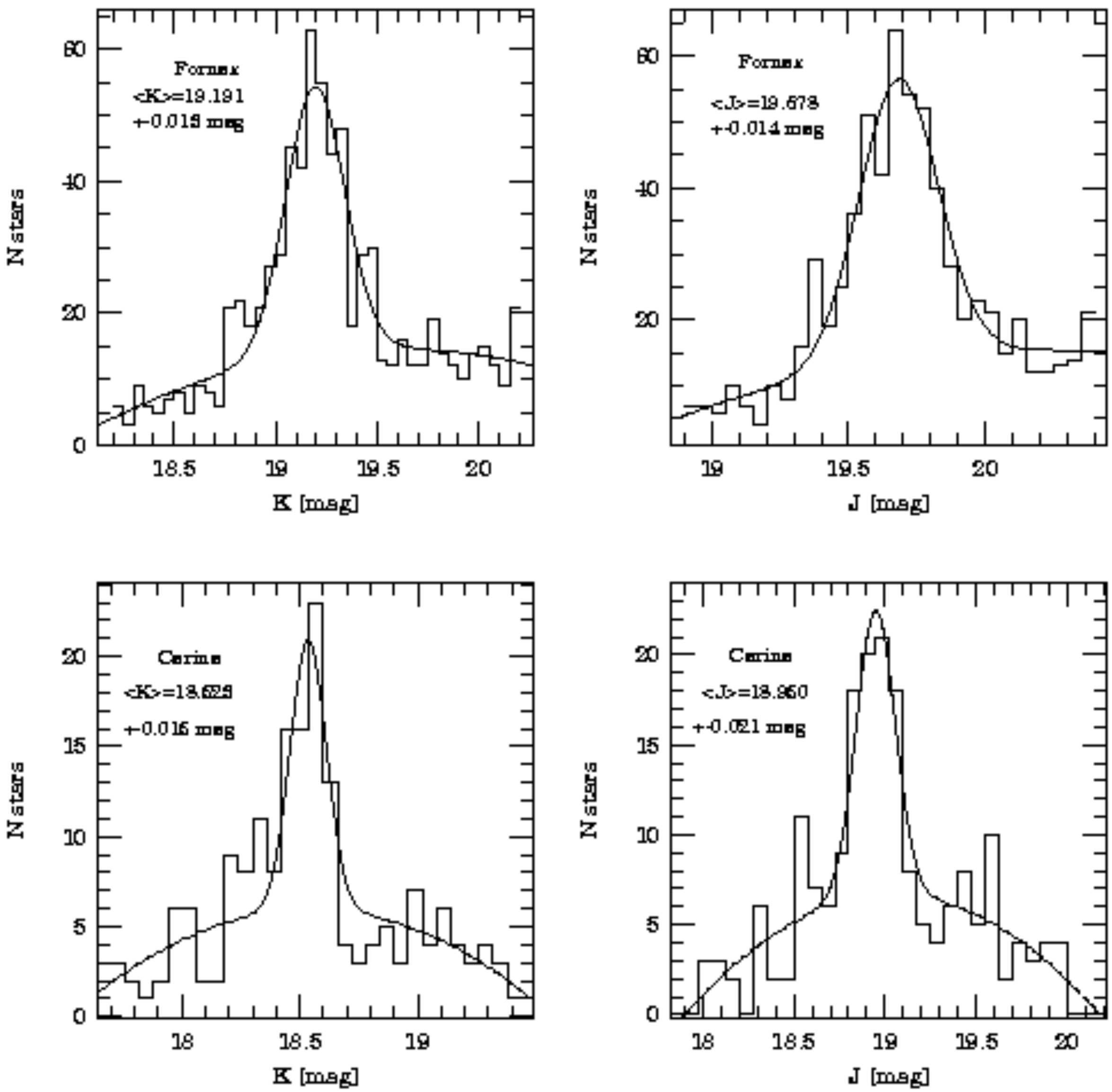
Finally Laney, Joner, Pietrzynski (2012) precision calibration of RC stars:

LMC m-M = 18.47 mag

RC in K band



RC in K band



Fornax
<K>=19.191
+-0.015 mag
N stars
K [mag]
Fornax
<J>=19.678
+-0.014 mag
N stars
J [mag]
Carina
<K>=18.625
+-0.016 mag
N stars
K [mag]
Carina
<J>=18.950
+-0.021 mag
N stars
J [mag]