Araucaria Project – Main Goal

Improve the cosmic distance scale based on observations of several primary distance indicators in nearby galaxies.

- **Cepheids (VIJK, HR Spec.)**
- **Blue supergiants (VIJK, MR Spec.)**
- **red clump (IJHK, HR Spec.)**
- **RR Lyrae (VIJK)**
- **TRGB (IJK)**
- **Eclipsing binaries (VIJK, HR Spec.)**

The principal sources of error in the calibration of the cosmic distance scale

- population effects
- extinction (internal extinction, reddening law)
- the zero point
- Blending / crowding
- physics of the distance indicators

Calibration of the Cepheid PL relation

Calibration of the Cepheid PL relation

Nearby galaxies

LMC or other galaxy

Individual distances

Gaia, HST parallaxes, BW

With binaries we can do both !

Eclipsing binaries

$$d(pc) = 1.337 \times 10^{-5} \times r(km) / \varphi(mas)$$

Light + RV curves analysis
=> ~ 1 % radii (e.g. Andersen 1991)

Late-type eclipsing binaries

$$d(pc) = 1.337 \times 10^{-5} \times r(km) / \varphi(mas)$$

φ is derived from the surface brightness - color relation, very well established for late-type stars based on interferometric data (di Benedetto 1998, 2005; Kervella et al. 2004)

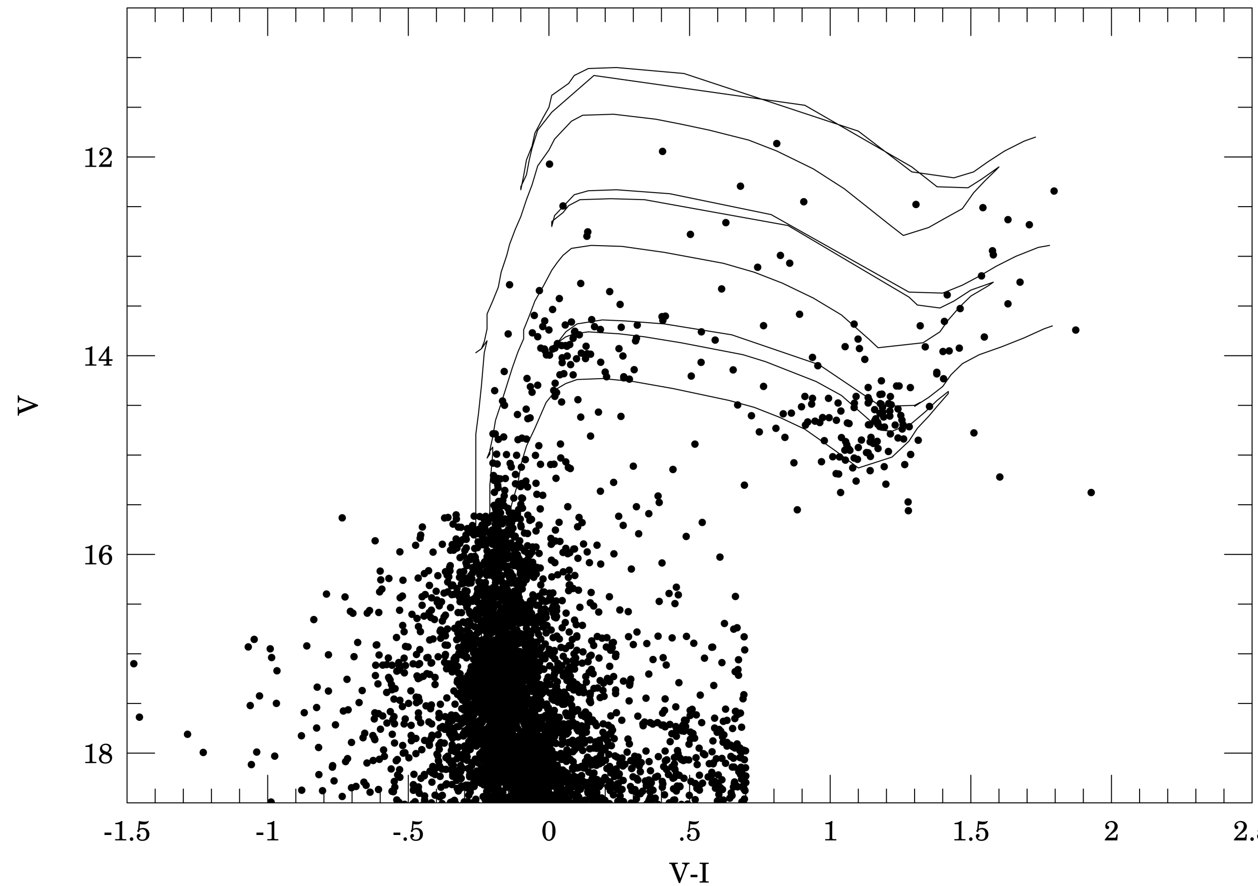
$$S_V = 2.656 + 1.483 \times (V-K)_0 - 0.044 \times (V-K)_0^2$$

$$\phi\ [\mathrm{mas}] = 10^{0.2\cdot(S-m_0)}$$

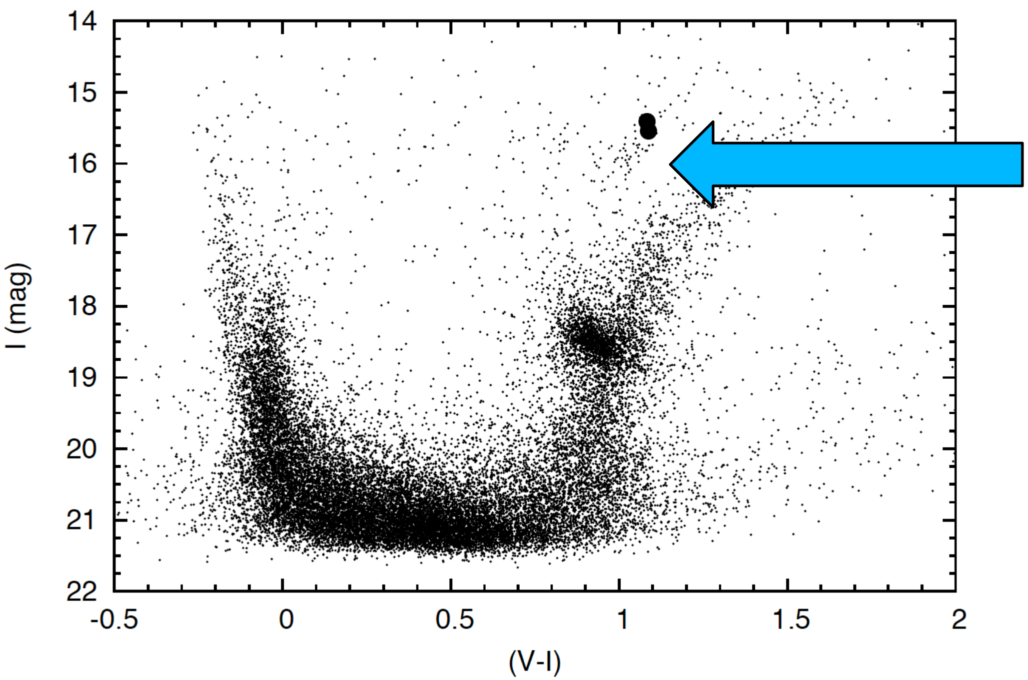
Currently rms on such relation is 0.03 mag (2 % !)

Therefore using late-type eclipsing binaries we should easily measure 3 % distances !

Unfortunately, even A5 MS stars in the LMC have V ~ 20.5 mag



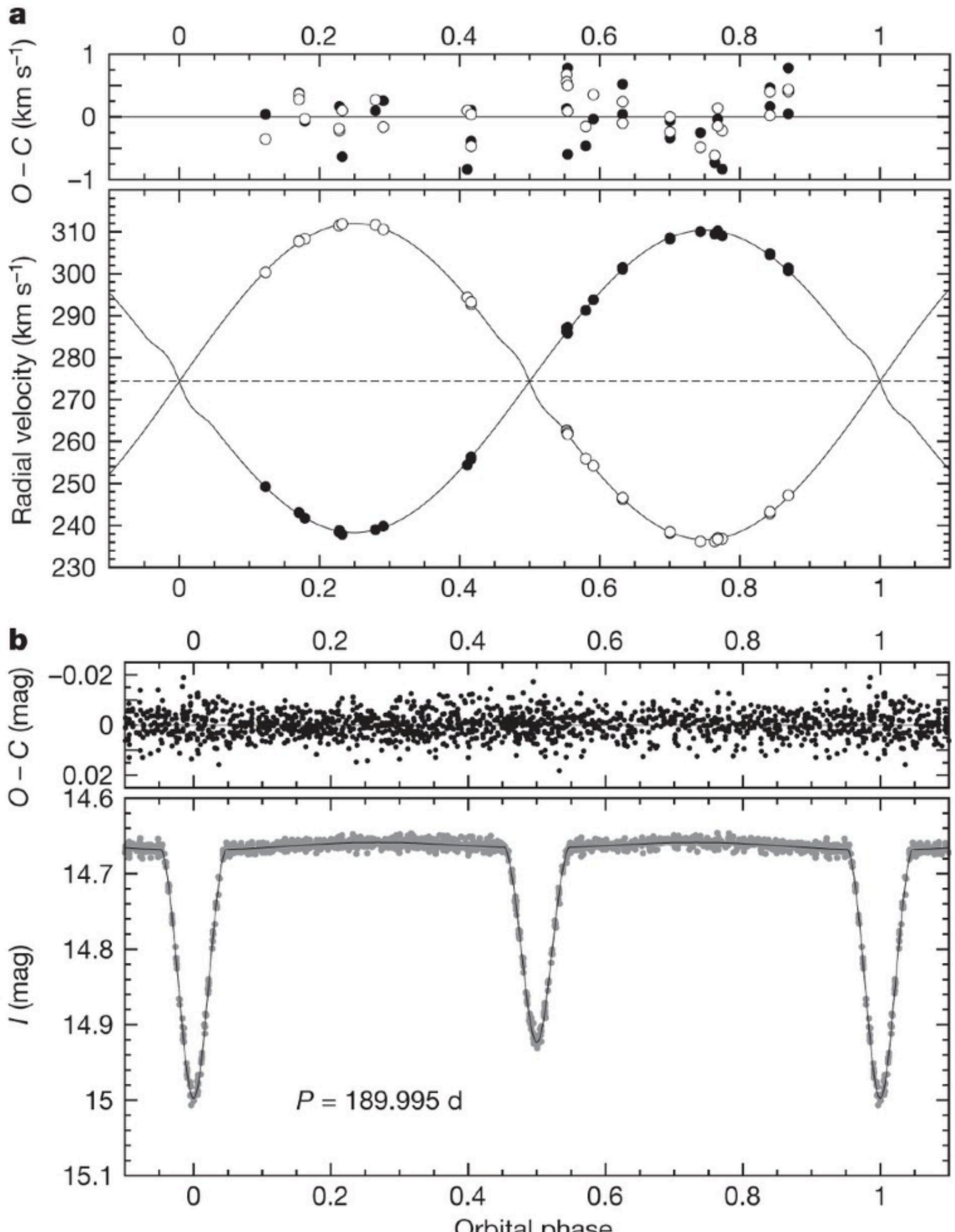
Eclipsing systems composed of clump giants



⇒ late type
⇒ metal poor (-0.5 dex)
⇒ no additional photometric variations
⇒ relatively bright
14 < V < 17.5 mag
⇒ small spectroscopic jitter

but such system have P ~ 300 days …
Fortunately, LMC has been monitored for 20 years by OGLE !
36 such very special systems discovered based on the OGLE data …

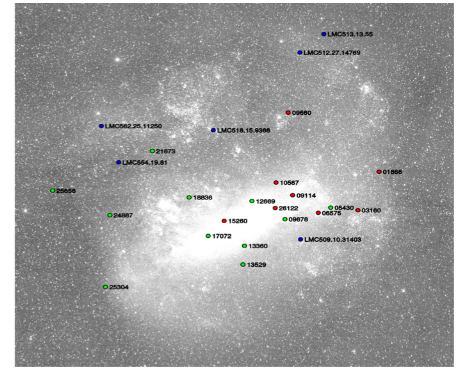
From 35 million stars (from 26 000 eclipsing binaries …)



a
O − C (km s−1)
Radial velocity (km s−1)
b
O − C (mag)
I (mag)
P = 189.995 d
Orbital phase

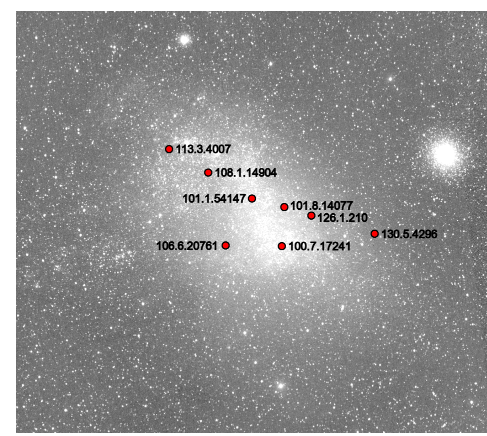
Table 3. Astrophysical parameters of OGLE-051019.64-685812.3

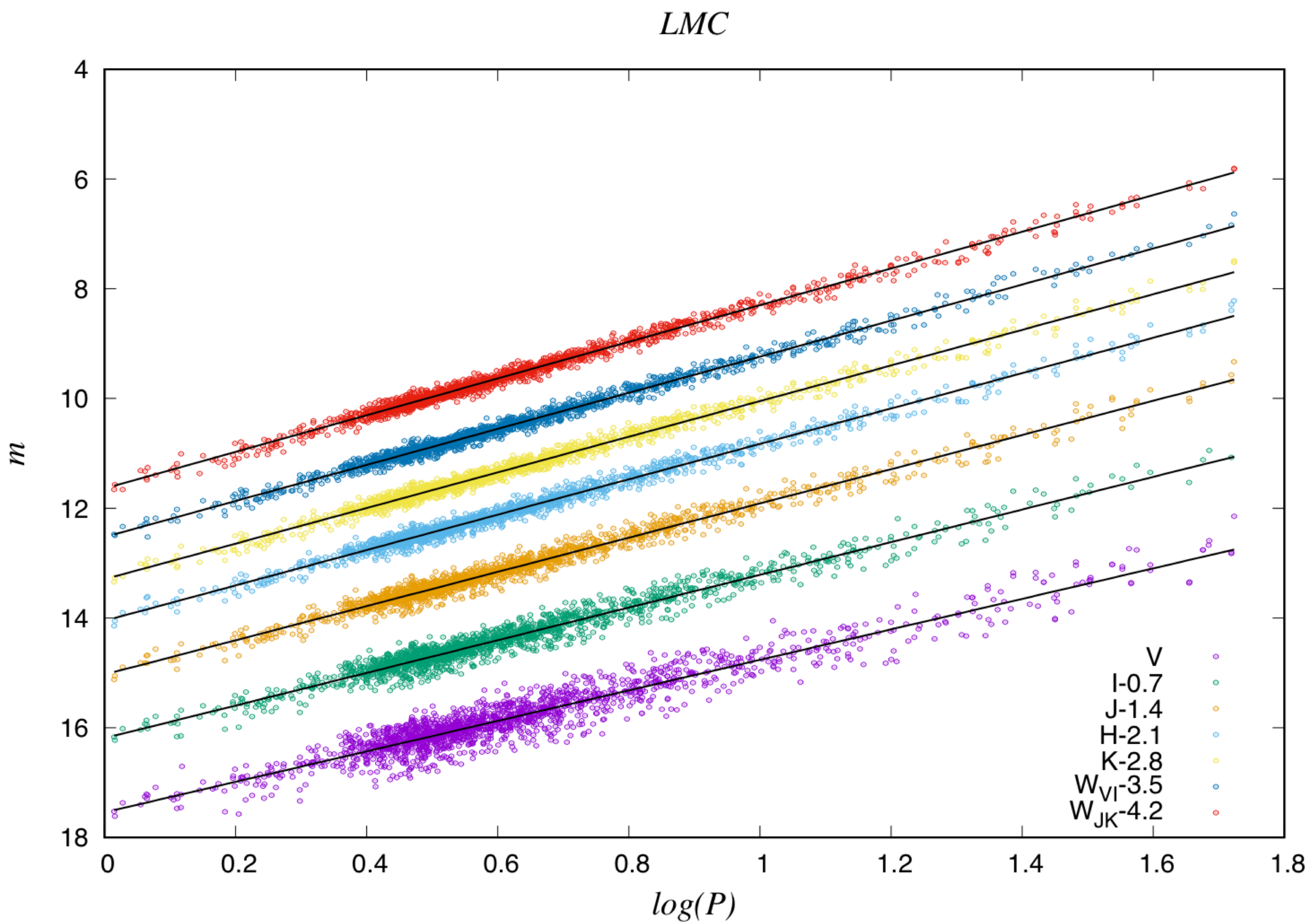
	Primary	Secondary
P [days]	214.370 ± 0.008	
i [deg]	88.20 ± 0.10	
a [$R_\odot$]	280.8 ± 1.1	
e	0.0395 ± 0.0025	
ω [deg]	96.53 ± 0.46	
φ	0.99850 ± 0.00003	
$q = m_1/m_2$	0.9695 ± 0.0068	
γ [km/s]	272.39 ±0.09	
K [km/s]	32.65 ± 0.14	33.67 ± 0.16
$M/M_\odot$	3.29 ± 0.04	3.19 ± 0.04
$R/R_\odot$	26.06 ± 0.28	19.76 ± 0.34
$T_{eff}[K]$	5300 ± 100	5450 ± 100
V [mag]	16.738	17.195
I [mag]	15.969	16.466
K [mag]	14.895	15.446
distance [kpc]	50.4 ±1.3	50.0 ±1.4
E(B-V) [mag]	0.146 ± 0.02	
Fe/H	-0.5 dex (assumed)	



8 systems in the LMC:
49 ± 0.19 (statistical) ± 1.11 (systematic) kpc
(Pietrzynski et al. 2013 Nature, 495, 76)

5 systems in the SMC:
62 ± 0.72 (st.) ± 1.11 (sys.) kpc
(Graczyk et al. 2014, ApJ, 780, 59)

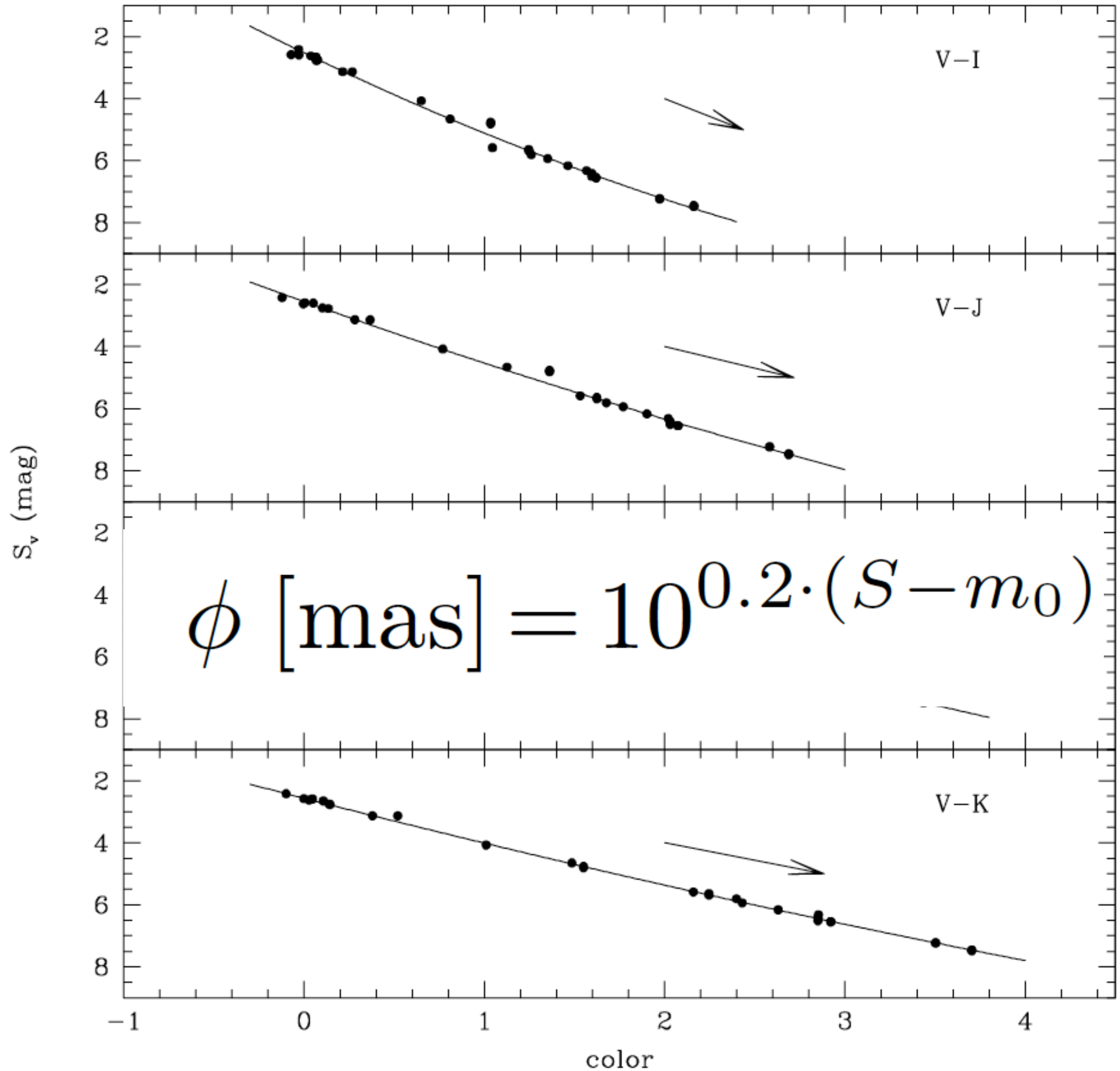




LMC
m
log(P)
V
I-0.7
J-1.4
H-2.1
K-2.8
W_{VI}-3.5
W_{JK}-4.2

Can we improve on this method ?
What is the limit ?

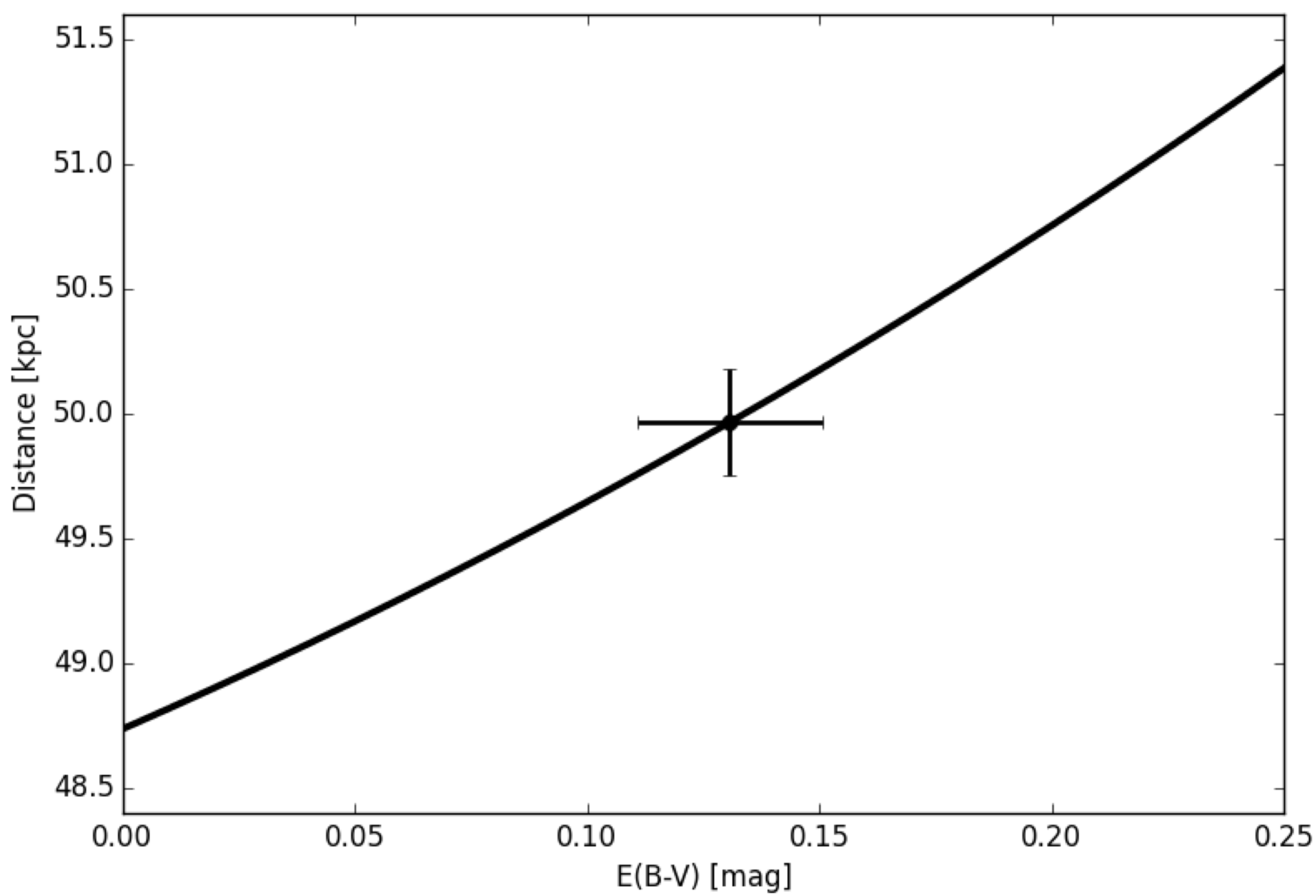
Let’s take a look at the error budget …



$$\phi\ [\mathrm{mas}] = 10^{0.2\cdot(S - m_0)}$$

FIG. 9.—Surface brightnesses of nearby stars in the V band is plotted against $V-I$, $V-J$, $V-H$, and $V-K$ colors. The solid lines are quadratic least-squares fits to the data, the coefficients of the fits are listed in Table 9. The arrows correspond to a reddening A_V of 1 mag.

Reddening 0.4 %   reddening law 0.2 %



0.003 mag (Sv) => 0.05 % on distance

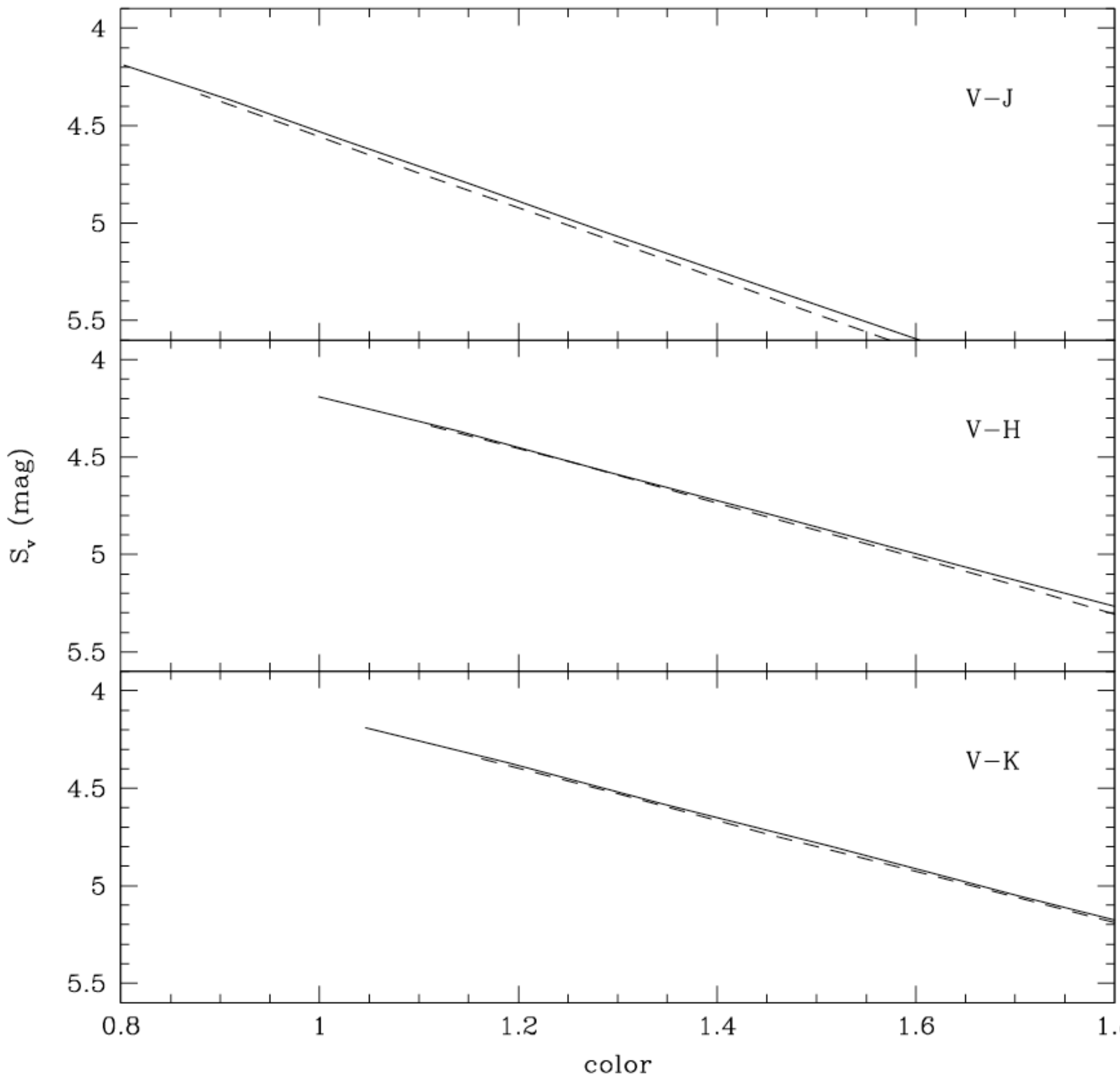
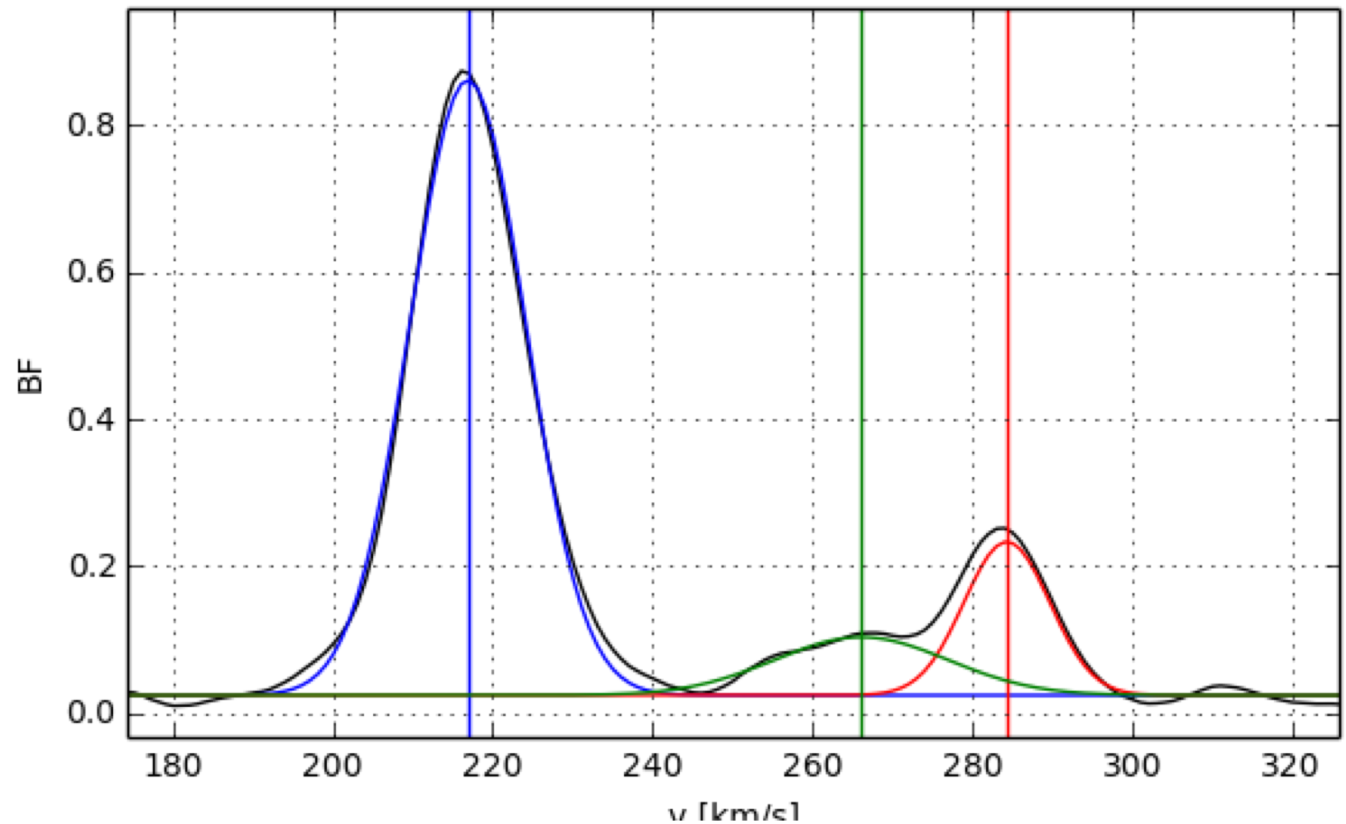


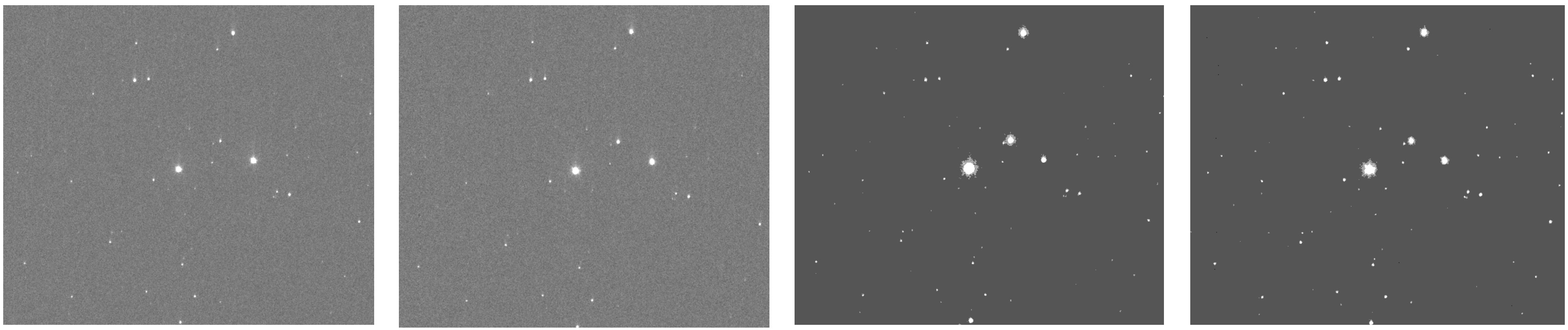
FIG. 10.—Synthetic relations S_V–$(V-K)$ for [Fe/H] = 0 (*solid lines*) and [Fe/H] = −2.0 (*dotted lines*).

Blending / crowding

We can detect and estimate it precisely !

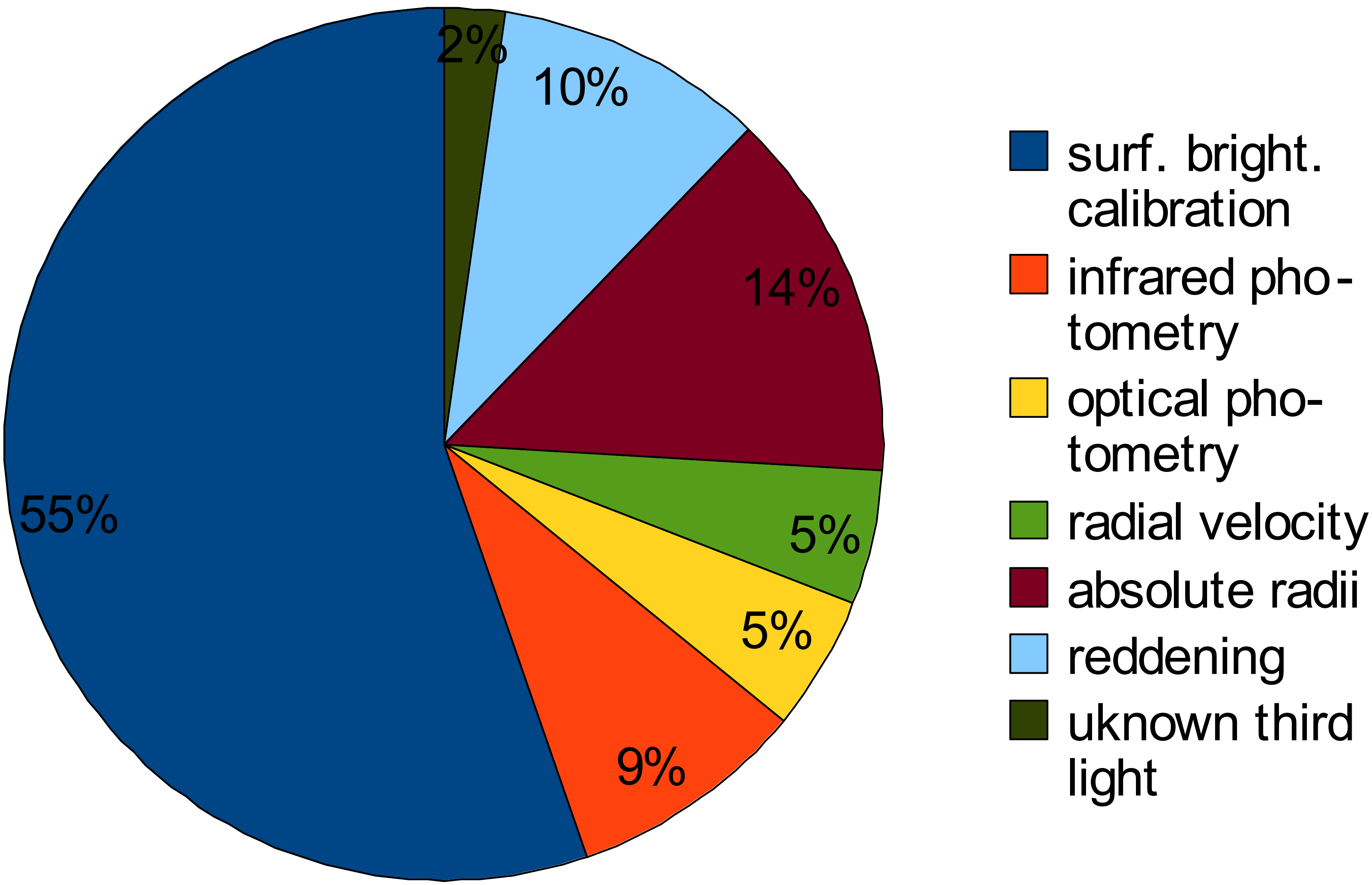


UBVI HST imaging

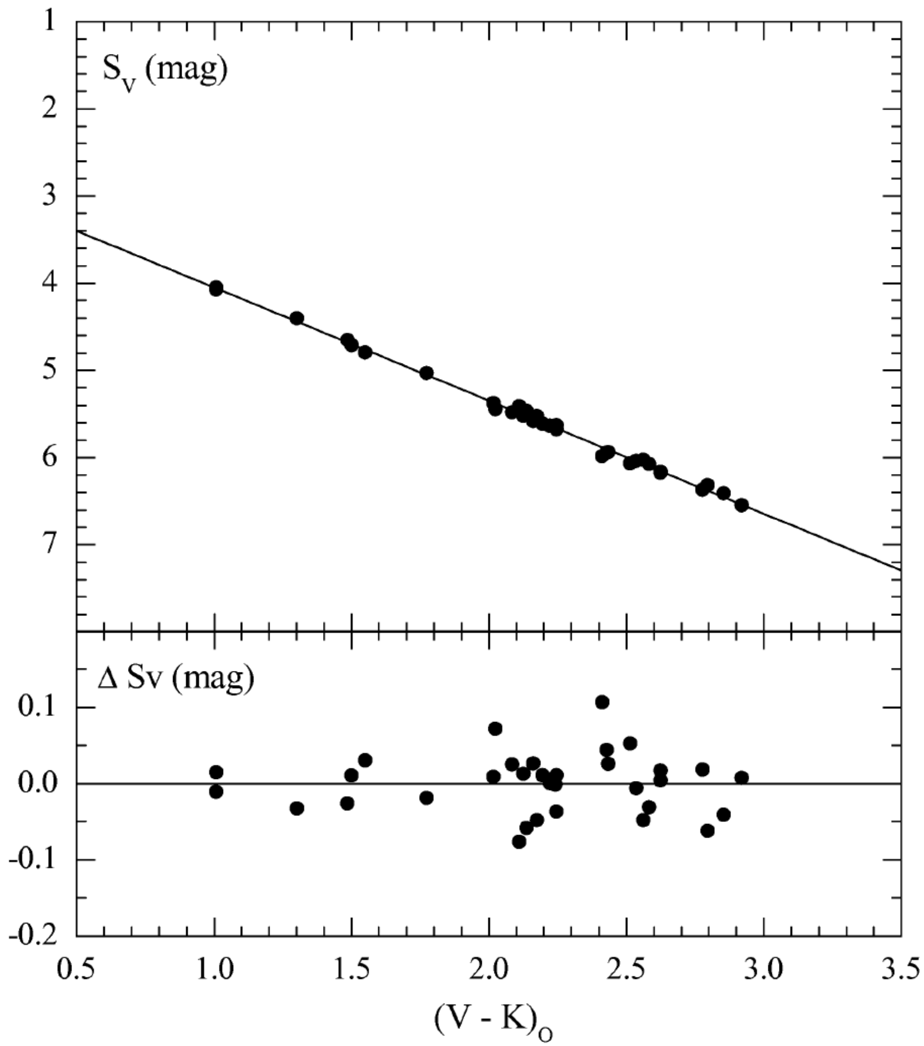


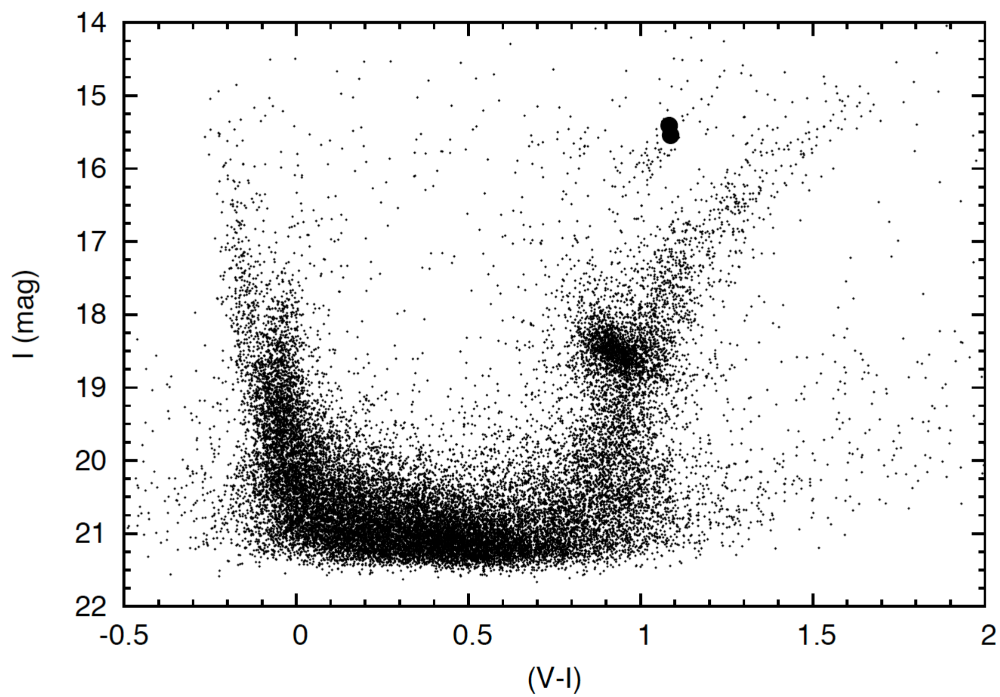
Third light can be also modelled !! < 1%

The distance error budget (2.5 % total error)

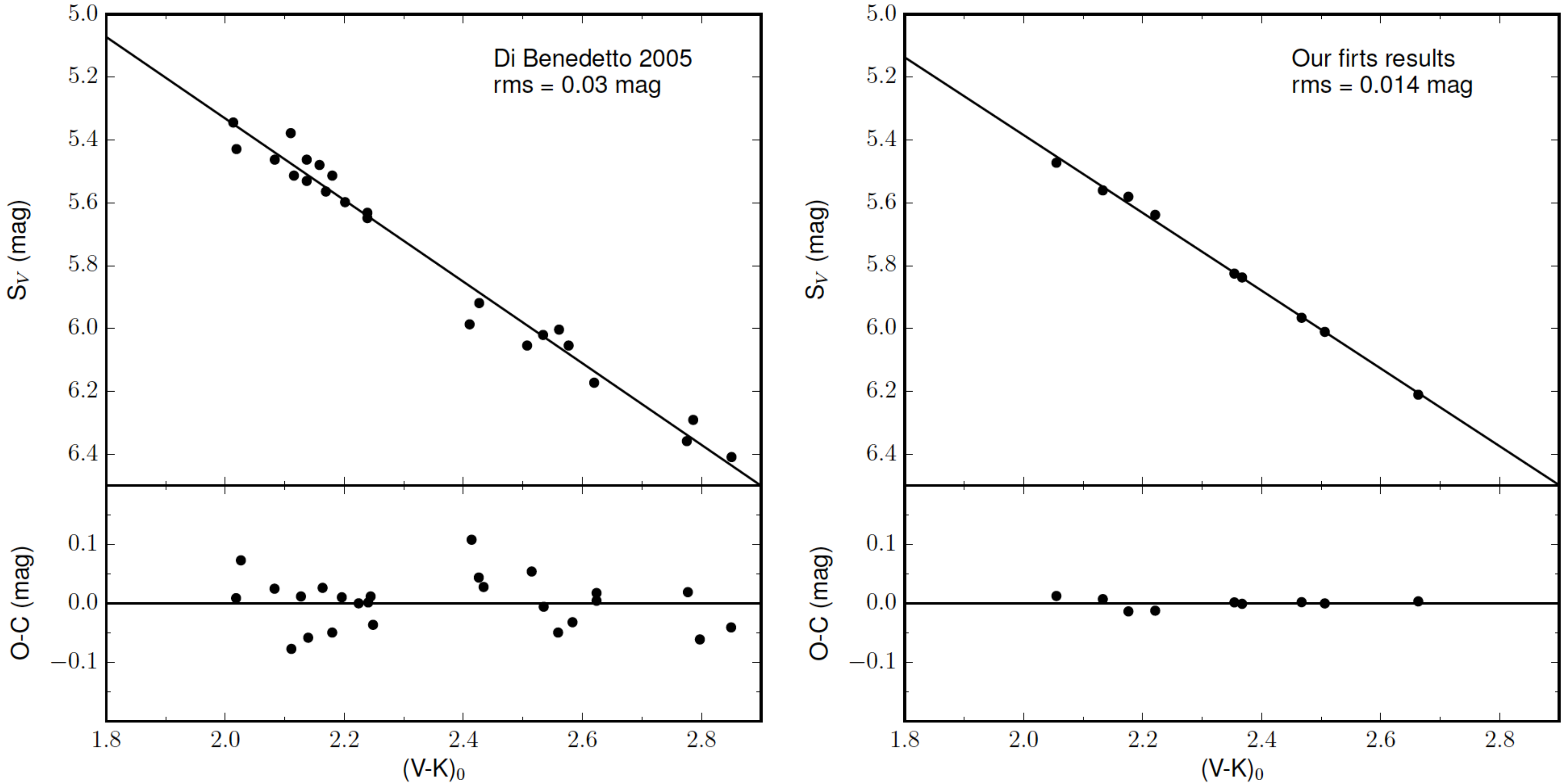


Improving $S_V \Leftrightarrow (V-K)_0$ relation

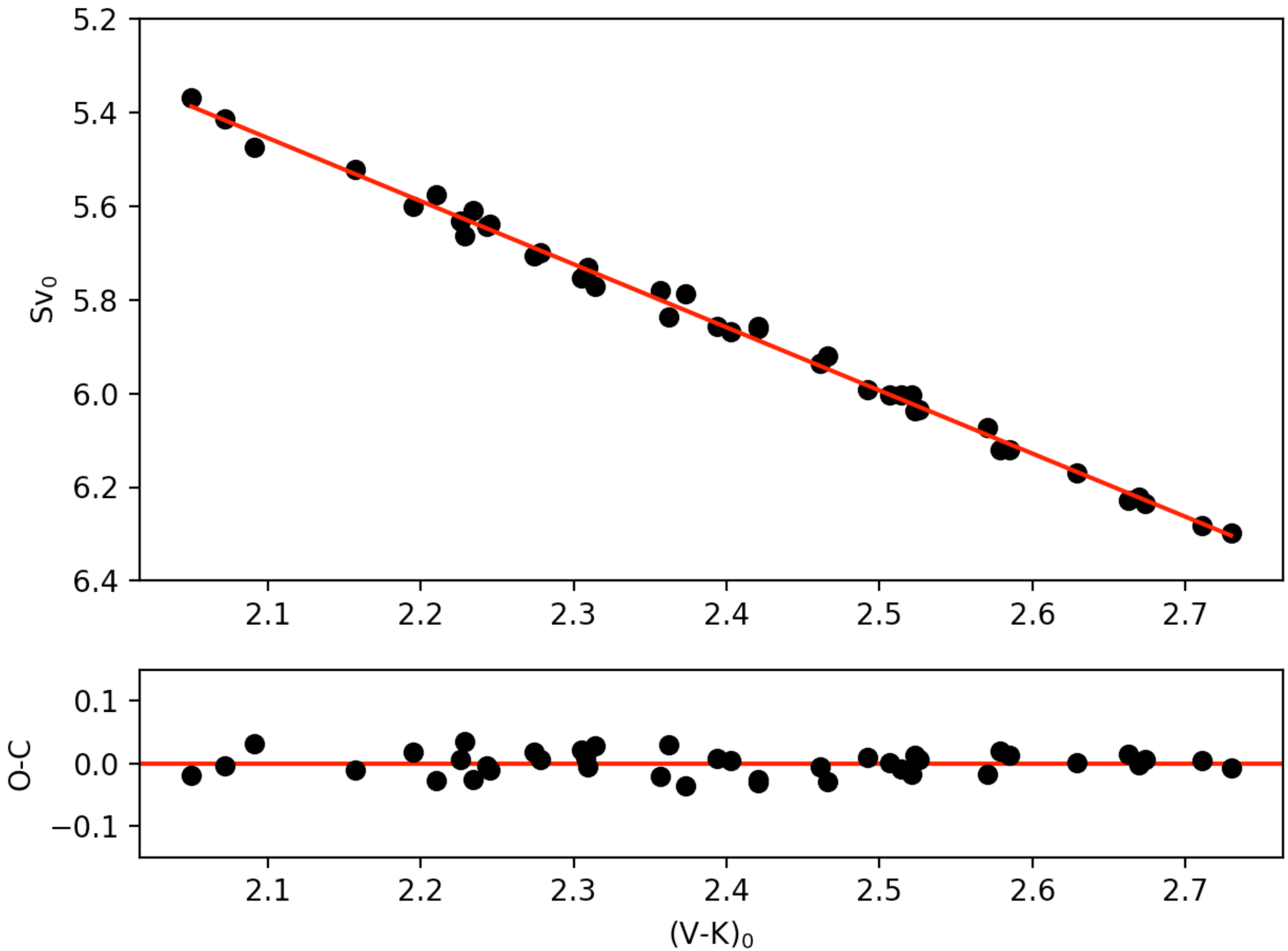




IR photometry SAAO
VLTI 1-2% angular diam.

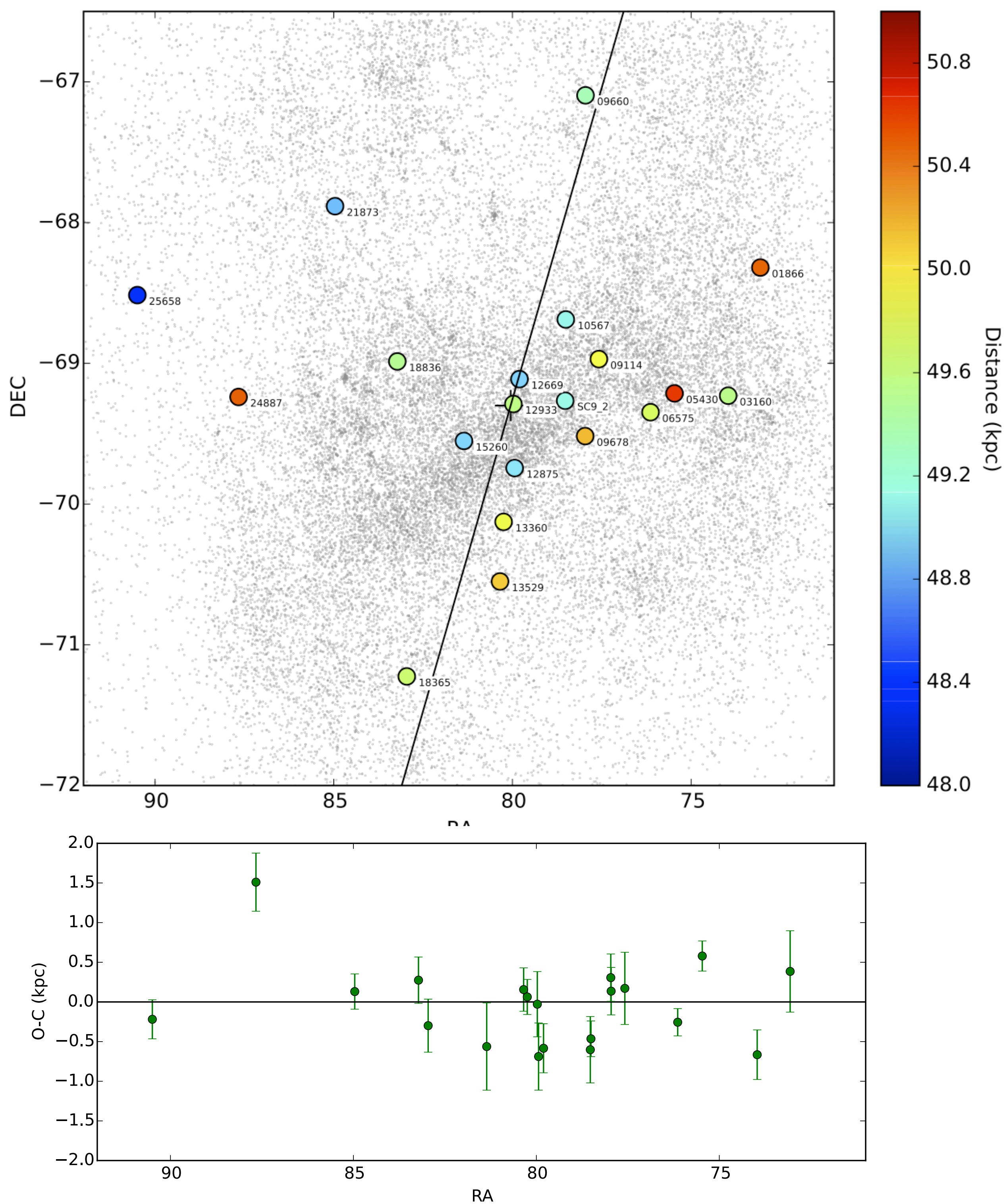


Di Benedetto 2005
rms = 0.03 mag
Our firts results
rms = 0.014 mag
S_V (mag)
O-C (mag)
(V-K)$_0$
5.0
5.2
5.4
5.6
5.8
6.0
6.2
6.4
0.1
0.0
−0.1
1.8
2.0
2.2
2.4
2.6
2.8



Sv = 1.330(±0.017) × [$(V\text{-}K)_0$ - 2.405] + 5.869(±0.003) mag

r.m.s. 0.018 mag (0.8% in angular diam.)



20 systems

Individual distances accurate to ~2%

Dominated by statistical errors

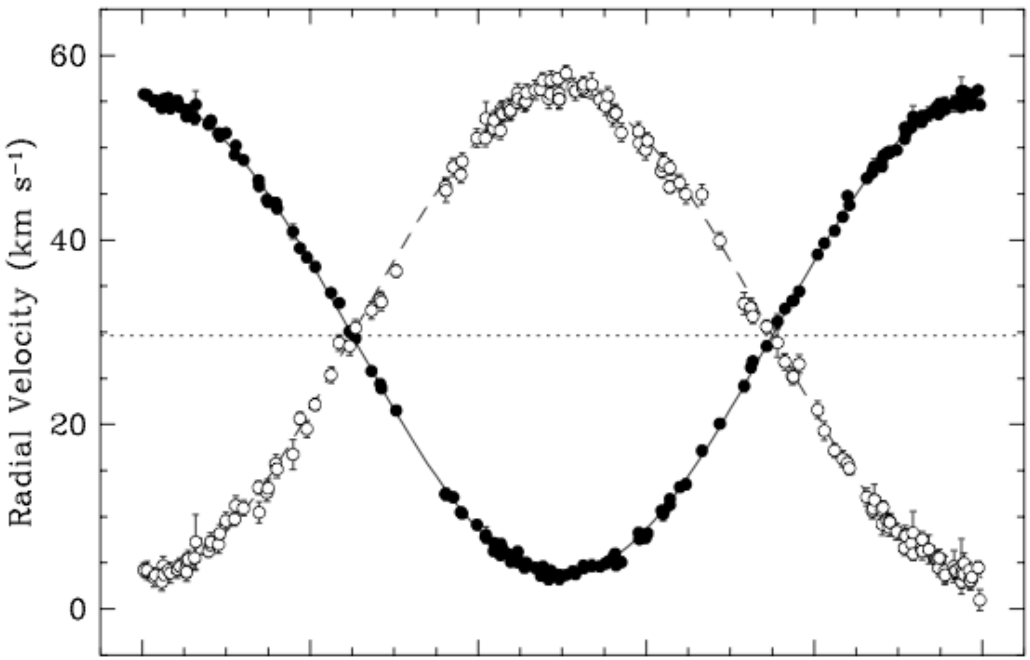
Final distance

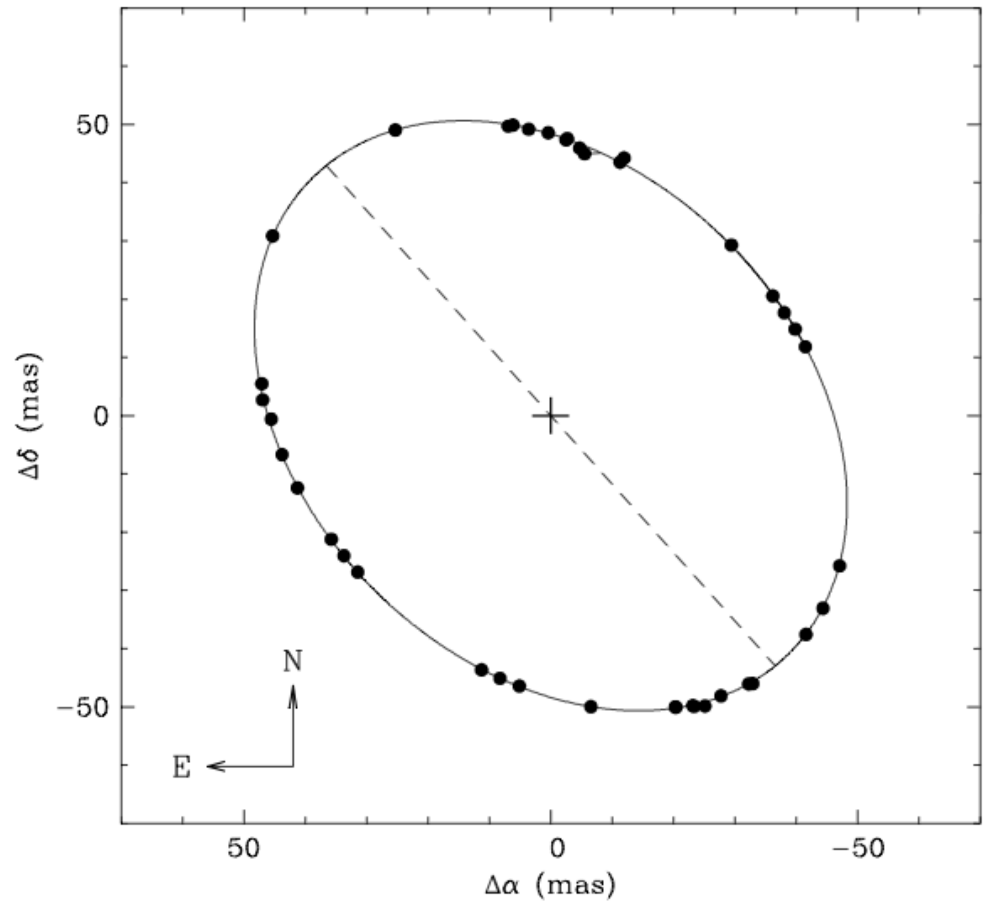
Simple mean: 18.476 ± 0.002 mag
Corrected for geometry (van der Marell) : 18.476 ± 0.002

Our own geometrical model:
the center of the LMC (R.A. = $5^{h}\ 20^{m}\ 12^{s}$, DEC = –69° 18’ 00” J2000.0)
inclination angle **of 25 ± 4 deg**, a positional angle of **132 ± 10 deg**, and a mean distance modulus of:
18.477 ± 0.004 mag, with a reduced χ^2 very close to unity.

Systematic errors 0.026 mag (SBCR, phot. zero points, reddening)

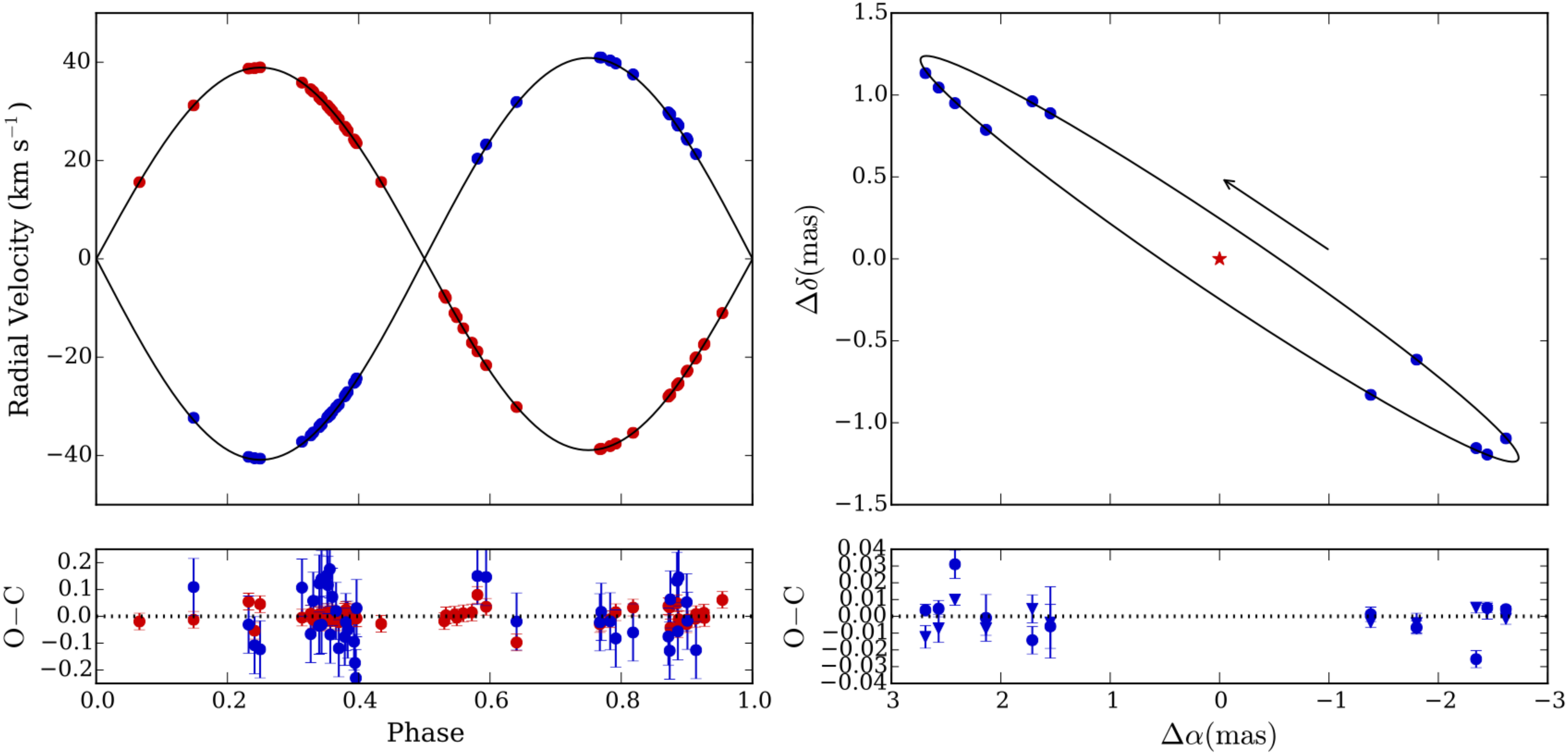
Pietrzynski et al. 2019, Nature, 567, 200





1% distance easily
Torres et al. 2009, ApJ, 700, 1349

We selected 12 eclipsing systems in the Solar neighbourhood for which interferometric orbits can be obtained (VEGA, PIONIER)
⇒Sv – color relation can be tested very precisely,
⇒WD modelling etc …



Radial Velocity (km s^{-1})
Phase
O−C
$\Delta\delta$(mas)
$\Delta\alpha$(mas)

Parameter	Andersen et al. (1991)	This work
$P_{\rm orb}$ (days)	75.6676 ± 0.0010	75.66647 ± 0.00006
$T_{\rm p}$ (HJD)	2445032.609 ± 0.002	2452599.29040
e	0.0	0.00002 ± 0.00003
K_1 (km s^{-1})	38.81 ± 0.06	38.90 ± 0.01
K_2 (km s^{-1})	40.80 ± 0.54	40.87 ± 0.02
γ_1 (km s^{-1})	17.42 ± 0.04	17.99 ± 0.03
γ_2 (km s^{-1})	16.30 ± 0.46	18.35 ± 0.11
ω (°)	–	269.93 ± 0.04
Ω (°)	–	65.99 ± 0.03
a (mas)[a]	2.97 ± 0.18	2.993 ± 0.030
a (AU)	0.555 ± 0.004	0.5564 ± 0.0001
i (°)	85.64 ± 0.05	85.68 ± 0.05
$\theta_{\rm LD,1}$[a]	0.418 ± 0.023	0.414 ± 0.010
$\theta_{\rm LD,2}$[a]	0.199 ± 0.012	0.197 ± 0.008
M_1 ($M_\odot$)	2.05 ± 0.06	2.057 ± 0.001
M_2 ($M_\odot$)	1.95 ± 0.03	1.958 ± 0.001
d (pc)	185 ± 10	185.9 ± 1.9
π (mas)	5.41 ± 0.29	5.38 ± 0.06
R_1 ($R_\odot$)	8.32 ± 0.12	8.28 ± 0.22
R_2 ($R_\odot$)	3.96 ± 0.09	3.94 ± 0.17
$\log L_1/L_\odot$	1.59 ± 0.04	1.57 ± 0.02
$\log L_2/L_\odot$	1.36 ± 0.03	1.36 ± 0.03

TZ For independent distances

Our method + new SBCR: 185.1 ± 2.0 (stat) ± 1.9 (sys) pc
The statistical error is dominated by error on the radius determination of the giant (better photometry needed). (Pietrzynski et al 2019)

spectroscopic and astrometric orbits 186.1 ± 1.0 (stat+syst) pc
(Gallenne et al. 2016)

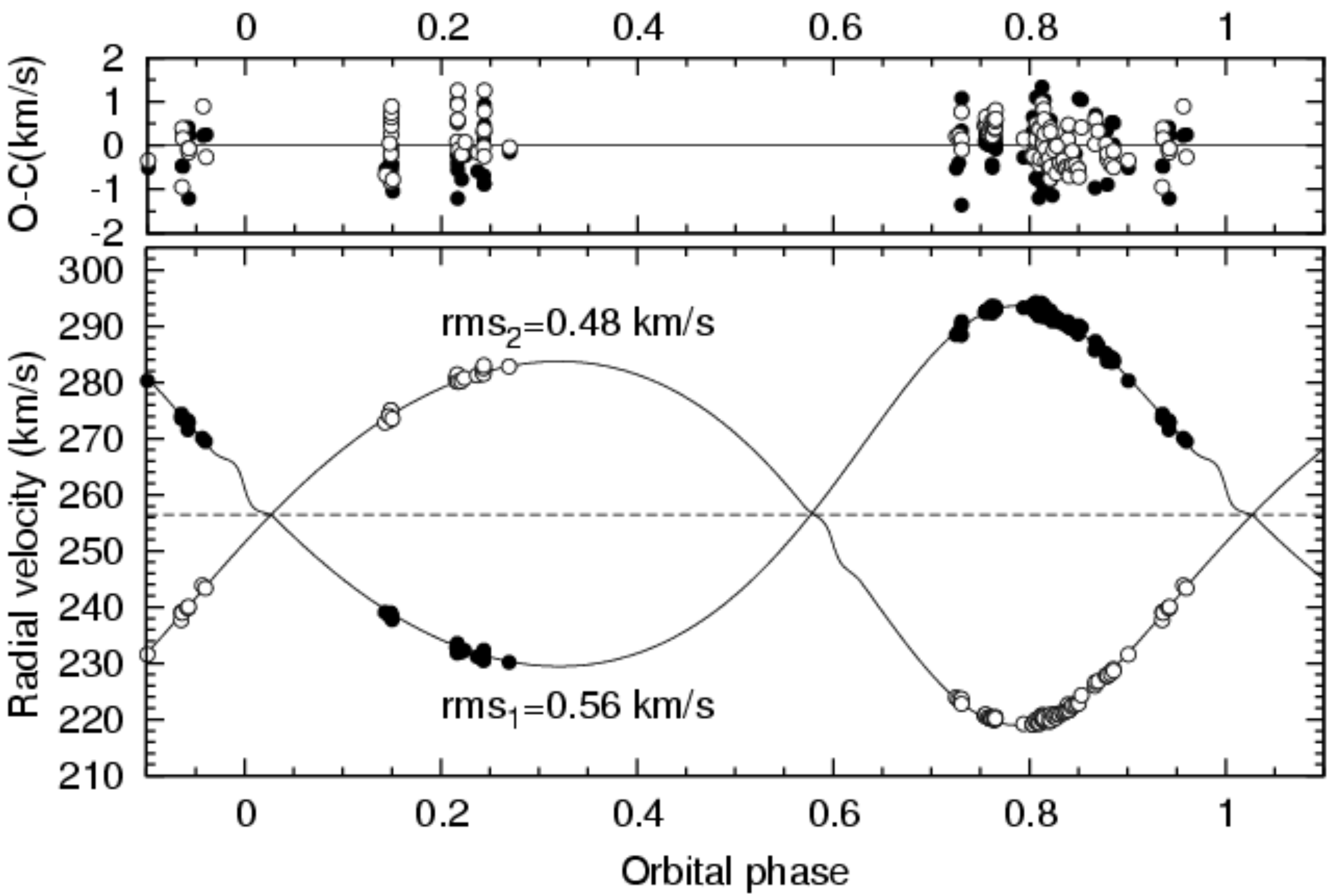
Gaia DR2 parallax is: 183.4 ± 0.8 (stat) pc
However TZ For is an astrometric binary whose aparent orbital motion is unmodeled in the DR2 data reduction.

We will provide a check on Gaia parallaxes at a 1% precision level in a large range of distances …

OGLE-LMC-CEP-0227: best studied system so far (Pilecki et al. 2013, MNRAS, 436, 953)

Results: **Masses to 0.5%, radii to 1%, p-factor to 3%**

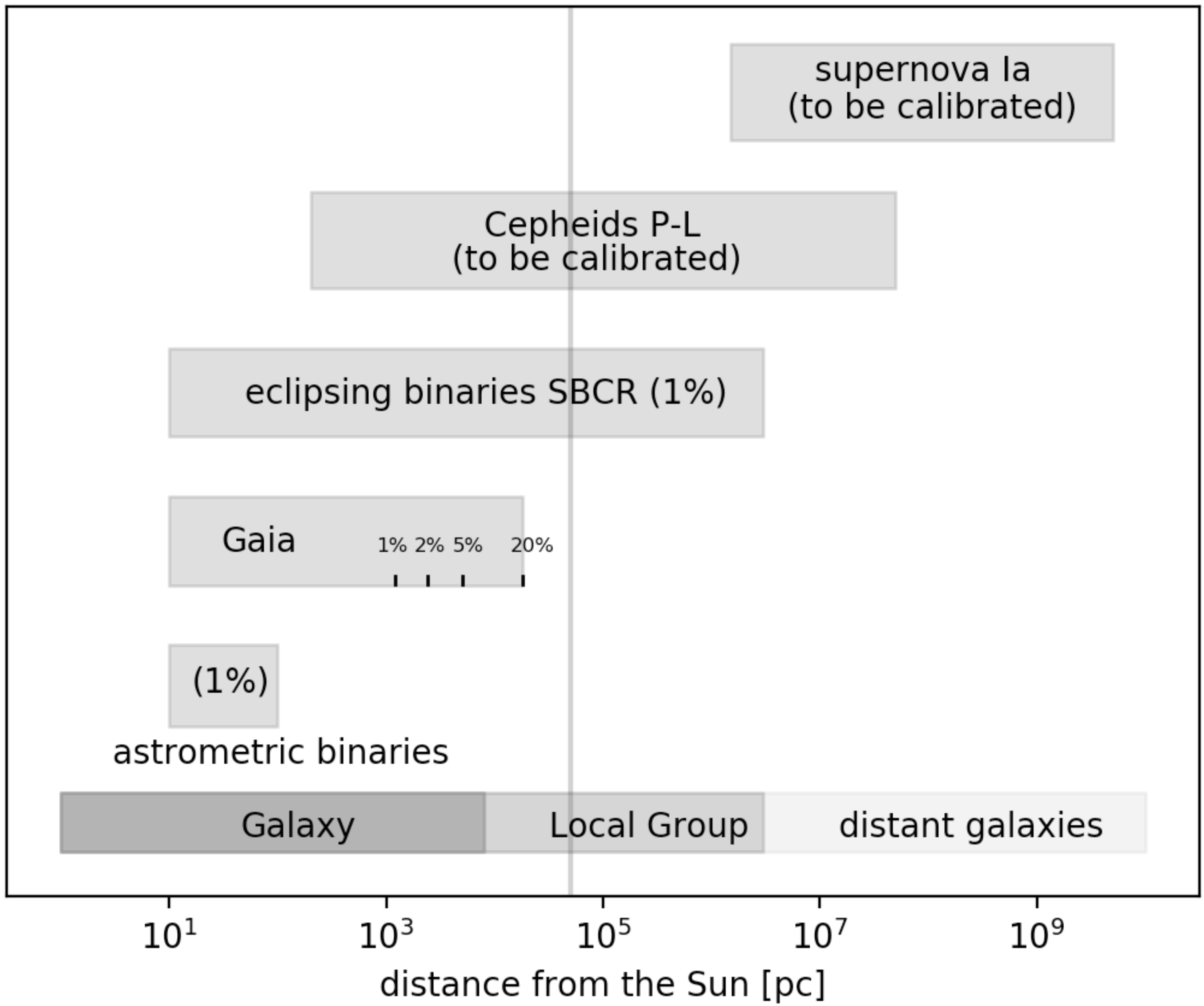
Optical limb darkening of Cepheid much higher than theory predictions!



EB - Summary

The principal sources of error

- population effects OK
- extinction OK
- the zero point OK
- blending / crowding OK
- physics of the distance indicators Cepheid OK
  parameters ~ 1%


supernova Ia
(to be calibrated)
Cepheids P-L
(to be calibrated)
eclipsing binaries SBCR (1%)
Gaia
1% 2% 5% 20%
(1%)
astrometric binaries
Galaxy
Local Group
distant galaxies
10^1
10^3
10^5
10^7
10^9
distance from the Sun [pc]

Wolfgang Gieren
Marek Górski
Alexandre Gallenne
Rolf Kudritzki
Fabio Bresolin
Miguel Urbaneja
Ian Thompson
Jesper Storm
Giuseppe Bono
Nicolas Nardetto
Radosław Smolec
Zbigniew Kolaczkowski
Paulina Karczmarek
Piotrk Wielgórski
Bogumił Pilecki
Bartek Zgirski
Monica Taormina

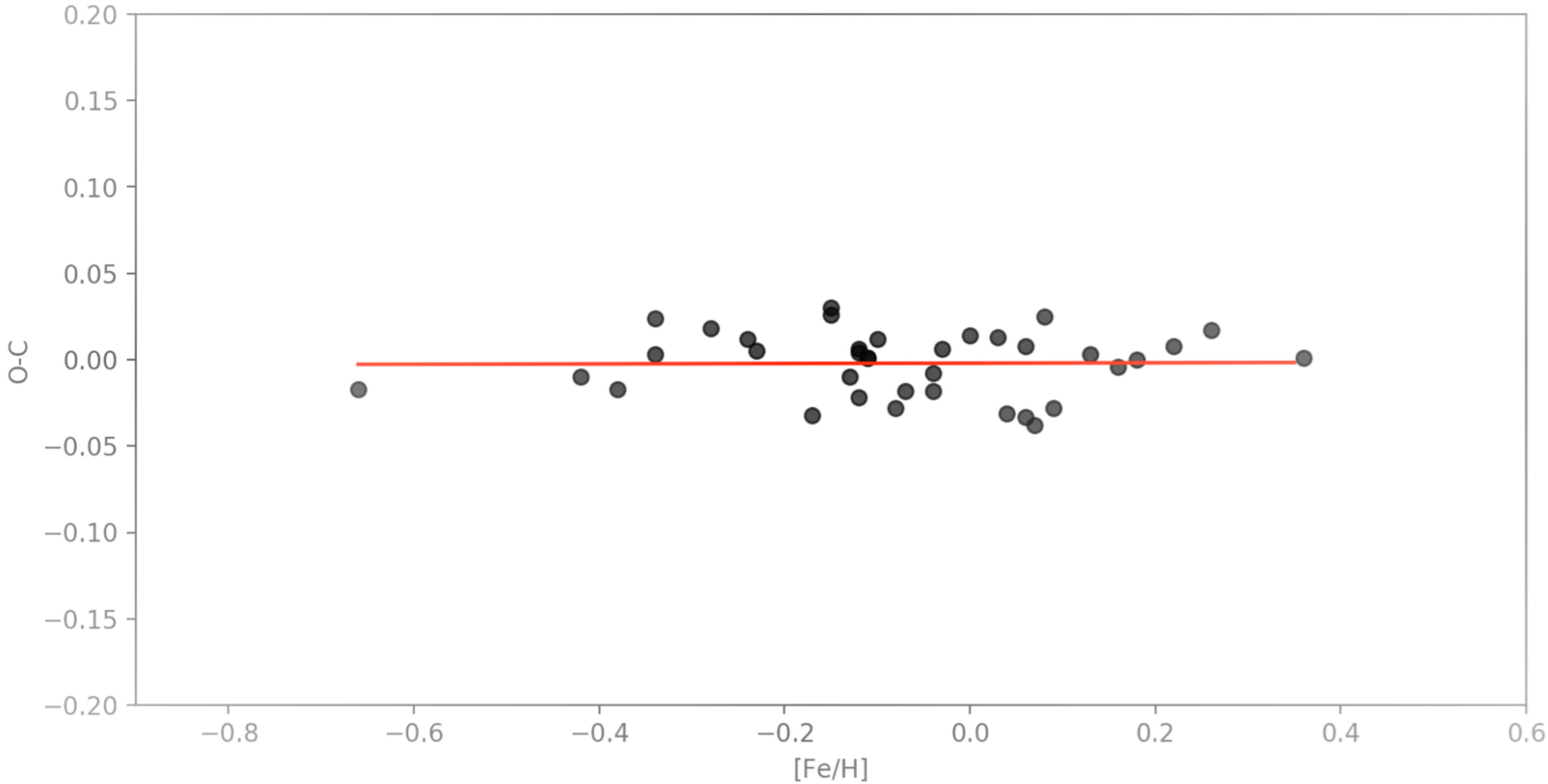
Grzegorz Pietrzyński

Limb darkening
Δ(m-M) of -0.0075 mag

System	$(m\text{-}M)_{fix}$	$(m\text{-}M)_{fit}$	Δ(m-M)
OGLE-LMC-ECL-09660	18.490	18.489	-0.001
OGLE-LMC-ECL-10567	18.490	18.506	0.016
OGLE-LMC-ECL-26122	18.469	18.482	0.013
OGLE-LMC-ECL-09114	18.481	18.465	-0.016
OGLE-LMC-ECL-06575	18.52	18.497	-0.023
OGLE-LMC-ECL-01866	18.496	18.496	0.000
OGLE-LMC-ECL-03160	18.511	18.505	-0.006
OGLE-LMC-ECL-15260	18.500	18.509	0.009

Eclipsing binaries
Classical („photometric”) distances

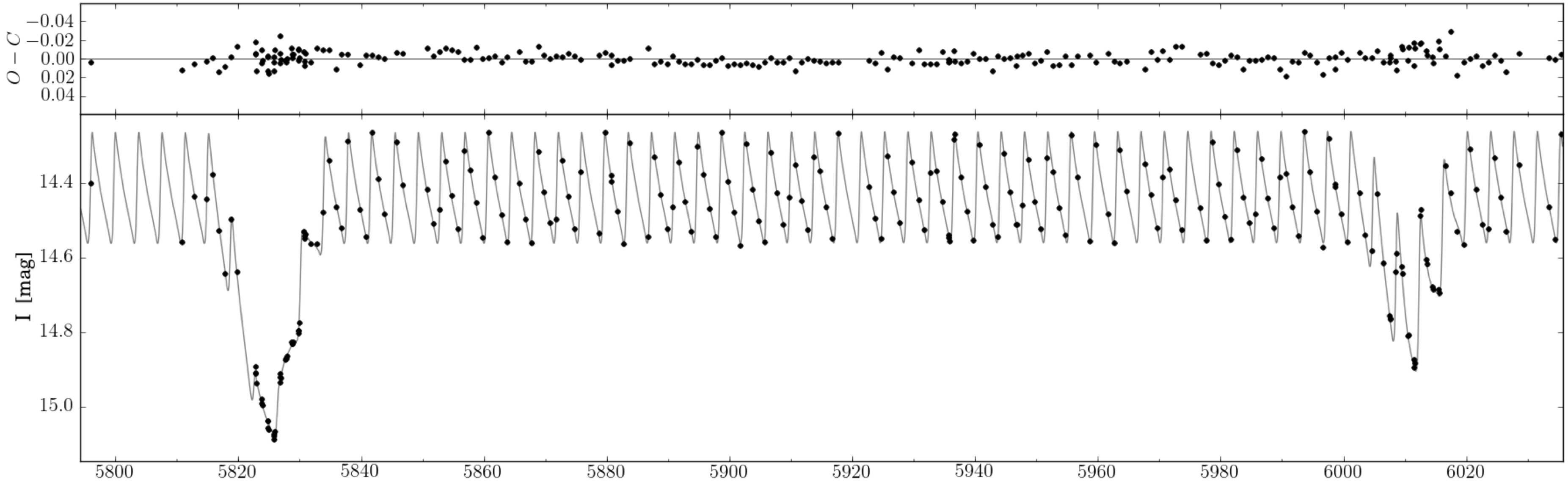
$$d_i(\mathrm{pc}) = 3.360 \cdot 10^{-8} R_i \, T_i^2 \, 10^{0.2(BC_i + V_i)}$$

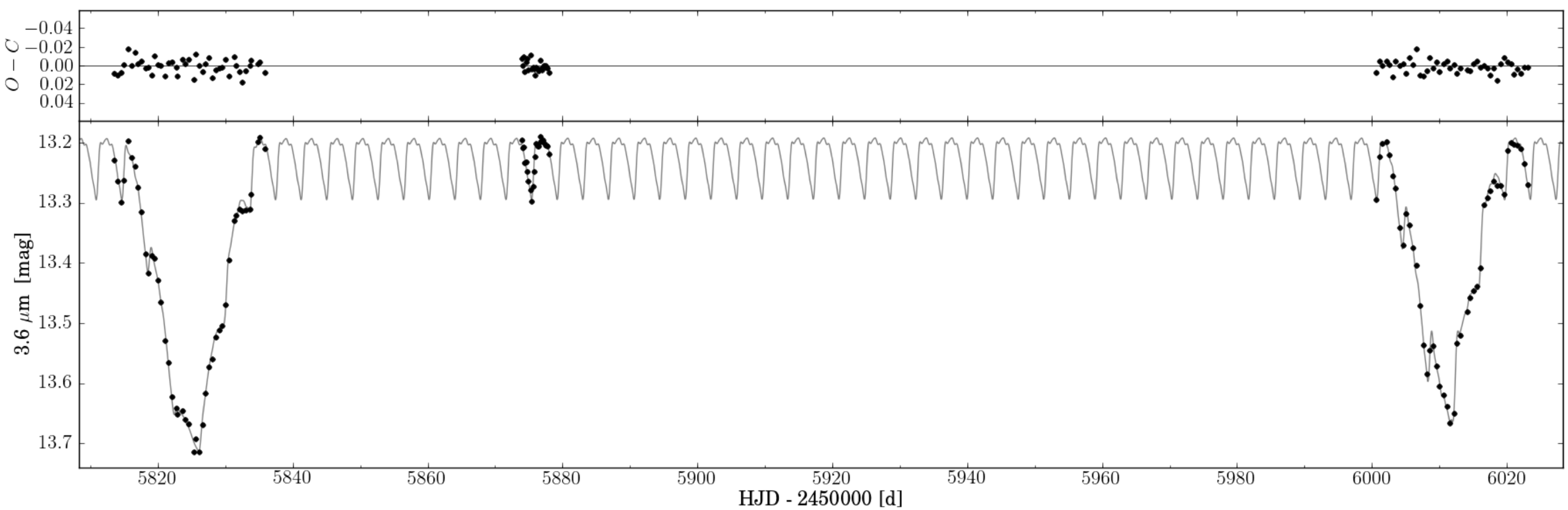


In a relatively large range of metallicities (about 1 dex) no correlation

is found. A formal linear fit gives O-C = 0.0009 x [Fe/H] – 0.002 dex with coefficient of determination $R^2 = 0.0001$.

Code of Pilecki et al., applied to Cep-0227 photometric data yields very accurate fits to the observed light curve eclipses





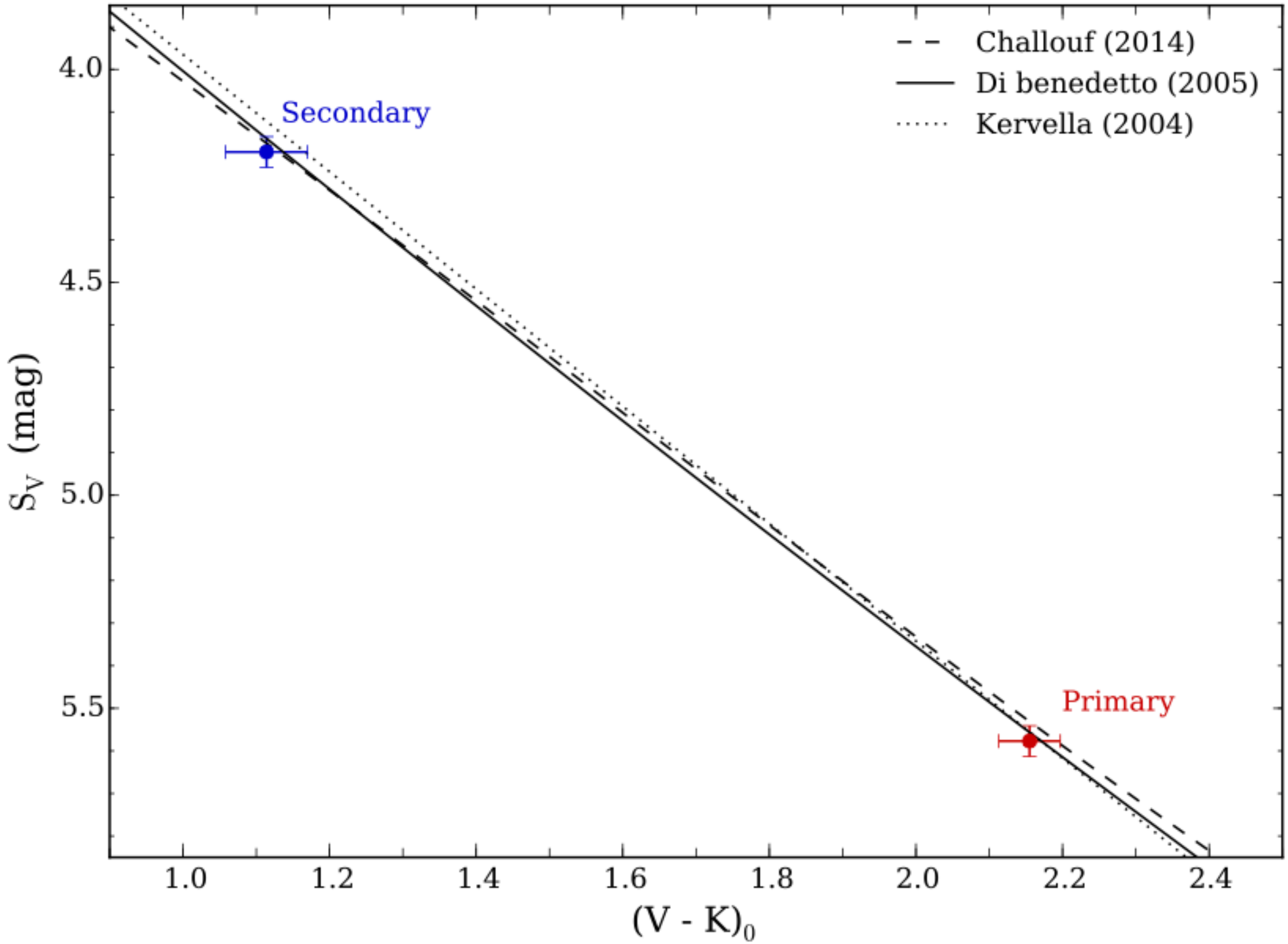


Fig. 5. Test of the existing SBC relations using our new precise distance of TZ For.

Araucaria observatory