Extragalactic Distance Scale lect. VIII
Pulsating stars − cont.

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

Cepheids

Easy to detect

Relatively bright (with the HST to 30-40 Mpc)

Easy to measure period and magnitude

Very wide range of magnitudes

In general we use them as a statistical tool

(sample of Cepheids) but we can calculate distances

to individual objects with 0.2 mag precision

Cepheids P-L

Problems:

Extinction

Absolute zero point

Malmquist bias

Uniform coverage of the IS

Metallicity effect

Is PL linear and universal ?

Binarity

Blending and crowding

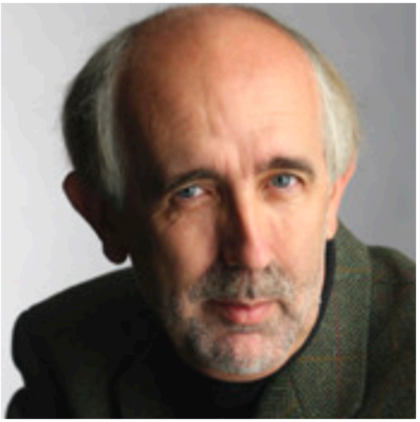
Many other less importnat (?) issues

Extinction

1) External determinations (e.g. Different kind of reddening maps etc)

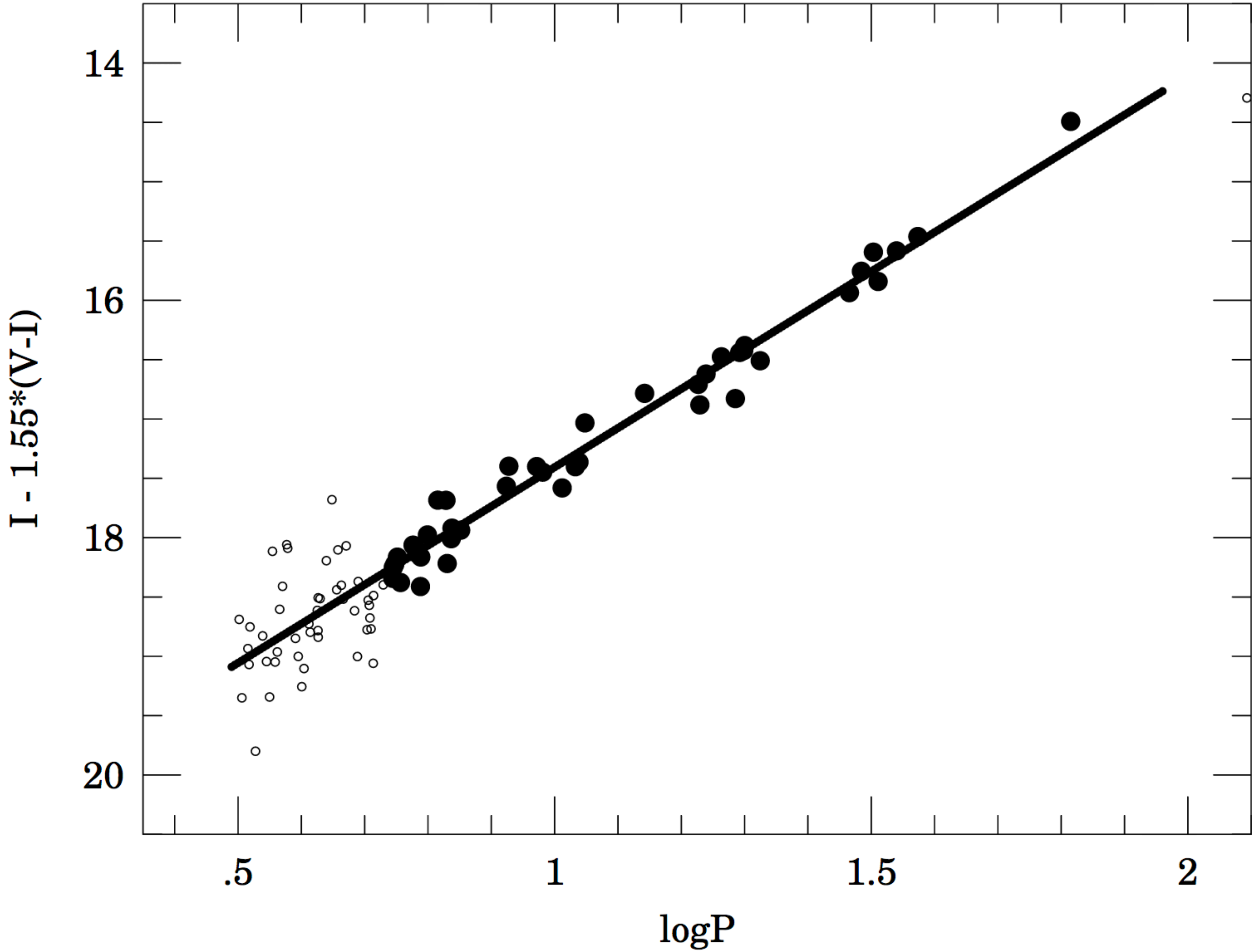
2) Wesenheit index (reddening free) (ger. essence)

$$W = V - R(B - V)$$
$$= V_0 + A_v - R(B-V)_0 - RE(B-V)$$
$$= V_0 - R(B-V)_0.$$



$$W(VI) = V - 10 + 5\,lg\,p(\text{mas}) - A_V - \frac{A_V}{E(V-I)}\cdot(V-I)_0 =$$

$$= M_V - \frac{A_V}{E(V-I)}\cdot(V-I)_0 \Rightarrow \boxed{W(VI) = M_V - \beta\cdot(V-I)_0}$$

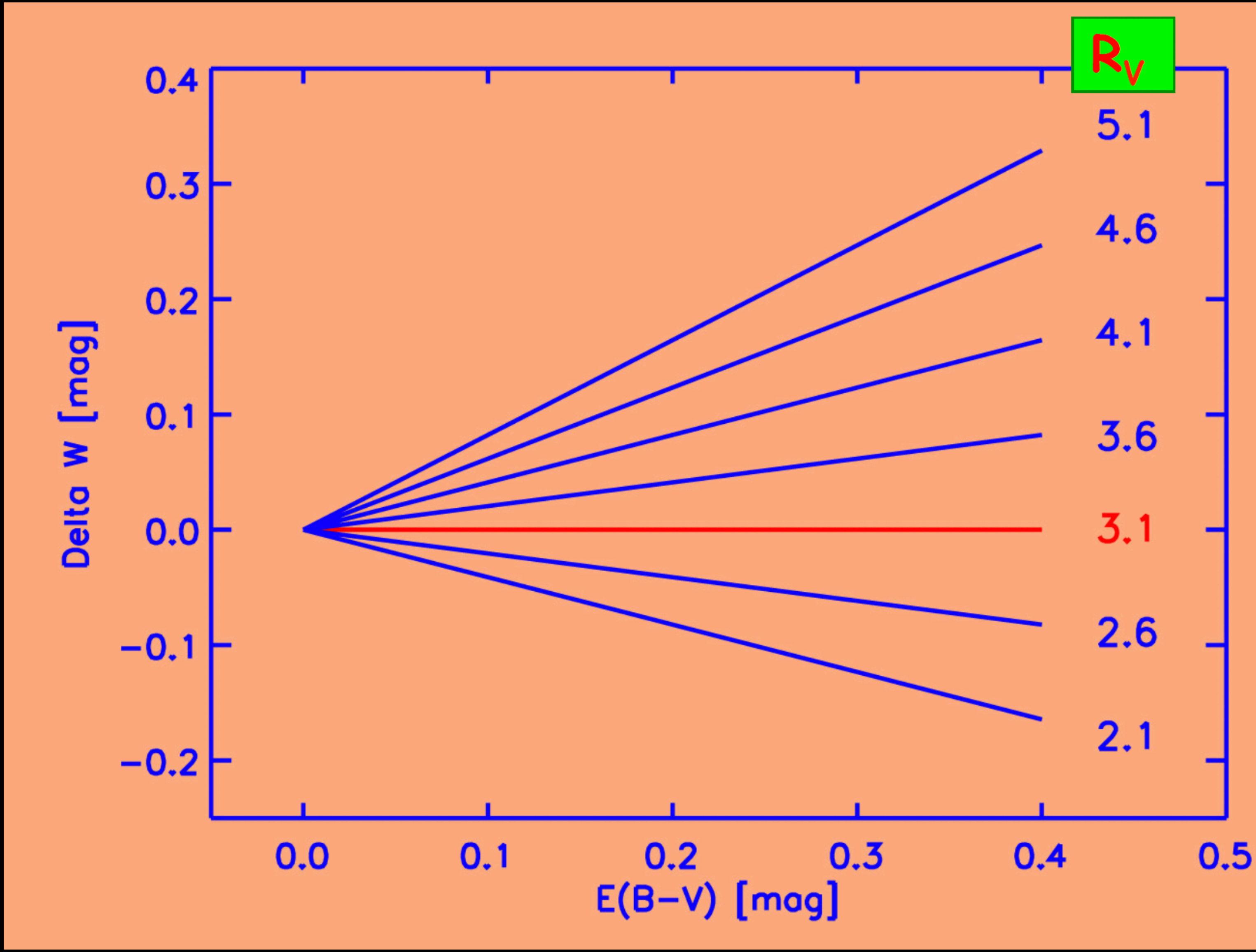


14
16
18
20
I - 1.55*(V-I)
.5
1
1.5
2
logP

"reddening free" W_{VI}: R_V and E(B-V)

$W_{VI}=V-2.45(V-I)$
"reddening free"
only for $R_V=3.1$

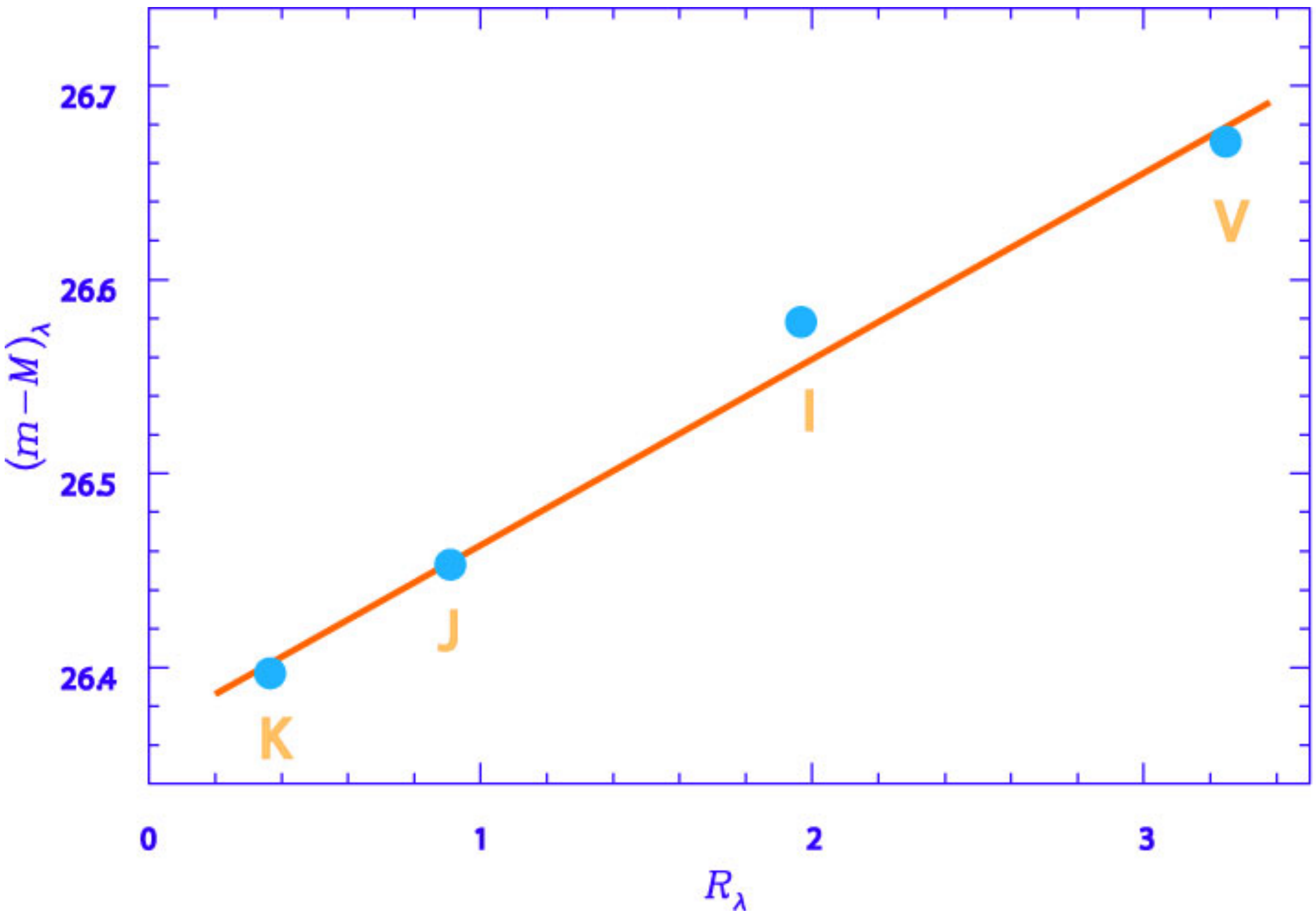
$\Delta R_V = 1.5 \rightarrow$
$\Delta W_{VI} = 0.25$ mag



Kudritzki & Urbaneja, 2012

Cepheid multi-λ distance solution

$$(m - M)_0 = (m - M)_\lambda - A_\lambda = (m - M)_\lambda - E_{B-V} R_\lambda$$

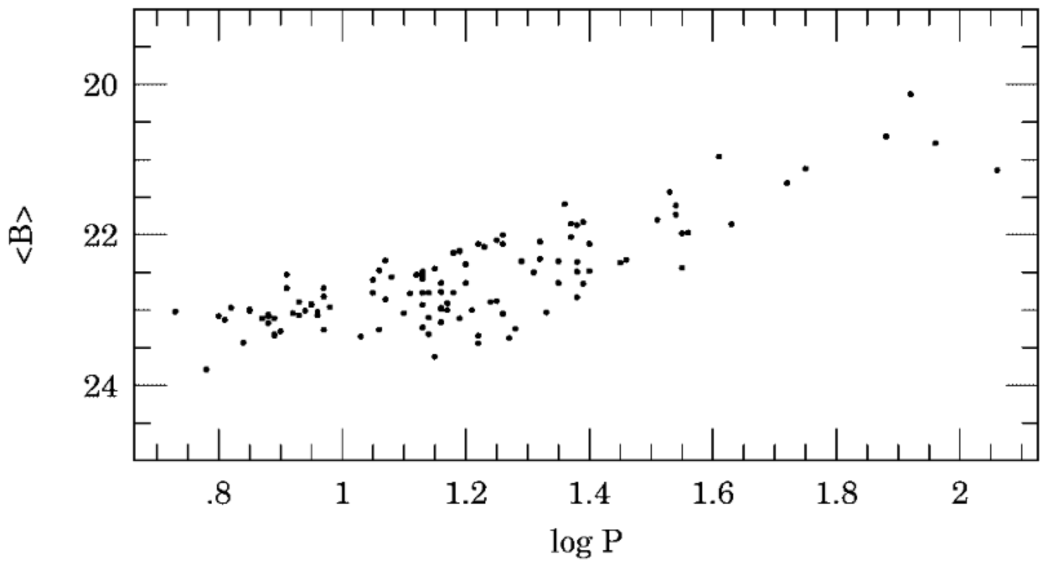


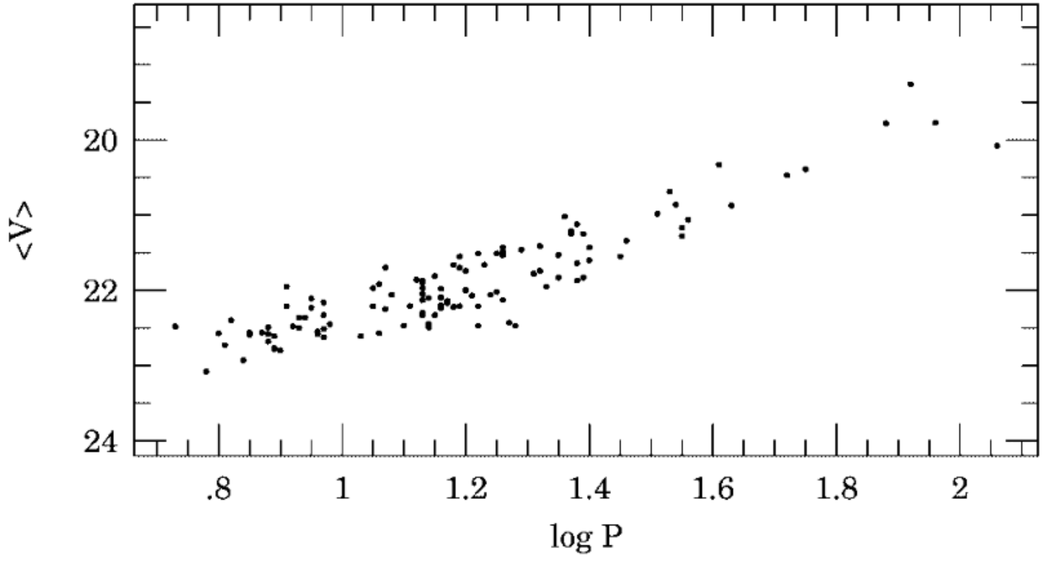
(m-M) = 26.37

D = 1.88 Mpc

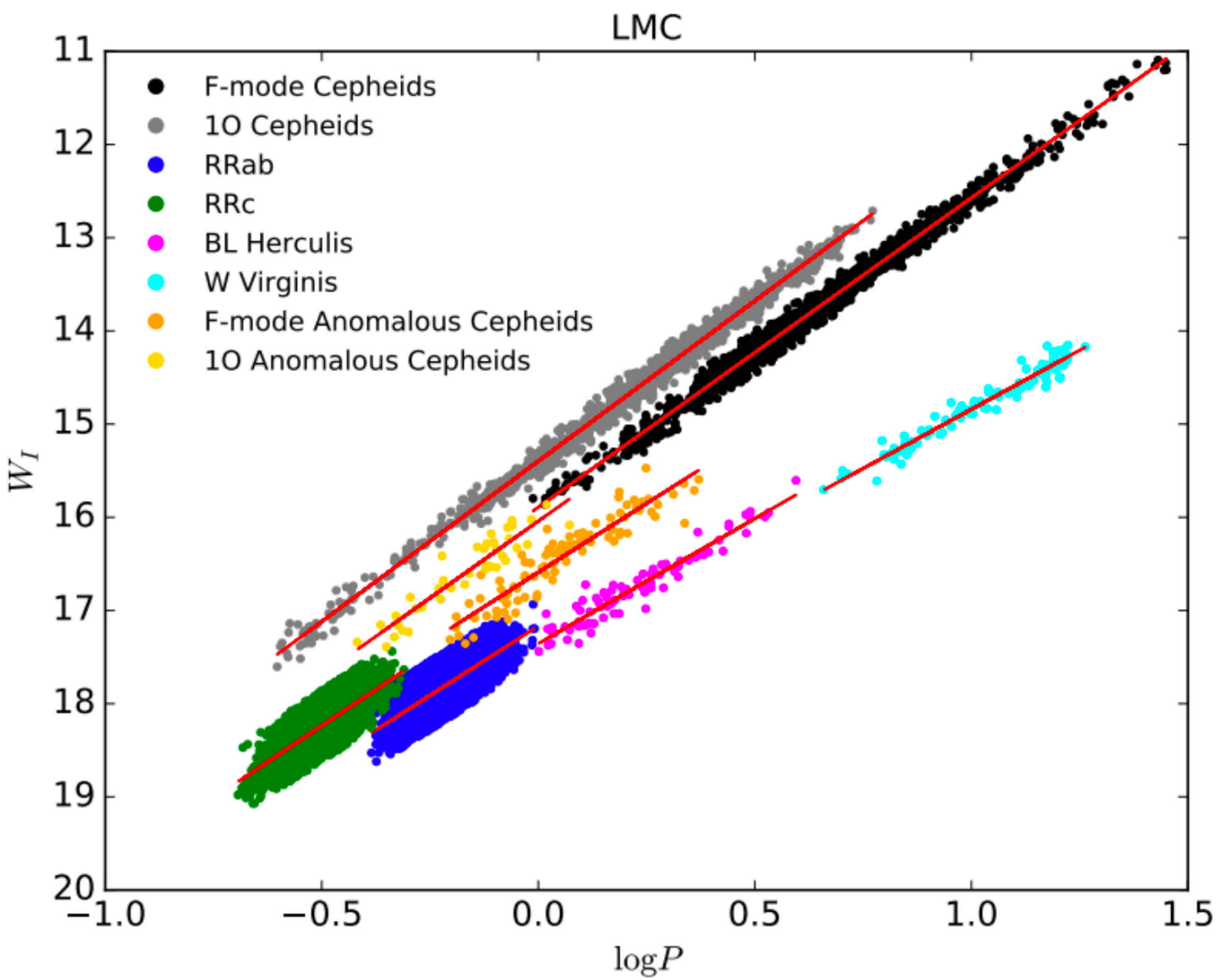
E(B-V) = 0.10

Malmquist bias

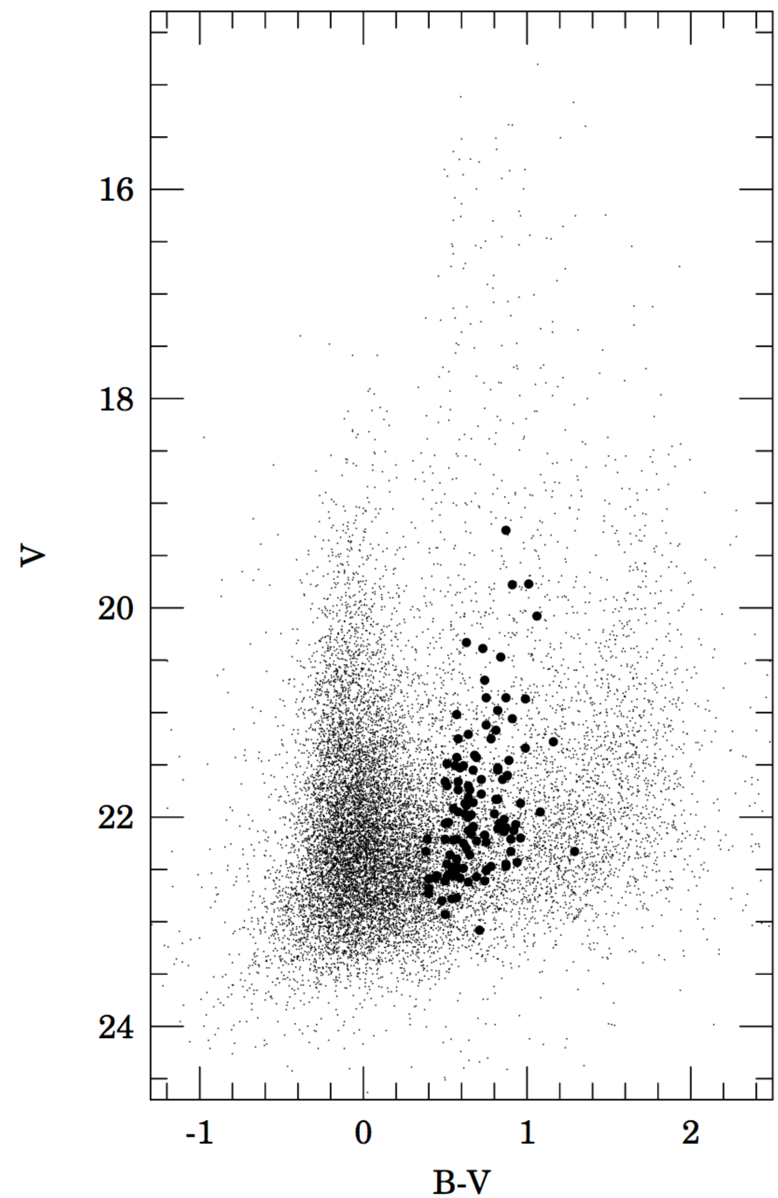




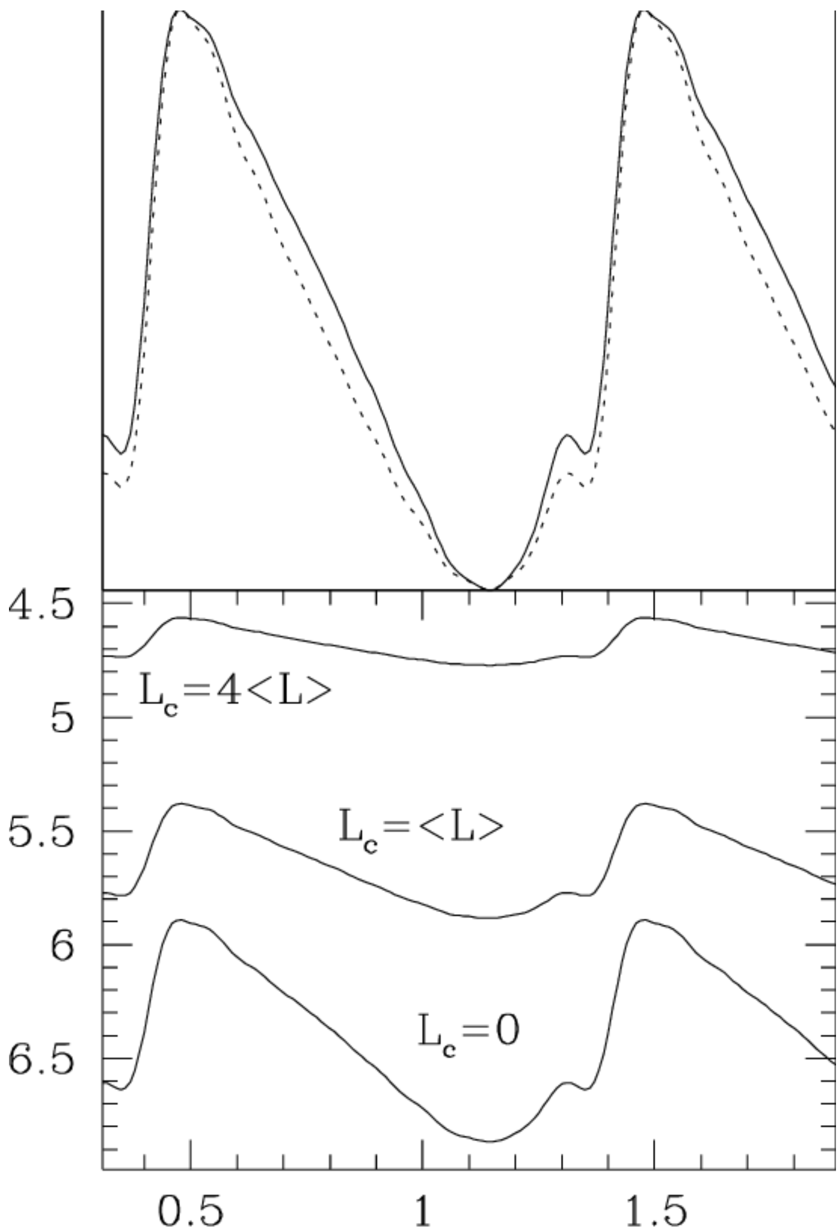
Distinguish FU (FO, Type II etc)

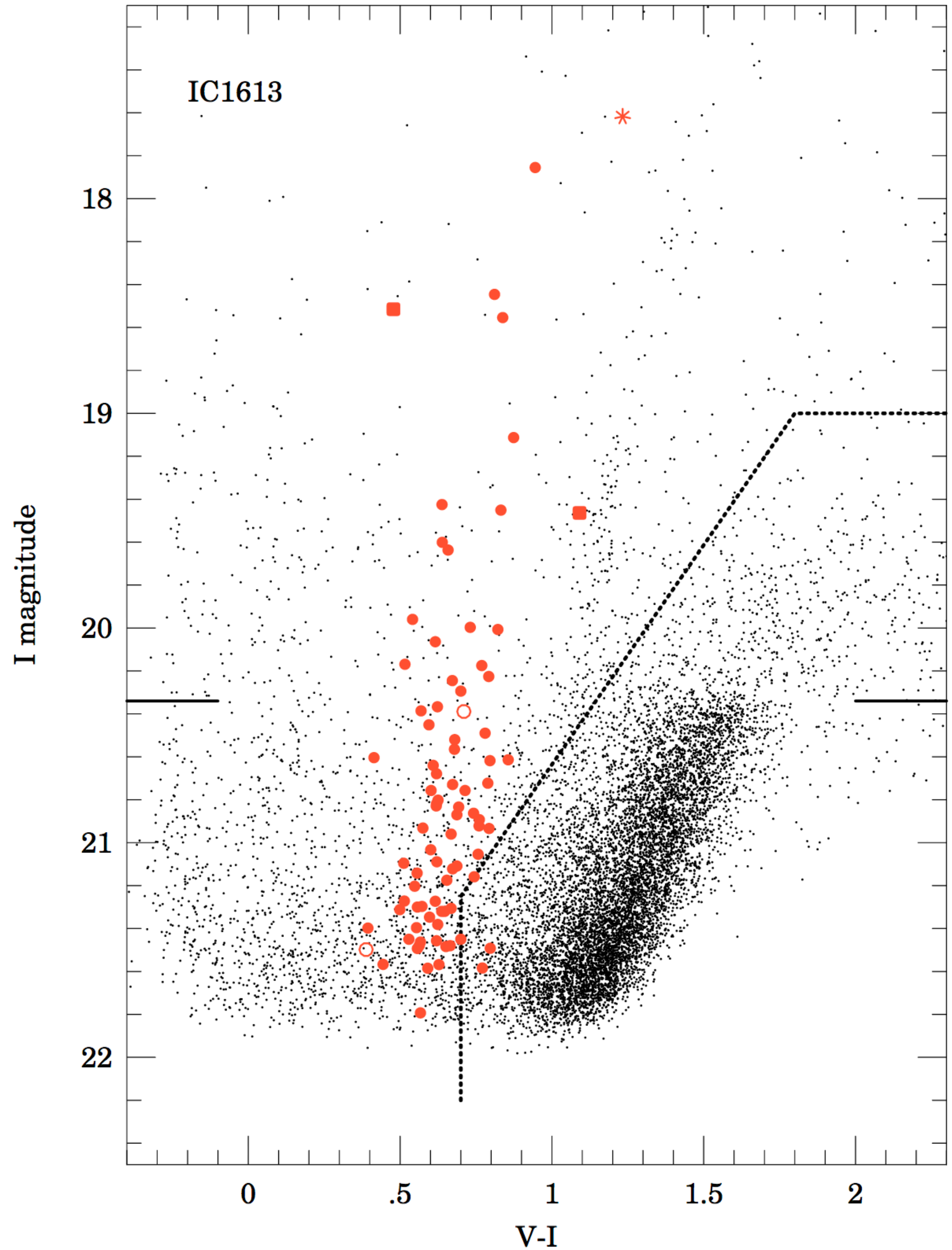


Uniform distribution in the IS

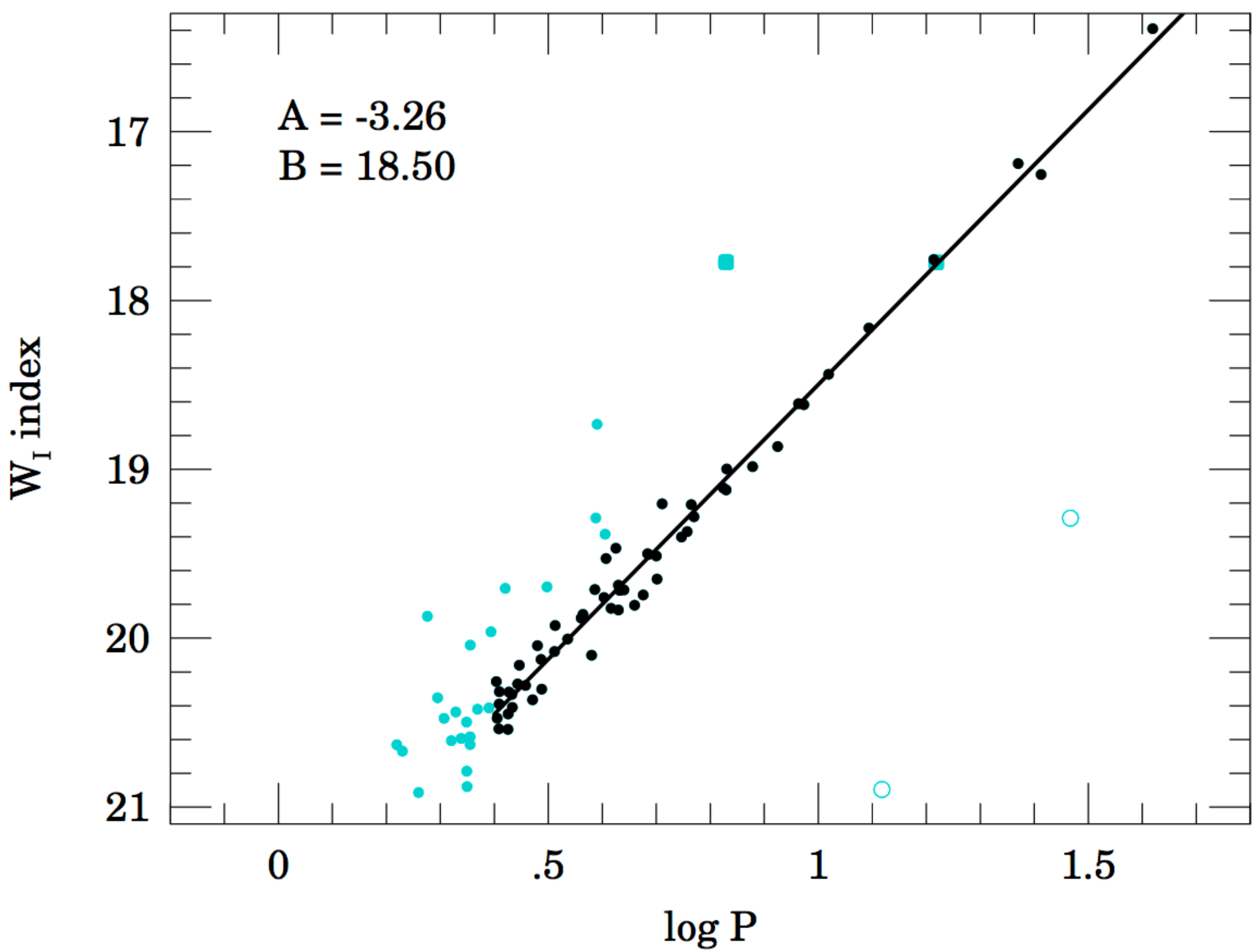


Blending / crowding

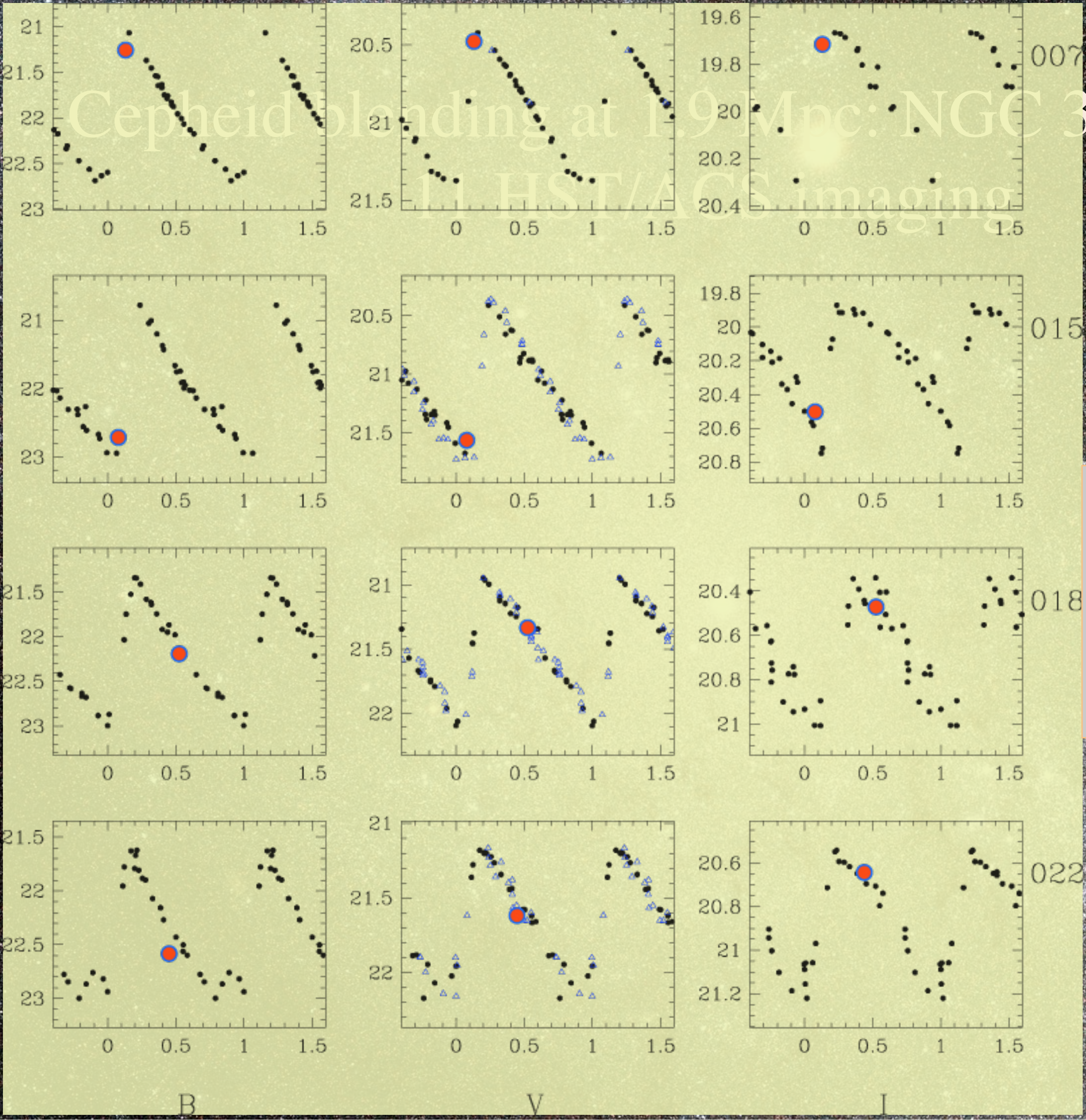




Blending / crowding



Cepheid blending at 1.9 Mpc: NGC 300 Cycle 11 HST/ACS imaging



Effects of blending studied using HST/ACS photometry

Bresolin, Gieren, Kudritzki et al. 2005, ApJ

The effect of blending at ~2 Mpc (NGC 300):

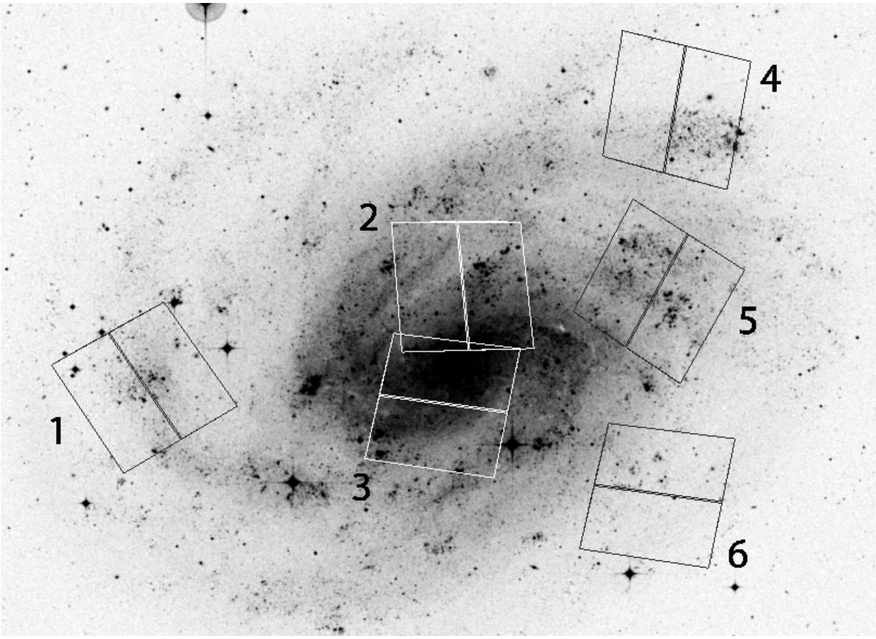
- we got single-phase HST/ACS images in BVI of six fields in NGC 300 containing 16 long-period Cepheids with well-known periods

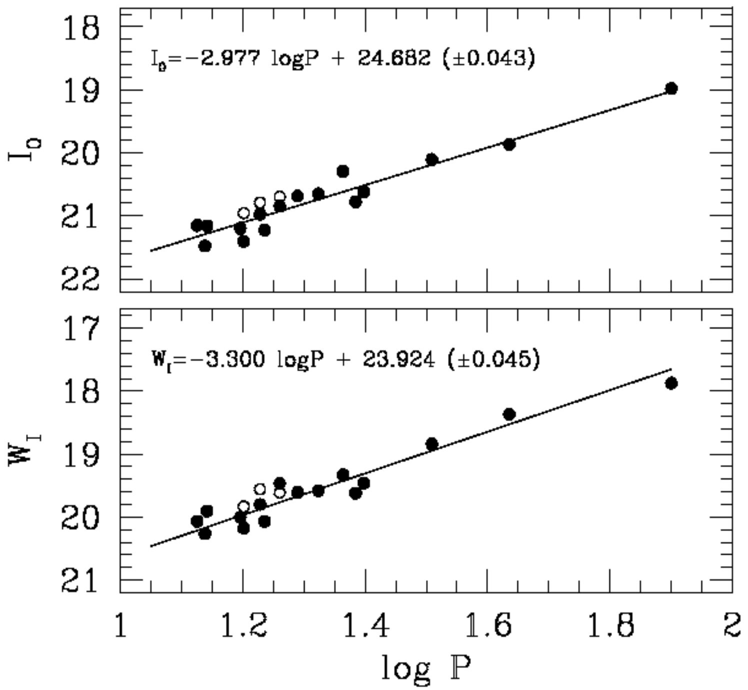
- out of these 16 objects-based images

- consistently, phased , only 3 are found to be significantly affected by nearby stellar objects unresolved in ground BVI data from HST/ACS are **fainter** than expected from light curves from the ground-based photometry of these 3 objects

- after correcting the ground-based magnitudes for the contribution of these projected companions to the flux, we find that the period-luminosity relation zero points in V, I and W are not significantly altered (contrary to DIRECT project results in M31 and M33)

- **upper limit of blending effect on optical distance modulus is 0.03 mag, or 1.5%** (Bresolin, Pietrzynski, Gieren, Kudritzki 2005, ApJ, 634, 1020)





Blending / crowding

Mochejska et al. Udalski et al. Very strong effect

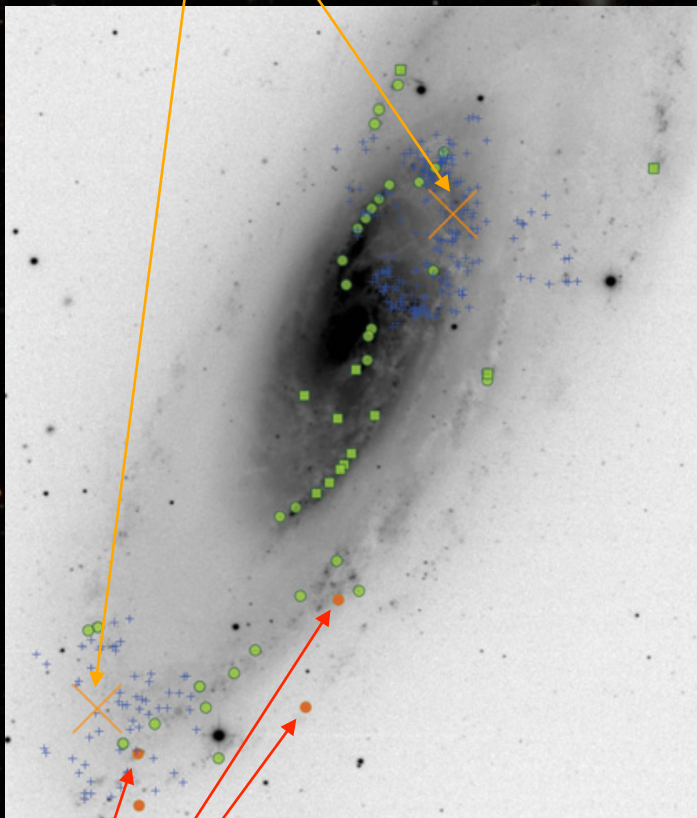
Bresolin et al. 2005   weak effect

Anderson et al. 2019 weak effect

How about HST observations of Cepheids in the central parts and outskirst of some galaxies !

Not metallicity, so WHAT ? Blending ?

Cepheids in NGC 4258



Macri et al. 2006, Riess et al., 2009

using Zaritsky et al., 1994

$$\gamma = \frac{\delta(m - M)}{[Z]} = -0.29$$

HII regions

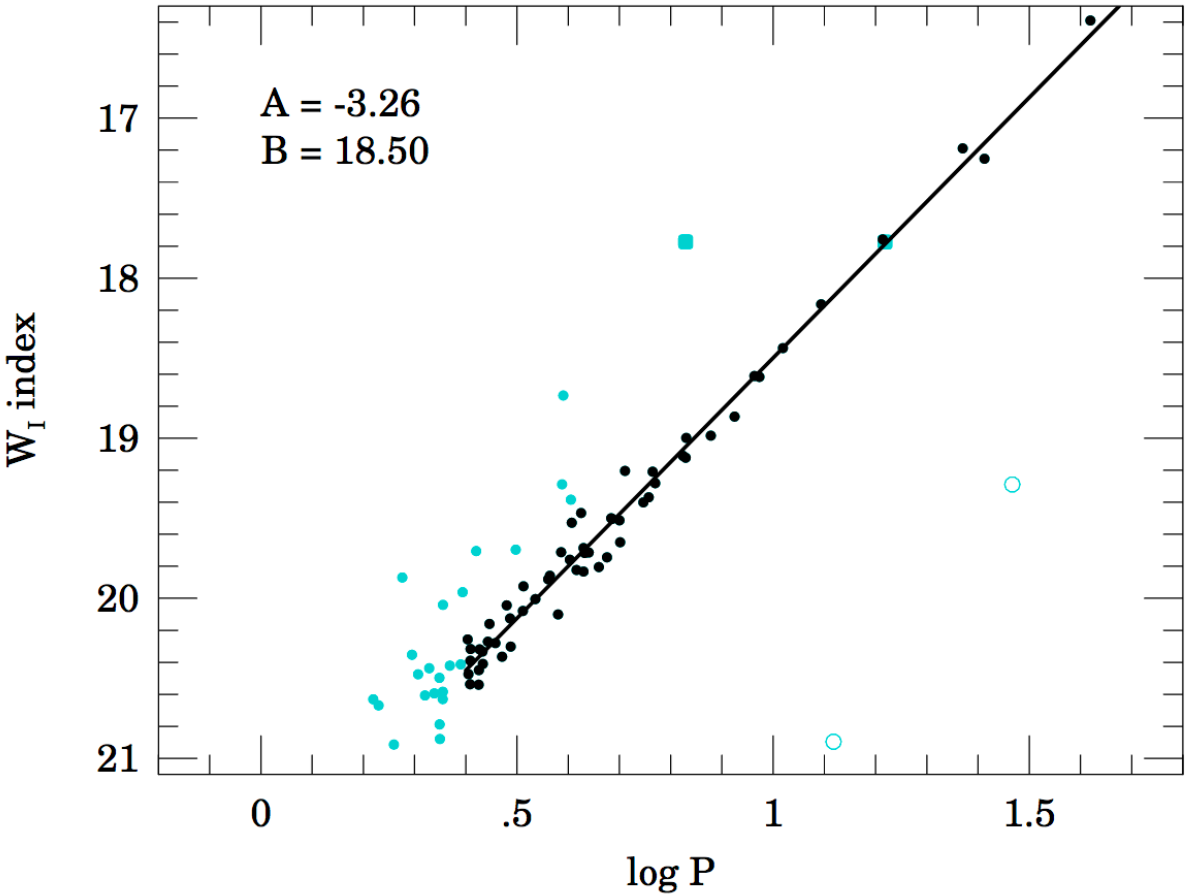
Bresolin 2011, ApJ 729, 56

$$\gamma = \frac{\delta(m - M)}{[Z]} = -0.69!!!$$

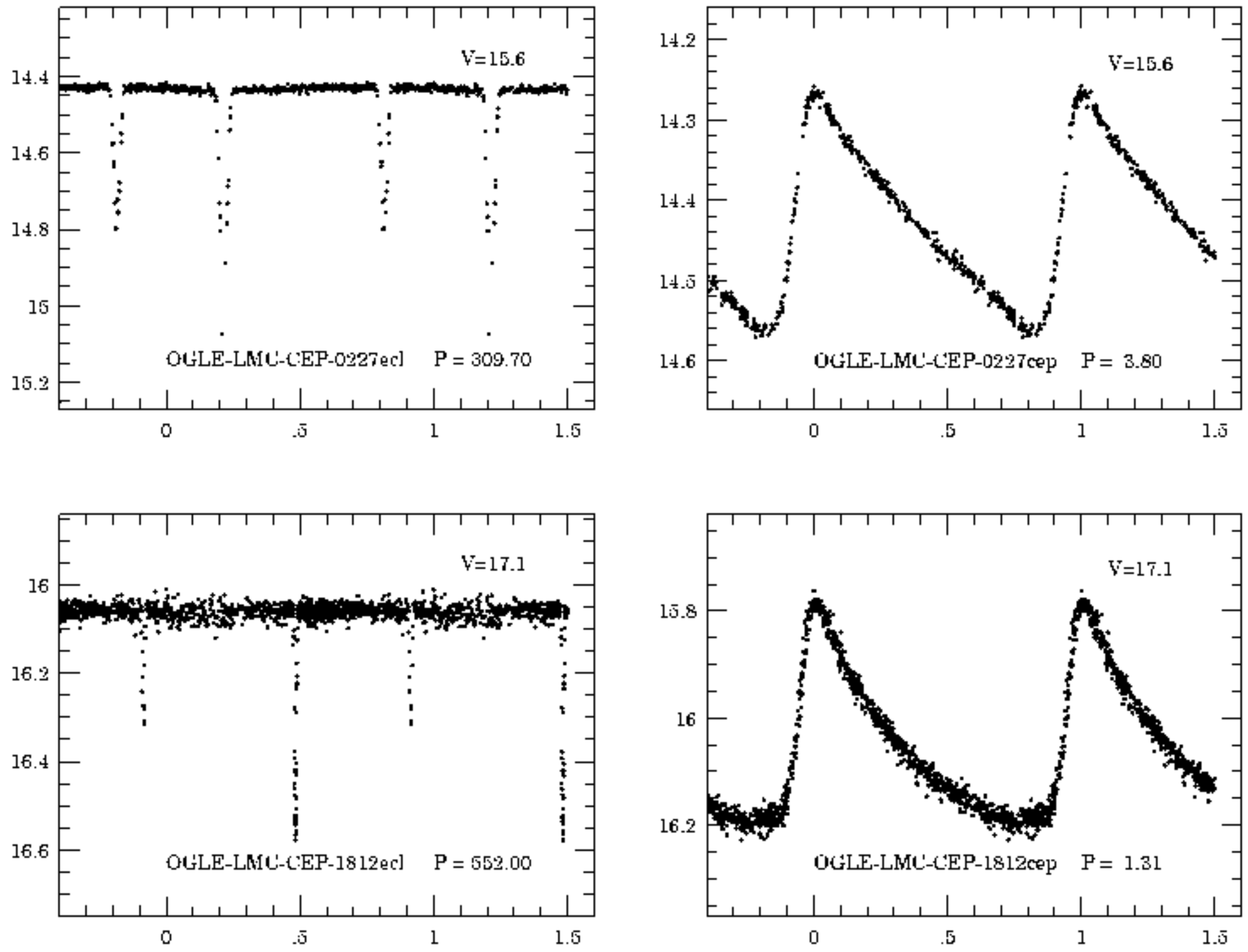
Problem: inner Cepheid are (more) affected by **crowding** (by an uncertain amount…)

Binarity

Between 30-80 % Cepheids in binary systems

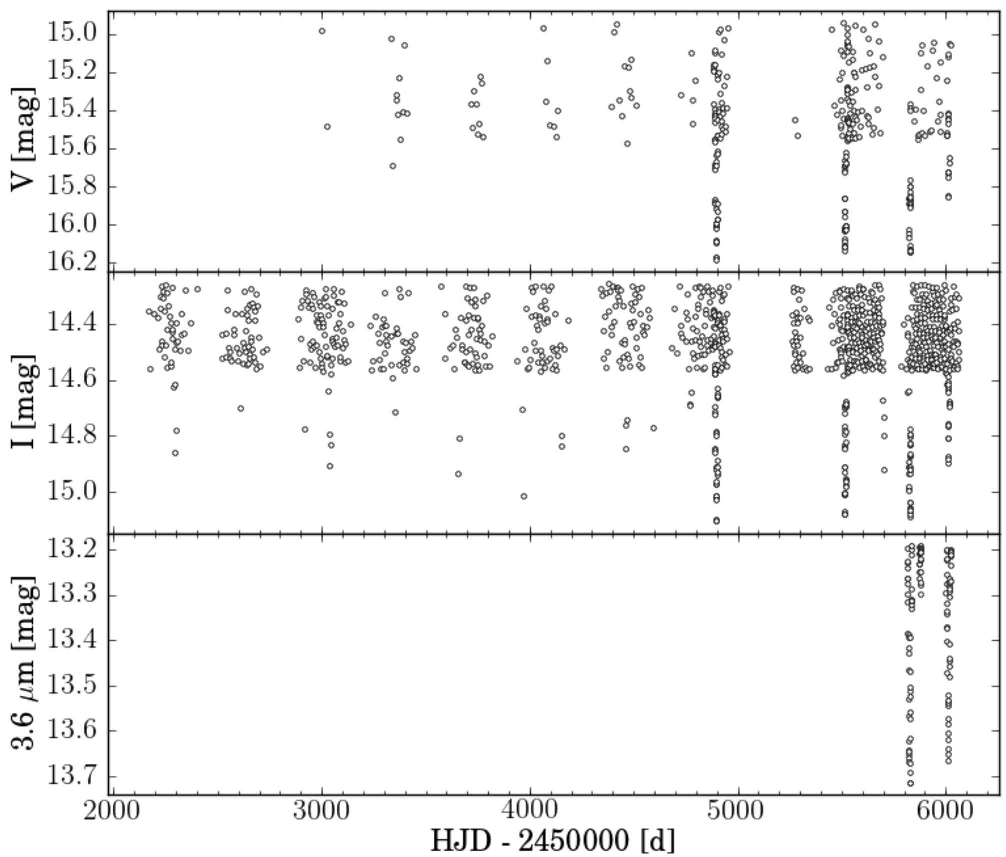


Improved Cepheid physics: LMC Cepheids in late-type eclipsing binary systems

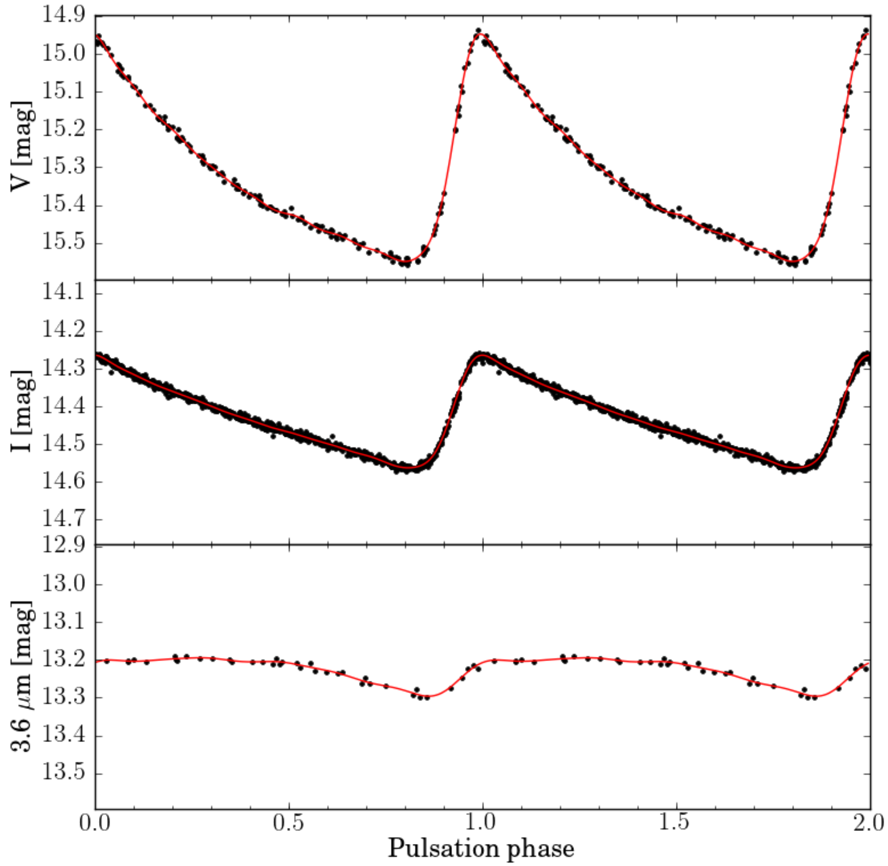


OGLE-LMC-CEP-0227: photometric data

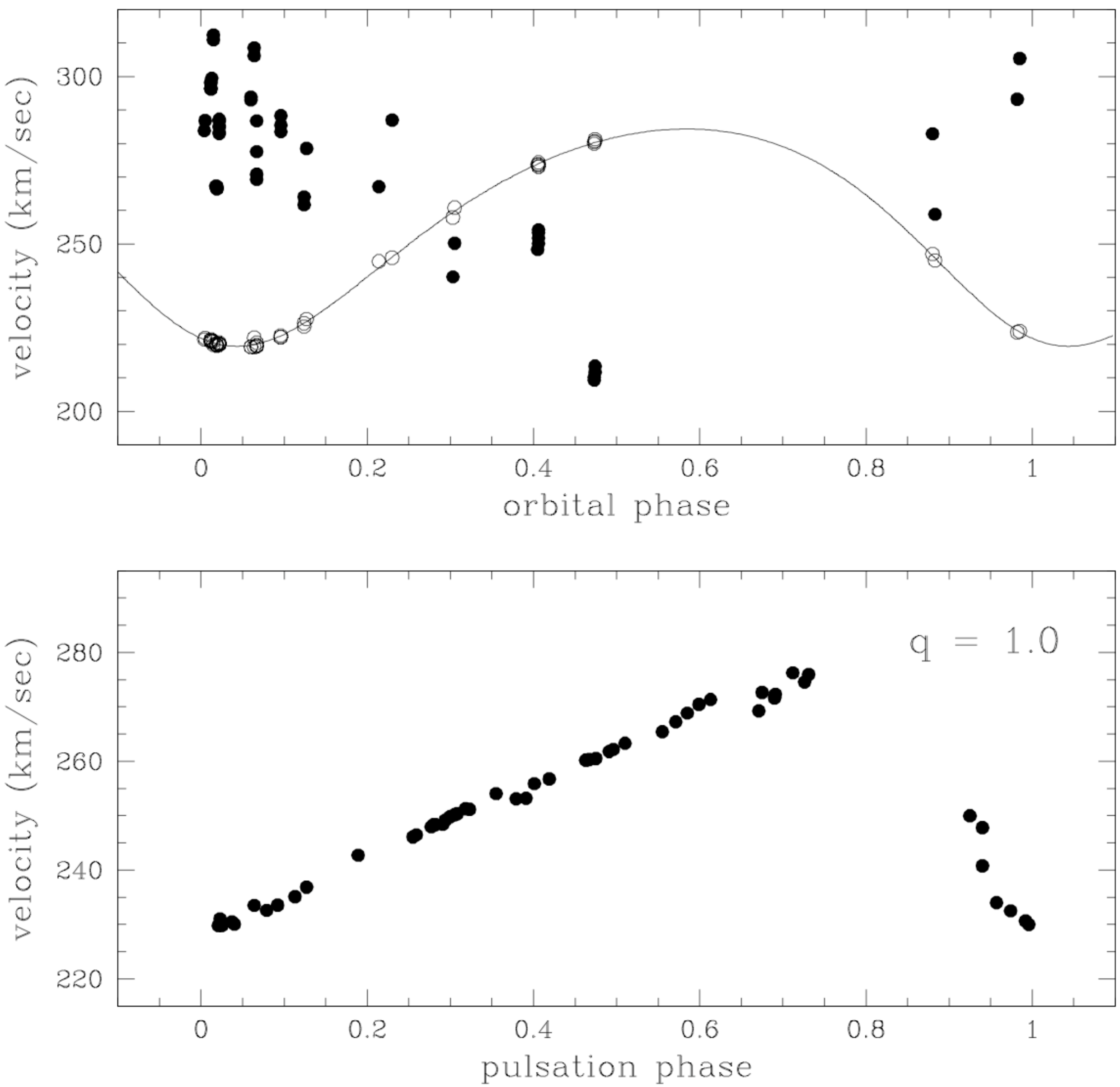
Photometry data



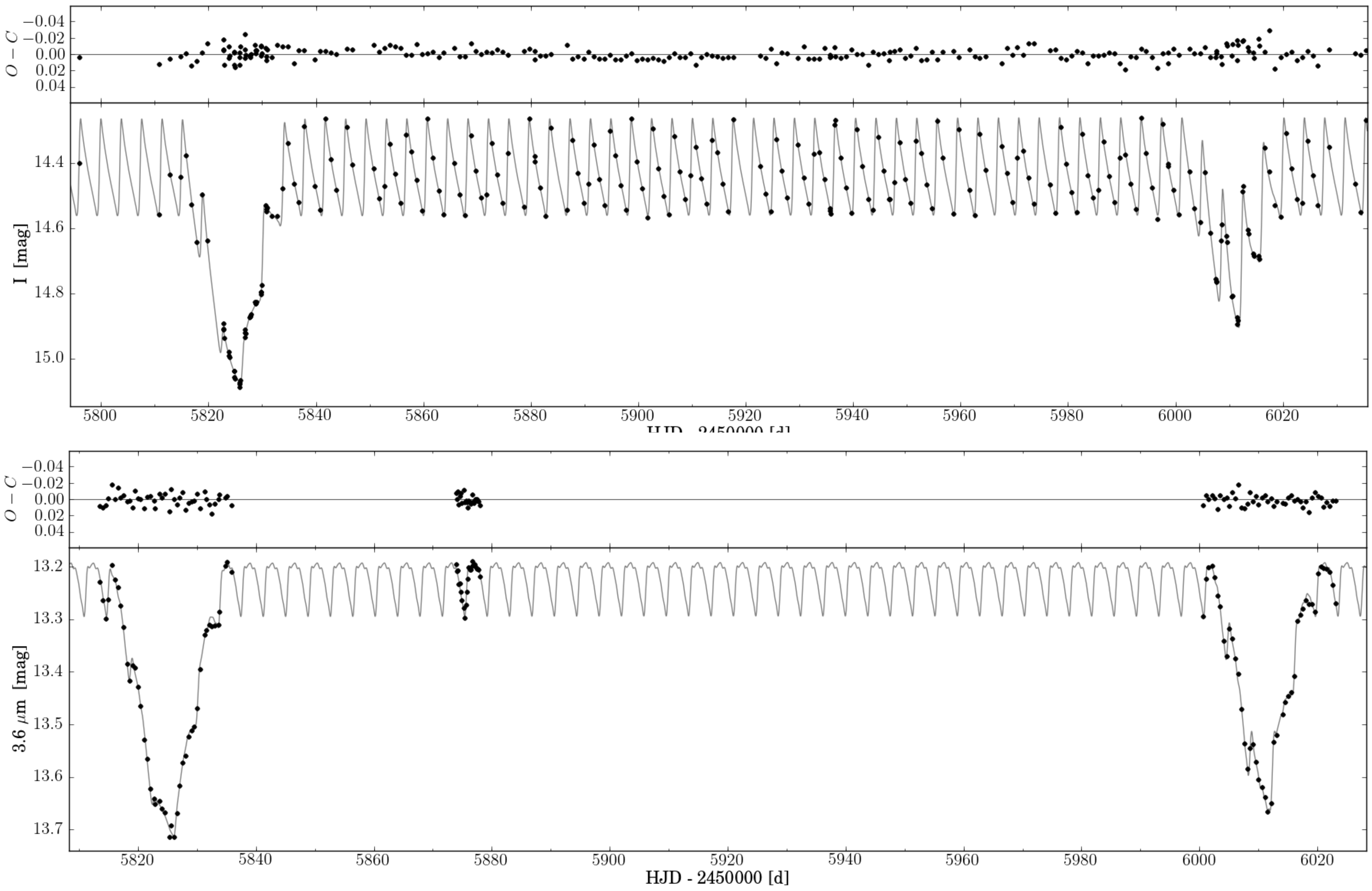
Out-of-eclipse pulsations



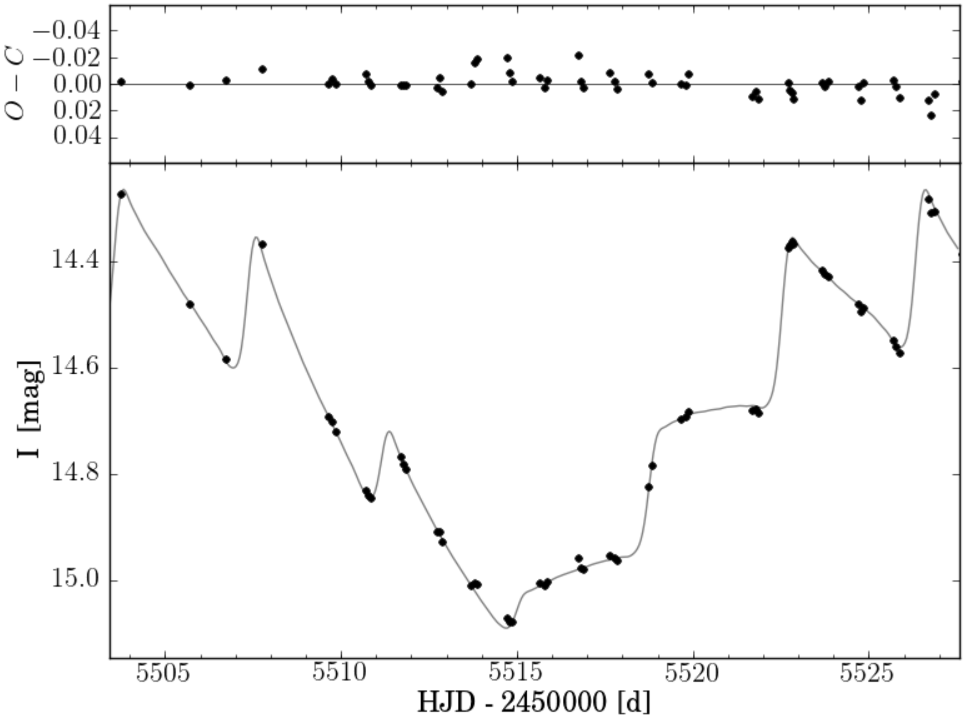
RV disentangling

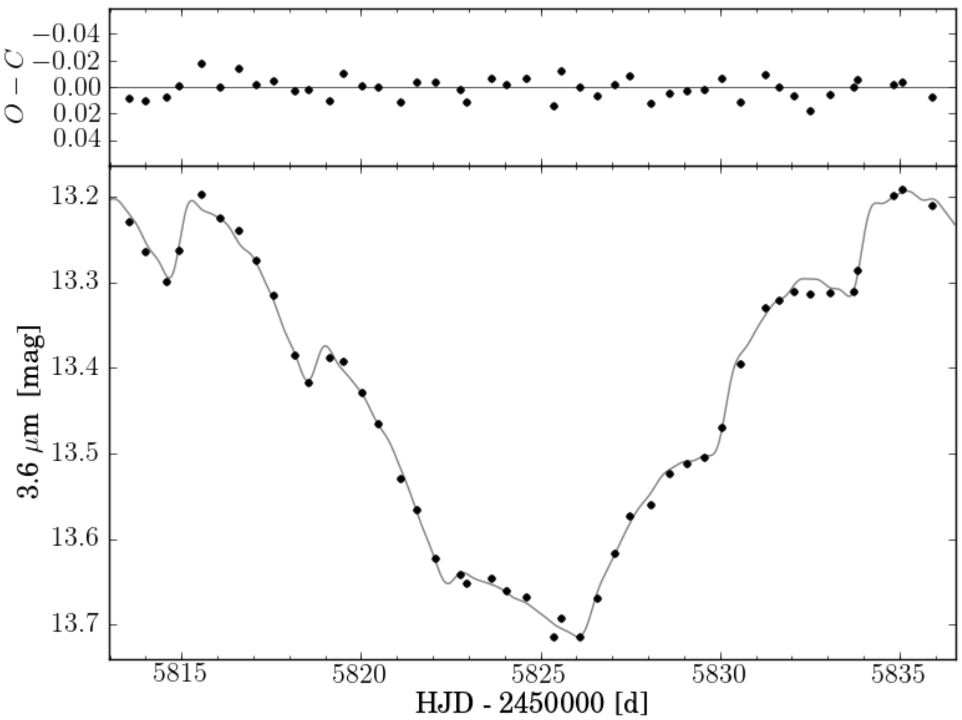


Code of Pilecki et al., applied to Cep-0227 photometric data yields very accurate fits to the observed light curve eclipses



eclipse fits: a closer look

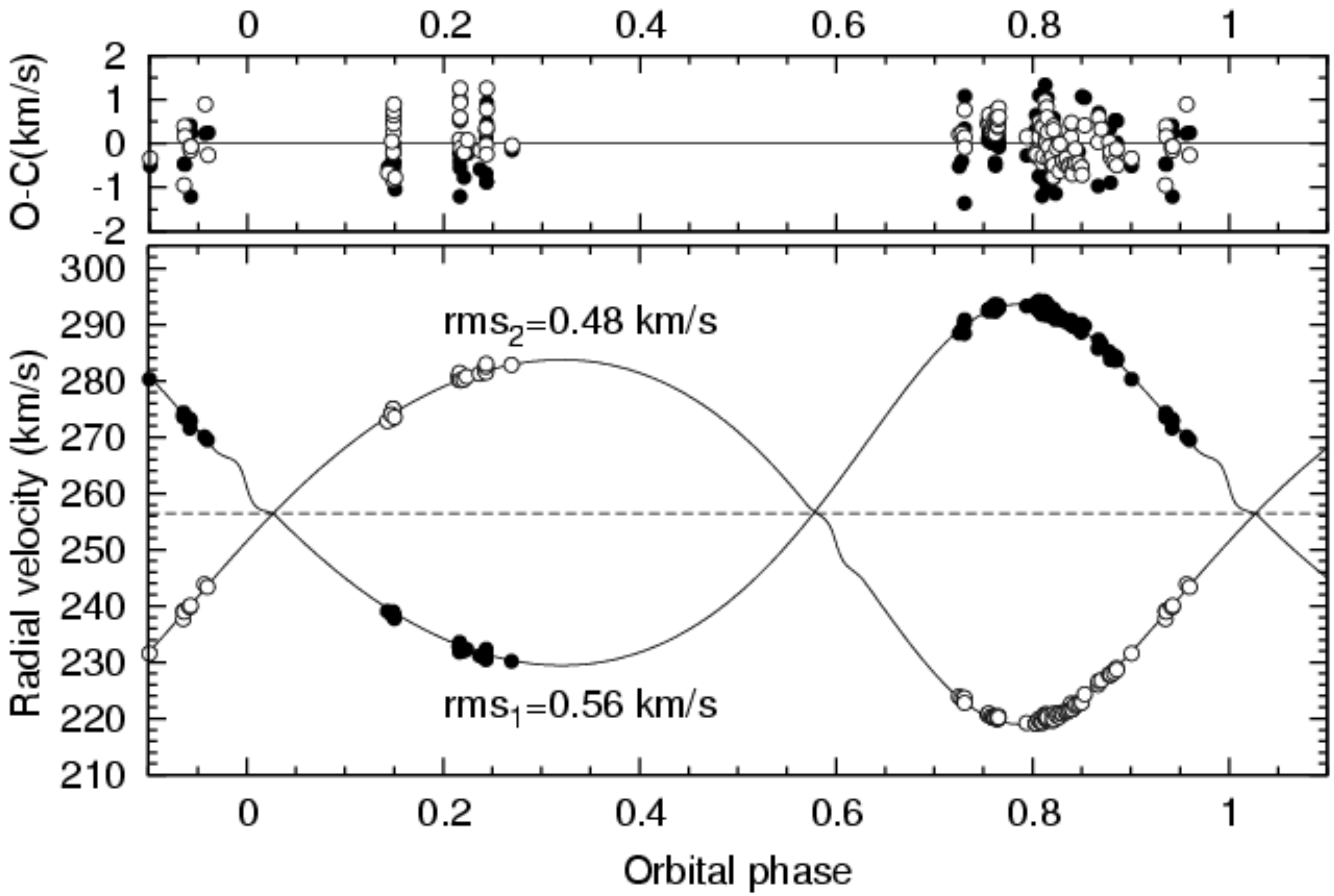


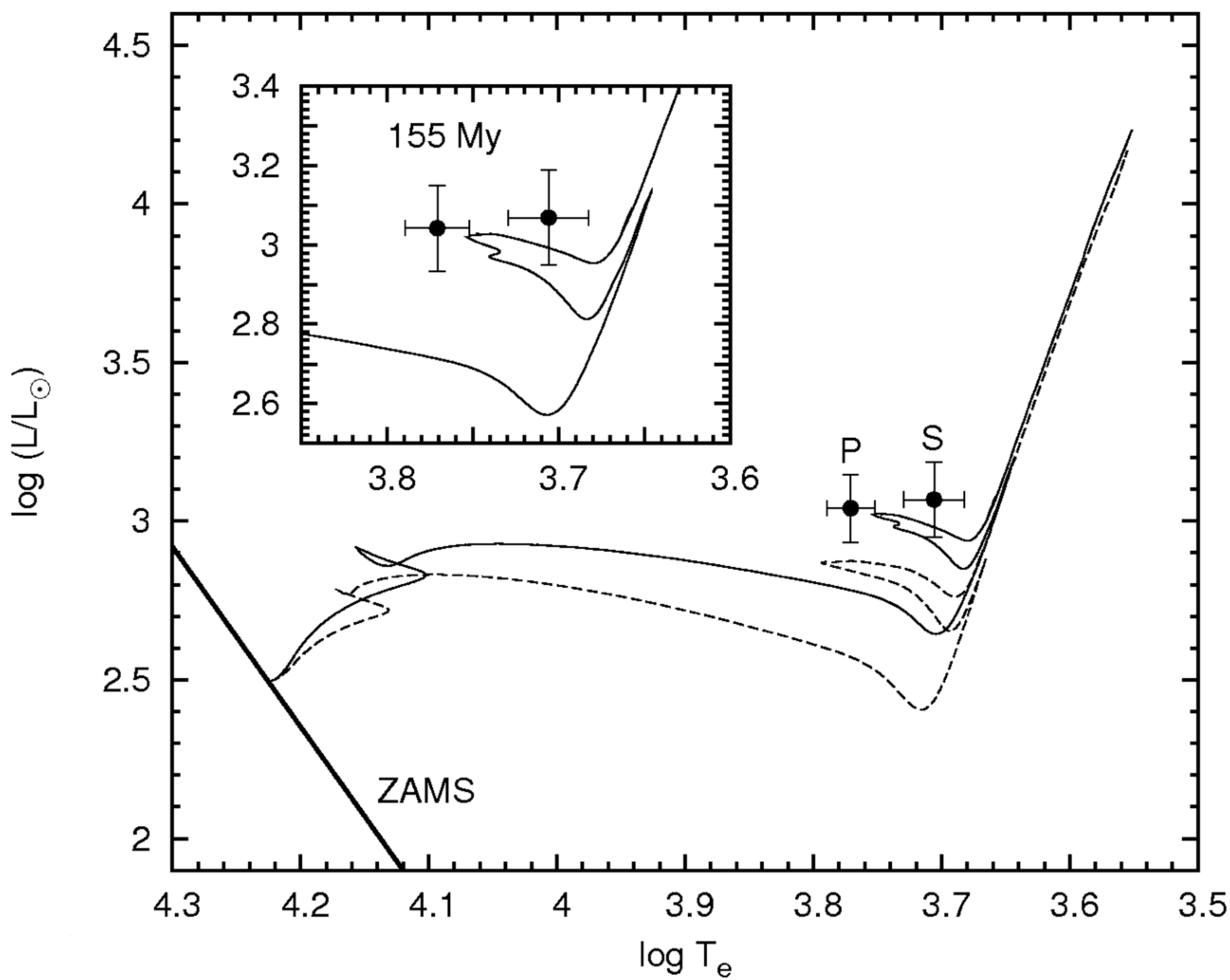


OGLE-LMC-CEP-0227: best studied system so far (Pilecki et al. 2013, MNRAS, 436, 953)

Results: **Masses to 0.7%, radii to 1%, p-factor to 3%**

Optical limb darkening of Cepheid much higher than theory predictions!





log (L/L☉)
log Te
155 My
P
S
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4
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3
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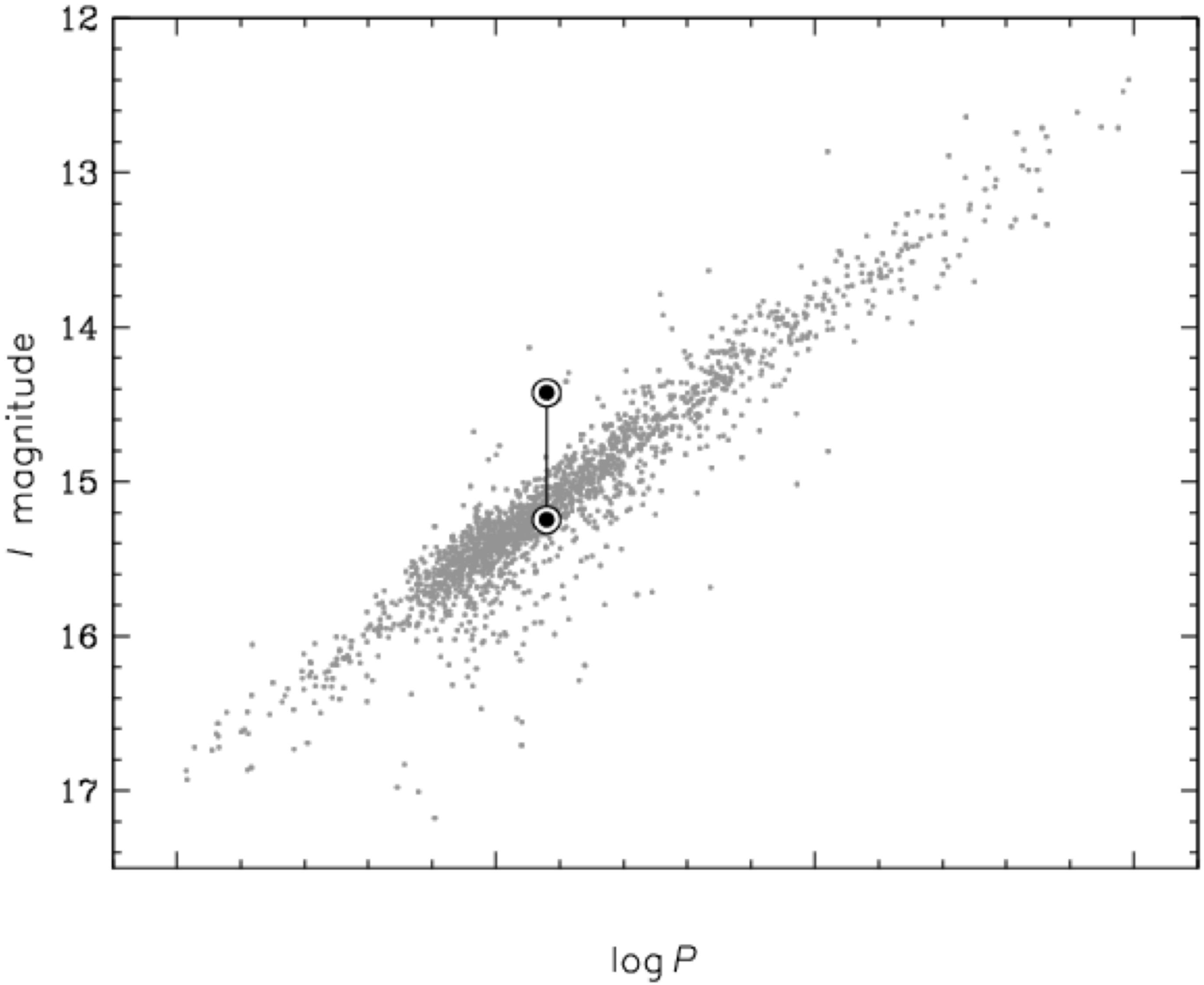
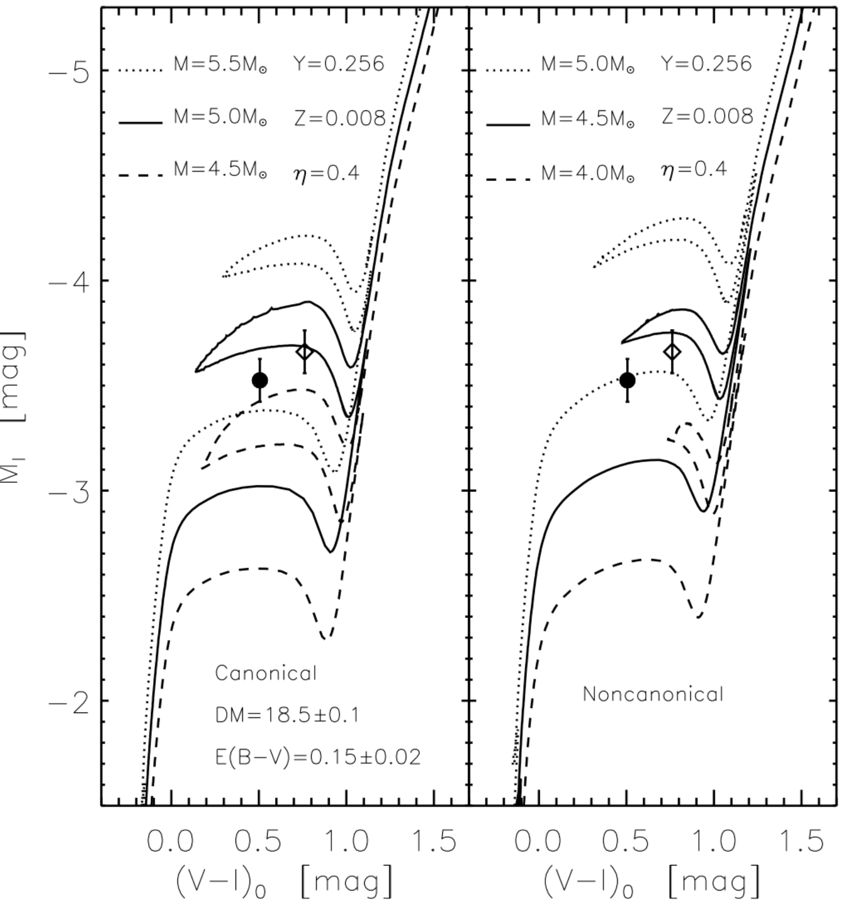

12
13
14
15
16
17
I magnitude
log P

Pulsational and evolutionary masses

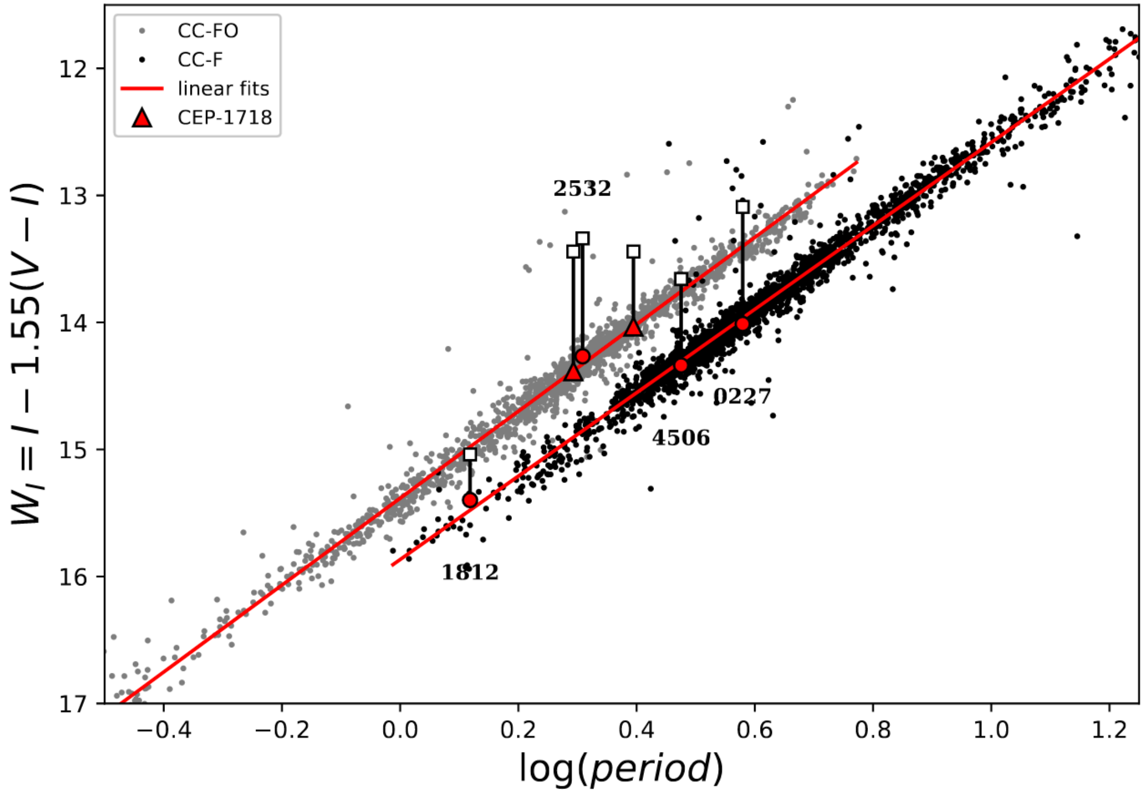


Dynamical	Pulsational	Evolutionary
4.14 ± 0.05	3.98 ± 0.29	4.5 - 5

1) Mass loss driven by radial motions and by shocks in the atmosphere

2) The existence of mild internal core mixing in the main-sequence progenitor of the Cepheid

Pietrzynski G., Thompson I., Gieren W., Graczyk D., Bono G., Udalski A., Soszynski I., Minniti D., Pilecki B., 2010 Nature 468, 542



ID	Type	Period [d]	P_F[d][a]	Mass [$M_\odot$]	Radius [$R_\odot$]	A_{RV} [km/s]	p-factor	Comment
LMC-CEP-0227	CC-F	3.797086	-	4.15 (3)	34.87 (12)	48.5	1.21 (5)	
LMC-CEP-4506	CC-F	2.987846	-	3.61 (3)	28.5 (2)	38.1	1.35 (9)	
LMC-CEP-2532	CC-FO	2.035349	2.833	3.98 (10)	29.2 (1.4)	23.6	-	OEPC
LMC-CEP-1718B	CC-FO	2.480917	3.460	4.22 (4)	33.1 (1.3)	21.5	-	OEPC
LMC-CEP-1718A	CC-FO	1.963663	2.732	4.27 (4)	27.8 (1.2)	17.6	-	OEPC
LMC-CEP-1812	CC-F	1.312903	-	3.76 (3)	17.85 (13)	54.3	1.26 (8)	

Another problem – Circumstellar envelopes around Cepheids

- CSEs around Cepheids seem fairly common (Kervella et al. 2009). Linked to past or ongoing mas loss from the Cepheid?

- CSE flux contribution to Cepheids in K: <4% (?)

δ Cep: 1.5% (Mérand et al. 2007)

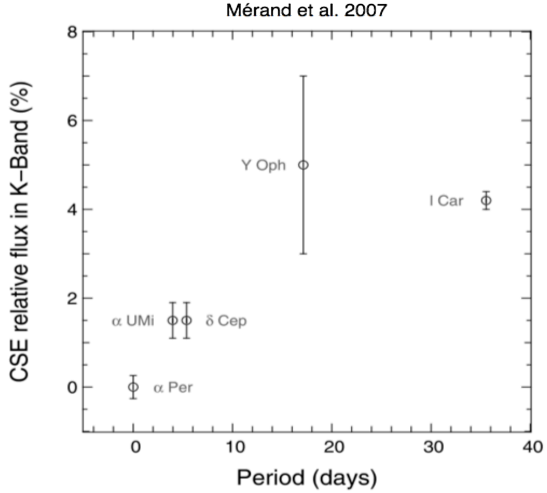
l Car: 4% (the only long-period Cepheid with an accurate measurement so far)

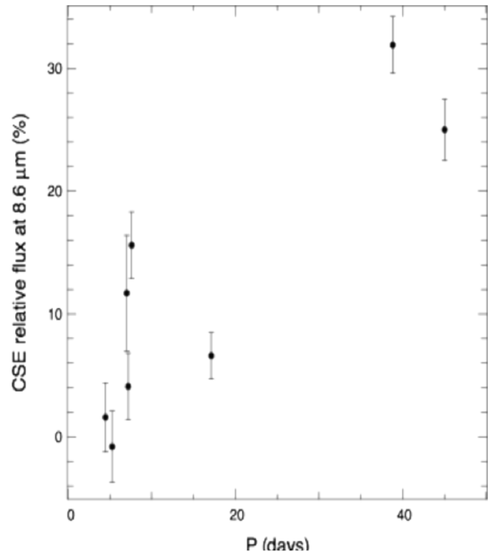
Problem appears to become worse for long-period stars: bad news!

Conclusion: CSE emission is likely to be a serious source of systematic error for mid-IR

PL relations, less serious but likely significant for distance work in near-IR bands too.

Detection of CSEs and measurement of their flux contribution needed for more Cepheids to get improved statistics (Gallenne et al., underway).





Is Cepheid P-L universal

In most galaxies we can only check stability of the slope of the P-L (limited precision). The slope seems to be stable.

Well known fact that Cepheids with P > 100d are located below mean P-L relation.

Linearity well checked only for the LMC and SMC:

SMC: Break at 2.5d (SMC) − Bauer et al. 1999, Udalski et al. 1999, also reported for 1d but not confirmed.

LMC: tiny break reported at 10d mostly visible in optical bands.

Several people reported breaks at 20d, 80d etc. Not confirmed so far.

Using Cepheids 10d < P < 100d

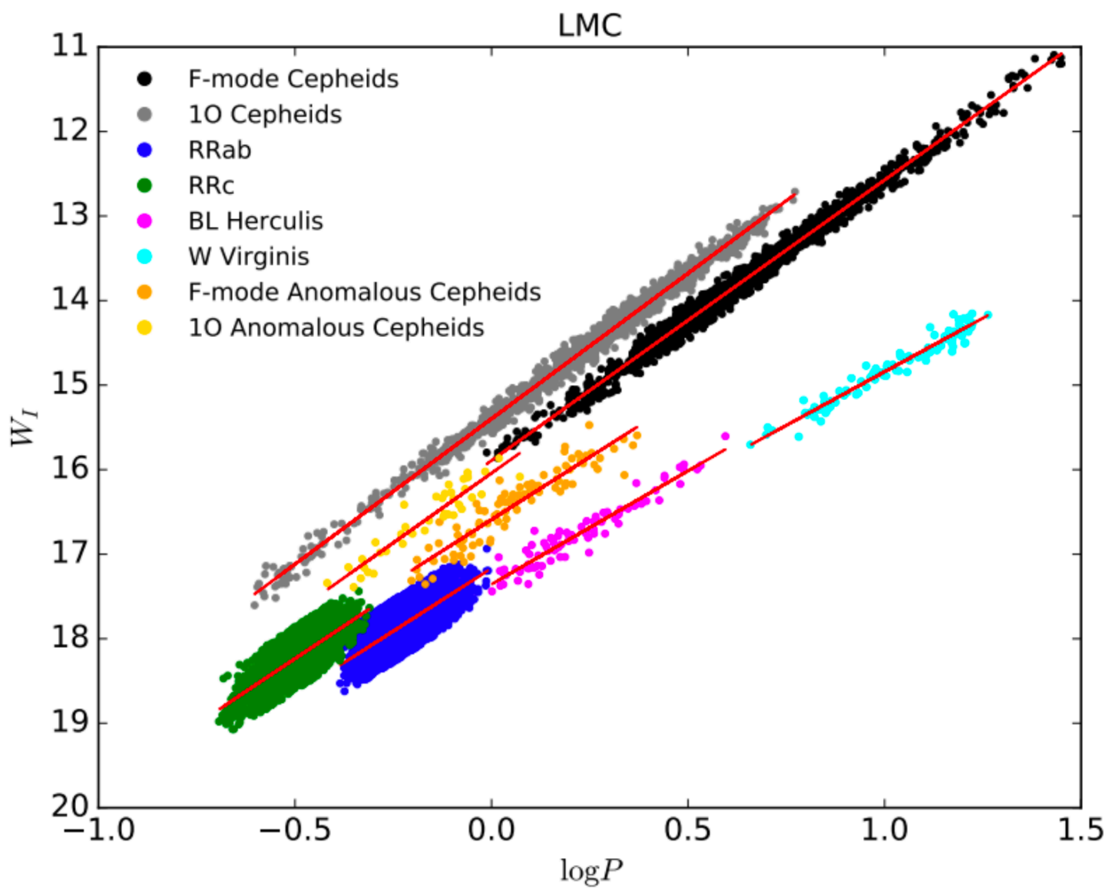
Reaasonable because we can avoid problems:

1) Breaks in P-L relations

2) Influence of FO Cepheids

3) Strong blends 3σ clipping

4) Binarity similar in different galaxies ? - Seems to be so (Karczmarek et al. in prep.)



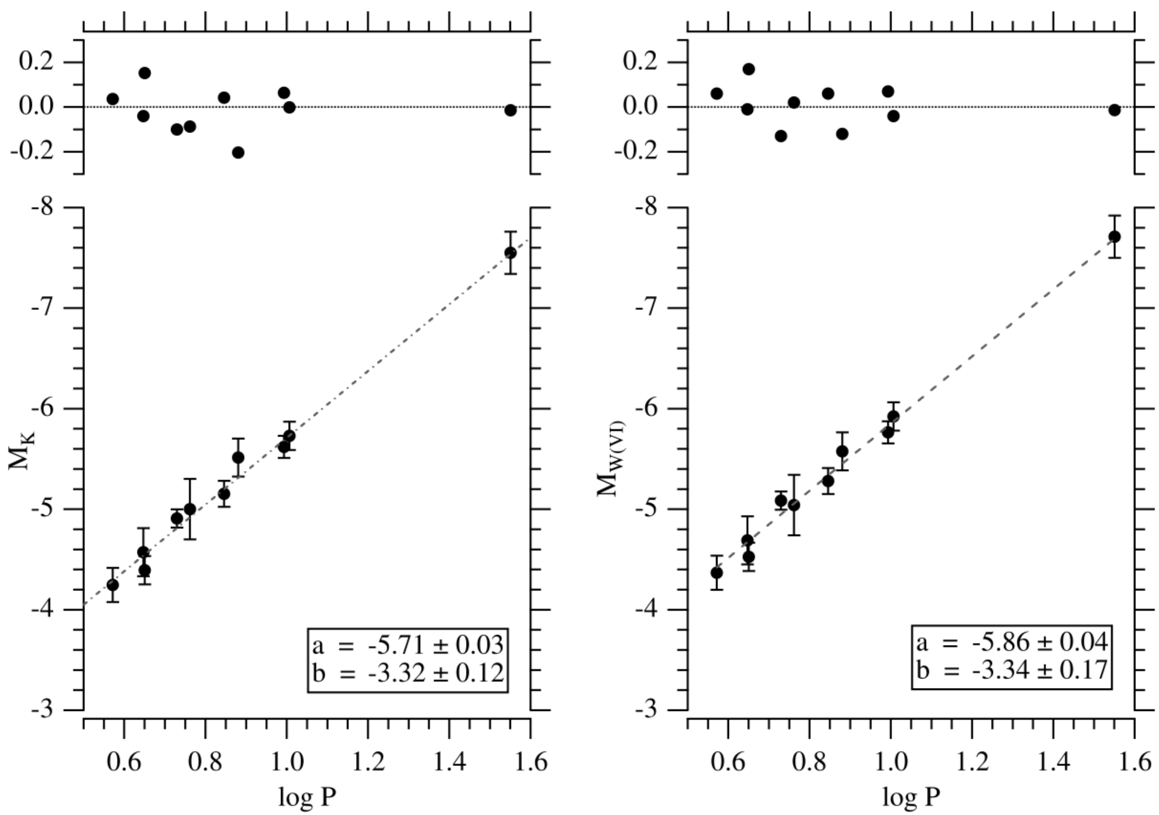
Using Cepheids 10d < P < 100d

Reasonable but: We discard something because we do not understand it ...

Not sure about breaks at other periods in other galaxies

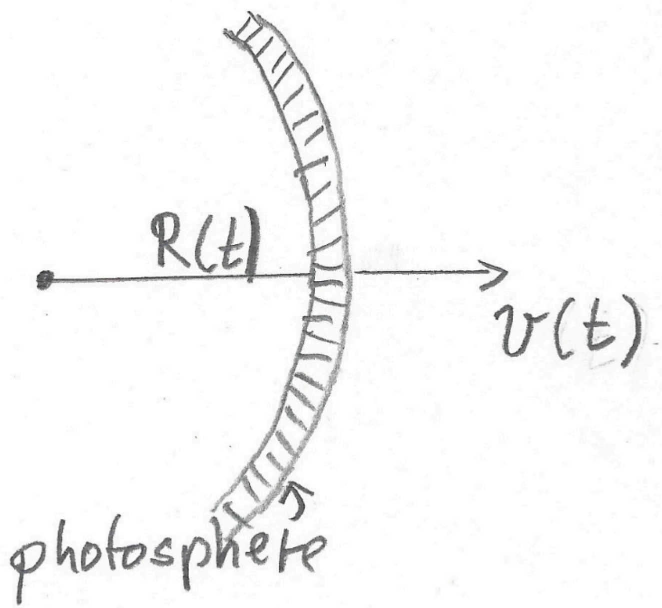
Low number of long period Cepheids.

Then calibration for short period MW Cepheids is used



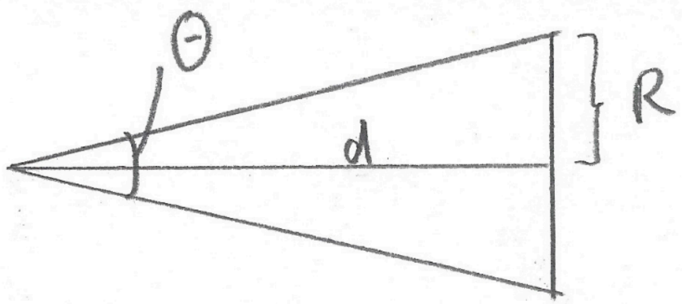
Baade-Wesselink Method (BWM):

distance determination method for stellar objects, for which the photosphere can be approximated as a spherically moving (expanding) shell



$$\Delta R = R(t) - R(t_0) = \int_{t_0}^{t} v(t)dt$$

change of radius determined by integral of velocity



radius R, angular diameter Θ and distance d are related

$$\frac{R}{d} = tan\frac{\Theta}{2} \approx \frac{\Theta}{2}$$

change in radius ΔR
change in angular diameter ΔΘ ➡ distance

$$d = \frac{2\Delta R}{\Delta\Theta}$$

measure ΔR from velocity
and find a way to measure ΔΘ → distance

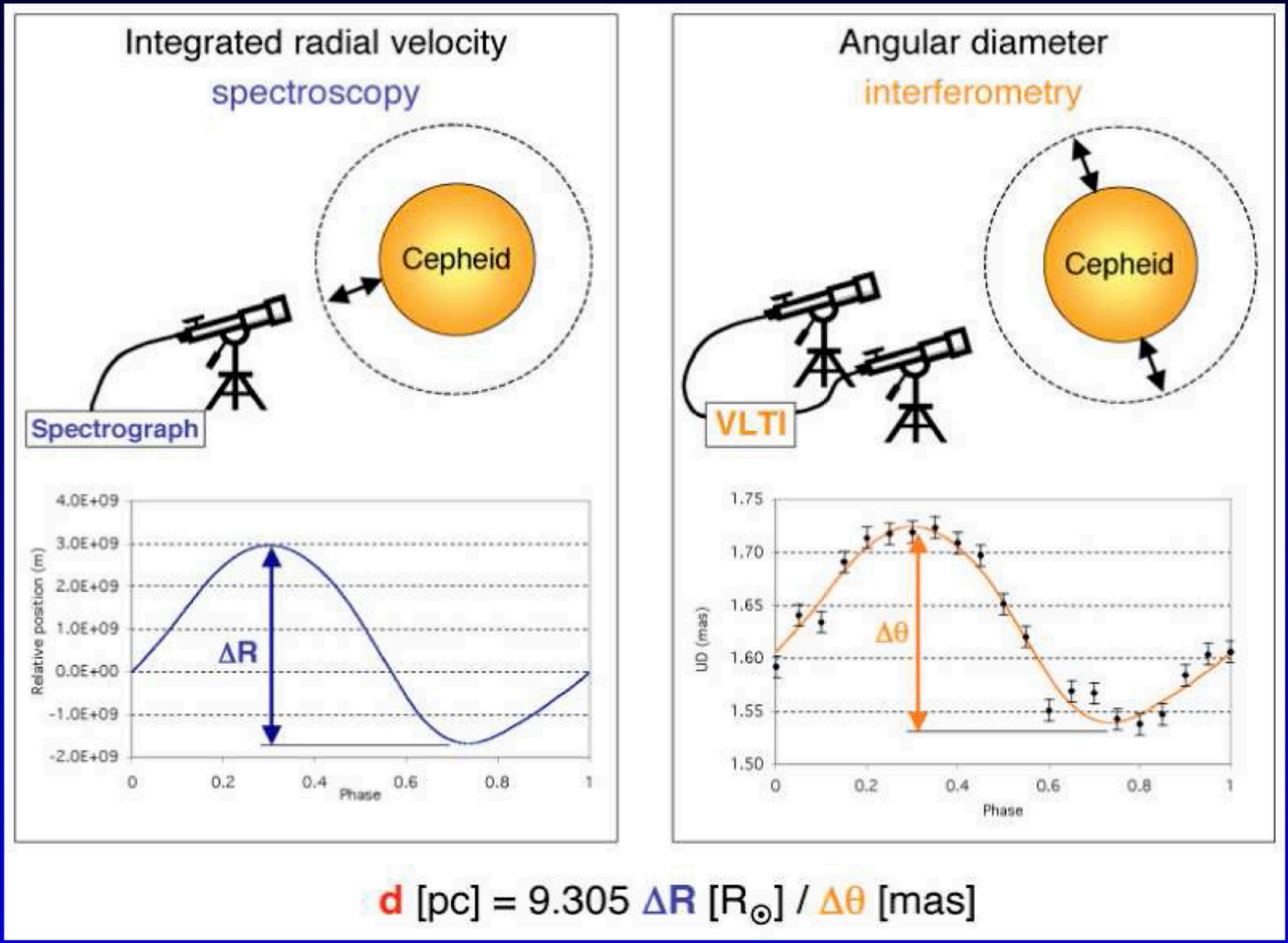
original idea: test pulsation hypothesis of Cepheids

- Walter Baade,
  1926, Astronomische Nachrichten 228, 359
  "Über eine Möglichkeit, die Pulsationstheorie der δ Cephei-Veränderlichen zu prüfen"

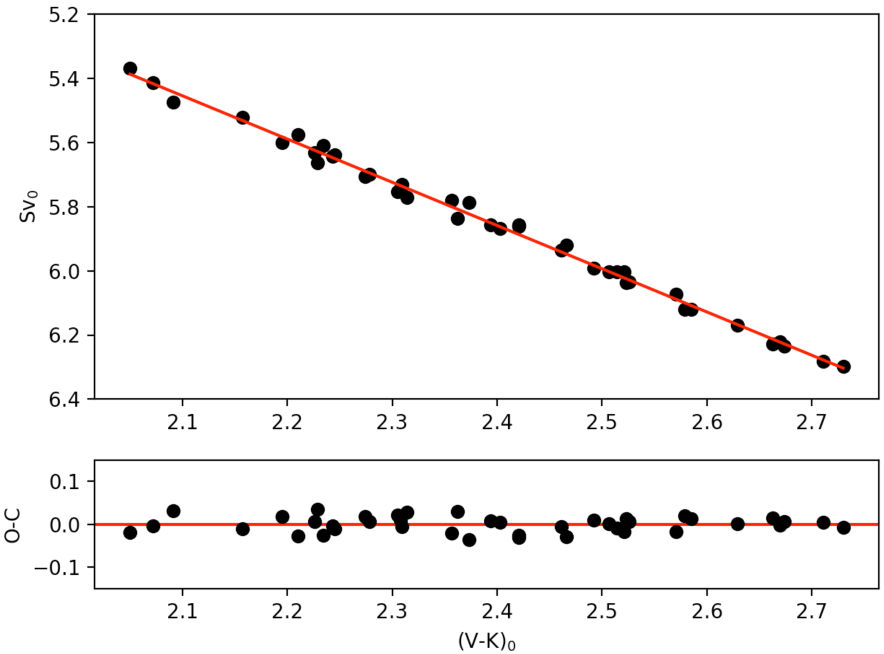
- Adriaan Jan Wesselink,
  1946, Bulletin of the Astronomical Institutes of the Netherlands 10, 91
  "The observations of brightness, colour and radial velocity of δ Cephei and the pulsation hypothesis"

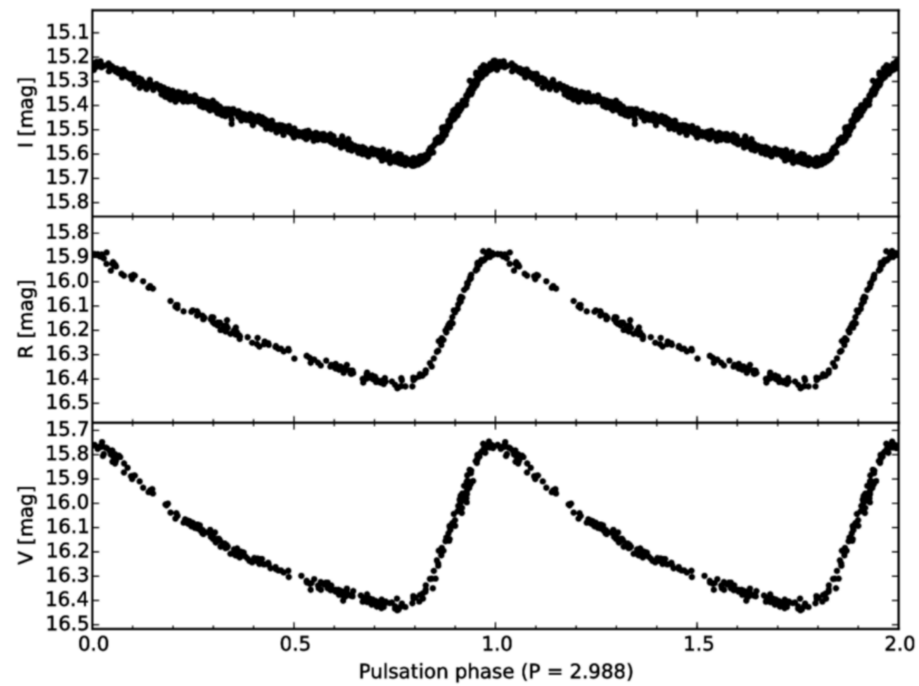
Then for measuring distances (before using this concept for binaries !)

Baade-Wesselink distances



Angular diameter from interferometry, or surface-brightness relation (i.e. lightcurve in colour)





BWM distances

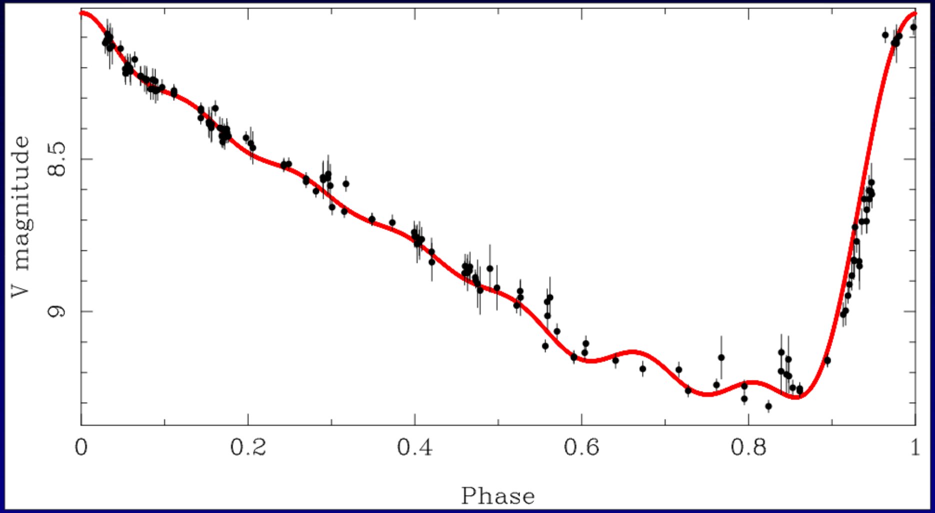
$SB[mag] = 2.656+1.483(V-K)_0+0.044(V-K)_0^2$ **SBCR**

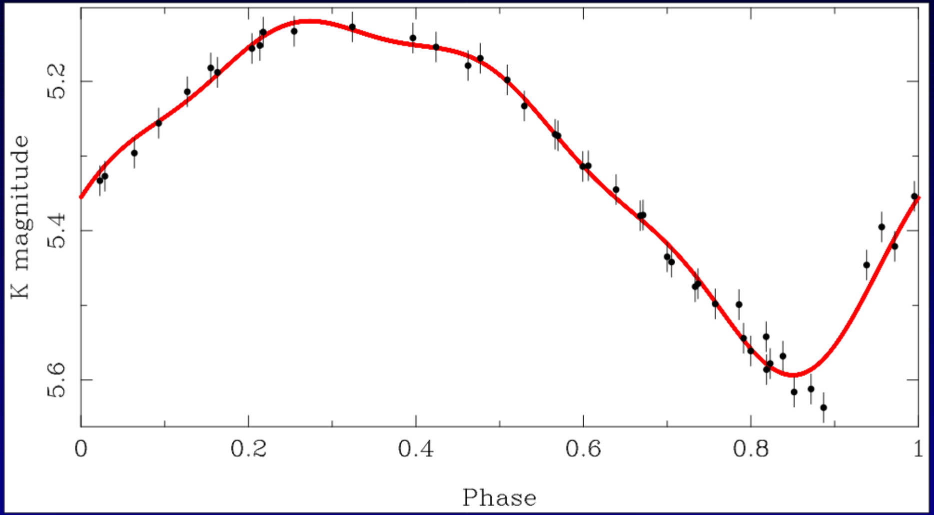
$\sigma = 0.03$ mag

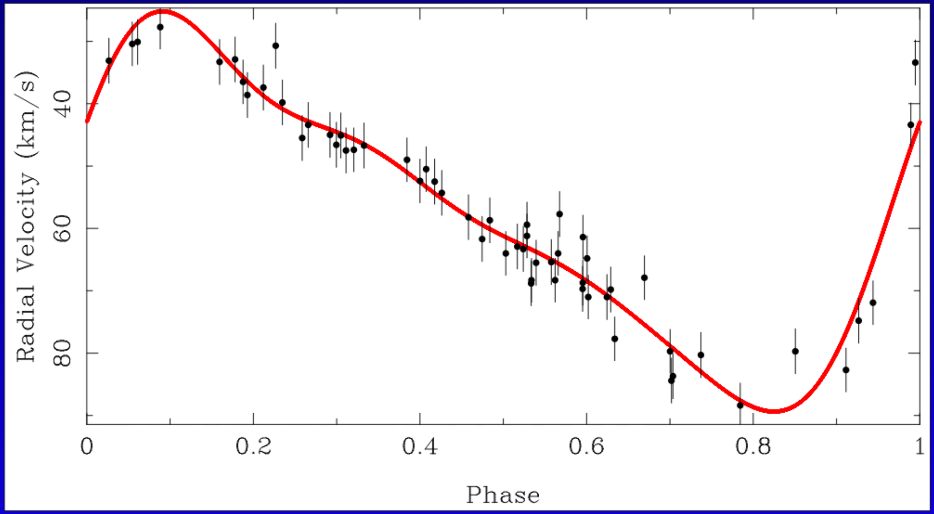
$\varphi[mas] = 10^{0.2(SB - V)}$ **angular diameter**

$d[pc] = 9.305\ \Delta R[R_{sun}]/\Delta\varphi[mas]$ **distance**

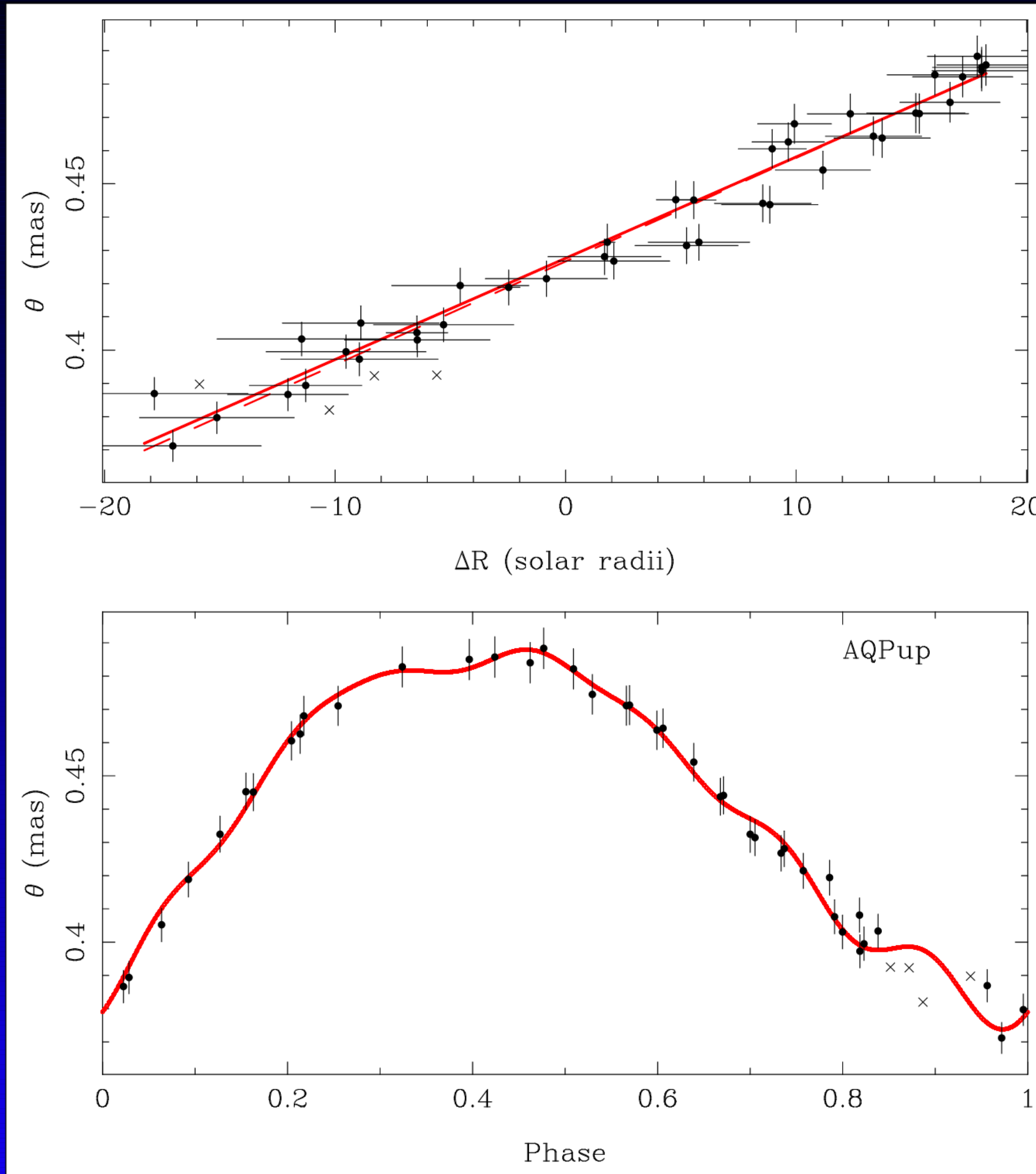
An Example





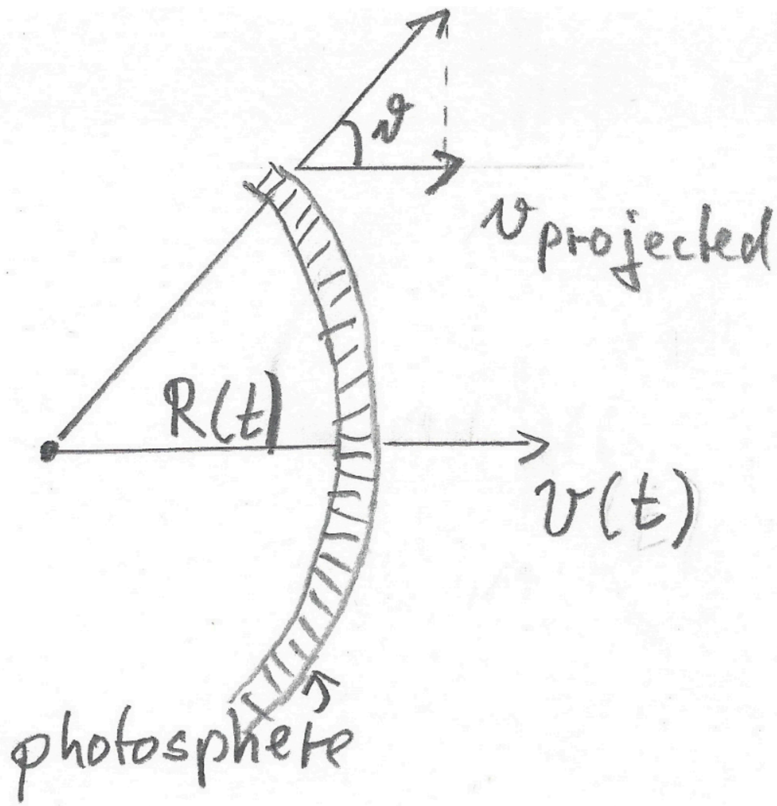


V, *K*, RV phased light curves for AQ Pup



θ vs. ΔR gives distance. AQ Pup simple straightforward method, but the devil is in the detail....

radial velocity from spectral lines ≠ radial expansion velocity v(t)



1. v_{rad} is integral over stellar surface

$$v(t) = p v_{rad}(t)$$

projection factor p, p > 1

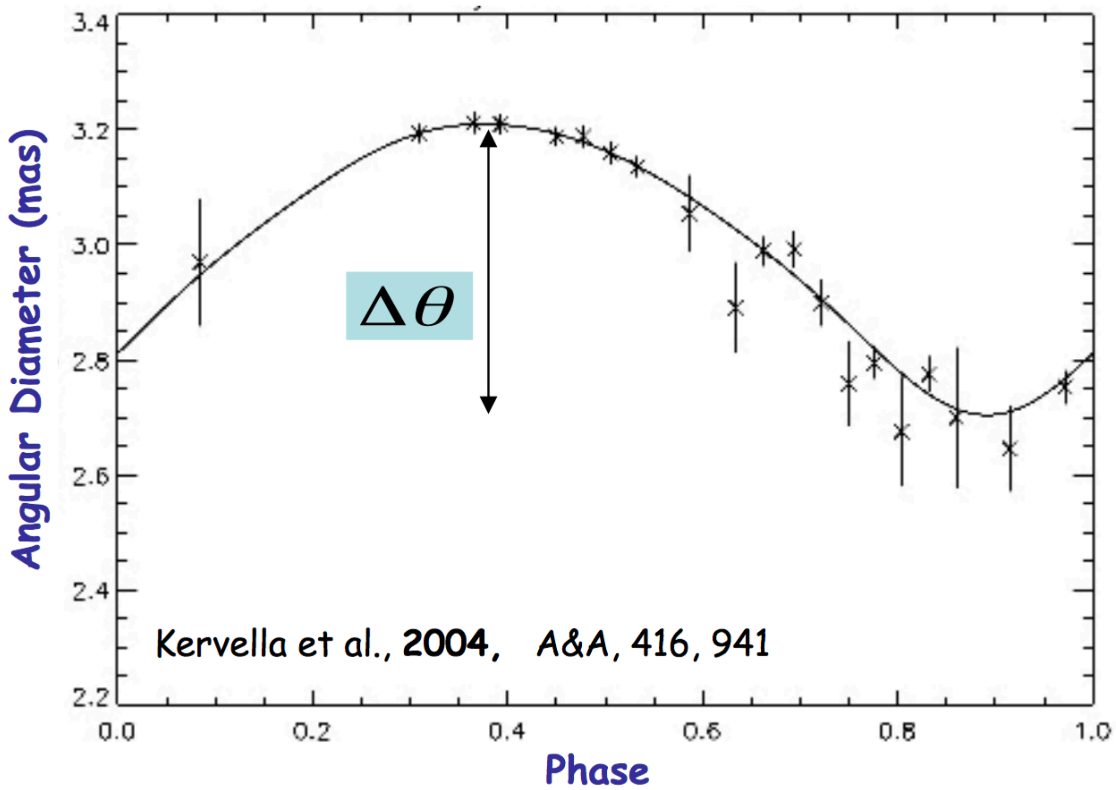
2. hydrodynamic motion of matter caused by pulsation
→ very likely velocity gradients in photosphere

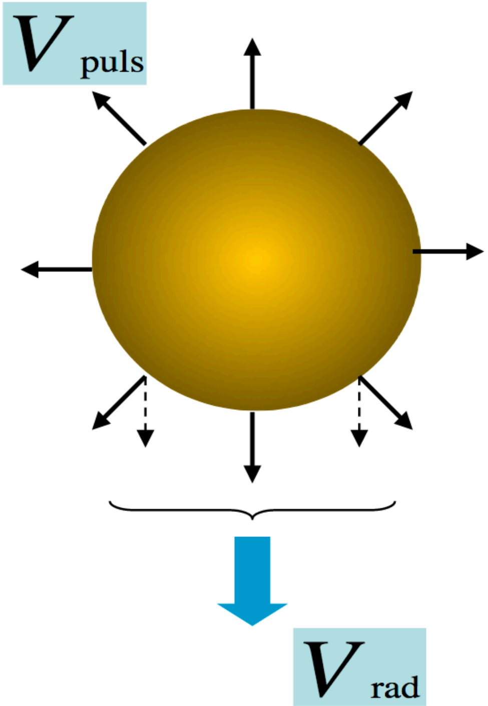
The Baade-Wesselink methods

Interferometry

or

IRSB





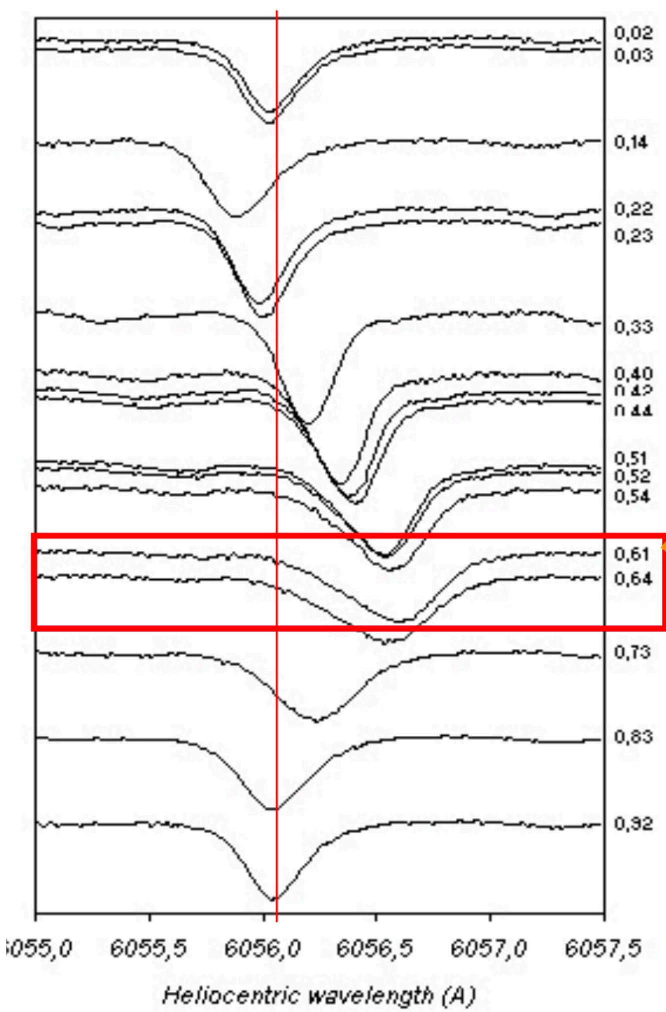
$$p = \frac{V_{puls}}{V_{rad}}$$

$$d \propto \frac{\Delta R}{\Delta\theta} \text{ with } R(t) = \int p V_{rad}\, dt$$

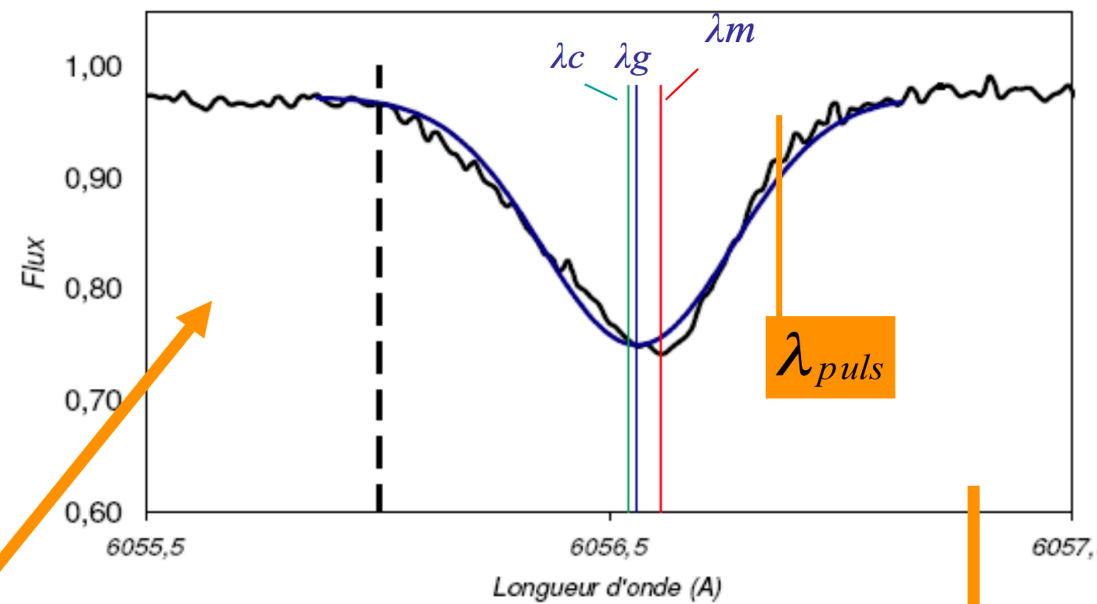
⚠ $\Delta R \Leftrightarrow \Delta\theta$

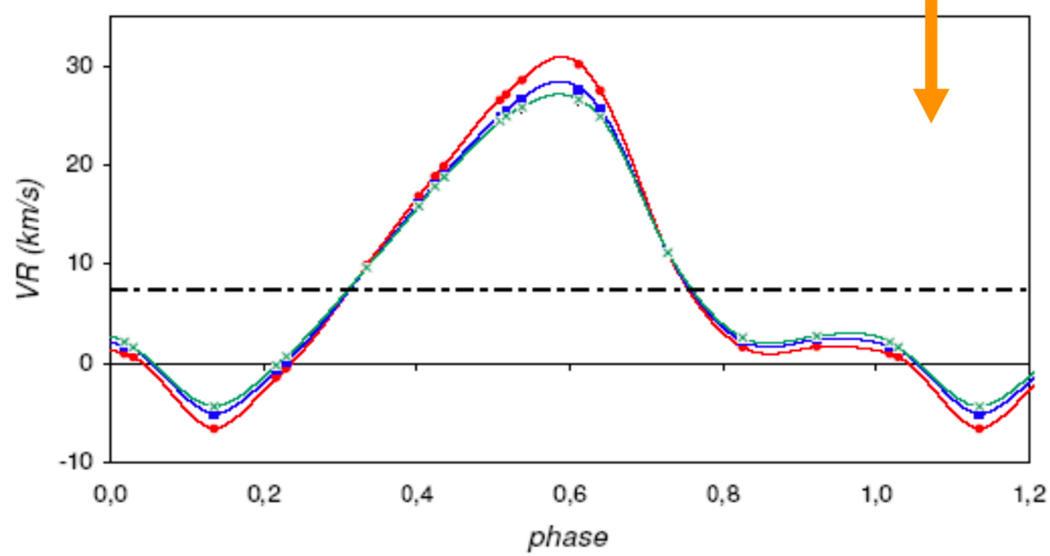
A direct linear relation

What do we measure ?

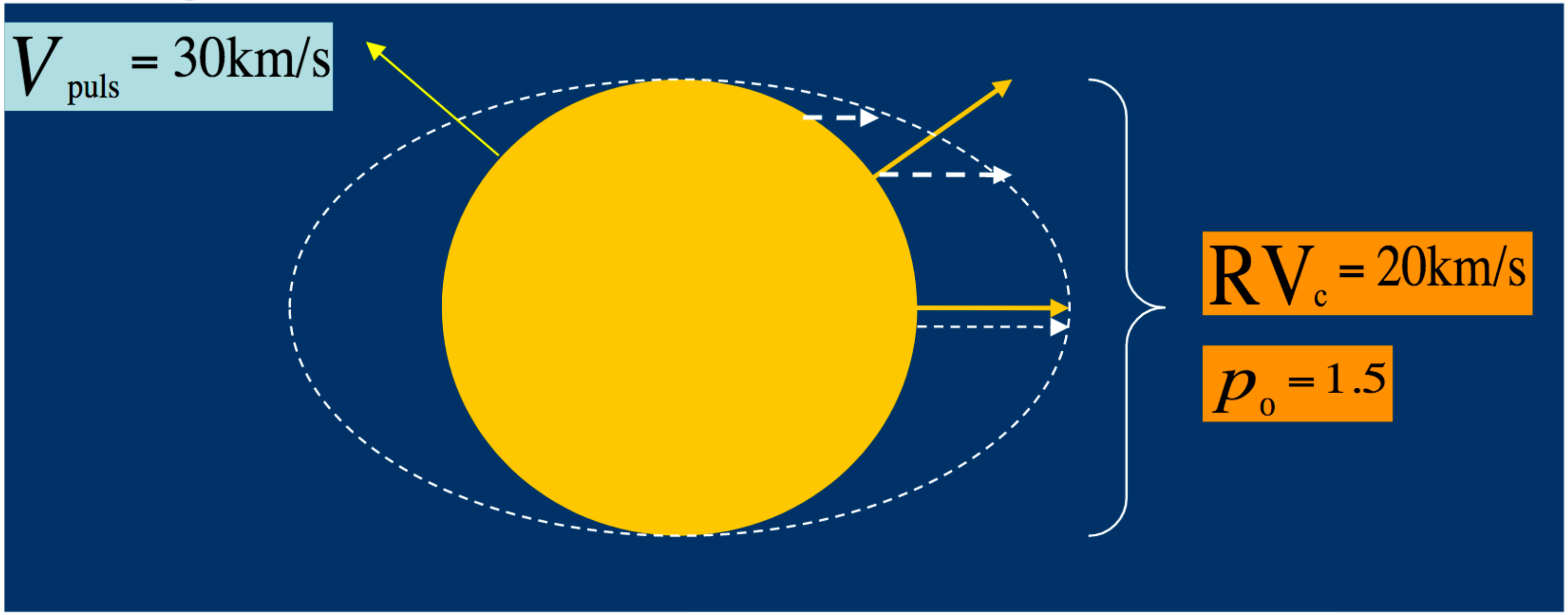


β Dor HARPS observations

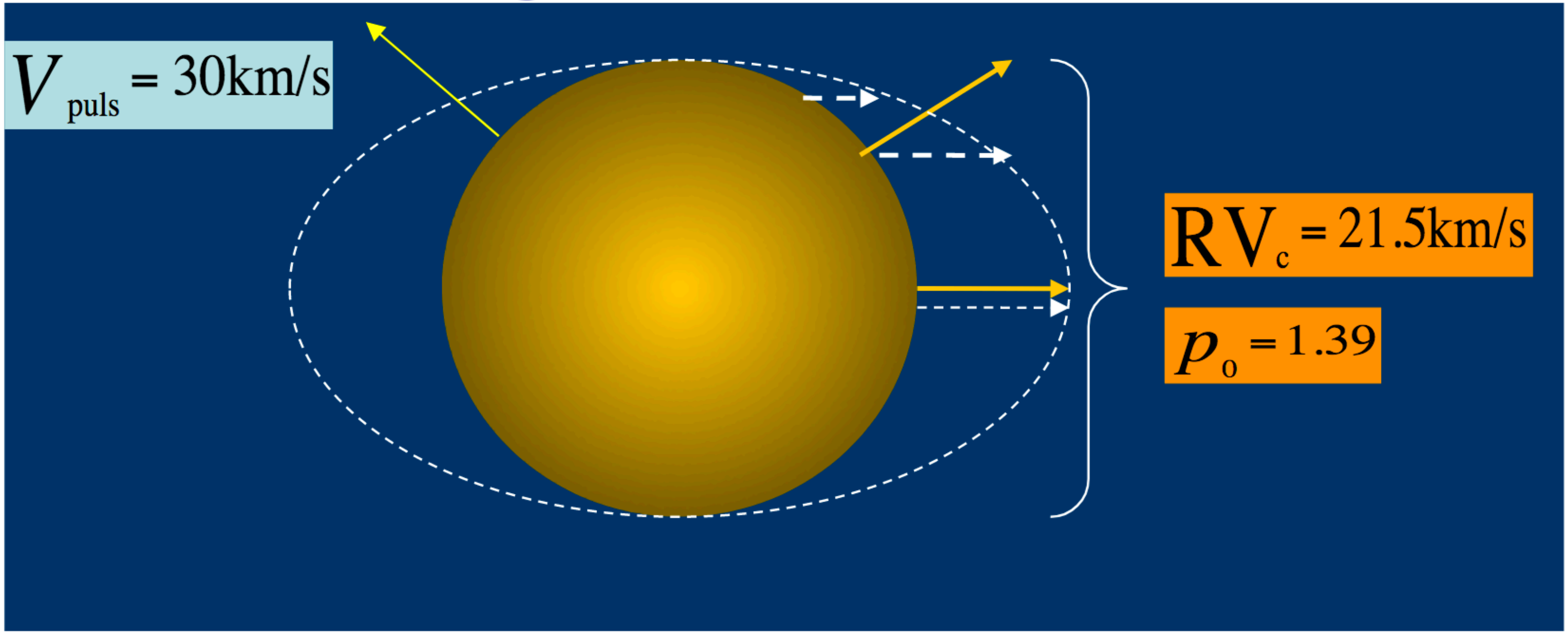




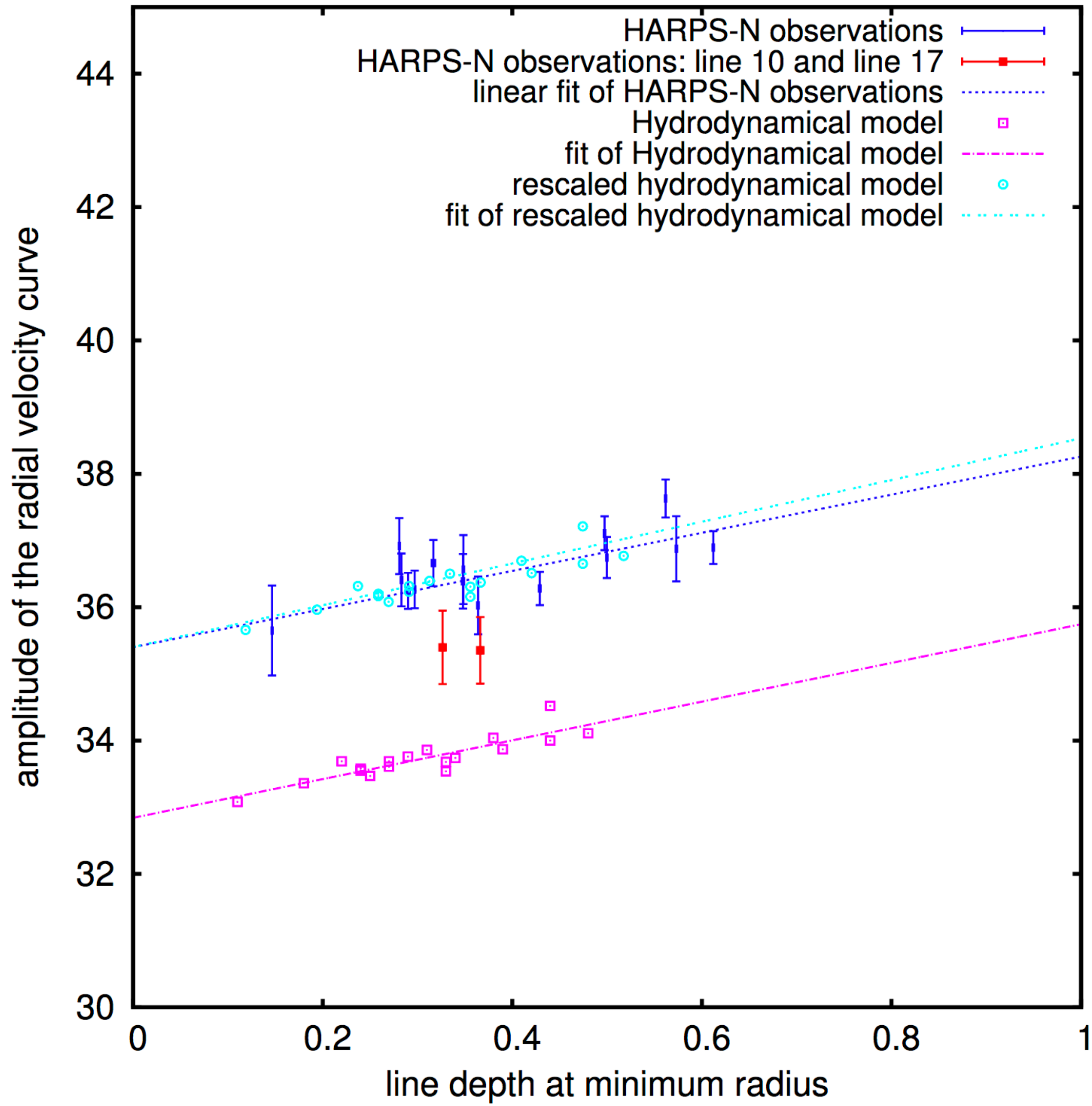
• A geometric effect (uniform disk)



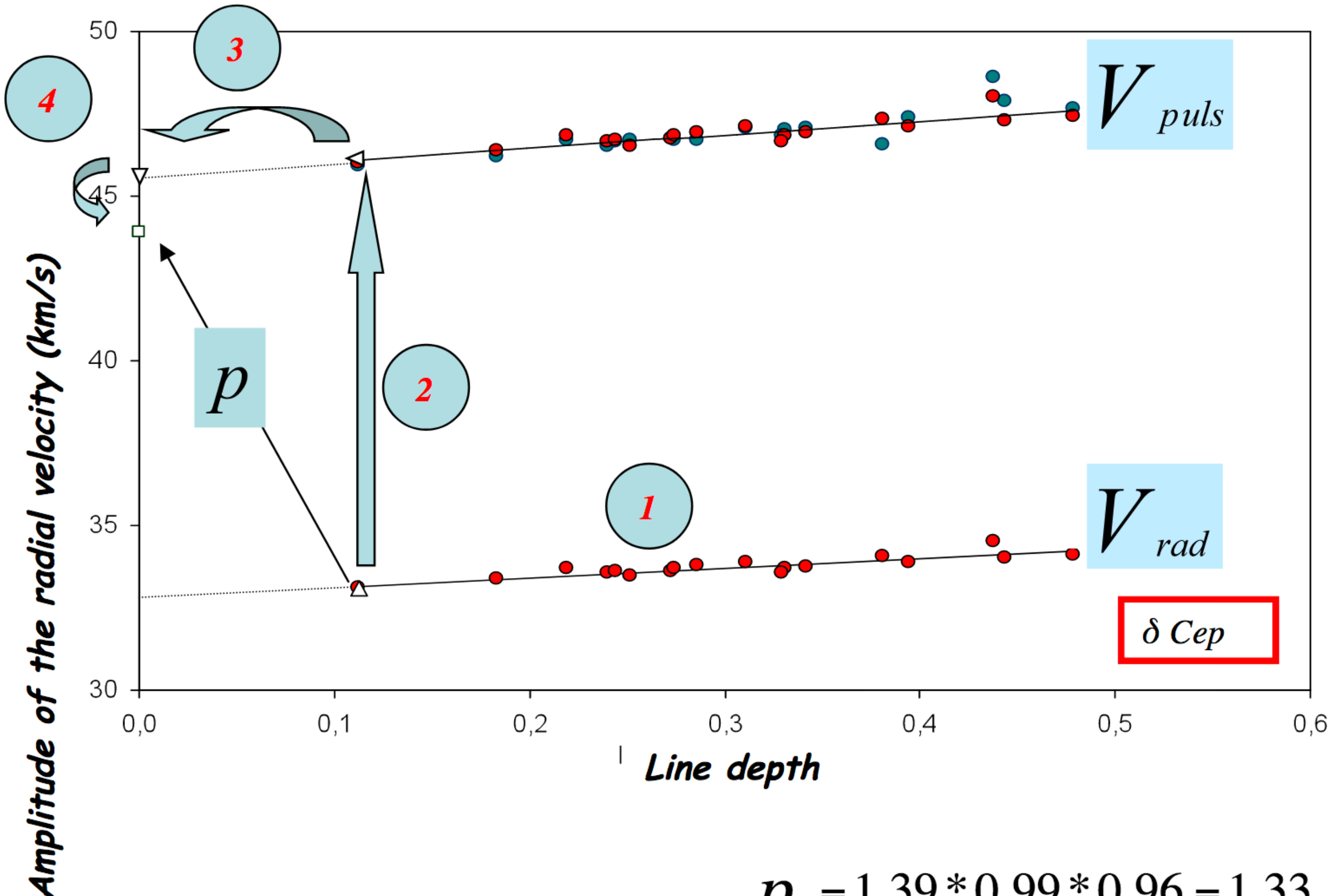
• Limb-darkening effect



Name	Wavelength (Å)
Fe I	4683.560
Fe I	4896.439
Fe I	5054.643
Ni I	5082.339
Fe I	5367.467
Fe I	5373.709
Fe I	5383.369
Ti II	5418.751
Fe I	5576.089
Fe I	5862.353
Fe I	6024.058
Fe I	6027.051
Fe I	6056.005
Si I	6155.134
Fe I	6252.555
Fe I	6265.134
Fe I	6336.824



The p-factor decomposition



p-factor decomposition : semi-theoretical approach

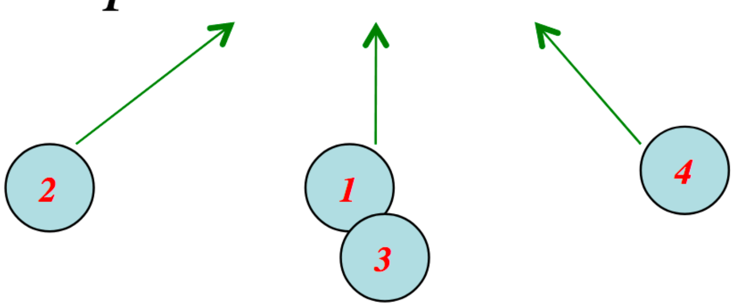
1 – Direct measure of the velocity gradient (HARPS)

2 – *geometric p-factor*

3 – *extrapolation to the photosphere*

4 – *optical/gas layers : hydro code*

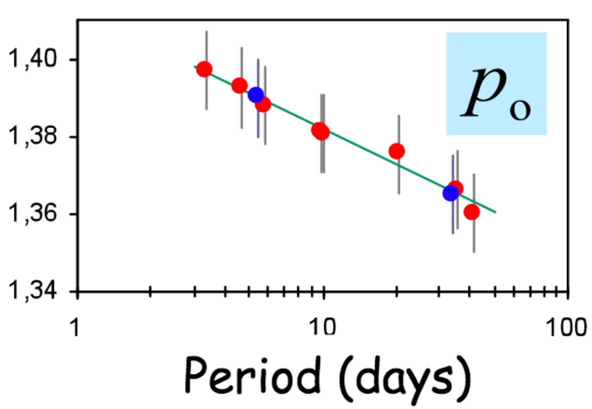
$$p = 1.39 * 0.99 * 0.96 = 1.33$$



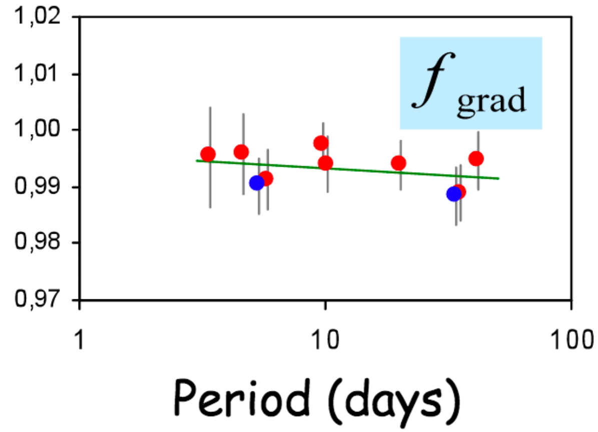
The Pp relation

High resolution spectroscopy for Cepheids distance determination II. A period-projection factor relation

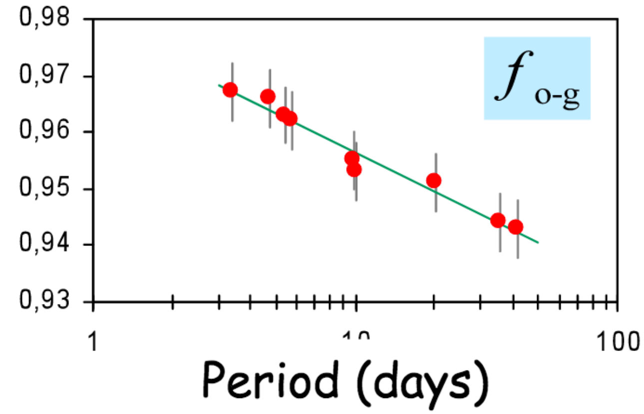
N. Nardetto, D. Mourard, Ph. Mathias, A. Fokin, D. Gillet, **2007**, *A&A*, **471**, **661**



Geometric model

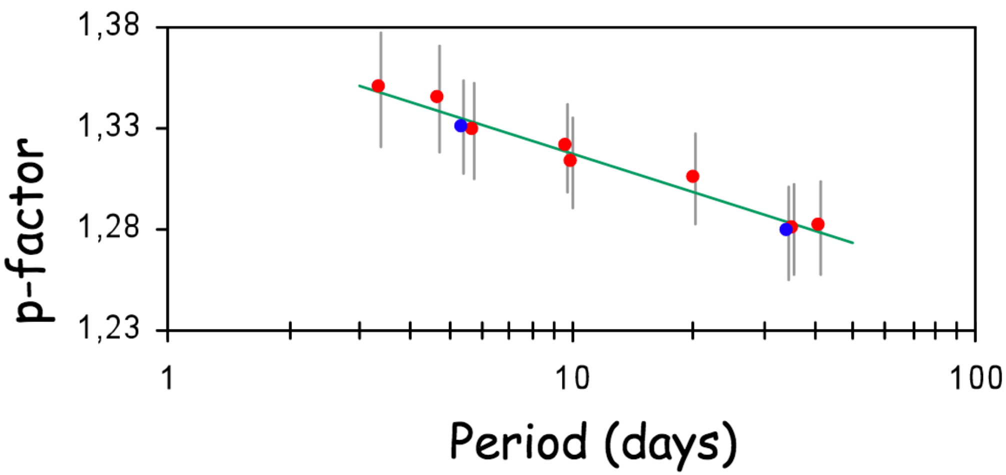


HARPS observations

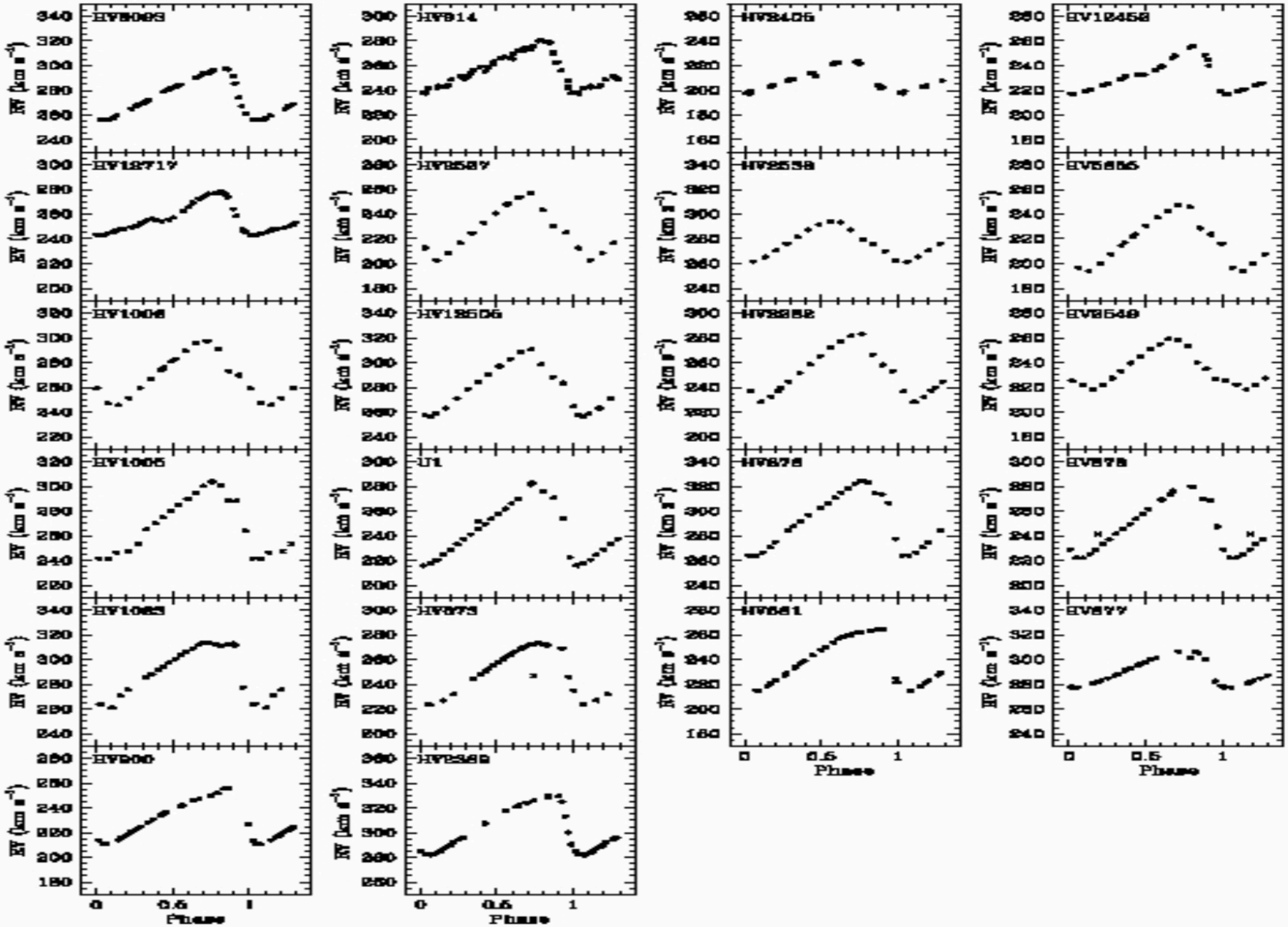


Hydrodynamical modelling

FeI 4896A

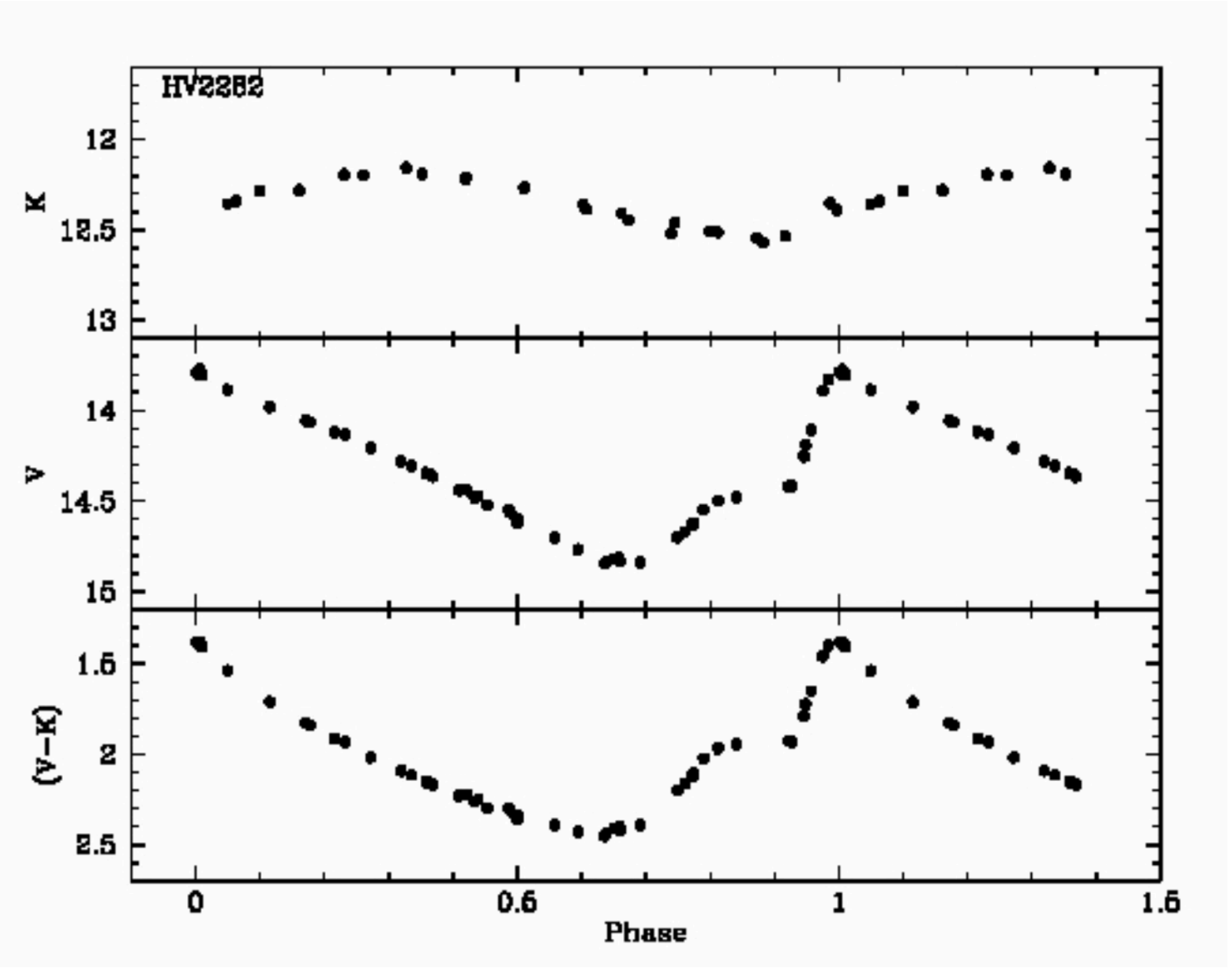


$$p = [-0.06 \pm 0.02] \log P + [1.38 \pm 0.02]$$



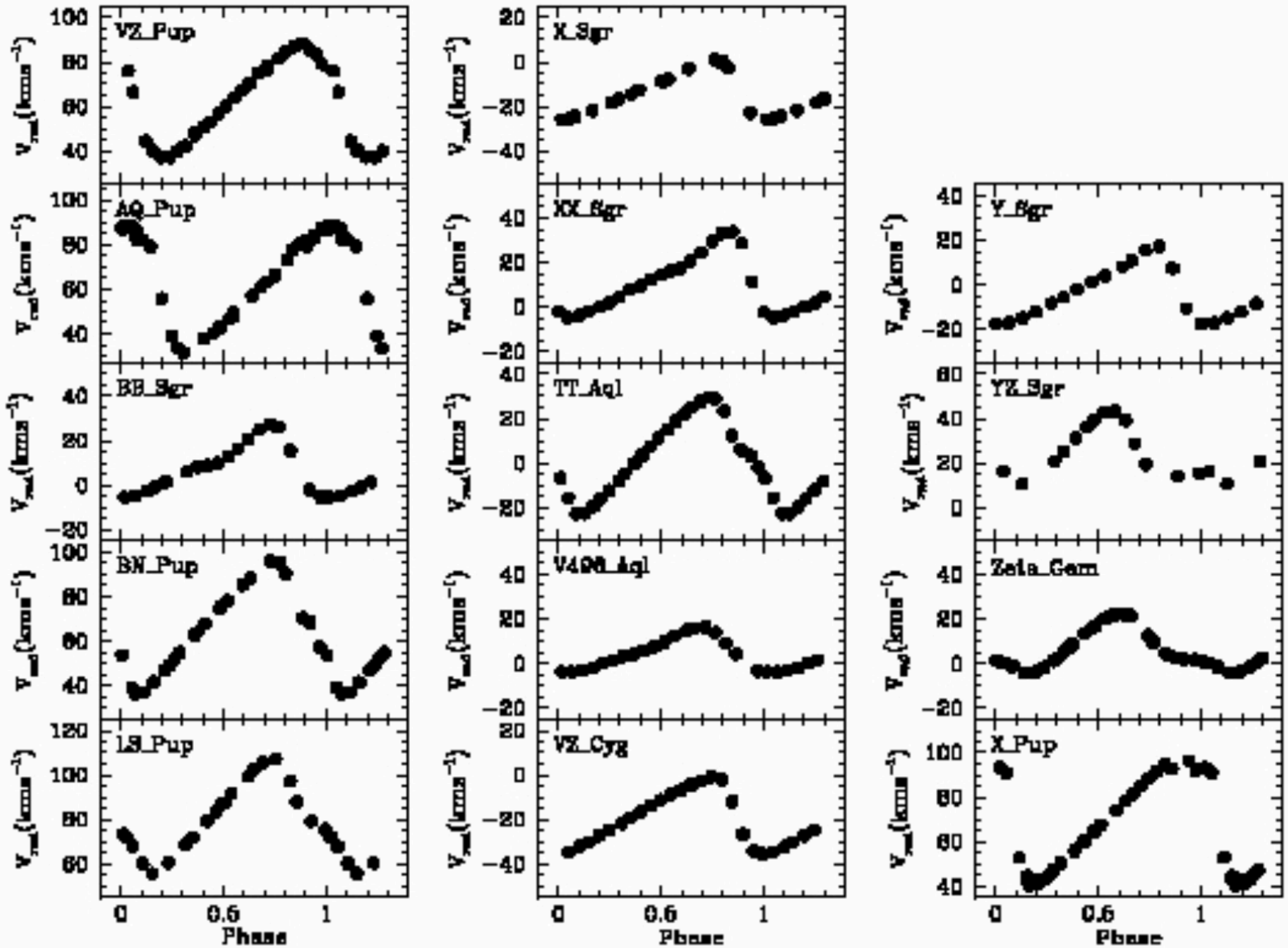
AIP

Storm, 2014, MIAPP WS

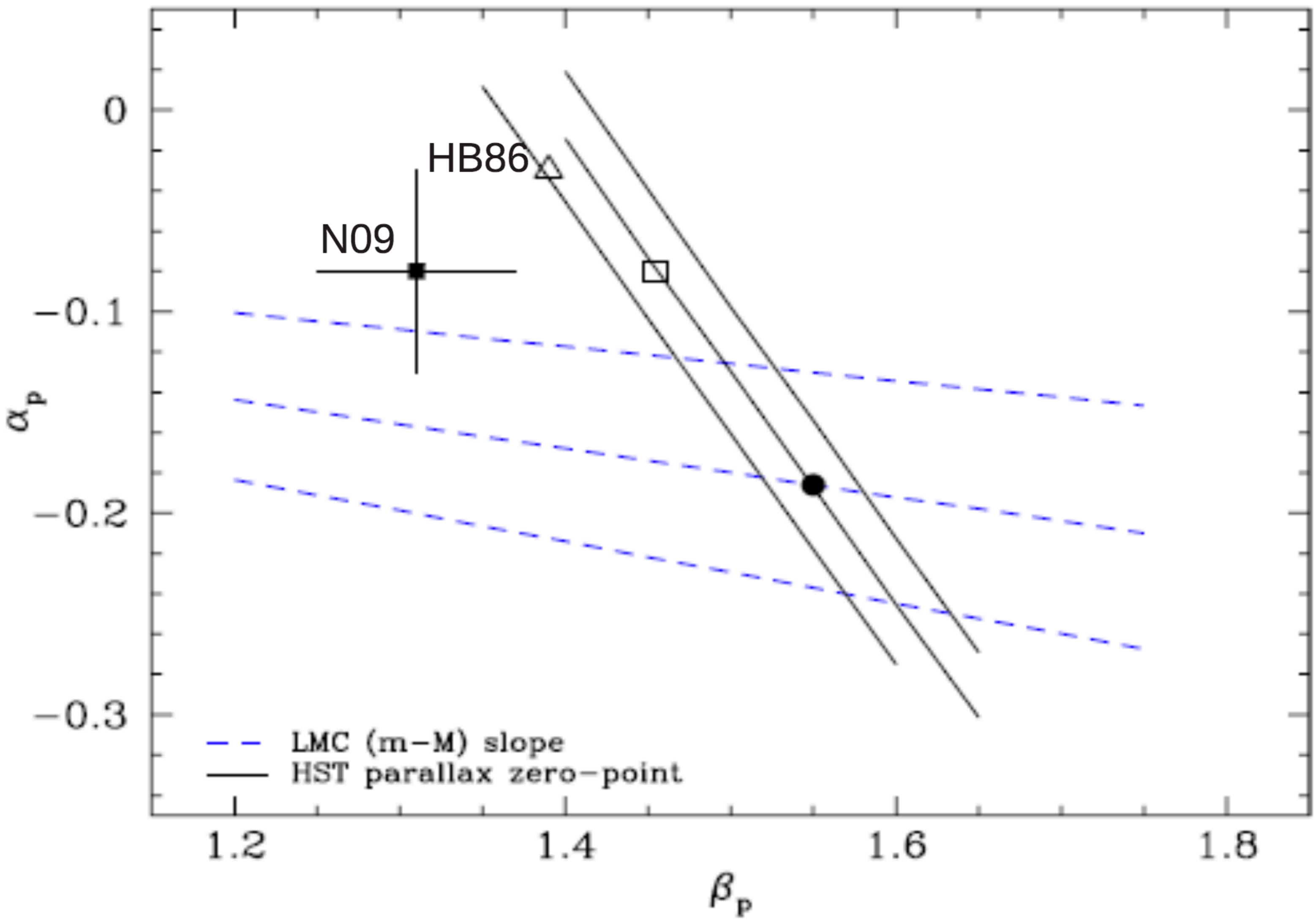


- LMC photometry
  - Persson et al. (2004)
  - OGLE-III Soszynski et al (2008)

Radial velocity curves for galactic Cepheids using the 1.2m STELLA-I robotic telescope on Tenerife with the SES fiber-fed echelle spectrograph. (Storm et al. 2011)

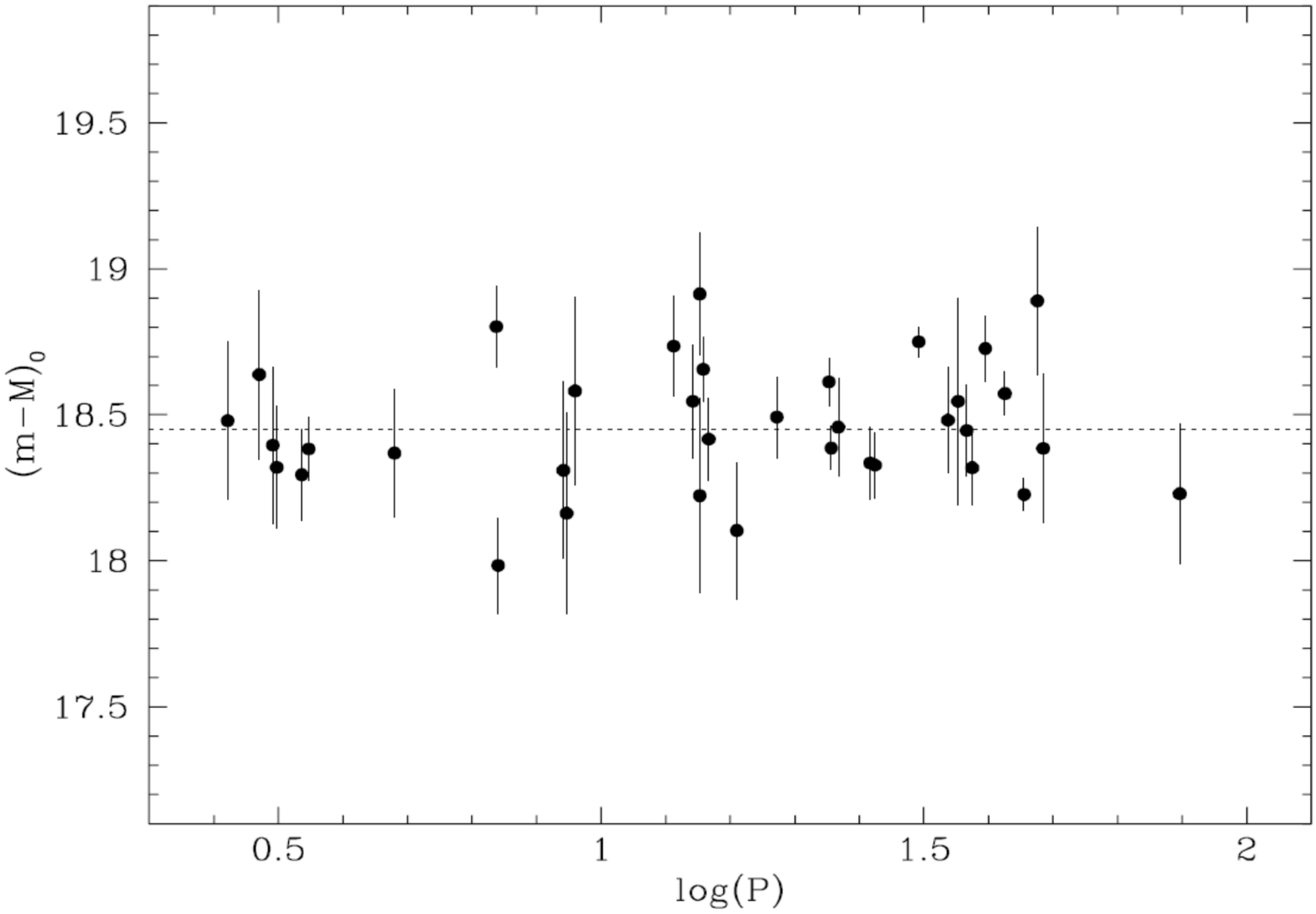


The new constraints on the p-factor, p = αlog(P) + β



Best estimate: p=1.550-0.186 log(P)

Distances to the LMC Cepheids using the revised p-factor relation



The distance to the LMC is measured to be (m-M)o=18.45(+-0.04)

results BWM

Nardetto et al., 2009

$$p = 1.38 - 0.06 logP$$

$$(m - M)_{LMC} = 18.26 \pm 0.02 mag$$

Groenewegen, 2014

$$p = 1.50 - 0.24 logP$$

$$(m - M)_{LMC} = 18.29 \pm 0.02 mag$$

Storm et al., 2014

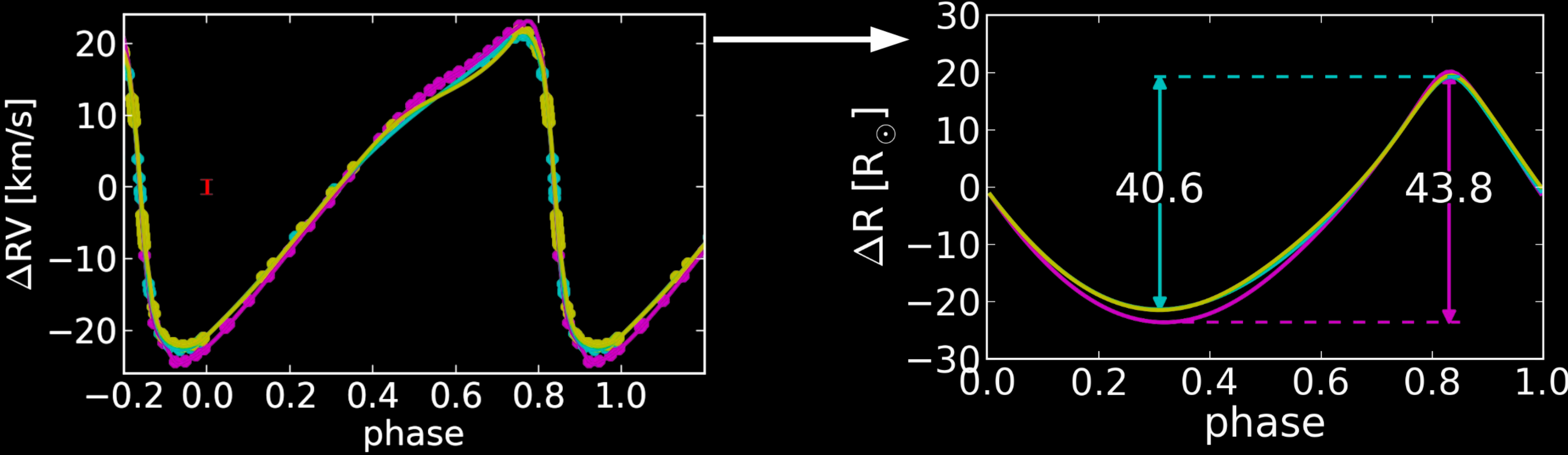
$$p = 1.55 - 0.19 logP$$

$$(m - M)_{LMC} = 18.45 \pm 0.04 mag$$

Richard Anderson, 2014

BWM error source: irregularities in v_{rad}

$$p \times \int RV(t)\,dt$$



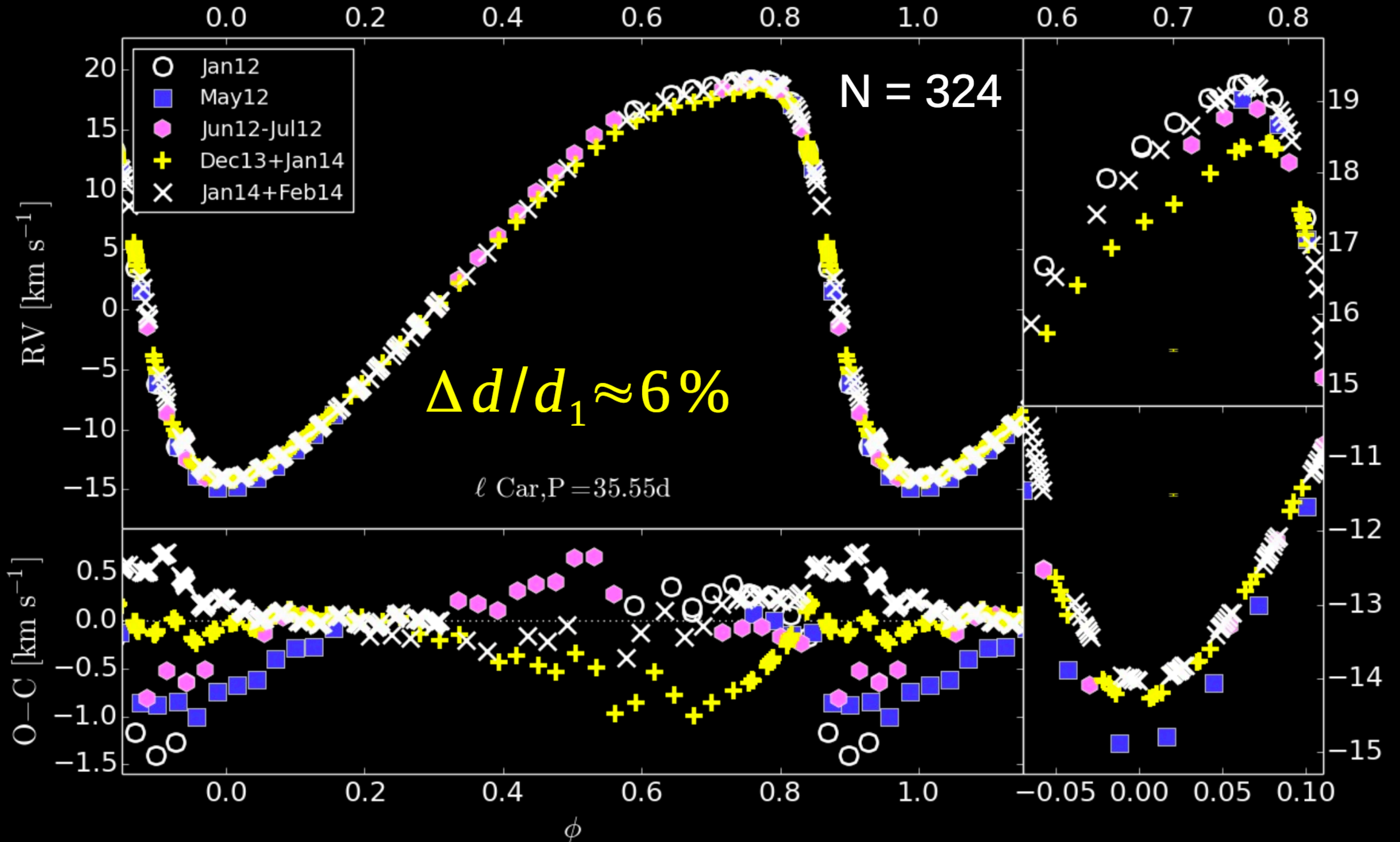
$$d = \frac{2\Delta R(t)}{\Delta\theta(t)}$$

$$\Delta d / d_1 = \frac{\Delta R_1 - \Delta R_2}{\Delta R_1} \approx 7\%$$

Independent of p-factor

Anderson, 2014 MIAPP WS

Cycle-to-cycle Modulation in l Car



Anderson, 2014 MIAPP WS

ΔΘ Modulation?

- Yes in space-based photometry
- Interferometry? (1-2% precision required)
- ΔR and ΔΘ must be observed contemporaneously (similar puls. cycle)