Extragalactic Distance Scale lect. VII
Pulsating stars

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

Pulsating stars

$$\frac{d^2R}{dt^2} = -g - \frac{1}{\rho}\frac{dP}{dr} \qquad P\sqrt{\rho_0} = \sqrt{\frac{3\pi}{G(3\gamma-4)}} = Q.$$

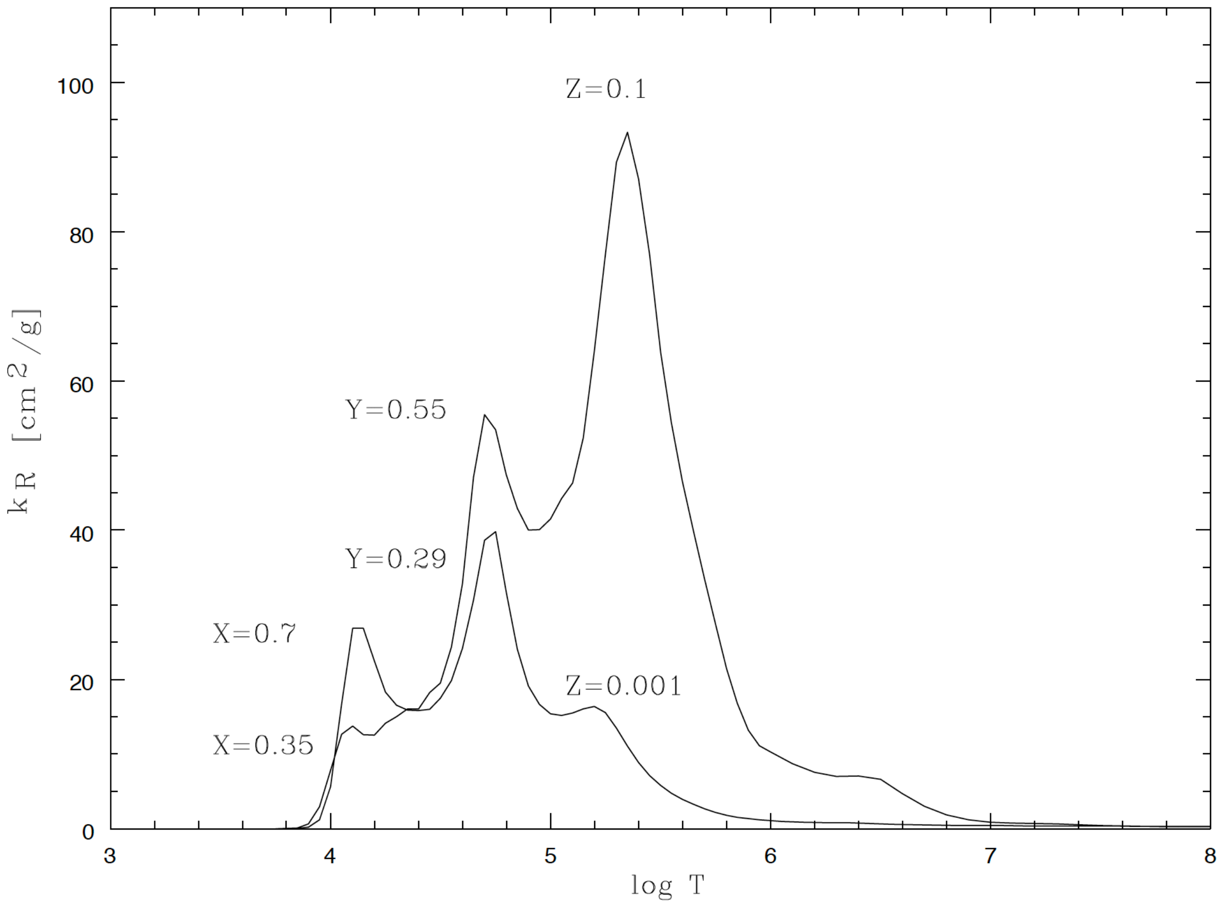
$$\log P - \frac{1}{4}\log \mathcal{M} + \frac{3}{4}\log g = \log Q.$$

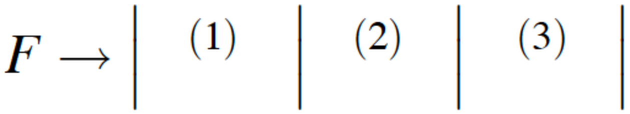
$$\log P + 0,5\log g + \log T_{ef} + 0,1(M_{bol} - M_{bol\odot}) = \log Q.$$

$$\log P + C(B-V)_0 + 0,1(M_{bol} - M_{bol\odot}) = \log Q$$

M. Kubiak Gwiazdy i materia międzygwiazdowa (in Polish)

Mechanism gamma - kappa





Ionisation (1) partial ionisation γ reduced (2) no ionisation (3)

Contraction (ρ grows) flux conserved in (2) due to both effects opacity much bigger in (2)
Expansion (ρ decreases) opacity much bigger in 1 and 3

Instability strips

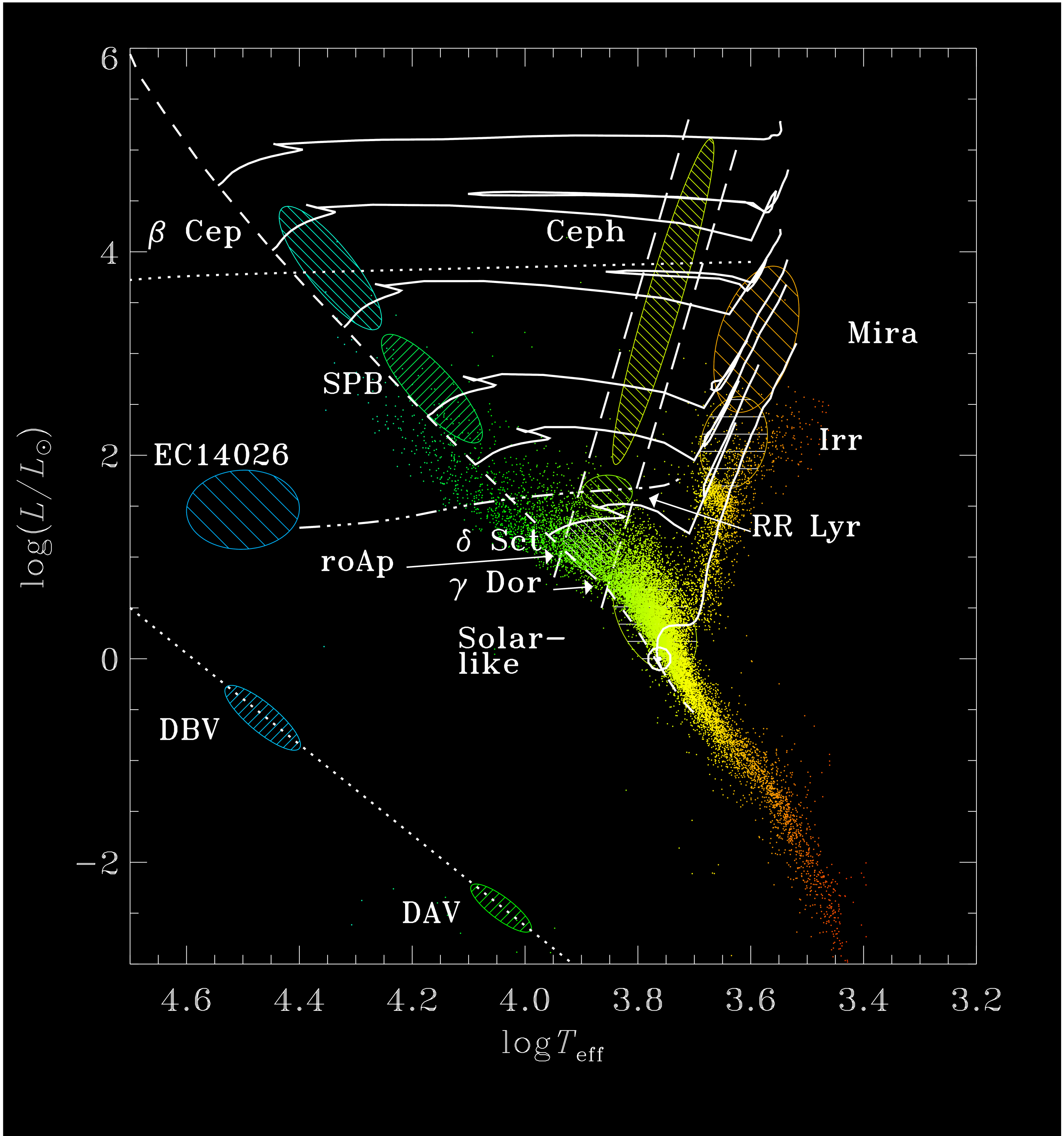
Partial ionisation zones exist in all stars, but they should be located at adequate depth to be efficient enough for pulsations (amplitud of changes of parameters like T, and density)

Hydrogen ionisation zones are located close to the photosphere, so they allow pulsation for only very big cool stars.

Second ionisation of helium – main instability strip

Different modes of pulsations (fundamental, first overtone, secon overtone, mix modes ect)

$$\log P + C(B-V)_0 + 0,1(M_{bol} - M_{bol\odot}) = \log Q$$



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

History

Edvard Pigott 1784 − discovery

P-L relation based on hundreds of photographic plates collected at Harvard College's observatory in Peru (1893 − 1906) Henrietta Leavitt produced a catalog of 1777 variable stars in the Magellanic Cloud.

Leavitt (1908) "It is worthy of notice that in Table VI the brighter variables have the longer periods."

Leavitt (1912) „A remarkable relation between the brightness of these variables and the length of their periods will be noticed"

„They resemble the variables found in globular clusters"

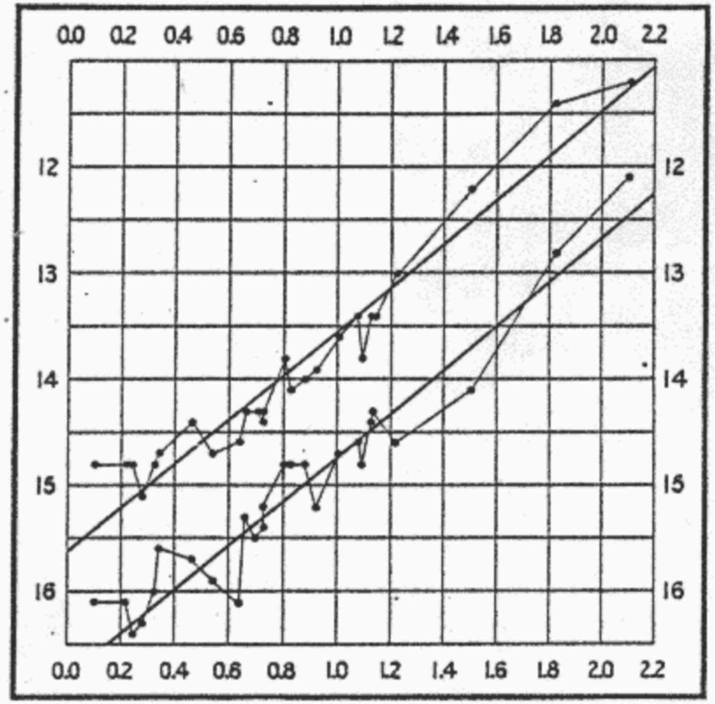


FIG. 2.

History

Ejnar Hertzsprung realised that if the PL relation could be calibrated, then the absolute magnitudes of members of this group of variable stars might be determined directly from their periods. Hertzsprung (1913) parallaxes

$\langle M_v \rangle = -0.6 - 2.1 \mathrm{Log} P$ *much lower distances, SMC at 10 kpc*

typographical error ? (most probably but we will never know)

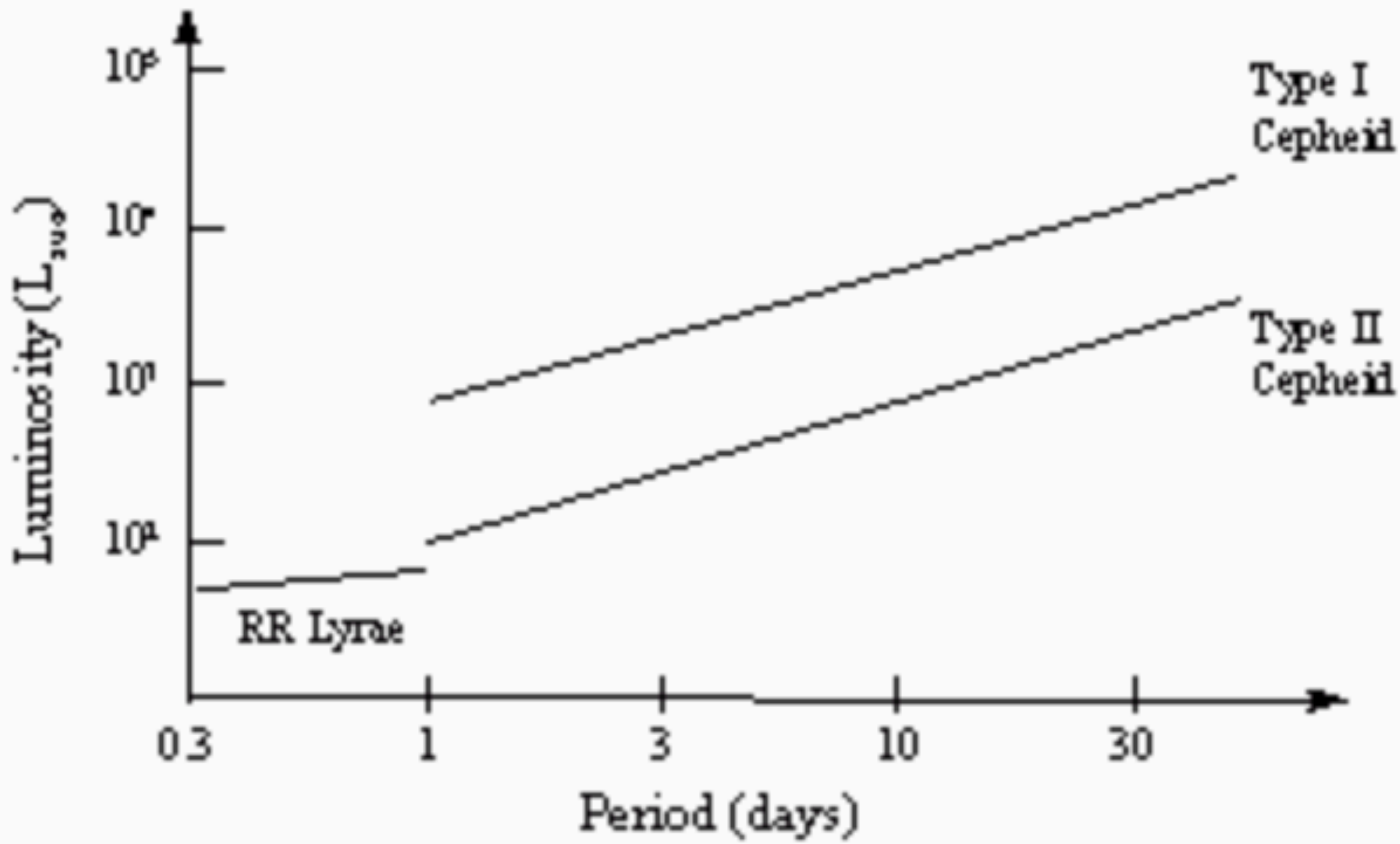
Shapley (1918) improved the calibration BUT due to systematic errors, and NOT taking into account extinction the ZP was 1.5 mag too dim. This was not realised for 30 years !

Shapley used „long period" variables in globular clusters and found for them similar slope of PL relation as for the SMC Cepheids. Shapley distinguised between long period (Type II Cep) and short period (RR Lyrae) variables. But he mixed up classical Cepheids and Type II Cep, which are dimmer by 1.5 mag !

He also introduced RR Lyrae as the standard candle

He was very sucessful in studying Galactic structure. In 1920 he presented a model of Galactic halo, bulge and disk.

Period-Luminosity Relationship



History Cepheids gives extragalactic distances

E. Hubble obtained the first Cepheid distance to NGC 6822 (214 kpc)

Modern distance to NGC 6822 is of 459 kpc (Gieren et al. 2005)

During the World War II Walter Baade was working at the Mount Wilson Observatory. He observed M31 and nearby „early type" galaxies M32 and NGC 205.

Baade and Hubble had already discussed at some length an apparent discrepancy in the distance calibration; they could not understand why the globular clusters associated with Andromeda appeared to be 1.5 magnitudes fainter than those in the Galaxy

Although the evidence presented in the preceding discussion is still very fragmentary, there can be no doubt that, in dealing with galaxies, we have to distinguish two types of stellar populations, one which is represented by the ordinary H-R diagram (type I), the other by the H-R diagram for the globular clusters (type II). Characteristic of the first type are highly luminous O- and B- type stars and open clusters; of the second globular clusters and short-period Cepheids. Early-type nebulae (E-Sa) seem to have populations of pure type II. Both types coexist, although differentiated by their spatial arrangement, in the intermediate spirals like the Andromeda nebula and our own Galaxy. (Baade 1944)

Miss Leavitt's cepheids in the Magellanic Clouds and the classical cepheids in our galaxy are clearly members of population I, while the cluster-type variables and the long-period cepheids of the globular clusters are members of population II. Since the color-magnitude diagrams of the two populations leave no doubt that .. we are dealing with stars in different physical states, there was no a priori reason to expect that two cepheids of the same period, the one a member of population I, the other of population II, should have the same luminosity. (Baade 1956)

History: Cepheids gives extragalactic distances

Baade also verified that the Population II Cepheids are dimmer by some 1.5 mag.

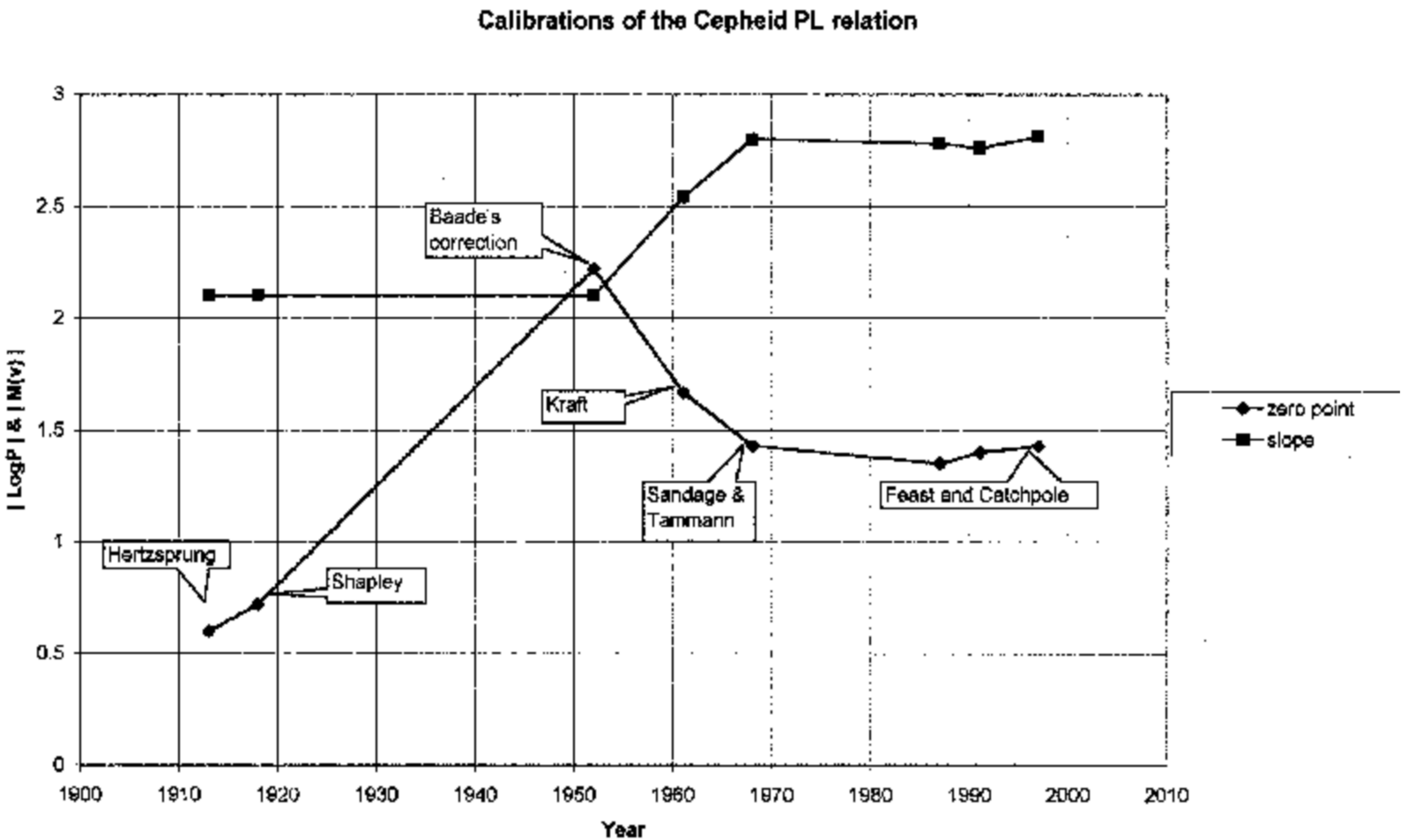
The cosmos was re-scaled (two-fold increase!) when Baade presented his findings to the International Astronomical Union in 1952.

One year before Hubble said: I do not expect any furhter important revision on P-L

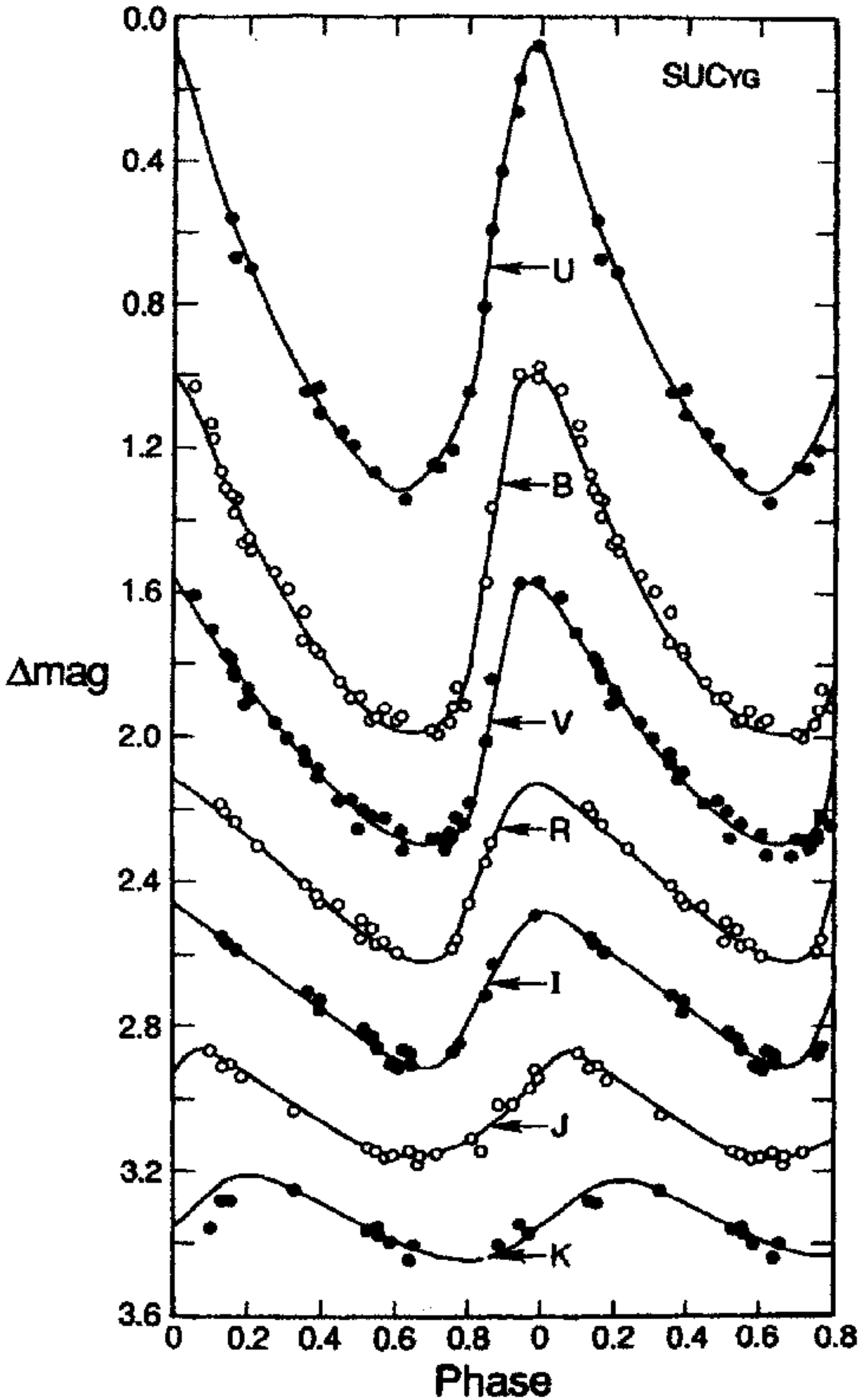
Surprisingly, the revision had no effect on the size of the Galaxy itself. This had been based principally upon studies of the globular clusters and the RR Lyraes. The zero point of Shapley's distance calibration had been based on Population I Cepheids and had *always* been 1.5 magnitudes in error, but when unwittingly applied to the Population II Cepheids, which were 1.5 magnitudes dimmer than realised, the mistake largely cancelled out. His RR Lyrae calibrations were similarly correct, because they too had been determined using the Population II Cepheids.

Fernie (1969): The definitive study of the herd instincts of astronomers has yet to be written, but there are times when we resemble nothing so much as a herd of antelope, heads down in tight formation, thundering with firm determination in a particular direction across the plain. At a given signal from the leader we whirl about, and, with equally firm determination, thunder off in a quite different direction, still in tight parallel formation.

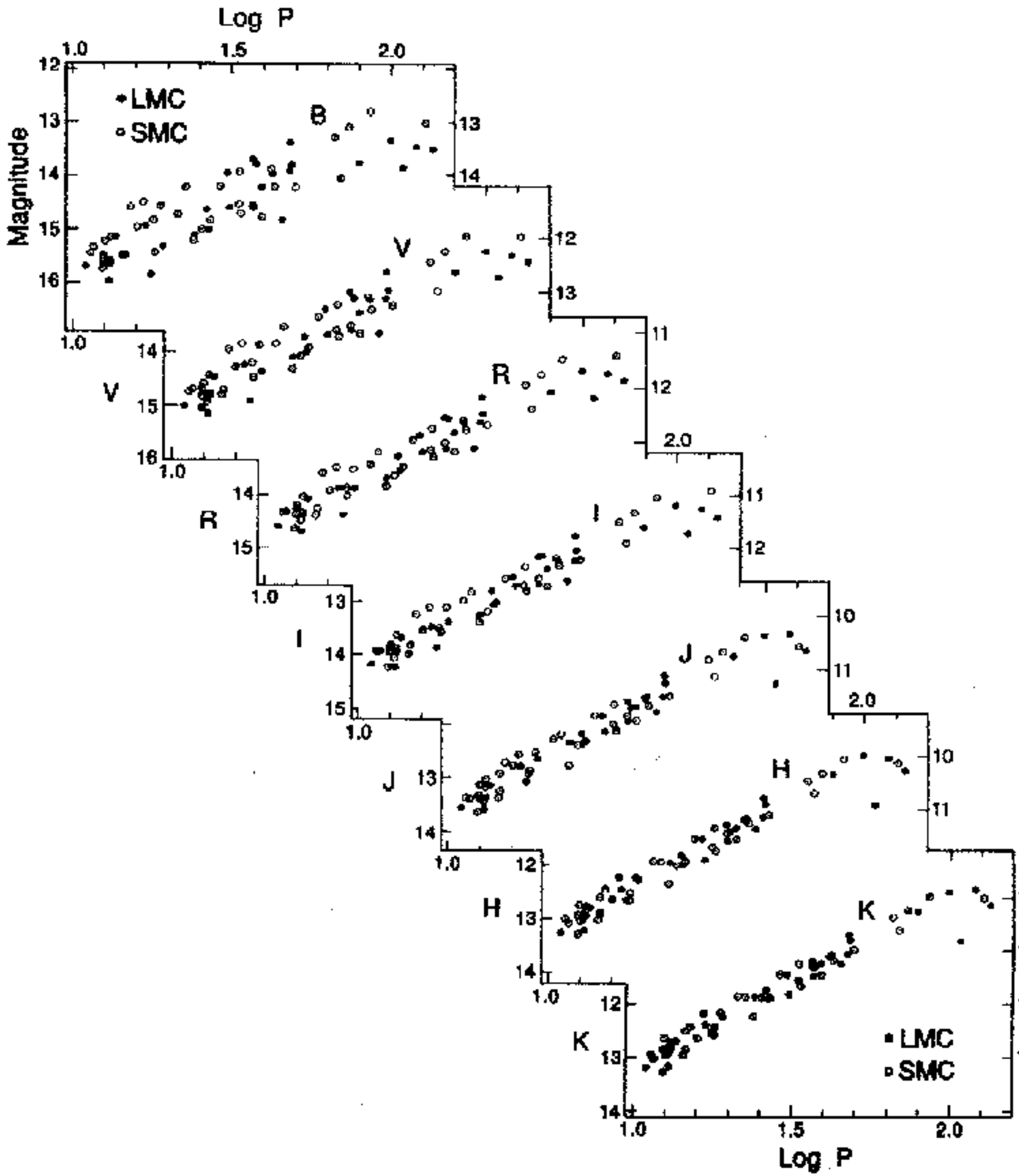
Calibration of Shapley was very precise at that time except of the ZP. When used in our Galaxy it gaved good results.



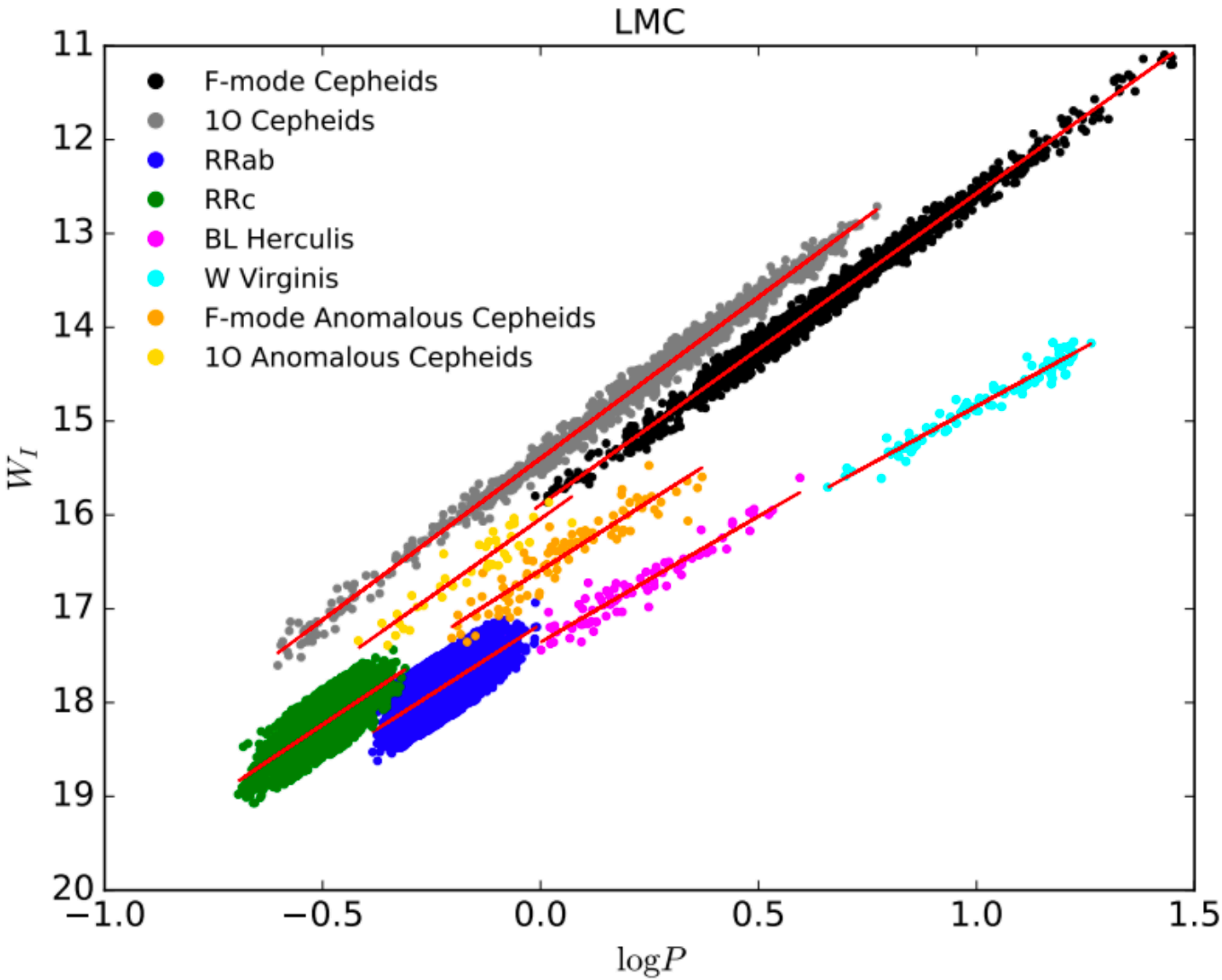
Calibrations of the Cepheid PL relation
| LogP | & | M(v) |
Year
Baade's correction
Kraft
Sandage & Tammann
Feast and Catchpole
Hertzsprung
Shapley
zero point
slope



SUCYG
U
B
V
R
I
J
K
Δmag
0.0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
0
0.2
0.4
0.6
0.8
0
0.2
0.4
0.6
0.8
Phase



Log P
LMC
SMC
Magnitude
B
V
R
I
J
H
K
LMC
SMC
Log P


LMC
F-mode Cepheids
1O Cepheids
RRab
RRc
BL Herculis
W Virginis
F-mode Anomalous Cepheids
1O Anomalous Cepheids
W_I
$\log P$
11
12
13
14
15
16
17
18
19
20
−1.0
−0.5
0.0
0.5
1.0
1.5

Cepheids

Easy to detect

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

Easy to measure period and magnitude

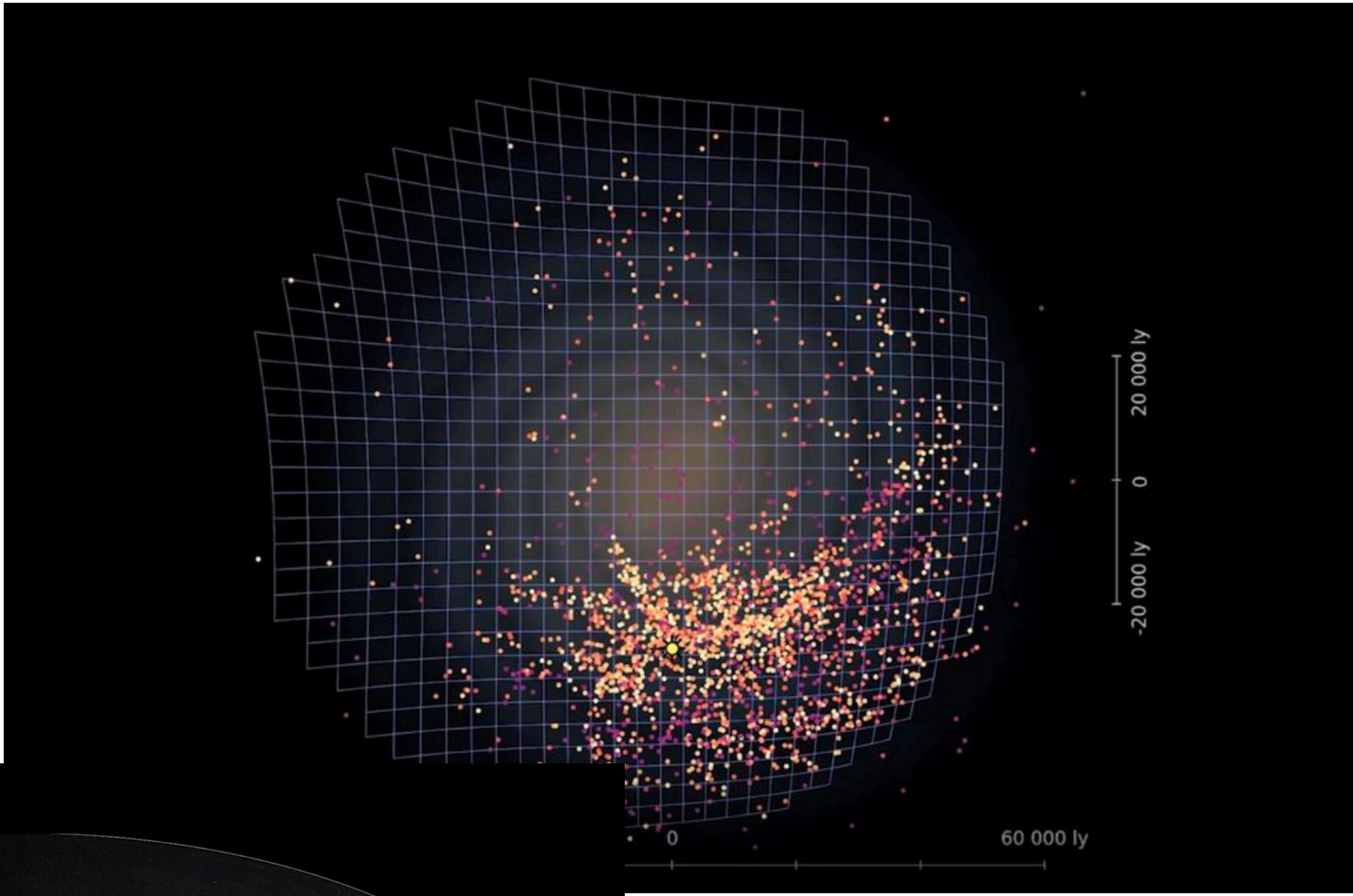
Very wide range of magnitudes

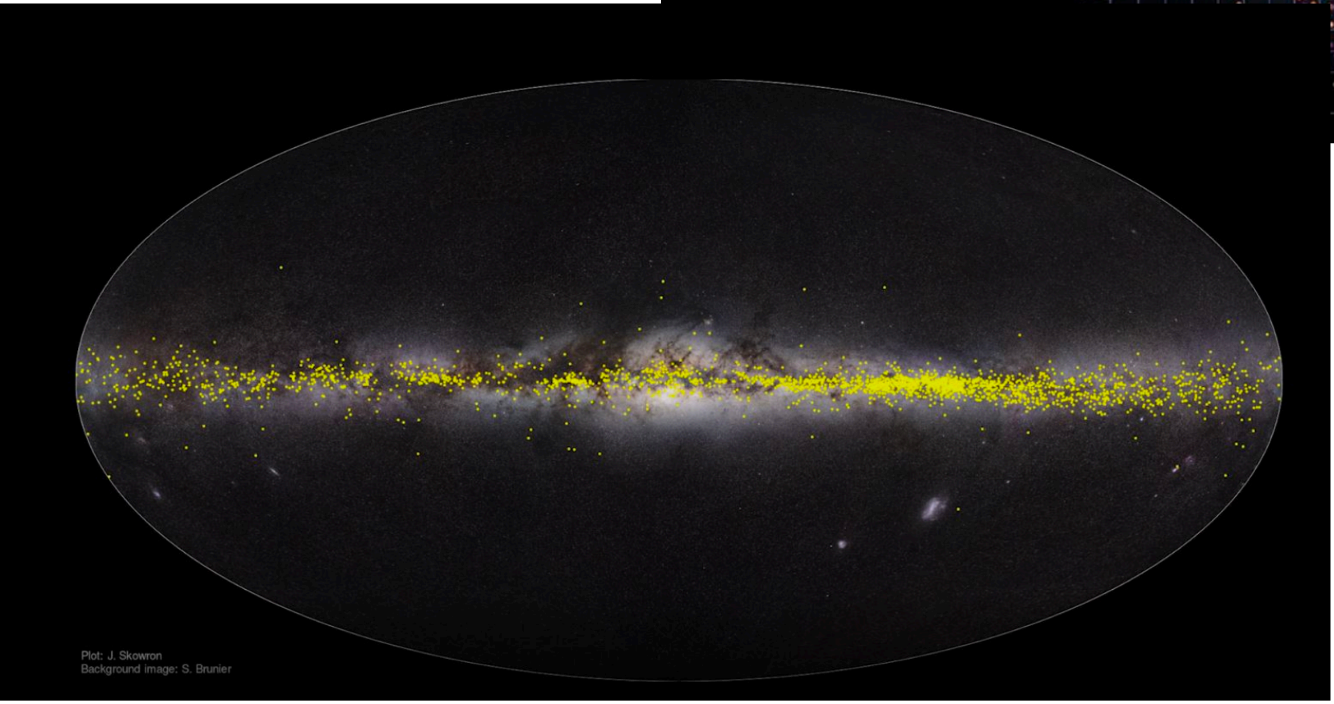
In general we use them as a statistical tool

(sample of Cepheids) but we can calculate distances

 to individual objects with 0.2 mag precision

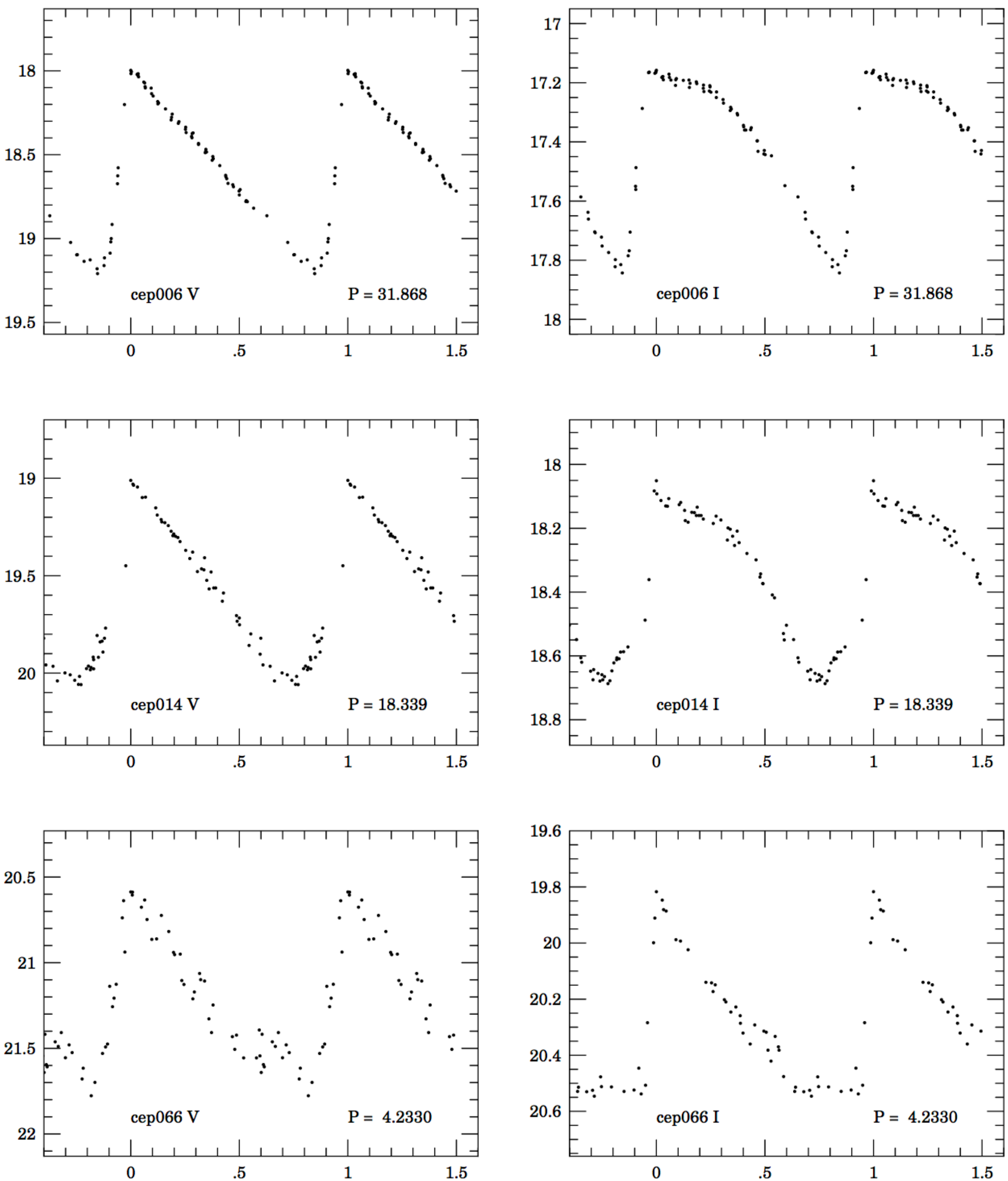
3D map of MW
Basen on
Cepheids





The map shows that the Milky Way disc is not flat but it is warped and twisted far and away from the galactic centre.

OGLE project
University of Warsaw



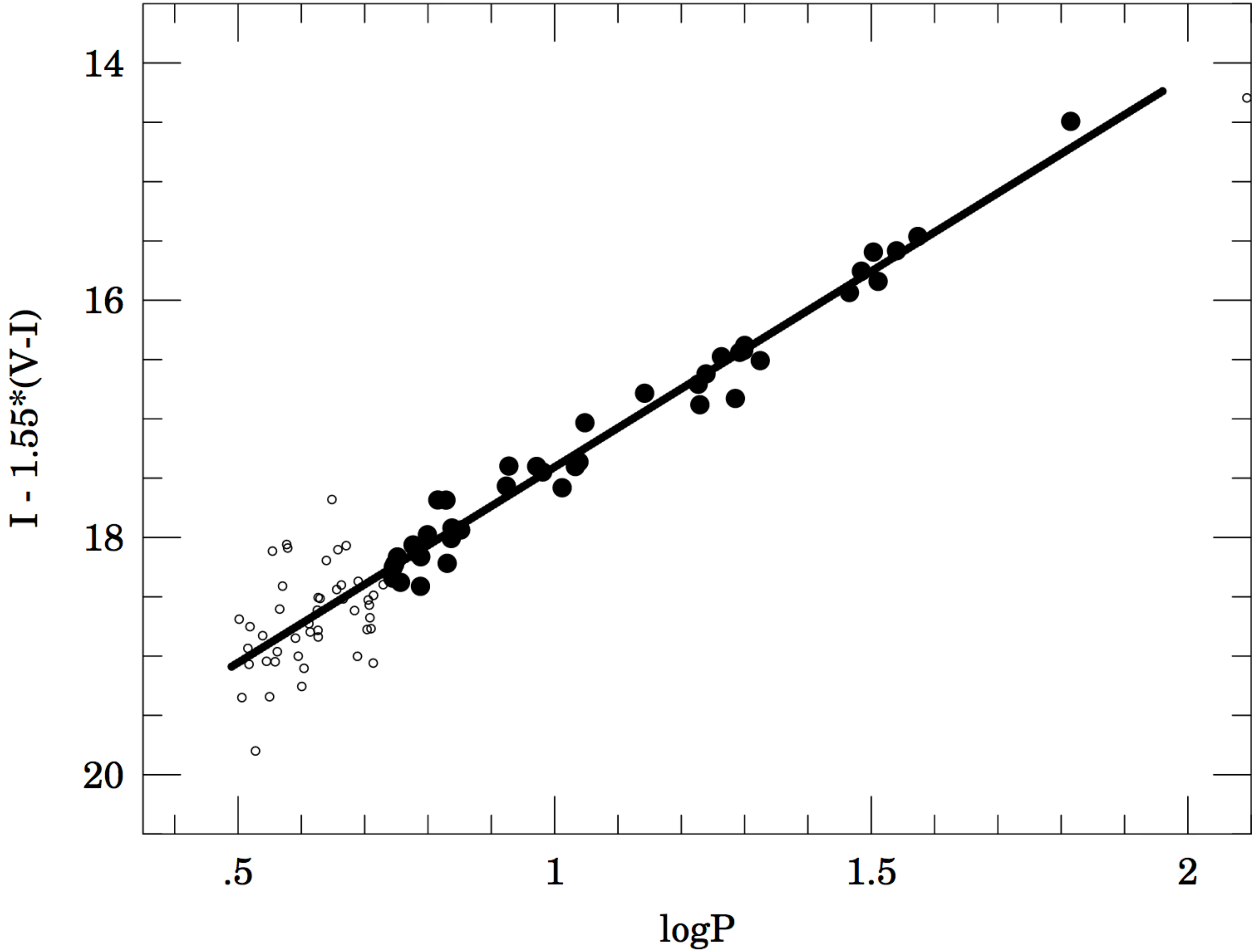
NGC 6822

Pietrzynski et al. 2004

1.3m telescope V+I band observations

77 nights

116 Cepheids detected
1.6 < P < 124


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

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

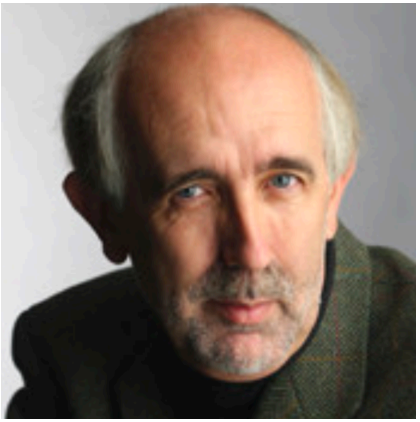
Many other less importnat (?) issues

Extinction

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

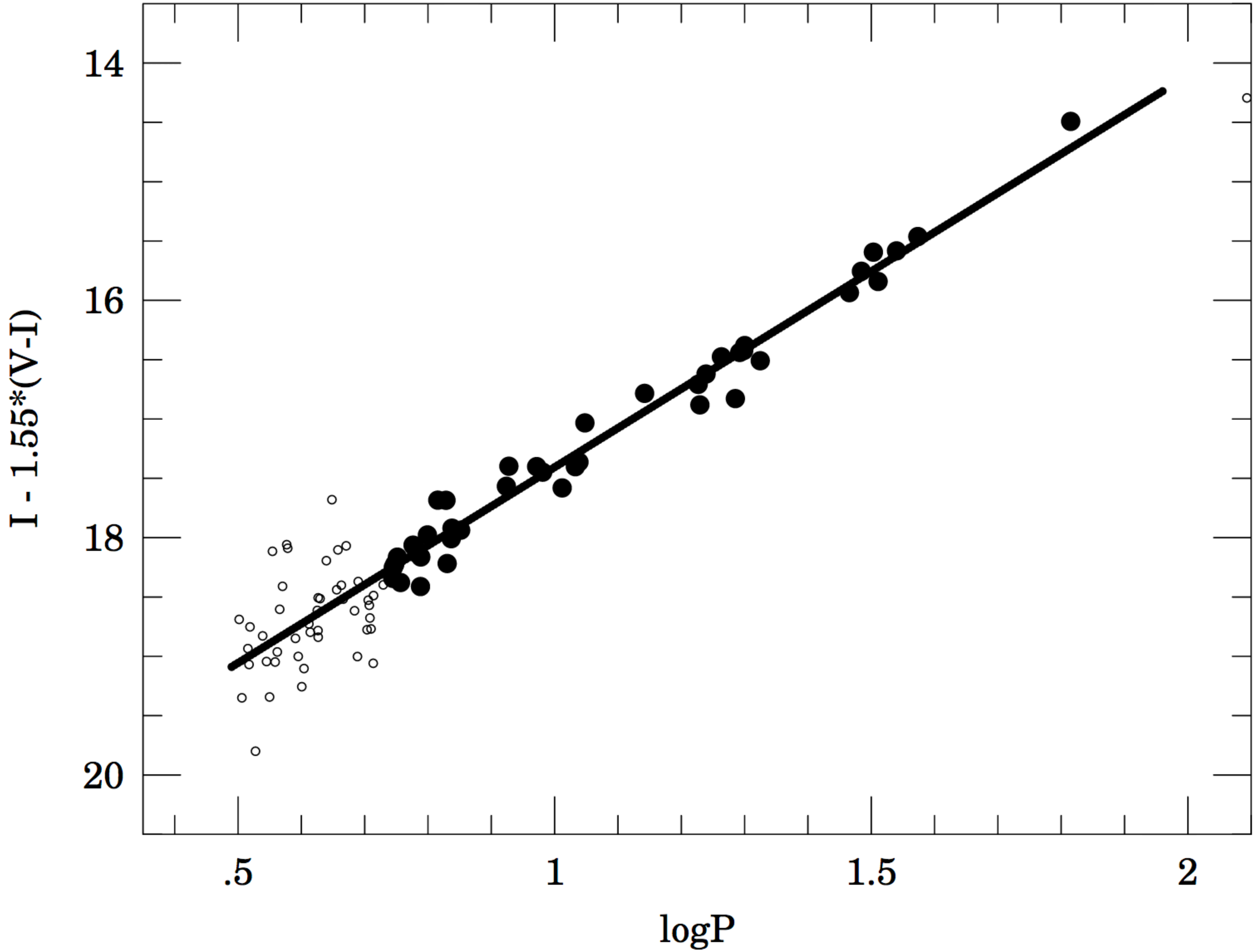
2) Wesenheit index (reddening free) (ger. essence)

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

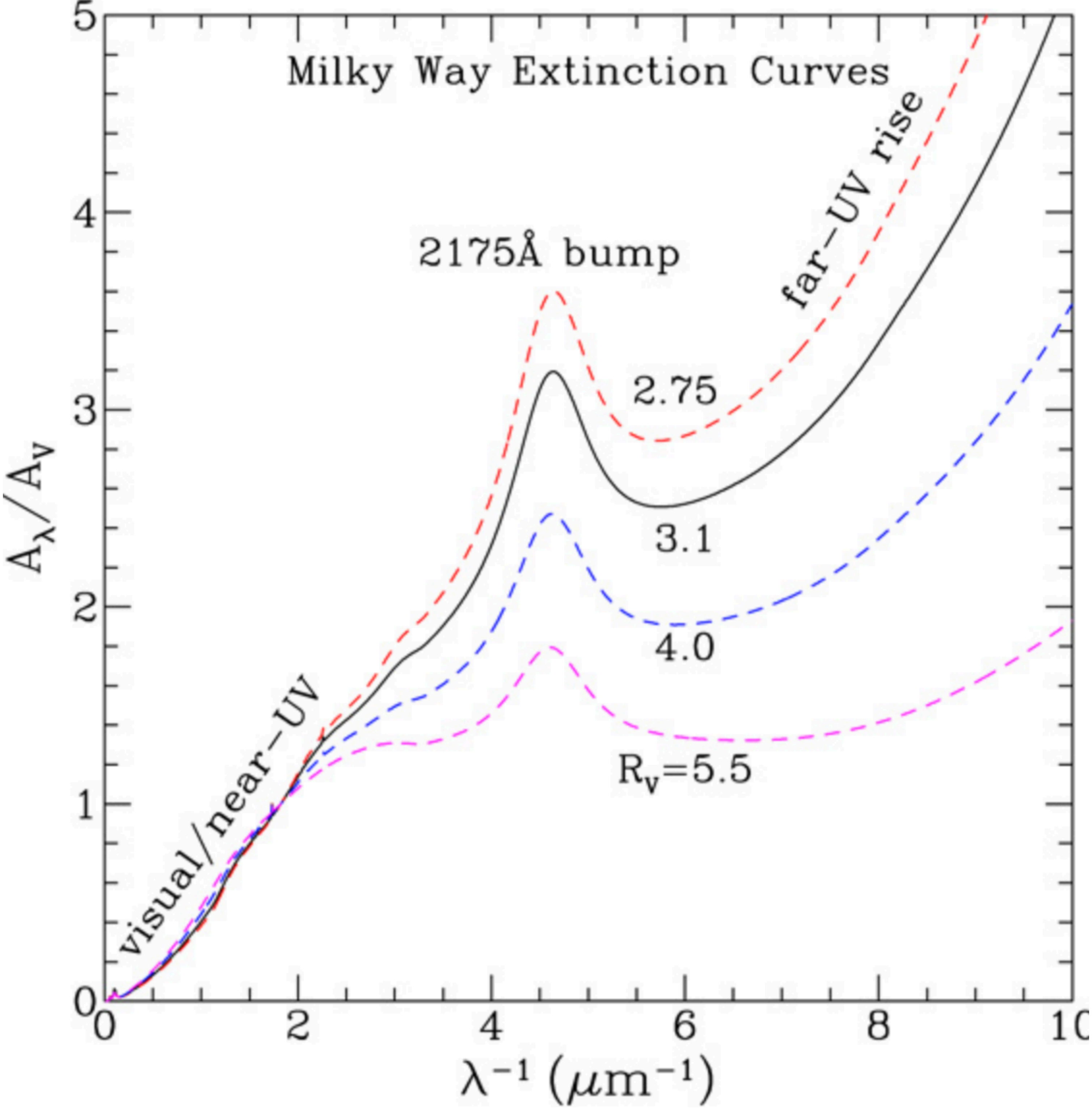


$$W(VI) = V - 10 + 5 lg\, p(\text{mas}) - A_V - \frac{A_V}{E(V-I)} \cdot (V-I)_0 =$$

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



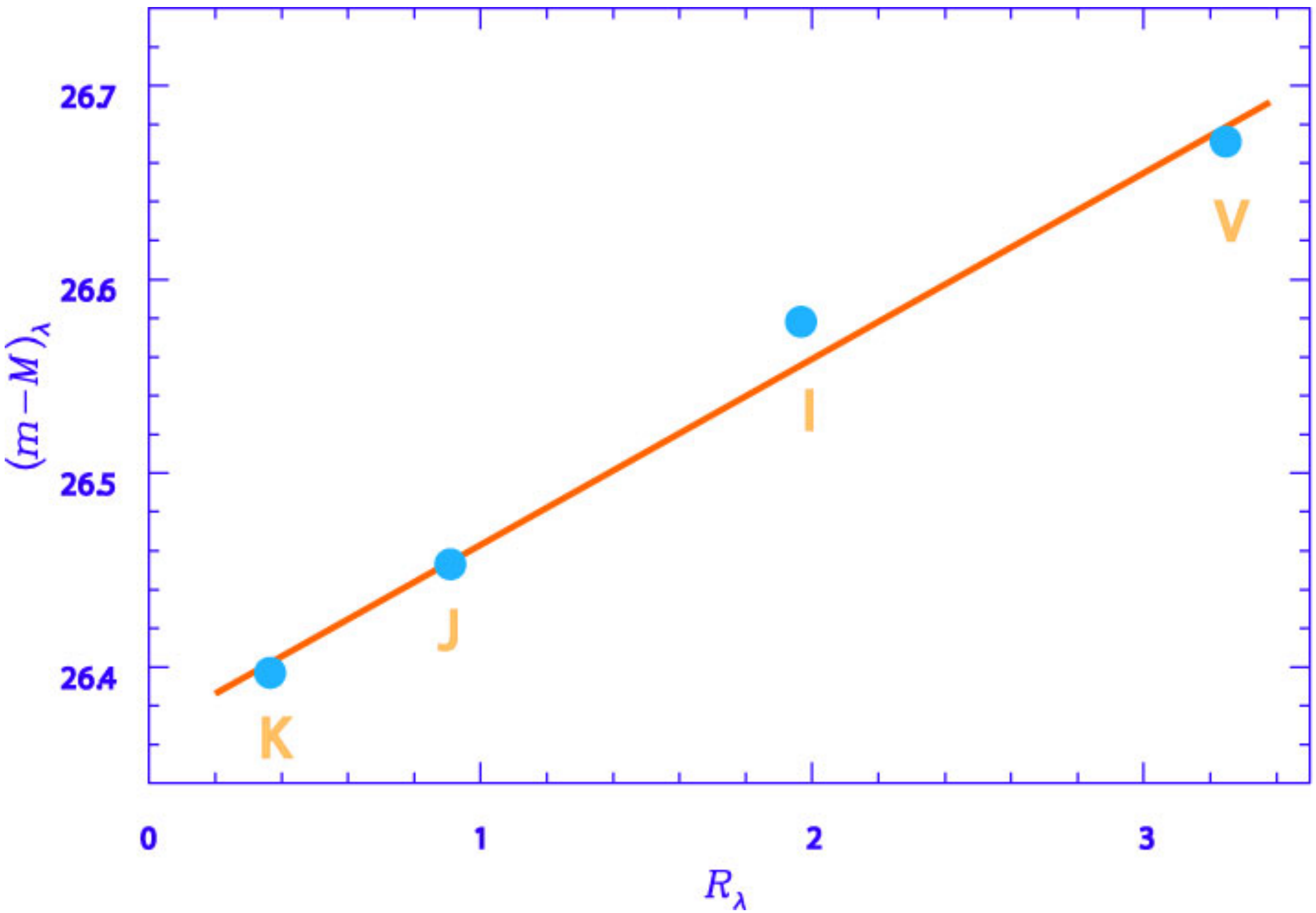
14
16
18
20
I - 1.55*(V-I)
.5
1
1.5
2
logP



Milky Way Extinction Curves
far–UV rise
2175Å bump
2.75
3.1
4.0
R_V=5.5
visual/near–UV
A_λ/A_V
λ^{-1} (μm^{-1})

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

Applications to 10 nearby galaxies

In all cases we showed that there is an „internal"

E(B-V) ~ 0.1 mag in addition to background (Galactic reddening)

Local distances changed by a few % ...

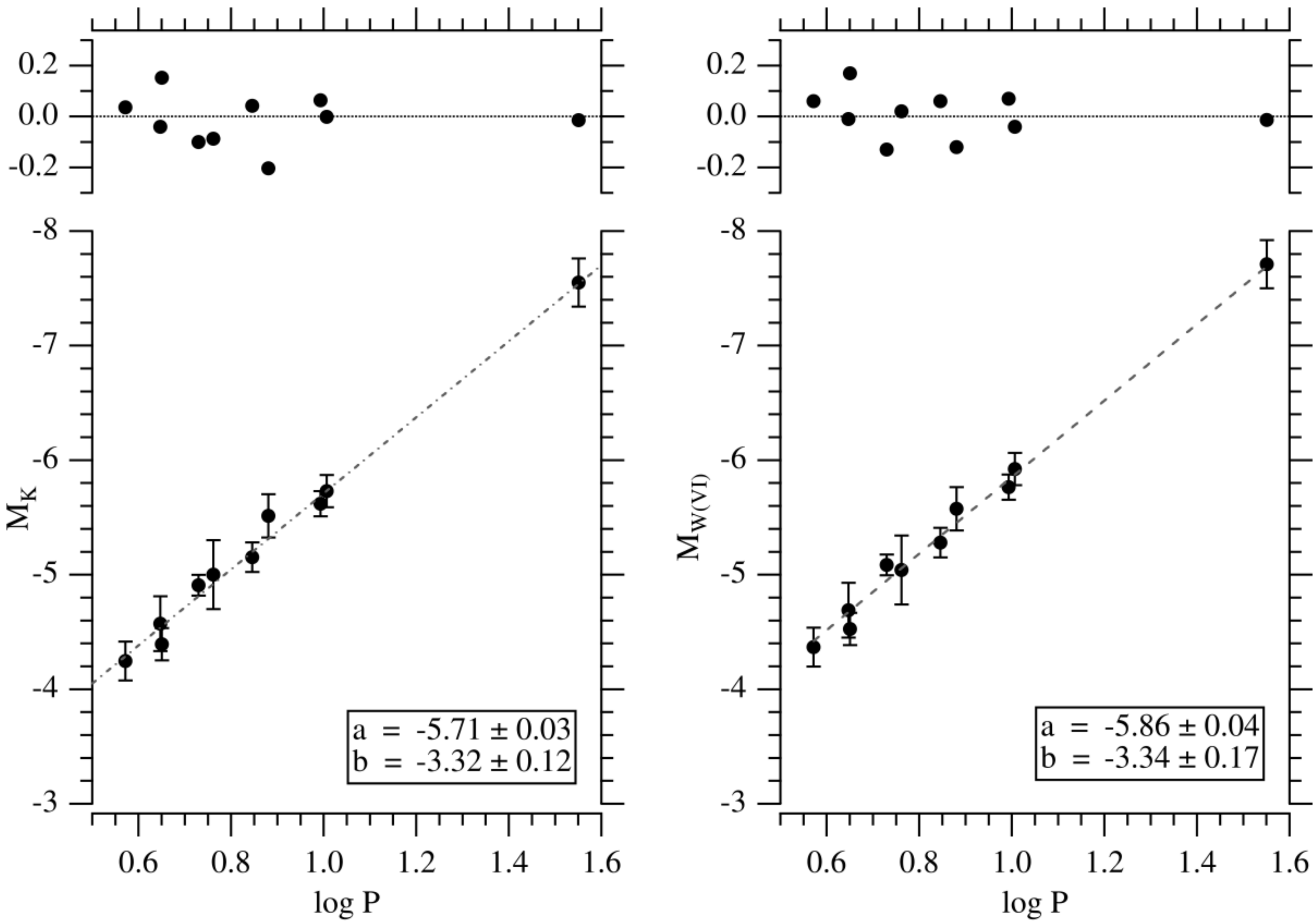
Absolute ZP

Two possibilities

1) Individual distances to Cepheids (Parallax, BW)

2) Distance to a galaxy with Cepheids obtained with other technique (LMC, NGC 5248)

Benedict et al. 2007, Freedman et al. 2013



Individual distances

Paralaxes:

Hipparcos: Feast and Catchpol 1997 van Leeuven 1999: 10 Cepheids

HST parallaxes Benedict 10 Cepheids

Scaning mode HST Cassertano et al.

Gaia first intents

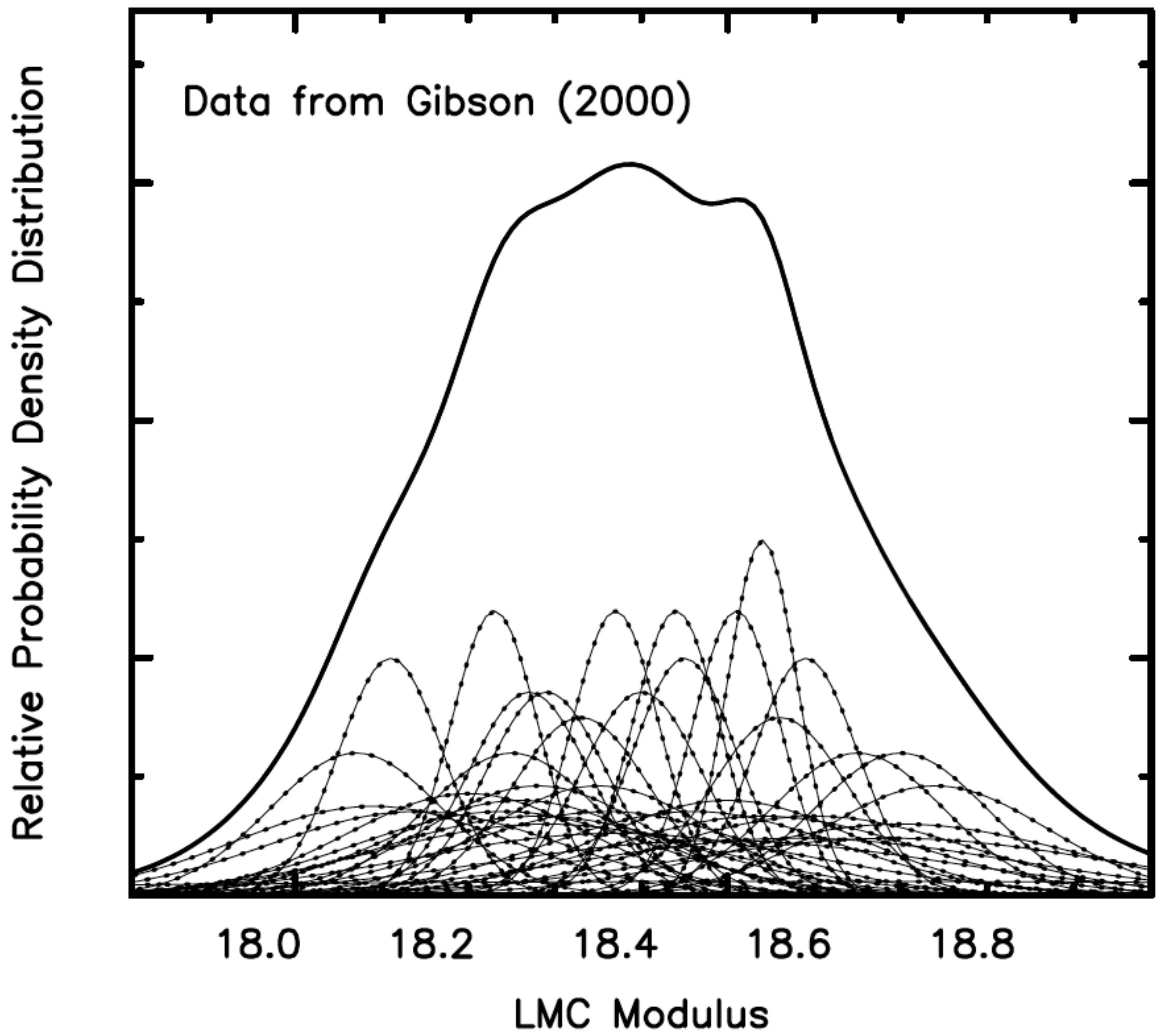
BW method a bit later (5%)

Still a lot of problems with systematics ...

HST Key Project

Assumed not measured LMC distance (10-15 % error)

(long lasting discussion about long versus short distance scale)



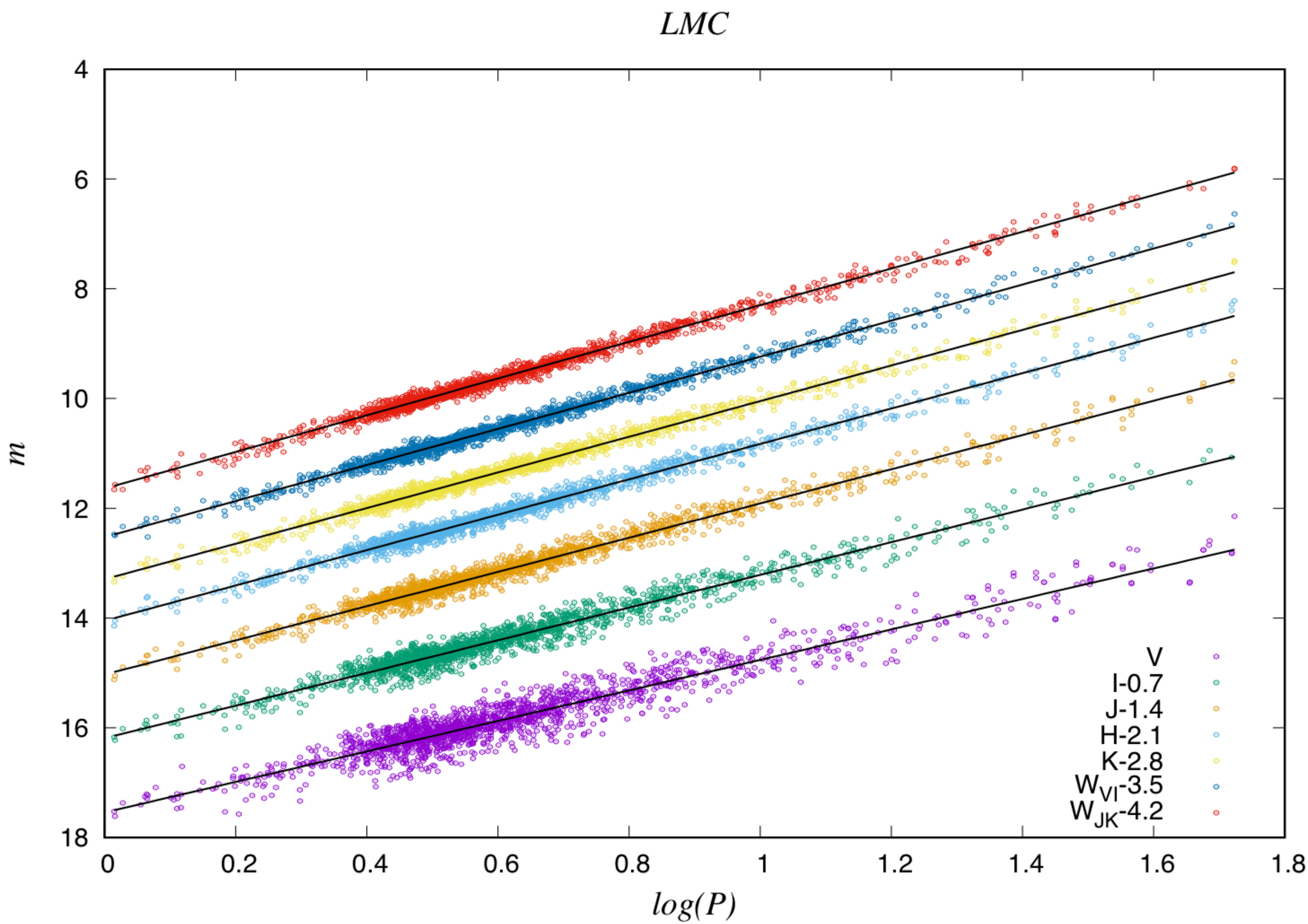
Distances to other galaxies

LMC HST Key project 10% 2001

LMC 1% Pietrzynski et al. 2019

NGC 4852 Reid et al. 2019 1.5% maser distance

Some people try to combine these determination to improve precision of the ZP − caution !



LMC
m
log(P)
4
6
8
10
12
14
16
18
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
V
I-0.7
J-1.4
H-2.1
K-2.8
W_VI-3.5
W_JK-4.2

Metallicity scales

$$Z = \sum_{i>\mathrm{He}} \frac{m_i}{M} = 1 - X - Y$$

Description	Solar value
Hydrogen mass fraction	$X_{\mathrm{sun}} = 0.7381$
Helium mass fraction	$Y_{\mathrm{sun}} = 0.2485$
Metallicity	$Z_{\mathrm{sun}} = 0.0134$

$$[\mathrm{Fe}/\mathrm{H}] = \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\mathrm{star}} - \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\mathrm{sun}}$$

HII regions:

$$R_{23} = \frac{[\mathrm{O\ II}]_{3727\ \text{Å}} + [\mathrm{O\ III}]_{4959\ \text{Å}+5007\ \text{Å}}}{\mathrm{H}_\beta}$$

$$S_{23} = \frac{[\mathrm{S\ II}]_{6716\ \text{Å}+6731\ \text{Å}} + [\mathrm{S\ III}]_{9069\ \text{Å}+9532\ \text{Å}}}{\mathrm{H}_\beta}$$

Metallicity effect

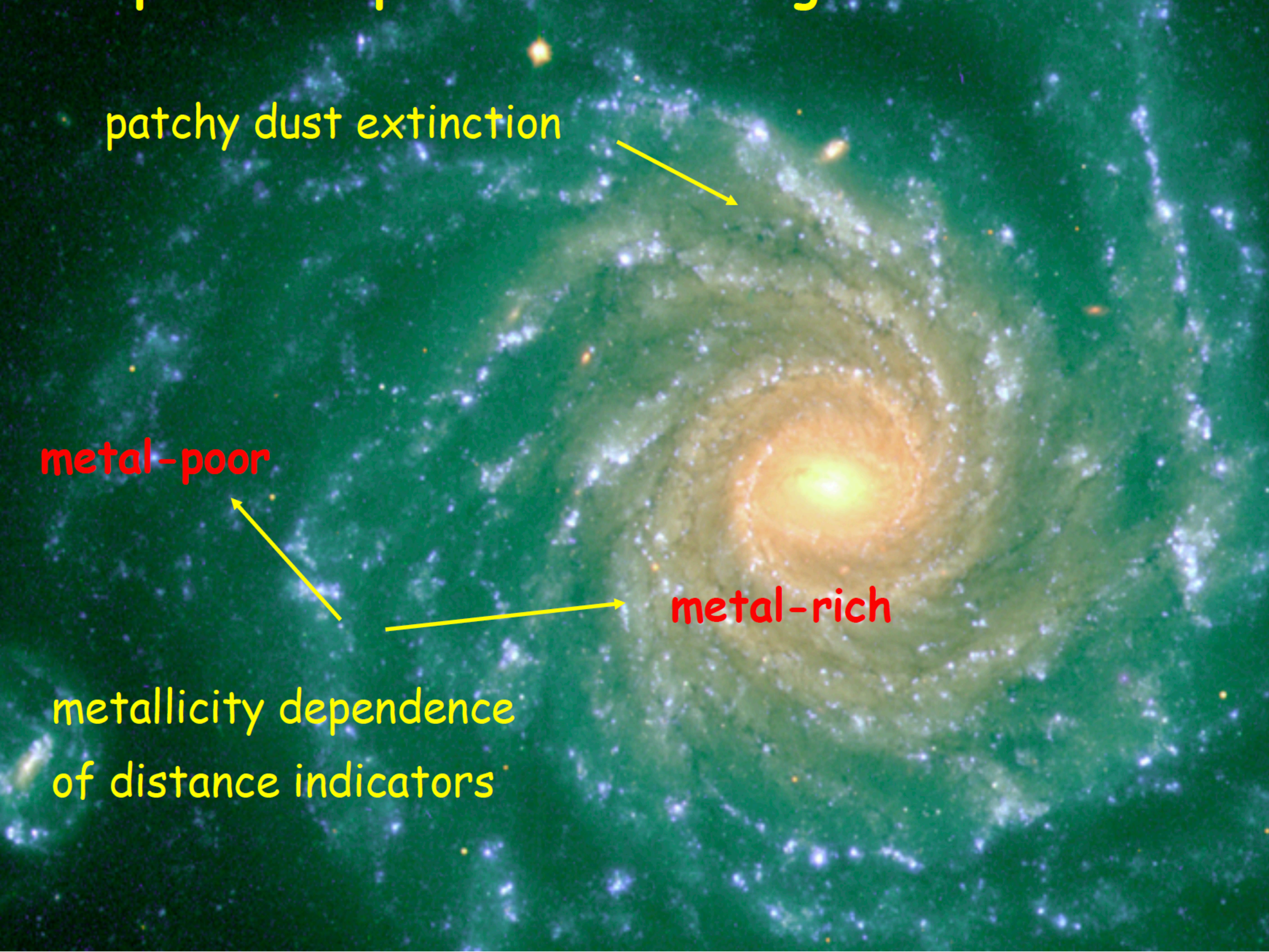
$$\Delta M = \gamma[\mathrm{Fe/H}] + \psi$$

Emprical (we need absolute or relative distances and matallicities)

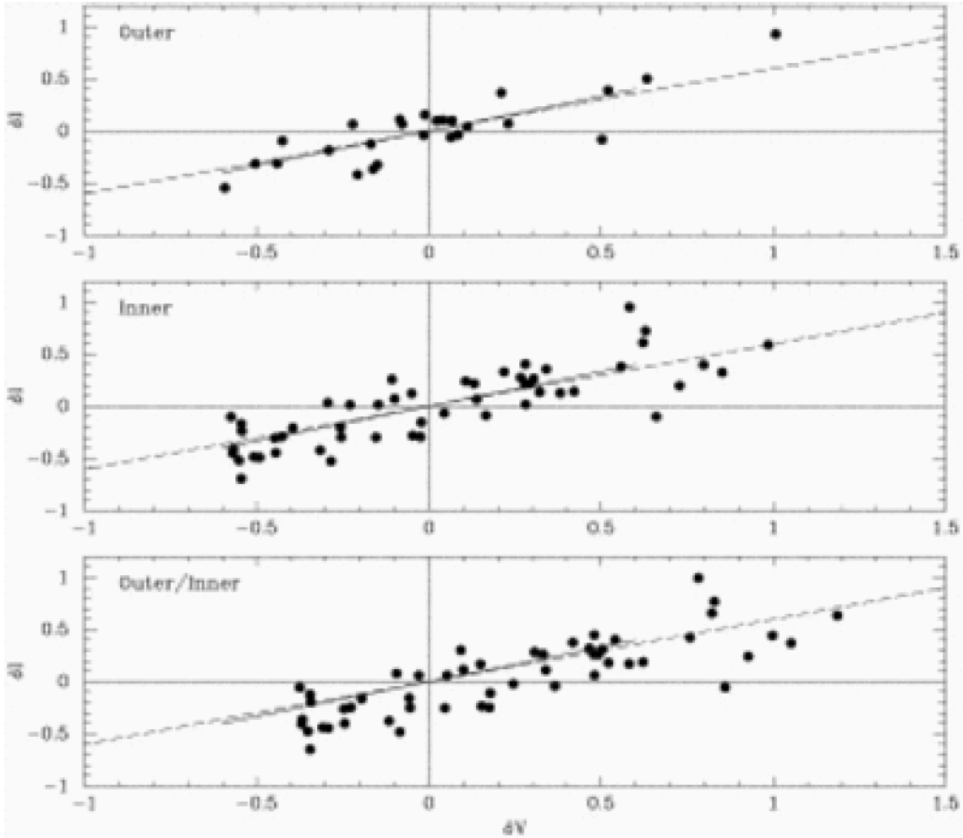
Using geometrical distances to nearby Cepheids / galaxies (parallaxes, eclipsing binaries, BW)

Or comparing with other standard candles (TRGB)

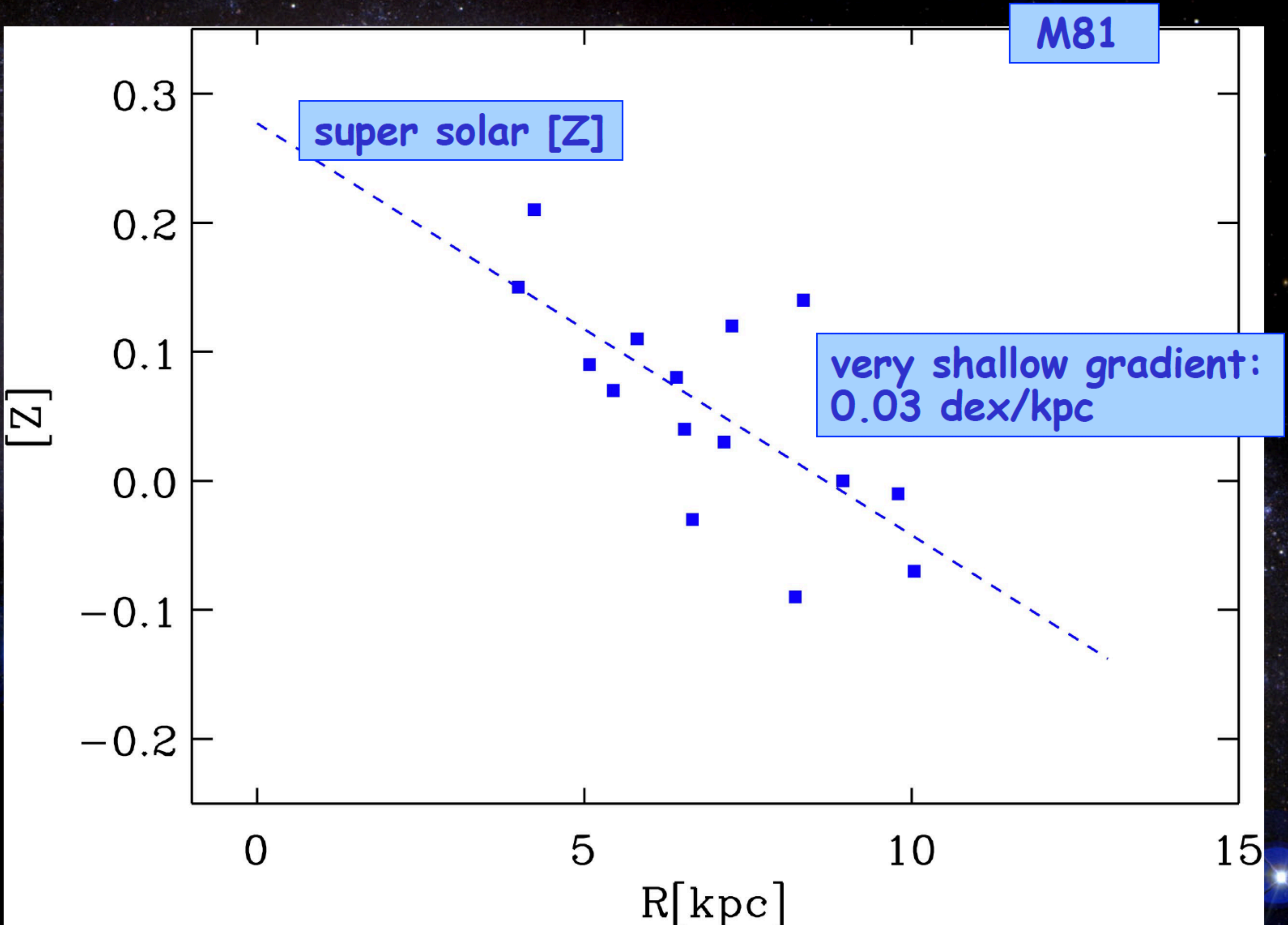
Theoretical (stellar evolution models)


patchy dust extinction
metal-poor
metal-rich
metallicity dependence
of distance indicators

M101, M81, M33, NGC 4852

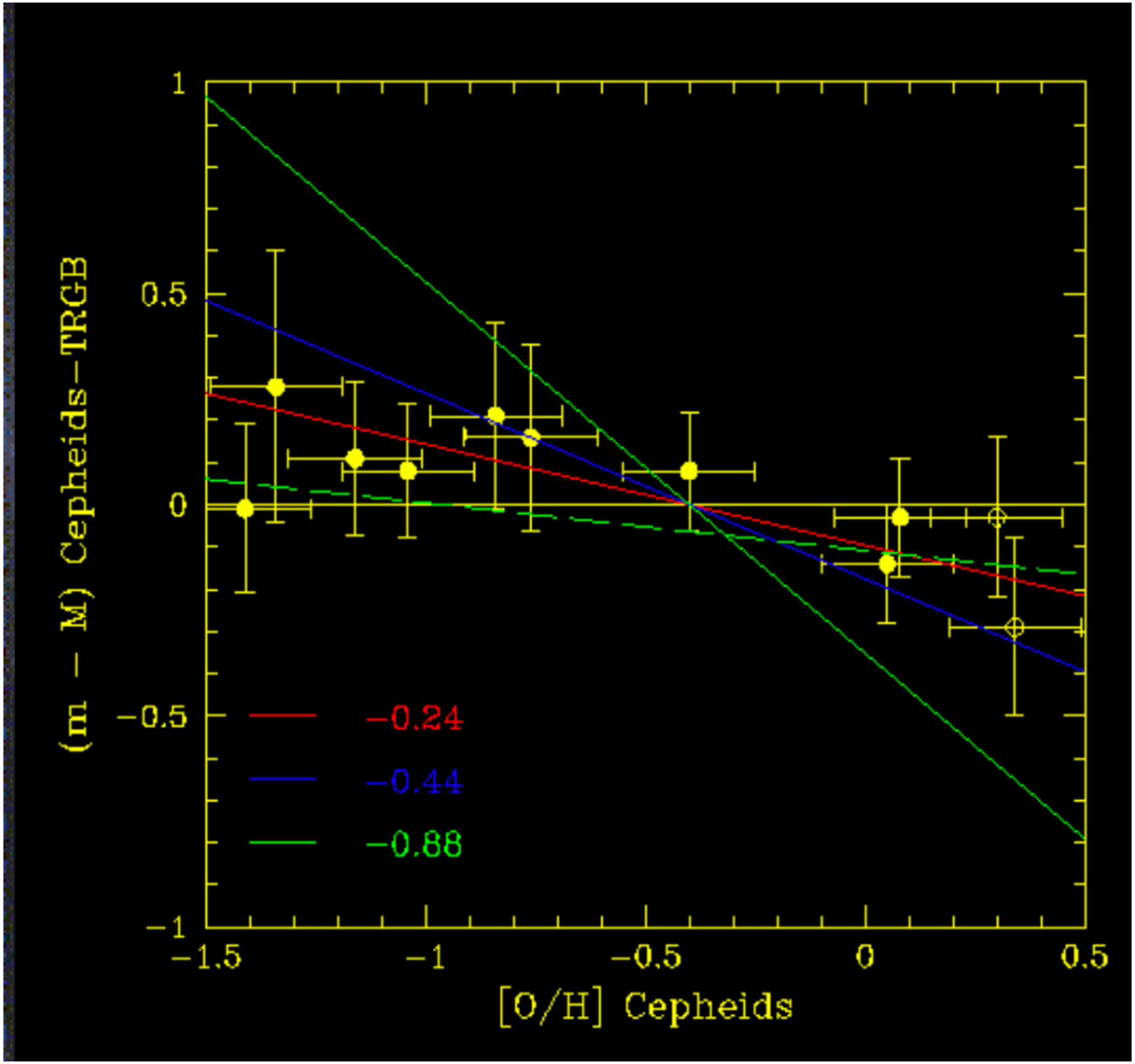


$\delta(M_V) = (-0.24 \pm 0.16) \times [Fe/H]$ Kennicutt et al. 1998

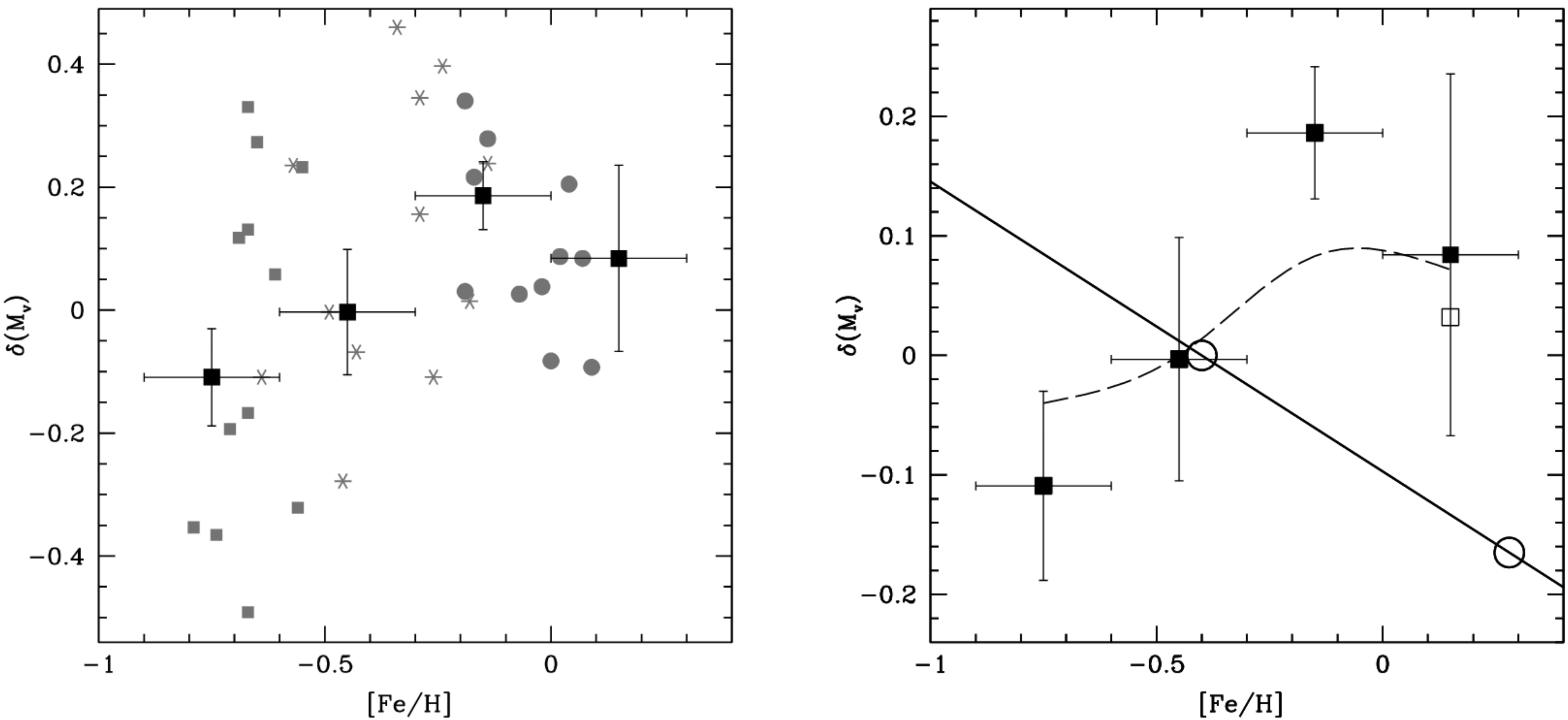


Kudritzki, Urbaneja, Gazak et al., 2012, ApJ 747, 15

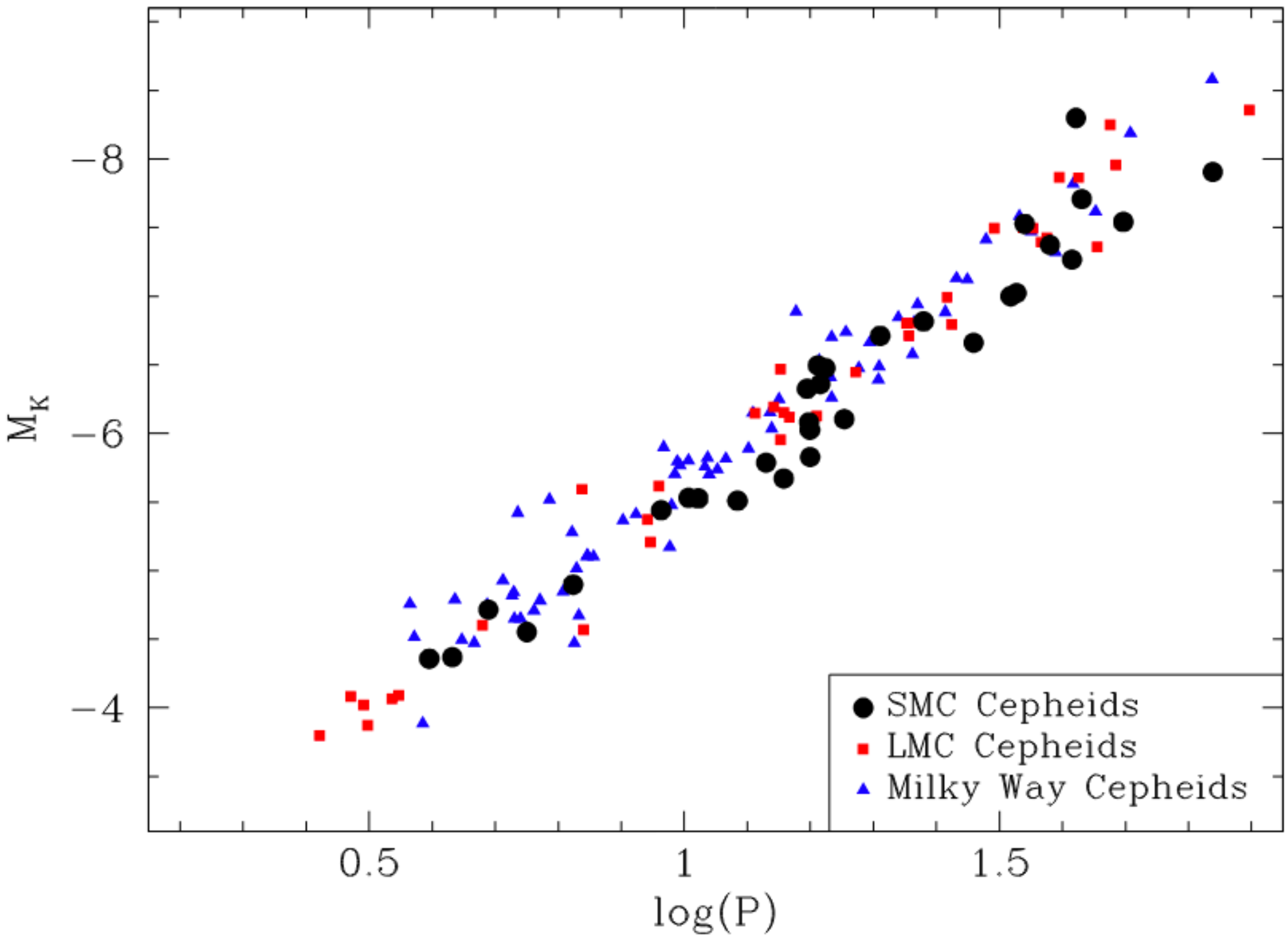
Cepheids vs TRGB

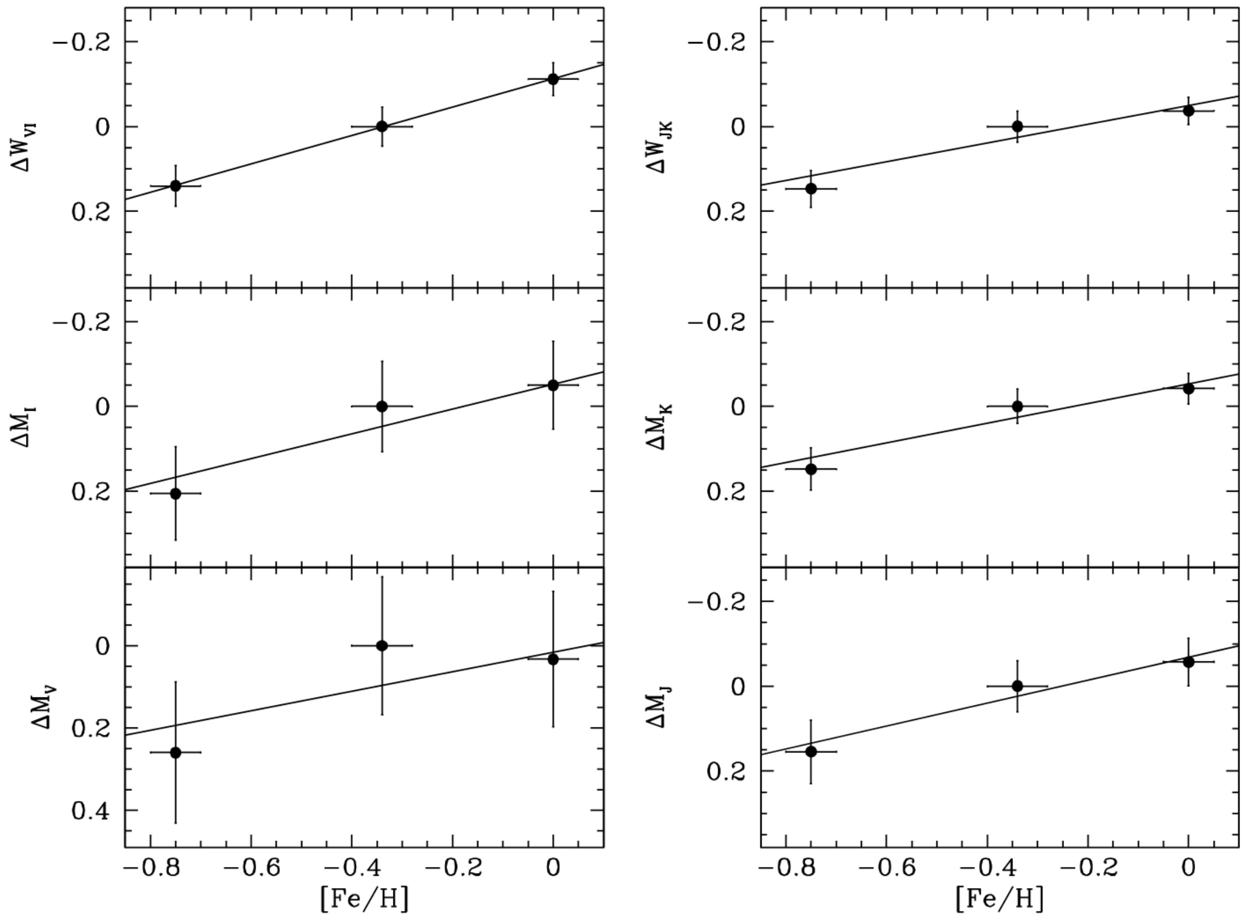


HR high S/N spectra => direct [Fe/H]
Romaniello et al. 2005



BW method: MW, LMC, SMC





Band	γ	$\sigma(\gamma)$	ψ	$\sigma(\psi)$
M_J	−0.270	0.108	−0.068	0.044
M_K	−0.232	0.064	−0.054	0.024
W_{JK}	−0.221	0.053	−0.049	0.019
M_V	−0.238	0.186	0.016	0.111
M_I	−0.293	0.150	−0.053	0.076
W_{VI}	−0.335	0.059	−0.113	0.023
	mag/dex	mag/dex	mag	mag

Comparing with eclipsing binaries

$$\gamma = \frac{\Delta(m-M)_0^{cep} - \Delta(m-M)_0^{ecl}}{\Delta[Fe/H]}$$

Filter	R_λ	$\Delta(m-M)$	$\Delta(m-M)_0^{cep}$	$\Delta(m-M)_0^{cep} - \Delta(m-M)_0^{ecl}$	γ
V	3.134	0.340 ± 0.017	0.481 ± 0.017	0.009 ± 0.031	-0.022 ± 0.076
I	1.894	0.393 ± 0.012	0.478 ± 0.012	0.006 ± 0.029	-0.015 ± 0.071
J	0.892	0.449 ± 0.010	0.489 ± 0.010	0.017 ± 0.028	-0.042 ± 0.069
H	0.553	0.452 ± 0.009	0.477 ± 0.009	0.005 ± 0.028	-0.012 ± 0.069
Ks	0.363	0.463 ± 0.008	0.479 ± 0.009	0.007 ± 0.028	-0.017 ± 0.069
W_{VI}	-	-	0.482 ± 0.008	0.010 ± 0.027	-0.025 ± 0.067
W_{JKs}	-	-	0.481 ± 0.008	0.009 ± 0.027	-0.022 ± 0.067

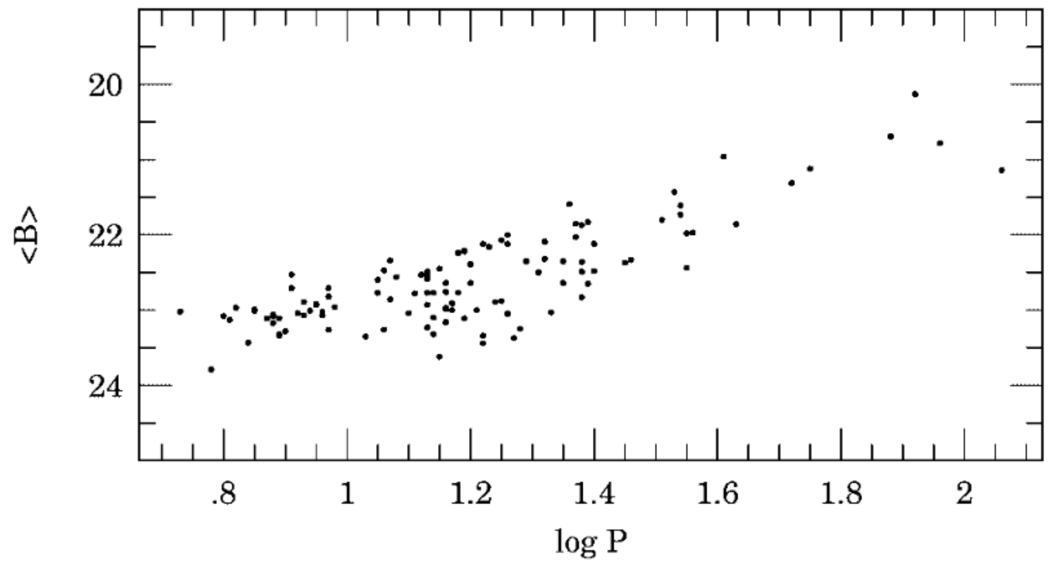
Wielgorski et al. 2017 (waiting for better mean distance to the SMC and precision Gaia parallaxes)

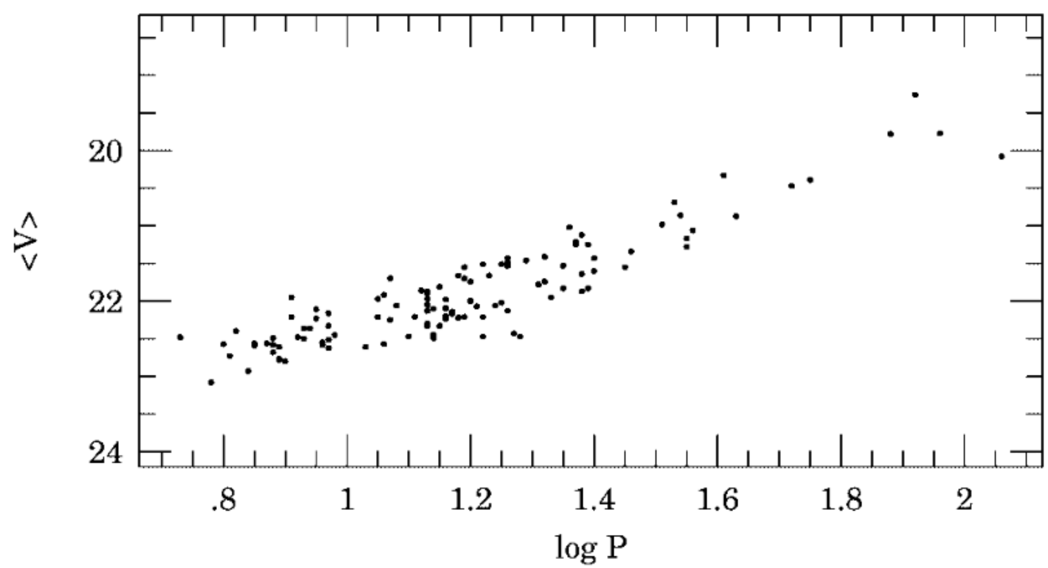
Theoretical results

In most cases in the line of Romaniello et al. results.

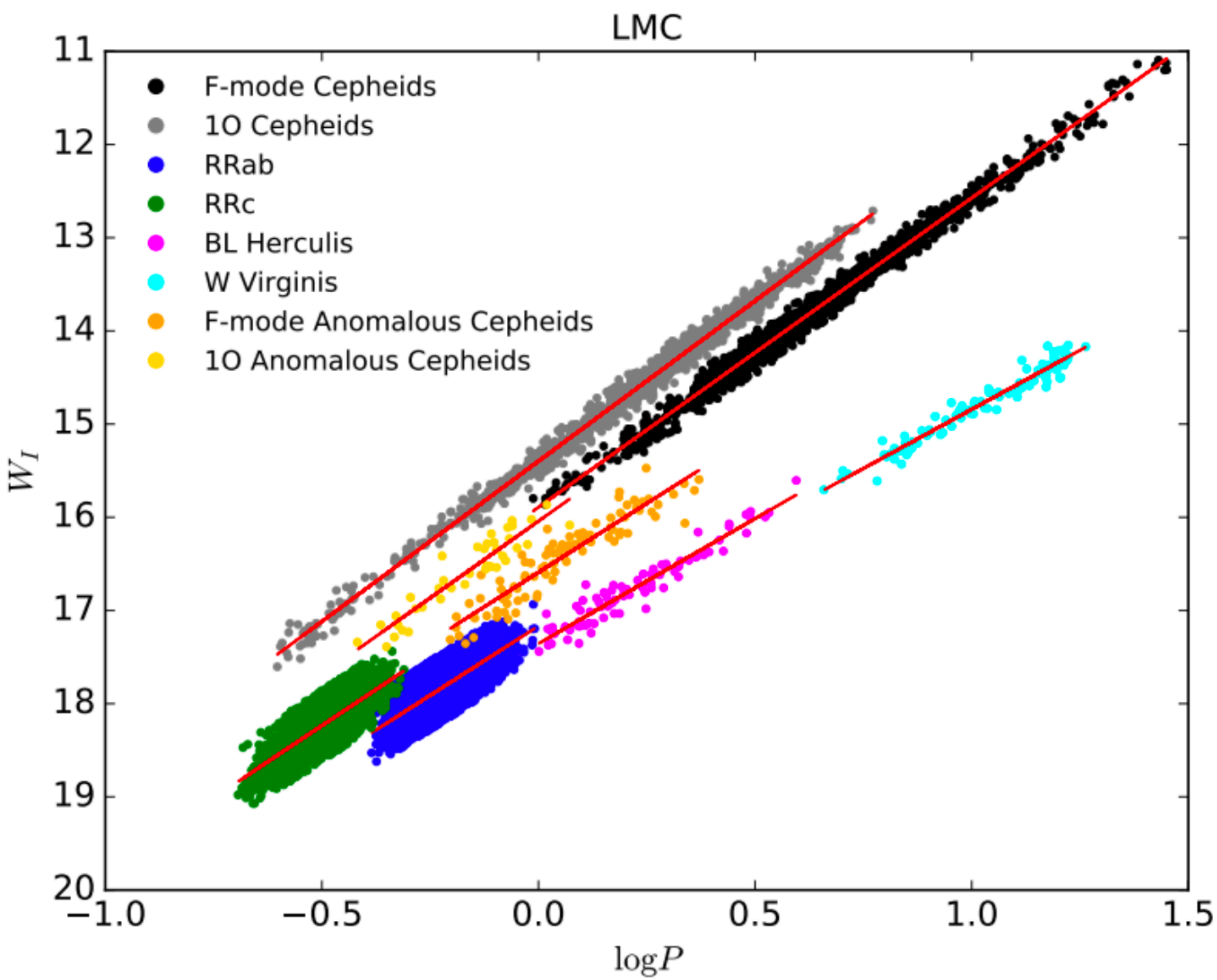
In general a wide range of metallicity effects can be found in the literarute (e.g. Bono 2000)

Malmquist bias

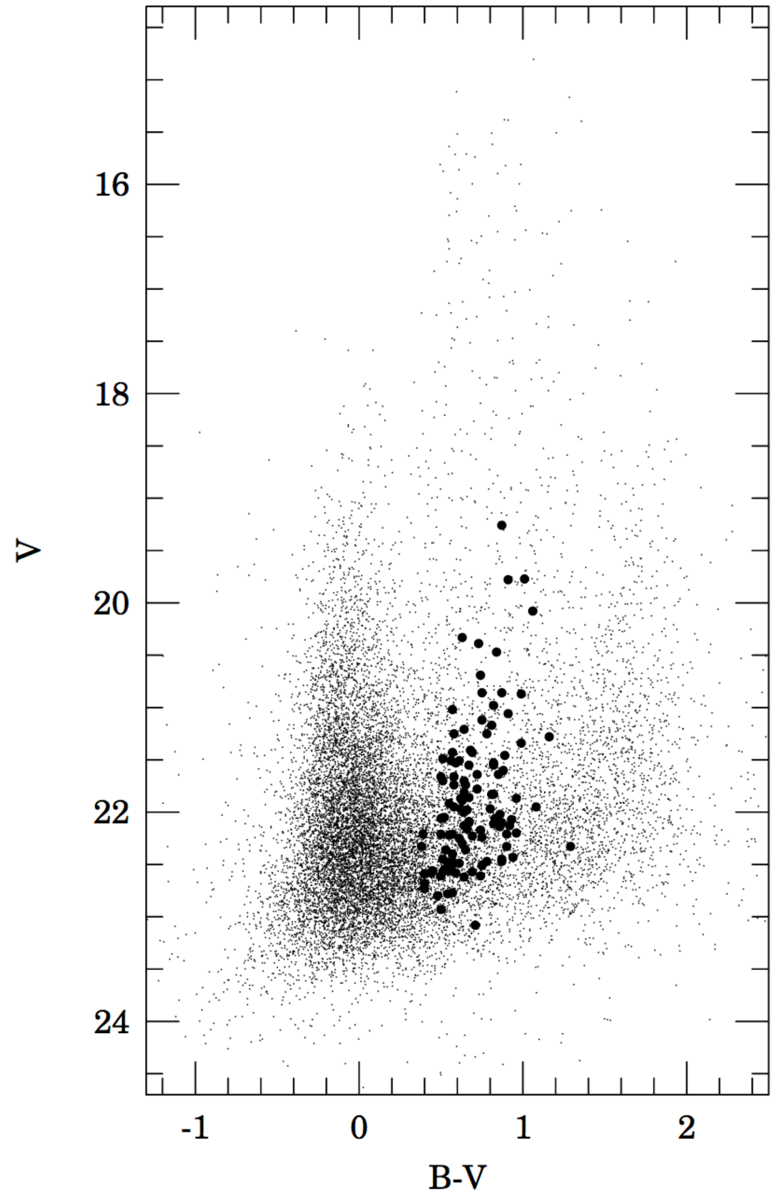




Distinguish FU (FO, Type II etc)



Uniform distribution in the IS



Is Cepheid P-L universal

In most galaxies we can only check stability of the slope of the P-L (precision 0.2). Within this precision 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.

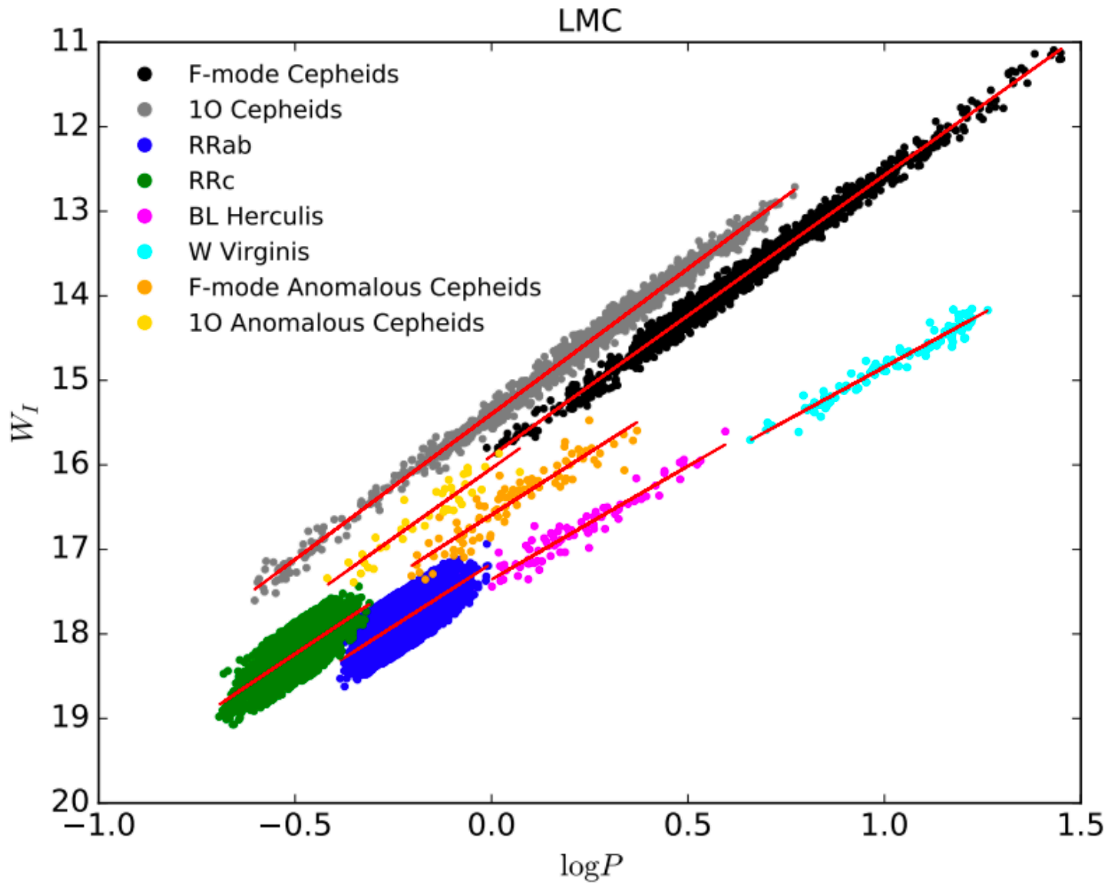
Several people reported breaks at 20d, 80d etc. Not confirmed so far.

Using Cepheids 10d < P < 100d

Reaasonable because we can avoid problems:

1) Breaks in P-L relations

2) Influence of FO Cepheids

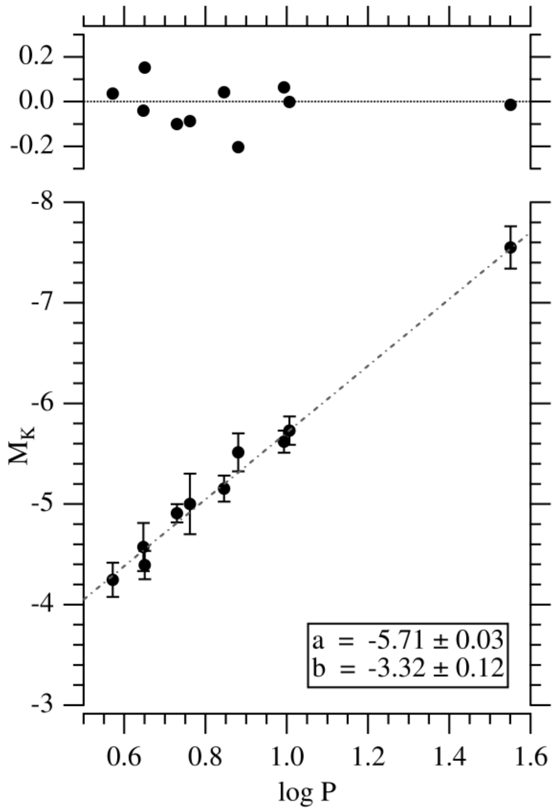


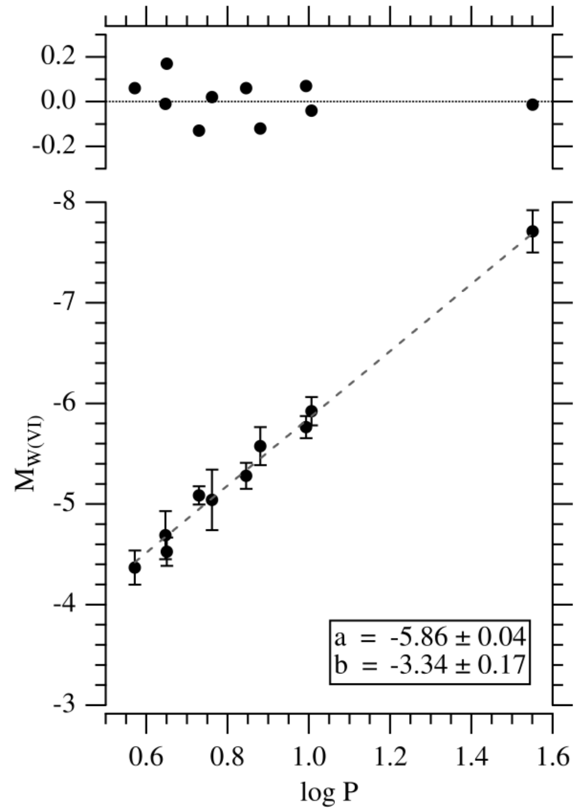
Using Cepheids 10d < P < 100d

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

Not sure about breaks at other periods in other galaxies

Then calibration for short period MW Cepheids is used





Blending / crowding

Mochejska et al.

Udalski et al. 199X   astro-ph

Bresolin et al. 2XXX

Anderson et al. XXX

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

Not metallicity, so WHAT ? Blending ?