Cepheid variables

Stellar Pulsation and the Distance Scale

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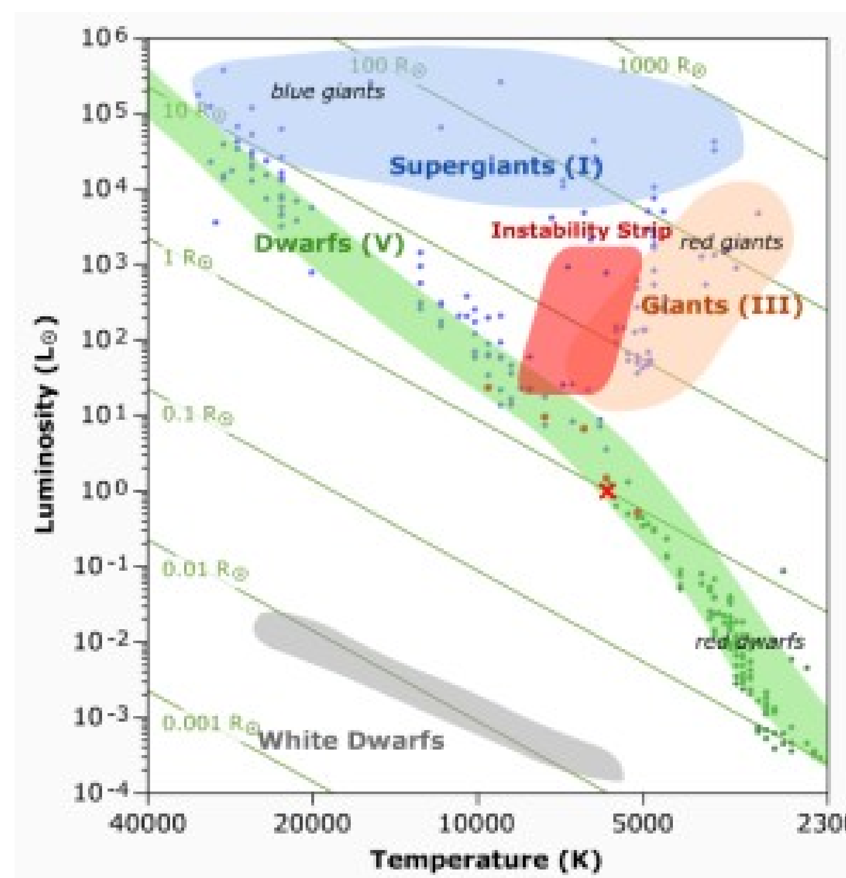
Cepheid variables

- Radially pulsating variables
- Classical or Type I Cepheids : Young, Pop I, massive, metal-rich stars
- Type II Cepheids : Old, Pop II, low-mass and metal-poor stars

- **Why are they important?**
- *Period-Luminosity relation*
- Classical Cepheids are Primary distance indicators
- Stellar tracers of extinction, metallicity and structure of the host galaxy
- *For understanding the theory of stellar pulsation and evolution*



Light curve analysis

- To explore constraints for stellar pulsation models
- A quantitative comparison of theoretical and observed Cepheid light curves at multiple wavelengths in the Galaxy and Magellanic Clouds

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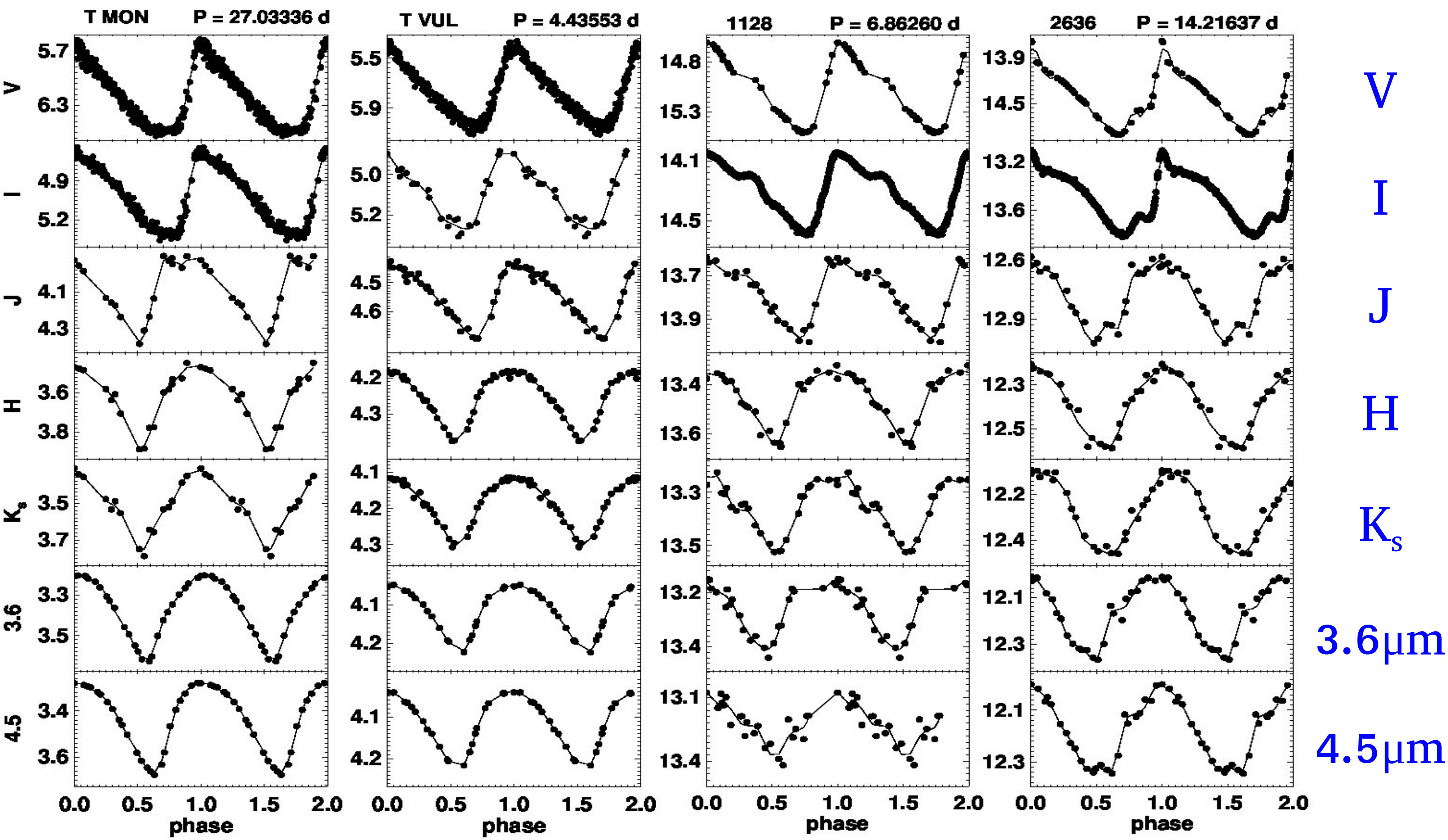
- *Fourier decomposition and Principal component analysis of Cepheid light curves*

Cepheid Light Curves



Milky Way

LMC

Bhardwaj et. al (2015)

Fourier analysis

- Fourier sine series is applied to periodic light curves -

$$m = m_0 + \sum_{k=1}^{N} A_k \sin(2\pi k x + \phi_k)$$

Observations Mean magnitudes Phase

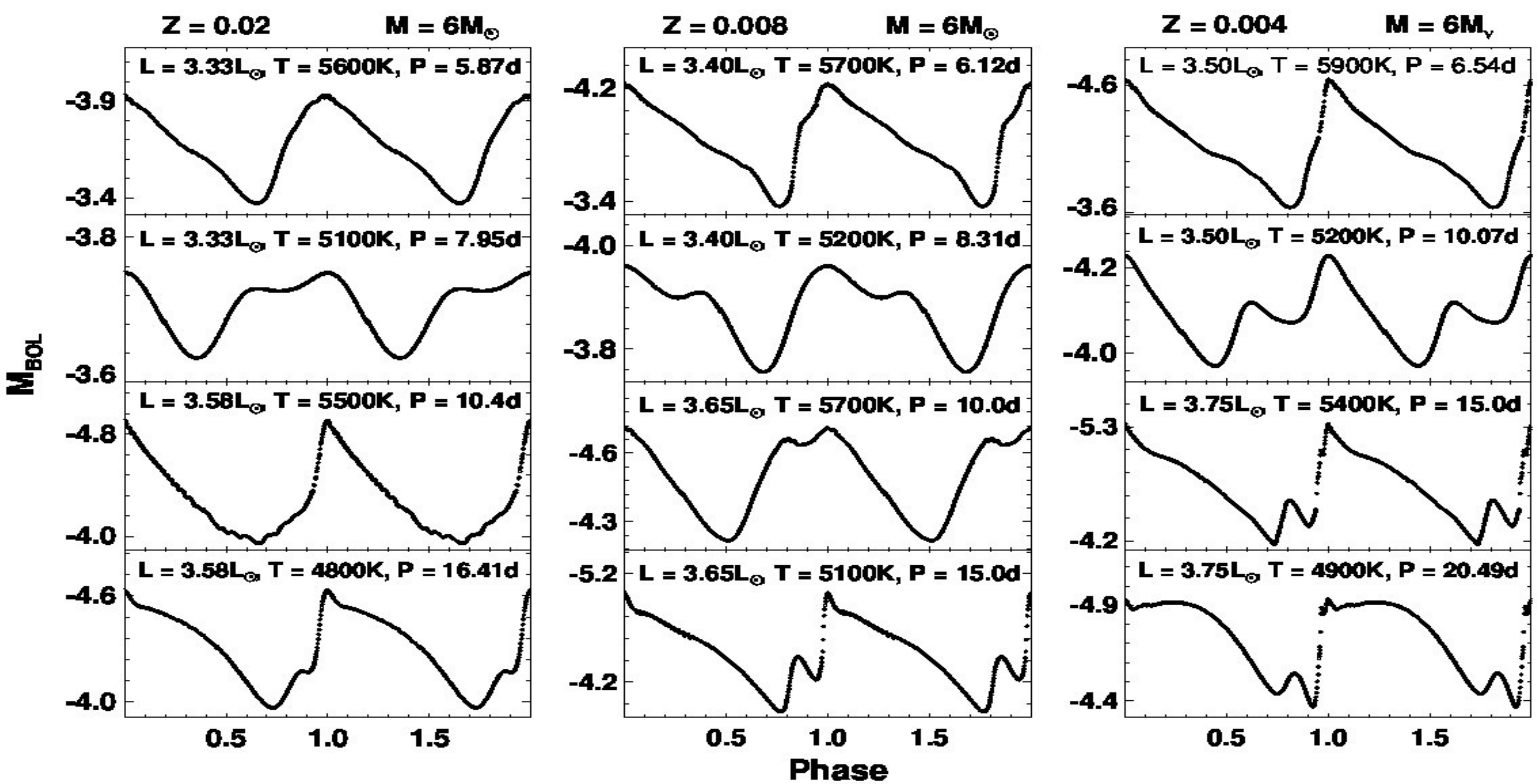
Fourier parameters for $k > 1$ -

$$R_{k1} = \frac{A_k}{A_1}; \phi_{k1} = \phi_k - k\phi_1$$

Amplitude ratios Phase differences

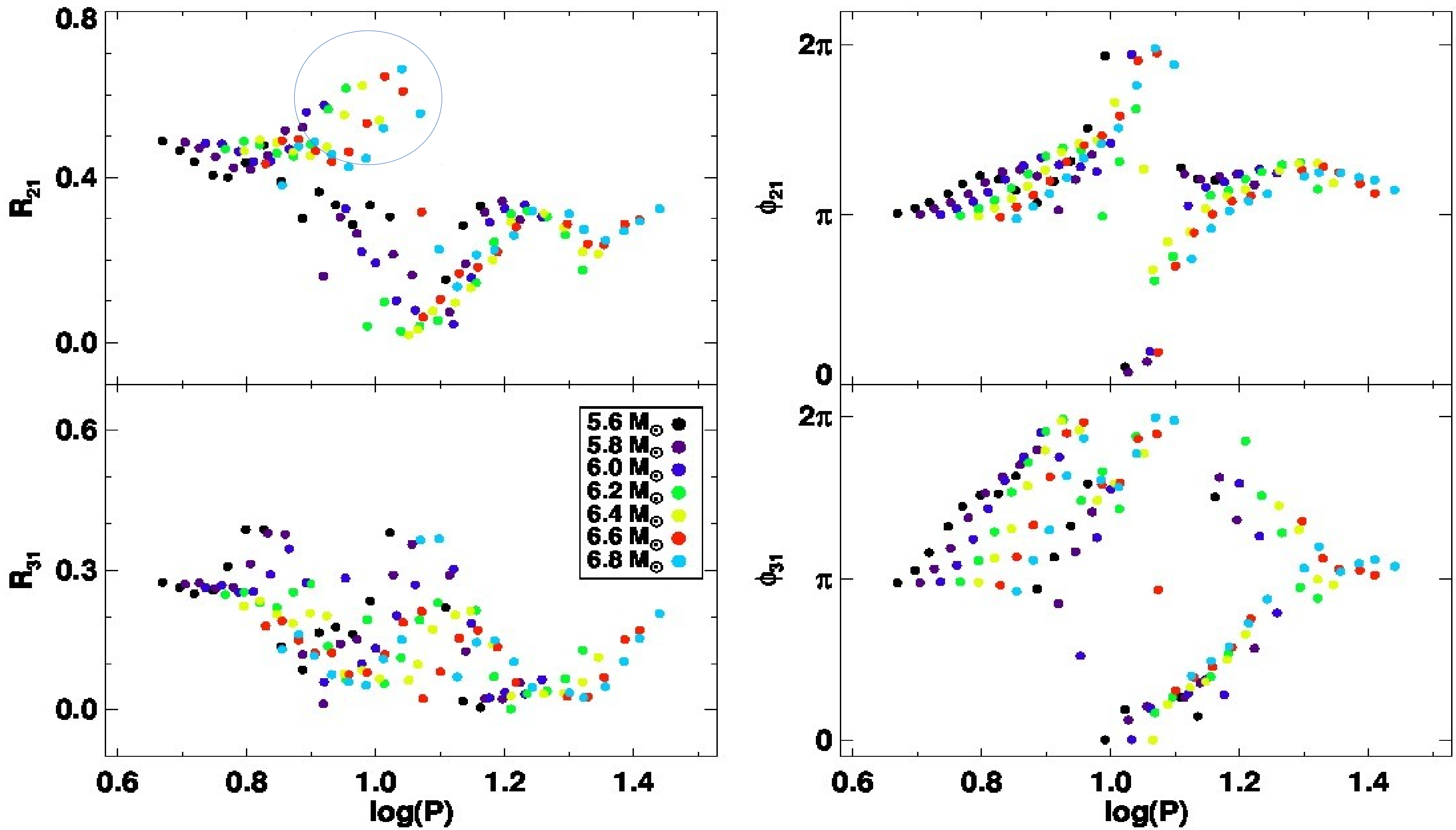
Theoretical light curves *(Marconi et al. 2013)*

- For a fixed chemical composition and mass-luminosity (M-L) levels from:
  - Stellar evolutionary calculations - Canonical M-L relations
  - Brighter luminosity levels by 0.25 dex - Non-canonical M-L relations
- Explore wide range of temperatures – Width of the Instability strip
- Each model represents a uniqe combination of – X, Y, Z, M, L and T



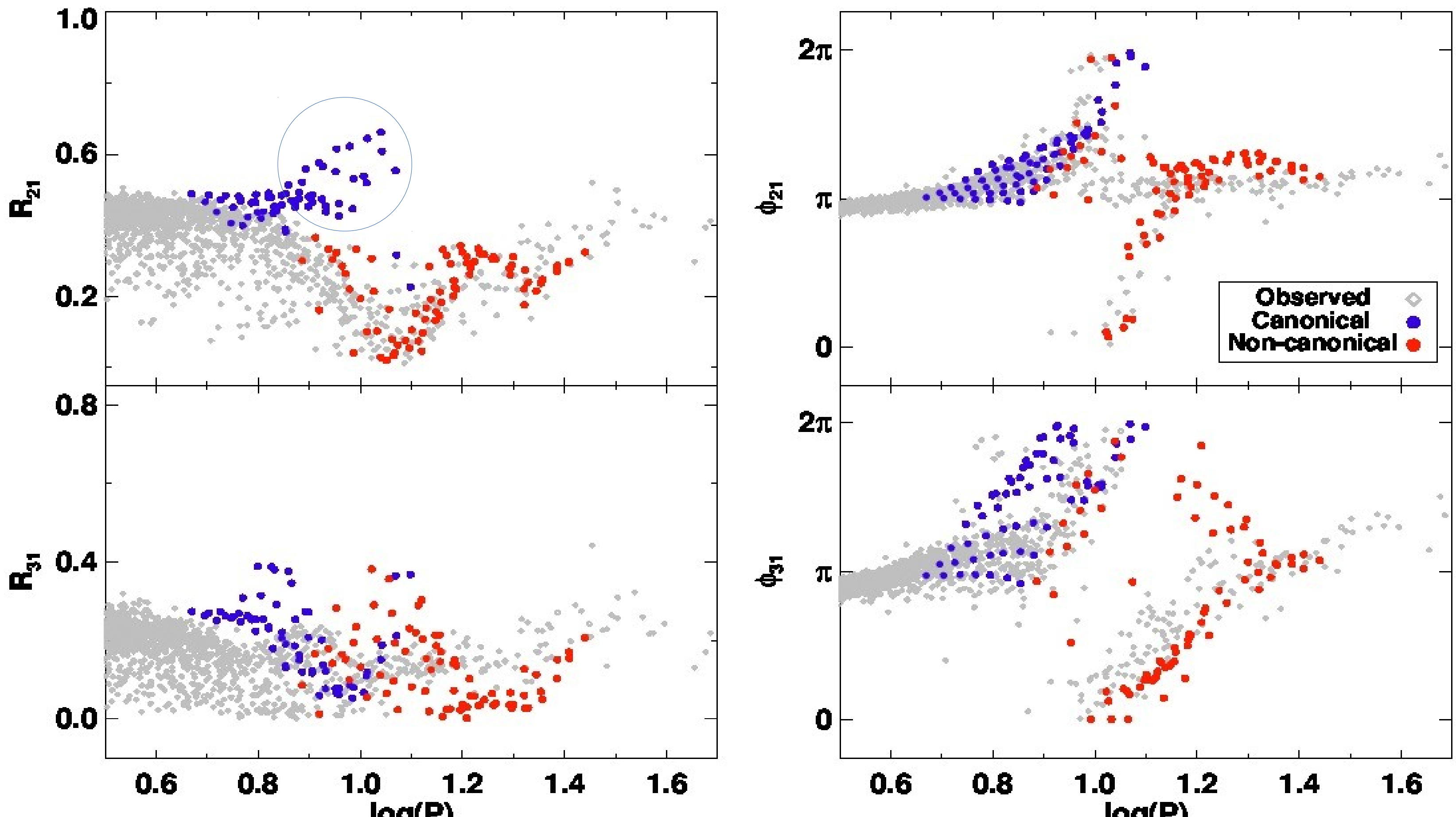
Theoretical Fourier parameters

- Cepheid models in the LMC (Y=0.25, Z=0.008)
- Transformation of bolometric magnitudes to multiple bands
- Fourier parameters in I-band



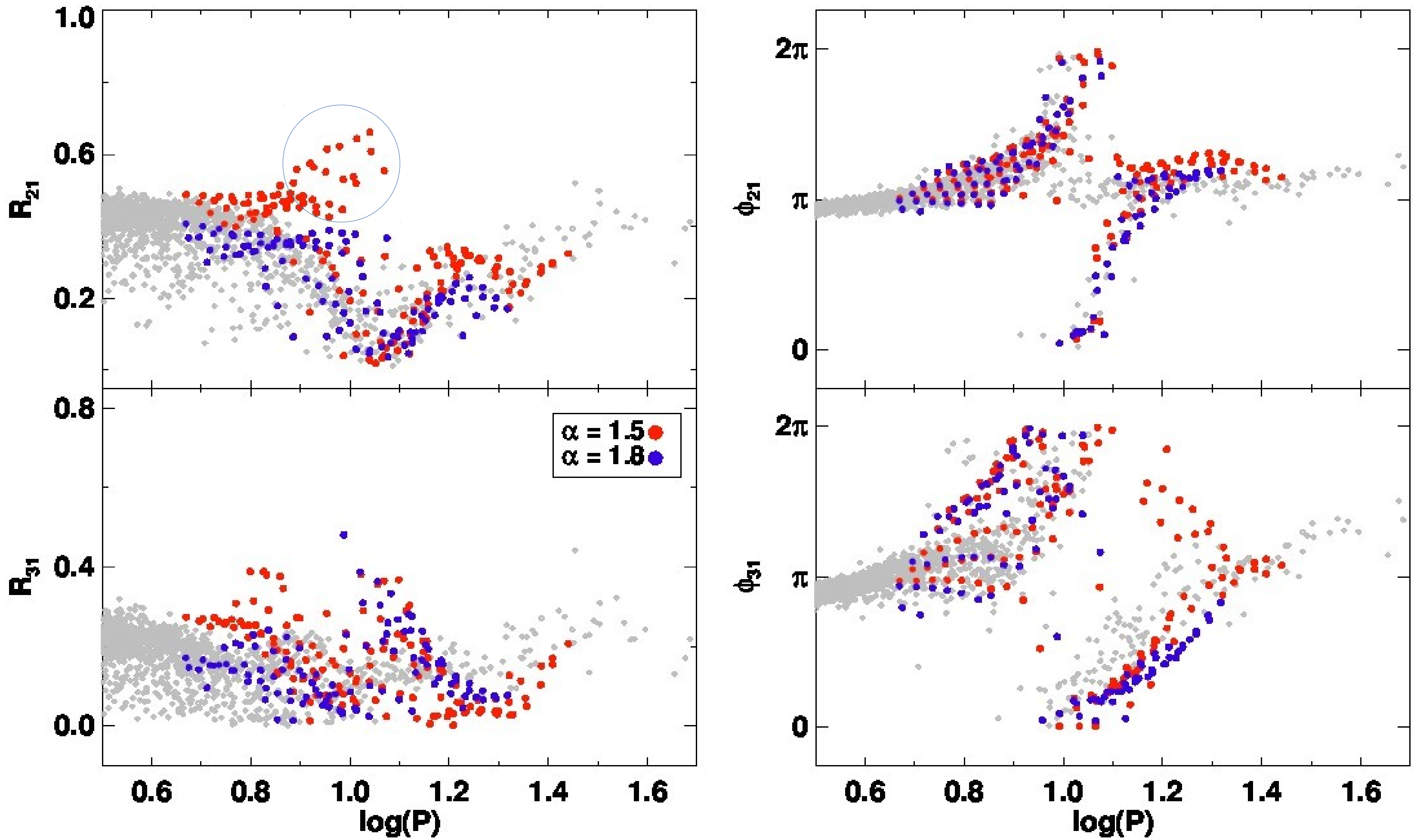
Observations vs. theory

- OGLE I-band LMC Cepheids vs. Cepheid models with Z=0.008
- Canonical set of models display large offset with respect to observations in amplitude parameters



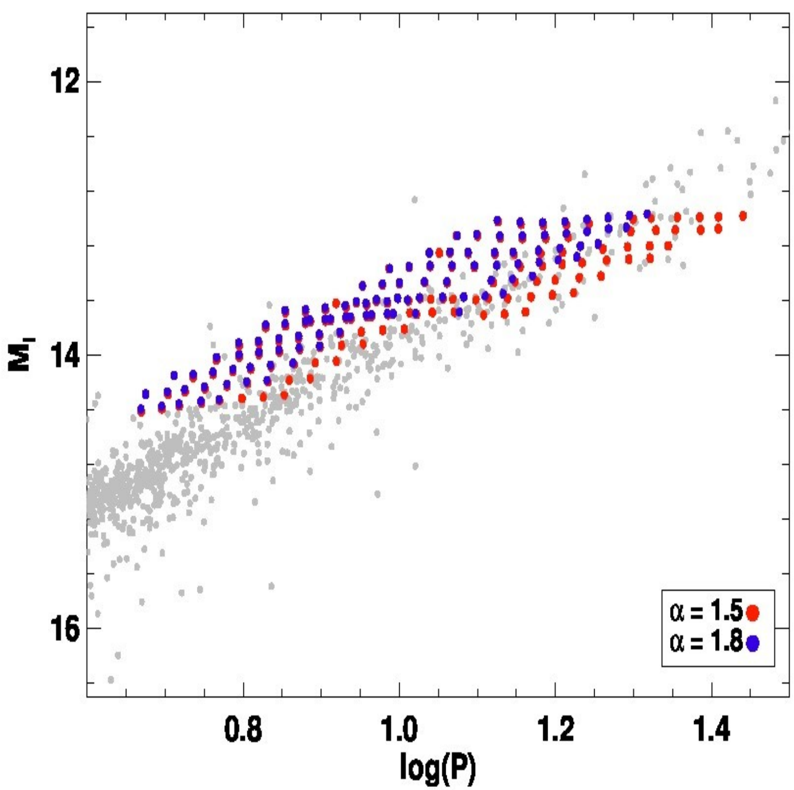
Mixing length parameter

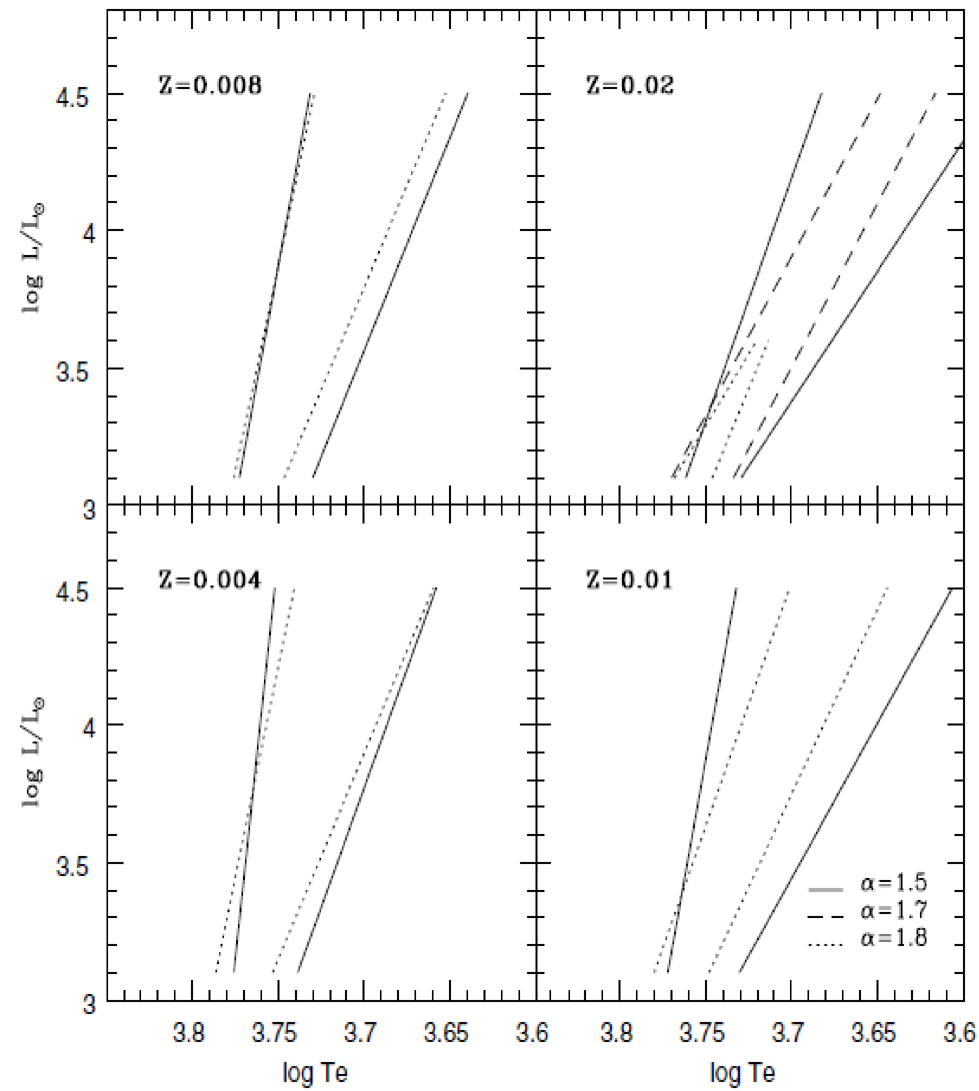
- Accounting for variation in the convective efficiency by increasing mixing length parameter
- A decrease in amplitude parameters



- Shift in slope and zero-point of P-L relations -

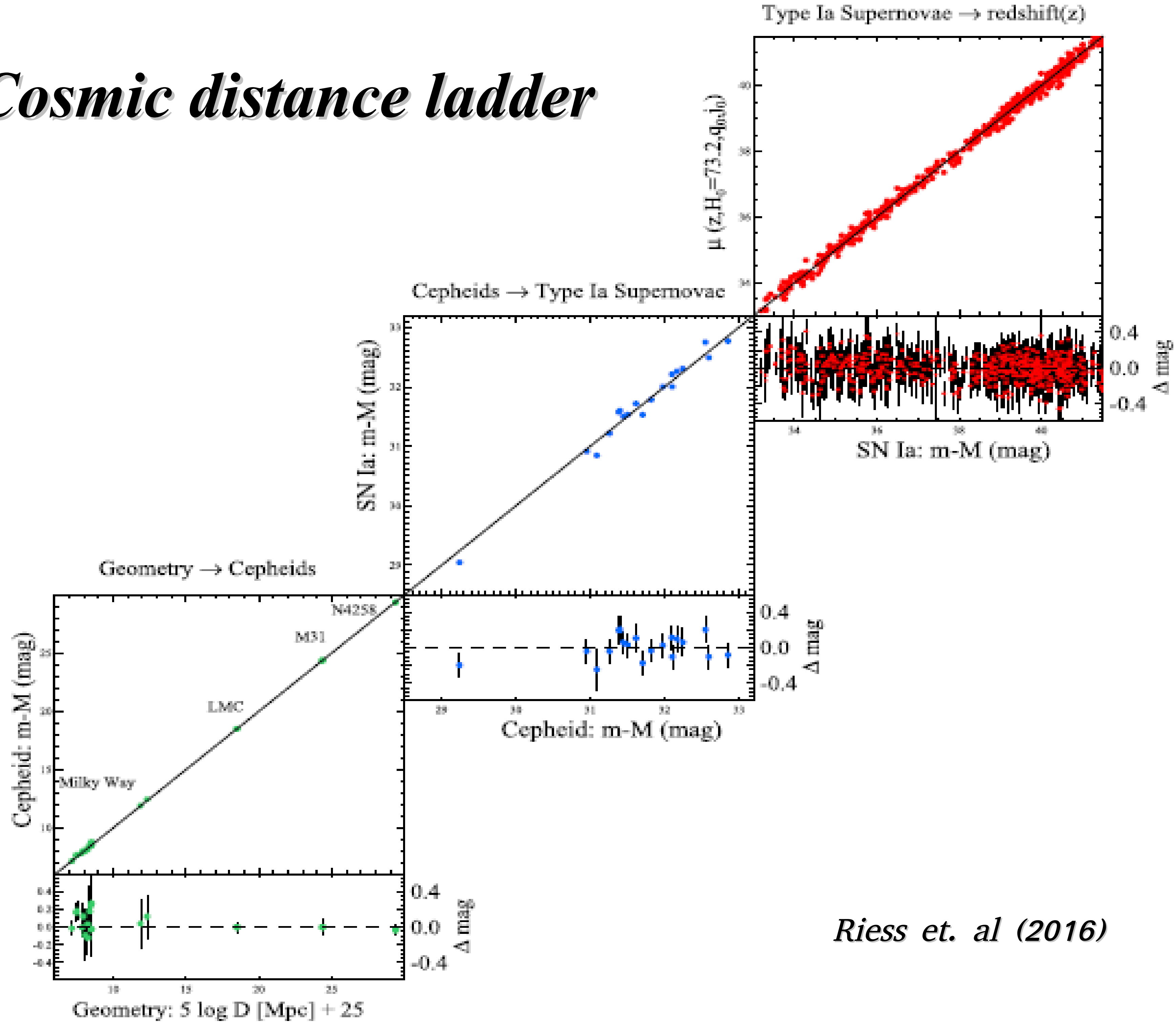
- Increasing mixing length narrows the width of the instability strip
- Red boundary gets bluer





See, Fiorentino et. al (2007)

Cosmic distance ladder



Riess et. al (2016)

Cepheids in the LMC synoptic survey

- Large Magellanic Cloud Near-Infrared Synoptic Survey (LMCNISS) *Macri et al., (2015)*

- Time-series observations (average of 16 epochs) of the central region covering 18 sq. deg. :- 1417 OGLE-III Cepheids

- Calibrated Cepheid P-L relations using LMC distance = 18.493±0.048, *Pietrzynski et al., (2013)*

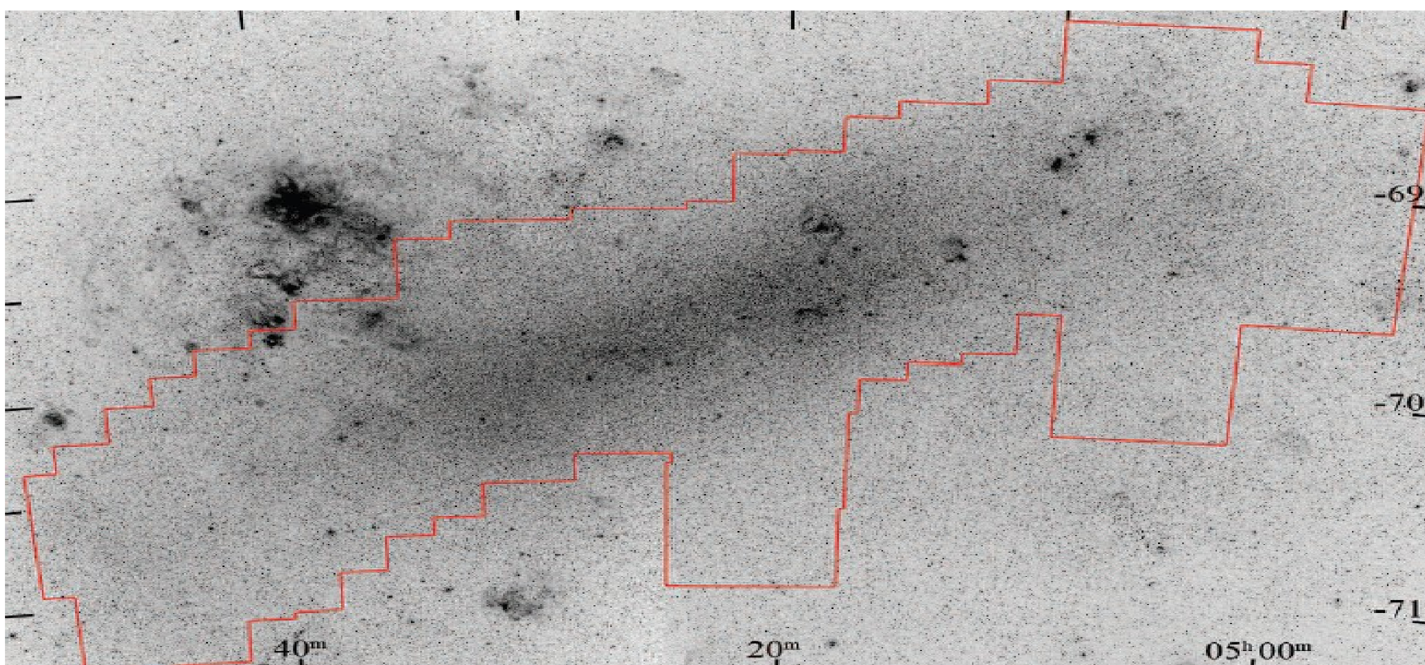


FIG. 1.— Digitized Sky Survey image of the Large Magellanic Cloud showing the area covered by our CPAPIR observations (red outline), which amounts to 18 sq. deg.

Period-Wesenheit relations

$$W_{\lambda_1,\lambda_2} = m_{\lambda_1} - \left[\frac{A_{\lambda_1}}{E(m_{\lambda_2} - m_{\lambda_1})}\right](m_{\lambda_2} - m_{\lambda_1})$$

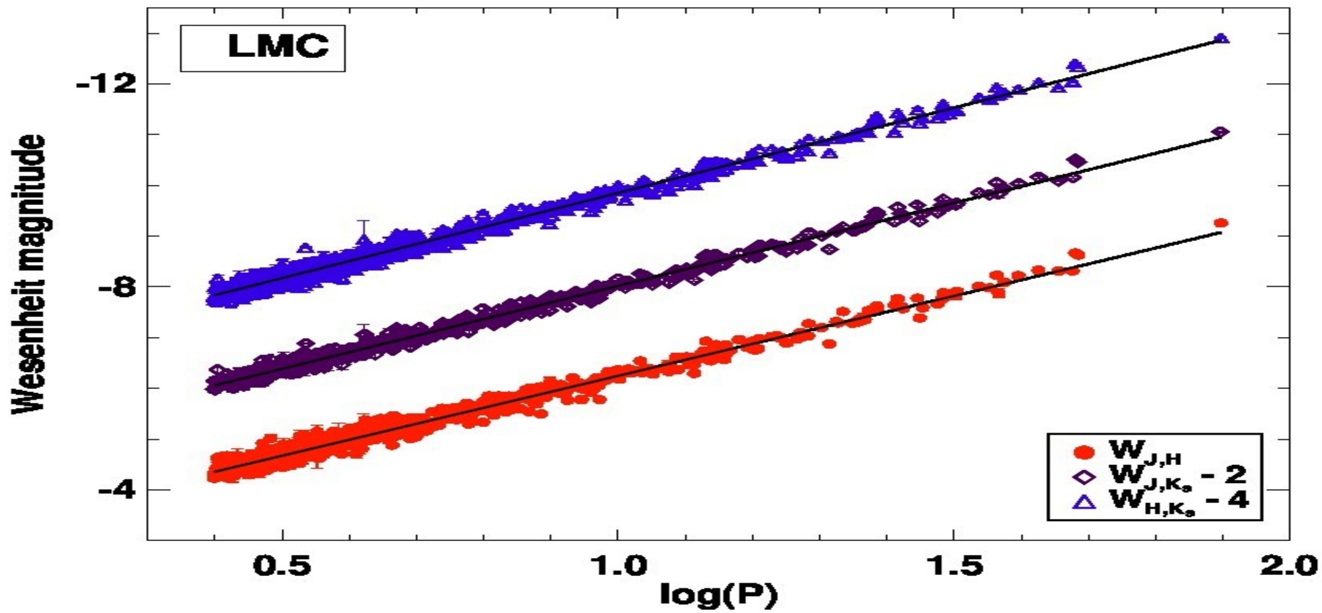
- $\lambda_1 > \lambda_2$
- *m* - apparent magnitude in a NIR band.
- Wesenheit functions *(Madore 1981)* are reddening independent.
- Term in square bracket is obtained using reddening law of *Cardelli et al. (1989)*.
- Wesenheit magnitudes :-

$$W_{J,H} = H - 1.63(J - H)$$

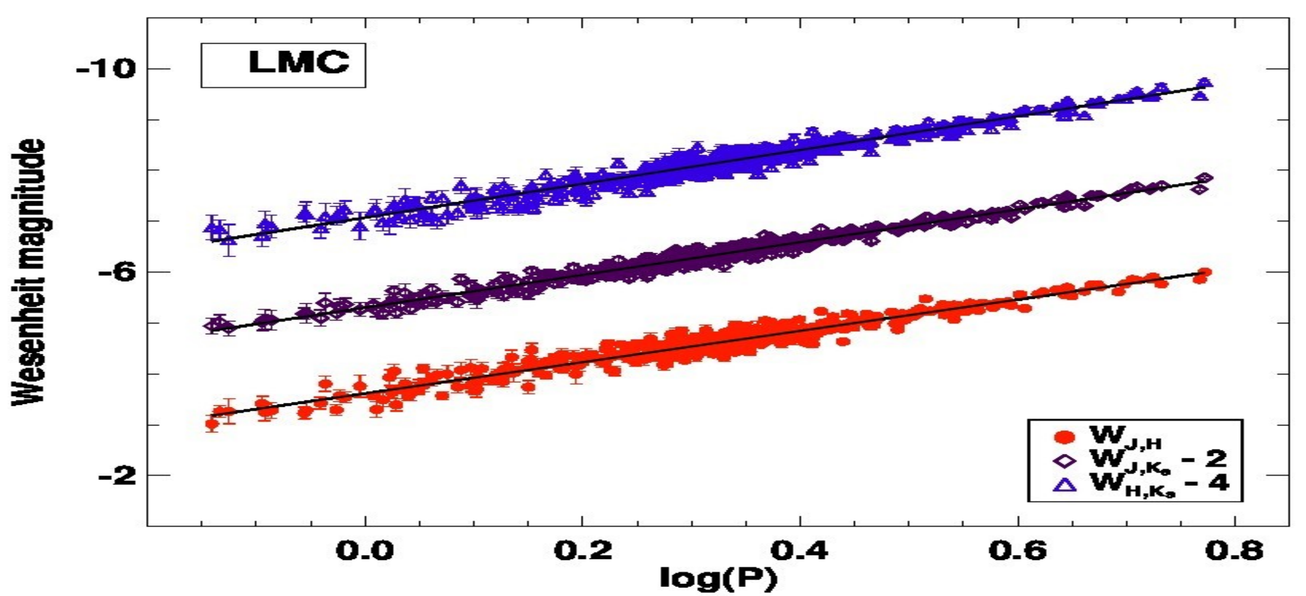
$$W_{H,K_s} = K_s - 1.92(H - K_s)$$

$$W_{J,K_s} = K_s - 0.63(J - K_s),$$

LMCNISS P-W relations

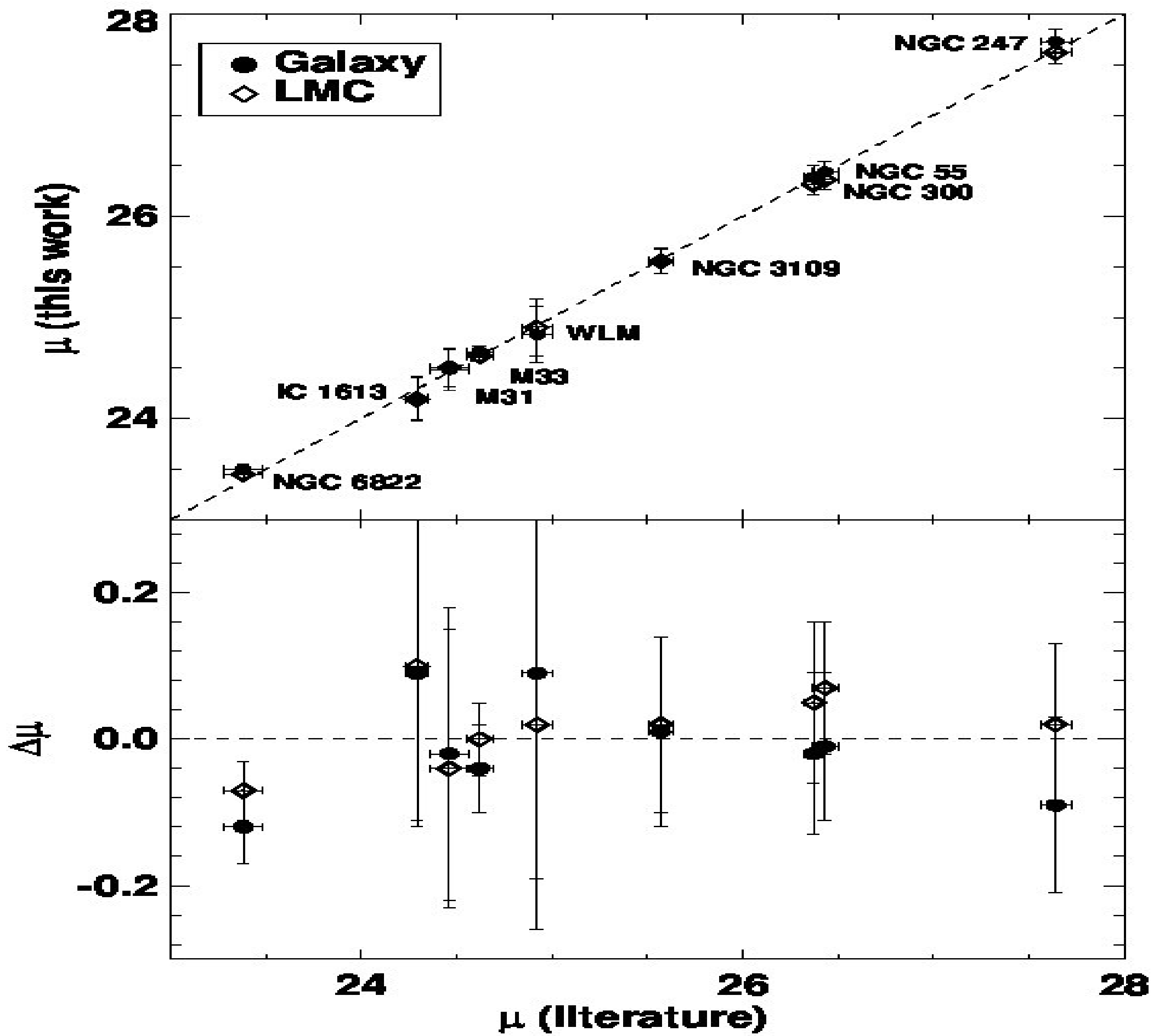


FU Cepheids



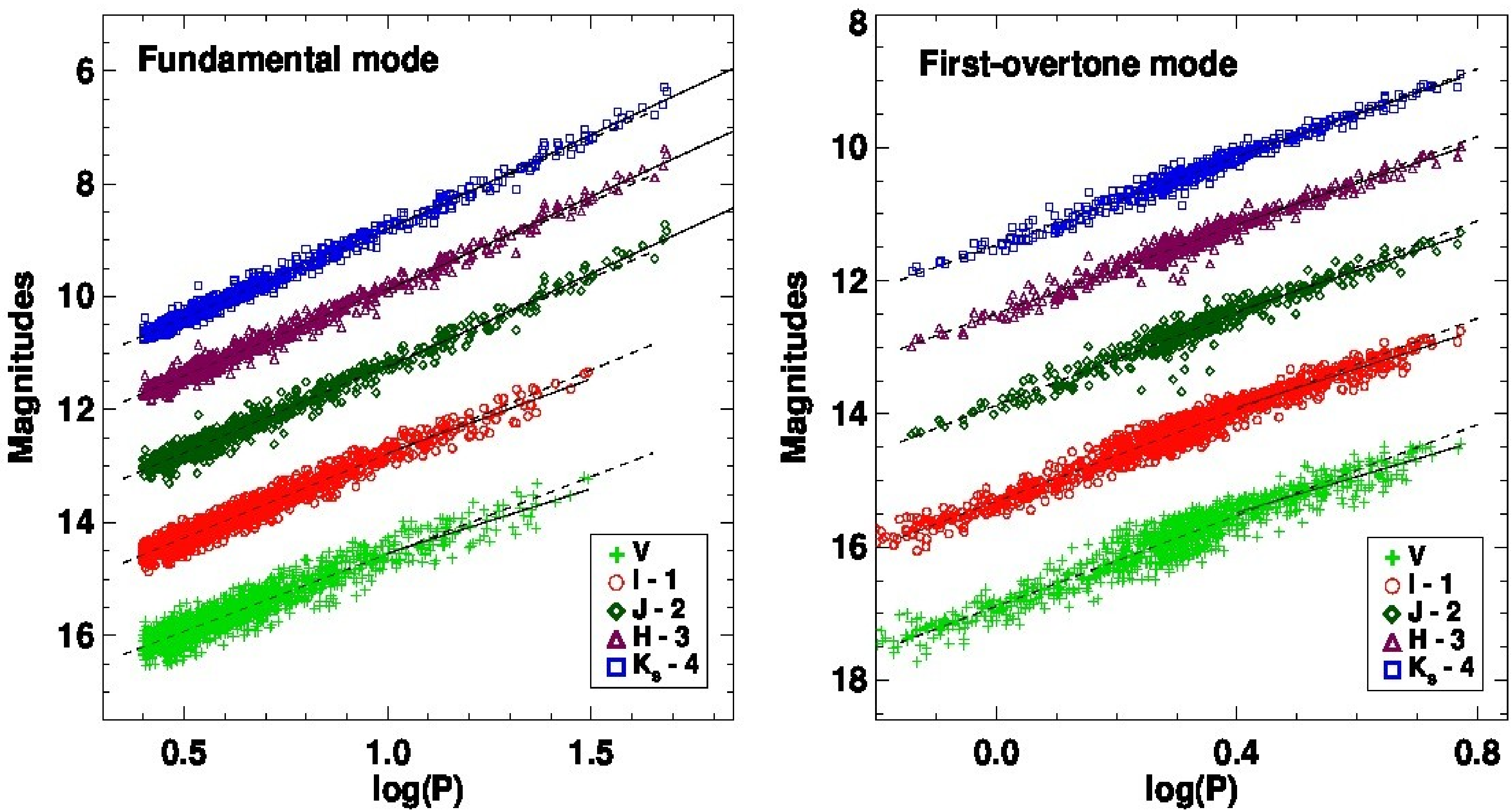
FO Cepheids

Distance to Local Group galaxies



(Non-) Linear P-L relations

- Miltiband Period - Luminosity relations or *Leavitt Law*
- *A statistical analysis of non-linearity in the Leavitt Law (Bhardwaj et al., 2016)*



Cepheid based Hubble constant

- Global fit to Cepheid and Supernovae Ia data from SHOES project (Riess et al., 2011)

- The LMC W(H,VI) Wesenheit used as calibrator in SH0ES project is found to be non-linear around 18 days.

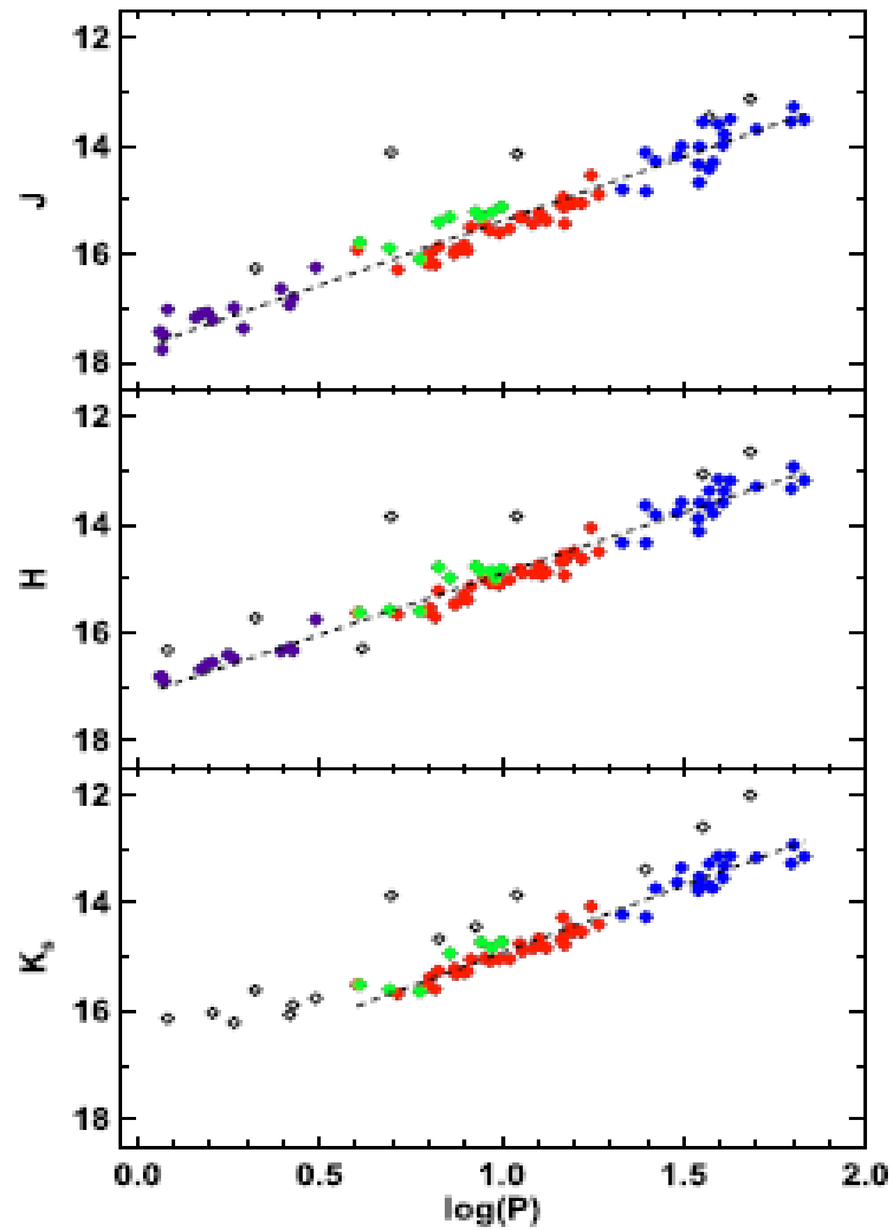
- Global slope is found to be consistent with the corresponding LMC relation at short periods, and significantly different to the long-period value.

- We do not find any significant difference in the slope of the global-fit solution using a linear or non-linear LMC PL relation as calibrator, but the linear version provides a two times better constraint on the slope and metallicity coefficient.

- *SH0ES III (Riess et al. 2016) used two slope model in the global-fit to account for the impact of non-linearities.*

Type II Cepheids

- Cross match with optical OGLE-III catalog of variable stars
- 81 Type II Cepheids with JHKs observations
- Mean-magnitudes using the Template-fit to the Type II Cepheids in the LMCNISS



- BL Herculis, P < 4 days
- W Virginis, 4 < P < 20 days
- Peculiar W Virginis, 4 < P < 10 days
- RV Tauris, P > 20 days

Type II Cepheid distance scale

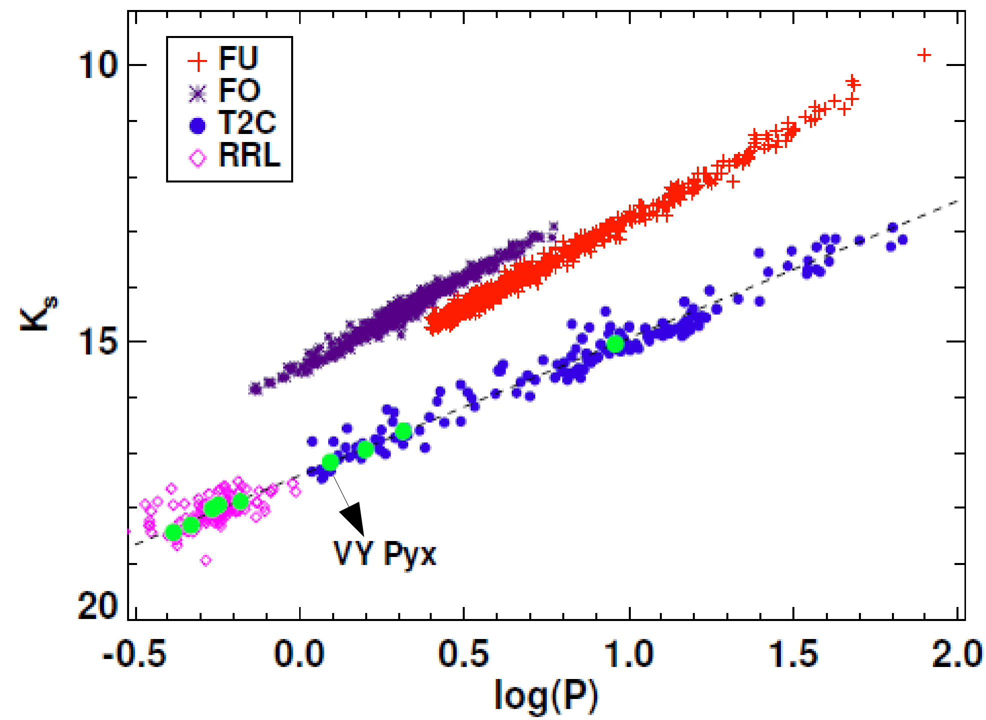
VY Pyx parallaxes -

Hipparcos

6.44 ± 0.23 mas

HST - 5.01 ± 0.44 mas

Gaia - 3.85 ± 0.28 mas



Estimates of the LMC Distance Modulus

Source	μ (mag)
T2C π	18.54 ± 0.11
RRL π	18.55 ± 0.10
T2C B–W	18.41 ± 0.09

- Comparison of Cepheid based distances with horizontal branch stars

Type II Cepheid-based Distance Estimates for Galactic Globular Clusters

Cluster	$\mu(J)$	$\mu(H)$	$\mu(K_s)$	μ_{M06}
NGC 1904	15.55 ± 0.09	15.40 ± 0.09	15.42 ± 0.10	15.57
NGC 2808	15.01 ± 0.09	15.27 ± 0.09	15.05 ± 0.11	14.90
NGC 5139	13.65 ± 0.08	13.77 ± 0.08	13.70 ± 0.11	13.62
NGC 5272	14.89 ± 0.07	15.01 ± 0.07	14.95 ± 0.07	15.10
NGC 5904	14.15 ± 0.12	14.22 ± 0.11	14.24 ± 0.11	14.37
NGC 5986	15.20 ± 0.06	15.03 ± 0.06	15.05 ± 0.07	15.11
NGC 6093	15.07 ± 0.07	15.17 ± 0.07	15.12 ± 0.07	15.04
NGC 6218	13.64 ± 0.08	13.68 ± 0.06	13.62 ± 0.08	13.45
NGC 6254	13.54 ± 0.08	13.58 ± 0.07	13.53 ± 0.08	13.23
NGC 6256	14.12 ± 0.10	14.24 ± 0.07	14.18 ± 0.08	14.57
NGC 6266	13.79 ± 0.08	13.93 ± 0.07	13.86 ± 0.09	14.19
NGC 6273	14.55 ± 0.07	14.73 ± 0.06	14.65 ± 0.07	14.71
NGC 6284	15.66 ± 0.08	15.85 ± 0.08	15.71 ± 0.10	15.93
NGC 6293	14.75 ± 0.09	15.04 ± 0.09	14.76 ± 0.13	14.76
NGC 6325	14.48 ± 0.07	14.57 ± 0.07	14.53 ± 0.07	14.51
NGC 6402	14.73 ± 0.07	14.95 ± 0.08	14.82 ± 0.09	14.86
NGC 6441	15.48 ± 0.07	15.59 ± 0.12	15.59 ± 0.11	15.60
NGC 6453	14.94 ± 0.07	14.98 ± 0.07	15.03 ± 0.07	14.93
NGC 6569	15.33 ± 0.13	15.06 ± 0.11	15.12 ± 0.12	15.11
NGC 6626	13.77 ± 0.10	13.77 ± 0.10	13.76 ± 0.10	13.74
NGC 6749	14.21 ± 0.07	14.51 ± 0.07	14.46 ± 0.08	14.51
NGC 6779	15.07 ± 0.08	15.22 ± 0.09	15.12 ± 0.12	15.08
NGC 7078	15.22 ± 0.07	15.30 ± 0.06	15.25 ± 0.06	15.13
NGC 7089	15.36 ± 0.06	15.43 ± 0.07	15.41 ± 0.07	15.33
HP 1	14.24 ± 0.07	14.34 ± 0.07	14.31 ± 0.07	14.36
Ter 1	13.56 ± 0.06	13.81 ± 0.06	13.97 ± 0.07	13.73

Summary

- Theoretical amplitudes in optical bands are systematically larger than the observed amplitudes over the entire period range except in the vicinity of 10 days.
- *Large discrepancy in Fourier amplitude parameters with respect to observations for canonical set of Cepheid models with* $M > 6M_0$ *and* $T < 5400K$ *at the short period* ($P < 10$ *days) end*
- *Discrepancy in amplitude parameters can be remedied with increase in mixing length parameter*
- *A combination of higher mixing length and non-canonical M-L relations may allow the best-fit with respect to observations*
- Near-infrared observations of Classical and Type II Cepheids provide robust P-L relations for distance scale
- Non-linearity in Cepheid P-L relations does not have any significant impact on the extragalactic distance scale.

Thank you