One Million Variable Stars from the OGLE Survey

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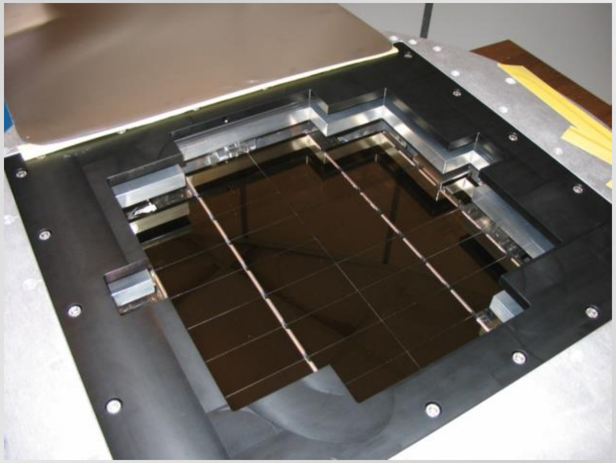
OGLE

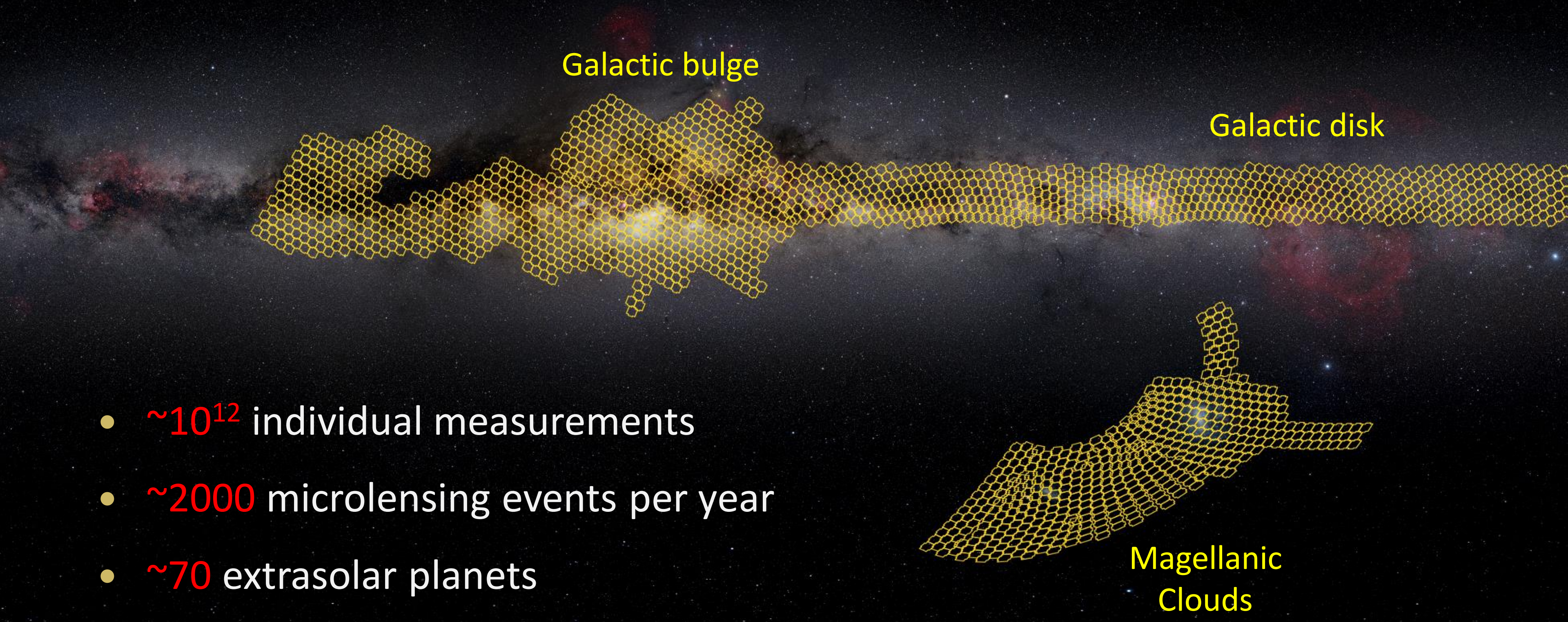
Optical Gravitational Lensing Experiment

- Original goal: search for microlensing events
- **1.3-meter Warsaw Telescope** at Las Campanas Observatory, Chile
- 32-chip CCD camera with a field of view of **1.4 square degrees**
- Standard Johnson-Cousins ***VI*** filters
- Typical cadence: from **20 minutes** to **several days**
- Time span: **1992 – now**
- Targets: **Galactic bulge, Galactic disk, Magellanic Clouds**
- Precision of the photometry: **4 mmag**



OGLE fields

- Sky coverage: ~3500 square degrees
- ~2 billion stars monitored



- ~10^{12} individual measurements
- ~2000 microlensing events per year
- ~70 extrasolar planets
- ~1 million discovered variable stars

THE OGLE COLLECTION OF VARIABLE STARS

The OGLE Collection of Variable Stars

ftp://ftp.astrouw.edu.pl/ogle/ogle4/OCVS/
http://ogledb.astrouw.edu.pl/~ogle/OCVS/

Type of variable stars	Environments	Number of stars
Classical Cepheids	LMC, SMC, GB, GD	9 756
Type II Cepheids	LMC, SMC, GB	1 262
Anomalous Cepheids	LMC, SMC, GB	289
RR Lyrae stars	LMC, SMC, GB	85 517
δ Scuti stars	LMC, GD	2 844
Long-Period Variables (Miras, SRVs, OSARGs)	LMC, SMC, GB	344 214
Eclipsing binaries	LMC, SMC, GB, GD	510 782
R Coronae Borealis stars	LMC	23
TOTAL		**954 687**

The OGLE Collection of Variable Stars

ftp://ftp.astrouw.edu.pl/ogle/ogle4/OCVS/
http://ogledb.astrouw.edu.pl/~ogle/OCVS/

OGLE Collection of Variable Stars

Welcome page
News/Changes
updated: 2017-07-16

Database Queries:

Classical Cepheids
Anomalous Cepheids
RR Lyr Stars
Eclipsing Stars

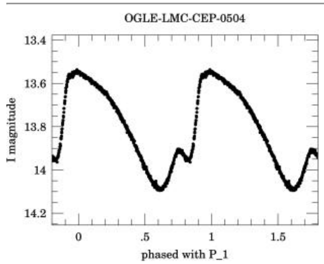
Query Help

OGLE-IV Photometry of OGLE-LMC-CEP-0504

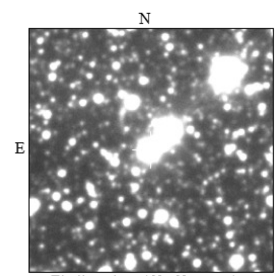
Download: object I-band V-band photometry Finding chart
PS lighcurve phased with P_1
All data

RA/Dec (J2000): 4:57:56.71 -68:48:57.6
Star type: Classical Cepheid, mode F
Identification: OGLE-III: LMC126.8.39800; OGLE-IV: LMC531.26.15716; OTHER: HV12505

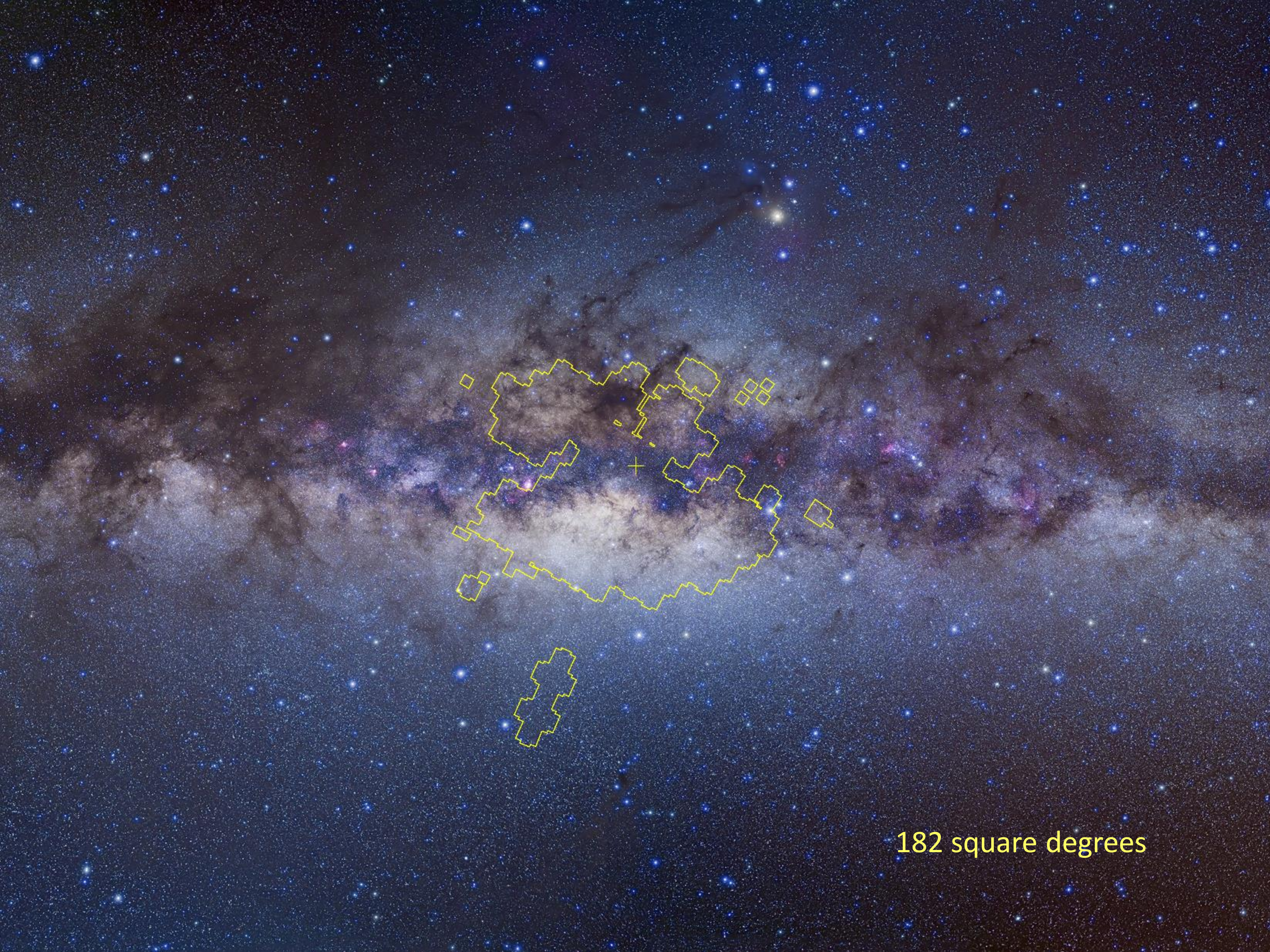
I = 13.792 V = 14.838
P_1 = 14.3929624 dP_1 = 0.0000849 T0_1 = 6004.74277 A_1 = 0.543 R21_1 = 0.142 phi21_1 = 4.935 R31_1 = 0.124 phi31_1 = 1.799



I-band			V-band		
HJD-2450000	mag	err	HJD-2450000	mag	err
5261.55766	13.814	0.005	5275.53339	14.926	0.004
5261.59934	13.814	0.005	5286.49075	14.567	0.004
5262.57508	13.911	0.005	5446.88766	14.780	0.004
5262.59343	13.906	0.005	5459.82123	14.614	0.004
5264.54162	14.077	0.005	5476.80761	14.894	0.004
5264.55655	14.080	0.005	5485.74144	14.374	0.004
5265.53651	14.078	0.005	5492.79336	15.091	0.004
5265.55794	14.079	0.005	5493.81582	15.232	0.004
5266.53828	13.968	0.005	5494.79239	15.319	0.004
5266.55394	13.968	0.005	5495.74952	15.290	0.004
5267.53706	13.920	0.005	5497.84555	14.970	0.004
5268.54889	13.923	0.005	5499.75278	14.411	0.004
5269.52105	13.581	0.005	5502.84388	14.604	0.004
5271.52978	13.578	0.005	5503.78122	14.698	0.004
5273.51901	13.641	0.005	5505.74792	14.921	0.004
5274.55023	13.707	0.005	5507.78337	15.175	0.004
5275.54859	13.773	0.005	5509.74954	15.313	0.004
5277.54465	13.951	0.005	5510.78355	15.199	0.004
5280.53091	14.027	0.005	5511.79364	14.966	0.004
5281.55299	13.916	0.005	5512.80250	14.986	0.004
5282.51135	13.952	0.005	5514.80476	14.389	0.004
5283.52552	13.716	0.005	5515.78189	14.440	0.004
5284.53111	13.566	0.005	5516.80728	14.556	0.004
5285.53135	13.559	0.005	5517.76835	14.642	0.004
5286.50586	13.601	0.005	5521.75616	15.114	0.004
5288.52397	13.677	0.005	5522.75458	15.243	0.004
5291.51612	13.917	0.005	5523.71488	15.310	0.004
5294.52567	14.066	0.005	5524.72428	15.281	0.004
5296.55517	13.935	0.005	5525.69027	15.057	0.004
5298.53965	13.573	0.005	5526.72705	14.967	0.004
5301.49980	13.615	0.005	5527.78808	14.874	0.004
5306.47901	13.987	0.005	5528.66248	14.383	0.004



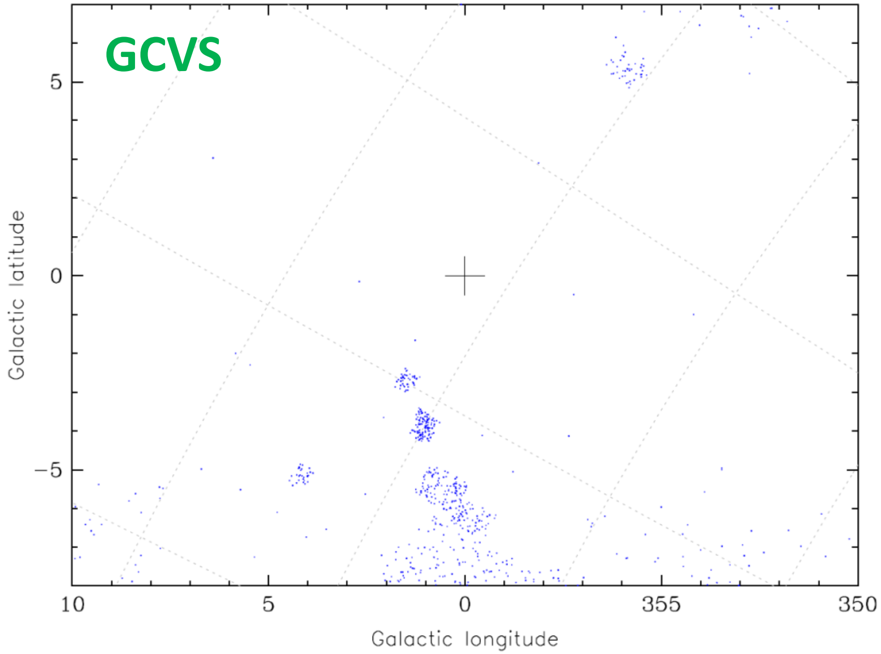
Finding chart (60x60 arcsec)


182 square degrees

Before and After OGLE

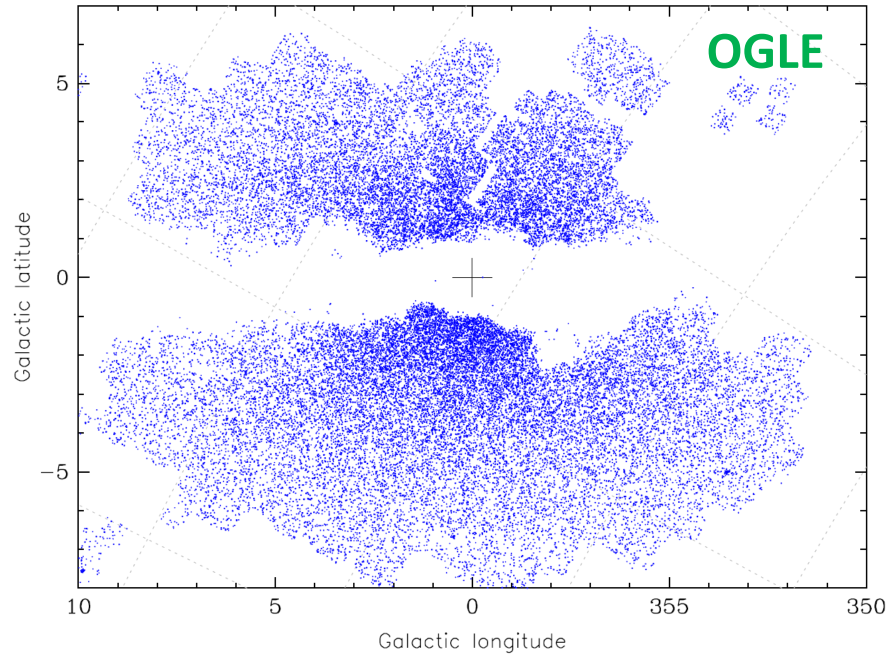
RR Lyrae stars in the Galactic Bulge

BEFORE



986 objects

AFTER

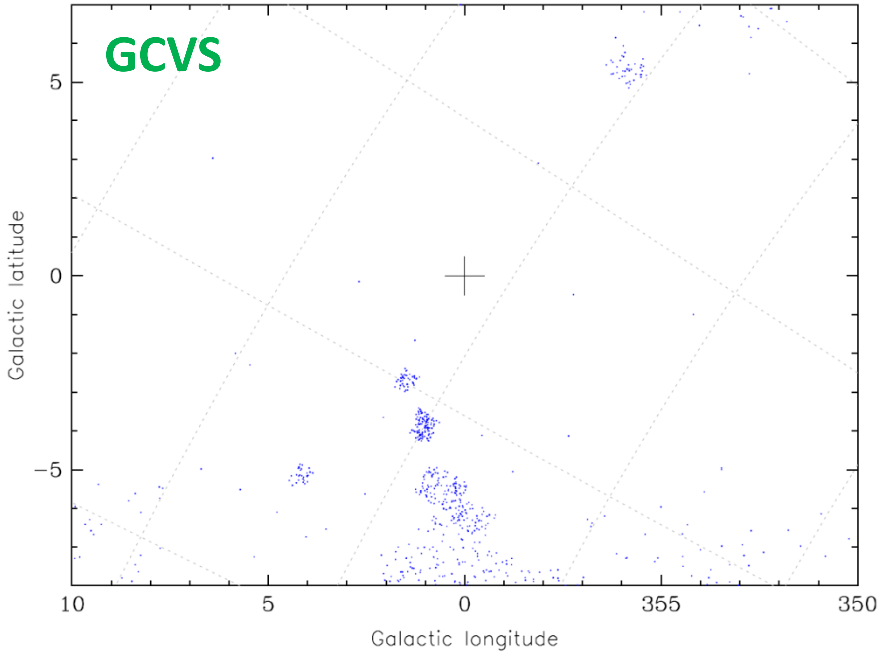


39 074 objects

Before and After OGLE

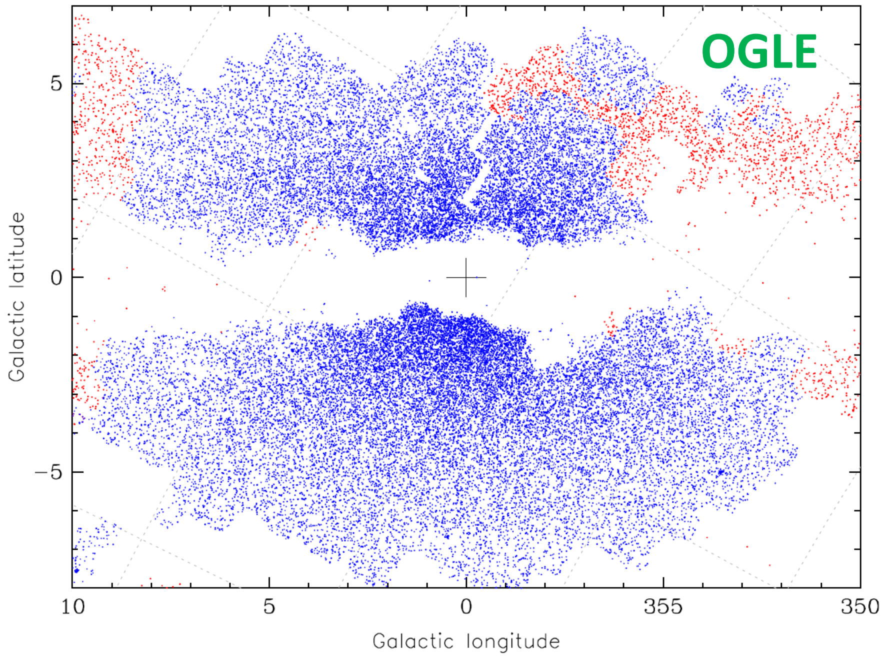
RR Lyrae stars in the Galactic Bulge

BEFORE



986 objects

AFTER

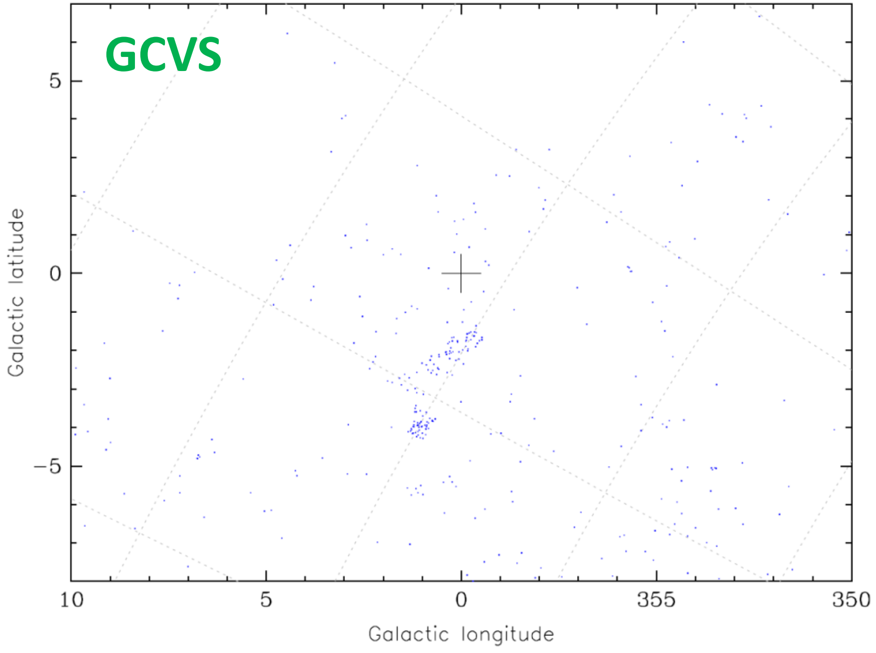


39 074+ objects

Before and After OGLE

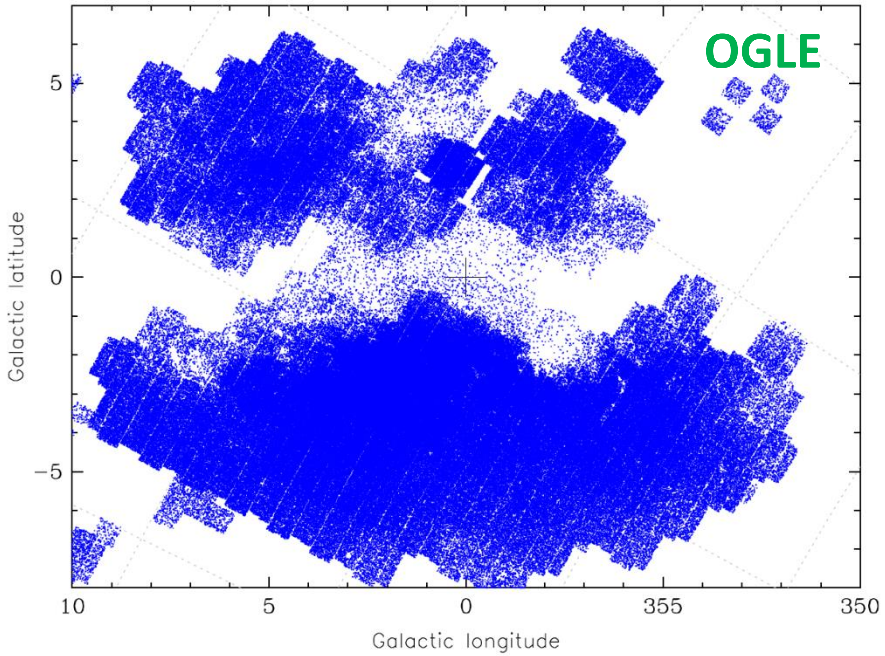
Eclipsing binaries in the Galactic Bulge

BEFORE



255 objects

AFTER

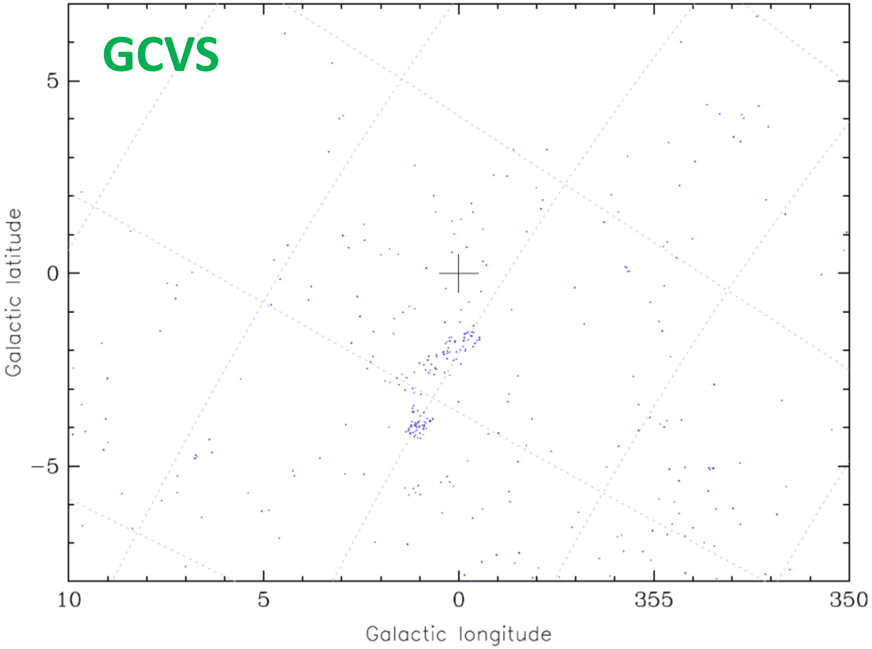


450 598 objects

Before and After OGLE

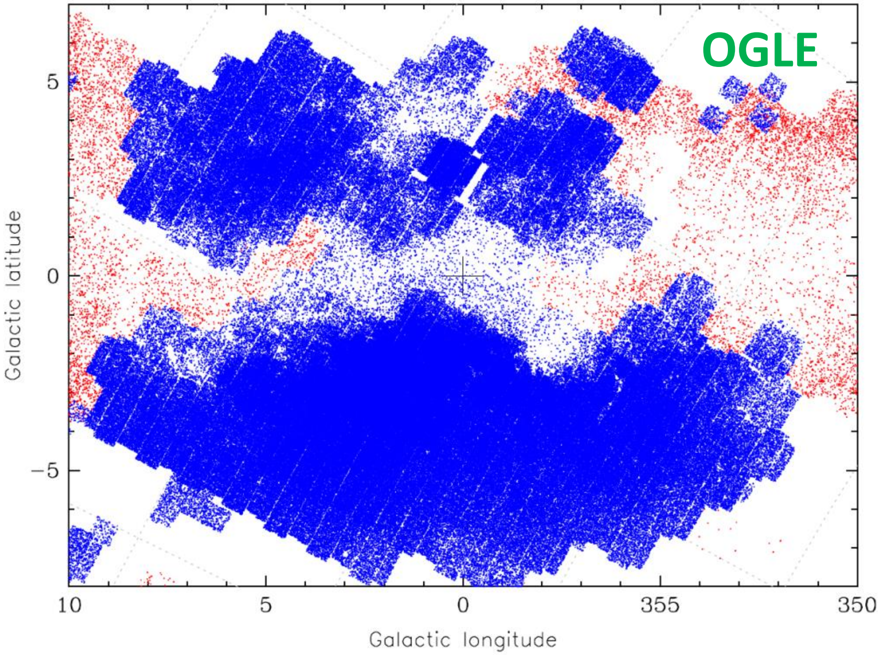
Eclipsing binaries in the Galactic Bulge

BEFORE

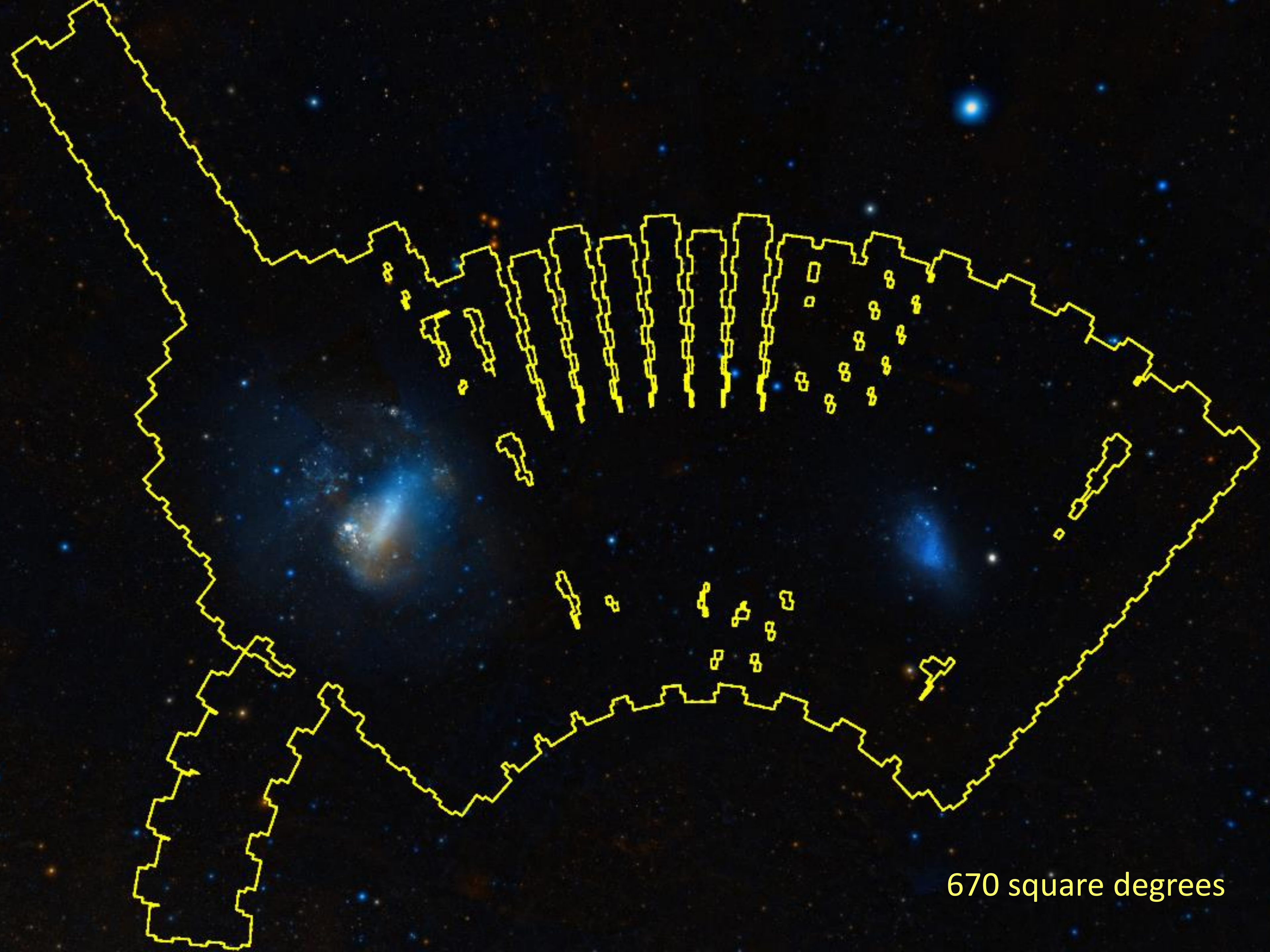


255 objects

AFTER



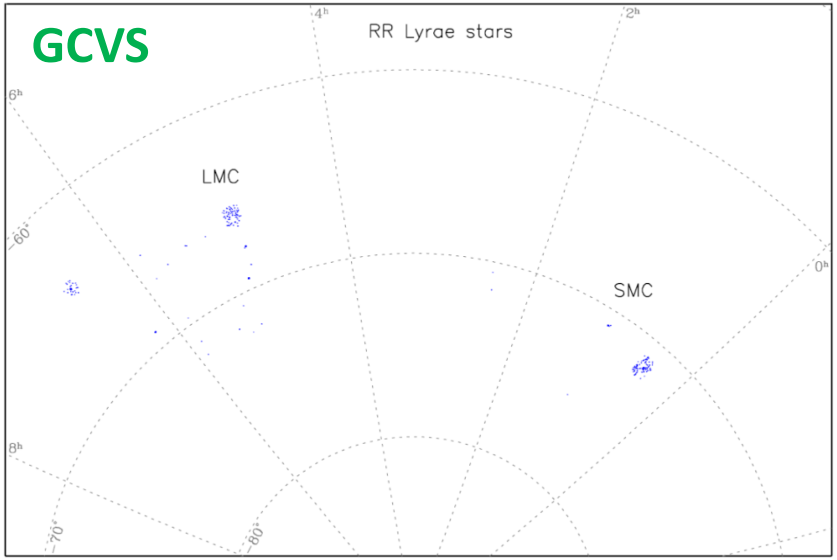
450 598+ objects


670 square degrees

Before and After OGLE

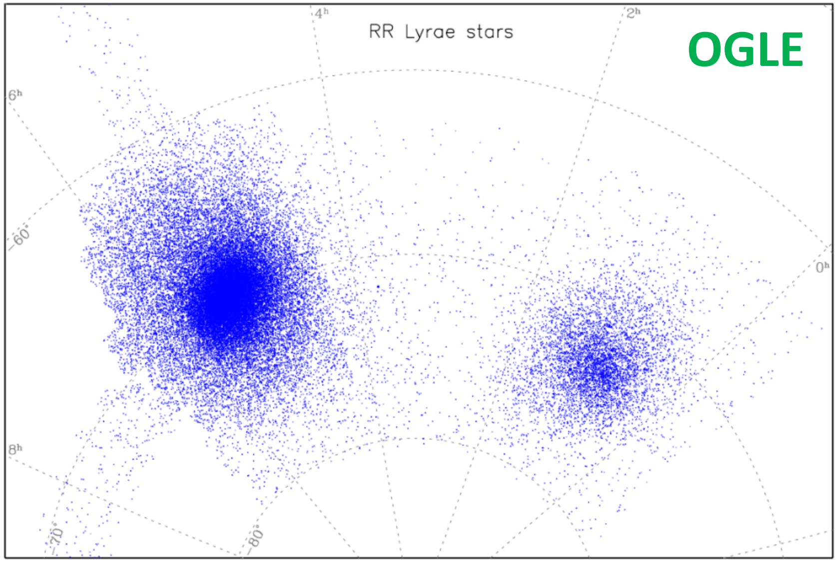
RR Lyrae stars in the Magellanic Clouds

BEFORE



291 objects

AFTER

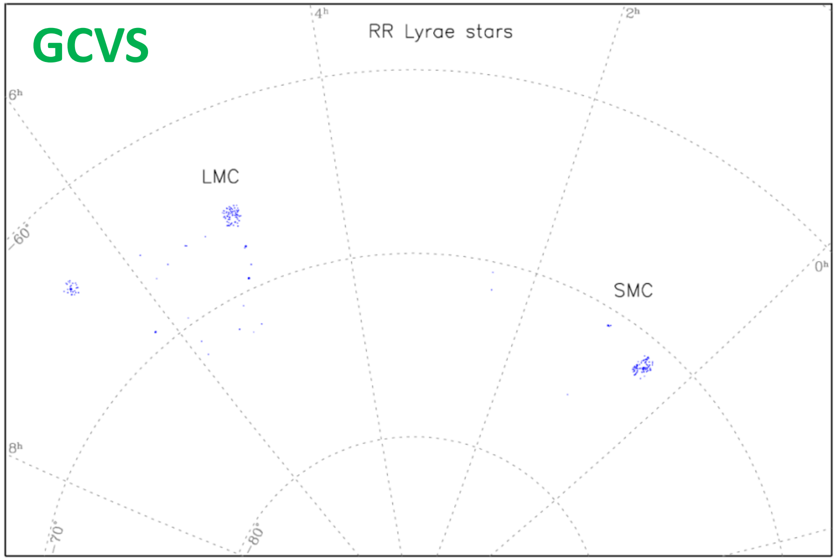


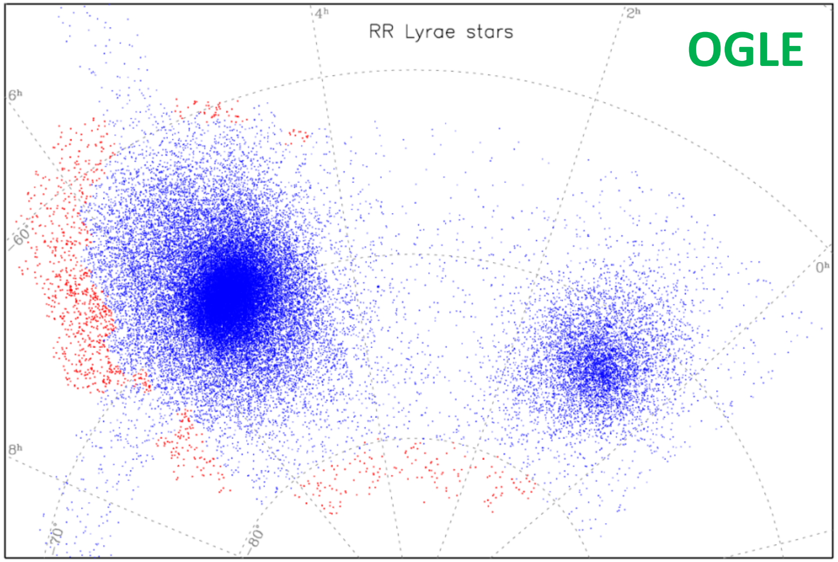
46 443 objects

Before and After OGLE

RR Lyrae stars in the Magellanic Clouds

BEFORE **AFTER**





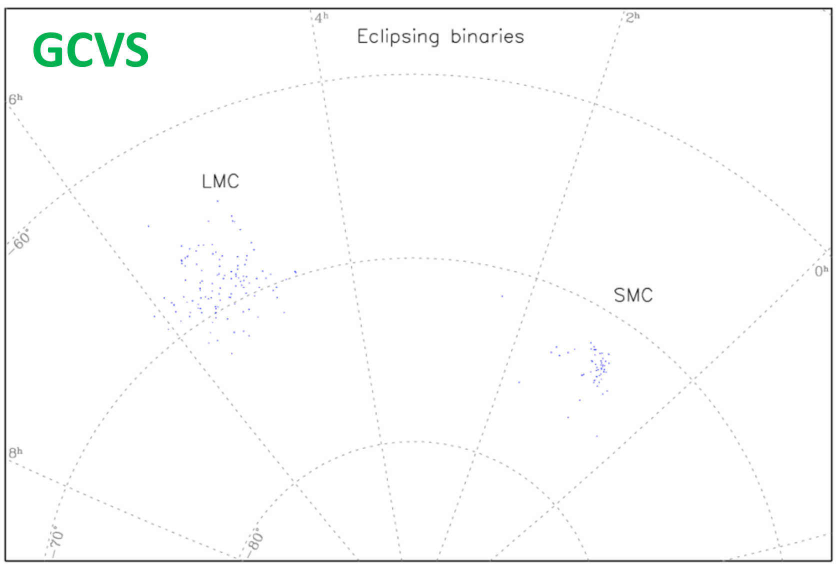
291 objects **46 443+ objects**

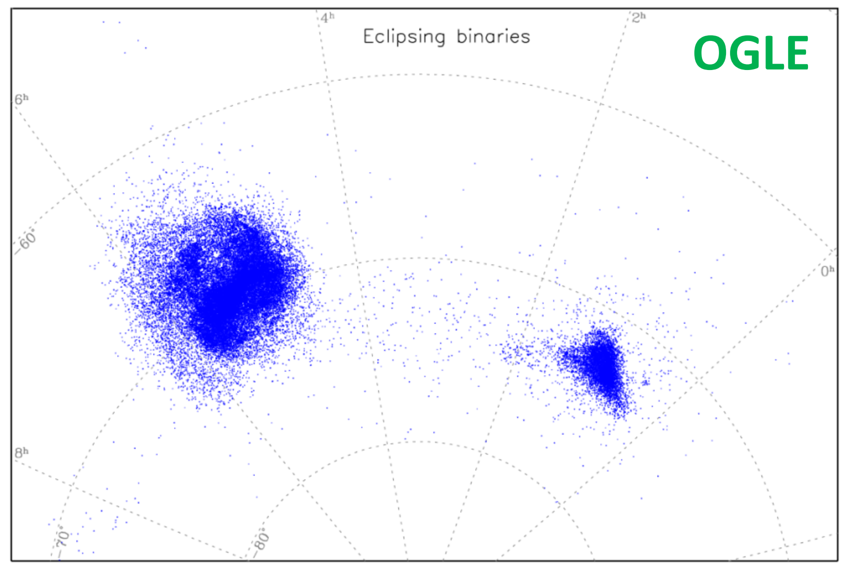
Before and After OGLE

Eclipsing binaries in the Magellanic Clouds

BEFORE

AFTER





173 objects

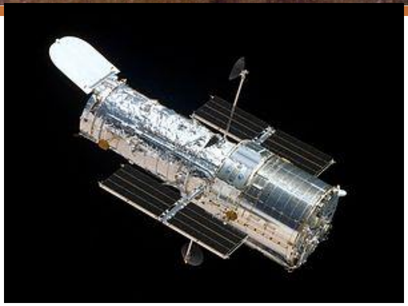
48 605 objects

Why do we need so many variable stars?

- To investigate their statistical properties (e.g. to calibrate the period-luminosity relations).
- To study the structure of the Milky Way and other galaxies.
- To discover extremely rare phenomena in stars or previously unknown types of stellar variability.

DISTANCE SCALE

HST Key Project



THE ASTROPHYSICAL JOURNAL, 553:47–72, 2001 May 20

FINAL RESULTS FROM THE *HUBBLE SPACE TELESCOPE* KEY PROJECT TO MEASURE THE HUBBLE CONSTANT[1]

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Received 2000 July 30; accepted 2000 December 19

(K. Sebo et al., in preparation), and these PL relations are in very good statistical agreement with those of Udalski et al., adjusting to a common distance to the LMC. For about 60 objects common to both samples, with $P > 8$ days and having both V and I magnitudes, the offsets are -0.004 ± 0.008 mag in I and $+0.013 \pm 0.010$ mag in V (Sebo et al.). The Sebo et al. sample extends to longer periods ($\sim$40 days), and has 10 Cepheids with periods greater than 30 days, the limit of the Udalski et al. sample. These 10 Cepheids are all well fitted by, and lie within 1 σ of, the period-luminosity slopes defined by the Udalski et al. sample. The Udalski et al. data are clearly the most extensive to date, and we thus adopt their apparent PL relations as fiducial for the reanalysis in this paper.

The Udalski et al. (1999) PL calibration adopts a distance modulus of 18.2 mag, based on a distance determined using the red clump technique, whereas, as discussed above, in this paper we adopt a true distance modulus to the LMC of 18.50 mag. With this modulus and the reddening-corrected Udalski et al. Cepheid data to define the slopes and errors, our adopted M_V and M_I PL relations become

$$M_V = -2.760[\pm 0.03](\log P - 1) - 4.218[\pm 0.02]$$
$$(\sigma_V = \pm 0.16)\,, \quad (1)$$

In this analysis we have (1) consistently adopted only the published Cepheid photometry, which were reduced using the ALLFRAME stellar photometry reduction package, whose phase points were converted to mean magnitudes using intensity-weighted averages (or their template-fitted equivalents).[20] (2) To compensate for the small ($\sim$0.01 mag) mean bias in the PL fits (see the discussion in § 8.4 and Appendix A), we have also applied period cuts to the PL relations, thereby eliminating the shortest period Cepheids, where magnitude incompleteness effects become important. In two cases (NGC 3368 and NGC 300), a single long-period Cepheid was also dropped because of stochastic effects at the bright (sparsely populated) end of the PL relation, which can similarly bias solutions. The mean correction for this magnitude-limited bias is small (+1% in distance), but it is systematic, and correcting for it results in larger distances than are determined without this faint-end debiasing. (3) We have adopted a -0.07 mag correction to the Hill et al. (1998) WFPC2 calibration to be consistent with Stetson (1998) and Dolphin (2000). Finally, (4) we have adopted the published slopes of the Udalski et al. (1999) PL relations.

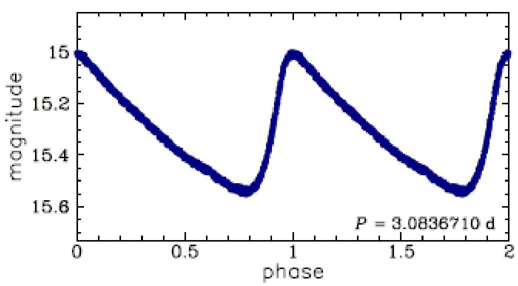
The adoption of the new Udalski et al. (1999) PL slopes alone has a dramatic and unanticipated effect on the previously published Cepheid distances based on the Madore

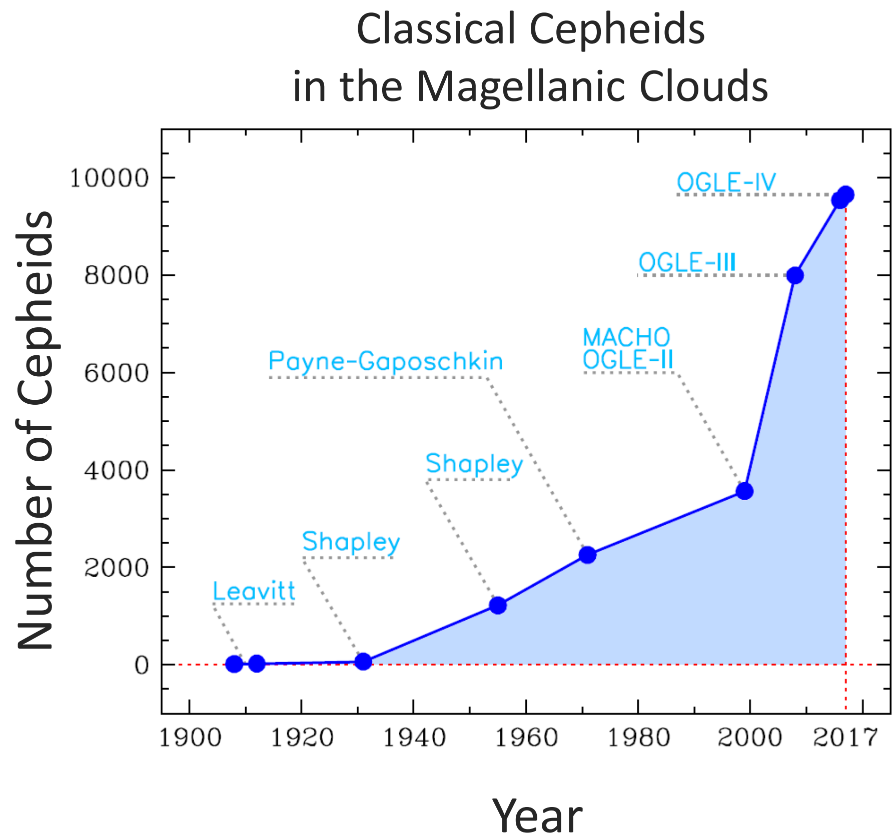
Classical Cepheids

LMC: **4704**

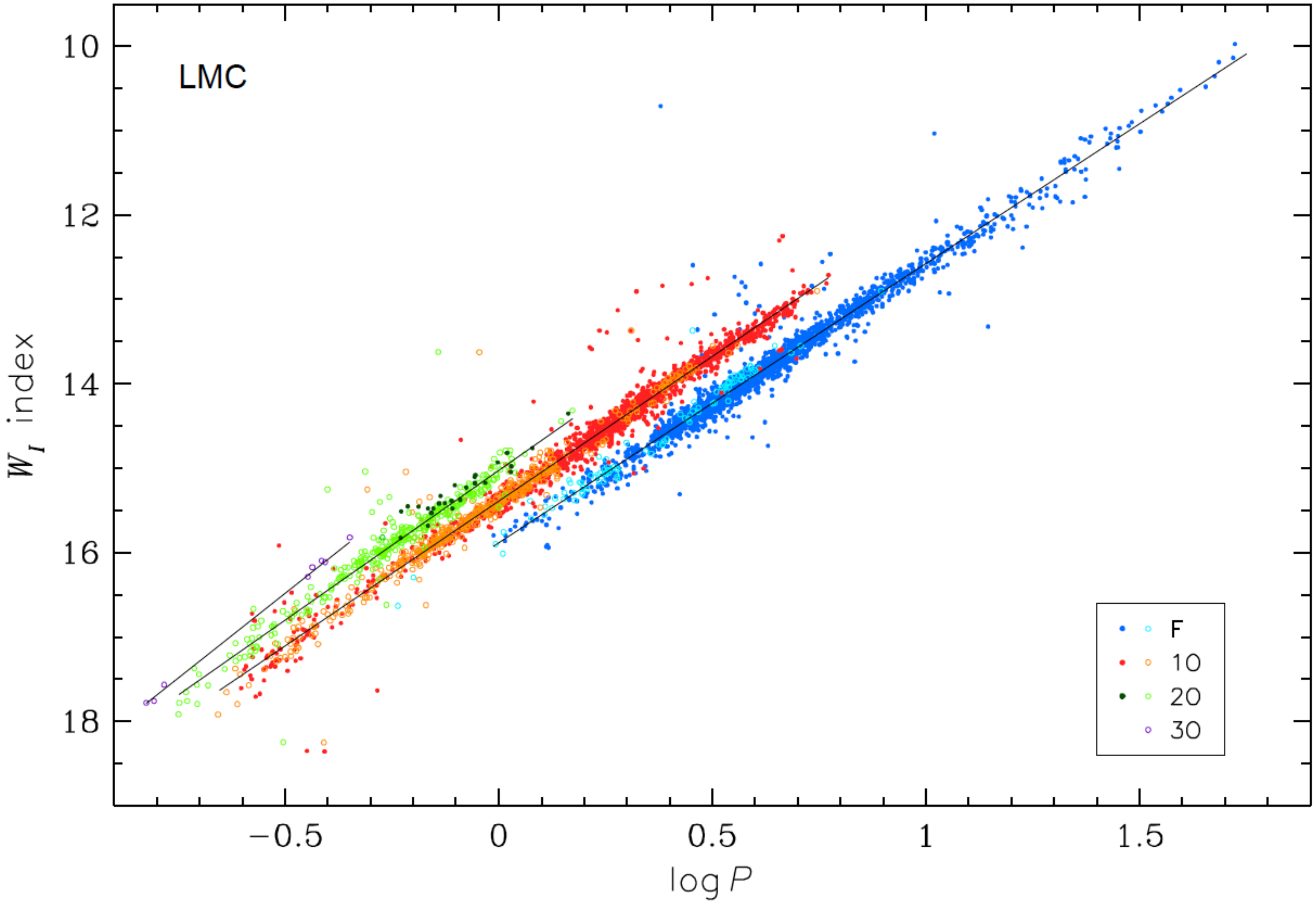
SMC: **4945**

GB: **87**



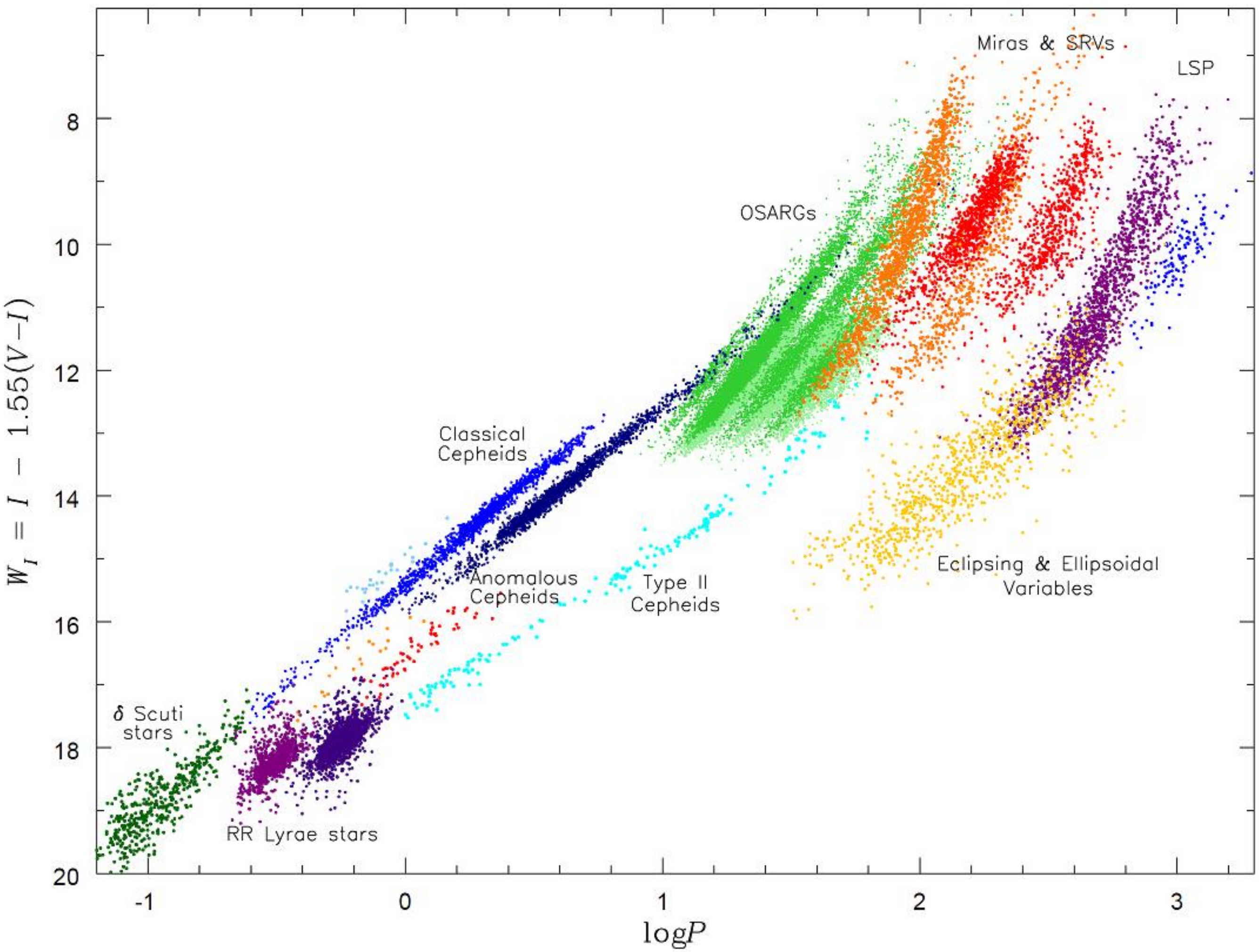


Period-luminosity relations for classical Cepheids

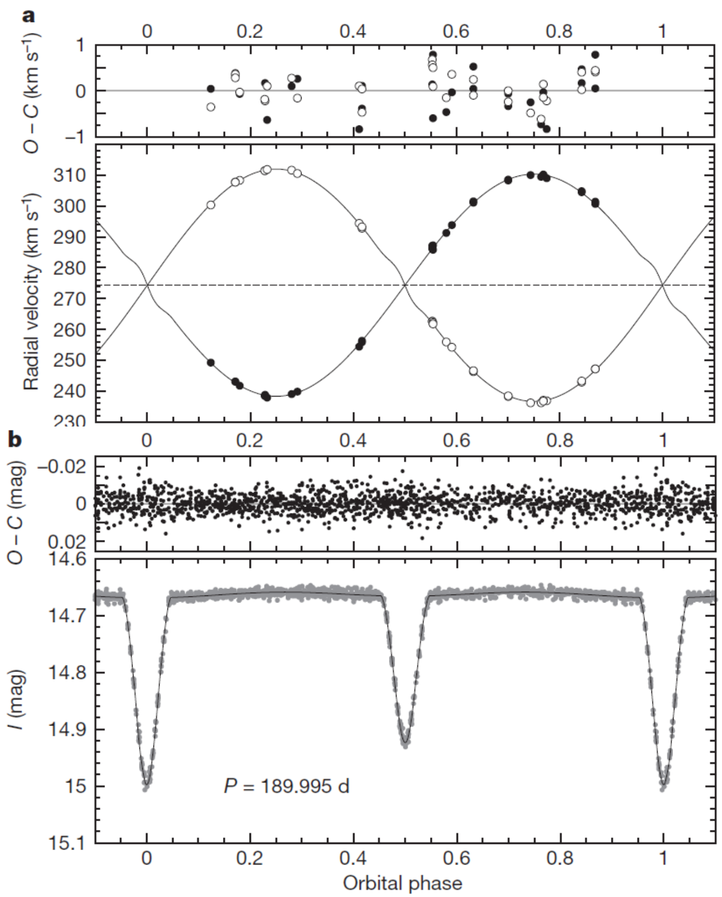


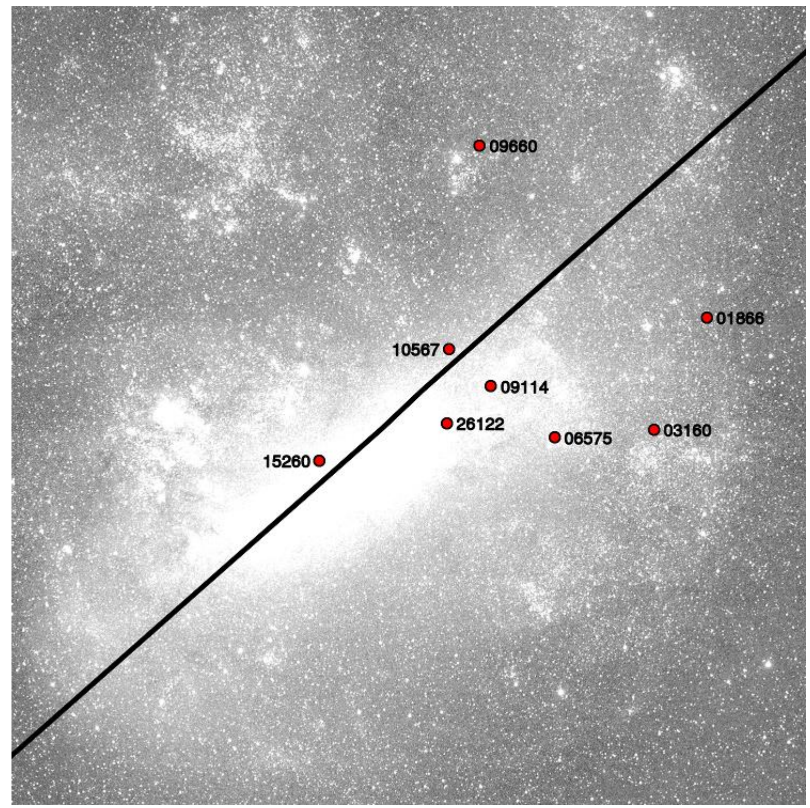
Soszyński et al. (2015)

Period-luminosity relations
for variable stars in the LMC



Distance to the Large Magellanic Cloud
from OGLE eclipsing binaries





Pietrzyński et al. (2013), Nature

Distance to the LMC: **50.0 ± 1.1 kpc**

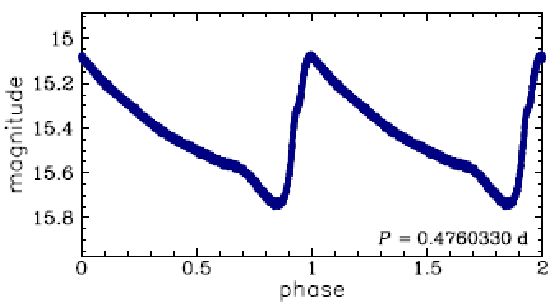
STRUCTURE OF GALAXIES

RR Lyrae stars

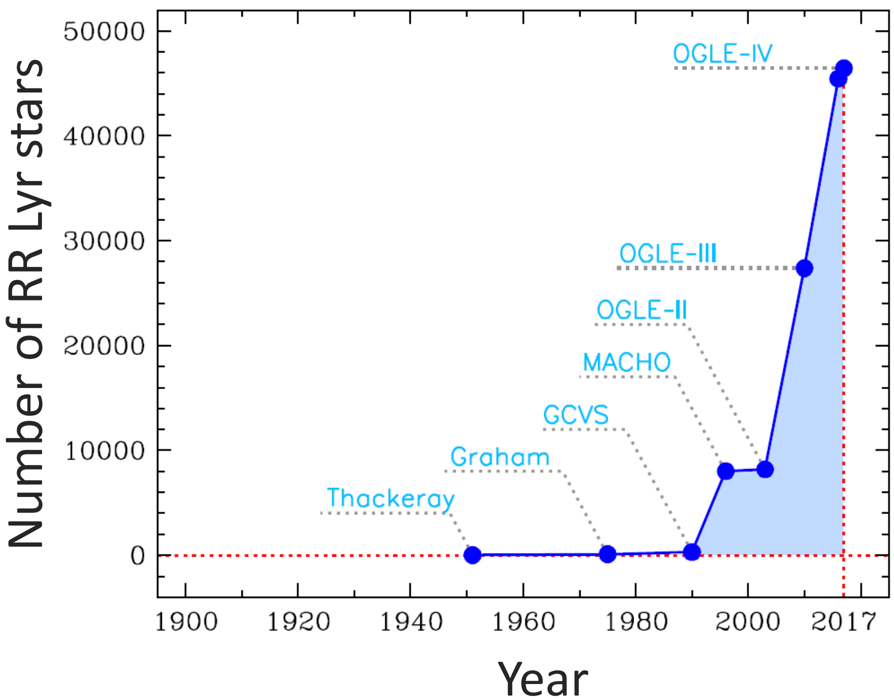
LMC: **39 871** objects

SMC: **6 572** objects

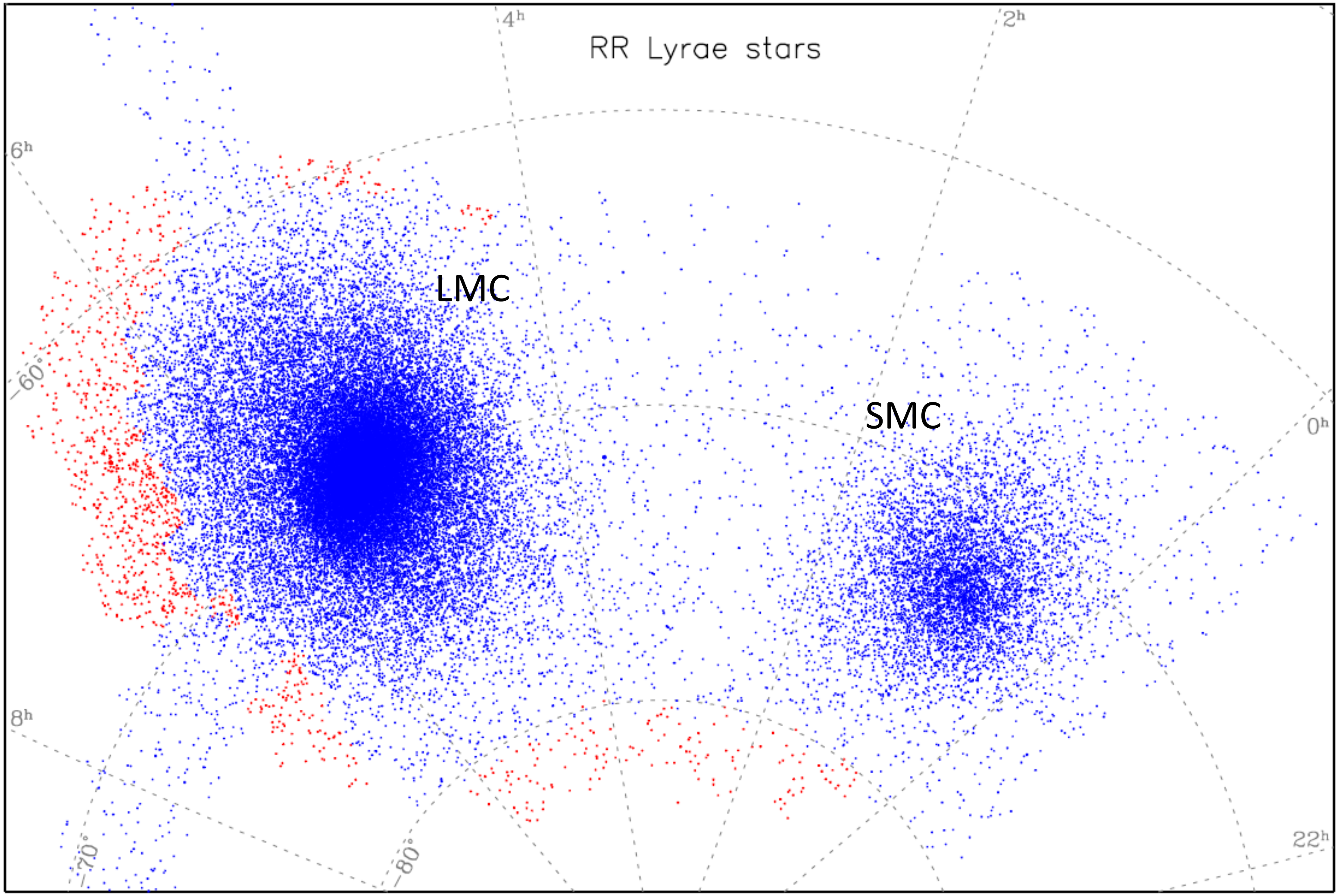
GB: **39 074** objects



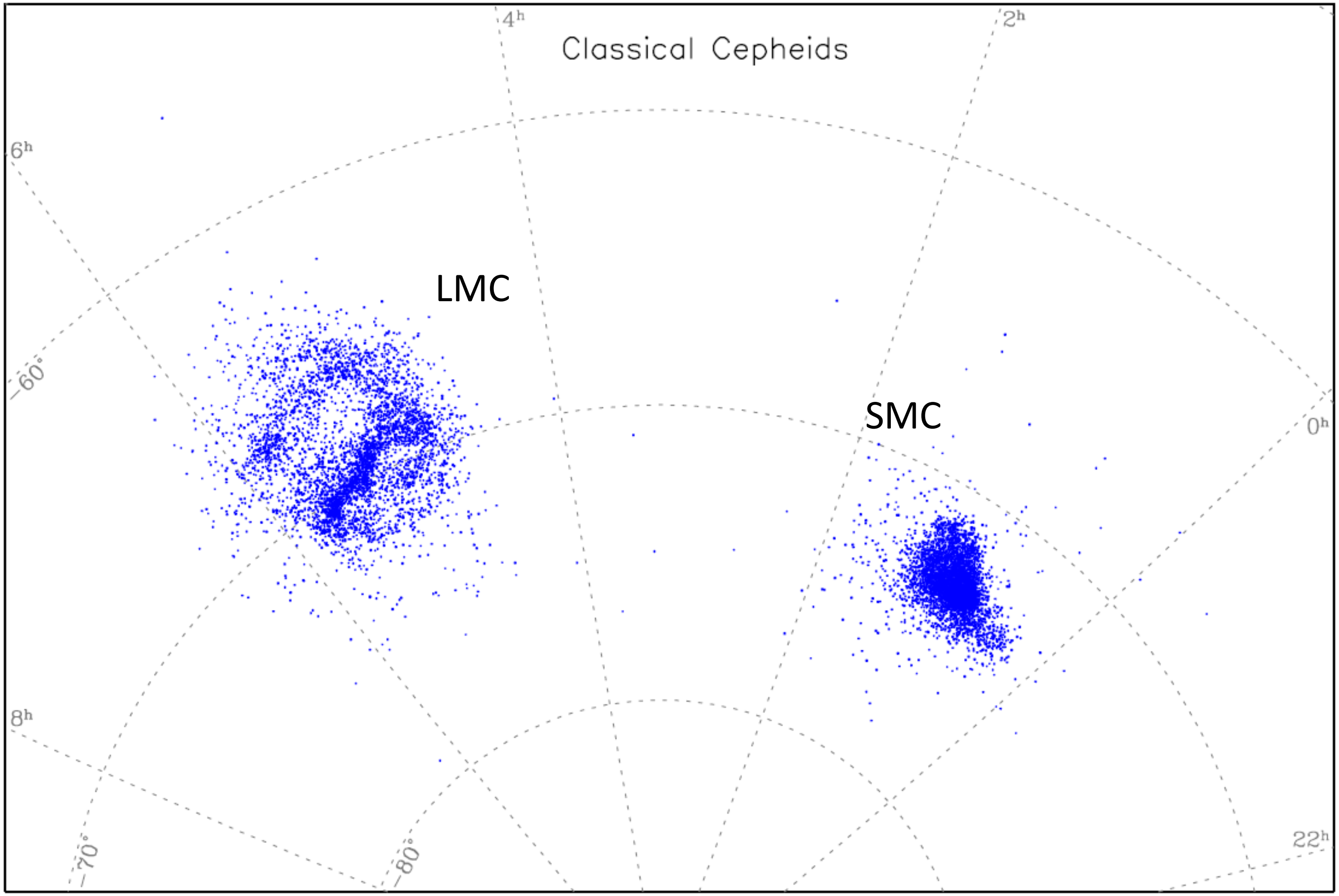
RR Lyrae stars
in the Magellanic Clouds



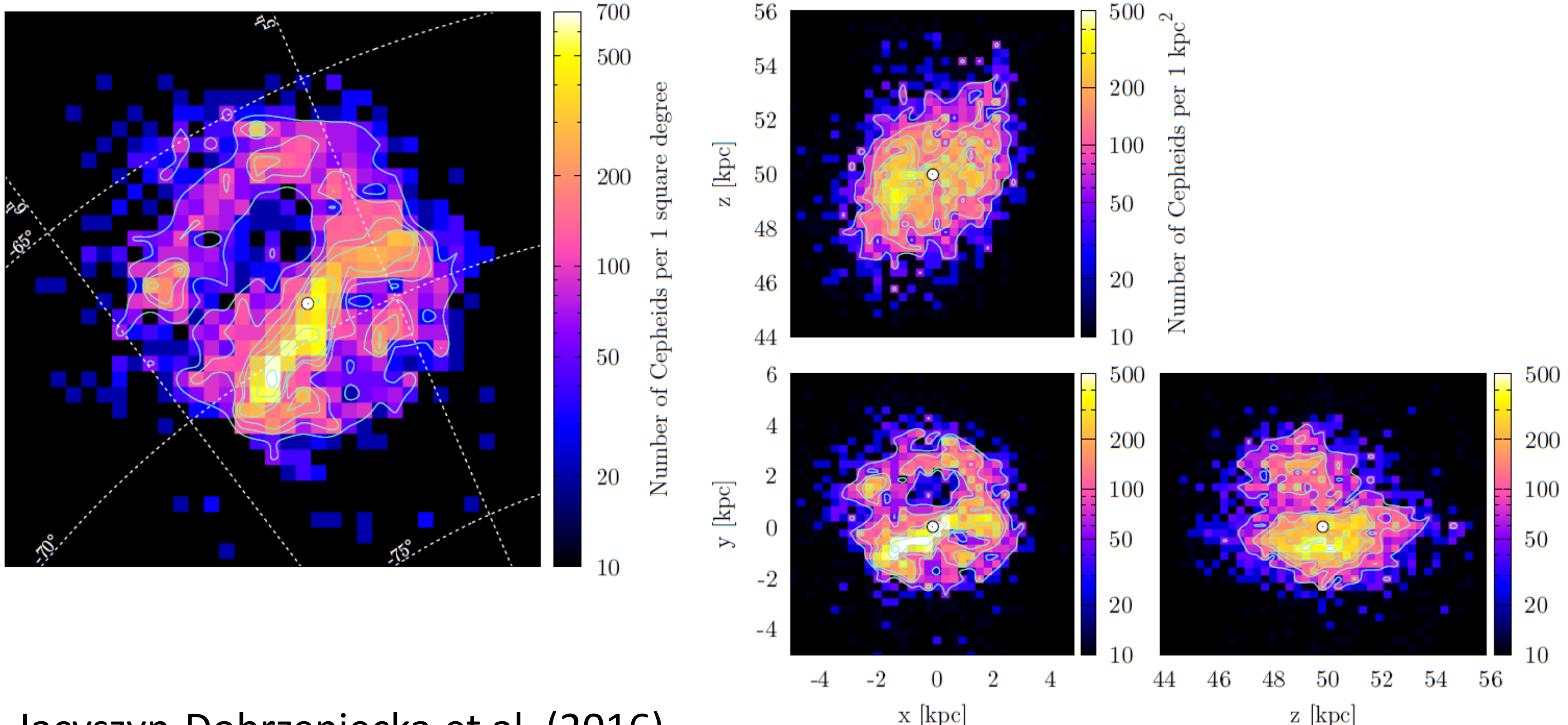
RR Lyrae stars in the MCs



Classical Cepheids in the MCs

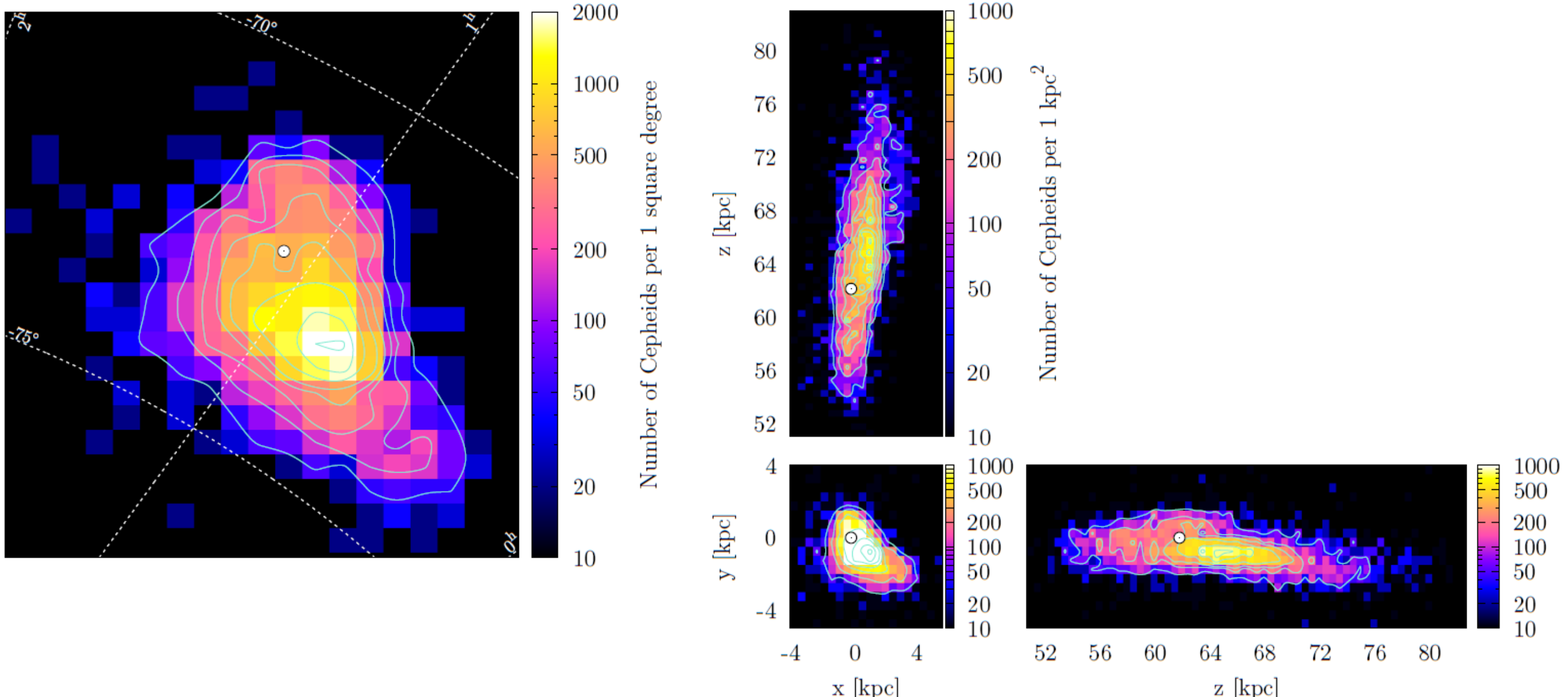


3D Structure of the LMC via Classical Cepheids



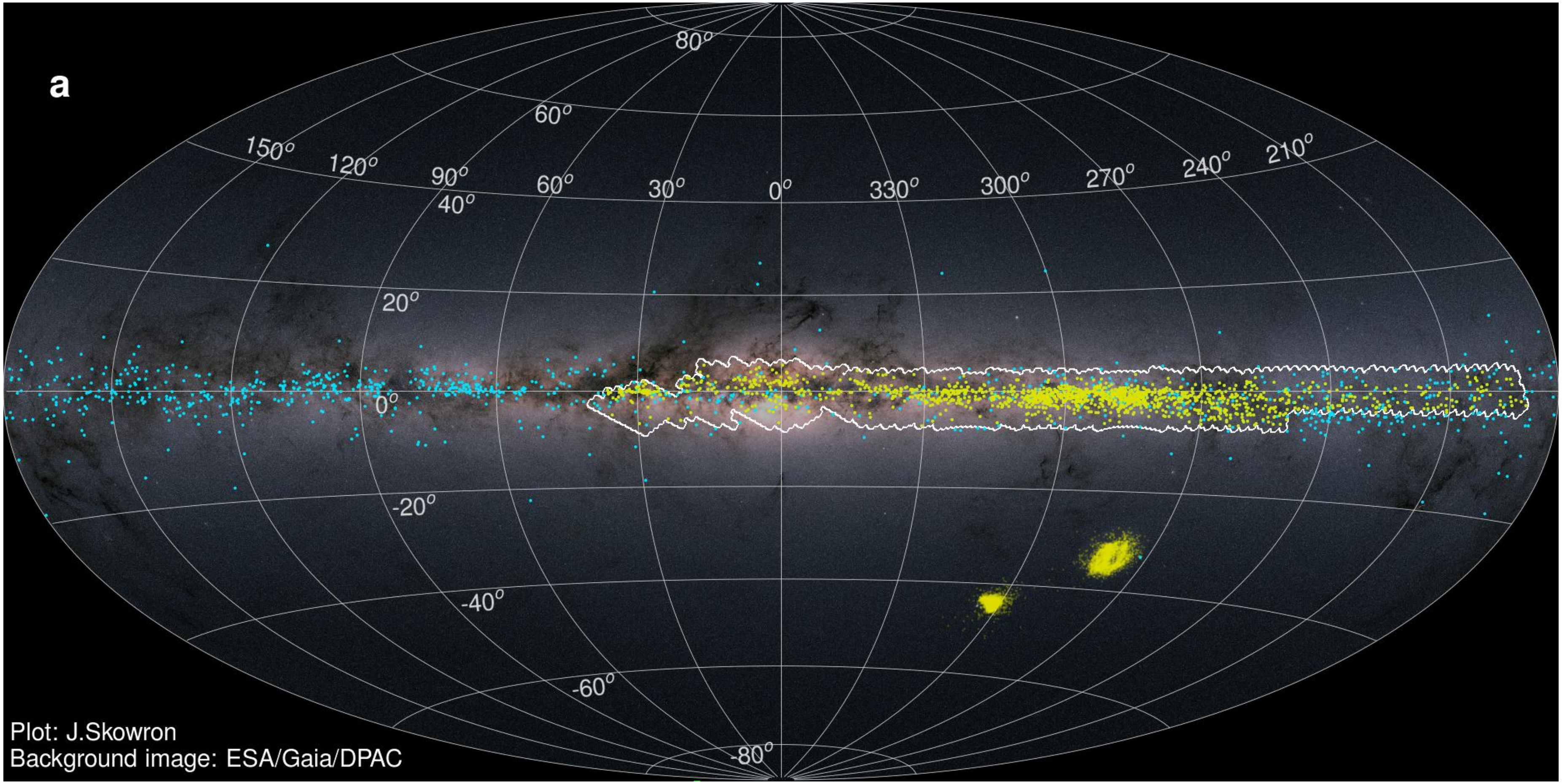
Jacyszyn-Dobrzeniecka et al. (2016)

3D Structure of the SMC via Classical Cepheids



Jacyszyn-Dobrzeniecka et al. (2016)

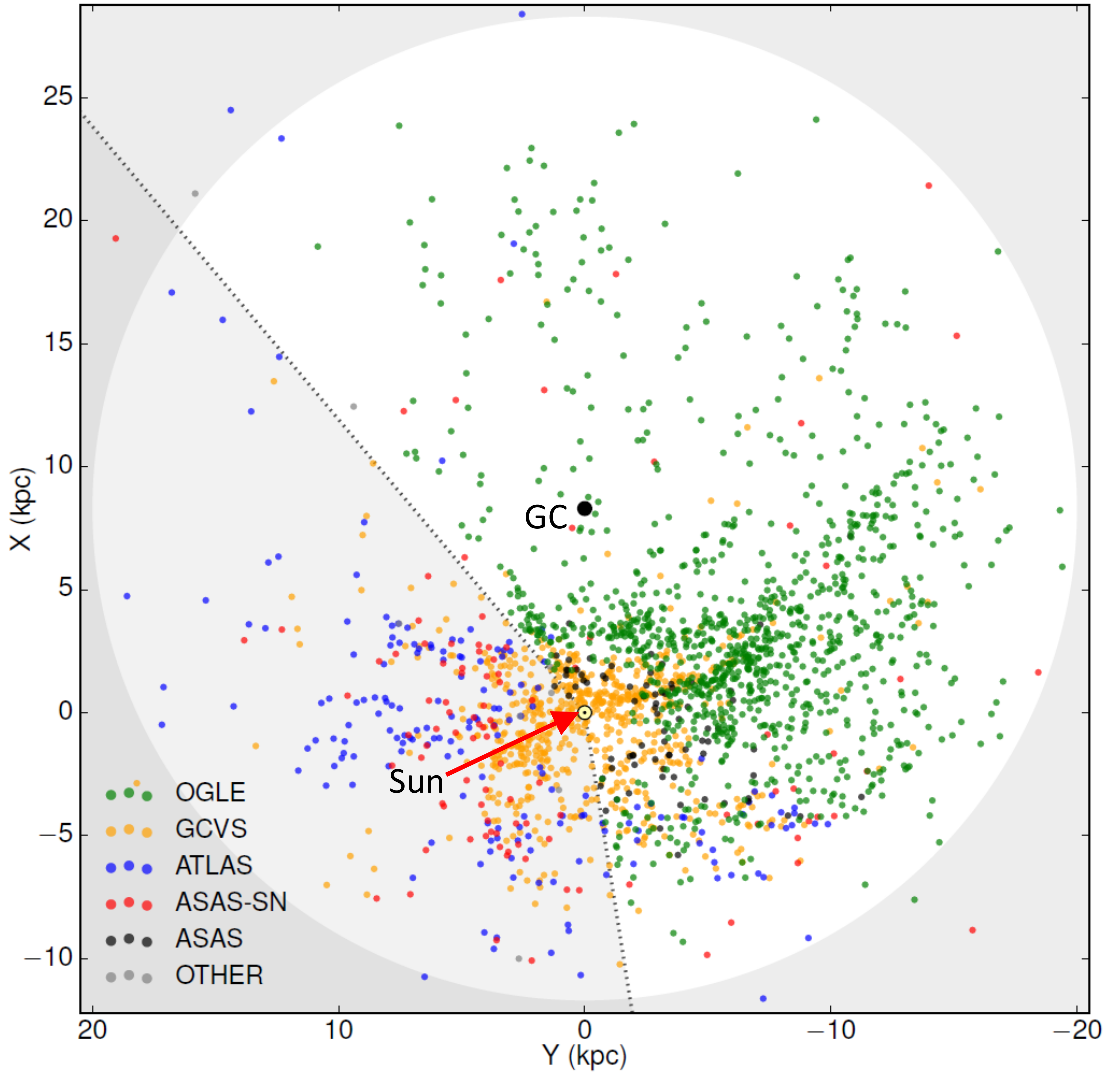
Classical Cepheids in the Milky Way



900 → 2400

Skowron et al. (2018)

Classical Cepheids in the Milky Way

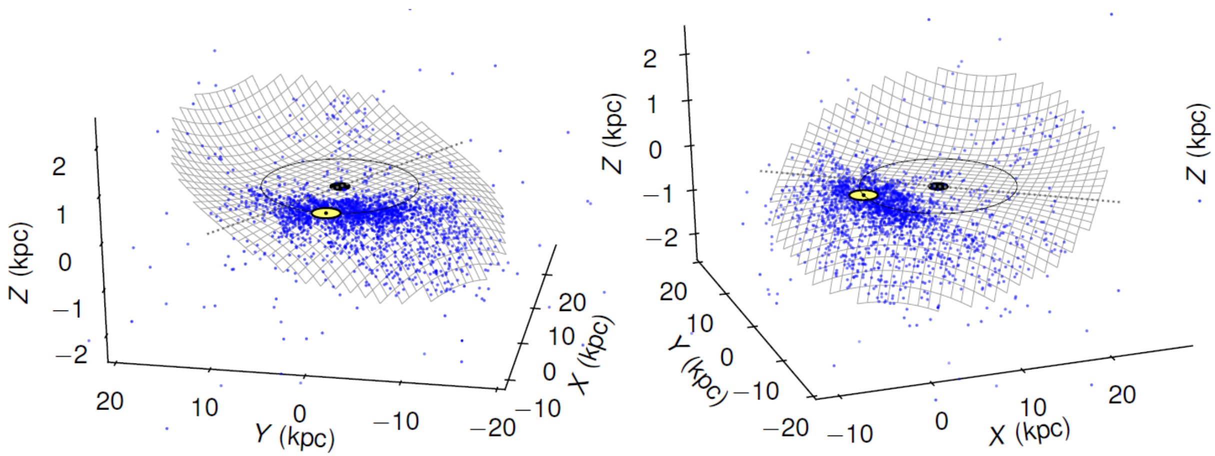


- OGLE
- GCVS
- ATLAS
- ASAS-SN
- ASAS
- OTHER

Skowron et al. (2018)

Classical Cepheids in the Milky Way

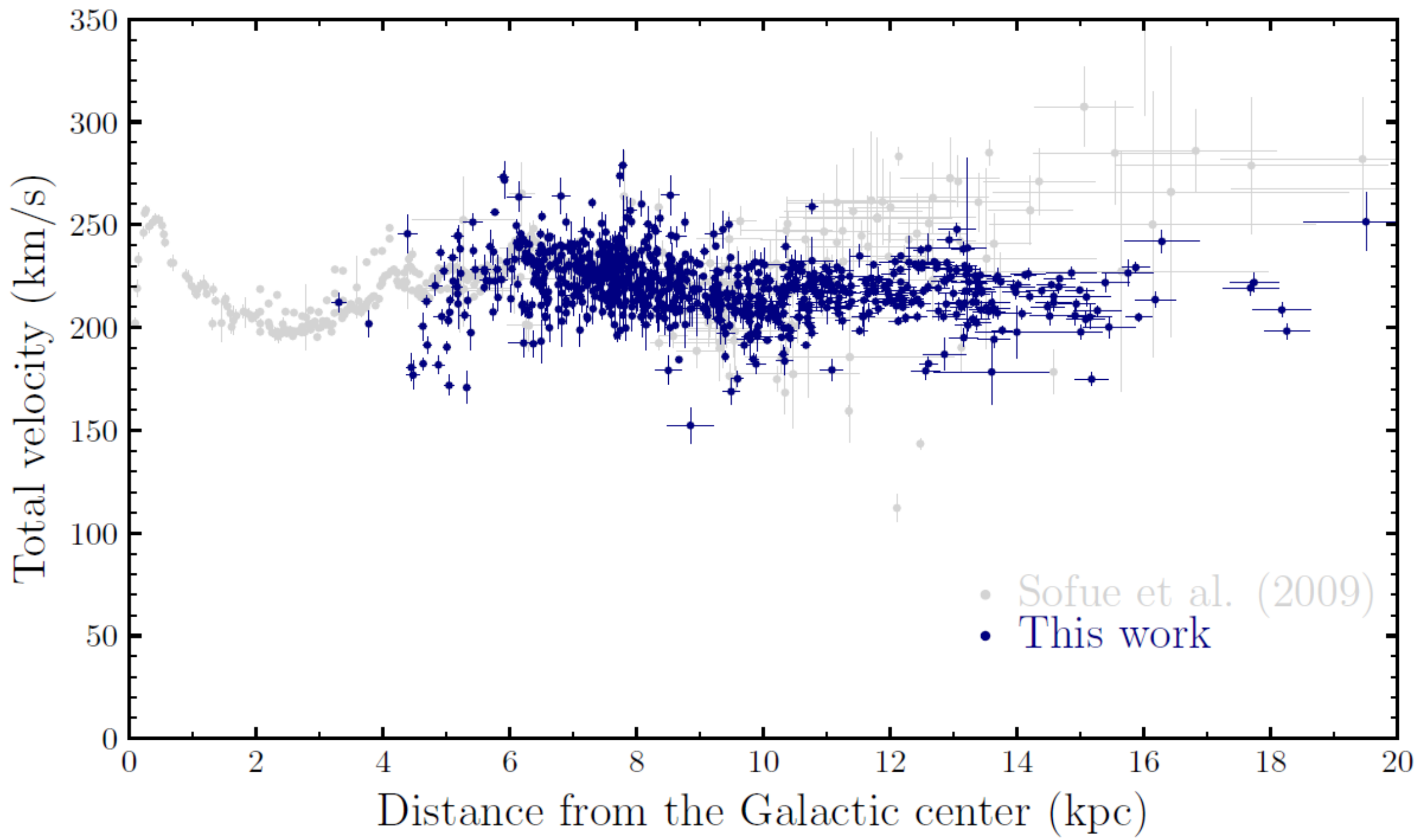
Warping of the Milky Way disk



Skowron et al. (2018)

Classical Cepheids in the Milky Way

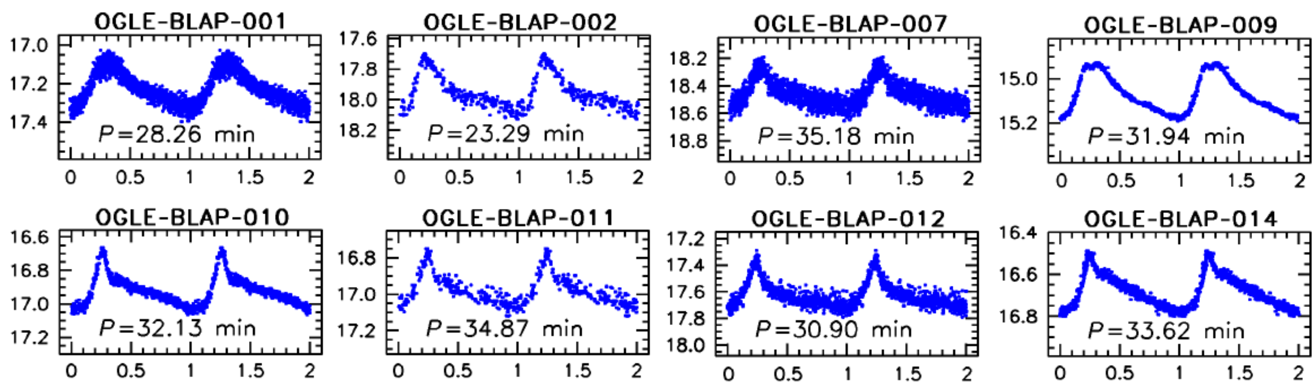
Flat rotation curve of the Milky Way



Mróz et al. (2018)

NEW TYPES OF VARIABLE STARS

Blue Large-Amplitude Pulsators (BLAPs)



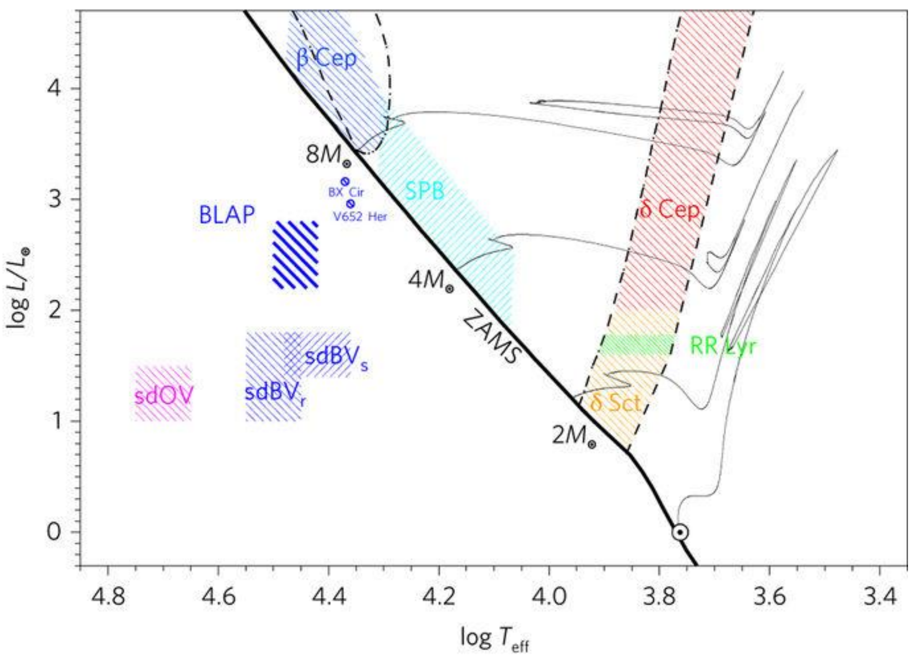
Pietrukowicz et al. (2017)

Fundamental-mode pulsating stars

Periods: P = 20 – 40 min

Eff. temperature: T_{eff} ~ 30 000 K

Surface gravity: log g ~ 4.6



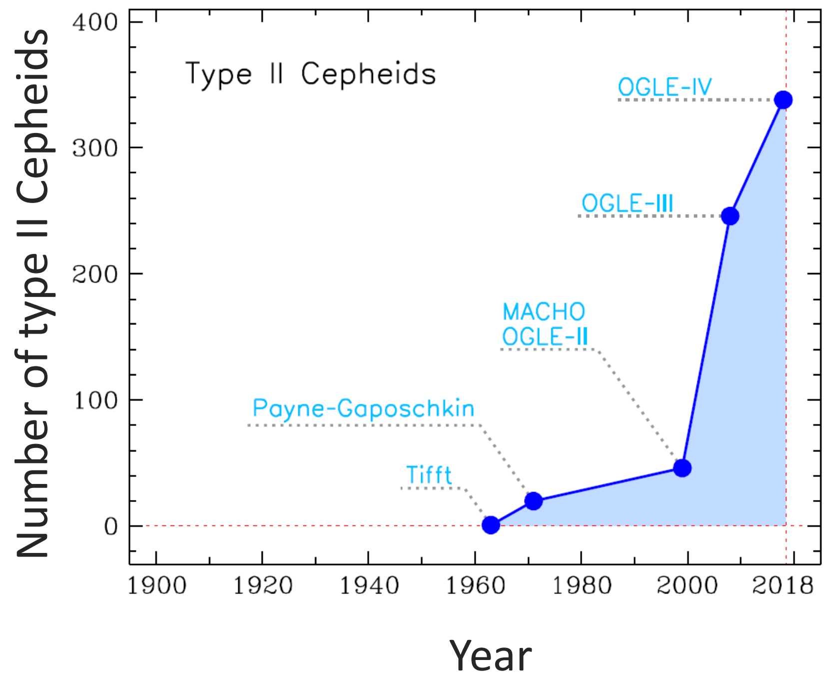
Type II Cepheids

LMC: **285** objects

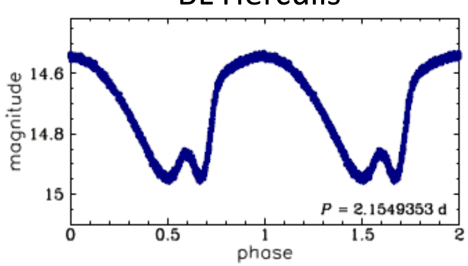
SMC: **53** objects

GB: **924** objects

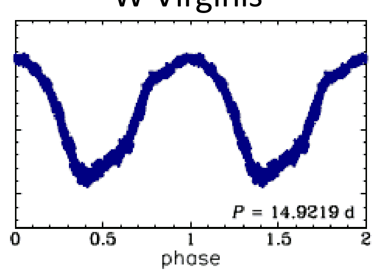
Type II Cepheids in the Magellanic Clouds



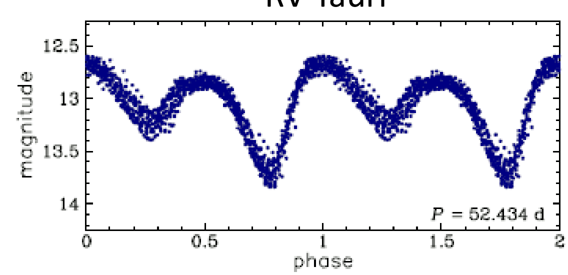
BL Herculis



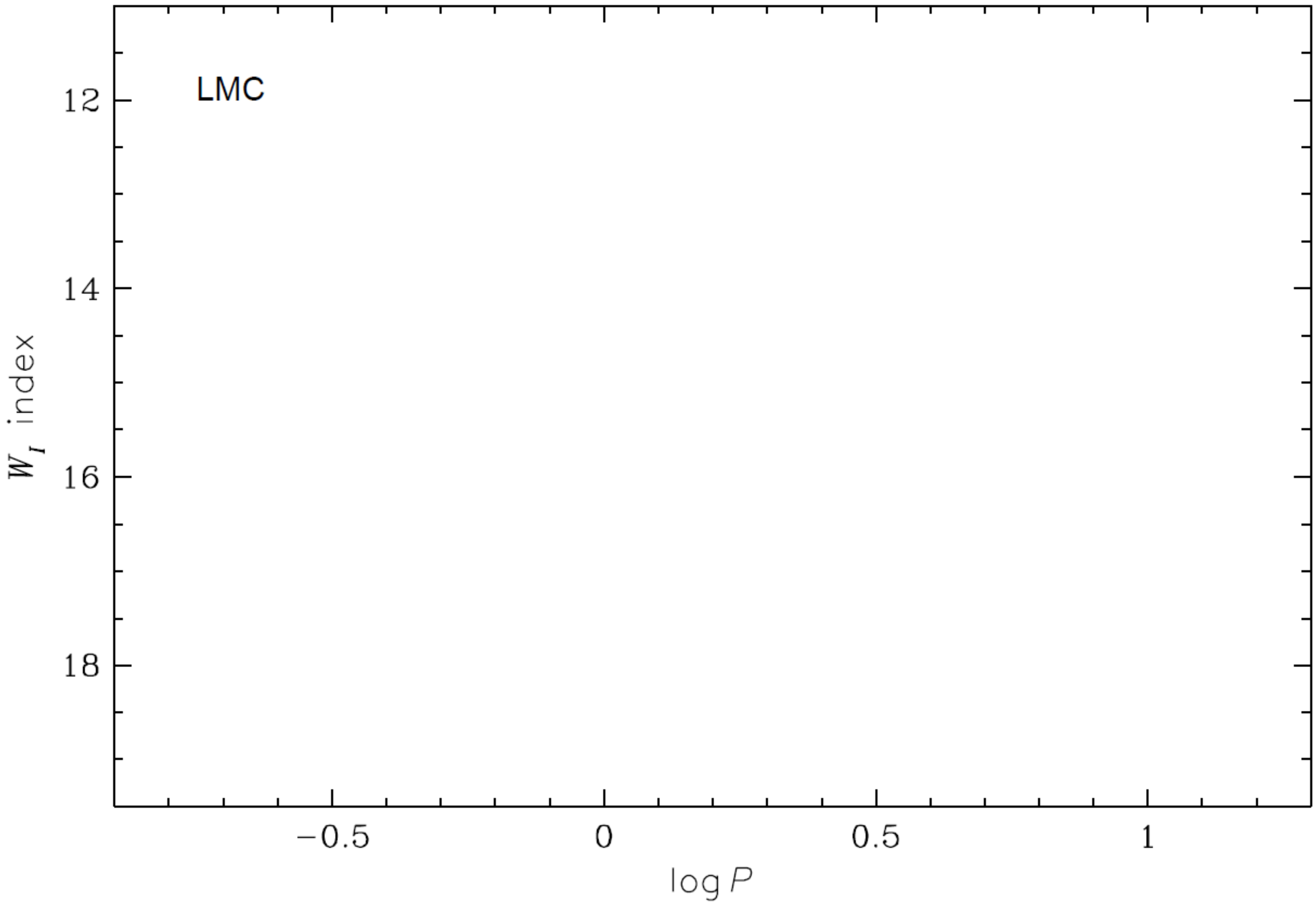
W Virginis



RV Tauri



PL relations for classical pulsators



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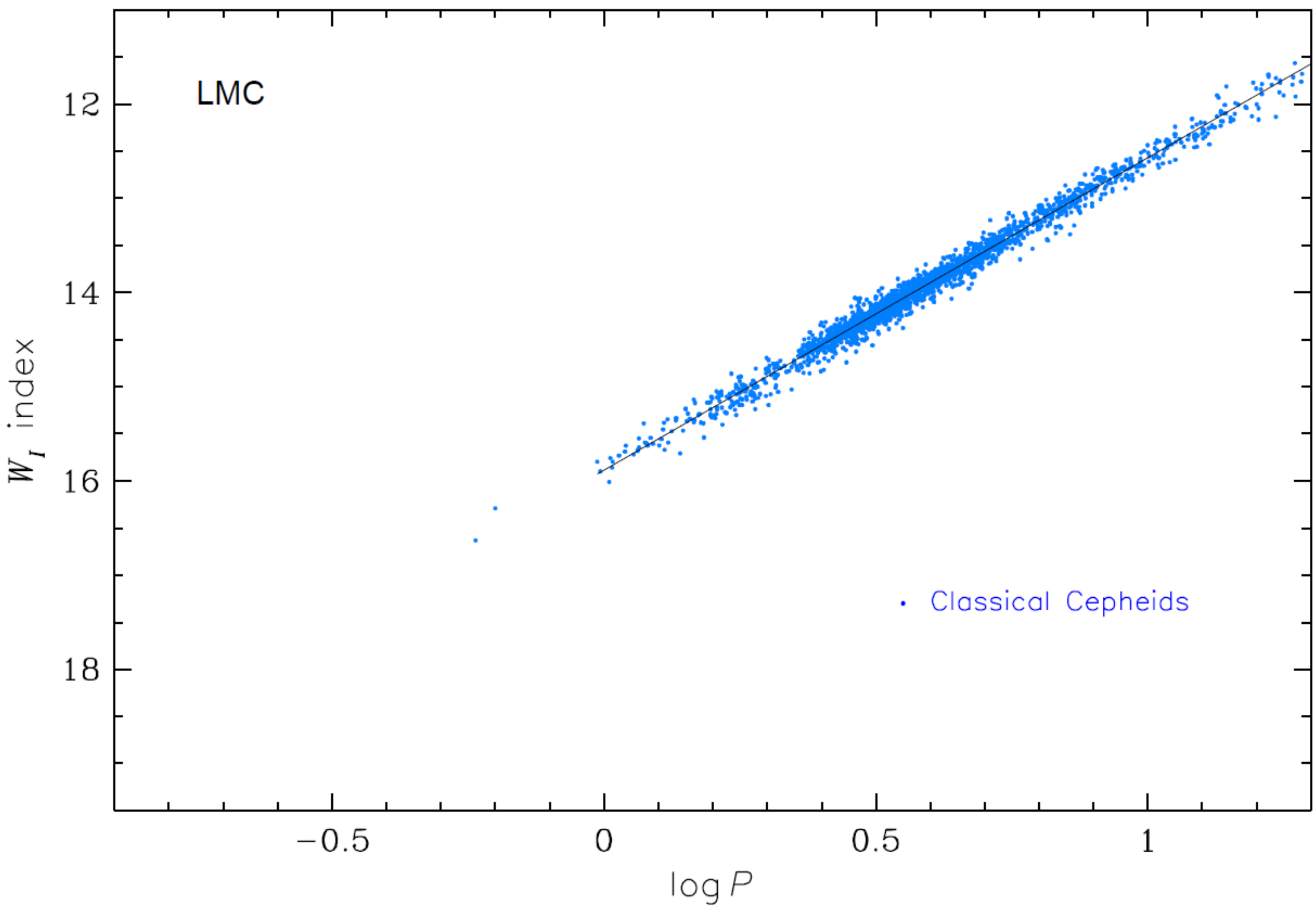

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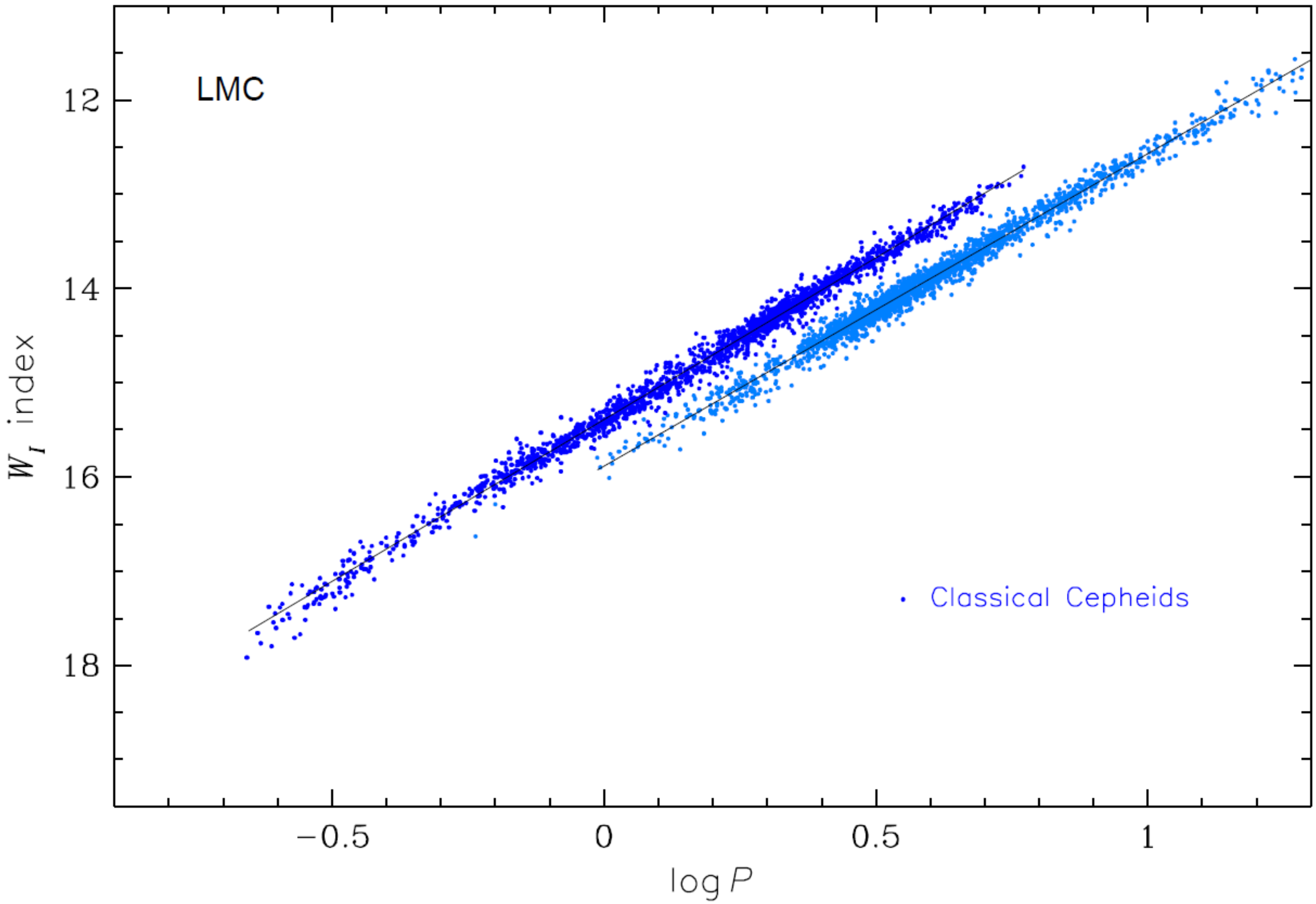

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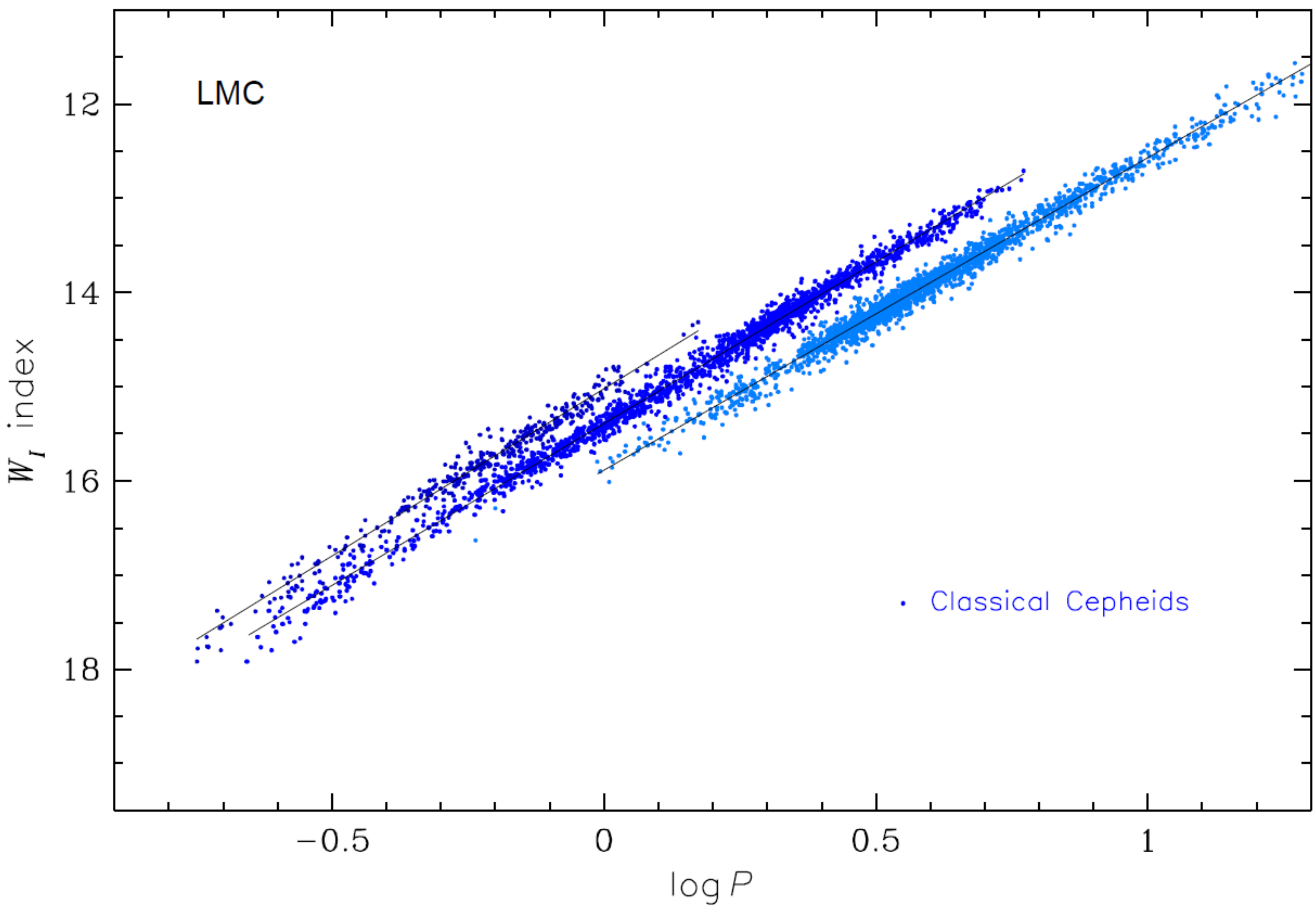

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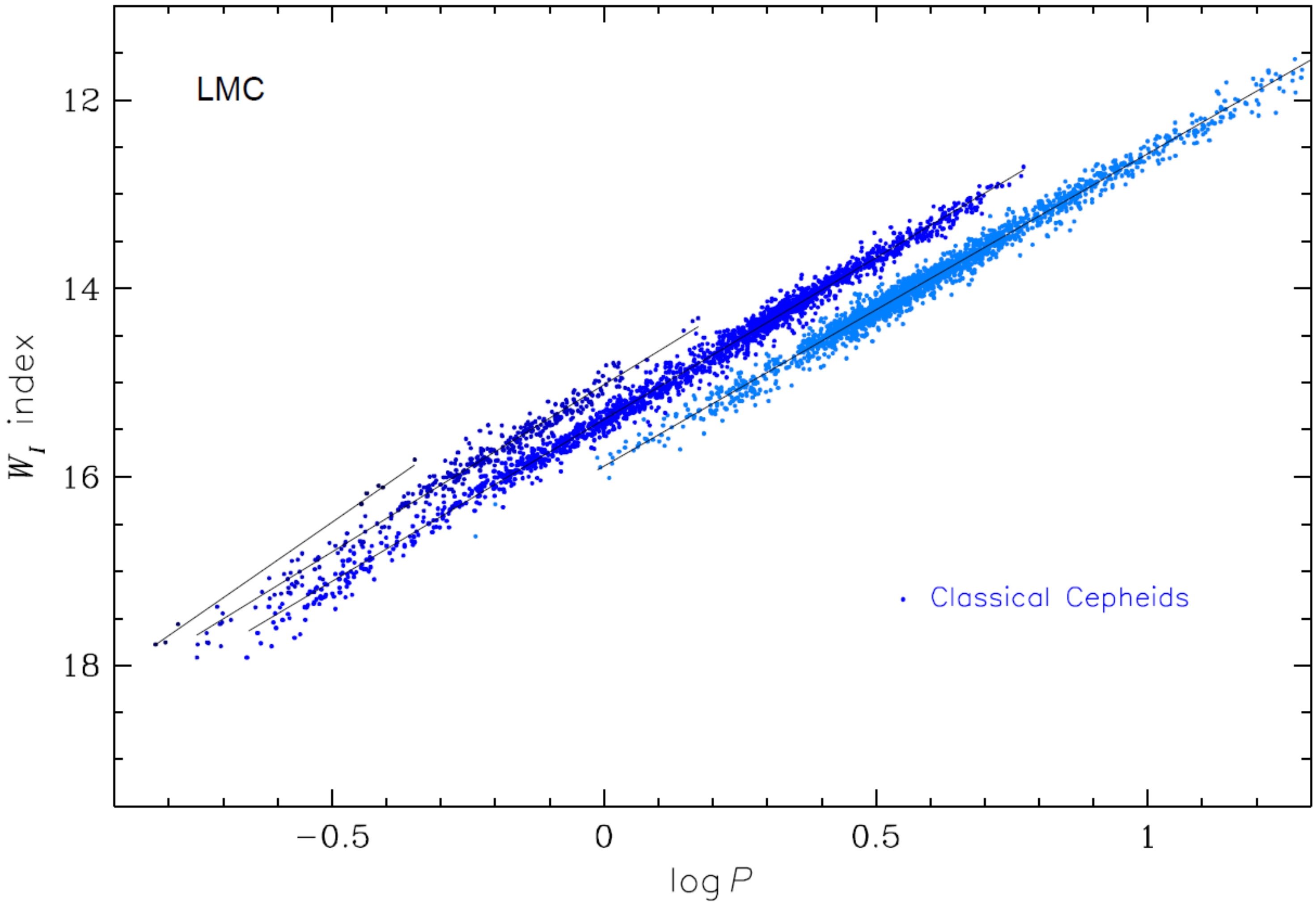

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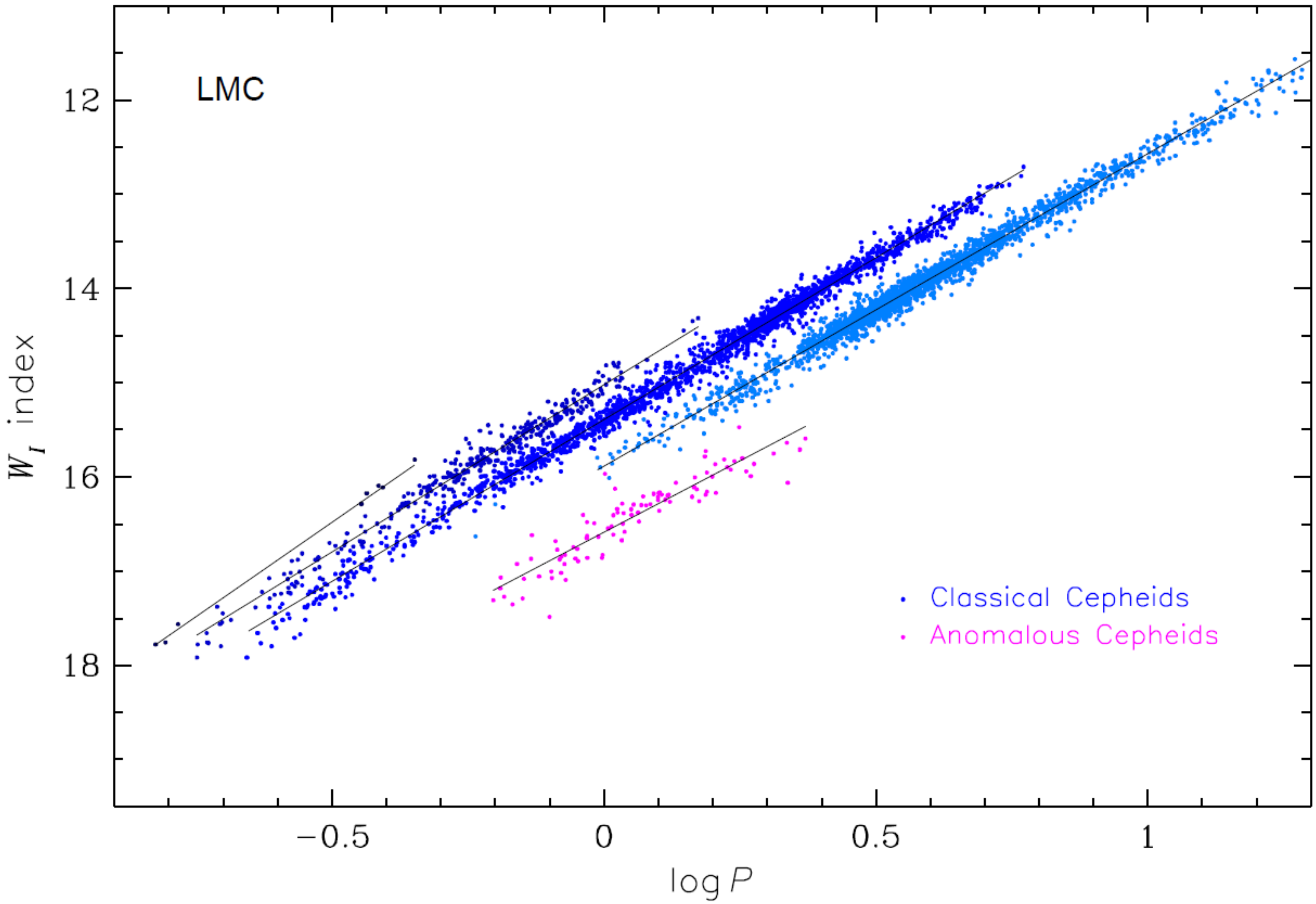

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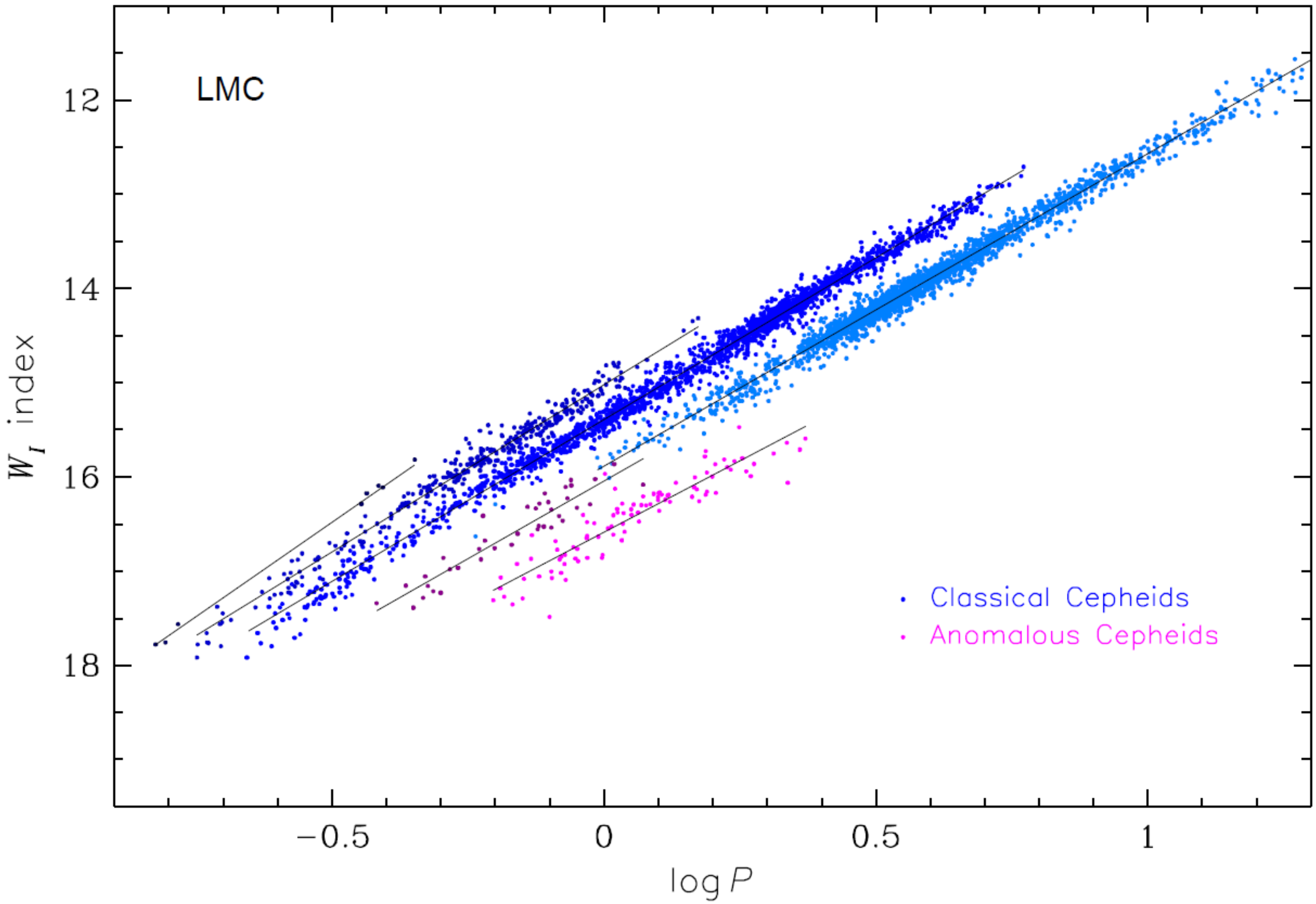

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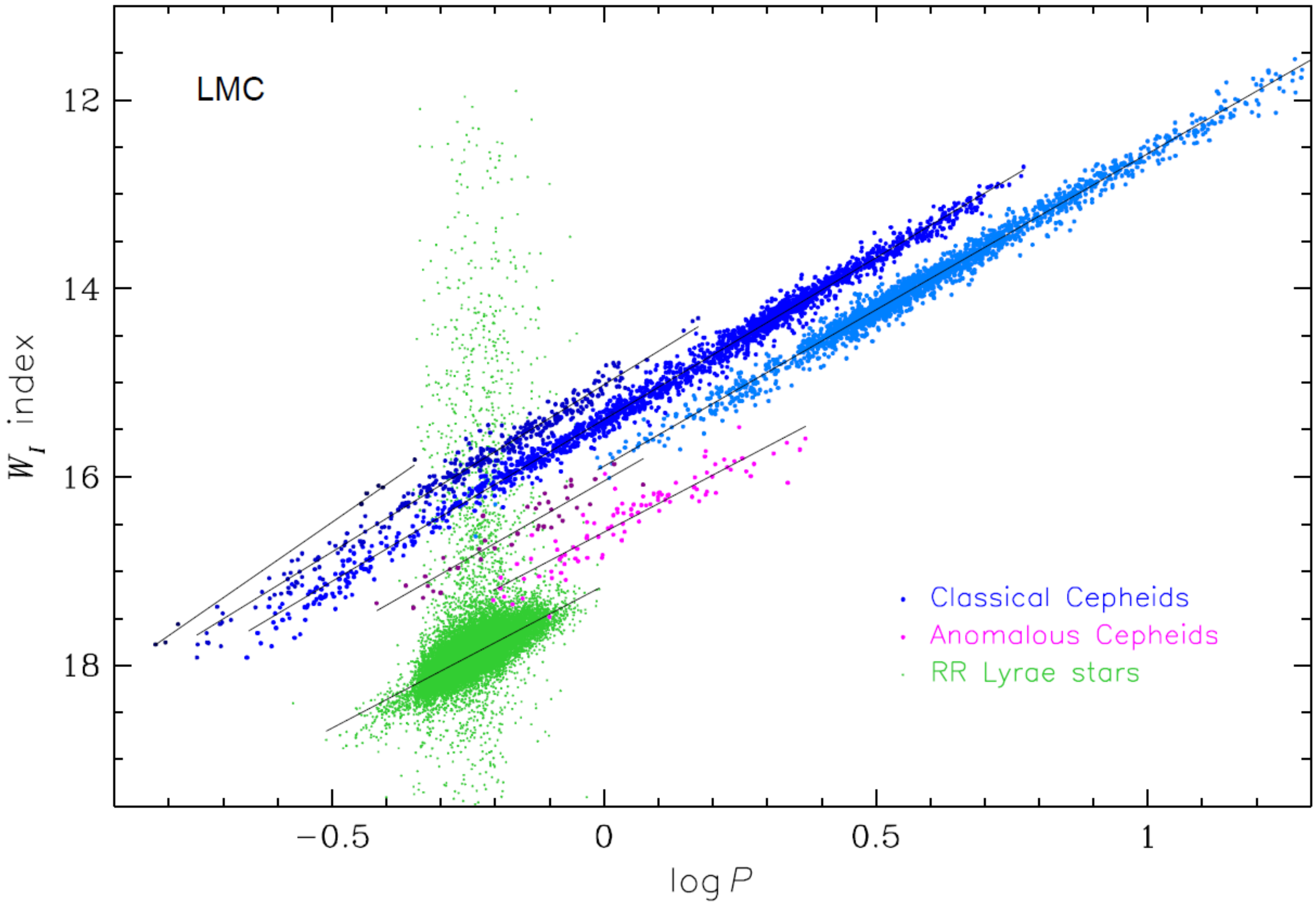

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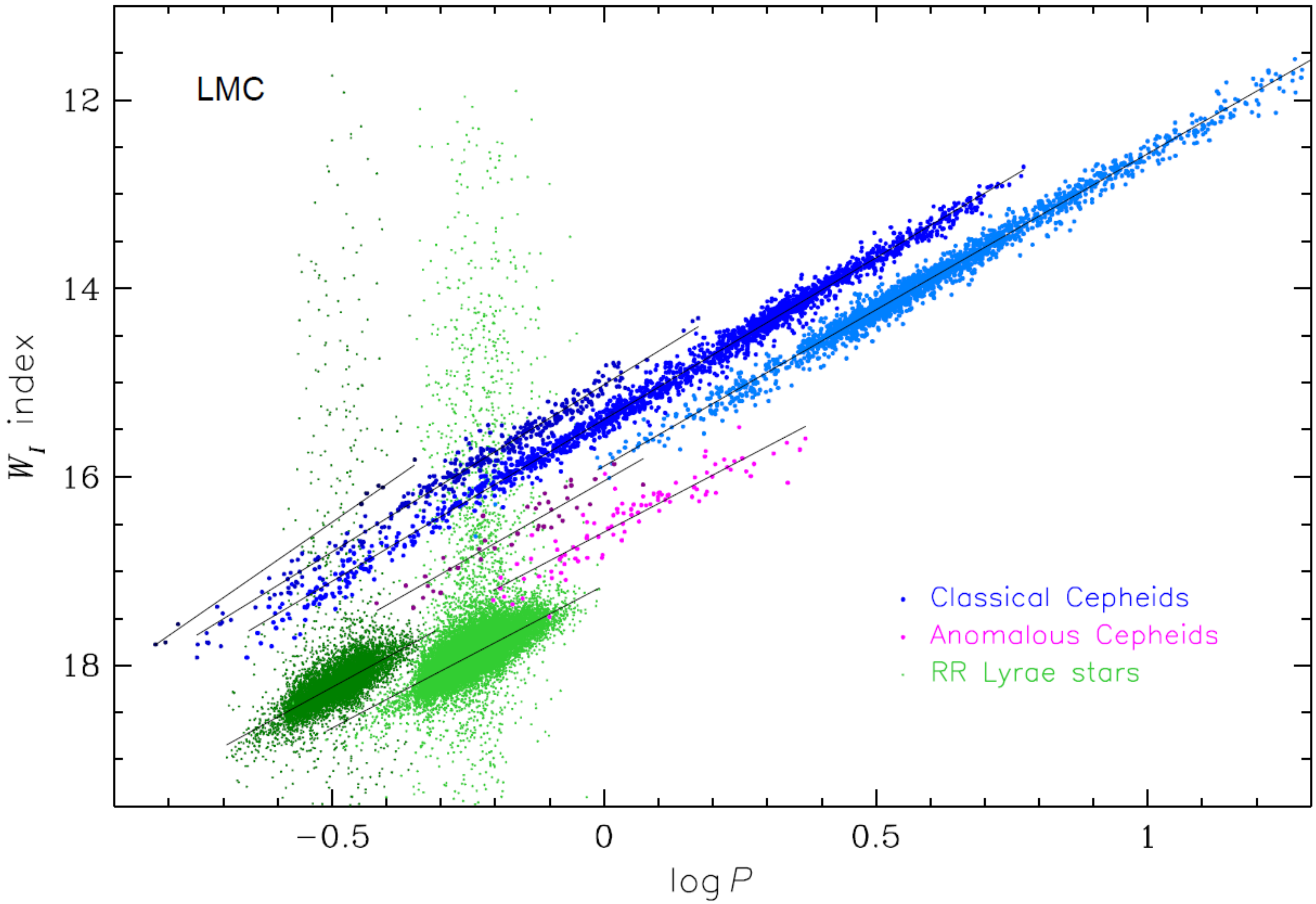

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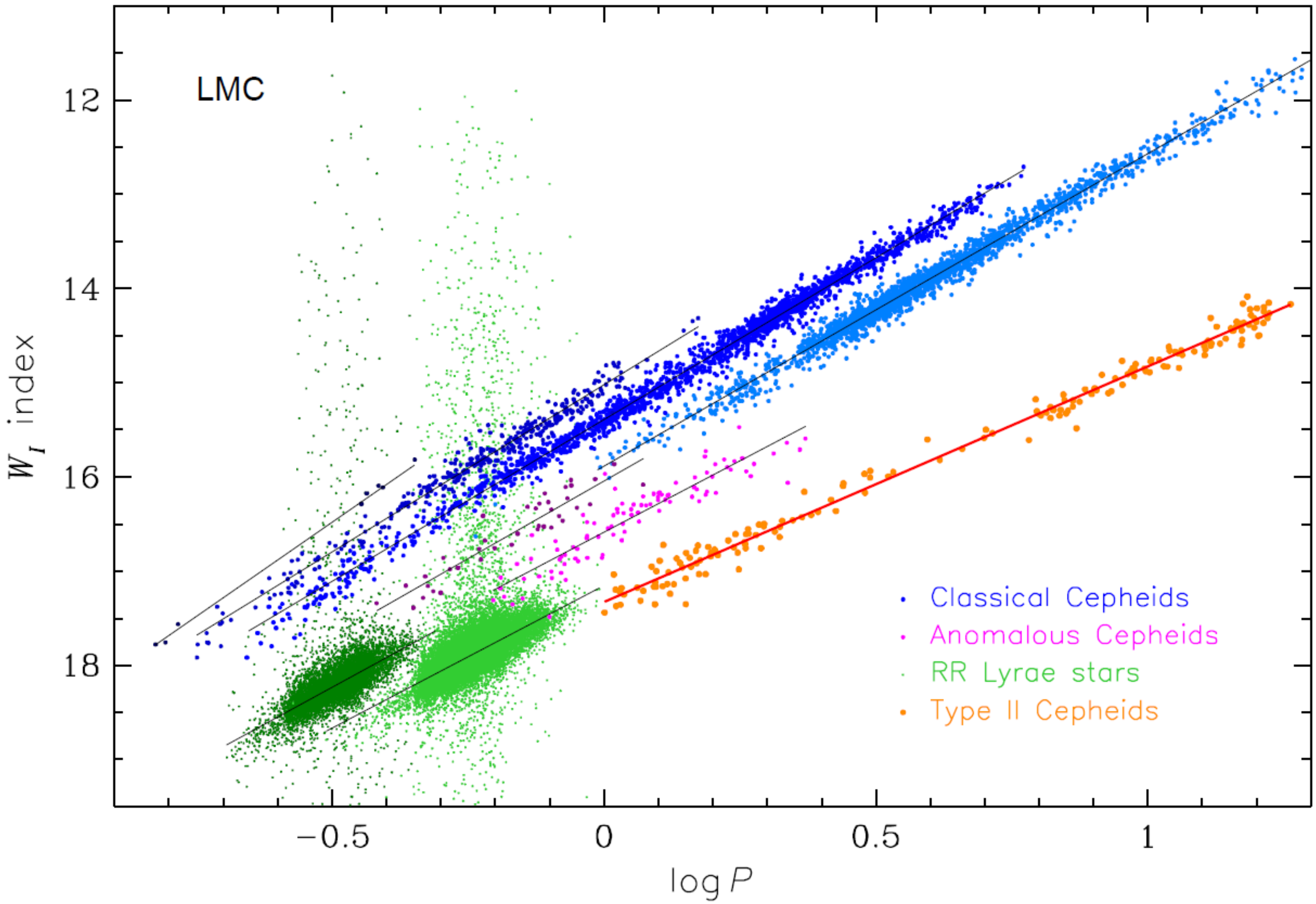
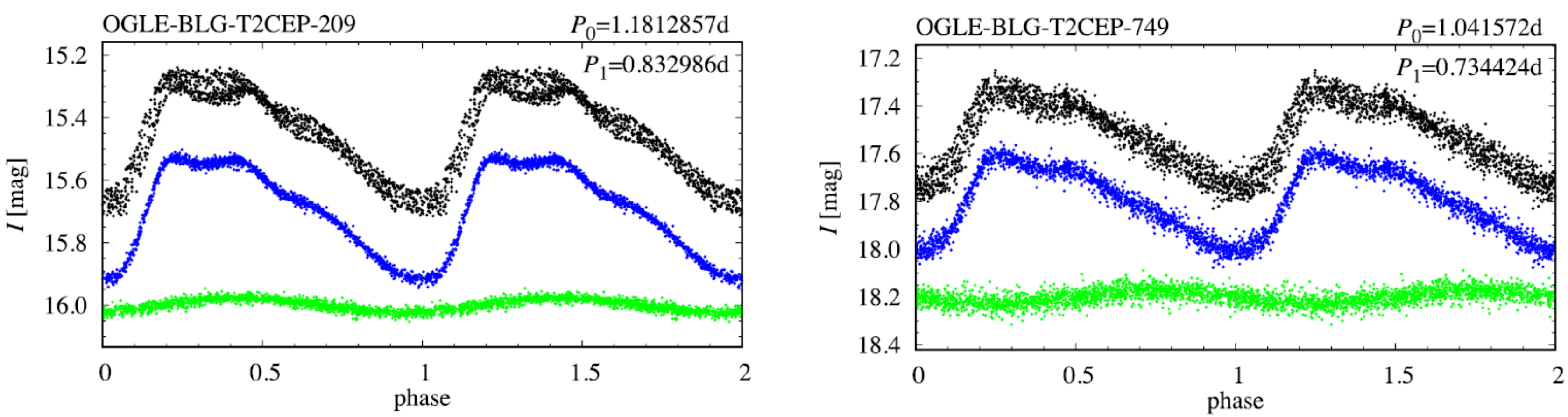


Double-mode type II Cepheids

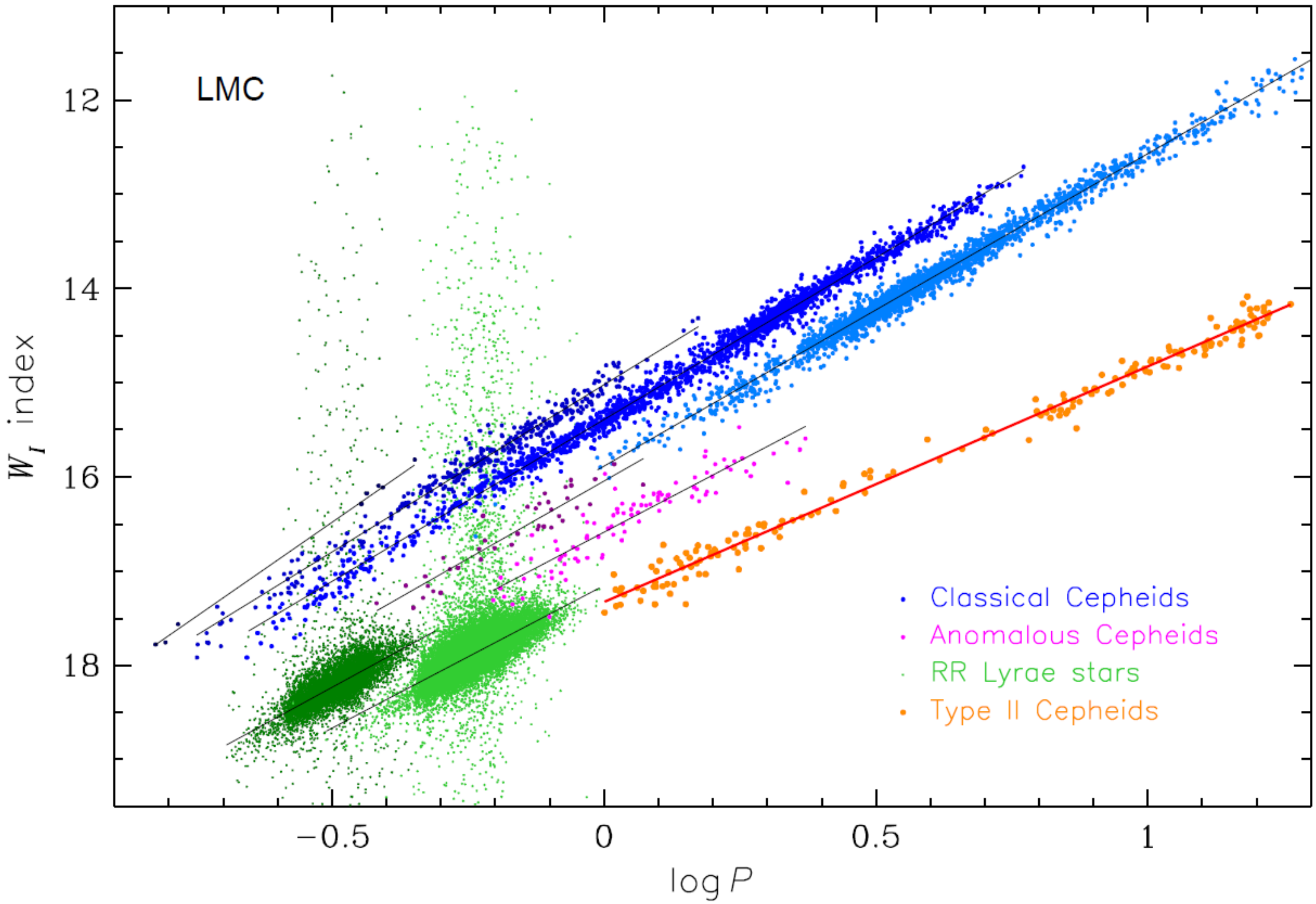
Smolec et al. (2018) – the first type II Cepheids (BL Herculis stars) with two radial modes excited.

$$P_{1O}/P_{F} \approx 0.7$$

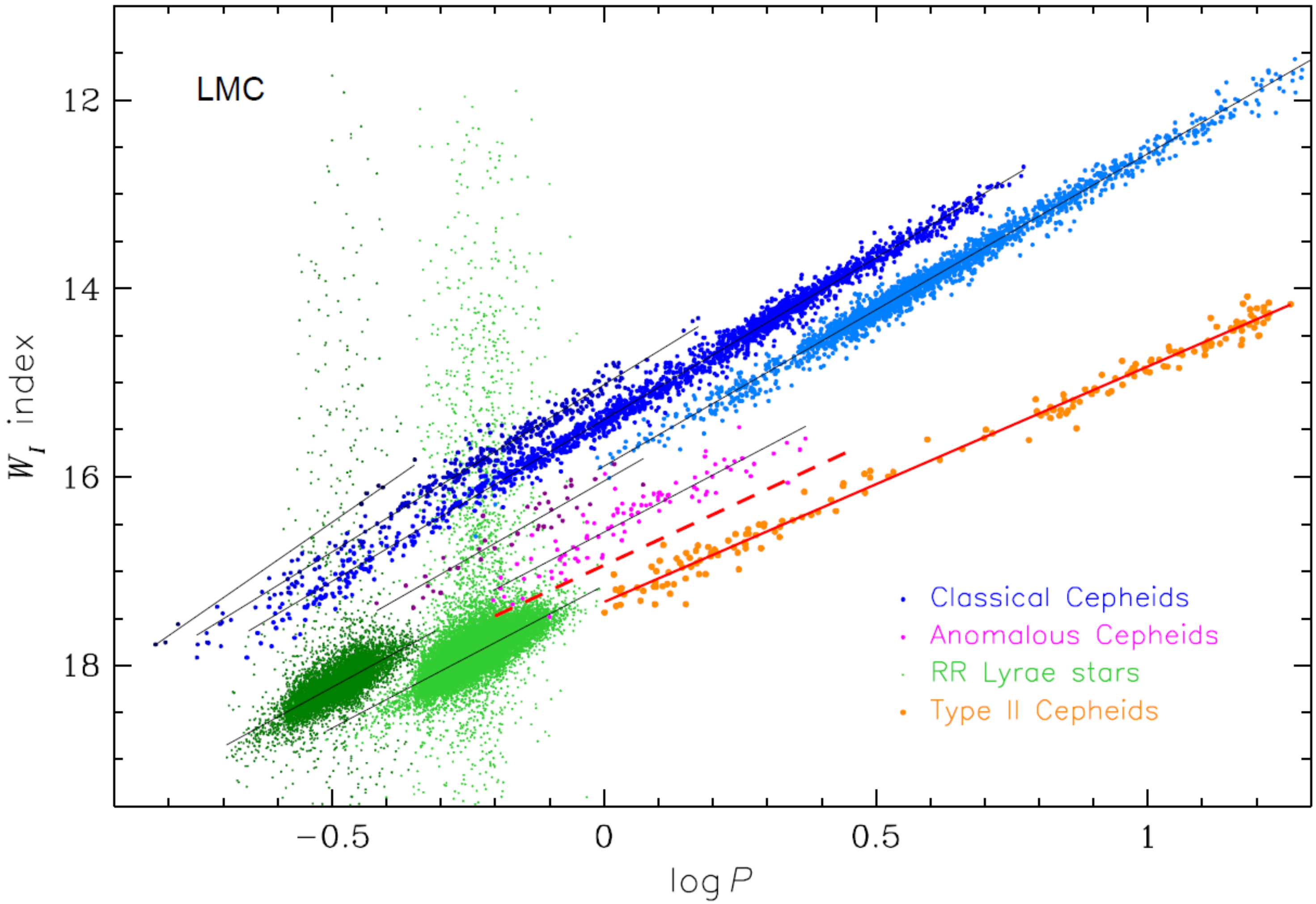


Smolec et al. (2018)

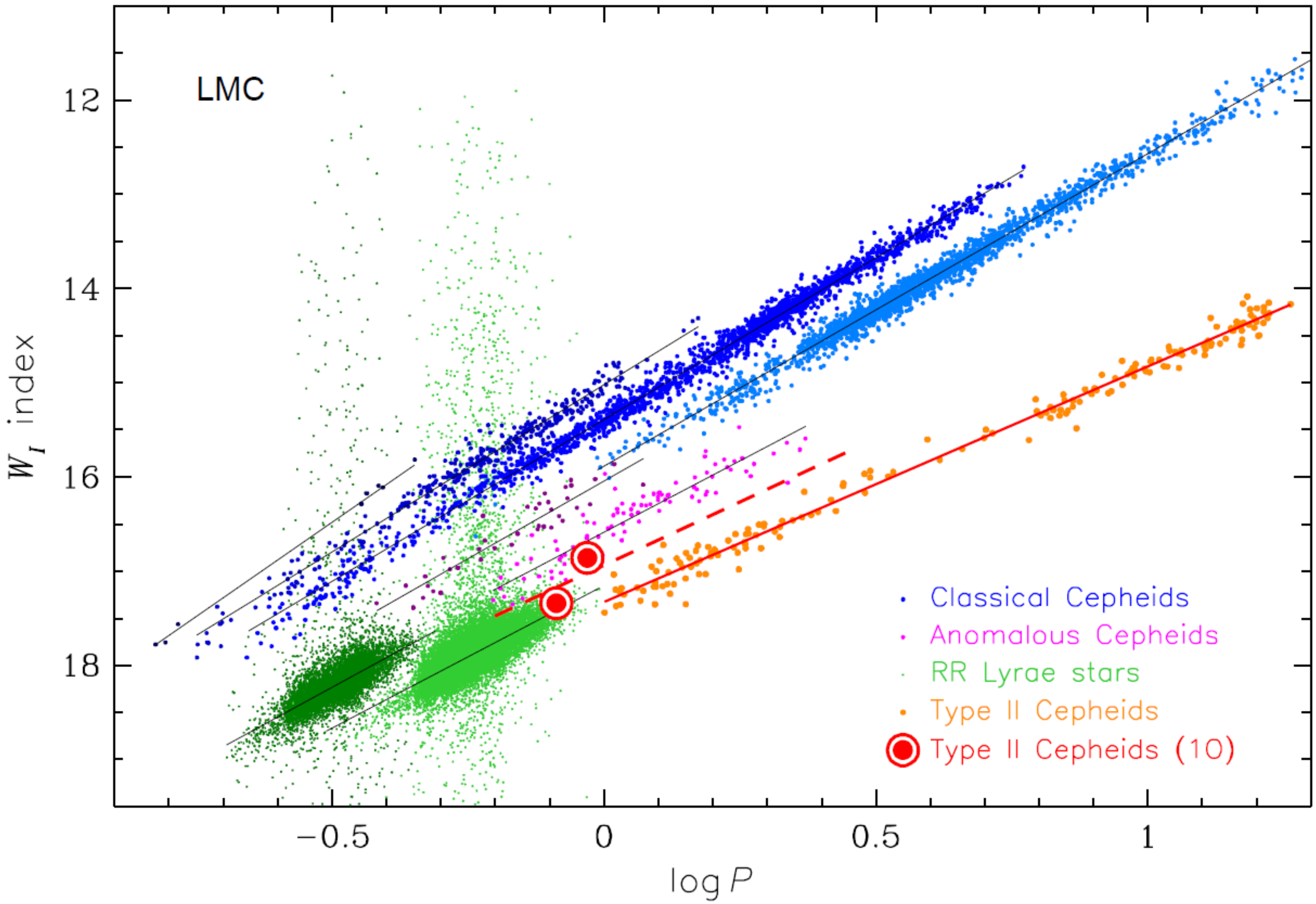
PL relations for classical pulsators



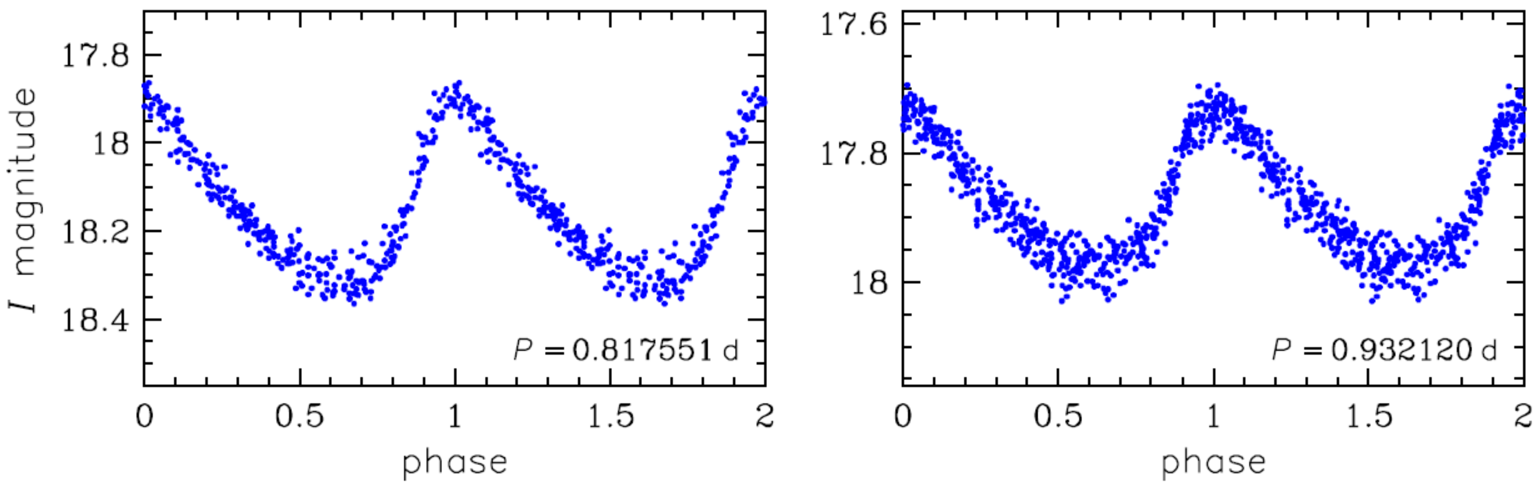
PL relations for classical pulsators



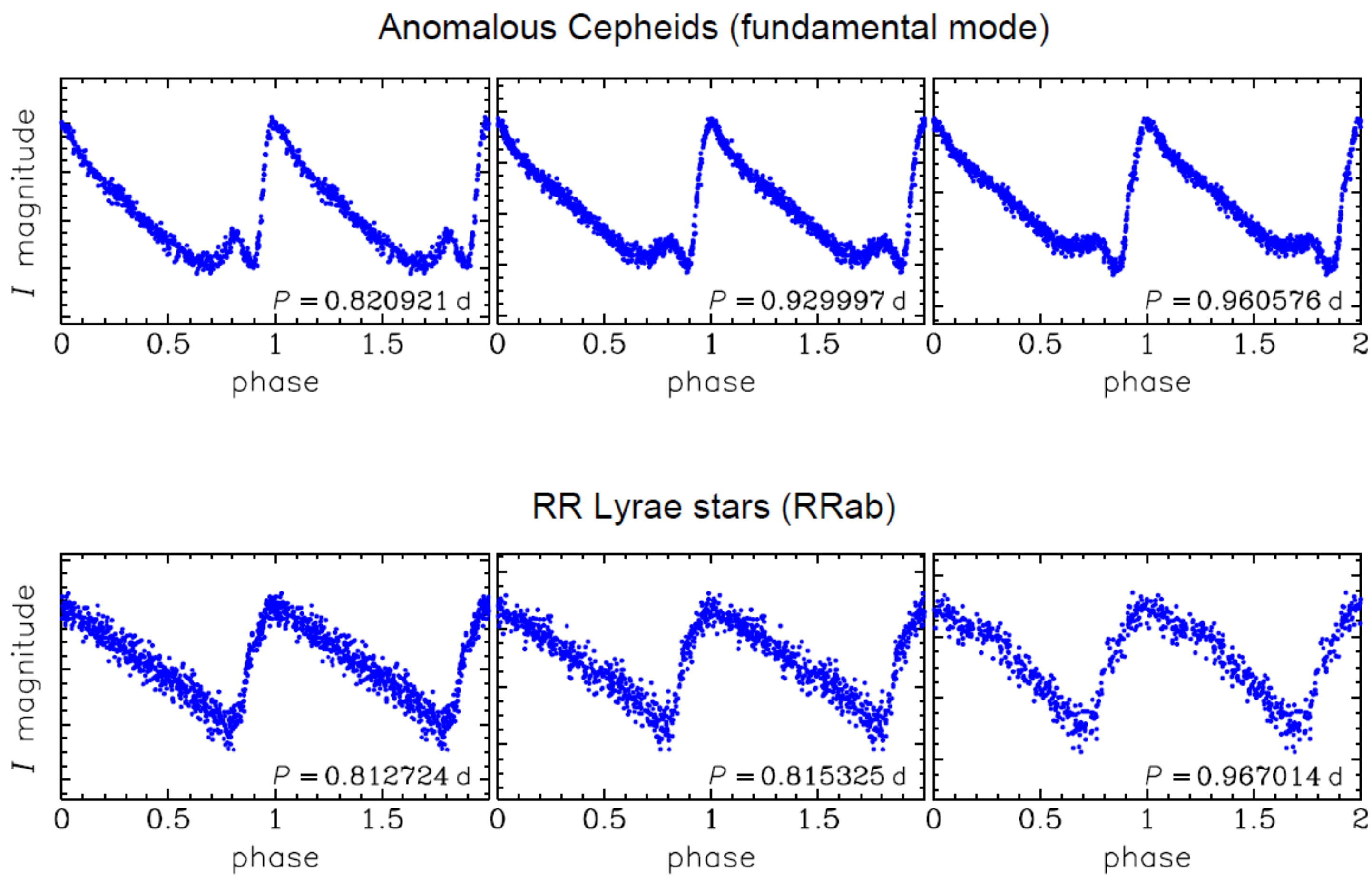
PL relations for classical pulsators



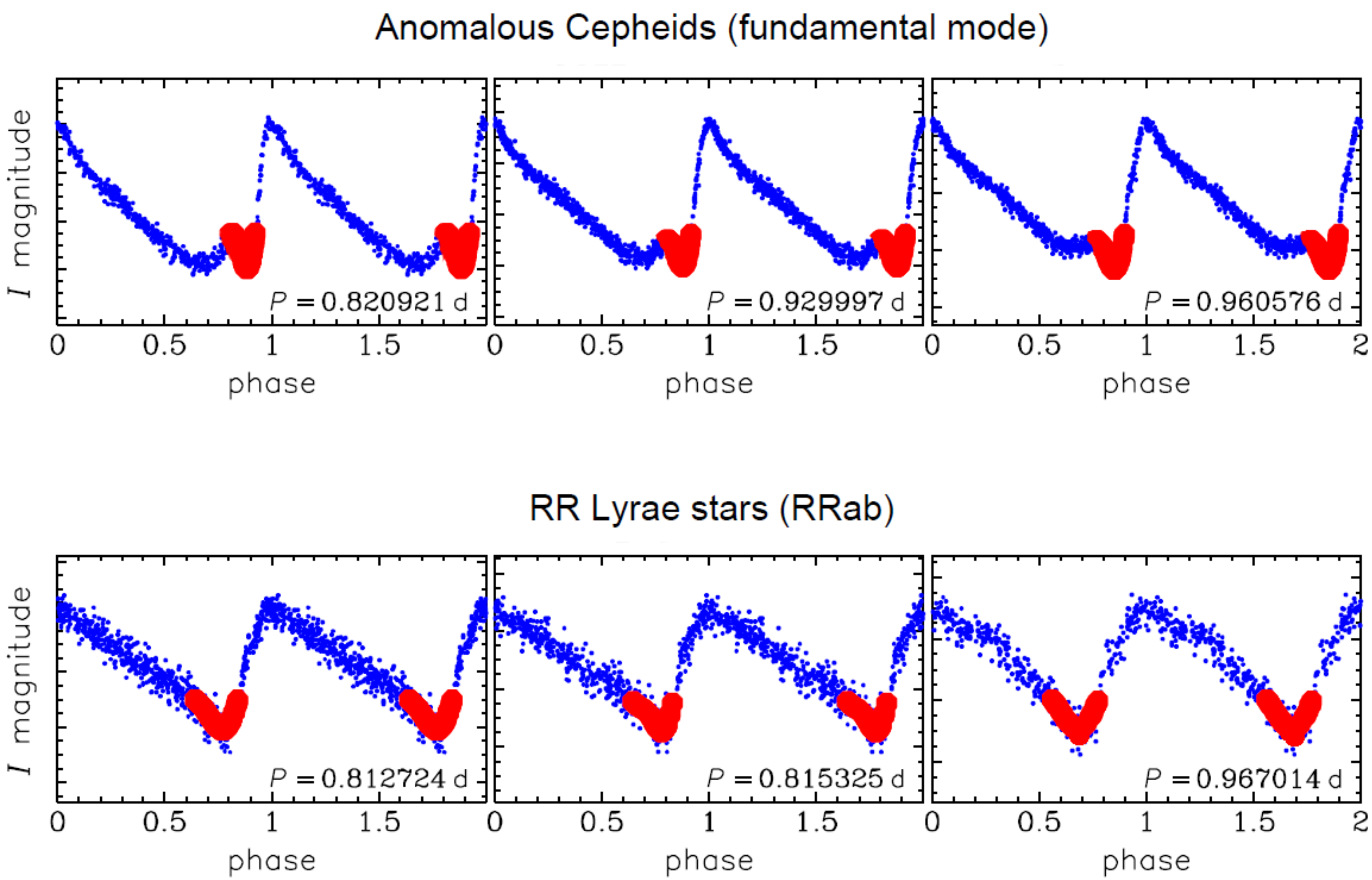
First-overtone type II Cepheids



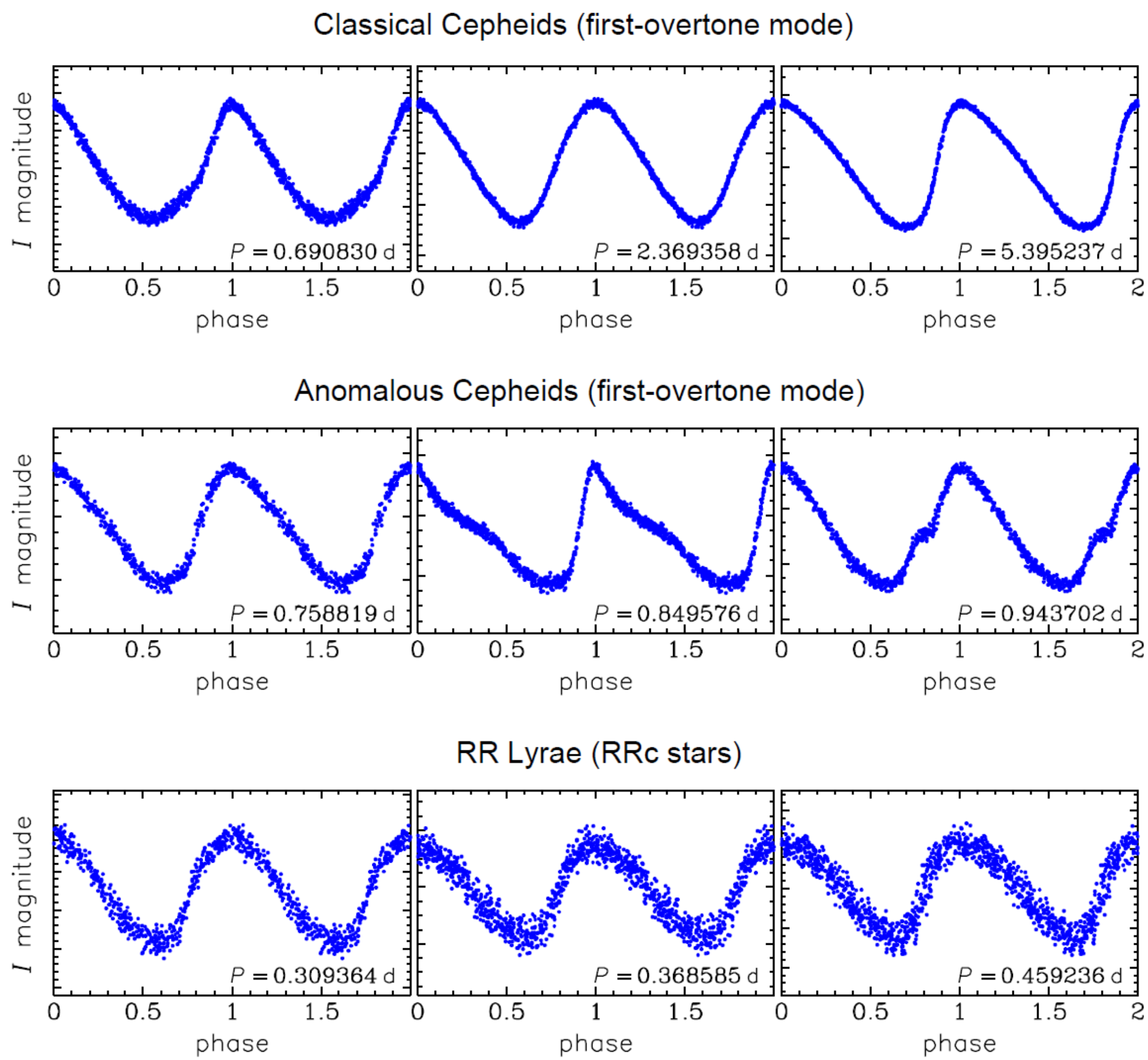
Fundamental-mode classical pulsators



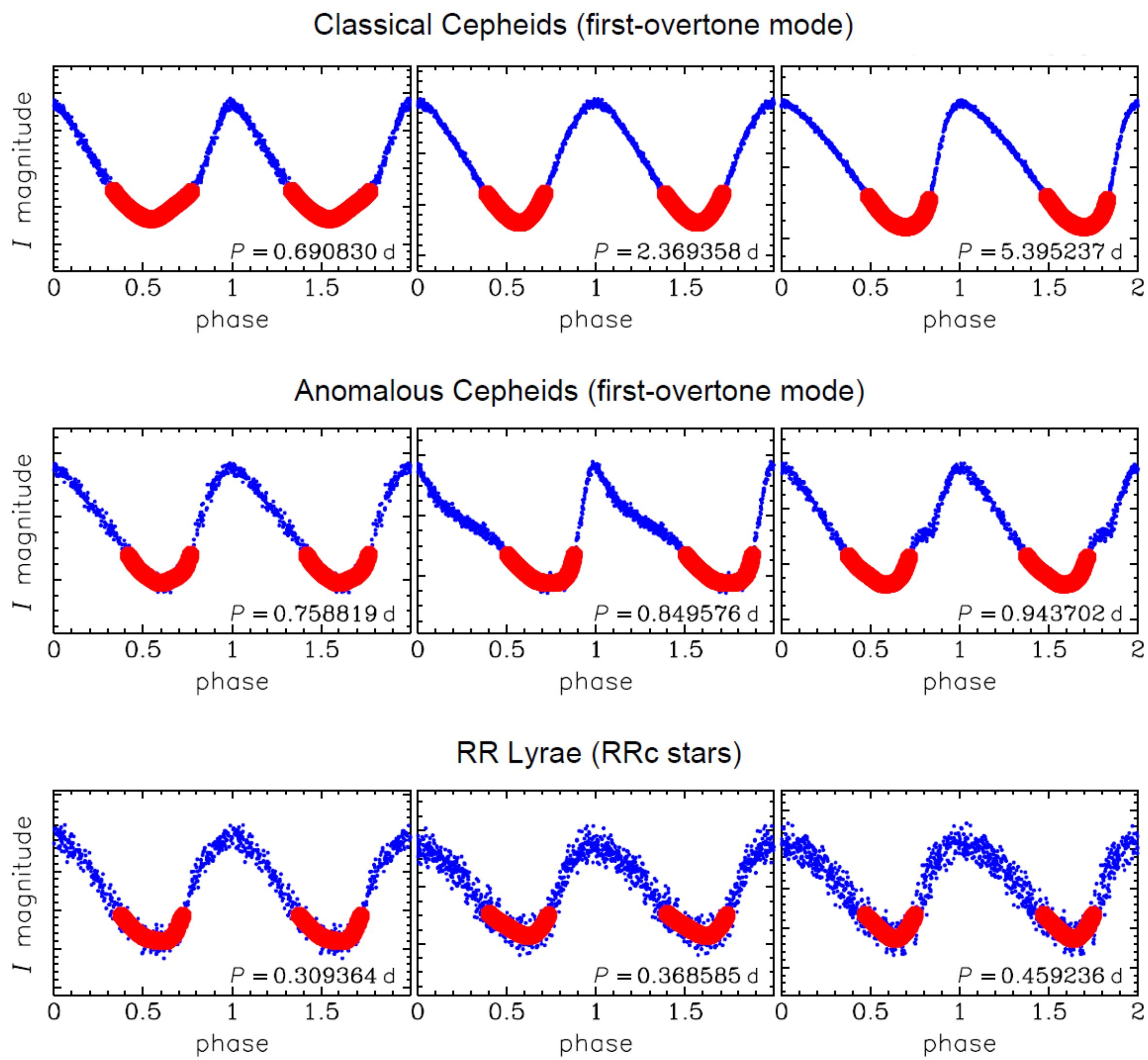
Fundamental-mode classical pulsators



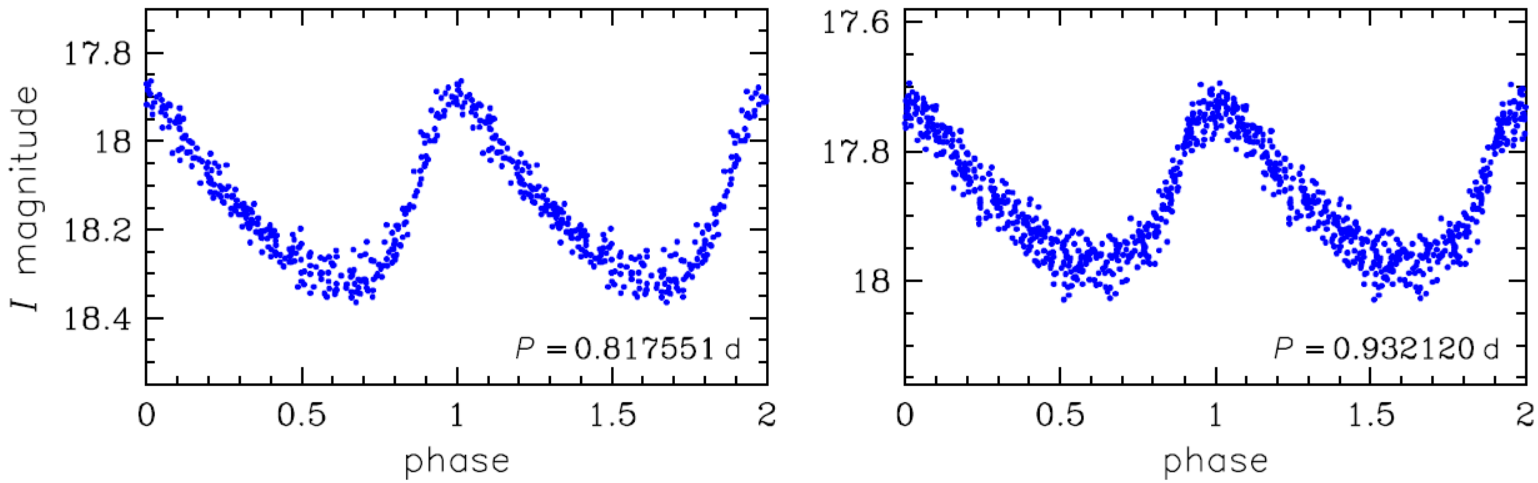
First-overtone classical pulsators



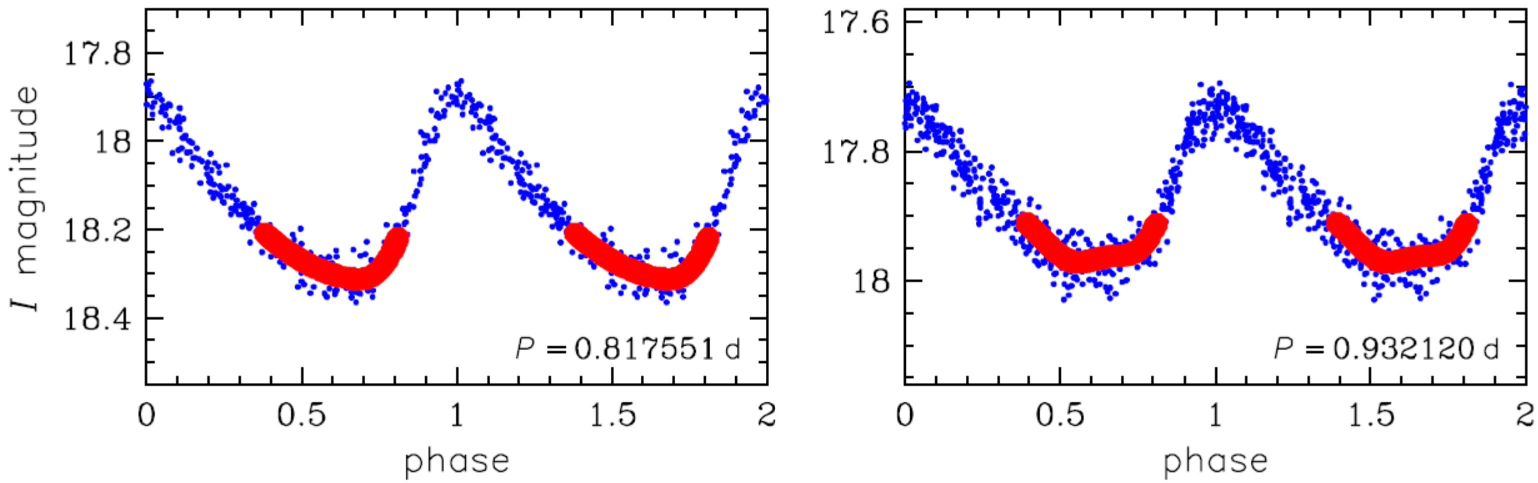
First-overtone classical pulsators



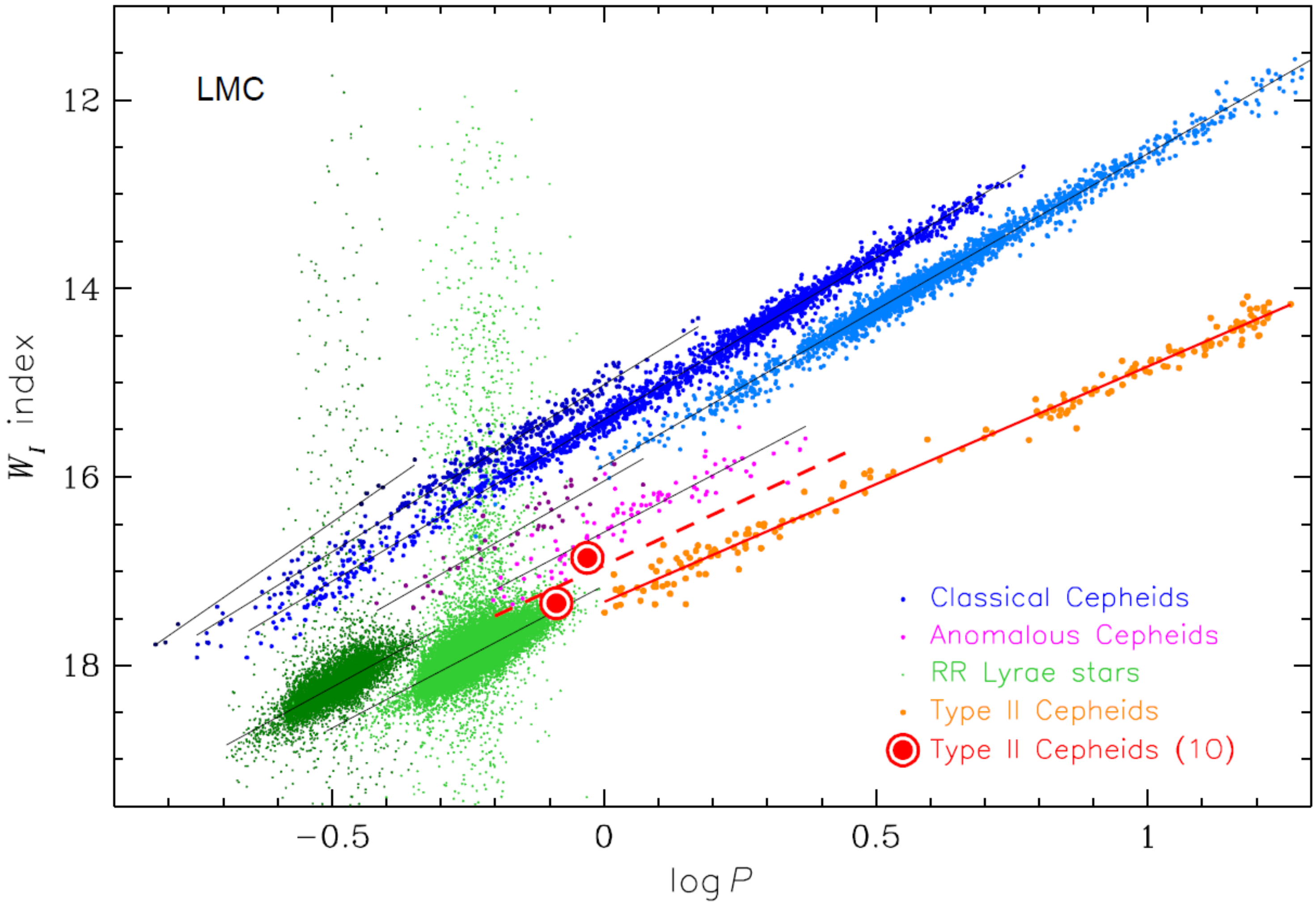
First-overtone type II Cepheids



First-overtone type II Cepheids



PL relations for classical pulsators



CONCLUSIONS

- The OGLE project has increased the number of known variable stars by an order of magnitude.
- Huge samples of variable stars are crucial for
  - exploring the statistical properties of stars
  - studying of the structures, formation and evolution of galaxies
  - detecting new types of behaviors and phenomena in variable stars
- Long-term OGLE photometry allows us to study non-stationary behaviors and evolutionary changes in variable stars.