OGLE photometry – an invaluable resource for stellar statistical and case studies

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- I am not the OGLE team member, but I am big fan of OGLE and frequent user of its data

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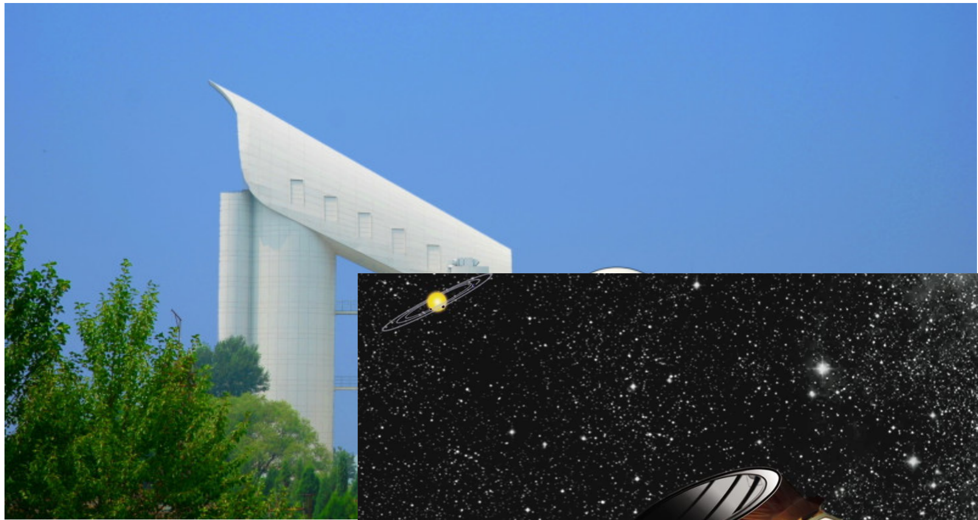
LAMOST, Kepler and OGLE

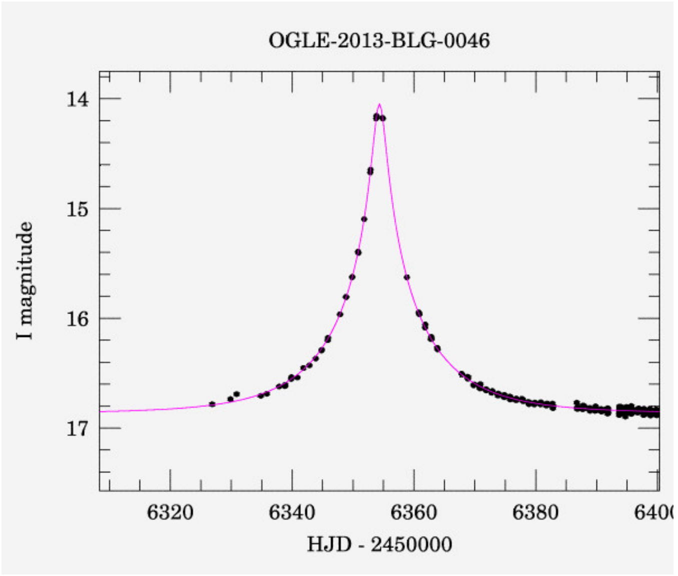
LAMOST, Kepler and OGLE



LAMOST, Kepler and OGLE

The OGLE project – idea, basic information

- The Optical Gravitational Lensing Experiment – OGLE – a long term project with the main goal of searching for the dark matter employing the microlensing events
- The idea was proposed by Bohdan Paczyński
- the project is led by the Warsaw University Observatory since 1992
- PI: prof. Andrzej Udalski
- OGLE telescope is located in Las Campanas Observatory, Chile
- project webpage: `http://ogle.astrouw.edu.pl/`



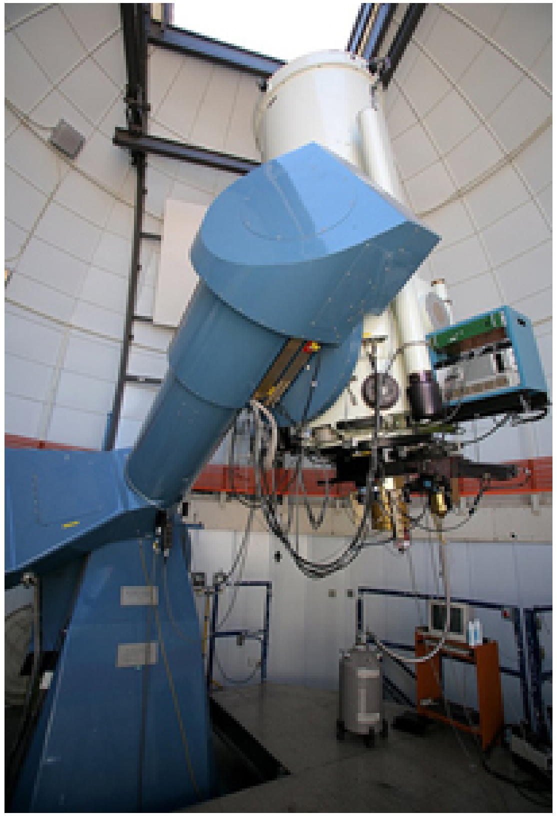
images: OGLE webpage and wikipedia.org

Four phases of the OGLE project

- **OGLE-I** (1992–1995)

⋆ 1m Swope telescope at Las Campanas was used, 2048×2048 CCD camera

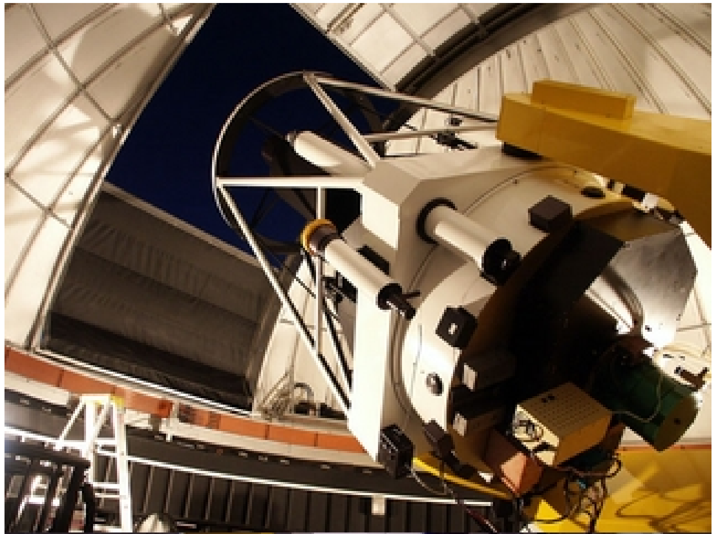
⋆ telescope time for the project was limited

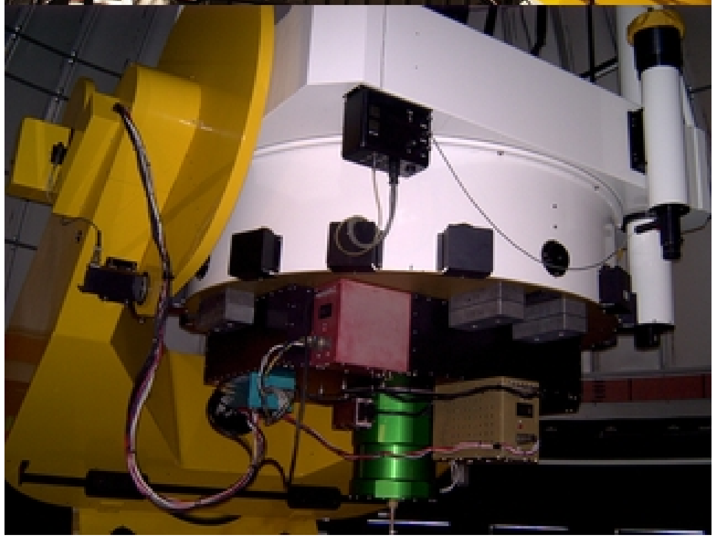


images: http://obs.carnegiescience.edu/swope

Four phases of the OGLE project

- **OGLE-II – OGLE-IV operate with the dedicated Polish telescope**





- 1.3m primary mirror diameter, Ritchey-Chretién system, two filters: I and V
- fully automated control

OGLE www, http://ogle.astrouw.edu.pl/

Four phases of the OGLE project

- **OGLE-II (1997–2001)**

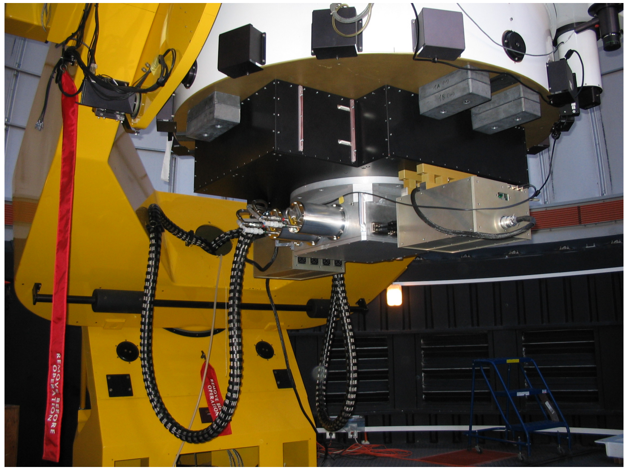
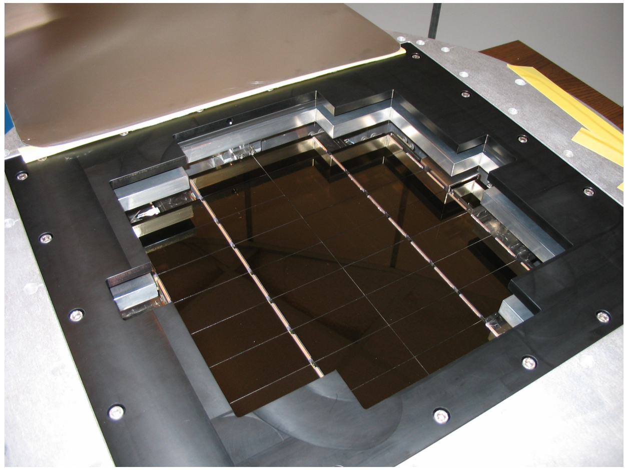
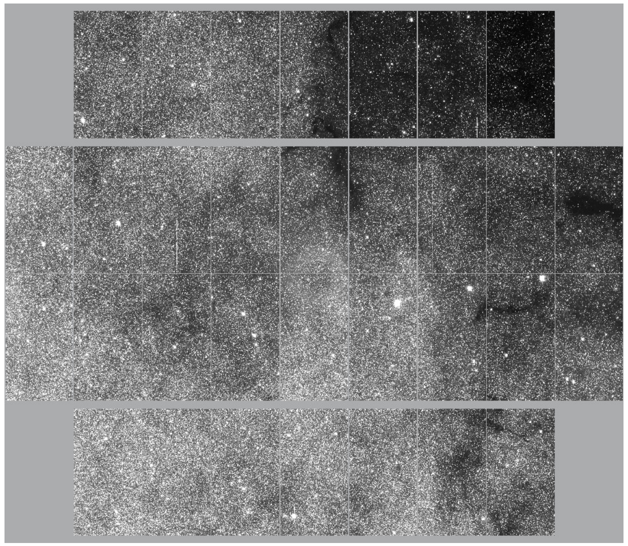
⋆ **single** 2048×2049 **CCD chip,** $0.42''/\mathrm{px}$**, driftscan mode, fov:** $14.2' \times 57'$

- **OGLE-III (2001–2009)**

⋆ **eight** 2048×4096 **CCD chips,** $0.26''/\mathrm{px}$**, fov:** $35' \times 35'$

- **OGLE-IV (2009–)**

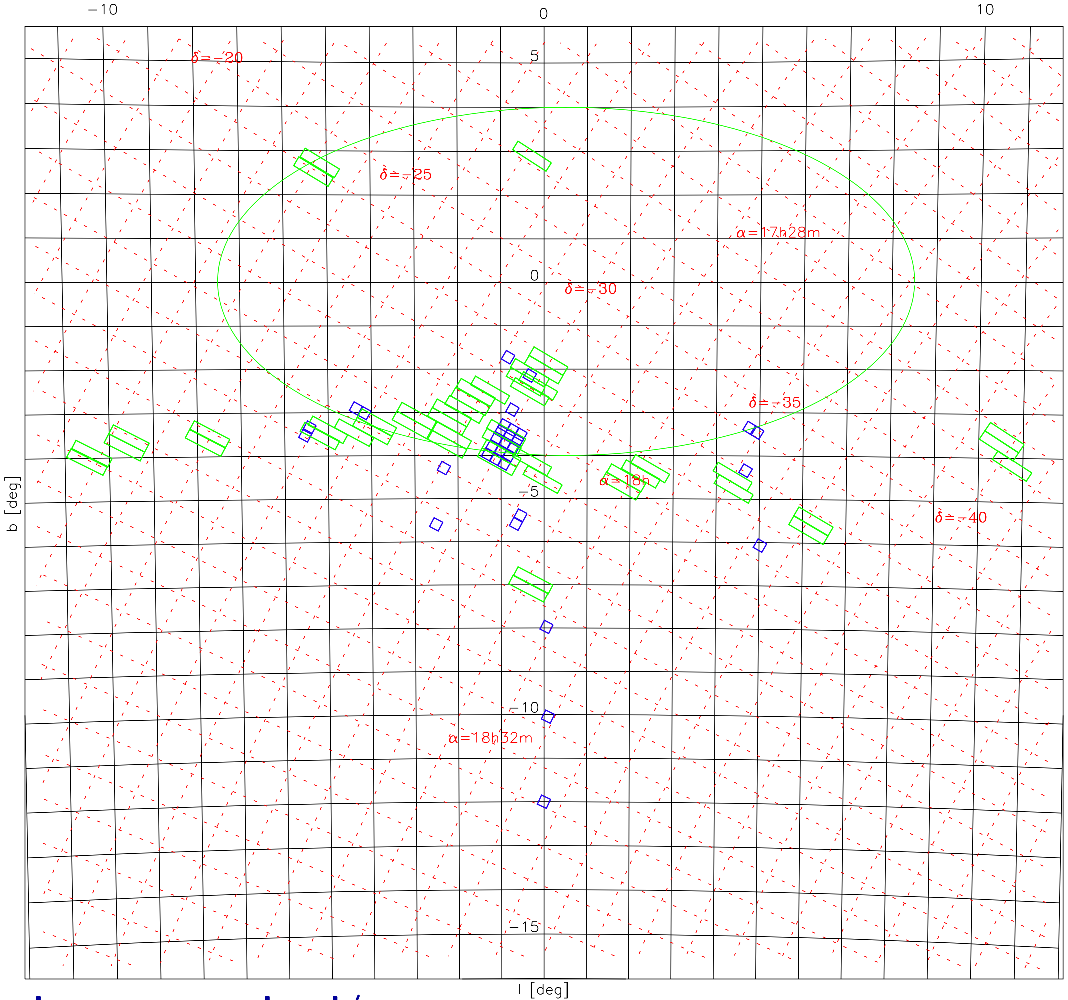
⋆ **thirty two** 2048×4096 **CCD chips,** $0.26''/\mathrm{px}$**, fov:** $1.4^\circ \times 1.4^\circ$

OGLE www, http://ogle.astrouw.edu.pl/

The OGLE sky – OGLE-I and OGLE-II

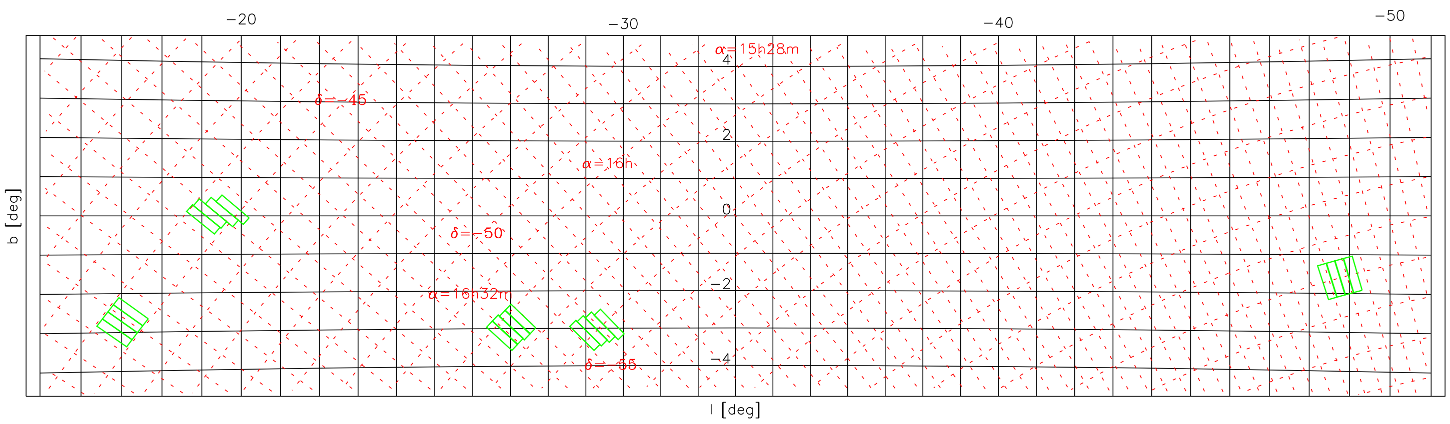
- OGLE-I observed only the Bulge
- OGLE-II observed Bulge,



OGLE www, http://ogle.astrouw.edu.pl/

The OGLE sky – OGLE-I and OGLE-II

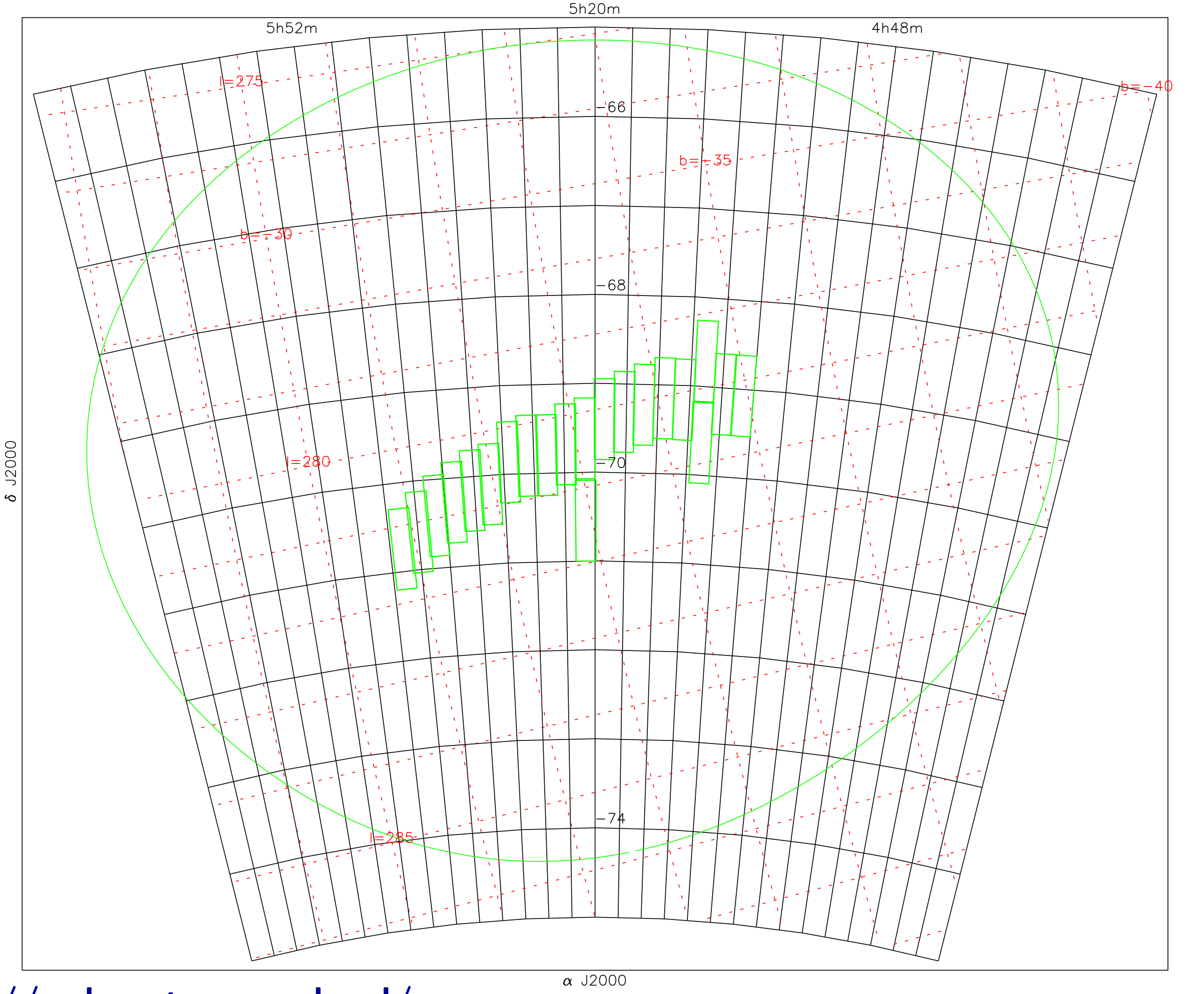
- OGLE-I observed only the Bulge
- OGLE-II observed Bulge, disk,



OGLE www, http://ogle.astrouw.edu.pl/

The OGLE sky – OGLE-I and OGLE-II

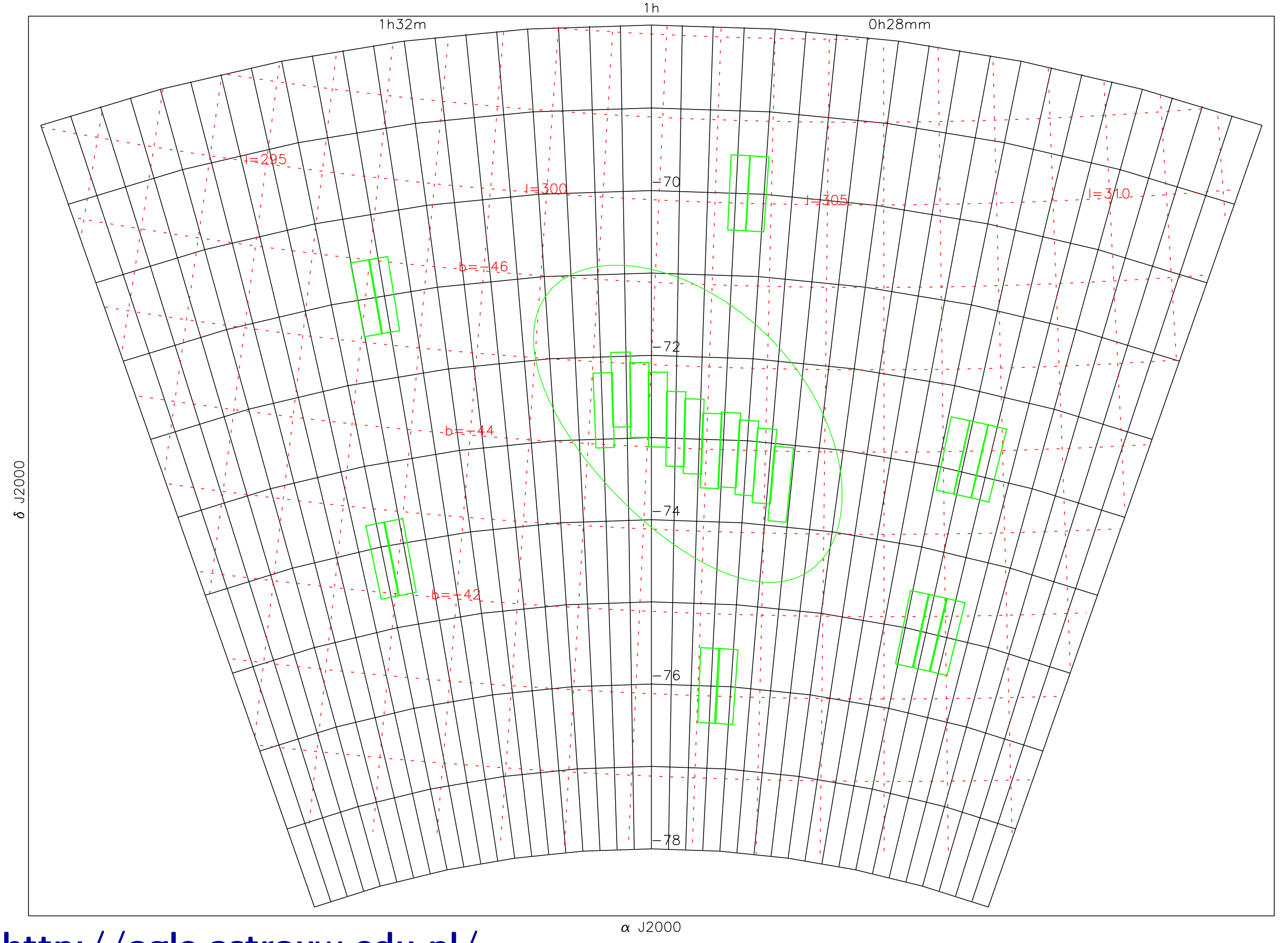
- OGLE-I observed only the Bulge
- OGLE-II observed Bulge, disk, LMC



OGLE www, http://ogle.astrouw.edu.pl/

The OGLE sky – OGLE-I and OGLE-II

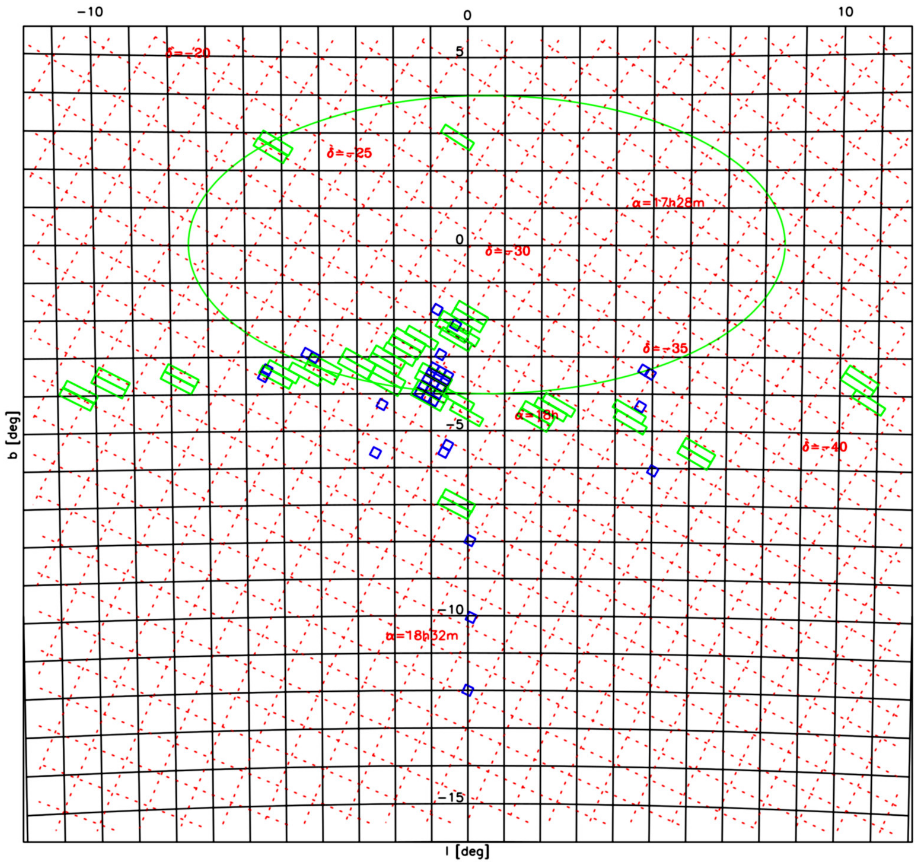
- OGLE-I observed only the Bulge
- OGLE-II observed Bulge, disk, LMC and SMC

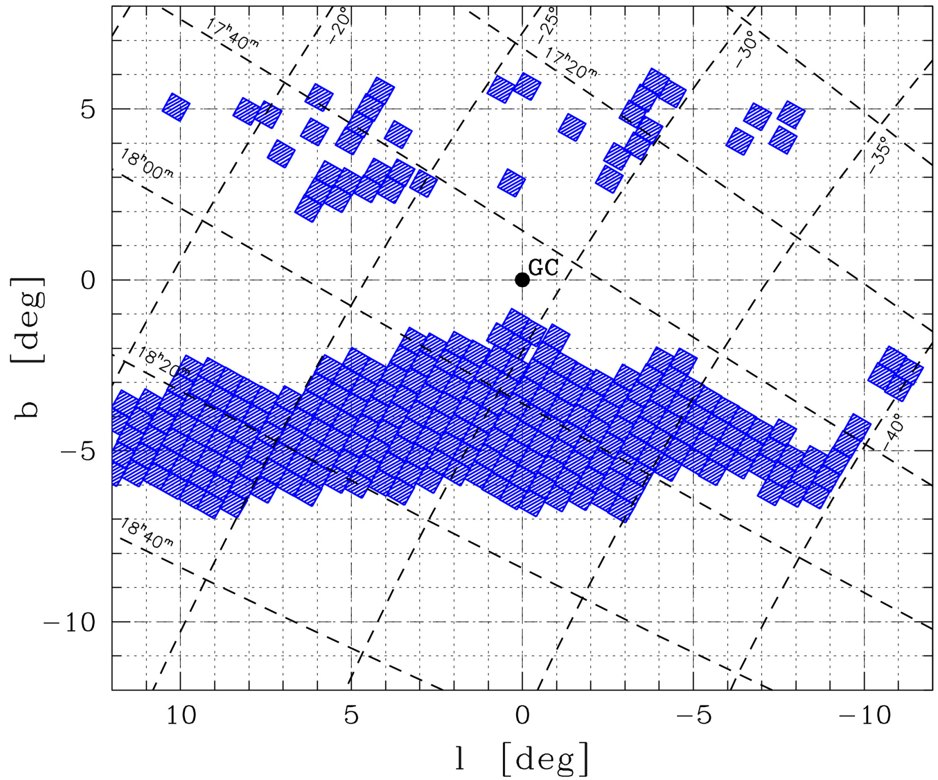


OGLE www, http://ogle.astrouw.edu.pl/

The OGLE sky – OGLE-III

- Galactic Bulge OGLE-I/II vs. OGLE-III

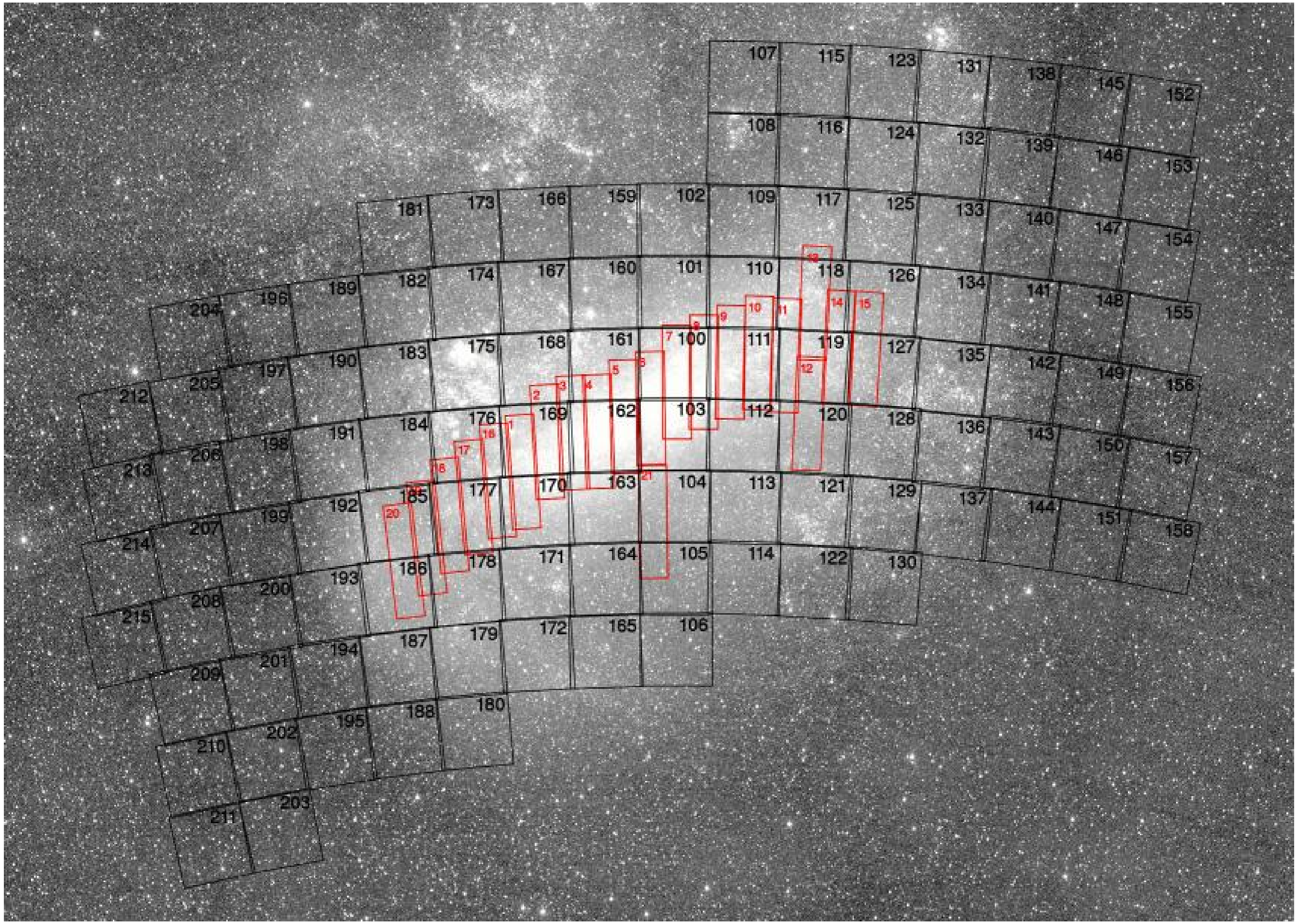




OGLE www, http://ogle.astrouw.edu.pl/

The OGLE sky – OGLE-III

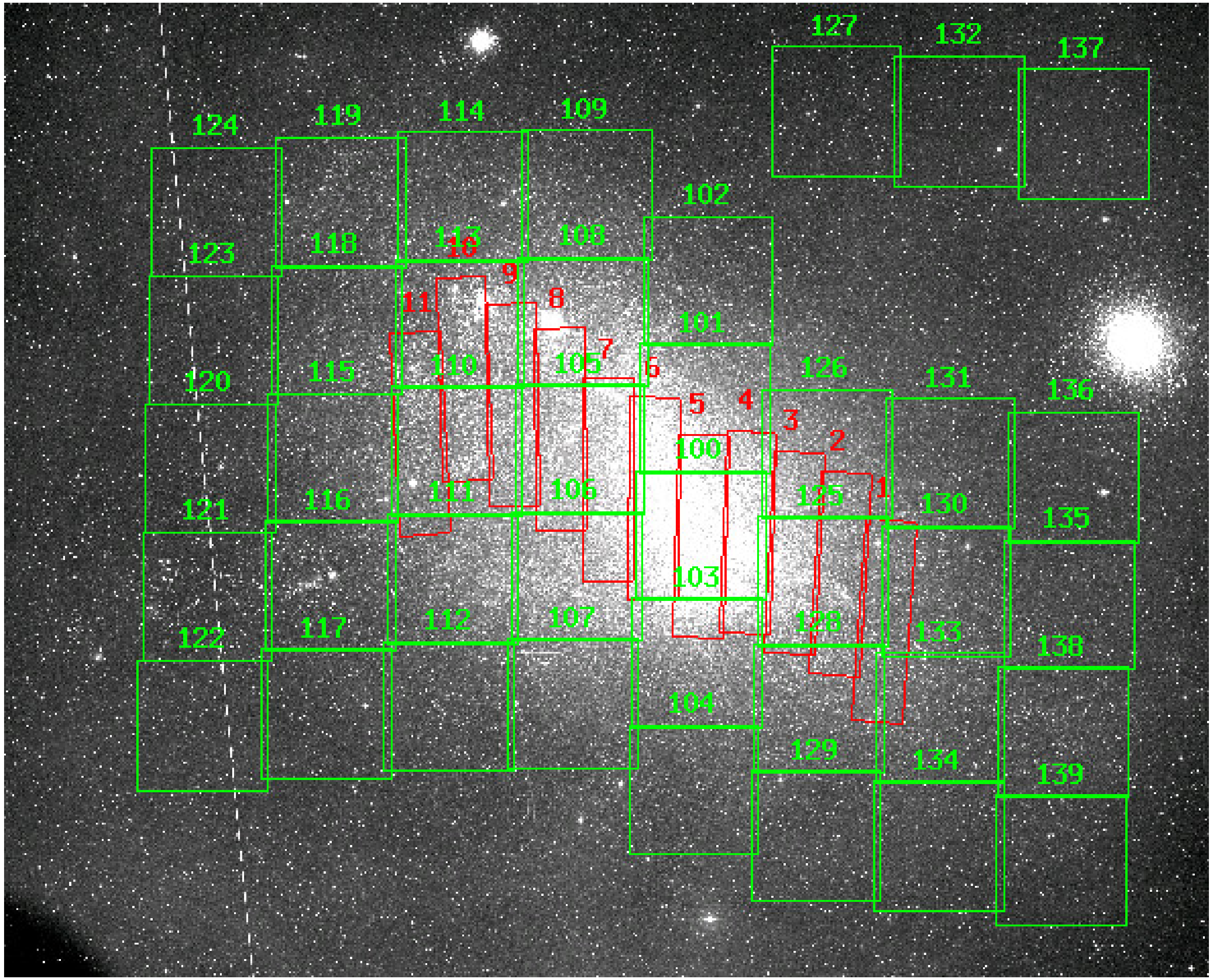
- LMC OGLE-I/II vs. OGLE-III



OGLE www, http://ogle.astrouw.edu.pl/

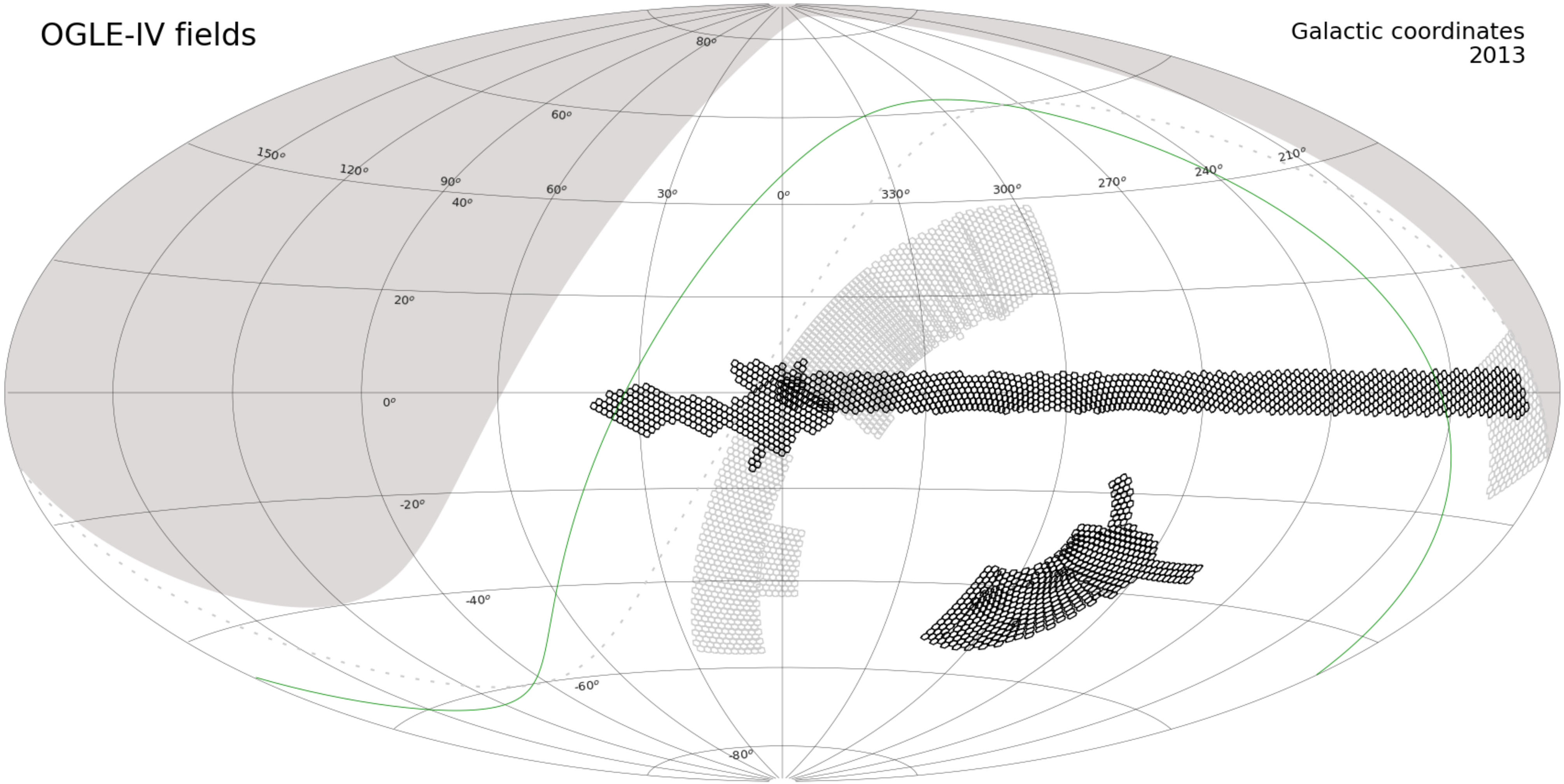
The OGLE sky – OGLE-III

- SMC OGLE-I/II vs. OGLE-III



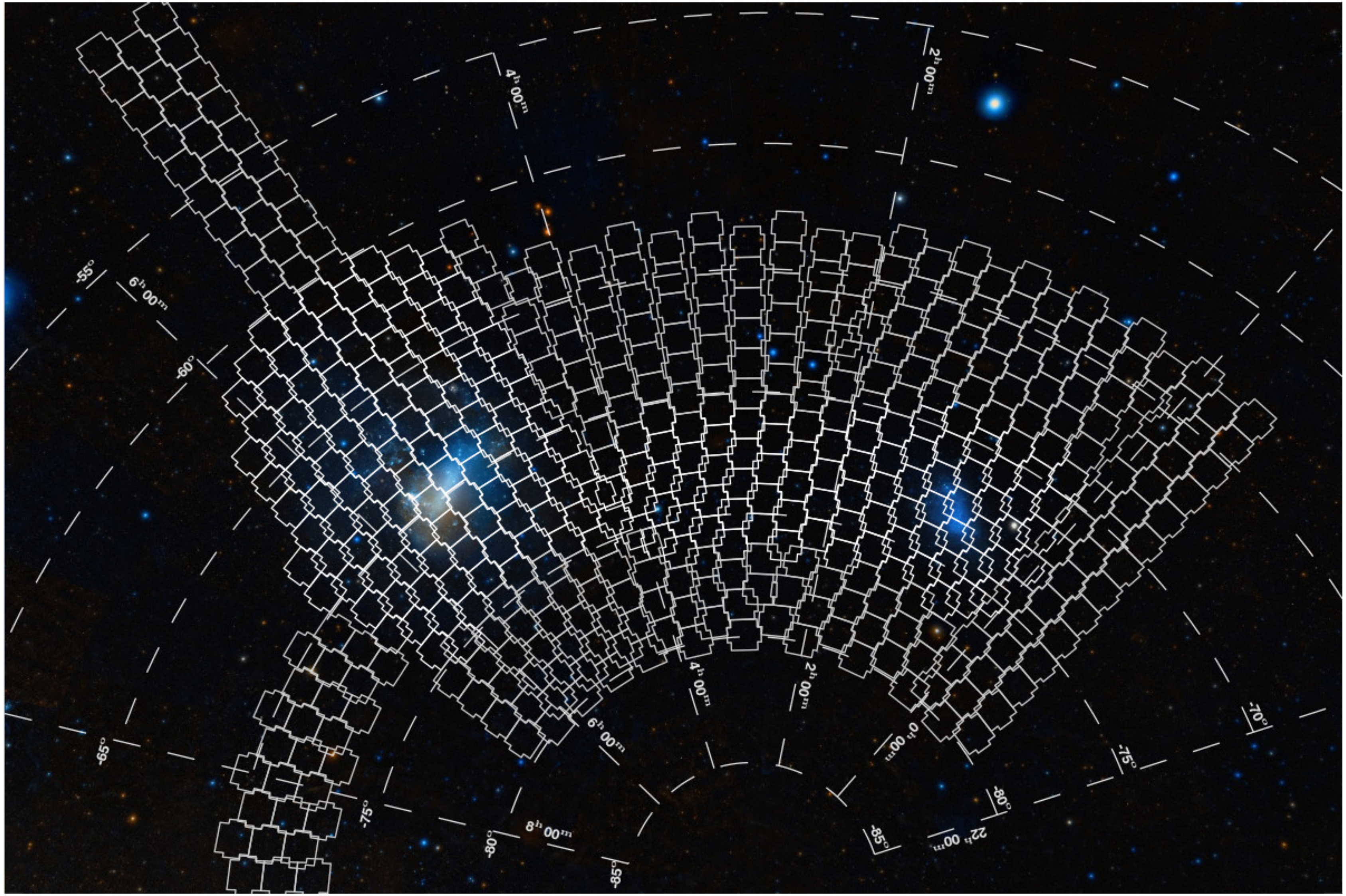
OGLE www, http://ogle.astrouw.edu.pl/

The OGLE sky – OGLE-IV



OGLE www; Jan Skowron

The OGLE sky – OGLE-IV



OGLE www; wikisky.org, DSS2, Jan Skowron

The OGLE project

- OGLE-I – OGLE-III data are in public domain
- OGLE-III catalog of variable stars contains $399\,679$ objects
- several real time data analysis systems are operational, e.g.
    - EWS: Real Time Microlensing Detection System
    - XROM: Real Time Monitoring of X-ray Sources
    - RCOM: Real Time Monitoring of R CrB Variables, and more
- 442 OGLE + 1039 OGLE-related papers, including 12 *Nature*/*Science* papers
- contributions to nearly all fields of astronomy: from astrometry and planetoid research to high energy astrophysics and cosmology
- this review is focused on stellar astrophysics/pulsating stars

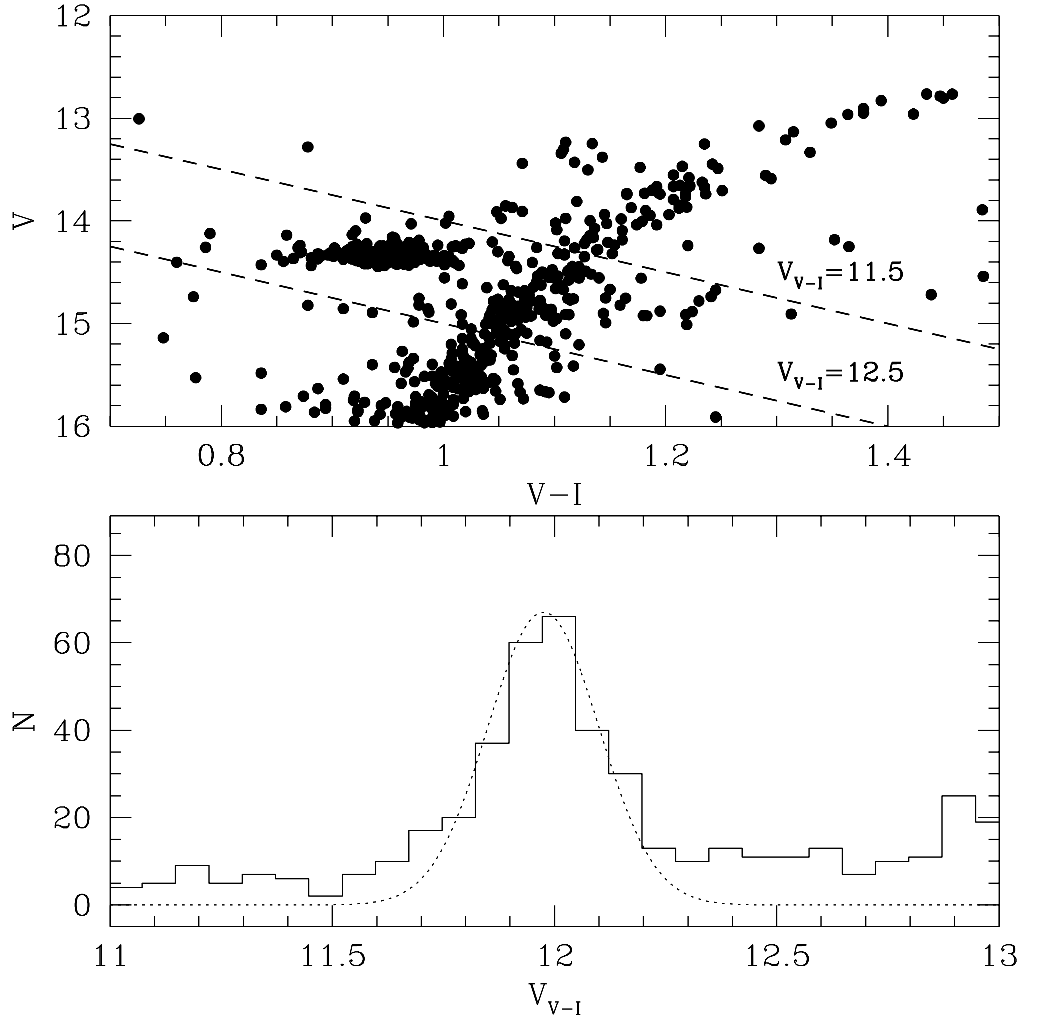
Galactic structure and statistical studies with OGLE

- structure studies – based on analysis of spatial distribution of standard candles: red clump stars, Cepheids and RR Lyrae stars
- studied systems: Galactic Bulge, LMC and SMC

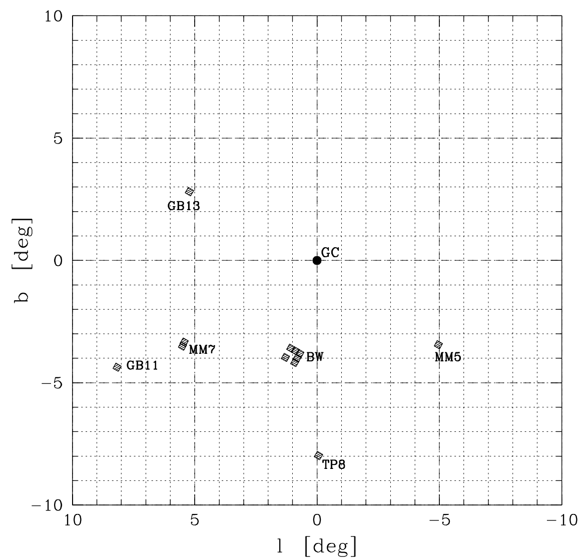
Galactic structure studies with OGLE: Galactic bulge

- red clump stars used as structure tracers
  - luminosity distribution of RC stars along many lines of sight
- analysis of OGLE-I (Stanek et al. 1994, 1997) OGLE-II (Rattenbury et al. 2007) and OGLE-III (Nataf et al. 2010, Poleski et al. 2013) data systematically improved our knowledge about the bulge structure

Galactic structure studies with OGLE: Galactic bulge

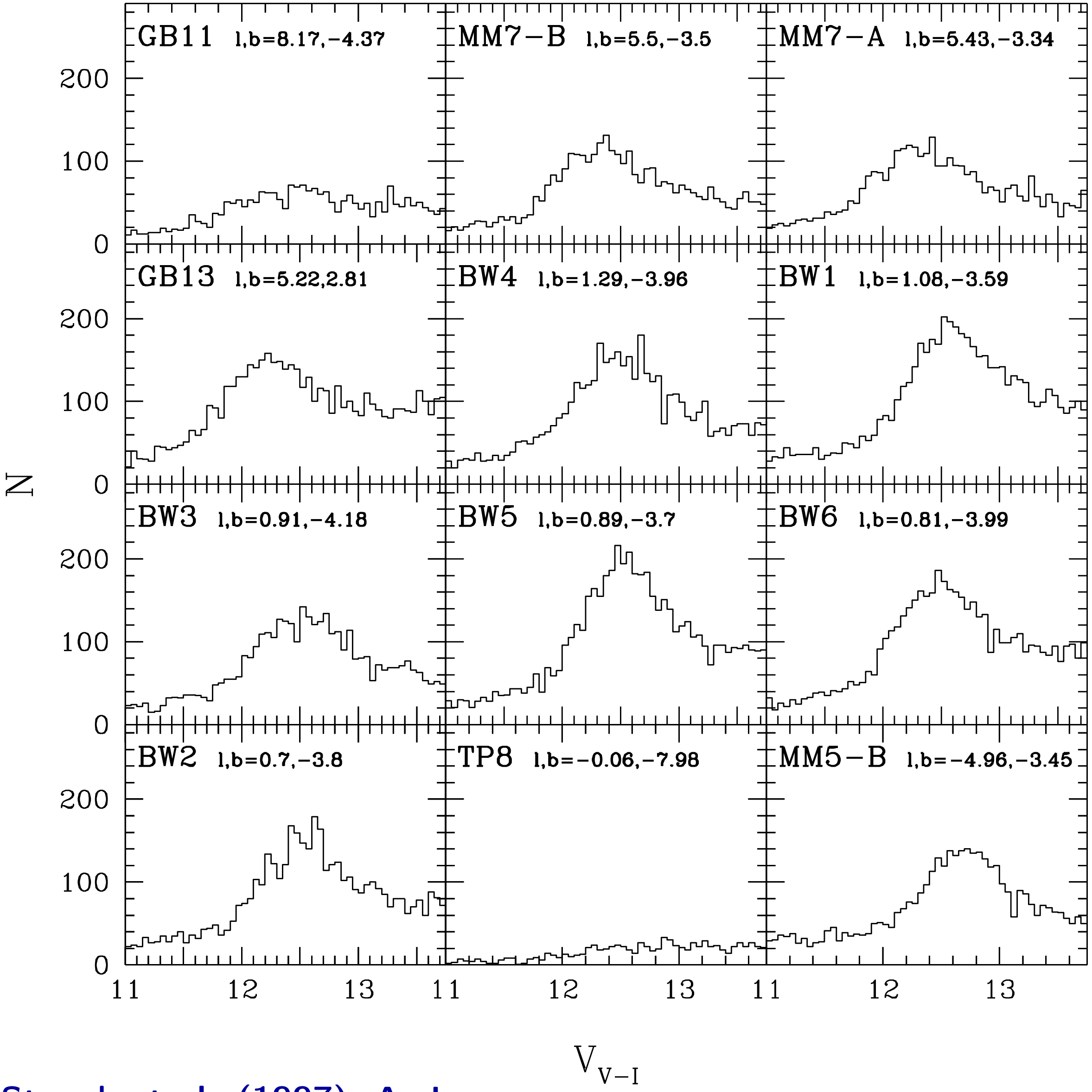


- ⋆ red clump dominated part of CMD: red clump giants and RGB stars
- ⋆ distribution of colors: red clump peak + RGB background
- ⋆ extinction-insensitive V_{V-I} parameter: $V_{V-I} \equiv V - \frac{A_V}{E_{V-I}}(V - I)$
- ⋆ distribution of V_{V-I} in OGLE-I fields



Stanek et al. (1997), ApJ

Galactic structure studies with OGLE: Galactic bulge



⋆ distributions fitted with the luminosity function

$$\Phi(L) = \left(\frac{N_0}{L_\odot}\right)\left(\frac{L}{L_\odot}\right)^{-\gamma} +$$

$$+\frac{N_{RC}}{\sigma_{RC}\sqrt{2\pi}} \exp\left[-\frac{(L-L_{RC})^2}{2\sigma_{RC}^2}\right] \quad [L_\odot^{-1}]$$

Stanek et al. (1997), ApJ

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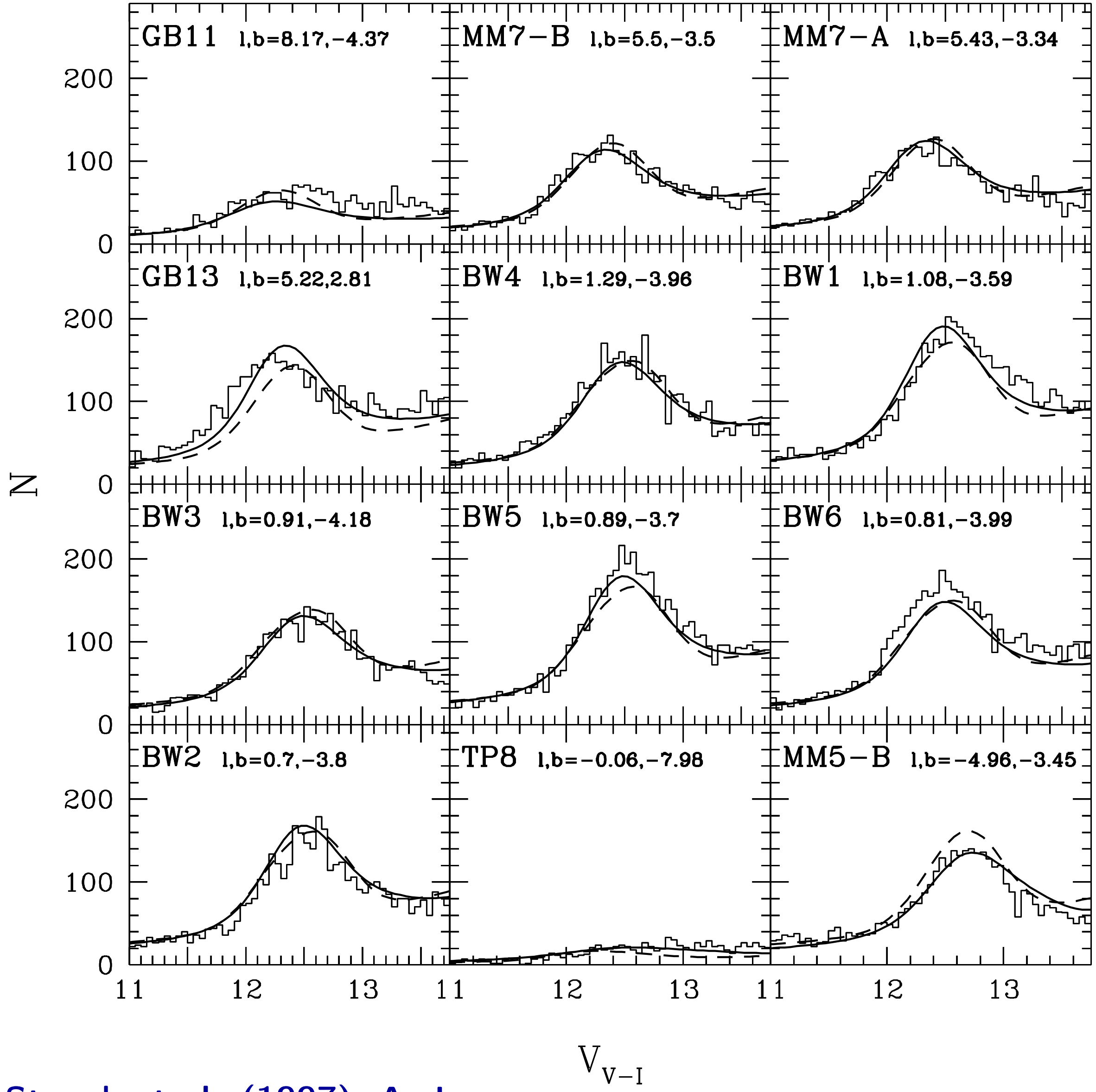

Stanek et al. (1997), ApJ

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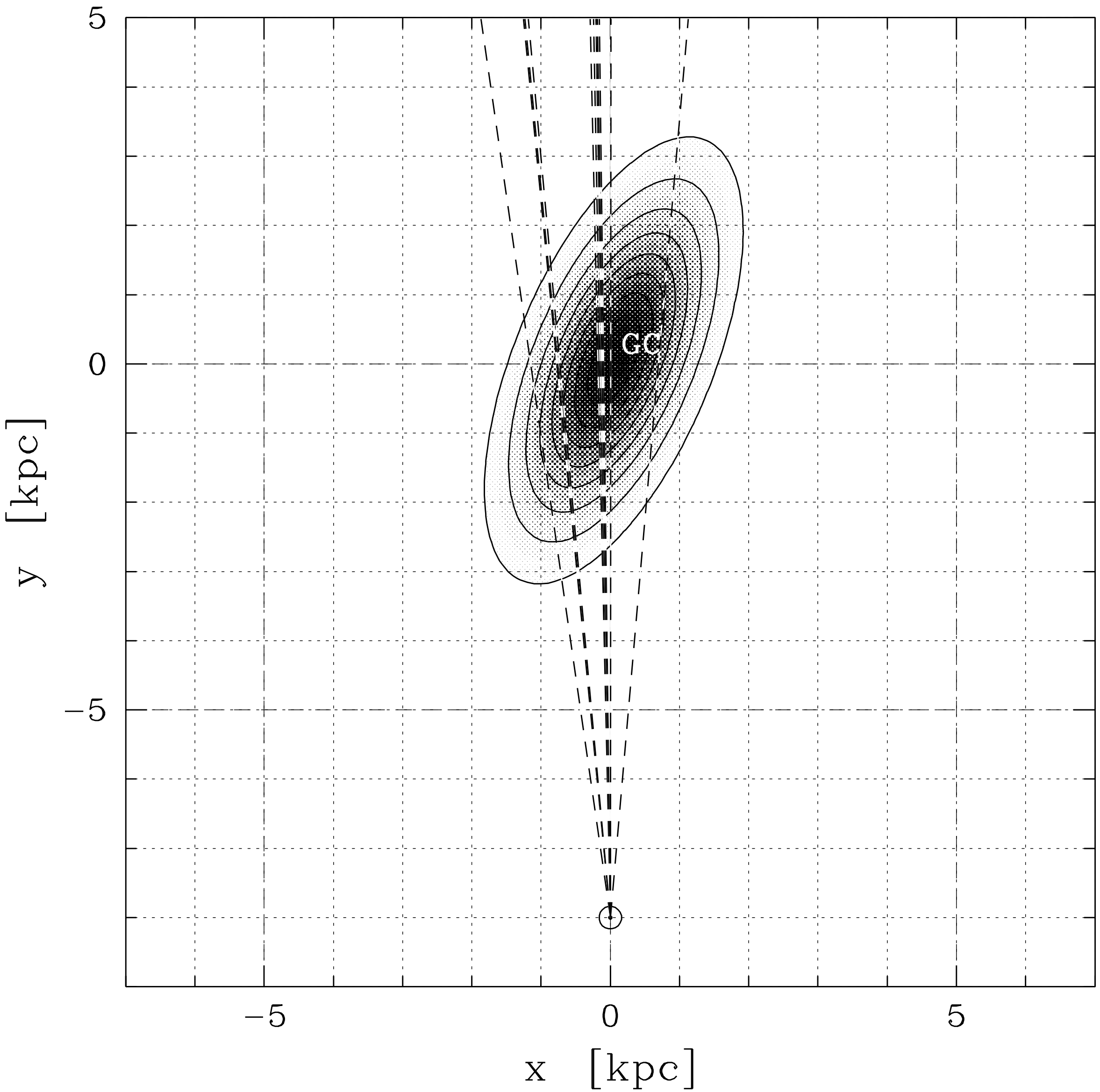
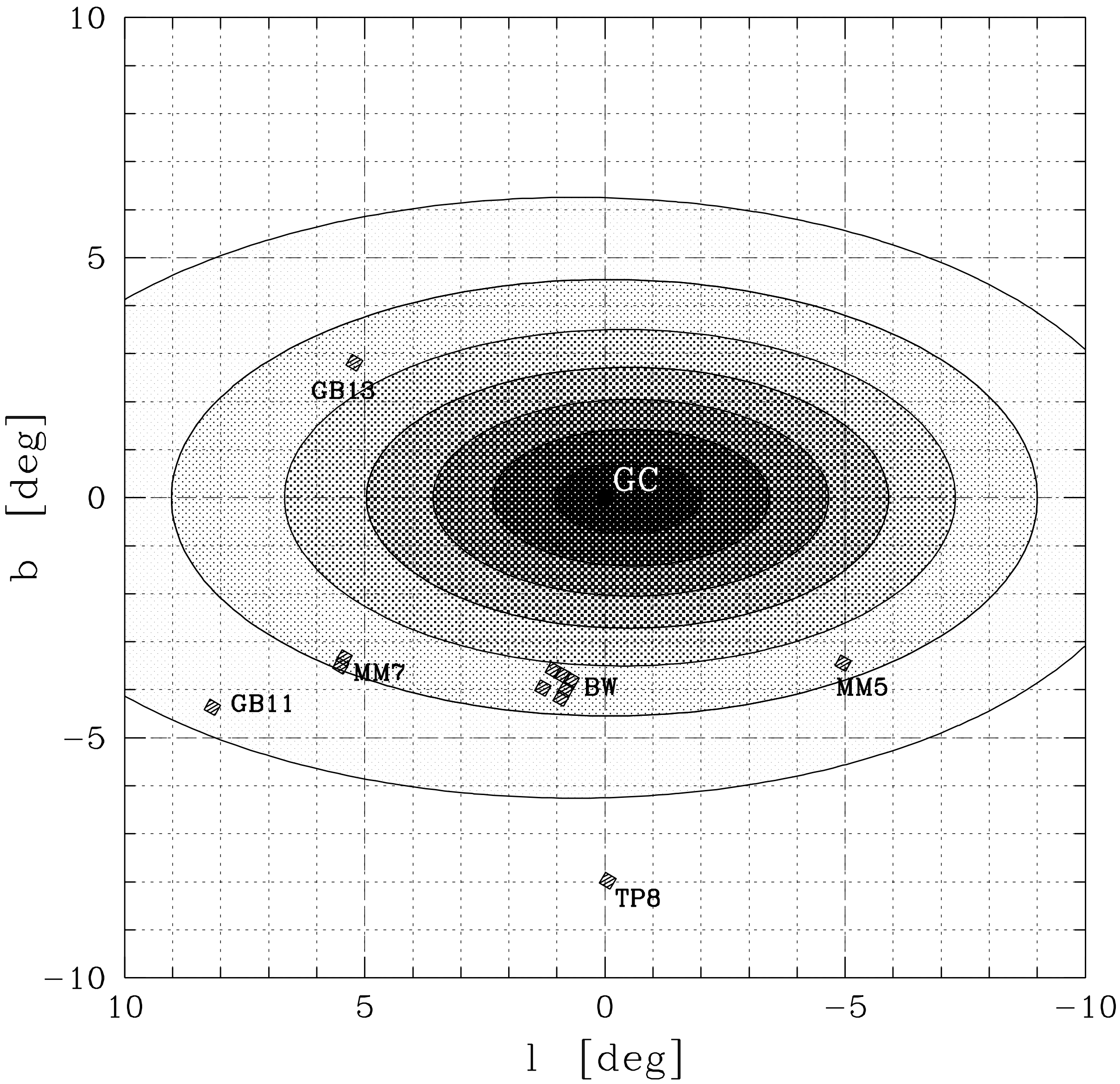
- ⋆ peak location: distance
- ⋆ peak width: depth of the RC population

Galactic structure studies with OGLE: Galactic bulge



Stanek et al. (1997), ApJ

Galactic structure studies with OGLE: Galactic bulge

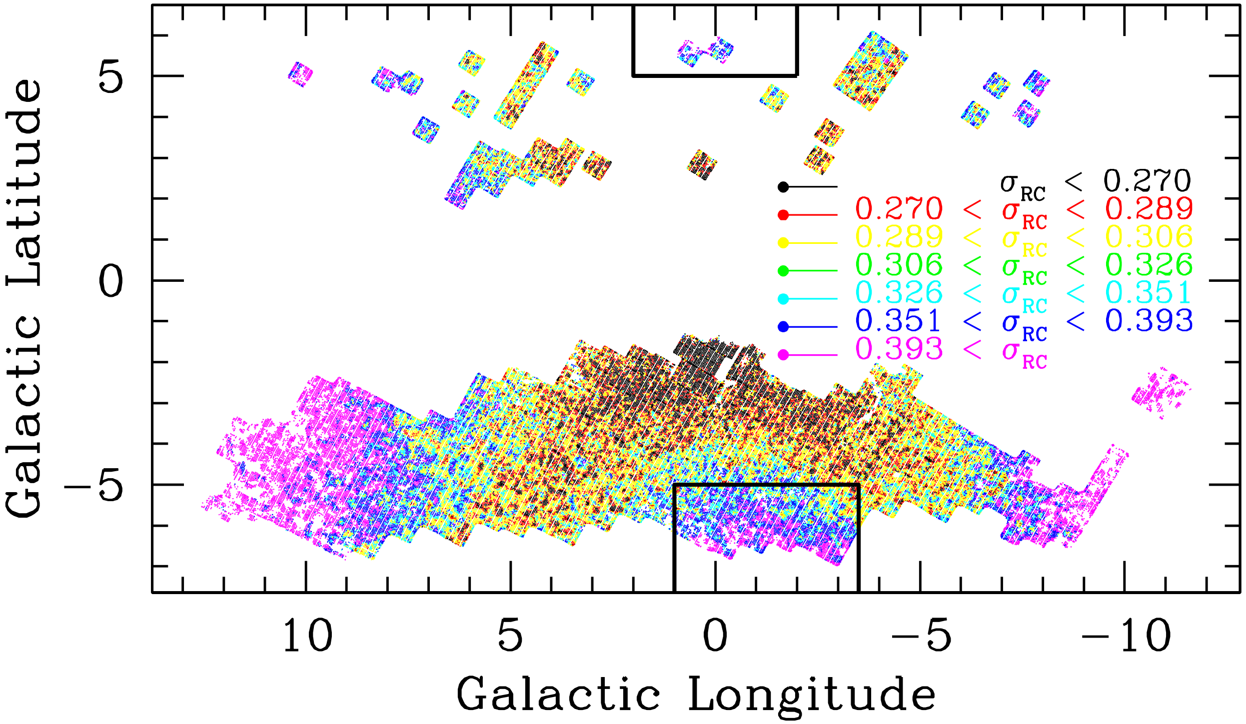


⋆ projected light from the inner part of the Galaxy

Stanek et al. (1997), ApJ

Galactic structure studies with OGLE: Galactic bulge

⋆ with OGLE-III a much more detailed study is possible



- regions with much wider brightness distribution function
- in fact double peak fitted with single Gaussian

Nataf et al. (2010), ApJ Lett.

Galactic structure studies with OGLE: Galactic bulge

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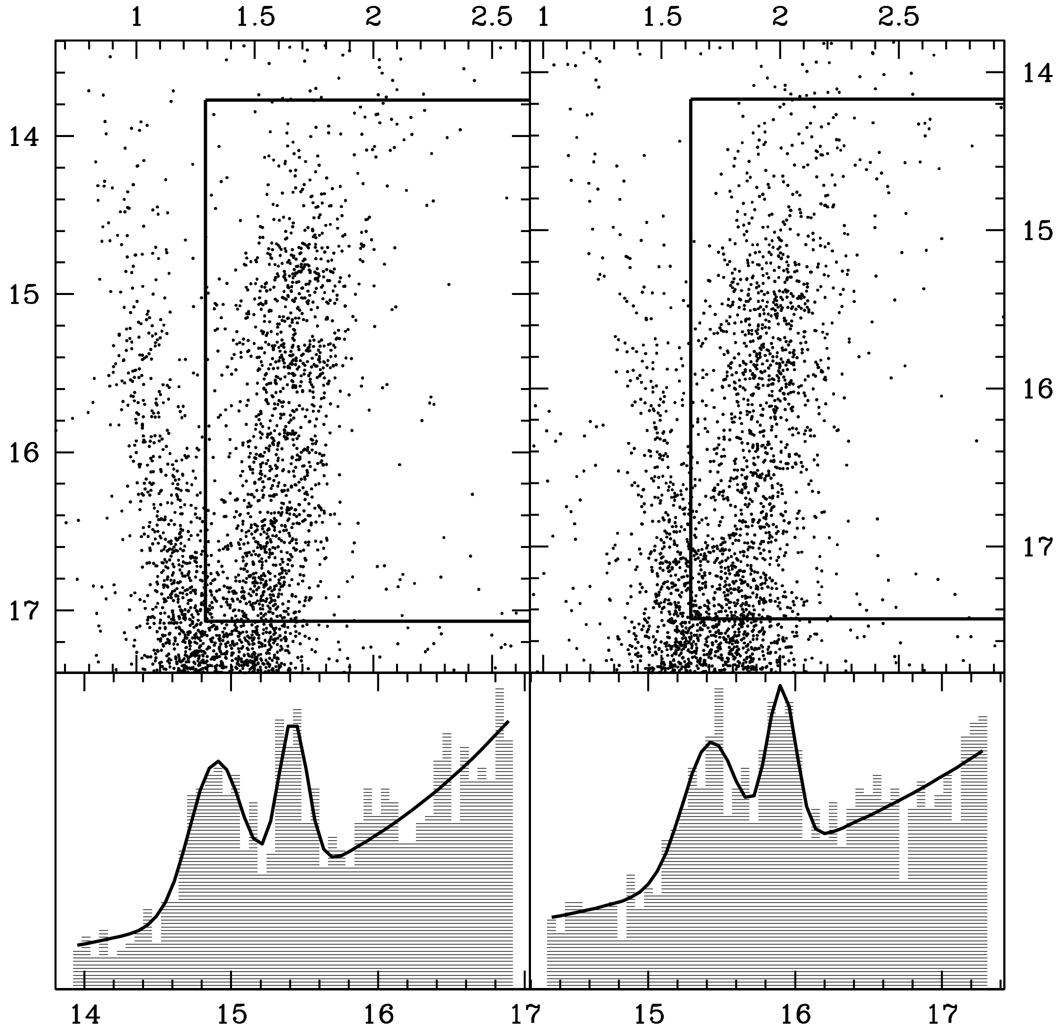

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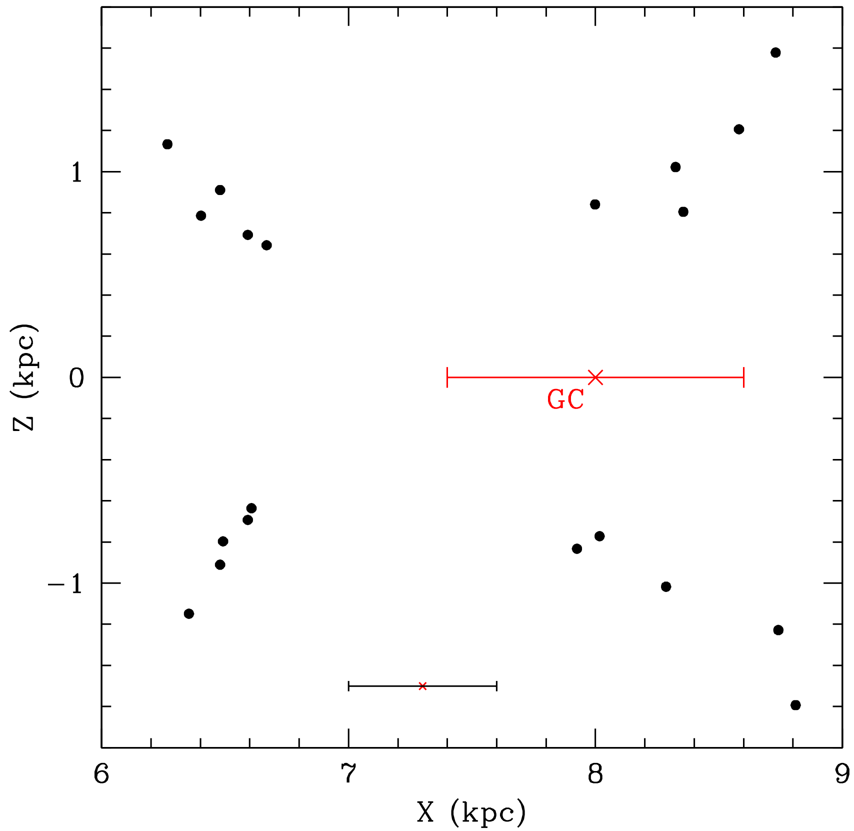
- in fact double peak fitted with single Gaussian

Nataf et al. (2010), ApJ Lett.

Galactic structure studies with OGLE: Galactic bulge

⋆ OGLE-III (and other) data indicate that the Galactic bulge contains an X-shaped structure aligned with a bar with arms significantly extended along the line of sight direction

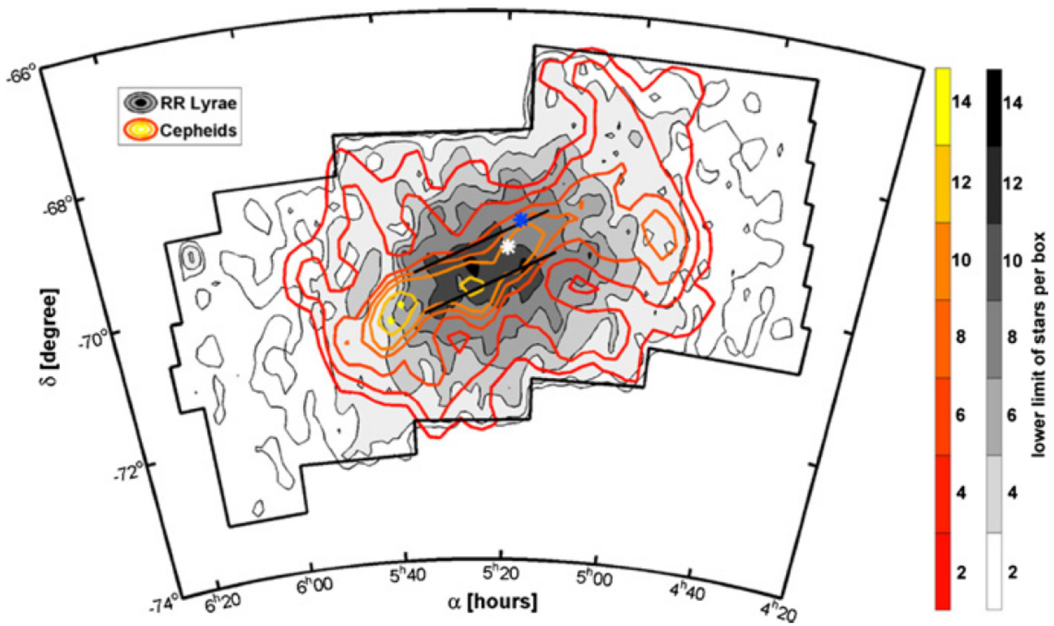


McWilliam & Zoccali (2010) study (2MASS+RC stars), distances to the two RC as a function of latitude

McWilliam & Zoccali (2010), ApJ

Galactic structure studies with OGLE: Magellanic Clouds

- several independent studies, including e.g. analysis of Pejcha & Stanek (2009), Subramanian & Subramaniam (2012), Haschke et al. (2012a,b)
- studies of Haschke et al. (2012a,b), based on
  - classical Cepheids ($P - L$ relation) which trace the young population
  - RR Lyrae stars ($M - [\mathrm{Fe/H}]$) relation which trace old population



projected densities of RR Lyrae stars (grey) and Cepheids (coloured) in the LMC

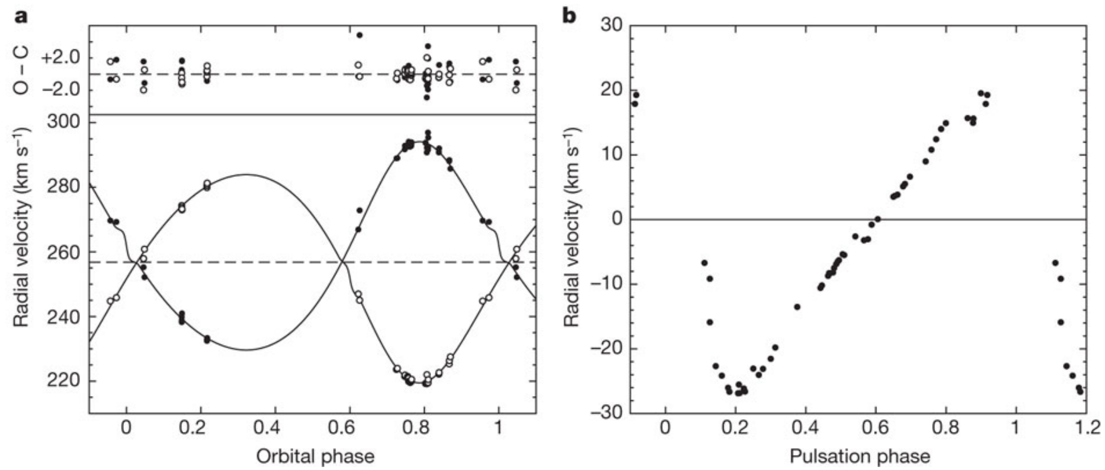
Haschke et al. (2010), AJ

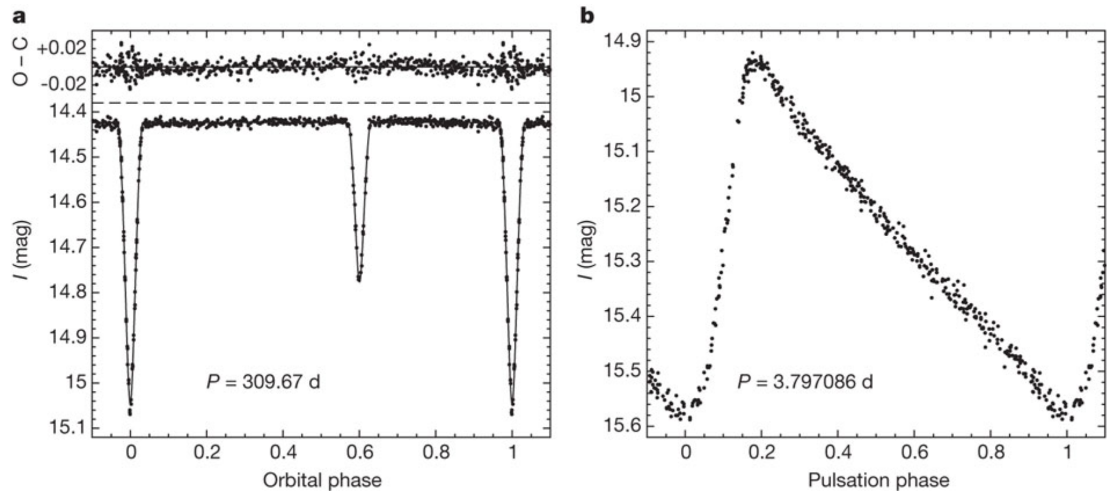
OGLE gems

- in its vast database OGLE finds very rare and important stars
- combined with high resolution spectroscopy some breakthrough results were reported, several connected to eclipsing binary systems
- **Araucaria** project (PI: prof. Grzegorz Pietrzyński) – the main goal is precise determination of the cosmic distance scale
- OGLE gems – a showcase

OGLE gems – LMC-CEP-227

- classical Cepheid in eclipsing binary system
- precise determination of stellar parameters possible
- dynamical mass $M = 4.165 \pm 0.032 M_{\odot}$
- pulsation theory wins the "pulsation vs. evolutionary" mass competition

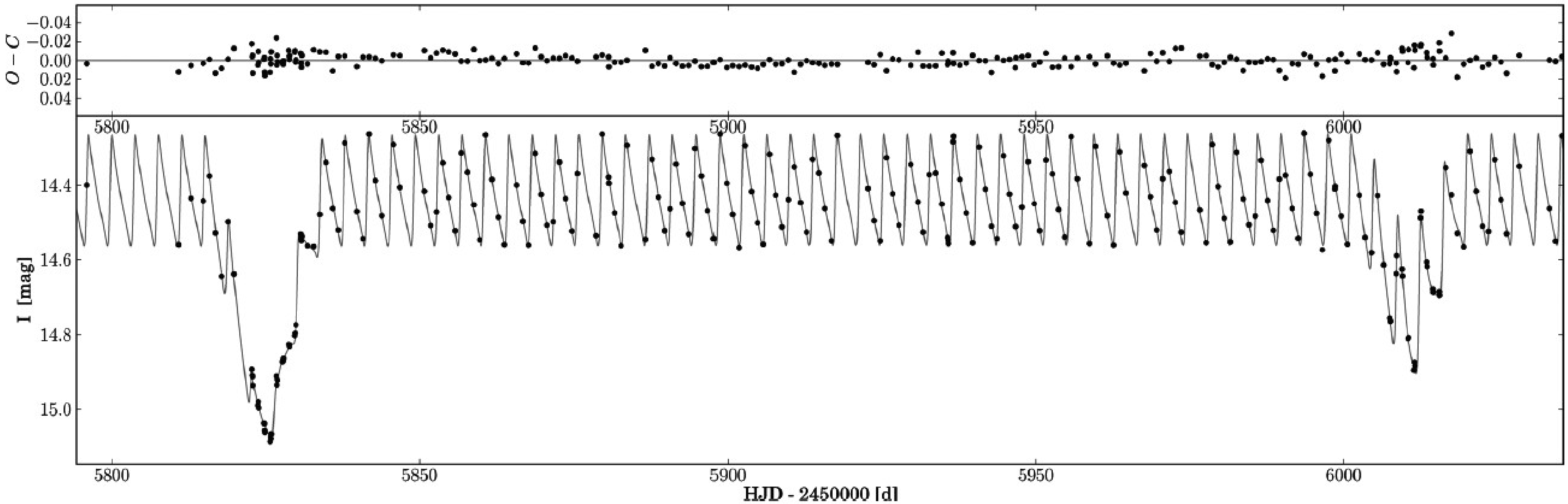




Pietrzyński et al. (2010), Nature

OGLE gems – LMC-CEP-227

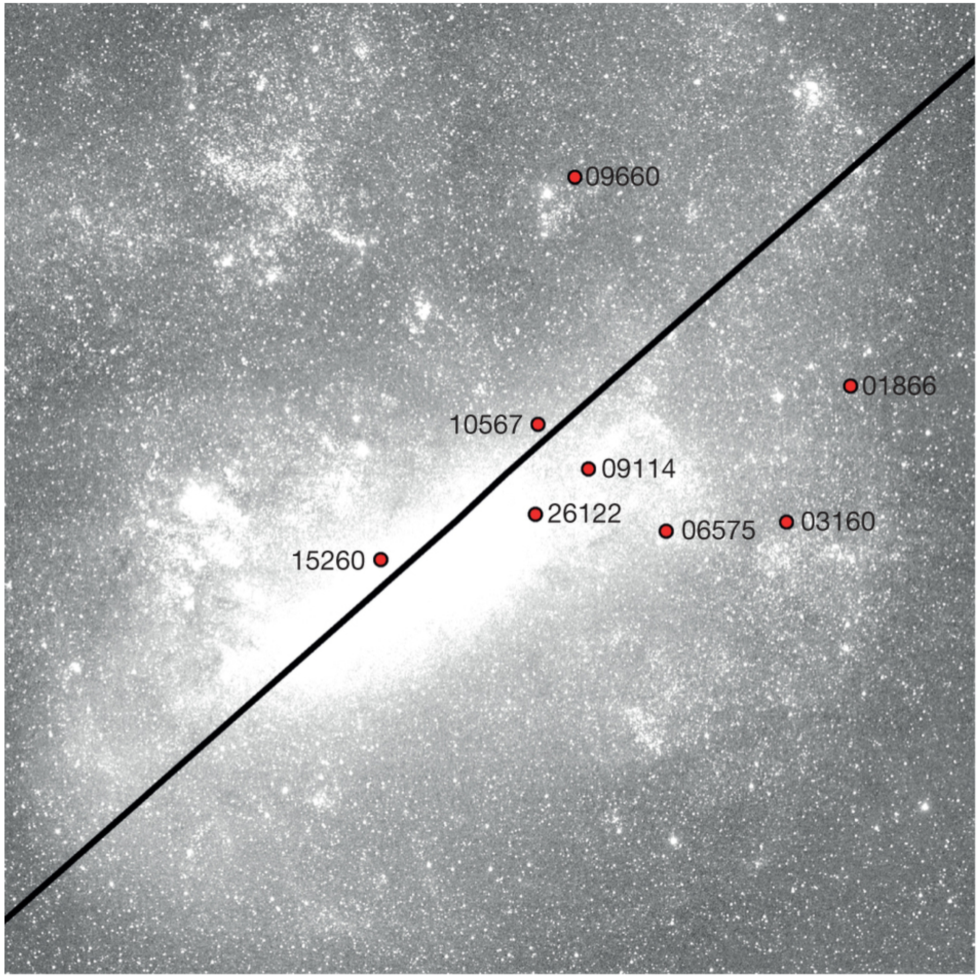
- modelling of the light curves including pulsation and eclipses resulted in first geometrical determination of the projection factor, $p = 1.21 \pm 0.03(\text{stat.}) \pm 0.04(\text{syst.})$

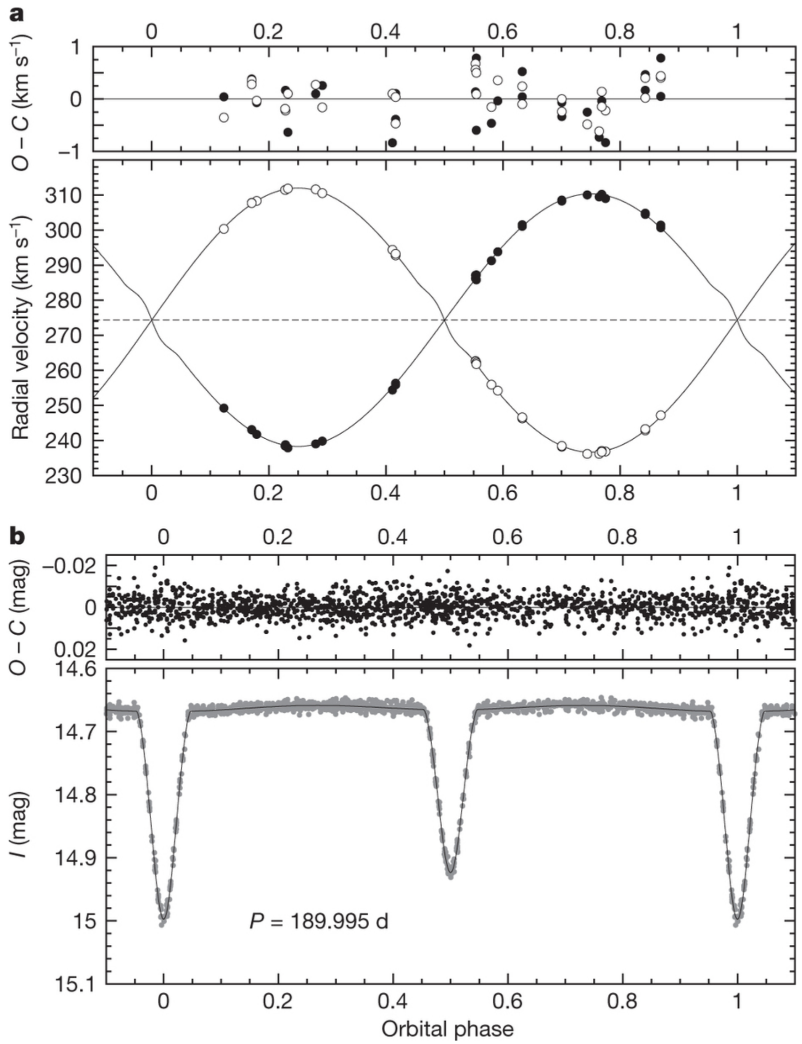


Pilecki et al. (2013), MNRAS

OGLE gems – clump giants in DLEB

- several clump giants discovered in eclipsing binary systems, perfect for distance determination





Pietrzyński et al. (2013), Nature

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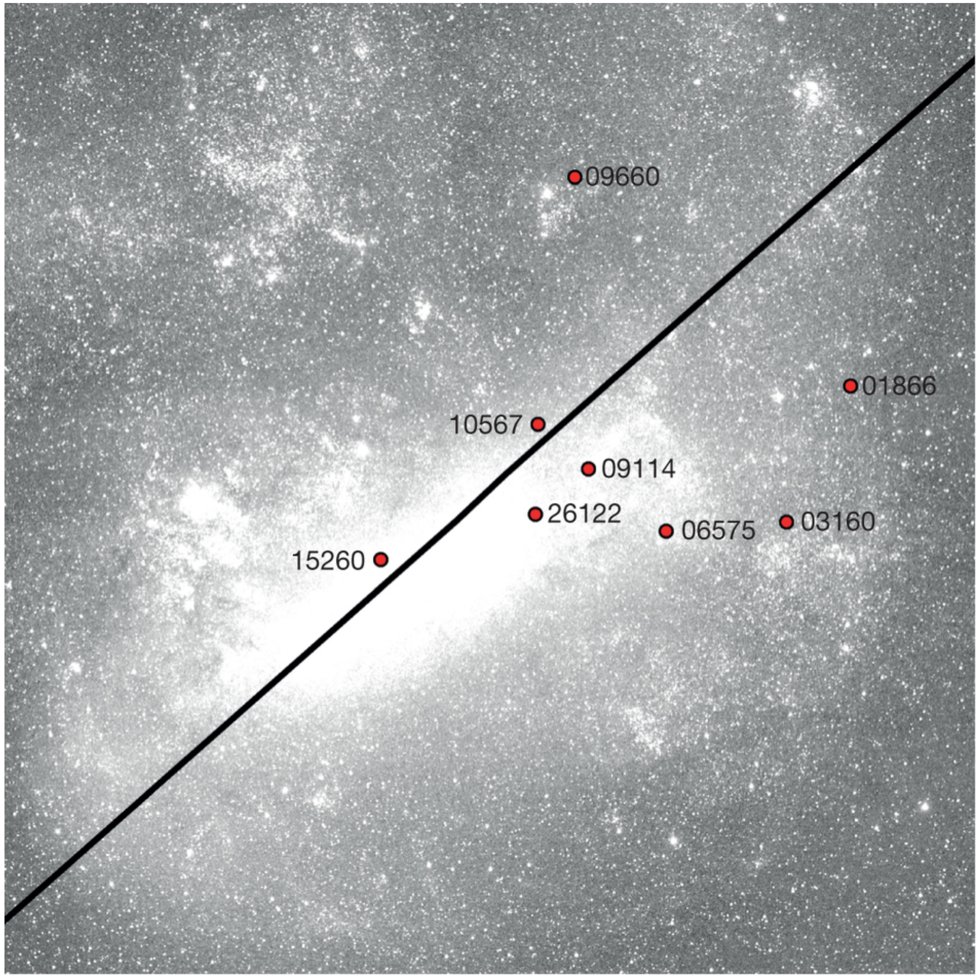
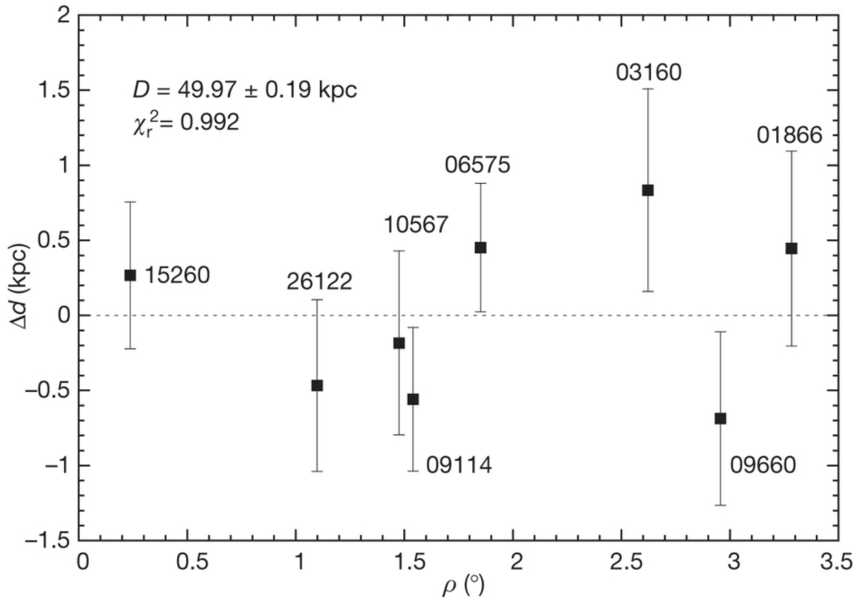


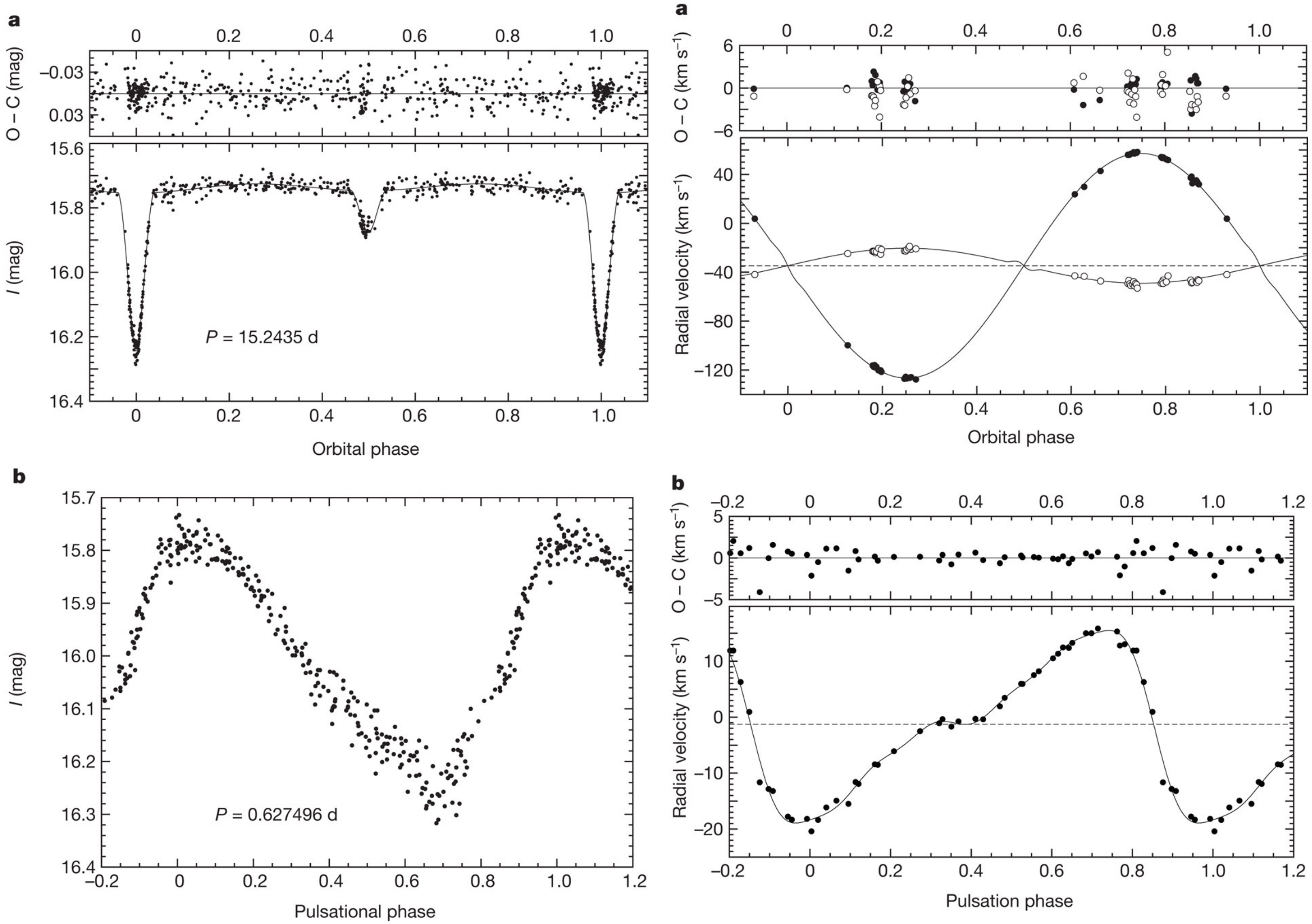


- $d_{\mathrm{LMC}} = 49.97 \pm 0.19(\mathrm{stat.}) \pm 1.11(\mathrm{syst.})$

Pietrzyński et al. (2013), Nature

OGLE gems – BLG-RRLYR-02792, the BEP

- a hope to measure the mass of RR Lyr star turned to new discovery



Pietrzyński et al. (2012), Nature

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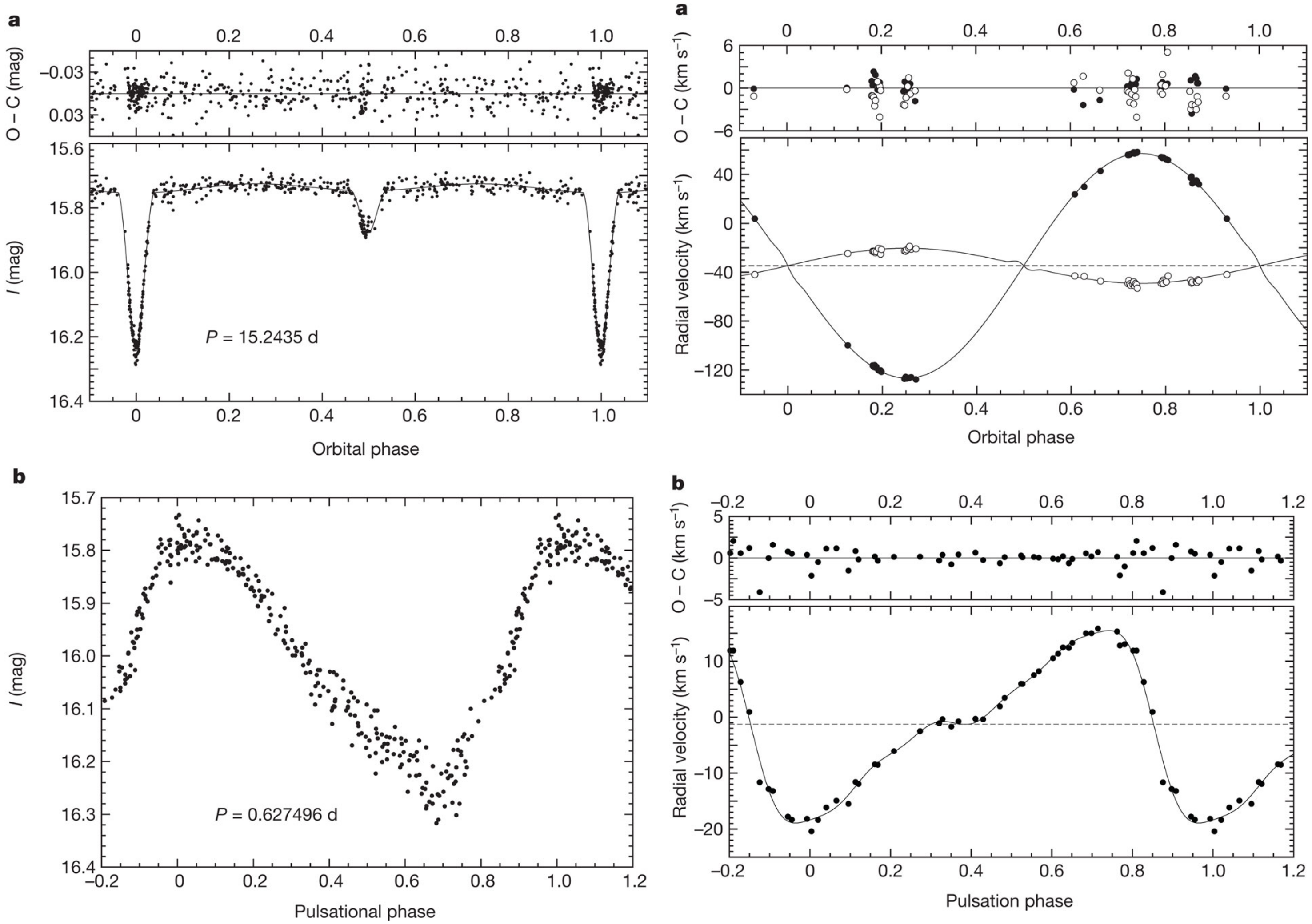

$$M = 0.261 \pm 0.015 \mathrm{M}_\odot$$

Pietrzyński et al. (2012), Nature

OGLE gems – BLG-RRLYR-02792, the BEP

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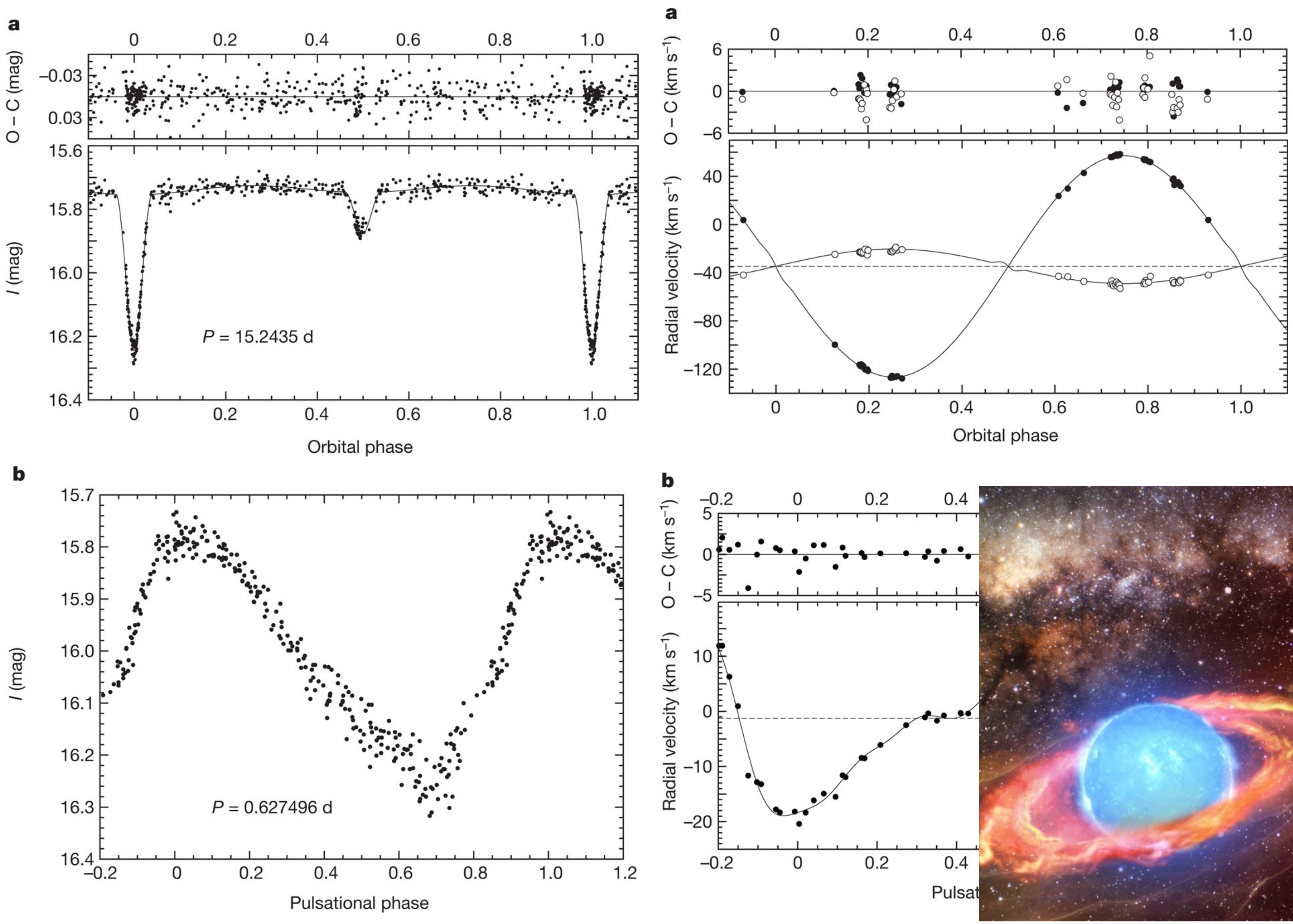

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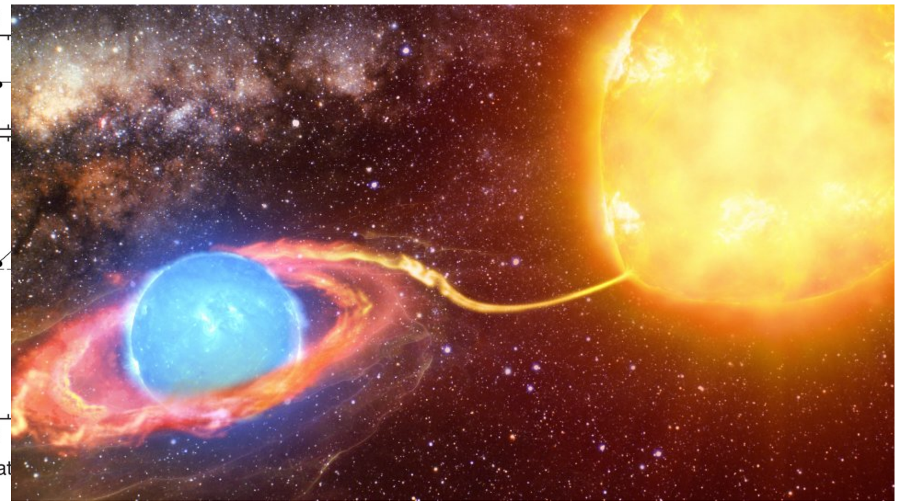
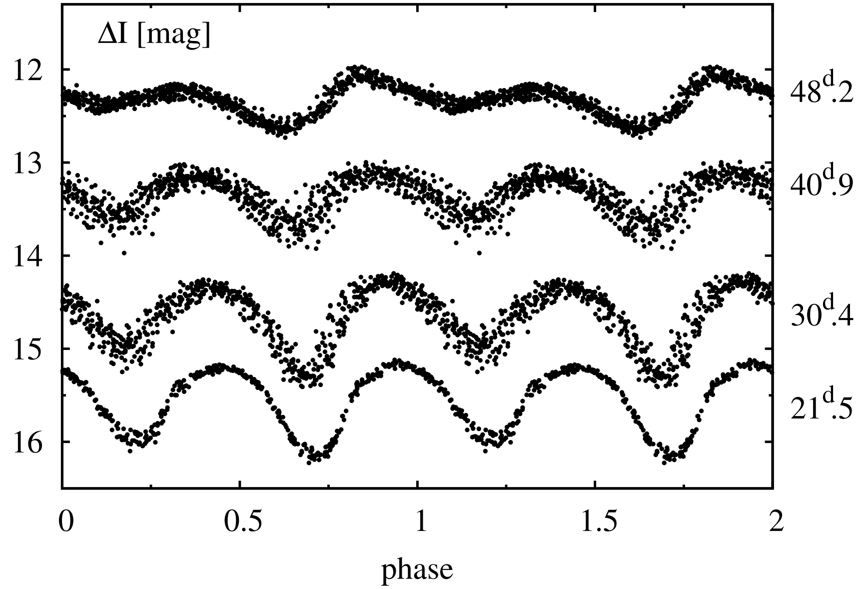


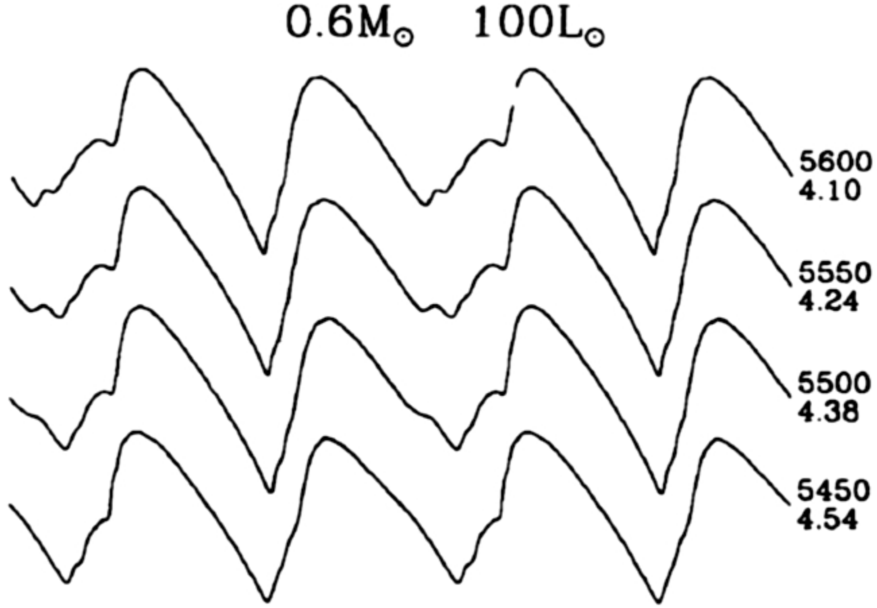
Pietrzyński et al. (2012), Nature; graphics: Janusz Bogucki

OGLE gems – OGLE-BLG-T2CEP-279: BL Her with period doubling

- 20 years old theoretical prediction confirmed!



⋆ period doubling in RV Tau stars



⋆ period doubling in BL Her models in period range 2.0–2.6 d

OGLE catalog; Buchler & Moskalik (1992), ApJ

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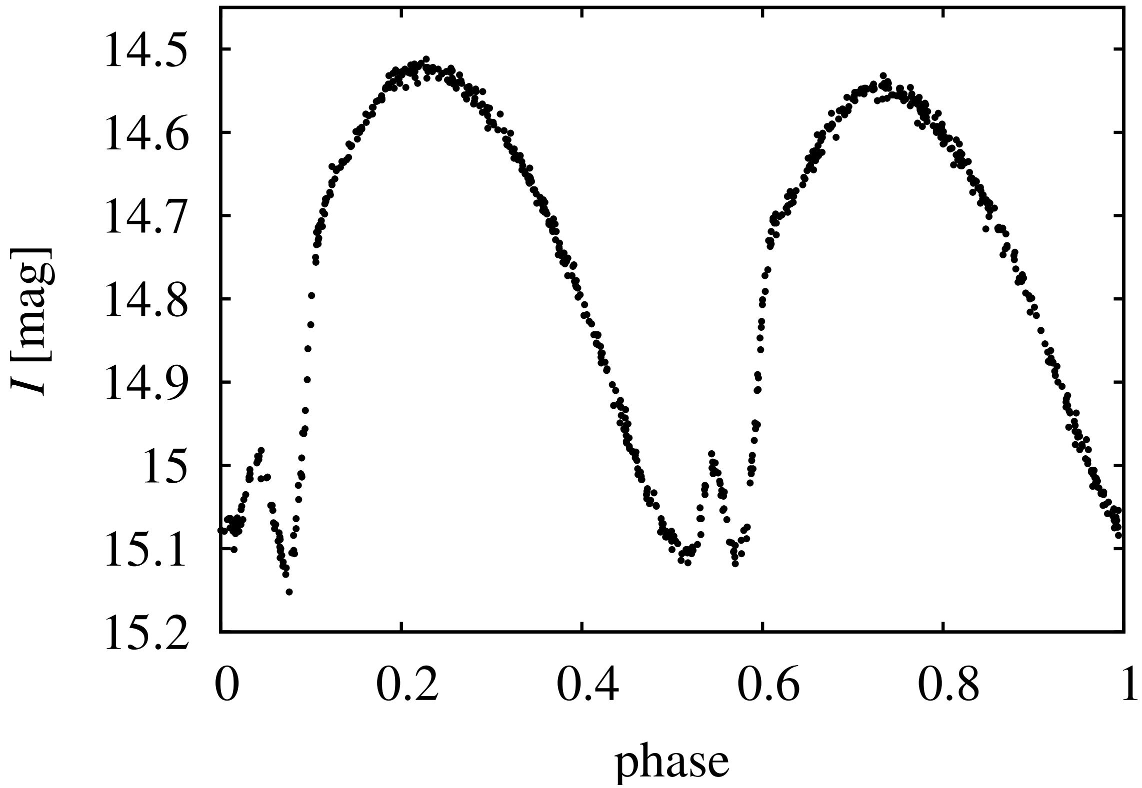

$P_{\mathrm{F}} \approx 2.4\,\mathbf{d}$

Smolec et al. (2012), MNRAS

OGLE gems – OGLE-BLG-T2CEP-279: BL Her with period doubling

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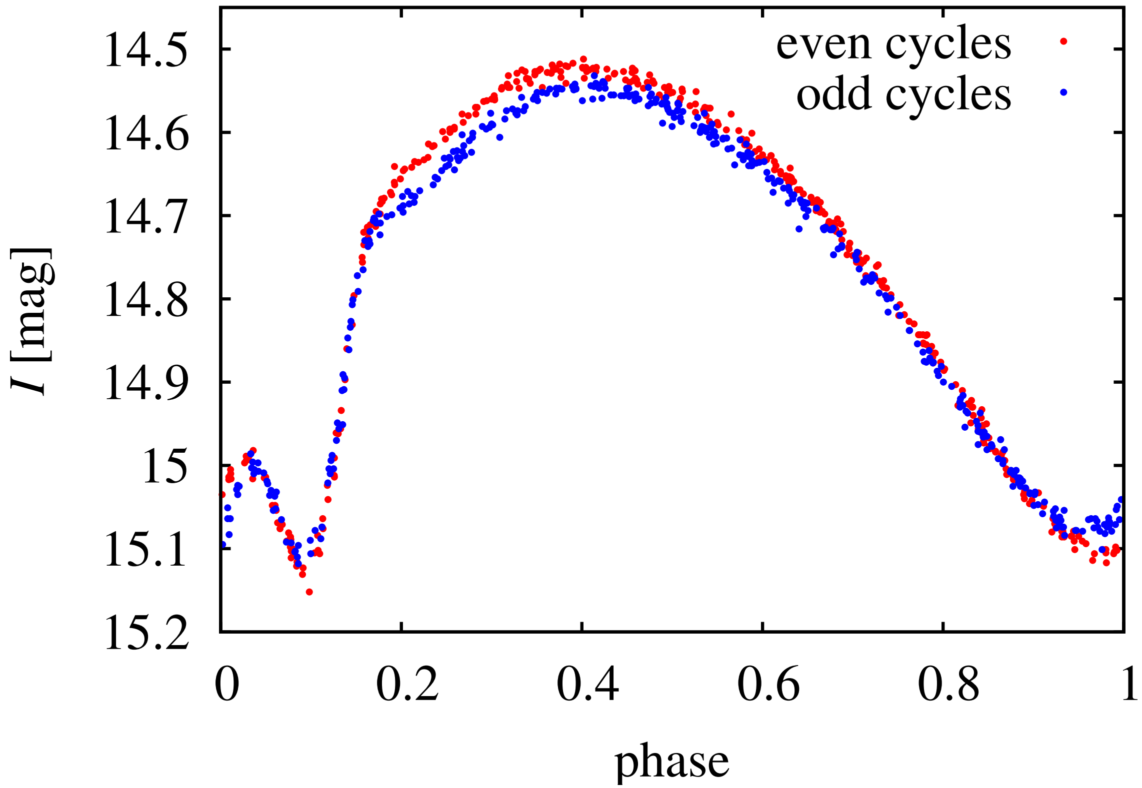

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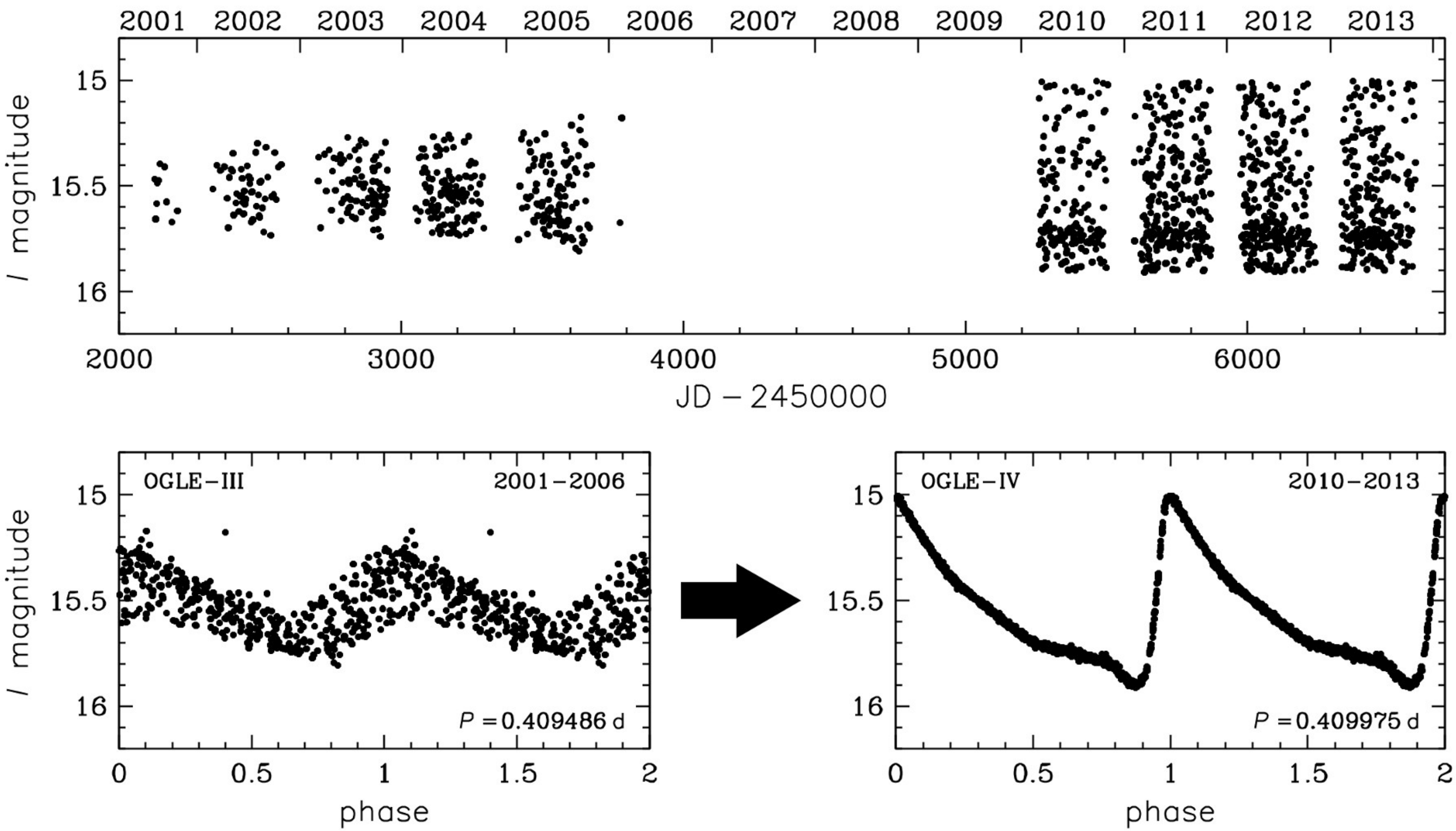
Smolec et al. (2012), MNRAS

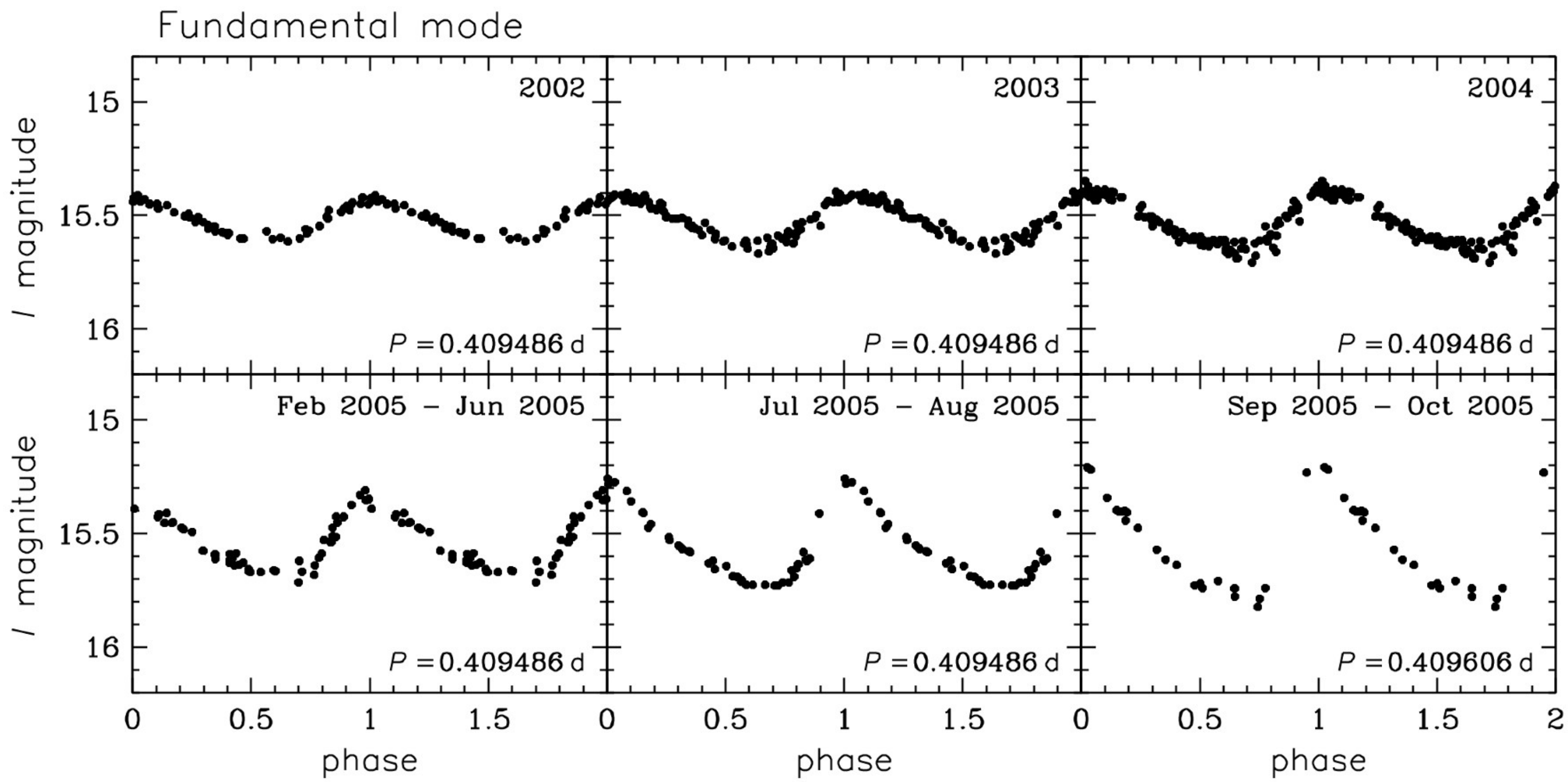
OGLE gems – OGLE-BLG-RRLYR-12245: RR Lyr caught at mode switching



F+1O(DM)→F

Soszyński et al. (2014)

OGLE gems – OGLE-BLG-RRLYR-12245: RR Lyr caught at mode switching



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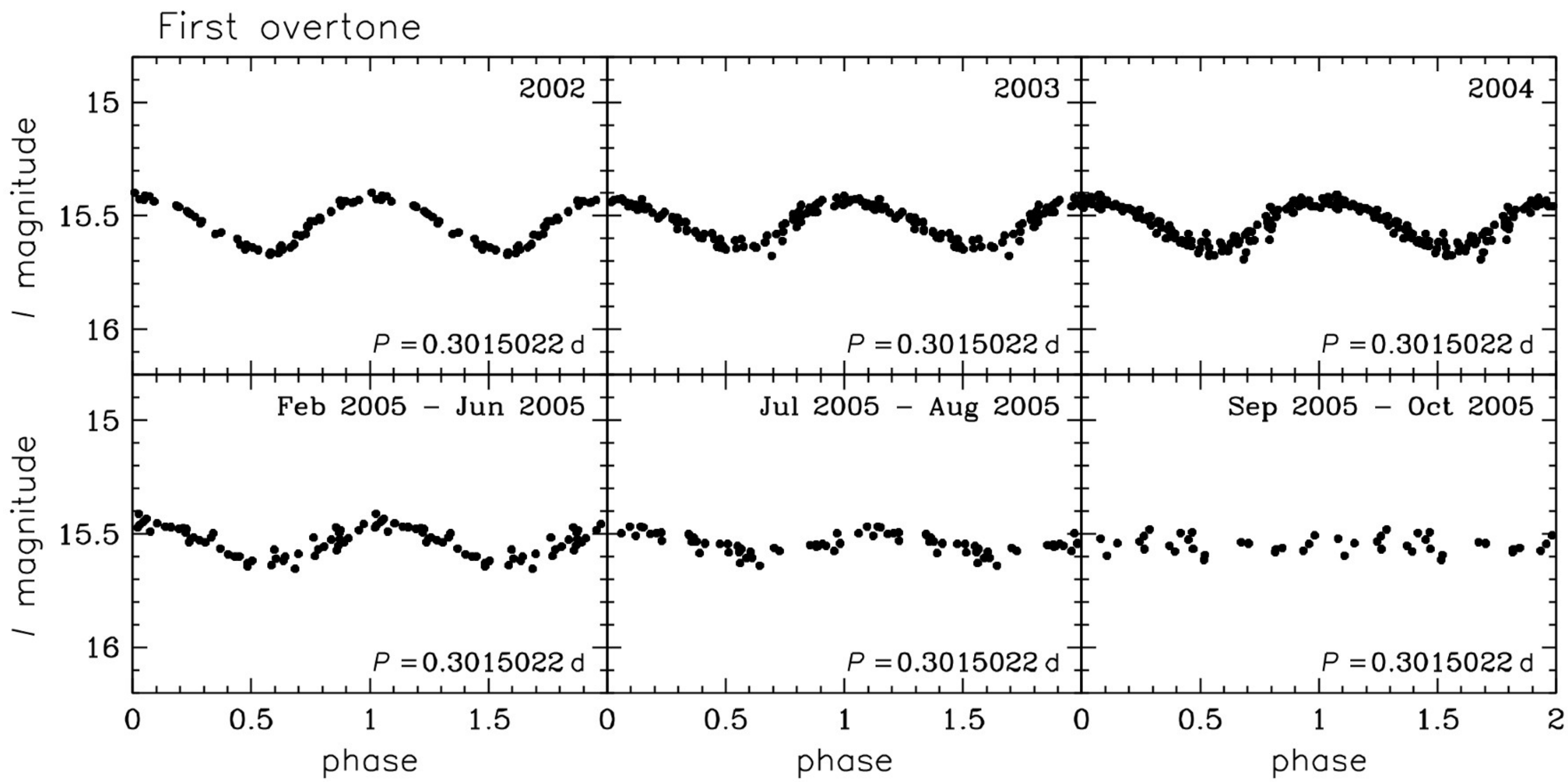

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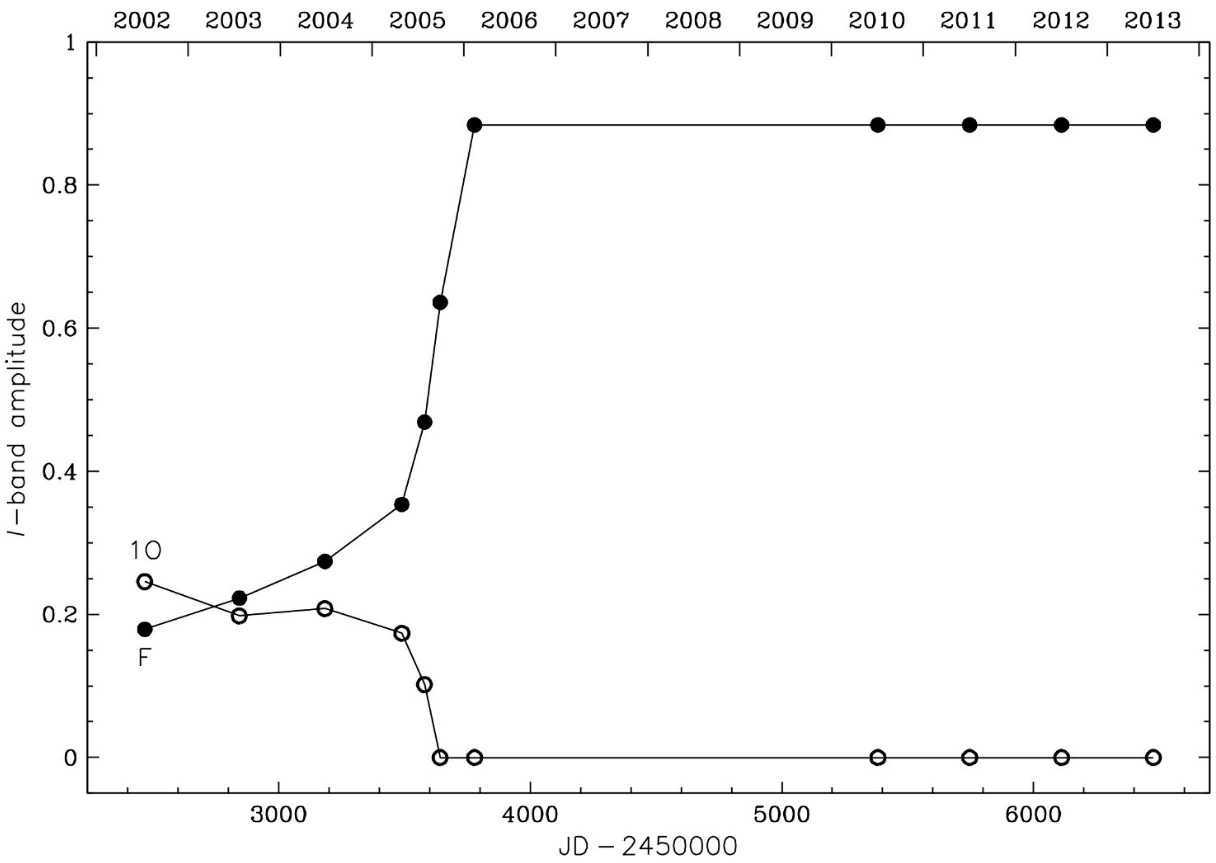
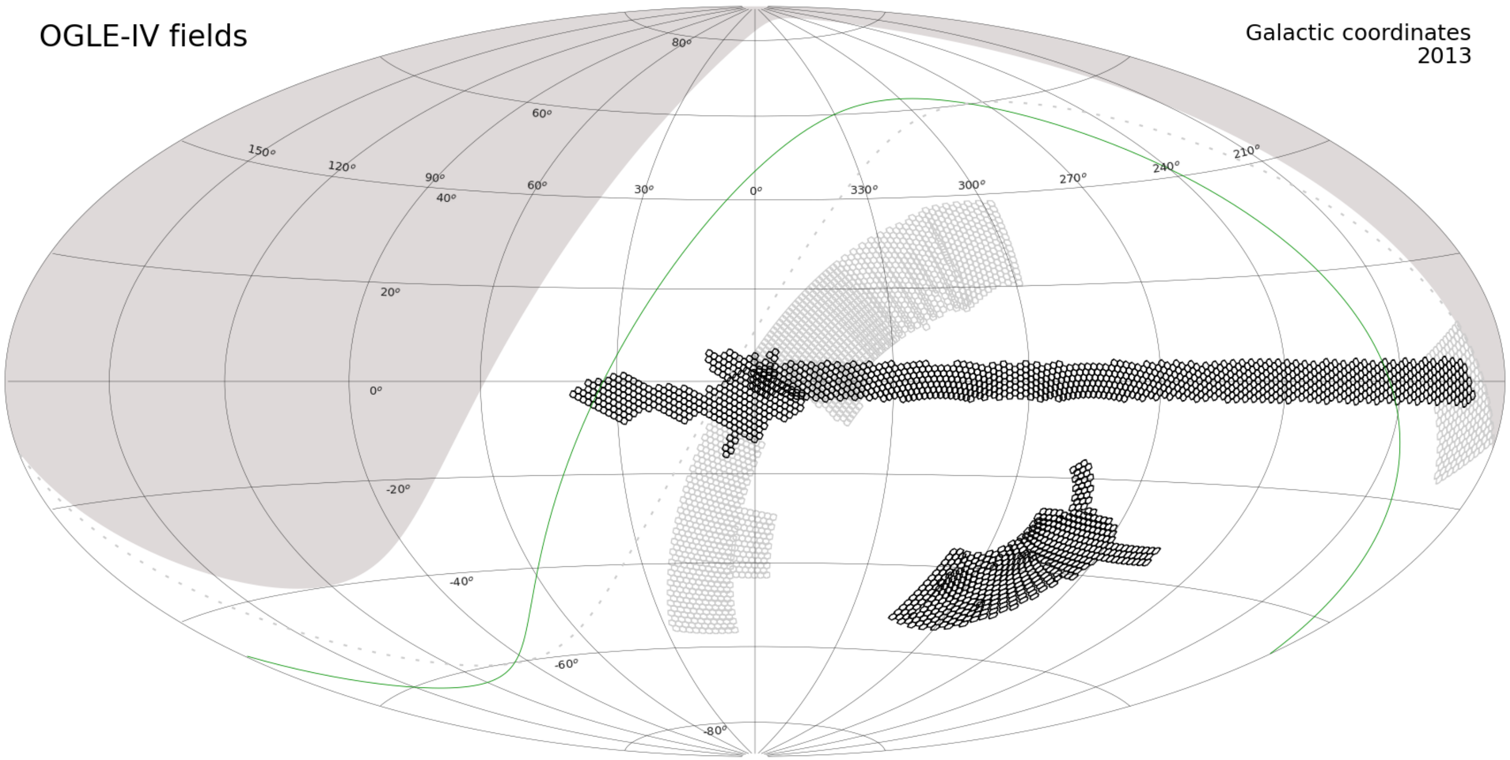


F+1O(DM)→F

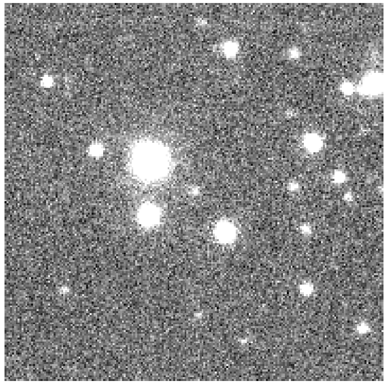
Soszyński et al. (2014)

OGLE gems – Transneptunian and Scattered Disc Objects

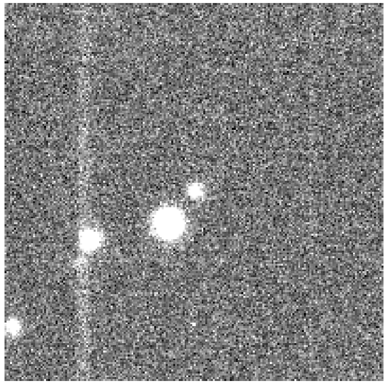
⋆ OCKS: OGLE Carnegie Kuiper Belt Survey – collaboration of OGLE and Department of the Terrestrial Magnetism of the Carnegie Institution of Washington



OGLE gems – Transneptunian and Scattered Disc Objects



2010 KZ39 (Transneptunian Object)
a = 46.414 a.u.
e = 0.003
P = 316 years
i = 25.6 deg



2010 EK139 (Scattered Disk Object)
a = 69.353 a.u.
e = 0.532
P = 578 years
i = 29.5 deg
D > 1000 km

The Kepler – OGLE connection: planets!

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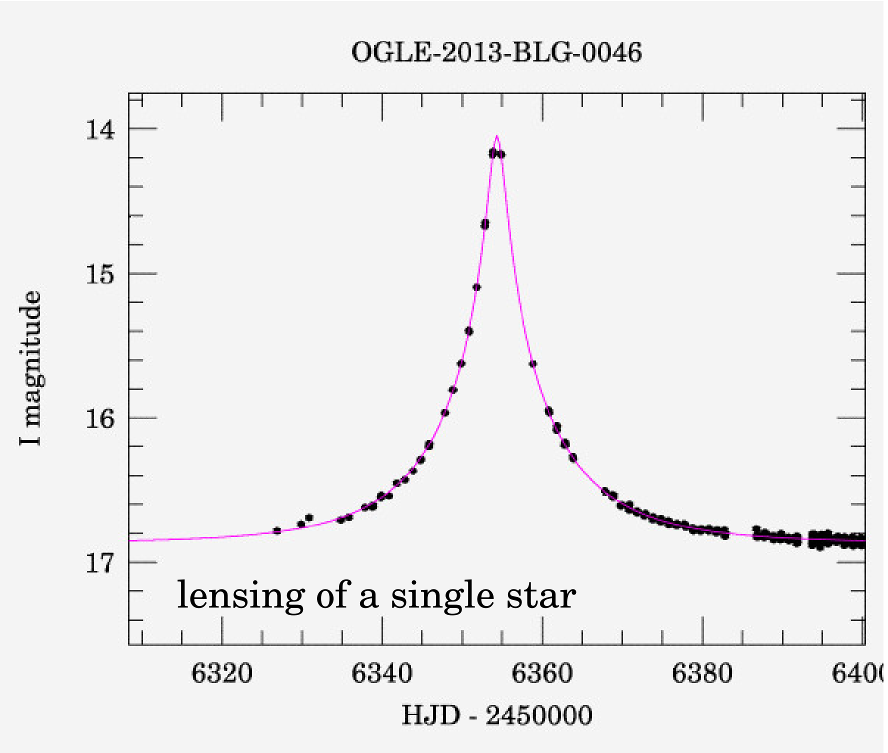
Confirmed Planets

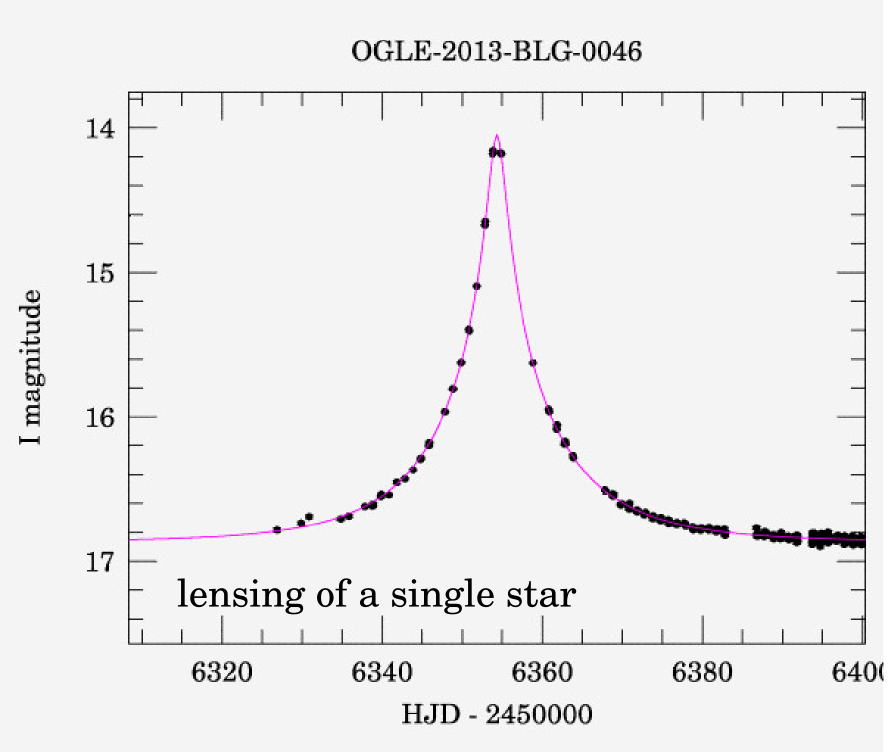
Row ID	Host Name	Discovery Method	Number of Planets in System	Orbit Semi-Major Axis [AU]	Planet Mass [Jupiter mass]	Distance [pc]
	OGLE					
1609	OGLE 2003-BLG-235L	Microlensing	1		2.60000±0.80000	
1610	OGLE 2005-BLG-71L	Microlensing	1		3.800±0.400	
1611	OGLE 2005-BLG-169L	Microlensing	1		0.04000	
1612	OGLE 2005-BLG-390L	Microlensing	1		0.01700	
1613	OGLE 2006-BLG-109L	Microlensing	2		0.71000±0.08000	
1614	OGLE 2006-BLG-109L	Microlensing	2		0.27000±0.03000	
1615	OGLE 2007-BLG-368L	Microlensing	1		0.06940	
1616	OGLE 2008-BLG-355L	Microlensing	1	$1.70^{+0.29}_{-0.30}$	$4.6^{+3.7}_{-2.2}$	6800±1100
1617	OGLE 2011-BLG-251L	Microlensing	1	2.72±0.75	0.53±0.21	2570±610
1618	OGLE 2012-BLG-026L	Microlensing	2	3.82±0.30	0.11±0.02	4080±300
1619	OGLE 2012-BLG-026L	Microlensing	2	4.63±0.37	0.68±0.10	4080±300
1620	OGLE 2012-BLG-358L	Microlensing	1	0.87±0.03	1.85±0.19	1760±130
1621	OGLE 2012-BLG-406L	Microlensing	1	3.45±0.26	2.73±0.43	4970±290
1622	OGLE 2013-BLG-341L B	Microlensing	1	0.883±0.043	0.0073±0.0008	1161±93
1623	OGLE2-TR-L9	Transit	1	0.0308±0.0005	4.5±1.5	
1624	OGLE-TR-10	Transit	1	$0.0434^{+0.0013}_{-0.0015}$	0.62±0.14	
1625	OGLE-TR-056	Transit	1	$0.02383^{+0.00046}_{-0.00051}$	$1.39^{+0.18}_{-0.17}$	
1626	OGLE-TR-111	Transit	1	$0.04689^{+0.00100}_{-0.00097}$	0.55±0.10	
1627	OGLE-TR-113	Transit	1	$0.02289^{+0.00016}_{-0.00015}$	1.26±0.16	600
1628	OGLE-TR-132	Transit	1	$0.03035^{+0.00057}_{-0.00053}$	$1.18^{+0.14}_{-0.13}$	2500±250
1629	OGLE-TR-182	Transit	1	0.051±0.001	1.01±0.15	
1630	OGLE-TR-211	Transit	1	0.051±0.001	1.03±0.20	

The Kepler – OGLE connection: planets!

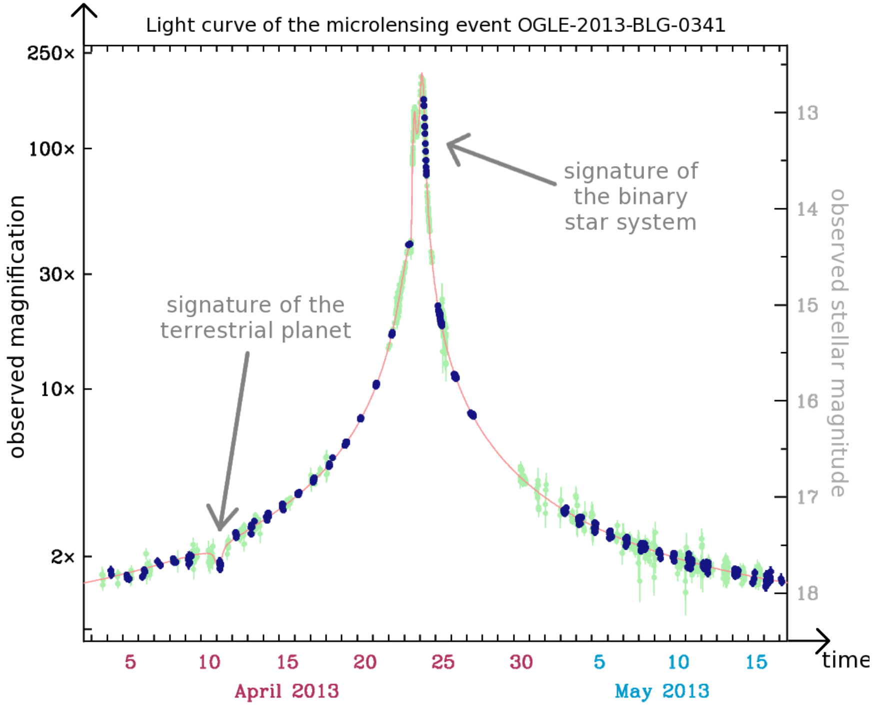


OGLE www;

The Kepler – OGLE connection: planets!

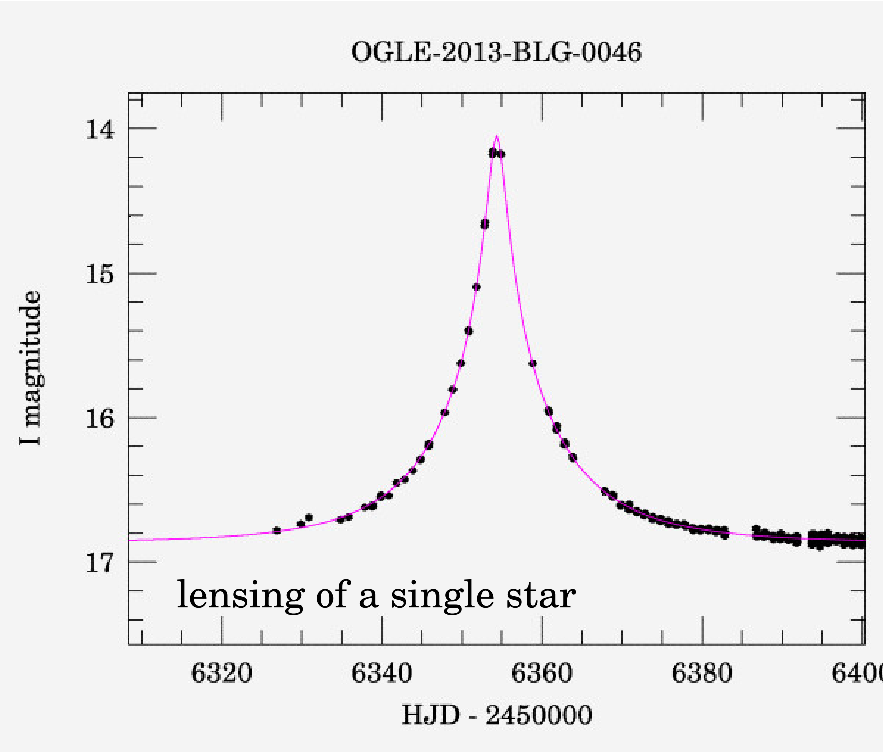


OGLE-2013-BLG-0341L



OGLE www; Gould et al. (2014), Science

The Kepler – OGLE connection: planets!



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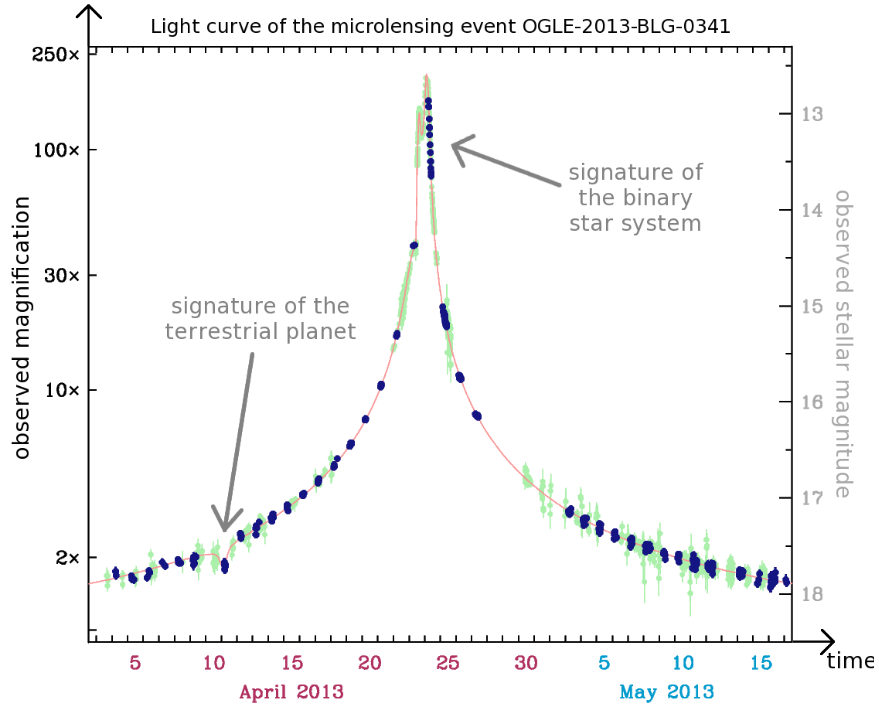
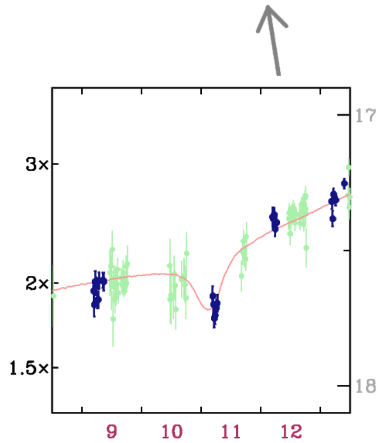
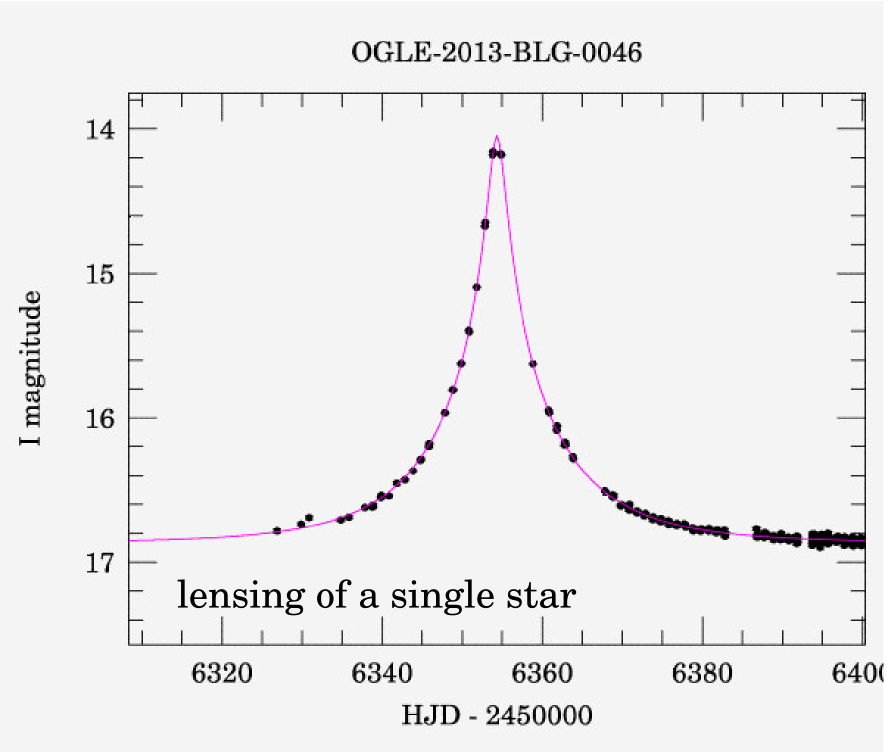


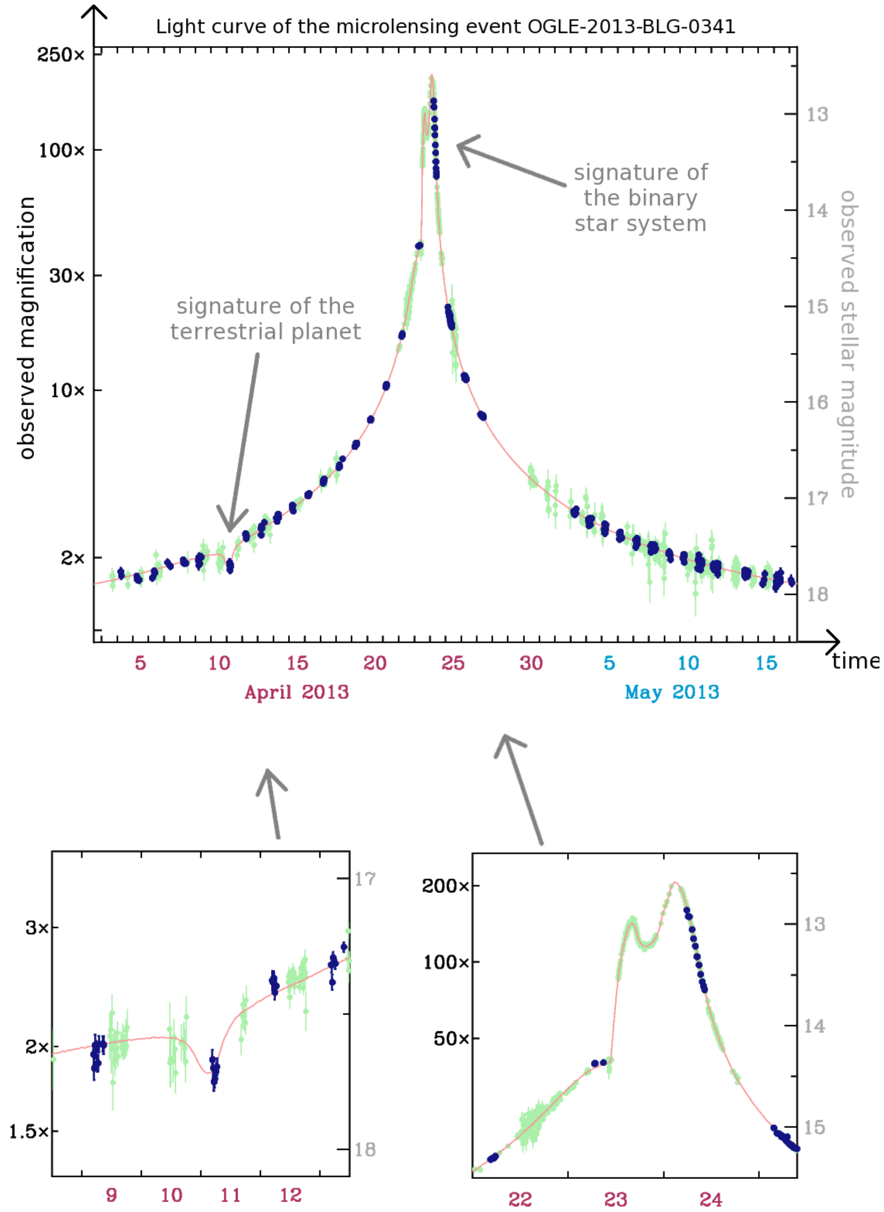


OGLE www; Gould et al. (2014), Science

The Kepler – OGLE connection: planets!

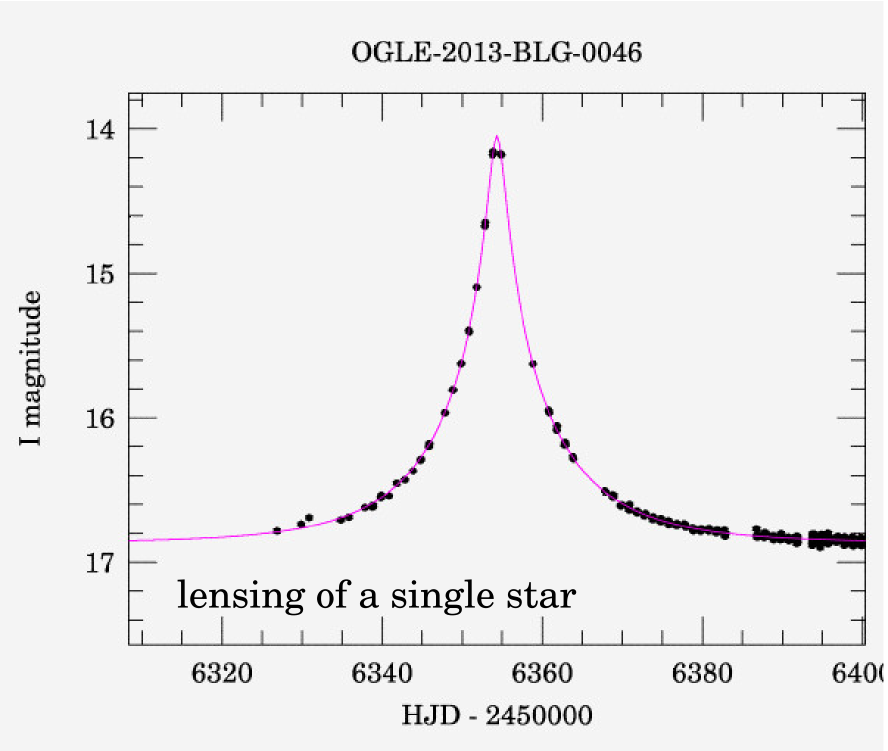


OGLE-2013-BLG-0341L

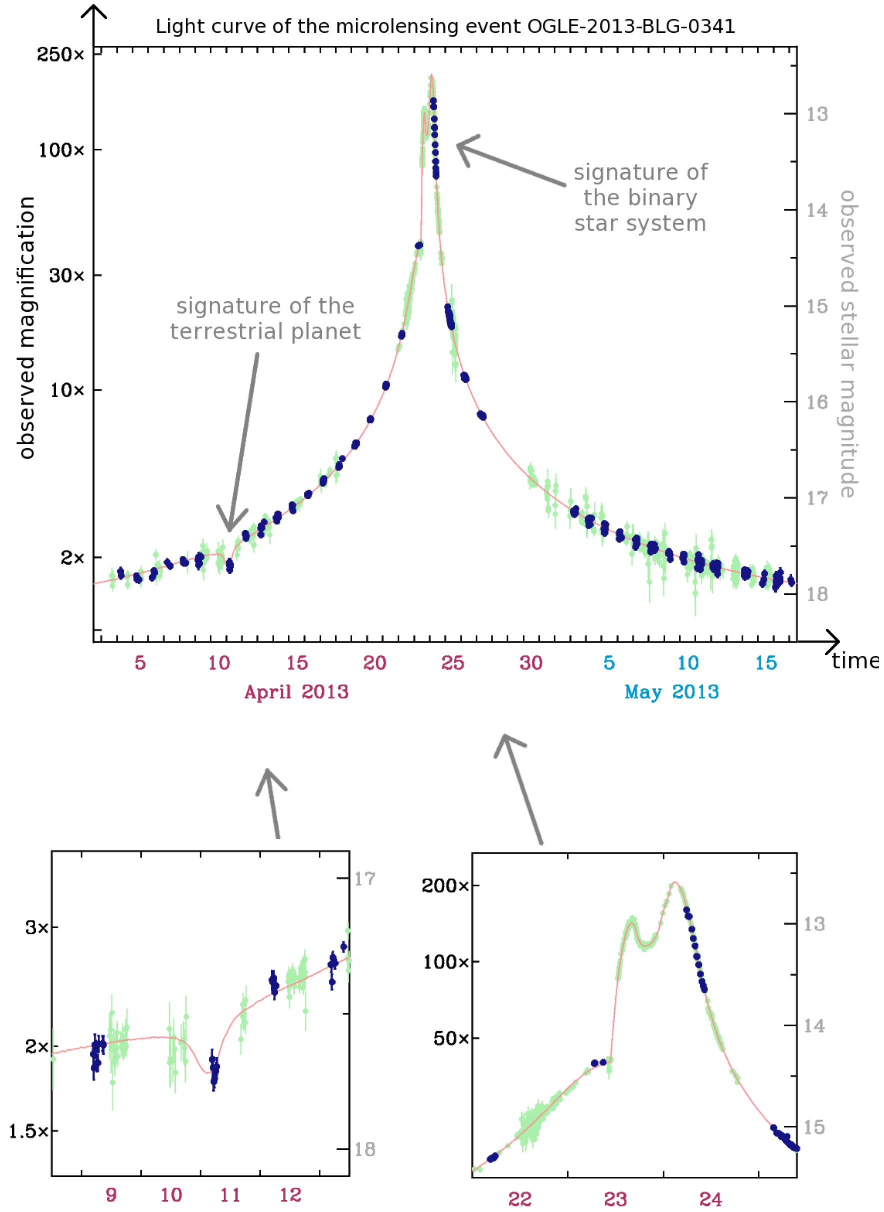


OGLE www; Gould et al. (2014), Science

The Kepler – OGLE connection: planets!



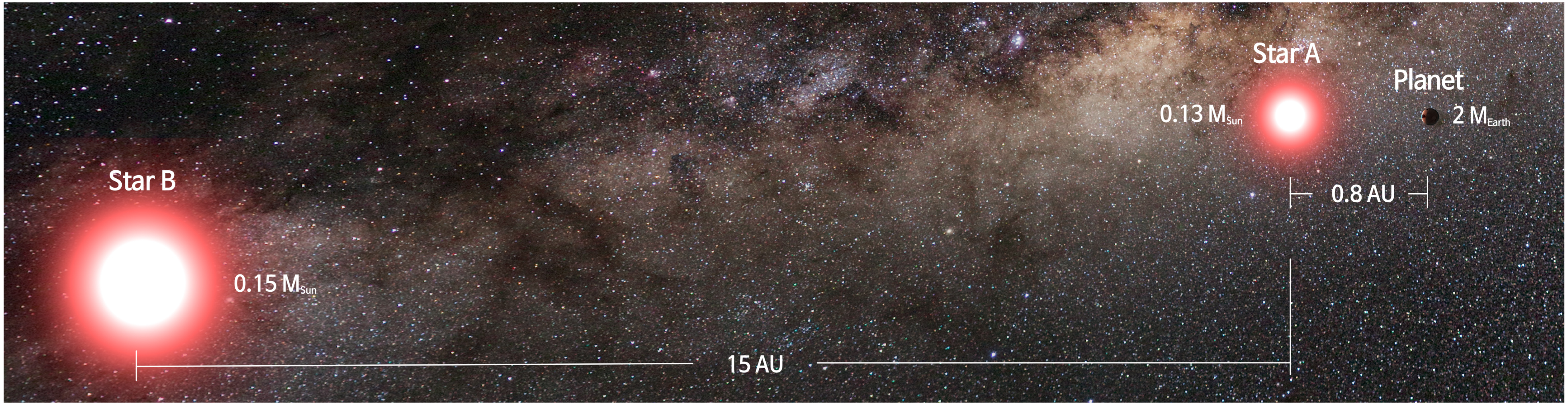
OGLE-2013-BLG-0341L



A terrestrial planet ($\approx 2\mathrm{M_E}$) in a $\sim$1 AU orbit around one member of a 15 AU binary

OGLE www; Gould et al. (2014), Science

The Kepler – OGLE connection: planets!



OGLE www; credit: C. Han, Chungbuk National University, Republic of Korea

The possible LAMOST – OGLE synergies

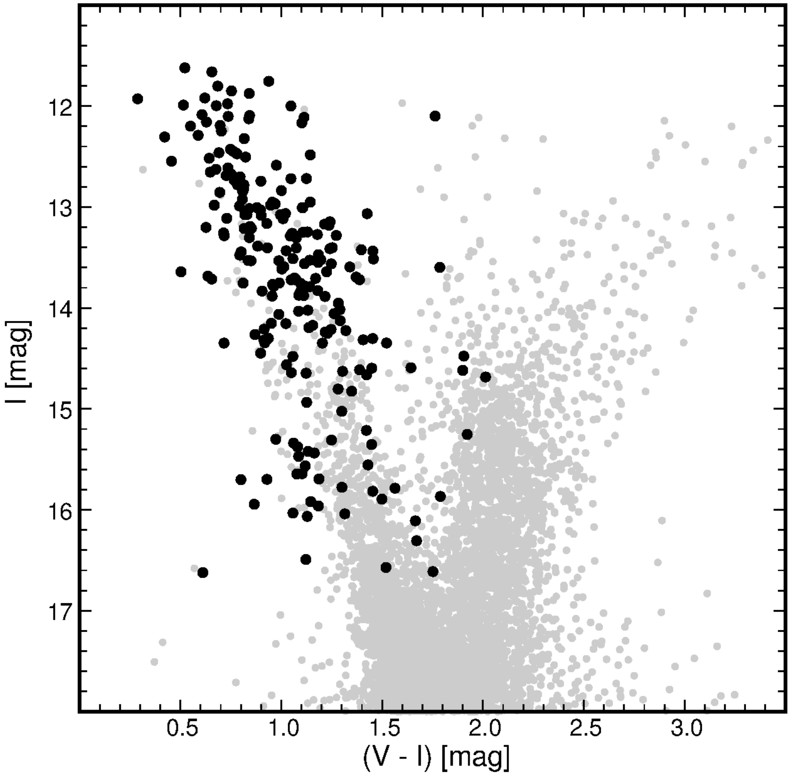
- ⋆ OGLE photometry (time sampling) is best for studying longer period, large amplitude classical pulsators (easy identification)
- ⋆ However, with long time coverage, OGLE finds many candidate pulsators close to main sequence
- ⋆ OIII-CVS contains 2788 δ Sct stars

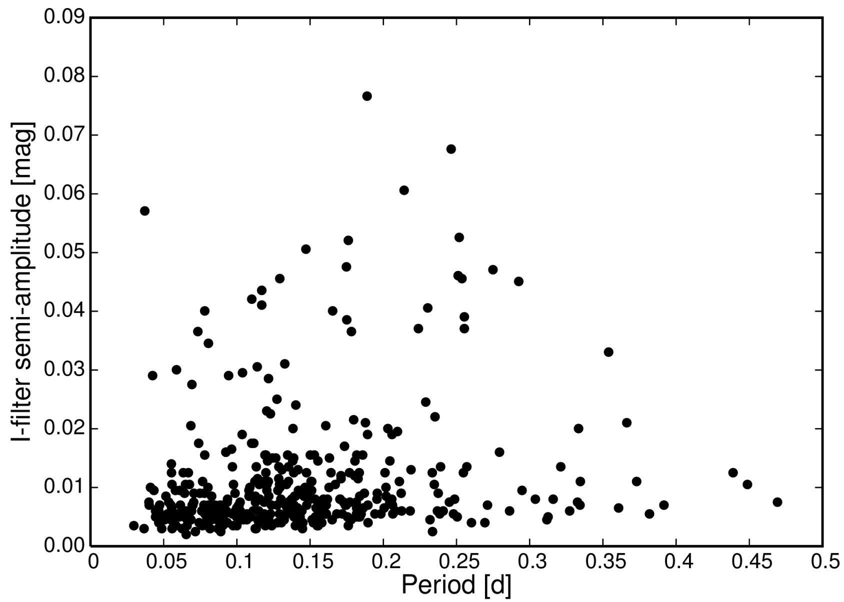
wikipedia.org, OGLE web-page

The possible LAMOST – OGLE synergies

⋆ many candidates for δ Sct, β Cep, SPB, γ Dor were found in OGLE-II data (among $200\,000$ candidate variable stars)

- Narwid et al. (2006), 230 δ Sct/β Cep
- Narwid et al. (2007), 600 SPB/γ Dor





Narwid et al. (2006)

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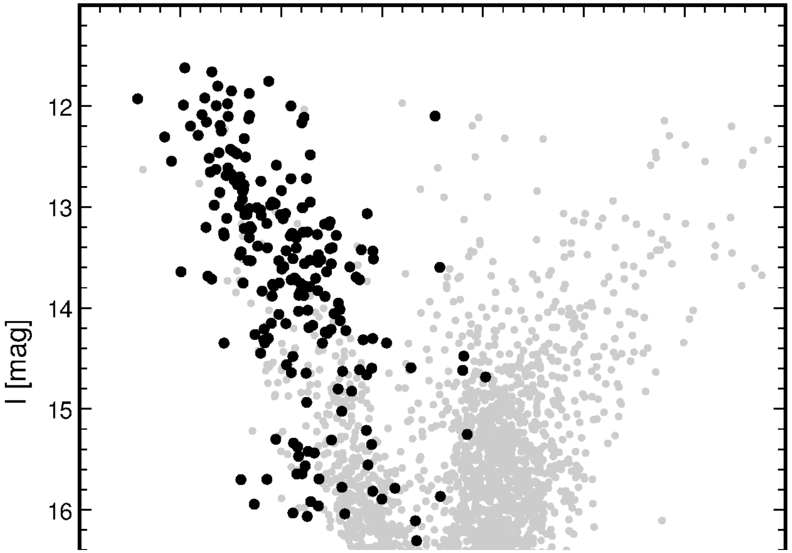

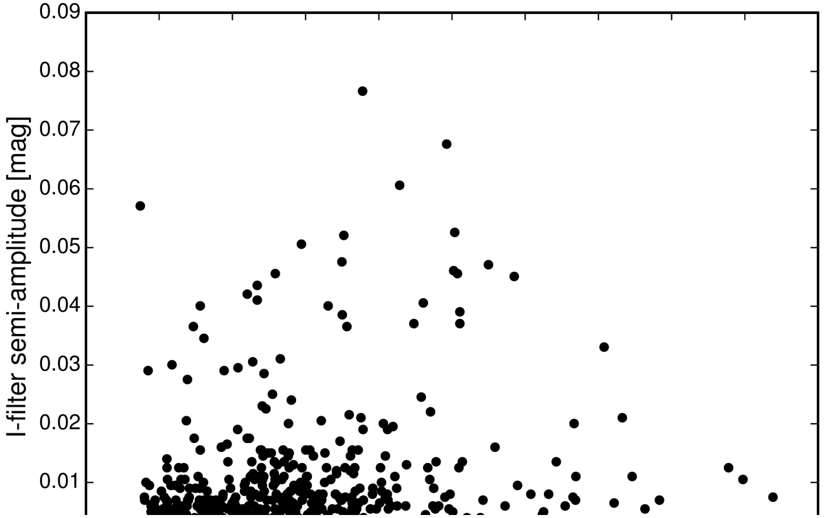

The periods, amplitudes and the position in the CMD are not sufficient to distinguish SPBs from γ Doradus stars. Therefore we are going to gather UBV photometry and/or low-resolution spectroscopy for stars from our sample, which will allow us to improve the classification of these stars.

Narwid et al. (2006)

The possible LAMOST – OGLE synergies

- ⋆ several thousands of candidate variables are expected in OGLE-IV fields
- ⋆ with its large field of view and possibility to observe many targets at once, LAMOST offers the best opportunity to gather supplementary low resolution spectroscopy to classify and characterize the candidate stars

wikipedia.org, OGLE web-page

Polish BRITE satellite launched with the Chineese rocket Long March 4B (19 Aug)